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Research Article

Use of the calcite saturation index as an indicator of environmental suitability for dreissenid mussels

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Abstract

Determining environmental suitability for dreissenid mussel survival is important in managing water resources. The saturation index for calcite ($SI_{calcite}$) was examined as a potential predictor of environmental suitability for dreissenids. $SI_{calcite}$ was calculated for 500 lakes from Ontario, Canada and Vermont and Wisconsin, USA. A lower limit of -0.9 was determined necessary for successful establishment of long-term mussel populations. This limit was then applied to sites in the California State Water Project. When compared with using calcium alone or paired calcium and pH values, $SI_{calcite}$ was better at identifying environmental suitability at the extremes of calcium and pH ranges.

Key words: aquatic invasions, water quality, saturation index for calcite, control, management

Introduction

The suitability of an environment for dreissenid mussel survival has typically been determined primarily by individual environmental variables, with calcium being the most important for shell formation and long-term survival, followed by pH (Mackie and Claudi 2010). Other variables such as dissolved oxygen, salinity and presence of suitable food also affect dreissenid survival, but only if adequate calcium is present (Karatayev et al. 1998; Mackie and Claudi 2010). Claudi and Prescott (2011) suggest that, as a minimum, calcium and pH should be considered in combination as paired values when examining the suitability of a body of water for dreissenid mussel survival. In their study, Claudi and Prescott (2011) examined paired calcium and pH values at 23 sites in the California State Water Project (SWP) for their potential suitability for dreissenid mussel survival. Sites were categorized as unable to support dreissenid mussels (Ca ≤ 12 mg/L and/or pH ≤ 7.3), potentially able to support dreissenid mussels (12 mg/L < Ca ≤ 15 mg/L and/or 7.3 < pH ≤ 7.8) and able to support dreissenid mussels (Ca > 15 m/L and/or pH >7.8). From these results, four sites were chosen for further examination under laboratory conditions (Claudi et al. 2012d). Water from the selected sites was delivered to San Justo Reservoir by truck, and zebra mussels (*Dreissena polymorpha* Pallas, 1771) placed in tanks filled with site water were examined for long-term survival. Unexpectedly, pH became elevated in low calcium waters (well above levels experienced at the water source site) and mussels were able to survive and reproduce. This finding emphasized the importance of considering calcium and pH in combination.

To more clearly define sites described as potentially able to support mussels in Claudi and Prescott (2011), we explored the option of using a one number index that would allow for the re-categorization of sites considered to be potentially able to support mussels into sites that were able or unable to support mussels. Oliveira et al. (2010a; 2010b) used the saturation index for calcite, along with other limnological variables, to predict environmental suitability for the golden mussel, *Limnoperna fortunei,* in North America. The saturation index for calcite ($SI_{calcite}$) is determined by the difference between the measured pH of the water and the pH of the water if it were in equilibrium with $CaCO_3$ at the existing calcium ion and bicarbonate ion concentrations. $SI_{calcite}$ can be calculated from calcium concentration (mg/L), water temperature (°C), total alkalinity (mg $CaCO_3$/L), conductivity (µS/cm), and pH (American Public Health Association - APHA 2005). Each of these variables on their own is considered important for determining environmental suitability for dreissenid mussels. To our knowledge, the variables have never before been considered in combination.

The purpose of this study was to examine the potential for using the $SI_{calcite}$ as an indicator for the suitability of sites for dreissenid mussel survival. Ideally, the $SI_{calcite}$ would provide a one number index that would identify sites as able or unable to support dreissenid mussels thereby assisting in management decisions for dreissenid mussel control.

Data collection and analysis

Between June and July 2011, we participated in a lake survey during which time we visited 31 lakes in Ontario, Canada. At 25 of the sites, temperature, pH, alkalinity and conductivity were measured. Temperature and conductivity were measured with an Oakton ECTestr 11+ multi-range pen, pH was measured with a Fisher Scientific pH pen (model S96275A) and total alkalinity was measured using a LaMotte Limnology Kit (model AM-02). Equipment was calibrated daily as per manufacturer instructions. Additionally, a water sample was collected at each of the 25 sites and submitted to Integrated Explorations (Guelph, ON) for laboratory analysis of calcium using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) following EPA Method 200.8. Observations were made about the accessibility of each lake and about the population of dreissenid mussels at each site. If mussels were not obviously visible, local residents were asked about their personal observations (e.g. have they noticed mussels on rocks, boats, docks, etc.) and a plankton sample was collected using a 63-micron mesh plankton net with a 30 cm opening. Approximately 300 L of water were collected through the plankton net by a series of oblique tows, and the resulting plankton sample was transferred to a 500 ml glass bottle and preserved with ethyl alcohol. Each sample was later examined in the laboratory using an American Optical compound scope equipped with a polarizer and 25x magnification. Each sample was examined in 10 ml subsamples until veligers were found or the entire sample was examined.

Additionally, data available for lakes in Vermont, USA (Vermont Department of Environmental Conservation, unpublished data) and Wisconsin, USA (Wisconsin Department of Natural Resources, unpublished data) were included in the data set for determining the calcite saturation index. Data sets for lakes in Vermont and Wisconsin were of varying quality due to differences in sampling programs. Data for each lake were used only if all five variables for the calcite equation were available. Some lakes had only one day of water quality data. Although not ideal, the one day of data was included as a snapshot representation of that particular lake. For sites which had many days of data, average values were calculated for each water quality parameter needed in the calcite saturation index equation. When data were available for all months of the year, only values from spring (March/April) to autumn (September/October) were used in calculating average values. This time period represents the season when conditions are typically favourable for dreissenid reproduction, and survival of the veligers is essential for long-term population survival. Available data were then entered into the formula for $SI_{calcite}$ (American Public Health Association - APHA 2005), and the resulting index values were plotted using Matlab. The information on the presence of dreissenid mussels in the lakes of the data set did not distinguish between quagga (*Dreissena rostriformis bugensis* Andrusov, 1897) and zebra mussels.

Calculation of $SI_{calcite}$

The saturation index for calcite ($SI_{calcite}$) was calculated using

$$SI_{calcite} = pH - pH_s \qquad (1)$$

where pH is the measured pH of the water and pH_s is the pH of the water when in equilibrium with calcium carbonate (American Public Health Association – APHA 2005). The equilibrium pH

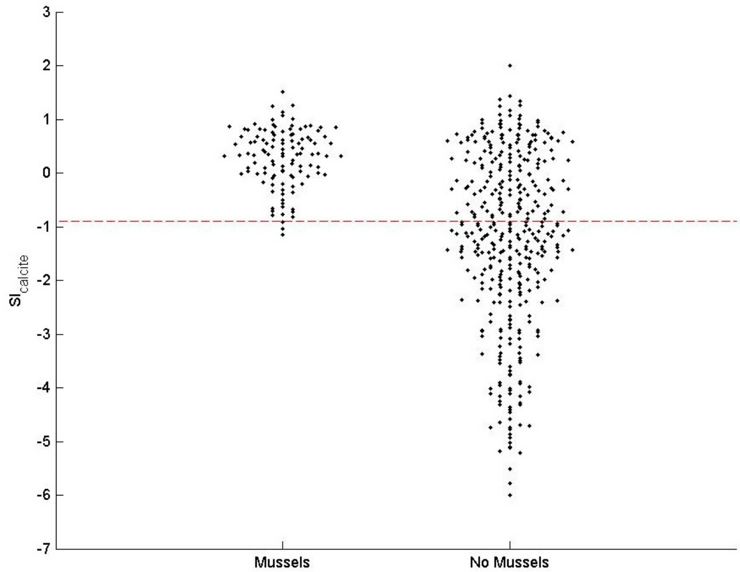

Figure 1. Calcite saturation index for North American lakes with and without dreissenid mussels. The dashed red line at -0.9 indicates the suggested lower calcite saturation index needed for lakes to support a long-term population of dreissenid mussels.

was calculated using

$$pH_s = pK_2 - pK_s + p[Ca^{2+}] + p[HCO_3^-] + 5pf_m \quad (2)$$

where K_2 is the second dissociation constant for carbonic acid, K_s is the solubility product constant for $CaCO_3$, $[Ca^{2+}]$ is the calcium ion concentration (g-moles/L), $[HCO_3^-]$ is the bicarbonate ion concentration (g-moles/L) and f_m is the activity coefficient for monovalent species (American Public Health Association – APHA 2005). Note that the p preceding each variable in Equation (2) represents the $-\log_{10}$ of that variable. For ease of calculation, the calcium ion concentration was assumed to be equivalent to the total calcium measurement and was not modified for calcium associated with ion pairs. The bicarbonate ion concentration was calculated from

$$[HCO_3^-] = \frac{Alk_t + 10^{(pf_m - pH)} - 10^{(pH + pf_m - pK_w)}}{1 + 0.5\,x\,10^{(pH - pK_2)}} \quad (3)$$

where Alk_t is the total alkalinity (g-equivalents/L) and K_w is the dissociation constant for water (American Public Health Association – APHA 2005). Values for pK_2, pK_s, and pK_w were calculated from

$$pK_2 = 107.8871 + 0.03252849T - \frac{5151.79}{T} - 38.92561\log_{10}T + \frac{563713.9}{T^2} \quad (4)$$

$$pK_s = 171.9065 + 0.077993T - \frac{2839.319}{T} - 71.595\log_{10}T \quad (5)$$

$$pK_w = \frac{4471}{T} + 0.01706T - 6.0875 \quad (6)$$

where T is temperature (K). The value for pf_m was calculated from

$$pf_m = 1.82\,x\,10^6(ET)^{-1.5}\left[\frac{\sqrt{I}}{1+\sqrt{I}} - 0.3I\right] \quad (7)$$

$$I = 1.6\,x\,10^{-5}C \quad (8)$$

$$E = \frac{60954}{T + 116} - 68.937 \quad (9)$$

where E is the dielectric constant, I is ionic strength and C is conductivity (µS/cm) (American Public Health Association – APHA 2005).

Results and discussion

Calcite saturation index values were plotted for lakes with and without dreissenid mussels (Figure 1). $SI_{calcite}$ values were generally above -0.9 for lakes examined with mussels present. Two sites with mussels, Station 25 (Malletts Bay) in Lake Champlain, Vermont and Pentenwell Lake in Wisconsin, had $SI_{calcite}$ values of -1.2 and -1.0, respectively. Although mussels were recorded at these two locations, established adult mussel populations may not be present at these sites. The presence of zebra mussels in Lake Champlain has been recorded since 1993. Movement of mussels into the northeastern arm of the lake has been slow. In 2012, Malletts Bay had the lowest veliger density of all sites sampled in Lake Champlain (approx. 200 veligers/m^3) and juvenile mussels were recorded only once in 2009 at a density of approximately 60 juveniles/m^2 (Vermont Department of Environmental Conservation 2012). These results suggest that water quality may not be able to support a long-term mussel population, as indicated by the $SI_{calcite}$ value, but transient populations may exist as a result of currents within the lake which move ready-to-settle veligers from locations with more favourable water quality (Johnson and Padilla 1996). Little is known about Pentenwell Lake. Public boat access is available at 16 launch stations around the lake (Wisconsin Department of Natural Resources 2013) which, if no signage or boat wash stations are available, could supply an influx of adults or veligers during the open water season.

Lakes without mussels had variable $SI_{calcite}$ values. Some lakes without mussels fell above -0.9; this result does not necessarily mean that dreissenid mussels are unable to survive in these waters, demonstrating that $SI_{calcite}$ cannot be used without some understanding of other variables. During the Ontario lake survey, lake accessibility was found to greatly influence the presence of dreissenid populations. Lakes may have water quality conditions that would support mussels, but if there is no public boat launch or if the lake is inaccessible mussels are unlikely to reach the lake and become established. The presence of invasive species warning signs and boat wash stations may also help prevent mussels from entering a lake that would otherwise be able to support dreissenids based on water chemistry. Additionally, the location of sampling sites within a lake may artificially identify lakes as able to support dreissenid populations. For example, a lake may have water chemistry that would be unable to support a reproducing population of mussels, but the site may be near an inflowing river that is part of an interconnected river-lake system that supports thriving mussel populations. The inter-connected river-lake system may supply veligers and adults (Stoeckel et al. 1997; Bobeldyk et al. 2005; Lucy et al. 2008) that are present when water sampling occurs in the lake resulting in data that suggest a reproducing population exists at the site being sampled. Alternatively, calcium inputs from a tributary, which are quickly diluted in the lake proper, may create a favourable zone for dreissenids at the mouth of the tributary (Winbush et al. 2009).

Application in the California State Water Project

Based on the results presented in Claudi and Prescott (2011), sampling sites in the California State Water Project (SWP) were organized according to their ability to support dreissenids based on paired calcium and pH values (Figure 2). The northern region was determined to be unable to support mussels, the central region was potentially able to support mussels and the southern region was able to support mussels. Ideally, a predictor of dreissenid suitability would be a one number value that indicated whether or not a body of water would support a long-term population of mussels. Using the saturation index for calcite, the SWP sites were examined in more detail to determine if the sites identified as potentially able to support mussels could be separated into sites that would or would not support dreissenids.

Data available for the sites in the California SWP allowed for the calculation of $SI_{calcite}$ for each sampling event and the results were plotted against time. A subset of sites was selected for further discussion (Figure 3). Frenchman Lake and Lake Oroville are located in the northern region of the SWP and were originally identified by the Ca-pH paired analysis as sites unable to support dreissenids. For Lake Oroville (Figure 3A), the average $SI_{calcite}$ value fell below the -0.9 limit. Three sampling events did extend slightly above the $SI_{calcite}$ limit, but these events did not last for long enough periods of time that would allow a mussel population to become established. Frenchman Lake (Figure 3B) had an average $SI_{calcite}$ value that was above the calcite limit for dreissenids. All sampling events for this lake produced $SI_{calcite}$ values above the limit with the exception of one in 2005 ($SI_{calcite}$ = -1.43). These results suggest that Frenchman Lake would be able to support dreissenids should they be introduced; however, a more detailed sampling program would provide greater assurance of the suitability of this lake for dreissenid mussels.

All sites in the central region of the California SWP, which were determined using paired calcium and pH values to be potentially able to support mussels (Claudi and Prescott 2011), were classified as able to support mussels based on average $SI_{calcite}$ values. Del Valle Check 7 (DV7) (Figure 3C) had almost all $SI_{calcite}$ values above the minimum limit of -0.9. Those sampling events at DV7 for which $SI_{calcite}$ values dropped just below the minimum limit did not last for long enough periods that would eliminate established mussel populations. Similarly, H. O. Banks Pumping Plant

Figure 2. The California State Water Project (SWP) showing different zones based on their ability to support dreissenid mussels. Zones were determined based on paired calcium and pH values. The green zone is unable to support mussels, the orange zone is potentially able to support mussels and the red zone is able to support mussels.

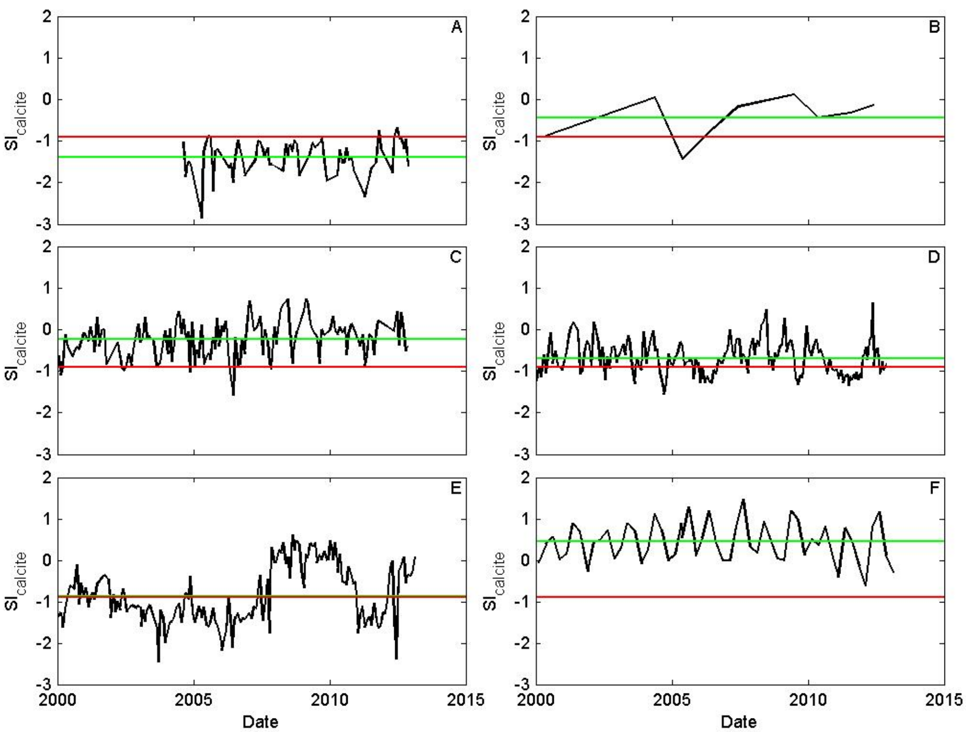

Figure 3. Variation in $SI_{calcite}$ with time for Lake Oroville (A), Frenchman Lake (B), Del Valle Check 7 (C), H. O. Banks Pumping Plant (D), California Aqueduct Check 29 (E) and Lake Perris (F) in the California State Water Project. The red line at -0.9 represents the minimum limit of $SI_{calcite}$ necessary for dreissenid survival, and the green line is the average $SI_{calcite}$ for each site.

Figure 4. The California State Water Project (SWP) showing different zones based on their ability to support dreissenid mussels as determined by $SI_{calcite}$ values. The green zone is unable to support mussels and the red zones are able to support mussels. California Aqueduct Check 29 (C29) has $SI_{calcite}$ values that vary above and below the dreissenid limit of -0.9 for extended periods of time making it potentially suitable for mussels depending on the duration of high and low SIcalcite values.

(Figure 3 D) had an average $SI_{calcite}$ value above the minimum limit, but a greater number of individual values occurred below -0.9. Although these periods of low $SI_{calcite}$ were longer in duration than those for DV7, they still did not last long enough to necessarily eliminate an established mussel population. California Aqueduct Check 29 (C29) had an average $SI_{calcite}$ value slightly above the minimum limit (Figure 3E). For this site, $SI_{calcite}$ values were either below or above the limit for extended periods of time. Prior to 2008, $SI_{calcite}$ was almost entirely below -0.9 suggesting that C29 would be unable to support mussels. Between 2008 and 2011, $SI_{calcite}$ values were above the limit. This 3-year period could be long enough for a dreissenid population to become established. Depending on the duration, an established population may be able to survive subsequent periods of low $SI_{calcite}$ values.

All sites located in the southern region of the SWP were able to support dressenids based on average $SI_{calcite}$ values. Lake Perris had the greatest average $SI_{calcite}$ (0.44) of all sites examined in that region and the $SI_{calcite}$ value for each sampling event was above the limit (Figure 3F). Should dreissenids be introduced to Lake Perris, a long-term population would likely become established.

Sites in the California SWP were reclassified as able or unable to support dreissenids based on their average $SI_{calcite}$ values (Figure 4). Locations in the northern region, with the exception of Frenchman Lake, were unable to support mussels, and sites in the central and southern regions were able to support mussels. The one exception is C29, which may or may not support a dreissenid population depending on the length of time the site has $SI_{calcite}$ values above or below the limit.

Practical application of $SI_{calcite}$ for lake managers

The determination of environmental suitability for dreissenids is often based on calcium concentrations alone. Claudi and Prescott (2011) suggested that suitability should be based on paired calcium and pH values to account for situations when calcium is moderated by pH (i.e. at the extremes of the calcium and pH ranges). This approach allowed for the separation of sites into three categories of suitability for dreissenids, but was not enough to confidently separate marginal sites into those able and unable to support mussels. Using $SI_{calcite}$ allowed for the separation of marginal sites.

Comparison between using calcium alone and using $SI_{calcite}$ for identifying environmental suitability showed that calcium alone was an adequate predictor in many cases. For the California SWP, the prediction of the suitability of all sites for dreissenid mussels was the same using calcium as it was using $SI_{calcite}$ with the exception of Frenchman Lake. For this lake, examining suitability using calcium alone indicated the lake was unsuitable due to low calcium concentrations. Frenchman Lake, though, has high pH (>7.8) which moderates the calcium and makes the lake suitable for supporting mussels. When calcium alone was used to predict environmental suitability for dreissenids using the lakes examined in Ontario, Vermont and Wisconsin, the results over-predicted suitability in 6% of sites compared to $SI_{calcite}$ and under predicted suitability in 2% of sites.

In other situations, such as the presence of zebra mussels in Irish Lakes, the calcite index can offer direct means of environmental suitability. Due to the generally low pH in many Irish lakes, zebra mussel populations do not become established until calcium levels reach at least 25 mg/l (Lucy et al. 2010). In North America, this calcium level would be considered likely to support a massive population.

The one unknown is if $SI_{calcite}$ is the same for both quagga and zebra mussels. From pH tolerance studies (Claudi et al. 2012a; Claudi et al. 2012b; Claudi et al. 2012c), adult quagga mussels appear to lose calcium from their shells more rapidly than zebra mussels and they experience greater mortality at the same pH. The $SI_{calcite}$ limit presented in this paper may be very conservative for quagga mussels and should be verified.

Conclusion

The suitability of a water body for supporting dreissenid mussels is typically determined by examining calcium concentrations alone. An earlier study by Claudi and Prescott (2011) suggested that calcium and pH need to be considered as paired values to more accurately predict environmental suitability particularly at extreme calcium and pH values. Using calcium and pH together, sites can be categorized as unable, potentially able, or able to support mussels. Separation of sites described as potentially able to support mussels into sites able or unable to support mussels can be done using the saturation index for calcite. This value provides a one-number result that indicates more definitively which sites may or may not support a long-term population of dreissenids. In this study, $SI_{calcite}$ was calculated for 500 sites from Ontario, Vermont and Wisconsin, and $SI_{calcite}$ values were plotted for lakes with and without dreissenids. A minimum $SI_{calcite}$ value for supporting dreissenids was determined to be -0.9. This limit was successfully applied to the California State Water Project to determine if sites would be suitable for supporting long-term dreissenid populations should mussels be introduced to the water system. With the exception of one location, all sites in the SWP identified as potentially able to support mussels based on paired calcium and pH values were determined to be able to support dreissenids using $SI_{calcite}$. The California Aqueduct Check 29 had extended periods of time where $SI_{calcite}$ was either above or below the limit. Further study is needed on extended periods of $SI_{calcite}$ variation to determine if mussels may become established during high calcite years and remain established during low calcite years.

When $SI_{calcite}$ is compared with using calcium alone as a predictor of environmental suitability for dreissenids, calcium is still a good predictor in many cases. $SI_{calcite}$ performs better than calcium alone when examining sites at the extremes of the calcium and pH ranges. Since the water quality parameters needed for calculating $SI_{calcite}$ are generally part of a normal water quality monitoring program, calculating $SI_{calcite}$ could be incorporated as part of the analysis of water quality measurements.

This study did not distinguish between quagga and zebra mussels. We hypothesize that $SI_{calcite}$ may be higher for quagga mussels than for zebra mussels because of their potential need for higher calcium and pH values. Future study on using $SI_{calcite}$ for predicting environmental suitability for dreissenid mussels should examine potential differences between quagga and zebra mussels.

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