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Examination of Calcium and pH as Predictors of Dreissenid Mussel Survival in the California State Water Project

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Date: 11 March 2011

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Executive Summary

California Department of Water Resources (DWR) engaged RNT Consulting Inc. to examine environmental variables in the State Water Project (SWP) to better understand how calcium in combination with pH may or may not limit the population size of dreissenid mussels should they be introduced into the system. At DWR's request, data obtained from water quality stations located in the SWP were examined to determine which bodies of water are susceptible to invasion by dreissenid mussels based on the combination of calcium and pH, two essential water quality parameters affecting shell formation.

From data collected in the last decade (2000-2010), it was determined that the sites examined fall into one of three possible categories: sites that are unable to support dreissenids, sites that are able to support dreissenids, and sites where additional data are required to determine if they could support dreissenids.

It was concluded that Antelope Lake, Lake Davis, Lake Oroville, Thermalito Diversion Pool, and Feather River would be unable to support long-term dreissenid mussel populations due to average calcium concentrations below the very conservative minimum required level of 12 mg/L. Frenchman Lake and Sacramento River at Hood had many samples below the minimum levels of calcium and pH however some samples had marginal calcium and/or pH conditions. Marginal conditions occurred in only 2.2% of samples for Sacramento River at Hood therefore survival of a long-term dreissenid population is unlikely at this site. Frenchman Lake had marginal conditions in 40-55% of samples. This site may be able to support adult dreissenids but is unlikely to support a long-term dreissenid population because marginal conditions are unfavorable for veligers.

California Aqueduct Check 41, Castaic Lake Outlet, Castaic Lake at Jensen Influent, Silverwood Lake at Devil Canyon, Devil Canyon Headworks, and Lake Perris Outlet have calcium (>15 mg/L) and pH (>7.8) conditions that are favorable for dreissenid mussels. These sites are expected to support long-term dreissenid populations should mussels be introduced.

At marginal calcium concentrations (i.e. 12 mg/L – 15 mg/L), the survival of adult dreissenid mussels may be aided by pH above 8. Barker Slough Pumping Plant, San Joaquin River near Vernalis, Clifton Court Forebay Inlet, Harvey O. Banks Pumping Plant, Delta Mendota Canal Headworks, Del Valle Check 7, Pacheco Pumping Plant, and California Aqueduct Checks 13, 21 and 29 had calcium and/or pH levels in the marginal category for much of the time period examined. Given the limited knowledge on survival of dreissenid populations under marginal conditions of calcium and pH we cannot reliably predict dreissenid survival at these sites.

It is recommended that sampling for both calcium and veligers be included in the regular water quality monitoring program for all sites in the SWP. Sites able to support mussels may require increased veliger monitoring to identify infestations early. The implementation of control measures at sites unable to support dreissenids is unnecessary at this time. Vulnerability assessments should be performed on all manmade structures, and mitigation plans should be available for quick implementation should mussels invade sites with favorable conditions. Sites with marginal calcium and/or pH require further analysis to determine more conclusively whether or not they will be able to support a long-term population of mussels. Exposing mussels to ambient SWP water or manipulating calcium and pH levels under laboratory conditions would help determine habitat suitability at the marginal sites. Additionally, a field study to examine existing lakes with marginal conditions and established populations of mussels may provide useful information for these sites.

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1 Introduction

When examining the suitability of the environment for dreissenid invasion, the level of calcium (Ca) present in the water is of primary concern. Without adequate calcium, introduced adults will not survive and veligers will not develop into reproducing adults. Calcium is essential for the production of shell material in dreissenids. For most mollusks, calcium is obtained from the water and their food. Increases in shell length occur by secretions of calcium carbonate by the outer fold of the mantle edge, and increases in shell thickness occur by secretions from the outer wall of the outer lamella of the mantle. Dreissenids have higher calcium requirements than most other fresh water mollusks. At low calcium levels, adult dreissenids will experience a negative shell growth due to loss of calcium from the shell to the surrounding water. Therefore, unless adequate calcium is present, all environmental parameters other than pH are irrelevant.

The shells of dreissenid mussels are comprised of approximately 40% (dry weight) calcium (Secor *et al.* 1993), primarily in the form of calcium carbonate. The examination of pH is important when determining the suitability of waters for dreissenid survival because the solubility of calcium carbonate increases as pH decreases. Regardless of the presence of adequate calcium for dreissenid growth, if pH is low then mussel shells will become thin and eroded.

Ranges of values for different parameters required for dreissenid survival are shown in Table 1. This table represents a compilation of data by various authors from Europe and North America. The minimum concentration of calcium required for long-term mussel survival is around 15 mg/L. Mackie and Claudi (2010) consider the range of 8 – 15 mg/L of calcium to have little potential for larval development of dreissenid mussels. The minimum pH required for long-term dreissenid survival is approximately 7.5. Claudi *et al.* (In press) found that adult mussels show evidence of calcium loss from their shells at pH levels of 7.3. Calcium loss was accelerated at pH levels of 7.1 and 6.9. Larval survival is unlikely under these low pH conditions.

The examination of the success of dreissenid mussels in different bodies of water has generally focused primarily on important parameters (i.e. calcium, pH, temperature) more-or-less independently of other parameters. Due to the connection between calcium and pH, in particular, we believe it is important to consider these two parameters in concert, primarily at marginal conditions.

This report examines calcium and pH data obtained from 23 water quality stations (Figure 1) located in the California State Water Project (SWP) to determine the suitability of various locations for supporting long-term dreissenid populations based on the criteria discussed above. Unlike other studies which have focused on calcium and pH independently, this study examines calcium and pH in combination and the suitability of locations to long-term mussel populations was determined based on a pairing of calcium and pH measurements collected at the same time.

Table 1. Criteria used in determining the levels of dreissenid infestation in the temperate zone of North America and Europe (Mackie and Claudi 2010).

Parameter	Adults do not survive long-term	Uncertainty of veliger survival	Moderate Infestation Level	High Infestation Level
Calcium (mg/L)	<8 to <10	<15	16-24	≥24
Alkalinity (mg $CaCO_3$/L)	< 30	30-55	45-100	>90
Total Hardness (mg $CaCO_3$/L)	<30	30-55	45-100	≥90
pH	<7.0 or >9.5	7.1-7.5 or 9.0-9.5	7.5-8.0 or 8.8-9.0	8.2-8.8
Mean Summer Temperature (°F)	<64	64-68 or >83	68-72 or 77-83	72-75
Dissolved Oxygen mg/L (% saturation)	<3 (25%)	5-7 (25-50%)	7-8 (50-75%)	≥8 (>75%)
Conductivity (µS/cm)	<30	<30-60	60-110	≥100
Salinity (mg/L) (ppt)	>10	8-10 (<0.01)	5-10 (0.005-0.01)	<5 (<0.005)
Secchi depth (m)	<0.1 >8	0.1-0.2 or >2.5	0.2-0.4	0.4-2.5
Chlorophyll a (µ/L)	<2.5 or >25	2.0-2.5 or 20-25	8-20	2.5-8
Total phosphorous (µg/L)	<5 or >50	5-10 or 30-50	15-25	25-35

Figure 1. The location of sites in the California State Water Project that were analyzed in this study.

2 Data Analysis

2.1 Grab and Continuous Data

Grab and continuous water quality data were collected at water quality stations located in the SWP. Data were obtained through the Water Data Library (WDL), the California Data Exchange Center (CDEC), and the Metropolitan Water District of Southern California (MWD) (Table 2). Discrete water quality data for Thermalito Diversion Pool sites were collected by DWR under a Federal Energy Regulatory Commission (FERC) water quality monitoring requirement. Grab data for electrical conductance, pH and dissolved calcium were available for all sites examined. Ten sites examined also had continuous electrical conductance (EC) and pH data. Continuous calcium data were not available. It has been documented (Mackie and Claudi 2010) that, in the absence of calcium data, calcium concentrations can be estimated from conductance using the following relationship:

Calcium (mg/L) = 0.141*Conductivity (µS/cm)

This relationship was based on data collected from a large number of lakes in Southern Ontario and it was anticipated that it may have to be modified for other areas.

Individual regression plots were created using grab calcium and EC data for each site in the SWP which also had continuous EC data. The resulting relationships differed from that given in Mackie and Claudi (2010) and many of the relationships were weak (r^2 <0.50). Conductance-calcium relationships developed for sites at Barker Slough Pumping Plant, Sacramento River at Hood, and San Joaquin River near Vernalis were fairly strong (i.e. r^2 > 0.70). Relationships for California Aqueduct Checks 13, 29 and 41, Clifton Court Forebay Inlet, Castaic Lake Outlet, Del Valle Check 7, and H. O. Banks Pumping Plant were weak (r^2 <0.50). For this reason, grab calcium data were used for analyses of sites with weak regression relationships and continuous data were examined for those sites with strong relationships. San Joaquin River near Vernalis had continuous data beginning only in 2008, therefore grab data were used for analyses on this site. Continuous data sets were used for examination of Sacramento River at Hood and Barker Slough Pumping Plant.

Continuous data are collected at 5 minute intervals and averaged each hour. Average daily values are the average of hourly values for a 24 hour period. Occasionally, missing or unusual values were found in the continuous daily data set for pH and conductivity. Hourly data were examined and if possible were used to correct unusual values or to fill data gaps in the average daily values. When no hourly data were available, the value was recorded as missing and was eliminated from further analyses. We did consider using interpolation to fill gaps resulting from missing data, however some periods of missing values were very long and it was decided that leaving gaps would be better than interpolating over large periods of time. When average pH values were calculated, the measured pH values were first converted to hydrogen ion concentrations. The hydrogen ion concentrations were then averaged and the resulting average hydrogen ion concentration was converted back to a pH value.

Table 2. Dates, data type, and data source for the sites examined in the State Water Project.

Site	Dates	Data Type	Data Source
Antelope Lake	May 2000 – Jun 2008	grab/discrete	WDL[a]
Frenchman Lake	May 2000 – May 2008	grab/discrete	WDL
Lake Davis	May 2000 – May 2008	grab/discrete	WDL
Lake Oroville (Station 1)	May 2002 – Sep 2010	grab/discrete	DWR[b], WDL
Thermalito Diversion Pool	Mar 2002 – Apr 2004	grab/discrete	DWR
Feather River	Aug 2000 – Aug 2008	grab/discrete	WDL
Sacramento River at Hood	Jan 2000 – Jul 2010, Jan 2000 – Sep 2010	grab/discrete, continuous	WDL, CDEC[c]
Barker Slough Pumping Plant	Jan 2000 – Aug 2010, Jan 2000 – Sep 2010	grab/discrete, continuous	WDL, CDEC
San Joaquin River near Vernalis	Jan 2000 – Nov 2010, Feb 2008 – Nov 2010	grab/discrete, continuous	WDL, CDEC
Clifton Court Forebay Inlet	Jan 2000 – Sep 2010, Jan 2000 – Sep 2010	grab/discrete, continuous	WDL, CDEC
Harvey O. Banks Pumping Plant	Jan 2000 – Aug 2010, Jan 2000 – Sep 2010	grab/discrete, continuous	WDL, CDEC
Delta Mendota Canal Headworks	Jan 2000 – Aug 2010	grab/discrete	WDL
Del Valle Check 7	Jan 2000 – Aug 2010, Jan 2000 – Sep 2010	grab/discrete, continuous	WDL, CDEC
California Aqueduct Check 13	Jan 2000 – Aug 2010, Jan 2000 – Sep 2010	grab/discrete, continuous	WDL, CDEC
Pacheco Pumping Plant	Mar 2000 – Sep 2010	grab/discrete	WDL
California Aqueduct Check 21	Jan 2000 – Aug 2010	grab/discrete	WDL
California Aqueduct Check 29	Jan 2000 – Aug 2010, Jan 2000 – Sep 2010	grab/discrete, continuous	WDL, CDEC
California Aqueduct Check 41	Jan 2000 – Aug 2010, Jan 2000 – Sep 2010	grab/discrete, continuous	WDL, CDEC
Castaic Lake Outlet	Feb 2000 – Aug 2010, Jan 2000 – Sep 2010	grab/discrete, continuous	WDL, CDEC
Castaic Lake at Jensen Influent	Jan 2000 – Aug 2010	grab/discrete	MWD[d]
Silverwood Lake Outlet at Devil Canyon	Jan 2000 – Aug 2010	grab/discrete	MWD
Devil Canyon Headworks	Jun 2001 – Aug 2010	grab/discrete	WDL
Lake Perris Outlet	Feb 2000 – Nov 2010	grab/discrete	WDL

[a] Water Data Library (WDL)
[b] California Department of Water Resources (DWR)
[c] California Data Exchange Center (CDEC)
[d] Metropolitan Water District of Southern California (MWD)

2.2 Calcium-pH Time Series Plots

On the calcium-pH plots contained in this report, 12 mg/L of calcium is given as a threshold for possible long-term survival of adult dreissenid mussels, provided the average pH is above 7.8. This conservative calcium value is based on experience from Lake Superior where the pH ranges from 7.9-8.2 but the average calcium level is 13 mg/l (Mackie 2010). Lake Superior has only isolated pockets of dreissenid mussels along the shoreline despite the fact that the first mussels were documented in Duluth Harbor more than 20 years ago.

Furthermore, studies by Nierzwicki-Bauer et al. (2000) documented that adult zebra mussels were able to survive in Lake George water (Ca=12 mg/L, pH=7.15), but the development of veligers failed unless both calcium and pH levels were raised. Lake George has had a minimal level of dreissenid infestation for the last ten years. It is hypothesized that the reason dreissenid mussels survive at all in Lake George is due to limestone outcroppings in various parts of the lake which provide microzones with higher calcium levels.

Hinks and Mackie (1997) tested adult survival, juvenile growth rates and veliger production against different concentrations of calcium, alkalinity, total hardness, chlorophyll and pH by rearing adults and newly settled juveniles collected from Lake St. Clair in water from 16 Ontario Lakes. Six of these lakes had mean calcium levels below 8.5 mg/L and mean pH of 8.4 or less. In these low calcium waters all adults died within 35 days, juvenile growth rates were near zero or negative, and no veligers were produced.

The threshold pH on the graphs is given as 7.3. This value is based on experimental data from a study conducted by RNT Consulting Inc. in 2009 (Claudi *et al.* In press). In the study, it was found that even at high calcium levels (40mg/L) if the pH is depressed to 7.3 mussels begin to show evidence of calcium loss from their shells. At pH levels of 7.1 and 6.9 the calcium loss is accelerated. After 12 weeks, the mortality of adult mussels was greater than 7% at a pH of 7.3, just under 15% at a pH of 7.1, and almost 40% at a pH of 6.9. The mortality in the control group was less than 3%. This experimental evidence is further supported by observations from Lough Allen which has an average calcium concentration of 25 mg/L and an average pH of 7.4 (Lucy *et al.* 2010). Although this lake is connected to lakes which support established zebra mussel populations, mussels have only casually been observed in Lough Allen suggesting this body of water may be unable to support a long-term population of dreissenids due to its low pH.

2.3 Pie charts

To quantify the ability of sites with marginal calcium and/or marginal pH to support dreissenids, both calcium and pH values were examined in combination to determine if the interaction of the two parameters was important for creating favorable conditions for established mussel populations. The calcium and pH results for each sample collected were examined and then assigned to one of nine categories based on their paired calcium and pH values.

The minimum limits of calcium and pH were set at 12 mg/L and 7.3, respectively. Samples having low calcium and/or low pH were deemed to represent conditions unsuitable for supporting dreissenids. Samples with calcium concentrations above 15 mg/L and pH levels above 7.8 were considered favorable for dreissenid mussels. Samples with marginal calcium ($12 \text{ mg/L} < Ca \leq 15 \text{ mg/L}$) and/or marginal pH ($7.3 < pH \leq 7.8$) were considered potentially able to support mussels. Following is a description of each combination of calcium and pH values and their corresponding suitability for dreissenid survival.

Low Calcium/Low pH: Samples with calcium below 12 mg/L and pH below 7.3 have conditions that are unsuitable for dreissenid mussels.

Low Calcium/Marginal pH: Samples with low calcium (<12 mg/L) and marginal pH (7.3<pH≤7.8) would be unable to support dreissenids due to insufficient calcium, regardless of pH levels above the minimum limit.

Low Calcium/High pH: Samples with low calcium (<12 mg/L) and high pH (>7.8) would be unable to support dreissenids due to insufficient calcium, regardless of pH levels above that deemed favorable for mussels.

Marginal Calcium/Low pH: Although marginal calcium levels (12 mg/L < Ca ≤15 mg/L) may be sufficient for adult mussels to survive, the low pH is expected to prevent established dreissenid populations. Samples with marginal calcium and low pH are unlikely to support mussels.

High Calcium/Low pH: Regardless of high calcium levels (>15 mg/L), a low pH would not support dreissenid mussels. Therefore samples with high calcium and low pH are considered unable to support long-term dreissenid populations.

Marginal Calcium/Marginal pH: Samples with marginal calcium (12 mg/L < Ca ≤15 mg/L) and marginal pH (7.3 < pH ≤7.8) may be able to support adult mussels. These conditions, however, are unsuitable for veligers.

Marginal Calcium/High pH: Since dreissenid success in marginal calcium levels (12 mg/L < Ca ≤15 mg/L) may be enhanced by high pH (>7.8), samples with marginal calcium and high pH are considered potentially able to support mussels.

High Calcium/Marginal pH: Adult dreissenids and veligers are believed to favor high calcium concentrations (>15 mg/L) however their success may be reduced under marginal pH conditions (7.3 < pH ≤7.8). Samples with high calcium and marginal pH are potentially able to support dreissenid populations.

High Calcium/High pH: Samples with high calcium (>15 mg/L) and high pH (>7.8) are considered favorable for dreissenid mussels and therefore able to support long-term populations.

At each site, the frequency of the above categories was plotted on pie charts to visually express the potential the site has for supporting mussels. The paired samples with calcium and/or pH below the required limits are presented in green, the samples with conditions potentially able to support mussels are presented in orange, and samples with both high calcium and high pH are presented in red (Table 3). The high calcium, high pH range was further divided into favorable conditions occurring during the height of the breeding season and those occurring during the remainder of the year. Based on data for San Justo Reservoir, the height of the dreissenid breeding season (maximum number of veligers present) in California is between May and June (Janik 2010). As such, samples with high calcium and high pH during May and June were separated from those samples with high calcium and high pH during July to April as representing the maximum potential for establishment of dreissenids.

During the analysis it was noted that some sites have shown marked changes in the last three years in terms of calcium and pH levels. In those instances, a separate analysis of data collected between January 2008 and September 2010 was performed. Changes in the percentage of samples unable, potentially able, and able to support dreissenids were compared to the percentages resulting from data collected over the last decade.

Table 3. Conditions of low, marginal, and high calcium and pH that are unable (green), potentially able (orange) and able (red) to support dreissenid mussels.

	Calcium Concentration		
pH Level	**Ca ≤ 12 mg/L**	**12 mg/L < Ca ≤ 15 mg/L**	**Ca > 15 mg/L**
pH ≤ 7.3	**unable**	**unable**	**unable**
7.3 < pH ≤ 7.8	**unable**	**potentially able**	**potentially able**
pH > 7.8	**unable**	**potentially able**	**able**

3 Results

Calcium and pH data were examined in combination for each of 23 sites in the California State Water Project. The sites were classified as unable to support, potentially able to support, and able to support long-term populations of dreissenid mussels. Table 4 categorizes each site examined based on its suitability for supporting long-term dreissenid populations.

Table 4. Categorization of sites examined as unable, potentially able, and able to support a long-term population of dreissenid mussels.

Unable to Support Dreissenids	Potentially Able to Support Dreissenids	Able to Support Dreissenids
Antelope Lake	Barker Slough Pumping Plant	California Aqueduct Check 41
Frenchman Lake	San Joaquin River near Vernalis	Castaic Lake Outlet
Lake Davis	Clifton Court Forebay Inlet	Castaic Lake at Jensen Influent
Lake Oroville	H. O. Banks Pumping Plant	Silverwood Lake Outlet at Devil Canyon
Thermalito Diversion Pool	Delta Mendota Canal Headworks	Devil Canyon Headworks
Feather River at Lake Oroville	Del Valle Check 7	Lake Perris Outlet
Sacramento River at Hood	California Aqueduct Check 13	
	Pacheco Pumping Plant	
	California Aqueduct Check 21	
	California Aqueduct Check 29	

3.1 Sites Unable to Support Dreissenids

Sites with low calcium concentrations (i.e. ≤12 mg/L) are considered unable to support dreissenid populations. In the California SWP, Antelope Lake, Lake Davis, Lake Oroville, Thermalito Diversion Pool and the Feather River had calcium levels in the last decade that were below 12 mg/L. Frenchman Lake and Sacramento River at Hood also had calcium concentrations below the minimum limit for supporting mussels, however there were times between January 2000 and September 2010 when both calcium and pH were within limits that could support dreissenids. These conditions occurred infrequently and the lower limits for dreissenid mussel survival were very conservative. This combination, in our opinion, would not allow for the establishment of a reproducing dreissenid population.

3.1.1 Antelope Lake

Figure 2 shows results for samples collected at the surface and bottom of Antelope Lake, at the east end of the dam. The average calcium concentration between May 2000 and June 2008, for both the surface and bottom of the site, is 8.4 mg/L. The average pH at the surface is 7.8 and at the bottom the average pH is 6.8. Given the low calcium concentrations at Antelope Lake, this site would be unable to support dreissenid mussels (Figure 3).

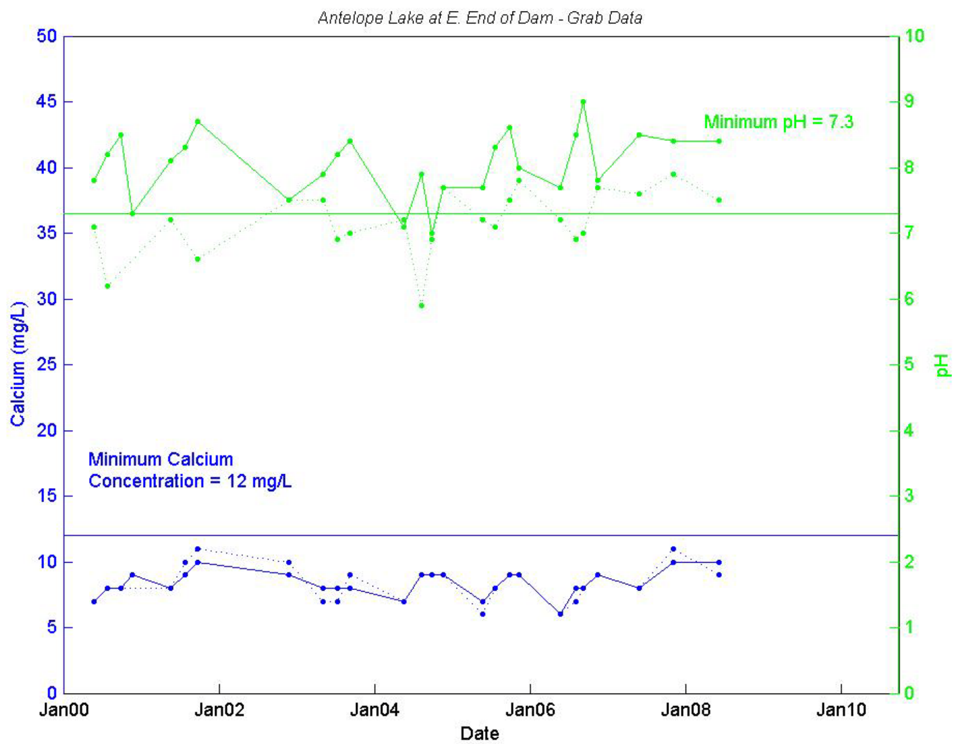


Figure 2. Calcium and pH values for Antelope Lake at East End of Dam. Measurements were taken at the surface (—) and at the bottom (····) of the lake.

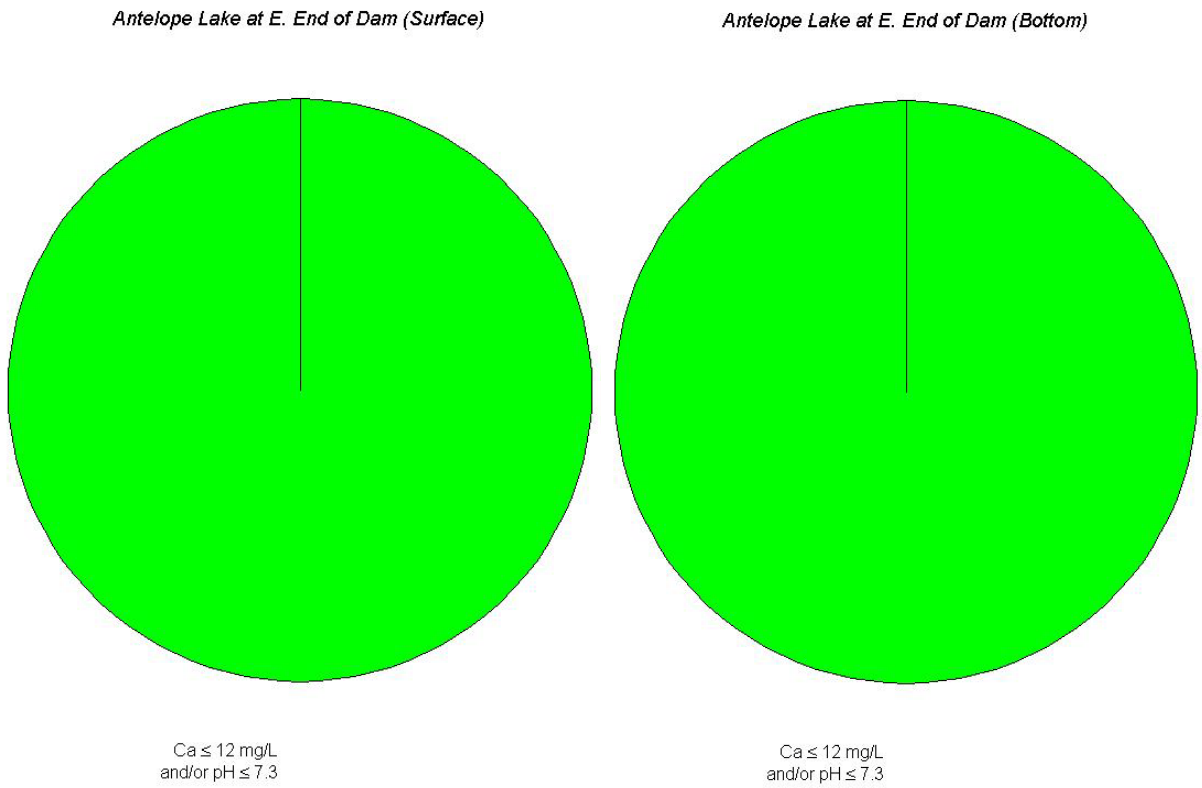


Figure 3. All samples collected at Antelope Lake at both the surface (left) and bottom (right) had calcium concentrations below the minimum required level for dreissenid mussels.

3.1.2 Frenchman Lake

Frenchman Lake at the west end of the dam has marginal calcium levels for dreissenid mussel survival. The average surface calcium for the period of time between May 2000 and May 2008 is 12.6 mg/L and the average calcium at the bottom of the lake is 13.2 mg/L (Figure 4). The surface and bottom average pH values are 8.1 and 7.2, respectively. In 54.5% of the samples collected at the surface of Frenchman Lake and 40% of samples collected at the bottom, calcium and pH conditions were both above minimum required levels (Figure 5). As such, it may be possible for adult mussels to survive at this location. Conditions remain unfavorable for veligers at all times therefore it is unlikely that a reproducing population would be supported at this site.

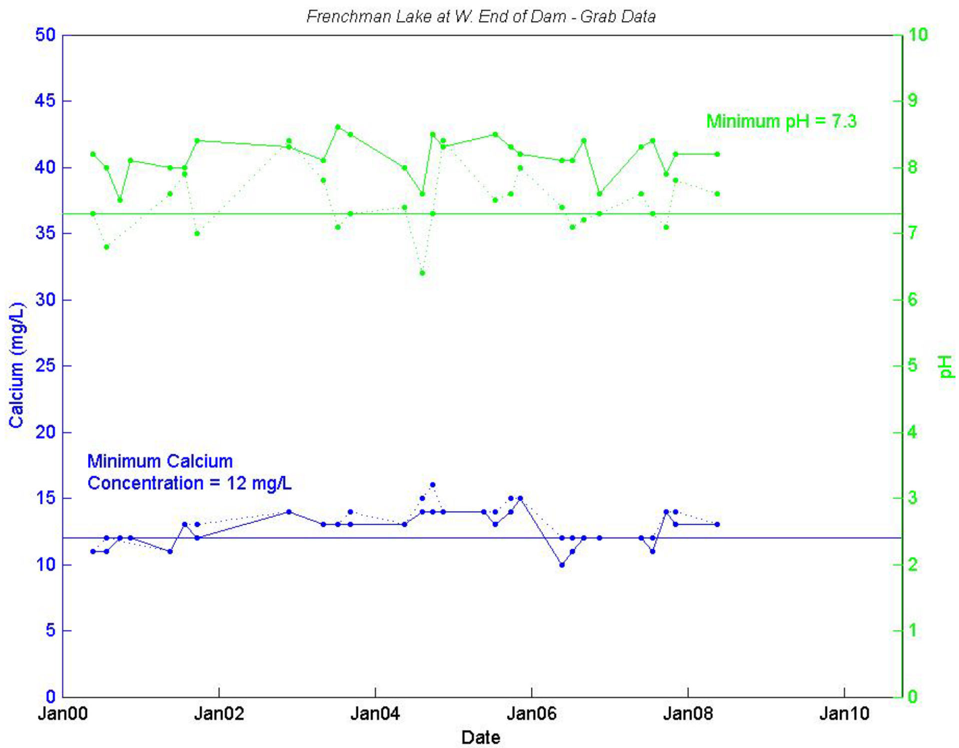
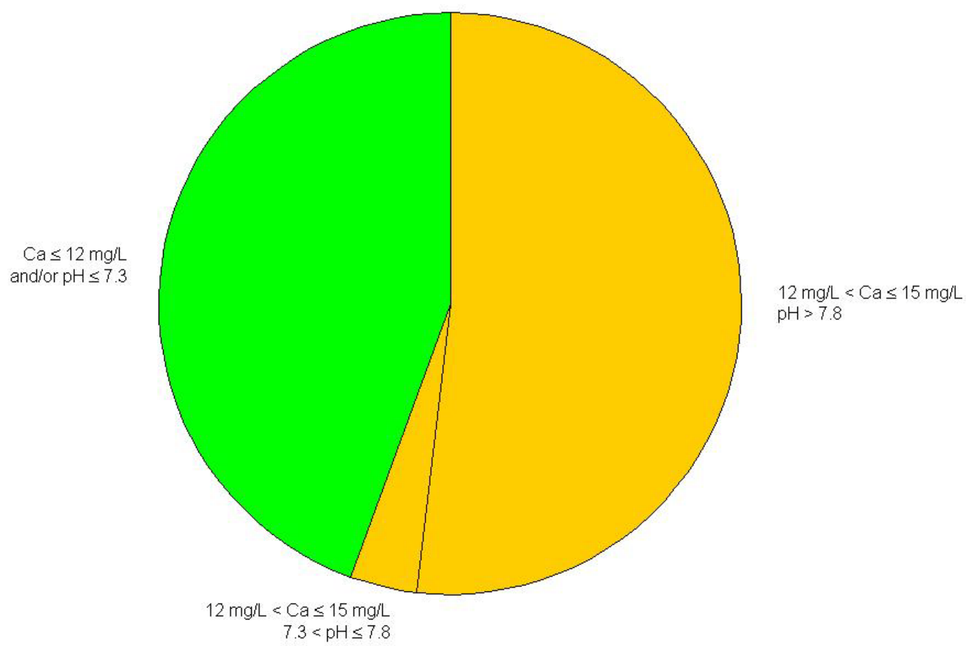


Figure 4. Calcium and pH values for Frenchman Lake at West End of Dam. Measurements were taken at the surface (—) and at the bottom (····) of the lake.

Frenchman Lake at W. End of Dam (Surface)



Frenchman Lake at W. End of Dam (Bottom)

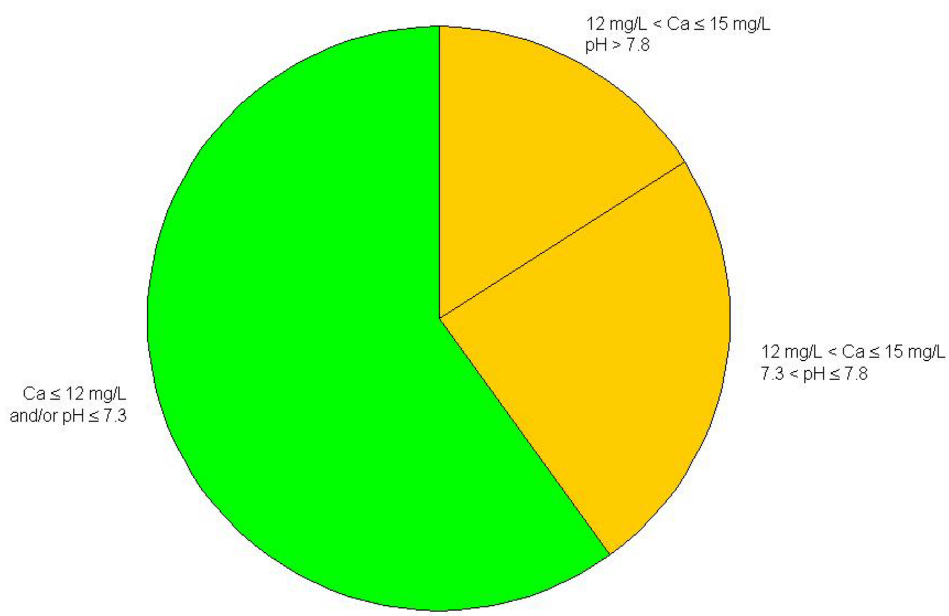


Figure 5. Calcium and pH results for samples collected in Frenchman Lake were above the minimum levels in 54.5% of the surface samples and 40% of the bottom samples.

3.1.3 Lake Davis

Samples collected from the surface and bottom of Lake Davis at the east end of the dam between May 2000 and May 2008 have calcium concentrations at or below 12 mg/L (Figure 6). The average calcium concentration at the surface of the site is 8.1 mg/L and it is 9.1mg/L at the bottom. Average pH values for the surface and bottom are 8.0 and 6.9, respectively. Although the pH level is high enough to support dreissenid mussels at the surface, the calcium levels at Lake Davis are too low for long-term mussel survival (Figure 7).

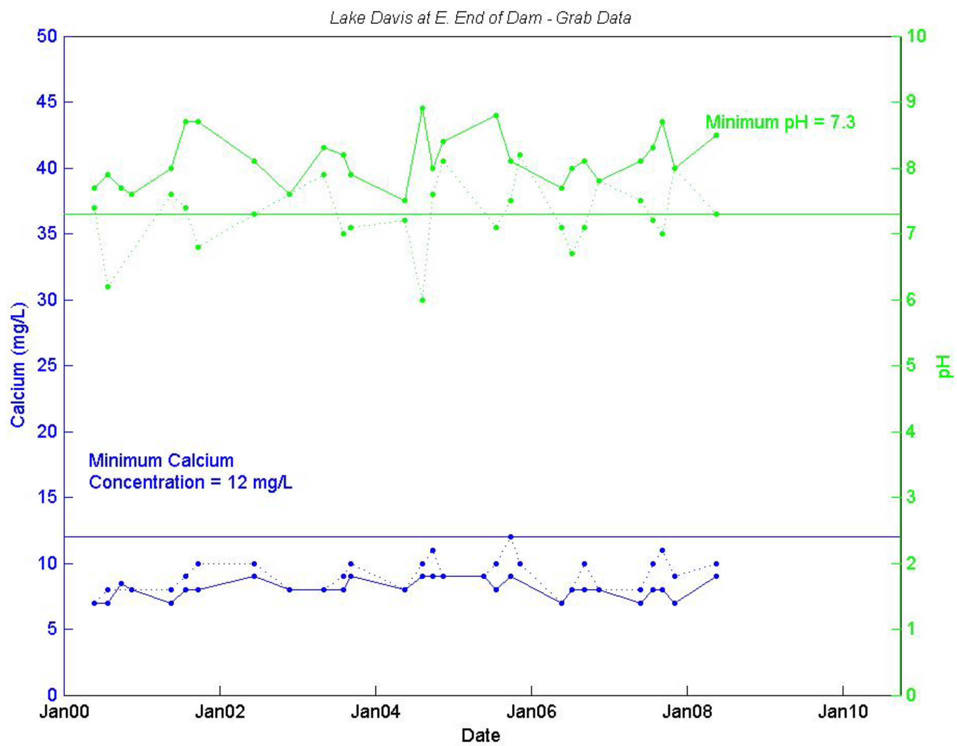


Figure 6. Calcium and pH values for Lake Davis at East End of Dam. Measurements were taken at the surface (—) and at the bottom (····) of the lake.

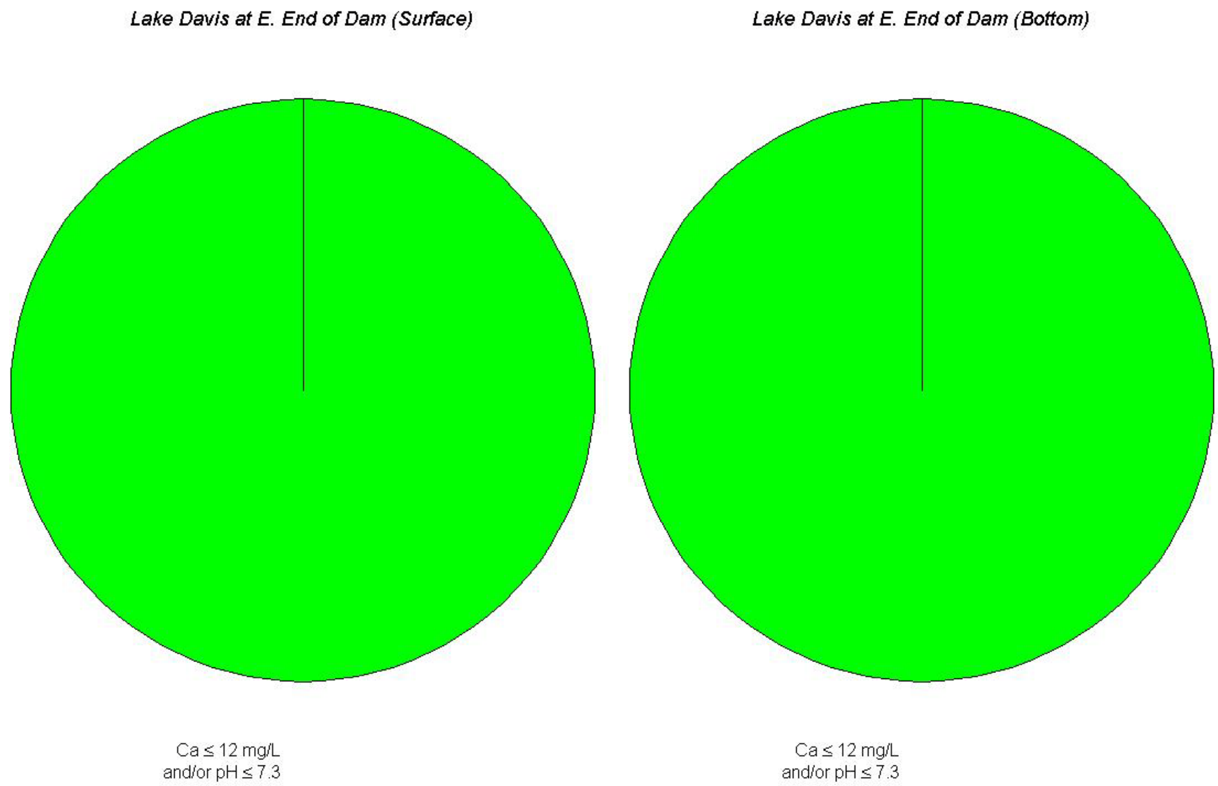


Figure 7. All samples collected for Lake Davis at both the surface (left) and bottom (right) had calcium levels below the minimum required levels for dreissenid mussels.

3.1.4 Lake Oroville

Figure 8 shows changes in dissolved calcium concentration and pH over time for Lake Oroville at Station 1. Calcium concentrations in all samples available from August 2004 to September 2010 have been below the minimum of 12 mg/L; the average dissolved calcium at Lake Oroville Station 1 for this period is 9.0 mg/L. The pH levels for samples collected at this site have an average value of 7.3. At Lake Oroville Station 1, approximately 35% of the available samples for the given time period have pH values at or below 7.3. This pH would have a negative impact on adult mussels even at high ambient calcium levels. We can only hypothesize that the impact of low pH would be even greater at low ambient calcium.

Analysis of paired calcium and pH values (Figure 9) shows no instance of even marginal conditions. Therefore, the low calcium levels and low average pH lead us to conclude that dreissenid mussels would not survive at this location as a reproducing population.

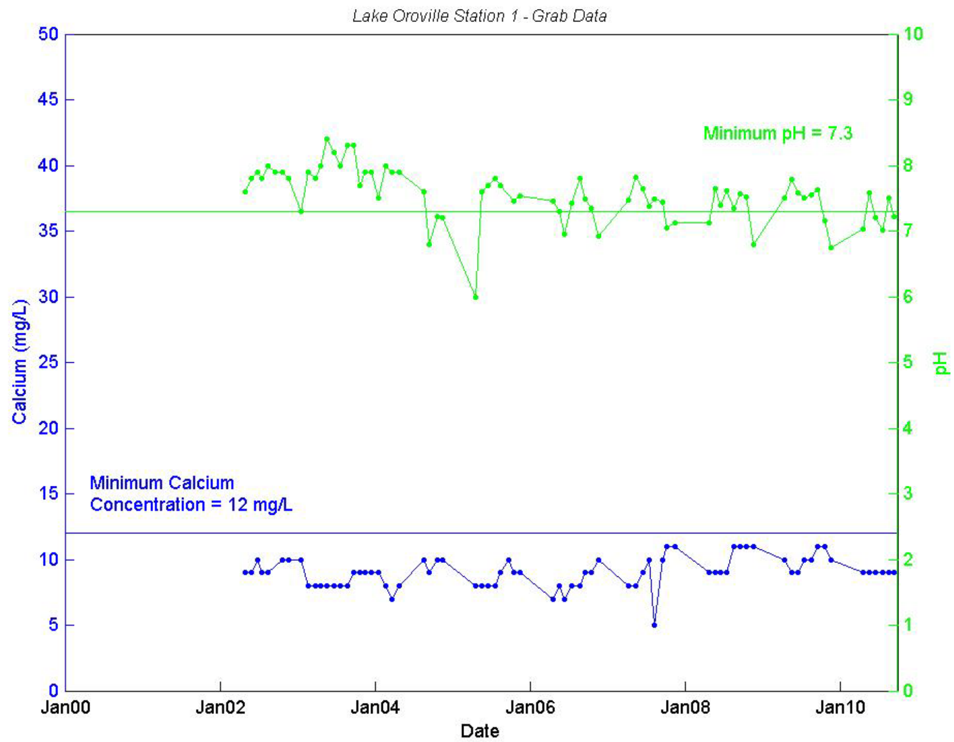


Figure 8.Changes in calcium concentration and pH for Lake Oroville at Station 1.

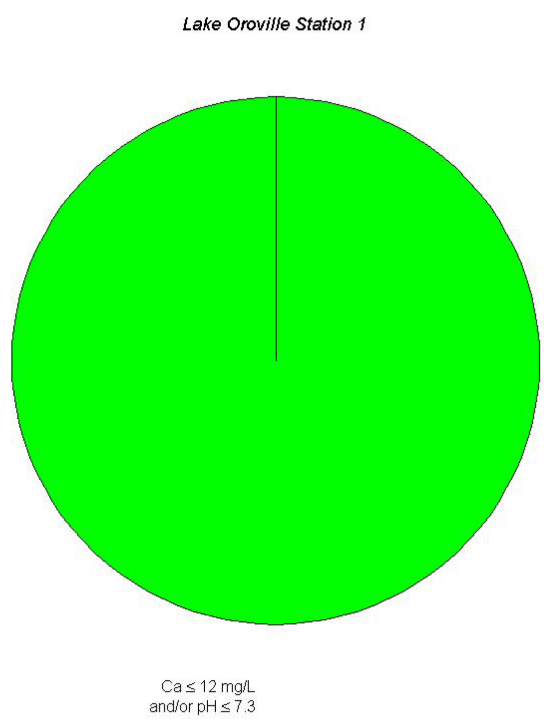


Figure 9. Conditions at Lake Oroville Station 1 between August 2004 and September 2010 were unsuitable for dreissenid mussels. All samples collected had calcium levels less than or equal to 12 mg/L, and approximately 35% of samples also had pH levels at or below 7.3.

3.1.5 Thermalito Diversion Pool

Thermalito Diversion Pool has a low total calcium concentration of 8 mg/L (Table 5), with three minor calcium sources: Glen Creek upstream of Glen Pond (Figure 10), Glen Pond (Figure 11), and Morris Ravine (Figure 12). Glen Creek and Morris Ravine transport storm water and urban runoff into the diversion pool. The calcium contribution of these sites does not affect the overall calcium concentration in the diversion pool, as evidenced in the lack of change of average calcium concentrations from upstream (Thermalito Diversion Pool upstream of Power Plant) to downstream sites (Thermalito Diversion Pool upstream of Dam). The average pH in the Thermalito Diversion Pool is 7.2. The residence time of water in the diversion pool averages 24 hours. Any veligers produced in this location would be transported downstream into the low calcium waters of the Feather River and Thermalito Forebay prior to settlement. The low calcium concentration and short residence time leads us to conclude that dreissenid mussels would not survive as a reproducing population at this site.

Table 5. Total calcium and pH for Thermalito Diversion Pool (DWR 2004).

Site	**Total Calcium (mg/L)**			**Average pH**
	Average	*Minimum*	*Maximum*	
Thermalito Diversion Pool upstream of Power Plant	8	7	10	7.2
Thermalito Diversion Pool downstream of Power Plant	8	7	9	7.2
Glen Creek upstream of Glen Pond	14	8	21	7.6
Glen Pond	13	8	20	7.8
Morris Ravine at Mouth	36	9	56	7.6
Thermalito Diversion Pool upstream of Dam (surface)	8	7	10	7.3
Thermalito Diversion Pool upstream of Dam (bottom)	8	7	10	7.3

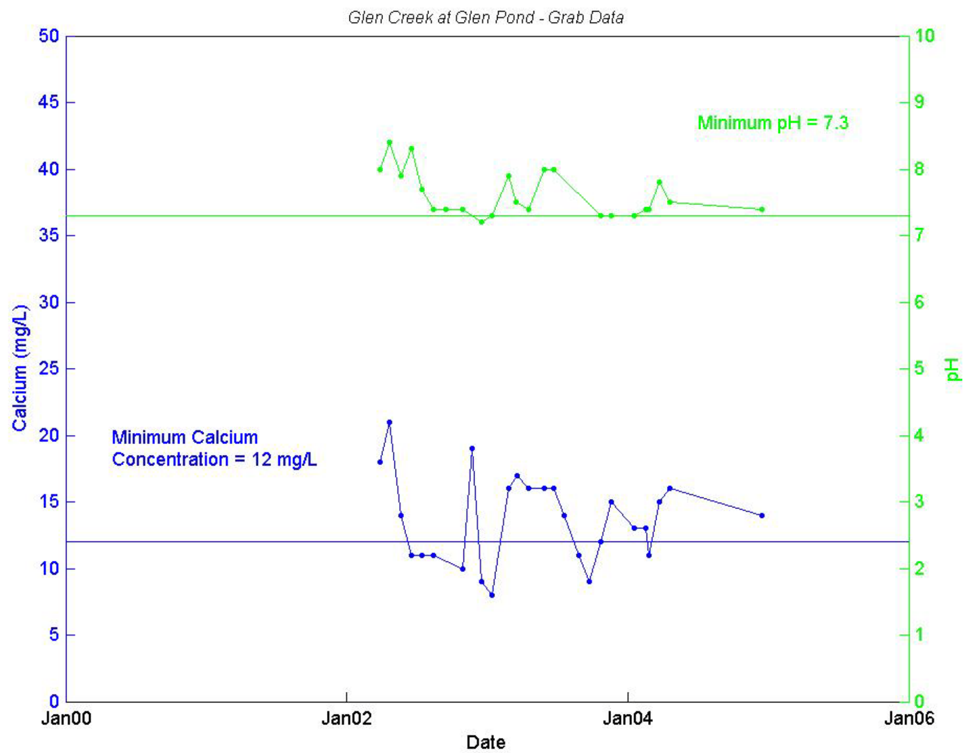


Figure 10. Changes in calcium concentration and pH for Glen Creek at Glen Pond.

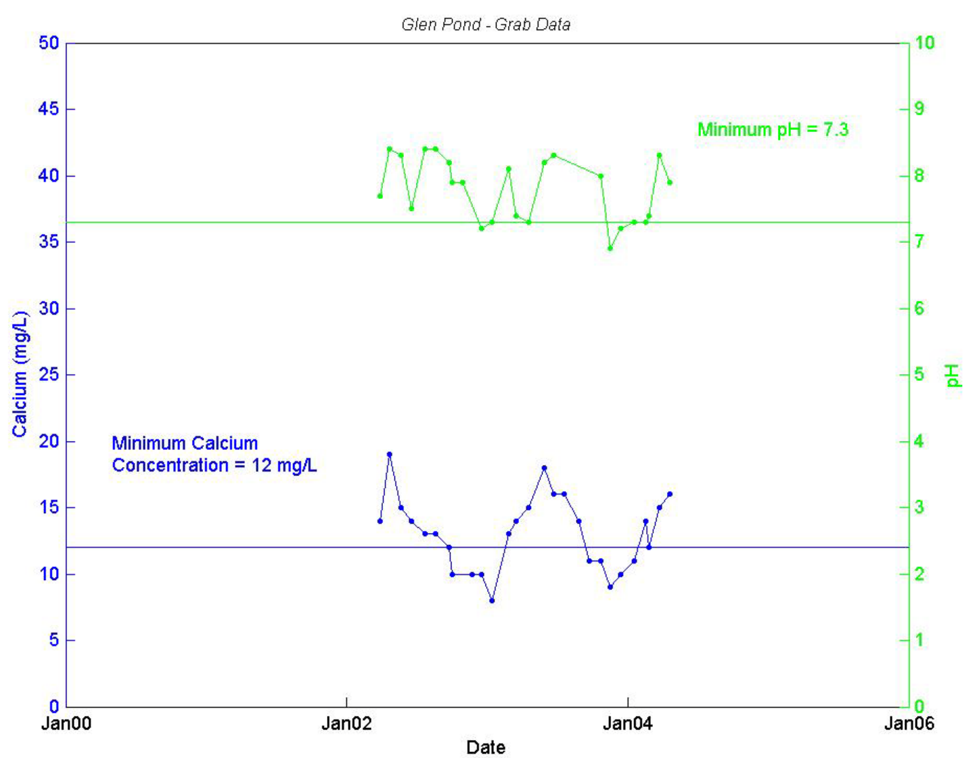


Figure 11. Changes in calcium concentration and pH in Glen Pond.

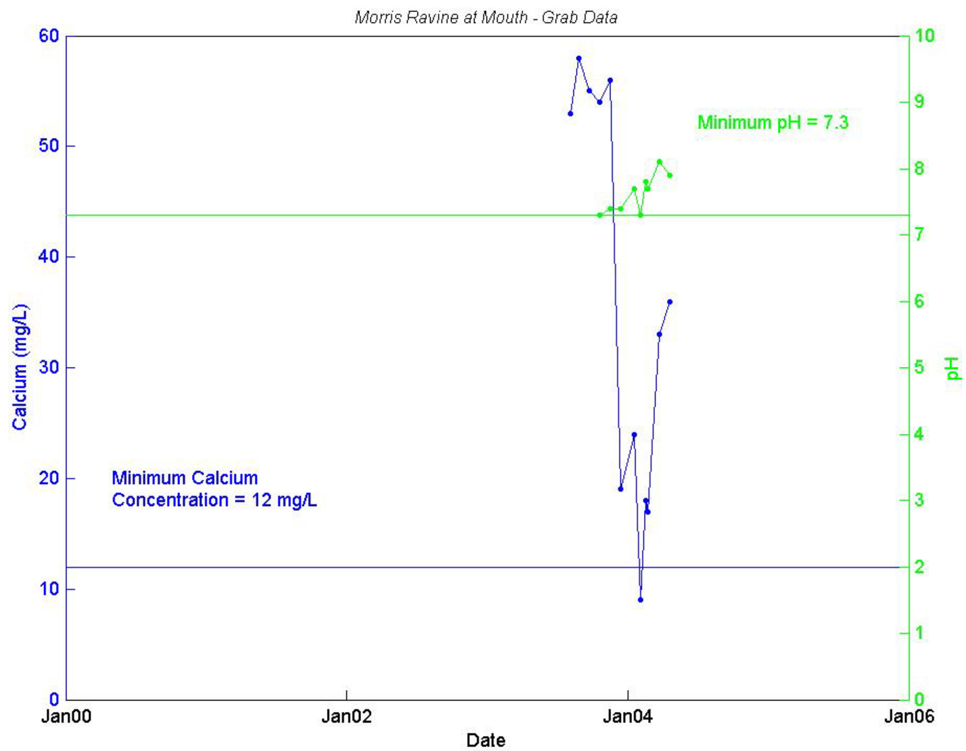


Figure 12. Changes in calcium concentration and pH in Morris Ravine.

3.1.6 Feather River at Lake Oroville

Feather River at Lake Oroville also shows low dissolved calcium concentrations (Figure 13). The average calcium concentration at this site for samples collected between August 2000 and August 2008 is 8.7 mg/L. As with Lake Oroville at Station 1, the pH at the Feather River at Lake Oroville site has an average value of 7.3. At this site, 67% of the samples had pH values at or below 7.3 during the 2000 to 2008 sampling period. Overall, 98% of the samples had combinations of calcium and pH conditions that were unable to support mussels (Figure 14). In 2% of the samples collected, the calcium levels were considered to be marginal (i.e. $12 \text{ mg/L} < Ca \leq 15 \text{ mg/L}$) and the pH was high (i.e. >7.8). At these levels dreissenid mussels might be able to survive, however because the occurrence of such conditions was very low during the sampling period, we conclude that dreissenid mussels would not survive as a reproducing population at this site.

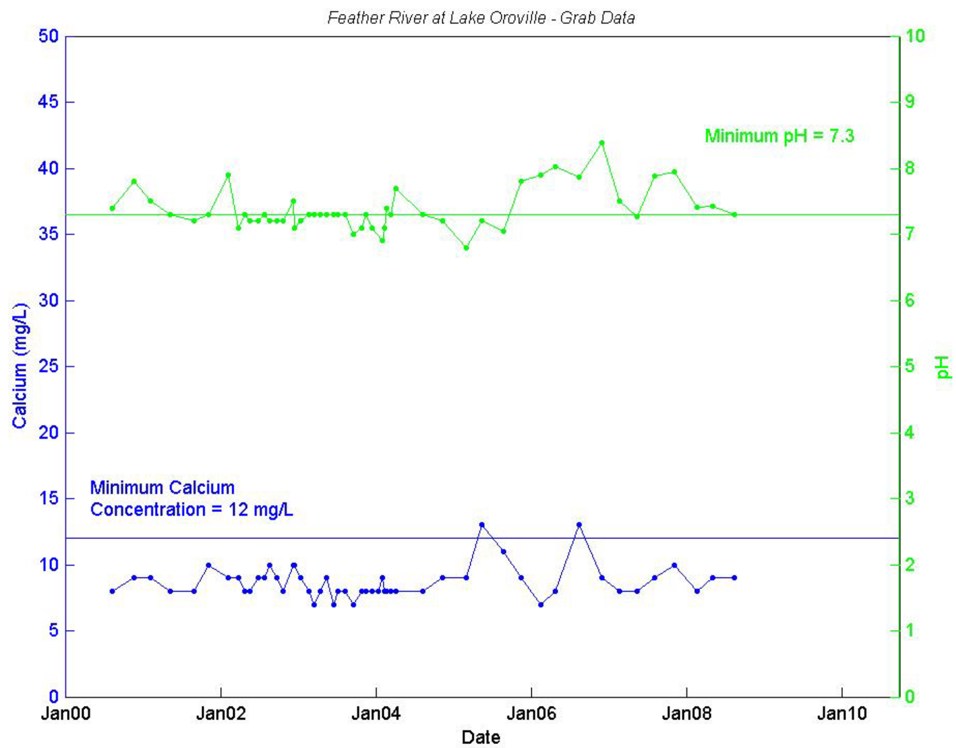


Figure 13. Changes in calcium concentration and pH for Feather River at Lake Oroville.

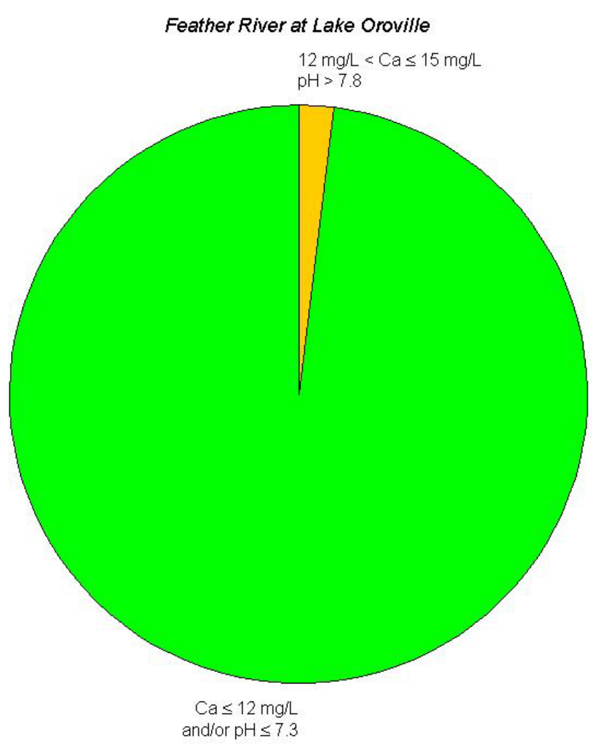


Figure 14. The majority of samples (98%) collected for the Feather River at Lake Oroville site had calcium and pH conditions that would be unable to support dreissenids. A small percentage (2%) of the samples had marginal calcium and high pH levels.

3.1.7 Sacramento River at Hood

For Sacramento River at Hood, grab and continuous data were available for the period January 2000 to September 2010. Figure 15 shows grab and continuous conductivity data for this time period and Figure 16 shows grab and continuous pH data. The average conductivity for the grab data is 169.9 µS/cm and the average conductivity for the continuous data is 163.8 µS/cm. The average pH for both the grab data and the continuous data is 7.4. A paired t-test between the grab and continuous data returned a statistically significant difference for conductivity ($p<0.05$) and for pH ($p<0.005$). The grab data are higher than the continuous data in 79% of the samples for conductivity and 59% of the samples for pH. The Department of Environmental Protection (DEP) in Florida has published standard operating procedures for continuous monitoring with installed meters (DEP 2008). DEP requires that grab samples be collected at the same location as the continuous meter and that the grab sample results be compared to the continuous meter reading taken at the same time the grab sample was collected. Differences of 10% between grab and continuous measurements for conductance and differences of no more than 0.2 pH units are considered acceptable by DEP.

The grab sample results for Sacramento River at Hood did occasionally differ from continuous readings by more than the acceptable limit of 10% for conductance and 0.2 units for pH, however, on average over the entire sampling period examined, the difference between the average grab conductance and the average continuous conductance was less than 10% and the difference between the average grab pH and the average continuous pH was less than 0.2 pH units. Therefore, even though the paired t-test returned a result indicating the grab and continuous data sets were significantly different from each other, the differences were considered to be within acceptable limits. Regular maintenance and calibration of the continuous equipment is performed and grab samples were collected at the location of the continuous meters.

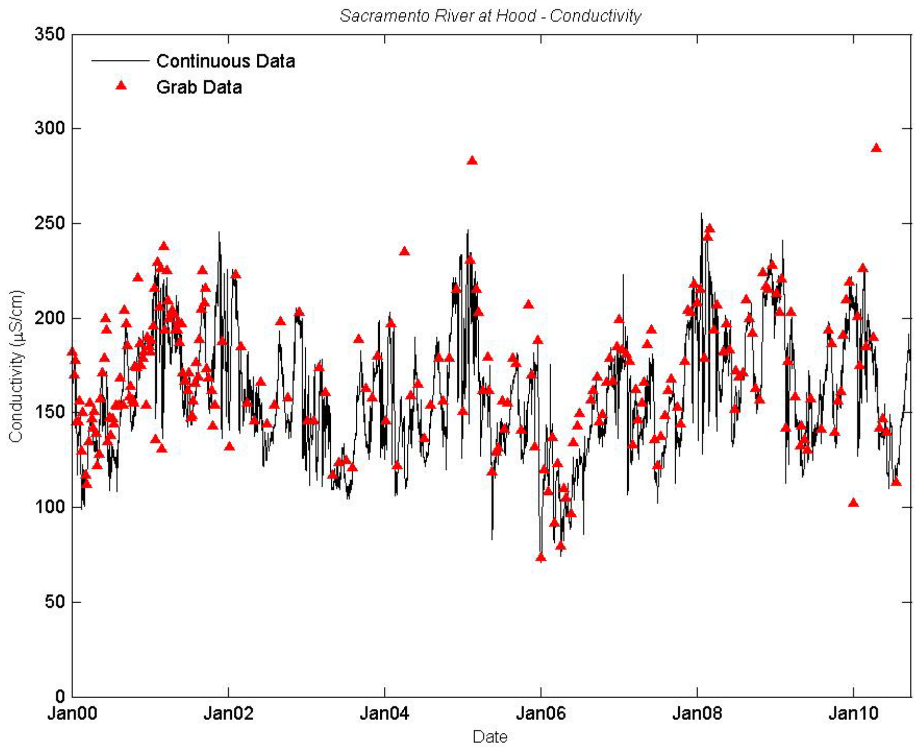


Figure 15. Grab and continuous conductivity data for Sacramento River at Hood.

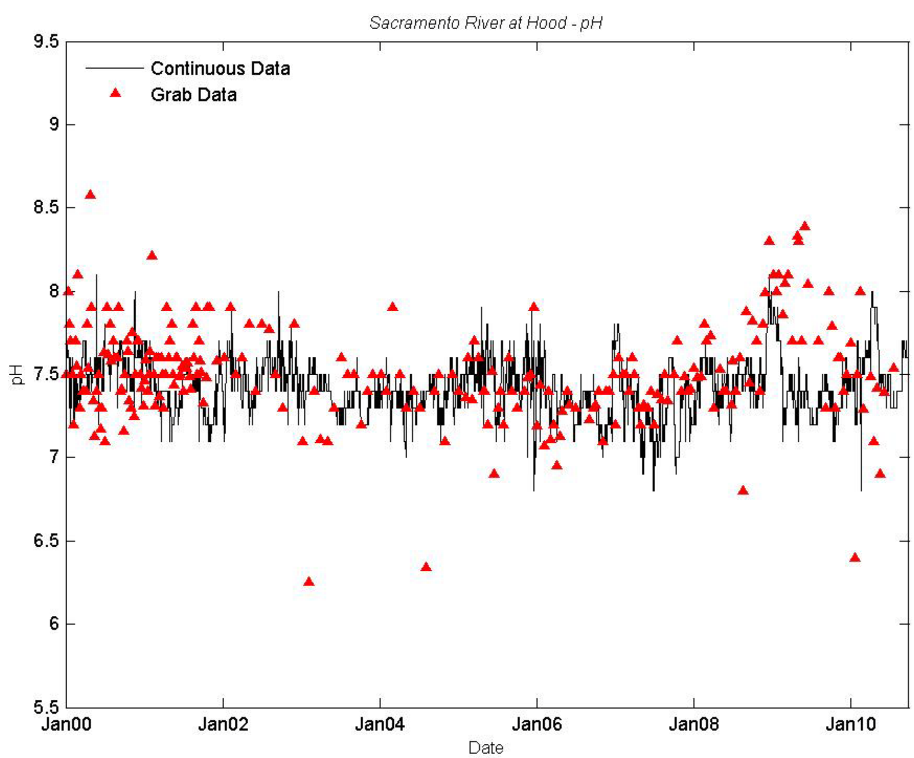


Figure 16. Grab and continuous pH data for Sacramento River at Hood.

The continuous data were examined to determine the suitability of Sacramento River at Hood for supporting a long-term dreissenid population. A moderately strong linear relationship (r^2 = 0.6986) resulted between conductivity and dissolved calcium in the grab data for Sacramento River at Hood (Figure 17). Data were further examined to determine if the strength of the conductivity-calcium relationship improved when wet water years were separated from dry water years however the resulting wet year (r^2 = 0.6935) and dry year (r^2 = 0.6893) relationships showed no improvement over the result for all years together. Therefore the linear relationship developed using the entire grab sample dataset was applied to the continuous conductivity data to estimate daily values for calcium for the period of record.

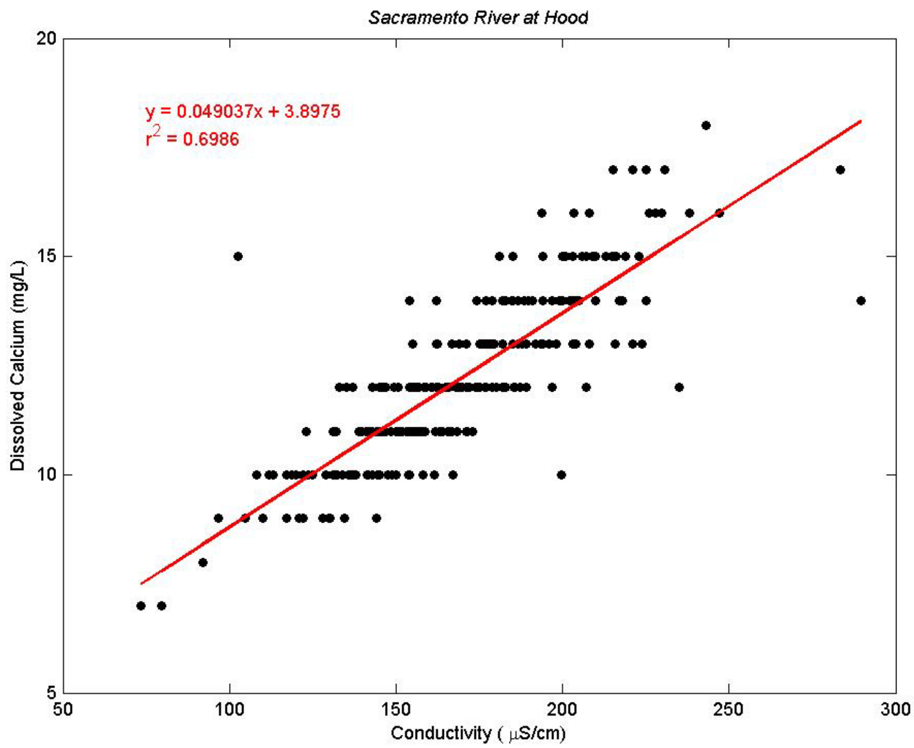


Figure 17. A linear relationship exists between conductivity and dissolved calcium at Sacramento River at Hood. The resulting linear equation was used to calculate daily calcium concentrations from continuous conductivity data.

Continuous calcium and pH data fluctuate around the minimum values of 12 mg/L and 7.3, respectively (Figure 18). In the last decade, calcium concentrations have been at or below the minimum limit on 60% of the days and pH values have been at or below the minimum limit on 21% of the days. Conditions favorable for supporting dreissenid mussels occurred on only 0.1% of the days in the period of time examined. During this time, 2.2% of the days had conditions that might support dreissenids whereas 97.7% of the days had conditions where the calcium and/or pH were too low to support mussels (Figure 19). Therefore, regardless of the fluctuation above the minimum limits for calcium and pH, Sacramento River at Hood is unlikely to be able to support a long-term dreissenid population.

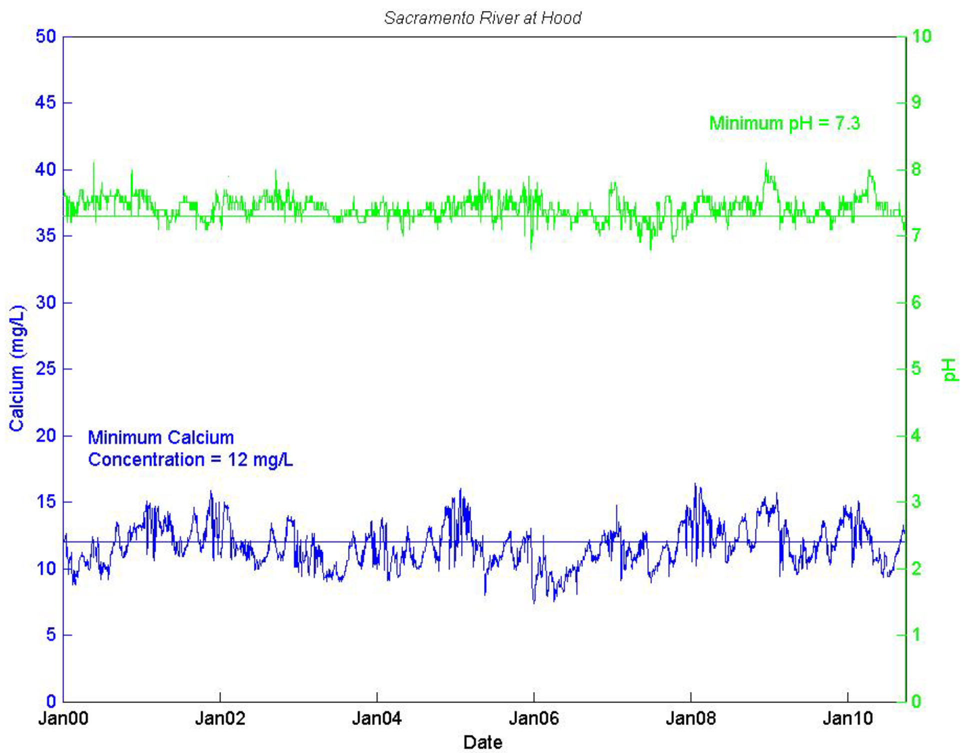


Figure 18. Changes in calculated daily calcium and measured pH data for Sacramento River at Hood.

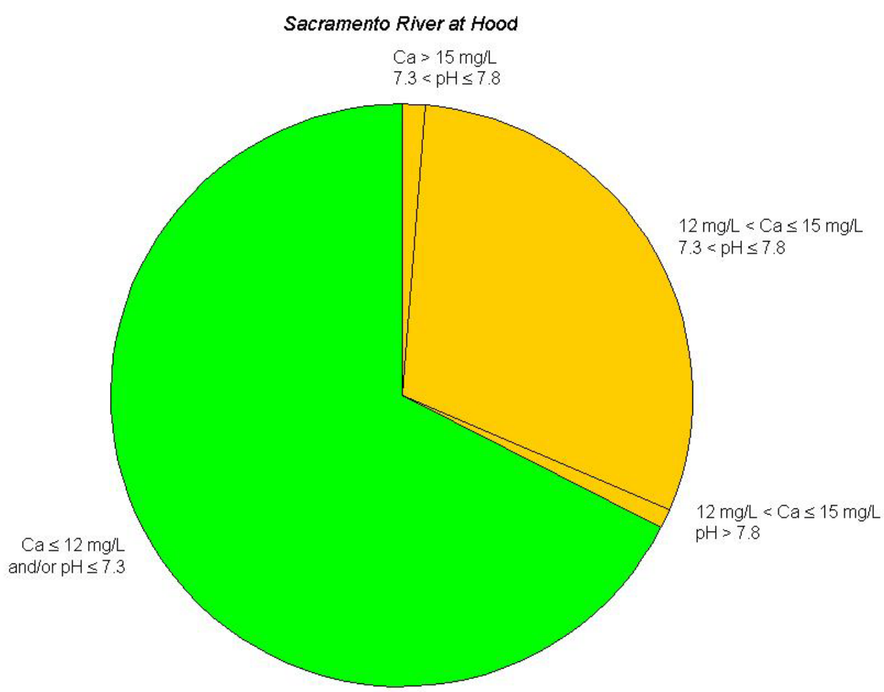


Figure 19. Calculated daily calcium and measured pH values at Sacramento River at Hood that will not (green) and that might (orange) support dreissenids.

3.2 Sites Able to Support Dreissenids

Castaic Lake Outlet, Castaic Lake at Jensen Influent, Silvewood Lake Outlet at Devil Canyon, Devil Canyon Headworks, and Lake Perris Outlet all have high calcium concentrations. The pH at each of these sites is also above limiting levels allowing these sites to support dreissenid populations. California Aqueduct Check 41 also has a majority of samples with high calcium and high pH however some samples collected at this site had lower calcium levels.

3.2.1 California Aqueduct Check 41

The average calcium concentration at the California Aqueduct Check 41 is 21.4 mg/L and the average pH is 8.0. All samples collected at this site between January 2000 and September 2010 had pH values above the minimum limit required for dreissenid mussels and all but two samples had calcium concentrations above the minimum limit (Figure 20). Only 1.6% of samples collected had conditions that would be unable to support mussels whereas 75.6% had high calcium and high pH (Figure 21). Based on these results, this site is likely to be able to support a long-term dreissenid population.

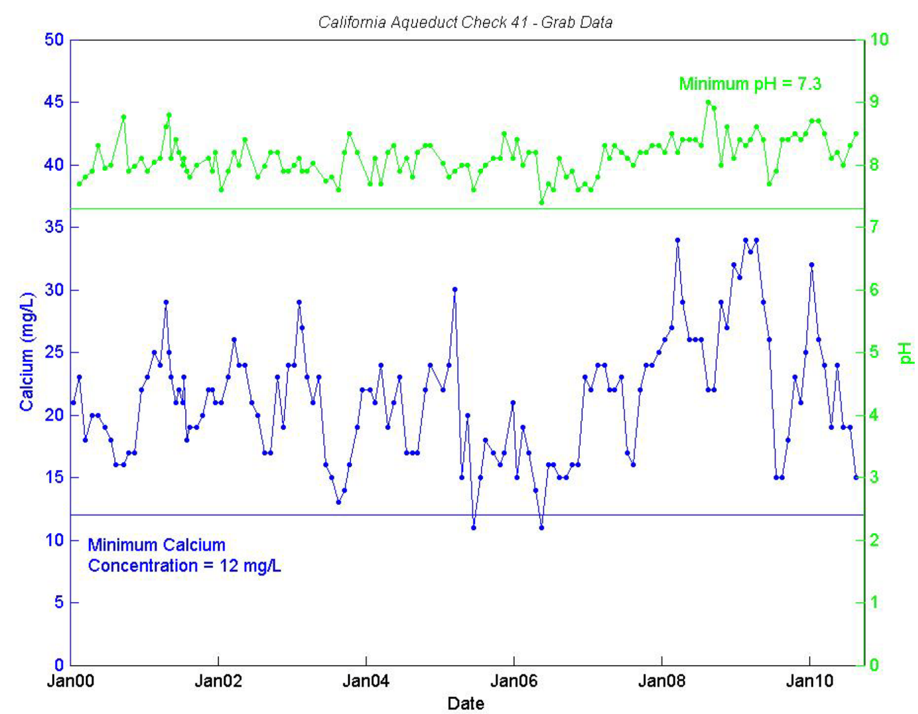


Figure 20. Changes in calcium and pH at Check 41 in the California Aqueduct.

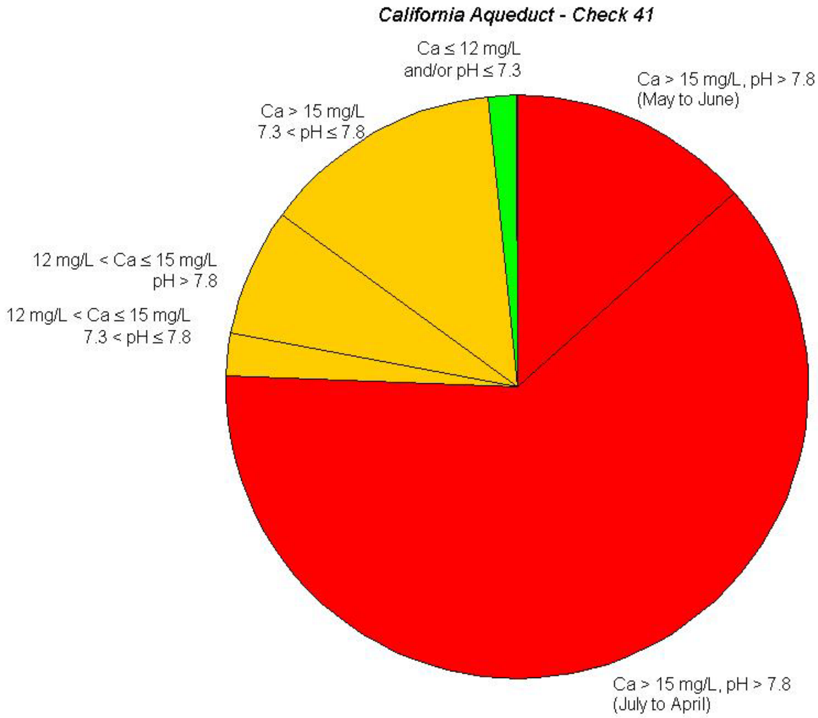


Figure 21. Distribution of samples from California Aqueduct Check 41 into zones of low, marginal, and high calcium and pH. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

3.2.2 Castaic Lake Outlet

Castaic Lake Outlet has very high calcium and pH levels (Figure 22). The average calcium concentration at this site is 27.3 mg/L and the average pH is 8.3. Figure 23 shows that the majority of samples (93.5%) collected between January 2000 and September 2010 have high calcium and high pH values. The remaining 6.5% of the samples have high calcium and marginal pH. Under these conditions, this site could support a long-term mussel population.

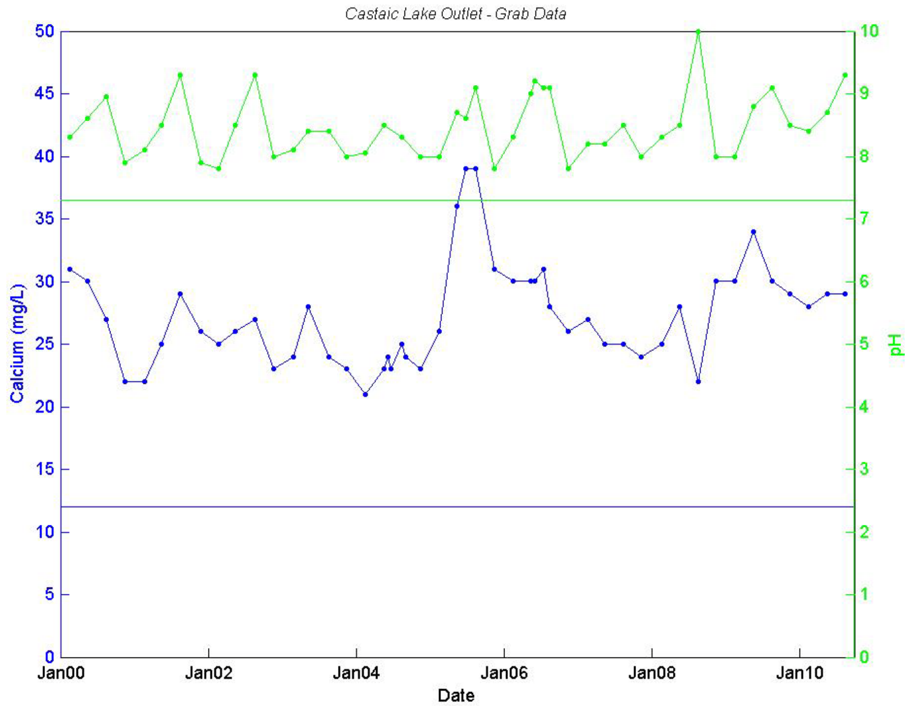


Figure 22. Changes in calcium concentrations and pH levels at Castaic Lake Outlet.

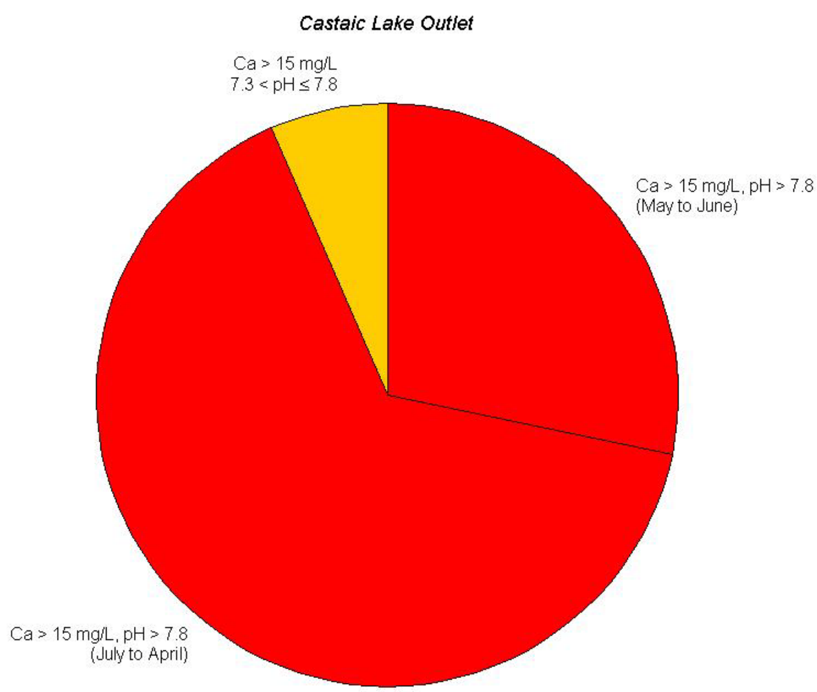


Figure 23. A large percentage (93.5%) of samples collected at Castaic Outlet has high levels of both calcium and pH (red). The remaining samples had high calcium and marginal pH (orange).

3.2.3 Castaic Lake at Jensen Influent

The calcium concentration in samples from Castaic Lake at Jensen Influent between January 2000 and September 2010 are all well above the minimum of 12 mg/L (Figure 24). The average calcium concentration during this time is 26.9 mg/L. The pH is also above the minimum limit in all samples with an average of 7.8. In 62.5% of samples collected, both the calcium and pH are high enough to support mussels (Figure 25). The remaining 36.5% of samples have high calcium levels and marginal pH. It is believed that a long-term dreissenid population could be supported at this site.

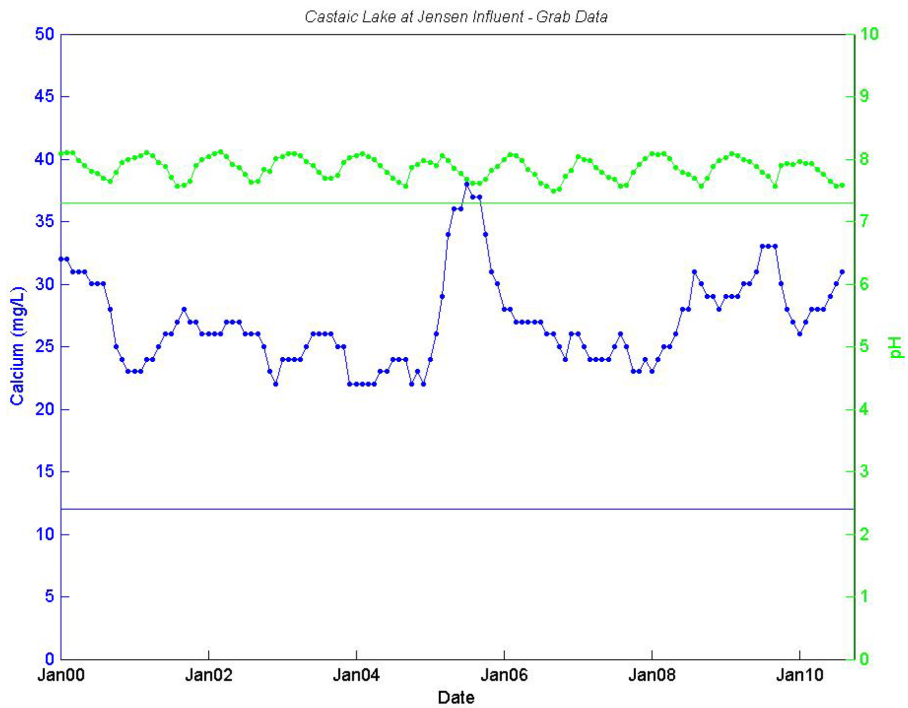


Figure 24. Changes in calcium and pH in samples from Castaic Lake at Jensen Influent.

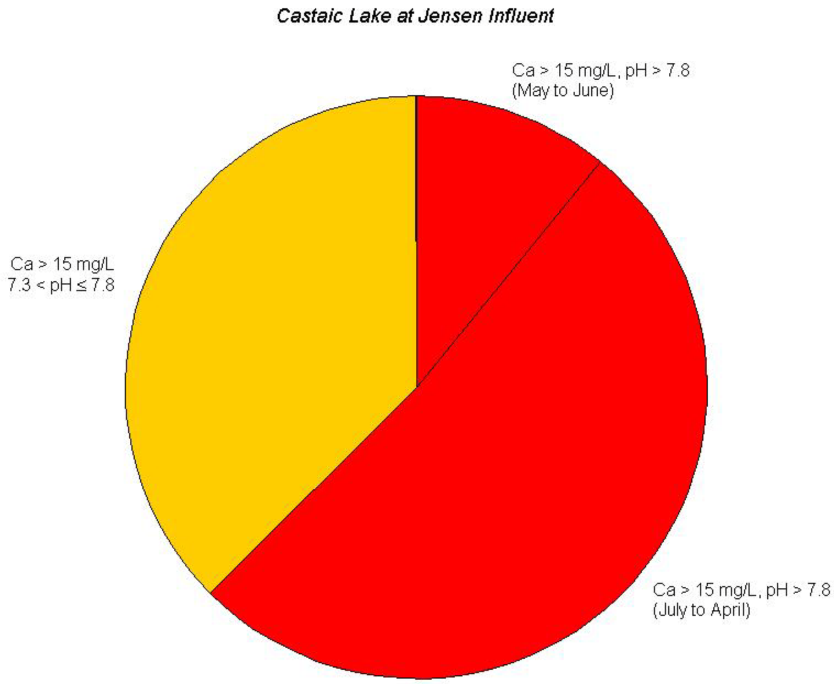


Figure 25. In samples from Castaic Lake at Jensen Influent, 62.5% had high calcium and high pH (red) whereas the remaining samples had high calcium with marginal pH (orange).

3.2.4 Silverwood Lake Outlet at Devil Canyon

Silverwood Lake Outlet at Devil Canyon has calcium concentrations above 12 mg/L with an average over the time period examined of 20.8 mg/L (Figure 26). The pH is also above the minimum limit of 7.3 in all but one sample collected and the overall average pH is 8.0. Silverwood Lake Outlet at Devil Canyon has a majority (92.1%) of samples with both high calcium and high pH (Figure 27). 6.9% of the samples are considered to be marginal and the remaining samples were unsuitable for mussel survival. This site is expected to support dreissenid mussels should they be introduced to the system.

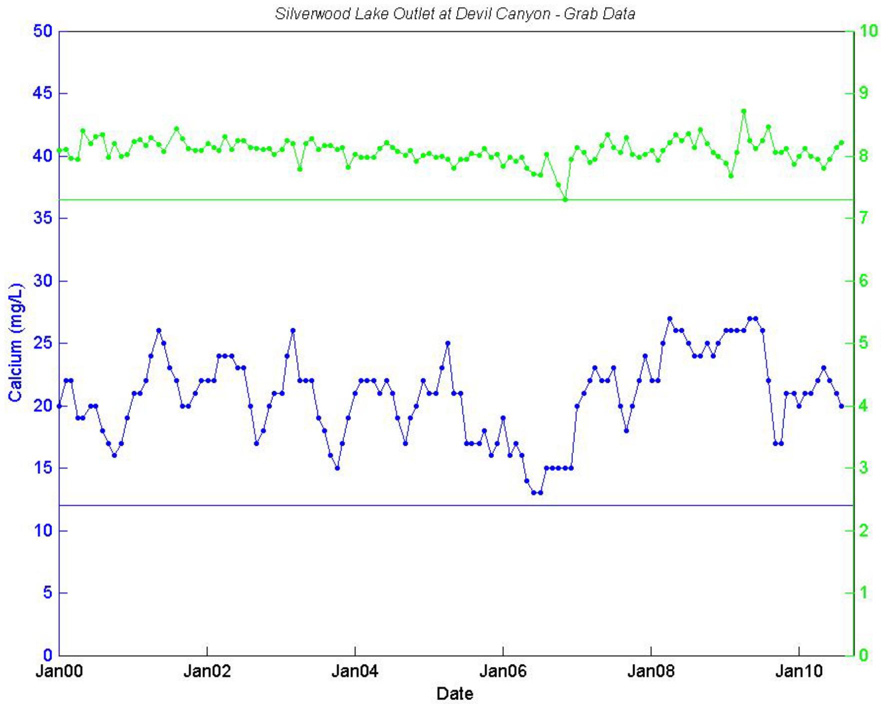


Figure 26. Changes in calcium and pH levels at Silverwood Lake Outlet at Devil Canyon.

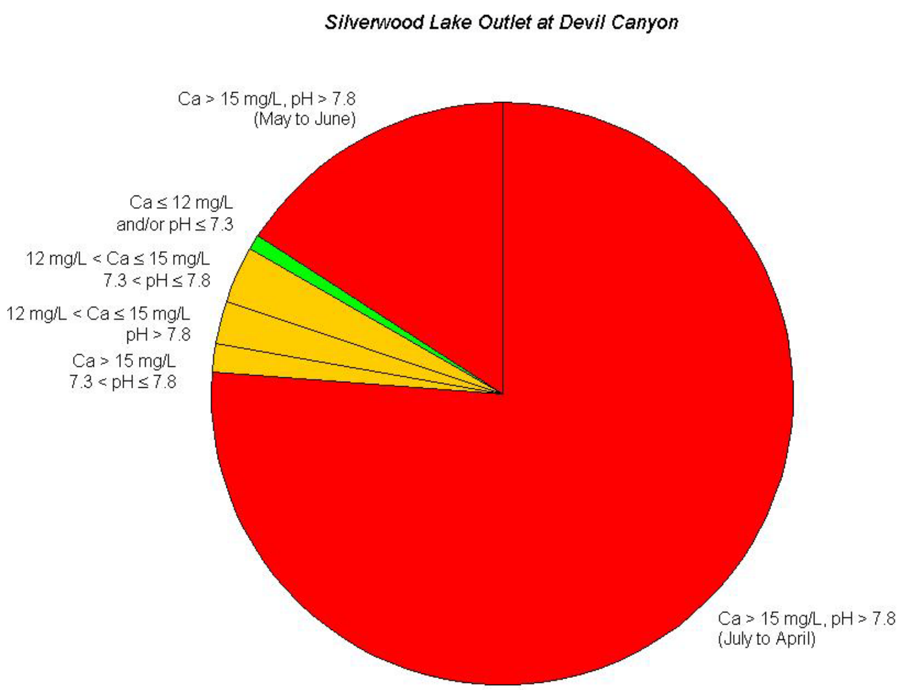


Figure 27. The majority (92.1%) of samples from Silverwood Lake at Devil Canyon have high calcium and high pH (red). A small percentage (1%) of samples had low calcium and low pH (green) whereas the remaining samples are considered to be marginal (orange).

3.2.5 Devil Canyon Headworks

The average calcium concentration at Devil Canyon Headworks is 21.1 mg/L and the average pH is 8.1. One sample in the last decade has a pH that dropped below the minimum level of 7.3 however all other samples are above the minimum levels for calcium and pH (Figure 28). Overall, the majority of samples (88.6%) have both high calcium and high pH. Marginal levels of calcium or pH are found in 10.4% of the samples collected and the one sample that had low pH accounted for the remaining 1% of the samples in the low calcium-low pH range (Figure 29). This site could support a dreissenid population.

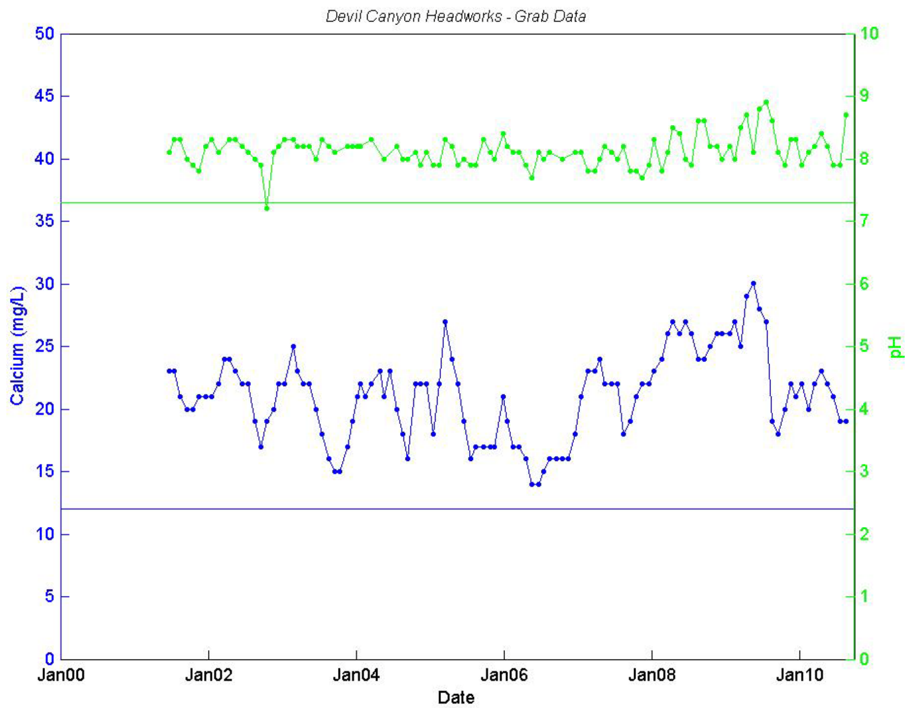


Figure 28. Changes in calcium and pH at Devil Canyon Headworks.

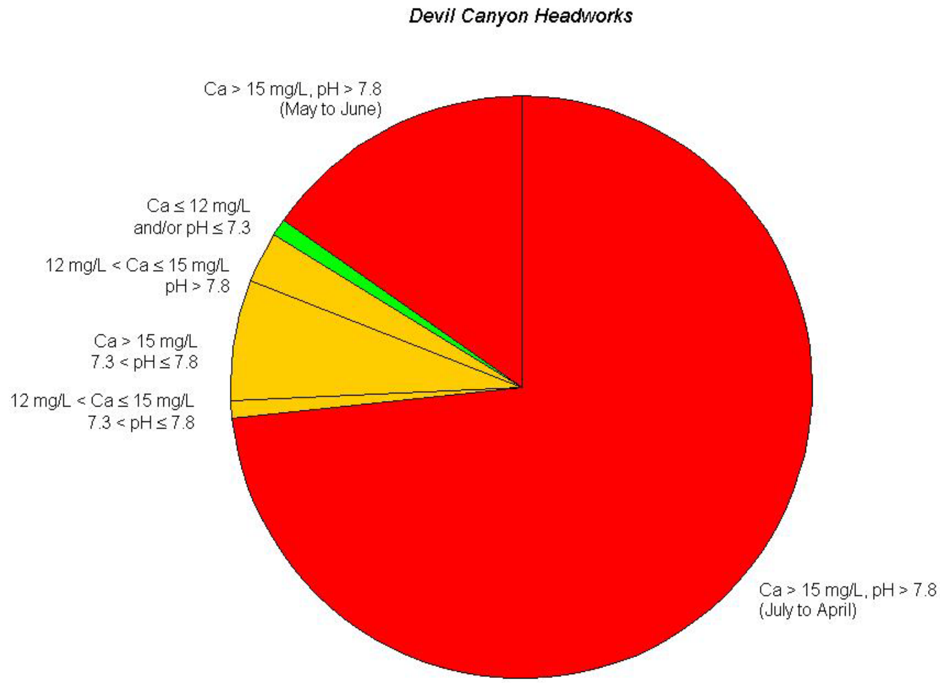


Figure 29. The majority (88.6%) of samples from Devil Canyon Headworks have high calcium and high pH (red). A small percentage (1%) of samples had low calcium and low pH (green) whereas the remaining samples are considered to be marginal and potentially able to support mussels (orange).

3.2.6 Lake Perris Outlet

All samples collected at Lake Perris Outlet have calcium concentrations above 15 mg/L and pH levels above 7.8 (Figure 30). The average calcium and pH at this site are 27.4 mg/L and 8.4, respectively. The high calcium and pH levels at the Outlet suggest that Lake Perris is at risk to dreissenids. Should mussels be introduced to this water body, a long-term population would likely be supported.

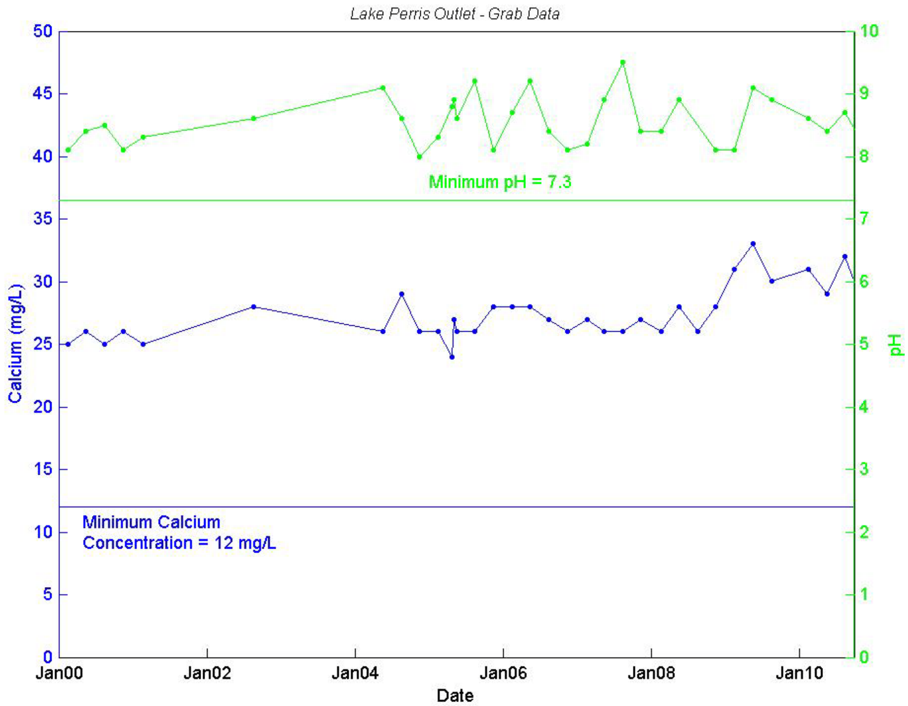


Figure 30. Changes in calcium and pH at the Lake Perris Outlet.

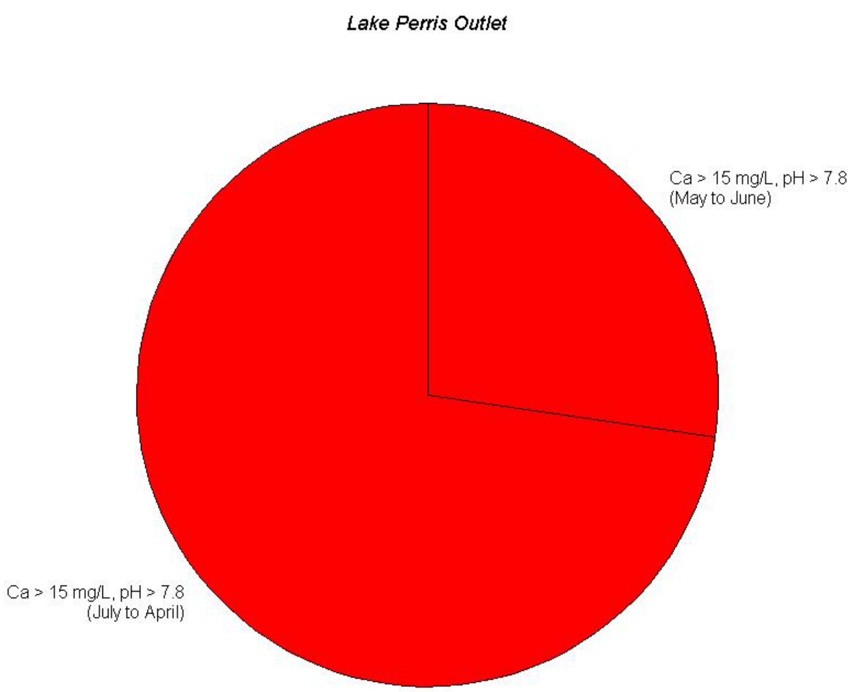


Figure 31. All samples collected at Lake Perris had both high calcium and high pH (red).

3.3 Sites Potentially Able to Support Dreissenids

Several sites examined had calcium concentrations and pH levels that were within tolerable ranges for dreissenid survival on several occasions in the last decade, but they also had periods of time when the conditions were limiting. Based on the current state of knowledge it is uncertain if these sites will be able to support long-term dreissenid populations. Each of these sites was examined in detail but conclusions should be verified with additional studies of dreissenid mussel survival under marginal conditions.

3.3.1 Barker Slough Pumping Plant

Barker Slough Pumping Plant had both continuous and grab data available. Figure 32 shows grab and continuous conductivity data for this time period and Figure 33 shows grab and continuous pH data. The average conductivity for the grab data is 307.8 μS/cm and the average conductivity for the continuous data is 309.2 μS/cm. The average pH for the grab data is 7.4 and for the continuous data is 7.3. A paired t-test between the grab and continuous data did not return statistically significant differences for conductivity ($p>0.05$) or pH ($p>0.05$).

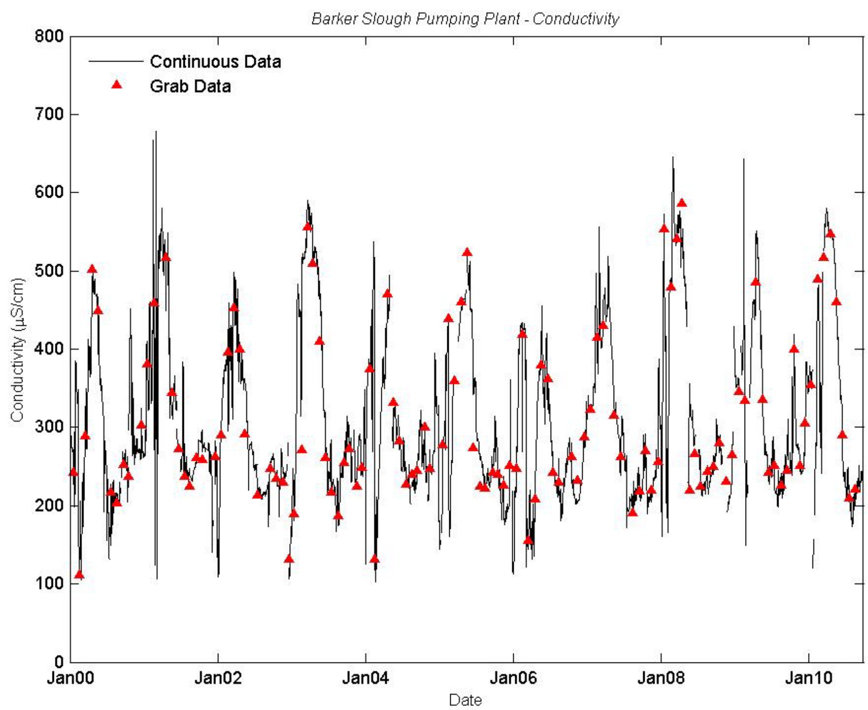


Figure 32. Grab and continuous conductivity data for Barker Slough Pumping Plant.

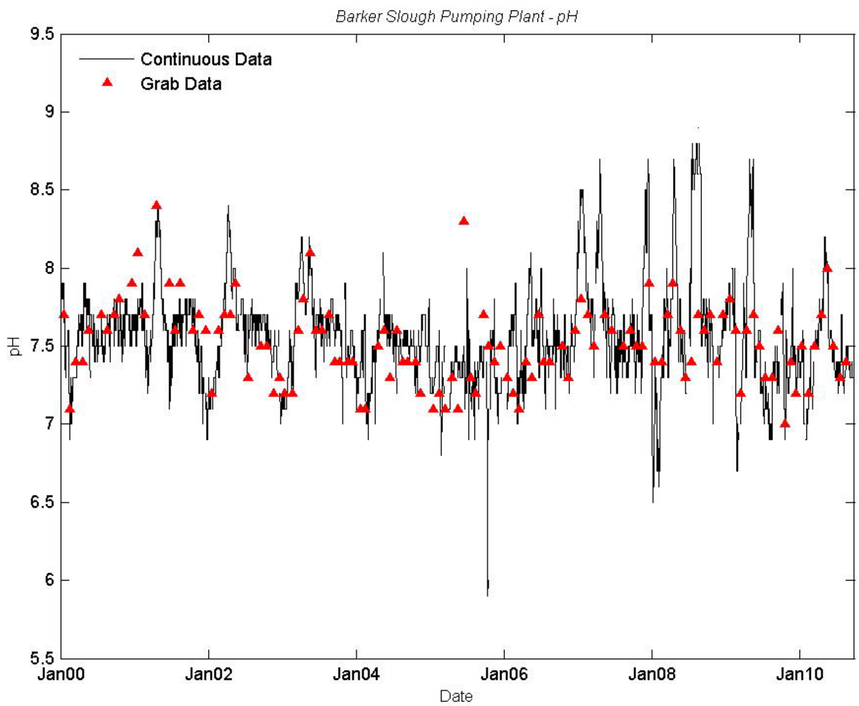


Figure 33. Grab and continuous pH data for Barker Slough Pumping Plant.

The relationship between electrical conductance and calcium in the grab data for Barker Slough Pumping Plant returned a moderately strong relationship (r^2 = 0.7101) (Figure 34). This relationship was used to calculate daily calcium values.

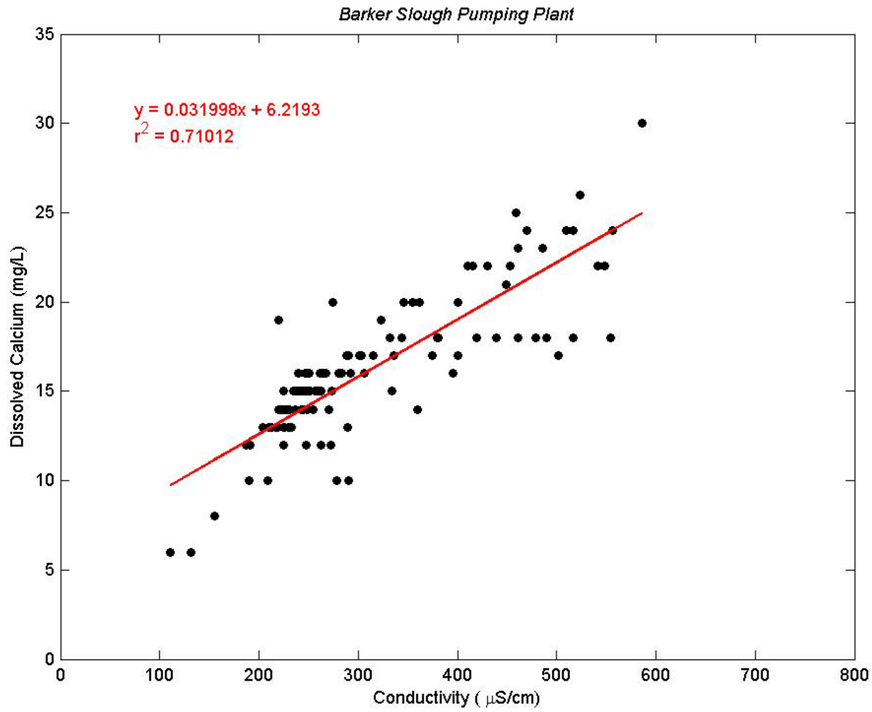


Figure 34. A linear relationship exists between conductivity and dissolved calcium at Barker Slough Pumping Plant. The resulting linear equation was used to calculate daily calcium data from continuous conductivity data.

The average calcium concentration at the Barker Slough Pumping Plant over the last decade is 16.1 mg/L and the average pH is 7.3 (Figure 35). These calcium levels are considered to be marginal but potentially able to support dreissenids. However, we believe that marginal calcium levels require a pH of 7.8 or greater to allow mussels to survive. Given that the average pH at the Barker Slough Pumping Plant is only 7.3, it is unlikely that mussels would be able to survive at this site. In fact, over the last decade, less than 10% of samples collected were at high enough calcium and pH levels to support a dreissenid population (Figure 36).

For the period of time from January 2008 to September 2010, the average calcium at this site increased to 16.8 mg/L and the average pH was 7.4. This calcium value is slightly higher than over the entire period examined (i.e. January 2000 to September 2010). The increase in calcium, though, may not be high enough to support mussels at the given pH. Furthermore, only 10.4% of the samples collected in the last three years had both calcium and pH levels that could support dreissenids (Figure 37). As such, we believe that this site is unlikely to be able to support mussels.

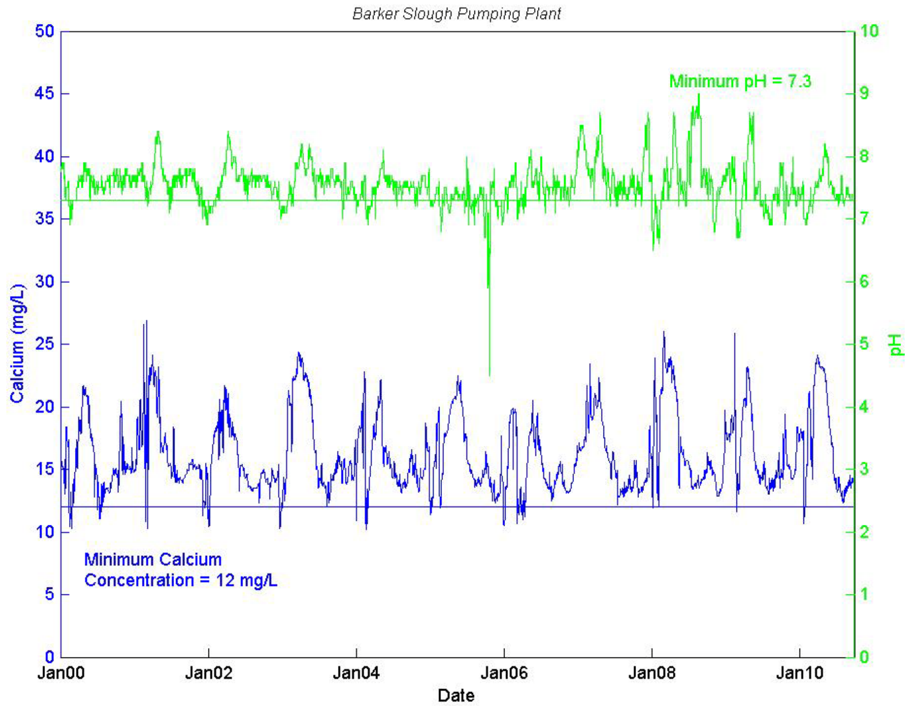


Figure 35. Fluctuations in calcium and pH at the Barker Slough Pumping Plant.

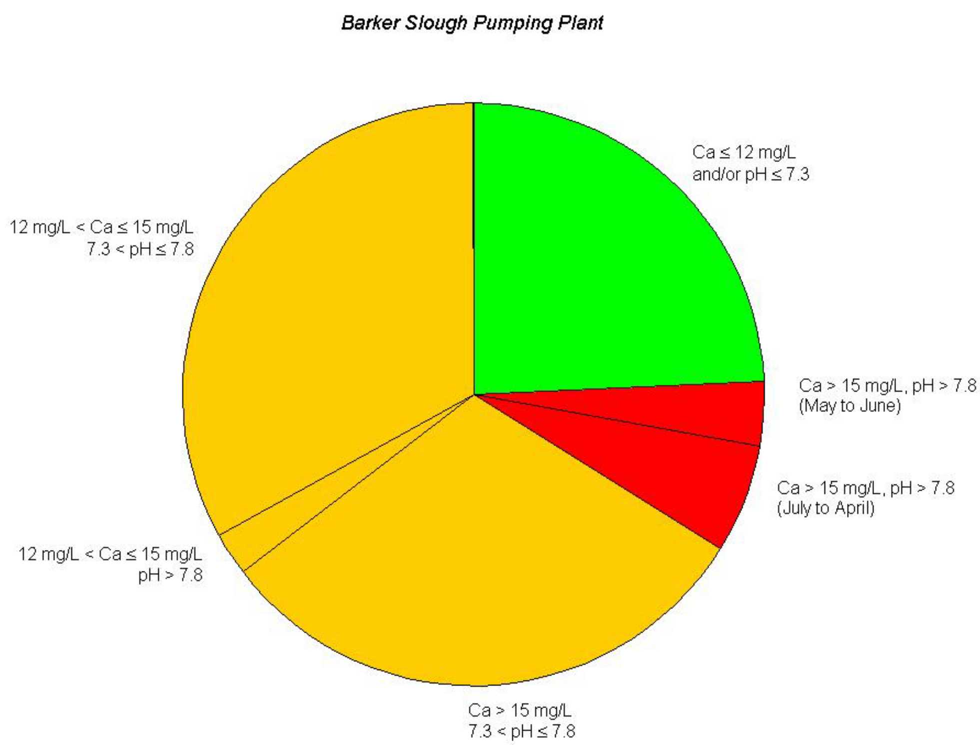


Figure 36. Distribution of samples from Barker Slough Pumping Plant into zones of low, marginal, and high calcium and pH. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

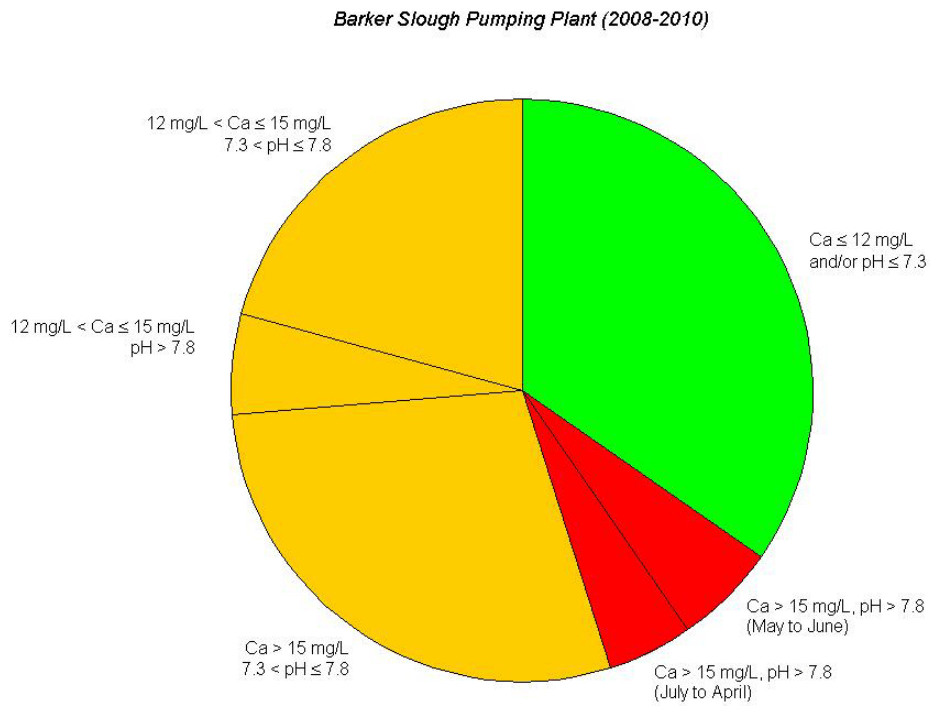


Figure 37. Distribution of samples from Barker Slough Pumping Plant into zones of low, marginal, and high calcium and pH for 2008 to 2010. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

3.3.2 San Joaquin River near Vernalis

San Joaquin River near Vernalis has an average calcium concentration of 29.4 mg/L and an average pH of 7.6. Calcium values appear to be lower in 2000, 2005 and 2010, however the average calcium concentration at this site is the highest of all sites examined (Figure 38). The fluctuations in calcium in the San Joaquin River near Vernalis, though, suggest that there may be a period of low calcium every 5 years.

Approximately 35% of samples collected at this site over the last decade are in the high calcium, high pH range for dreissenids (Figure 39). This increases to 55.2% when examining samples collected between 2008 and 2010 (Figure 40). Only 10% to 11% of samples have conditions which are unfavorable for mussels. As such, dreissenids may be able to survive in the San Joaquin River near Vernalis however it is uncertain if a long-term population could be sustained given the periodic fluctuations in calcium.

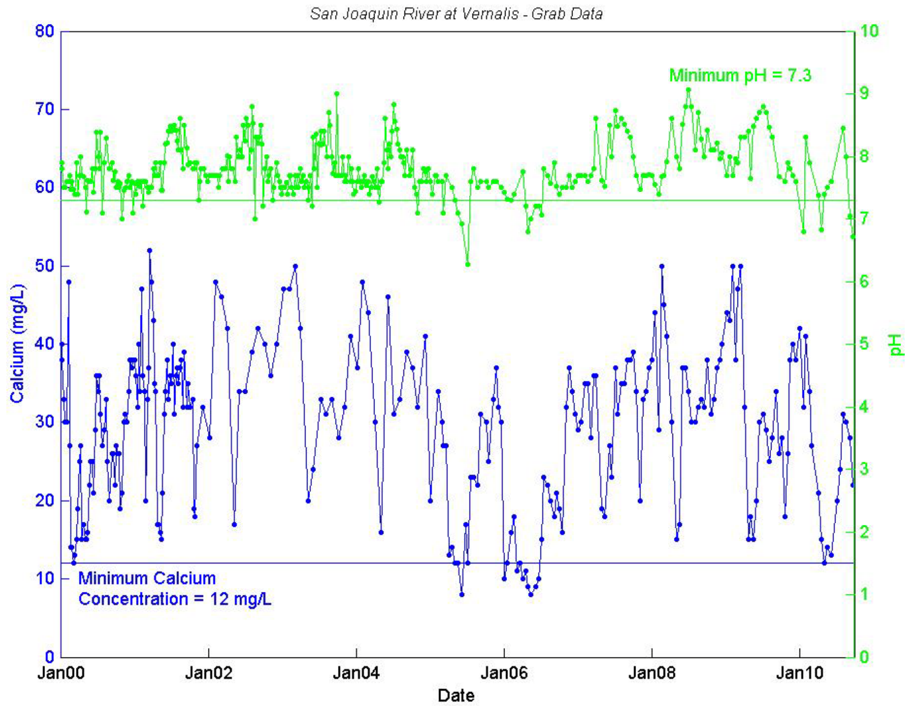


Figure 38. Changes in calcium and pH in the San Joaquin River near Vernalis.

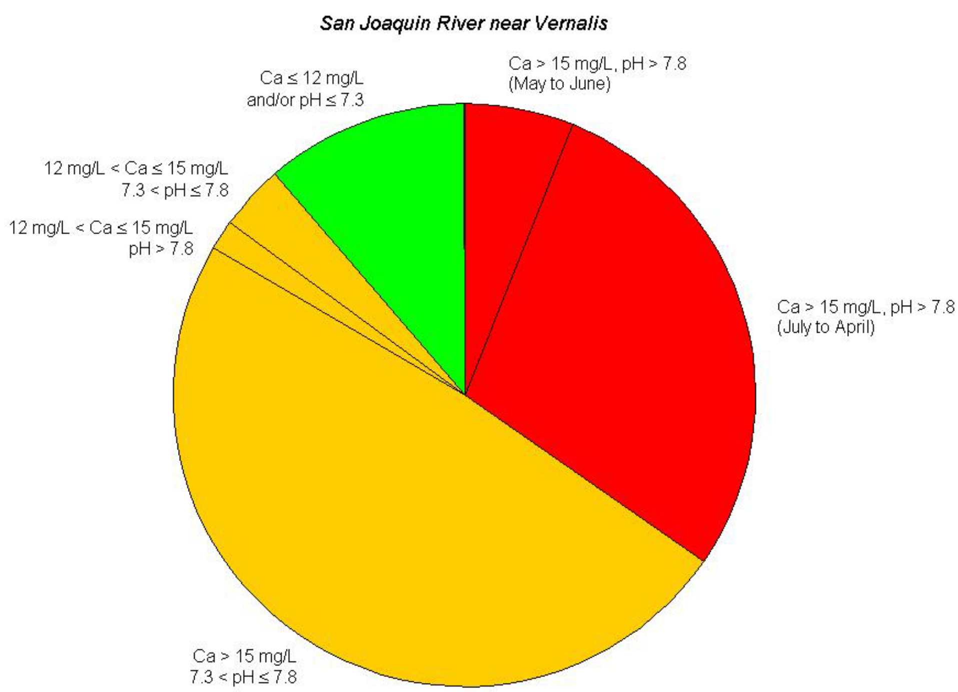


Figure 39. Distribution of samples from San Joaquin River near Vernalis into zones of low, marginal, and high calcium and pH. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

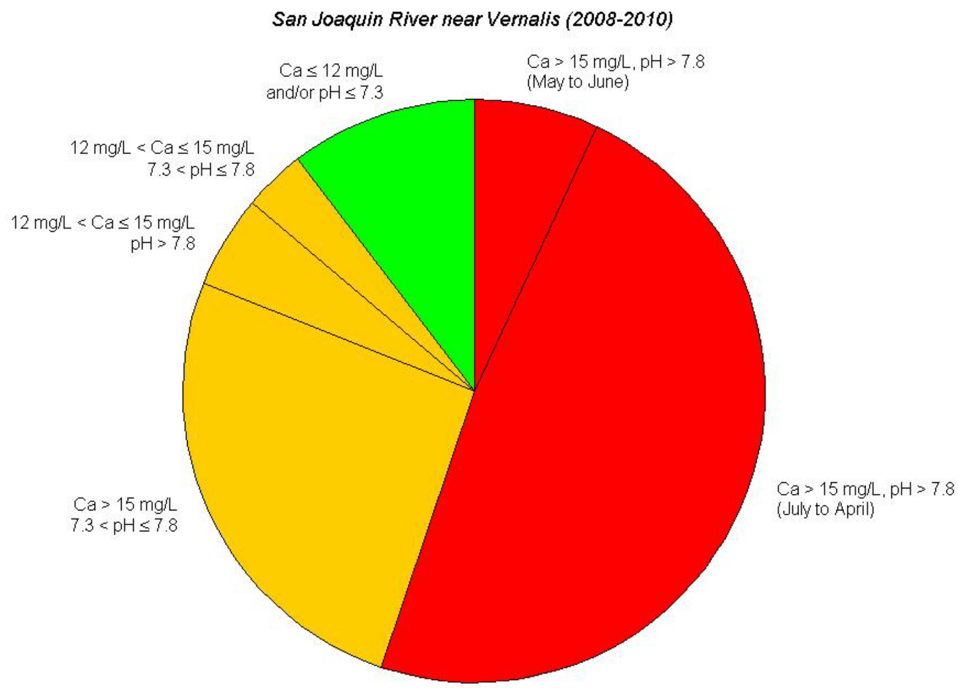


Figure 40. Distribution of samples from San Joaquin River near Vernalis into zones of low, marginal, and high calcium and pH for 2008 to 2010. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

3.3.3 Clifton Court Forebay Inlet

The average calcium concentration at Clifton Court Forebay Inlet is 17.9 mg/L and the average pH is 7.4. In the last decade, large fluctuations in calcium between a minimum of 9 mg/L and maximum of 49 mg/L were noted, and pH ranged from 5.9 to 9.1 (Figure 41). During this time, 8.6% of samples had calcium concentrations and pH levels that were high enough to support mussels (Figure 42). When examining samples from 2008 to 2010 only, the percentage of high calcium, high pH samples drops to 6.3% (Figure 43). Since few samples collected at Clifton Court Forebay Inlet have conditions favorable for dreissenids, it is unlikely that this site has the potential to support a long-term dreissenid population.

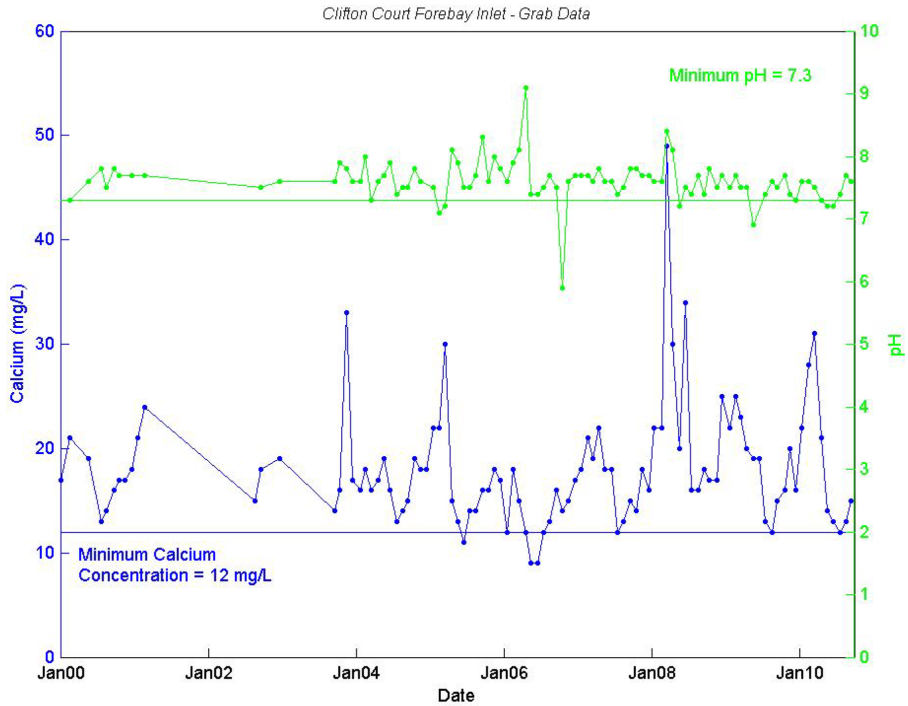


Figure 41. Changes in calcium and pH at the Clifton Court Forebay Inlet.

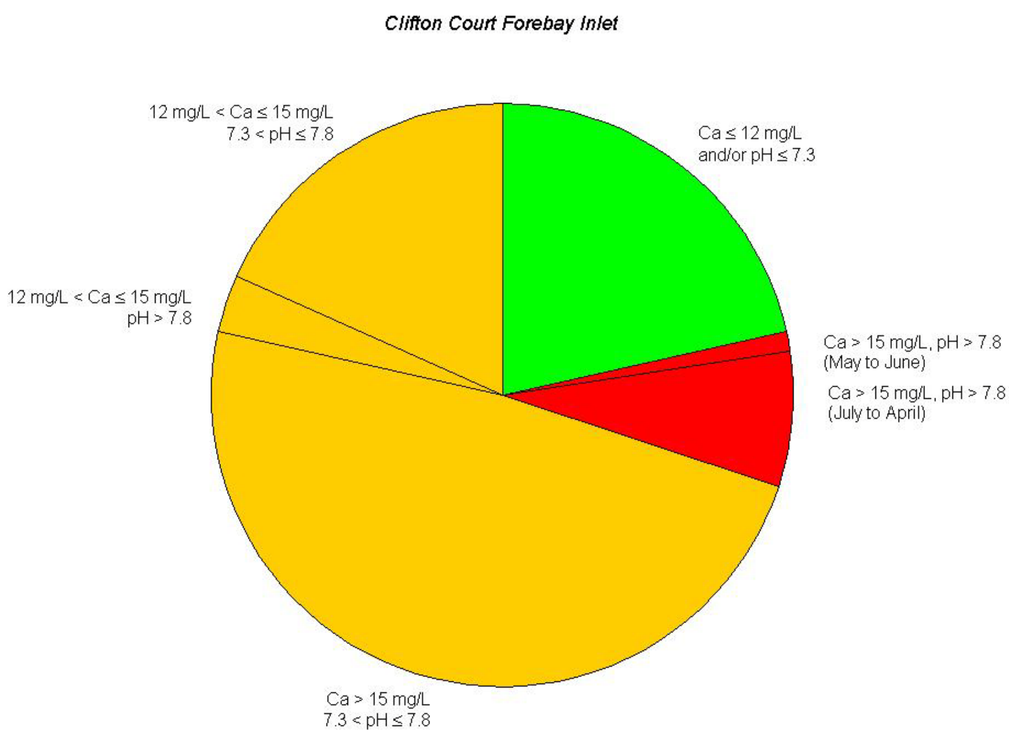


Figure 42. Distribution of samples from Clifton Court Forebay Inlet into zones of low, marginal, and high calcium and pH. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

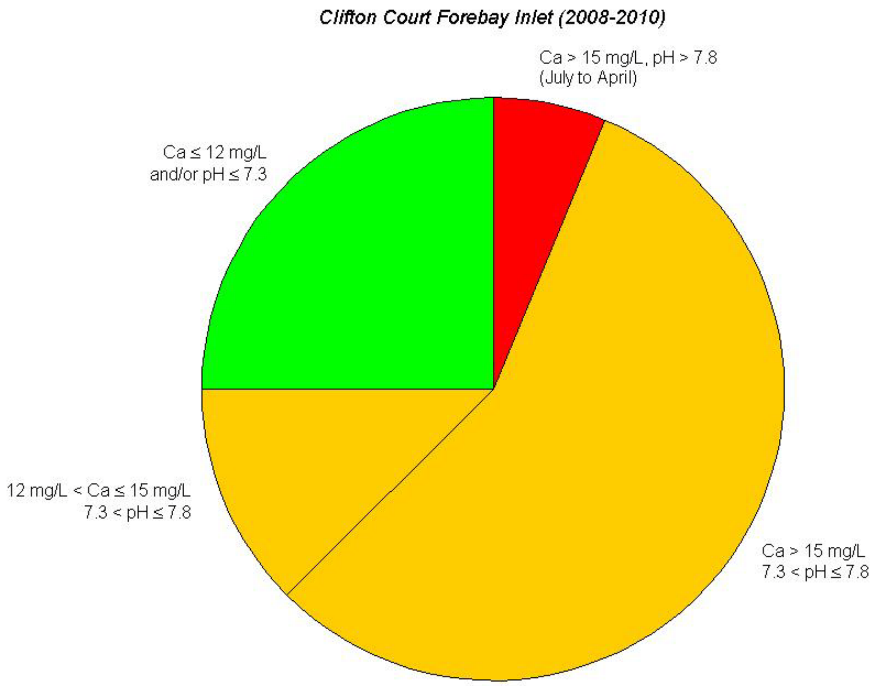


Figure 43. Distribution of samples from Clifton Court Forebay Inlet into zones of low, marginal, and high calcium and pH for 2008 to 2010. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

3.3.4 H. O. Banks Pumping Plant

Figure 44 shows changes in calcium and pH over the last decade at H.O. Banks Pumping Plant. The average calcium at this site is 17.8 mg/L and the average pH is 7.6. Of all samples collected at H.O. Banks Pumping Plant, 25.4% had high calcium and high pH (Figure 45). This percentage increases to 28.1% for samples collected between 2008 and 2010 (Figure 46). A greater percentage of samples (65.6%) are in the marginal range between 2008 and 2010 compared to samples (56.8%) for the entire 2000-2010 period. Based on these findings, H.O. Banks Pumping Plant has the potential to support a dreissenid population however further investigation of this site is warranted.

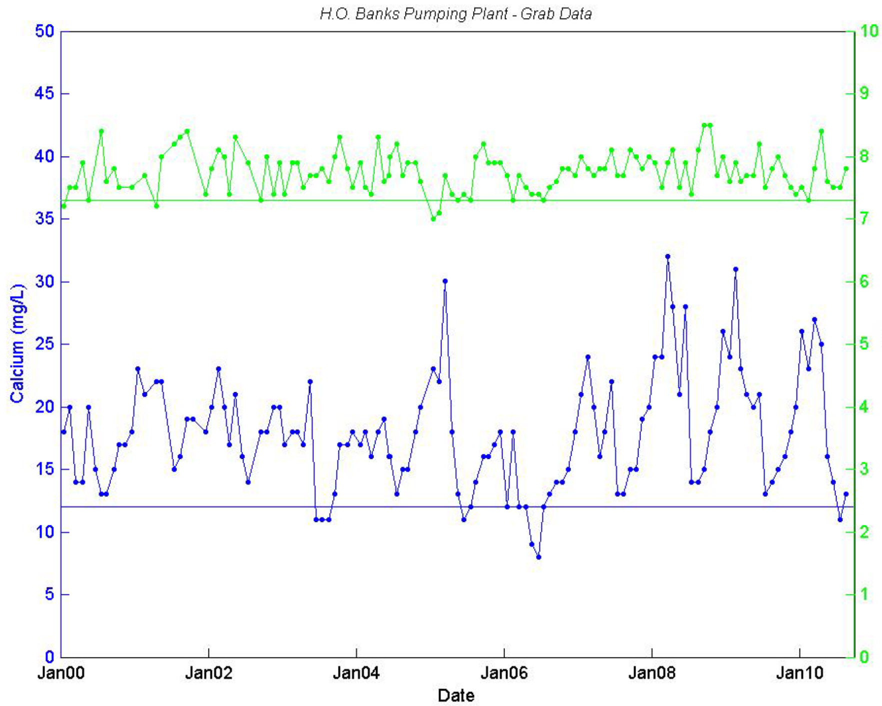


Figure 44. Changes in calcium and pH at H. O. Banks Pumping Plant.

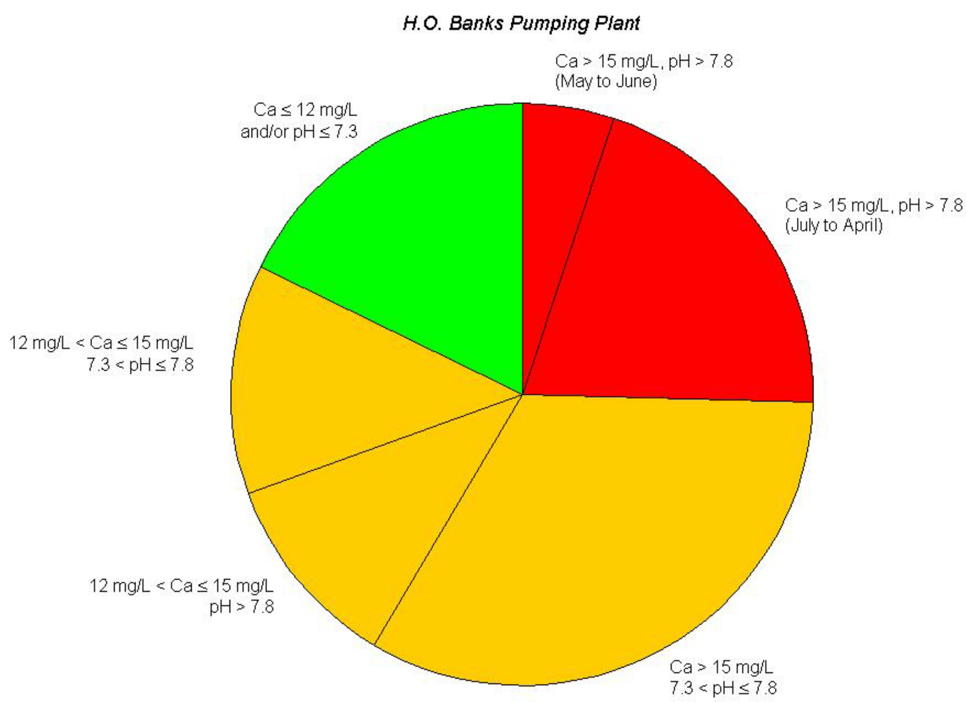


Figure 45. Distribution of samples from H. O. Banks Pumping Plant into zones of low, marginal, and high calcium and pH. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

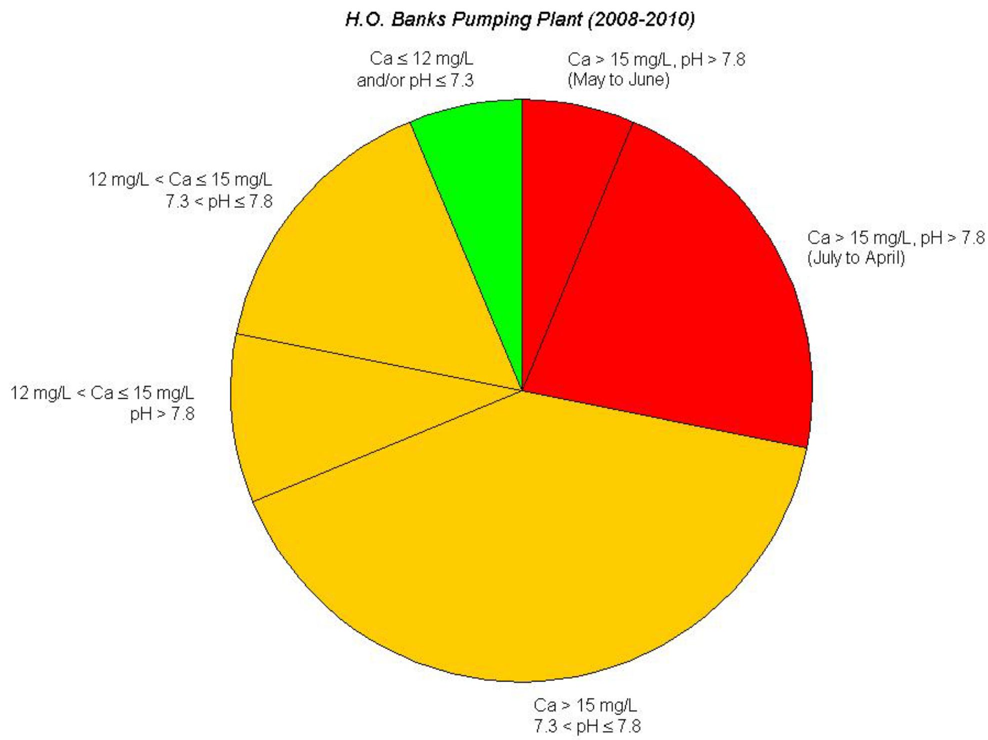


Figure 46. Distribution of samples from H. O. Banks Pumping Plant into zones of low, marginal, and high calcium and pH for 2008 to 2010. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

3.3.5 Delta Mendota Canal Headworks

Large fluctuations in calcium concentrations were noted in the data for Delta Mendota Canal Headworks (Figure 47). The average calcium concentration at this site is 22.6 mg/L and the average pH is 7.1. Between 2000 and 2010, Delta Mendota Canal Headworks had 19.2% of samples with high calcium and high pH (Figure 48). Since 2008 though, only 12.5% of samples were in the favorable range for mussels (Figure 49). Furthermore, when examining the last three years of data alone, no samples collected are in the high calcium, high pH range during the mussel breeding season. There is the potential for adults introduced at this site to survive and reproduce, however conditions during the peak breeding season do not appear to be favorable for the growth and survival of veligers. As such, this site may not be able to support a long-term dreissenid population.

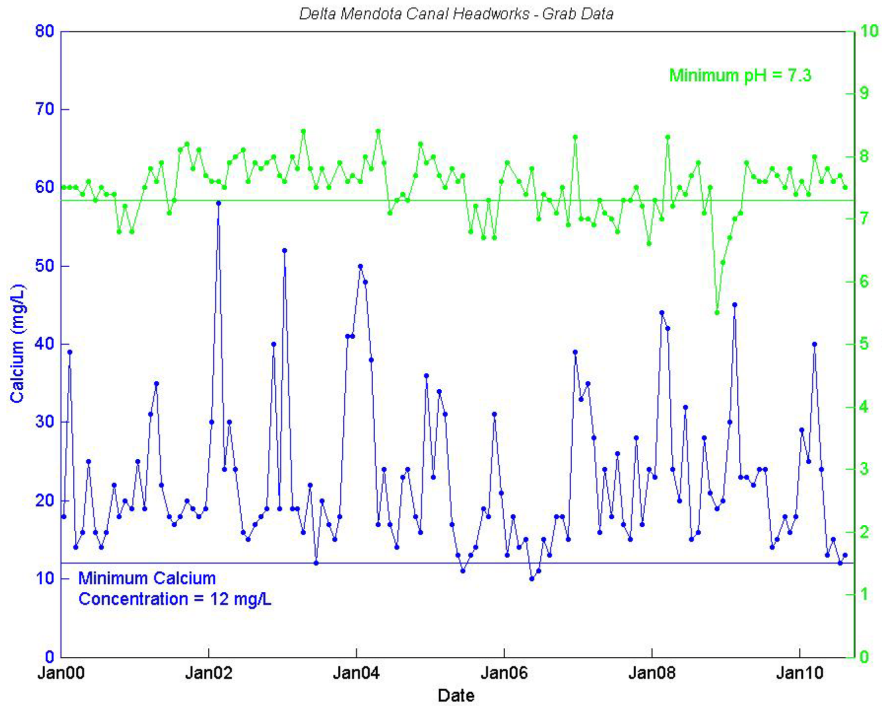


Figure 47. Changes in calcium and pH at the Delta Mendota Canal Headworks.

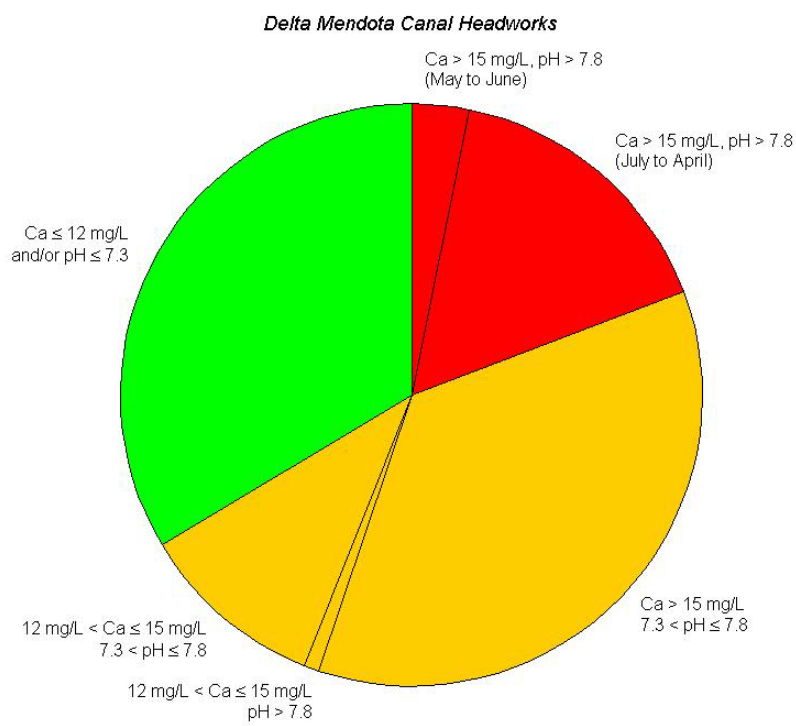


Figure 48. Distribution of samples from Delta Mendota Canal Headworks into zones of low, marginal, and high calcium and pH. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

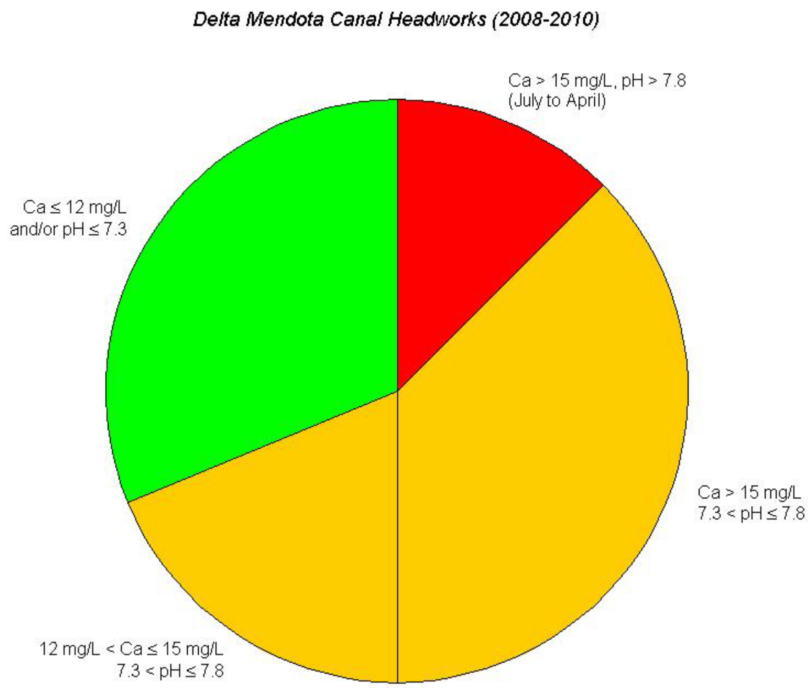


Figure 49. Distribution of samples from Delta Mendota Canal Headworks into zones of low, marginal, and high calcium and pH for 2008 to 2010. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

3.3.6 Del Valle Check 7

Samples collected at Del Valle Check 7 between January 2000 and September 2010 had an average calcium concentration of 17.5 mg/L and an average pH of 7.9. Figure 50 shows that 17 (14%) samples had calcium concentrations at or below 12 mg/L and two samples were at or below a pH of 7.3. Overall, 46.0% of samples collected over the last decade fall in the high calcium, high pH range (Figure 51). This percentage increases when looking at 2008 to 2010 only (Figure 52). We believe that this site may support dreissenid mussels, however further investigation is needed.

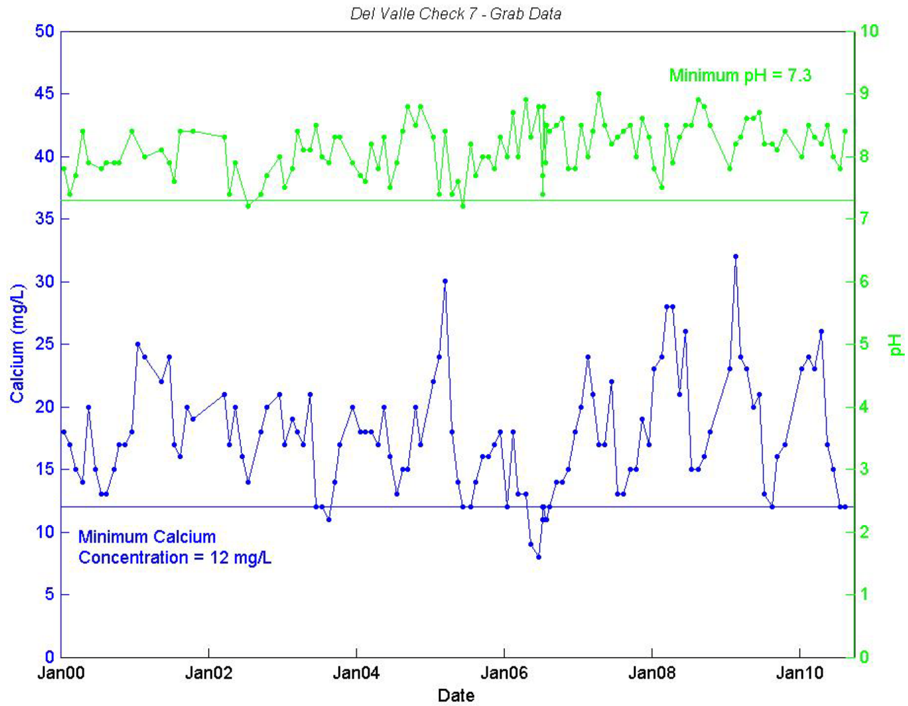


Figure 50. Changes in calcium and pH at Del Valle Check 7.

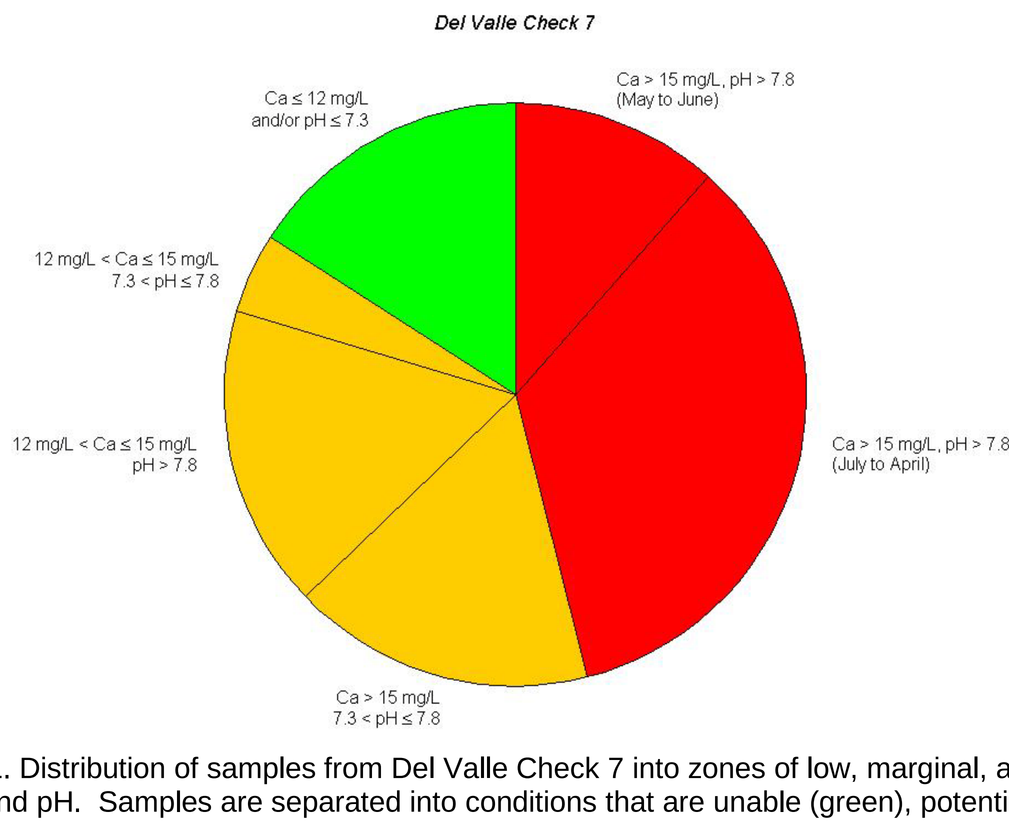


Figure 51. Distribution of samples from Del Valle Check 7 into zones of low, marginal, and high calcium and pH. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

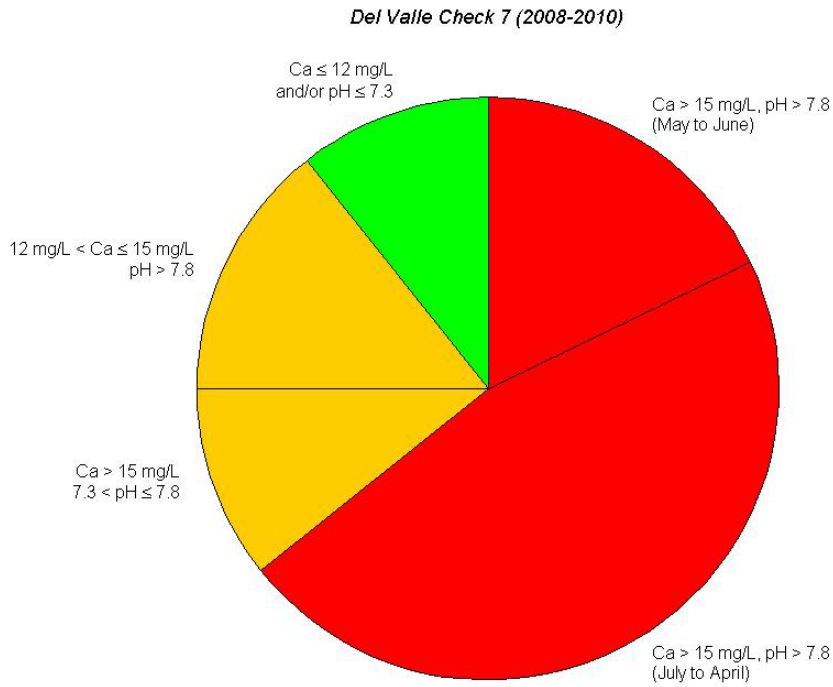


Figure 52. Distribution of samples from Del Valle Check 7 into zones of low, marginal, and high calcium and pH for 2008 to 2010. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

3.3.7 California Aqueduct Check 13

The average calcium concentration at California Aqueduct Check 13 over the last decade is 20.1 mg/L and the average pH is 7.4. During the time period examined, two samples had calcium concentrations at the minimum level whereas all other samples had calcium concentrations higher than 12 mg/L (Figure 53). The pH was at or below the minimum level in 26 (~21%) samples collected, with most of these low pH values occurring between 2005 and 2008. In 25% of samples collected, the calcium concentration was above 15 mg/L and the pH was above 7.8 (Figure 54).

Since 2008, calcium and pH values appear to be rising at Check 13. Between January 2008 and September 2010, 34% of samples have both high calcium and high pH compared to 25% over the entire decade (Figure 55). Given that almost two thirds of samples remain in the low and marginal ranges for calcium and pH, it is unlikely that this site could support a long-term population of dreissenids, however further examination of the effect of marginal calcium and pH levels on dreissenids is necessary.

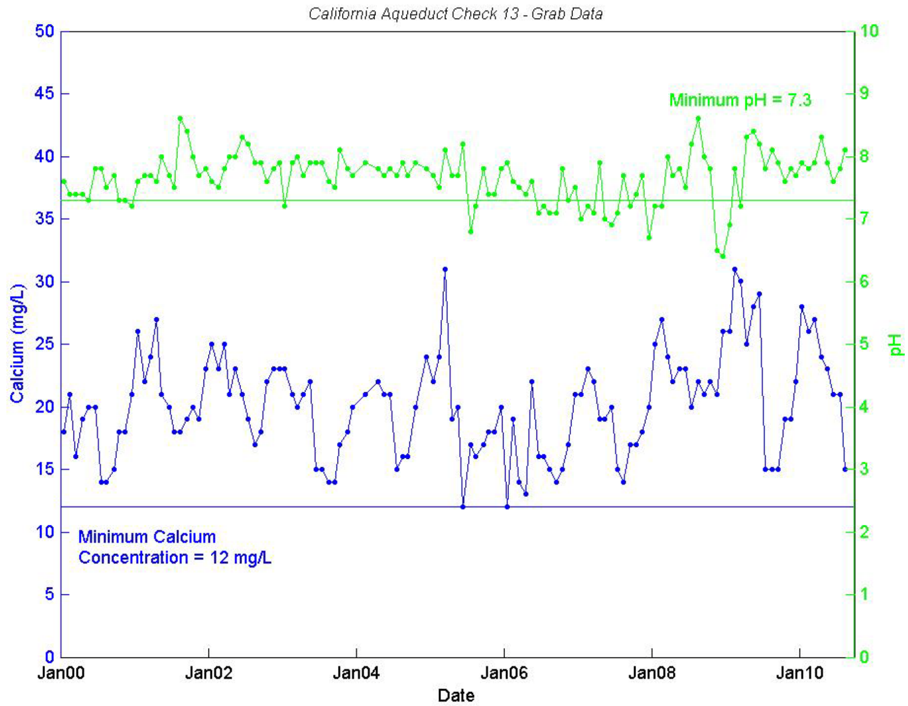


Figure 53. Changes in calcium and pH at Check 13 in the California Aqueduct.

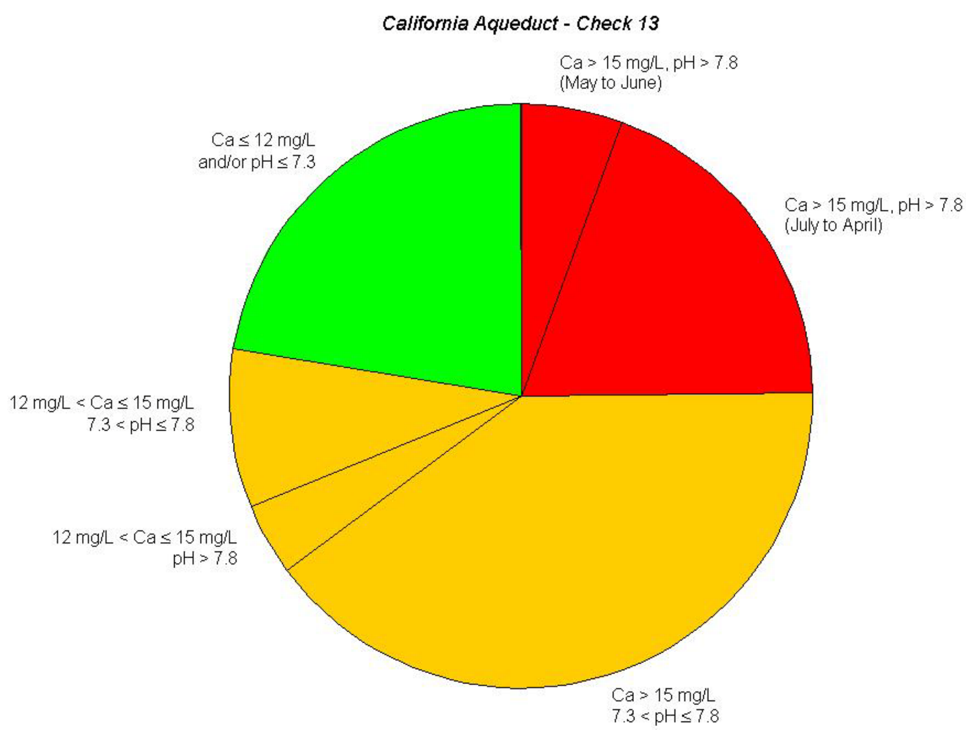


Figure 54. Distribution of samples from 2000 to 2010 in the California Aqueduct Check 13 into zones of low, marginal, and high calcium and pH. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

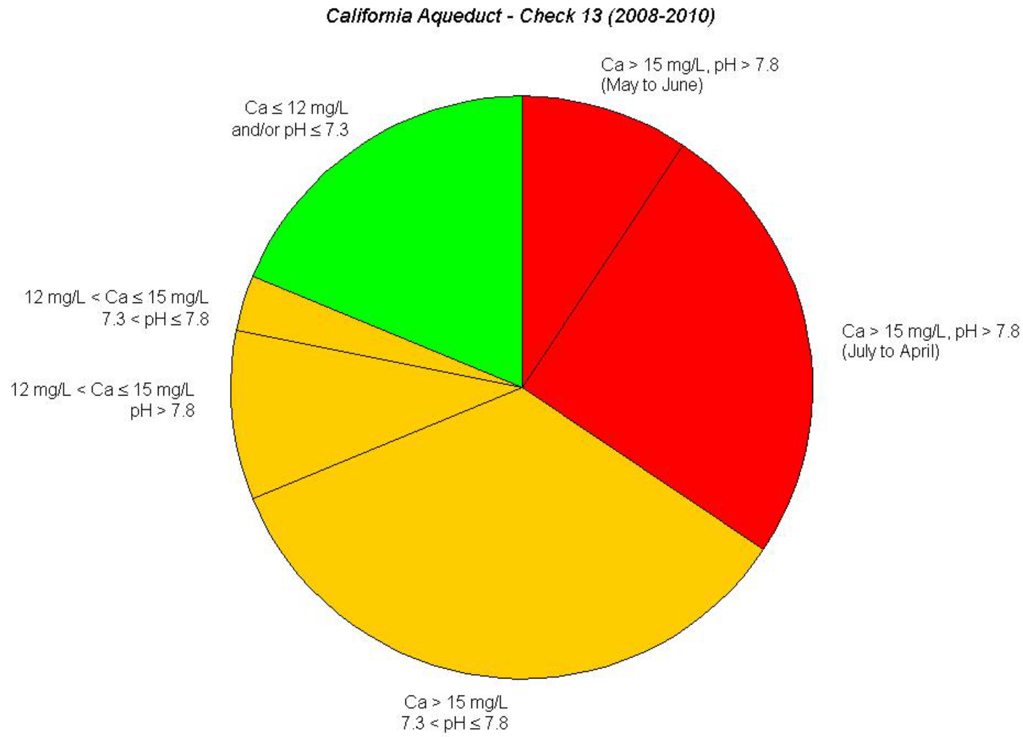


Figure 55. Distribution of samples from January 2008 to September 2010 in the California Aqueduct Check 13 into zones of low, marginal, and high calcium and pH. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

3.3.8 Pacheco Pumping Plant

Calcium concentrations at Pacheco Pumping Plant have been above the minimum limit in all samples collected during the period of time examined (Figure 56). The average calcium concentration at this site is 21.6 mg/L and, with the exception of a larger peak in concentration in 2009, calcium values have fluctuated moderately during the last decade. The average pH at Pacheco Pumping Plant is 7.4 with pH values ranging between 6.2 and 8.6.

When examining all samples together for this site, 32% have high calcium and high pH, and 43% have high calcium and marginal pH (Figure 57). Between 2008 and 2010, the percentage of samples in the marginal pH range increases to 52% whereas those in the low pH and high pH ranges drop to 21% and 28%, respectively (Figure 58). Given that most samples appear to be in the marginal range for supporting dreissenids at Pacheco Pumping Plant, with approximately one third of samples in the high calcium, high pH range, it is possible that this site will support a long-term population. However, further investigation is recommended.

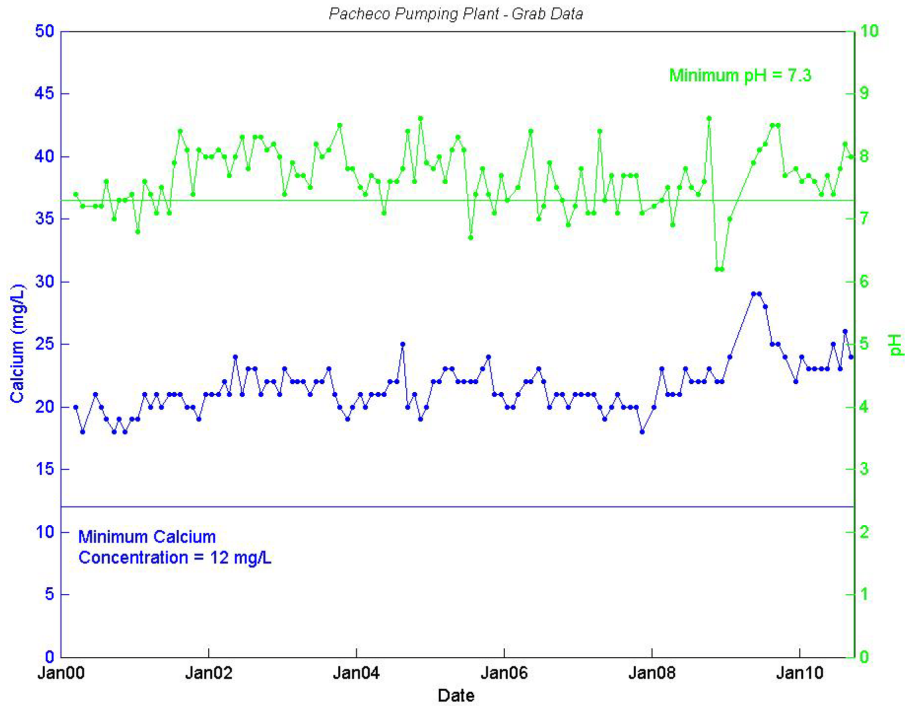


Figure 56. Changes in calcium and pH at Pacheco Pumping Plant.

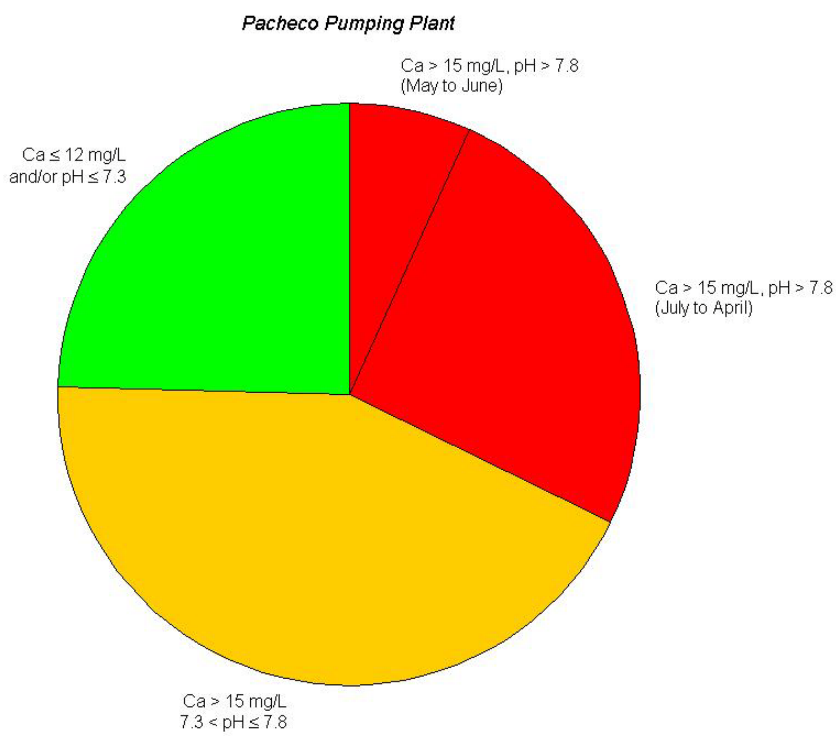


Figure 57. Distribution of samples from Pacheco Pumping Plant into zones of low, marginal, and high calcium and pH. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

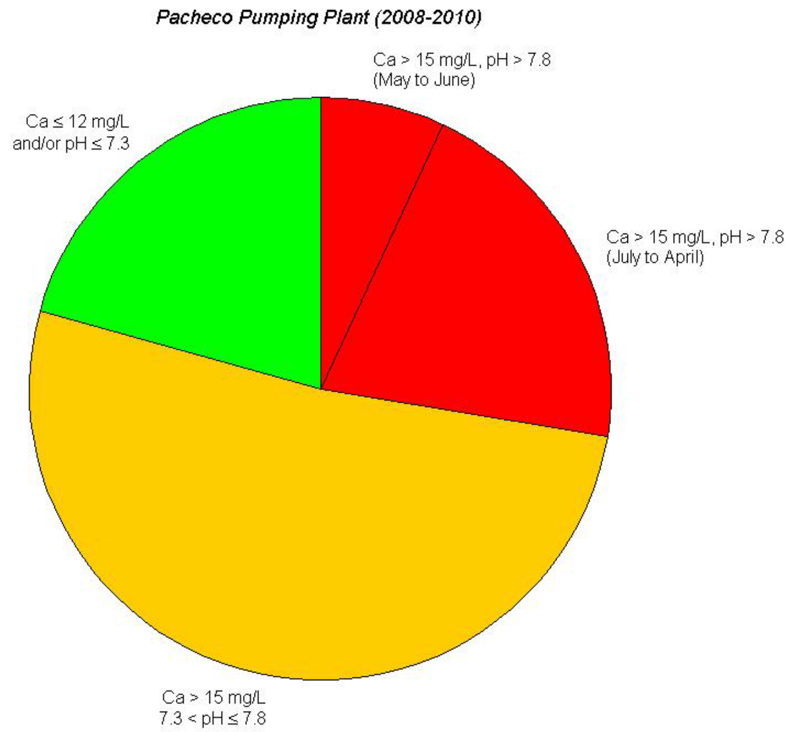


Figure 58. Distribution of samples from Pacheco Pumping Plant into zones of low, marginal, and high calcium and pH for 2008 to 2010. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

3.3.9 California Aqueduct Check 21

The average calcium concentration at California Aqueduct Check 21 over the last decade is 20.1 mg/L and the average pH is 7.4. During the time period examined, only one sample had a calcium concentration at the minimum level whereas all other samples had calcium concentrations higher than 12 mg/L (Figure 59). The pH was at or below the minimum level in 27 (20%) samples collected, with most of these low pH values occurring between 2005 and 2008. In 43% of samples collected, the calcium concentration was above 15 mg/L and the pH was above 7.8 (Figure 60).

As with Check 13, calcium and pH values appear to be rising since 2008 at Check 21. Between January 2008 and September 2010, 61% of samples have both high calcium and high pH compared to 43% over the entire decade (Figure 61). Based on overall data for the last decade and more specifically data for the last three years, California Aqueduct Check 21 may have a greater chance of supporting mussels than other marginal sites.

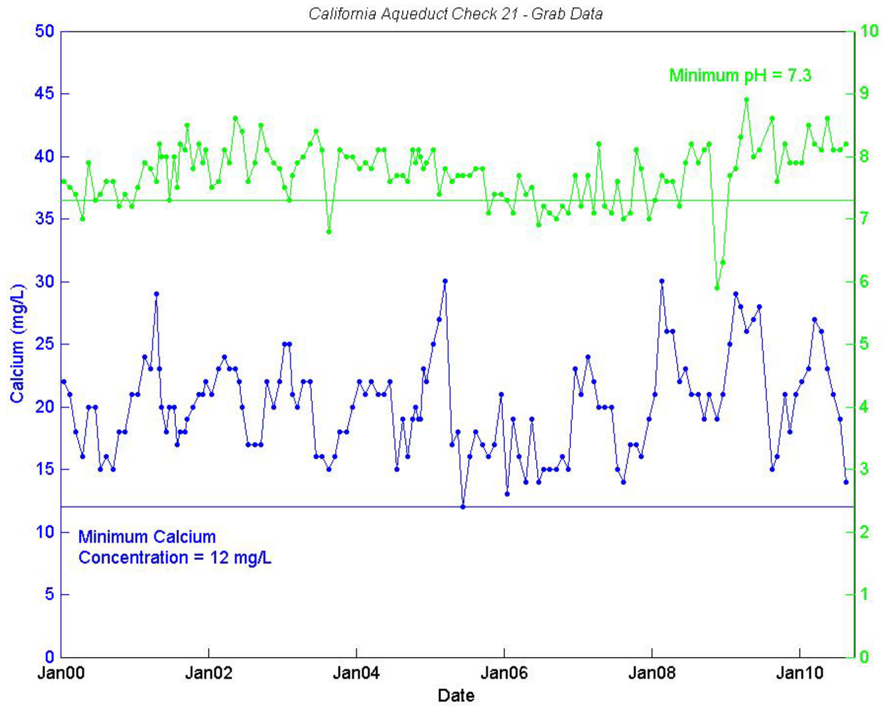


Figure 59. Changes in calcium and pH at Check 21 in the California Aqueduct.

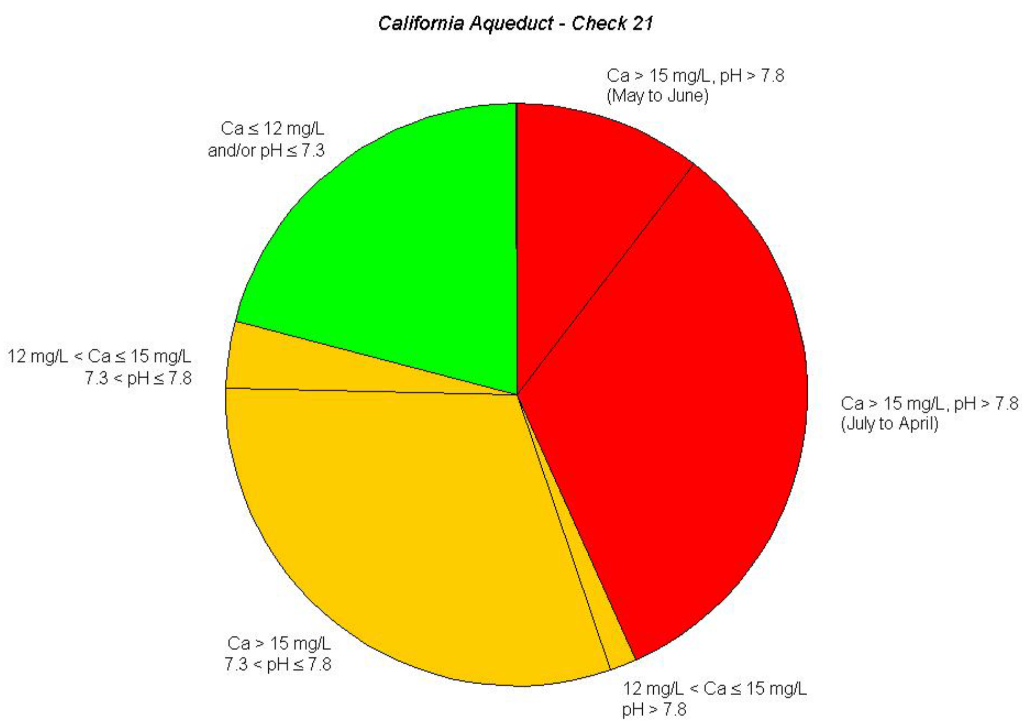


Figure 60. Distribution of samples from 2000 to 2010 in the California Aqueduct Check 21 into zones of low, marginal, and high calcium and pH. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

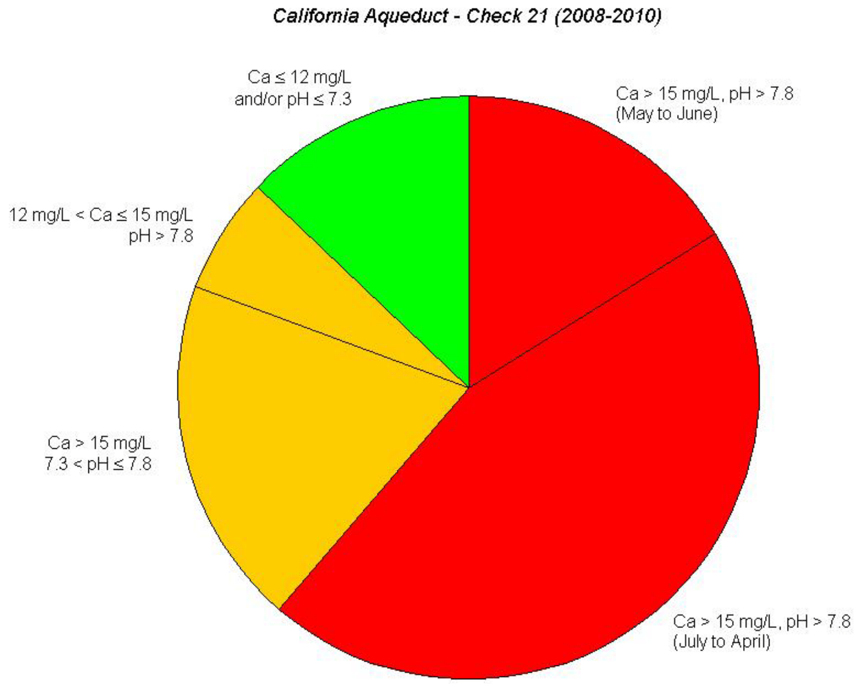


Figure 61. Distribution of samples from 2008 to 2010 in the California Aqueduct Check 21 into zones of low, marginal, and high calcium and pH. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

3.3.10 California Aqueduct Check 29

Figure 62 shows the changes in calcium and pH for California Aqueduct Check 29. The average calcium concentration is 21.2 mg/L and the average pH is 7.1. Since 2000, three samples at Check 29 had calcium concentrations at or below 12 mg/L. In contrast, the pH was almost always below the minimum value of 7.3, particularly in samples collected between 2002 and 2008. For the last three years, though, pH has risen to values well above the minimum limit in all samples.

Overall, 24% of samples collected at Check 29 have calcium concentrations above 15 mg/L and pH values above 7.8 (Figure 63). Since 2008, this percentage has increased to 81% (Figure 64). Under current conditions, it is likely that dreissenid mussels would be supported at Check 29. These recent changes further illustrate that conditions in the system are not static and that continued monitoring is essential.

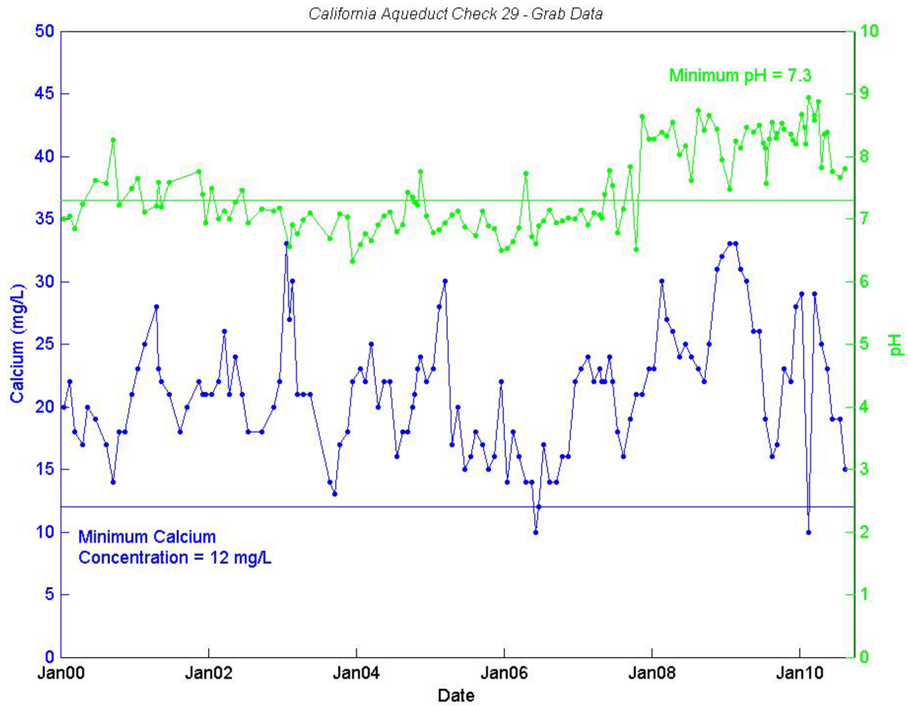


Figure 62. Changes in calcium and pH at Check 29 in the California Aqueduct.

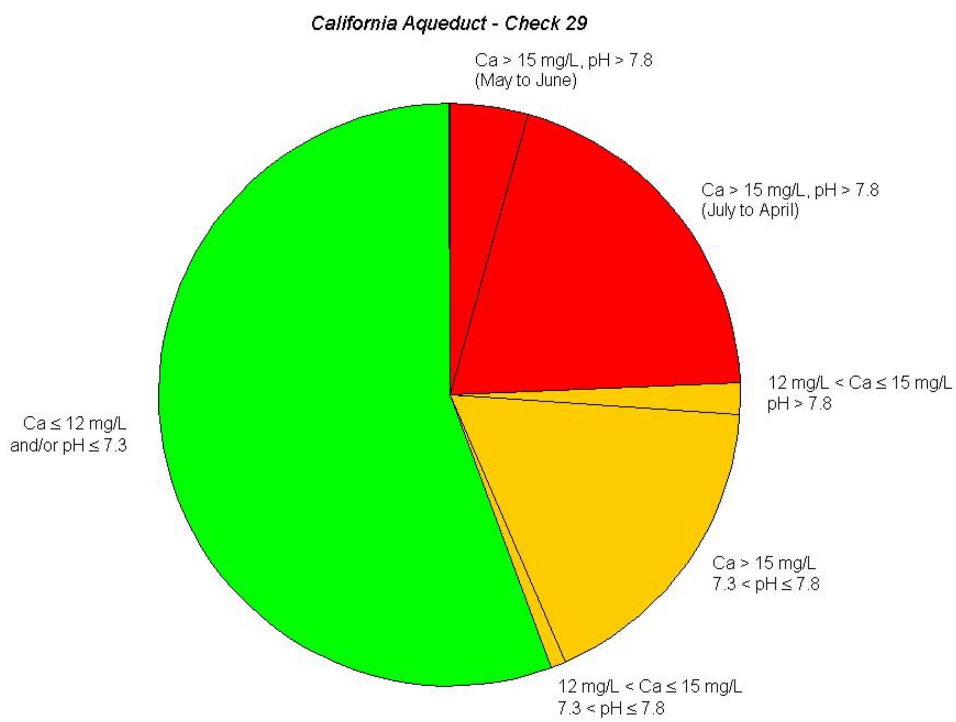


Figure 63. Distribution of samples from California Aqueduct Check 29 into zones of low, marginal, and high calcium and pH. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

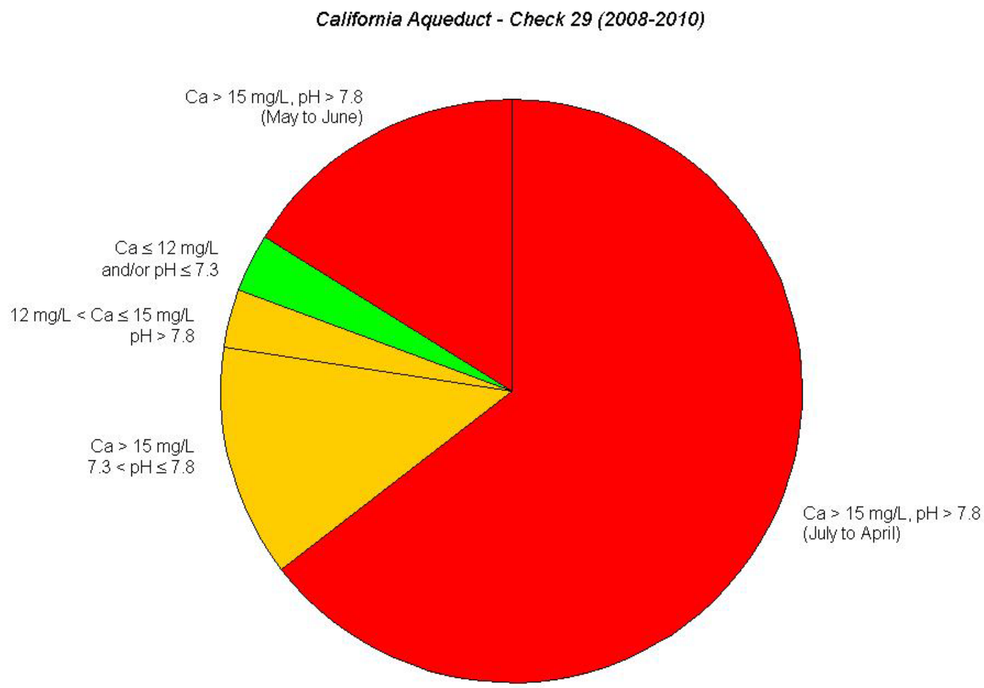


Figure 64. Distribution of samples from 2008 to 2010 in the California Aqueduct Check 29 into zones of low, marginal, and high calcium and pH. Samples are separated into conditions that are unable (green), potentially able (orange), and able to support dreissenid mussels (red).

3.4 Calcium-pH Quadrant Graph

Sites considered potentially able to support dreissenid mussels require further analysis in order to determine more conclusively whether or not they will be able to support a long-term population of mussels. We examined average calcium and pH data for lakes in North America and Ireland with established populations of dreissenid mussels (Table 6) and plotted the results on a scatter plot (Figure 65). The axes on this plot cross at the minimum calcium (i.e. 12 mg/L) and pH (i.e. 7.3) values. Dividing lines are also plotted at 15 mg/L for calcium and 7.8 for pH to separate lakes with high calcium and high pH from those with low or marginal values.

Mackie (Appendix I) prepared a report examining the relationship between chalk variables (calcium, pH, conductivity, alkalinity) and zebra mussel presence in lakes in Ontario, Canada. He also plotted results on a scatter graph (**Error! Reference source not found.**) and found that the minimum concentration of calcium in lakes with established populations of mussels was 12 mg/L and the minimum pH was 7.45.

The results of this study and those in Mackie (Appendix I) suggest that established populations of dreissenids require calcium and pH levels above 12 mg/L and 7.3, respectively. We continue to seek out calcium and pH data for other lakes with established dreissenid populations in order to confirm that these levels are appropriate as minimum values for long-term mussel success and to examine the impact of marginal calcium and pH on dreissenid mussel populations.

Table 6. Average calcium and pH values for lakes with established dreissenid populations.

Lake	Calcium (mg/L)	pH
Ballyquirke[a]	48.2	8.5
Lake Bomoseen[b]	17.6	7.5
Lake Champlain - South Lake B (Station 2)[b]	28.3	7.7
Lake Champlain - Missisquoi Bay (Station 50)[b]	13.5	8.0
Lake Ontario[c]	40.0	8.5
Lake Superior[d]	13.0	8.2
Lough Corrib[a]	52.4	7.5
Lough Key[a]	86.3	8.1
Lough Mask[a]	60.8	8.5
Ross Lake[a]	84.7	8.1

[a] Lucy *et al.* (2010)
[b] Vermont Department of Environmental Conservation (2010)
[c] Claudi (2010)
[d] Mackie and Claudi (2010)

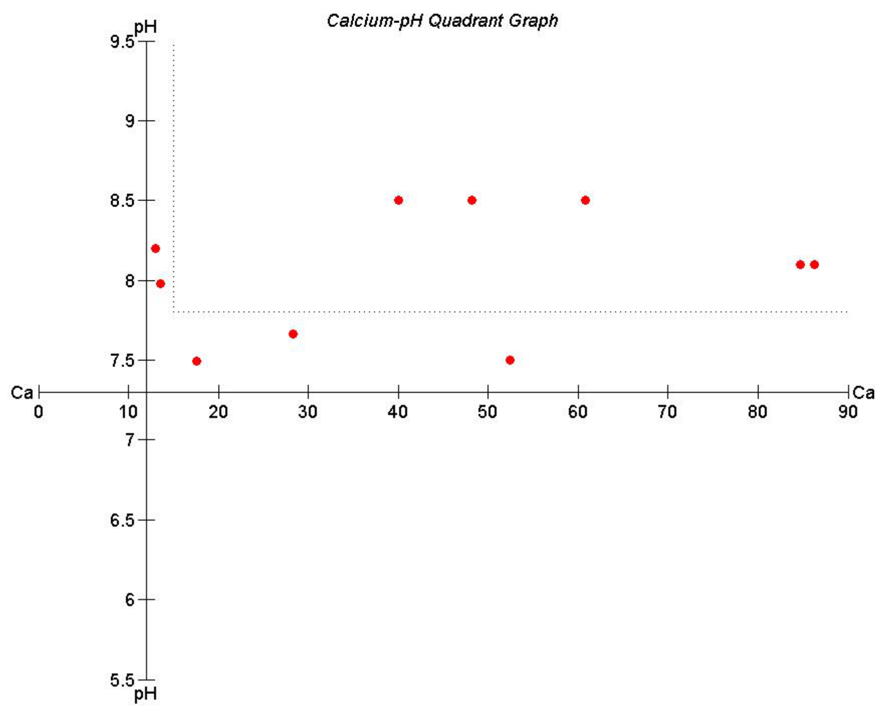


Figure 65. A plot of average calcium and pH values for North American and Irish lakes with established dreissenid mussel populations. Lakes with marginal calcium and pH may offer insight into determining whether or not other locations will support dreissenid populations.

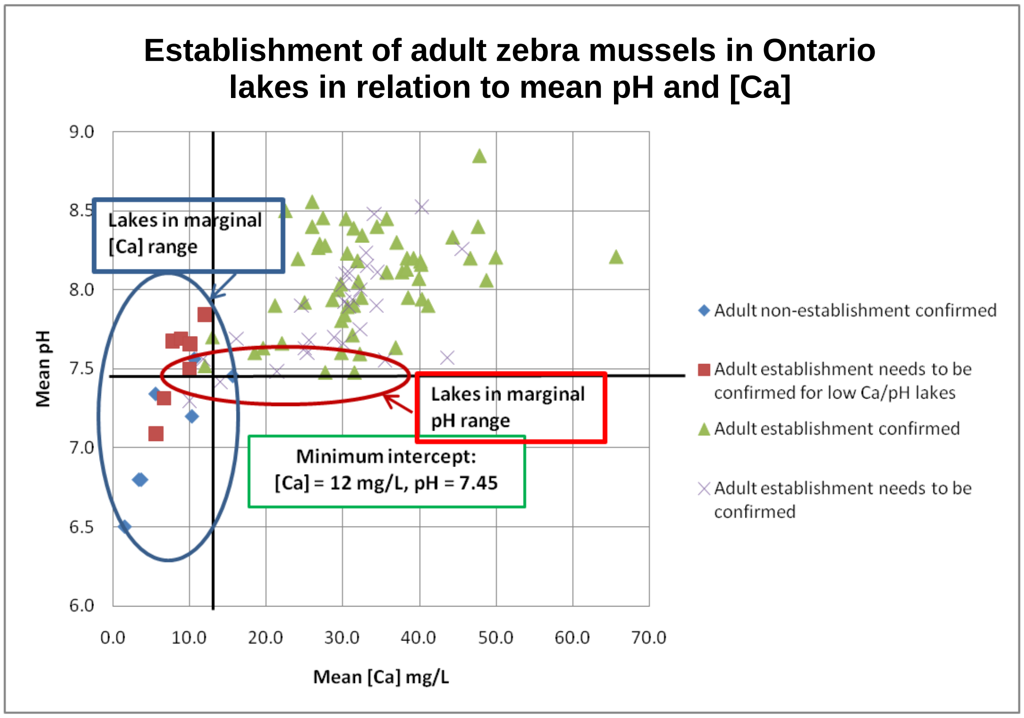


Figure 66. Status of information on establishment of adult mussels in Ontario lakes in relation to mean pH and calcium content. See Appendix I for details.

4 Recommendations

Based on calcium and pH data collected at various sites in the California State Water Project between January 2000 and September 2010, we separated sites into those unable, potentially able, and able to support long-term dreissenid populations.

Antelope Lake, Frenchman Lake, Lake Davis, Lake Oroville, Thermalito Diversion Pool, Feather River at Lake Oroville, and Sacramento River at Hood are sites considered to be unable to support mussels at this time. Water quality monitoring at these sites should continue so that any changes in conditions can be identified early. We consider the implementation of control measures, such as boat inspections, unnecessary for these sites at this time.

Those sites considered able to support mussels (i.e. California Aqueduct Check 41, Castaic Lake Outlet, Castaic Lake at Jensen Influent, Silverwood Lake Outlet at Devil Canyon, Devil Canyon Headworks, and Lake Perris Outlet) may require increased monitoring for dreissenid mussels to identify infestations at an early stage so that these sites could be quarantined if necessary. Control measures to prevent the introduction of mussels to these sites should be vigorously pursued (e.g. signage, boat inspections, boat wash stations, controlled access). Vulnerability assessments should be performed on all manmade structures associated with these sites and mitigation plans should be available for quick implementation should dreissenids invade these locations.

Sites that are considered potentially able to support dreissenid populations require further examination. There is insufficient data in the literature to determine the success of dreissenid survival and reproduction under marginal conditions of calcium and pH. Regular water quality sampling and analysis should continue at these sites. Additionally, one or more of the following projects may be considered to determine the suitability of these sites for supporting a long-term mussel population.

Temporary Flow Laboratory:
A temporary flow lab can be installed on-site at one or more of the locations potentially able to support mussels to test adult mussels in site specific conditions. Such a lab is designed to expose adult mussels to real-time environmental conditions and examine their survivability. Water flowing through the laboratory set-up must be carefully treated upon discharge to ensure contamination of the site does not occur. This can be done by discharging the outflow to land as well as treating the discharge water using filters and chlorine.

Alternatively, the flow lab can remain at an already infested location such as San Justo Reservoir and water from sites of interest can be trucked to the lab and used in the flow through aquaria containing captive adult mussels. The advantage of this arrangement is that water from several sites may be tested at the same time. A disadvantage is the mussels are not exposed to the seasonal fluctuations of calcium and pH.

Laboratory Study:
As an alternative to a temporary flow lab, a laboratory study can be performed where calcium and pH are artificially modified under controlled conditions to determine the impact of low, marginal, and high calcium and pH on adult mussels. This type of study can be carried out at any location.

Research Study on Lakes with Dreissenid Populations:
A research study on worldwide lakes with marginal pH and calcium levels currently supporting dreissenid populations may provide valuable insight into California State Water Project sites that are potentially able to support mussels. Such a study might involve an extension of the calcium-pH quadrant graph described in this study (Section 3.4). Additionally, the calcium carbonate saturation index may be explored as a way to determine the risk of infestation of water bodies that do not currently have dreissenid mussel populations. This approach has been used to model the expansion of the golden mussel, *Limnoperna fortunei*, in Brazilian and North American water systems (Oliveira *et al.* 2010a; Oliveira *et al.* 2010b)

Field Study:
A field study that examines existing lakes with marginal conditions and established populations of mussels would provide real life verification of the limits used in this study.

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Appendix I

A RE-EXAMINATION OF CHALK CRITERIA FOR RISK ASSESSMENT OF ZEBRA MUSSEL INFESTATIONS IN ONTARIO WATERS

Gerald L. Mackie

Introduction

Based on the known world wide distribution of the zebra mussel in the late 1990s Claudi and Mackie (1994) proposed criteria for assessing level of risk for infestations in North American freshwaters. The assessment was basically done for waters in the Great Lakes Watershed because that was the limit of the North American distribution at the time. Their risk assessment was based on several chemical and physical variables including: chalk criteria (pH, calcium concentration, total alkalinity, total hardness), physical criteria (temperature, conductivity, total dissolved solids, salinity, turbidity, total suspended solids), and nutrient variables (dissolved oxygen, chlorophyll *a*, total phosphorous, total nitrogen, Secchi depth). Seasonal variations in these variables were considered more reliable in predicting levels of infestation than mean values. However, many lakes had very little information on seasonal variations so mean values were more often used than seasonal variations in the values.

Of the chemical, physical and nutrient criteria, the chalk variables were deemed the most reliable by Claudi and Mackie (1994), mainly because of several laboratory (e.g. Hincks and Mackie, 1989) and field studies (e.g. Neary and Leach, 1992; Baker et. al., 1993). The distribution of zebra mussels has increased dramatically since their introduction into the Great Lakes in 1986 (Mackie and Claudi, 2010) and several other studies have examined the importance of chalk criteria in predicting the distribution of zebra mussels (e.g. Koutnik and Padilla 1994; Cohen and Weinstein, 1998, 2001; Cohen, 2001, 2007; Jones and Ricciardi , 2005; Whittier et. al., 2008).

Zebra and quagga mussels have greatly widened their distribution in Ontario waters (rivers, lakes, impoundments) since their introduction to the Great Lakes in 1986. An “Invasives Tracking System” in Ontario waters was created by Ontario Federation of Anglers and Hunters (OFAH) and Ontario Ministry of Natural Resources (OMNR). As of February 2011 larval (veligers) dreissenid mussels have been reported (see http://www.comap.ca/its/index.php) in more than 130 Ontario water bodies. A survey of the levels of chalk variables in these lakes was performed using data provided by Ontario Ministry of Natural Resources, cottage associations, publications (e.g. annual reports, peer-reviewed journal articles), and the author’s own surveys. The survey revealed the presence of veligers in waters that Mackie and Claudi (2010) predicted should not be present. However, the presence of veligers alone does not necessarily mean that adults will establish themselves. Levels of all chalk variables were not available in all sources so regressions were performed on the available dataset to predict pH, calcium level, and total alkalinity from each other and from conductivity.

The distribution of lakes throughout a variety of bedrocks in Ontario offers an excellent opportunity to examine the distribution of dreissenid mussels in waters with very different chemical properties. For example, in the Kawartha Lakes region there is Precambrian Shield rock that is not necessarily granite and quartz. Within Southern Ontario's shield region, the Central Metasedimentary Belt Boundary Zone (CMBBZ) runs diagonally northeast to southwest through the Kawartha Lakes watershed; it defines a rough boundary between the Central Gneiss Belt (CGB) in the Muskokas and consists of hard rock (quartz, granite) that contributes little or no alkalinity, while the other side is the Central Metasedimentary Belt (CMB) of eastern Ontario, which contains a variety of rocks and minerals, including metamorphosed limestone, which contributes considerable alkalinity (and phosphorus) to surface or ground waters. To the south of this in eastern Ontario are the Cambrian sandstone and the Palaeozoic and Quaternary sediments (Kevin Walters, pers. comm.).

As well, the northern reservoirs are located on or either side of the CMBBZ, meaning that some of them have extremely soft water, while others, being located on metasediments, often being marble, have a higher Ca content; release rates from the various reservoirs may vary depending on the operation by the Trent Severn Waterway (TSW).

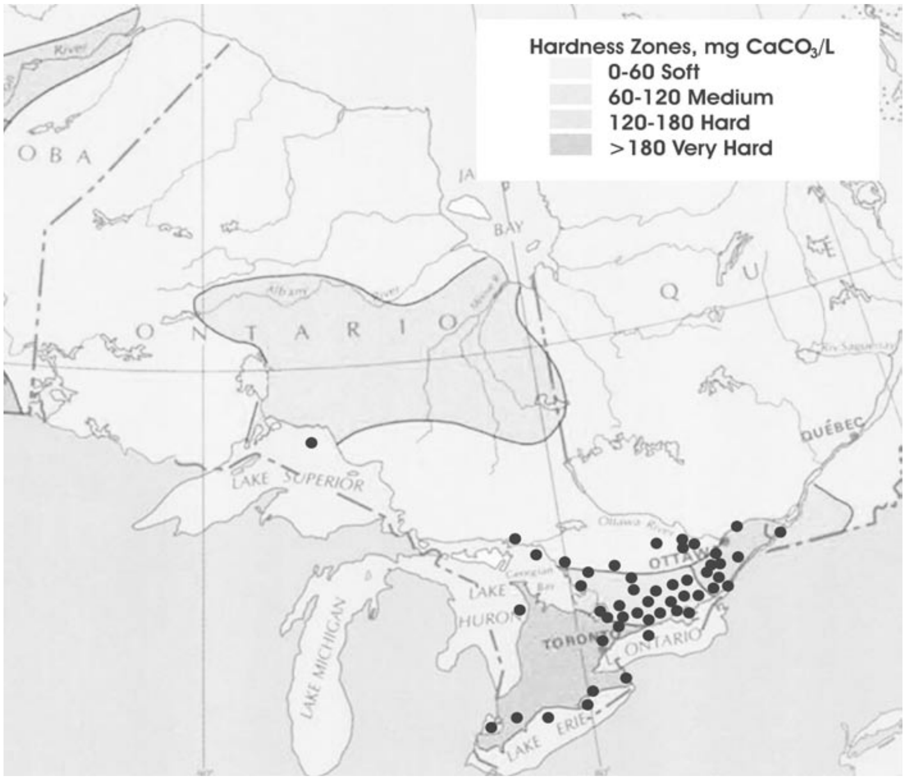
The objectives of this study are to determine: (1) the presence of larval and adult zebra mussels in the entire ranges of chalk values provided as gleaned from available sources; (2) the minimum levels of pH, calcium, and total alkalinity required for establishment of adults; (3) linear regressions of the chalk variables and conductivity for predictive value of missing variables.

Methodology

The first step was to obtain a list of the waters that have been reported to contain either larval or adult zebra mussels. The list was obtained from the "Invasives Tracking System" on http://www.comap.ca/its/index.php. The list of waters included their county, township, and the number and dates of records. Counties and townships were important because many lakes have the same name. Waters with numerous (>3) records from different years were deemed to contain adults. Waters with only one or two records, especially from the same year were deemed to contain larvae only but a survey was taken from cottage associations in each county to request information on: (1) presence of adults (yes or no); (2) how long have adults been present, if known; (3) are they considered a nuisance, if known; (4) any impact, positive (e.g. increased water clarity) or negative (e.g. plugged intakes). We propose this survey be followed up by visiting lakes with marginal pH and calcium values to verify levels of chalk variables and determine if adults have become established. The lakes were selected to represent the four hardness zones of Ontario (Figure 1). There is excellent representation of waters in the medium to hard zones, with fewer in the soft and very hard zones (Figure 1). The low numbers of water bodies in the very hard zone is probably because the area is riddled with rivers and has very few lakes.

Water chemistry data were obtained mostly from the Ontario Ministry of Natural Resources, but water chemistry data in the author's own databases were also used. Many cottage associations produce annual reports that provide some water chemistry data of lakes in their jurisdiction. Cottage association representatives were contacted for any water chemistry data in their possession (much of which was obtained from the Ontario Ministry of Environment). These data were then plotted to determine: (1) the presence of larval and adult zebra mussels in the entire ranges of chalk values provided; (2) the minimum levels of pH, calcium, total

Figure 1. Hardness zones in Ontario showing distribution of waters with zebra mussel veligers. Zone map from Fisheries and Environment Canada. 1978. Hydrological atlas of Canada. Map 28A.



alkalinity and conductivity required for establishment of adults; and (3) linear regressions of the chalk variables and conductivity for predictive value of missing variables. Linear regressions were determined using Analyse-it statistical analysis add-in for Microsoft Excel, Analyse-it Software, Ltd. (2010).

Results

A total of 133 lakes were found with either dreissenid mussel veligers and/or adults. Complete data sets (all four variables) were rarely obtained. pH was the most commonly measured variable. Most (98) had both pH and calcium measurements but fewer had pH and total alkalinity and/or conductivity measurements.

Figure 2 shows waters in different regions of Ontario for which larval veligers and/or adults have been reported. Veligers only have been reported for all lakes in the figure. Lakes with both veligers and adults are shown in green triangles; the minimum values for calcium content and pH are 12 mg/L and 7.45, respectively (Figure 2). Several lakes have more than two records (in different years) of veligers but adult establishment has never been confirmed; these are shown as X's in Figure 2. Some lakes in the marginal pH range (red oval) have adult establishment confirmed (green triangles), some unconfirmed (X's). Lakes in the marginal [Ca] range (blue oval) have more than two records of veligers present but there is confirmation that adults have never established themselves (red squares); other lakes have marginal [Ca] but no adults have ever been reported (blue diamonds) and need to be confirmed as absent. Still, lakes in overlapping marginal pH (red oval) and [Ca] ranges (blue oval) have records confirming adult establishment (green triangles) as well as confirmation of no adult establishment (red squares). It is clear that lakes within the red and blue ovals (marginal water chemistry) need to be revisited to confirm adult establishment or non-establishment.

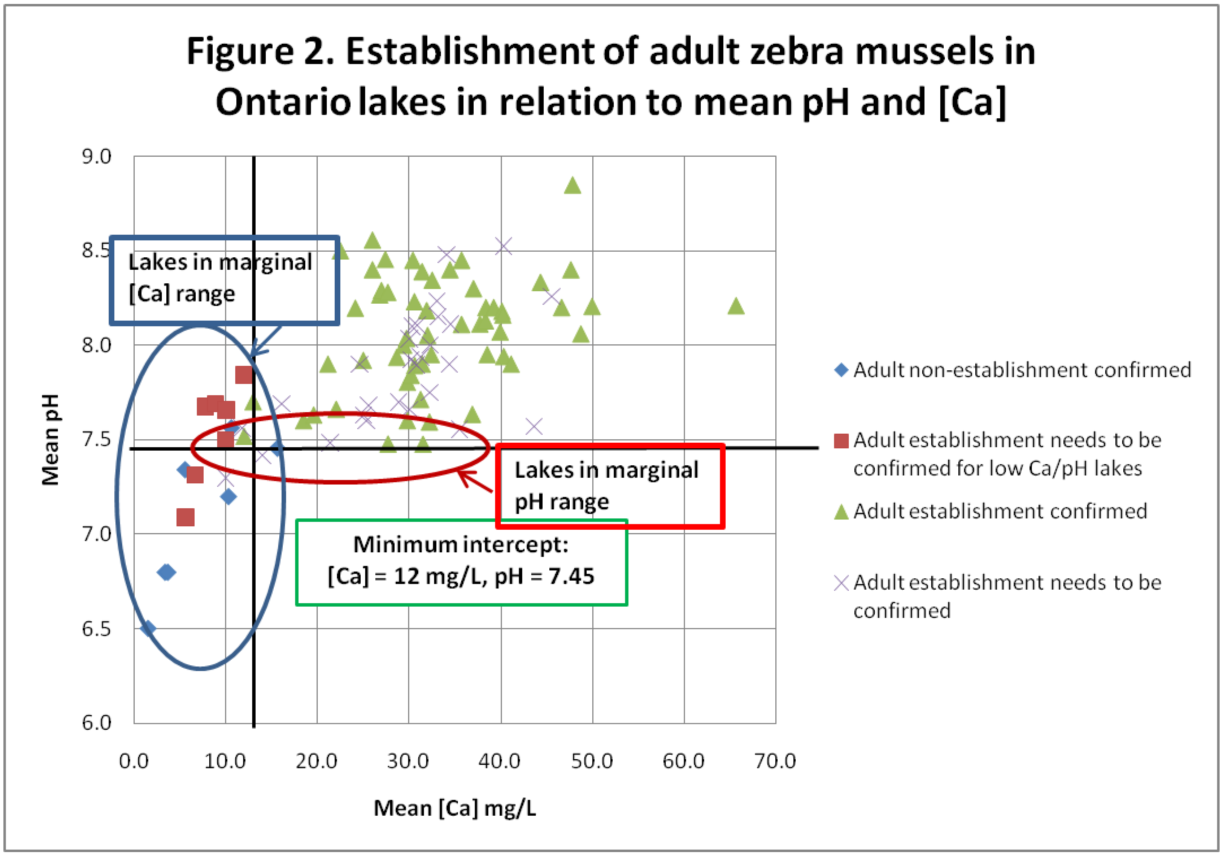


Table 1 lists the lakes within the red and blue ovals of Figure 2. Some water bodies (shaded rows) have numerous records of veligers over several years but either water chemistry is suspect or adults can establish themselves in water with low chalk values (lakes in blue and red ovals of Figure 2). Lakes that have veligers only (red squares) have chemical characteristics to indicate adult mussels will not establish themselves but this needs to be verified by visiting the waters and looking for adults. The intercept at pH = 7.45 and [Ca] = 12 mg/L are the lowest values with known established zebra mussel populations in Ontario.

Table 2 lists waters with calcium levels greater than 15 mg/L but establishment of adult mussel populations is unknown (X’s in Figure 2). Some water bodies (shaded rows) have only a few records of veligers but either water chemistry is suspect and/or adults have in fact established themselves.

Table 1. Low-calcium level (< 15 mg/L) water bodies with reported zebra mussel veligers but adult establishment is unknown. Water bodies arranged from lowest to highest calcium level. Number of records for each lake is given after the township (Twp) name. Shaded rows have numerous reports over several years in low [Ca] waters and water chemistry needs to be confirmed.

Water bodies with zebra mussel veligers	pH	Total alkalinity mg $CaCO_3$/L	Conductivity µS/cm	[Ca] mg/L	Adults present
Round Lake, Lanark Co, Tay Valley Twp; 4 records 2 from 2005-07-25 2 from 2009-07-29	7.1	15.2	56.4	5.6	?
Beaver Lake, Peterborough Co, Galway, Cavendish, Harvey Twp; 11 records from 1998 to 2006	7.3	14.6	50.7	6.7	?
Diamond Lake, Hastings Co, Herschel Twp; 2 records, both for 2007-08-19	7.7	24.66	65.8	7.8	?
Kashagawigamog Lake, Haliburton Co, Minden Twp; 1 record 1998	7.7	27.3	84.6	8.9	?
Kashwakamk Lake, Frontenac Co, Barrie Twp; 5 records from 1998 to 2004	7.3	38.0	105.5	10.0	?
Shadow Lake, Peterborough Co.; 2009-07-20, 10->100 veligers found	7.5	22.7	80.2	10.0	?
Golden Lake, Renfrew Co, N Algona Twp; 5 records 3 in 2005, 2 in 2006	7.7	31.4	95.4	10.1	?
Kashagawigamog Lake, Haliburton Co, Minden Twp; 1 in 1998	7.6	37.5	106.0	11.8	?
Black Donald Lake, Renfrew Co, Greater Madawask Twp; 3 in 2005	7.8	36.0	98.3	12.0	?
Head Lake, Muskoka District Municipality, Dysart Twp; 2 in 1998	7.4	33	78.1	14.0	?

Table 2. High-calcium level (> 15 mg/L) water bodies with reported zebra mussel veligers but adult establishment is unknown. Water bodies arranged from lowest to highest calcium level. Number of records for each lake is given after the township (Twp) name. Shaded rows have only a few records of veligers but either water chemistry is suspect and/or adults have in fact established themselves. All lakes are shown in Figure 2 as X's.

Water bodies with zebra mussel veligers	pH	Total alkalinity mg $CaCO_3$/L	Conductivity µS/cm	[Ca] mg/L	Adults present
Eagle Lake, Frontenac Co, Hinchinbrooke Twp; 1 in 2007	7.7	44.2	124.0	16.1	?
Cameron Lake, Kawartha Lakes Division, Fenelon Twp; 1 in 2006	7.5	45.6	145.3	21.4	?
Fermoy Lake, Frontenac Co, Bedford Twp; 1 in 2006	7.6	-	-	25.3	?
Steenburg Lake, Hastings Co, Tudoe/Casshel Twp; 4 records, 2 in 2005, 2 in 2006	7.9	59.50	134.40	24.6	?
Little Lake, Peterborough Co, Peterborough Twp; 5 records, 1995 to 1996	7.6	55.7	190.0	25.0	?
Glouchester Pool, Muskoka District, Baxter Twp; 1 in 1996	7.7	59.6	204.0	25.6	?
Sand Lake, Frontenac Co, Clarendon Twp; 2 in 2006	7.7	82.00	-	28.8	?
Mill Pond, Lanark Co, Tay Valley Twp; 2 in 2005	8.0	152.5	-	30.0	?
McCausland Lake, Frontenac Co, Barrie Twp; 2 records, 1- 2002, 1-2008	7.7	17.5	-	30.0	?
Jack Lake, Peterborough Co, Methuen Twp; 1 in 2009	7.9	55	136.1	30.2	?
Howes Lake, Frontenac Co, Portkand Twp, 1 in 2009	8.1	93.0	-	30.3	?
Canonto Lake, Frontenac Co, S. Canonto Twp; 2 records, 2001, 2002	7.9	87.1	19.9	30.8	?
Green Lake, Leeds & Grenville United Cos, Landsdowne Twp; 1 in 2009	8.1	73.3	165.1	30.9	?
Picard Lake, Peterborough Co. Cavendish Twp; 1 in 1998	7.9	85.0	173.3	31.3	?
Joes Lake, Lanark Co, Lavant Twp; 1 in 2009	7.8	88.5	-	32.2	?
McLaren Lake, Lanark Co, Burgess Twp; 1 in 2006	8.0	-	-	32.3	?
Patterson Lake, Lanark Co, Dalhousie Twp; 1 in 2009	8.2	99.7	195.0	33.0	?
Crystal Lake, Peterborough Co, Galway Twp; 2 records, 2001, 2002	8.2	87.5	179.3	33.1	?
Chestley Lake, Bruce Co, Amambel Twp; 2 in 1998	8.5	124.0	266.0	34.1	?
Little Crosby Lake, Leeds & Grenville United Cos, N Crosby Twp; 1 in 2006	7.9	48.2	-	34.4	?
Malcolm Lake, Frontenac Co, Clarendon Twp; 1 in 2009	8.1	103.0	-	34.5	?
Big Gull Lake, Frontenac Co, Clarendon Twp; 1 in 2006	7.6	30.2	-	35.5	?
Grippen Lake, Leed & Grenville United Co, Leeds Twp; 1 in 2008	8.5	125.7	282.0	40.3	?
Dalrymple Lake, Kawartha Lake, Carden Twp; 1 in 2001-07-20	7.6	119.0	285.0	43.6	?
Flower Round Lake, Lanark Co, Lavant Twp; 2 in 2006	8.3	69.3	-	45.5	?

Discussion

Lakes in shaded rows in Tables 1 and 2 especially need to be surveyed, either because the lakes are in different counties/townships or water chemistry is suspect. Most noteworthy is Beaver Lake, Peterborough Co, Galway, Cavendish, Harvey Twp with 11 records from 1998 to 2006 (Table 1); the values for all four chalk variables are very low, yet there are 11 records of veligers from 1998 to 2006. Similarly, Kashwakamk Lake, Frontenac Co, Barrie Twp with 5 records from 1998 to 2004 and Golden Lake, Renfrew Co, N Algona Twp with 5 records, 3 in 2005 and 2 in 2006 have reported veligers over several years, yet the chalk values are marginal (Table 1).

There are other considerations when evaluating risk assessment based on chalk variables. The chemistry of lakes can also be highly variable both seasonably and annually. Soft-water lakes have little buffering capacity (alkalinity) and pH can vary substantially due to spring snowmelt (pH drops) and summer photosynthesis (pH rises) (which explains why alkalinity is important in risk assessments). The spring pH crashes are due mostly to the hydrogen ions migrating downward in the snow pack, resulting in a spring pH depression, but this probably has little impact on zebra mussels because they don't really become active until 10-12^{o}C, which occurs well after the pH depression. The summer pH variations are more important because mussels are very active and need calcium for their shells. Since most/all of the calcium is available to them as calcium bicarbonate and most of the total alkalinity is due to bicarbonate alkalinity (at pH < 8.2), alkalinity becomes more important as pH drops. Seasonal variations in water chemistry are preferred in order to examine the extent of variations in each of the chalk variables and their limitations on mussel survival over the long term. However, seasonal data are usually difficult to find and use of mean values are of some help in risk assessments.

These seasonal variations become more complex in the Precambrian sandstone (north) and the Palaeozoic sediment (south) regions. In spring the high flush from both sources, provides a mixture of hard and soft water. However, if snowfall is low, little comes from the north in spring because it is retained by reservoirs for the Trent system. As a result, the main inflow is the hard water of the south. During the summer if rainfall is moderate, most incoming water will be hard, being sourced from the uncontrolled south, while much of the northern waters continue to be held back. In dry summers and in the late fall, releases from the northern reservoirs are made, softening the lake water considerably (Kevin Walters, pers. comm.).

The importance of these seasonal and spatial variations can be evaluated by examining seasonal data for the chalk variables to determine if the high values correspond to the growing and reproductive seasons of the zebra mussels. Perhaps the mean values in chalk variables do not accurately represent the lower tolerance levels of zebra mussel veligers and adults.

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