Zebra Mussel Monitoring and Habitat Assessment For Deep Creek Lake, Maryland

September 2022

Department of Natural Resources
Resource Assessment Service

MARYLAND
DEPARTMENT OF
NATURAL RESOURCES

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Cover Photo: Zebra Mussels *(Dreissena polymorpha)* (Photo credit : Seth Metheny)

ACKNOWLEDGMENTS

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Executive Summary

The weight of evidence from evaluations performed in this study indicates that zebra mussels are currently absent (or present in numbers difficult to detect) and water chemistry is currently not suitable for the proliferation of zebra or quagga mussels in Deep Creek Lake. No zebra or quagga mussels were found at any sampled location in Deep Creek Lake. The low suitability of Deep Creek Lake water could explain why none were found and likely means that substantial growth and reproduction (even if an introduction occurs), while not impossible, seems unlikely. While dissolved oxygen and temperature in Deep Creek Lake were indicative of high or medium zebra mussel colonization risk at most times and locations, calcium and hardness from all locations and times indicated very low or low zebra mussel colonization risk. Most samples also indicated low or very low colonization risk regarding pH. Furthermore, calcium and pH in Deep Creek Lake were substantially lower than levels in nearby waters with zebra or quagga mussels. It is possible that there are zebra or quagga mussels in portions of Deep Creek Lake not searched and conditions could be suitable in areas not sampled. However, given the results from evaluating abundant data collected from multiple locations over multiple years, it seems unlikely there are currently large numbers of these mussels anywhere in Deep Creek Lake.

Introduction

Background

Zebra mussels (*Dreissena polymorpha*) and quagga mussels (*Dreissena rostriformis bugensis*) are small mollusks native to Eurasia. They are prolific and invasive, causing significant ecological and economic impacts where they have become established in North America (Strayer 2009, Nalepa and Schloesser 2013). Zebra and quagga mussels can be transported to a new waterbody via ballast/bilge water or attached to boat hulls, engines, propellers, trailers, and other gear. Once in a waterbody, adults can produce hundreds to thousands of microscopic planktonic larvae (veligers). Zebra mussels attach to hard and quagga mussels to hard or sometimes soft substrates where they grow into adults (Nalepa and Schloesser 2013, Garton et al. 2013).

These mussels can survive desiccation for days under certain weather conditions (Hoddle 2019), facilitating the spread from one waterbody to another. Large infestations can result in biofouling and the effects of biofouling can be severe such as clogging intake pipes (Kovalak et al. 1993, Aldridge et al. 2004, Elliott et al. 2007) and extirpating native bivalves (Riccardi et al. 1998), for example. As filter feeders, they can deplete a water body of plankton (Holland 1993, Nichols and Hopkins 1993), alter water chemistry and clarity, displace native mussels, reduce food for fish, and affect aquatic plant growth and survival ([a]Benson et. al., 2022).

Since their introduction, zebra and quagga mussels have spread throughout much of the United States ([a]Benson et al. 2022, [b]Benson et al. 2022). So far there have been no known quagga mussel introductions in Maryland. Zebra mussels are presently restricted to a small portion of the upper Chesapeake Bay and the Susquehanna River. They were also found in an inland quarry in 2018 that was subsequently treated for eradication. They were first found in the upper reaches of the Chesapeake Bay in 2007 (Ashton and Klauda 2015) and have since been found as far south as the Middle River near Baltimore. Regionally, zebra or quagga mussels have been found in portions of Virginia, Pennsylvania, and West Virginia ([a]Benson et al. 2022, [b]Benson et al. 2022). Given their occurrence in neighboring states and the high use of Deep Creek Lake by regional boaters, the likelihood of introduction into Deep Creek Lake seems high.

Colonization Risk

Except for quagga mussels having a slightly lower maximum temperature tolerance and a higher minimum calcium tolerance limit, zebra and quagga mussels have similar habitat requirements (Garton et al. 2013). Many variables have been investigated for (especially zebra mussel) habitat suitability (e.g., calcium, pH, alkalinity, hardness, dissolved oxygen, chlorophyll, total phosphorus, total nitrogen, Secchi depth, temperature, conductivity, salinity, turbidity, and total suspended solids; Mackie and Claudi 2010).

Most studies suggest the most important factors for zebra mussels in North America include salinity, temperature, calcium, hardness, pH, and dissolved oxygen (e.g., O'Neill 1996, Cohen and Weinstein 1998, Cohen 2005, Mackie and Claudi 2010, Garton et al. 2013). High, medium, and low colonization risk or suitability have been estimated for these and a few other factors. Magnesium (Hallsan et al. 2010, Karatayev et al. 2015), flow (Hasler et al. 2019), and chloride (Karatayev et al. 2015) may also be important predictors of zebra mussel invasion. Magnesium may be important because of its importance for mussel physiology (Hallston et al. 2010). Magnesium is a component of hardness - one of the factors that has been used to help generate categories of colonization risk. Flow has also been incorporated into evaluations of zebra mussel colonization risk, but chloride concentration has not.

There is variability among publications regarding tolerance thresholds. Using calcium as an example, according to Cohen and Weinstein (1998), distribution potential is low at less than 15 mg/L. According to the literature review by [a]Benson et al. (2022), North American zebra mussels need a minimum of 10 mg/L to initiate shell growth and 25 mg/L to sustain growth. Ramcharan et al. (1992) reported that zebra mussels were not found in European lakes with calcium concentrations below 28.3 mg/L. Garton et al. (2013) listed 8.0 mg/L as a low threshold for zebra mussel adaptation and zebra mussels have apparently been found in waters with mean calcium concentrations as low as 4.0 mg/L (Cohen 2005).

Deep Creek Lake

Deep Creek Lake is a man-made freshwater lake located in Garrett County, Maryland. The lake resulted from the damming of Deep Creek in 1925 for the purposes of hydroelectric power. Once the lake was created, development ensued along the shoreline and in the adjacent watershed with the majority of development happening after 1960. The lake provides hydroelectric power via the dam, which is owned, operated, and maintained by Brookfield Renewable. The lake is a four-season resort destination for visitors from Maryland and nearby states. Visitors often originate from the Washington D.C and Baltimore metropolitan areas as well as the suburbs of Pittsburgh, Pennsylvania; Morgantown, West Virginia; and the Ohio Valley. The lake has over 68 miles of shoreline with an average depth of roughly 22 feet. There are several shallow coves and fingers of the lake and the deepest point in the lake is located near the dam and is approximately 75 feet deep. Most of the development around the lake is residential with some commercial and agricultural land as well.

Zebra Mussel Monitoring in Deep Creek Lake

Brookfield Renewable has been conducting temperature monitoring and visual surveys for zebra mussels (using zebra mussel monitoring plates hung at the water intake) since at least 2009. Brookfield Renewable submits an annual report of monitoring results to the Maryland Department of the Environment at the end of each year. To date, no evidence of zebra mussels has been reported at that location.

The Maryland Department of Natural Resources has conducted water sampling at select locations in Deep Creek Lake since 2009. Along with other factors, annual sampling included some of the factors considered important for zebra mussels (i.e., dissolved oxygen, pH, and temperature). Salinity is not included as this is an entirely freshwater lake. Calcium and hardness were included with sampling during 2009, and 2018 - 2021, specifically for use in helping determine the risk of zebra mussel colonization.

This report describes results from work by the Maryland Department of Natural Resources, in collaboration with Brookfield Renewable and the Deep Creek Watershed Foundation Inc. to search for zebra or quagga mussels and examine water quality data in Deep Creek Lake.

Methods

Water sampling data were available from 18 locations in Deep Creek Lake (Table 1; Figure 1). Four of these locations (DPR0021, DPR0056, DPR0082, and DPR0103) were in the main, deep-water portion of Deep Creek Lake. The positions where sampling took place were consistent for all sampling events at these four locations as they are well-established long-term water monitoring stations. Eleven sampling locations were within coves. Samples were taken from different positions within coves during different sampling events. For this study, all sampling results from anywhere and any time within a cove were combined and reported as results from a single location (cove). The remaining three locations included the Deep Creek Lake Dam, the State Park Ramp, and the Deep Creek Yacht Club Ramp. The water sampling period varied by location but took place during 2009 - 2021 (Figure 2). Thirteen locations had zebra mussel monitoring plates deployed in May and retrieved in September or October. Five locations were visually surveyed using SCUBA and/or snorkel/mask three times each year during May or June, July or August, and September or October 2018, 2019, and 2021. These locations were selected for visual monitoring because they are near boat ramps and the dam, and, as a result, are the most likely locations for zebra mussel introduction.

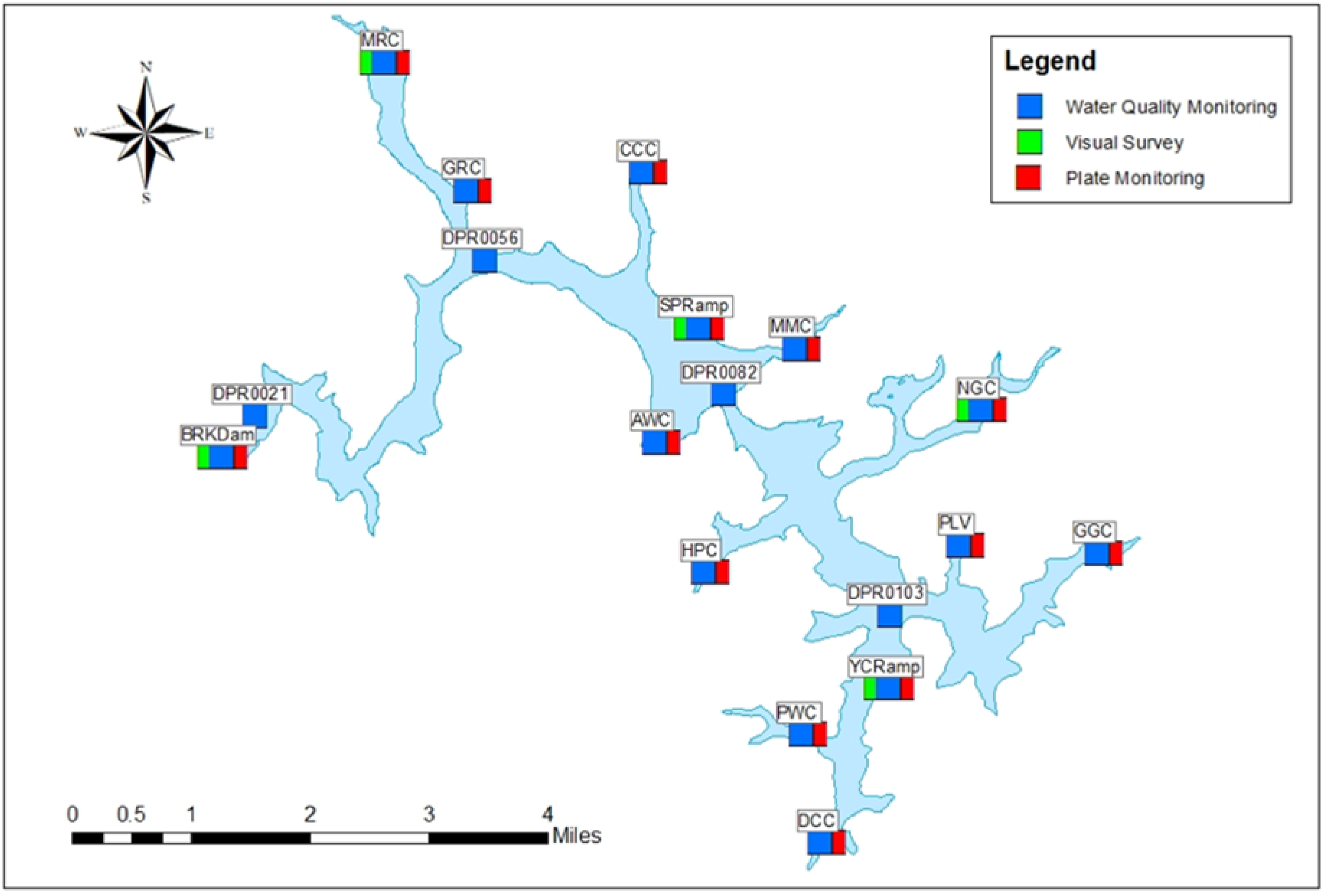


Figure 1. Locations in Deep Creek Lake with water sampling, monitoring plates, and visual surveys.

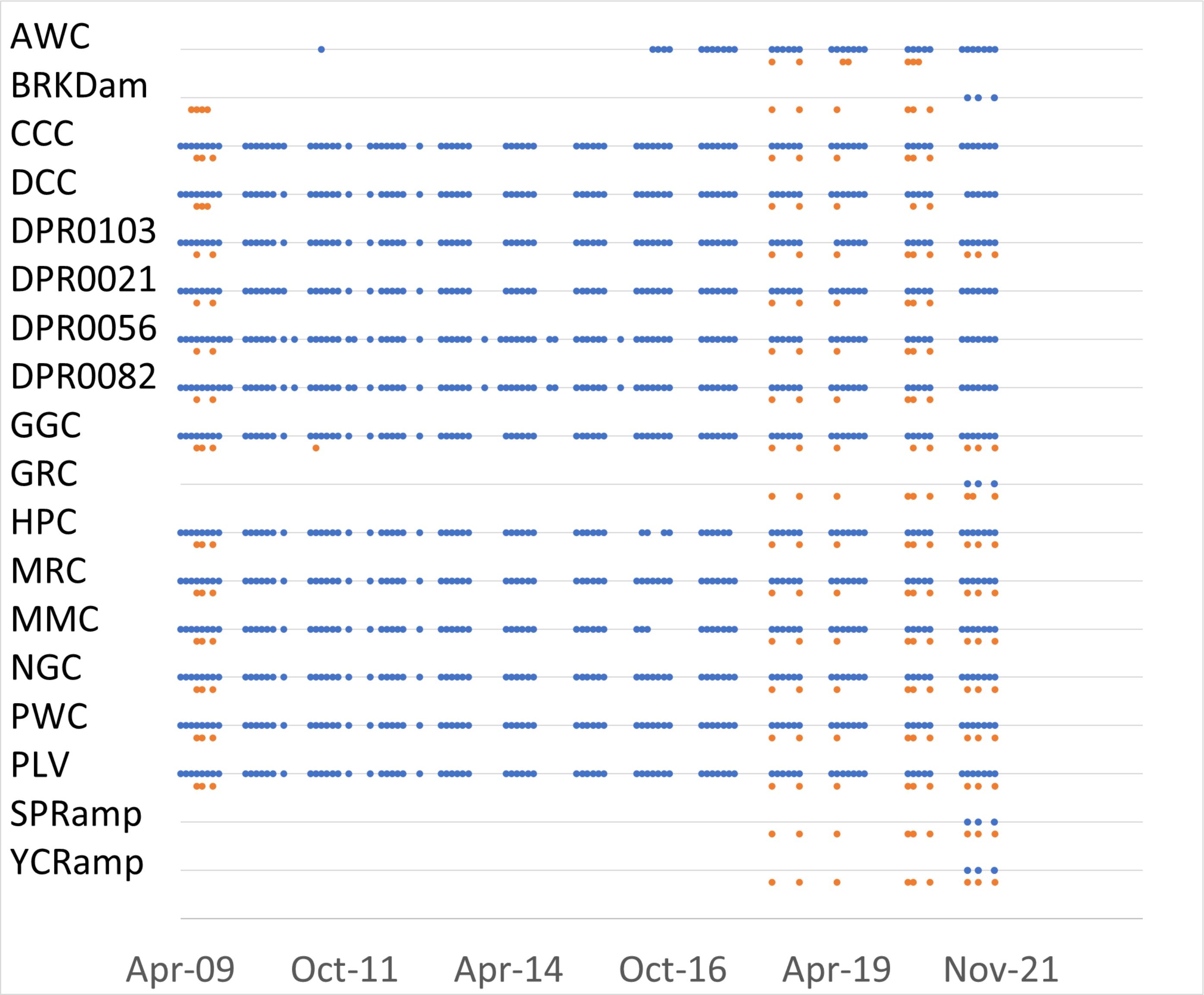


Figure 2. Timeline showing when water sampling was conducted at each location. Blue = pH, dissolved oxygen, and temperature, Orange = calcium and hardness.

Water Sampling Data

A calibrated multi-parameter meter (datasonde) was used to measure water temperature, pH, and dissolved oxygen during 2009 - 2021. The specific years and months of sampling by location varied substantially (Figure 2). At locations with sufficient depth, samples were taken from the surface to the bottom in approximately 1.0 m intervals.

Water samples for calcium and hardness were taken from within 1.0 m below the surface and/or from within 1.0 m of the bottom during 2009, 2018, 2019, 2020, and/or 2021. The years and months of sampling by location varied substantially (Figure 2). Whole water samples were delivered on ice, the same day to the University of Maryland Appalachian Laboratory in Frostburg, Maryland where they were filtered and analyzed for calcium and magnesium concentrations (mg/L) by flame atomic absorption spectroscopy (National Environmental Methods Index APHA 3111 B : https://www.nemi.gov/methods/method_summary/5703/). Once determined, hardness was calculated based on calcium and magnesium concentrations using the following equation:

Total Hardness = 2.497 * **Calcium Hardness** + 4.118 * **Magnesium Hardness**
(mg/L CaCO3) [Ca, mg/L] Mg, mg/L]

Estimating Colonization Risk

A number of publications have summarized information on colonization risk and habitat suitability for zebra mussels into categories like low, medium, and high risk for zebra mussel establishment. We utilized the basic low, medium, and high colonization risk threshold categories adopted by the Illinois-Indiana Sea Grant (ilma-lakes.org/Artwork/zebra7.pdf) as derived from O'Neill (1996) for five variables: temperature, pH, oxygen, calcium, and hardness. But, since additional information is available indicating zebra mussels may be able to survive more extreme conditions, to be conservative, a category (very low colonization risk) was added beyond which zebra (or quagga) mussels would be unlikely to survive, grow, or reproduce (Table 2). Because the very low threshold included more extreme values than in the original Sea Grant table, the low colonization risk range of values needed to be expanded to include the entire range of possible values between medium colonization risk and very low colonization risk. Additionally, only the lower pH tolerance limit was used because no measurements from Deep Creek Lake were near the upper tolerance ranges. We assumed any values higher than the highest value listed for oxygen in the high colonization risk category were suitable (that oxygen could not be too high for zebra or quagga mussels). Although conductivity and flow were included in the Sea Grant publication, they were not included in this report. Conductivity was not included because the types of ions (e.g., calcium or magnesium already included in this table) are important for determining the suitability of conductivity (Hallston et al. 2010, Karatayev et al. 2015) and so conductivity would be redundant. Flow data were not available from Deep Creek Lake. Only summer (June - August) temperature readings were used because the Sea Grant temperature colonization risk categories were for "sustained maximum summer water temperature".

For each location, we examined all five variables from all years measured and determined, by variable, the percent of measurements in each category of colonization risk - high, medium, low, or very low.

Table 2. Modified zebra mussel colonization risk categories for summer temperature, pH, dissolved oxygen, calcium, and hardness from Illinois/Indiana Sea Grant (ilma-lakes.org/Artwork/zebra7.pdf) as originally taken from O'Neill (1996). The Very Low category was added, and the Low category was expanded, to provide a more conservative assessment of colonization risk. These modifications were based on Cohen (2005), Garton et al. (2013), and Mackie and Claudi (2010). The high dissolved oxygen category was also modified to not have an upper limit based on an assumption that oxygen could not be too high to support zebra mussels.

Colonization Risk	Temperature (^{o}C)	pH	Dissolved Oxygen (mg/L)	Calcium (mg/L)	Hardness (mg equivalent CaCO3/L)
Very Low	<9 or >32	<6.6	<4	<8	<25
Low	9 - <16 or >28 - 32	6.6 – 7.2	4 - 6	8 - 20	25 - 45
Medium	16 - <18 or >25 - 28	>7.2 – 7.5 and >8.7 – 9.0	>6 - <8	>20 - 25	>45 - 90
High	18 - 25	>7.5 – 8.7	≥8	>25	>90

Comparison with Nearby Waters

Calcium and pH data were acquired from nearby waters where zebra or quagga mussels were known to occur. The data were compared with those from Deep Creek Lake. Specifically, data were acquired from the following:

- Susquehanna River Basin Commission (SRBC) for sections of the Susquehanna River and select tributaries in New York and Billmeyer Quarry in Pennsylvania.
- The Pennsylvania Department of Environmental Protection for the Monongahela and Allegheny Rivers in western Pennsylvania.
- The Virginia Department of Game and Inland Fisheries from Millbrook Quarry, where zebra mussels were present and then eradicated.
- The Carroll County (Maryland) Department of Land and Resource Management and the city of Westminster (Maryland) from Hydes Quarry, where zebra mussels were present and then eradicated.
- West Virginia Department of Environmental Protection from the Lower Kanawa, Little Kanawha, Monongahela, and Elk Rivers. Kevin Eliason (West Virginia Wildlife Diversity Program) provided the list of waters in West Virginia with zebra mussels. - Although water data from the Little Kanawha and Elk Rivers did not coincide with exact zebra mussel locations in those rivers, all were included in this report.
- Maryland Department of Natural Resources from the Upper Chesapeake Bay and Middle River.

Visual Monitoring

Underwater surveys followed guidelines established by the Pennsylvania Department of Environmental Protection's invasive mussel monitoring guide (seagrant.psu.edu/sites/default/files/2012zmbrochure.pdf). In brief, this consisted of searching for about 30 minutes covering approximately 50 square meters of area in depths ranging from about 0.5 m to 5 meters - using either one individual snorkeling or two individuals with SCUBA.

Zebra mussel monitoring plates were deployed in early summer and retrieved in the fall. The plates consisted of a series of four hard PVC plates (each measuring 6" x 8") fashioned with 1/2" spacers along an eyebolt and secured with a washer and nut. The plates hung roughly 1m below the water surface at each location. A small brick was suspended from the bottom of the plates, as a weight to limit the plates from moving due to wave energy.

Results

Visual Monitoring for Zebra Mussels

No zebra or quagga mussels were found at any of the locations where underwater surveys were conducted or on any of the monitoring plates.

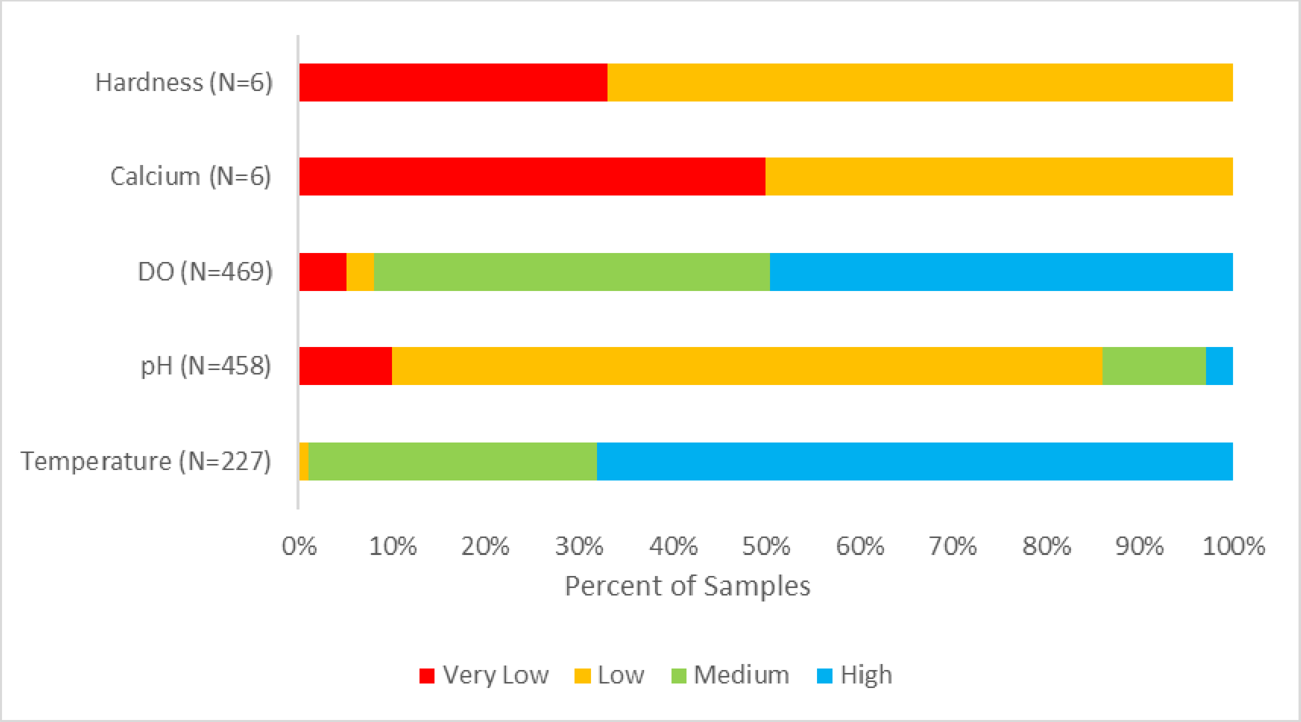
Estimating Colonization Risk

Dissolved oxygen and temperature were indicative of high or medium zebra mussel colonization risk at most times and locations (Figure 3). Most of the small percent of the total dissolved oxygen and temperature measurements indicating low or very low colonization risk came from deep water. All but one temperature reading in the low or very low-risk categories were from more than six meters deep. The exception was a single temperature reading (taken 0.5 m from the surface) from North Glade Cove, in July 2016, which exceeded the medium risk threshold by 0.3ºC (28.3ºC). The vast majority of dissolved oxygen readings in the low and very low-risk categories were from five meters deep or deeper. Exceptions include one reading from Arrowhead Cove at 2.3 m (the shallowest low-risk category value for dissolved oxygen); one from DPR021 at 3.0 m and one at 4.0 m; six from depths between 3.5 m and 4.2 m at Deep Creek Cove; three from depths ranging between 3.9 m and 4.7 m at Green Glade Cove; one at 4.3 m and one at 4.8 m at Meadow Mountain Cove; six between 4.4 and 4.9 m at North Glade Cove; and one at 4.5 m depth at Pawn Run Cove.

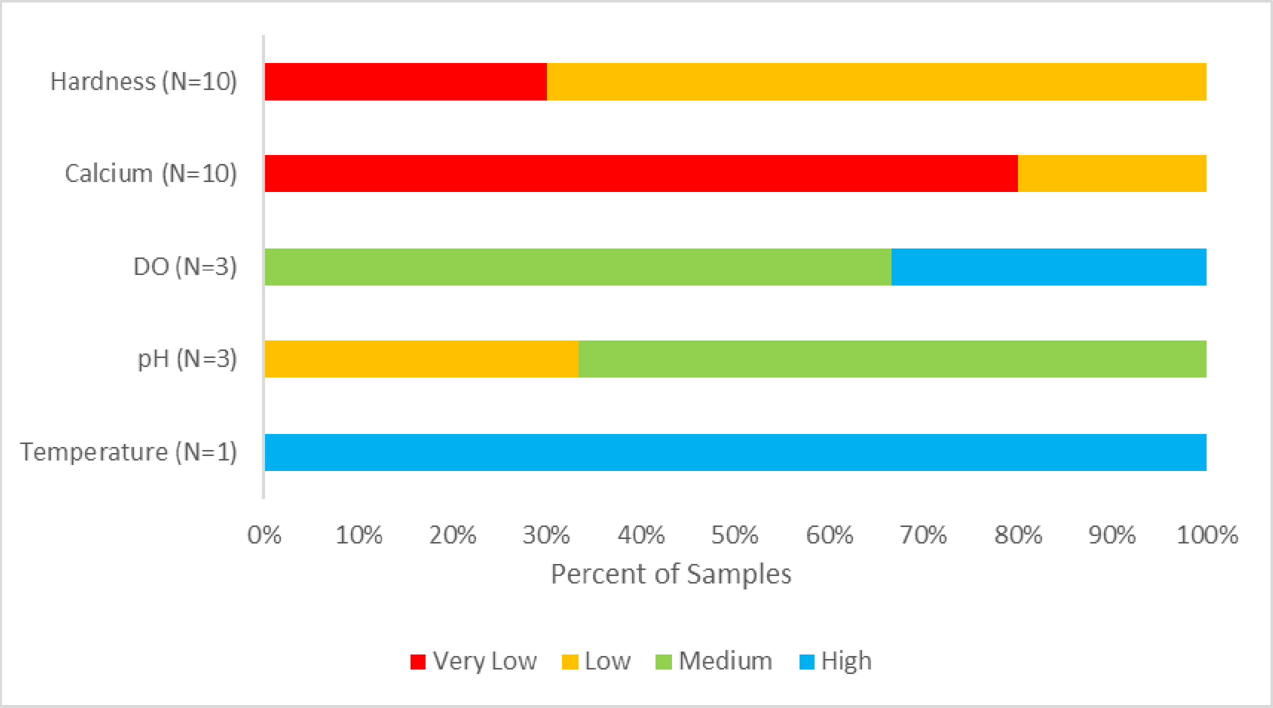
Calcium and hardness from all locations and times indicated very low or low zebra mussel colonization risk. Most samples indicated low or very low colonization risk for pH. More than 50% of measurements from all but three locations (Brookfield Dam, State Park Ramp, and Yacht Club Ramp) were in the low or very low category. Only three pH measurements were available from each of these locations. The percentage of pH measurements from Deep Creek Cove in the low or very low categories barely exceeded 50% (208 out of 398).

Figure 3. Estimates of the percent of water samples by location indicating high, medium, low, or very low zebra/quagga mussel colonization risk in Deep Creek Lake based on calcium, hardness, dissolved oxygen, summer temperature, and pH results from 18 Deep Creek Lake water sampling locations. Concentrations of these variables were compared with colonization risk categories defined in this report.

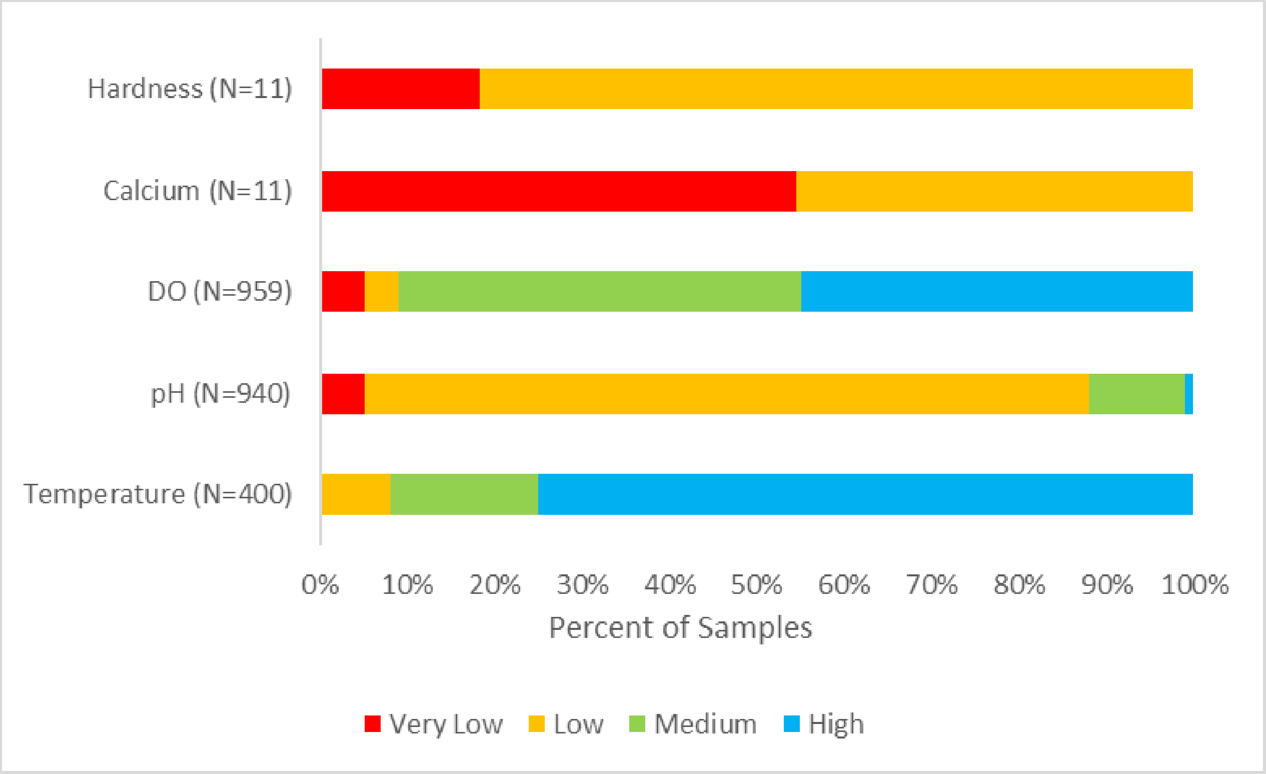
Arrowhead Cove (AWC)



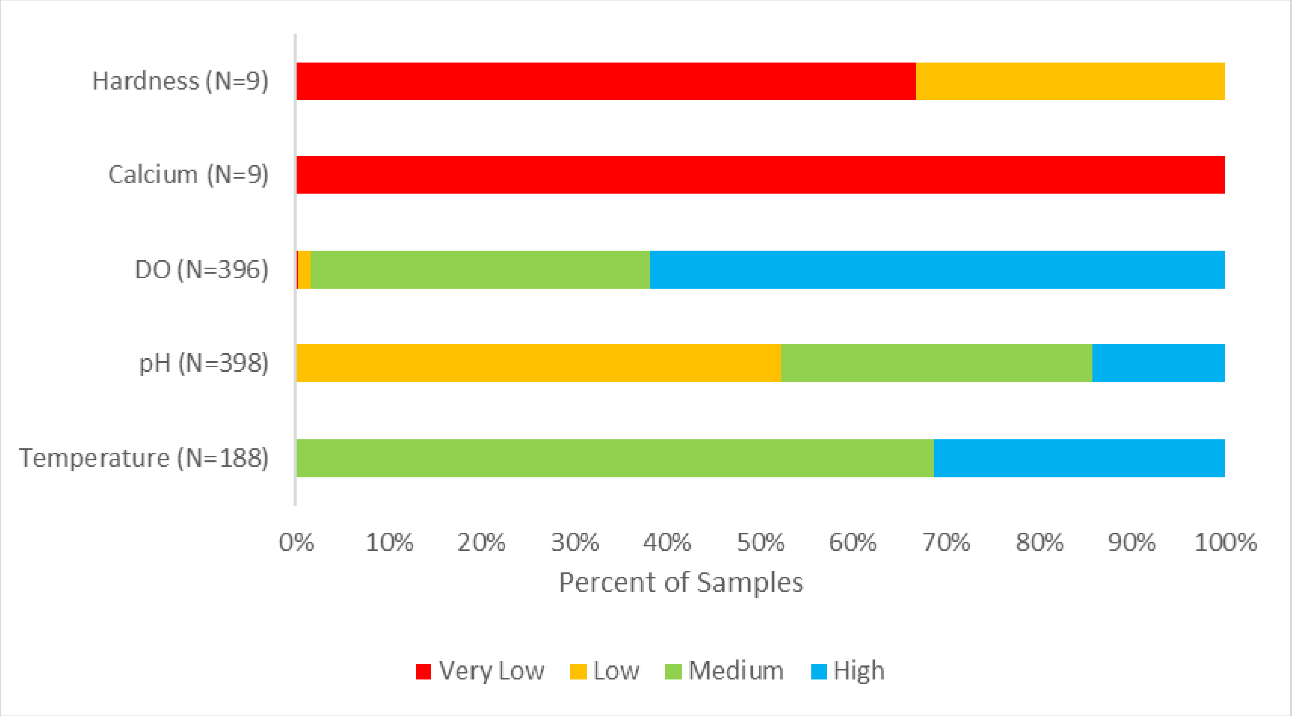
Brookfield Dam (BRKDam)



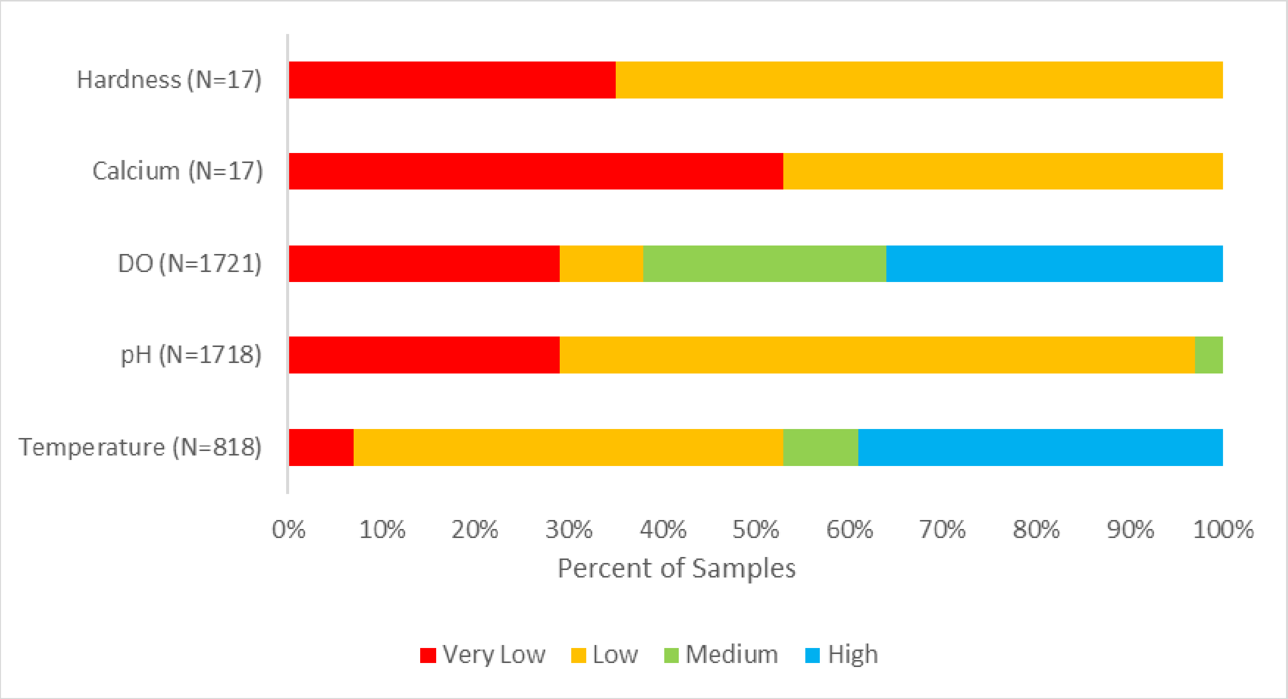
Cherry Creek Cove (CCC)



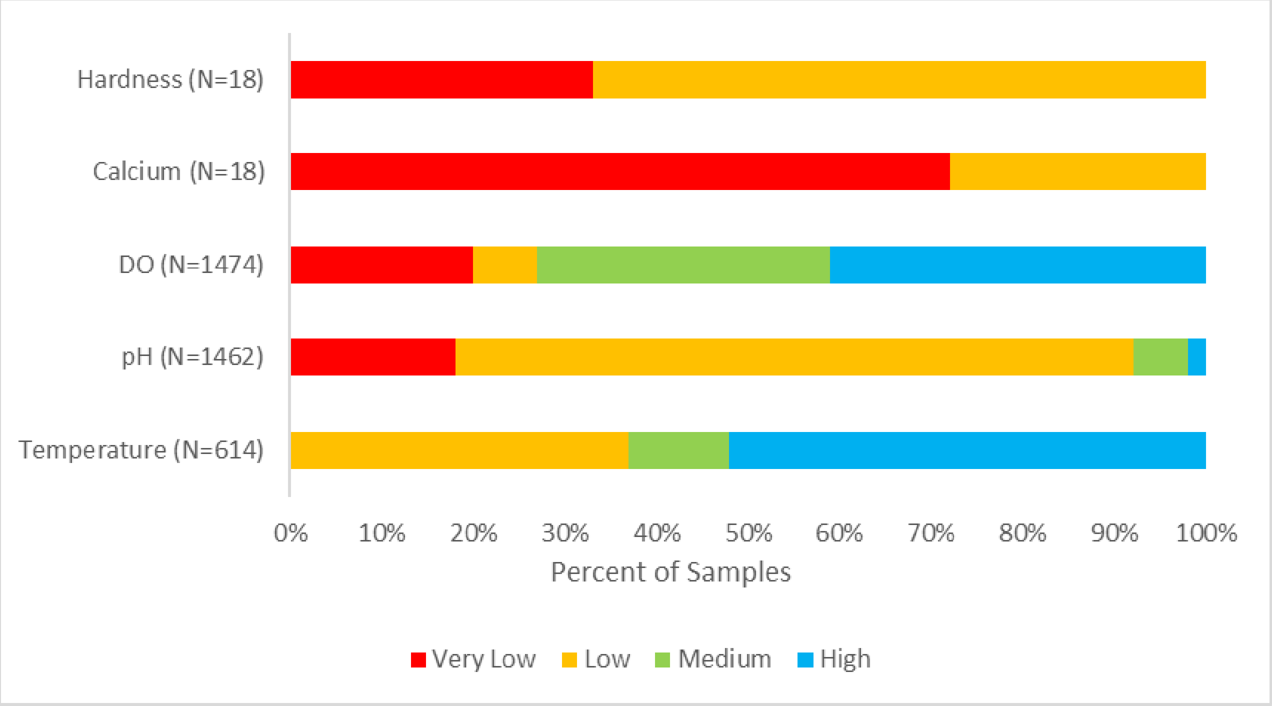
Deep Creek Cove (DCC)



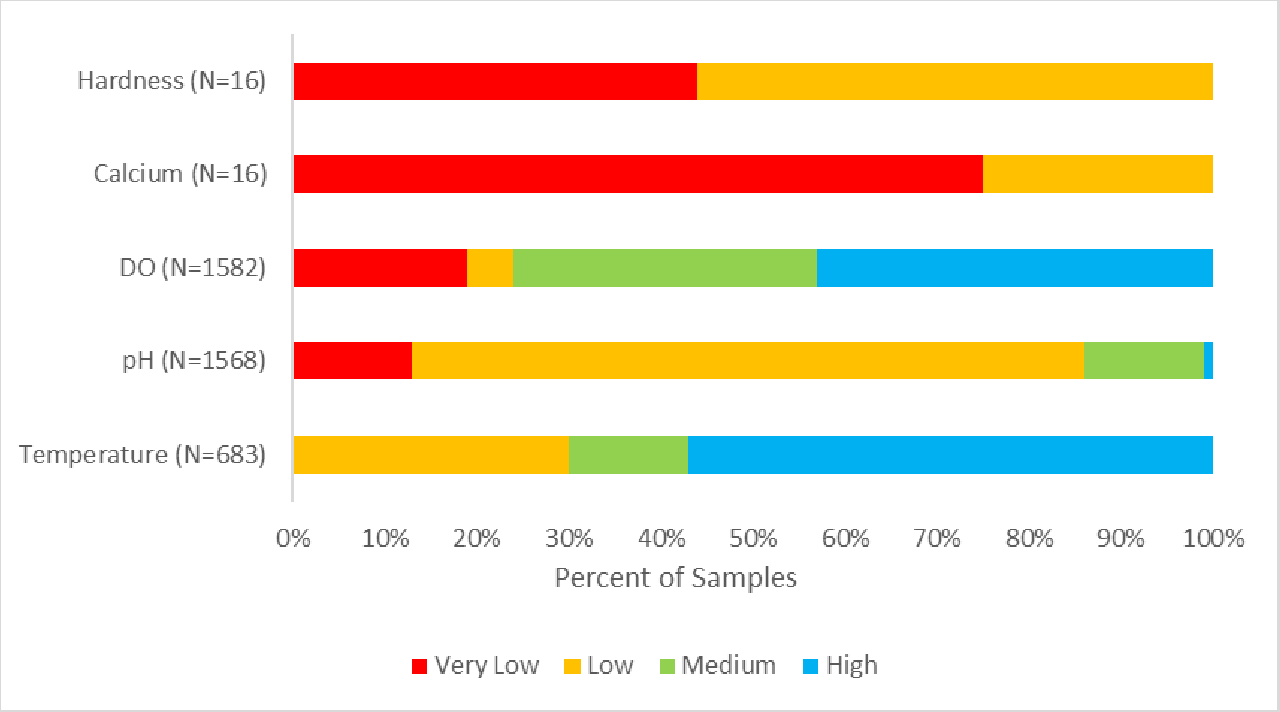
Deep Creek Lake Near Slide Hollow, 0.4 miles from Deep Creek Lake Dam (DPR0021)



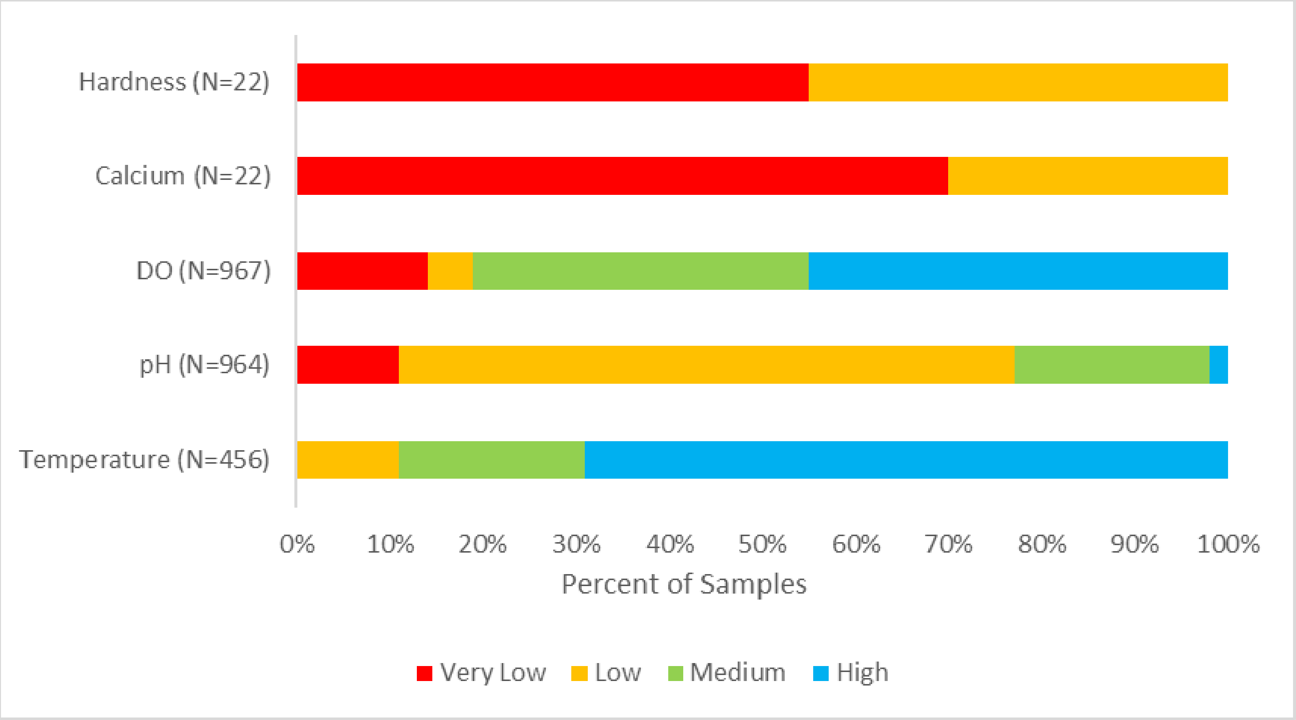
Deep Creek Lake at West Deep Creek Bridge (DPR0056)



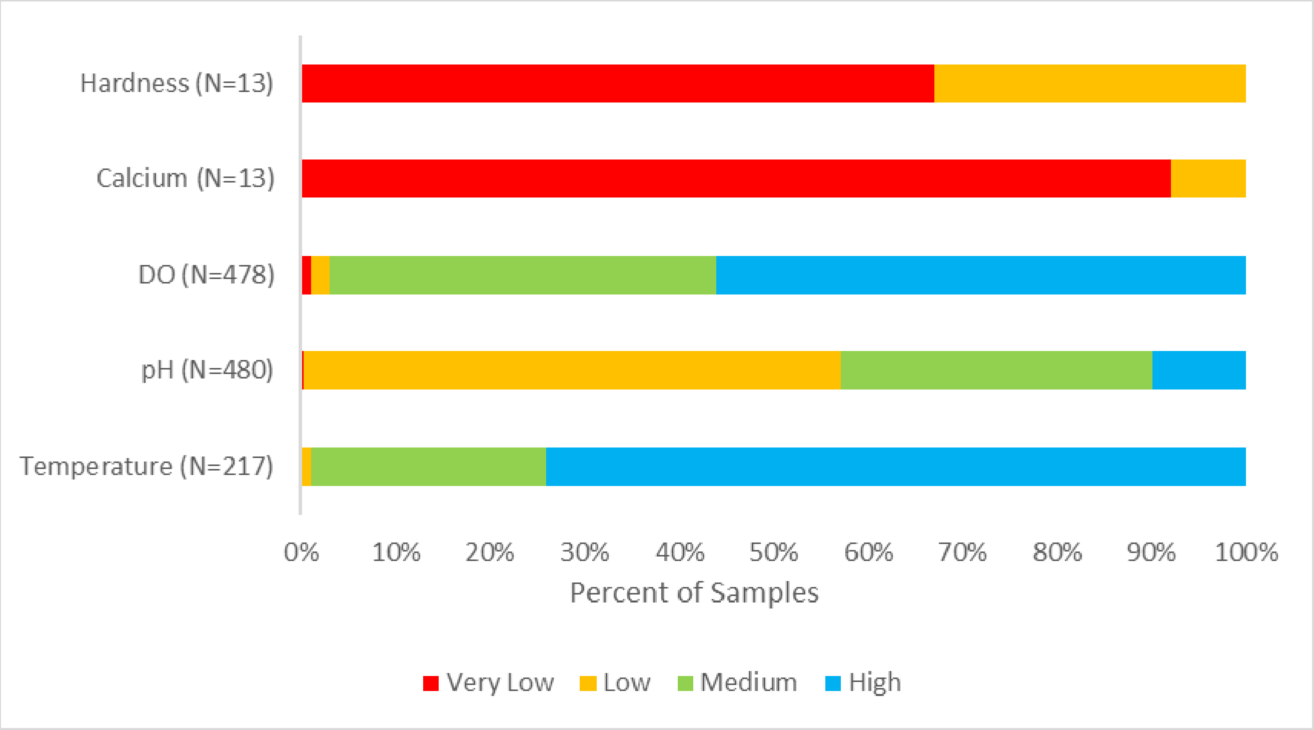
Deep Creek Lake - North Side of Glendale Bridge (DPR0082)



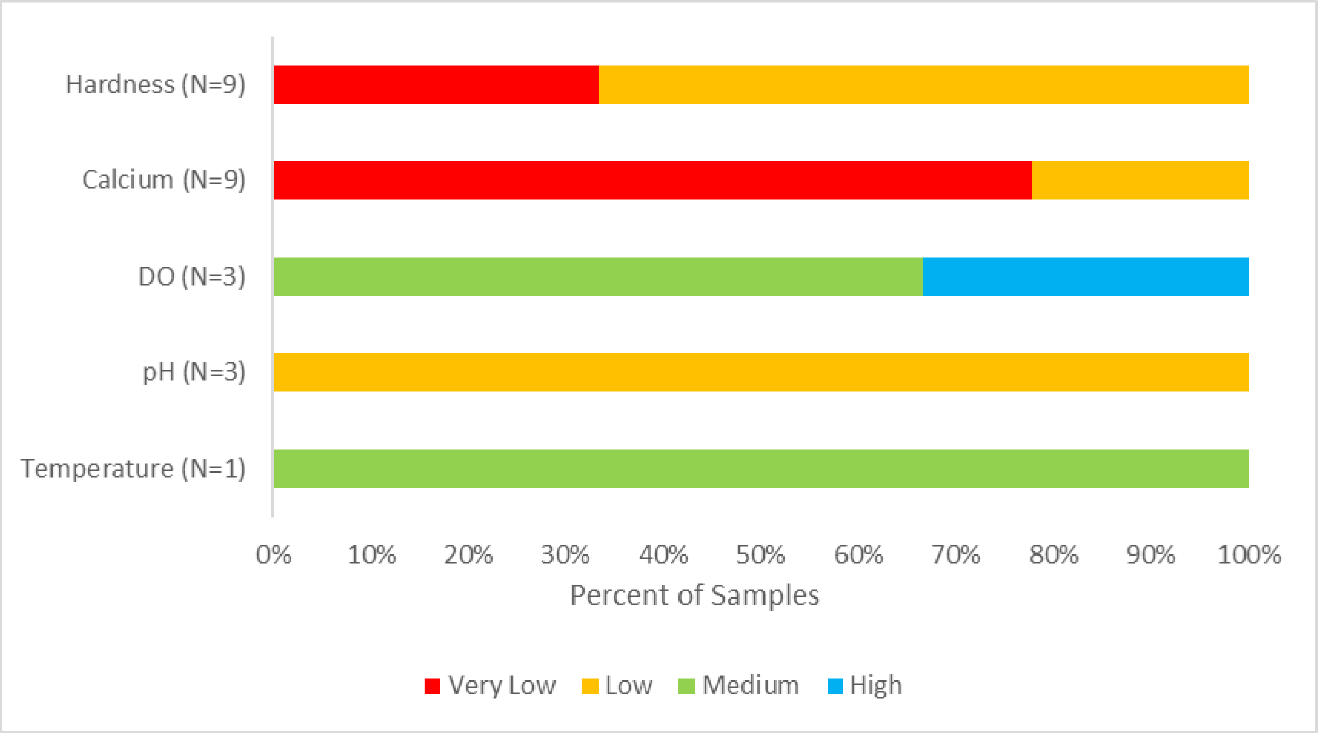
Deep Creek Lake Northwest of Turkey Neck (DPR0103)



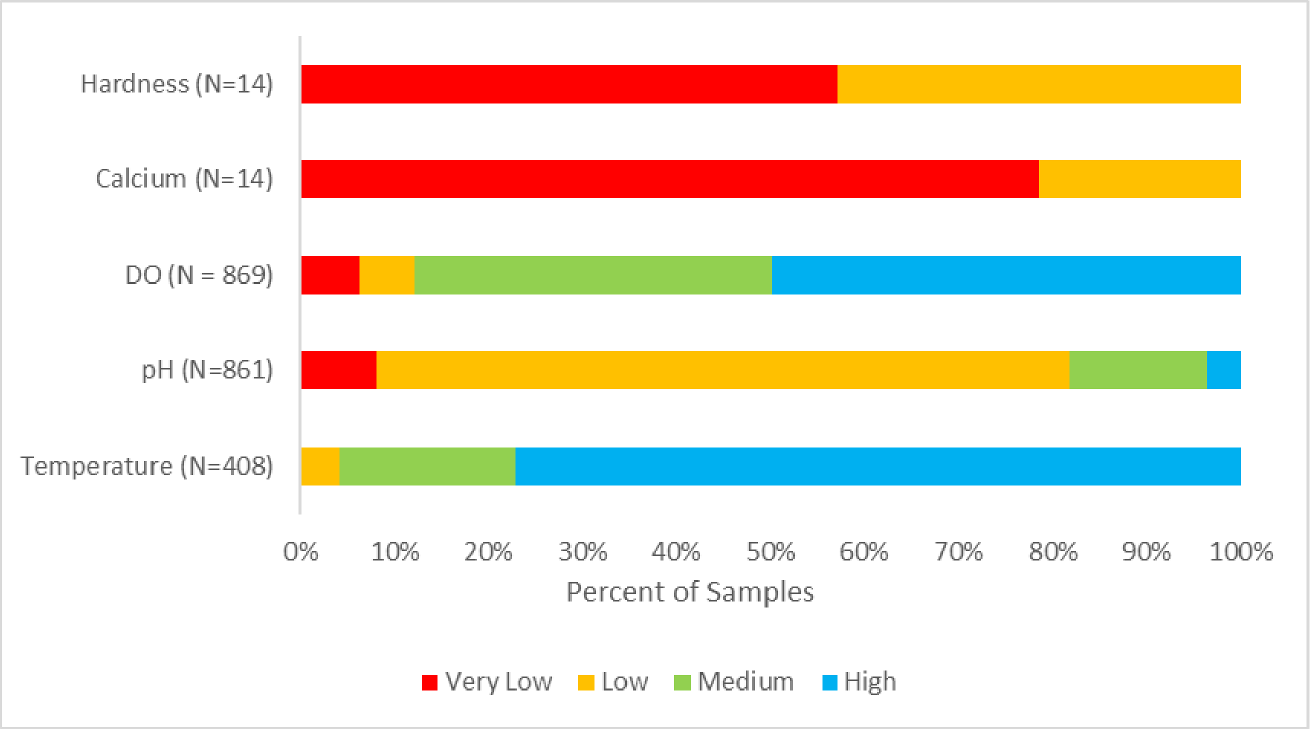
Green Glade Cove (GGC)



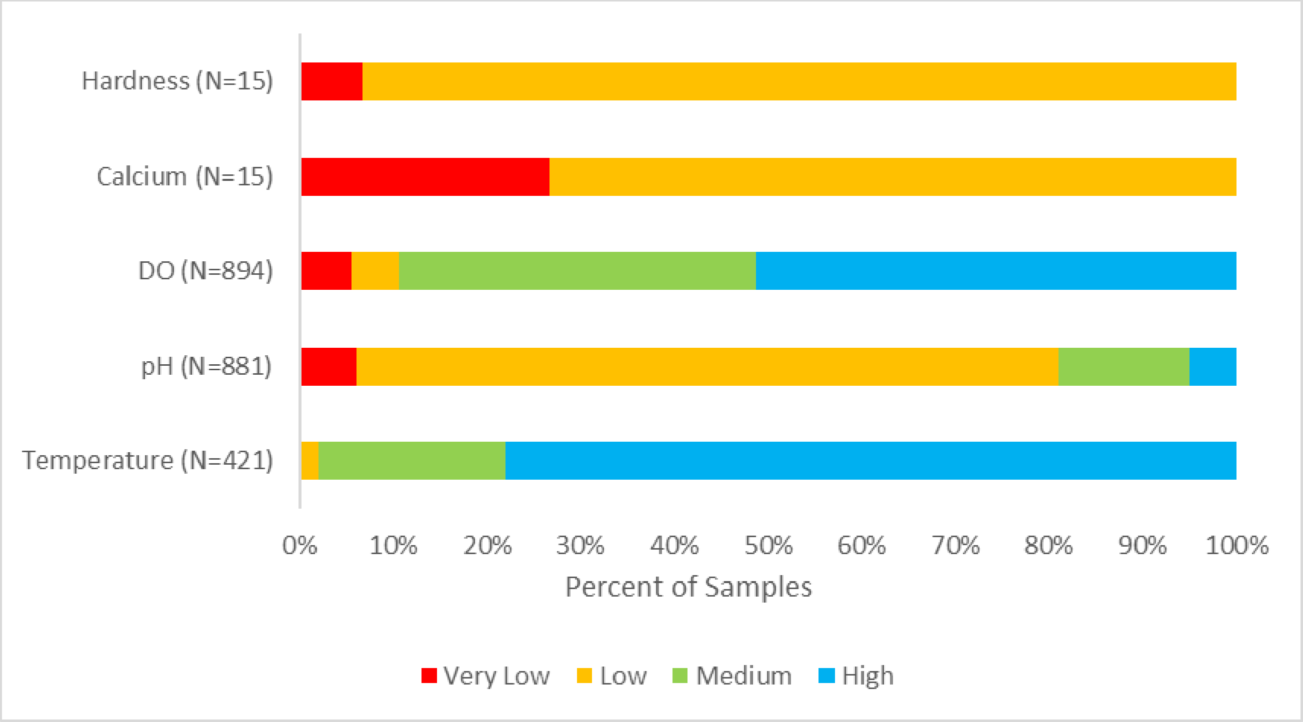
Gravelly Run Cove (GRC)



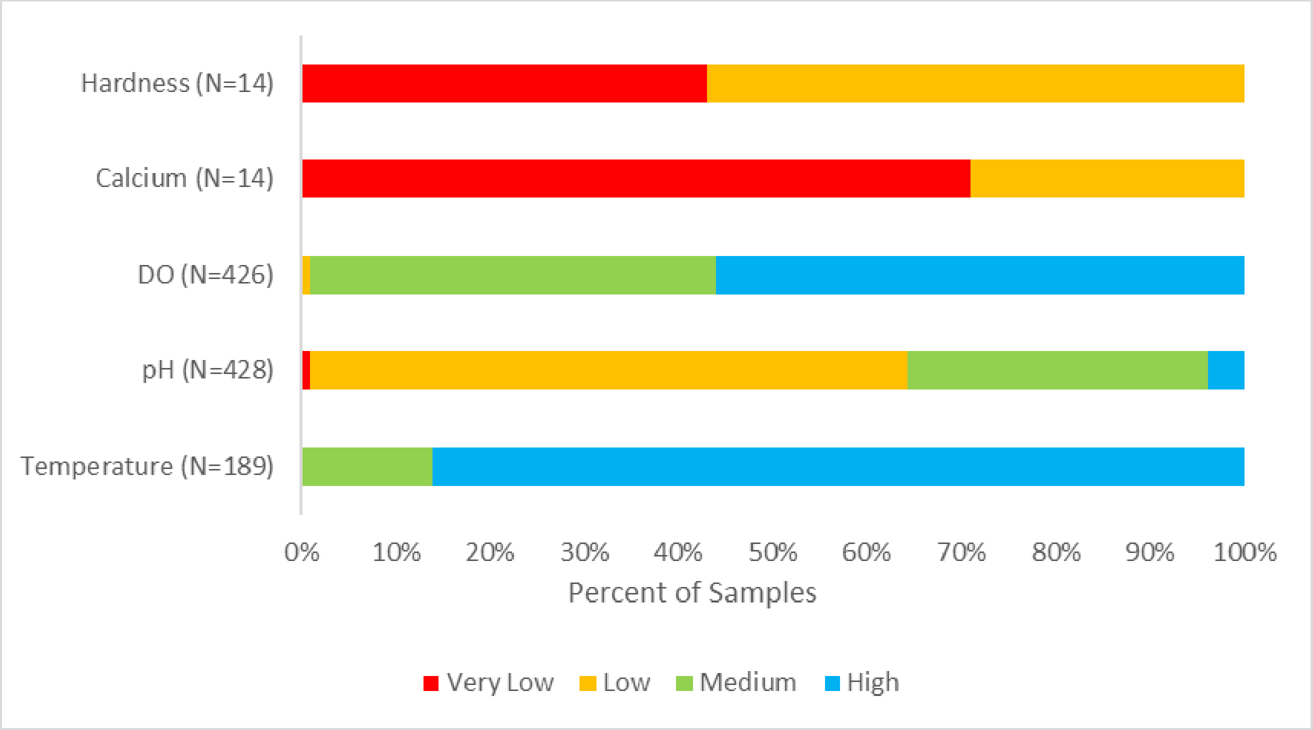
Hoop Pool Cove (HPC)



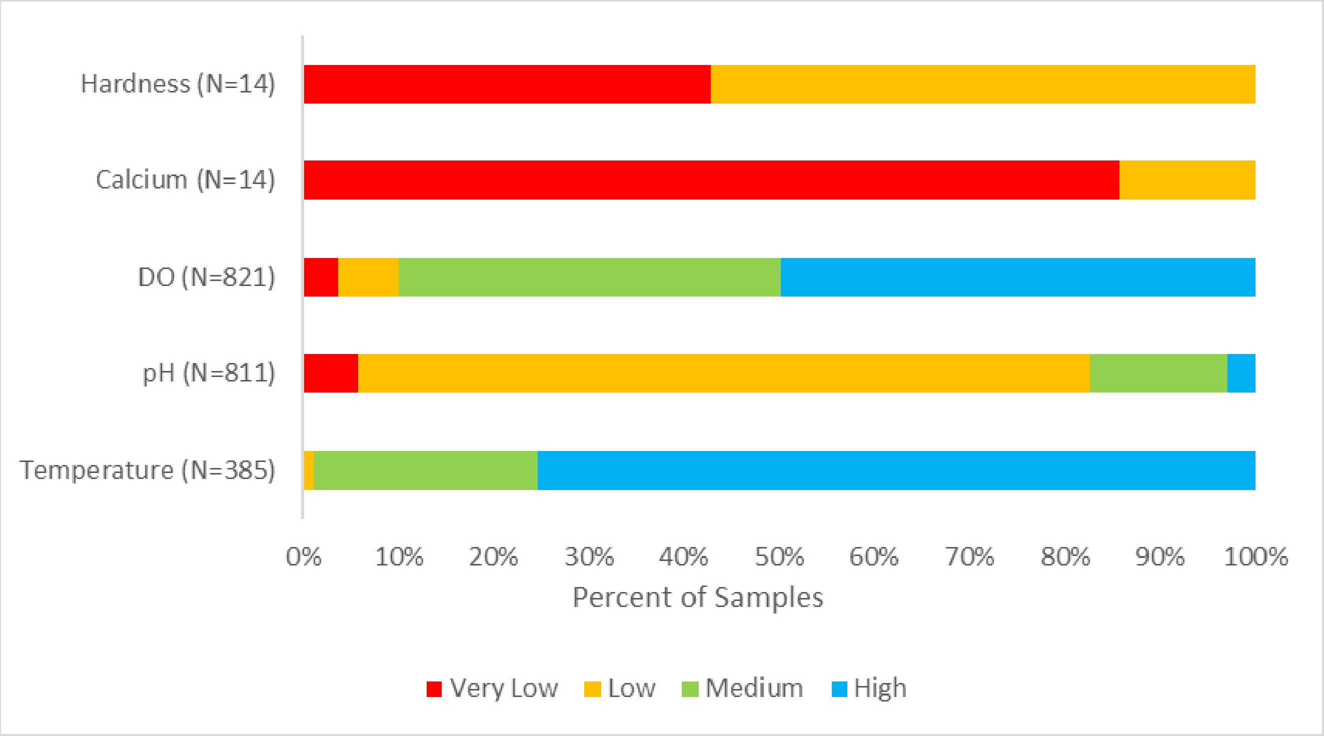
Marsh Run Cove (MRC)



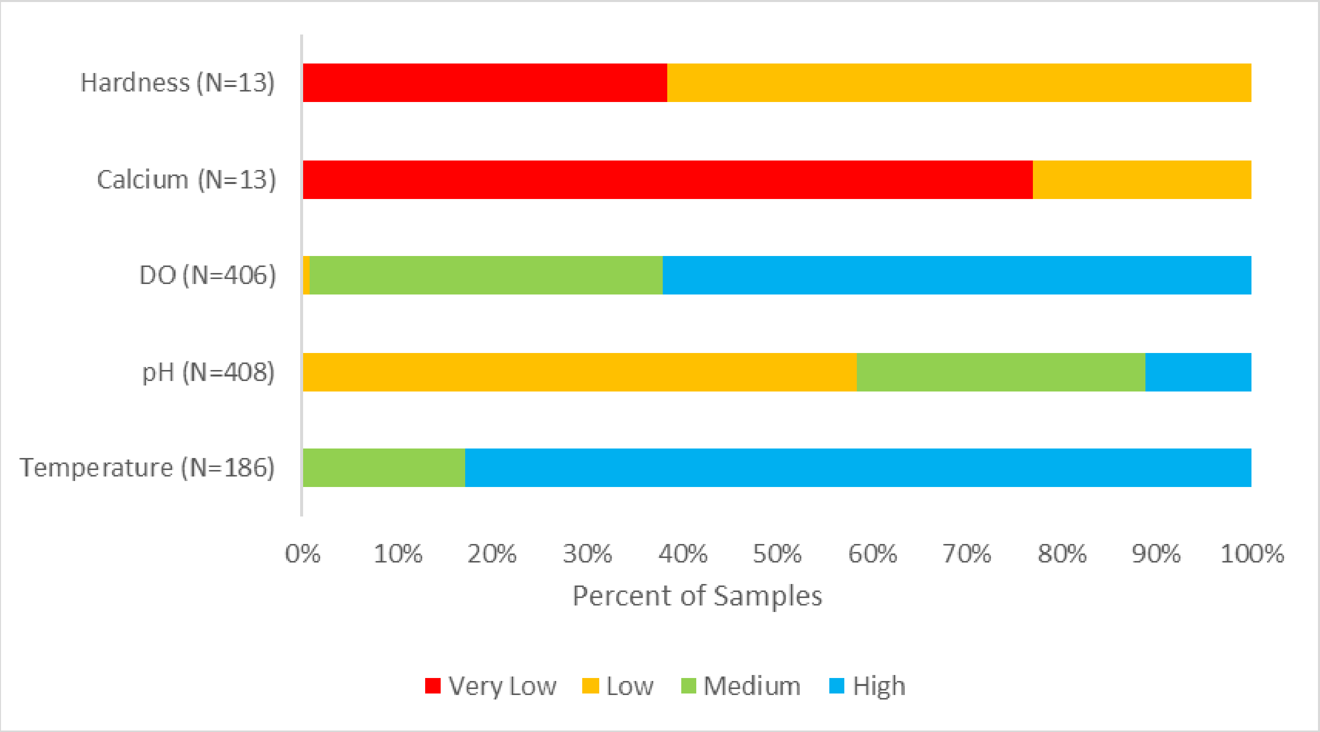
Meadow Mountain Run Cove (MMC)



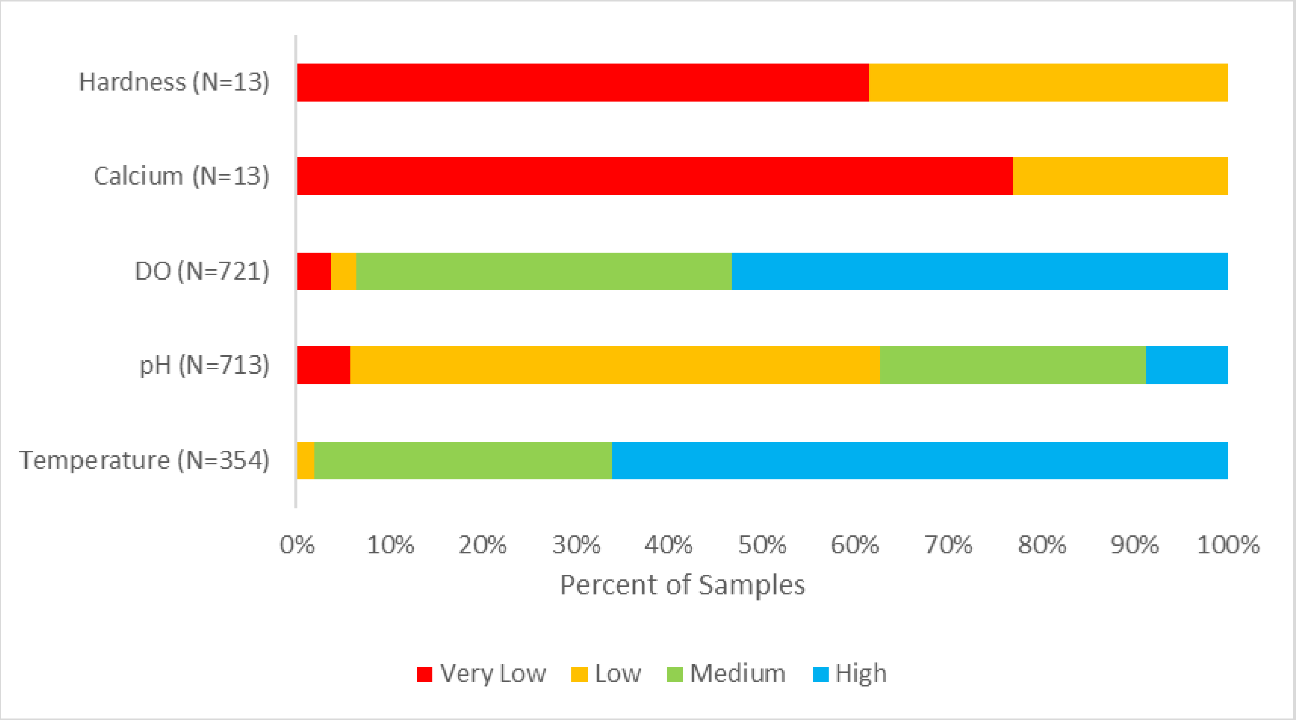
North Glade Cove (NGC)



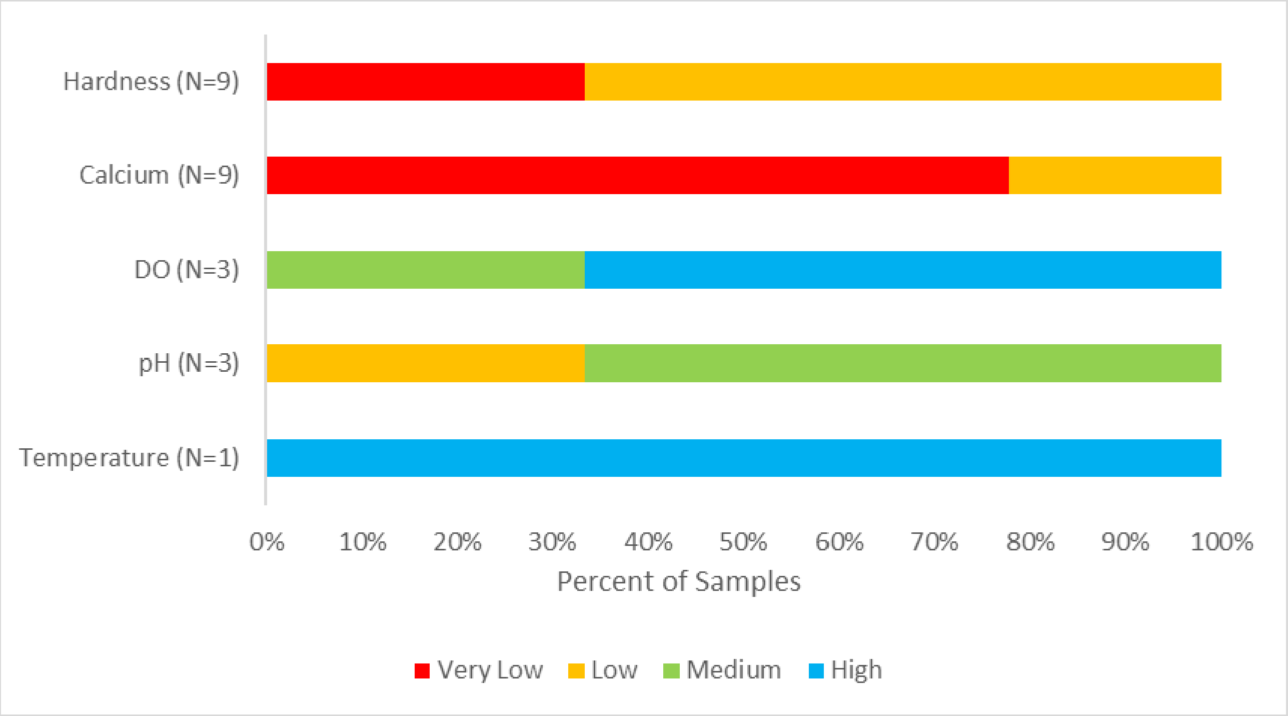
Pawn Run Cove (PWC)



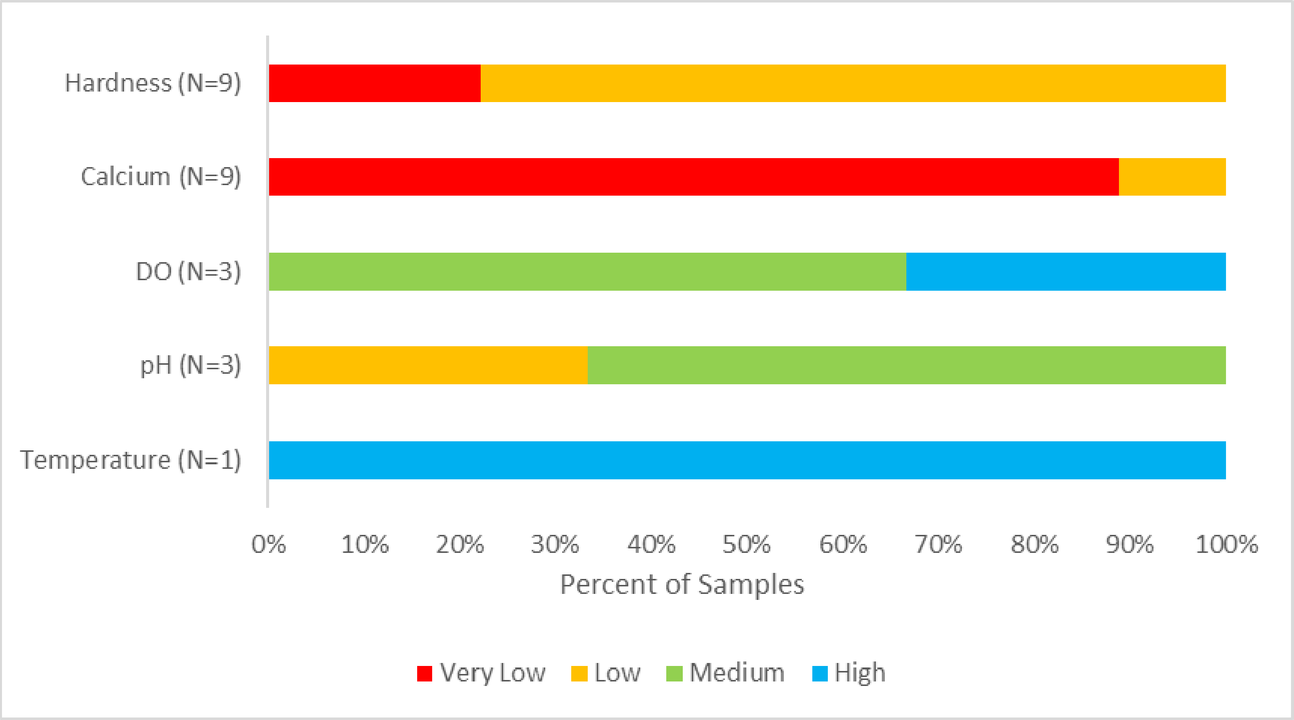
Poland Run Cove (PLV)



State Park Ramp (SPRamp)



Yacht Club Ramp (YCRamp)



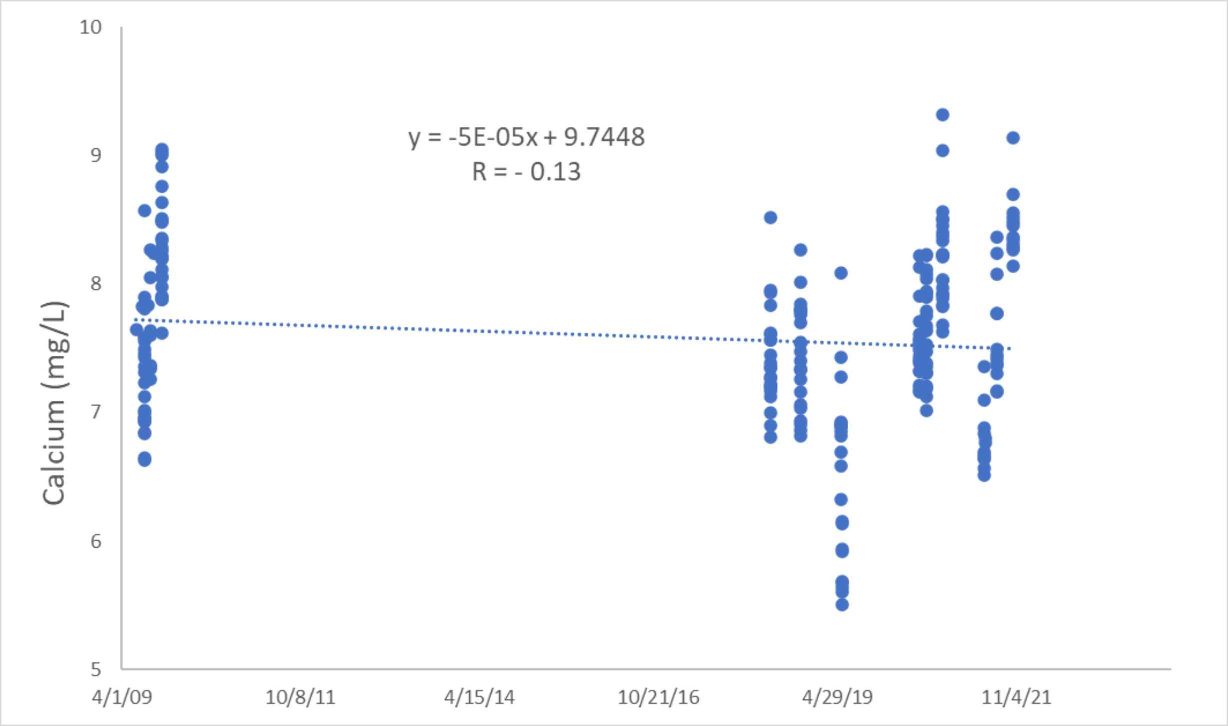
Calcium and pH Trend Results

Calcium concentration and pH varied over time and by location but remained within a narrow range of values (≥5.5 mg/L and ≤9.3 mg/L for calcium and ≥5.1 and <9.4 for pH; Appendix A). These two variables were selected for trend analysis because they are two of the three (calcium, hardness, and pH) factors most likely to be limiting for zebra mussel colonization in Deep Creek Lake. Calcium was the variable most often in the very low zebra mussel colonization risk category. The Deep Creek Lake hardness concentrations were strongly correlated with calcium concentrations (R = 0.91). Substantially more data from many more years, lake depths, and locations were available for pH (total N for all locations = 12,102 for pH versus 232 for calcium and hardness) and pH was often in the low zebra mussel colonization risk category.

Based on data from all locations combined, there was a slight decline in calcium concentration over time (R = - 0.13; Figure 4). Most individual locations also showed a declining trend (Appendix A). Only two locations with the entire time series of data showed increasing calcium trends (Marsh Run Cove R= 0.05 and DPR0103 R= 0.07). Three locations, without data from 2009, showed positive correlations between calcium concentration and time (Arrowhead Cove R= 0.71, State Park Ramp R=0.22, and Yacht Club Ramp R = 0.36).

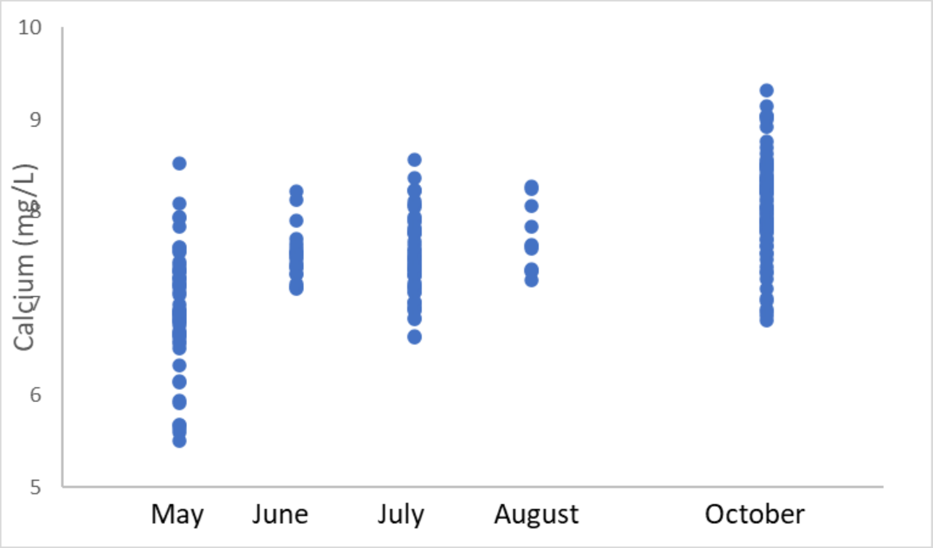
Data from most locations indicated a slightly declining trend in pH (Appendix A). Meadow Mountain Run Cove showed the largest negative pH correlation (R = -0.41) with time. Five other locations had negative pH correlations coefficients with time larger than -0.30 (Poland Run R = -0.37, DPR0021 R = -.033, DPR0056 R = -0.36, DPR0082 R = -0.34, and Cherry Creek Cove R = -0.32). All but three locations (Deep Creek Cove R = 0.03, Green Glade Cove R = 0.002, and Pawn Run Cove R = 0.005) with the full 2009 - 2021 time series of pH data showed negative correlations over time. The largest positive pH correlation over time was from a cove with a short time series (Gravelly Run Cove R = 0.32, 2016 - 2021).

Figure 4. Calcium concentration in Deep Creek Lake over time using data from all 18 Deep Creek Lake water sampling locations.



Regardless of year, across all locations, on average, samples from May tended to have the lowest calcium concentrations (mean 6.92 ± 0.92 standard error, N = 56) and October the highest (mean 8.08 ± 0.89 standard error, N = 83). The mean calcium concentration for July (7.49 ± 0.97 standard error, N = 60) was lower than in October but higher than in May (Figure 5). Fewer samples were taken in June (N = 22) and August (N = 11) compared with these other months.

Figure 5. Calcium concentrations by month across all locations.



Comparison with Nearby Waters

Calcium and/or pH data were received from a total of 15 water bodies in West Virginia, Pennsylvania, Virginia, New York, and Maryland where zebra or quagga mussels currently or recently occurred (Table 3).

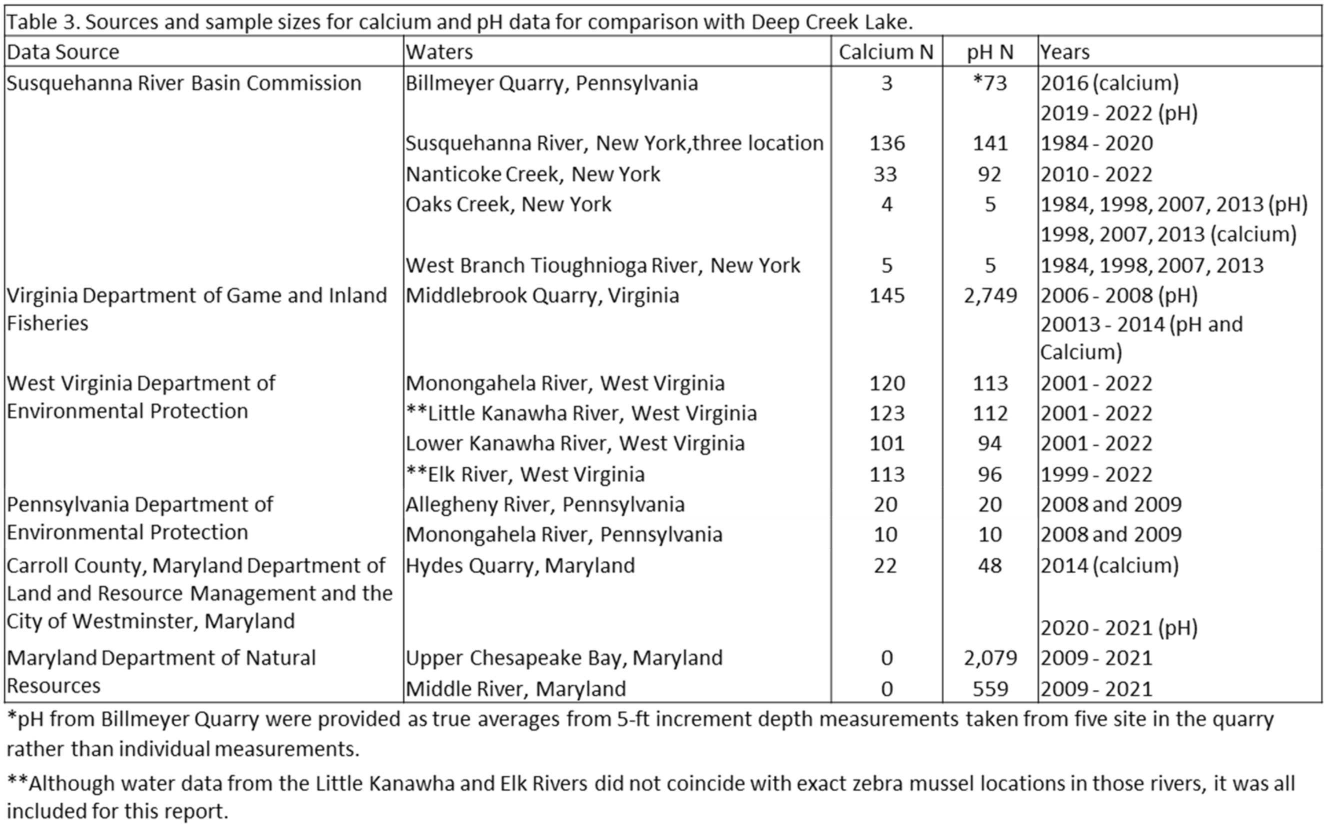


Table 3. Sources and sample sizes for calcium and pH data for comparison with Deep Creek Lake.

Data Source	Waters	Calcium N	pH N	Years
Susquehanna River Basin Commission	Billmeyer Quarry, Pennsylvania	3	*73	2016 (calcium) 2019 - 2022 (pH)
	Susquehanna River, New York,three location	136	141	1984 - 2020
	Nanticoke Creek, New York	33	92	2010 - 2022
	Oaks Creek, New York	4	5	1984, 1998, 2007, 2013 (pH) 1998, 2007, 2013 (calcium)
	West Branch Tioughnioga River, New York	5	5	1984, 1998, 2007, 2013
Virginia Department of Game and Inland Fisheries	Middlebrook Quarry, Virginia	145	2,749	2006 - 2008 (pH) 20013 - 2014 (pH and Calcium)
West Virginia Department of Environmental Protection	Monongahela River, West Virginia	120	113	2001 - 2022
	**Little Kanawha River, West Virginia	123	112	2001 - 2022
	Lower Kanawha River, West Virginia	101	94	2001 - 2022
	**Elk River, West Virginia	113	96	1999 - 2022
Pennsylvania Department of Environmental Protection	Allegheny River, Pennsylvania	20	20	2008 and 2009
	Monongahela River, Pennsylvania	10	10	2008 and 2009
Carroll County, Maryland Department of Land and Resource Management and the City of Westminster, Maryland	Hydes Quarry, Maryland	22	48	2014 (calcium) 2020 - 2021 (pH)
Maryland Department of Natural Resources	Upper Chesapeake Bay, Maryland	0	2,079	2009 - 2021
	Middle River, Maryland	0	559	2009 - 2021

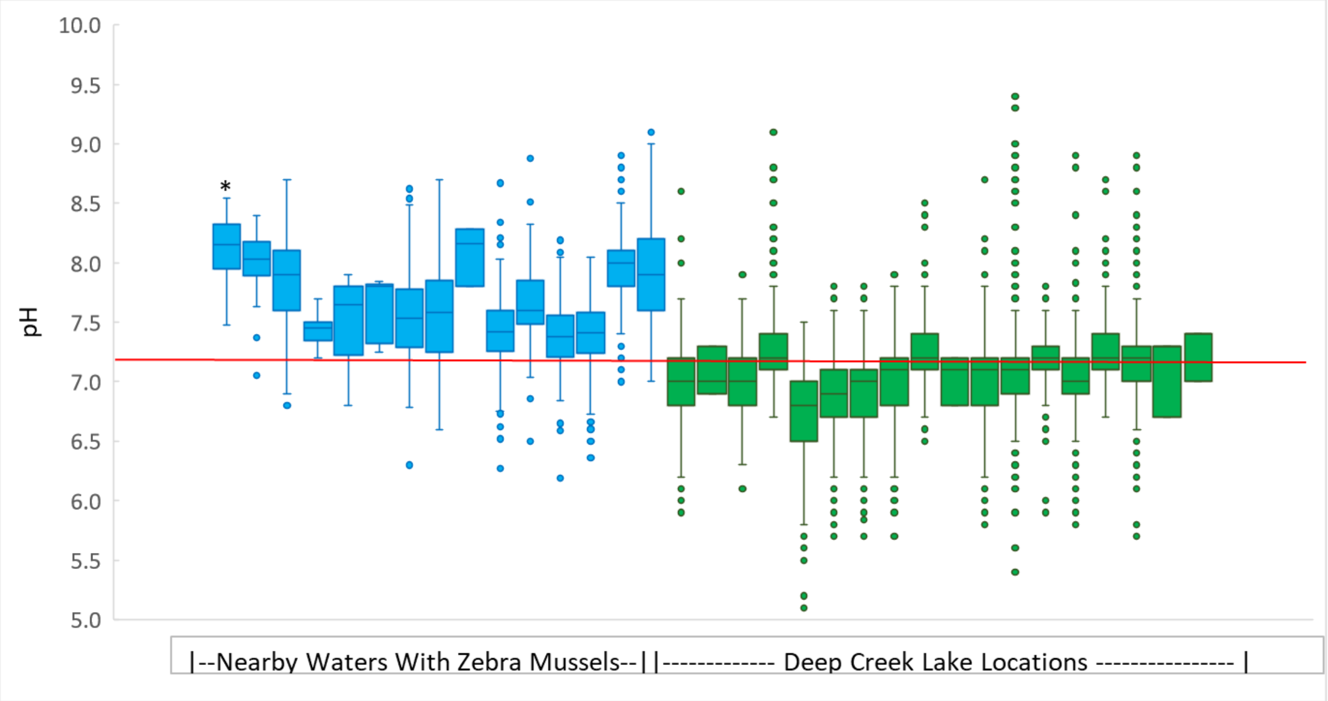
*pH from Billmeyer Quarry were provided as true averages from 5-ft increment depth measurements taken from five site in the quarry rather than individual measurements.

**Although water data from the Little Kanawha and Elk Rivers did not coincide with exact zebra mussel locations in those rivers, it was all included for this report.

The pH at Deep Creek Lake sampling locations tended to be lower compared with nearby waters known to have zebra mussels (Figure 6). All pH readings equal to or greater than the 25th percentile exceeded 7.2 (the threshold used in this report between low and medium zebra mussel colonization risk) at waters known to have zebra or quagga mussels. The highest median pH of 7.2 for any Deep Creek Lake locations (Poland Run Cove, Pawn Run Cove, Meadow Mountain Run Cove, Green Glade Cove, and Deep Creek Cove) with more than three total pH measurements was lower than the lowest median pH of any of the nearby waters with zebra or quagga mussels (7.38 Elk River, WV).

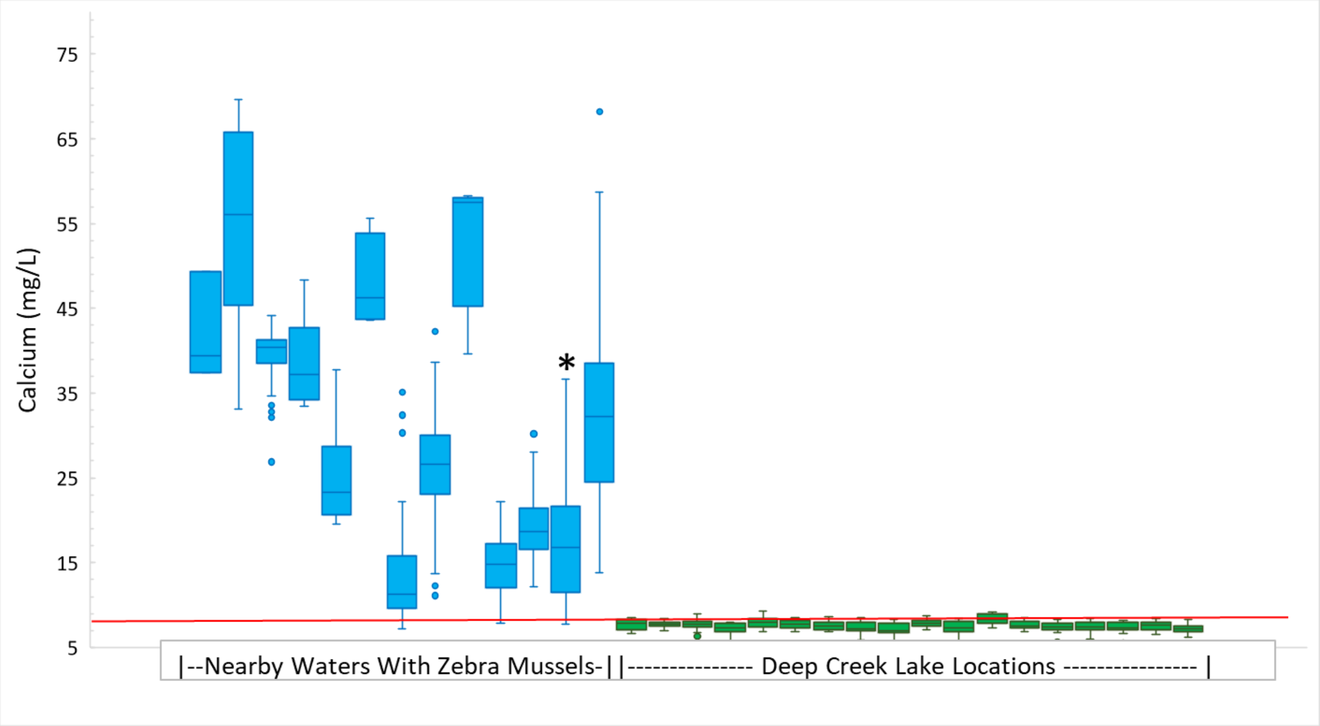
Calcium concentrations at Deep Creek Lake locations were lower than in nearby waters with zebra or quagga mussels (Figure 7). Fewer than 3.3% (27 of 835) of the measurements from waters with zebra or quagga mussels were lower than the highest measurement (9.32 mg/L) from any Deep Creek Lake calcium sample. A total of five (<1 %) of the measurements from waters with zebra or quagga mussels were below 8.0 mg/L. Seventy-two percent of measurements from Deep Creek Lake were less than 8.0 mg/L.

Figure 6. Comparison of pH from Deep Creek Lake sampling locations (green) with pH from nearby waters known to currently have or recently had zebra or quagga mussels (blue). From left to right - Billmeyer Quarry, PA; Hydes Quarry, MD; Millbrook Quarry, VA; Monongahela River, PA; Allegheny River, PA; Oak Creek, NY; Nanticoke Creek, NY; three Susquehanna River locations combined, NY; West Branch Tioughnioga River, NY; Little Kanawha River, WV; Lower Kanawha River, WV; Elk River, WV; Monongahela River, WV; Upper Chesapeake Bay, MD, and Middle River, MD. Arrowhead Cove; Brookfield Dam; Cherry Creek Cove; Deep Creek Cove; Deep Creek Lake Near Slide Hollow; Deep Creek Lake at West Deep Creek Bridge; Deep Creek Lake - North Side of Glendale Bridge; Deep Creek Lake Northwest of Turkey Neck; Green Glade Cove; Gravelly Run Cove; Hoop Pool Cove; Marsh Run Cove; North Glade Cove; Pawn Run Cove; Poland Run Cove; State Park Ramp; Yacht Club Ramp; The red line is at the threshold between low and medium zebra mussel colonization risk pH level (7.2).



*pH data for Billmeyer Quarry, PA were true averages from 5-foot increment depth measurements taken from five sites in the quarry, rather than individual measurements.

Figure 7. Comparison of calcium from Deep Creek Lake sampling locations (green) with calcium from nearby waters known to currently have or recently had zebra or quagga mussels (blue). From left to right - Billmeyer Quarry, PA; Hydes Quarry, MD; Millbrook Quarry, VA; Monongahela River, PA; Allegheny River, PA; Oak Creek, NY; Nanticoke Creek, NY; three Susquehanna River locations combined, NY; West Branch Tioughnioga River, NY; Little Kanawha River, WV; Lower Kanawha River, WV; Elk River, WV; Monongahela River, WV; Arrowhead Cove; Brookfield Dam; Cherry Creek Cove; Deep Creek Cove; Deep Creek Lake Near Slide Hollow; Deep Creek Lake at West Deep Creek Bridge; Deep Creek Lake - North Side of Glendale Bridge; Deep Creek Lake Northwest of Turkey Neck; Green Glade Cove; Gravelly Run Cove; Hoop Pool Cove; Marsh Run Cove; North Glade Cove; Pawn Run Cove; Poland Run Cove; State Park Ramp; Yacht Club Ramp; The red line is at the threshold between low and very low zebra mussel colonization risk calcium level used in this study (8.0 mg/L).



* Two outliers from Elk River, WV of 105 and 145 mg/L are not shown.

Discussion

It is possible there are zebra or quagga mussels in portions of Deep Creek Lake not searched and conditions could be suitable in areas not sampled. However, it seems unlikely there would be large numbers of these mussels in any portion of the lake given the results of this study. Abundant water sampling from 18 locations distributed throughout Deep Creek Lake provided an opportunity to thoroughly characterize pH, temperature, and dissolved oxygen from thousands of samples collected at various water depths over 13 years - as well as hundreds of calcium and hardness samples collected during five separate years, spanning the same 13-year period. Based on examining these data and comparing them with data from nearby waters, the water in Deep Creek Lake appears to offer low zebra or quagga mussel colonization risk. It is possible that the complete absence of zebra mussels from visual surveys is because none (or very few) have been introduced into the lake. However, the low suitability of Deep Creek Lake water could explain why none were found and likely means that substantial growth and reproduction (even if an introduction occurs), while not impossible, seems unlikely.

According to information from the Maryland Department of Natural Resources Maryland Park Service, zebra mussels were found attached to 23 inspected boats at the State Park Ramp during 2016 - 2021. Although inspections of boats at the State Park Ramp, and subsequent cleaning, likely reduced the potential for zebra mussel introduction, there are other boat ramps, where inspections did not occur, thus there is a strong possibility that zebra mussels have been introduced into Deep Creek Lake.

According to this study, temperature and dissolved oxygen were largely within ranges suitable for zebra mussels. The single temperature reading exceeding the low colonization risk threshold is likely not relevant because the temperature ranges defining the colonization risk categories used herein (ilma-lakes.org/Artwork/zebra7.pdf), were reported as sustained summer maxima.

Although additional factors, beyond those examined in this study (Cohen 2005, Mackie and Claudi 2010, Garton et al. 2013, Karatayev et al. 2015) could also be important for zebra mussels, the suitability of such factors (as well as temperature and dissolved oxygen) is probably moot given the low suitability of pH, hardness, and calcium. Calcium is particularly important for shell growth (Hincks and Mackie 1997). Although survival may be possible, it seems unlikely (despite the potential suitability of other factors) that abundant zebra mussel growth and reproduction (Cohen and Weinstein 2001, Whittier et al. 2013) would occur in Deep Creek Lake unless calcium concentrations increase. If calcium concentrations were to increase, examining other factors would become more relevant to evaluating colonization risk.

Calcium and alkalinity have been shown to be increasing in many U.S. waters (Kaushal et al. 2013). However, calcium and pH may be decreasing over time in Deep Creek Lake, according to the results of this study. But, the exact sampling position (especially within coves) and depths were not consistent from year to year. Moreover, the years with available data and depths of sampling varied across sites, and the months during which sampling occurred within each year also varied (Figure 2). Although combining data taken from all positions within each cove improved the characterization of conditions by location, it hampered the ability to rigorously evaluate and interpret potential temporal trends. Furthermore, locations with different time series tended to show different trend results, indicating that perhaps conditions may simply vary from year to year.

Whether there is a consistent trend over time or variability from year to year, calcium and pH were consistently within narrow ranges and indicated low suitability for zebra and quagga mussels.

While the importance of calcium seems to be well established, there is inconsistent information available about the levels required by zebra mussels (Cohen 2005). This may be because tolerances to this and other factors may differ between distinct populations and individuals. For example, zebra mussels are present in North American waters with lower calcium compared to European waters (Mackie and Schloesser 1996, [a]Benson et. al. 2022). Despite this difference, Mackie and Schloesser (1996) reported that the abundance of North American zebra mussels would likely remain relatively low at calcium levels less than 15 mg/L. This study's examination of other waters in the general vicinity of Deep Creek Lake, without regard to zebra mussel abundance, showed that concentrations were very rarely less than 8.0 mg/L. While there are likely to be different levels of tolerance among different populations and individuals even in this region of North America, no examinations of zebra mussel colonization risk or suitability anywhere have used levels below 8.0 mg/L. That, combined with the results of this study, indicates the 8.0 mg/L calcium threshold seems to currently be useful for evaluating colonization risk in this area.

Although spatial and temporal variability within Deep Creek Lake was low, slightly higher calcium concentrations later in the year (e.g., October) compared with earlier in the year (e.g., May) could help focus future monitoring or the selection of data for future zebra mussel suitability analysis. Furthermore, locations with the highest calcium (e.g., Marsh Run Cove) or with calcium added in tributaries (e.g., lime dosing in Cherry Creek; Resource Assessment Service 2019) may also help focus future monitoring. However, the low spatial variability in calcium concentration indicates that relatively few samples could potentially be used to represent the calcium concentrations throughout the lake.

The weight of evidence from evaluations performed in this study indicates that zebra mussels are currently absent (or present in numbers difficult to detect) and water chemistry is not suitable for the abundant proliferation of zebra or quagga mussels in Deep Creek Lake. The evaluations performed in this study provide useful information for helping manage a potential zebra mussel threat in Deep Creek Lake and may also offer a thorough process for evaluating other regional waters for potential colonization.

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[b]Benson, A.J., M.M. Richerson E. Maynard, J. Larson, A. Fusaro, A.K. Bogdanoff, M.E. Neilson, and A. Elgin. 2022. *Dreissena rostriformis bugensis* (Andrusov, 1897): U.S. Geological Survey, Nonindigenous Aquatic Species Database, Gainesville, FL, https://nas.er.usgs.gov/queries/FactSheet.aspx?speciesID=95, Revision Date: 7/19/2022, Access Date: 8/3/2022.

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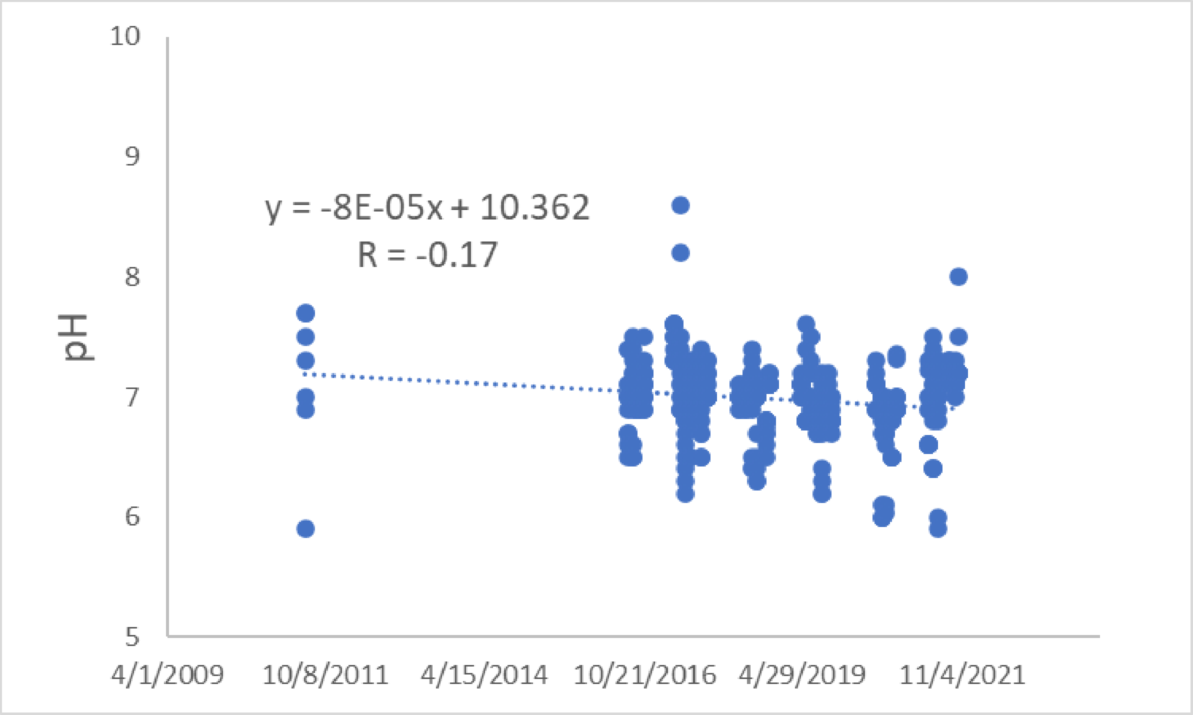
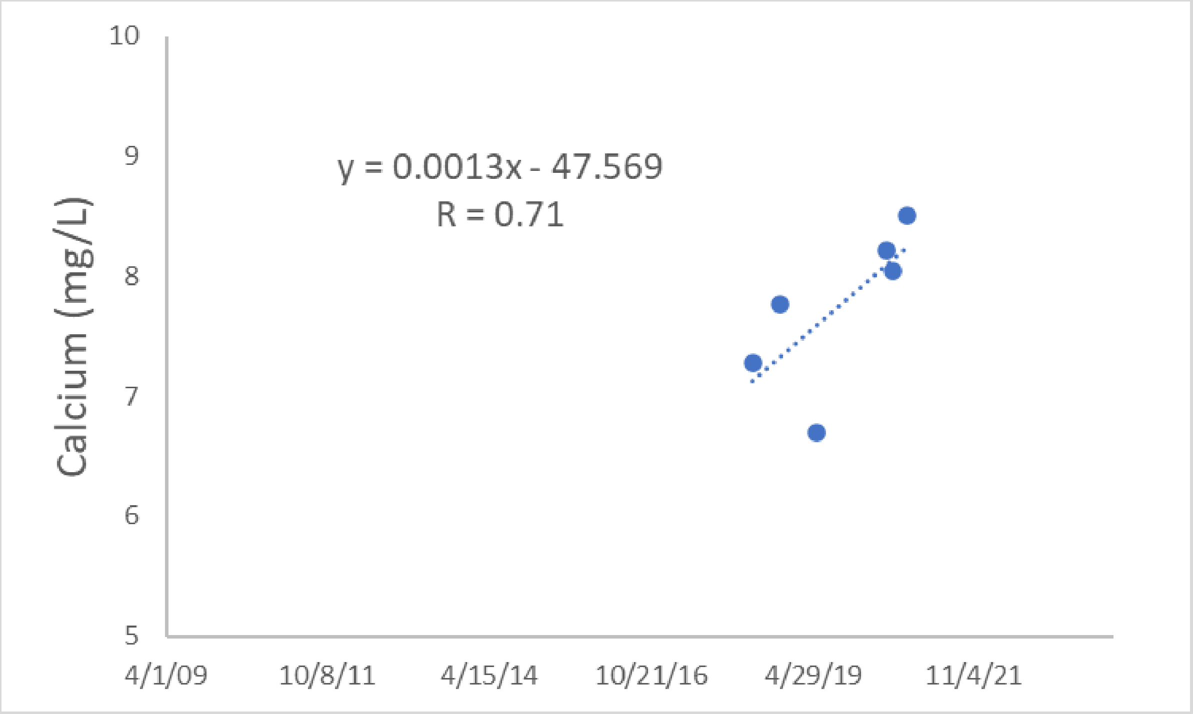
Appendix A

Calcium concentration and pH over time from 18 Deep Creek Lake water sampling locations

Arrowhead Cove (AWC)





Brookfield Dam (BRKDam)

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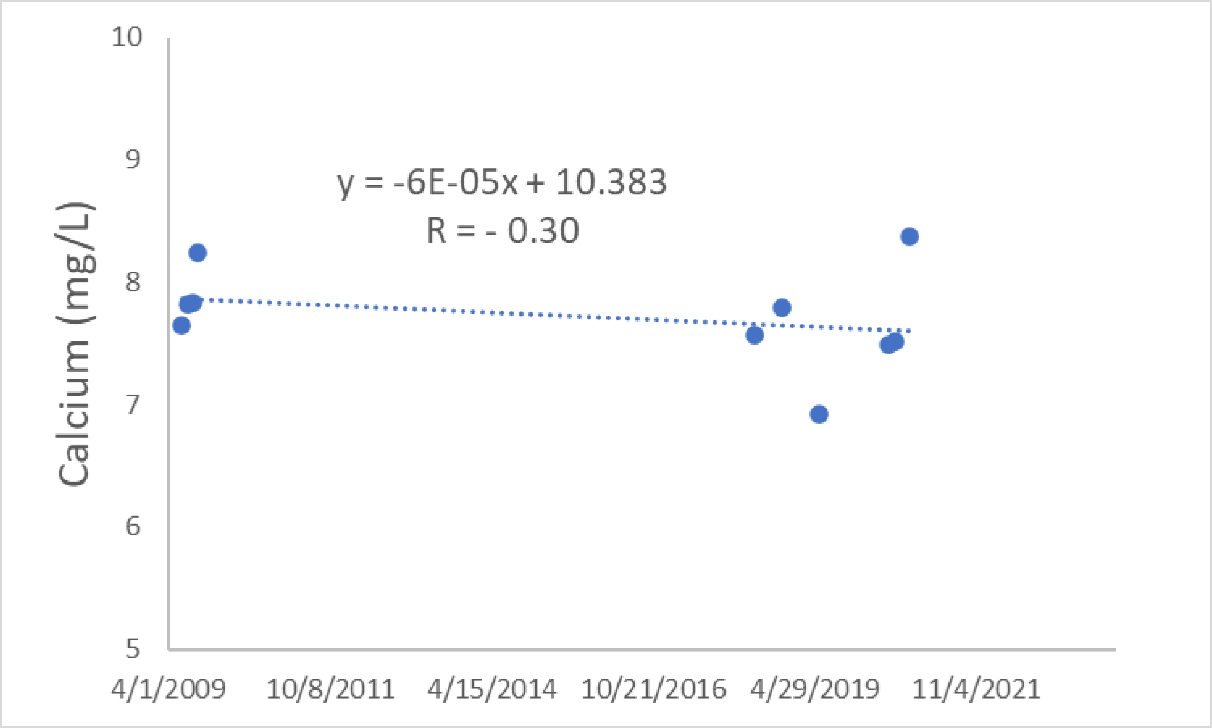
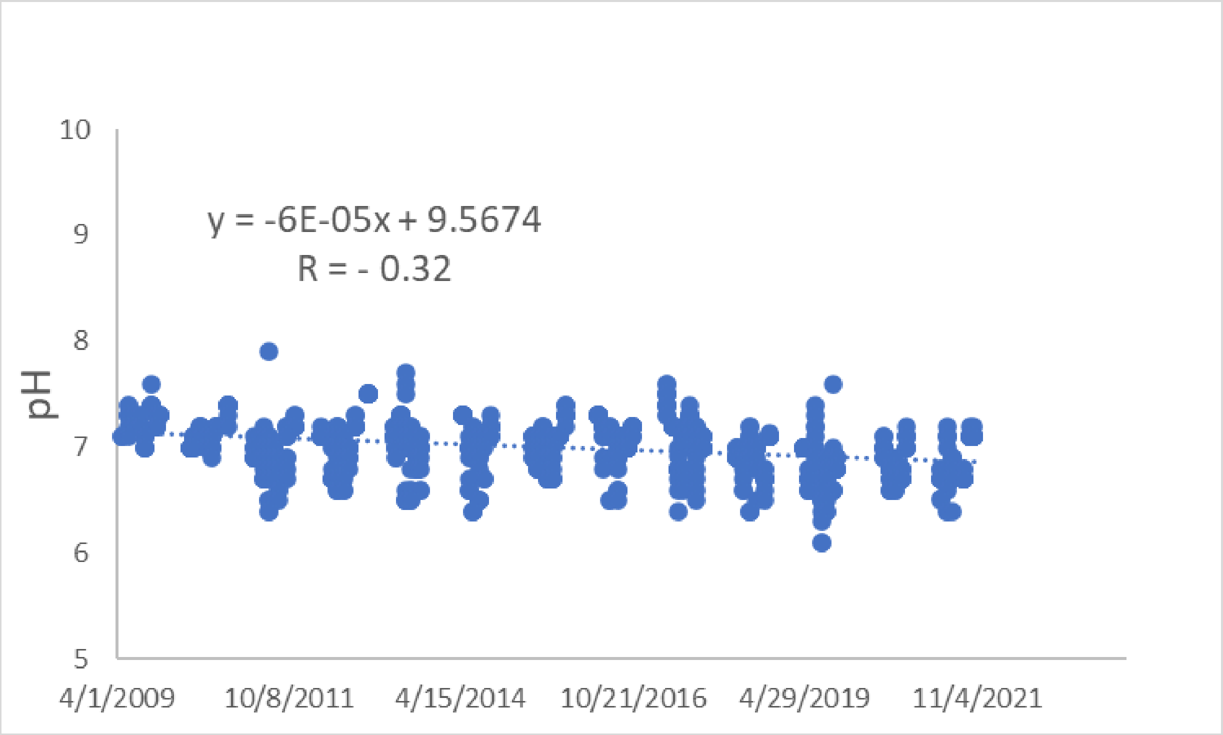
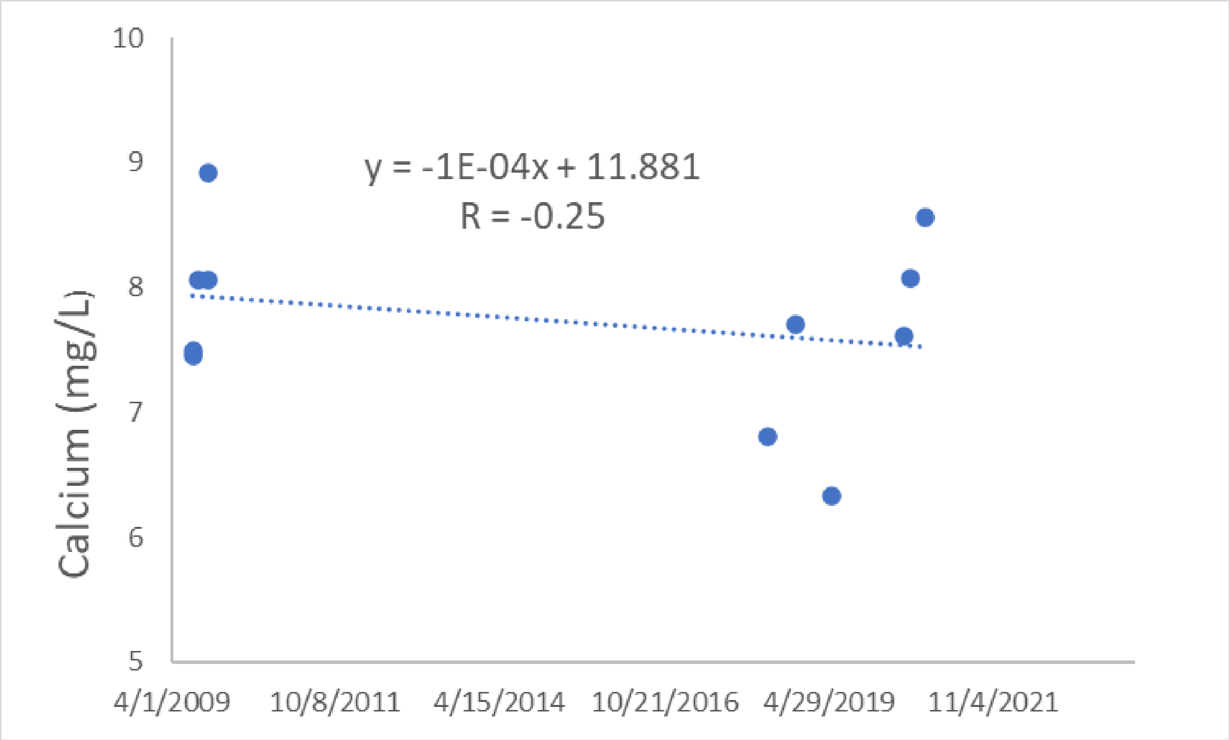
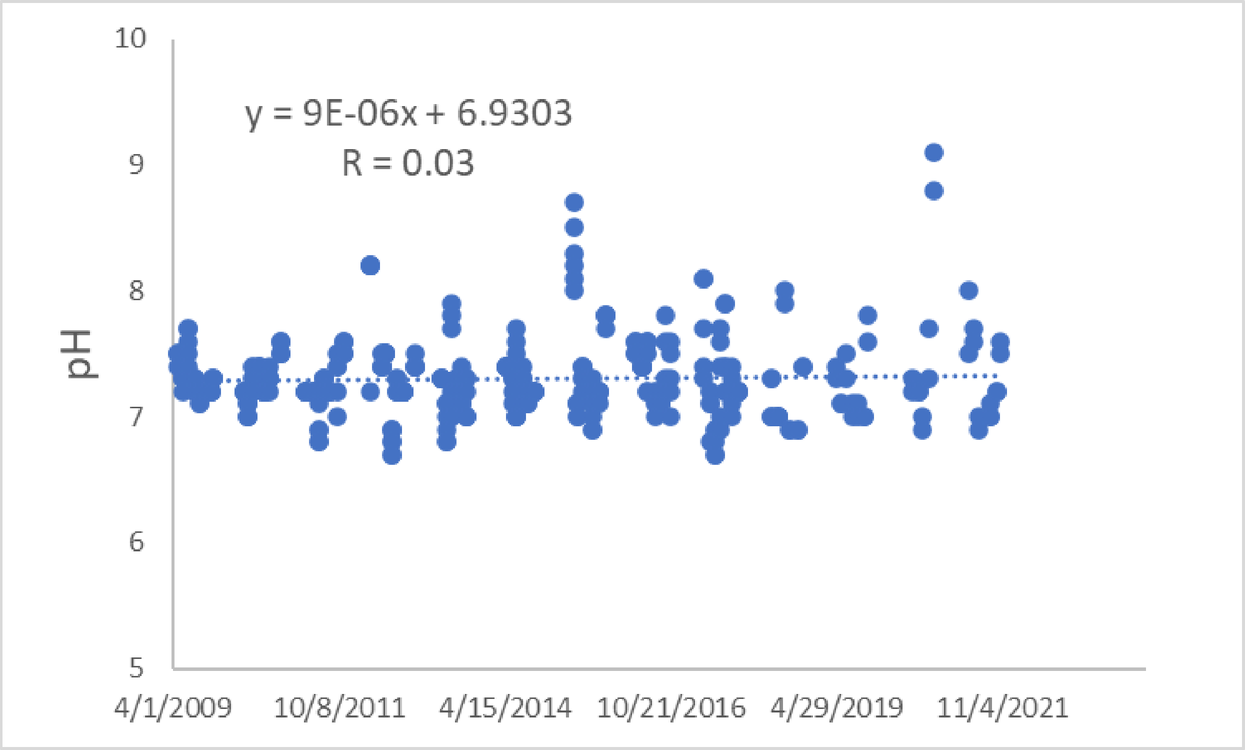


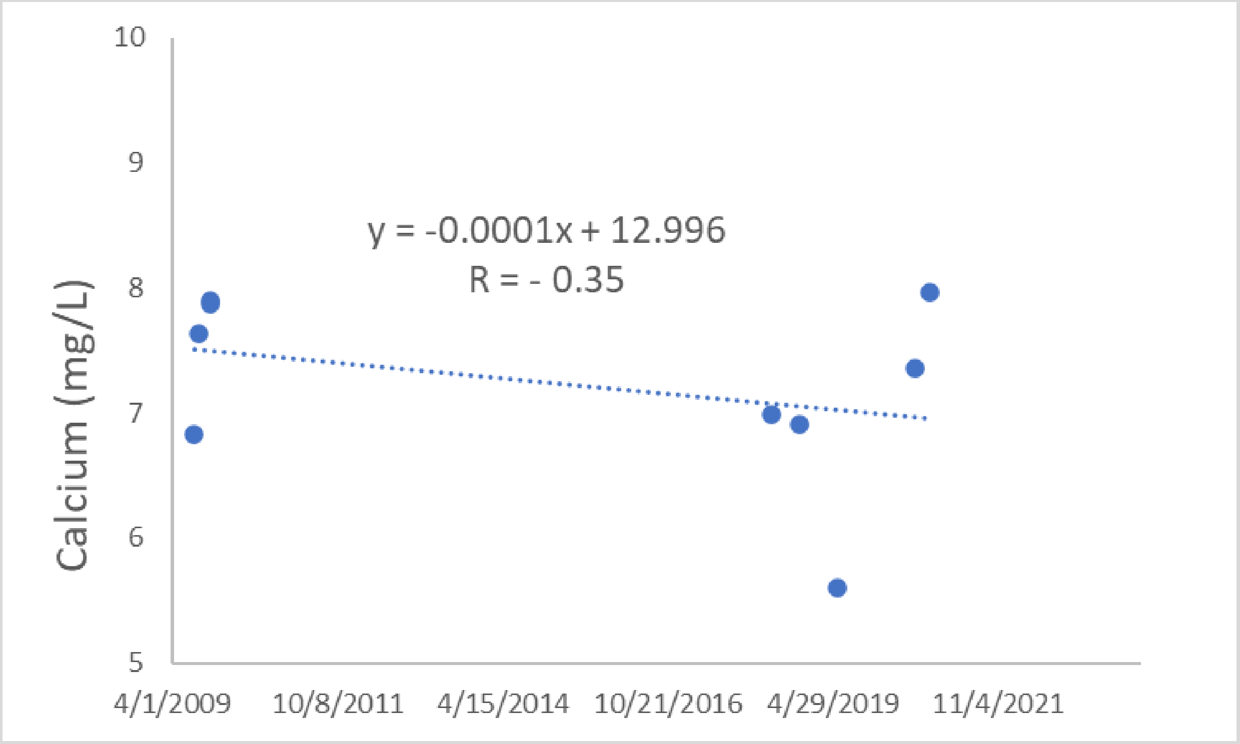
Cherry Creek Cove (CCC)



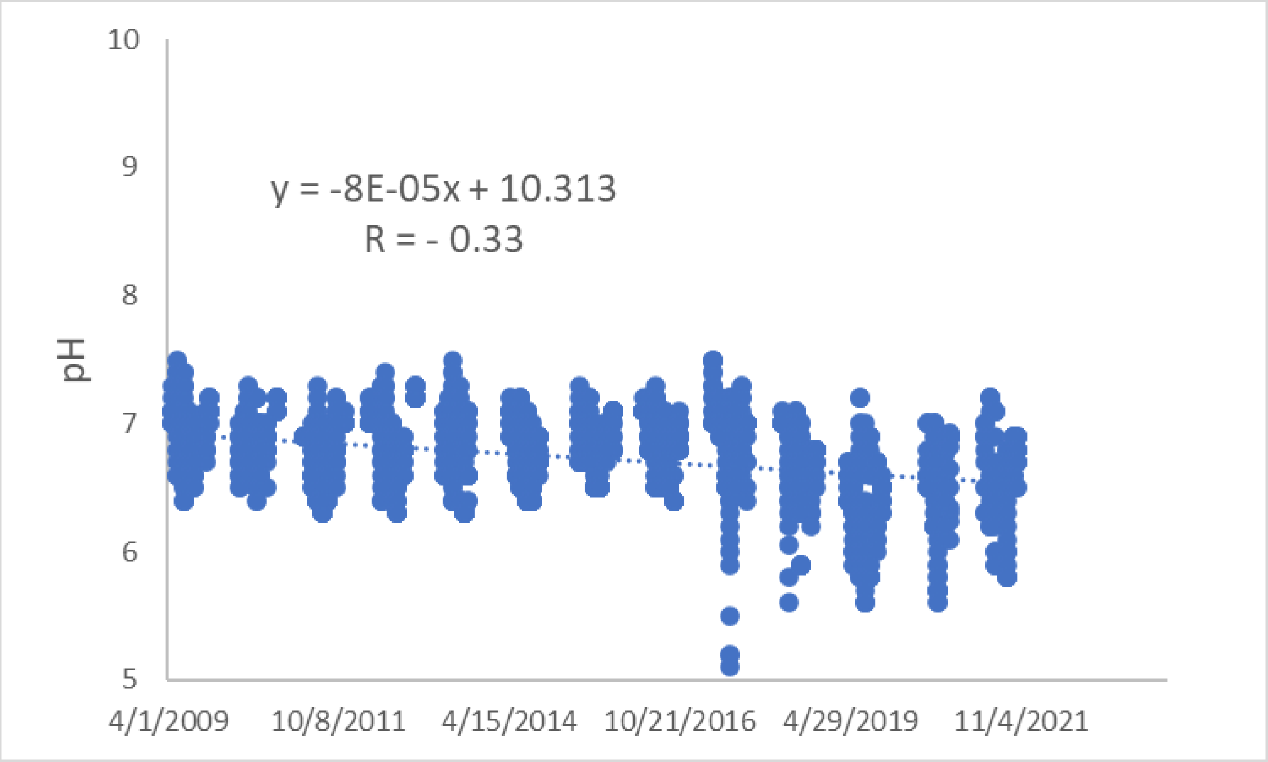


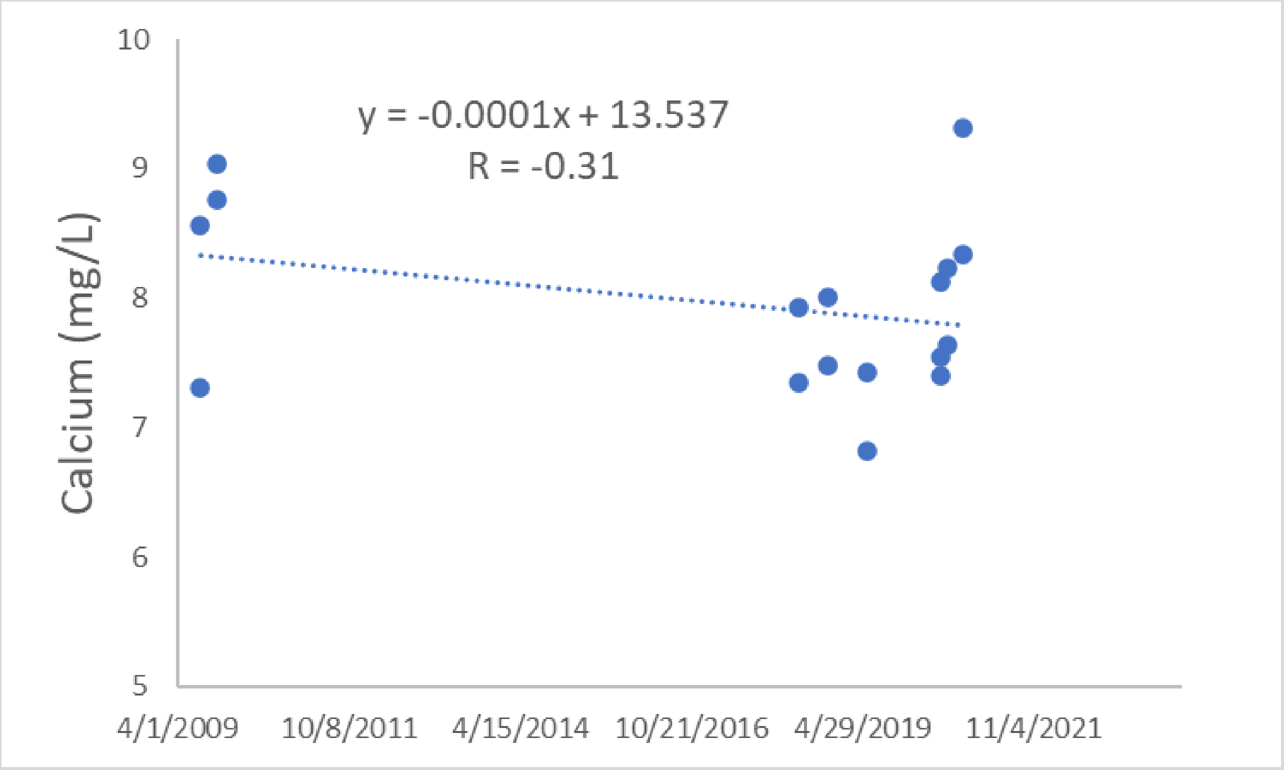
Deep Creek Cove (DCC)



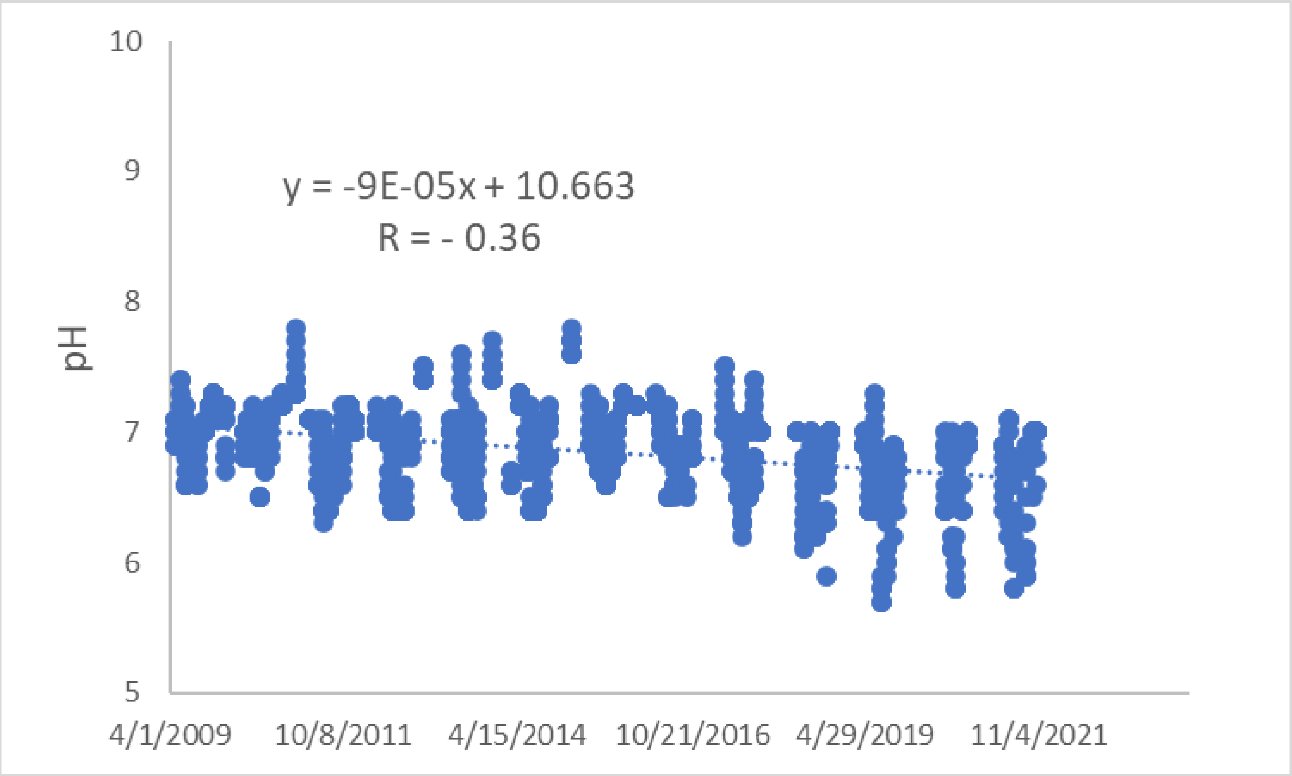


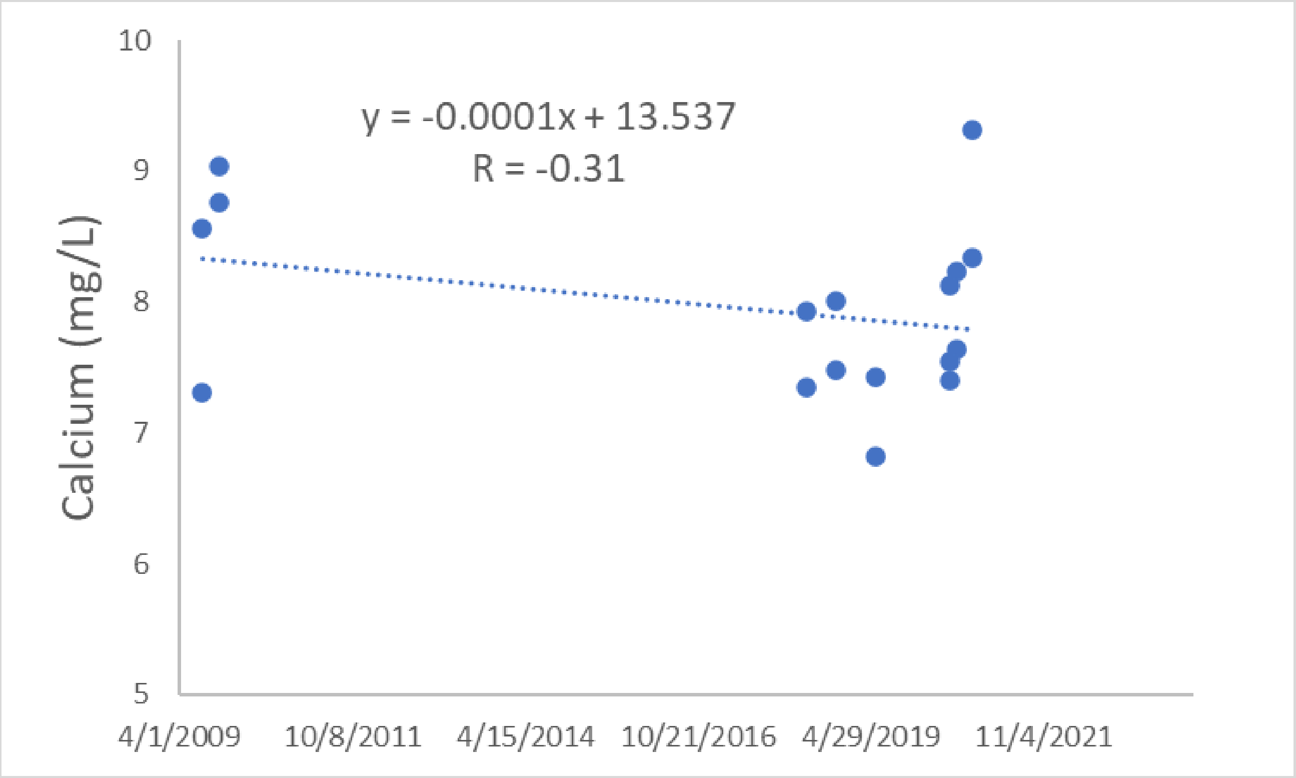
Deep Creek Lake Near Slide Hollow, 0.4 miles from Deep Creek Lake Dam (DPR0021)



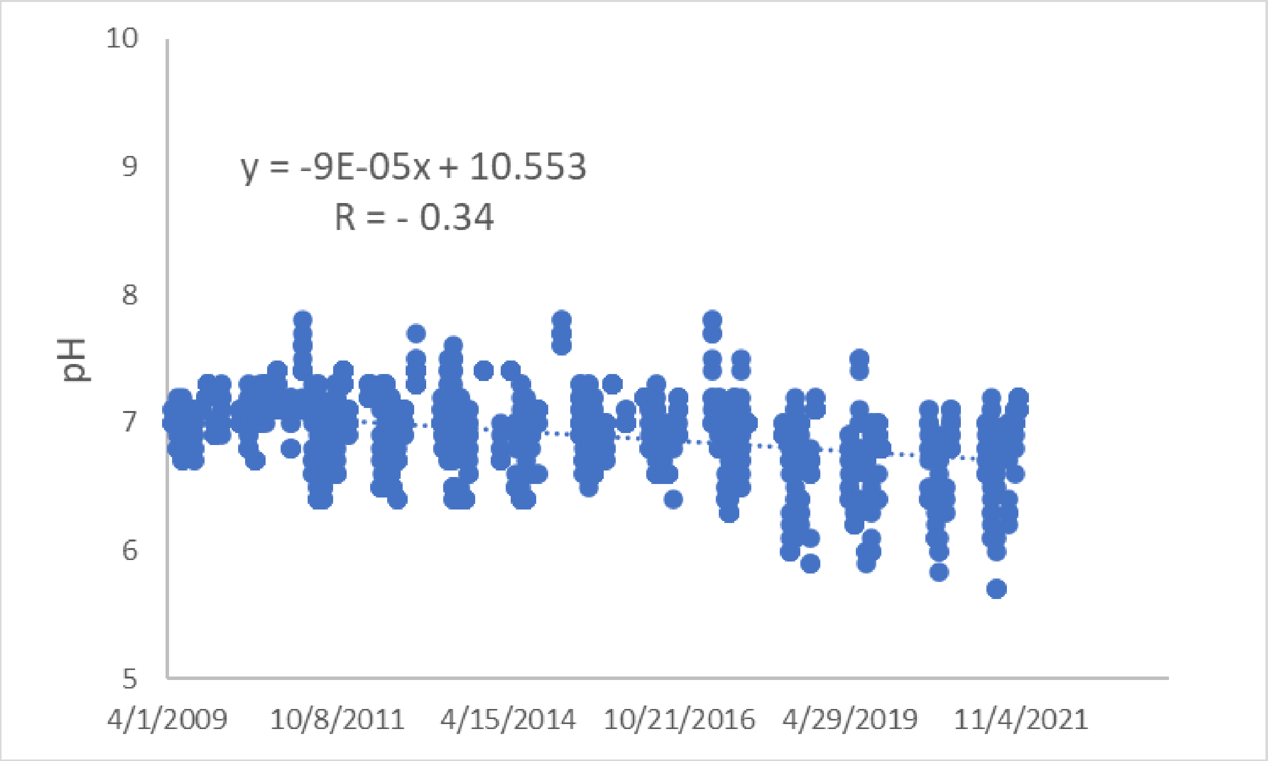


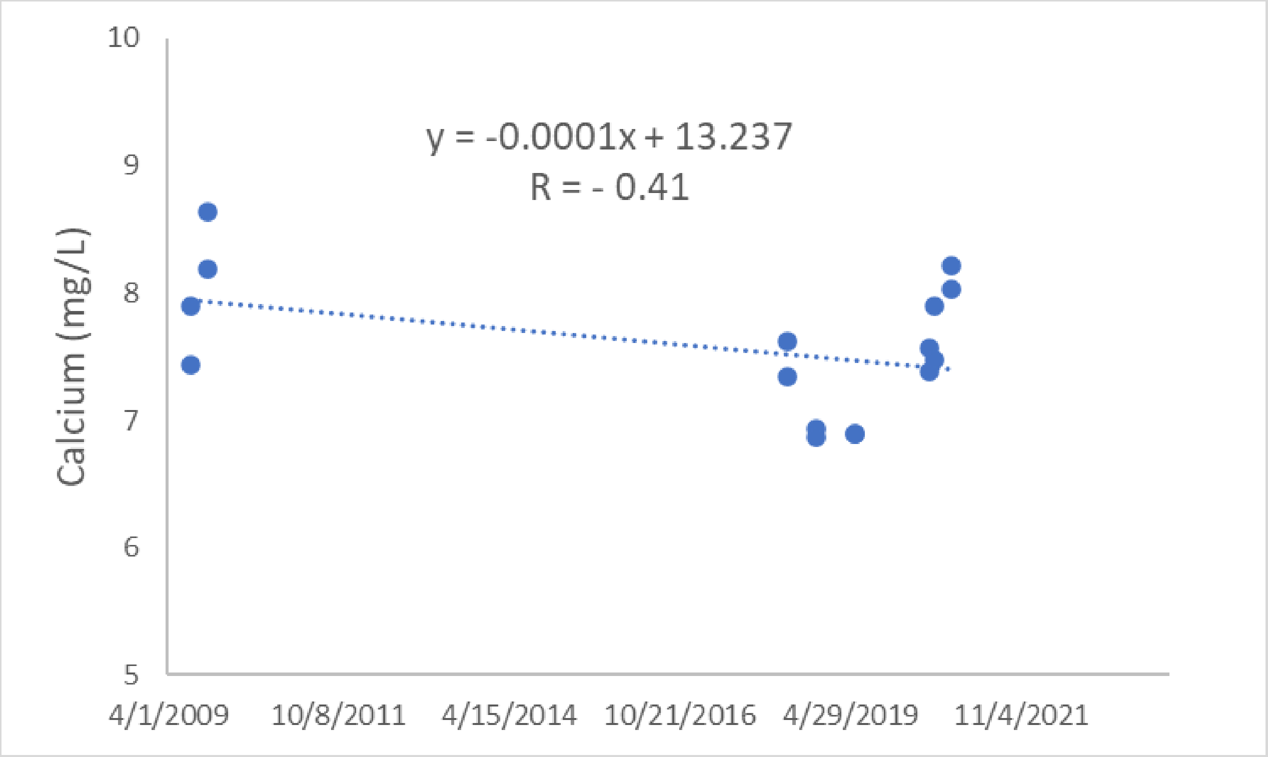
Deep Creek Lake at West Deep Creek Bridge (DPR0056)



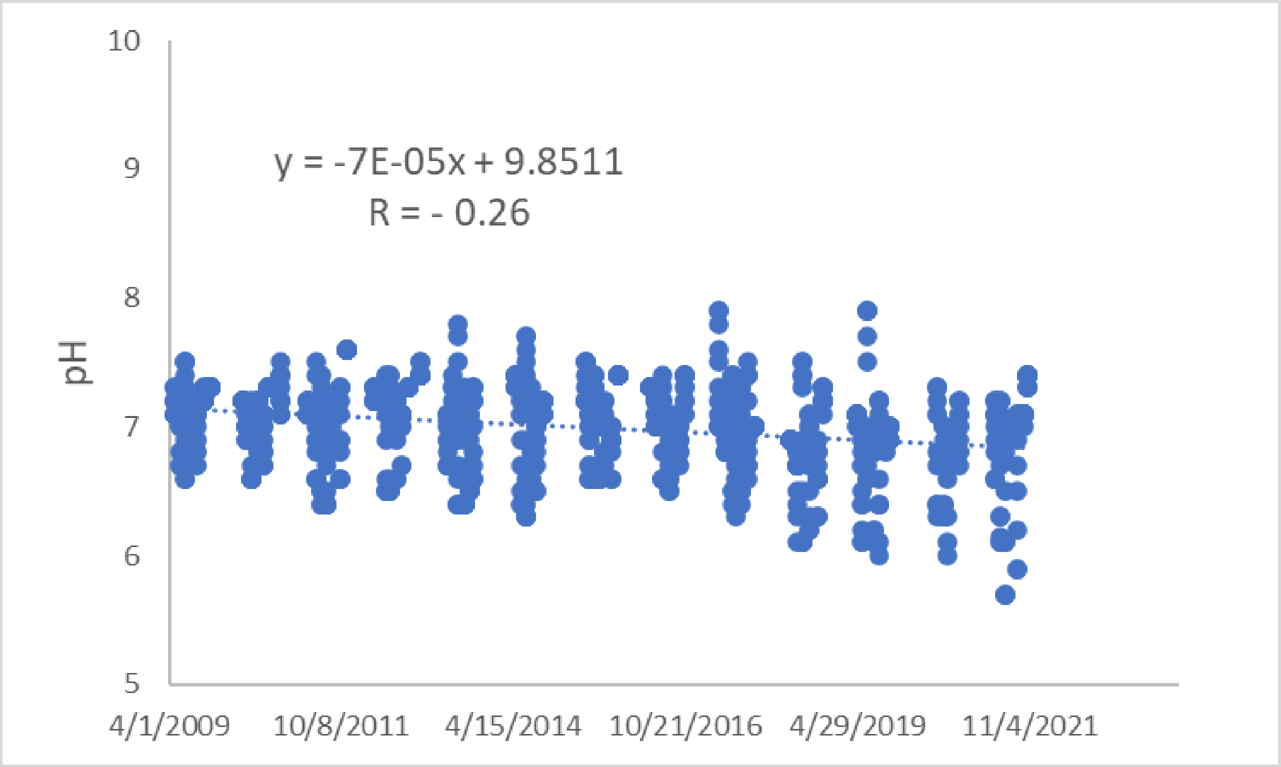


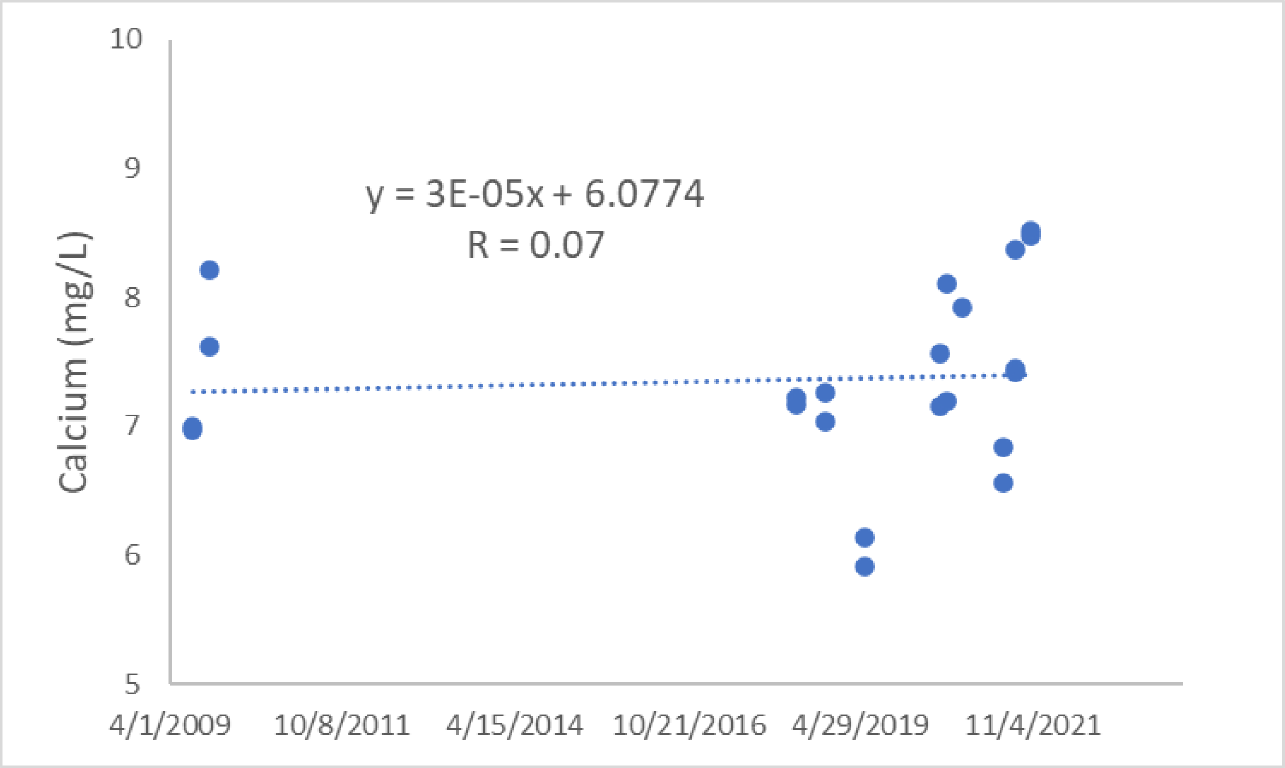
Deep Creek Lake - North Side of Glendale Bridge (DPR0082)



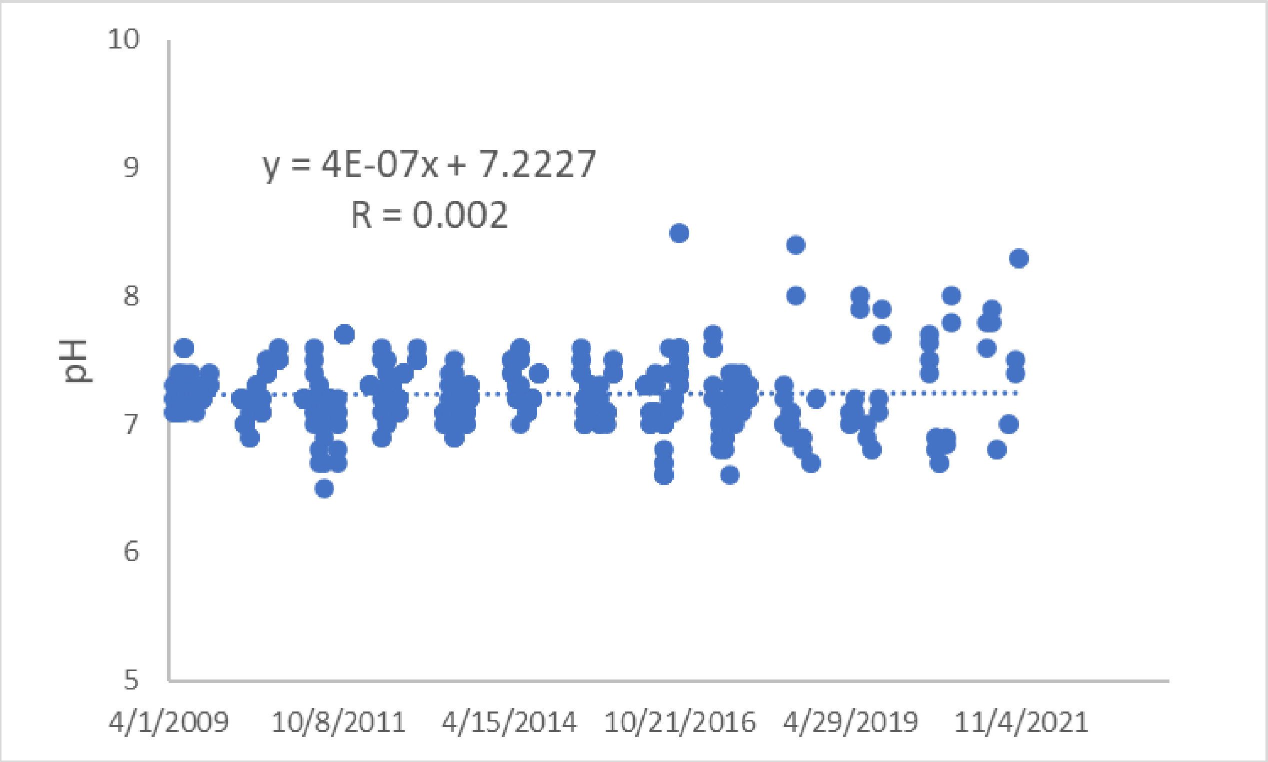


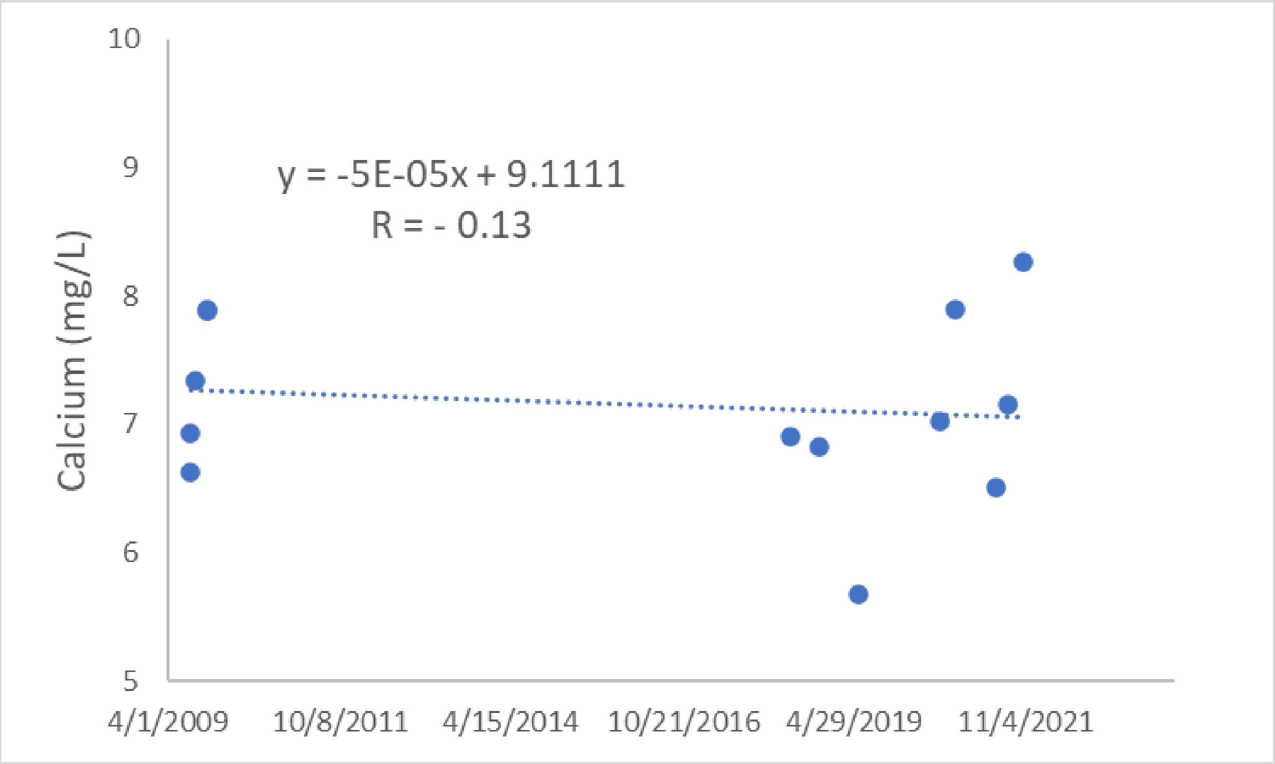
Deep Creek Lake Northwest of Turkey Neck (DPR0103)





Green Glade Cove (GGC)





Gravelly Run Cove (GRC)

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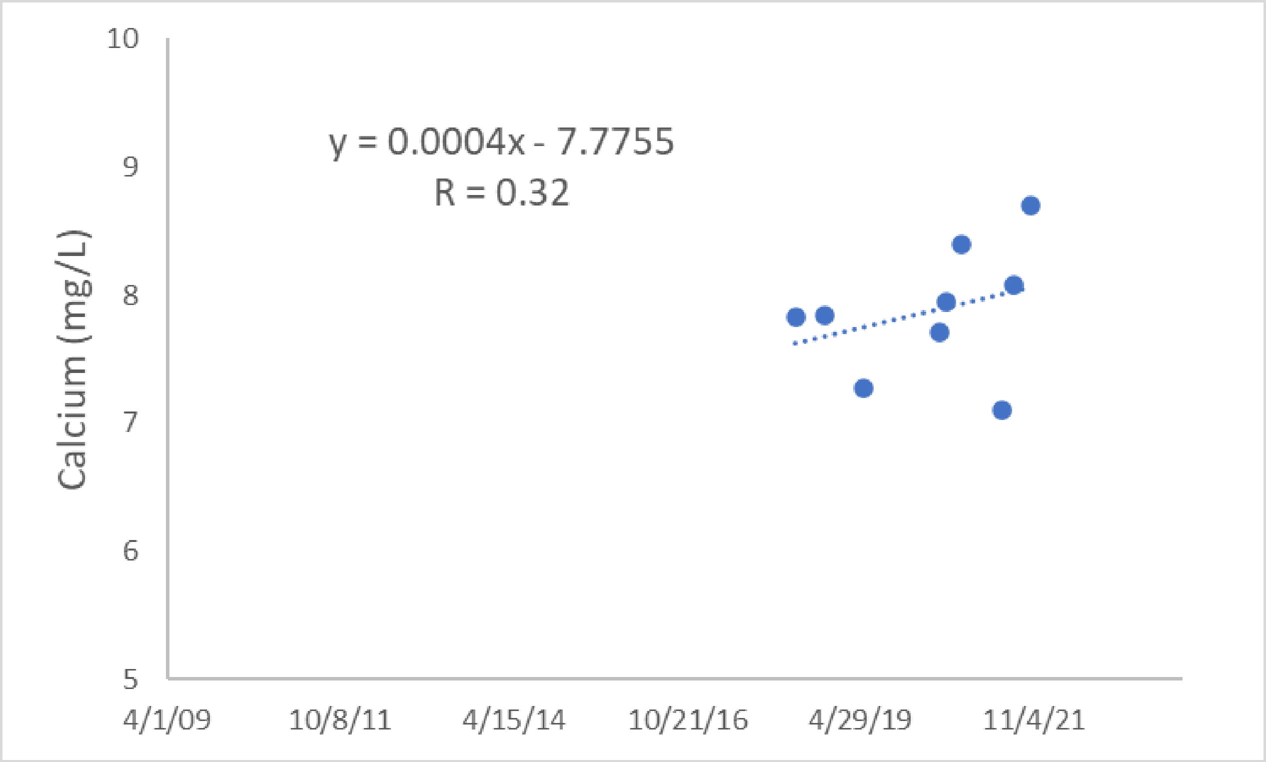
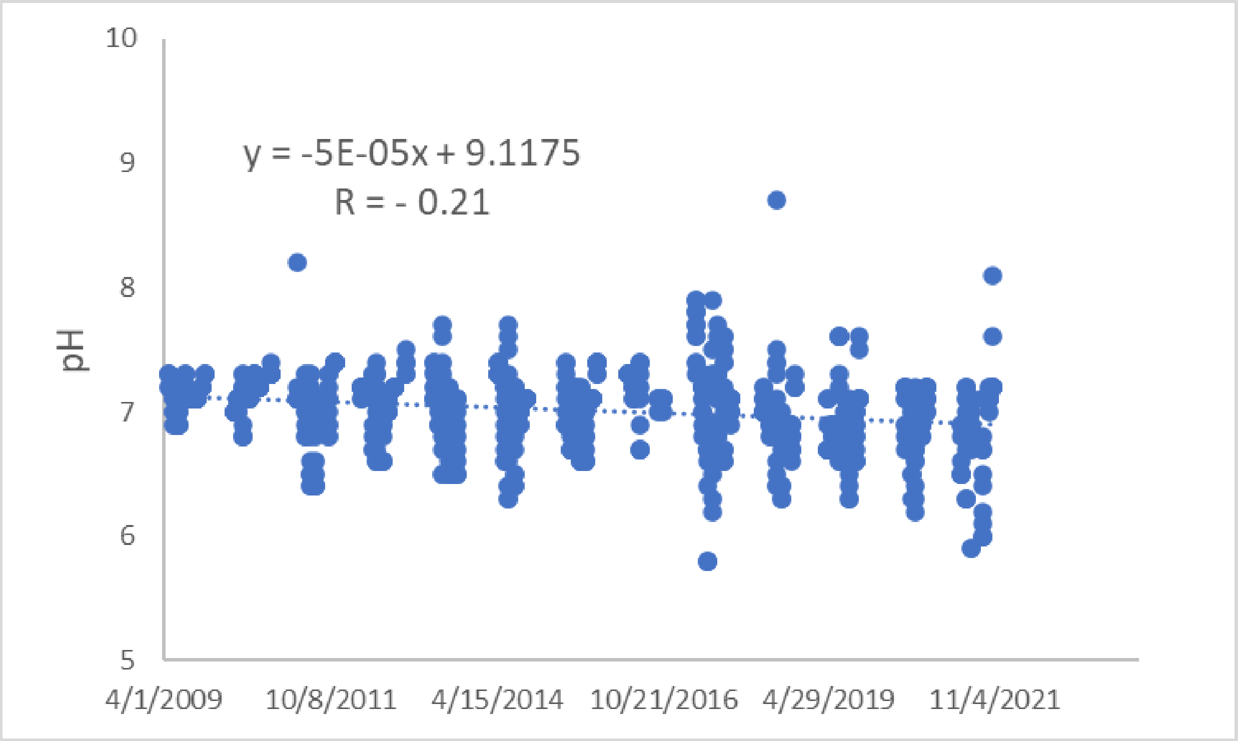
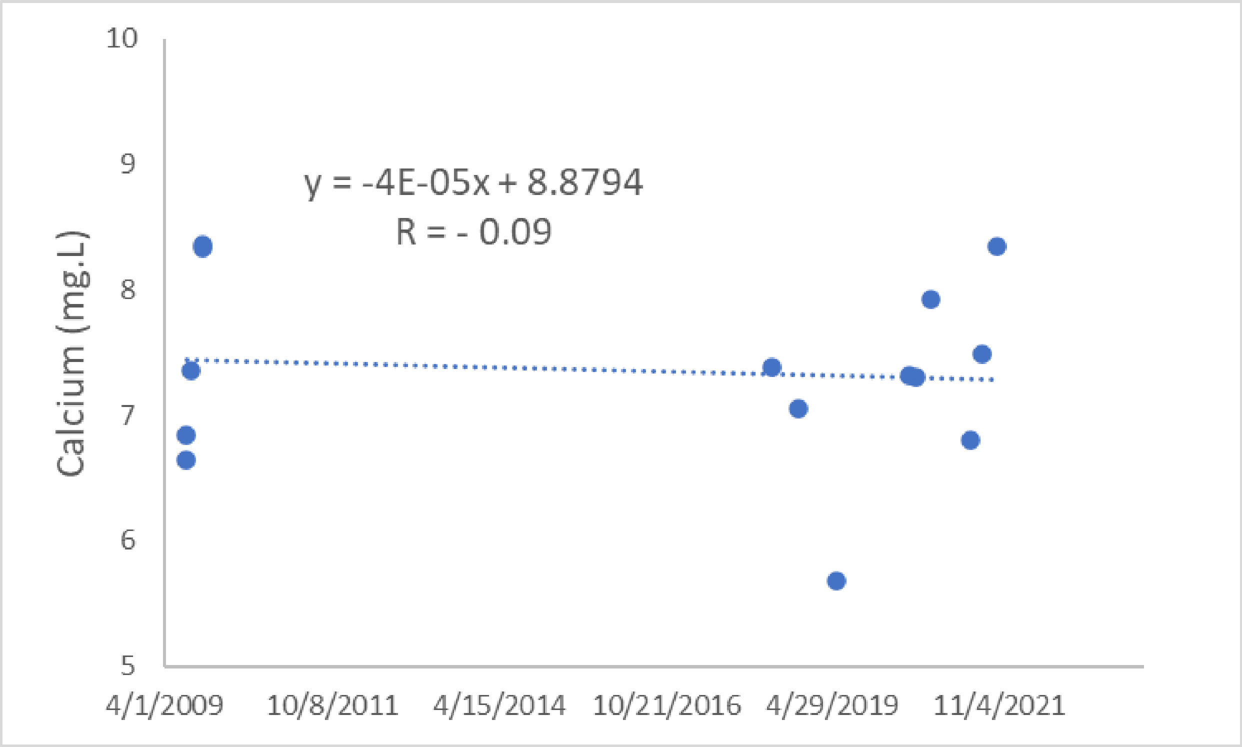
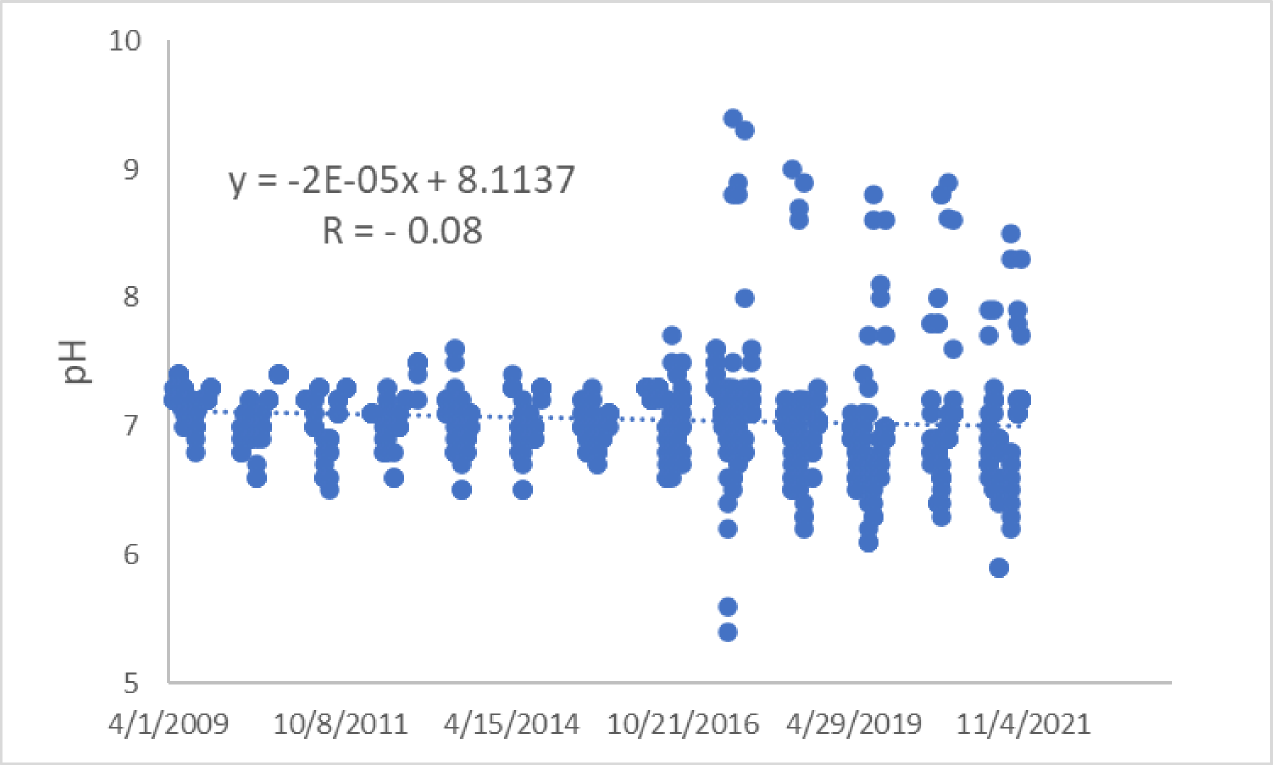


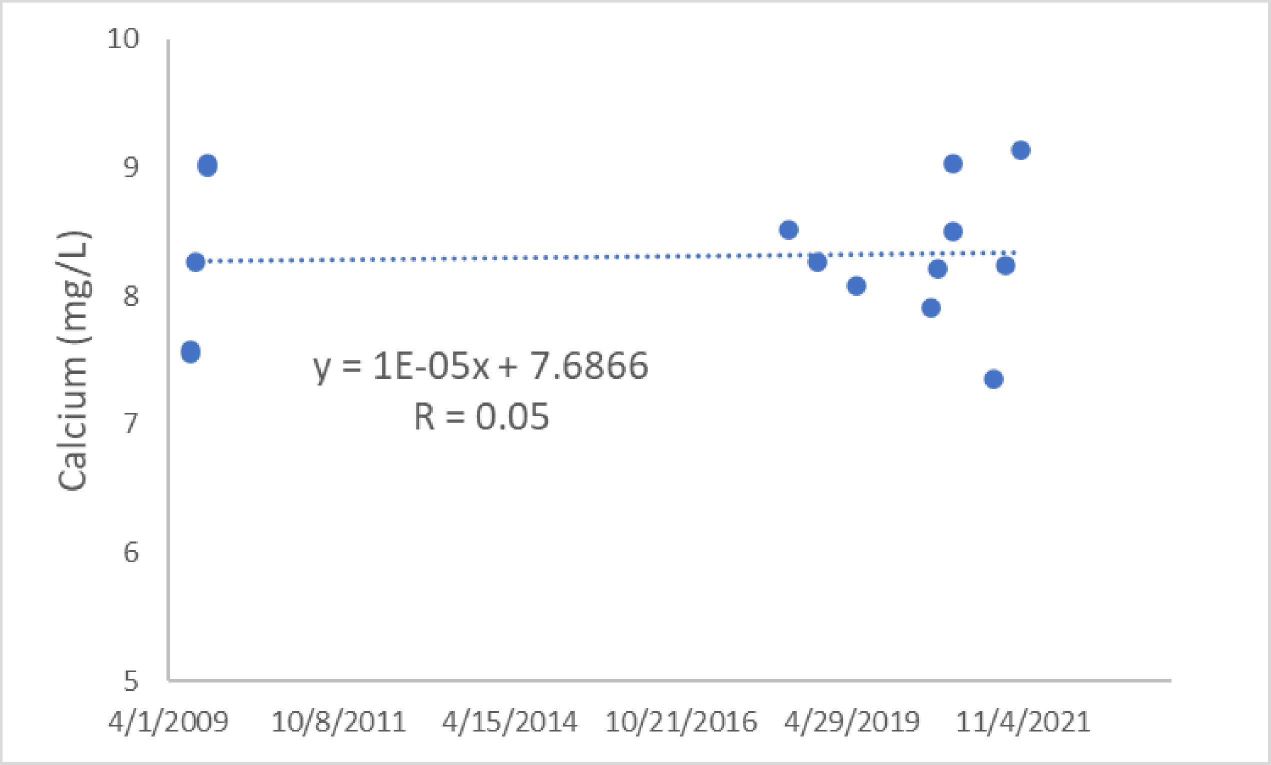
Hoop Pool Cove (HPC)



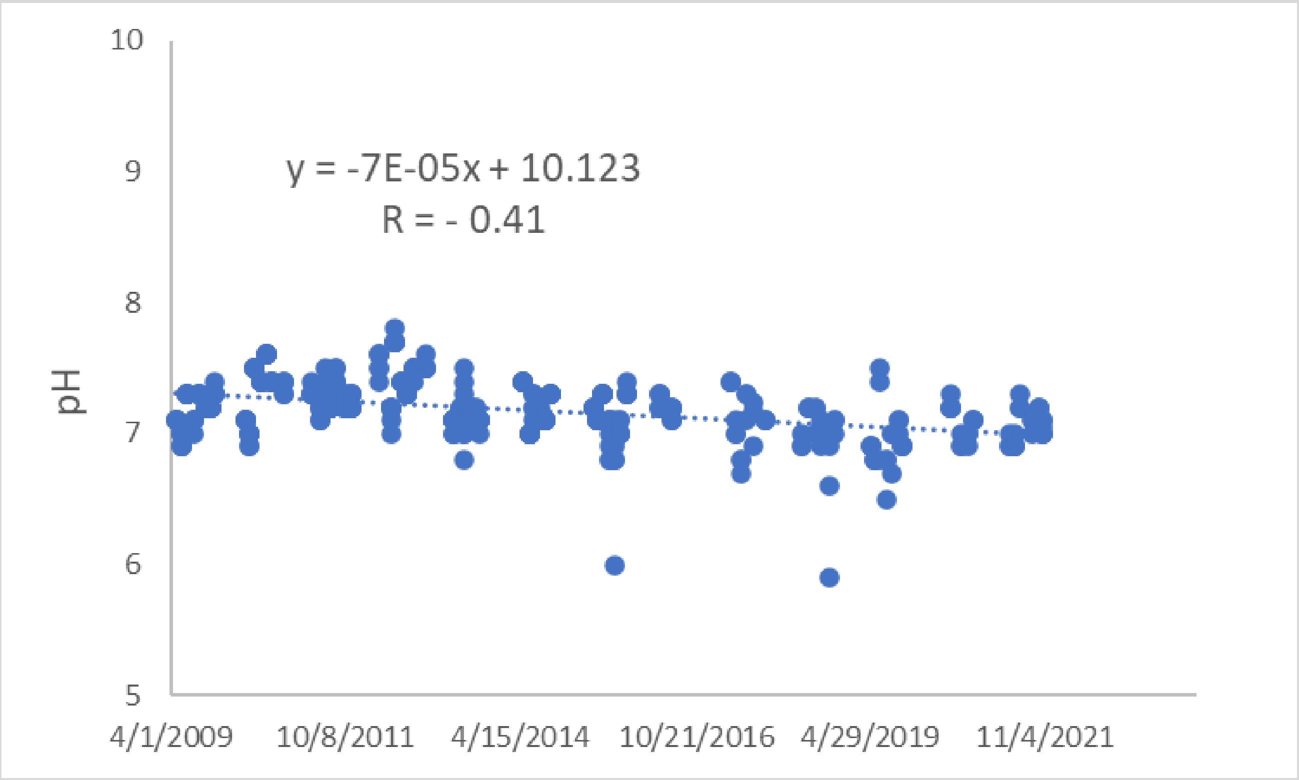


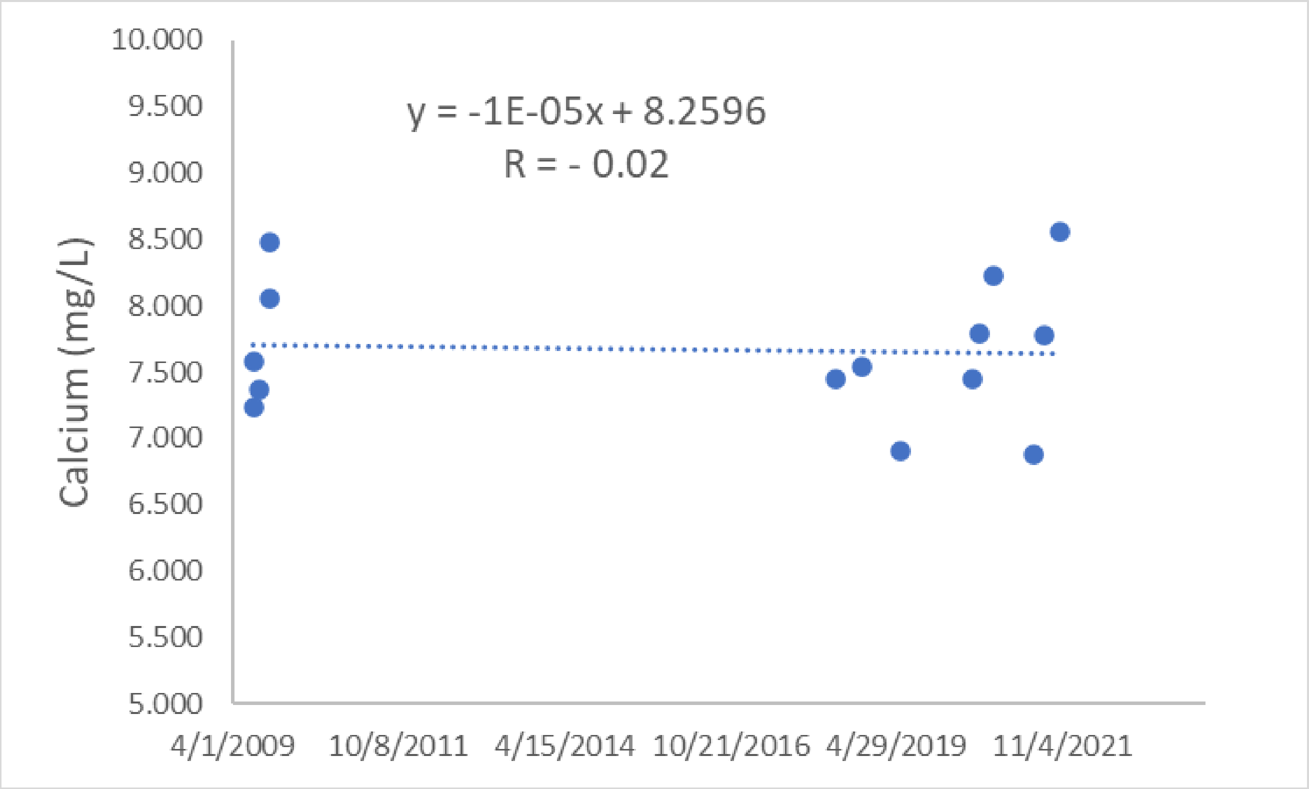
Marsh Run Cove(MRC)



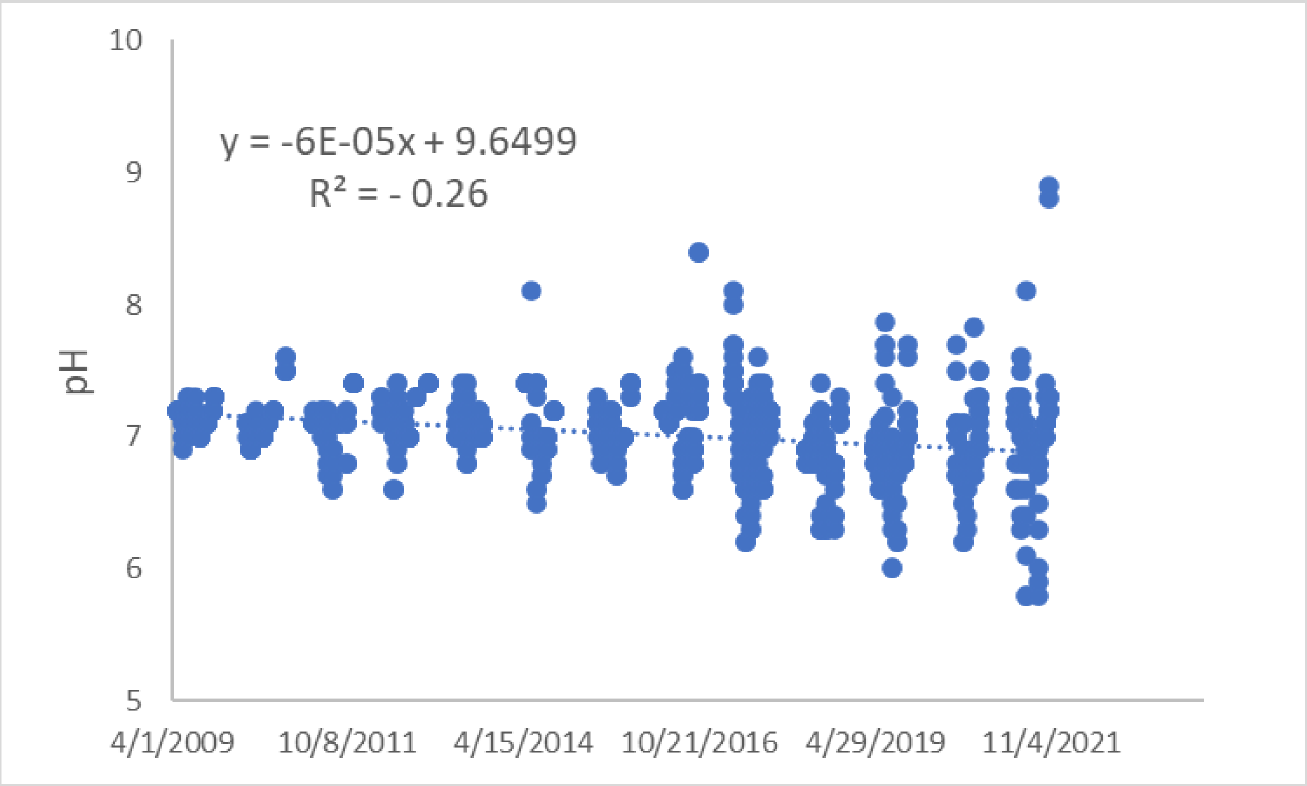


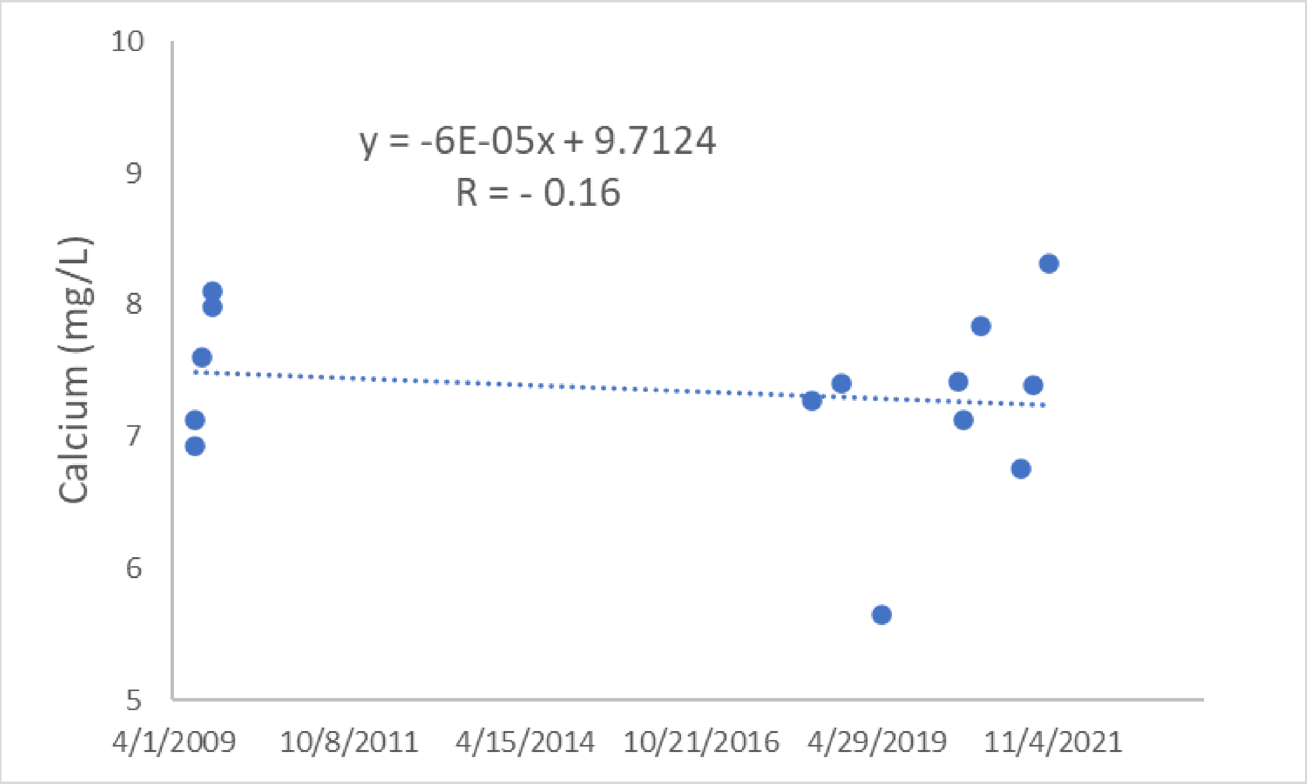
Meadow Mountain Run Cove (MMC)



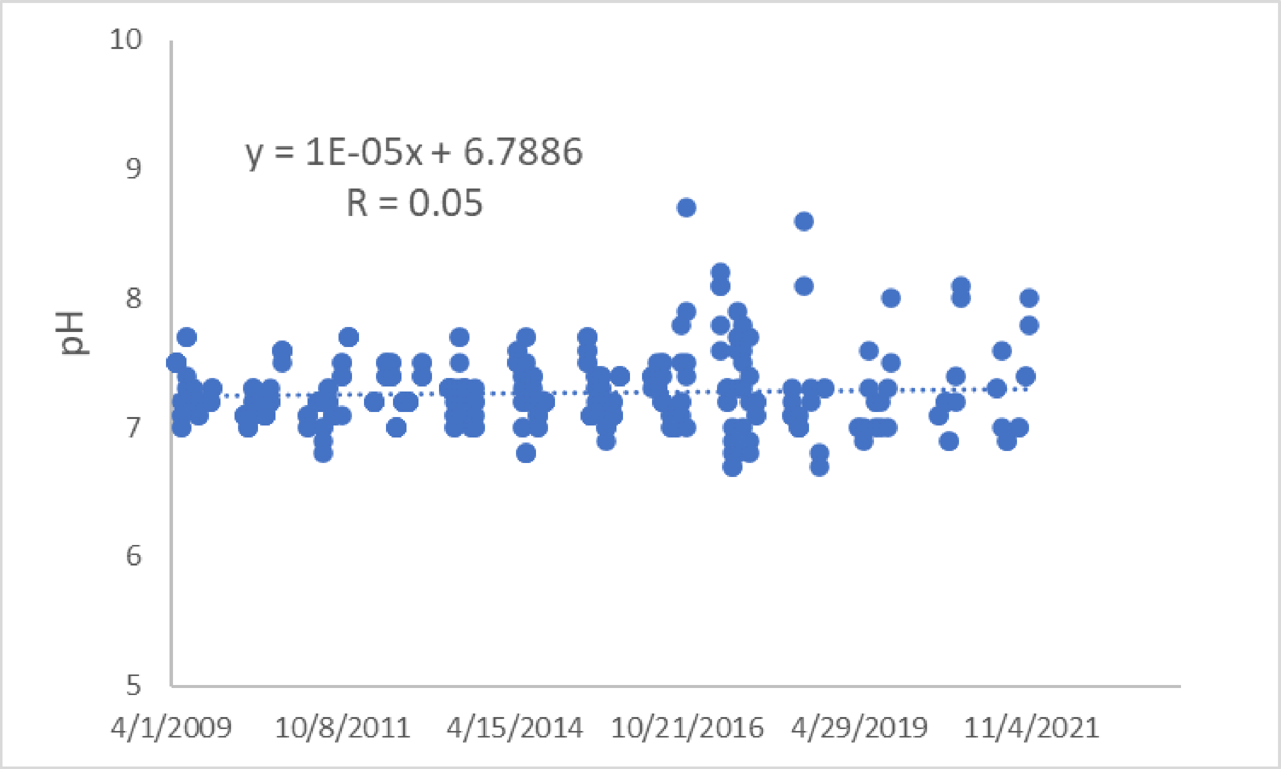


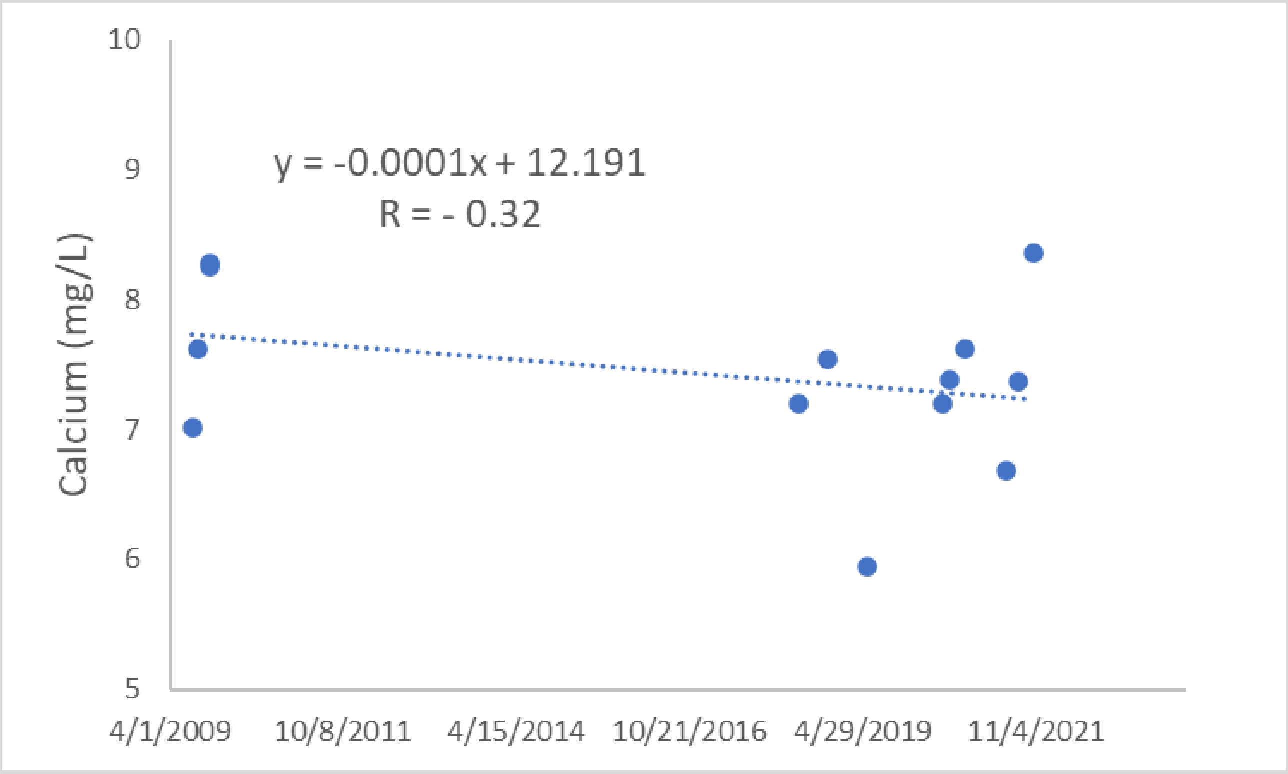
North Glade Cove (NGC)



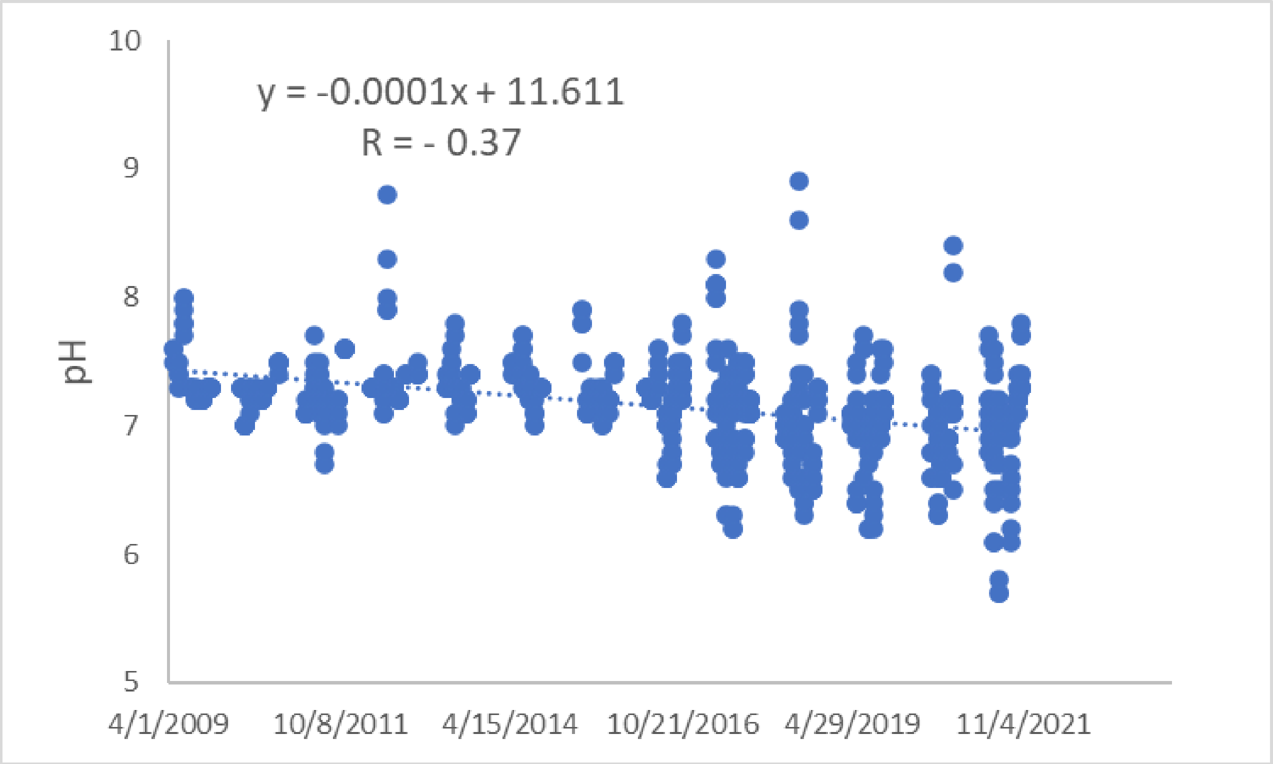


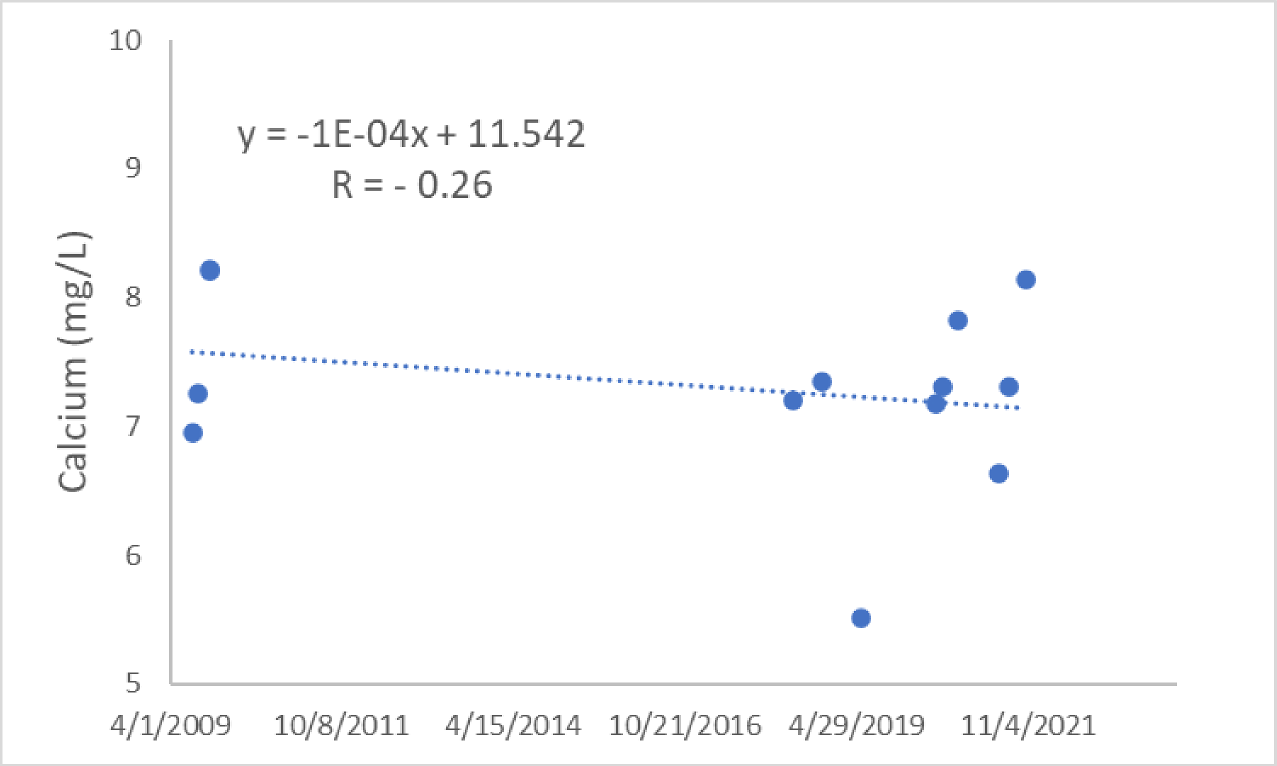
Pawn Run Cove (PWC)





Poland Run Cove (PLV)





State Park Ramp (SPRamp)

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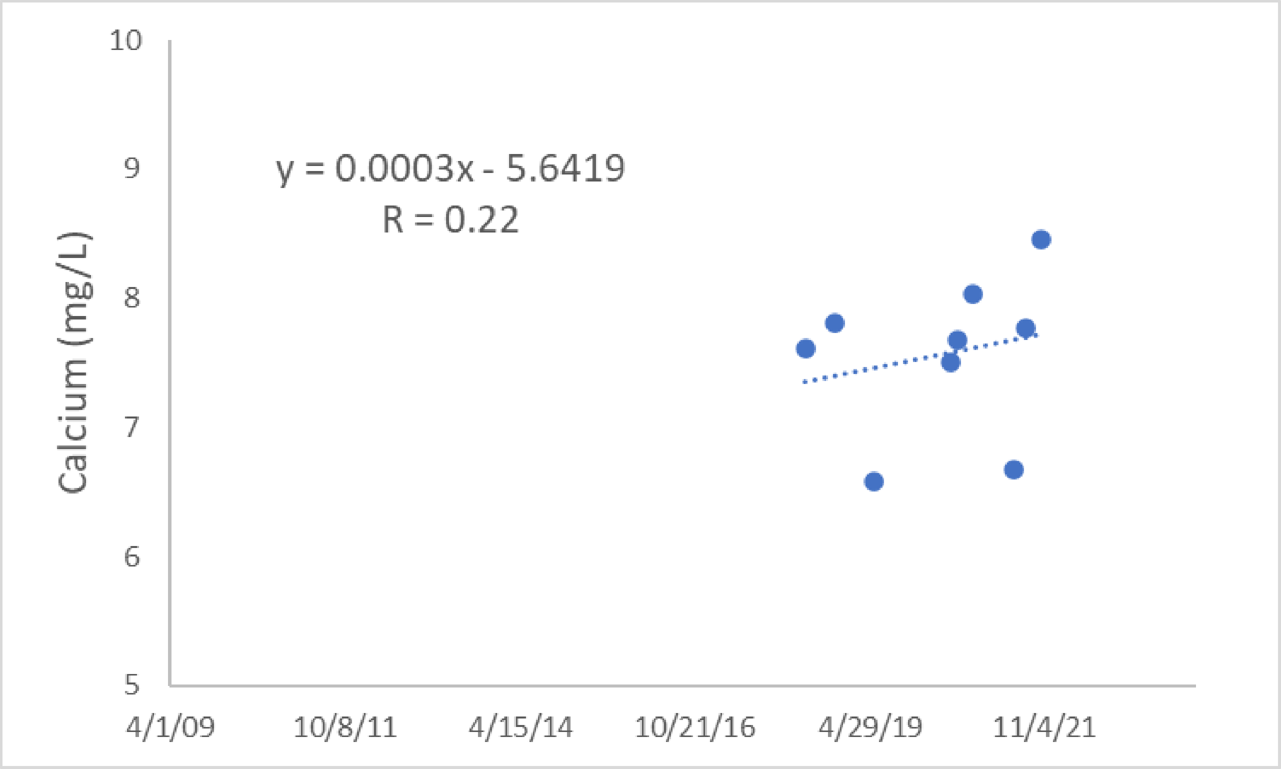

Yacht Club Ramp (YCRamp)

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