Deep Creek Lake
Water and Habitat Quality
2009-2016

Resource Assessment Service
Maryland Department of Natural Resources

November 2017

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Executive Summary

The Department of Natural Resources began a water quality monitoring program in Deep Creek Lake in April 2009. Most of the sampling occurs from April through September, with limited sampling in October through March if weather conditions allow. Sampling is done at mainstem lake and tributary cove stations.

Water quality and habitat conditions were evaluated using the data collected from 2009-2016. Water temperature, dissolved oxygen, water pH and conductivity were examined to determine conditions above and below the thermocline. Algal and nutrient levels and water clarity measures were compared to thresholds and the trophic state of the lake was determined. Water quality was compared between upstream and downstream areas of the lake and between coves and the nearest lake station.

Water and habitat quality in the lake generally followed consistent patterns moving from the Dam station upstream to the Turkey Neck station. Below thermocline water temperature increased as the water depth decreased moving upstream. Below thermocline dissolved oxygen levels were lower in upstream areas in some years. Water pH above the thermocline increased while conductivity decreased moving upstream. Algal levels increased and water clarity decreased moving upstream.

Water and habitat quality in the coves was generally different from the nearest lake station. Surface water temperatures were warmer, dissolved oxygen levels and water pH were higher, and conductivities were lower than at the lake stations. Algal levels and total nitrogen levels were higher but total phosphorus levels were not always higher than at the nearest lake station. Water clarity was lower in the coves, and total suspended solids were more important to determining water clarity than at the lake stations.

Some years had notably different water quality and habitat conditions. In 2012, May-September total precipitation was lower than the other years of the monitoring program and lake levels were lower. Surface water temperatures were warmer and conductivity was lower. Below thermocline dissolved oxygen levels were somewhat higher at many stations. Algal levels, total phosphorous levels and total nitrogen levels were lower, and the lake was at a lower trophic state (oligotrophic instead of mesotrophic). Water clarity was the best of all years of the monitoring program.

Conversely, in 2013 algal levels were the highest measured and the trophic state was at its highest level (eutrophic) at all stations except the station at the Dam. Below thermocline water temperatures were higher and dissolved oxygen levels were lower. Conductivity was higher in upstream areas and total nitrogen levels were higher.

Differences were also found regionally. Marsh Run Cove (Region 1) had the highest conductivities even compared to the nearest lake station at the US 219 Bridge. Meadow Mountain Run Cove (Region 2) had lower algal levels and higher water pH. North Glade Cove (Region 2) had higher algal levels, higher total phosphorus levels and the lowest water clarity.

More specific summary information is provided below.

Watershed Conditions

- The largest land use in the entire Deep Creek Lake watershed is forest (56 percent). Region 0 is the most forested (72 percent). Region 1 and Region 3 are also mostly forested (approximately 60 percent) but agricultural land use is also important (approximately 15 percent). Region 2 has less forested area (46 percent) and more agricultural area (28 percent). Region 4 is approximately equally divided into agricultural and forest land use (40 percent each). Suburban/urban land use is roughly the same amount of each of the four regions (18-25 percent combined); Region 1 has the most urban land use (almost five percent) and Region 2 has the largest amount of suburban and urban combined (almost 25 percent). Surface mining is found predominately in Region 1 but is also present in Region 2.

- Annual total precipitation averaged 53.5 inches per year during the 2011-2016 period. May-September total precipitation averaged 24.2 inches per year, and varied from 38-51 percent of the total annual precipitation. Annual total precipitation was highest in 2011 (63.6 inches), but the same increase was not seen in the May-September total. May-September total precipitation was similar in all years except 2012 when it was lower (20.2 inches).

Water and Habitat Conditions

- Surface water temperatures were similar between the coves and nearest lake stations for individual months, but the seasonal average water temperatures at the cove stations were slightly warmer than the nearest lake station. Seasonal average water temperatures above the thermocline were fairly consistent each year, though somewhat higher in 2012 at all four lake stations. Below the thermocline, seasonal average water temperatures were move variable and increased moving upstream from the Dam station to Turkey Neck. A seasonal thermocline also developed in Cherry Creek Cove and Hoop Pole Cove in the early summer but usually was no longer present by August.

- Dissolved oxygen levels in surface waters remained above five milligrams per liter (defined as adequate to support healthy fish populations) throughout the year. At lake stations, dissolved oxygen levels below the thermocline began decreasing as early as May and June, and were extremely low (less than one milligram per liter) in June, July and August. Surface water dissolved oxygen levels in the coves were higher than at the lake stations, possibly due to higher photosynthesis by algae and underwater grasses and more mixing. Dissolved oxygen levels in the below thermocline waters of Cherry Creek Cove and Hoop Pole Cove were very low in June and July, but were replenished in August and September when the seasonal thermocline dissipated. Seasonal average dissolved oxygen levels above the thermocline were fairly consistent each year at both the lake and cove stations. Below the thermocline, dissolved oxygen was at unhealthy levels (less than three milligrams per liter) in almost all years at the lake stations and at very unhealthy levels (less than one milligram per liter) in 2013 at the Glendale Bridge and Turkey Neck lake stations.

- Water pH was in the healthy range (between 6.5 and 8.5) throughout the year and at most depths at lake stations, but decreased to less than 6.5 in June, July and August in below thermocline waters. No pH values below 6 were recorded in Cherry Creek Cove during the monitoring period. Water pH in coves was higher than at the nearest lake station (but generally still between 6.5 and 8.5). Seasonal average water pH above the thermocline was higher than below the thermocline in all years. Water pH increased moving upstream from the Dam station to Turkey Neck in the above thermocline layer, but the pattern was less consistent in the below thermocline layer. Seasonal average water pH in the above thermocline waters was higher in the coves than the nearest lake station, especially in Meadow Mountain Run Cove.

- Conductivity was much higher in the waters below the thermocline in the summer at all of the lake stations and generally continued to increase from the onset of the thermocline in June through the mixing of the water column again in October. Conductivity was highest in Marsh Run Cove in Region 1, which is the area with the greatest urban land use impacts. Conductivity was often lowest at the Cherry Creek Cove station, also in Region 1. Seasonal average conductivity decreased moving upstream from the Dam station to Turkey Neck. Conductivity below the thermocline was higher than above the thermocline in almost all years at the lake stations. Conductivity above the thermocline was lower at the cove stations than at the nearest lake stations with the exception of Marsh Run Cove. Below thermocline conductivity at Cherry Creek Cove and Hoop Pole Cove was more similar to the surface layer water than to the below thermocline waters of the nearest lake station.

<u>Trophic State- Algal levels, Nutrients and Water Clarity</u>

- Algal levels at most stations and most years indicated mesotrophic conditions in Deep Creek Lake. Exceptions to this were high oligotrophic conditions in 2011 at the Dam lake station, high oligotrophic conditions in 2012 at the three downstream lake stations, low eutrophic conditions at all stations except the Dam lake station in 2013, and low eutrophic conditions in 2015 at North Glade Cove, Poland Run Cove and Green Glade Cove.

- Algal levels (measured by chlorophyll *a* levels) were highest in Region 2, though high levels indicating algal blooms occurred in all regions at different times. Seasonal average algal levels were highest at all stations in 2013. Algal levels generally increased moving upstream from the Dam station to Turkey Neck. In most years the algal levels were highest in the coves compared to the nearest lake station, with the exception of Meadow Mountain Run Cove. Patterns were generally consistent between stations but there was a lot of variation between years.

- Phosphorus levels were highest in some of the coves, especially in North Glade Cove (Region 2). Nitrogen concentrations were also highest in the coves, with the exception of a spike throughout the lake stations in June 2016. Seasonal average phosphorus levels generally increased moving upstream from the Dam to Turkey Neck. Seasonal average nitrogen levels were not consistently higher or lower at a particular lake station but instead varied between years. Phosphorus levels were not always higher in the coves than the nearest lake station. Nitrogen levels were usually higher in the coves than at the nearest lake station. Phosphorus levels were lower in 2012 than in other years at all stations, and unusually high in 2010 at the Dam and US 219 Bridge lake stations and in Poland Run Cove and Pawn Run Cove. Based on the ratios of total nitrogen relative to total phosphorus, algal growth is likely phosphorus limited in April through June and limited by both nutrients or by light availability in July through September. The presence and impact of underwater grasses is also important in determining the nutrient dynamics of Deep Creek Lake.

- Water clarity was lower at the cove stations compared to the nearest lake station. Seasonally, Secchi depths continued to get worse throughout the summer. Seasonal average water clarity generally decreased (measured by both Secchi depth and turbidity) moving from the Dam station upstream to Turkey Neck. Secchi depths were deeper at the nearest lake stations than in the coves, and water clarity measured by Secchi depth was the worst in North Glade Cove and Green Glade Cove. Secchi depths were deepest in 2012 at most stations. Unlike Secchi depths, however, turbidity was not as different in 2012 compared to other years. Total suspended solids levels were extremely variable between years and between stations. Algal levels were a main source of light attenuation (and therefore lower water clarity) in Deep Creek Lake in most years. Total suspended solids were also important to determining the water clarity at the cove stations.

Introduction

History

Deep Creek Lake is the largest reservoir completely within the Maryland's boundaries. The lake was created in 1925 by impounding Deep Creek with an earthen dam. The purpose of the dam was to provide a controlled water source for a hydroelectric generating station located about a mile downslope from the lake on the banks of the Youghiogheny River.

The earliest water quality studies in Deep Creek Lake were reported in the late 1940s by fisheries managers who were assessing the potential for developing sportfishing opportunities in the lake. Beginning in the early 1970s, occasional water monitoring activities in the lake were conducted by the United States Environmental Protection Agency (EPA) and were focused on determining nutrient levels. Deep Creek Lake was one of several reservoirs in Maryland included in EPA's National Eutrophication Survey. These earlier water quality surveys were focused mostly on samples collected from the mainstem lake between the Dam and Turkey Neck.

After Maryland purchased the lake property in 2000, Department of Natural Resources (DNR) managers needed information to support decisions regarding lake management activities. In 2007, DNR contracted with the United States Geological Survey (USGS) to establish stream load monitoring sites on Cherry Creek and Poland Run to assess the rate of sedimentation in the lake. In April 2009, DNR began a water quality monitoring program. Initially, eight mainstem lake and nine tributary cove monitoring sites were sampled. Beginning in July 2014, the mainstem lake sampling effort was reduced to four sites. In July 2016, the previously established cove sites were discontinued and effort was redirected to increasing the number of cove sites monitored for physical water quality parameters (but no longer monitored for chemical sample analysis).

Figure 1 shows the station locations where physical and chemical analysis sampling was completed for 2009-2016. Station descriptions are given in Table 1. Most of the sampling occurred from April through September. Limited sampling was done from October through March at only a few stations, if weather conditions allowed.

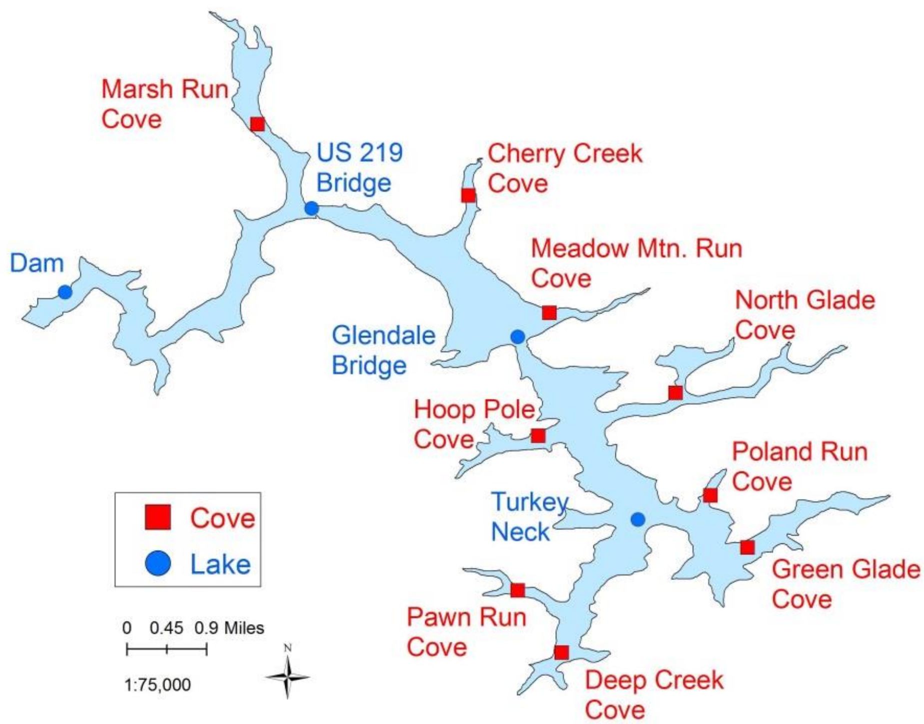

Figure 1. Deep Creek Lake water quality and habitat condition monitoring stations, 2009-2016.

Table 1. Deep Creek Lake water quality and habitat condition monitoring stations 2009-2016. Coordinates are in NAD 83m.

Station name	Description, Station Depth	Latitude	Longitude
■ Marsh Run Cove (MRC0011)	Between ski area and McHenry, 7.6 meters	39.542	-79.354
■ Cherry Ck Cove (CCC0008)	Mid-distance between head and mouth of Cherry Ck. Cove, 9.2 meters	39.530	-79.319
■ Meadow Mtn. Run Cove (MMR0005)	0.5 mi NE of Glendale Rd. bridge, 5.5 meters	39.511	-79.306
■ Hoop Pole Cove (UDC0004)	N of end of Boy Scout Rd, 8.9 meters	39.491	-79.308
■ North Glade Cove (NGC0010)	SW of Harvey Peninsula, 6.1 meters	39.498	-79.286
■ Poland Run Cove (PLV0004)	Mid-distance between mouth and head of Poland Run Cove, 4.4 meters	39.481	-79.280
■ Green Glade Cove (GGC0015)	0.5 mi E of Turkey Neck, 0.2 mi NW of Hazelhurst at deepest cross section point, 5.7 meters	39.473	-79.274
■ Deep Creek Cove (DPR0119)	Center of Deep Creek Cove - 0.5 mi S of Pawn Run Cove mouth, 4.4 meters	39.456	-79.304
■ Pawn Run Cove (PWC0004)	Mid-distance between head and mouth of Pawn Run Cove, 4.8 meters	39.466	-79.311
● Dam (DPR0021)	N of Slide Hollow, 0.4 m above spillway, 19.2 meters	39.514	-79.385
● US 219 Bridge (DPR0056)	N side of US Route 219 Bridge, 14.6 meters	39.528	-79.345
● Glendale Bridge (DPR0082)	N side of Glendale Rd. bridge, 12.7 meters	39.507	-79.311
● Turkey Neck (DPR0103)	NW Turkey Neck, deepest location, 10.1 meters	39.477	-79.292

Deep Creek Lake's seasonal cycles

Deep Creek Lake's water quality varies in response to annual and seasonal cycles. For example, water temperature in the surface waters follows a fairly predictable pattern from year to year (Figure 2). This pattern in water temperature also creates a seasonal pattern in mixing of the water column. Water density is principally a function of its temperature – warmer water is less dense than colder water. As waters warm from spring into summer, the density differences between the surface and bottom waters increase. Once the density differences are large enough, a seasonal thermocline develops. The thermocline prevents the warmer surface-layer (epilimnion) water from regularly mixing with the cooler lower-layer (hypolimnion) water. Wind-driven mixing of the surface waters can change/redefine the thermocline and increase the depth of the surface layer for short periods of time (wind energy mixing the water can overcome the density stratification), but in general the separation of the surface and bottom layers lasts until the water temperatures begin to cool in the fall. As the upper layer waters cool and become denser, the density differences between the upper and lower waters decrease until the surface and bottom waters again can mix (this is called the fall turnover). However, the relationship of water temperature and water density is not linear, especially as water temperatures approach freezing; water is most dense at four degrees Celsius (39.2 degrees Fahrenheit) and the coldest waters are less dense than waters a few degrees warmer. This is why ice floats, and why a second density stratification occurs in the winter months. Once spring water temperatures again warm, another mixing event (the spring turnover) occurs and then summer water temperatures begin this seasonal cycle again. As a result, Deep Creek Lake has strong density stratified patterns in the summer, well mixed conditions in the spring and fall, and a less density stratified pattern in the winter.

Total precipitation varies from year to year (Figure 3) and month to month (Figure 4). Precipitation amounts also vary in different locations of the lake. Seasonal prevailing winds flow from the northwest much of the year (October-June), but in the late summer (July-September), prevailing winds come from the southwest. Around the mostly northern portion of the lake, the close mountain ridges interrupt winds and create local rain shadows such that flows in tributary streams to the lake vary. Lake segments and embayments that are aligned with prevailing winds may have significant wave action mixing waters, creating turbid conditions and eroding some shore areas while other sections oriented perpendicular to these winds are comparatively calm.

Water levels in Deep Creek Lake are also seasonally managed to meet competing needs for power generation and recreation levels in the lake (Figure 5). Outfall from Deep Creek Lake downstream to the Youghiogheny River is used to support management of seasonal flows in the Youghiogheny River for recreational needs, to meet minimum flows to support aquatic species and to reduce threats of downstream flooding. The water release structure in Deep Creek Lake is a nine-foot tall intake gate located near the dam at an elevation 43 to 51 feet below summer normal pool elevation so much of the water released from the lake during the summer is from the water layer above the thermocline.

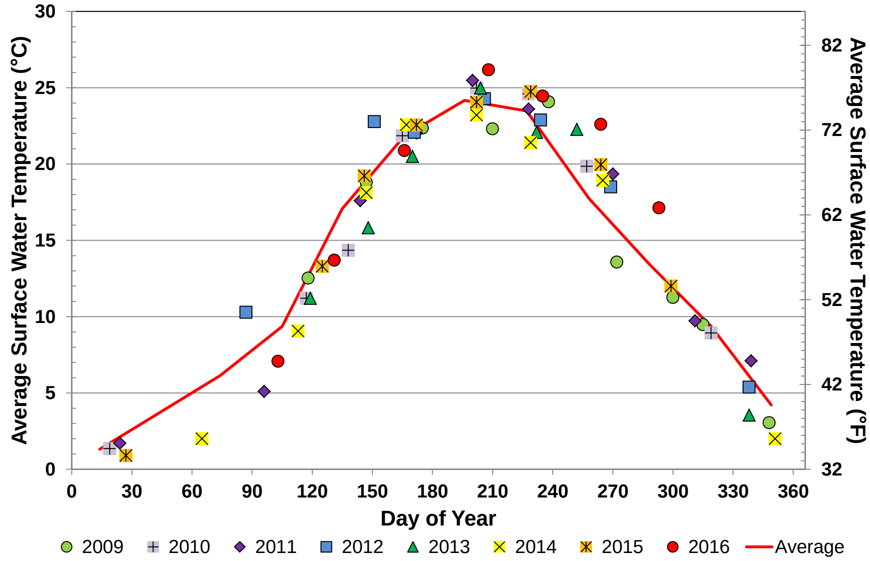

Figure 2. Monthly surface water temperature by year.
Each value is the mean of the four lake stations for each month in each year (single sampling per month). Day of year is used on the x-axis to compare years most accurately. Mean surface temperature is shown on the y-axis in both degrees Celsius (°C, left side of graph) and degrees Fahrenheit (°F, right side of graph). The red line shows the overall monthly mean for 2009-2016. Note that data for January- March (days 0-90) and October-December (days 274-365) are limited to two stations in most years of the monitoring program.

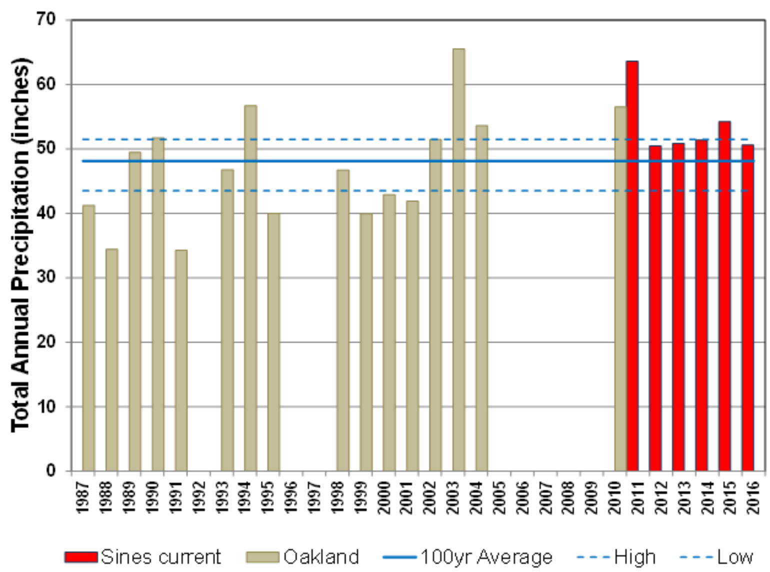

Figure 3. Annual total precipitation at Deep Creek lake and vicinity.
Data available from the National Weather Service at ncdc.noaa.gov/cdo-web/datatools. Annual total shown only if at least 364 days of data are available. The blue line shows the 100-year mean total precipitation; blue dashed lines show the 25th and 75th percentiles. Data at Sines Deep Creek Lake station (USC00188315) available for 1929-1963 and 2011-2016 (red bars). Data from Oakland station (USC00186620) available for 1917-1928 and 1964-2010 (tan bars).

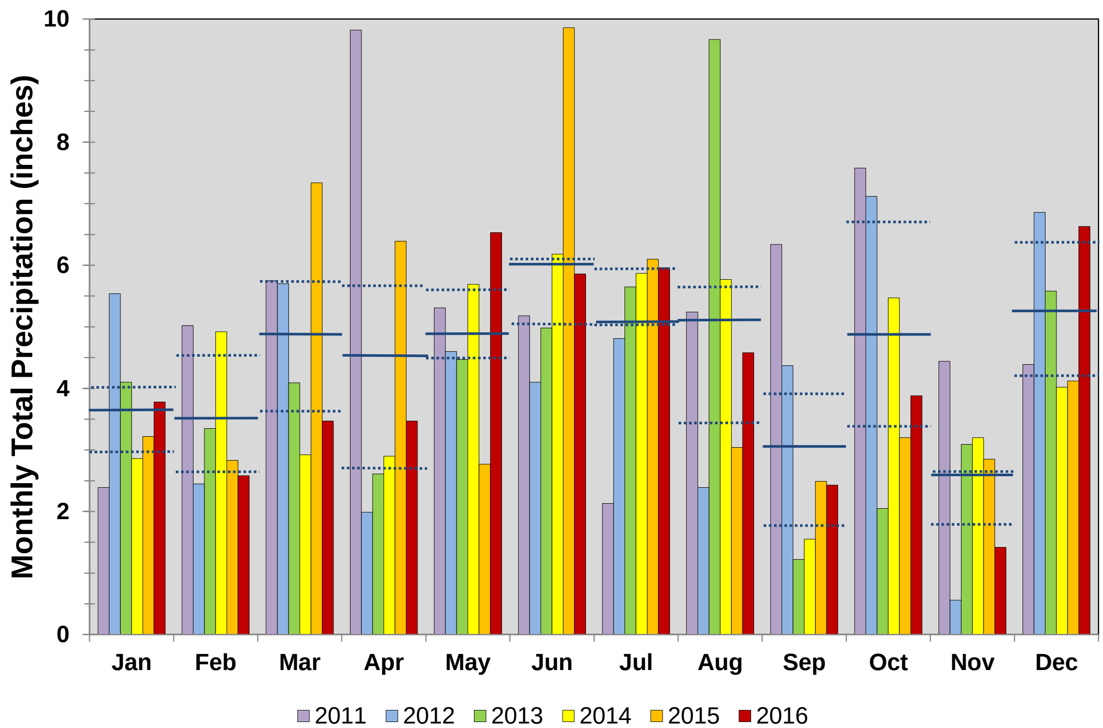

Figure 4. Monthly total precipitation by year.
Each value is the total precipitation for a single month, color-coded by year. The blue solid line shows the monthly mean for the period 2011-2016; blue dashed lines show the 25^{th} and 75^{th} percentiles. Data are available at mde.state.md.us/programs/water/water_supply/Pages/DeepCreekLakePeriodicReports.aspx

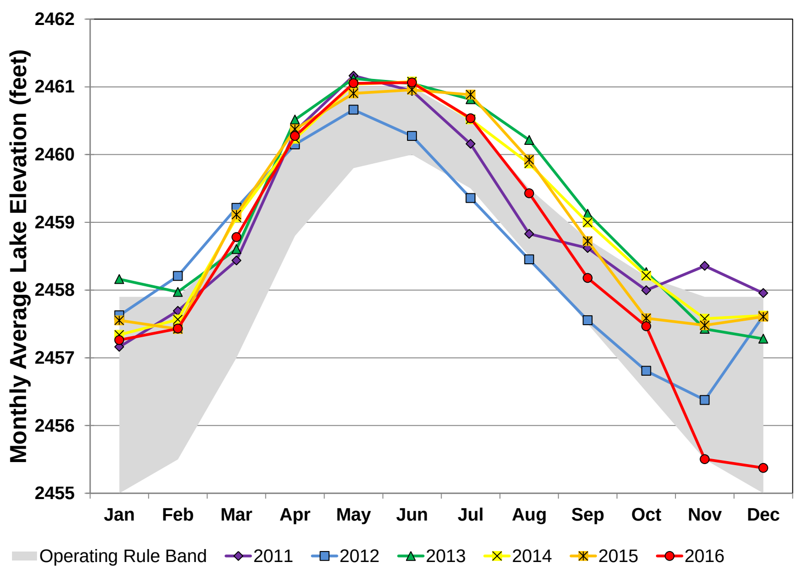

Figure 5. Monthly mean lake elevation (feet) for 2011-2016.
Lake elevation is measured at the dam by the dam operator on a daily basis. Water elevations are managed to remain within the Operating Rule Band (gray area). Data are reported annually to Maryland Department of the Environment and available at mde.state.md.us/programs/water/water_supply/Pages/DeepCreekLakePeriodicReports.aspx.

Deep Creek Lake's land use

The Deep Creek Lake's overall watershed is made up of three 12-digit watersheds (Figure 6). The location of the water quality monitoring stations is not well represented by the separation of the overall watershed into the 12-digit watersheds. A smaller sub-watershed grouping is more useful (Figure 7) to relate the monitoring data to the surrounding watershed. This sub-watershed delineation is at the level of individual coves and was used in the Deep Creek Lake 2007 Assessment report (Environmental Resource Management, 2007). The sub-watershed designations are available electronically online at garrettcounty.org/watershed/deep-creek-lake/maps-dcl.

The type of land use within the watershed varies with location, and each type of land use has different impacts on water quality. Overall, the largest land use is forest in all three 12-digit watersheds (Figure 8, Table 2). The watershed (05020303050027) that includes the upper lake and most of the monitored tributary coves has the largest amount of agricultural lands, but also nearly as much suburban land use as the lower lake watershed (05020303050028). The lower lake watershed has the most urban land use, largely clustered around Marsh Run (the town of McHenry) and near the Glendale Road Bridge (the state park area is also part of this urban land use). The watershed (05020303050029) that includes Cherry Creek and Meadow Mountain Run is about half the size of the other two watersheds and has the most surface mining (the largest urban land use for this watershed) and is similar to the upper watershed in percent agriculture.

When the land use is broken down by region (Table 3), other patterns emerge. Region 0 is mostly forested (72 percent). Region 1 and Region 3 are also mostly forested (approximately 60 percent) but agricultural land use is also important (approximately 15 percent); note however that Region 3 is much smaller than Region 1. Region 2 has less forested area (46 percent) and more agricultural area (28 percent), and Region 4 is approximately equally divided into agricultural and forest land use (40 percent each).

Suburban/urban land use is roughly the same amount of each of the regions (18-25 percent combined); Region 1 has the most urban land use (almost five percent of the area) and Region 2 has the largest amount of suburban and urban combined (almost 25 percent). Surface mining is found predominately in Region 1 but is also present in Region 2. Also worth noting is that most of the wetland area in the overall Deep Creek Lake watershed is in Region 1.

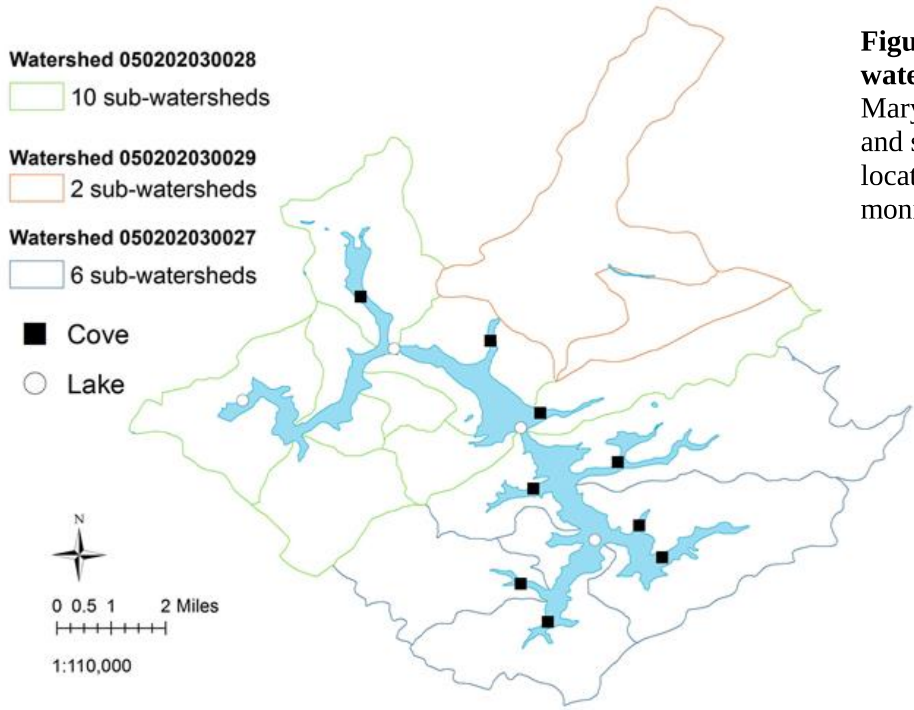

Figure 6. Deep Creek Lake watersheds.
Maryland 12-digit watersheds and sub-watersheds and the locations of the water quality monitoring stations.

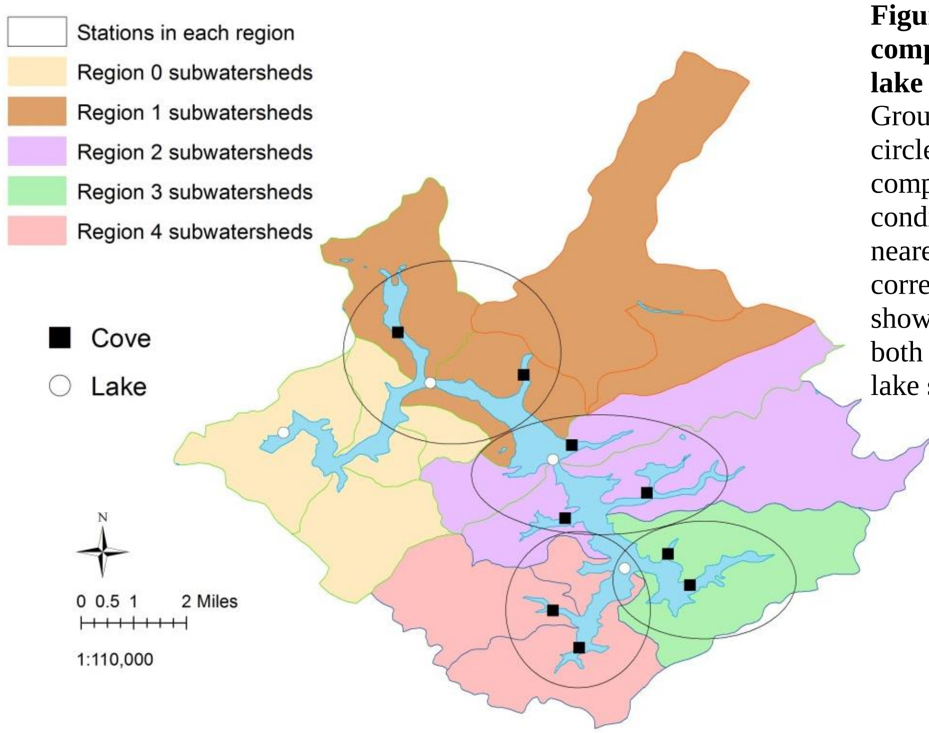

Figure 7. Lake regions for comparison of coves to nearest lake station.
Groups of stations (numbered circled region on this map) to compare the water quality conditions in the coves with the nearest lake station. Best corresponding sub-watersheds also shown. Note that Region 3 and 4 both compare cove locations to the lake station at Turkey Neck.

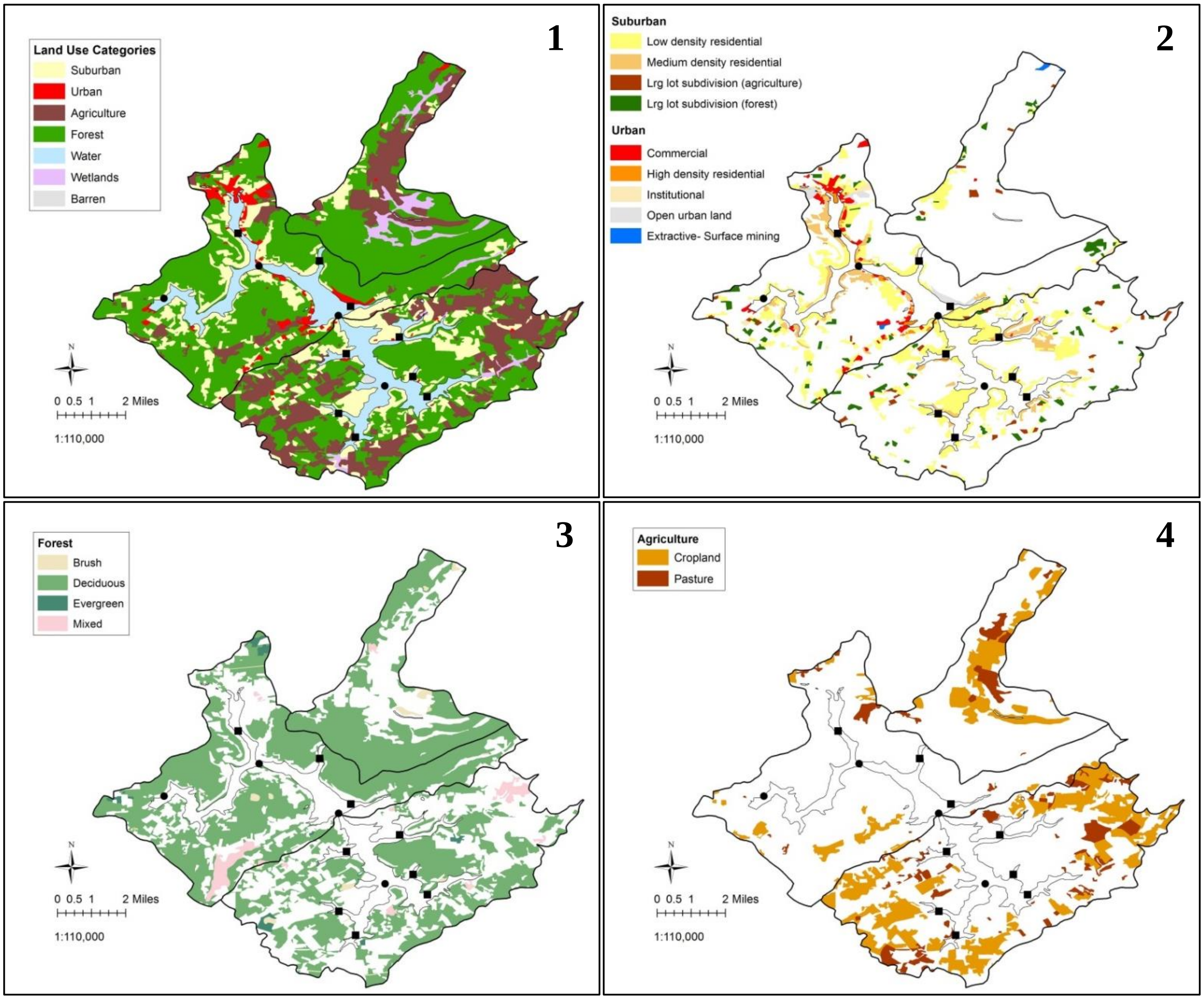

Figure 8. Deep Creek Lake land use in 2010.
Maryland Department of Planning 2010 land use data for the Deep Creek Lake watershed (available online at planning.maryland.gov/OurProducts/downloadFiles.shtml). Outlines of 12-digit watersheds are shown. Panel 1 shows all major categories of land use. Panels 2-4 show individual major categories (suburban/urban, forest and agriculture) broken down into subcategories as noted in the legend with each frame; definitions of the subcategories can be found online at planning.maryland.gov/PDF/OurWork/LandUse/AppendixA_LandUseCategories.pdf. Urban land uses include high-density residential development, commercial, industrial uses and surface mining operations; suburban land uses include low- and medium density residential uses. Agricultural land uses include cropland and pasture land. Black markers show the locations of the water monitoring program stations.

Table 2. Land use in 2010 by Deep Creek Lake 12-digit watershed.
Bold typeface is used for land-use categories where percentage of land area is more than 20 percent.

Land use category	12-digit watershed 050202030027		050202030028		050202030029		TOTAL	
	Area in square miles	Percentage of Land Area	Area in square miles	Percentage of Land Area	Area in square miles	Percentage of Land Area	Area in square miles	Percentage of Land Area
Urban	0.08	0.4%	1.28	5.8%	0.05	0.4%	1.41	2.4%
Suburban	4.88	**20.6%**	4.81	**21.8%**	0.57	4.6%	10.27	17.6%
Forest	10.52	**44.3%**	14.52	**65.6%**	7.55	**61.2%**	32.59	**56.0%**
Agriculture	7.88	**33.2%**	1.37	6.2%	2.94	**23.8%**	12.20	**21.0%**
Wetlands	0.31	1.3%	0.12	0.6%	1.23	10.0%	1.66	2.9%
Barren	0.06	0.2%	0.01	0.1%	0.00	0.0%	0.07	0.1%
Water	3.00		2.75		0.02		5.77	
Total	26.73		24.87		12.36		63.96	

Table 3. Land use in 2010 by Deep Creek Lake region.
Bold typeface is used for land-use categories where percentage of land area is more than 20 percent.

Land use category	Region 0		Region 1		Region 2		Region 3		Region 4	
	Area in square miles	Percentage of Land Area	Area in square miles	Percentage of Land Area	Area in square miles	Percentage of Land Area	Area in square miles	Percentage of Land Area	Area in square miles	Percentage of Land Area
Urban	0.13	1.3%	0.89	4.6%	0.36	2.6%	0.01	0.1%	0.02	0.3%
Suburban	2.14	**21.5%**	2.44	12.6%	2.95	**21.6%**	1.17	18.4%	1.56	17.8%
Forest	7.20	**72.3%**	11.50	**59.2%**	6.34	**46.4%**	4.04	**63.5%**	3.51	**40.0%**
Agriculture	0.49	4.9%	3.36	17.3%	3.83	**28.1%**	0.97	15.2%	3.55	**40.4%**
Wetlands	0.00		1.23	6.3%	0.15	1.1%	0.18	2.8%	0.11	1.2%
Barren	0.00		0.01	0.1%	0.03	0.2%	0.00		0.03	0.3%
Water	0.96		1.57		1.45		0.98		0.82	
Total	10.92		21.00		15.11		7.33		9.61	

Designated uses and water quality impairments

The federal Clean Water Act requires states to define uses of their waters and identify how these waters are defined. In Maryland, defined uses for waters in Deep Creek Lake watershed are documented in the Code of Maryland Regulations (COMAR 26.08.02.02 and 26.08.02.02-1). Every two years, the Department of the Environment releases an Integrated Water Quality Report which lists waterbodies in which defined water uses are 'impaired' because of one or more pollutants. Impaired waters in the Deep Creek Lake watershed are identified within the Deep Creek watershed (basin code 05020203); reports are available online at mde.maryland.gov/programs/Water/TMDL/Integrated303dReports/Pages/index.aspx.

The Department of the Environment classifies Deep Creek Lake (and all waters in the lake watershed) as Class III-P for supporting uses that can include:

- swimming, boating, fishing and all other recreational activities involving water contact,
- protection of aquatic life and wildlife,
- agricultural supply and industrial water supply,
- propagation and growth of natural trout waters, and
- public water supply

Specific criteria are defined to protect/maintain these uses with defined maximum/minimum limits on water temperature, dissolved oxygen and pH. Other regulated parameters are not measured in the current water quality monitoring program such as bacteria, metals, inorganic and organic contaminants (COMAR 26.08.02.03-1 and 26.08.02.03-2).

Surface water temperatures during the summer often exceed the temperature criterion for Class III-P use maximum (68 ºF/ 20 ºC). The Clean Water Act states that a natural process (like solar heating) cannot create an impairment, so Deep Creek Lake waters warmed by the sun are not impaired.

At the deeper lake stations, dissolved oxygen below the thermocline can drop to very low levels (less than one milligram oxygen per liter, called hypoxia) or be completely absent (zero milligrams oxygen per liter, called anoxia). Seasonally low oxygen in the waters below the thermocline is not considered an impairment for Class III-P use because the development of the thermocline and the oxygen depletion are existing, natural processes.

Cherry Creek, the largest tributary watershed to Deep Creek Lake, is considered to be impaired due to low water pH. The concern results from past mining practices that released acid mine wastewater into the tributary stream. Water pH levels were so low (acidic) that aquatic life was nearly absent. In 1996, the Department of the Environment documented this problem, identified sources and defined a Total Maximum Daily Load that, if met, would reduce acidic mine drainage in the tributary stream and allow aquatic animals to repopulate the stream. The Total Maximum Daily Load report for pH in Cherry Creek was approved in 2006 (available online at mde.maryland.gov/programs/water/TMDL/ApprovedFinalTMDLs/Pages/tmdl_cherrycreek_final_ph.aspx.) No low pH values (pH less than 6) were measured in Cherry Creek Cove during the monitoring program sampling.

Water quality and habitat conditions

Water temperature and seasonal thermocline

Water temperature is an important water quality measure as it governs seasonal stratification of the lake and the rate of biogeochemical and ecological processes. Water temperature impacts habitat quality for some species, and can impact reproduction and growth of aquatic organisms.

Water density differences between the surface and bottom waters increase as the surface waters warm in the spring and early summer; once the density differences are large enough, a seasonal thermocline develops. In this report, the depth of the seasonal thermocline is defined by a Relative Thermal Resistance to Mixing index.[1] This is a unitless index that quantifies thermal stratification in lakes based on differences in water density due to temperature differences. For this report, the upper thermocline depth is indicated at the depth where the index first exceeds 25 where the water depth is at least five meters (thermoclines were not determined for stations less than five meters in depth). The measurement of this upper thermocline depth is limited because water temperature measurements are made at one-meter increments through the water column.

At the four lake sites, water temperature was similar throughout the water column in April in some but not in all years (Figure 9). As the thermocline begins to develop in May, the surface waters and bottom waters were not completely distinct (note that the water temperature was still similar in the surface and lower layers), but in general the surface layer was two to three degrees Celsius (ºC)/four to five degrees Fahrenheit, ºF) warmer than the lower layer waters. From June through August, the depth of the thermocline deepens from around 5 meters to 10 meters below the water surface, and surface water temperature was eight to ten °C (14-18 ºF) warmer. This seasonal pattern was similar between years. September water temperature patterns were not as consistent between years (compare 2014 to 2016 in Figure 9) as the fall turnover and mixing begins to occur. By October mixing was generally complete and the water temperatures were again similar throughout the water column (as shown in Figure 10 for the single station at the Route 219 Bridge).

A seasonal thermocline also develops in some of the deeper cove stations, including Cherry Creek Cove, Hoop Pole Cove and in some months in other coves. Compared to the nearest lake station (see Figure 7), the differences in water temperature in the coves were not as great between the above thermocline and below thermocline waters because depths were shallower (Figure 11) but still can result in different habitat conditions when a thermocline was present. Surface water temperatures were similar between the coves and nearest lake stations.

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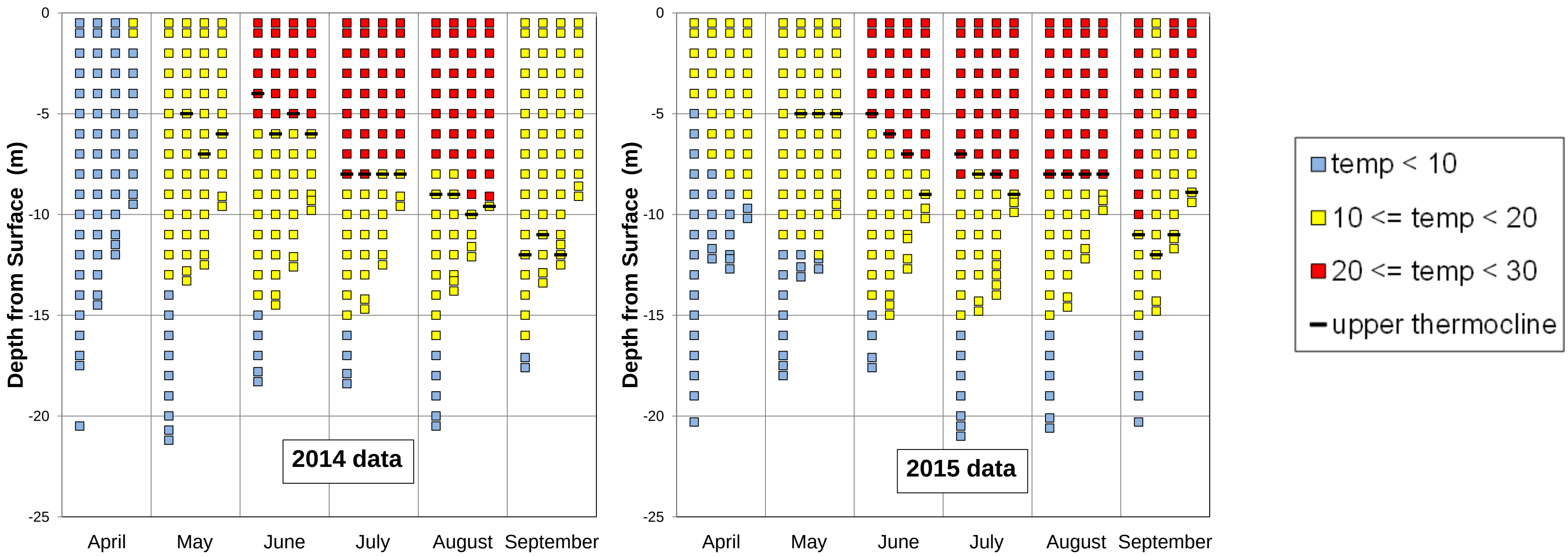
[1] A very good explanation of Relative Thermal Resistance to Mixing index is available online at ecosystemconsulting.com/pdfs/AAA%20RTRM.pdf



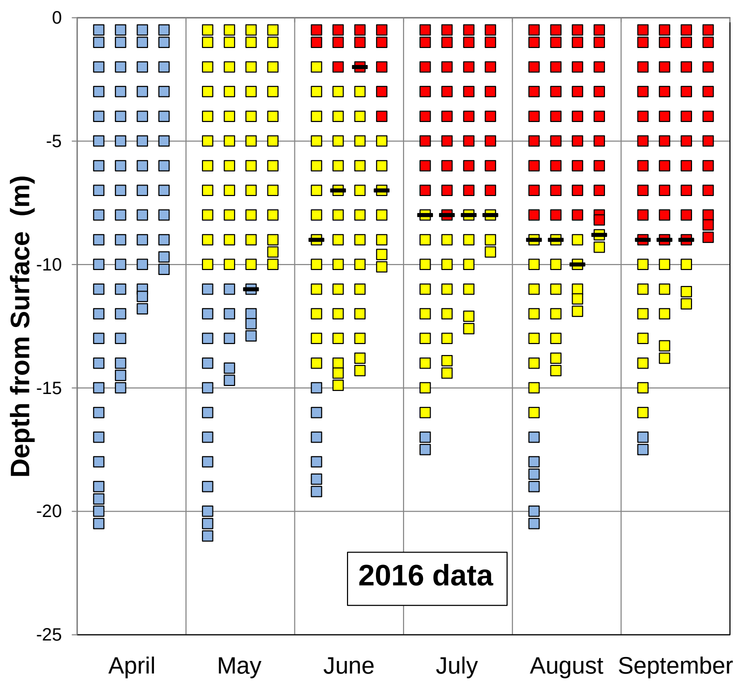


Figure 9. Water temperature for the four lake stations, 2014-2016.
Each month block displays water temperature (in degrees Celsius, ºC) at each depth from the surface to the bottom (moving from top to bottom of the graph). A single column within each month block shows the data from a station, moving from the station at the Dam (far left, deepest station) up to the station at Turkey Neck (far right, shallowest station).
Color coding is shown in the legend in degrees Celsius (ºC), and corresponds to degrees Fahrenheit (ºF) as follows:

[temp < 10 ºC] = [temp < 50 ºF]
[10 ºC < = temp < 20 ºC] = [50 ºF < = temp < 68 ºF]
[20 ºC < = temp < 30 ºC] = [68 ºF < = temp < 86 ºF]

Upper thermocline is the depth where density differences first exceed the threshold to limit mixing between the water layer above and below that depth, but is not necessarily the depth of the maximum density difference.

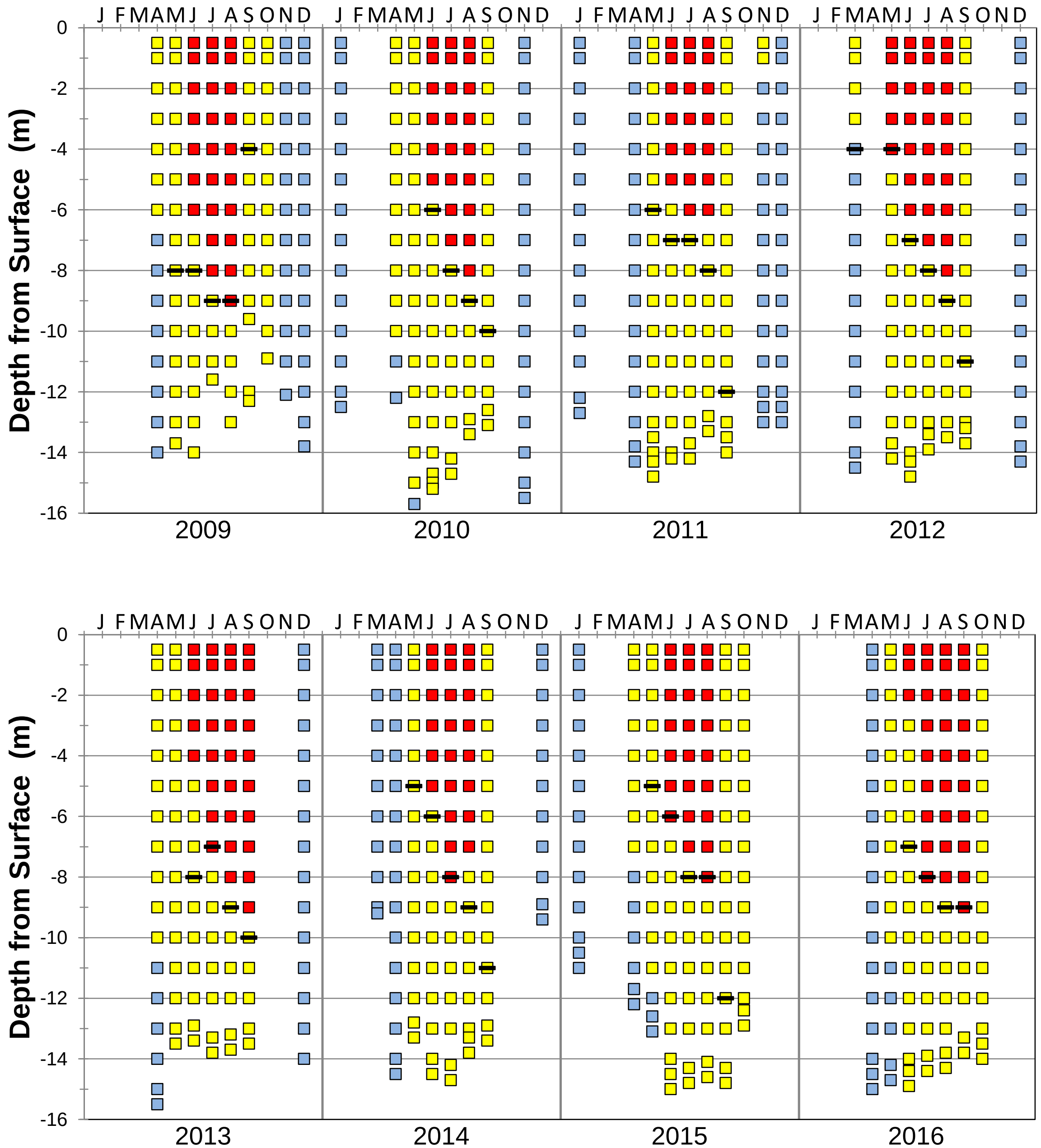
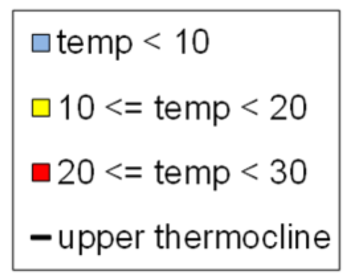


Figure 10. Water temperature for the Route 219 Bridge lake station, 2009-2016.
Each block displays water temperature (in degrees Celsius, ºC) for a year, each column within a block shows data from a single month at each depth from the surface to the bottom (months labeled at the top of the graph). Color coding is shown in the legend in degrees Celsius (ºC), and corresponds to degrees Fahrenheit (ºF) as follows:

[temp < 10 ºC] = [temp < 50 ºF]
[10 ºC < = temp < 20 ºC] = [50 ºF < = temp < 68 ºF]
[20 ºC < = temp < 30 ºC] = [68 ºF < = temp < 86 ºF]

Upper thermocline is the depth where density differences first exceed the threshold to limit mixing between the water layer above and below that depth, but is not necessarily the depth of the maximum density difference.



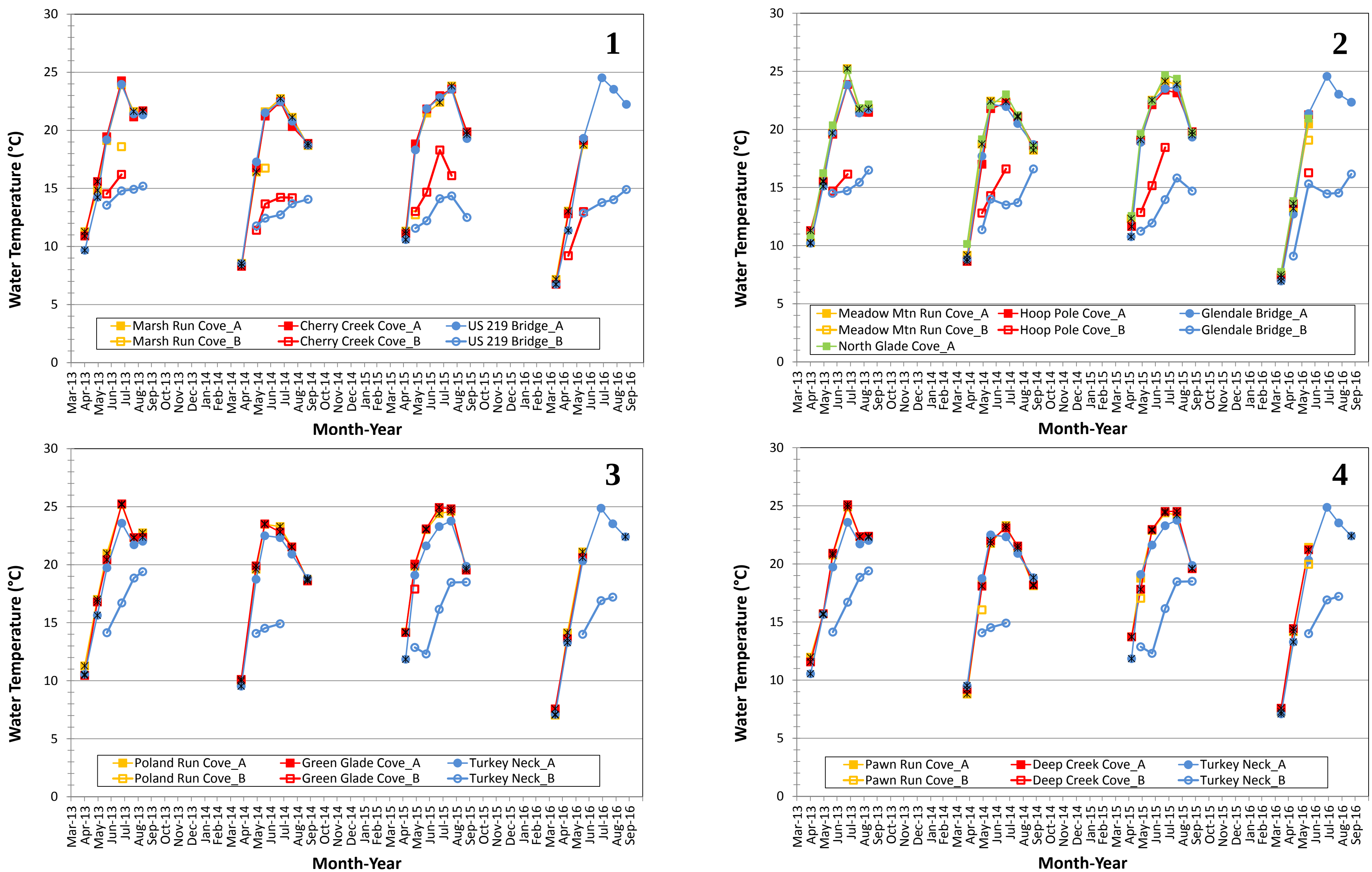


Figure 11. Water temperature by region, 2013-2016.
Each numbered graph (in upper right hand corner of panel) corresponds to a numbered circled region on the map in Figure 7 to compare the water temperature (in degrees Celsius, ºC) in the coves with the nearest lake station. Measurements are means for layer Above (_A, filled markers) and Below (_B, open markers) the upper thermocline depth from April to September for each year. Values for dates when there was no thermocline are marked with a *. Cove station monitoring was ended in July 2016.

Dissolved oxygen

Once the seasonal thermocline develops the above thermocline and below thermocline waters do not regularly mix. Dissolved oxygen in the waters below the thermocline is not replenished and can become depleted as organisms respire and organic matter is decomposed. There is no photosynthesis to provide oxygen in the deeper areas. In general, dissolved oxygen levels above five milligrams per liter are considered healthy habitat conditions. Dissolved oxygen levels below three milligrams per liter are not considered to be good habitat conditions, and very low dissolved oxygen levels (less than one milligram oxygen per liter, called hypoxia) are considered poor habitat conditions.

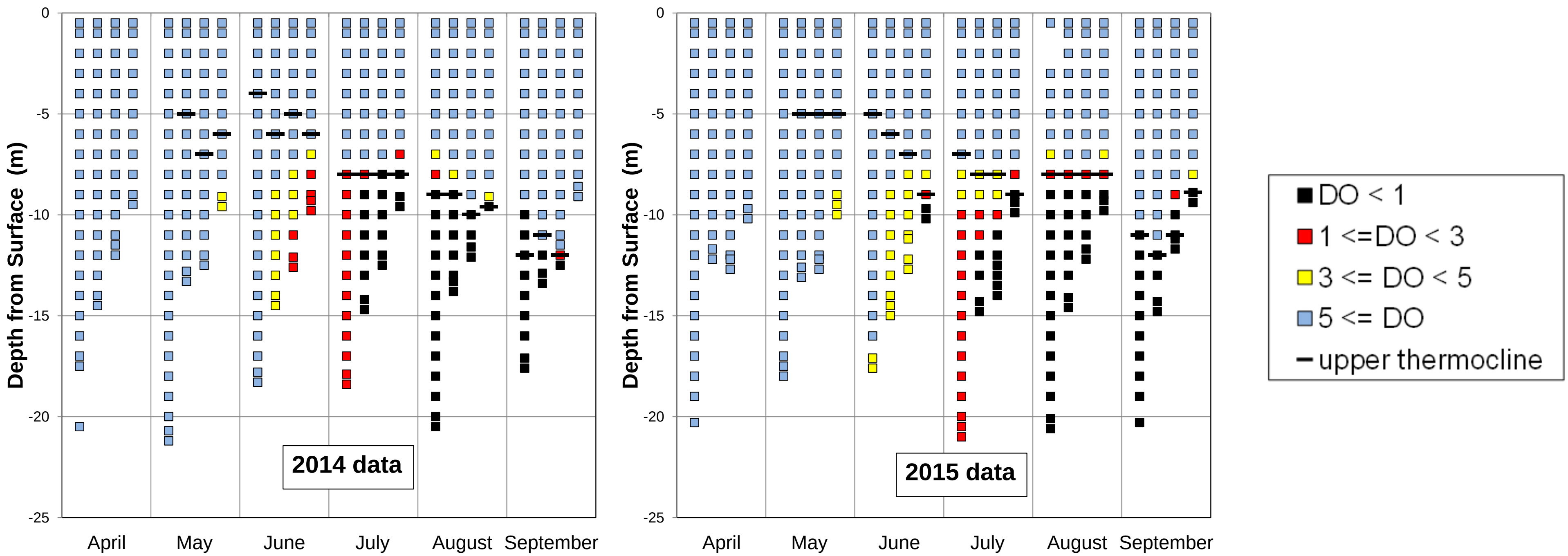
At the four lake sites, dissolved oxygen levels in surface waters remained above five milligrams per liter throughout the year (Figure 12). Below the thermocline, dissolved oxygen levels began decreasing as early as May and June. In some years the dissolved oxygen levels were less than three milligrams per liter in the below thermocline waters as early as June. In July, August and September, dissolved oxygen levels were extremely low (less than one milligram per liter) in the below thermocline waters. By October, fall turnover and mixing was generally complete and dissolved oxygen levels in the entire water column were at or above five milligrams per liter (Figure 13).

Dissolved oxygen levels in surface waters of all the coves remained above five milligrams per liter throughout the year, and were even higher in the coves, especially in Region 3 and 4. Note that the dissolved oxygen levels in the surface waters decrease from highest values in the spring to lower values in the summer because warm water holds less dissolved oxygen than cooler water. Dissolved oxygen levels below the thermocline of the deeper coves (Cherry Creek Cove, Hoop Pole Cove) were very low in June and July (Figure 14). The thermocline was disrupted in August and September as water temperatures became more similar throughout the water column, and dissolved oxygen levels were replenished as deeper waters again mixed with surface waters.

Water pH

Water pH that is too acidic (pH less than 6.5) or too basic (pH greater than 8.5) can have negative impacts on aquatic organisms. Water pH at the lake stations remained in the healthy range (between 6.5 and 8.5) throughout the year and at most depths (Figures 15 and 16). Deeper waters below the thermocline had lower water pH values and decreased to less than 6.5 in June, July, August and September of some years as the result of the limited mixing and biologic, geologic and chemical processes occurring in the bottom sediments and waters. Water pH can be different between the layers because of photosynthesis in the surface water (which can increase pH), due to differences in pH in runoff from the watershed that impacts the surface layer but not the lower layer, or due to differences in groundwater seeping into the below thermocline layer.

Water pH in surface waters of all the coves was higher (but generally still between 6.5 and 8.5) than at the nearest lake station (Figure 17). Occasional spikes in surface layer pH (pH above 8) likely represent high algal photosynthesis. Water pH levels in the below thermocline waters of the deeper coves (Cherry Creek Cove, Hoop Pole Cove) were similar to the lake stations.



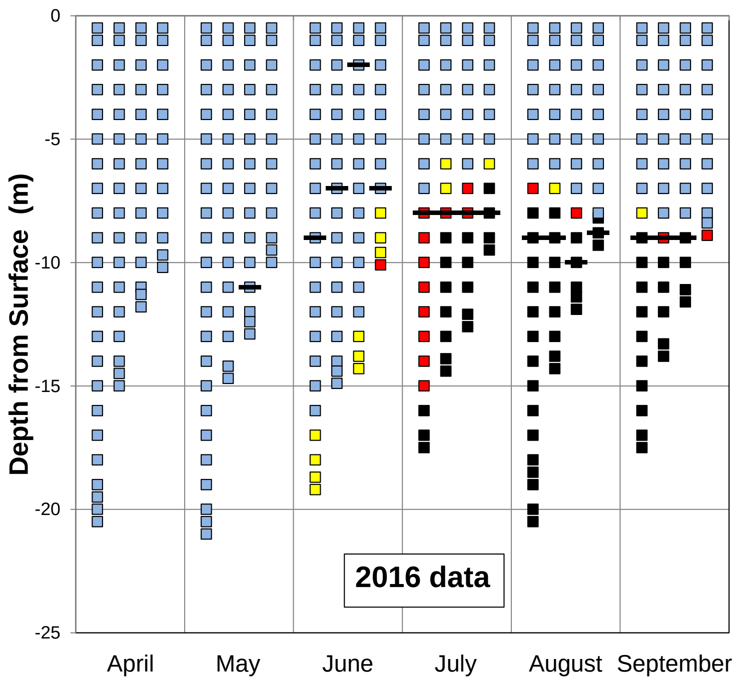


Figure 12. Water dissolved oxygen for the four lake stations, 2014-2016.

Each month block displays water dissolved oxygen (in mg/L) at each depth from the surface to the bottom (moving from top to bottom of the graph). A single column within each month block shows the data from a station, moving from the station at the Dam (far left, deepest station) up to the station at Turkey Neck (far right, shallowest station).

Upper thermocline is the depth where density differences first exceed the threshold to limit mixing between the water layer above and below that depth, but is not necessarily the depth of the maximum density difference.

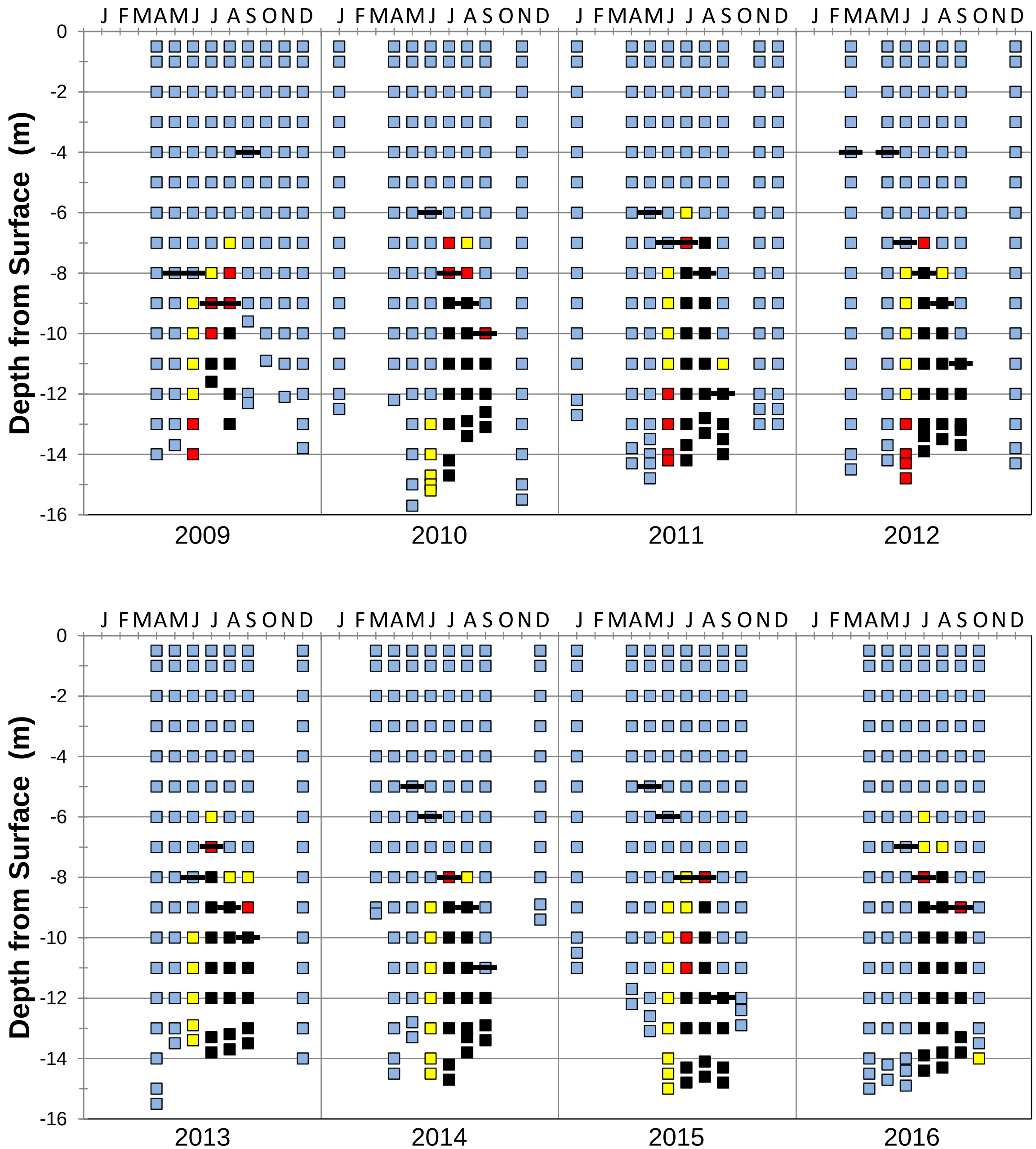
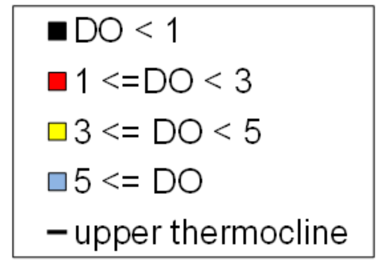


Figure 13. Water dissolved oxygen for the Route 219 Bridge lake station, 2009-2016.
Each block displays dissolved oxygen levels (in mg/L) for a year, each column within a block shows data from a single month at each depth from the surface to the bottom (months labeled at the top of the graph). Color coding is shown in the legend. Upper thermocline is the depth where density differences first exceed the threshold to limit mixing between the water layer above and below that depth, but is not necessarily the depth of the maximum density difference.



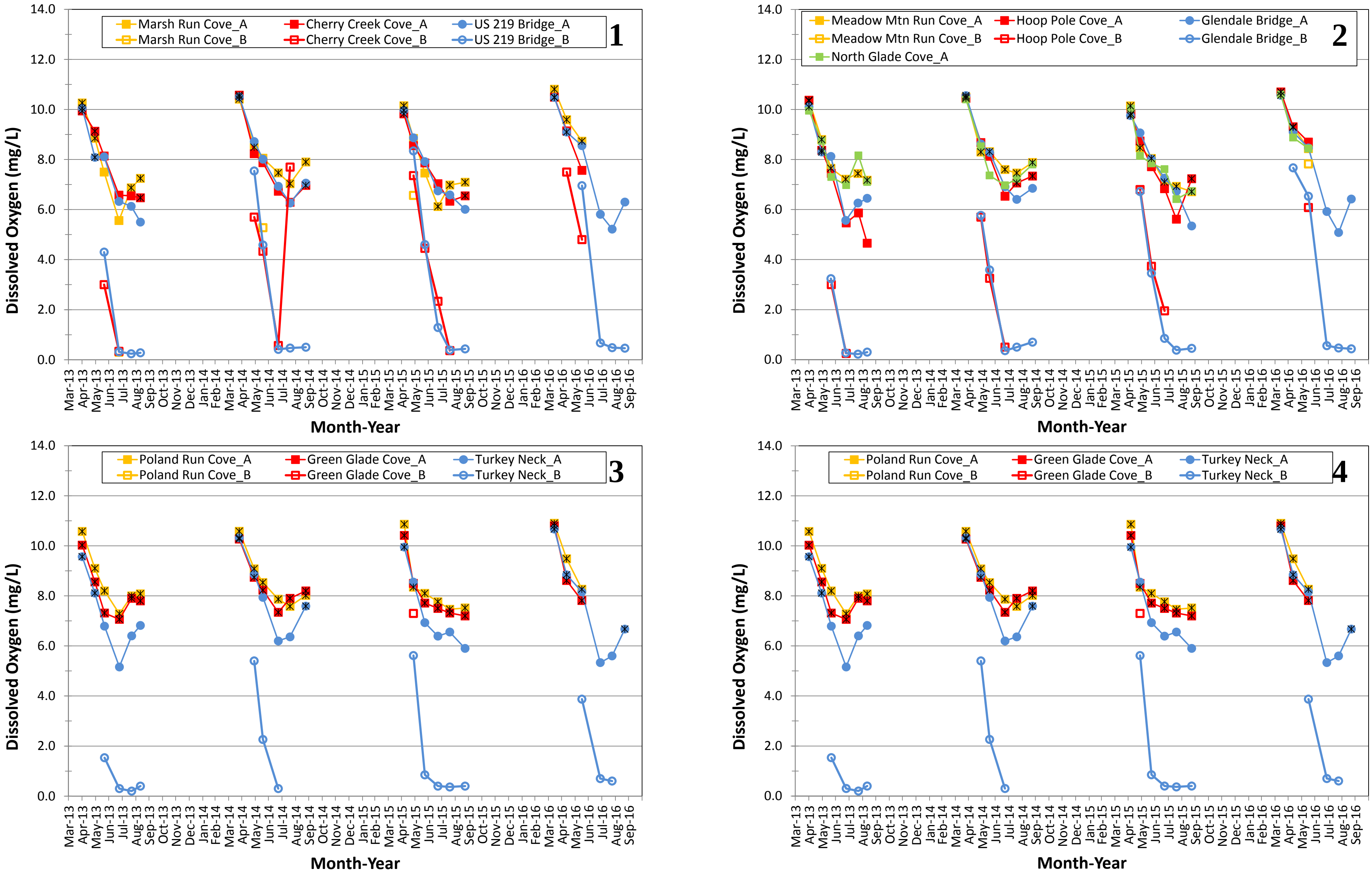
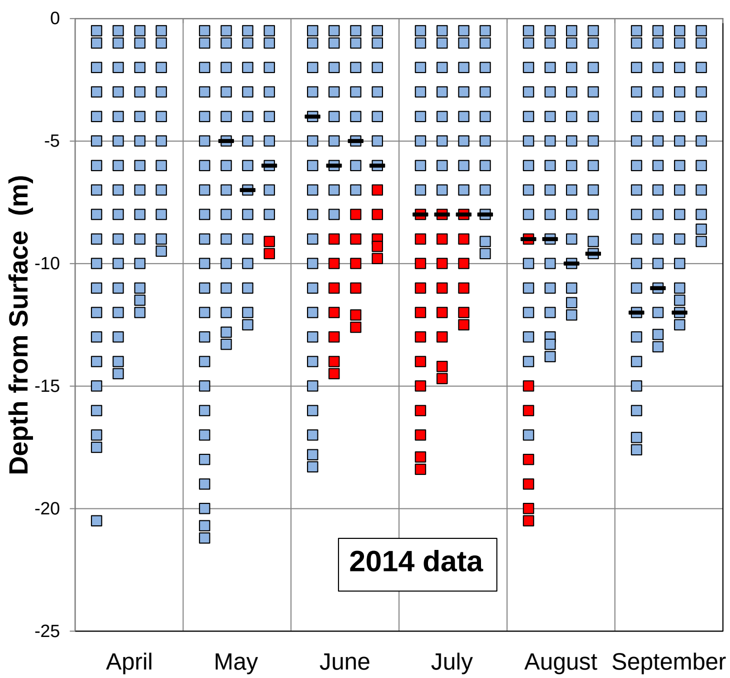
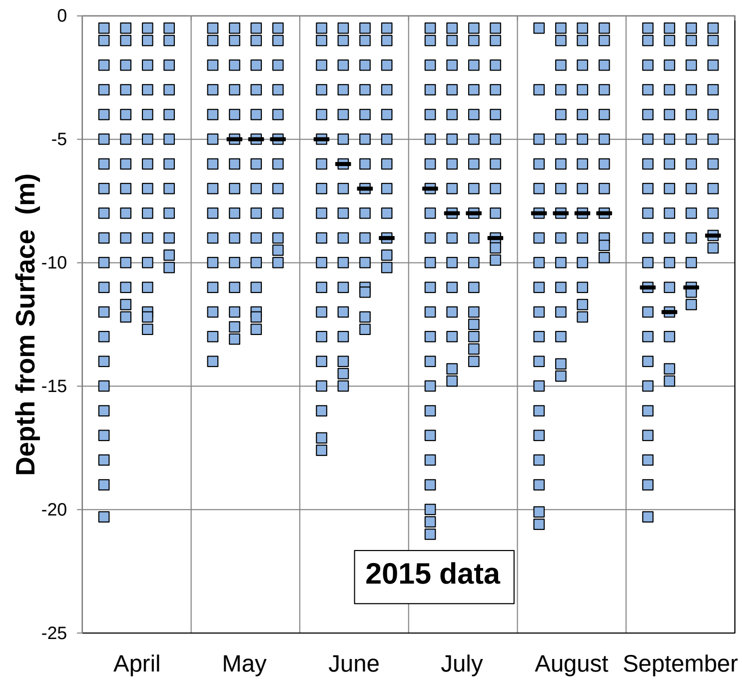
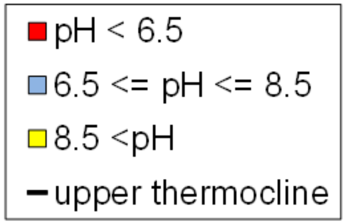


Figure 14. Water dissolved oxygen by region, 2013-2016.

Each numbered graph (in upper right hand corner of panel) corresponds to a numbered circled region on the map in Figure 7 to compare the dissolved oxygen levels in milligrams per liter (mg/L) in the coves with the nearest lake station. Measurements are means for layer Above (_A, filled markers) and Below (_B, open markers) the upper thermocline depth from April to September for each year. Values for dates when there was no thermocline are marked with a *. Cove station monitoring was ended in July 2016.







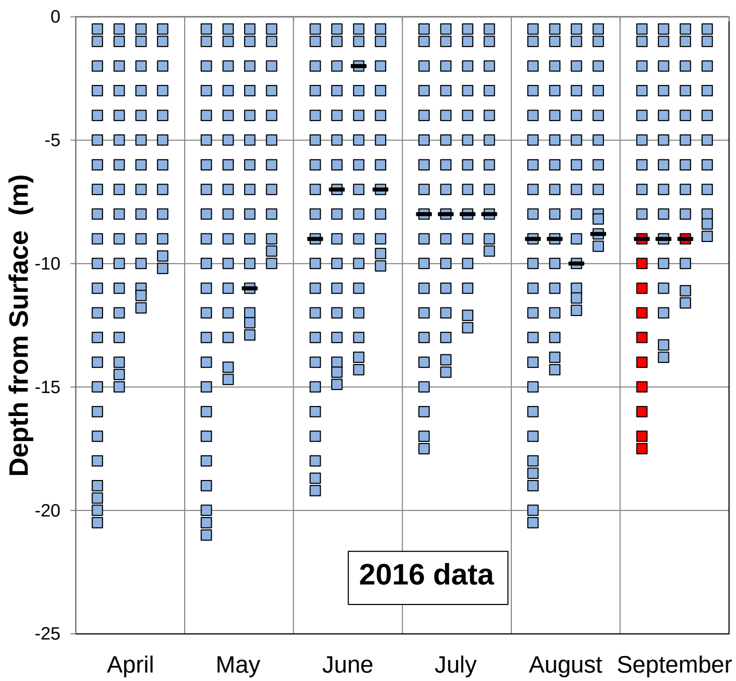


Figure 15. Water pH for the four lake stations, 2014-2016.
Each month block displays water pH at each depth from the surface to the bottom (moving from top to bottom of the graph). A single column within each month block shows the data from a station, moving from the station at the Dam (far left, deepest station) up to the station at Turkey Neck (far right, shallowest station).

Upper thermocline is the depth where density differences first exceed the threshold to limit mixing between the water layer above and below that depth, but is not necessarily the depth of the maximum density difference.

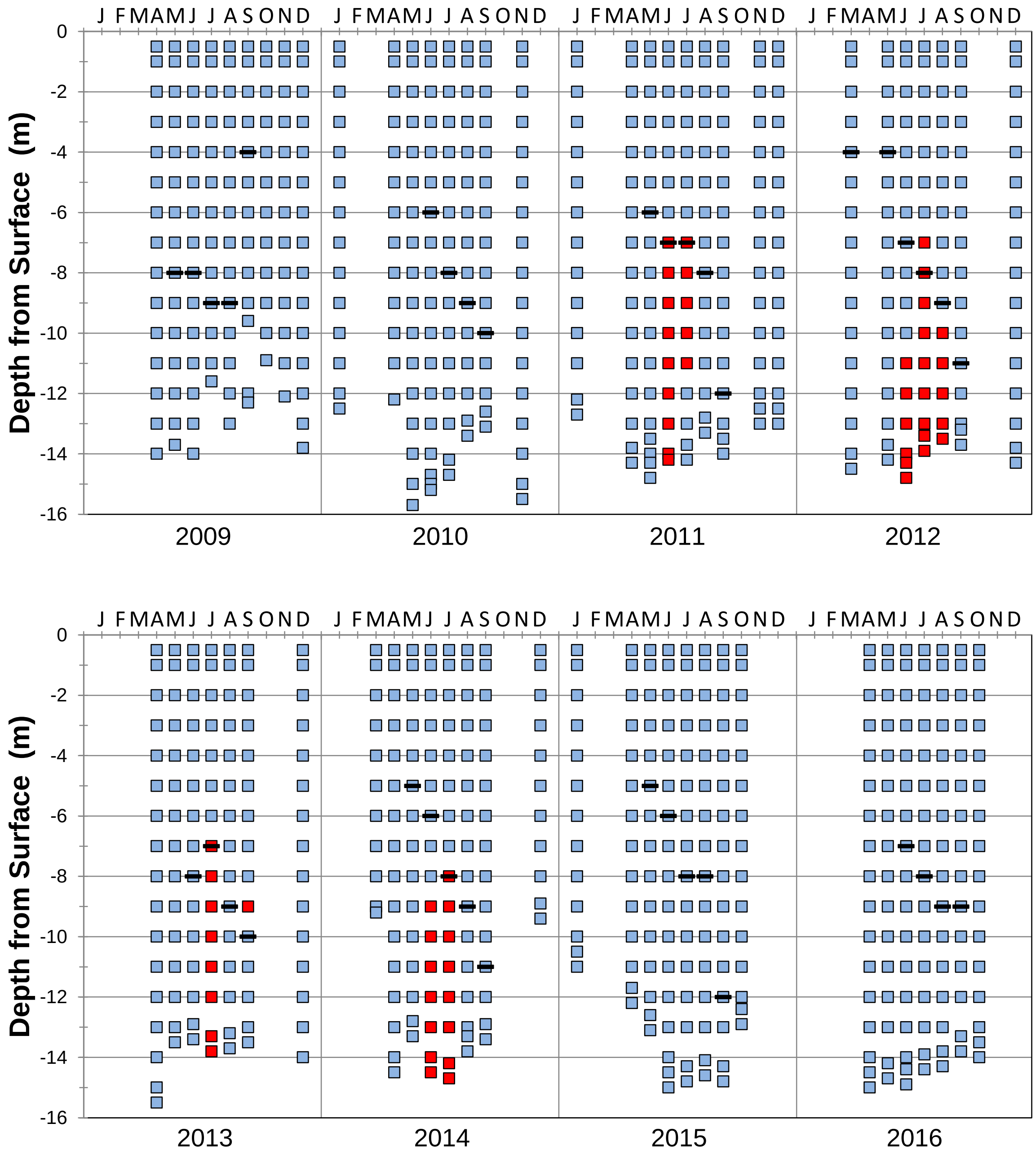
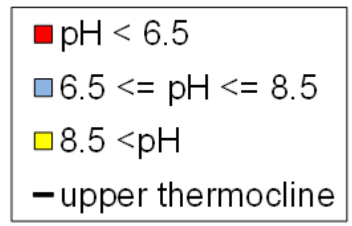


Figure 16. Water pH for the Route 219 Bridge lake station, 2009-2016.
Each block displays water pH for a year, each column within a block shows data from a single month at each depth from the surface to the bottom (months labeled at the top of the graph). Color coding is shown in the legend. Upper thermocline is the depth where density differences first exceed the threshold to limit mixing between the water layer above and below that depth, but is not necessarily the depth of the maximum density difference.



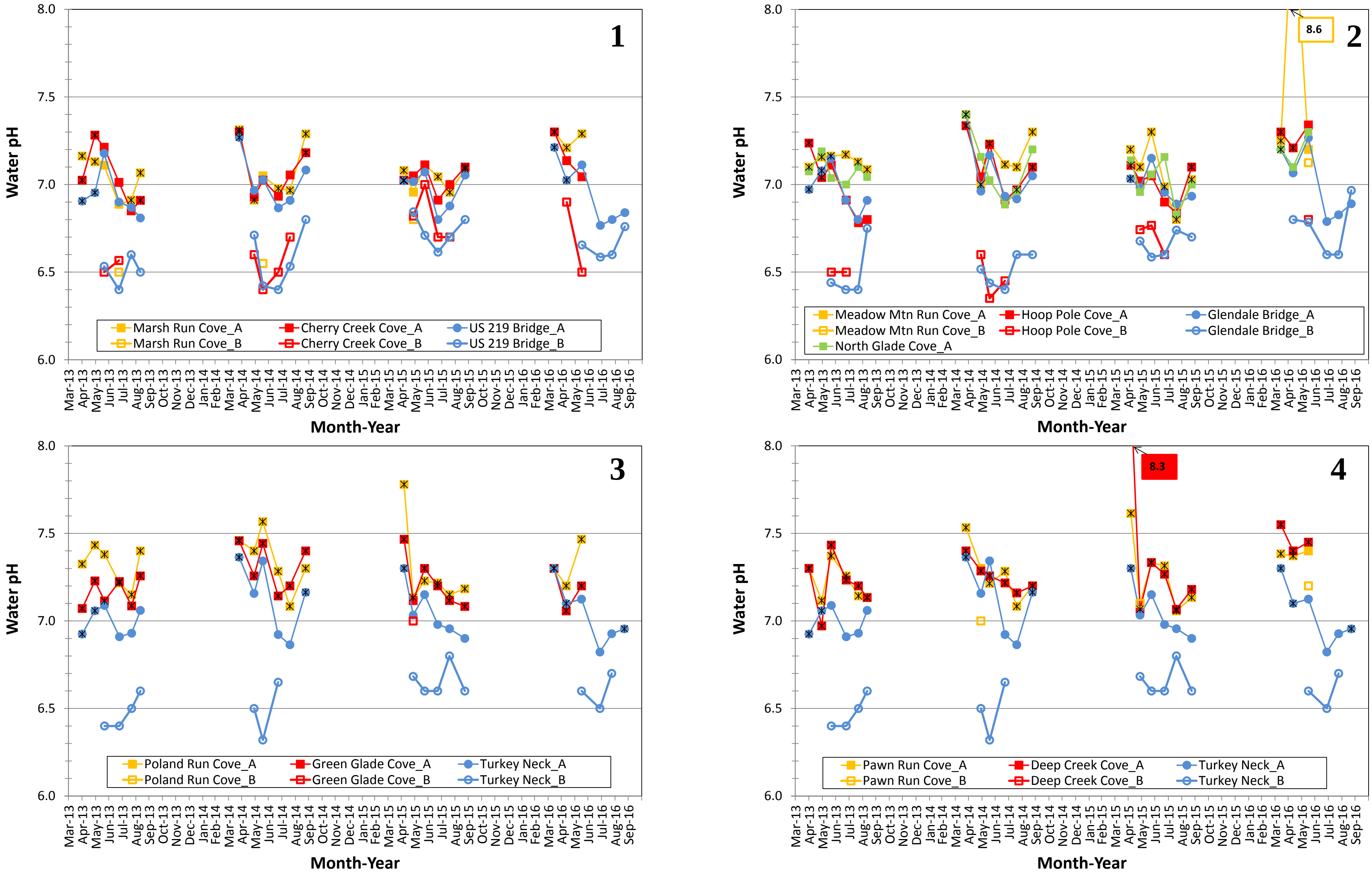


Figure 17. Water pH by region, 2013-2016.
Each numbered graph (in upper right hand corner of panel) corresponds to a numbered circled region on the map in Figure 7 to compare the water pH levels in the coves with the nearest lake station. Measurements are means for layer Above (_A, filled markers) and Below (_B, open markers) the upper thermocline depth from April to September for each year. Values for dates when there was no thermocline are marked with a *. Values that exceed the scale of the y-axis are noted in the color coded box on the graph. Cove station monitoring was ended in July 2016.

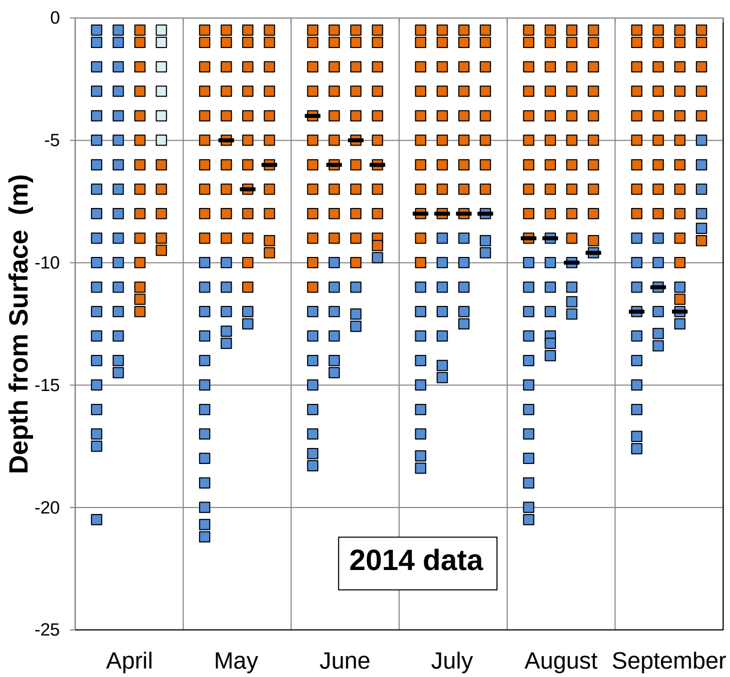
Conductivity

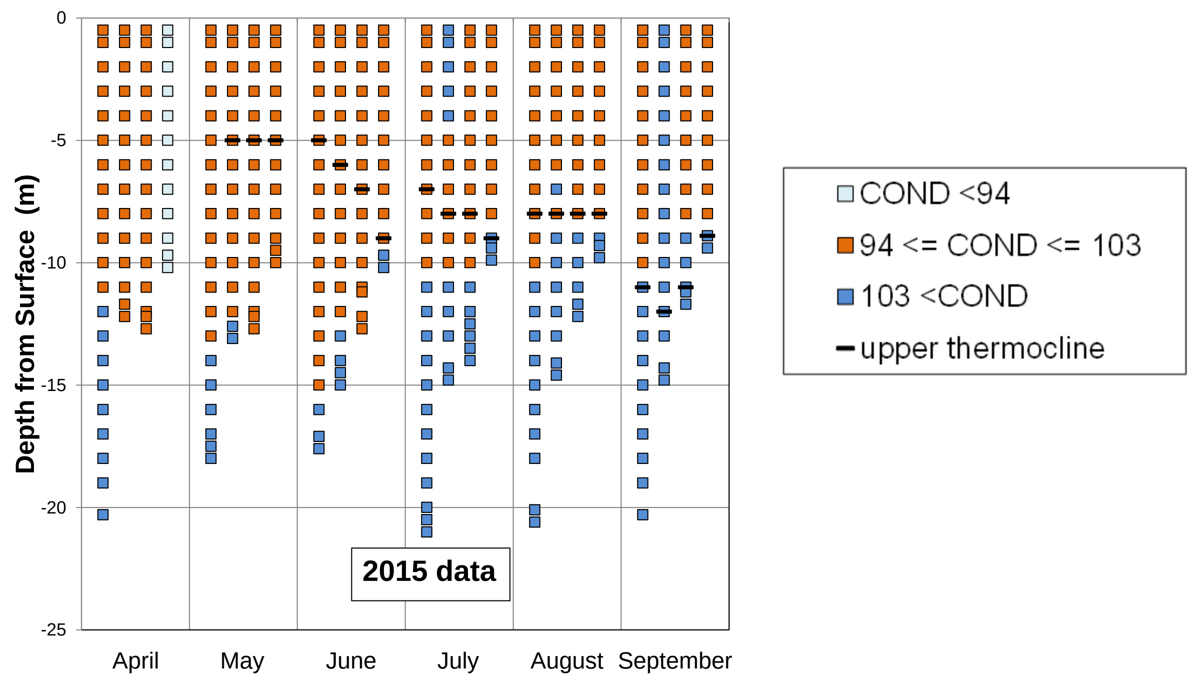
Conductivity measures the ability of water to conduct an electric current. Conductivity in water is affected by the presence of inorganic dissolved solids (for example, chloride, nitrate, phosphate, sodium, magnesium, calcium, iron, and aluminum).[2] Conductivity is affected primarily by the geology of the area through which the water flows. Conductivity is also affected by temperature: the warmer the water, the higher the conductivity. For this reason, conductivity is reported as conductivity at 25 degrees Celsius (77 degrees Fahrenheit).

At the four lake sites, water conductivity was lower at the uppermost station at Turkey Neck and higher at the station at the Dam, especially in April (Figure 18) but there was a lot of variability from year to year (Figures 19 and 20). Conductivity was much higher in the waters below the thermocline in the summer at all of the lake stations and generally continued to increase from the onset of the thermocline in June through the mixing of the water column again in October. Rainfall and runoff impacts surface waters but not below thermocline waters, and the variations in rainfall between months and between years contribute to the patterns in conductivity.

In general, water conductivity in surface waters of coves was also lower in the uppermost regions (Regions 3 and 4) and higher in the lower regions (Regions 1 and 2, Figure 20), likely due to differences in land use and how much freshwater input comes from upstream areas into those coves. Conductivity was highest in Marsh Run Cove in Region 1, which is the area with the greatest urban land use impacts. Conductivity was often lowest at the Cherry Creek Cove station, also in Region 1. Conductivity in the coves was somewhat lower than in surface waters at the nearest lake station, and conductivity in the below thermocline waters of the deeper coves (Cherry Creek Cove, Hoop Pole Cove) was higher than in the surface waters.

[2]The presence of inorganic dissolved solids such as chloride, nitrate, sulfate, and phosphate anions (ions that carry a negative charge) or sodium, magnesium, calcium, iron, and aluminum cations (ions that carry a positive charge). Organic compounds like oil, phenol, alcohol, and sugar do not conduct electrical current very well and therefore have a low conductivity when in water. A failing sewage system would raise the conductivity because of the presence of chloride, phosphate, and nitrate; an oil spill would lower the conductivity. archive.epa.gov/water/archive/web/html/vms59.html





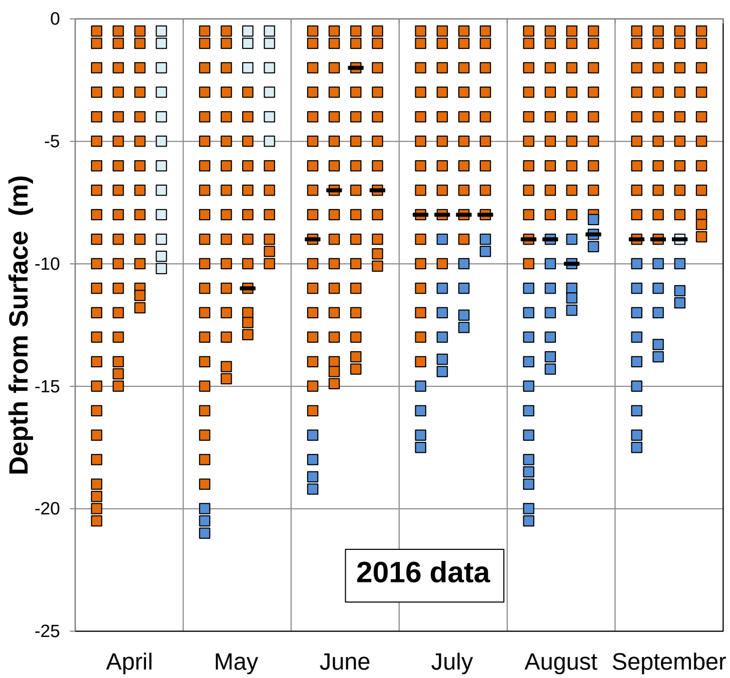


Figure 18. Water conductivity for the four lake stations, 2014-2016. Each month block displays water conductivity in micromhos per centimeter (µmhos/cm, corrected to 25 degrees Celsius) at each depth from the surface to the bottom (moving from top to bottom of the graph). A single column within each month block shows the data from a station, moving from the station at the Dam (far left, deepest station) up to the station at Turkey Neck (far right, shallowest station).

Categories used in the legend represent the 25th percentile (conductivity = 94) and 75th percentile (conductivity = 103) for all conductivity measurements made between 2009-2016 at both lake and cove stations.

Upper thermocline is the depth where density differences first exceed the threshold to limit mixing between the water layer above and below that depth, but is not necessarily the depth of the maximum density difference.

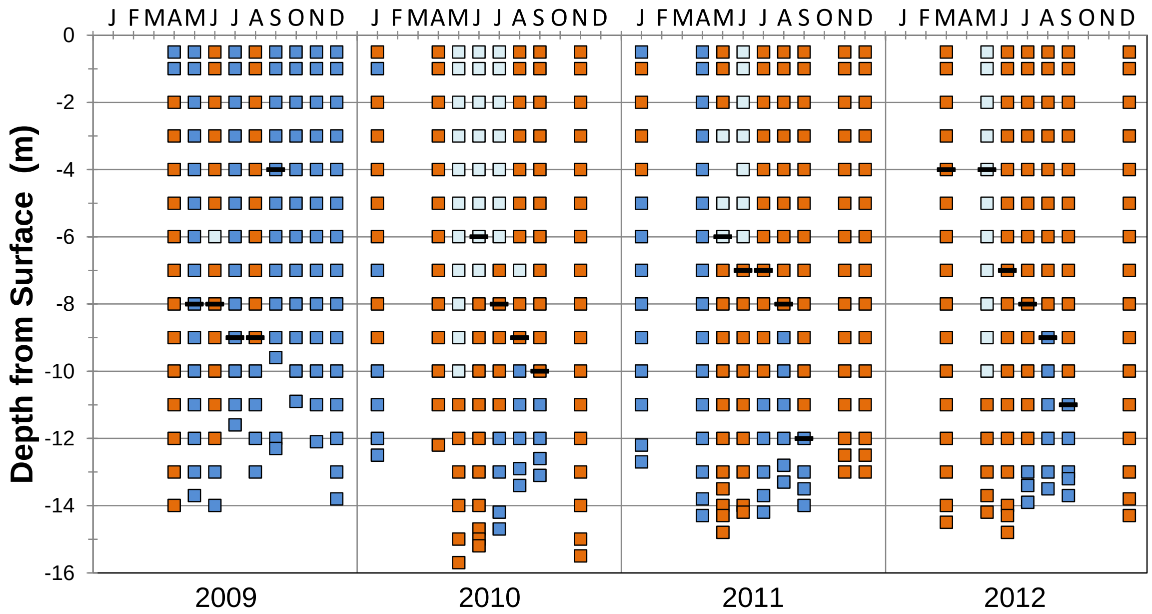
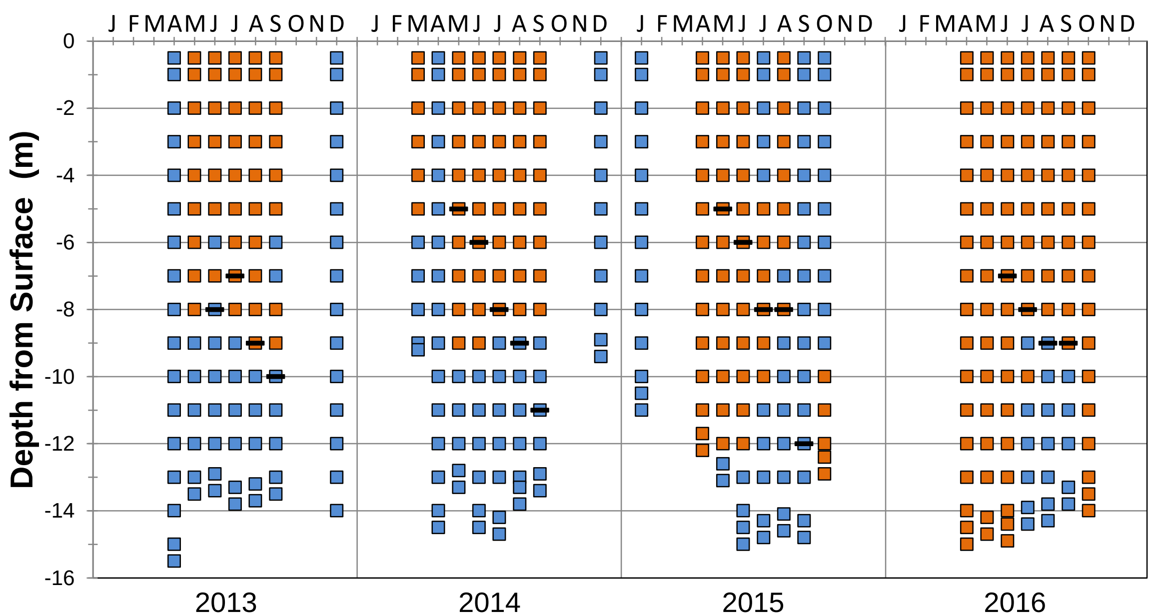
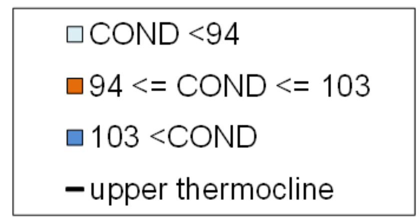


Figure 19. Water conductivity for the Route 219 Bridge lake station, 2009-2016.
Each block displays water conductivity in micromhos per centimeter (µmhos/cm, corrected to 25 degrees Celsius) for a year, each column within a block shows data from a single month at each depth from the surface to the bottom (months labeled at the top of the graph). Color coding is shown in the legend.

Categories used in the legend represent the 25th percentile (conductivity = 94) and 75th percentile (conductivity = 103) for all conductivity measurements made between 2009-2016 at both lake and cove stations.

Upper thermocline is the depth where density differences first exceed the threshold to limit mixing between the water layer above and below that depth, but is not necessarily the depth of the maximum





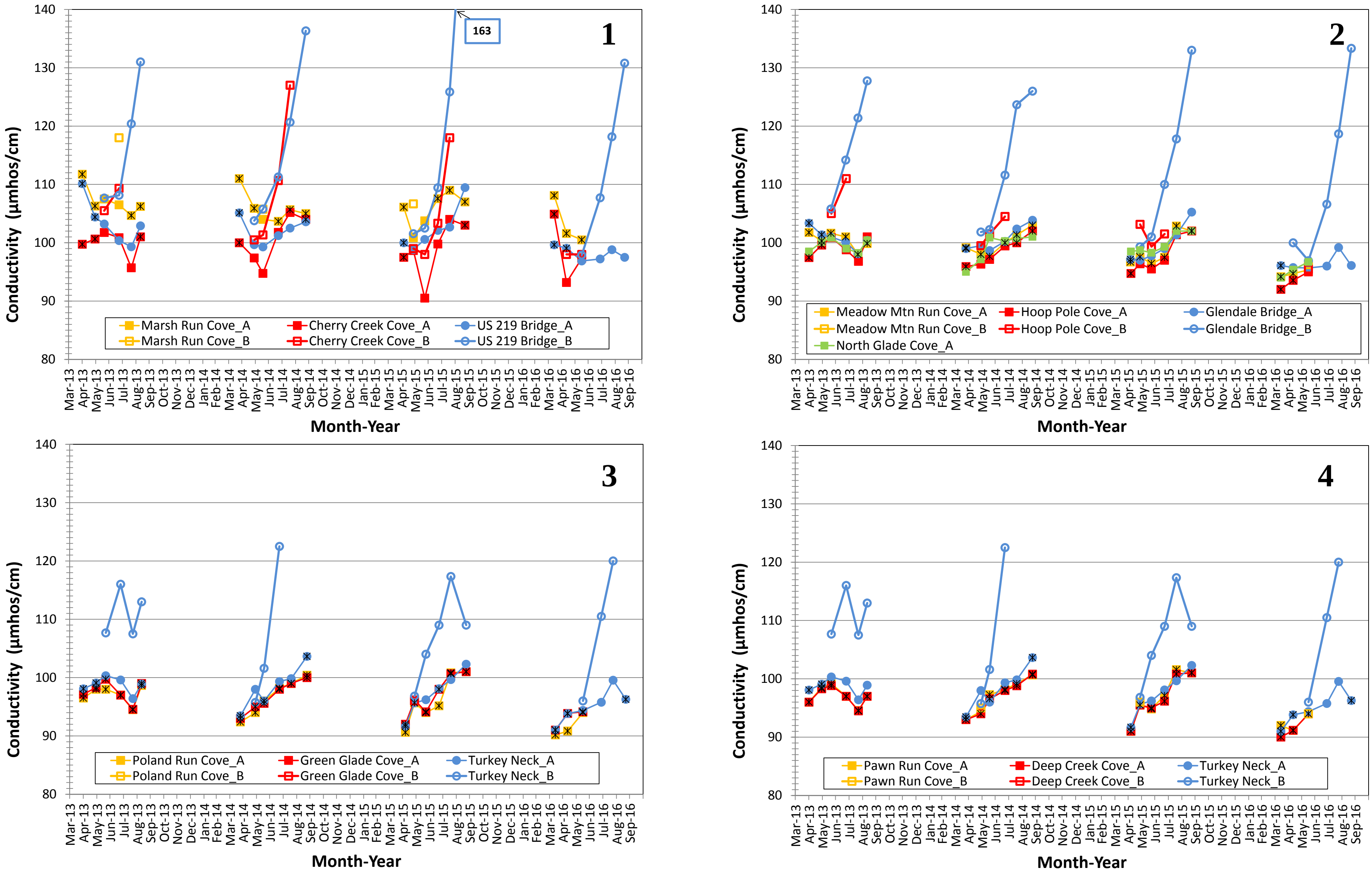


Figure 20. Water conductivity by region, 2013-2016.

Each numbered graph (in upper right hand corner of panel) corresponds to a numbered circled region on the map in Figure 7 to compare the water conductivity micromhos per centimeter (µmhos/cm) in the coves with the nearest lake station. Measurements are means for layer Above (_A, filled markers) and Below (_B, open markers) the upper thermocline depth from April to September for each year. Values for dates when there was no thermocline are marked with a *. Values that exceed the scale of the y-axis are noted in the color coded box on the graph. Cove station monitoring was ended in July 2016.

Trophic state: algal levels, nutrient levels and water clarity

Trophic state is defined as the total weight of living biological material (biomass) in a waterbody, often with specific reference to algal biomass. Trophic state changes (either an increase or decrease in algal biomass) in response to factors such as nutrient additions, season, grazing, mixing depth, etc. As a result, trophic state does not define a static type of lake, but a status within a continuum. A lake defined as 'eutrophic' has attributes of production that remain constant no matter what the use of the water or where the lake is located.

A trophic state index is used to categorize the trophic state of a lake using measurements of the algal biomass (Carlson, 1977). Related trophic state index levels are also defined for total phosphorus concentrations and water clarity measured by Secchi disc depth (Carlson 1977, Carlson and Simpson 1996).[3] Depending on the biological and physical dynamics in a lake, the trophic state category determined based on one measure may be different from the trophic state category determined based on a different measure (for example, the trophic state index for chlorophyll may be different than the trophic state index for total phosphorus). For this report, the trophic state index for chlorophyll is used to define the trophic state of Deep Creek Lake and is determined from the summer (May-September) mean chlorophyll *a* concentration at each station for each year. The other trophic state index equations are used to define the thresholds shown in Table 4 and used for comparing the water quality data at both lake and cove stations.

Five trophic states[4] are defined for Deep Creek Lake based on the measurements made from 2009-2016 and have different resulting habitat characteristics in the lake:

Low Oligotrophic: Clear water, oxygen throughout the year in the hypolimnion. Water may be suitable for an unfiltered water supply.

High Oligotrophic: Hypolimnia of shallower lakes may become anoxic.

Mesotrophic: Water moderately clear; increasing probability of hypolimnetic anoxia during summer. Iron, manganese, taste, and odor problems worsen.

Low Eutrophic: Anoxic hypolimnia, macrophyte problems possible.

High Eutrophic: Blue-green algae dominate, algal scums and macrophyte problems. Episodes of severe taste and odor possible. Nuisance macrophytes, algal scums, and low transparency may discourage swimming and boating.

[3] For a very good explanation of the Trophic State Index please see secchidipin.org/index.php/monitoring-methods/trophic-state-equations/

[4] Based on Carlson and Simpson (1996).

Table 4. Trophic State Index thresholds by component.
Trophic State Index for chlorophyll (TSI_CHLA) is used to define the trophic state of Deep Creek Lake. The other trophic state index equations are used to define the thresholds used for comparing the water quality data at both lake and cove stations. Note that while chlorophyll (CHLA) and total phosphorus (TP) concentrations increase with increasing trophic state index (TSI) value, Secchi depth decreases with increasing TSI value. Chlorophyll concentrations are in micrograms per liter (µg/L). Total phosphorus concentrations are in milligrams per liter (mg/L). Secchi depths are in meters (m).

Trophic State	TSI Value	CHLA (µg/L)	TP (mg/L)	Secchi (m)
Low Oligotrophic	< 30	< 0.94	< 0.0060	> 8.0
High Oligotrophic	30 – 40	> 0.94 - 2.61	> 0.0060 - 0.0120	4.0 - < 8.0
Mesotrophic	40 – 50	> 2.61 - 7.23	> 0.0120 - 0.0240	2.0 - < 4.0
Low Eutrophic	50 – 60	> 7.23 - 20.02	> 0.0240 - 0.0481	1.0 - < 2.0
High Eutrophic	60 – 70	> 20.02 - 55.50	> 0.0481 - 0.0962	0.5 - < 1.0

Table 5. Trophic State of Deep Creek Lake, 2009-2016.
Trophic State Index for chlorophyll (TSI_CHLA) is used to define the trophic state of Deep Creek Lake. Trophic State Index (TSI) range is based on the summer (May-September) mean chlorophyll *a* concentration ([CHLA]) for the surface sample at each of the four lake and nine cove stations to determine the range of conditions for each year. Chlorophyll concentrations are in micrograms per liter (µg/L). Colored text is used to link the table categories to the categories shown in Figure 21 (Mesotrophic is yellow in Figure 21). *Note that trophic state determination for 2016 is only based on lake stations because monitoring was discontinued at the cove stations in July 2016.

year	Trophic State Category	TSI	[CHLA] in mg/L
2009	High Oligotrophic - Mesotrophic	38 - 47	2.13 - 5.18
2010	Mesotrophic	40 - 47	2.68 - 5.49
2011	High Oligotrophic - Low Eutrophic	38 - 53	2.06 - 9.95
2012	High Oligotrophic - Mesotrophic	38 - 49	2.21 - 6.24
2013	Mesotrophic - Low Eutrophic	48 - 59	6.06 - 18.15
2014	Mesotrophic - Low Eutrophic	42 - 52	3.19 - 8.65
2015	Mesotrophic - Low Eutrophic	42 - 55	3.32 - 12.55
2016*	High Oligotrophic - Mesotrophic	39 - 44	2.38 - 3.98

Deep Creek Lake trophic state fluctuated between High oligotrophic and Low eutrophic in the summer season (when the monitoring program has the most data for the most locations, see Table 5 and Figure 21). Trophic state varied from year to year as various factors effect chlorophyll *a* concentrations, and even in years where the lake was classified as oligotrophic, the bottom waters had very low dissolved oxygen levels (hypoxic or anoxic, see Figure 14). Trophic state was highest in 2013, when all but the lake station at the Dam had low eutrophic conditions.

Trophic state conditions also differed spatially. Some of the cove stations (Hoop Pole Cove, North Glade Cove, Poland Run Cove, Green Glade Cove) had higher chlorophyll *a* concentrations (Figure 22), moving them into low eutrophic conditions in some years. Secchi depths had similar patterns to chlorophyll *a* relative to the trophic state thresholds, suggesting that algal levels were a main component that determines water clarity in the summer. Phosphorus was not as closely in agreement with the chlorophyll *a* concentrations, and generally the trophic state index for phosphorus was lower than the tropic state index for chlorophyll, suggesting that phosphorus concentration limits algal growth, especially in the downstream regions (Region 1 and 2). Please see the sections below for more information on differences between months, years and locations.

Chlorophyll a

As described above, the measure of chlorophyll *a* provides a direct measure of algal biomass and is directly related to the trophic state of the lake. In most years, chlorophyll *a* levels were higher in Region 2, though high levels indicating algal blooms occurred in all regions at different times (Figure 22). Chlorophyll *a* levels were higher in the coves than at the closest lake station. In some cases, the chlorophyll *a* concentrations were high enough to indicate high eutrophic conditions (above the red dotted line in the Figure 22) during algal blooms but were not at those levels for more than a single monthly measurement, suggesting that algal blooms were quickly reduced by zooplankton grazing or nutrient limitation and did not persist for an entire summer. Algal levels in 2013 were much higher than other years throughout the lake system, which led to the trophic state classification being at its highest within the period of the monitoring program (2009-2016).

Phosphorus and nitrogen

Phosphorus is needed for plant growth, and can either limit algal growth when concentrations are low or fuel algal blooms when levels are too high. Ranges of total phosphorus concentrations are associated with expected amounts of algal biomass in lakes so can be linked to trophic state as well (see Table 4). Phosphorus originates from a variety of sources, including human and animal wastes, soil erosion, detergents and runoff from land into waterways. Phosphorus concentrations were highest in the coves, especially in North Glade Cove, but rarely high enough to be classified as low eutrophic conditions in any area (Figure 23). Phosphorus concentrations were generally lowest in the downstream region (Region 1). Seasonal patterns in total phosphorus were not consistent.

Nitrogen, like phosphorus, is needed for algal growth but can also contribute to excessive algal growth if levels are too high. Nitrogen originates from a variety of sources, including human and animal wastes, deposition from the air, septic systems and runoff from land into waterways. Nitrogen concentrations were highest in the coves, with the exception of a spike throughout the lake stations in June 2016 (Figure 24). Nitrogen concentrations were highest in April and generally decreased throughout the summer as algae used up the available nitrogen in surface waters.

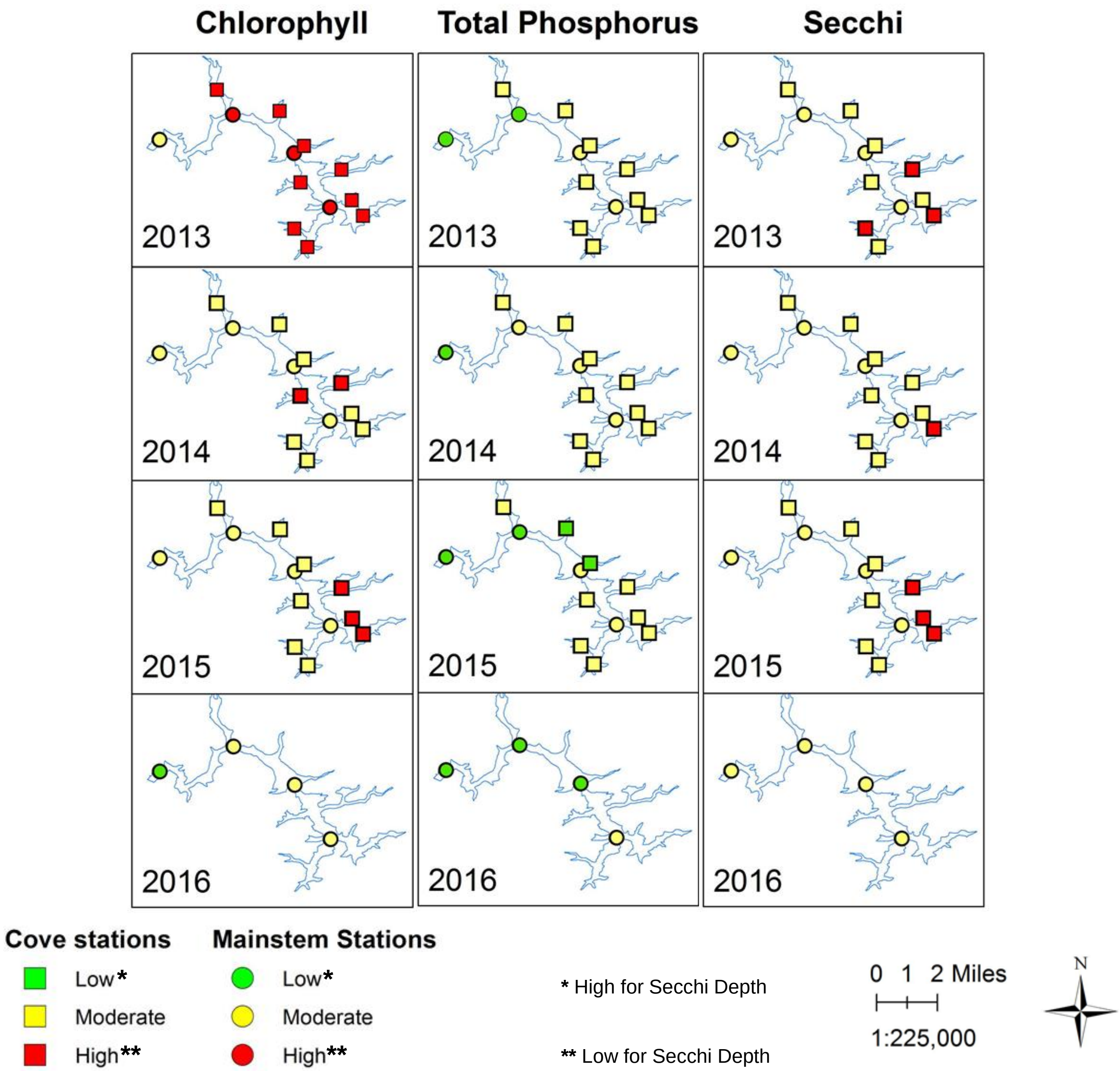


Figure 21. Trophic State measures, Summer mean 2013-2016.
Chlorophyll *a*, total phosphorus and Secchi depth relative to trophic state index thresholds (Table 4) at cove and lake stations. Each value is the summer (May-September) mean by year. See Figure 1 for station names. Each column is the same water quality parameter, labeled at the top. Each row is the same year of data. Green markers indicate Oligotrophic conditions, yellow markers indicate Mesotrophic conditions, and red markers indicate Low Eutrophic conditions. Please note that for Secchi depth, green indicates high conditions (deeper Secchi depths) and red indicates low conditions (shallower Secchi depths). Cove station monitoring was discontinued in June 2016 so data is not included in the 2016 maps for those stations.

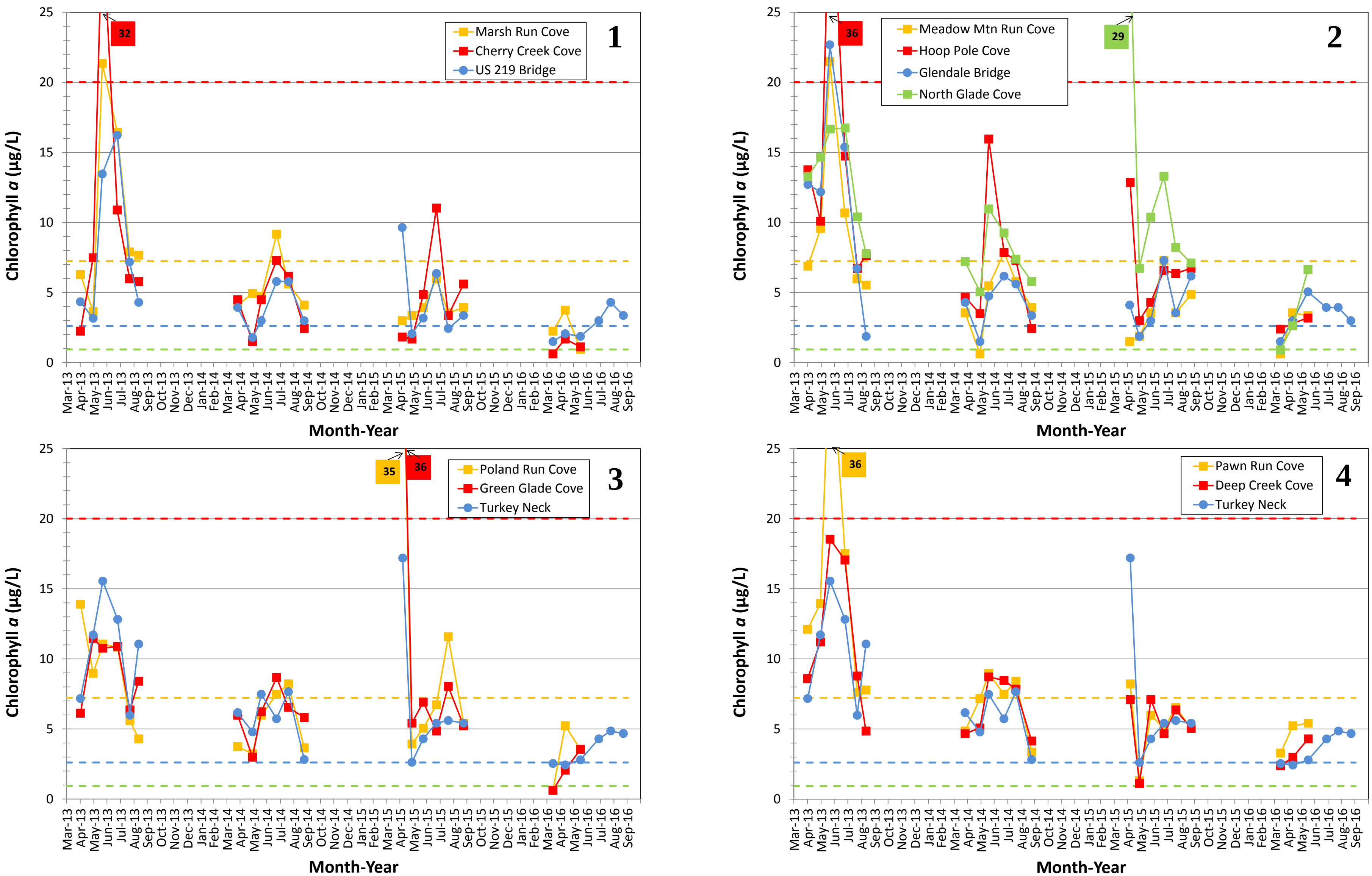


Figure 22. Chlorophyll *a* concentration by region, 2013-2016.

Graphs of stations in each region (numbered to match Figure 7) to compare the chlorophyll *a* concentration (in µg/L) in the coves with the nearest lake station. Measurements for the surface layer sample (1.0 meter depth) from April to September for each year. Values that exceed the scale of the y-axis are noted in the color coded box on the graph. Cove station monitoring was ended in July 2016. Colored reference lines indicate the thresholds between trophic states (Table 4): Green between Low oligotrophic/ High oligotrophic, blue between High oligotrophic/ Mesotrophic, orange between Mesotrophic/ Low eutrophic, and red between Low eutrophic/High eutrophic. April data are shown in the graphs but are not used to determine the summer mean concentrations used to define tropic state in Table 5.

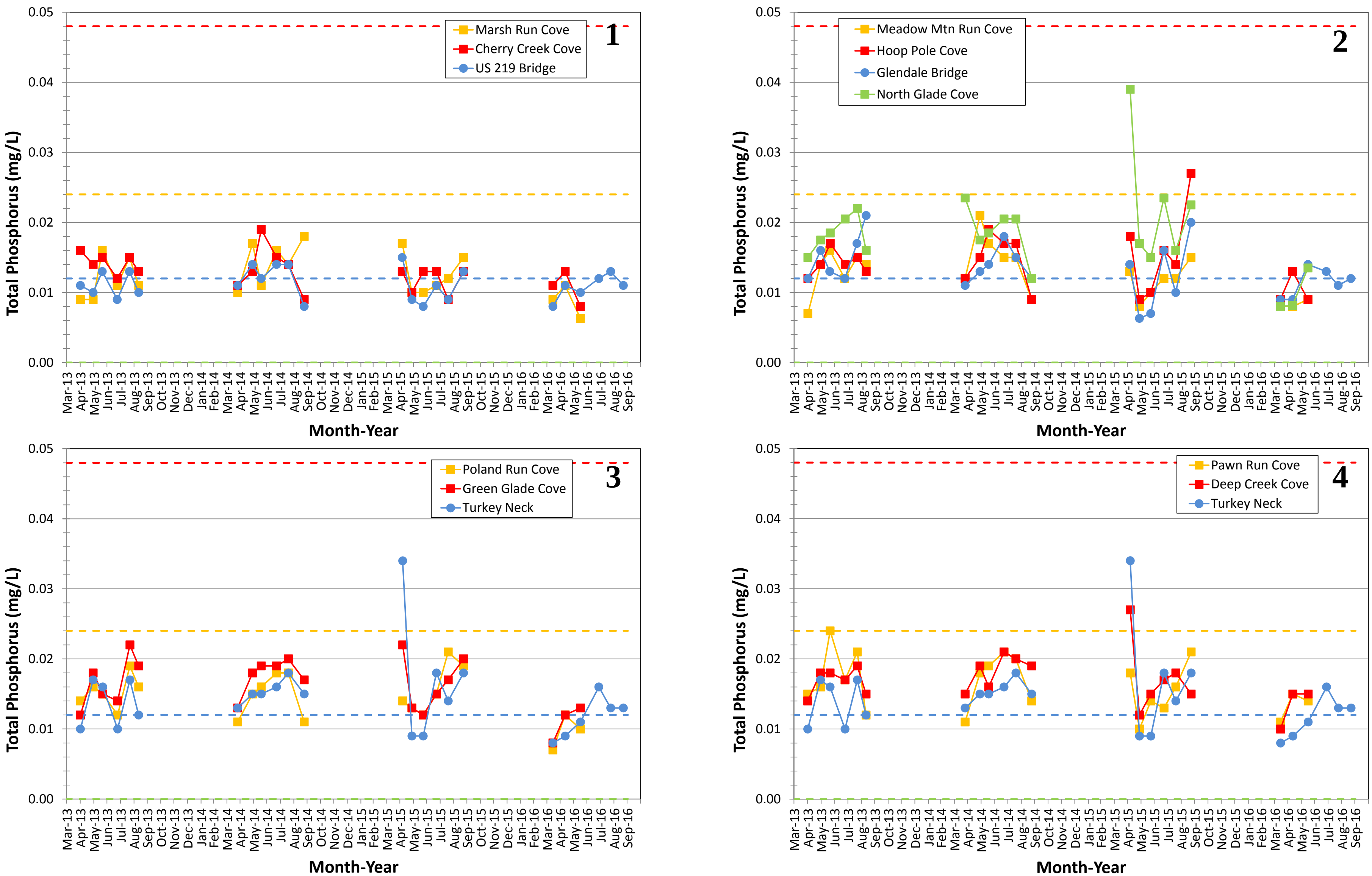


Figure 23. Total phosphorus concentration by region, 2013-2016.
Graphs of stations in each region (numbered to match Figure 7) to compare the total phosphorus concentration (in mg/L) in the coves with the nearest lake station. Measurements for the surface layer sample (1.0 meter depth) from April to September for each year. Values that exceed the scale of the y-axis are noted in the color coded box on the graph. Cove station monitoring was ended in July 2016. Colored reference lines indicate the thresholds between trophic states (Table 4): Green between Low oligotrophic/ High oligotrophic, blue between High oligotrophic/ Mesotrophic, orange between Mesotrophic/ Low eutrophic, and red between Low eutrophic/High eutrophic.

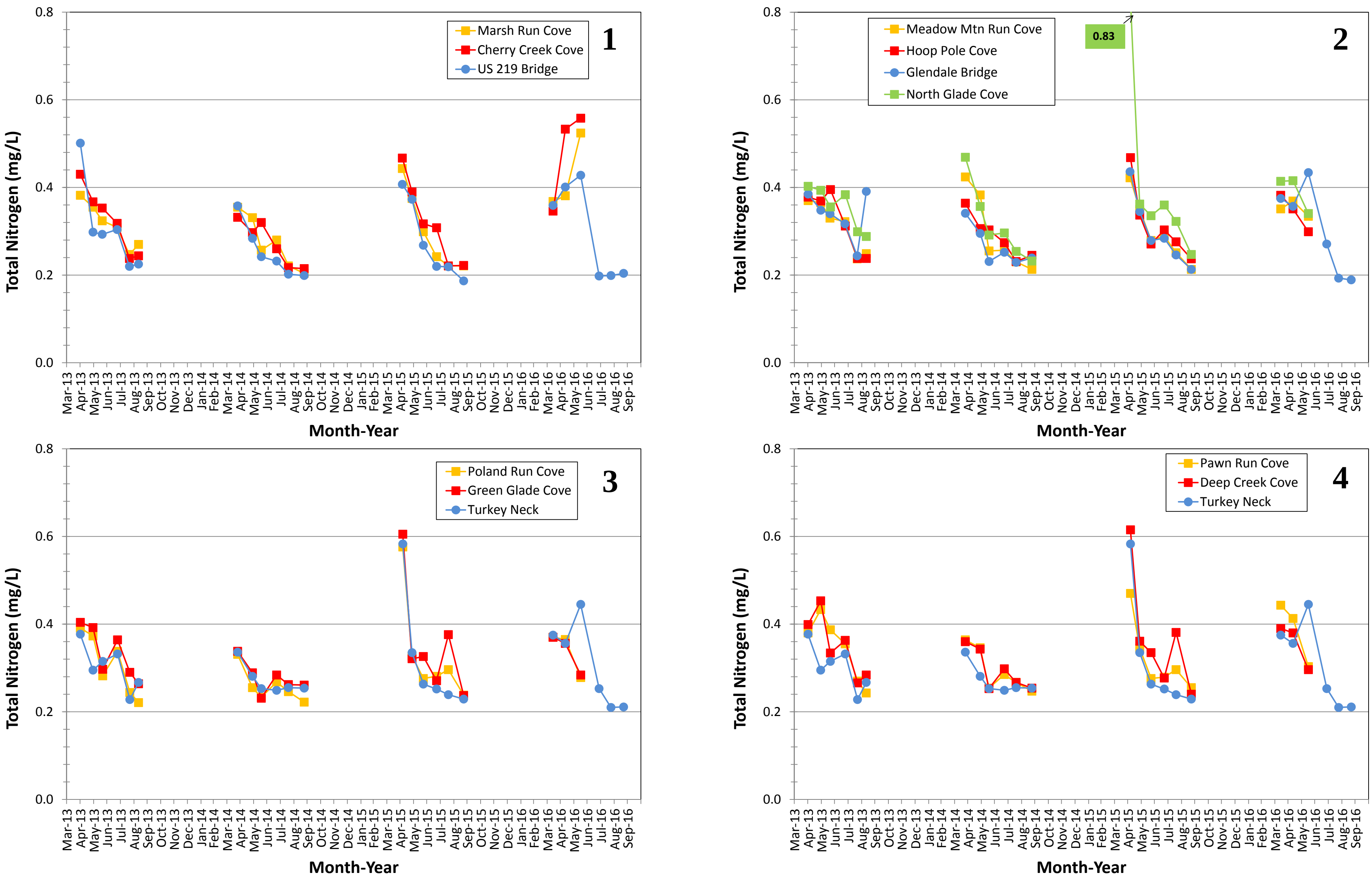


Figure 24. Total nitrogen concentration by region, 2013-2016.
Graphs of stations in each region (numbered to match Figure 7) to compare the total nitrogen concentration (in mg/L) in the coves with the nearest lake station. Measurements for the surface layer sample (1.0 meter depth) from April to September for each year. Values that exceed the scale of the y-axis are noted in the color coded box on the graph. Cove station monitoring was ended in July 2016.

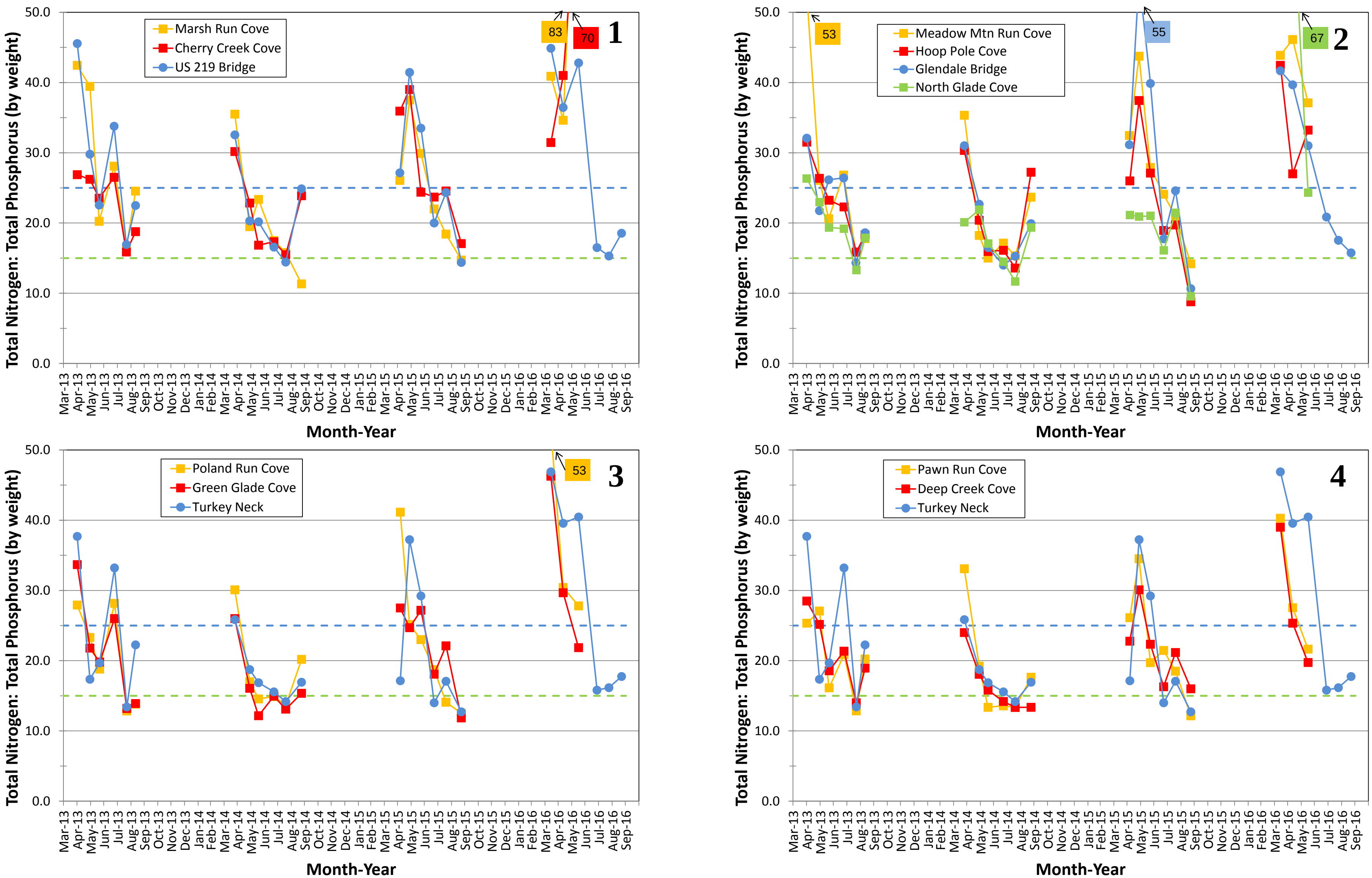


Figure 25. Total nitrogen to total phosphorus ratios by region, 2013-2016.
Graphs of stations in each region (numbered to match Figure 7) to compare the total nitrogen (TN) to total phosphorus (TP) ratio (by weight) in surface waters in the coves with the nearest lake station. Measurements for the surface layer sample (1.0 meter depth) from April to September for each year. Values above 25 (blue dotted line) indicate phosphorus is the limiting nutrient. Values below 15 (green dotted line) indicate nitrogen is the limiting nutrient. Values between 15-25 indicate that both nitrogen and phosphorus limitation may occur. Note that light limitation of algal growth is not assessed using TN to TP ratios and may also be important.
Thresholds based on values in Table 3 of Kolzau et al. (2014) available online at doi.org/10.1371/journal.pone.0096065

The trophic state analysis (see section above) indicates that there may be phosphorus limitation of algal growth in the downstream regions (Regions 1 and 2). Algae need both phosphorus and nitrogen in certain proportions relative to each other in order to grow and bloom. Phosphorus limitation, if it occurs, depends on the ratio of nitrogen to phosphorus. The actual concentrations of phosphorus (Figure 23) were generally not low enough to lead to a limitation of algal growth but because nitrogen levels were so high in the spring and early summer (April-June, see Figure 24), any limitation on algal growth would be due to the amount of phosphorus available. In the late summer (July-September), nitrogen levels were much lower. Based on the ratios of total nitrogen relative to total phosphorus (see Figure 25), algal growth was either limited by both nutrients, by nitrogen alone, or possibly by light availability in the late summer (July-September).[5] Patterns in nutrient limitation were similar in all regions and between the cove and nearest lake station.

The presence and impact of underwater grasses (also called submerged aquatic vegetation, or SAV) is also important in determining nutrient dynamics in Deep Creek Lake. Please see the separate annual report for the status of the underwater grasses from the Department of Natural Resources monitoring program.

Water clarity

Water clarity is often measured using a Secchi disk to determine how far into the water column light is penetrating, and therefore is available to plants for photosynthesis. The deeper the light penetrates (the higher the Secchi disk measurement), the clearer the water. Higher water clarity is considered to be an indication of better water quality.

Water clarity is also measured by collecting samples for laboratory analysis of turbidity. Turbidity measures how much the material suspended in water, which can include algae, microbes, plankton, soil particles and other substances. Turbidity can affect the color of the water.[6] As discussed in previous sections, chlorophyll *a* is measured to determine the amount of algal biomass. Samples are also collected and analyzed in the laboratory to determine total suspended solids, which contributes to the turbidity and can reduce water clarity.

Secchi depth and turbidity were significantly negatively correlated (as turbidity increases Secchi depth decreases) in each year of the monitoring program at both cove and lake stations (Table 6). Secchi depth and turbidity were also significantly negatively correlated when the stations were grouped by region over all years (Table 7, see Figure 7 for regions).

The results from the trophic state analysis (see section above) suggest that algal levels were likely a main source of light attenuation (and therefore lower water clarity) in Deep Creek Lake in most years. Chlorophyll *a* concentration was significantly negatively correlated with Secchi depth (as chlorophyll *a* concentration increased, Secchi depth decreased) in all years at the cove

[5] Thresholds based on values in Table 3 of Kolzau et al. (2014) available online at doi.org/10.1371/journal.pone.0096065

[6] From archive.epa.gov/water/archive/web/html/vms55.html

stations, and significantly positively correlated with turbidity (as chlorophyll *a* concentration increased, turbidity increased) in most years. Chlorophyll *a* was correlated with Secchi depth or turbidity at the lake stations in most years, and in the years when there was a correlation it was a very strong relationship. The relationship between chlorophyll *a* and Secchi depth was significant when the stations were grouped by region but were not as well correlated. All regions had similar results for the relationship of chlorophyll *a* to Secchi depth, both for cove and for lake stations. This relationship works from both directions- algal cells need enough light to grow so are dependent on enough water clarity, but as they bloom they can also lead to lower water clarity.

The relationship between Secchi depth and total suspended solids was significant in some years at cove stations, indicating that sediment particles also contribute to reduced water clarity at cove stations. Secchi depth was less related to total suspended solids at the lake stations. Turbidity and total suspended solids were significantly correlated in all years at the cove stations. At the lake stations, turbidity and total suspended solids were only correlated in three of the eight years of monitoring.

Secchi depths were lower (more shallow, indicating less water clarity) in the cove stations compared to the nearest lake station in most cases (Figure 26). Seasonally, Secchi depths continued to get worse throughout the summer, though improved substantially in some cases between months but quickly returned to shallower readings (see May 2016). Secchi depths were lower in North Glade Cove (Region 2) and the upstream coves (Regions 3 and 4). Turbidity increased throughout the summer in most cases and was higher in the coves than the nearest lake station (Figure 27). Total suspended solids levels were less consistent and had more variation between months and years and on some occasions were higher at the lake stations than in the coves (Figure 28).

Table 6. Correlation analysis results of water clarity parameters by year.
Secchi depth is compared to turbidity (TURB), chlorophyll *a* concentration (CHLA) and total suspended solids concentrations (TSS) for April-September data by year (rows) and by station type: cove and lake (columns). Values in the table are Pearson Correlation coefficients; bold correlations are greater than 0.5. Typeface indicates the direction of the correlations: blue for positive, black for negative. Significance of the correlation is indicated by the asterisks: *** p<= 0.001, ** 0.001 < p <= 0.01, * 0.01 < p <0.05. Blank (white) cells indicate there was not a significant correlation. Grey cells indicate duplicate correlation not included in table, or missing data (for cove 2016).

		COVE STATIONS			LAKE STATIONS		
year	Variable	TURB	CHLA	TSS	TURB	CHLA	TSS
2009	Secchi	**-0.534** ***	-0.319 *	-0.349 *	**-0.733** ***	**-0.589** *	
	TURB			0.467 ***			**0.561** **
	CHLA						
2010	Secchi	**-0.730** ***	-0.414 **		**-0.714** ***		
	TURB			0.299 *			
	CHLA						
2011	Secchi	**-0.501** ***	**-0.627** ***		**-0.634** ***		
	TURB		0.307 *	0.406 **		0.491 *	
	CHLA						
2012	Secchi	-0.440 **	-0.407 **	**-0.531** ***	**-0.707** ***	**-0.612** **	
	TURB		**0.544** ***	0.449 **			
	CHLA			0.350 *			
2013	Secchi	**-0.641** ***	-0.402 **	-0.447 ***	**-0.845** ***	**-0.607** **	
	TURB		0.275 *	0.359 **		**0.623** **	
	CHLA			0.396 **			
2014	Secchi	**-0.672** ***	**-0.652** ***	**-0.704** ***	-0.405 *	**-0.710** ***	
	TURB		0.392 **	**0.592** ***		0.413 *	**0.716** ***
	CHLA			**0.613** ***			
2015	Secchi	**-0.704** ***	-0.293 *	**-0.515** ***	**-0.570** **		
	TURB		0.307 *	**0.734** ***			0.470 *
	CHLA						
2016	Secchi				**-0.723** ***	**-0.693** ***	
	TURB					**0.739** ***	
	CHLA						

Table 7. Correlation analysis results of water clarity parameters by region.
Secchi depth is compared to turbidity (TURB), chlorophyll *a* concentration (CHLA) and total suspended solids concentrations (TSS) for April-September data by year (rows) and by station type: cove and lake (columns). Values in the table are Pearson Correlation coefficients; bold correlations are greater than 0.5. Typeface indicates the direction of the correlations: blue for positive, black for negative. Significance of the correlation is indicated by the asterisks: *** p<= 0.001, ** 0.001 < p <= 0.01, * 0.01 < p <0.05. Blank (white) cells indicate there was not a significant correlation. Grey cells indicate duplicate correlation not included in table, or no data (there are no lake stations included in Region 4 because Turkey Neck station is included in Region 3). See Figure 7 for stations within regions. Region 0 is the lake station at the Dam.

		COVE STATIONS			LAKE STATIONS		
region	Variable	TURB	CHLA	TSS	TURB	CHLA	TSS
0	Secchi				**-0.648** ***		
	TURB					0.385 ***	
	CHLA						
1	Secchi	**-0.620** ***	-0.428 ***	-0.307 **	-0.484 ***	-0.385 **	
	TURB		0.292 **	0.234 *			
	CHLA			0.274 *			
2	Secchi	**-0.674** ***	-0.466 ***	-0.298 ***	**-0.540** ***	-0.497 ***	
	TURB		0.445 ***	0.351 ***			0.438 **
	CHLA			0.226 **			
3	Secchi	**-0.537** ***	-0.335 **	-0.244 *	**-0.588** ***	-0.343 **	
	TURB						
	CHLA						
4	Secchi	-0.360 ***	-0.378 ***	-0.308 **			
	TURB			0.266 *			
	CHLA						

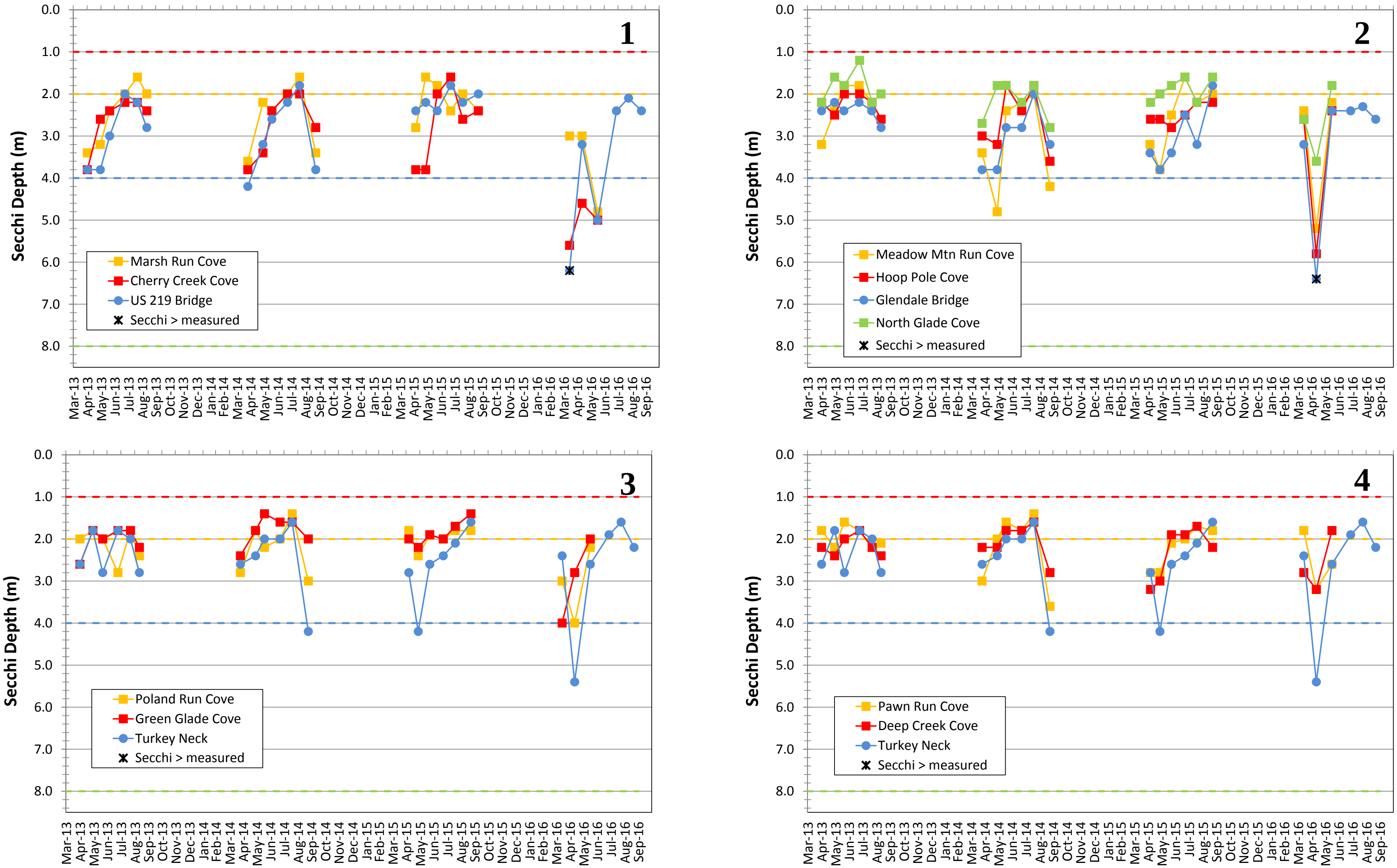


Figure 26. Water clarity (measured by Secchi disk depth) by region, 2013-2016.
Graphs of stations in each region (numbered to match Figure 7) to compare the water clarity measure by Secchi depth in meters (m) in the coves with the nearest lake station. Measurements are from April to September for each year. Note that depth is shown from the water surface and Secchi depth increases from top to bottom of the graph. Values that exceed measurement recorded are marked with an asterisk (*). Cove station monitoring was ended in July 2016. Colored reference lines indicate the thresholds between trophic states (Table 4): Green between Low oligotrophic/ High oligotrophic, blue between High oligotrophic/ Mesotrophic, orange between Mesotrophic/ Low eutrophic, and red between Low eutrophic/High eutrophic.

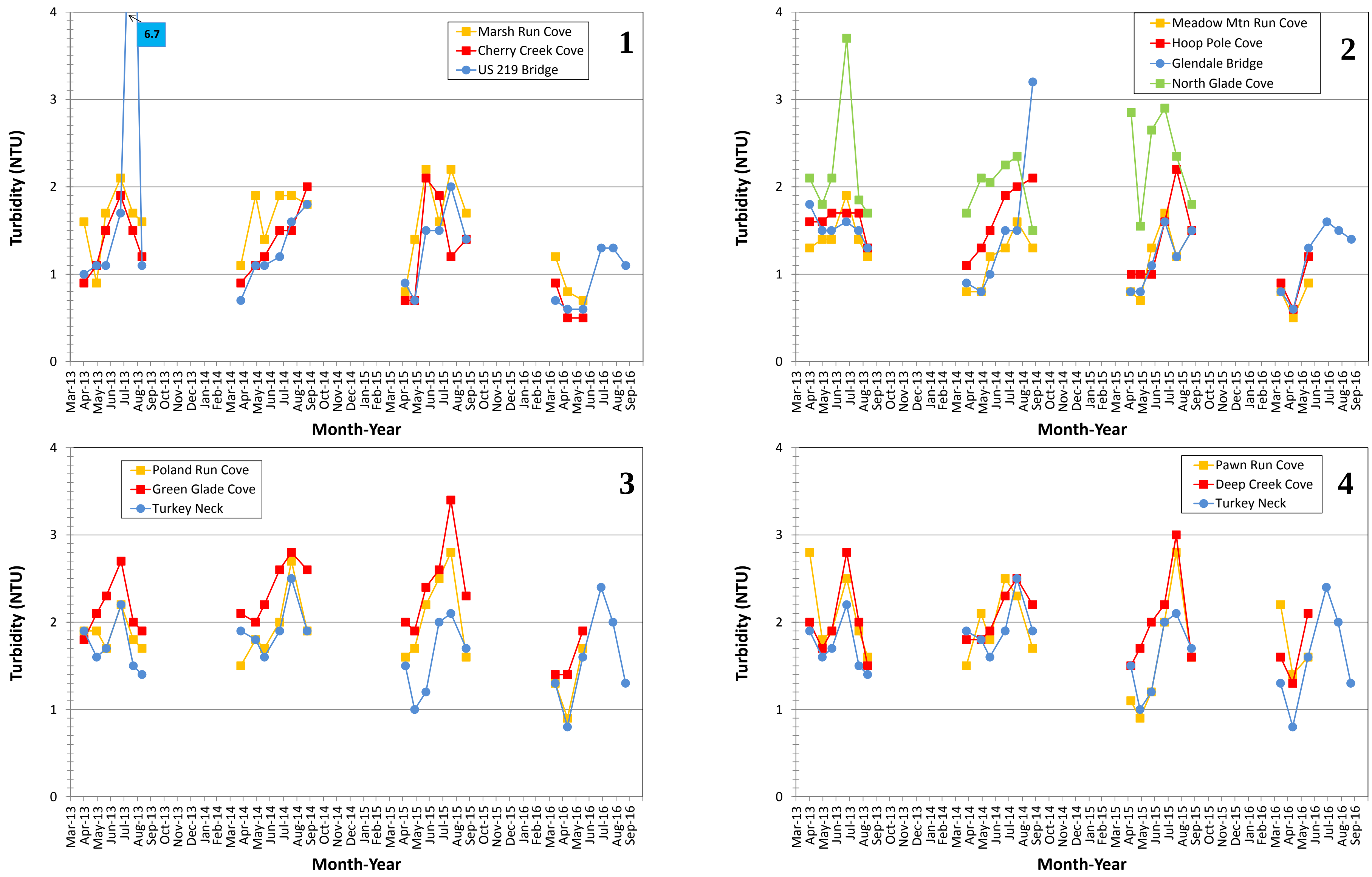


Figure 27. Turbidity by region, 2013-2016.
Graphs of stations in each region (numbered to match Figure 7) to compare turbidity in Nephelometric Turbidity Units (NTU) in the coves with the nearest lake station. Measurements for the surface layer sample (1.0 meter depth) from April to September for each year. Values that exceed the scale of the y-axis are noted in the color coded box on the graph. Cove station monitoring was ended in July 2016.

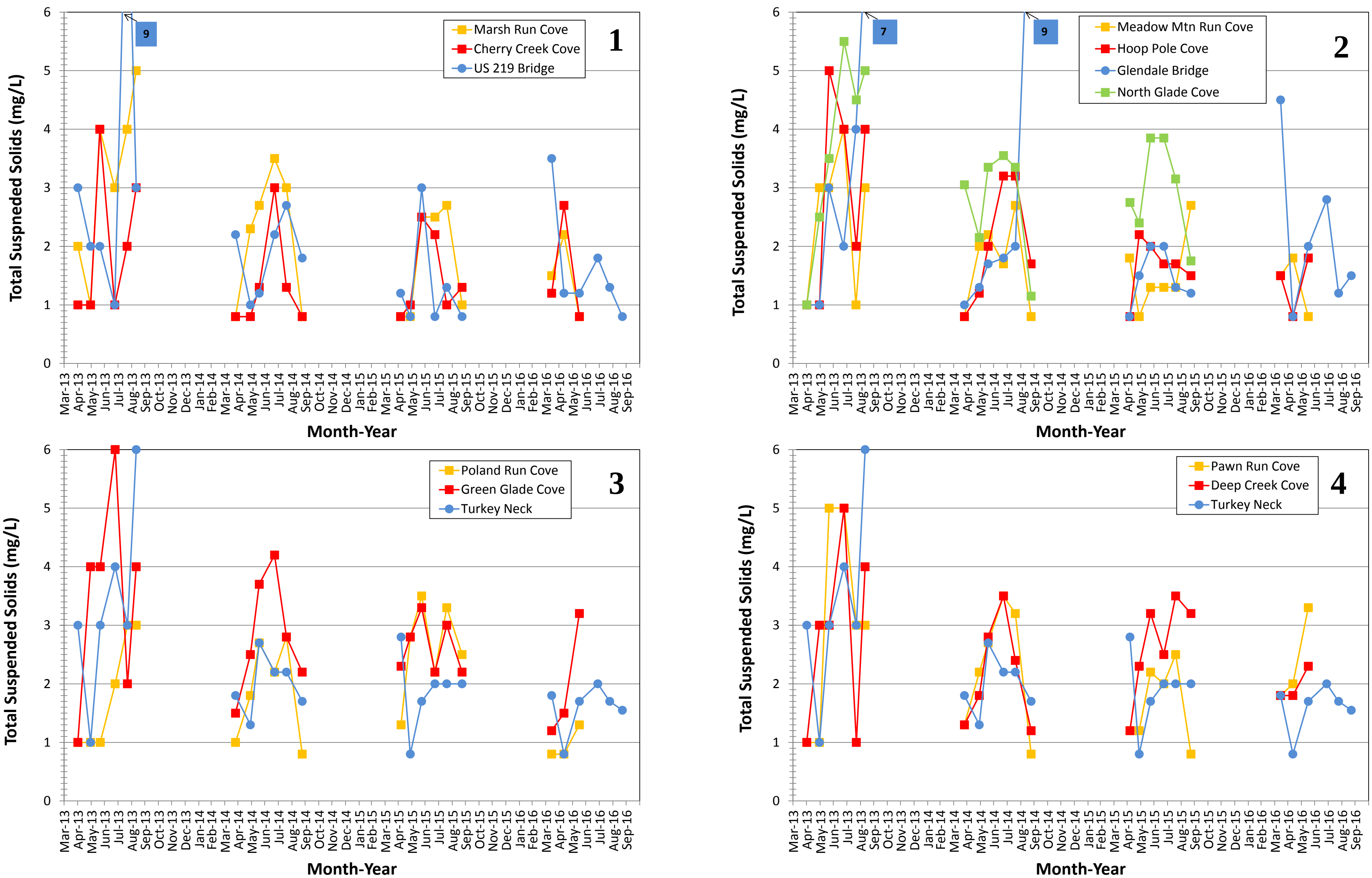


Figure 28. Total suspended solids concentration by region, 2013-2016.

Graphs of stations in each region (numbered to match Figure 7) to compare total suspended solids levels in milligrams per liter (mg/L) in the coves with the nearest lake station. Measurements for the surface layer sample (1.0 meter depth) from April to September for each year. Values that exceed the scale of the y-axis are noted in the color coded box on the graph. Cove station monitoring was ended in July 2016.

Long-term water quality

The Deep Creek Lake monitoring program is designed to provide the data needed to determine current water and habitat quality conditions in the lake mainstem and the tributary coves. Maintaining consistent monitoring at the same stations over time is important to expand the use of the data to also allow managers to evaluate changes over time. In general, statistical testing of trends in water quality data requires consistent monitoring for approximately 10 years. The Deep Creek Lake monitoring program is close to this threshold, with eight years of monitoring from 2009-2016. Graphical analyses of patterns between years are discussed below. Future reports will examine statistical trend testing of changes over time at the four lake stations where monitoring is continuing beyond 2016.

Water quality and habitat conditions

Water quality and habitat conditions were examined using the May-September means for each year. This period was used to correspond to the presence of the seasonal thermocline and to match the period used to determine trophic state for the lake (see section above). Data are shown for both the layer above the thermocline for all stations and for below the seasonal thermocline for the lake stations and for Cherry Creek Cove (Region 1) and Hoop Pole Cove (Region 2). If a seasonal thermocline was not present for the majority of the year then no bottom layer data are shown (see Turkey Neck station in 2009 and several years for the cove stations). Deeper stations have more data points that are used to determine the overall mean for the above thermocline layer. The number of data points also changes as the seasonal thermocline gets deeper throughout the season (see Figure 9).

<u>Precipitation</u>

Changes in some water quality conditions are related to fluctuations in precipitation, so looking at changes in precipitation between years can be helpful for understanding the changes in the water quality. Figure 29 shows the total precipitation by year and for the January-April and the May-September periods. Data were limited to 2011-2016 so that it was from the same weather monitoring location at the Dam. January- April precipitation sets the stage for the conditions in the lake prior to the main period of the water monitoring sampling. May-September total precipitation is useful for comparing to inter-annual changes in water quality parameters that respond more quickly to inputs from the watershed. January-April total precipitation varied from 26-36 percent of the total annual precipitation from 2011-2016. May-September precipitation varied from 38-51 percent of the total annual precipitation. Annual total precipitation was highest in 2011, as was the January-April total precipitation, but not the May-September total. January-April precipitation was also higher in 2015 but the other years were very similar. May-September total precipitation was similar in all years except 2012 when it was lower.

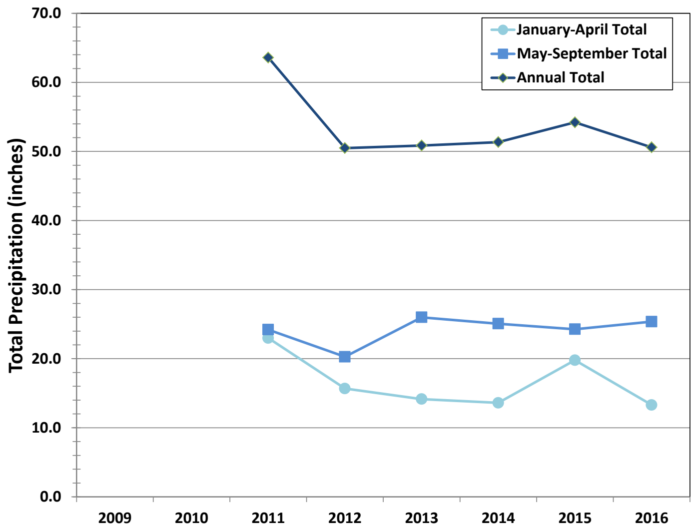


Figure 29. Precipitation for January-April and May-September by year. Annual, January-April and May-September total precipitation by year. Data is from annual reports available at mde.state.md.us/programs/water/water_supply/Pages/DeepCreekLakePeriodicReports.aspx

<u>Water Temperature</u>

Water temperatures above the thermocline were fairly consistent each year, though somewhat elevated in 2012 at all four lake stations (Figure 30). Below thermocline layer water temperatures were move variable and increased moving upstream from the Dam station to Turkey Neck, which was in part due to the greater depth of water below the thermocline at the deepest Dam site compared to the stations moving upstream (see Figure 9). Seasonal average water temperatures at the cove stations were slightly warmer than the nearest lake station in all four regions.

<u>Dissolved Oxygen</u>

Dissolved oxygen levels above the thermocline were fairly consistent each year at both the lake and cove stations (Figure 31). Average dissolved oxygen levels below the thermocline varied more from year to year. Dissolved oxygen was at unhealthy levels of less the three milligrams per liter in almost all years at the lake stations, and at very unhealthy levels of less than one milligram per liter in 2013 at the Glendale Bridge and Turkey Neck lake stations.

<u>Water pH</u>

Water pH above the thermocline was higher than below the thermocline in all years, but the difference between the layers was larger in some years (2011-2014, Figure 32). Water pH levels were fairly consistent each year but water pH was lower below the thermocline in those same years (2011-2014). Water pH increased moving upstream from the Dam station to Turkey Neck in the above thermocline layer. The pattern was less consistent in the below thermocline layer and in some years pH was at the low of 6.5 throughout the lake. Water pH in the above thermocline waters was higher in the coves than the nearest lake station, especially at Meadow Mountain Run Cove (Region 2). Below thermocline water pH at Cherry Creek Cove and Hoop Pole Cove was generally similar to the nearest lake station.

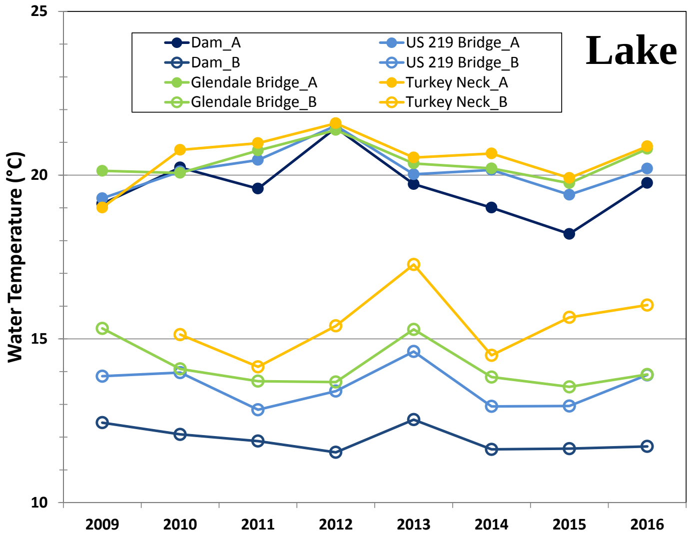
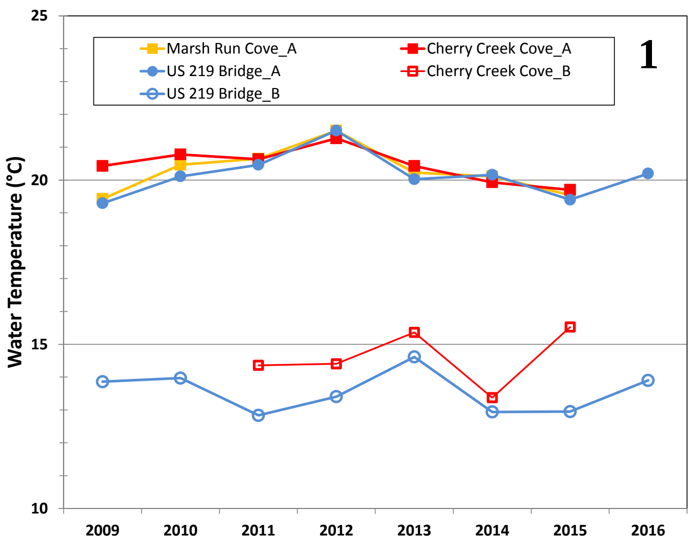
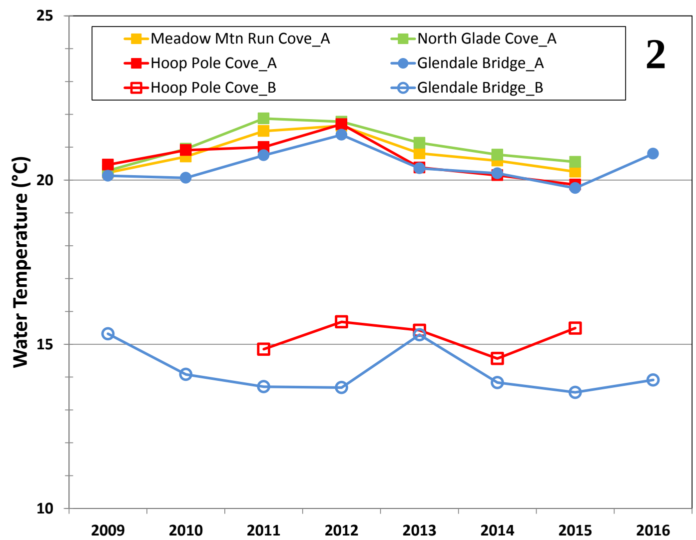
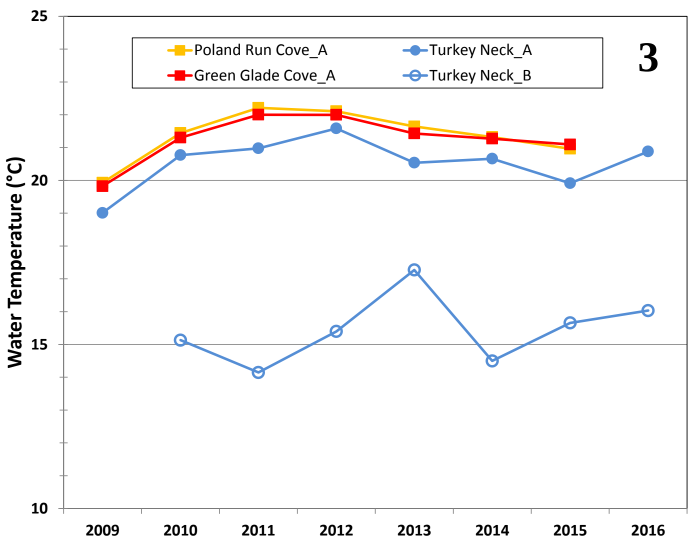
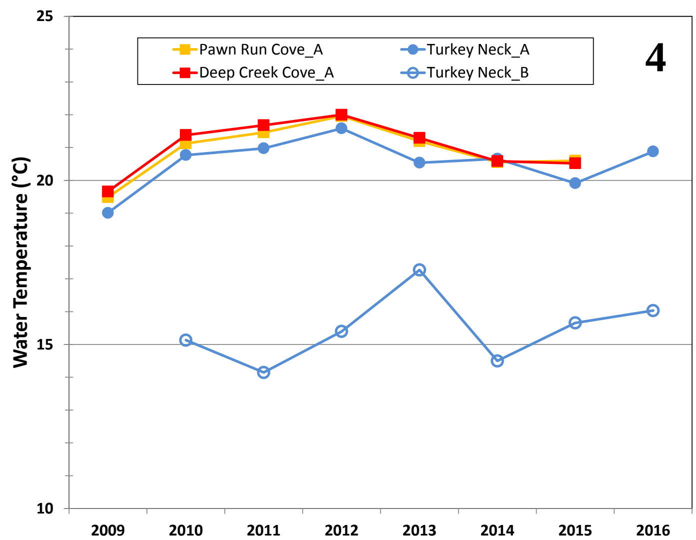


Figure 30. Seasonal average water temperature. Seasonal average water temperatures for May-September. Top left panel is the four lake stations. Each numbered graph in rows two and three (in upper right hand corner of panel) corresponds to a numbered circled region on the map in Figure 7 to compare the water temperature in degrees Celsius (°C) in the coves with the nearest lake station. Measurements are overall means for layer Above (_A, filled markers) and Below (_B, open markers) the upper thermocline depth. Cove station monitoring was ended in July 2016 so is not included in the graphs.









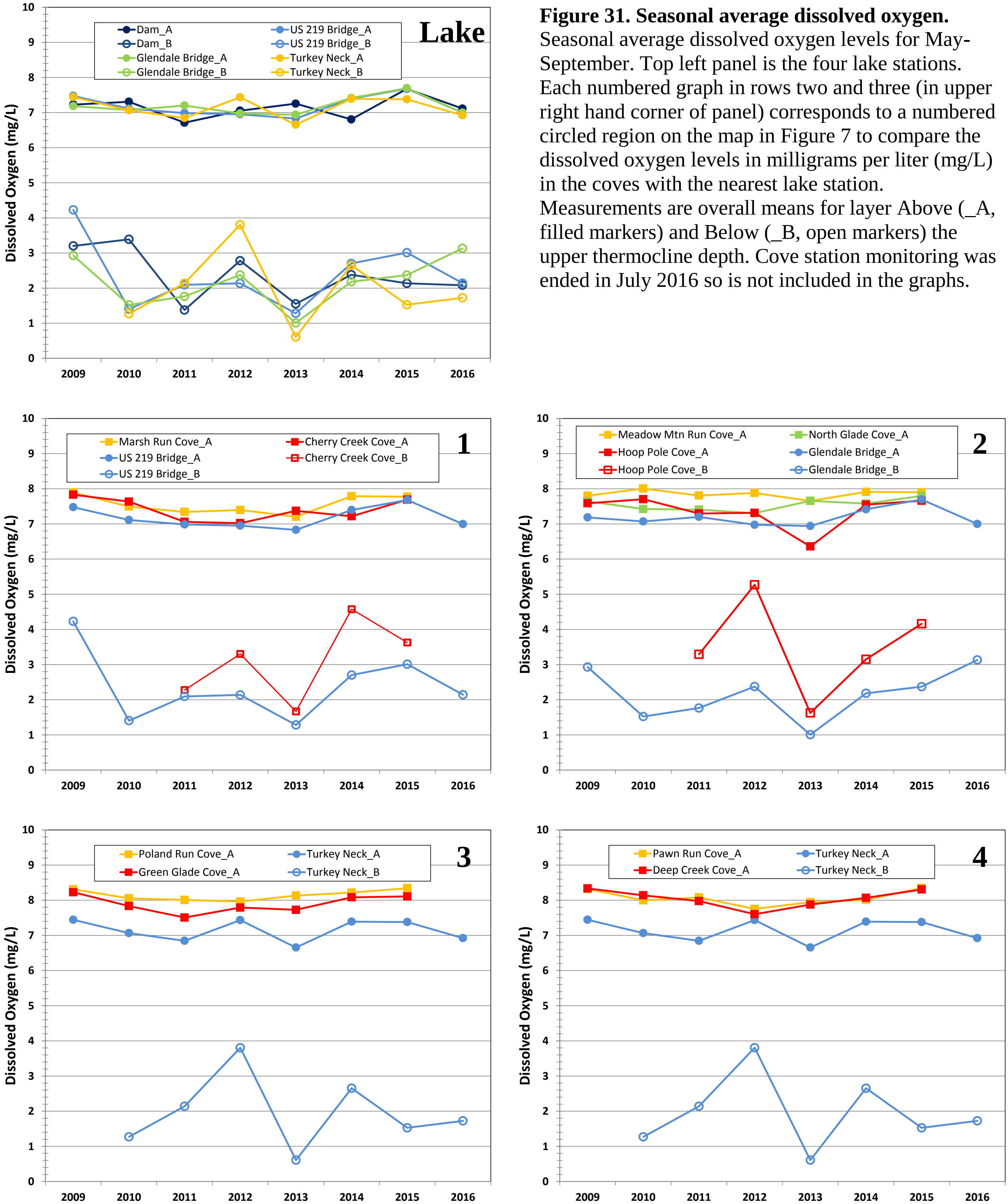


Figure 31. Seasonal average dissolved oxygen. Seasonal average dissolved oxygen levels for May-September. Top left panel is the four lake stations. Each numbered graph in rows two and three (in upper right hand corner of panel) corresponds to a numbered circled region on the map in Figure 7 to compare the dissolved oxygen levels in milligrams per liter (mg/L) in the coves with the nearest lake station. Measurements are overall means for layer Above (_A, filled markers) and Below (_B, open markers) the upper thermocline depth. Cove station monitoring was ended in July 2016 so is not included in the graphs.

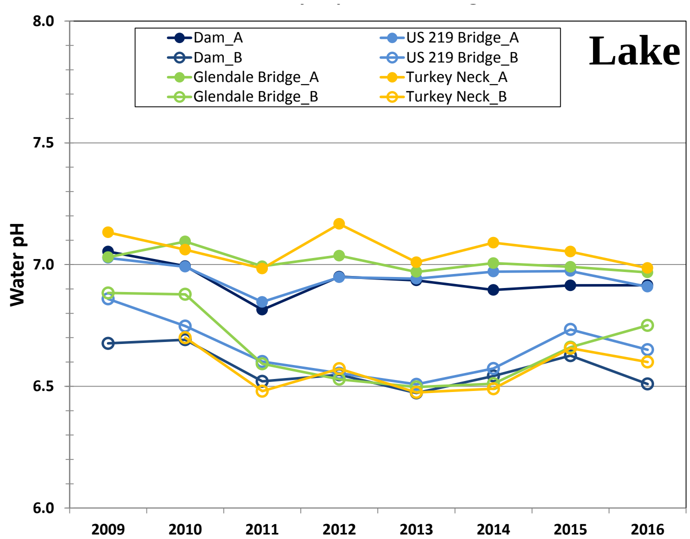
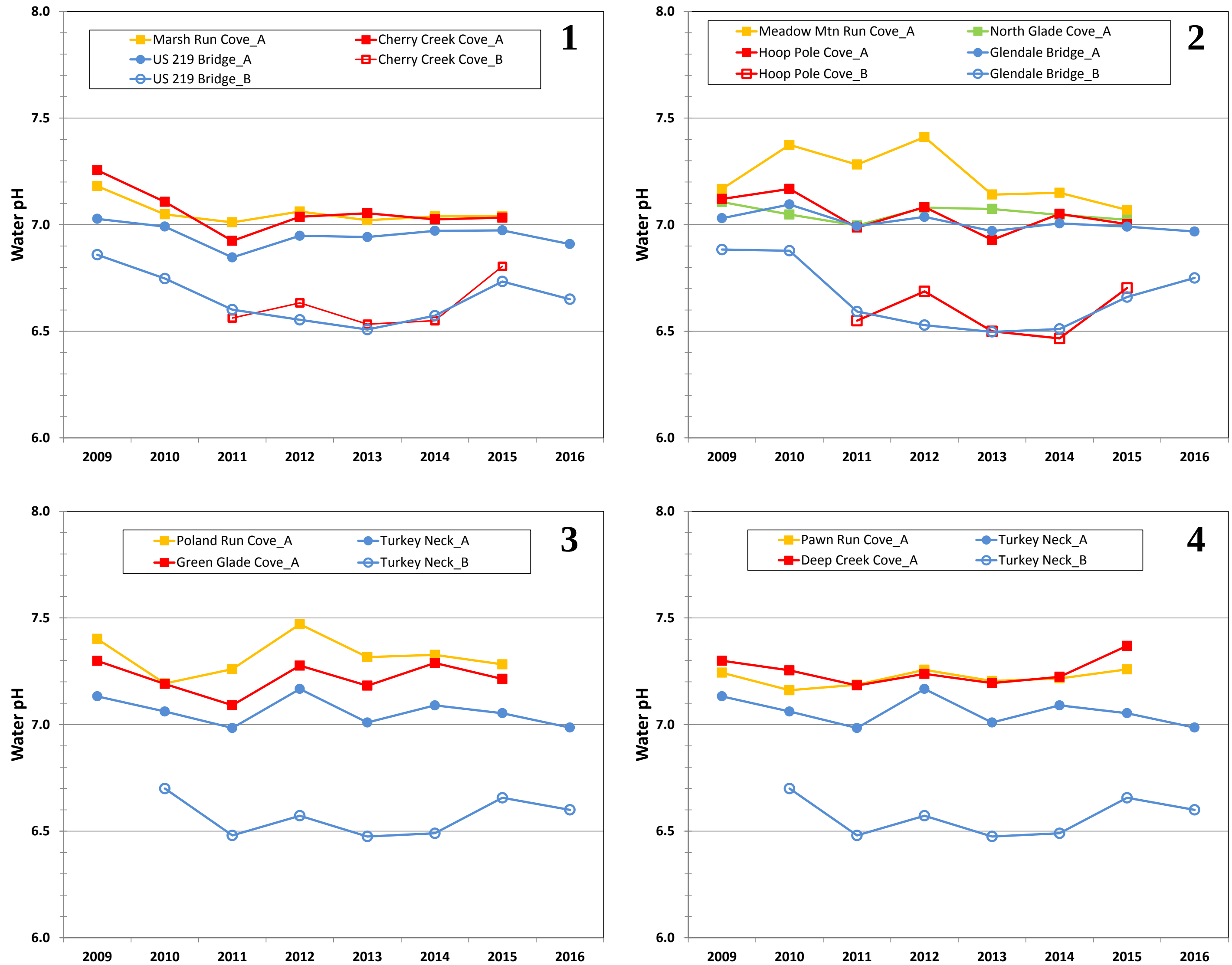


Figure 32. Seasonal average water pH. Seasonal average water pH for May-September. Top left panel is the four lake stations. Each numbered Top left panel is the four lake stations. Each numbered graph in rows two and three (in upper right hand corner of panel) corresponds to a numbered circled region on the map in Figure 7 to compare the water pH in the coves with the nearest lake station. Measurements are overall means for layer Above (_A, filled markers) and Below (_B, open markers) the upper thermocline depth. Cove station monitoring was ended in July 2016 so is not included in the graphs.



Conductivity

Conductivity decreased moving upstream from the Dam station to Turkey Neck (Figure 33). Conductivity below the thermocline was higher than above the thermocline in almost all years at the lake stations. The exception was in 2012 at the Turkey Neck station, when conductivity was the same in both layers. Conductivity in both layers was lower in 2010-2012 than the other years of the monitoring program; total rainfall was higher in 2011 than other years so more freshwater input likely contributed to lower conductivity even though the May-September total rainfall was actually lower in 2011-2012 (Figure 29). Conductivity above the thermocline was lower in the cove stations than at the nearest lake stations with the exception of Marsh Run Cove. Annual patterns were consistent between stations but there was a lot of variation between years. Below thermocline conductivity at Cherry Creek Cove and Hoop Pole Cove was more similar to the surface layer water than to the below thermocline waters of the nearest lake station.

Trophic state: algal levels, nutrient levels and water clarity

Trophic state related parameters were examined using the May-September means for each year. This period was used to correspond to the presence of the seasonal thermocline and because it was the period used to determine trophic state for the lake (see section above). Data for all measurements except Secchi depth are from the surface layer sample collected at one meter depth. Trophic state thresholds are also shown for chlorophyll *a*, total phosphorus and Secchi depth (see Table 4).

Chlorophyll *a*

Chlorophyll levels were highest at all stations in 2013 (Figure 34). Chlorophyll *a* levels generally increased moving upstream from the Dam station to Turkey Neck, though in some years levels were slightly higher at Glendale Bridge than at Turkey Neck. In most years the chlorophyll *a* levels were highest in the coves compared to the nearest lake station, with the exception of Meadow Mountain Run Cove. Patterns were generally consistent between stations but there was a lot of variation between years. Most stations and most years indicate mesotrophic conditions in Deep Creek Lake. Exceptions to this were high oligotrophic conditions in 2011 at the Dam lake station, high oligotrophic conditions in 2012 at the three downstream lake stations, low eutrophic conditions at all stations except the Dam lake station in 2013, and low eutrophic conditions in 2015 at North Glade Cove, Poland Run Cove and Green Glade Cove.

Phosphorus

Phosphorus levels generally increased moving upstream from the Dam to Turkey Neck, but the reverse pattern was seen in 2010 when levels at the Dam and US 219 Bridge station were unusually high (Figure 35). Phosphorus levels were unusually high in 2010 at Poland Run Cove and Pawn Run Cove as well. The highest phosphorus levels were in North Glade Cove, and levels were much higher at this station in 2011. Phosphorus levels were not always higher in the coves compared to the nearest lake station, and were lower in 2012 than in other years at all stations (note that 2012 had the lowest May-September total precipitation as well).

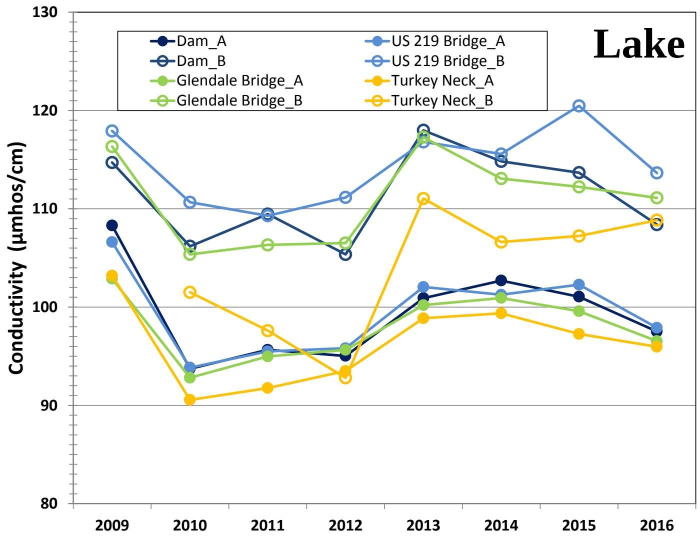
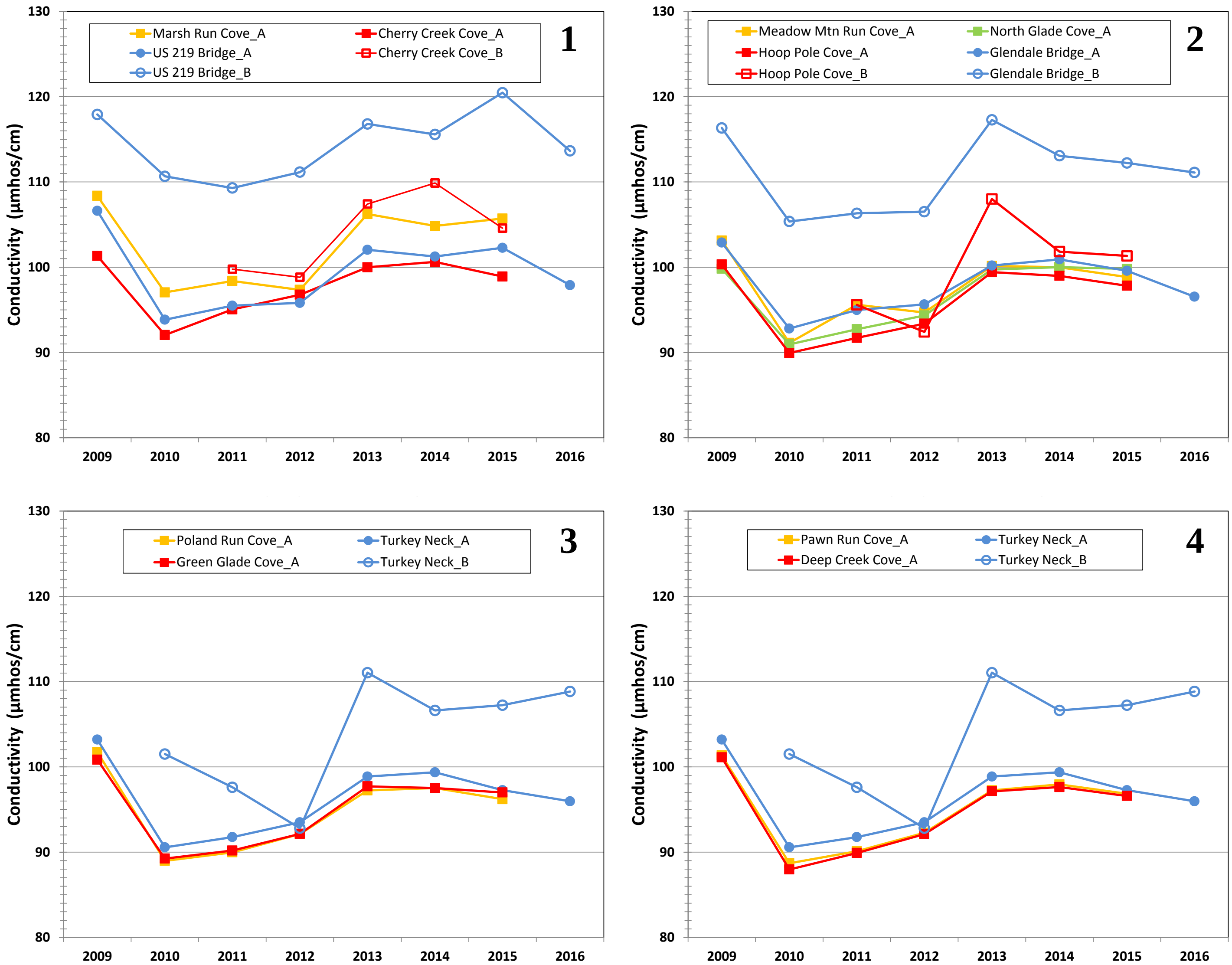


Figure 33. Seasonal average conductivity. Seasonal average conductivity for May-September. Top left panel is the four lake stations. Each numbered Top left panel is the four lake stations. Each numbered graph in rows two and three (in upper right hand corner of panel) corresponds to a numbered circled region on the map in Figure 7 to compare the water conductivity in micromhos per centimeter (µmhos/cm) in the coves with the nearest lake station. Measurements are overall means for layer Above (_A, filled markers) and Below (_B, open markers) the upper thermocline depth. Cove station monitoring was ended in July 2016 so is not included in the graphs.



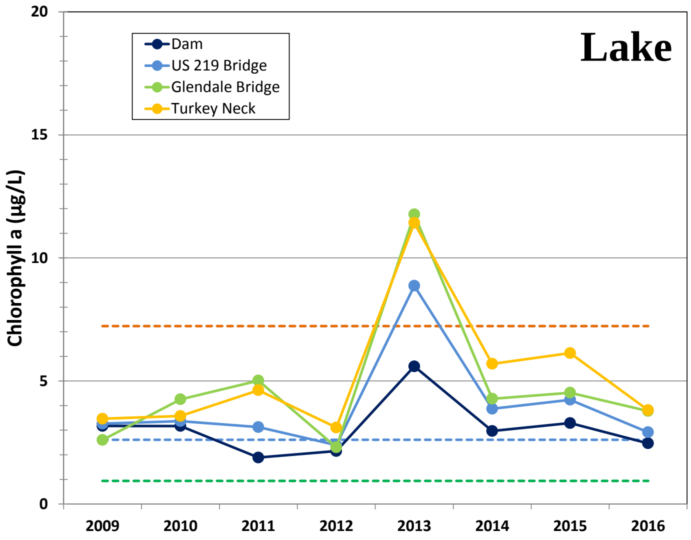
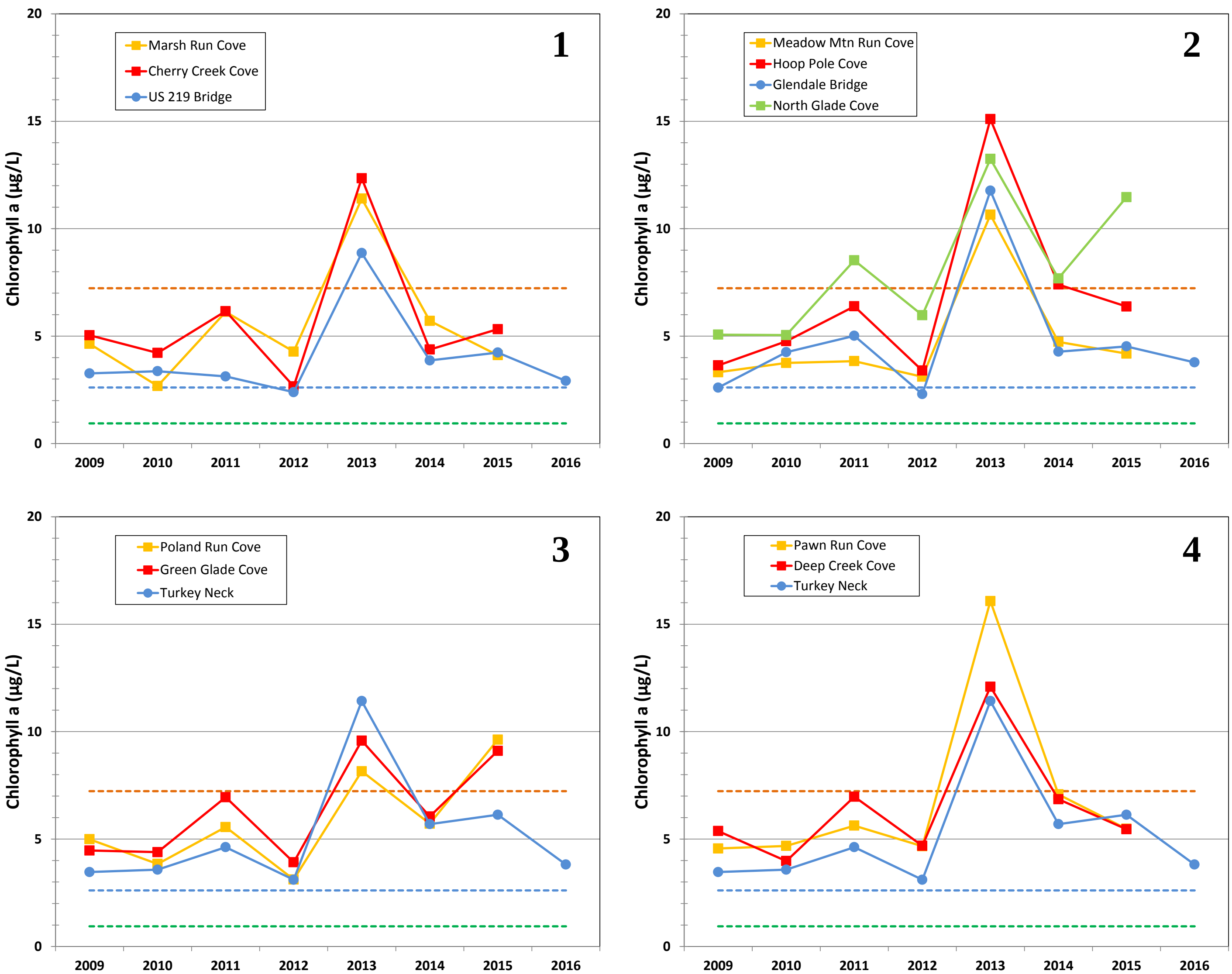


Figure 34. Seasonal average chlorophyll *a*. Seasonal average chlorophyll *a* levels for May-September. Top left panel is the four lake stations. Each numbered Top left panel is the four lake stations. Each numbered graph in rows two and three (in upper right hand corner of panel) corresponds to a numbered circled region on the map in Figure 7 to compare the mean surface layer chlorophyll *a* levels in micrograms per liter (µg/L) in the coves with the nearest lake station. Cove station monitoring was ended in July 2016. Colored lines indicate the thresholds between trophic states (Table 4): Green between Low oligotrophic/ High oligotrophic, blue between High oligotrophic/ Mesotrophic, orange between Mesotrophic/ Low eutrophic. These results provide additional detail to support the trophic state information in Table 5 and Figure 21.



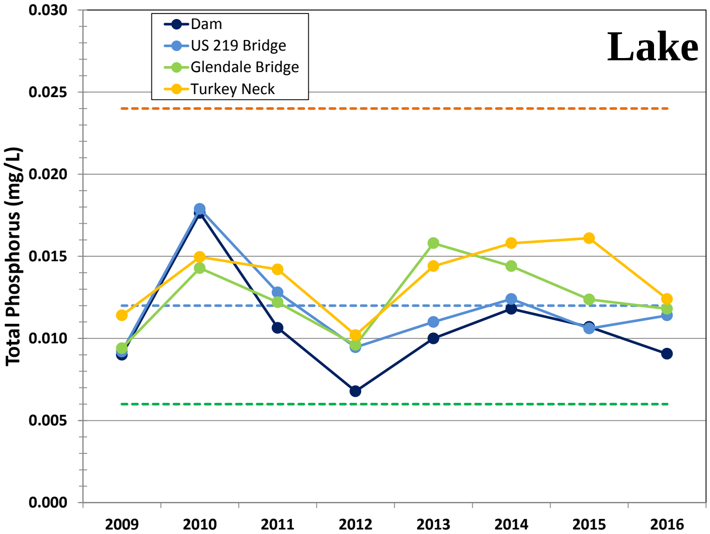
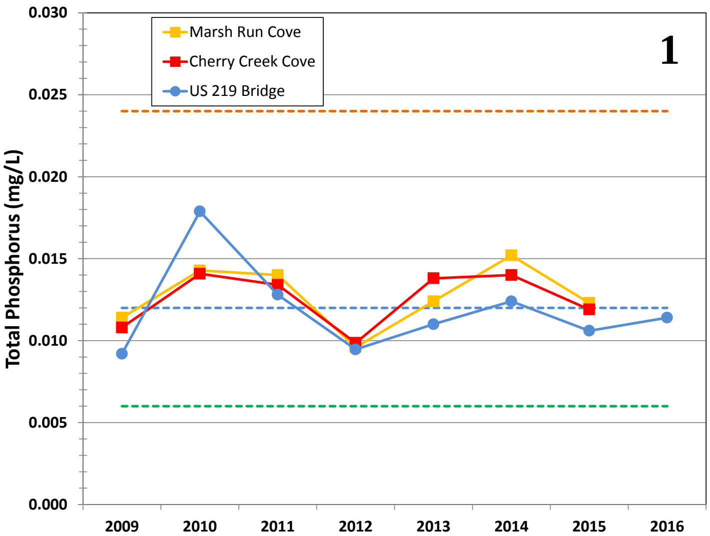
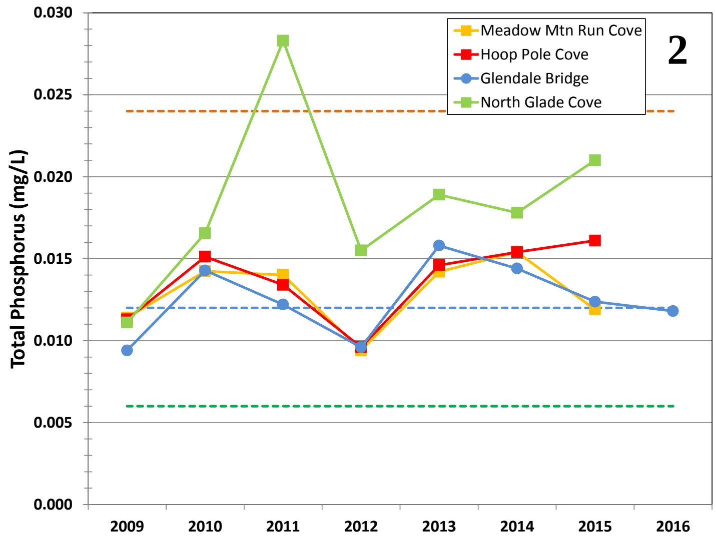
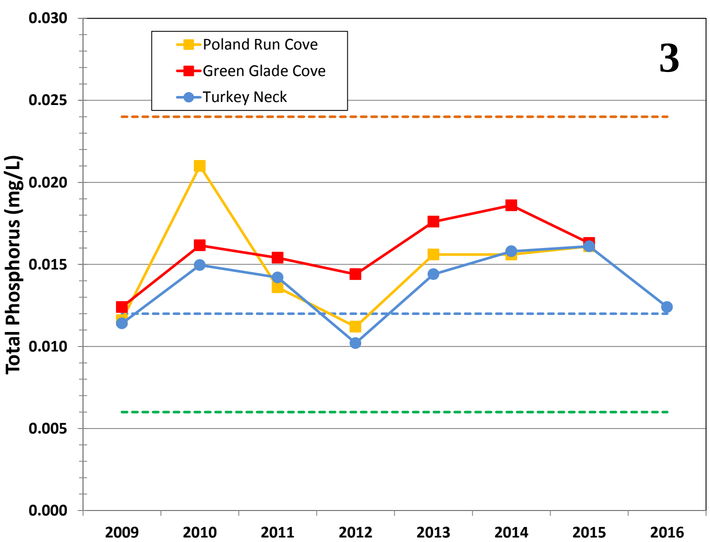
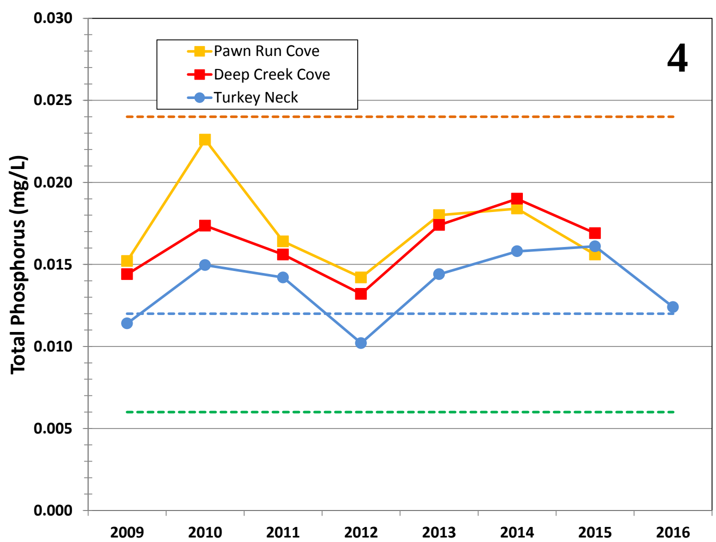


Figure 35. Seasonal average total phosphorus. Seasonal average total phosphorus levels for May-September. Top left panel is the four lake stations. Each numbered Top left panel is the four lake stations. Each numbered graph in rows two and three (in upper right hand corner of panel) corresponds to a numbered circled region on the map in Figure 7 to compare the mean surface layer total phosphorus levels in milligrams per liter (mg/L) in the coves with the nearest lake station. Cove station monitoring was ended in July 2016 so is not included in the graphs. Colored reference lines indicate the thresholds between trophic states (Table 4): Green between Low oligotrophic/ High oligotrophic, blue between High oligotrophic/ Mesotrophic, orange between Mesotrophic/ Low eutrophic.









Nitrogen

Nitrogen levels were not consistently higher or lower at a particular lake station but instead varied between years (Figure 36). The highest levels were at the Glendale Bridge station in 2013. Nitrogen levels were usually higher in the coves than at the nearest lake station, and also higher in the coves in 2013 and 2015.

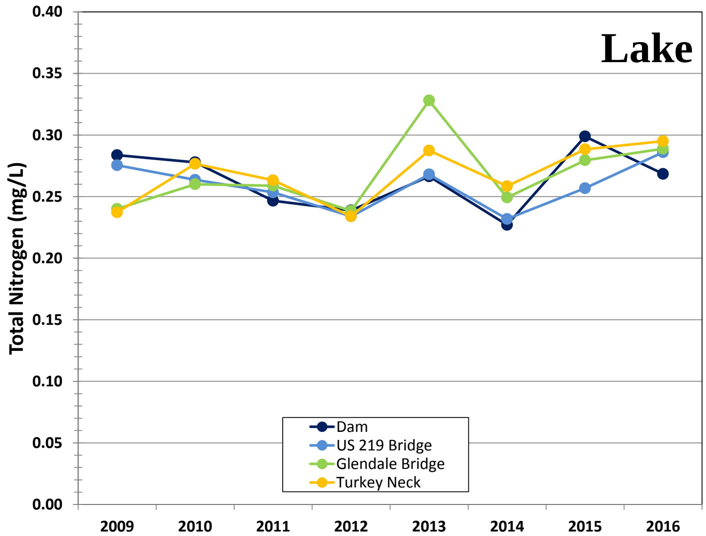
Water Clarity

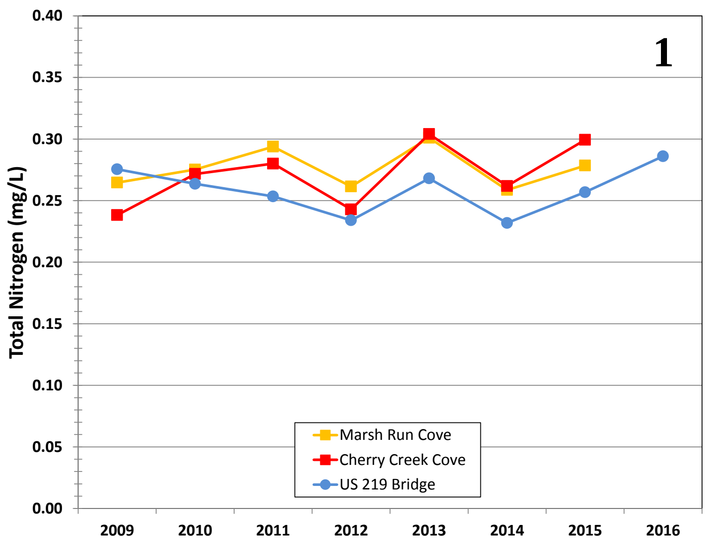
Water clarity generally decreased (Secchi depths were shallower) moving from the Dam upstream to Turkey Neck (Figure 37). Secchi depths were deeper at the nearest lake stations than in the coves, and water clarity measured by Secchi depth was the worst in North Glade Cove and Green Glade Cove. Secchi depths were deepest (best water clarity) in 2012 at most stations.

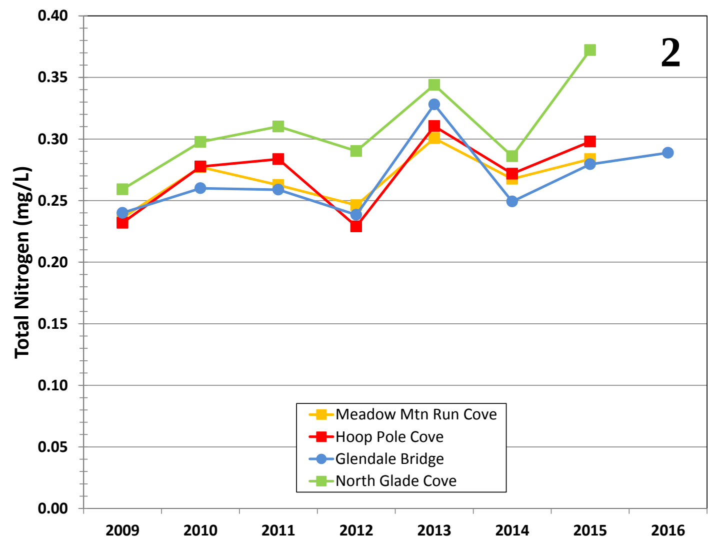
Water clarity measured by turbidity also generally decreased (higher turbidity) moving from the Dam upstream to Turkey Neck and turbidity was higher in the coves than at the nearest lake station (Figure 38). Unlike Secchi depths, however, turbidity was not as different in 2012 compared to other years. Water clarity measured by turbidity was also the worst in North Glade Cove and Green Glade Cove.

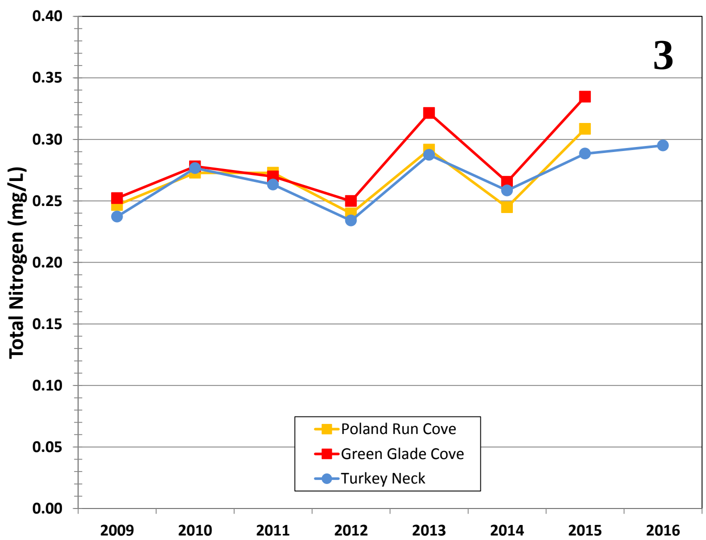
Total suspended solids levels were extremely variable between years and between stations (Figure 39). Levels in the coves were not consistently higher than at the nearest lake stations. The highest total suspended solids were measured in Hoop Pole Cove, North Glade Cove, Poland Run Cove and Pawn Run Cove in 2012, but all of these locations had lower total suspended solids levels than nearby stations in other years.

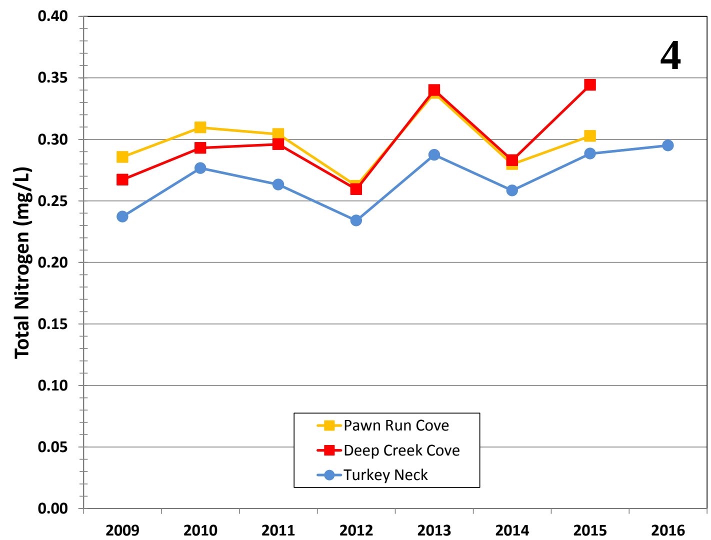
Figure 36. Seasonal average total nitrogen. Seasonal average total nitrogen levels for May-September. Top left panel is the four lake stations. Each numbered Top left panel is the four lake stations. Each numbered graph in rows two and three (in upper right hand corner of panel) corresponds to a numbered circled region on the map in Figure 7 to compare the mean surface layer total nitrogen levels in milligrams per liter (mg/L) in the coves with the nearest lake station. Cove station monitoring was ended in July 2016 so is not included in the graphs.











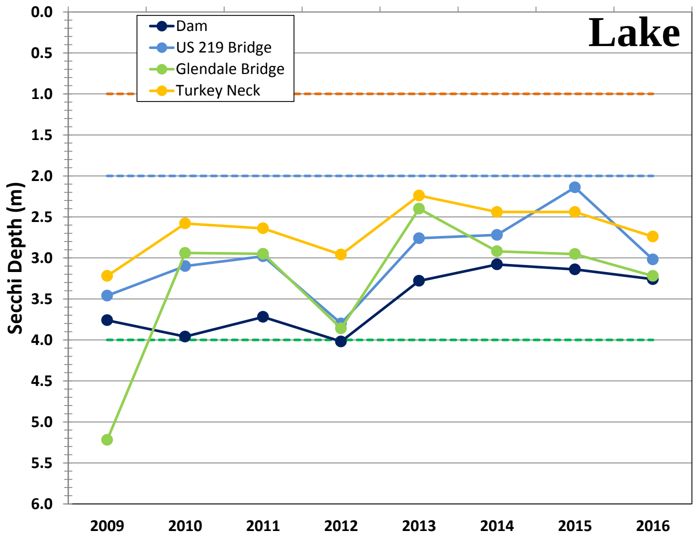
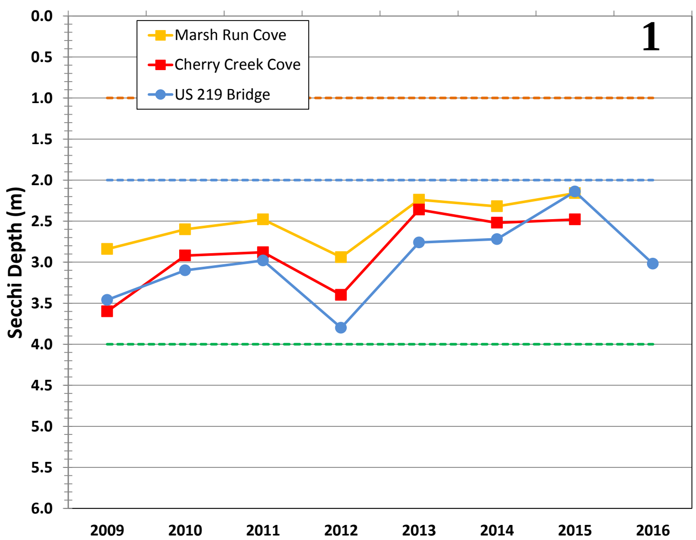
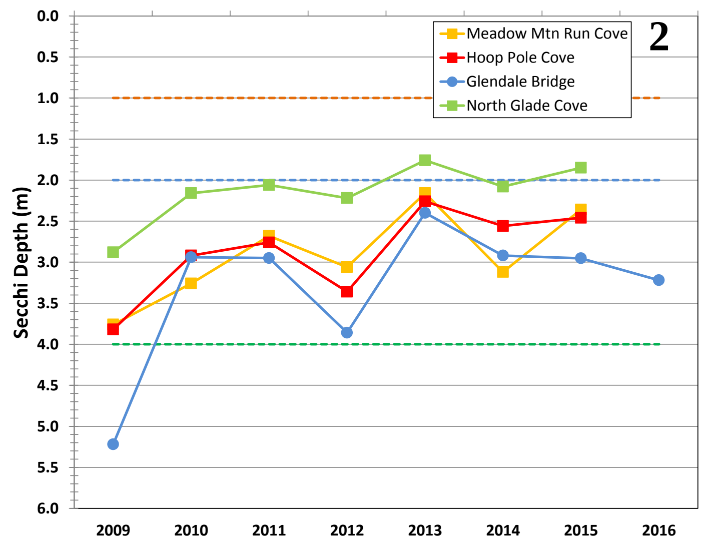
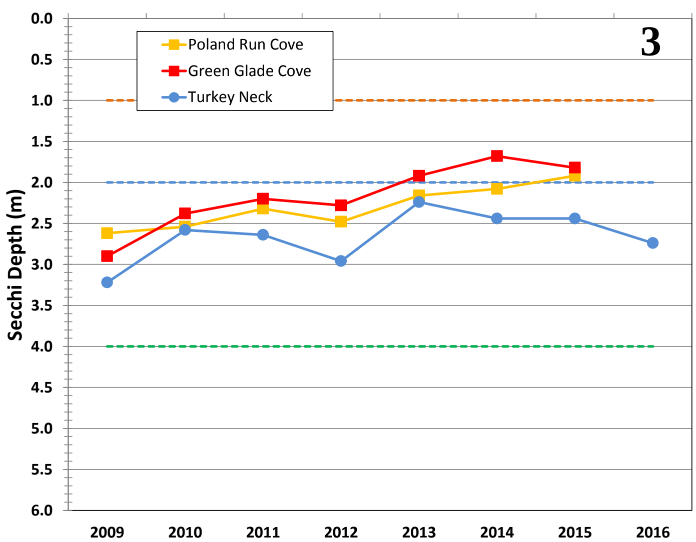
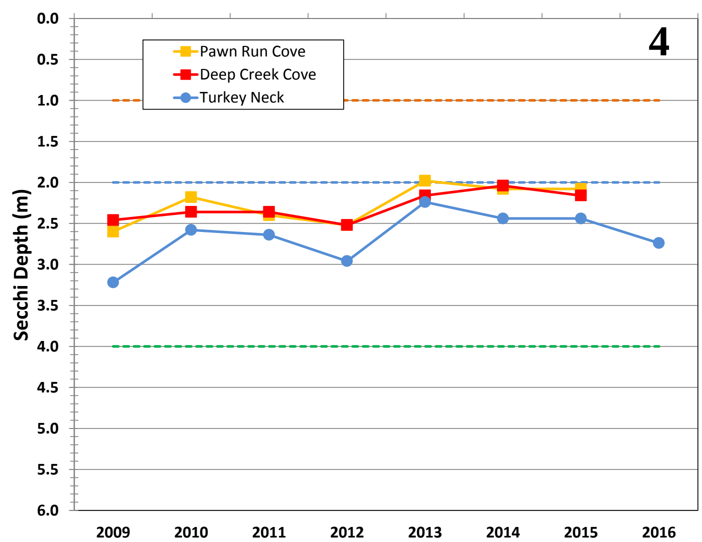


Figure 37. Seasonal average Secchi depth. Seasonal average Secchi depth for May-September. Top left panel is the four lake stations. Each numbered Top left panel is the four lake stations. Each numbered graph in rows two and three (in upper right hand corner of panel) corresponds to a numbered circled region on the map in Figure 7 to compare the mean Secchi depth in meters (m) in the coves with the nearest lake station. Cove station monitoring was ended in July 2016 so is not included in the graphs. Colored reference lines indicate the thresholds between trophic states (Table 4): Green between Low oligotrophic/ High oligotrophic, blue between High oligotrophic/ Mesotrophic, orange between Mesotrophic/ Low eutrophic. Note that the y-axis values are reversed to show depth from the water surface at the top of the graph.









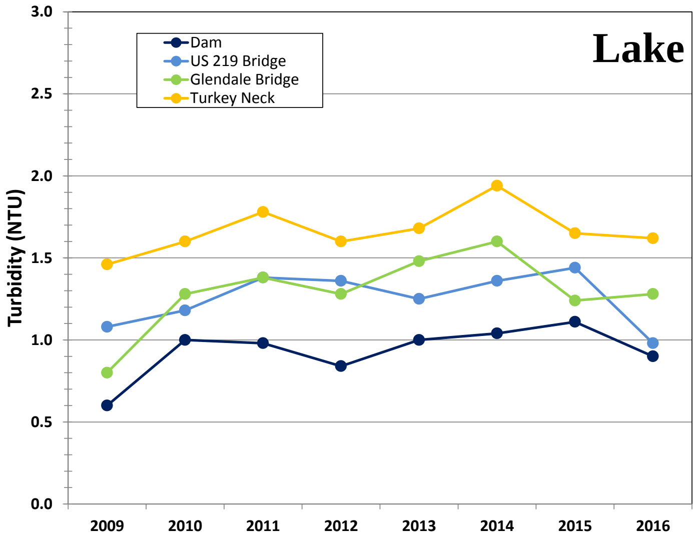
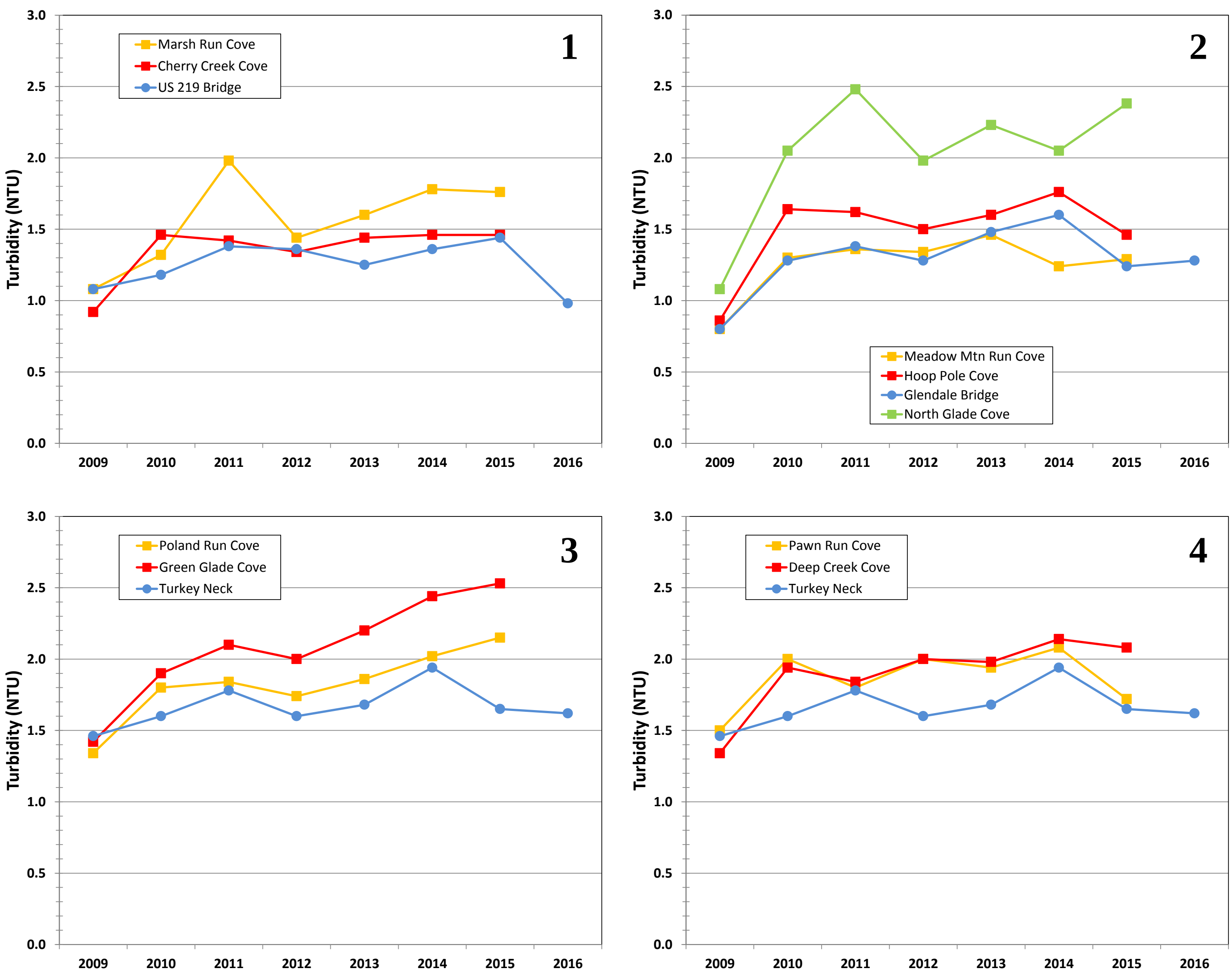


Figure 38. Seasonal average turbidity. Seasonal average turbidity for May-September. Top left panel is the four lake stations. Each numbered Top left panel is the four lake stations. Each numbered graph in rows two and three (in upper right hand corner of panel) corresponds to a numbered circled region on the map in Figure 7 to compare the mean surface layer turbidity levels in Nephelometric Turbidity Units (NTU) in the coves with the nearest lake station. Cove station monitoring was ended in July 2016 so is not included in the graphs.



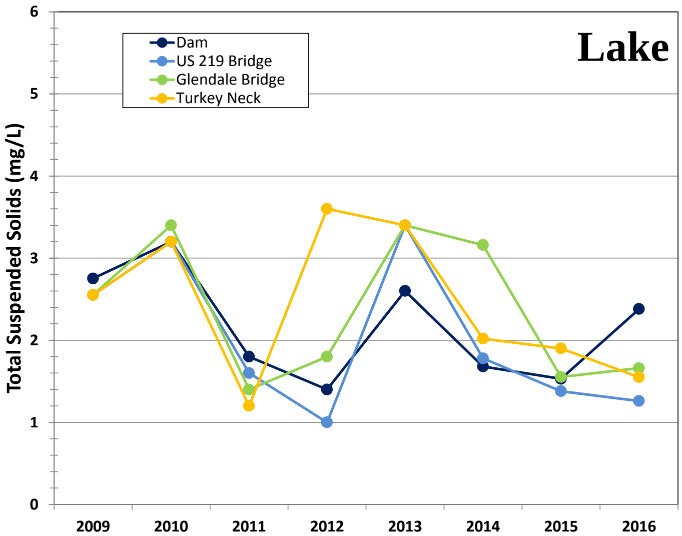
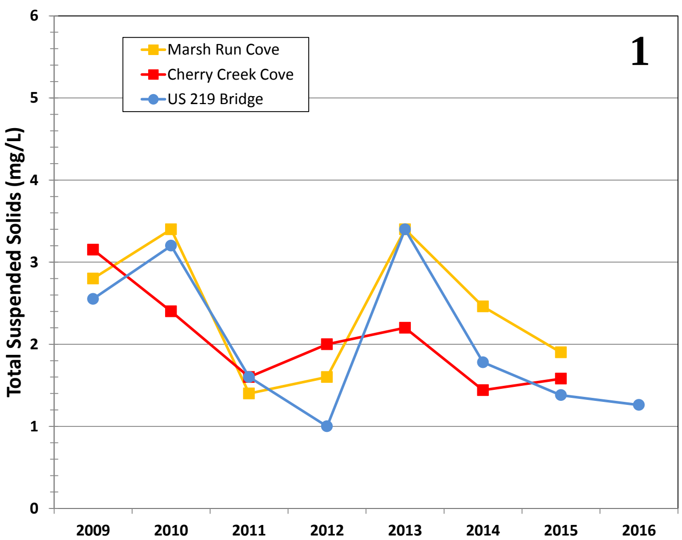
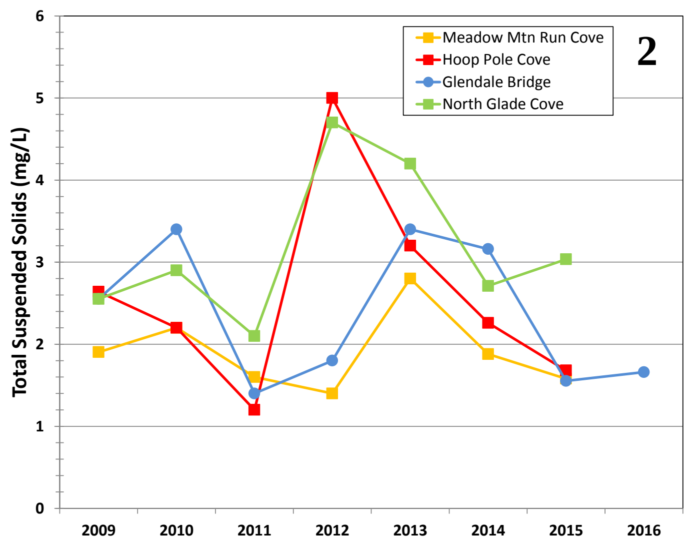
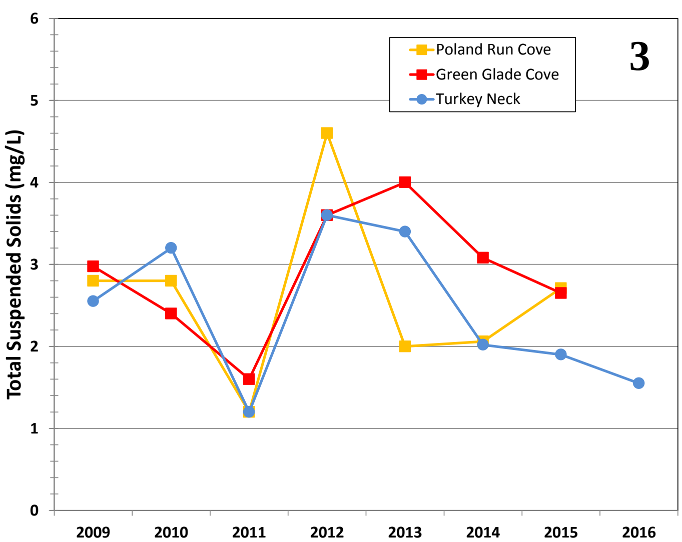
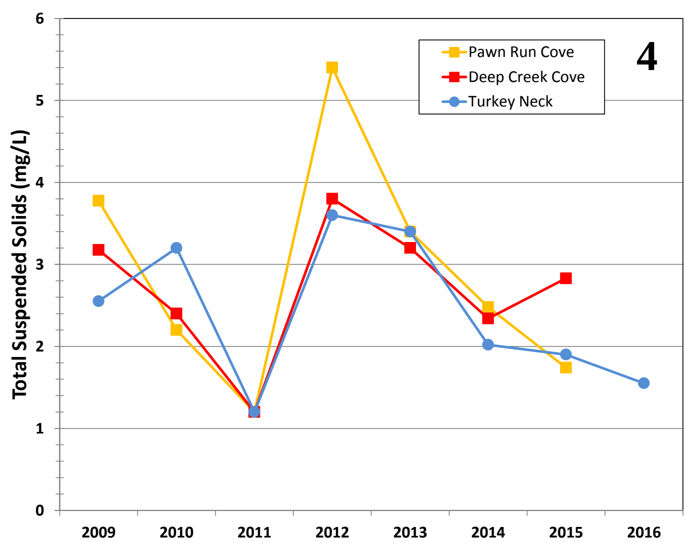


Figure 39. Seasonal average total suspended solids. Seasonal average total suspended solids levels for May-September. Top left panel is the four lake stations. Each numbered Top left panel is the four lake stations. Each numbered graph in rows two and three (in upper right hand corner of panel) corresponds to a numbered circled region on the map in Figure 7 to compare the mean surface layer total suspended solids levels in milligrams per liter (mg/L) in the coves with the nearest lake station. Cove station monitoring was ended in July 2016 so is not included in the graphs.









Summary of results

Data from 2009-2016 were used to evaluate water quality conditions in Deep Creek Lake. Lake station profiles of water temperature, dissolved oxygen, water pH and conductivity were used to track the changes in water quality throughout the annual cycle, and to determine different water quality characteristics in the above thermocline layer and below thermocline layer. Dissolved oxygen and water pH levels were compared to thresholds for healthy habitat conditions.

The monitoring stations were also grouped into four regions to allow comparison between the water quality in the coves and the nearest lake station. Water temperature, dissolved oxygen, water pH and conductivity were compared between the coves and the lake stations. Chlorophyll levels, phosphorus levels and water clarity depths were compared to thresholds and the trophic state of the lake was determined. Nutrient ratios were examined to determine if and when phosphorus or nitrogen limitation occurs in Deep Creek Lake. Water clarity parameters were compared to determine what components contribute to reducing water clarity in the lake and the coves. Seasonal averages (mean of May-September data) were also compared between above thermocline and below thermocline layers and between lake and cove stations.

Land-use

Overall, the largest land use in the Deep Creek Lake watershed is forest (56 percent). Region 0 is the most forested (72 percent). Region 1 and Region 3 are also mostly forested (approximately 60 percent) but agricultural land use is also relevant (approximately 15 percent); note however that Region 3 is much smaller than Region 1. Region 2 has less forested area (46 percent) and more agricultural area (28 percent), and Region 4 is approximately equally divided into agricultural and forest land use (40 percent each). Suburban/urban land use is roughly the same amount of each of the four regions (18-25 percent combined); Region 1 has the most urban land use (almost five percent of the area) and Region 2 has the largest amount of suburban and urban combined (almost 25 percent). Surface mining is found predominately in Region 1 but is also present in Region 2.

Precipitation

January-April total precipitation varied from 26-36 percent of the total annual precipitation from 2011-2016. May-September precipitation varied from 38-51 percent of the total annual precipitation. Total precipitation was highest in 2011, as was the January-April total precipitation, but not the May-September total. January-April precipitation was also higher in 2015 but the other years were very similar. May-September total precipitation was similar in all years except 2012 when it was lower.

Water temperature

April through August water temperatures at the lake stations were similar between years, but the timing of the fall turnover varied between years. In general, the water column was mixed from top to bottom by October. A seasonal thermocline also develops in Cherry Creek Cove (Region 1) and Hoop Pole Cove (Region 2).

Surface water temperatures were similar between the coves and nearest lake stations for individual months, but the seasonal average water temperatures at the cove stations were slightly warmer than the nearest lake station. Seasonal average water temperatures above the thermocline were fairly consistent each year, though somewhat elevated in 2012 at all four lake stations. Below the thermocline, seasonal average water temperatures were move variable and increased moving upstream from the Dam station to Turkey Neck.

<u>Dissolved oxygen</u>

Dissolved oxygen levels in surface waters remained above five milligrams per liter throughout the year. At lake stations, dissolved oxygen levels below the seasonal thermocline began decreasing as early as May and June, and were extremely low (less than one milligram per liter) in June, July and August. Dissolved oxygen levels in the shallower coves were higher than at the lake stations, possibly due to higher photosynthesis of algae and underwater grasses and more mixing. Dissolved oxygen levels in below thermocline waters of Cherry Creek Cove and Hoop Pole Cove get very low in June and July, but were replenished in August and September when the seasonal thermocline dissipates. This pattern of low dissolved oxygen in the below thermocline waters is predicted by the mesotrophic to eutrophic trophic state of the lake.

Seasonal average dissolved oxygen levels above the thermocline were fairly consistent each year at both the lake and cove stations. Below the thermocline, dissolved oxygen was at unhealthy levels in almost all years at the lake stations, and at very unhealthy levels (less than one milligram per liter) in 2013 at the Glendale Bridge and Turkey Neck lake stations.

<u>Water pH</u>

Water pH at the lake stations stayed in the healthy range (in between 6.5 and 8.5) throughout the year and at most depths, but decreased to less than 6.5 in June, July and August in below thermocline waters. No pH values below 6 were recorded in Cherry Creek Cove during the monitoring period. Water pH in surface waters of the coves was higher than at the nearest lake station (but generally still between 6.5 and 8.5), and occasional spikes of pH to above 8 likely resulted from high photosynthesis during algal blooms. Water pH levels in the below thermocline waters of Cherry Creek Cove and Hoop Pole Cove were similar to the lake stations,

Seasonal average water pH above the thermocline was higher than below the thermocline in all years. Water pH increased moving upstream from the Dam station to Turkey Neck in the above thermocline layer, but the same pattern was less consistent in the below thermocline layer and in some years pH was at the low of 6.5 throughout the lake. Water pH in the above thermocline waters was higher in the coves than the nearest lake station, especially at Meadow Mountain Run Cove (Region 2). Below thermocline water pH at Cherry Creek Cove and Hoop Pole Cove was generally similar to the nearest lake station.

Conductivity

Conductivity was much higher in the waters below the thermocline in the summer at all of the lake stations and generally continued to increase from the onset of the thermocline in June through the mixing of the water column again in October. Conductivity in the coves was somewhat lower than conductivity in surface waters at the nearest lake station. Conductivity in the below thermocline waters of Cherry Creek Cove and Hoop Pole Cove was higher than in the surface waters. Conductivity was highest in Marsh Run Cove in Region 1, which is the area with the greatest urban land use impacts. Conductivity was often lowest at the Cherry Creek Cove station, also in Region 1. Conductivity generally continued to increase throughout the April-September period.

Seasonal average conductivity decreased moving upstream from the Dam station to Turkey Neck. Conductivity below the thermocline was higher than above the thermocline in all years at the lake stations except in 2012 at the Turkey Neck station, when conductivity was the same in both layers. Conductivity in both layers was lower in 2010-2012 than the other years of the monitoring program. Conductivity above the thermocline was lower in the cove stations than at the nearest lake stations with the exception of Marsh Run Cove.

Trophic State

Most stations and most years had mesotrophic conditions in Deep Creek Lake. Exceptions to this were high oligotrophic conditions in 2011 at the Dam lake station, high oligotrophic conditions in 2012 at the three downstream lake stations, low eutrophic conditions at all lake stations except the Dam lake station in 2013, and low eutrophic conditions in 2015 in North Glade Cove, Poland Run Cove and Green Glade Cove.

Chlorophyll *a*

Chlorophyll *a* levels were higher in Region 2, though high levels indicating algal blooms occurred in all regions at different times. Chlorophyll *a* levels were consistently higher in the coves than at the closest lake station. During algal blooms, chlorophyll a concentrations were high enough to indicate high eutrophic conditions (above the red dotted line in the Figure 22) but were quickly reduced by zooplankton grazing or nutrient limitation and did not persist for an entire summer.

Seasonal average chlorophyll *a* levels were highest at all stations in 2013. Chlorophyll *a* levels generally increased moving upstream from the Dam station to Turkey Neck. In most years the chlorophyll *a* levels were highest in the coves compared to the nearest lake station, with the exception of Meadow Mountain Run Cove. Patterns were generally consistent between stations but there was a lot of variation between years.

Phosphorus and Nitrogen

Phosphorus concentrations were highest in some of the coves, especially in North Glade Cove (Region 2) but rarely high enough to be classified as low eutrophic conditions in any area.

Phosphorus concentrations were generally lowest in Region 1. Nitrogen concentrations were also highest in the coves, with the exception of a spike throughout the lake stations in June 2016. Nitrogen concentrations were highest in April and generally decreased throughout the summer as algae used up the available nitrogen in surface waters. Based on the ratios of total nitrogen relative to total phosphorus, algal growth was likely phosphorus limited from April through June and limited by both nutrients or by light availability from July through September. Patterns in nutrient limitation were similar in all regions and between the cove and nearest lake station. The presence and impact of underwater grasses is also important in determining the nutrient dynamics of Deep Creek Lake.

Seasonal average phosphorus levels generally increased moving upstream from the Dam to Turkey Neck. Phosphorus levels were not always higher in the coves compared to the nearest lake station. Phosphorus levels were lower in 2012 than in other years at all stations. Phosphorus levels were unusually high in 2010 at the Dam and US 219 Bridge lake stations and in Poland Run Cove (Region 3) and Pawn Run Cove (Region 4).

Seasonal average nitrogen levels were not consistently higher or lower at a particular lake station but instead varied between years. Nitrogen levels were usually higher in the coves than at the nearest lake station.

Water Clarity

The results from the trophic state analysis suggest that algal levels were likely a main source of light attenuation (and therefore lower water clarity) in Deep Creek Lake in most years. The relationship between Secchi depth and total suspended solids was similar to that between Secchi depth and chlorophyll *a* in some years at the cove stations, indicating an importance of sediment particles to determining the water clarity for those stations. Turbidity and total suspended solids were significantly correlated in all years at the cove stations, but not as consistently at the lake stations.

Secchi depths lower (indicating less water clarity) in the cove stations compared to the nearest lake station. Seasonally, Secchi depths continued to get worse throughout the summer. Secchi depths were lower in North Glade Cove (Region 2) and the upstream coves (Regions 3 and 4).

Seasonal average water clarity generally decreased (measured by both Secchi depth and turbidity) moving from the Dam upstream to Turkey Neck. Secchi depths were deeper at the nearest lake stations than in the coves, and water clarity measured by Secchi depth was the worst in North Glade Cove (Region 2) and Green Glade Cove (Region 3). Secchi depths were deepest (best water clarity) in 2012 at most stations. Unlike Secchi depths, however, turbidity was not as different in 2012 compared to other years. Total suspended solids levels were extremely variable between years and between stations.

References

Carlson, R. 1977. A trophic state index for lakes. Limnol. Oceano. 22:361-369 onlinelibrary.wiley.com/doi/10.4319/lo.1977.22.2.0361/epdf

Carlson, R.E. and J. Simpson. 1996. *A Coordinator's Guide to Volunteer Lake Monitoring Methods*. N. Am. Lake Mgmt. Society. 96 pp.

Code of Maryland Regulation (COMAR). Online at: dsd.state.md.us/COMAR/ComarHome.html

Environmental Resource Management (ERM). 2007. Assessment of Water Quality Impacts from Potential Land Development, Deep Creek Lake, Garrett County, Maryland. Annapolis, MD. 80p. Available online garrettcounty.org/resources/planning-land-development/pdf/Comprehensive%20Planning/dclwaterquality-final5-07.pdf

Kolzau, S., Wiedner, C., Rücker, J., Köhler, J., Köhler, A., & Dolman, A. M. (2014). Seasonal Patterns of Nitrogen and Phosphorus Limitation in Four German Lakes and the Predictability of Limitation Status from Ambient Nutrient Concentrations. *PLoS ONE*, *9*(4), e96065. doi.org/10.1371/journal.pone.0096065