SUMMARY REPORT OF CHEMICAL AND BIOLOGICAL CONDITIONS IN HIGGINS LAKES BETWEEN 2018 AND 2021

PREPARED BY:

Mark R. Luttenton, Ph.D.

PREPARED FOR:

Higgins Lake Foundation

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Nutrient loading to Higgins Lake via groundwater has been documented since the mid-1990s (Minnerick 2001) and was likely occurring in the early 1980s (Schultz and Fairchild 1984). More recent studies by Michigan State University have quantified elevated concentrations of phosphorus (TP and SRP) in groundwater along much of the nearshore region around Higgins Lake, and has coupled these concentrations with quantified rates of groundwater flow from upland areas toward the lake (Martin 2014, 2019). Given these data, the general conclusion would be that measured concentrations of TP in the lake should reflect the elevated concentrations in groundwater. However, data from a study I conducted concurrently with the MSU study, using the same sample sites, indicated that TP concentrations in shallow areas are generally low. Because of data like these (and data from deeper areas of the lake) there is a general conclusion that Higgins Lake is a high quality, oligotrophic system.

But the high concentrations of TP in groundwater and the low concentrations in the lake beg the question, "if there are high TP concentrations in the groundwater but not in the surface water, where does the phosphorus go"? Addressing this question requires digging deeper into the current biology of Higgins Lake, and developing a deeper understanding of how biological communities can alter a system like Higgins Lake. Indeed, the current conditions in Higgins Lake may require reevaluating the long-held notions and criteria used to assign lakes to a particular trophic status (e.g., the TSI) based on certain metrics.

For Higgins Lake, it appears that conditions around and within the lake have resulted in a system that functions as two connected but separate regions. First, the shallow nearshore area is being driven by nutrient loading through nutrients delivered via groundwater from under and through the sediments. The second region is the deeper offshore areas that appear to be responding to the presence of zebra mussels and now quagga mussels, a relative of the zebra mussel that was recently discovered in Higgins Lake (M. Luttenton, personal observation).

In shallow areas during 2018, groundwater TP concentrations averaged between 0.02 mg/L and 0.033 mg/L whereas surface water TP concentrations ranged between 0.013 mg/L and <0.006 mg/L, the level of reliable detection. In nearshore areas, where a significant fraction of groundwater and associated TP likely enter the lake, a substantial quantity of TP is probably taken up by bottom dwelling algae (Photos 1 - 3). The concentration of chlorophyll a, a measure of the quantity of algal pigments, is extremely high (Figs. 1 - 23) when compared to other studies measuring algal chlorophyll associated with lake sediments. Consequently, the shallow water above the nearshore sediments may have consistently low TP concentrations (Figs. 1 – 23 and 35 - 38) because it is being used very rapidly by the algae growing on the sediment.

Nitrate-nitrogen (NO_3) concentrations varied across sample locations, but in general, NO_3 concentrations tended to decline from spring to late summer (Figs. 1 – 23 and 24 - 30). Because of the low TP concentrations, and the reduction in NO_3 during the summer, this ultimately leads to the shallow nearshore area being limited by both nitrogen and phosphorus. We have confirmed this through an experiment conducted by a Grand Valley State University graduate student (N. Akey). Using standard experimental methods, we added phosphorus alone, nitrogen alone, and phosphorus and nitrogen together. The only treatment that resulted in increased algal growth was the combination of nitrogen and phosphorus. This clearly indicates that the community is limited by both nutrients by mid-summer.

Photo 1. Arrow identifies crust of sand that is a complex of sand grains bound together by algal growth.

Photo 2. Right shows top of a flake of sand, left shows the bottom of a flake of sand. The green coloration is the algal growth that binds the sand grains together.

Photo 3. An individual sand grain with a coating of algae.

Farther offshore in slightly deeper water (4 feet to 6 feet), filamentous green algae have begun to establish thick growths at sites with zebra and/or quagga mussels. These are the same type of filamentous algae that became very abundant in Saginaw Bay during the 1990s shortly after the introduction of Zebra Mussels (Photos 4 - 6).

Photo 4. Shallow area with zebra/quagga mussels and extensive algal growth.

Photo 5. Shallow area with zebra/quagga mussels and extensive algal growth.

Photo 6. Mooring tires covered with zebra/quagga mussels and filamentous algal growth.

As zebra/quagga mussels filter water to remove food particles and excrete the waste products, it may cause nutrients to concentration in the area around the zebra/quagga mussels beds.

This can provide a localized nutrient rich environment that facilitates the growth of filamentous algae that do well in higher nutrient environments.

In offshore areas aquatic plants, including Eurasian Watermilfoil (EWM), very likely influences the lake in two ways. First, we know that aquatic plants take up nutrients from both sediments and from the water column. So, some fraction of the nutrients entering Higgins Lake are bound in plant biomass. In some cases, the amount of plant biomass is very high. For example, the biomass of EWM at some locations in Higgins Lake was similar to the biomass observed in areas of Muskegon Lake and White Lake, two very eutrophic lake systems.

The second way aquatic plants influence the Higgins Lake system is due to the fact that zebra/quagga mussels will use the plants as an attachment point. Because aquatic plants provide a 3-dimensional surface, they offer both mussels much more attachment surface than a flat, 2-dimensional surface. Our work has determined that a 1 m^2 area of EWM will support an average of 1,600 zebra/quagga mussels. We measured the TP content of mussels in Higgins Lake and found they contain an average of 0.013 mg of TP per gram of mussel tissue. Consequently, 1,600 mg of mussel tissues contains approximately 20.8 mg of TP/m^2. If there are 20 acres of EWM in Higgins Lake, that equals 80,937 m^2, and from this I estimated the area would contain approximately 1.6 million mg of TP in zebra/quagga mussel tissue. Mussels also excrete TP which can be taken up by algae that can then be consumed again by mussels. This cycle is all part of a common and well documented process of nutrient cycling. Consequently, invasive mussels have likely become a major source and sink of phosphorus.

Obviously, just measuring TP in the water collected from the middle of the lake does not provide a complete picture, and has led many to the conclusion that Higgins Lake has been, and remains an oligotrophic lake. These analyses only help confirm that mussels are likely removing a major fraction of the phytoplankton from the water column, and redirect the nutrients from the water column to the bottom sediments. A similar process was previously documented in Saginaw Bay in the 1990s.

Appreciating the ecological role of these two invasive species makes it clear why traditional metrics (TP concentrations and Secchi Disk depth) may not be good indicators of trophic condition for lakes with invasive mussels. The North American Lake Management Society (NALMS) has clearly laid out the argument that nutrients should not be used to define trophic status. In the case of Higgins Lake, the water column has become clearer in recent years, not because the lake is "as good as always", but because the plankton is being removed and the biomass redirected to the bottom of the lake by mussels.

As noted in the NALMS statement (Defining Trophic State), production, the accumulation of biological matter (biomass) is the best indicator of the problems a lake may be facing. In Higgins Lake, there is an abundance of biomass that is now based in the tissues of invasive mussels, aquatic plants, algal growth in the nearshore areas, and even in the extensive algal growth that now occurs at depths down to 80 feet. This deep plant growth is likely the result of accumulating nutrient-rich sediments and the fact that water clarity now allows light to penetrate to a depth of almost 100 feet.

The accumulation of nutrient-rich sediments is one additional factor that clearly indicates Higgins Lake has and continues to change. We have measured the amount of organic material that has accumulated on the bottom of the lake in several locations. Partially decomposed organic material (muck) now accounts for between 7.8% to 67.3% of the sediment composition. The amount of TP bound in that organic sediment ranges from 370 mg/kg to 1514 mg/kg. The presence of this muck is even more concerning because this material has mostly accumulated since the late 1980s to mid-1990s. Taking the area below the 80-foot depth contour, I have estimated that there is about 12 million kg of organic sediment. This translates into approximately 8424 kg of TP in the sediments, or 18,571 lbs.

The accumulation of organic sediments has a secondary impact, that is, declining oxygen concentrations due microbial activity. The organic sediments provide an extensive food source for microbes allowing this community to increase in numbers. As the microbes work to decompose the accumulated sediments they consume the oxygen available in the deeper portions of the lake. In Higgins, that is exactly what we see in the summer and now it appears to happen in the winter; dissolved oxygen concentrations are being reduced, likely due to microbial respiration.

Finally, another clear indicator that Higgins Lake has changed is the seasonal development of blue-green algal blooms. During 2020, the bloom occurred later in the summer, but in 2021, it was present by late June (Photo 7). The blue-green algae likely accumulate phosphorus from the phosphorus-rich sediments that have accumulated on the bottom.

Photo 7. Cyanobacteria in plankton samples collected from Higgins Lake during 2020-2021. Because this blue-green alga has the capacity to generate ammonia, they don't have to rely on nitrogen in the water column for their metabolic needs. This gives this blue-green algae a competitive advantage over other algae. And it now appears, based on data for 2020 and 2021, that the density of cyanobacteria in the water column may be playing a role in the concentration of ammonia in Higgins Lake, actually increasing the concentration of ammonia (Figs. 47-50, and 57 and 58).

CONCLUSIONS:
Higgins Lake has clearly changed during the past few decades. Using just traditional metrics that are generally employed by lake consulting firms would lead to the conclusion that Higgins Lake is an oligotrophic system. However, following the recommendations of the North American Lake Management Society, a much more thorough analysis of the biological conditions in Higgins Lake along with chemical and physical conditions leads to a much more complete and accurate representation of the current state of Higgins Lake. The amount of biomass that is present in the lake, including aquatic plants, zebra/quagga mussels, algae in the nearshore areas, and algae growing in deeper portions of the lake, clearly indicate that Higgins Lake is moving away from an oligotrophic condition and toward a much more productive ecosystem.

Summary of 2018 Nearshore Surface Water Quality Assessment of Higgins Lake

The data summarized in this section were collected as part of a collaborative study with MSU, and was a continuation of a study initiated in 2014 by MSU. The goal of the 2014 MSU study was to assess the condition of groundwater and shallow surface water, both in the nearshore area of Higgins Lake. The 2018 assessment employed the sites established by MSU for the 2014 study, with surface water samples collected at the same location as groundwater samples. The results of the groundwater assessment is presented in a separate report (2019 Higgins Lake Report – Final Report).

The shallow surface water data are presented in five sections including: 1) a comparison of total phosphorus concentrations, nitrate concentrations, and chlorophyll a concentrations associated with surface sediments, 2) nitrate concentrations, 3) chlorophyll a concentrations associated with surface sediments (not included in the 2014 MSU study), 4) phosphorus concentrations, and 5) chloride concentrations.

Average total phosphorus for groundwater and surface water samples collected during three different studies during three different time periods.

Study	Year	Location	Species	Concentration (ug/L)
USGS	1996-2000	SW	TP	7.1
USGS	1996-2000	GW	TP	47.4
MSU	2014	SW	Tp	12.9
MSU	2014	GW	TP	22.9
GVSU	2018	SW	TP	8.0
MSU	2018	GW	TP	20.9-33.6

Average nitrate-nitrogen at sample sites adjacent to Camp Curnalia

Study	Year	Surface water (mg/L)	Groundwater (mg/L)	
USGS – 23	1996-2000	0.017	0.0045	
USGS – 24	1996-2000	0.024	0.877	
MSU – 22	2014	0.070	<0.001	
MSU – 23	2014	0.006	<0.001	
GVSU/MSU - 22	2018	0.055	<0.05	
GVSU/MSU - 23	2018	0.052	<0.05	

TOTAL PHOSPHORUS AND NITRATE IN SURFACE WATER, AND CHLOROPHYLL a ASSOCIATED WITH SURFACE SEDIMENTS

Figure 1. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 1. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 2. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 2. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 3. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 3. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 4. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 4. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 5. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 5. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 6. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 6. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 7. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 7. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 8. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 8. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 9. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 9. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 10. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 10. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

0.00

500.00

1000.00

1500.00

2000.00

2500.00

3000.00

0

0.02

0.04

0.06

0.08

0.1

May

June

July

August

Sept

Chlorophyll a

mg/m

(

^{2}

)

mg/L

(

TP, NO

$_3$

)

2018

MSU 11

TP

NO3

Chl a

0.00

500.00

1000.00

1500.00

2000.00

2500.00

3000.00

0

0.02

0.04

0.06

0.08

0.1

May

June

July

August

Sept

Chlorophyll a

mg/m

(

2

)

mg/L

(

TP, NO

3

)

2018

MSU 11

TP

NO3

Chl a

Figure 11. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 11. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 12. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 12. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 13. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 13. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 14. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 14. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

0.00

500.00

1000.00

1500.00

2000.00

2500.00

3000.00

0

0.05

0.1

0.15

0.2

May

June

July

August

Sept

Chlorophyll a

mg/m

(

2

)

mg/L

TP, NO

(

3

)

2018

MSU 15

TP

NO3

Chl a

0.00

500.00

1000.00

1500.00

2000.00

2500.00

3000.00

0

0.05

0.1

0.15

0.2

May

June

July

August

Sept

Chlorophyll a

mg/m

(

^{2}

)

mg/L

TP, NO

(

$_3$

)

2018

MSU 15

TP

NO3

Chl a

Figure 15. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 15. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 16. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 16. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

0.00

500.00

1000.00

1500.00

2000.00

2500.00

3000.00

0

0.02

0.04

0.06

0.08

May

June

July

August

Sept

Chlorophyll a

(

mg/m

2

)

mg/L

(

TP, NO

3

)

2018

MSU 17

TP

NO3

Chl a

0.00

500.00

1000.00

1500.00

2000.00

2500.00

3000.00

0

0.02

0.04

0.06

0.08

May

June

July

August

Sept

Chlorophyll a

(

mg/m

2

)

mg/L

(

TP, NO

3

)

2018

MSU 17

TP

NO3

Chl a

Figure 17. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 17. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 18. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 18. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

0.00

500.00

1000.00

1500.00

2000.00

2500.00

0

0.02

0.04

0.06

0.08

May

June

July

August

Sept

Chlorophyll a

mg/m

(

^{2}

)

mg/L

TP, NO

(

^{3}

)

2018

MSU 19

TP

NO3

Chl a

0.00

500.00

1000.00

1500.00

2000.00

2500.00

0

0.02

0.04

0.06

0.08

May

June

July

August

Sept

Chlorophyll a

mg/m

(

^{2}

)

mg/L

TP, NO

(

3

)

2018

MSU 19

TP

NO3

Chl a

Figure 19. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 19. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

0.00

500.00

1000.00

1500.00

2000.00

2500.00

3000.00

0

0.02

0.04

0.06

0.08

May

June

July

August

Sept

Chlorophyll a

(
mg/m
2
)
mg/L
(
TP, NO
3
)
2018
MSU 20
TP
NO3
Chl a

0.00
500.00
1000.00
1500.00
2000.00
2500.00
3000.00
0
0.02
0.04
0.06
0.08
May
June
July
August
Sept
Chlorophyll a

(

mg/m

2

)

mg/L

(

TP, NO

3

)

2018

MSU 20

TP

NO3

Chl a

Figure 20. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 20. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 21. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 22. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

0.00

500.00

1,000.00

1,500.00

2,000.00

2,500.00

3,000.00

0

0.01

0.02

0.03

0.04

0.05

0.06

0.07

May

June

July

August

Sept

Chlorophyll a

(

mg/m

2

)

mg/L

(

TP, NO

3

)

2018

MSU 23

TP

NO3

Chl a

0.00

500.00

1,000.00

1,500.00

2,000.00

2,500.00

3,000.00

0

0.01

0.02

0.03

0.04

0.05

0.06

0.07

May

June

July

August

Sept

Chlorophyll a

(

mg/m

2

)

mg/L

(

TP, NO

3

)

2018

MSU 23

TP

NO3

Chl a

Figure 22. Trend in total phosphorus, nitrate, and chlorophyll a concentrations at sample site MSU 23. Concentrations of total phosphorus <0.006 mg/L are below detection levels.

Figure 23. Average concentrations of total phosphorus, nitrate, and chlorophyll a for all sample sites on each sample date.

NITRATE

0.00

0.05

0.10

0.15

0.20

May

June

July

Aug

Sept

mg/L

2018

2018

Nitrate Concentrations

MSU 1

MSU 2

MSU 3

0.00

0.05

0.10

0.15

0.20

May

June

July

Aug

Sept

mg/L

2018

2018

Nitrate Concentrations

MSU 1

MSU 2

MSU 3

Figure 24. Trends in nitrate concentrations at sample sites MSU 1, 2, and 3.

0.00

0.02

0.04

0.06

0.08

0.10

0.12

0.14

May

June

July

Aug

Sept

mg/L

2018

Nitrate Concentrations

2018

MSU 4

MSU 5

MSU 6

0.00

0.02

0.04

0.06

0.08

0.10

0.12

0.14

May

June

July

Aug

Sept

mg/L

2018

Nitrate Concentrations

2018

MSU 4

MSU 5

MSU 6

Figure 25. Trends in nitrate concentrations at sample sites MSU 4, 5, and 6.

0.00

0.05

0.10

0.15

0.20

0.25

0.30

0.35

0.40

0.45

May

June

July

Aug

Sept

mg/L

2018

2018

Nitrate Concentrations

MSU 7

0.00

0.05

0.10

0.15

0.20

0.25

0.30

0.35

0.40

0.45

May

June

July

Aug

Sept

mg/L

2018

2018

Nitrate Concentrations

MSU 7

Figure 26. Trend in nitrate concentrations at sample site MSU 7.

0.00

0.02
0.04
0.06
0.08
0.10
0.12
0.14
May
June
July
Aug
Sept
mg/L
2018
2018

Nitrate Concentrations

MSU 8
MSU 9
MSU 10
MSU 12

0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
May
June

July

Aug

Sept

mg/L

2018

2018

Nitrate Concentrations

MSU 8

MSU 9

MSU 10

MSU 12

Figure 27. Trends in nitrate concentrations at sample sites MSU 8, 9, 10, and 12.

0.00

0.02

0.04

0.06

0.08

0.10

0.12

0.14

May

June

July

Aug

Sept

Axis Title

2018

Nitrate Concentrations

2018

MSU 13

MSU 14

MSU 15

0.00

0.02

0.04

0.06

0.08

0.10

0.12

0.14

May

June

July

Aug

Sept

Axis Title

2018

Nitrate Concentrations

2018

MSU 13

MSU 14

MSU 15

Figure 28. Trends in nitrate concentrations at sample sites MSU 13, 14, and 15.

0.00

0.02

0.04

0.06

0.08

0.10

May

June

July

Aug

Sept

mg/L

2018

2018

Nitrate Concentrations

MSU 16

MSU 17

MSU 18

0.00

0.02

0.04

0.06

0.08

0.10

May

June

July

Aug

Sept

mg/L

2018

2018

Nitrate Concentrations

MSU 16

MSU 17

MSU 18

Figure 29. Trends in nitrate concentrations at sample sites MSU 16, 17, and 18.

0.00

0.02

0.04

0.06

0.08

0.10

May

June

July

Aug

Sept

mg/L

2018

2018

Nitrate concentrations

MSU 19

MSU 20

MSU 22

MSU 23

0.00

0.02

0.04

0.06

0.08

0.10

May

June

July

Aug

Sept

mg/L

2018

2018

Nitrate concentrations

MSU 19

MSU 20

MSU 22

MSU 23

Figure 30. Trends in nitrate concentrations at sample sites MSU 19, 20,22, and 23.

SEDIMENT CHLOROPHYLL a CONCENTRATIONS

Figure 31. Trends in chlorophyll a concentrations at sample sites MSU 1, 2, 3, 4, 5, and 6.

0.00

500.00

1000.00

1500.00

2000.00

2500.00

3000.00

May

June

July

August

September

Chlorophyll a

mg/m

(

2

)

2018

Sediment Chlorophyll a

MSU 7

MSU 8

MSU 9

MSU 10

MSU 11

0.00

500.00

1000.00

1500.00

2000.00

2500.00

3000.00

May

June

July

August

September

Chlorophyll a

mg/m

(

²

)

2018

Sediment Chlorophyll a

MSU 7

MSU 8

MSU 9

MSU 10

MSU 11

Figure 32. Trends in chlorophyll a concentrations at sample sites MSU 7, 8, 9, 10, and 11.

0.00

500.00

1000.00

1500.00

2000.00

2500.00

3000.00

3500.00

4000.00

May

June

July

August

September

Chlorophyll a

(

mg/m

^{2}

)

2018

Sediment Chlorophyll a

MSU 12

MSU 13

MSU 14

MSU 15

0.00

500.00

1000.00

1500.00

2000.00

2500.00

3000.00

3500.00

4000.00

May

June

July

August

September

Chlorophyll a

(

mg/m

^{2}

)

2018

Sediment Chlorophyll a

MSU 12

MSU 13

MSU 14

MSU 15

Figure 33. Trends in chlorophyll a concentrations at sample sites MSU 12, 13, 14, and 15.

Figure 34. Trends in chlorophyll a concentrations at sample sites MSU 16, 17, 18, 19, 20, 22, and 23.

0

0.002

0.004

0.006

0.008

0.01

0.012

May

June

July

August

Sept

Phosphorus mg/L

Surface Water TP Concentrations 2018

1

2

3

4

5

6

0

0.002

0.004

0.006

0.008

0.01

0.012

May

June

July

August

Sept

Phosphorus mg/L

Surface Water TP Concentrations 2018

1

2

3

4

5

6

Figure 35. Trends in TP concentrations during 2018 at sample sites in Higgins Lake. The black dashed line (0.006 mg/L) is the lower level of detection and the red dashed line (0.012 mg/L) is used to define oligotrophic versus mesotrophic conditions.

Figure 36. Trends in TP concentrations during 2018 at sample sites in Higgins Lake. The black dashed line (0.006 mg/L) is the lower level of detection and the red dashed line (0.012 mg/L) is used to define oligotrophic versus mesotrophic conditions.

Figure 37. Trends in TP concentrations during 2018 at sample sites in Higgins Lake. The black dashed line (0.006 mg/L) is the lower level of detection and the red dashed line (0.012 mg/L) is used to define oligotrophic versus mesotrophic conditions.

Figure 38. Trends in TP concentrations during 2018 at sample sites in Higgins Lake. The black dashed line (0.006 mg/L) is the lower level of detection and the red dashed line (0.012 mg/L) is used to define oligotrophic versus mesotrophic conditions.

CHLORIDE CONCENTRATIONS

Figure 39. Trends in chloride concentrations at sites 1, 2, 3, 4, 5, and 6.

0

5

10

15

20

25

30

May

June

July

August

Sept

mg/L

2018

Chloride

MSU 7

MSU 8

MSU 9

MSU 10

MSU 11

0

5

10

15

20

25

30

May

June

July

August

Sept

mg/L

2018

Chloride

MSU 7

MSU 8

MSU 9

MSU 10

MSU 11

Figure 40. Trends in chloride concentrations at sites 7, 8, 9, 10, and 11.

0

5

10

15

20

25

30

May

June

July

August

Sept

mg/L

2018

Chloride

MSU 12

MSU 13

MSU 14

MSU 15

0

5

10

15

20

25

30

May

June

July

August

Sept

mg/L

2018

Chloride

MSU 12

MSU 13

MSU 14

MSU 15

Figure 41. Trends in chloride concentrations at sites 12, 13, 14, and 15.

Figure 42. Trends in chloride concentrations at sites 16, 17, 18, 19, 20, 22, and 23.

Summary of 2020 Offshore Water Quality Assessment of Higgins Lake

0.00

0.02

0.04

0.06

0.08

0.10

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

Nitrate

-

Nitrogen 2020

NDS

NDM

NDB

0.00

0.02

0.04

0.06

0.08

0.10

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

Nitrate

-

Nitrogen 2020

NDS

NDM

NDB

Figure 43. Trend in nitrate-nitrogen concentrations at the deepest location in the North Basin. NDS = surface, NDM = mid-depth, NDB = 1 m from bottom.

0.00

0.02

0.04

0.06

0.08

0.10

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

Nitrate

-

Nitrogen 2020

H1

H2

H3

H4

H5

0.00

0.02

0.04

0.06

0.08

0.10

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

Nitrate

-

Nitrogen 2020

H1

H2

H3

H4

H5

Figure 44. Trends in nitrate-nitrogen concentrations at five sites within the North Basin. Samples were collected from between the 100-foot and 120-foot depth contour.

0.00

0.02

0.04

0.06

0.08

0.10

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

Nitrate

-

Nitrogen 2020

SDS

SDM

SDB

0.00

0.02

0.04

0.06

0.08

0.10

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

Nitrate

-

Nitrogen 2020

SDS

SDM

SDB

Figure 45. Trends in nitrate-nitrogen concentrations at a deep site (103 feet) in the South Basin. SDS = surface, SDM = mid-depth, SDB = 1 m from the bottom.

0.00

0.02

0.04

0.06

0.08

0.10

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

Nitrate

-

Nitrogen 2020

H6

H7

H8

H9

H10

0.00

0.02

0.04

0.06

0.08

0.10

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

Nitrate

-

Nitrogen 2020

H6

H7

H8

H9

H10

Figure 46. Trends in nitrate-nitrogen at five sites within the South Basin. Samples were collected from between the 80-foot and 90-foot depth contour.

0.000

0.050

0.100

0.150

0.200

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

NH

3

-

Nitrogen 2020

NDS

NDM

NDB

0.000

0.050

0.100

0.150

0.200

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

NH

3

-

Nitrogen 2020

NDS

NDM

NDB

Figure 47. Trend in ammonia-nitrogen concentrations at the deepest location in the North Basin. NDS = surface, NDM = mid-depth, NDB = 1 m from bottom.

0.000

0.020

0.040

0.060

0.080

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

NH

3

-

Nitrogen 2020

H1

H2

H3

H4

H5

0.000

0.020

0.040

0.060

0.080

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

NH

3

-

Nitrogen 2020

H1

H2

H3

H4

H5

Figure 48. Trends in ammonia-nitrogen at five sites within the North Basin. Samples were collected from between the 100-foot and 120-foot depth contour.

0.000

0.050

0.100

0.150

0.200

0.250

0.300

0.350

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

NH

3

-

Nitrogen 2020

SDS

SDM

SDB

0.000

0.050

0.100

0.150

0.200

0.250

0.300

0.350

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

NH

3

-

Nitrogen 2020

SDS

SDM

SDB

Figure 49. Trends in ammonia-nitrogen concentrations at a deep site (103 feet) in the South Basin. SDS = surface, SDM = mid-depth, SDB = 1 m from the bottom.

0.000

0.050

0.100

0.150

0.200

0.250

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

NH

3

-

Nitrogen 2020

H6

H7

H8

H9

H10

0.000

0.050

0.100

0.150

0.200

0.250

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

NH

3

-

Nitrogen 2020

H6

H7

H8

H9

H10

Figure 50. Trends in ammonia-nitrogen at five sites within the South Basin. Samples were collected from between the 80-foot and 90-foot depth contour.

0

0.002

0.004

0.006

0.008

0.01

0.012

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

TP Concentrations 2020

NDS

NDM

NDB

0

0.002

0.004

0.006

0.008

0.01

0.012

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

TP Concentrations 2020

NDS

NDM

NDB

Figure 51. Trend in total phosphorus concentrations at the deepest location in the North Basin.
NDS = surface, NDM = mid-depth, NDB = 1 m from bottom.

0

0.002

0.004

0.006

0.008

0.01

0.012

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

TP Concentrations 2020

H1

H2

H3

H4

H5

0

0.002

0.004

0.006

0.008

0.01

0.012

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

TP Concentrations 2020

H1

H2
H3
H4
H5

Figure 52. Trends in total phosphorus at five sites within the North Basin. Samples were collected from between the 100-foot and 120-foot depth contour.

0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
6/19/2020
7/19/2020
8/19/2020
9/19/2020
10/19/2020
mg/L
TP Concentrations 2020
SDS
SDM
SDB

0
0.002
0.004
0.006

0.008

0.01

0.012

0.014

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

TP Concentrations 2020

SDS

SDM

SDB

Figure 53. Trends in total phosphorus concentrations at a deep site (103 feet) in the South Basin. SDS = surface, SDM = mid-depth, SDB = 1 m from the bottom.

0

0.002

0.004

0.006

0.008

0.01

0.012

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

TP Concentrations 2020

H6

H7

H8

H9

H10

0

0.002

0.004

0.006

0.008

0.01

0.012

6/19/2020

7/19/2020

8/19/2020

9/19/2020

10/19/2020

mg/L

TP Concentrations 2020

H6

H7

H8

H9

H10

Figure 54. Trends in total phosphorus concentrations at five sites within the South Basin. Samples were collected from between the 80-foot and 90-foot depth contour.

Summary of 2021 Offshore Water Quality Assessment of Higgins Lake

0.00

0.01

0.02

0.03

0.04

0.05

0.06

0.07

0.08

1/2021

/

6

1/2021

/

7

8

1/2021

/

9

/

1/2021

mg/L

Nitrate

-

Nitrogen 2021

NBD-S

NBD-D

NB21-1S

NB21-1b

0.00

0.01

0.02

0.03

0.04

0.05

0.06

0.07

0.08

1/2021

/

6

1/2021

/

7

8

1/2021

/

9

/

1/2021

mg/L

Nitrate

-

Nitrogen 2021

NBD-S

NBD-D

NB21-1S

NB21-1b

Figure 55. Trends in nitrate-nitrogen concentrations at two sites in the North Basin. NBD-S and NBD-B are surface and bottom samples at the 135-foot site, and NB21-1S and NB21-1b are surface and bottom samples at an 85-foot site.

0.00

0.01

0.02

0.03

0.04

0.05

0.06

0.07

0.08

0.09

1/2021

/

6

1/2021

/

7

8

/

1/2021

9

/

1/2021

mg/L

Nitrate

-

Nitrogen 2021

Hils Bd-S

Hils Bd-b

SBD-S

SBD-b

0.00

0.01

0.02

0.03

0.04

0.05

0.06

0.07

0.08

0.09

1/2021

/

6

1/2021

/

7

8

/

1/2021

9

/

1/2021

mg/L

Nitrate

-

Nitrogen 2021

Hils Bd-S

Hils Bd-b

SBD-S

SBD-b

Figure 56. Trends in nitrate-nitrogen concentrations at two sites in the South Basin. SBD-S and SBD-B are surface and bottom samples at the 103-foot site, and Hils Bd-S and Hils Bd-b are surface and bottom samples at an 85-foot site South of Flag Point.

0.00

0.10

0.20

0.30

0.40

0.50

0.60

0.70

1/2021

/

6

1/2021

7

/

8

/

1/2021

9

1/2021

/

mg/L

NH

3

-

Nitrogen 2021

NBD-S

NBD-D

NB21-1S

NB21-1b

0.00

0.10

0.20

0.30

0.40

0.50

0.60

0.70

1/2021

/

6

1/2021

7

/

8

/

1/2021

9

1/2021

/

mg/L

NH

3

-

Nitrogen 2021

NBD-S

NBD-D

NB21-1S

NB21-1b

Figure 57. Trends in ammonia-nitrogen concentrations at two sites in the North Basin. NBD-S and NBD-B are surface and bottom samples at the 135-foot site, and NB21-1S and NB21-1b are surface and bottom samples at an 85-foot site.

0.00

0.05

0.10

0.15

0.20

0.25

0.30

0.35

0.40

1/2021

/

6

1/2021

/

7

/

1/2021

8

9

/

1/2021

mg/L

NH

3

-

Nitrogen 2021

Hils Bd-S

Hils Bd-b

SBD-S

SBD-b

0.00

0.05

0.10

0.15

0.20

0.25

0.30

0.35

0.40

1/2021

/

6

1/2021

/

7

/

1/2021

8

9

/

1/2021

mg/L

NH

3

-

Nitrogen 2021

Hils Bd-S

Hils Bd-b

SBD-S

SBD-b

Figure 58. Trends in ammonia-nitrogen concentrations at two sites in the South Basin. SBD-S and SBD-B are surface and bottom samples at the 103-foot site, and Hils Bd-S and Hils Bd-b are surface and bottom samples at an 85-foot site South of Flag Point.

0.000

0.002

0.004

0.006

0.008

0.010

0.012

0.014

6

1/2021

/

7

/

1/2021

8

/

1/2021

9

/

1/2021

mg/L

TP Concentrations 2021

NBD-S

NBD-D

NB21-1S

NB21-1b

0.000

0.002

0.004

0.006

0.008

0.010

0.012

0.014

6

1/2021

/

7

/

1/2021

8

/

1/2021

9

/

1/2021

mg/L

TP Concentrations 2021

NBD-S

NBD-D

NB21-1S

NB21-1b

Figure 59. Trends in total phosphorus concentrations at two sites in the North Basin. NBD-S and NBD-B are surface and bottom samples at the 135-foot site, and NB21-1S and NB21-1b are surface and bottom samples at an 85-foot site South of Flag Point.

0.000

0.001

0.002

0.003

0.004

0.005

0.006

0.007

0.008

0.009

1/2021

/

6

1/2021

/

7

/

1/2021

8

9

/

1/2021

mg/L

TP Concentrations

Hils Bd-S

Hils Bd-b

SBD-S

SBD-b

0.000

0.001

0.002

0.003

0.004

0.005

0.006

0.007

0.008

0.009

1/2021

/

6

1/2021

/

7

/

1/2021

8

9

/

1/2021

mg/L

TP Concentrations

Hils Bd-S

Hils Bd-b

SBD-S

SBD-b

Figure 60. Trends in total phosphorus concentrations at two sites in the South Basin. SBD-S and SBD-B are surface and bottom samples at the 103-foot site, and Hils Bd-S and Hils Bd-b are surface and bottom samples at an 85-foot site South of Flag Point.