LARRATT AQUATIC

Okanagan Lake Collaborative Monitoring Agreement
2019 Update Report
FINAL

Prepared for BC Ministry of Environment and Climate Change Strategy, Environmental Protection Division

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Executive Summary

The British Columbia Ministry of Environment and Climate Change Strategy (BC ENV) in partnership with local municipalities, commissioned a multi-year collaborative monitoring program to sample long-term water quality in Okanagan Lake, monthly (March to September) at four locations from 2011 to 2019. A primary function of the monitoring was to determine attainment of Okanagan Lake water quality objectives, along with increasing the temporal resolution of water quality data for Okanagan Lake, specifically with the goal of determining trends in nutrient and biological data. Similar to previous years, parameters such as temperature and dissolved oxygen were measured throughout the water column as well as several chemical parameters including silica, nitrogen, and phosphorus at discrete depths. Biological data ranging from phytoplankton and zooplankton biomass to specific taxonomic identification, were also collected. This report summarizes the 2019 findings and analyzes data from 2011-2019 for trends.

Weather during 2019 returned to normal for the Okanagan after the extreme weather and flooding of 2017 and 2018. The results to date indicate that the Armstrong Arm is the most impacted by human activities and watershed degradation, including agriculture, cattle range, logging and shoreline septic. This site had the most exceedances and the most parameters trending towards greater exceedances. Weather was the dominant factor on water quality at the three southern sites.

Physical

Okanagan Lake is typically stratified from May to November and then freely mixes over the winter. Secchi depth was highest in late winter and decreased each spring in response to increased phytoplankton activity. Water clarity was typical for Okanagan Lake in 2019 after two years of poor water clarity from the 2017 and 2018 flooding events. Only the Armstrong Arm failed to meet the Secchi depth objective in 2019.

Chemical

Dissolved oxygen (DO) is essential for all aquatic animals and is high throughout Okanagan Lake at all times except in the Armstrong Arm. DO in the deep water of the Armstrong Arm fell below the water quality objective each summer including 2019; however, there were no fully anaerobic conditions in 2019, an improvement over 2016-2018. Silica concentrations were higher in the Armstrong Arm than the rest of Okanagan Lake as they were in most years. Silica increased at all sites from 2013-2018 but there was a decline at all sites during 2019.

Total nitrogen averaged 0.255 ± 0.038 mg/L as N in Okanagan Lake and exceeded the objective at Summerland, Kelowna, and Okanagan Centre but not in the Armstrong Arm during 2019. Total nitrogen increased at the Armstrong Arm but was stable at the three southern sites from 2011-2019.

Nitrate increased significantly in the surface waters of the Armstrong Arm and in the hypolimnion at all sites from 2011-2019. This is part of a decades long increasing trend in hypolimnetic nitrate in Okanagan Lake that has continued through multiple wet-dry climate cycles and is likely caused by increasing human impacts within the Okanagan region.

Total phosphorus (TP) averaged 0.008 ± 0.006 mg/L as phosphorus (P) in Okanagan Lake during 2019. TP had a year-over-year increasing trend in the Armstrong Arm, where it also exceeded the objective in 2019, and also in the epilimnion at Okanagan Centre. TP includes phosphorus associated with suspended sediment carried into the lake and it increased in Okanagan Lake during wet years and decreased during dry years (see 2017 comprehensive report). TP was therefore lower at all sites during 2019 compared to 2017-2018 because it was a drier year. Dissolved phosphorus followed similar patterns to TP and increased in the Armstrong and the epilimnion at Okanagan Centre from 2011-2019.

The ratio of nitrogen to phosphorus (N:P) available to phytoplankton will play a major role in which types of phytoplankton proliferate in a lake. A lower N:P ratio (abundant phosphorus relative to nitrogen) will favour the growth of less desirable cyanobacteria. The N:P ratio failed to meet the objective in the Armstrong Arm in 2019 with a downwards trend (farther from meeting objective). Okanagan Centre met the objective but had significant downwards trends in the N:P ratio from 2011-2019.

Biological

Chlorophyll-a was used as a measure of photosynthetic activity in Okanagan Lake. An increasing south to north trend in the chlorophyll-a data occurred over the course of this study. All sites met the chlorophyll-a objectives during 2019. Chlorophyll-a was lower during 2019 compared to the very high 2018 values because of the drier conditions and lower freshet nutrient inputs but there was still a significant increasing trend at Kelowna, Okanagan Centre, and the Armstrong Arm from 2011-2019. Previous research by ENV has identified a one-year lag between major nutrient inputs and increases in phytoplankton productivity so 2019 productivity was expected to be high despite the normal freshet. This pattern did repeat in 2019 so while chlorophyll-a concentrations were lower than 2018, biovolume was very high during 2019

Phytoplankton abundance during 2019 was lower than 2018 and typical for Okanagan Lake while biovolume was very high compared to previous years because of a large spring diatom bloom. Kelowna exceeded the phytoplankton biovolume objective during 2019; this was the first year that a site exceeded the phytoplankton biovolume objective over the course of this study. Cyanobacteria numerically dominated phytoplankton counts but only 1/7 and 2/7 samples exceeded the taxonomic objective at Summerland and Kelowna respectively during 2019.

Zooplankton biomass met the objective at Kelowna but not at Summerland in 2019; Summerland has failed to meet the objective in 3 of the past 5 years. Kelowna and Summerland both met the objective of >5% cladocerans in 2019. There were no significant trends in zooplankton data to date. Unfortunately, sample preservation issues meant that the April to July samples were lost and this does affect the results and their comparability to previous years.

The following areas of concern have been identified that may require further investigation on the part of the Ministry:

- Chronically low Secchi depth in the Armstrong Arm
- Increasing nitrate in hypolimnion of Okanagan Lake since 1970s
- Increasing total phosphorus and dissolved phosphorus in the Armstrong Arm
- Decreasing N:P ratio in the Armstrong Arm
- Trends in several parameters at Okanagan Centre may indicate that elevated nutrients from the Armstrong Arm are affecting the main body of the Lake that far south and causing similar trends as in Armstrong Arm but at a reduced intensity.

Water Quality Objectives, 2019 Values, and Trends for Okanagan Lake

Table 0-1: Okanagan Lake water quality objectives

Parameter (Nordin, 2005)	**Summerland**	**Kelowna**	**Ok Centre**	**Armstrong Arm**
Secchi Depth (growing season average: Apr-Sep)	>7m	>6m	>6m	>5m
Dissolved Oxygen (minimum in bottom waters)	-	-	-	>5 mg/L
TP (mg/L as P) (maximum at spring overturn)	<0.008	<0.008	<0.007	<0.01
Chlorophyll-a (µg/L) (maximum seasonal average)	<4.5	<4.5	<4	<5
TN (mg/L as N) (maximum at spring overturn)	<0.230	<0.230	<0.230	<0.250
N:P Ratio (spring weighted ratio)	>25:1	>25:1	>25:1	>25:1
Algae Taxonomy (% heterocystous cyanobacteria)	<5%	<5%	<5%	<5%
Algae Biomass (µL/L) (growing season average)	<0.75	<0.75	<0.75	<0.75
Zooplankton Biomass (µg/L) (growing season average)	>50	>50	>50	>50
Zooplankton Taxonomy (% cladocerans)	>5%	>5%	>5%	>5%

Table 0-2: Attainment of Okanagan Lake water quality objectives during 2019

Parameter		Summerland	Kelowna	Ok Centre	Armstrong Arm
Secchi Depth		8.9	8.1	8.0	4.0
Dissolved Oxygen		10.00	10.11	10.69	2.70
TP (mg/L)	0:10m:	0.004	0.007	0.007	0.010
	20-45m:	0.004	0.004	0.005	0.018
Chlorophyll-a (µg/L)		1.68	2.51	2.37	4.95
TN (mg/L)	0-10m:	0.231	0.229	0.231	0.248
	20-45m:	0.278	0.267	0.256	0.296
N:P Ratio	0-10m:	53:1	41:1	37:1	30:1
	20-45m:	64:1	62:1	51:1	18:1
Algae Taxonomy (% heterocystous cyanobacteria)		2%	3%		
Algae Biomass (µg/L)		0.295	0.822		
Zooplankton Biomass (µg/L)		34.9	51.6		
Zooplankton Taxonomy (% cladocerans)		7.0%	6.0%		

Legend:

Met objective in 2019	Did not meet objective in 2019	No Data/ No Objective

Table 0-3: Summary of trends (2011-2019) compared to attainment of water quality objectives in Okanagan Lake during 2019

Parameter	Summerland	Kelowna	Ok Centre	Armstrong Arm
Secchi Depth	-	-	-	-
Dissolved Oxygen	-	-	-	-
TP (mg/L)	-	-	↑	↑
Chlorophyll-a (µg/L)	-	↑	↑	↑
TN (mg/L)	-	-	-	↑
N:P Ratio	-	-	↓	↓
Algae Taxonomy (% heterocystous cyanobacteria)	-	-		
Algae Biomass (µL/L)	↑	↑		
Zooplankton Biomass (µg/L)	-	-		
Zooplankton Taxonomy (% cladocerans)	-	-		

Legend:

Met objective in 2019	Did not meet objective in 2019	No Data/ No Objective
↑ = Increasing Trend	↓ = Decreasing Trend	- = No Trend

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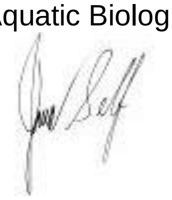

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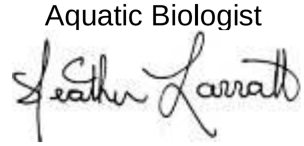

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Definitions

The following terms are defined as they are used in this report.

Term	Definition
Algae bloom	A superabundant growth of algae
Anaerobic/anoxic	Devoid of oxygen
Bioavailable	Available for use by plants or animals
Chlorophyll-a	Primary photosynthetic pigment in algae; used as a measure of photosynthetic activity
Cyanobacteria	Bacteria-like algae having cyanochrome as the main photosynthetic pigment
Diatoms	Algae that have hard, silica-based "shells" frustules
Fall overturn	Surface waters cool and sink, until a fall storm mixes the water column
Eutrophic	Nutrient-rich, biologically productive water body
Littoral	Shoreline between high and low water; the most productive area of a lake
Macronutrient	The major constituents of cells: nitrogen, phosphorus, carbon, sulphate, H
Micronutrient	Small amounts are required for growth; Si, Mn, Fe, Co, Zn, Cu, Mo etc.
Microflora	The sum of algae, bacteria, fungi, *Actinomycetes,* etc., in water or biofilms
Monomictic	"One Mixing": describes lakes that are thermally stratified in summer and mixed in winter
Nutrient limitation	A nutrient will limit or control the potential growth of organisms e.g. P or N
Peak biomass	The highest density, biovolume or chl-a attained in a set time on a substrate
Periphyton	Algae that are attached to aquatic plants or solid substrates
Phytoplankton	Algae that float, drift or swim in water columns of reservoirs and lakes
Plankton	Those organisms that float or swim in water
Residence time	Time for a parcel of water to pass through a reservoir or lake (flushing time)
Riparian	The interface between land and a stream or lake
Secchi depth	Depth where a 20 cm Secchi disk can be seen; measures water transparency
Seiche	Wind-driven tipping of lake water layers in the summer, causes oscillations
Thermocline	The lake zone of greatest change in water temperature with depth (> $1^oC/m$); it separates the surface water (epilimnion) from the cold hypolimnion below
Zooplankton	Minute animals that graze algae, bacteria and detritus in water bodies

Term	Definition
AFDM	Ash-free dry mass
Chl-a	Chlorophyll-a units µg/L
DO	Dissolved oxygen units mg/L
N	Nitrogen units mg/L as N
Ortho-P	Orthophosphate ≈ SRP monomeric inorganic phosphorus units mg/L as N
P	Phosphorus units mg/L as P
DIN	Dissolved inorganic nitrogen = ammonia + nitrate + nitrite units mg/L as N
TDN	Total dissolved nitrogen = ammonia + nitrate + nitrite + dissolved organic N units mg/L as N
TDP/DP	Total dissolved phosphorus units mg/L as P
TN	Total nitrogen: organic + dissolved units mg/L as N
TP	Total phosphorus: organic + dissolved units mg/L as P

Lake Classification by Trophic Status Indicators (Nordin, 1985)

Trophic Status	chlorophyll-a ug/L	Total P ug/L	Total N ug/L	Secchi disc m	primary production mg $C/m^2/day$
Oligotrophic	0 – 2	1 – 10	<100	> 6	50- 300
Mesotrophic	2 – 5	10 – 20	100 – 500	3 – 6	250 – 1000
Eutrophic	>5	> 20	500-1000	< 3	>1000

Nutrient Balance Definitions for Microflora (Dissolved Inorganic N : Dissolved Inorganic P) (Nordin,1985)

Phosphorus Limitation	Co-Limitation of N and P	Nitrogen Limitation
>15 : 1	<15 : 1 – 5 : 1	5 : 1 or less

1.0 Introduction

1.1 Overview

The British Columbia Ministry of Environment and Climate Change Strategy (BC ENV) in partnership with the City of Kelowna, the Regional District of Central Okanagan, and the District of Summerland began a seasonal sampling program on Okanagan Lake in 2011 to increase the temporal resolution of water quality data being gathered. This program was performed collaboratively between ENV staff, Okanagan Nation Alliance (ONA; 2011), and Larratt Aquatic Consulting (2012-2019). Okanagan Lake was sampled monthly from March to September from 2011-2019 at four key sites (Figure 1.1-1, Table 1.1-1).

Table 1.1-1: GPS coordinates of sampling sites

Site Name	EMS ID	Latitude	Longitude
Summerland	0500454	49.600550°	-119.628030°
Kelowna	0500236	49.861350°	-119.513420°
Ok Centre	0500730	50.089900°	-119.478270°
Armstrong Arm	0500239	50.315450°	-119.357180°

Note: EMS = Environmental Monitoring System and serves as ENV's database of water quality

Sampling focused on three broad subjects at each site: physical parameters, water chemistry, and biological activity.

Physical parameters including temperature profiles were taken at each site on each date to build a composite image of conditions in Okanagan Lake over time (Figure 2.1-1). Secchi depth, a measure of water clarity, was also recorded for each site.

In addition, dissolved oxygen profiles were taken and a range of parameters were chemically analyzed from samples taken in the epilimnion (1-5-10 m composite) and the hypolimnion (20-32-45 m composite). Chemistry focused on the major nutrients in their various forms. Chemistry results were analyzed by ALS Environmental.

Biological sampling included generic parameters such as chlorophyll-a concentration and biomass, as well as detailed taxonomic classification of phytoplankton (algae) and zooplankton.

The 2019 data were added to the existing 2011 – 2018 database upon which all the analyses in this report were performed. Water quality objectives were based upon Nordin (2005) (Appendix 1).

Figure 1.1-1: Okanagan Basin Watershed with four sampling locations identified

1.2 Weather and Climate Conditions in 2019

The weather during any given year will have a major impact on physical conditions, water chemistry, and biological activity in Okanagan Lake during that year. The weather during 2017 and 2018 was very unusual for the Okanagan region. 2017 had the record highest flooding of Okanagan Lake followed immediately by the driest summer recorded. 2018 had a long, cold, and snowy winter followed by a wet spring, that combined to create a very intense freshet and minor flooding throughout the valley (Figure 1.2-1). The 2018 spring flooding was followed by a very hot and dry summer in which the Okanagan experienced weeks of intense smoke and ash from wildfires. Weather conditions during 2019 were much closer to the historic normal for the Okanagan and the and this led to more normal water quality across the suite of measured parameters.

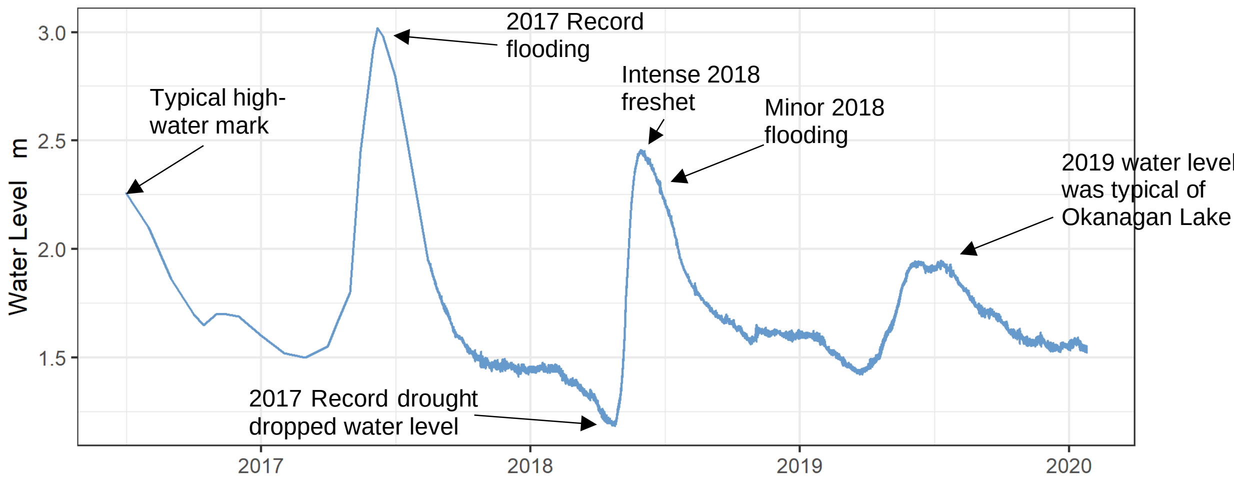

Figure 1.2-1: **Water level in Okanagan Lake at Kelowna from Jun 2016 – Jan 2020**
Source: (Water Office, 2020)

2.0 Results & Discussion

2.1 Physical

2.1.1 Temperature

Okanagan Lake is a deep monomictic lake. This means that typically from May to November each year, the surface water (epilimnion) is thermally isolated from the deep water (hypolimnion) by a thermocline. The sun warms the epilimnion to over 20 °C each summer while water below 20 m changes temperature by less than 4 °C annually (Figure 2.1-1).

The three southern sites (Summerland, Kelowna, and OK Centre) exhibit similar thermal behavior while the northern Armstrong Arm site is shallower and behaves differently. The later reaches a higher surface temperature and experiences oxygen depletion in the deep water each summer (Figure 2.1-1). Thermal stratification in Okanagan Lake breaks down each November and the water column freely circulates through the winter. There were no statistically significant trends in the 2011–2019 temperature data either annually, seasonally, or monthly (Mann-Kendall trend tests).

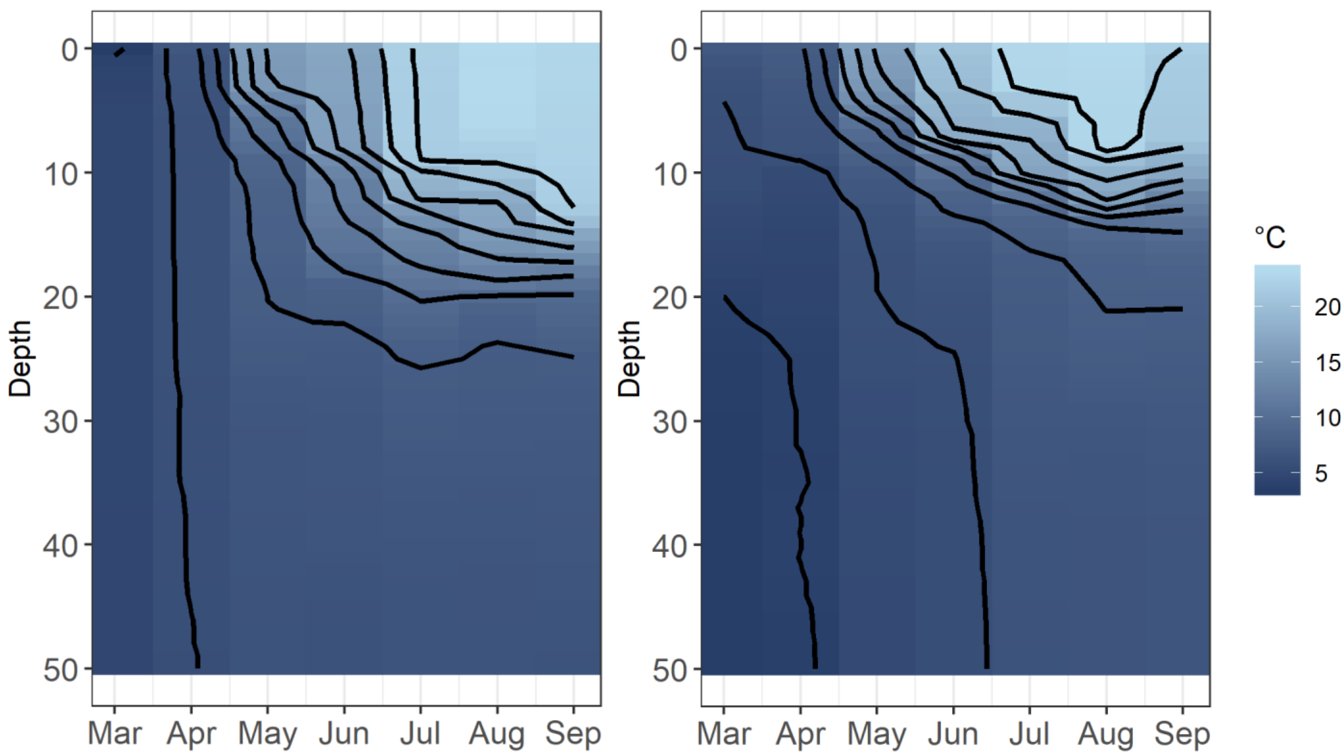

Figure 2.1-1: Temperature profiles for Okanagan Lake at Summerland (left) and Armstrong Arm (right), 2019

Lines represent contours of same temperature or dissolved oxygen within the water column through time.

Surface water temperatures of Okanagan Lake at all four sites was close to average throughout 2019 (Figure 2.1-2).

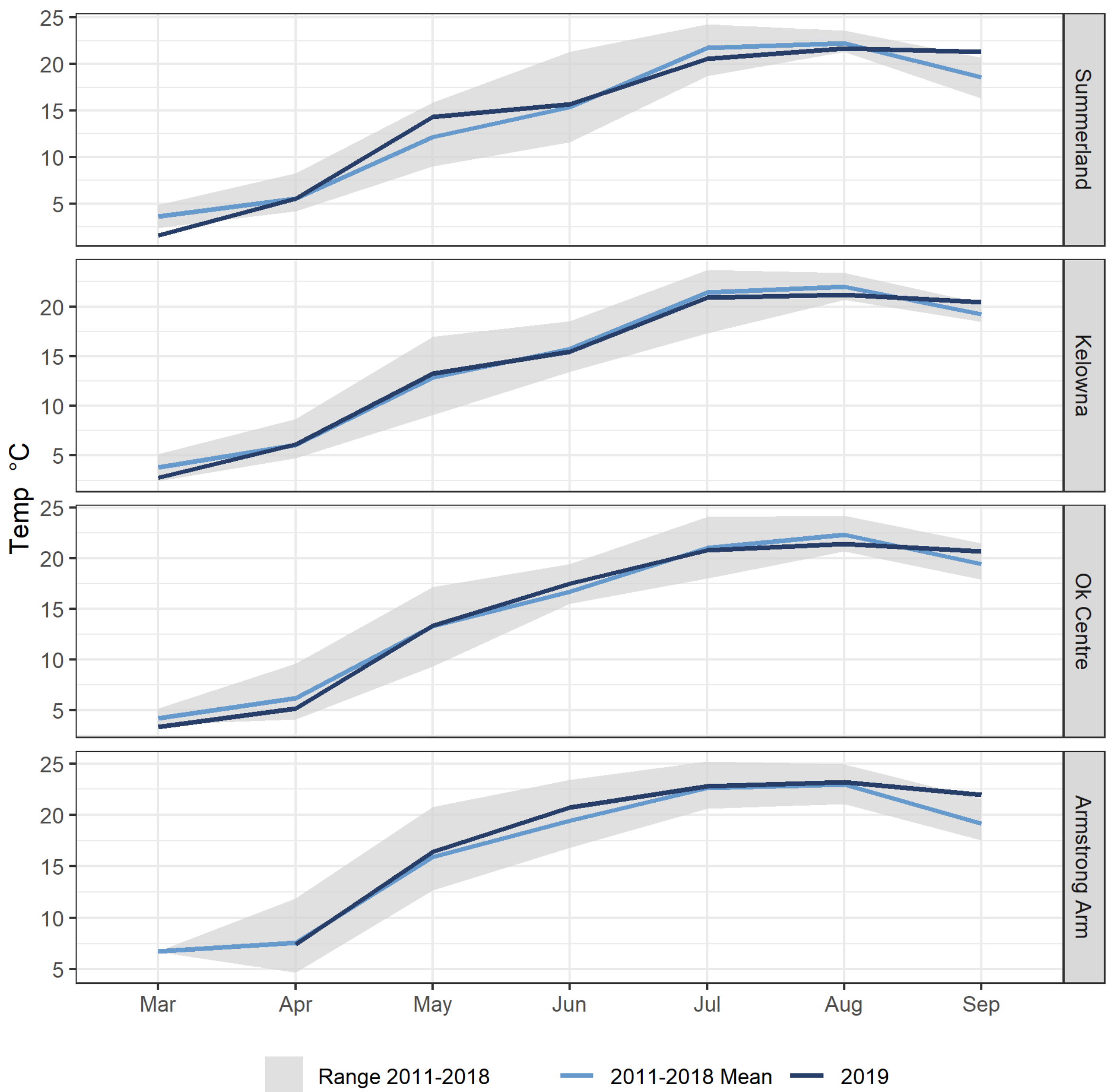

Figure 2.1-2: Temperature at Okanagan Lake sampling sites during 2019 compared to 2011-2018

2.1.2 Water Clarity and Secchi Depth

Secchi depth during 2019 ranged from a minimum of only 1.2 m at Armstrong Arm in August to a maximum of 13.7 m at Summerland in March (Table 2.1-1). Secchi depth averages returned to near the historical average after the below average water clarity of 2018 (**Error! Reference source not found.**, Figure 2.1-3). Armstrong Arm was the only site to fail to meet the objective during 2019, a significant improvement compared to 2018 when all sites failed to meet the water clarity objectives. The overall average for Okanagan Lake historically has been 6.5-6.6 m and averaged 7.2 ± 3.2 m in 2019 (Andrusak et al., 2006; Nordin, 2005).

Secchi depth followed a consistent pattern each year. Maximum Secchi depths occurred in the late-winter when biological activity was the lowest. During the spring algae bloom and freshet, the Secchi depth dropped dramatically to the lowest of the year at all sites. As nutrients were used up, algae concentrations diminished and water clarity increased through the summer and into the fall (Figure 2.1-3).

The Secchi depth in the Armstrong Arm was much lower throughout 2019 than at the other sites in Okanagan Lake. This is clearly illustrated in Figure 2.1-3. There were no statistically significant year-over-year trends in the Secchi depth data from 2011-2019 but there was a distinct drop in Secchi during 2017-2018 (Figure 2.1-4).

Table 2.1-1: Growing Season (Apr-Sep) Secchi depth in meters at Okanagan Lake sampling sites, 2019

Site	Objective	Average	StdDev	Max	Min
Summerland	7.0	8.9	3.0	13.7	5.4
Kelowna	6.0	8.1	2.8	12.0	4.3
Ok Centre	6.0	8.0	3.1	12.9	3.5
Armstrong Arm	5.0	4.0	1.2	5.5	2.6

Note: Objective refers to growing season average (Apr-Sep); Coloured shading indicates status of objective during that year with green meaning met objective and red meaning failed to meet objective

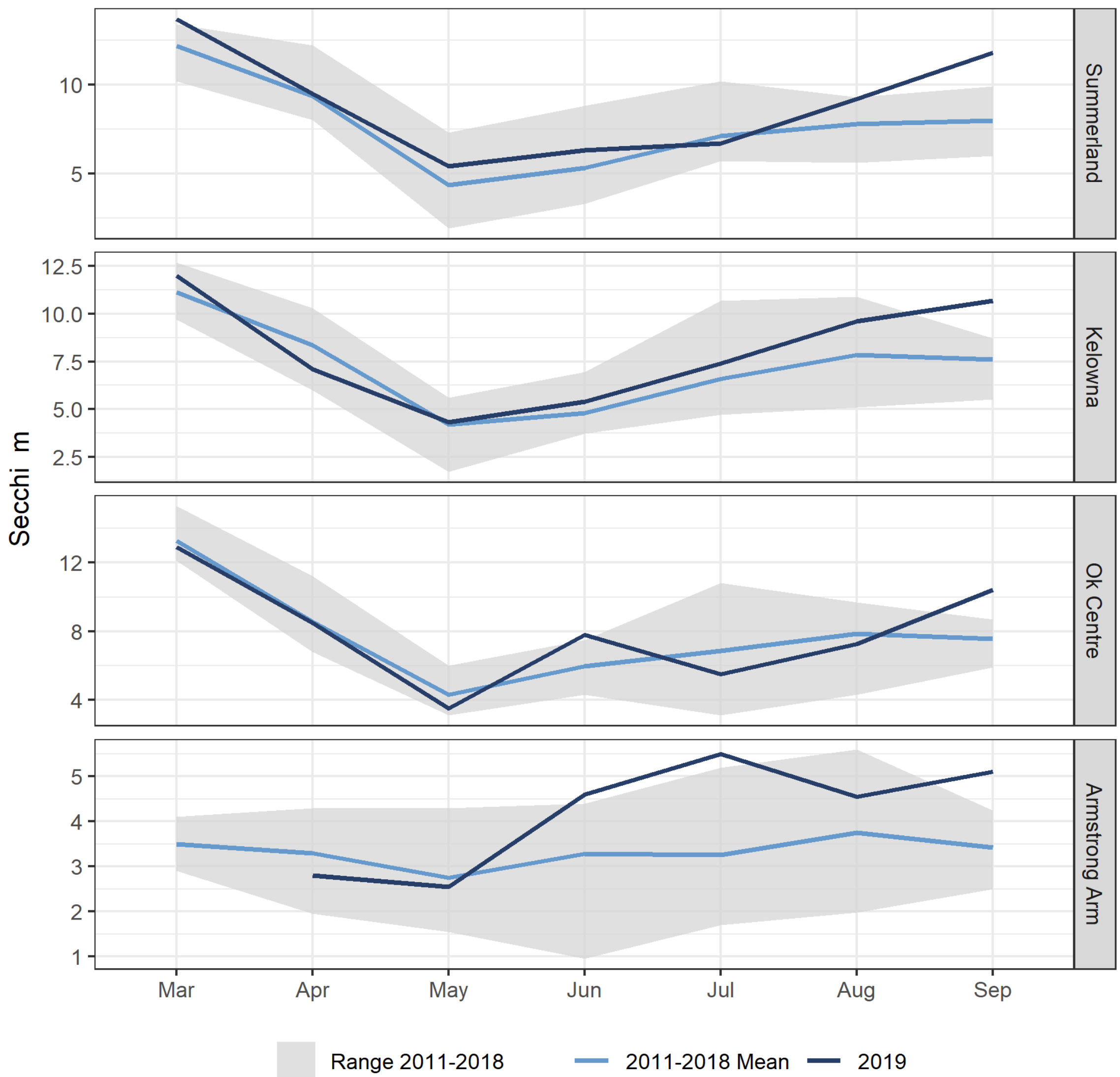

Figure 2.1-3: Secchi depth at Okanagan Lake sampling sites during 2019 compared to 2011-2018

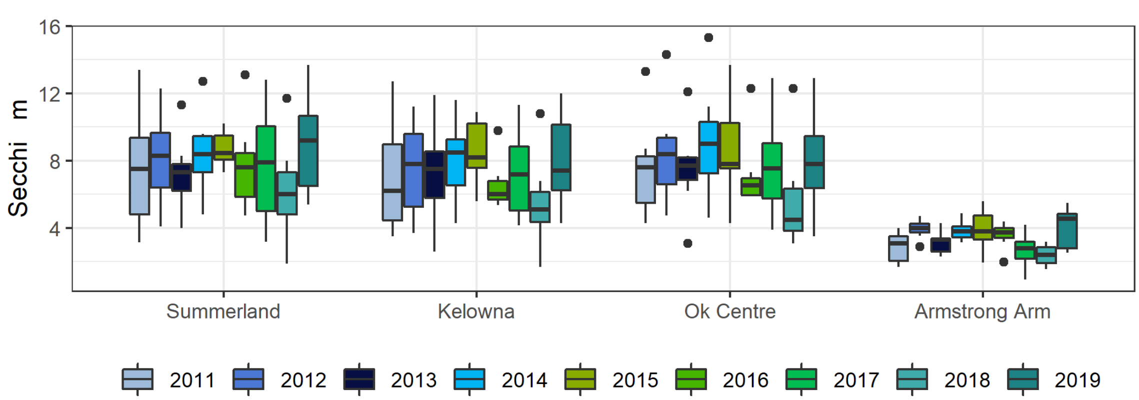

Figure 2.1-4: Secchi depth in Okanagan Lake at Kelowna during Summer (June-Aug) from 2011-2019

2.2 Chemistry

Chemistry sampling focused on dissolved oxygen, nitrogen and phosphorus (the most important aquatic nutrients) and silica, a key micronutrient. Increasing nutrient trends are frequently the result of human activities such as wastewater effluent disposal, riparian degradation, agriculture, fertilizer use, storm water, etc. These human-caused impacts are gradual and are easiest to detect as year-over-year trends. As the database grows, it will become easier to separate climatic impacts from human impacts.

2.2.1 Dissolved Oxygen

Dissolved oxygen (DO) is essential for all aquatic animals. Low DO will stress fish and possibly preclude them from certain portions of the water column. Anaerobic conditions occur when DO is very low (≤2 mg/L) and this has a profound impact on water chemistry through the mobilization of nutrients and metals from the sediment. The three southern sites (Summerland, Kelowna, and OK Centre) exhibit similar thermal and dissolved oxygen behavior while the northern Armstrong Arm site is shallower and behaves differently. The later reaches a higher surface temperature and experiences oxygen depletion in the deep water each summer (Figure 2.2-1). Oxygen depletion is caused by decomposition of organic material in the sediment and deep water. The Armstrong Arm is the only site with a dissolved oxygen objective (>5 mg/L in bottom water), a threshold that it fails to meet every year. By September 2019, the low dissolved oxygen zone (volume below red line in Figure 2.2-1) had expanded to 21 m thick while there was no fully anaerobic water (≤2 mg/L) during 2019, an improvement over the particularly large 2018 low-oxygen zone.

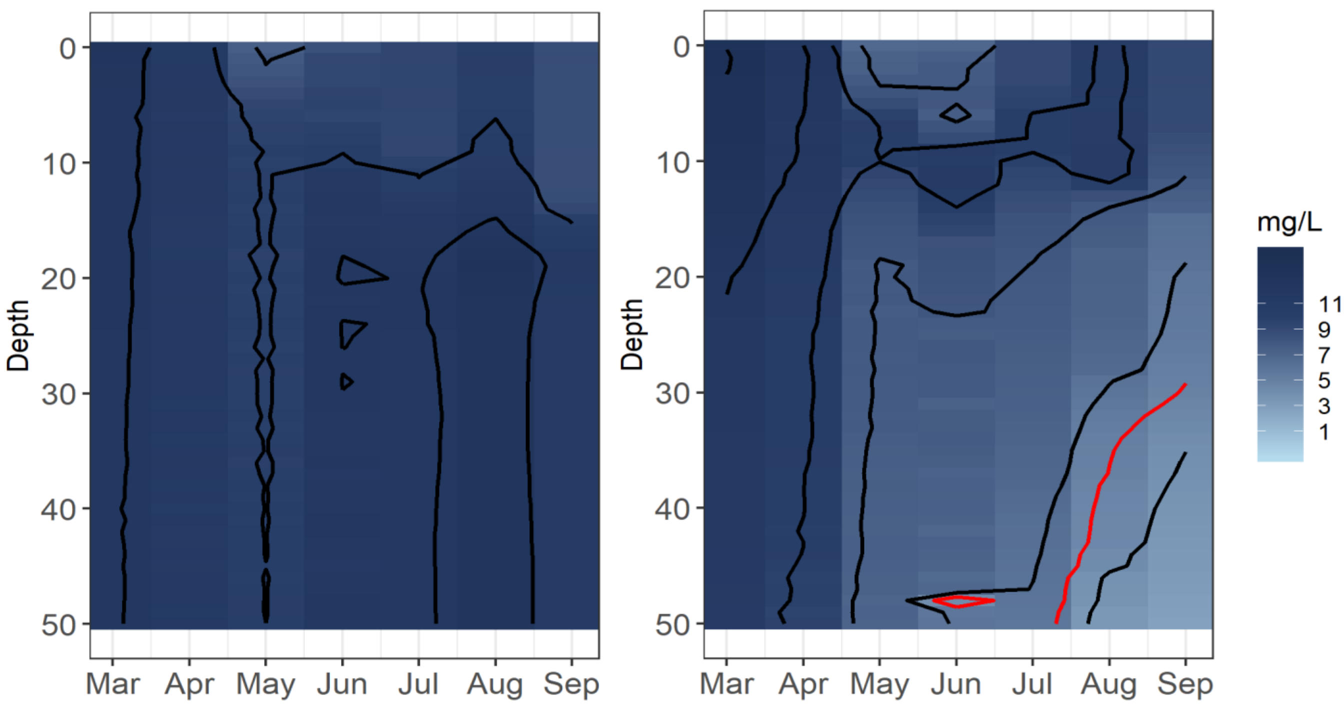

Figure 2.2-1: Dissolved oxygen profiles for Okanagan Lake at Summerland (left) and Armstrong Arm (right) during 2019

Dissolved oxygen profile illustrates high dissolved oxygen concentrations at Summerland and characteristic oxygen depletion in deep waters of the Armstrong Arm. Lines represent contours of same dissolved oxygen within the water column through time. Note: The red line on dissolved oxygen plot represents Water Quality Objective; all water below this line does not meet the objective.

Surface dissolved oxygen concentrations vary throughout the year and have been stable throughout the lake from 2012-2019[1] (Figure 2.2-2).

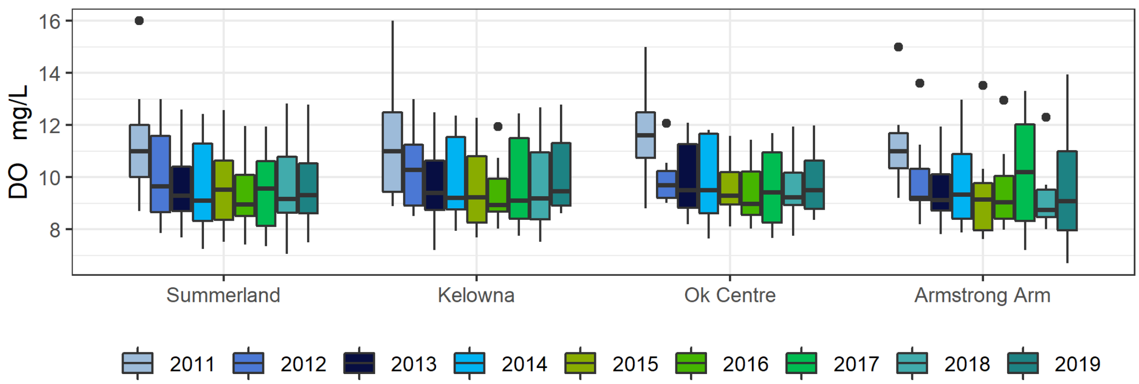

Figure 2.2-2: Surface dissolved oxygen concentrations at Okanagan Lake sampling sites grouped by year, 2011-2019

2.2.2 Silica

Diatoms, a major group of algae in Okanagan Lake, use silica (measured as dissolved silica) as a structural building block for their cell walls. While no objectives for silica concentrations in Okanagan Lake have been set, monitoring continues as it is a key micronutrient for this important group of algae. Silica sampling shifted to only March and September beginning in 2015 because it did not change significantly over the course of the growing season from 2011-2014. Silica was higher in the Armstrong Arm than the three southern sites which were similar to each other during most years (Table 2.2-1, Figure 2.2-3). Silica increased at all sites from 2013-2018 but there was a decline at all sites during 2019. The decrease in silica may relate to the large diatom concentrations observed at Kelowna and Summerland during 2019 (Figure 2.3-6) because diatoms take-up dissolved silica reducing its concentration (Schelske, 1988).

Table 2.2-1: Silica concentration in mg/L at Okanagan Lake sampling sites, 2019

Site	Average	StdDev	Max	Min
Armstrong Arm	7.49	0.85	8.23	6.36
Kelowna	7.48	0.80	8.13	6.34
Ok Centre	7.14	0.84	7.84	5.98
Summerland	7.60	1.50	9.09	5.74

[1] DO concentrations in 2011 were above average and including this year in the trend analysis generates artificial decreasing trends. Previous reports identified these decreasing trends as an area of concern but additional years of data have revealed that DO is stable in Okanagan Lake.

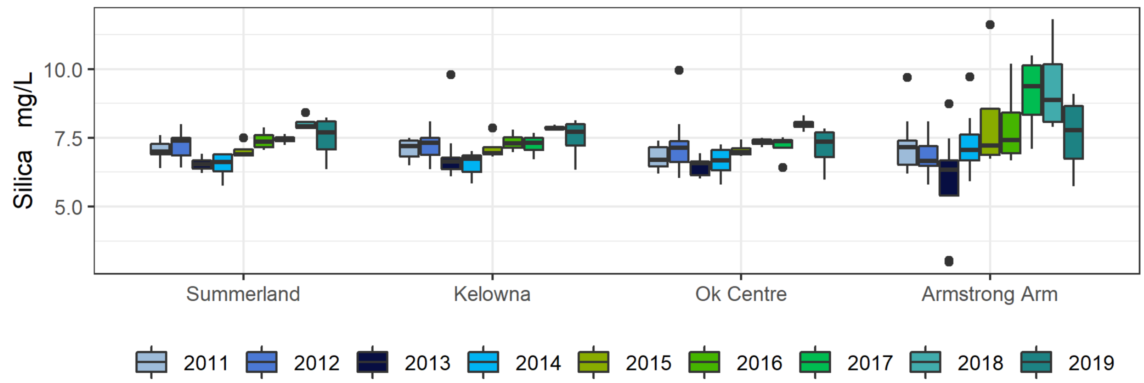

Figure 2.2-3: Silica concentration in Okanagan Lake at each sampling site by year with trends highlighted, 2011-2019

2.2.3 Nitrogen and Phosphorus

Nitrogen and phosphorus are the most important nutrients in most aquatic environments. Nutrient limitation occurs when an essential element (typically nitrogen or phosphorus) is in relatively short supply. Algae production is limited by the availability of that nutrient despite potential abundance of other nutrients. In the Okanagan, phosphorus is the main limiting nutrient and its concentration is directly linked to the amount of algae that the lake produces (Nordin, 2005).

Nitrogen

Total nitrogen (TN) averaged 0.255 ± 0.038 mg/L as N in Okanagan Lake during 2019 (**Error! Reference source not found.**). The objective for Okanagan Lake was set as a spring value (March sample date) of 0.230 mg/L for the main basins and 0.250 mg/L for the Armstrong Arm. The objective was exceeded at the three southern sites while the Armstrong Arm met the objective during 2019. TN increased in the Armstrong Arm from 2011-2018 (Mann-Kendall, $p<0.001$) but fortunately the trend appears to have stabilized or reversed since 2017 and was stable at the three southern sites (Table 2.2-2).

Table 2.2-2: Total nitrogen in mg/L as N concentration at Okanagan Lake sampling sites, 2018

Site	Depth	Objective	Exceeded in 2019?	Trend	Avg	SD	Max	Min
Summerland	<10m	0.230	Yes	-	0.231	0.028	0.255	0.198
	>20m		Yes	-	0.278	0.036	0.346	0.248
Kelowna	<10m	0.230	Yes	-	0.229	0.021	0.262	0.202
	>20m		Yes	-	0.267	0.031	0.332	0.246
Ok Centre	<10m	0.230	Yes	-	0.231	0.021	0.267	0.205
	>20m		Yes	-	0.256	0.057	0.373	0.194
Armstrong	<10m	0.250	No	↑	0.248	0.023	0.292	0.228
Arm	>20m		No	↑	0.296	0.022	0.319	0.257

Note: Statistical significance of general trends derived from all data for a site may disappear when depths are split apart due to smaller sample size; Objective is lower at the southern sites leading to exceedances there despite lower overall concentrations

Nitrate increased in the Armstrong Arm throughout the water column (Mann-Kendall, $p<0.001$; Figure 2.2-4) and in the hypolimnion throughout the entire lake from 2011-2019 (Mann-Kendall, $p<0.001$). Analysis of the entire Okanagan Lake water chemistry database indicates that this trend has been ongoing for decades (Figure 2.2-5). This suggests a connection to human activities in the region because the trend has continued through several wet-dry climate cycle.

Nitrate is rapidly consumed by algae in the epilimnion each spring and thermal stratification prevents replenishment from the deeper water during the summer (Figure 2.2-4). Nitrate increased dramatically each summer in the hypolimnion of the Armstrong Arm because of chemistry associated with the low-DO conditions, rising from 0.0032 mg/L as N in the epilimnion to 0.113 mg/L as N in the hypolimnion by Sept 2019. Average TN values were comparable to those found in the literature for Okanagan Lake (0.17-0.23 mg/L as N; Andrusak et al.,2000).

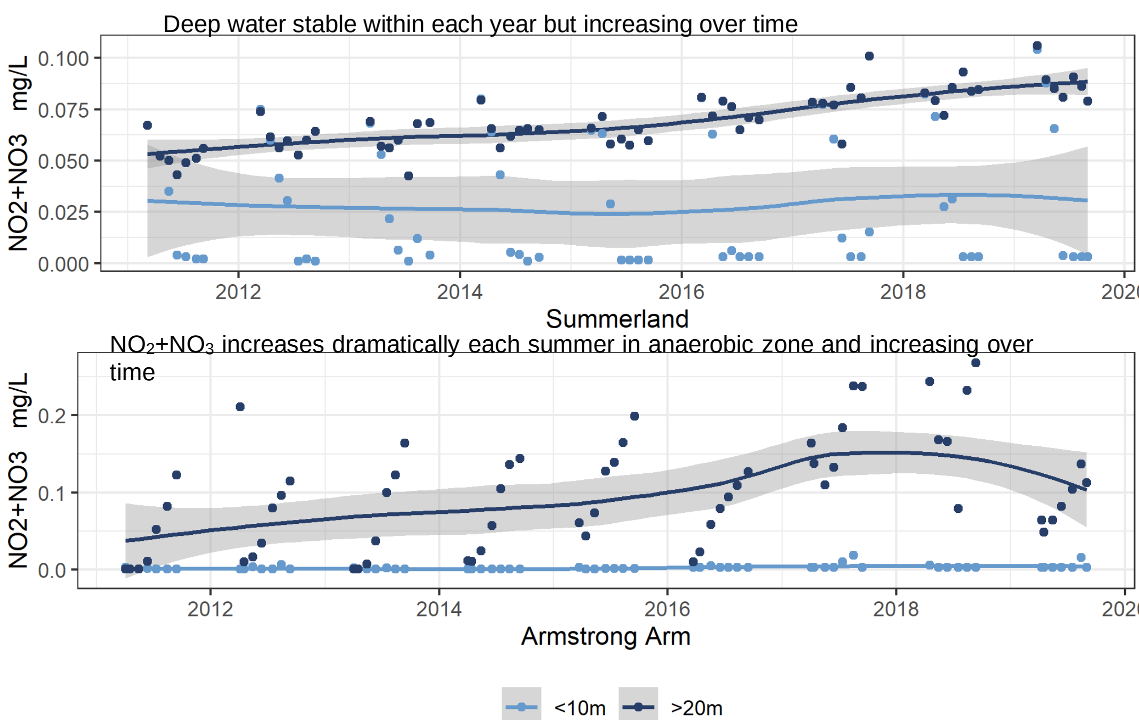

Figure 2.2-4: Nitrite (NO_2) + nitrate (NO_3) in mg/L as N in the surface and deep water of Okanagan Lake at Summerland and in the Armstrong Arm, 2011-2019
Note: Different scales between Summerland and Armstrong Arm

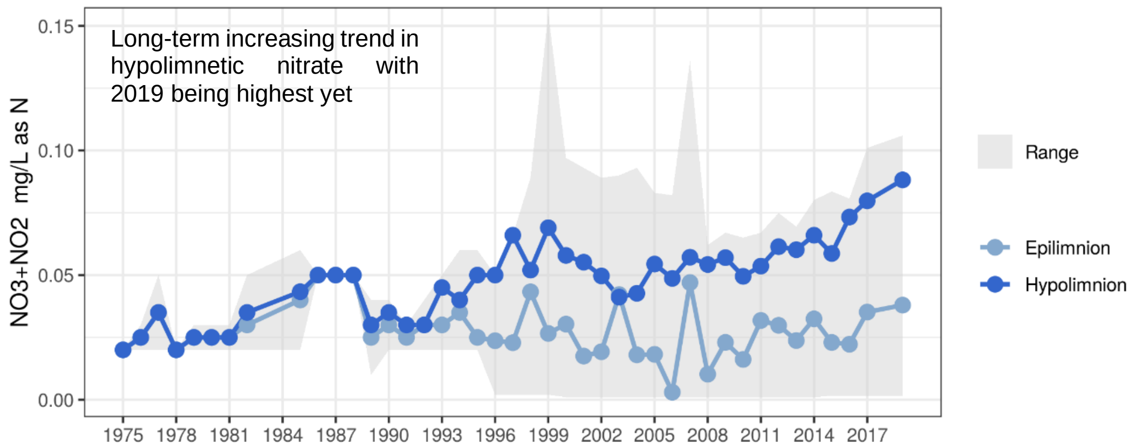

Figure 2.2-5: Nitrate + nitrite in Okanagan Lake at Summerland from 1975-2019 illustrating clear increasing trend in hypolimnetic nitrate

Phosphorus

Total phosphorus (TP) measures all forms of phosphorus including those that may not be bioavailable. Total phosphorus averaged 0.008 ± 0.006 mg/L as P across Okanagan Lake during 2019 (Table 2.2-3). The TP objective for Okanagan Lake applies to the maximum phosphorus concentration at the spring overturn (Nordin, 2005; taken as March). The objectives range from 0.007 mg/L in the south basin to 0.010 mg/L in the Armstrong Arm. The TP objective was exceeded in the epilimnion and hypolimnion of Armstrong Arm in 2019. There were increasing trends in TP at both depths in the Armstrong Arm (MK test, p≤0.002), and Okanagan Centre (Epilimnion; MK test, p=0.002) from 2011-2019 (Table 2.2-3, Figure 2.2-6). The trends in TP were driven by the high phosphorus results from 2017 and 2018, caused by the intense freshets and flooding during those years. TP includes phosphorus associated with suspended sediment carried into the lake and it increases in Okanagan Lake during wet years and decreases during dry years (see 2017 comprehensive report).

Table 2.2-3: Total phosphorus (mg/L as P) at Okanagan Lake sampling sites, 2018

Site	Depth	Objective	Exceeded in 2019?	Trend	Avg	SD	Max	Min
Summerland	<10m	0.007	No	-	0.004	0.001	0.005	0.003
	>20m		No	-	0.004	0.000	0.005	0.004
Kelowna	<10m	0.008	No	-	0.007	0.004	0.016	0.003
	>20m		No	-	0.004	0.001	0.006	0.003
Ok Centre	<10m	0.008	No	↑	0.007	0.002	0.010	0.004
	>20m		No	-	0.005	0.001	0.006	0.004
Armstrong	<10m	0.010	Yes	↑	0.010	0.005	0.019	0.004
Arm	>20m		Yes	↑	0.018	0.008	0.031	0.012

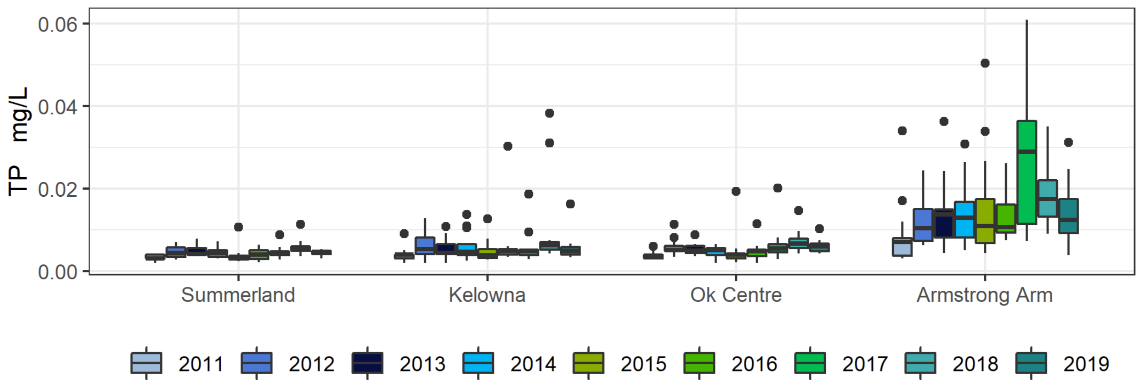

Figure 2.2-6: Total phosphorus in Okanagan Lake at the four sampling sites by year, 2011-2019

Note: increasing trends related to wet-dry climate cycle, 2017-2018 = wet years

Dissolved phosphorus (DP) measures the more bioavailable forms of phosphorus and is a good indicator of potential impacts to biota. Dissolved phosphorus increased dramatically from 2011-2017 in the Armstrong Arm but declined again from 2017-2019. There were also small increasing trends in DP at Okanagan Centre (Mann-Kendall, $p<0.001$). Ortho-phosphate measures only the soluble reactive phosphorus fraction of the DP. No significant trends in ortho-phosphate data occurred at the three southern sites but a significant increasing trend was detected in the Armstrong Arm hypolimnion (Mann-Kendall, $p=0.03$). The increasing trend DP and ortho-P in the Armstrong Arm indicates anthropogenic sources.

N:P Ratio

The ratio of nitrogen to phosphorus is a key factor in determining which types of phytoplankton will proliferate. Many species of cyanobacteria can fix atmospheric nitrogen and are therefore limited primarily by available phosphorus. These algae are more likely to bloom when phosphorus is abundant relative to nitrogen. The Okanagan Lake objective for the spring ratio of nitrogen to phosphorus is >25:1 in March samples. All three southern sites met the objective in 2019 while the Armstrong Arm had higher phosphorus concentrations than the rest of Okanagan Lake and did not meet the objective in 2098 (Figure 2.2-6, Table 2.2-4). The N:P ratio (TN:TP) decreased in the Armstrong Arm and at Okanagan Centre from 2011-2019 (Mann-Kendall, $p<0.05$) (Figure 2.2-6). The decline at Okanagan Centre may indicate that elevated nutrients from the Armstrong Arm are affecting the main body of the Lake that far south and causing similar trends but at a reduced scale.

Table 2.2-4: Ratio of average TN to average TP during spring at Okanagan Lake sampling locations, 2019

Site	Depth	TN	TP	Avg Ratio	Objective	Exceeded in 2019?	Trend
Summerland	<10m	0.254	0.0053	48:1	>25:1	No	-
	>20m	0.260	0.0049	53:1	>25:1	No	-
Kelowna	<10m	0.262	0.0056	47:1	>25:1	No	-
	>20m	0.246	0.0059	42:1	>25:1	No	-
Ok Centre	<10m	0.237	0.0068	35:1	>25:1	No	↓
	>20m	0.255	0.0063	49:1	>25:1	No	↓
Armstrong Arm	<10m	0.558	0.0326	17:1	>25:1	Yes	↓
	>20m	0.611	0.0252	24:1	>25:1	Yes	↓

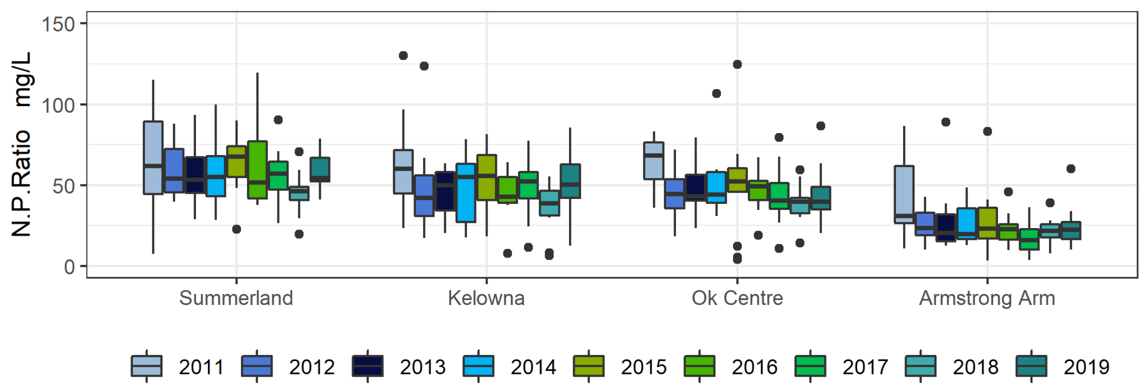

Figure 2.2-7: Nitrogen to phosphorus ratio at Okanagan Lake sampling sites 2011-2019

2.3 Biology

2.3.1 Phytoplankton

Phytoplankton and zooplankton samples were taken at the Summerland and Kelowna sites. Biomass analysis and taxonomic identification were performed on samples from both sites. Chlorophyll-a concentrations were monitored at all sites as a productivity metric for phytoplankton abundance. The Armstrong Arm of Okanagan Lake is shallower and has the potential to produce more phytoplankton and zooplankton than the deep basins of Okanagan Lake regardless of human activity.

Chlorophyll-a

Chlorophyll-a is a photosynthetic pigment found in most freshwater algae species and in many photosynthetic bacteria. As expected, chlorophyll-a followed an inverse trend to Secchi depth (Figure 2.1-3, Figure 2.3-1). Chlorophyll-a was lowest in the late winter and peaked in April-May during the spring algae bloom before decreasing through the summer (Figure 2.3-3). During 2019, chlorophyll-a concentrations met the objectives at all sites but the growing season average was very close to the Armstrong Arm Objective (Table 2.3-1). The Armstrong Arm failed to meet the chlorophyll-a objective during 2017 and 2018 because of blooms fueled by nutrients from the flooding during those years. Spring chlorophyll-a concentrations were high in June in the Armstrong Arm, at up to 10.4 µg/L chl-a and were sufficient to colour the entire Arm green (Table 2.3-1, Figure 2.3-2).

In most years, including 2019, there was a north to south decreasing trend in the chlorophyll-a data with the Armstrong Arm having the highest and Summerland having lowest average concentrations. A significant increasing trend for chlorophyll-a occurred at all sites except Summerland from 2011-2019 (Mann-Kendall, $p \leq 0.004$). The increasing trends at Kelowna and Okanagan Centre were related to the high chlorophyll-a concentrations during 2018 while in the Armstrong Arm, there were year-over-year increases 2011-2019 (Figure 2.3-1).

Table 2.3-1: Chlorophyll-a in µg/L at Okanagan Lake sampling sites, 2018

Site	Objective	Exceeded in 2019?	Trend	Average	StdDev	Max	Min
Summerland	4	N	-	1.68	0.91	3.51	0.84
Kelowna	4.5	N	↑	2.51	1.26	4.55	1.20
Ok Centre	4.5	N	↑	2.37	1.82	6.28	0.90
Armstrong Arm	5	N	↑	4.95	3.06	10.40	1.90

Note: Based on growing season only (Apr-Sep)
Note: Increase at Ok Centre based on increase between 2015 and 2016

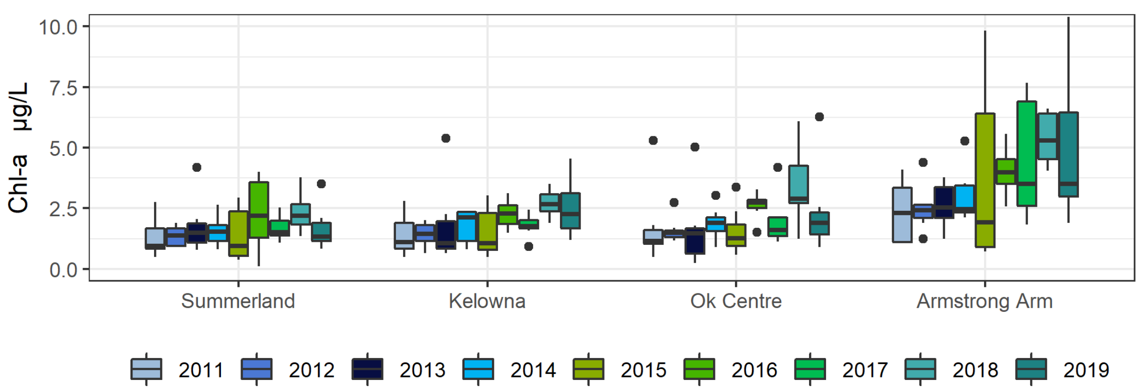

Figure 2.3-1: Annual chlorophyll-a concentration at the four Okanagan Lake sampling sites, 2011-2019

Figure 2.3-2: Water colored green with algae at Armstrong Arm in May 2019

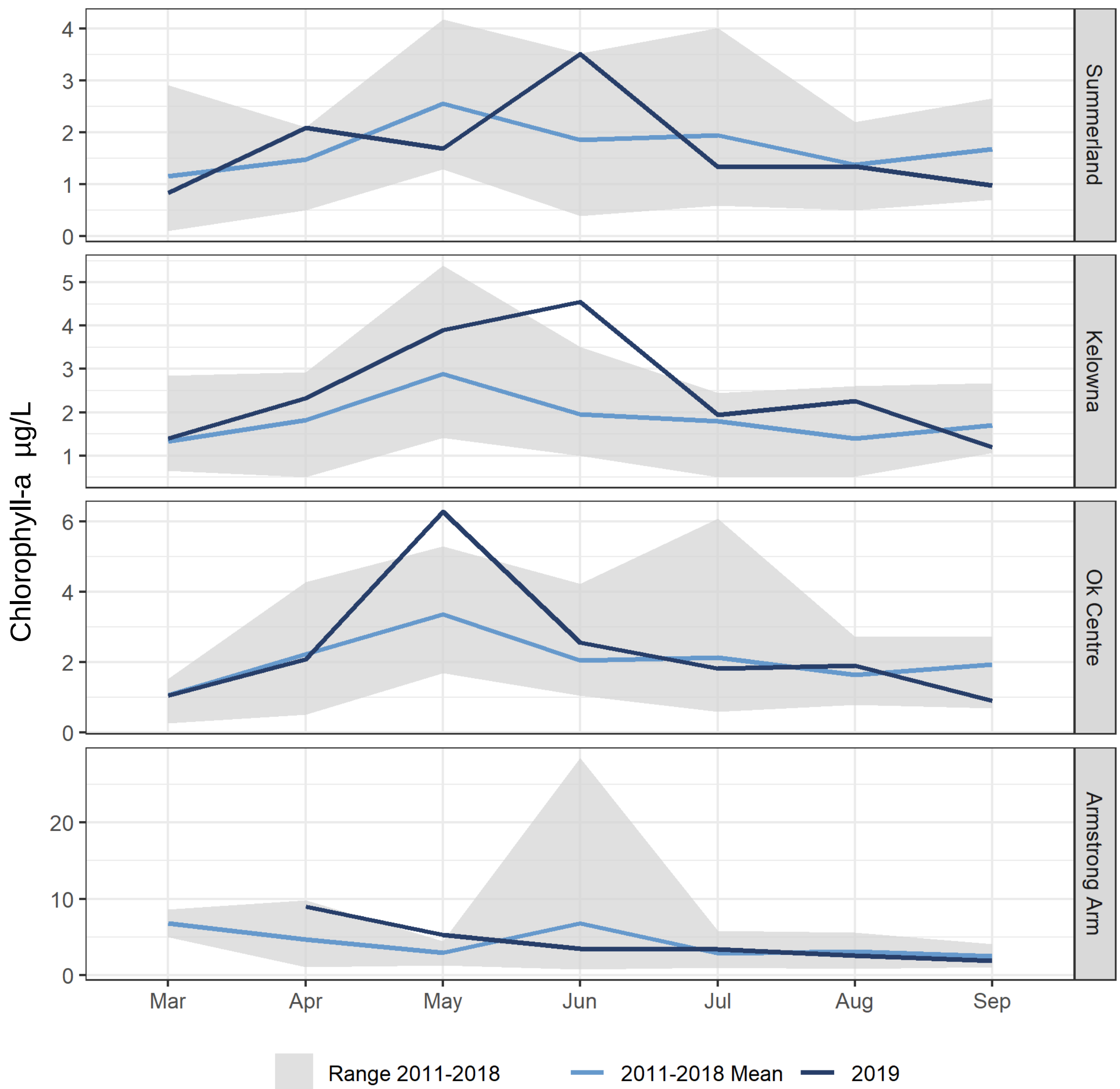

Figure 2.3-3: Chlorophyll-a at Okanagan Lake sample sites during 2019 compared to 2011-2018

Biovolume

Phytoplankton biovolume samples were collected as one litre composites from 1-10 m and the biovolumes were determined taxonomically. From 2011-2014, biomass was determined using ash-free dry mass (AFDM). It is not possible to directly compare the results from the two methodologies and only the 2015-2019 results are considered here.

All samples from Summerland were below the objective of 0.75 µL/L with a growing season average of 0.29 µL/L during 2019 (Table 2.3-2). At Kelowna, there was a diatom bloom (*Tabilleria sp.*) that increased biovolume to a maximum of 2.14 µL/L (185% of objective) and caused a growing season average of 0.82 µL/L during 2019. This was the first year that any site did not meet the phytoplankton biovolume objective. Diatom cells are relatively large and will disproportionately affect biovolume compared to very small cyanobacteria cells.

Phytoplankton biovolume increased significantly from 2015-2019 at Summerland (MK test, p=0.004) and Kelowna (MK test, p=0.002), a trend that matches chlorophyll-a and is related to the increase in nutrients during the large 2017 and 2018 freshets (Figure 2.3-4). A 1-year lag has been observed between wet years and elevated productivity in Okanagan Lake and this explains why 2019 production was very high despite the much smaller freshet.

Table 2.3-2: Phytoplankton biovolume in µL/L at Okanagan Lake sampling sites, 2019

Site	Obj	Apr	May	Jun	Jul	Aug	Sep	Avg	SD
Kel.	<0.75	0.0713	0.0939	**0.9852**	**2.1370**	**1.6062**	0.0407	**0.8223**	0.9028
Sum.	<0.75	0.0340	0.1239	0.3671	0.7015	0.4013	0.1393	**0.2945**	0.2463

Note: Growing season average based on Apr-Sep only

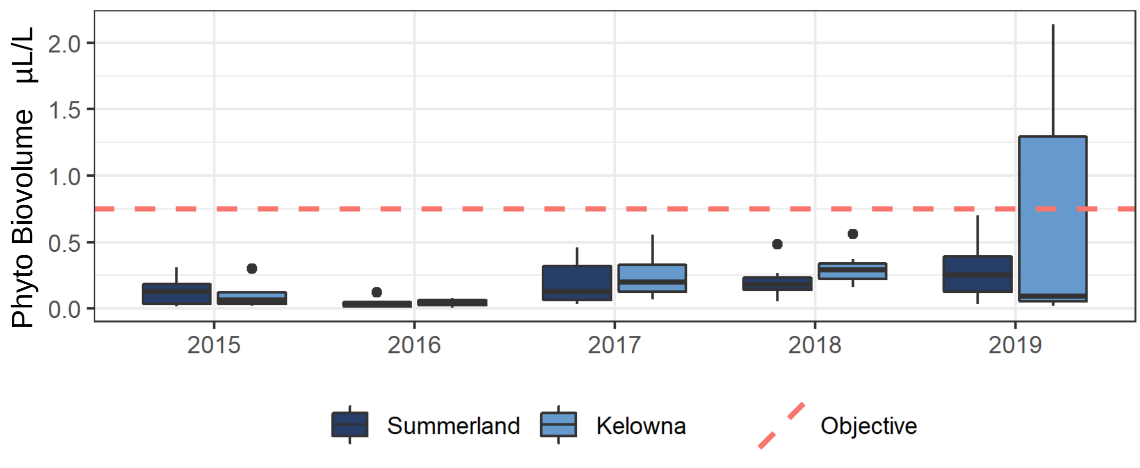

Figure 2.3-4: Phytoplankton Biovolume at Summerland and Kelowna, 2015-2019

Phytoplankton Taxonomy

Algae samples were identified to the species level and then grouped into broad algae types for analysis in this report. Diatoms tend to bloom in the spring and their numbers decrease through the summer. Diatom densities were lower in 2015-2019 than in 2011-2014 although the cause is not clear but may relate to the decreasing trend in the N:P ratio that would favour cyanobacteria; cyanobacteria were more numerous from 2015-2019 compared to 2011-2014. Cyanobacteria were always numerous throughout the growing season in Okanagan Lake, but typically peaked in the late-summer. Cyanobacteria dominated the algae counts at 6,842 cells/mL in the Kelowna June 2019 sample (Figure 2.3-5, Table 2.3-3).

Algae counts, led by cyanobacteria counts, were moderate in 2019 and were lower compared to 2018 despite higher biovolume because of fewer cyanobacteria that affect counts but do not meaningfully contribute to biovolume (Figure 2.3-6).

Table 2.3-3: Average phytoplankton counts by major algae groups in cells/mL, 2019

	2019 Averages	
Algae Type	**Kelowna**	**Summerland**
Diatoms	271	140
Greens	88	97
Yellow-Brown	942	436
Cyanobacteria	1986	1367
Dinoflagellates	12	8
Euglenoids	7	7
Total Algae	3307	2054

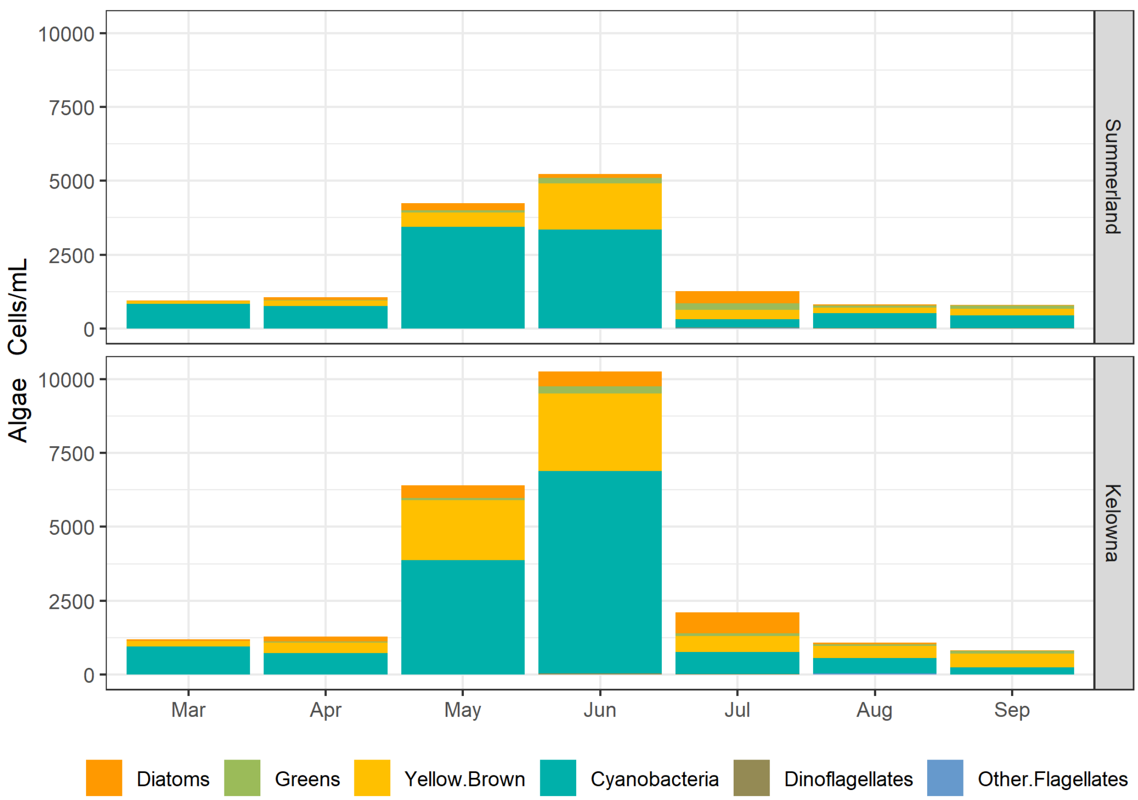

Figure 2.3-5: Taxonomic breakdown of algae by major types at Summerland (top) and Kelowna (bottom), 2019

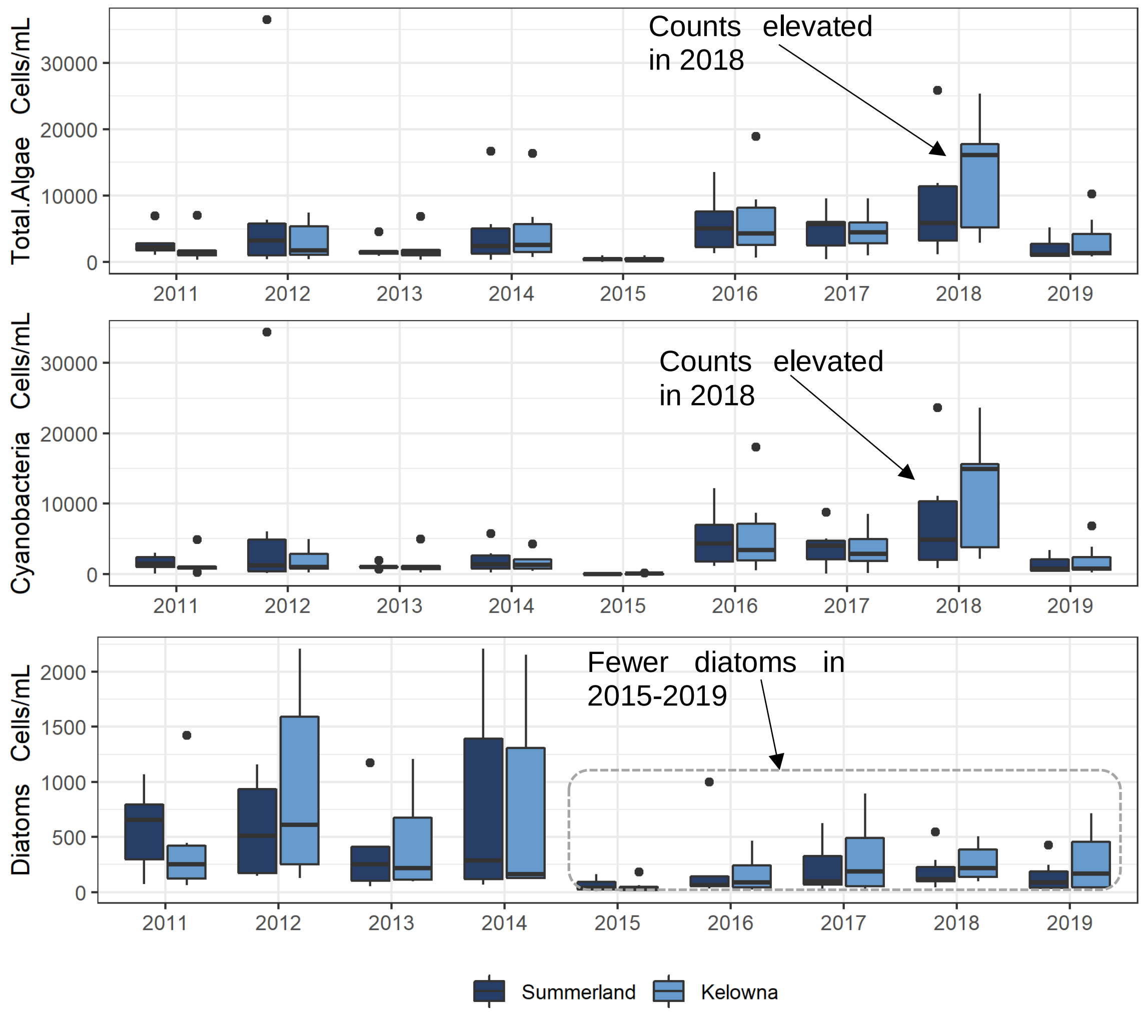

Figure 2.3-6: Total algae, cyanobacteria, and diatom counts at Summerland and Kelowna, 2011-2019

The Okanagan Lake objective for phytoplankton taxonomy states that no more than 5% of total cell counts should be heterocystous cyanobacteria. These phytoplankton can fix atmospheric nitrogen and they can produce toxins that are harmful to human health when they are present in high concentrations. During 2019, 2 of 7 samples exceeded this objective at Kelowna while only 1 of 7 samples exceeded this at Summerland. The maximum heterocystous cyanobacteria percentages occurred during August 2019 with 12% at Kelowna and 11% at Summerland (Figure 2.3-7); this represents fewer and small exceedances than 2018. There were no significant year-over-year trends in the heterocystous cyanobacteria counts from 2011-2019.

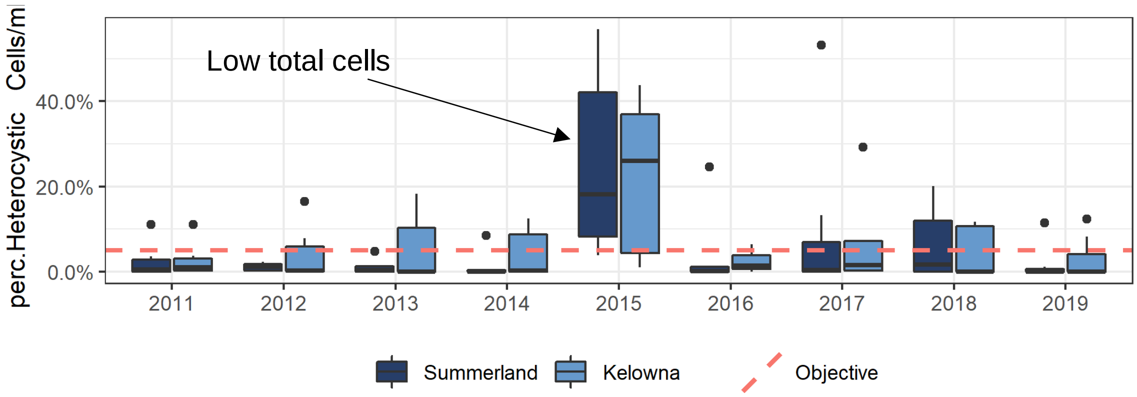

Figure 2.3-7: Percent of total algae counts that were heterocystous cyanobacteria, 2011-2019

2.3.2 Zooplankton

Biomass

Zooplankton biomass samples were obtained using a 150 µm net lowered to 45 m and raised vertically at a rate of approximately 0.5 m/second. The 150 µm net mesh size lets most phytoplankton pass through, while collecting most zooplankton. Samples were identified taxonomically and the biomass was calculated from the abundance. There was an issue with sample preservation in 2019 and the April to July samples were lost.

The Okanagan Lake objective is a growing season average of >50 µg/L (Nordin, 2005). This objective was met at Kelowna but not at Summerland in 2019. Summerland did not meet this objective in 2016, 2017, or 2019 (Table 2.3-4). There were no significant trends in zooplankton biomass from 2015-2019 beyond the interannual variation.

Table 2.3-4: Zooplankton biomass in µg/L at Okanagan Lake sampling sites, 2019

Site	Objective	Avg	SD	Max	Min	Trend
Kelowna	>50	**51.6**	25.3	74.7	24.5	-
Summerland	>50	**34.9**	31.1	68.2	6.5	-

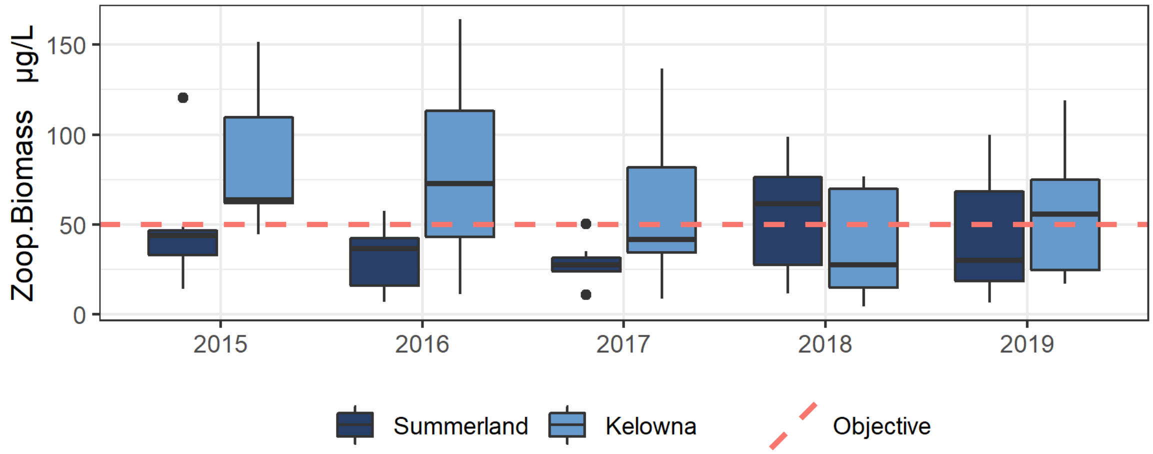

Figure 2.3-8: Zooplankton Biomass at the Kelowna and Summerland sampling locations by year, 2015-2019
Notes: There was a change in lab methodology in 2015, preventing comparison with previous years' data; Sample preservation issues resulted in the loss of April-July samples during 2019

Zooplankton Taxonomy

Zooplankton samples were taxonomically identified to the species level and then grouped for analysis in this report. Copepods were the most numerous and averaged 75% at Kelowna and 76% at Summerland in 2019 (Table 2.3-5).

The objective for Okanagan Lake is a minimum of 5% of the sample counts be cladocerans. 33% of samples at Kelowna and 60% of samples at Summerland met the objective during 2019. The Okanagan Lake average was 6 % of zooplankton counts were cladocerans during 2019. Since this program began in 2011, only 2013 and 2019 have had growing season averages above the zooplankton taxonomic objective.

The average zooplankton abundances were consistent with values found in the literature (Andrusak et al., 2000; Rae and Andrusak, 2006; Andrusak et al., 2006). There were no longer term year-over-year trends in the zooplankton taxonomic data.

Table 2.3-5: Growing Season average zooplankton by major taxonomic groups, 2019

Zooplankton Type	Kelowna	Summerland
Copepods	75%	76%
Cladocerans	**6%**	**7%**
Rotifers	19%	17%
Mysids	0%	0%
Chironomids	0%	0%
Total Zooplankton	100%	100%

3.0 Conclusions

3.1

This report summarizes the 2019 results and extracts trends from the data accumulated by the Okanagan Lake Collaborative Sampling program to date (2011-2019). Weather during 2019 was average for the Okanagan, a welcome reprieve after the extreme weather of 2017 and 2018. The results to date indicate that the Armstrong Arm is impacted by human activities and watershed degradation. This site had the most exceedances and the most problematic trends, that is, trends moving parameters towards greater exceedances and poorer water quality.

Dissolved Oxygen Each year the temperature of Okanagan Lake increases seasonally in the surface waters until the lake becomes thermally stratified, usually in May. This physical dynamic isolated the deep water from the atmosphere and leads to oxygen depletion below the thermocline in Armstrong Arm. The Armstrong Arm therefore failed to meet the dissolved oxygen objective in 2019, as it has in each year of this study, but the thickness of the low-oxygen zone was much smaller than 2018.

Nutrients
Silica analysis of water samples revealed increasing trends in silica concentrations.

Total nitrogen has been stable at the southern sites but increased in the Armstrong Arm from 2011-2019. Total nitrogen exceeded the water quality objectives at the three southern sites during 2019. Nitrate increased significantly in the Armstrong Arm and in the hypolimnion at all sites from 2011-2019. This is part of a decades long increasing trend in hypolimnetic nitrate in Okanagan Lake that has continued through multiple wet-dry climate cycles and is likely caused by increasing human impacts within the Okanagan region.

Phosphorus concentrations were highest in the Armstrong Arm where they exceeded the objective during 2019. There were increasing trends in TP from 2011-2019 at Okanagan Centre and particularly in the Armstrong Arm where the increase was greatest. The Armstrong Arm is more heavily impacted by human activities and has numerous phosphorus sources and the rise in TP at Okanagan Centre may indicate that the impact of nutrient enrichment in the Armstrong Arm is extending into the north basin. Dissolved phosphorus (DP) and ortho-P represent the more bioavailable forms of phosphorus and were stable at the southern sites while DP increased at the Armstrong Arm. Samples from the Armstrong Arm exceeded the nitrogen-phosphorus ratio objective in 2019, with a decreasing trend in that ratio from 2011-2019 because of increased TP over the same time.

Phytoplankton Productivity Chlorophyll-a concentrations increased each spring during the annual spring bloom and then decreased over the summer and into the fall. Chlorophyll-a was high in the Armstrong Arm while the southern sites decreased compared to 2017-2018 but remained above their 2011-2019 averages. Previous research by ENV has identified a one-year lag between major nutrient inputs and increases in phytoplankton productivity so it was expected that 2019 productivity would be high even though there was a normal freshet. There was an increasing year-over-year trend detected for chl-a at the Armstrong Arm and Okanagan Centre from 2011-2019. Chlorophyll-a concentrations in the Armstrong Arm were close to the objective of 5 µg/L but the objective was met at all sites during 2019. Phytoplankton biovolume exceeded the objective at Kelowna during 2019 and increased from 2015-2018 at Kelowna and

Summerland. The particularly high Kelowna biovolume was caused by a diatom algae bloom.

The taxonomic data indicated that cyanobacteria numerically dominated the phytoplankton samples in 2019, as in every year studied, while overall counts were comparable to previous years and down from the very high 2018 results. Samples from Kelowna and from Summerland exceeded the phytoplankton objective of <5% of algae as heterocystous cyanobacteria during 2019 although the number and scale of exceedances were smaller than 2018.

Zooplankton Productivity Zooplankton biomass was stable from 2015-2019. Zooplankton biomass met the objective of >50 µg/L at Kelowna but not at Summerland during 2019. Copepods numerically dominated most samples. The water quality objective of >5% of zooplankton as cladocerans was achieved in one third of the samples from Summerland while two thirds of Kelowna samples met the objective in 2019.

Table 3.1-1 and Table 3.1-3 summarize the findings of this report for 2019 by pairing trends to objective exceedances. Special focus should be paid to parameters that did not meet the objective and for which the data trended in the adverse direction over the course of the sampling program.

The following areas of concern have been identified that may require further investigation on the part of the Ministry:

- Chronically low Secchi depth in the Armstrong Arm
- Increasing nitrate in hypolimnion of Okanagan Lake since 1970s
- Increasing total phosphorus and dissolved phosphorus in the Armstrong Arm
- Decreasing N:P ratio in the Armstrong Arm

Armstrong Arm frequently exceeds most objectives and is the site most at risk of water quality degradation including nuisance algae blooms, poor drinking water quality, anaerobic conditions, and further eutrophication. It must be acknowledged that Armstrong Arm is shallower and therefore would be more productive than the deep basins of Okanagan Lake regardless of human activity. However, human activities in the North Okanagan watershed have impacted this northern-most basin of the lake.

Table 3.1-1: Okanagan Lake Water Quality Objectives and 2019 values with exceedances

Objectives (Nordin, 2005)	**Summerland**	**Kelowna**	**Ok Centre**	**Armstrong Arm**
Secchi Depth (growing season average)	7m	6m	6m	5m
Dissolved Oxygen (minimum in bottom waters)	-	-	-	>5 mg/L
TP (mg/L as P) (maximum at spring overturn)	0.008	0.008	0.007	0.01
Chlorophyll-a (µg/L) (maximum seasonal average)	<4.5	<4.5	<4	<5
TN (mg/L as N) (maximum at spring overturn)	0.230	0.230	0.230	0.250
N:P Ratio (spring weighted ratio)	>25:1	>25:1	>25:1	>25:1
Algae Taxonomy (% heterocystous cyanobacteria)	<5%	<5%	<5%	<5%
Algae Biomass (µL/L) (growing season average)	<0.75	<0.75	<0.75	<0.75
Zooplankton Biomass (µg/L) (growing season average)	>50	>50	>50	>50
Zooplankton Taxonomy (% cladocerans)	>5%	>5%	>5%	>5%

Table 3.1-2: Attainment of Okanagan Lake water quality objectives in 2019

Objective	**Summerland**	**Kelowna**	**Ok Centre**	**Armstrong Arm**
Secchi Depth	8.9	8.1	8.0	4.0
Dissolved Oxygen	10.00	10.11	10.69	2.70
TP (mg/L) 0:10m:	0.004	0.007	0.007	0.010
20-45m:	0.004	0.004	0.005	0.018
Chlorophyll-a (µg/L)	1.68	2.51	2.37	4.95
TN (mg/L) 0-10m:	0.231	0.229	0.231	0.248
20-45m:	0.278	0.267	0.256	0.296
N:P Ratio 0-10m:	53:1	41:1	37:1	30:1
20-45m:	64:1	62:1	51:1	18:1
Algae Taxonomy (% heterocystous cyanobacteria)	2%	3%		
Algae Biomass (µg/L)	0.295	0.822		
Zooplankton Biomass (µg/L)	34.9	51.6		
Zooplankton Taxonomy (% cladocerans)	7.0%	6.0%		

Legend:

Met objective in 2019	Did not meet objective in 2019	No Data/ No Objective

Table 3.1-3: Summary of trends and the water quality objectives for Okanagan Lake collaborative sampling program. Modified from Nordin 2005.

Objective	Summerland	Kelowna	Ok Centre	Armstrong Arm
Secchi Depth	-	-	-	-
Dissolved Oxygen	-	-	-	-
TP (mg/L)	-	-	↑	↑
Chlorophyll-a (µg/L)	-	↑	↑	↑
TN (mg/L)	-	-	-	↑
N:P Ratio	-	-	↓	↓
Algae Taxonomy (% heterocystous cyanobacteria)	-	-		
Algae Biomass (µL/L)	↑	↑		
Zooplankton Biomass (µg/L)	-	-		
Zooplankton Taxonomy (% cladocerans)	-	-		

Legend:

Met objective in 2019	Did not meet objective in 2019	No Data/ No Objective
↑ = Increasing Trend	↓ = Decreasing Trend	- = No Trend

4.0 Recommendations

The Okanagan Collaborative Program is currently in a three-year (2018-2020) term. No changes to the sampling program are recommended at this time. However, if additional funding is available, adding phytoplankton taxonomy to the Armstrong Arm samples would be useful, given the impacts at that site, and the potential for cyanotoxin production.

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6.0 Appendices

6.1 Appendix 1: 2019 Sampling Data

All data used in this report can be found in the data transfer file
MoE-Synth-DB.xlsx

6.2 Appendix 2: Statistics and Graphing Overview

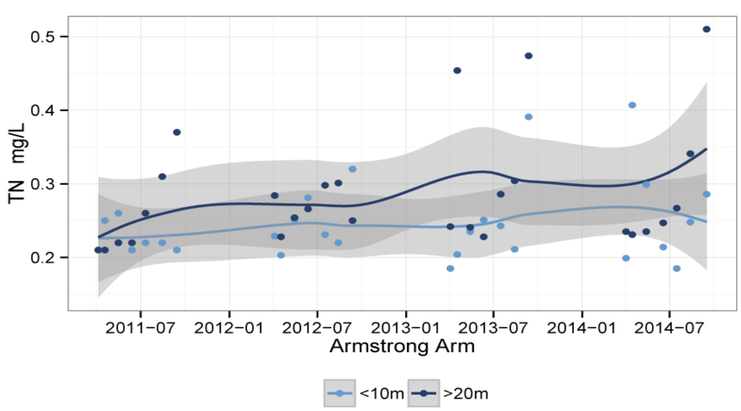
Statistical analyses were performed on data to support interpretations made throughout this report. The use of the word 'significantly' within this report is understood to signify that the claim being made has stood up under statistical analysis. Unless otherwise stated, all statistical analyses were performed to a confidence of greater than or equal to 95% ($p \leq 0.05$). The ± symbol indicates plus or minus the standard deviation throughout this report.

Water quality data often contains non-detect values for many parameters. Non-detect values were converted to ½ detection limit for all calculations.

Trends were determined through Mann-Kendall linear regression. Mann-Kendall is a non-parametric test for linearity in data. The test produces a Tau-value and a p-value. The Tau value gives the direction of the data and the p-value indicates whether the trend is statistically significant.

Throughout this report the monthly sampling data was grouped seasonally for additional analyses. March, April, and May data were combined as "Spring"; June, July, and August as "Summer"; and September as "Fall".

Correlations were performed using the Pearson's Correlation method and all R values reported at Pearson's Correlation Coefficients.



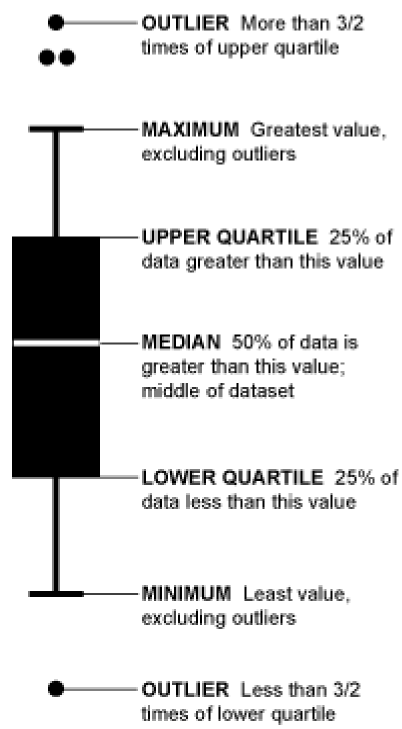


Figure i: Example scatterplot and boxplot
Includes all data for a parameter sorted by depth, LOESS polynomial trendlines and the standard errors of those trendlines are also included. Example boxplot is labeled with key information. Whiskers represent the distance to the highest or lowest point within 1.5 * IQR where IQR represents the range between the upper and lower quartiles.

How to Read Temperature/DO Profile Plot

Temperature and dissolved oxygen profiles were routinely collected as part of this study. They are displayed in several locations throughout this report. An example of a temperature graph and a dissolved oxygen graph, descriptions of their key features and how to read them are presented here.