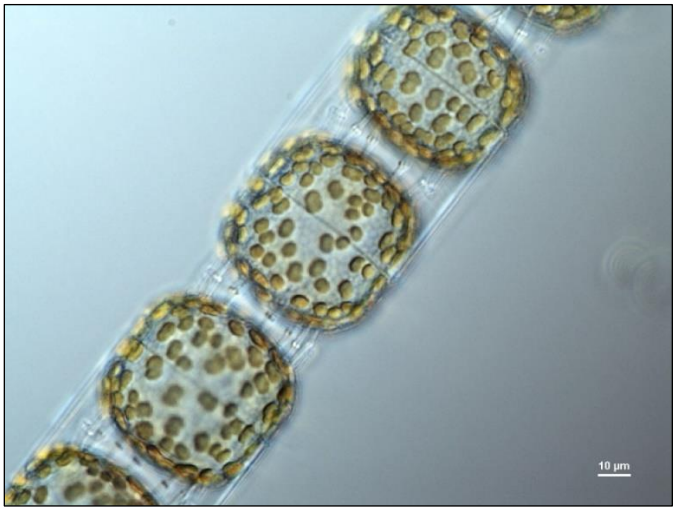
Marine Conditions 2008–2019 Report Series: Chlorophyll and Pheophytin



December 2022

King County

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Marine Conditions 2008–2019 Report Series: Chlorophyll and Pheophytin

Submitted by:

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Cover photo: *Stephanopyxis palmeriana* photographed by Gabriela Hannach

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Department of
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Acknowledgements

The author would like to thank the King County Environmental Laboratory Field Science Unit for sample collection and the Conventionals Unit for sample analysis. Katherine Bourbonais and Erin McCabe provided laboratory project management. Brian Prosch, the Conventionals Unit Supervisor, provided data review.

Daniel Nidzgorski, King County Water and Land Resources Division, provided technical assistance with R Studio and conducted the statistical trend analyses.

Citation

King County. 2022. Marine Conditions 2008–2019 Report Series: Chlorophyll and Pheophyton Results. Prepared by Kimberle Stark, Water and Land Resources Division, Seattle, Washington.

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1.0 INTRODUCTION

For over 50 years, King County has conducted extensive water quality monitoring to assess conditions in King County marine waters within the Central Puget Sound Basin. The King County Marine Monitoring Program is managed by scientists in the Water and Land Resources Division within the Department of Natural Resources. The program includes two types of monitoring (1) baseline monitoring to assess background conditions (ambient monitoring) and (2) monitoring to assess conditions near King County's wastewater treatment plant (TP), combined sewer overflow (CSO), and CSO wet weather treatment station (TS), and marine outfalls (outfall monitoring).

The goals of the Marine Monitoring Program are to characterize water quality and food web (phytoplankton and zooplankton) conditions in King County receiving waters, provide information for management decisions, and evaluate the status and trends of marine waters within King County. These data provide insight into both short and long-term variations and form a baseline from which water quality and food web conditions can be assessed on multiple temporal and spatial scales. Please see *Marine Conditions Report Series 2008-2019: Marine Monitoring Program Overview* (King County, 2022a) for a more detailed description of the background and purpose of the Marine Monitoring Program.

The Marine Monitoring Program collects data for multiple types of media and parameters. This report presents results for the chlorophyll and pheophtyin monitoring component of the program collected between 2008 and 2019 as well as long-term trend analysis for chlorophyll *a*. These data are used to:

- Assess potential water quality impacts following TP upset discharges by comparing against historical data.
- Assist in special studies such as siting new wastewater treatment plant outfalls (King County, 2001).
- Evaluate how primary producers (phytoplankton) respond to nutrients and potential effects to the Puget Sound food web.
- Provide an understanding of the Puget Sound food web lower trophic levels within the Central Basin.
- Measure variability in biomass over seasonal and interannual cycles.
- Assist in development of lower food web indicators.
- Assess influences of large-scale and regional climate patterns on phytoplankton abundance. Support regional efforts and collaborations such as the Puget Sound Ecosystem Monitoring Program (PSEMP) Marine Waters Workgroup, Puget Sound Marine Waters Annual Report (PSEMP Marine Waters Workgroup, 2019), Puget Sound Phytoplankton and Primary Productivity Vital Sign Indicator Development effort, Washington Dept. of Ecology's Nutrient Reduction Effort, and regional modeling efforts.
- Evaluate how phytoplankton respond to climate and water conditions.

Chlorophyll is a green pigment produced by algae and other green plants and used during the process of photosynthesis to convert light, carbon dioxide, and water to sugar. Chlorophyll *a* and *b* are the two main types of chlorophyll pigments. Chlorophyll *a* is present in all phytoplankton species and is the primary light absorbing pigment involved in photosynthesis while chlorophyll *b* is an accessory pigment. The Marine Monitoring Program measures both chlorophyll *a* and chlorophyll using laboratory and in situ methods. However, in situ fluorescence methods cannot distinguish between chlorophyll *a* and *b* therefore results are reported as chlorophyll; whereas laboratory methods specifically measure chlorophyll *a* (see Section 2.0).

The amount of chlorophyll present is often used as a proxy for phytoplankton biomass. However, while there is generally good agreement between chlorophyll concentration and phytoplankton biomass, the amount of chlorophyll in each cell varies with algal species and environmental conditions. Therefore, chlorophyll does not always provide an accurate estimate of phytoplankton biomass. Pheopigments, such as pheophytin *a.* are degradation products of chlorophyll and produced when phytoplankton cells are grazed on by zooplankton. As such, pheopigments can be used as an indicator of physiological condition and amount of grazing on the phytoplankton. High concentrations of pheopigments relative to chlorophyll indicate a high level of grazing. Several factors influence chlorophyll concentrations including amount of solar radiation, grazing, water temperature, nutrient availability, water column stratification, and surface mixing from wind.

Multiple parameters were collected concurrently at each sampling location for both offshore and beach waters. A summary of the types of data collected at each station is provided in *Marine Conditions Report Series 2008–2019: Marine Monitoring Program Overview* (King County, 2022). Results for other Marine Monitoring Program components between 2008–2019 (except pH) are provided in separate reports. These data summary reports are provided in separate reports with hyperlinks (click on titles to access reports) below and include the following topics:

- Marine Monitoring Program overview
- Nutrients in offshore waters
- Nutrients in beach waters
- Dissolved oxygen in offshore waters
- Temperature, salinity, and density in offshore waters
- Temperature and salinity in beach waters
- Water clarity in offshore waters
- Fecal indicator bacteria in beach and offshore waters
- Phytoplankton
- Zooplankton
- Chemical and physical parameters and benthic infauna in beach (intertidal) and offshore (subtidal) sediments

- Chemical parameters in clam tissues.

2.0 METHODS

The following sections describe the sampling locations, field, and laboratory methods used to assess chlorophyll and pheophytin in marine waters. A summary of the data analysis methods is also included. A more detailed description of sampling and analysis methods can be found in the *Marine Offshore and Beach Water Monitoring: Sampling and Analysis Plan* (King County, 2020).

2.1 Sampling Locations

Sampling locations are located within the Puget Sound Central Basin, extending south to Dumas Bay and north to Point Wells. Elliott Bay, a large urban embayment, which includes the City of Seattle waterfront, is located within the monitoring area (Figure 1). The eastern shoreline of Vashon Island and Quartermaster Harbor, an embayment between Vashon and Maury Islands, are also included in the sampling area.

The term 'mainstem' is used to refer to all sampling areas except Elliott Bay and Quartermaster Harbor, while 'offshore' refers to all locations. Stations are designated as either "outfall" or "ambient". Outfall stations are located at/near the end of a TP TS, or CSO discharge point.

Chlorophyll samples from 7 outfall and 7 ambient long-term offshore monitoring stations were collected between 2008 – 2019 (Table 1, Figure 1). In situ fluorescence measurements used to estimate chlorophyll were also collected at four ambient mooring locations over varying timeframes (Table 2, Figure 2).

Table 1. Offshore monitoring stations, depths, and first year of chlorophyll data collection.

Station Locator	Central Basin Region	Station Rationale	Station Type	First Year of Record	Average Station depth (m)
JSUR01	North	**Brightwater TP** outfall diffuser	outfall	2005	178
KSBP01	North	**Point Jefferson** -represents conditions in the northern Central Basin	ambient	1992	262
CK200P	North	**Carkeek Wet Weather TS** outfall	outfall	2000	63
KSSK02	North	**West Point TP** outfall diffuser	outfall	1997	65
LTBC43	Middle – Elliott Bay	**Denny Way/Elliott West Wet Weather TS** outfall	outfall	2005	17.5
LTED04	Middle – Elliott Bay	**Inner Elliott Bay -** represents Elliott Bay conditions	ambient	1997	85

Station Locator	Central Basin Region	Station Rationale	Station Type	First Year of Record	Average Station depth (m)
LSEP01	Middle	**South Plant TP** north outfall diffuser	outfall	1997	185
LSKQ06	Middle	**Alki Wet Weather TS** outfall	outfall	1997	43
LSNT01	Middle	**Point Williams** - represents conditions in mid Central Basin	ambient	1992	205
LSVV01	Middle	**Fauntleroy Cove**	ambient	2007	12.5
MSJN02	South	**Vashon TP** outfall	outfall	2005	63
MSWH01	Quartermaster Harbor	**Inner Quartermaster Harbor -**shallow embayment	ambient	2006	5.5
NSAJ02	Quartermaster Harbor	**Outer Quartermaster Harbor -**shallow embayment	ambient	2006	9
NSEX01	South	**East Passage** - represents conditions in southern Central Basin	ambient	2003	173

Table 2. Mooring stations, depths, and first year of data collection.

Station Locator	Central Basin Region	Station Location	Station Type	First Year of Record	Sampling Depth (m)
SeaQYSI	Middle-Elliott Bay	Seattle Aquarium, near pump house	ambient	2008	1, 10
PTWILLBuoy	Middle	Pt. Williams	ambient	2013	1
MSWH01	Quartermaster Harbor	Inner Quartermaster Harbor	ambient	2008, then 2011	1
NSAJ02	Quartermaster Harbor	Outer Quartermaster Harbor	ambient	2009	~4 – 9.5, depth varies with tide

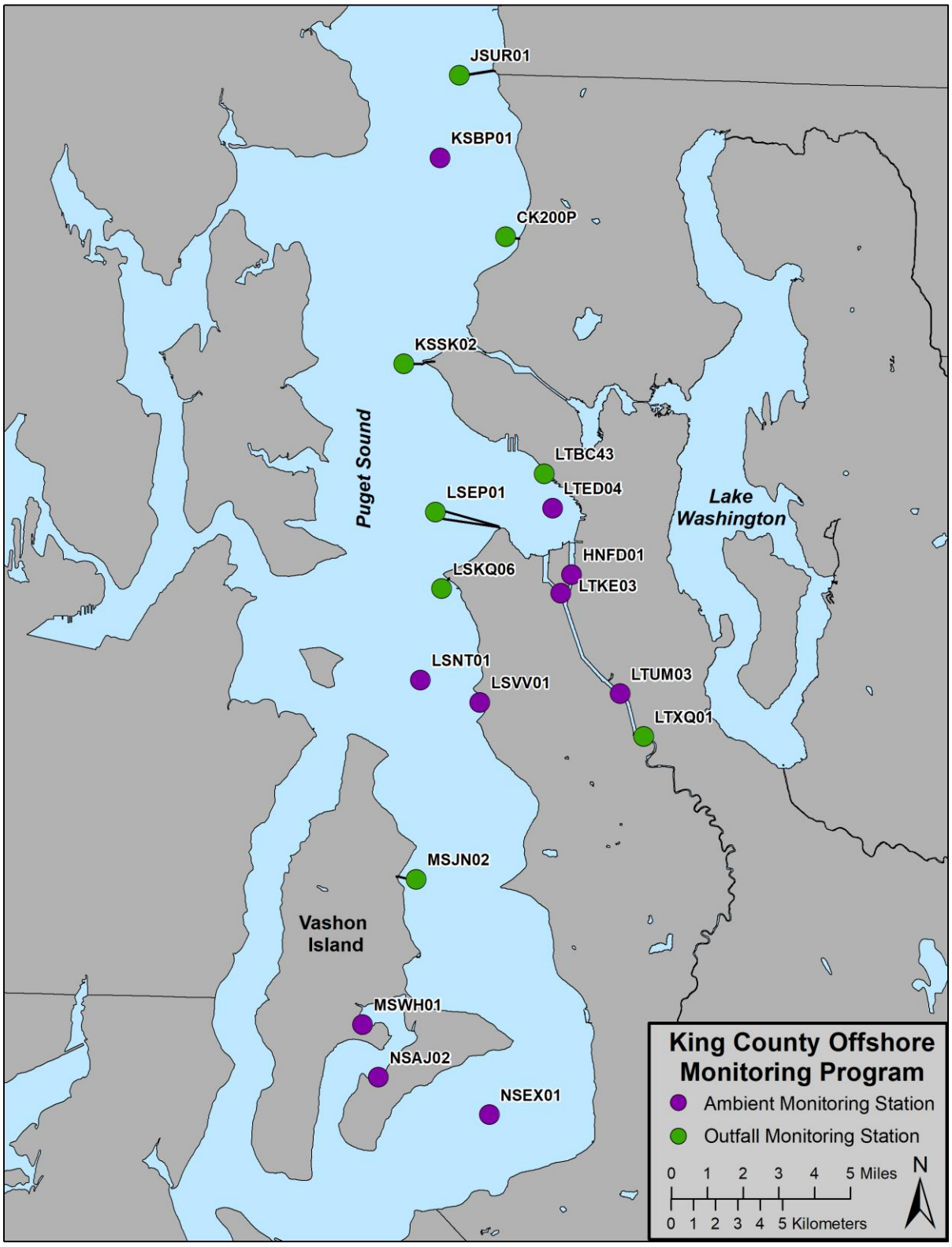


Figure 1. Offshore marine chlorophyll monitoring sampling locations. Note chlorophyll *a* was not sampled at the four Duwamish River stations.

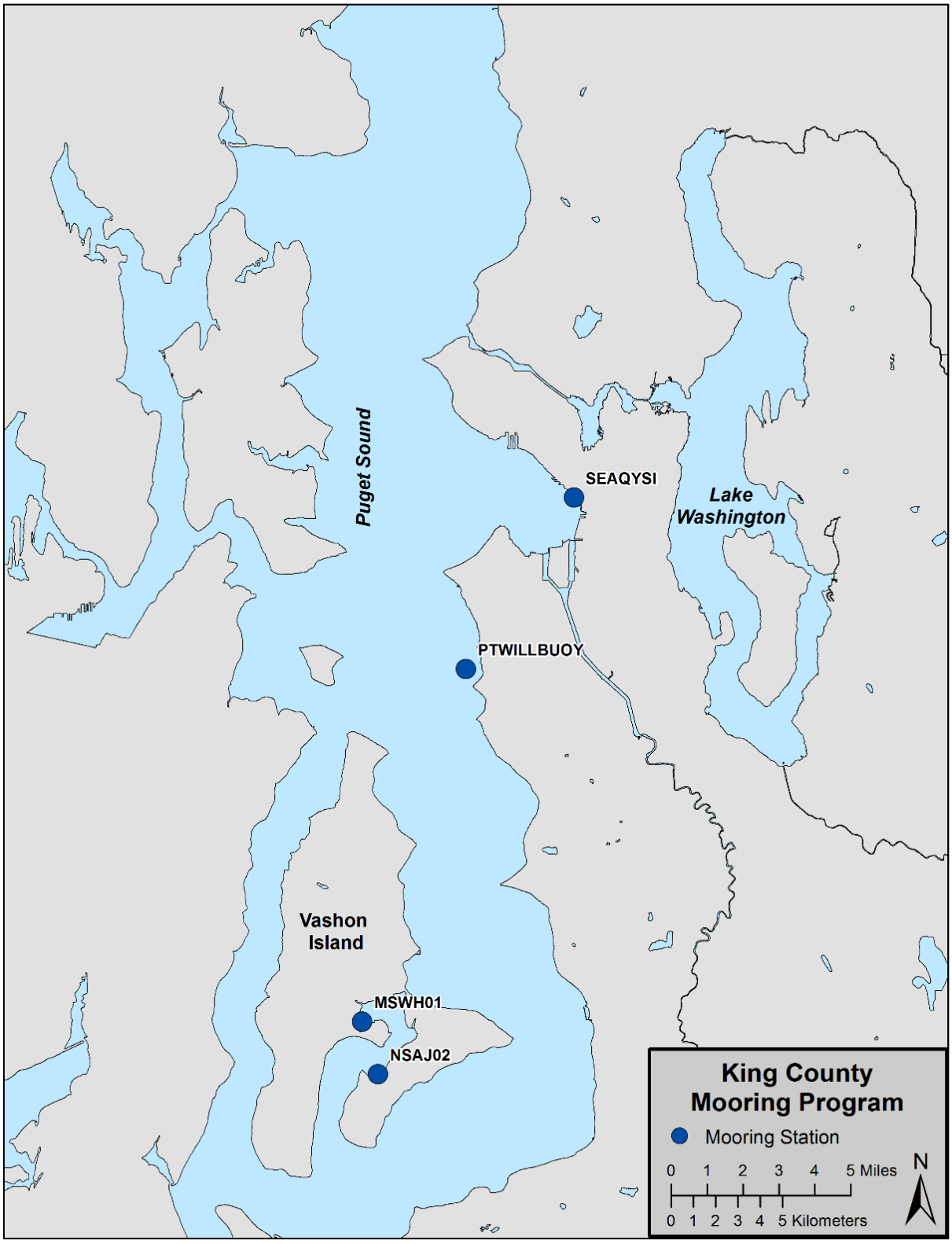


Figure 2. Mooring sampling locations.

2.2 Sampling and Analysis Methods

Samples for chlorophyll *a* and pheophytin *a* laboratory analyses were collected at 1, 15, 25, and 35 m at the 10 stations deeper than 35 m (Table 1). Samples were not collected below 35 m since there is insufficient light for phytoplankton growth below this depth. Samples were collected at 1 m and a deeper depth at the four shallow stations (Elliott West TS outfall-LTBC43, Fauntleroy Cove-LSVV01, inner Quartermaster Harbor-MSWH01, outer Quartermaster Harbor-NSAJ02). The deeper samples were collected at 15 m at the Elliott West TS outfall station and 5 m at the Fauntleroy Cove station. Depth of deeper samples varied with tide height for the two Quartermaster Harbor stations but were generally between 2 – 5.5 m in the inner harbor and 4.5 – 7 m in the outer harbor.

In situ fluorescence measurements used to estimate chlorophyll concentration were made throughout the water column at the 12 stations sampled by boat (all but the two Quartermaster Harbor stations). In situ fluorescence measurements were also collected near the surface at all four moorings as well as 10 m at the Seattle Aquarium mooring. Except for chlorophyll data collected by the moorings, results presented in this report are focused on laboratory measurements since they provide a more accurate quantitative measurement of chlorophyll, particularly when concentrations are high.

Chlorophyll samples were collected monthly from 2008-2013 and then twice monthly from 2014-2019 (monthly in Jan and Dec). From April 2008 - 2014, samples at 1 m and the chlorophyll maximum depth were collected twice monthly at three stations: Point Jefferson (KSBP01), East Passage (NSEX01), and Quartermaster Harbor (NSAJ02). The phytoplankton monitoring component of the Marine Monitoring Program began in 2008 at these three sites and chlorophyll samples were collected concurrently with phytoplankton samples. In situ fluorescence measurements at the mooring locations were collected every 15-minutes.

2.2.1 Field Methods

Offshore water column samples were collected by the King County Environmental Laboratory (KCEL) in accordance with the *Recommended Guidelines for Sampling Marine Sediment, Water Column, and Tissues in Puget Sound* (PSEP; 1991, 1997) and the *Standard Operating Procedure (SOP) for Chlorophyll a and Pheophytin a* (King County, 2007).

All but the two Quartermaster Harbor stations (MSWH01, NSAJ02) were sampled using a KCEL research vessel. Multiple five-liter Niskin bottles were mounted onto the rosette containing the conductivity-temperature-depth (CTD) profiler to collect water samples on the upcast at the pre-determined depths. The rosette was then brought on deck. Samples were placed into appropriate sample containers and held on ice at 4°C until they were transported to the laboratory for analyses.

Samples from the two Quartermaster Harbor (MSWH01 and NSAJ02) stations were collected from docks. Water samples for laboratory analyses were collected using a four-liter Scott bottle lowered by hand via a rope to the selected depth and samples placed into

appropriate sample containers for laboratory analyses. Following collection, samples were placed on ice and held at 4°C and transported to the laboratory.

Field quality control (QC) measures included use of a field filtration blank. Detailed information regarding field methods is provided in the *Marine Offshore and Beach Water Monitoring: Sampling and Analysis Plan (SAP)* (King County, 2020; https://your.kingcounty.gov/dnrp/library/2020/kcr3135/kcr3135.pdf).

YSI 6600 V2 multi-parameter data sondes were used for data collection at the four mooring locations between 2008 - 2016. Between 2017 – 2019, SeaBird HydroCAT-EP (HC-EP) instruments were used. Both instruments included a fluorometric sensor for chlorophyll measurements.

The Seattle Aquarium mooring system (SeaQYSI) is comprised of two sensor arrays that are deployed from the Aquarium's pump house at the end of Pier 59. A weighted-pulley system allows the two instruments to remain relatively consistent at the 1 and 10 m depths. The mooring system at Dockton Park (NSAJ02) is deployed as a fixed, piling-mounted system, one meter above the bottom on the outermost pier at the Dockton Marina. As a fixed system, the water depth fluctuates with tides. The inner Quartermaster Harbor mooring system (MSWH01) is located at the Quartermaster Yacht Club on a floating dock and collects data at approximately one meter. The mooring system located in Central Puget Sound adjacent to Point Williams (PTWILLBuoy) is deployed from an oceanic buoy. Instruments at this location are deployed one meter below the surface.

2.2.2 Analytical Methods

Chlorophyll *a* and pheophytin *a* analyses were conducted according to EPA method 445.0 and the KCEL SOP (SOP #3014 v4). The sample was concentrated by filtering a measured volume through a glass fiber filter under a low vacuum. The pigments were extracted from the phytoplankton by ultrasonic disruption of the cells in an acetone medium. The concentration of chlorophyll *a* was determined fluorometrically using a Turner Designs Fluorometer. As pheophytin *a* is a positive interferent, chlorophyll *a* was converted to pheophytin *a* by acidification. The extract was then remeasured and the concentration of pheophytin *a* determined by calculating the difference from the first measurement.

All analyses were performed using appropriate QC procedures for each parameter. QC measures included the use of method blanks, check standards, and laboratory duplicates. Detailed information regarding analytical methods is provided in the SAP (King County, 2020).

The method detection limits (MDL) for chlorophyll *a* and pheophytin *a* were 0.05 and 0.1 µg/L, respectively. The MDL is defined as the minimum concentration that can be reliably detected by a particular method.

2.2.3 Data Analysis Methods

Data validation was conducted on all sample results included in this report prior to data analysis. Laboratory QC checks were reviewed, including data qualifiers. Data that were assigned a "B" or "B3" (blank contamination), "SH" (sample handling criterion not met), or "J" (estimated value) qualifier were assessed for usability. Data that were deemed suspect or unusable were removed prior to data analysis. Mooring QC checks and data qualifiers were reviewed and data that were deemed suspect or unusable were removed prior to data analysis.

To calculate monthly average concentrations for each station and year by depth, results for the two sample concentrations in a given month (when available) for each depth were averaged to obtain a single monthly average. These monthly averages were then used to calculate annual averages. Concentrations over the entire 2008 – 2019 period for each depth range were used to calculate a single average. When concentrations were <MDL, the MDL value was used to calculate both monthly and annual averages for all data analyses, except trend analysis.

To assess long-term chlorophyll *a* trends, a non-parametric Seasonal Kendall (SK) test was conducted using R and the censeaken function (NADA2 package) using months as a season. Rather than use the MDL if a concentration was <MDL, the censeaken function estimates concentration based on the entire data set for a given month. The SK test provides a *p* value and the Thiel-Sen slope. The *p* value is the probability of describing how likely the data would have occurred by random chance. A *p* value < .05 is typically considered a significant trend and the smaller the *p* value, the less likely to have occurred by chance. The Thiel-Sen slope is an estimator of the magnitude and direction of change from year to year, with higher values indicating a greater amount of change.

Trends during two different time periods were assessed to account for data availability; monitoring at some stations did not begin until 2007. Therefore, the SK test was conducted with data for all 14 stations collected between 2007 - 2019, and for 7 stations with data collected between 1997 - 2019. The SK test was used to assess both annual and monthly trends over each of the two data ranges.

3.0 RESULTS

A phytoplankton bloom occurs when there is a large increase in phytoplankton abundance. The magnitude, duration, and spatial extent of a bloom depends on a variety of factors, including light and nutrient availability, temperature, physical processes, and grazing by other organisms. Over time, chlorophyll in the bloom is degraded during the natural senescence of algal cells, as well as by zooplankton grazing.

3.1.1 Spring Phytoplankton Bloom

During the reporting period 2008 - 2019, the spring phytoplankton bloom typically occurred in early spring when more light was available, surface water temperatures increased, and the upper water column became stratified. The highest chlorophyll *a* levels were usually during the spring bloom as phytoplankton can rapidly reproduce during optimal growth conditions (sufficient light and nutrients, ideal temperature, and minimal losses from vertical mixing and zooplankton grazing). In most years at all sites except in Quartermaster Harbor, the spring bloom was evident in April as indicated by surface chlorophyll *a* levels increasing to 20–35 µg/L. Weekly sampling at five sites in spring 2017 following the West Point Treatment Plant (TP) flooding event showed a pattern of alternating higher and lower chlorophyll *a* values that corresponded to the strength of observed water column stratification.

Compared to the other areas in the Central Basin, the bloom season starts earlier in Quartermaster Harbor due to the shallow depth and solar warming of the harbor. The spring bloom was typically evident in February or March in most years at this location.

Chlorophyll *a* concentrations typically increased earlier in the spring at the northern and southern stations compared to mid-basin stations. Departures from the typical April spring bloom timing were observed during several years:

- Chlorophyll *a* concentrations in 2008 were not > 5 µg/L until June at all stations except the two Quartermaster Harbor stations (MSWH01 and NSAJ02).
- An early bloom occurred in February 2009 at the two northern stations, JSUR01 (Brightwater TP outfall; 9.08 µg/L) and KSBP01 (Pt. Jefferson; 14.1 µg/L), but the primary spring bloom occurred in April.
- The 2011 spring bloom was delayed until May at all stations except the two Quartermaster Harbor stations.
- An unusual early bloom in February 2015 was observed at all stations except the four northernmost sites and mid-Basin site LSVV01 (Fauntleroy Cove) which was likely due to atypical density stratification. Chlorophyll *a* increased to 9.35 and 6.82 µg/L, respectively at stations CK200P (Carkeek Park CSO outfall) and JSUR01 on March 2, but the primary spring bloom occurred in April.

- A slightly early bloom was observed on March 21, 2016, at the four northernmost stations and NSEX01 (East Passage).The highest chlorophyll *a* concentrations were measured at JSUR01 (14.2 µg/L) and KSBP01 (11.6 µg/L).
- An early bloom was seen at stations JSUR01and CK200P in March 2018 and JSUR01 and KSBP01 in March 2019, but elsewhere the spring bloom was delayed until early May (excluding Quartermaster Harbor stations) both years.

Figure 3 shows surface (<2 m) chlorophyll *a* levels (2008 – 2019) at all stations during the typical spring bloom months (March–May). Twice monthly sampling did not start until May 2014 except at stations KSBP01, NSEX01, and NSAJ02 (outer Quartermaster Harbor). Figure 4 indicates when chlorophyll *a* levels > 5 µg/L were first observed at all stations.

3.1.2 Seasonal Patterns

The chlorophyll *a* seasonal cycle started with the spring bloom and typically decreased by September to < 10 µg/L at all but the two Quartermaster Harbor stations. The main exceptions to this pattern were chlorophyll *a* concentrations >10 µg/L at northern sites in September 2012, and relatively high concentrations at most stations in 2014 when waters first warmed due to the start of the marine heat wave in Puget Sound. Chlorophyll *a* concentrations at KSSK02 (West Point TP outfall) and LTBC43 (Elliott West outfall in Elliott Bay) were higher than other locations in September 2017 when persistent stratification was observed in summer and early fall. Table 3 shows monthly average chlorophyll *a* concentrations in surface waters (< 2 m) at all stations in August and September. Fall concentrations varied between years but were lower in the last several years (2016 – 2019) than typical for the period of record (2008 - 2019).

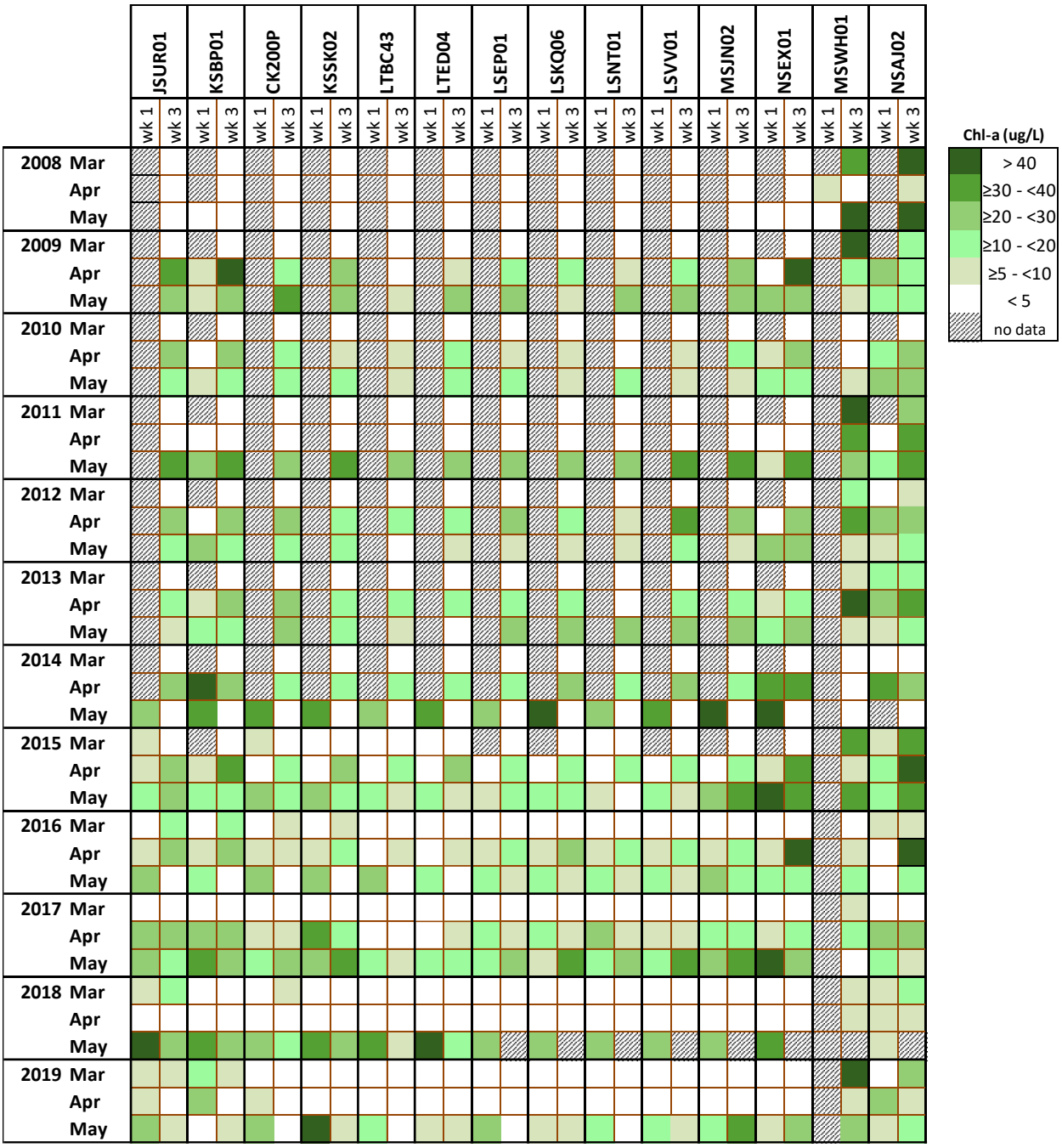


Figure 3. Surface chlorophyll *a* concentrations in March, April and May by station (2008 - 2019). Stations are ordered north to south.

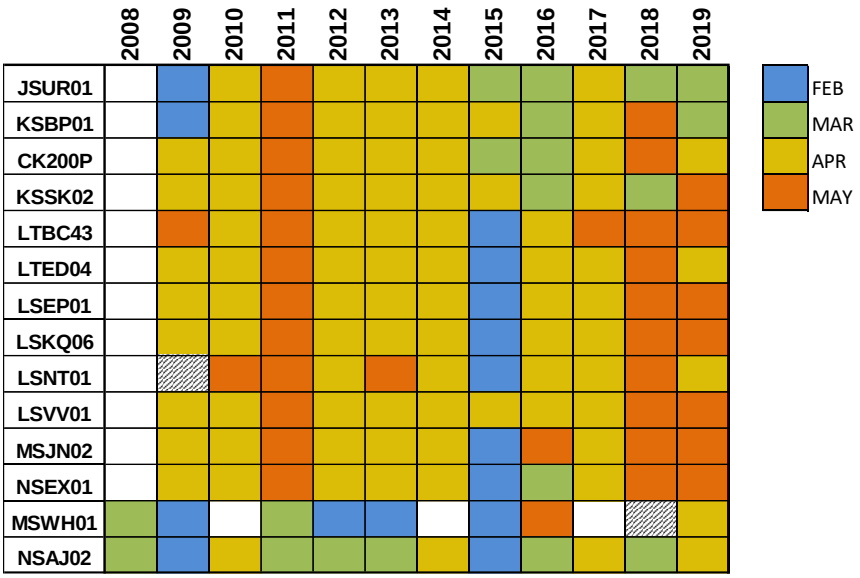


Figure 4. Month with first occurrence of chlorophyll *a* > 5.0 µg/L (2008 - 2019). Boxes with diagonal lines indicate no data and white boxes indicate concentrations < 5.0 µg/L.

Table 3. Chlorophyll *a* monthly average concentrations in surface waters (< 2 m) during August and September by location and year (2008 - 2019).

AUGUST	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
JSUR01	2.7	24.3	1.0	5.2	10.2	15.7	3.2	14.0	11.2	11.8	3.0	5.9
KSBP01	10.4	32.7	14.5	12.8	13.0	26.5	7.2	14.1	10.3	12.6	3.0	2.6
CK200P	18.5	12.9	1.5	1.7	4.1	20.0	2.6	7.2	7.7	6.1	2.0	1.8
KSSK02	5.4	7.6	5.8	3.5	6.0	14.6		13.5	10.7	7.5	4.1	3.7
LTBC43	9.2	3.0	8.9	2.1	8.8	11.0		7.2	7.6	4.3	2.8	0.9
LTED04	2.9	3.5	15.3	1.8	7.0	13.6		10.5	6.8	4.1	2.5	0.7
LSEP01	4.1	7.5	5.3	2.4	4.2	13.4		3.6	9.8	6.5	2.1	4.4
LSKQ06	4.3	5.1	5.2	1.7	3.4	14.1		3.8	11.0	8.0	4.1	5.6
LSNT01	3.8	2.8	7.3	2.6	5.1	6.7		3.2	4.7	5.6	5.6	2.4
LSVV01	4.7	2.2	14.4	1.2	2.4	9.9		2.1	13.4	6.2	4.1	1.1
MSJN02	3.2	26.4	5.4	18.5	3.9	14.7		4.5	15.6	8.6	14.9	7.9
NSEX01	5.8	13.2	20.8	6.8	3.3	36.1	6.5	15.0	25.1	22.7	3.8	1.3
MSWH01	7.6	28.1	5.1	20.7	10.1	5.2	3.8	17.0	6.3	8.3	17.6	2.7
NSAJ02	5.8	53.5	5.8	3.5	4.5	7.8	4.3	2.8	4.9	4.7	10.5	8.0
SEPTEMBER												
JSUR01	7.5	0.8	1.1	5.4	10.5	2.2	17.3	3.1	0.9	7.8	2.4	1.4
KSBP01	7.4	0.9	3.0	3.9	13.6	14.4	17.7	2.3	0.8	5.1	2.2	1.8
CK200P	4.3	0.8	1.3	5.6	8.5	2.0	12.4	2.7	1.2	3.3	1.1	2.4
KSSK02	9.3	0.7	1.8	10.9	13.3	2.7	24.1	2.5	1.1	15.4	2.3	2.0
LTBC43	5.3	0.9	1.1	0.9	8.1	2.7	22.6	6.7	1.0	13.5	1.7	0.7
LTED04	4.8	0.5	1.9	1.8	18.5	3.1	13.8	6.1	0.9	5.3	1.6	0.6
LSEP01	9.3	0.9	1.5	9.8	10.0	1.2	6.4	7.5	1.1	4.4	2.5	1.6
LSKQ06	8.0	1.5	1.7	4.7	7.4	1.6	9.7	6.1	0.7	3.3	2.1	1.7
LSNT01	5.0	1.4	1.1	2.8	5.1	1.3	4.5	8.8	1.0	2.0	3.6	2.0
LSVV01	4.3	1.1	2.5	2.7	3.3	2.3	12.7	5.8	0.7	3.5	2.5	1.4
MSJN02	8.0	2.0	0.7	12.8	6.9	2.4	18.5	12.2	1.2	6.5	3.1	1.6
NSEX01	6.4	5.3	9.3	6.3	20.0	7.1	32.2	15.3	1.8	3.7	3.6	1.0
MSWH01	21.3	5.0	3.6	2.4	67.0	8.1	30.6	24.8	12.4	14.3	38.4	12.3
NSAJ02	15.2	12.2	3.6	11.3	5.5	5.0	7.9	13.1	10.8	27.3	35.6	20.8

Chl-a (ug/L)
>30
≥20-<30
≥15-<20
≥10-<15
≥5-<10
<5
no data

Typically, the highest annual chlorophyll *a* concentrations were measured in May, but in some years the highest levels were observed in April. However, the highest average monthly concentration did not occur in April or May during 2008, 2013, and 2019 when the spring bloom was either delayed or very small. Summer chlorophyll *a* concentrations varied between years. Low levels were observed in both June and July 2011 at all sites except KSBP01 (Pt. Jefferson) and NSEX01 (East Passage) where levels > 10 µg/L were detected (Table 4). Concentrations were high at all mainstem sites during June and July 2017 when persistent water column stratification was observed throughout the spring and summer. Levels were also high in June and July 2019 at most sites when water column stratification was favorable for phytoplankton growth. In 2019, chlorophyll levels were highest in June and July at most stations, an unusual occurrence since the highest concentrations typically occur earlier in the year. Average monthly chlorophyll *a* concentration for surface waters for all stations combined (except the two Quartermaster Harbor and the two shallow stations [LTBC43 and LSVV01]) are summarized in Figure 5.

Table 4. Chlorophyll *a* monthly average concentrations in surface waters (<2 m) during June and July by location and year (2008 - 2019).

JUNE	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
JSUR01	9.4	14.4	2.6	0.6	8.9	12.4	8.2	12.1	10.1	15.7	7.7	22.7
KSBP01	11.0	14.8	9.0	12.0	10.2	11.2	7.0	14.7	11.4	16.5	10.2	25.9
CK200P	3.6	16.9	1.9	0.4	6.4	2.3	7.1	7.5	13.1	16.5	7.1	19.2
KSSK02	4.0	10.3	2.0	0.7	4.0	1.2	8.6	12.0	13.8	15.5	2.8	19.4
LTBC43	2.1	10.0	1.3	0.3	3.4	0.4	1.8	17.1	12.2	6.7	2.5	11.9
LTED04	6.0	13.2	1.6	0.6	5.2	0.5	4.0	16.4	9.3	10.8	2.1	15.6
LSEP01	13.9	13.0	2.6	0.7	8.1	1.3	8.5	12.1	12.2	19.5	6.6	21.0
LSKQ06	15.8	14.0	1.4	0.5	6.0	1.5	8.7	9.0	9.1	12.3	3.5	21.1
LSNT01	12.8	14.9	0.1	1.0	3.9	1.7	8.1	3.8	10.5	13.4	5.5	13.0
LSVV01	8.0	2.1	3.8	1.0	8.5	1.9	7.5	4.8	8.3	12.3	7.4	15.6
MSJN02	8.5	11.0	16.3	2.9	3.8	1.1	12.4	5.0	8.8	22.9	5.9	26.6
NSEX01	24.3	12.3	6.7	18.2	4.7	8.1	18.3	14.0	9.8	21.9	7.8	9.1
MSWH01	6.3	4.4	12.4	5.7	9.1	15.5	2.4	4.7	8.1	6.4	5.7	2.5
NSAJ02	25.1	3.0	6.9	5.9	12.8	11.2	8.2	4.5	4.0	7.0	5.5	2.6
JULY												
JSUR01	0.3	6.9	0.5	0.5	5.9	23.0	8.1	17.9	11.1	18.2	7.0	14.6
KSBP01	8.3	10.6	10.6	11.0	9.4	18.3	9.6	15.5	8.2	16.2	5.8	16.5
CK200P	0.3	6.9	0.7	0.2	1.2	14.5	9.4	13.9	4.2	15.9	1.7	8.1
KSSK02	0.6	6.3	1.1	0.6	5.3	17.6	10.3	16.6	5.5	16.6	2.5	19.0
LTBC43	0.3	5.8	1.0	0.3	4.5	27.0	4.0	16.2	4.9	8.6	2.3	17.1
LTED04	0.4	3.0	1.4	0.4	4.7	20.1	7.1	7.8	5.3	13.5	2.8	11.8
LSEP01	0.6	13.4	6.2	0.9	5.3	21.6	9.0	3.1	6.7	19.8	4.4	21.2
LSKQ06	0.9	5.6	3.3	0.5	4.9	24.0	7.9	3.5	5.8	17.5	3.8	20.0
LSNT01	0.6	10.0	14.2	0.6	3.6	19.8	7.5	1.9	5.5	11.0	2.6	20.2
LSVV01	1.3	4.5	22.2	0.8	9.7	7.8	7.7	2.7	8.6	12.3	5.7	18.0
MSJN02	0.6	10.9	11.9	0.8	11.7	17.9	7.8	4.6	8.6	18.1	5.8	30.1
NSEX01	0.7	10.6	18.0	12.2	9.3	16.0	4.8	4.5	11.7	19.0	8.3	22.9
MSWH01	3.3	6.3	14.7	6.2	1.1	12.3	10.4	15.6	4.3	3.2	7.8	6.2
NSAJ02	1.1	8.5	4.4	4.6	4.8	10.1	14.0	3.6	3.0	4.8	5.3	13.8

Chl-a (ug/L)
>30
≥20-<30
≥15-<20
≥10-<15
≥5-<10
<5
no data

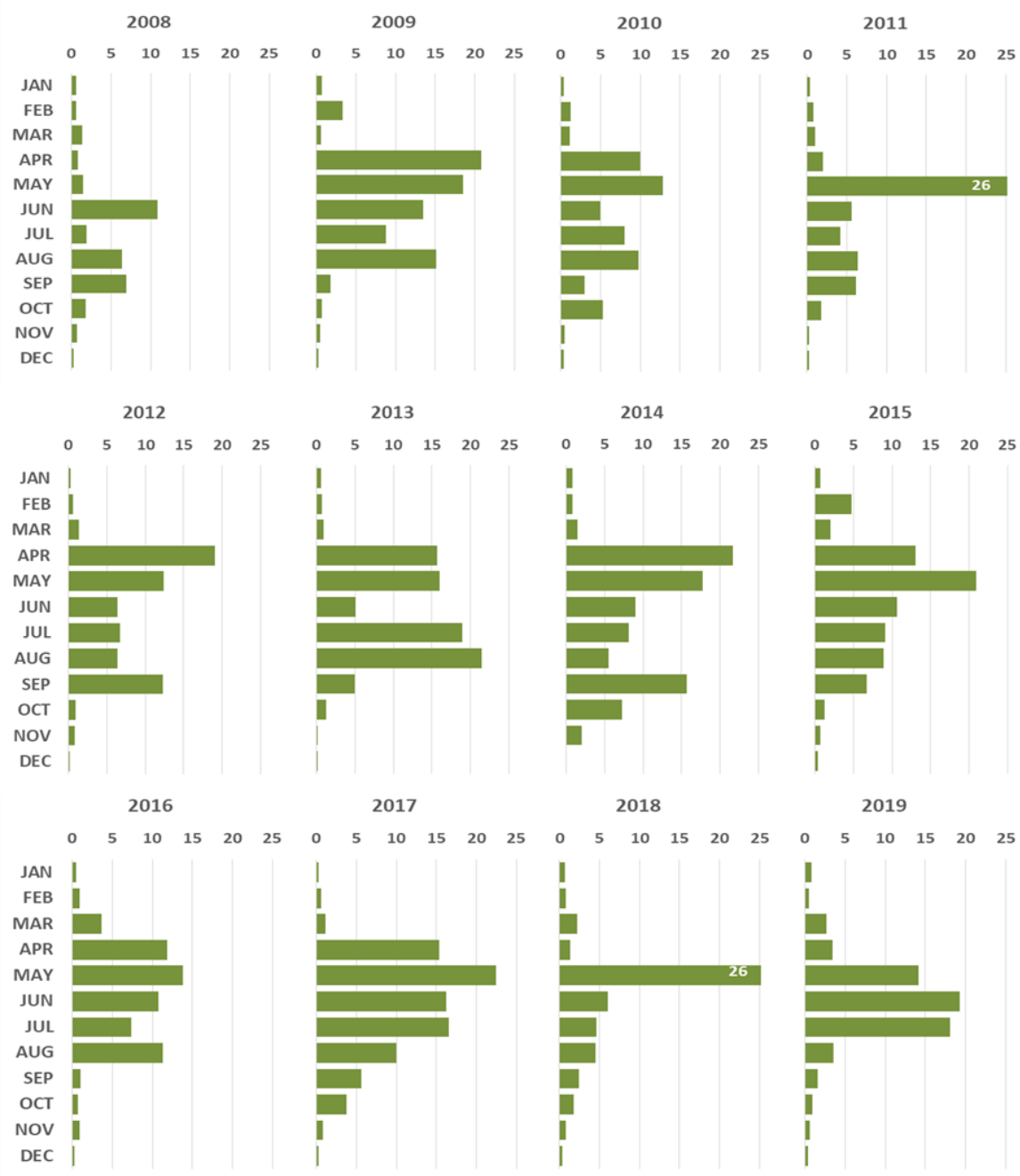


Figure 5. Average monthly chlorophyll *a* concentrations by year; all data for 10 stations (2008 - 2009) combined.

Average monthly chlorophyll *a* concentrations in surface waters for the entire data record at each station are summarized in Table 5.

Table 5. Average monthly surface chlorophyll *a* concentrations by location; all data combined over the entire data record for each station.

	JSUR01	KSBP01	CK200P	KSSK02	LTBC43	LTED04	LSEP01	LSKQ06	LSNT01	LSVV01	MSJN02	NSEX01	MSWH01	NSAJ02
	2004-2019	1997-2019	1997-2019	1997-2019	2005-2019	1997-2019	1997-2019	1997-2019	1997-2019	2007-2019	2005-2019	2003-2019	2006-2019	2006-2019
JAN	0.65	0.56	0.46	0.54	0.37	0.40	0.55	0.49	0.52	0.48	0.59	0.87	1.32	1.54
FEB	2.08	2.61	0.93	1.01	1.14	0.87	1.17	1.22	0.90	0.96	1.17	1.51	4.93	4.40
MAR	2.43	1.90	1.65	1.44	1.11	1.11	1.13	1.19	1.02	1.27	1.42	1.71	8.72	9.87
APR	13.13	13.30	10.18	11.23	6.08	7.34	9.77	9.39	7.02	10.71	11.84	14.23	10.87	15.31
MAY	15.84	15.97	16.45	15.17	9.79	10.88	14.31	13.36	13.47	18.55	19.79	20.53	8.00	8.54
JUN	13.54	15.14	12.55	10.39	6.43	7.67	12.38	11.96	9.40	6.92	11.92	15.72	7.09	8.20
JUL	9.26	12.56	8.45	9.62	8.55	9.12	8.99	8.23	7.88	8.04	10.33	10.90	7.17	6.05
AUG	9.60	12.73	7.47	8.01	6.64	7.25	6.20	6.09	4.30	6.90	12.11	14.15	10.03	9.32
SEP	4.18	5.86	2.99	5.24	6.62	4.33	4.64	4.33	4.18	3.41	5.62	8.66	19.98	13.44
OCT	1.82	2.20	1.19	1.74	1.31	1.35	1.88	1.93	1.90	2.58	3.07	3.22	23.93	11.22
NOV	0.66	0.76	0.60	0.65	0.57	0.61	0.71	0.82	0.68	0.81	0.68	0.86	2.47	3.08
DEC	0.36	0.36	0.34	0.35	0.36	0.30	0.28	0.32	0.23	0.33	0.32	0.34	1.28	1.07

3.1.3 Annual Patterns

Considerable variation in average annual chlorophyll *a* concentrations was seen between the northern, mid-basin, and southernmost stations (Figure 6). However, the lowest overall annual concentration (2008 - 2019) was observed in 2008 at all sites except the two Quartermaster Harbor stations. Chlorophyll *a* levels were also low in 2006 at the southern sites, and 2018 had the lowest annual average at all but the Quartermaster Harbor stations since 2012.

Conversely, productivity was high in 2014 at most stations, in part due to the high fall chlorophyll *a* levels observed, likely in response to warmer water temperatures at the start of the marine heat wave. Chlorophyl a was also high in 2005, 2009, and 2017. The growing season was unusually short in 2019, with no fall bloom. The compressed growing season in 2019 was likely related to the atypical density stratification patterns in 2019 as a result of low rainfall and unusually high salinities throughout the water column. Monthly and annual mean chlorophyll *a* concentrations at the treatment plant outfalls were not higher than other locations and were consistent with spatial differences within the Central Basin.

Chlorophyll levels at all deeper (> 50 m) stations were highest in the upper water column, particularly the top 2 m, and decreased to essentially undetectable levels <40 m as indicated by entire water column fluorometric profiles. Concentrations decreased to < 4 µg/L at about the 32 m depth, even during the spring bloom. Figure 7 shows mean monthly (2008 - 2019) chlorophyll *a* concentration in April by depth strata for all stations (pattern seen for April is representative of other months). Chlorophyl *a* levels at the two deeper depths sampled (~25 and 35 m), were slightly higher at mid-Basin stations from Alki Point (LSKQ06) south to the Vashon outfall (MSJN02) than at the northern stations and southernmost station, East Passage. Although not shown in Figure 7, chlorophyll *a* levels in inner Quartermaster Harbor (MSWH01), were typically higher at the deeper depth (~4 m) than in the top 2 m. The inner harbor is shallow with an average depth of about 6 m (King County, 2014), and it is likely that photoinhibition at the surface is occurring at this location.

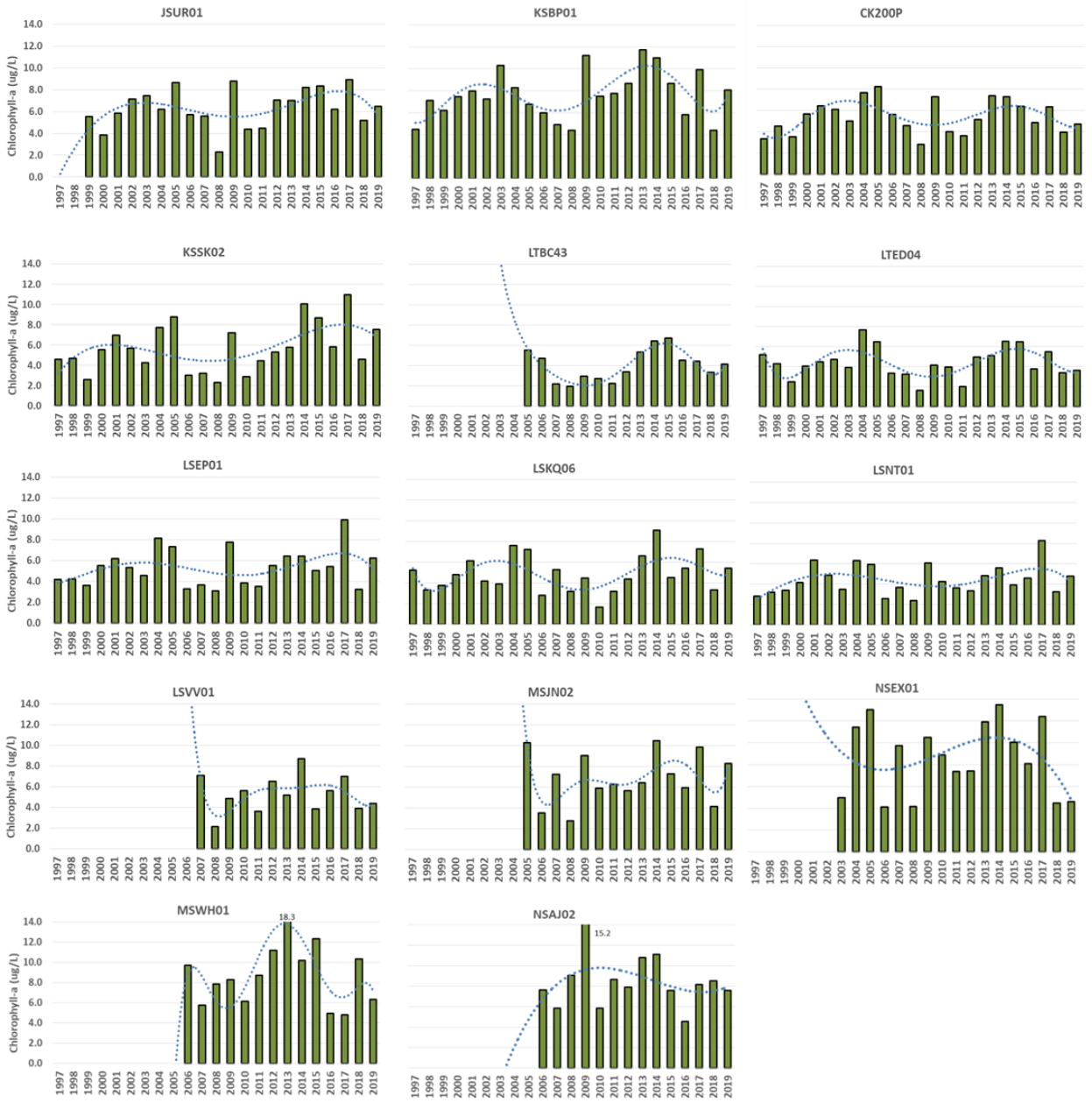


Figure 6. Average annual chlorophyll *a* concentrations in surface water (≤ 2 m) by location and year for the period of record at each station (polynomial trend line shown in blue).

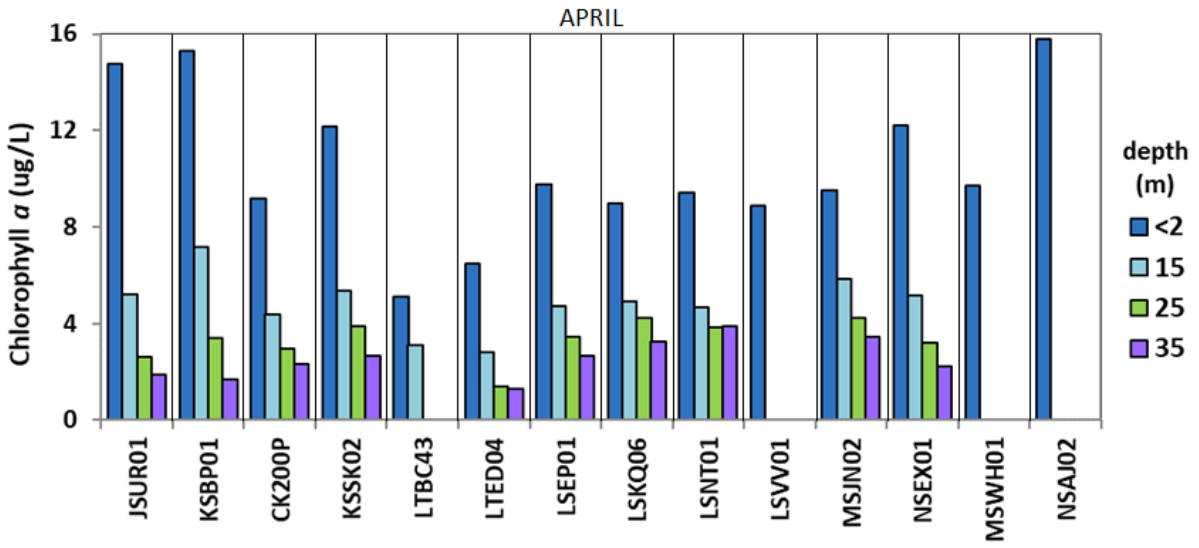


Figure 7. Monthly average chlorophyll concentrations in April by location and depth interval (2008 – 2019).

Results all but the shallowest sites indicated that maximum chlorophyll *a* concentrations most often occurred at depths between 2 and 8 m, and occasionally at 10 m. There was no consistent month or year when the chlorophyll *a* maximum was deepest; however, most chlorophyll *a* maximum observations deeper than 8 m were recorded at NSEX01 (East Passage).

Time series results (Figure 8) for each sampling event at all locations (2008 - 2019) indicate spatial differences. Higher chlorophyll *a* levels were seen at the nothern stations, KSBP01 (Pt. Jefferson) in particular, and NSEX01 (East Passage) than at mid-basin stations. Two distinct chlorophyll *a* peaks were seen in some years (e.g., 2012 and 2013), while multiple peaks (e.g., 2014) or sustained levels during the growing season (e.g., 2017) were seen in other years. Although the magnitude of peaks varied by location, typically the same pattern in terms of number of peaks was consistent between stations, except Quartermaster Harbor, for each year. The inner and outer Quartermaster Harbor stations (MSWH01 and NSAJ02) typically exhibited a different pattern than seen at other locations. Although multiple peaks occurred throughout the extended growing season in Quartermaster Harbor the highest peaks typically occurring in late fall. Annual chlorophyll *a* levels were highest in inner Quartermaster Harbor and decreased in the outer harbor. This pattern was particularly pronounced during the spring bloom which occurred earlier in the inner harbor than in the outer harbor.

High temporal resolution chlorophyll data collected at 15-minute intervals at the inner and outer Quartermaster Harbor moorings showed a similar pattern to the monthly/twice-monthly chlorophyll *a* data. In addition, mooring data showed a high amount of temporal variability and short-term chlorophyll increases lasting a week or less. Although there were gaps in the data record, the extended growing season typically started in early March and ended near late October/early November in inner Quartermaster Harbor (Figure 9).

The physical characteristics of Quartermaster Harbor enable the water to warm earlier in the year than other areas in the Central Basin. The increased solar radiation in early spring and surface stratification due to increased freshwater runoff initiate the growing season. It is likely that nutrient depletion limited chlorophyll levels between April and late summer/early fall until nutrients were replenished by freshwater inputs and biogeochemical pathways (see *Marine Conditions 2008 – 2019 Report Series: Nutrient Results for Offshore Waters* [King County, 2022b]).

Unlike other areas in the Central Basin that showed a likely biological response (increased chlorophyll levels) to the warmer than normal waters in fall 2014 due to the marine heat wave, Quartermaster Harbor chlorophyll levels did not increase. Quartermaster Harbor water is warmer than other Central Basin waters and the additional warming from Pacific Ocean waters at the start of the marine heat wave did not elicit an observable chlorophyll response in the harbor.

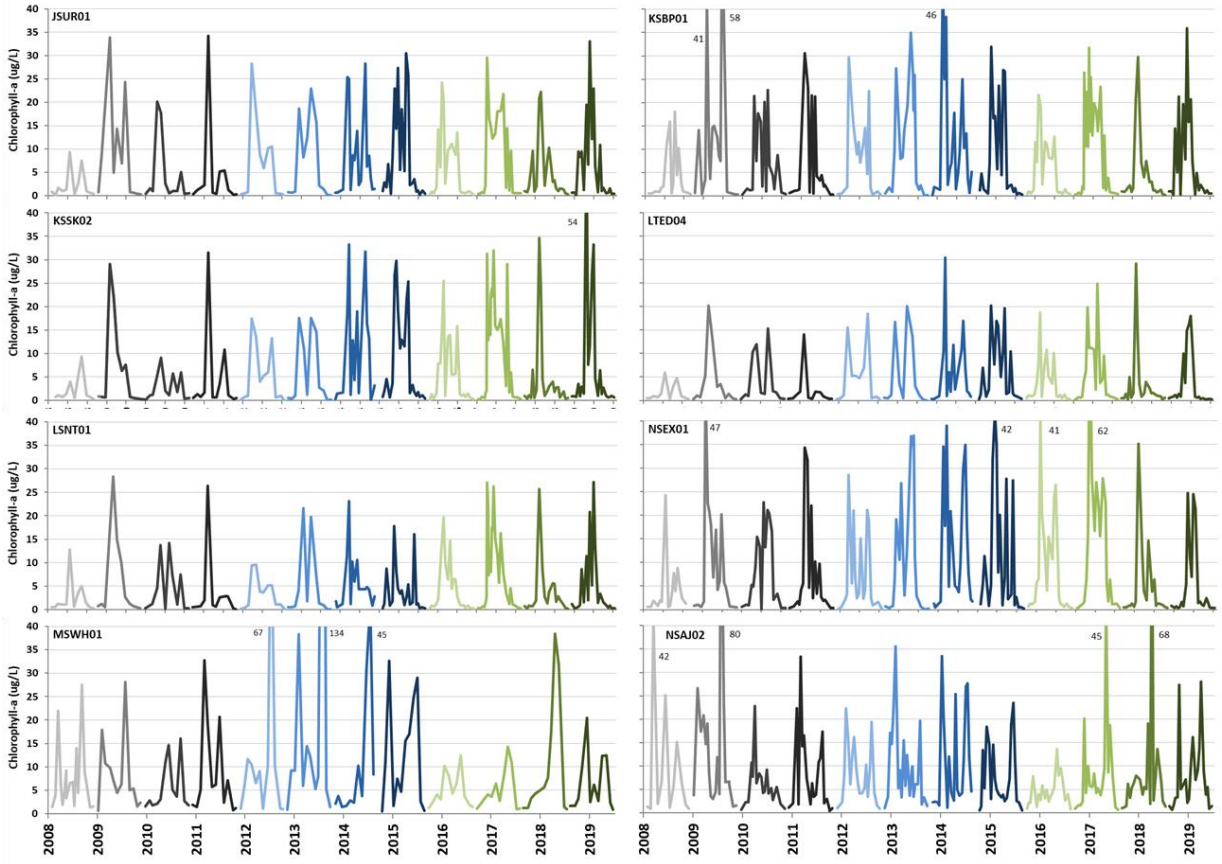


Figure 8. Chlorophyll *a* concentration time series data for surface waters (< 2 m) by station and year (colors represent year) (2008 - 2019).

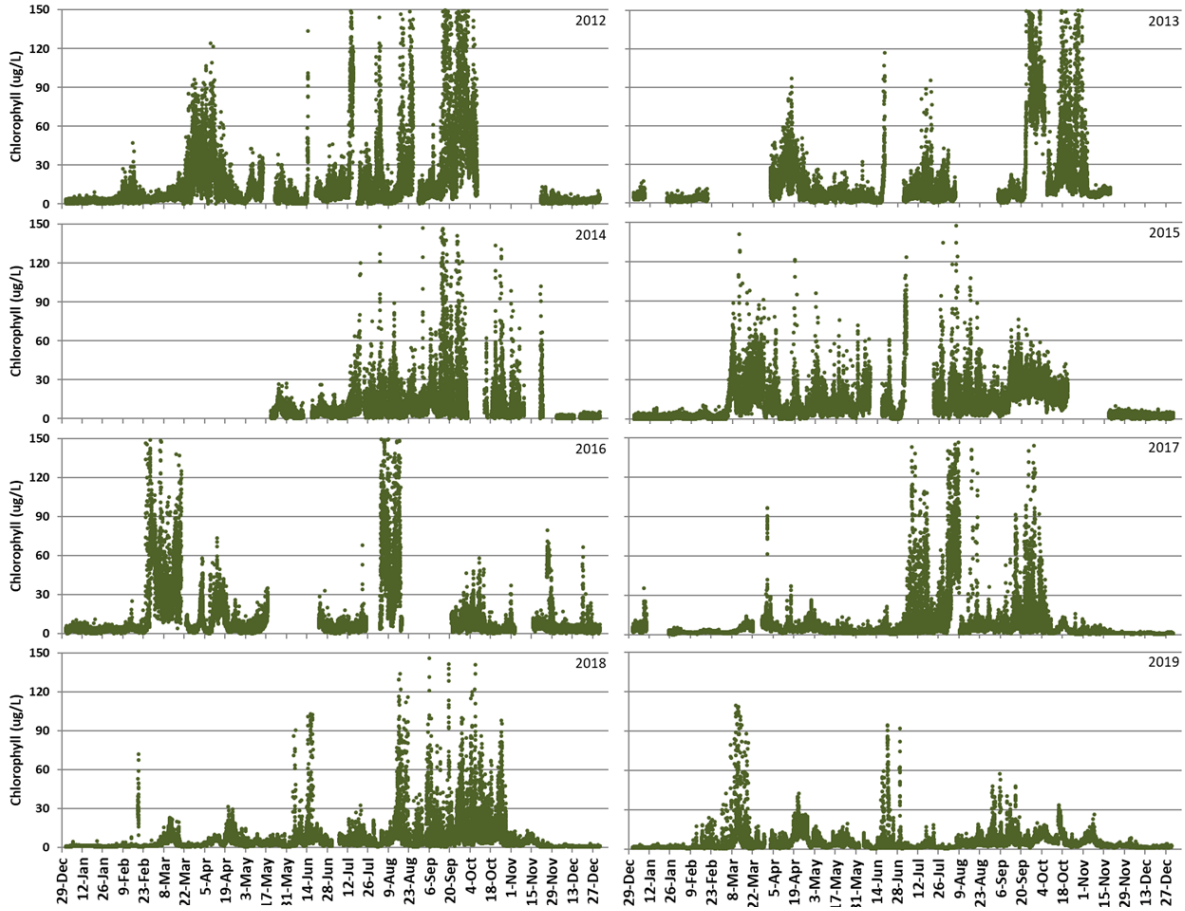


Figure 9. Chlorophyll concentration time series results by year and month for inner Quartermaster Harbor (MSWH01) mooring (15-min data).

3.1.4 Trend Analysis

To assess long-term trends, a non-parametric Seasonal Kendall (SK) statistical test was conducted in R using the NADA2 package and using months as a season. Trends during two time periods were assessed since monitoring did not begin at one station until 2007. The SK test was conducted for14 stations using data collected from 2007 - 2019 and for 7 stations between 1997- 2019. The SK test was used to assess trends in both annual and monthly chlorophyll *a* concentrations for the two time periods. The Thiel-Sen slope was obtained during this analysis and provides direction (increasing or decreasing) and magnitude of significant trends.

Annual Trends

Annual trend results are summarized in Table 6. Significant increasing trends in chlorophyll *a* ($p < .05$) were seen at the West Point TP outfall station (KSSK02) for both time periods in surface waters (< 2 m). Increasing trends in chlorophyl a were measured at this station for the 10-20 m and 20-30 m depth ranges only for the 2007–2019 period. The only other statistically significant trend detected was a slightly decreasing trend at station

LTED04 (Elliott Bay) for the 20-30 m depth range (2007 - 2019). No statistically significant trends were observed for the longer (1997–2019) data set.

It is likely that the significant chlorophyll *a* trends at KSSK02 were driven by higher concentrations between 2014 and 2017, and to some extent in 2019, compared to prior years. Chlorophyll *a* concentrations from 1997 - 2013 were relatively consistent between years, except for atypically low levels in 2008 and 2010. The higher concentrations present during marine heat wave years (2014–2016) and latter part of the reporting period (2017 and 2019) had a strong influence on the trend results.

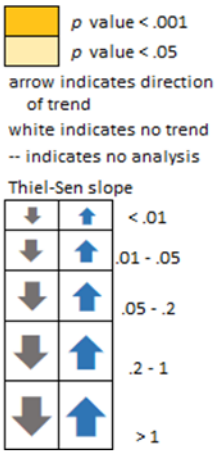
Monthly Trends

Monthly trend results for multiple depths are shown in Table 7, Table 8, and Table 9. No significant trends were observed in January, April, June, August, or September (2007 - 2019) at any depth. The 30–40 m results are not shown but were similar to results for the 20–30 m depth range except one increasing trend (July) and two decreasing trends (October and November) were seen. Significant trends were most frequently seen for February and July. All significant February trends (p <.05) were decreasing with relatively small magnitudes, while all significant July trends were increasing, mostly with a magnitude of 0.2–1 mg/L per year. The increasing trend at The Brightwater TP outfall (JSUR01) (10-20 m) in July was significant at p <.001. The increasing trend in May at the West Point TP outfall site (KSSK02) at multiple depths (< 2m and 10-20 m) is driving the significant annual trends at this site.

Trend analysis results for the longer (1997–2019) data range indicated fewer significant trends. A significant increasing trend in chlorophyll *a* levels was seen for May at the West Point TP outfall site (KSSK02) for all depths except 30–40 m. The only significant trend measured at the 30–40 m depth range was a slightly decreasing trend at Point Jefferson (KSBP01) in January when chlorophyll levels are quite low.

Table 6. Results for seasonal Kendall annual trend analysis for chlorophyll *a* concentrations, by location, depth and date range.

	Chlorophyll *a*							
	<2 m		10-20* m		20-30 m		30-40 m	
	2007--2019	1997--2019	2007--2019	1997--2019	2007--2019	1997--2019	2007--2019	1997--2019
JSUR01		--		--		--		--
KSBP01								
CK200P								
KSSK02	↑	↑	↑		↑			
LTBC43		--		--	--	--	--	--
LTED04					↓			
LSEP01								
LSKQ06								
LSNT01								
LSVV01		--		--	--	--	--	--
MSJN02		--		--		--		--
NSEX01		--		--		--		--
MSWH01		--		--	--	--	--	--
NSAJ02		--		--	--	--	--	--



* LSVV01: 6-13 m, MSWH01: 3-8 m, NSAJ02: 4-9 m

Table 7. Results of Seasonal Kendall monthly trend analysis for chlorophyll a concentrations in surface waters (<2 m) by location and date range.

Chlorophyll *a* <2 m 2007–2019

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
JSUR01							↑					
KSBP01												
CK200P		↓										
KSSK02					↑							
LTBC43					↑							
LTED04							↑					
LSEP01												
LSKQ06												
LSNT01		↓										
LSVV01												
MSJN02			↓									
NSEX01												
MSWH01												↓
NSAJ02											↑	

p value < .001
p value < .05
arrow indicates direction of trend
white indicates no trend
-- indicates no analysis
Thiel-Sen slope
< .01
.01 - .05
.05 - .2
.2 - 1
> 1

1997–2019

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
JSUR01	--	--	--	--	--	--	--	--	--	--	--	--
KSBP01												
CK200P												
KSSK02					↑						↑	
LTBC43	--	--	--	--	--	--	--	--	--	--	--	--
LTED04												
LSEP01												
LSKQ06												
LSNT01												
LSVV01	--	--	--	--	--	--	--	--	--	--	--	--
MSJN02	--	--	--	--	--	--	--	--	--	--	--	--
NSEX01	--	--	--	--	--	--	--	--	--	--	--	--
MSWH01	--	--	--	--	--	--	--	--	--	--	--	--
NSAJ02	--	--	--	--	--	--	--	--	--	--	--	--

Table 8. **Results of Seasonal Kendall monthly trend analysis for chlorophyll *a* locations and date range** for 10–20 m.

Chlorophyll *a* 10-20 m 2007–2019

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
JSUR01							↑					
KSBP01												
CK200P												
KSSK02					↑							
LTBC43												
LTED04		↓										
LSEP01		↓					↑					
LSKQ06							↑					
LSNT01		↓										
LSVV01		↓										
MSJN02		↓										
NSEX01												
MSWH01												
NSAJ02												

p value < .001
p value < .05
arrow indicates direction of trend
white indicates no trend
-- indicates no analysis

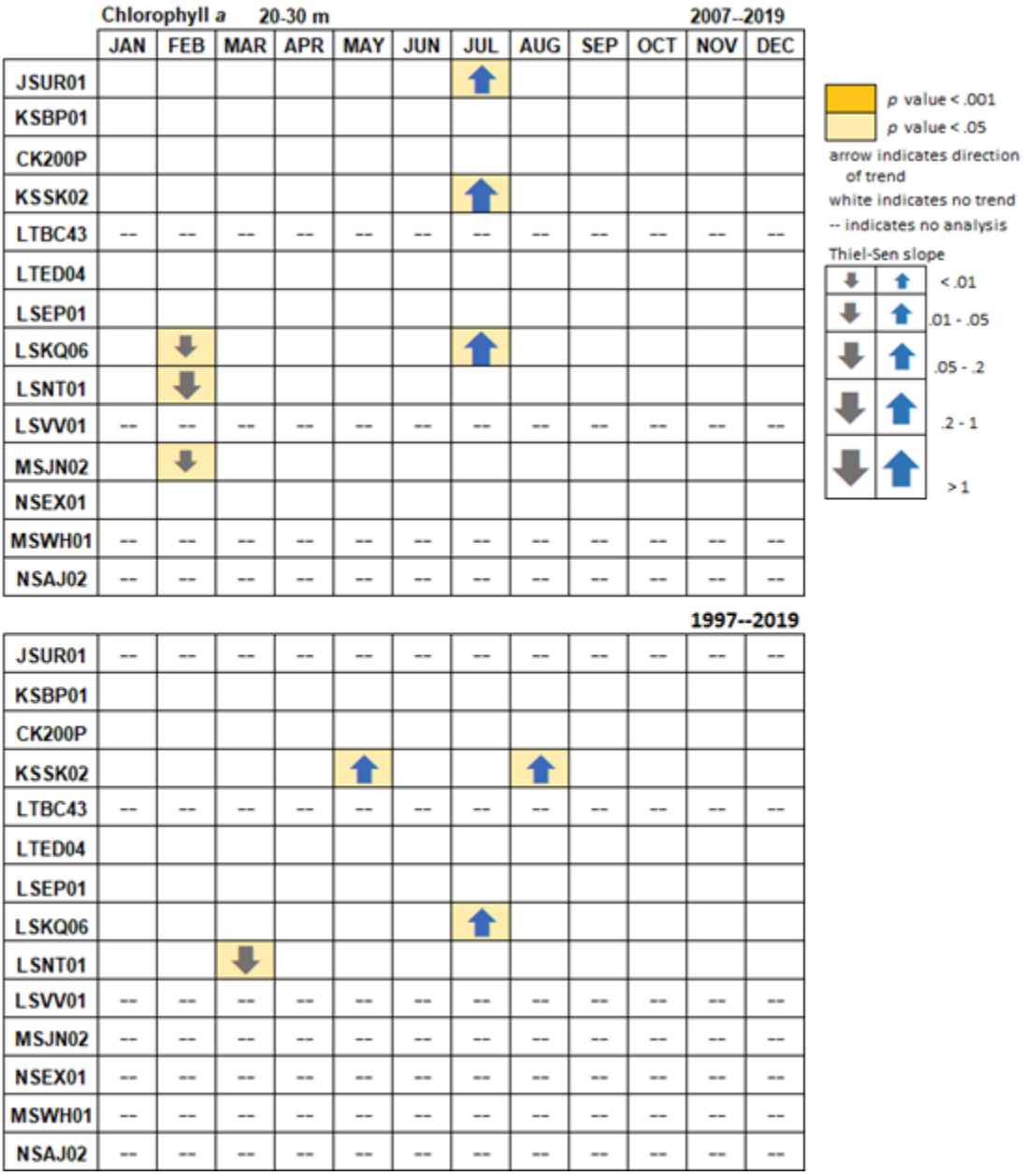
Thiel-Sen slope

↓ ↑	< .01
↓ ↑	.01 - .05
↓ ↑	.05 - .2
↓ ↑	.2 - 1
↓ ↑	> 1

1997–2019

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
JSUR01	--	--	--	--	--	--	--	--	--	--	--	--
KSBP01												
CK200P										↑		
KSSK02					↑							
LTBC43	--	--	--	--	--	--	--	--	--	--	--	--
LTED04												
LSEP01												
LSKQ06							↑					
LSNT01												
LSVV01	--	--	--	--	--	--	--	--	--	--	--	--
MSJN02	--	--	--	--	--	--	--	--	--	--	--	--
NSEX01	--	--	--	--	--	--	--	--	--	--	--	--
MSWH01	--	--	--	--	--	--	--	--	--	--	--	--
NSAJ02	--	--	--	--	--	--	--	--	--	--	--	--

Table 9. Results of Seasonal Kendall monthly trend analysis for chlorophyll *a* concentrations by location and date range for 20–30 m.



3.1.5 Pheophytin *a*

Pheophytin *a* (pheophytin) is a breakdown pigment of chlorophyll and can be used as an indicator of physiological condition of phytoplankton and the amount of grazing on phytoplankton.

A seasonal cycle was evident for pheophytin, similar to that of chlorophyll. Surface pheophytin concentrations (2008 - 2019) were typically highest following the spring bloom and tended to occur in May at mainstem stations and April in Quartermaster Harbor

(Figure 10). Concentrations at all sites were lowest in winter. In 2010 and 2019, surface water pheophytin concentrations were high in July at all sites and did not correspond to high chlorophyll *a* levels. Chlorophyll *a* concentrations in July 2010 were low at most stations and the high pheophytin concentrations during this month may be indicative of zooplankton grazing. Although zooplankton data are not available for 2010, a peak in abundance is typically seen in July.

A shift in timing of elevated pheophytin concentrations was observed at the mainstem stations between 2008 and 2019. The highest concentrations were seen in May from 2009 - 2013, and in June most years from 2015 - 2019. Low pheophytin concentrations in Quartermaster Harbor for several months in 2016 and 2017 reflect lower chlorophyll *a* concentrations in those years, particularly in the inner harbor. Similar seasonal patterns described above were seen at the other depths sampled for all sites.

A summary of average monthly chlorophyll *a*/pheophytin ratios in surface waters for all mainstem sites (March – September) is presented in Figure 11. A higher ratio indicates higher chlorophyll *a* levels with respect to pheophytin. The highest ratios during most years occurred in April and May, corresponding with the spring phytoplankton bloom. Years with a relatively high August or September ratio corresponded to the magnitude of the fall phytoplankton bloom. The low ratios in 2010, 2018, and 2019 for most months may be due to zooplankton grazing and/or samples collected near the end of a phytoplankton bloom when cells were degrading. Ratios were generally similar between stations and depths sampled, except for the Elliott Bay (LTED04 and LTBC43) and Quartermaster Harbor stations (MSWH01 and NSAJ02). Ratios in Elliott Bay were overall lower than other sites as there is typically less chlorophyll *a* and phytoplankton in this area. Ratios varied between months and years at the two Quartermaster Harbor stations.

The instrument used to analyze pheophytin changed in 2017 and resulted in slightly lower pheophytin concentrations compared to prior data. Data collected prior to 2017 were not comparable to data generated with the new instrument. As a result, there was insufficient data to conduct trend analysis for pheophytin.

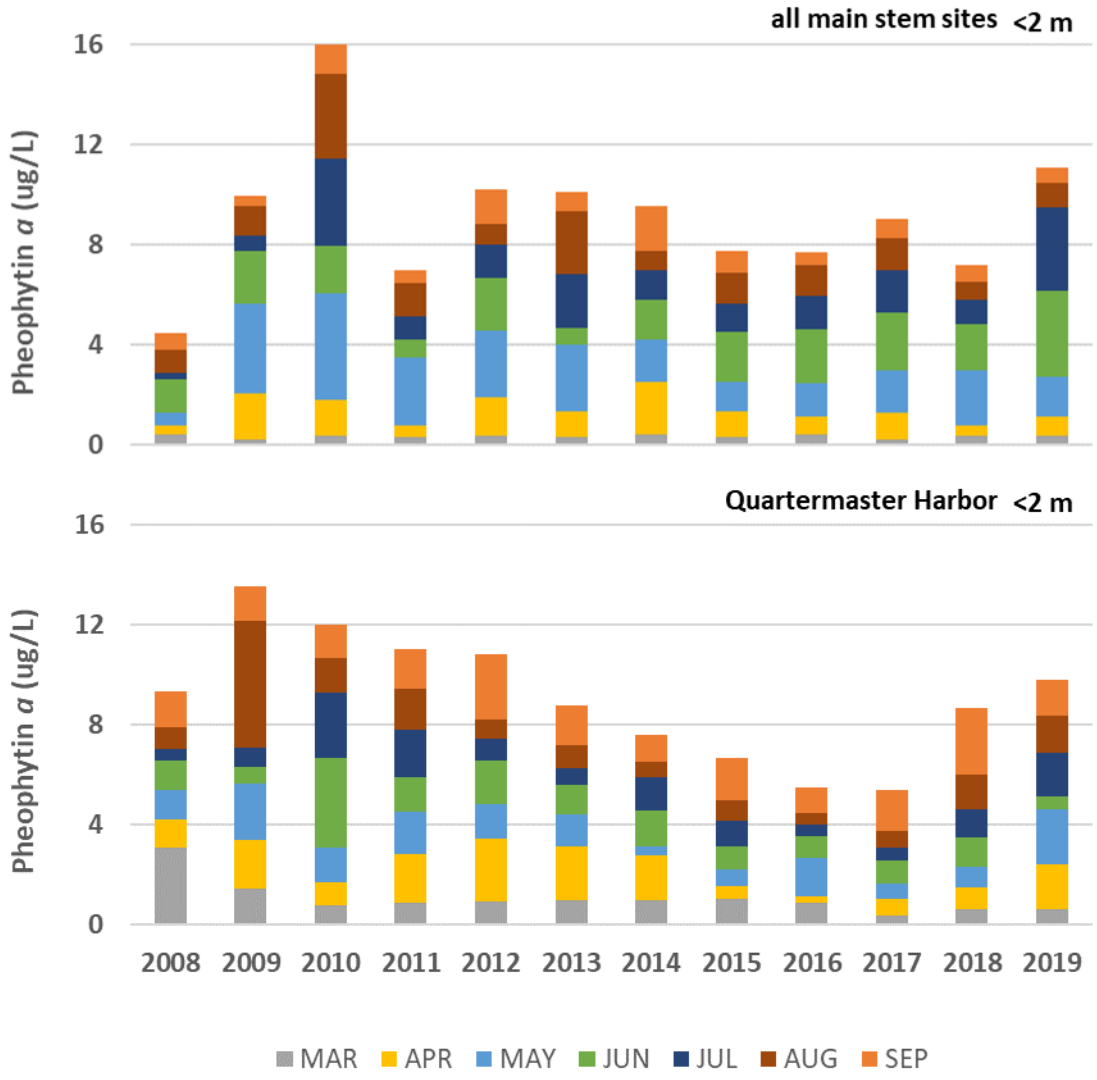


Figure 10. Average monthly pheophytin concentrations in surface waters (< 2 m) March - September (2008 - 2019); Elliott Bay stations were excluded in the top panel and the bottom panel includes both Quartermaster Harbor stations.

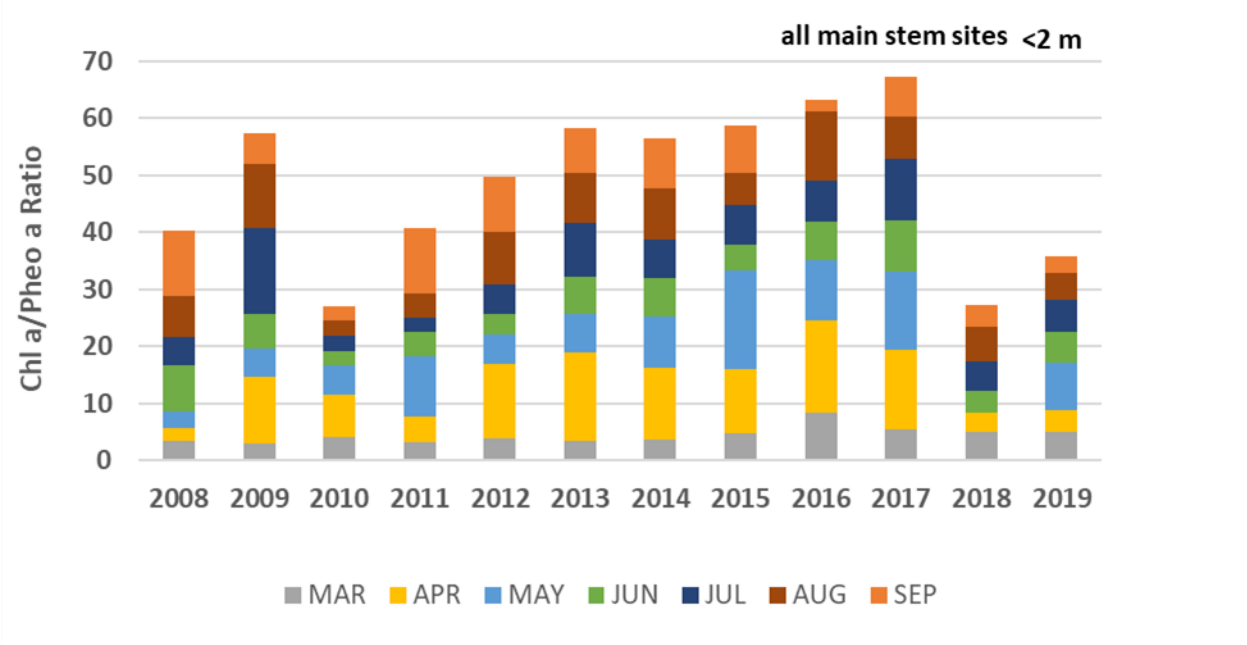


Figure 11. Average monthly chlorophyll *a* to pheophytin ratios between March and September (2008 - 2019) in surface waters. Elliott Bay stations were excluded.

The relationship between chlorophyll *a* and pheophytin at three representative sites (2008 - 2019) is summarized in Figure 12. Peaks in pheophytin that occurred in the summer months often did not correspond with high chlorophyll *a* concentrations, indicating degradation of a phytoplankton bloom or zooplankton grazing. As mentioned above, zooplankton abundance tends to peak in the summer—particularly in July—which coincides with many of the observed pheophytin peaks.

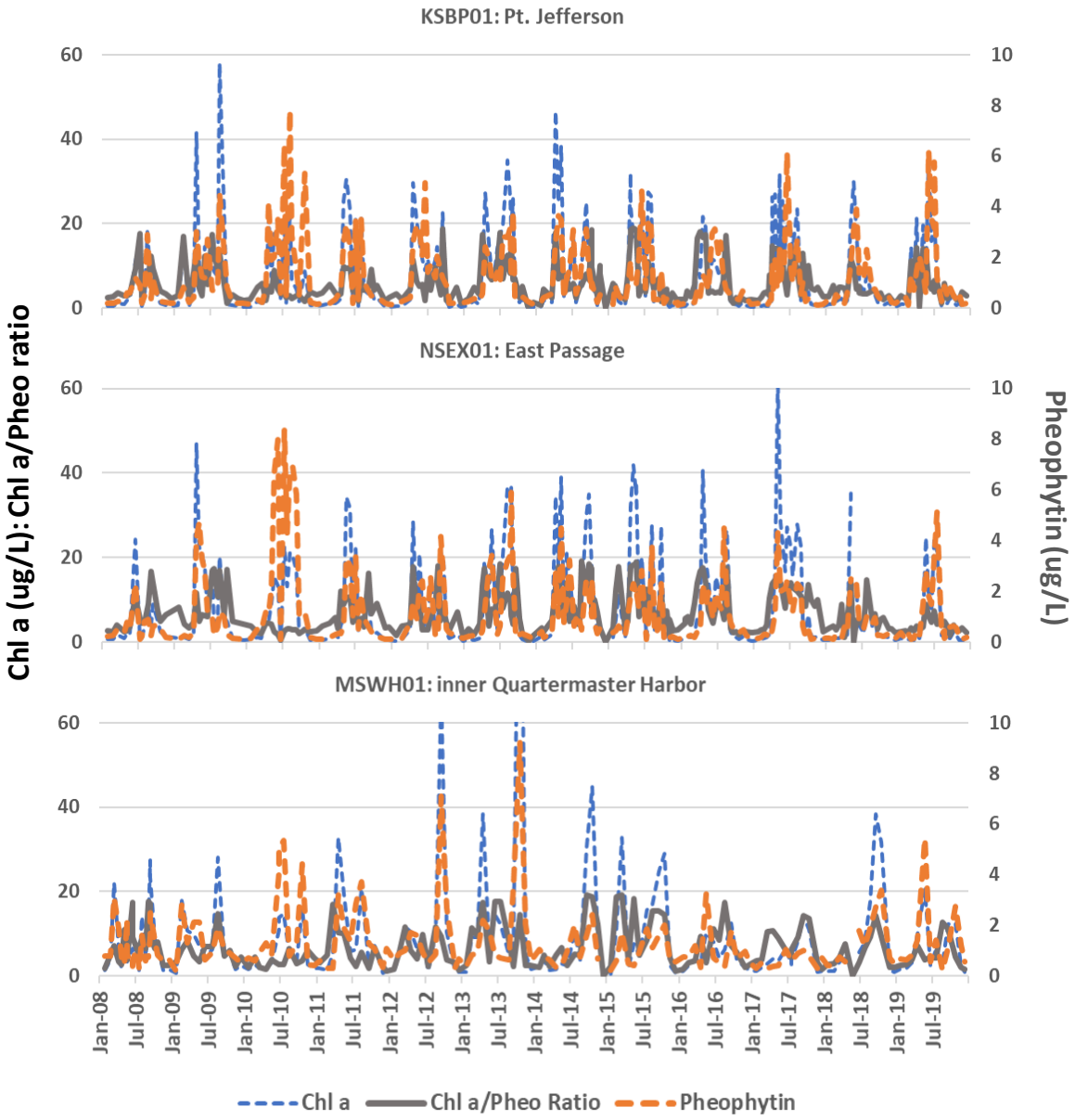


Figure 12. Time series data for chlorophyll *a* and pheophytin concentrations, and chlorophyll *a* to pheophytin ratios by month and year in surface waters (< 2 m) (2008 - 2019) at 3 locations.

3.2 Summary

During the reporting period 2008 - 2019, the spring phytoplankton bloom (indicated by chlorophyll *a* levels) typically occurred in early spring when more light was available, surface water temperatures increased, sufficient nutrients were available, and the upper water column became stratified. The highest chlorophyll *a* levels of the year were usually during the spring bloom as phytoplankton can rapidly reproduce during optimal growth conditions. In most years at all sites except in Quartermaster Harbor, the spring bloom was

evident in April indicated by surface chlorophyll *a* levels increasing to 20–35 µg/L. Compared to other areas in the Central Basin, the bloom season started earlier in Quartermaster Harbor due to the shallow depth and solar warming of the harbor. The spring bloom was typically evident in February or March in most years at this location.

The chlorophyll *a* seasonal cycle started with the spring bloom and typically decreased by September to < 10 µg/L at all but the two Quartermaster Harbor stations. A notable exception was relatively high concentrations at most stations in September 2014 when waters warmed due to the start of the marine heat wave in Puget Sound. Summer chlorophyll *a* concentrations varied between years, however, concentrations were high at all mainstem sites during June and July 2017 and 2019 when persistent water column stratification was observed.

Spatial variation was seen between the northern, mid-basin, and southernmost stations in both timing of the spring bloom and annual average chlorophyll *a* concentrations. Higher chlorophyll *a* concentrations during the spring bloom were seen at the northern and southern stations, compared to mid-basin sites.

Chlorophyll levels at all deeper (> 50 m) stations were highest in the upper water column, particularly the top 2 m, and decreased to < 4 µg/L at about the 32 m depth indicated by entire water column fluorometric profiles. Results for all but the shallowest sites indicated that maximum chlorophyll *a* concentrations most often occurred at depths between 2 and 8 m, and occasionally at 10 m. Chlorophyll *a* levels in inner Quartermaster Harbor were typically higher at the deeper depth (~4 m) than in the top 2 m. The inner harbor is shallow and it is likely that photoinhibition at the surface is occurring at this location.

Chlorophyll *a* trend analysis showed statistically significant increasing trends at the West Point TP outfall station in surface waters (< 2 m) that was likely driven by higher concentrations between 2014 and 2017, and to some extent in 2019, during May and July. The only other statistically significant trend detected was a slightly decreasing trend at the Elliott Bay station for the 20-30 m depth range (2007 – 2019 data period). No statistically significant trends were observed for the longer (1997–2019) data set.

A seasonal cycle was evident for pheophytin, a breakdown pigment of chlorophyll, similar to that of chlorophyll. Surface pheophytin concentrations were typically highest following the spring bloom.

A few chlorophyll observations of note are provided below:

- Chlorophyll *a* concentrations in 2008 were not > 5 µg/L until June at all stations except the two Quartermaster Harbor stations, a highly unusual occurrence.
- The spring bloom was delayed until May in 2011, 2018, and 2019 at most stations except the two Quartermaster Harbor stations.,

- Fall 2014 chlorophyll *a* levels in Quartermaster Harbor did not show the same biological response as other areas to warmer waters at the start of the marine heat wave.,
- The highest chlorophyll *a* levels of the year were seen in May at most stations, however, the highest values of the year in Quartermaster Harbor were seen in September and October.
- An unusual early bloom in February 2015 was observed at all stations except the four northernmost sites and one shallow mid-Basin site, likely due to atypical density stratification.,
- In 2019, chlorophyll *a* levels were highest in June and July at most stations, an unusual occurrence as the highest concentrations typically occur earlier in the year.
- The growing season was unusually short in 2019, with no fall bloom and likely related to atypical density stratification patterns due to low rainfall and unusually high salinities throughout the water column.

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