Marine Conditions 2008–2019 Report Series: Marine Monitoring Program Overview

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King County

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1.0 INTRODUCTION AND BACKGROUND

King County Department of Natural Resources and Parks (DNRP) and its predecessor agency, Municipality of Metropolitan Seattle (Metro) have a long history of implementing water quality improvements and monitoring water quality in Puget Sound marine waters. As part of an ongoing effort to maintain and improve Puget Sound's water quality, the King County Wastewater Treatment Division (WTD) is responsible for regional sewage collection, treatment processes, and disposal systems that discharge wastewater to the Central Puget Sound Basin (Central Basin). King County's Marine and Sediment Assessment Group (within DNRP) manages a comprehensive long-term marine monitoring program that assesses water quality, food web, and environmental conditions in the Central Basin on behalf of, and in coordination with, the WTD.

The primary objective of the Marine Monitoring Program is to provide an understanding of water quality, food web lower trophic levels, and environmental conditions in King County receiving waters, including areas near discharges from the County's four wastewater treatment plants (TP), numerous combined sewer overflow (CSO) outfalls, and four CSO wet weather treatment stations (TS). The County maintains a long-term dataset for a variety of water quality focused parameters. Data have been collected at some monitoring locations for over 50 years. These data provide insight into both short and long-term variations and form a basis from which water quality conditions can be assessed on multiple temporal and spatial scales. The monitoring data are further used to:

- Provide supporting data for analysis of contaminant sources and pathways.
- Complement the County's required monitoring on regulated and non-regulated parameters for wastewater and stormwater discharges and potential effects in receiving waters.
- Assess potential water and sediment quality effects following TP upset discharges by comparing against historical data.
- Assist in special studies and support science-based management decisions such as siting new TP outfalls (King County, 2001) and evaluating marine conditions and dynamics in specific areas with suspected water quality issues (King County, 2014).
- Assess influence of large-scale and regional climate patterns on riverine and freshwater inputs and water quality.
- Evaluate water and sediment quality data against applicable Washington State Water and Sediment Quality Standards.
- Evaluate spatial and temporal differences in benthic community assemblages as well as compare results to Puget Sound-wide benthic community data.
- Measure variability in phytoplankton and zooplankton community composition, size distribution and abundance.
- Establish baseline phytoplankton and zooplankton community patterns and variability and monitor for long-term changes.

- Assess zooplankton prey availability for specific organisms, such as juvenile salmonids and forage fish.
- Evaluate how food web lower trophic levels respond to climate variations and water quality conditions spatially and temporally.
- Support development of regional environmental indicators such as the Puget Sound Partnership (PSP) Zooplankton, Primary Productivity, and Dissolved Oxygen Vital Signs.
- Support regional efforts and collaborations such as the Puget Sound Ecosystem Monitoring Program (PSEMP) Marine Waters Workgroup marine conditions monthly update meetings, Puget Sound Marine Waters Annual Report (PSEMP Marine Waters Workgroup, 2019), Washington Department of Ecology's (Ecology) Puget Sound Nutrient Source Reduction Project, and regional modeling efforts.

This report provides an overview of King County's Marine Monitoring Program for data collected between 2008–2019 as well as an overview of large-scale and regional weather patterns that occurred during this period. This report provides background information on the program and an overview of sites monitored, matrices sampled (water, sediment, phytoplankton, zooplankton, clam tissue), parameters measured, and field and laboratory methods.

Results for the Marine Monitoring Program components described here and monitored between 2008–2019 are provided in separate reports with hyperlinks (click on titles to access reports) below and include the following topics:

- 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
- Chlorophyll in offshore waters
- Phytoplankton
- Zooplankton
- Chemical and physical parameters and benthic infauna in beach (intertidal) and offshore (subtidal) sediments
- Chemical parameters in clam tissues.

Summary reports for Marine Monitoring Program data collected from 1995 - 2007 can be found in annual *Water Quality Status Report for Marine Waters* accessible at: https://green2.kingcounty.gov/ScienceLibrary/default.aspx?&CategoryID=2.

1.1 Other Puget Sound Central Basin Monitoring Programs

Several regional organizations also monitor water and sediment quality and/or environmental health in the Central Basin. These include:

- Washington State Department of Ecology (water and sediment quality)
- University of Washington (water quality, phytoplankton, and fish habitat)
- Washington Department of Fish & Wildlife (contaminants in fish and zooplankton tissues)
- Washington Department of Natural Resources (nearshore vegetation)
- National Oceanic and Atmospheric Administration (harmful algal blooms and biotoxins)
- Washington Department of Health (fecal indicator bacteria and biotoxins).

These organizations monitor areas within the Central Basin including King County marine waters. While there is some overlap (spatial area/parameters measured) between regional monitoring programs, King County's program includes a larger number of monitoring stations within a given area, sampling occurs at a higher temporal frequency, and many sampling locations are targeted near wastewater TP discharges. King County's and other organizations' monitoring stations do not overlap which allows a broader area of Puget Sound marine waters to be monitored. Nearshore vegetation and biotoxins are not components of King County's monitoring programs.

1.2 Wastewater Collection and Treatment

Wastewater from homes, businesses, and industries within King County and southern Snohomish County is transported through pipes owned by local sewer agencies, to King County's system of larger pipes, which convey wastewater to the County's treatment plants. Solids are separated from liquids at the plants and the resulting water (effluent) is treated, disinfected, and discharged into receiving waters. A portion of the treated water is used to irrigate golf courses, play fields, and farms. The separated solids are turned into nutrient-rich organic material (biosolids and compost) and subsequently used to enrich agricultural and forest soils.

King County currently operates four wastewater treatment plants and four wet weather treatment stations that discharge into Central Basin marine waters via outfall pipes (Figure 1). The West Point, South, and Vashon TPs provide secondary wastewater treatment. The Brightwater TP provides advanced secondary treatment. The Alki, Carkeek, Elliott West, and Henderson/Martin Luther King (MLK) TS store combined wastewater and stormwater

flow during high rain (wet weather) events. These TSs later transport combined wastewater and stormwater flow to the West Point TP or provide the equivalent of primary treatment and disinfection before discharging to marine waters or the Duwamish River via outfall pipes. Descriptions of the various treatment plants and processes are available at https://kingcounty.gov/depts/dnrp/wtd/system/treatment-process.aspx. Treatment plant outfall depths vary by location (Table 1).

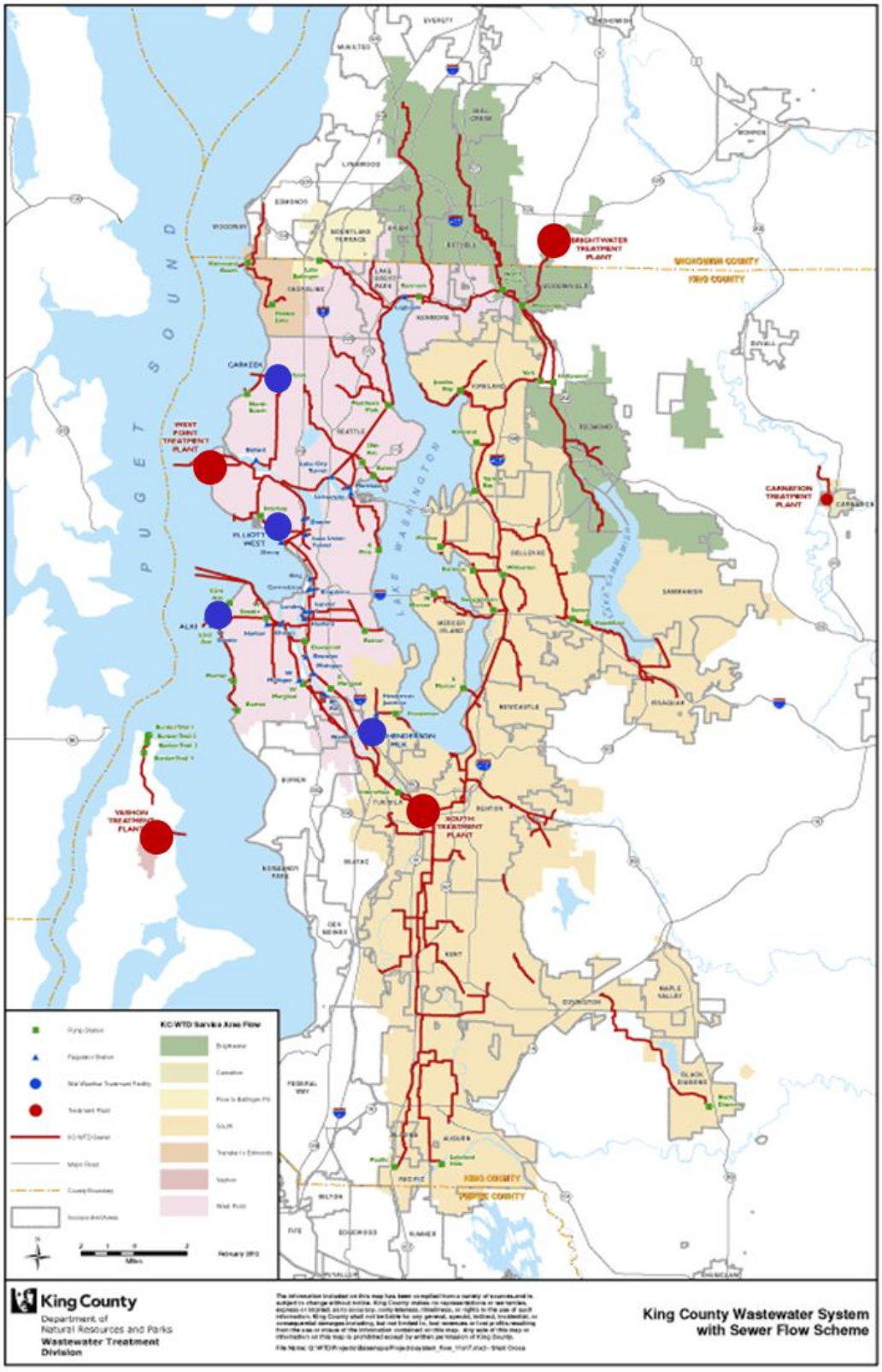

Figure 1. King County TP, TS, and outfall locations. Secondary TPs shown in red, TSs shown in blue.

Table 1. TP and TS outfall discharge depths.

Facility	Outfall discharge depth (meters)
South TP	190
Brightwater TP	183
West Point TP	70
Vashon TP	61
Carkeek Wet Weather TS	61
Alki Wet Weather TS	44
Elliott West Wet Weather TS	19
Henderson/MLK Wet Weather TS	surface

As a large amount of the West Point TP service area includes combined sewer and stormwater conveyance pipes, it discharges the largest volume of effluent of the four secondary treatment facilities followed by the South, Brightwater, and Vashon TPs, respectively. The monthly mean of daily average effluent discharge volumes from the two largest TPs are shown in Figure 2. The higher discharge volumes in some months and years at West Point correspond to frequency and intensity of rainfall events (e.g., January and November 2006) as this plant receives a high volume of stormwater. The rainfall total in January 2006 was over twice the 30-year average for that month and the total in November 2006 was almost two and half times the 30-year average. Effluent discharges reflect annual rainfall patterns as discharges peak during high rainfall months.

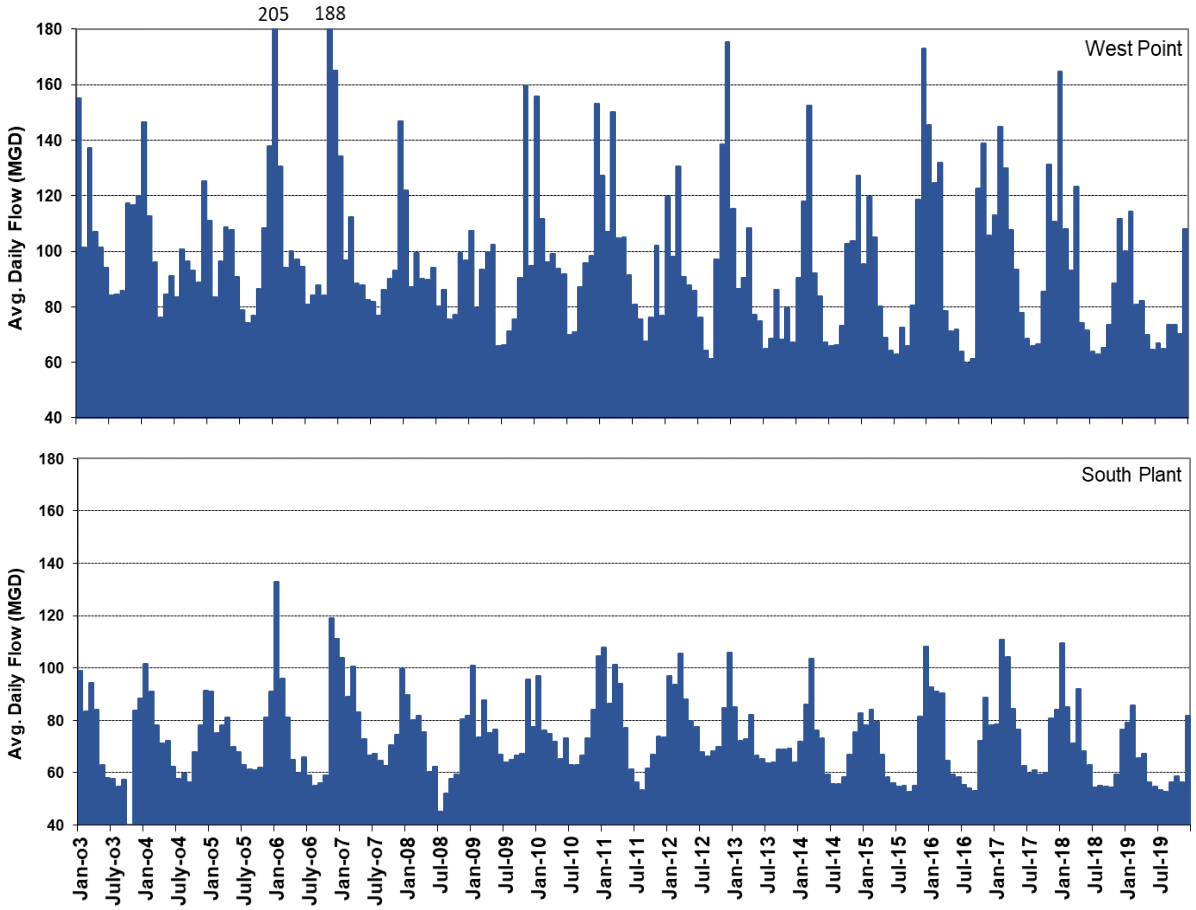

Figure 2. Monthly means of average daily effluent discharge for the West Point and South TPs.

1.2.1 Permit and Sampling Requirements

The Federal Clean Water Act (CWA) states that all sewage treatment plants that discharge effluent from a point source into surface waters must have a National Pollutant Discharge Elimination System (NPDES) permit. The permit delineates conditions and quantities that a municipality can discharge to a receiving waterbody. In Washington, Ecology administers the NPDES permit program by delegation from the U.S. Environmental Protection Agency (EPA).

King County has individual NPDES permits for the secondary treatment plants that authorize treated wastewater discharges into Central Basin receiving waters (Table 2). All NPDES permits are available at:
https://www.kingcounty.gov/depts/dnrp/wtd/system/npdes.aspx .

Table 2. King County's NPDES permits and associated discharges.

NPDES Permit	Discharges Covered
West Point Permit #WA0029181	West Point TP Alki, Carkeek, Elliott West, and Henderson/Martin Luther King TSs King County CSOs
South Plant Permit #WA0029581	South TP
Vashon Plant Permit #WA0022527	Vashon TP
Brightwater Permit #WA0032247	Brightwater TP

1.2.2 King County Treatment Plant Descriptions

West Point Wastewater Treatment Plant

The West Point TP service area includes the City of Seattle (Seattle) and areas north and west of Lake Washington. Most neighborhoods in the north Lake Washington area were constructed with separate sanitary and storm sewers, but within Seattle, approximately 75% of the sewer system was constructed with combined sewers that carry both sanitary sewage (wastewater) and stormwater. Sanitary and combined flows from Seattle are merged prior to arriving at the West Point TP. In addition to domestic sewage, most of Seattle's industrial areas discharge to the West Point TP.

The plant is designed to provide secondary treatment of wastewater flows up to 300 million gallons per day (MGD), with an additional 140 MGD capacity to provide primary treatment of wet-weather flows that are then blended with the secondary flow prior to disinfection. Effluent is discharged to Puget Sound off Discovery Park through a 2.44-meter (m) diameter concrete outfall with a 183 m long diffuser, located approximately 1,036 m offshore at a depth of -70 m mean lower low water (MLLW) (Figure 1).

South Wastewater Treatment Plant

The South TP service area includes the areas and cities east of lakes Washington and Sammamish, Muckleshoot tribal lands and cities of Renton, Tukwila, Kent, Black Diamond, and Auburn. The service area includes 32 jurisdictions and utility districts. All flows to the South TP originate from separated sanitary systems, except a small portion (~ 4%) of the Seattle system that is a combined system. The plant's design criteria for maximum monthly average flow is 144 MGD, but it can handle wet weather flows of up to 325 MGD. The facility produces Class A water for reuse from a small portion of the plant's flow.

Pumps transport treated wastewater from the plant in Renton to the marine outfall located off a point of land north of Alki. The outfall includes two pipes, each with a 152 m long diffuser at the end and terminating about 3,048 m offshore at a depth of approximately 190 m MLLW.

Brightwater Treatment Plant

The Brightwater TP is the County's newest treatment plant which began operation in September 2011. The service area includes the northeastern portion of King County and

the southeastern portion of Snohomish County. The facility treats sewage from residential, commercial, and industrial customers. Although the plant discharges less flow than the West Point and South TPs plants, it was designed for 30 MGD average flow and 44 MGD peak flow. The facility produces Class A water for reuse from a small portion of the plant's flow.

Pumps and conveyance lines transport treated wastewater from the plant in Woodinville to the marine outfall located off Point Wells. The outfall includes two side-by-side pipes, each with a 76 m long diffuser at the end. The diffusers are arranged in a staggered configuration to form a total diffuser length of 152 m. The outfall terminates 1,585 m offshore at a depth of approximately -183 m MLLW.

Vashon Wastewater Treatment Plant

The Vashon TP serves the Vashon Sewer District and treats wastewater from residential and commercial customers in and around Vashon Island's main business area, located near the northeastern portion of the island. Major upgrades to the plant, including extension of the outfall from a depth of 12 to 61 m, were completed in 2006. The plant has an instantaneous maximum capacity to treat 1.0 MGD and a design criteria maximum monthly average of 0.52 MGD, and an average design flow of 0.18 MGD.

Effluent is discharged to Puget Sound on the east side of the island off Gorsuch Creek through the outfall approximately 853 m offshore, at a depth of approximately -61 m MLLW.

Alki Wet Weather Treatment Station

The Alki TS located in West Seattle near Alki Point was constructed in 1958 as a primary treatment plant. The service area is primarily residential with some commercial activity mainly along portions of California Avenue and SW Alaska Street. No significant industrial users discharge to the Alki TS. The plant was upgraded and remodeled in 1987 to operate as a near-fully automated CSO treatment plant.

The Alki TS operates intermittently, only when flow in the Alki service area exceeds 18.9 MGD and the West Seattle storage tunnel is full. When flow is less than 18.9 MGD, it is transferred directly to the West Point TP for secondary treatment. Wet weather flow greater than 18.9 MGD and the 7.1 million gallon storage capacity of the West Seattle tunnel are diverted to the Alki TS for treatment. Treated flows are discharged to Puget Sound through an outfall that is 346 m offshore at a depth of -44 m MLLW.

Carkeek Wet Weather Treatment Station

The Carkeek TS was constructed in 1962 as a primary treatment plant to serve the Carkeek Basin, in North Seattle within Carkeek Park. In 1994, the plant was converted to a pump station/CSO treatment facility. During dry weather and normal flow conditions, the facility operates as a pump station only pumping wastewater to the West Point TP. The Carkeek TS operates intermittently, only when the combined sanitary/storm water flow during a storm exceeds the capacity of the Carkeek Pump Station (9.2 MGD). Excess flow is stored and treated in the plant and then returned to the pump station at the end of the storm.

Flow is pumped from the pump station to the West Point TP. If flows exceed the storage capacity, treated effluent is discharged to Puget Sound via a 1,280 m long outfall at a depth of approximately -61 m MLLW. After a storm, any stored flow remaining in the plant is pumped to the West Point TP.

Elliott West Wet Weather Treatment Station

The Elliott West wet weather TS became operational in May 2005 and is the largest CSO control facility in the County's wastewater conveyance system. The facility has two modes of operation. During storm events, the facility directs combined stormwater and sanitary sewer flows into the Mercer Street wastewater storage tunnel. Following each storm, the facility pumps stored flows from the tunnel to the Elliott Bay interceptor, which directs flows to the West Point TP. During larger storm events, (expected ~10 to 20 times/yr.), the Mercer Street tunnel fills to capacity and the facility treats stored flows prior to discharge to Elliott Bay via an outfall (149 m long and depth of -19 m MLLW).

During very large storms (expected to occur no more than once per year on average), flows may exceed the facility's 250 MGD storage and pumping capacity. When this occurs, untreated flows are discharged through the shorter (30 m) and shallower (-6.1 m MLLW) marine outfall at Myrtle Edwards Park .

Henderson/Martin Luther King Wet Weather Treatment Station

The Henderson/Martin Luther King (MLK) wet weather TS became operational in July 2005. The facility has a 3.2 MG storage tunnel with treatment capabilities and conveyance lines that store flows during storm events and routes flow to either the South or West Point TPs for treatment. The Henderson Pump Station was upgraded to add capacity to the system and further reduce the potential for overflow events.

After a storm event subsides, stored flows are conveyed primarily to the South TP, but can also be conveyed to the West Point TP. In the event the storage tunnel reaches capacity during extreme storms and water continues to flow into the tunnel, the flow is treated and then pumped and discharged through the Norfolk outfall into the Duwamish River at approximately river mile (RM) 6.5.

1.3 Other Puget Sound Discharges

Several types of anthropogenic inputs enter Puget Sound marine waters. A brief description of the major inputs is provided below.

1.3.1 Other Wastewater Treatment Plant Discharges

Effluent from numerous municipal TPs that originates from city, county, tribal, federal, and privately operated wastewater treatment facilities discharge into Puget Sound. In addition to King County's facilities, 50 other permitted wastewater facilities discharge to Puget Sound, excluding facilities on the outer coast and north of Admiralty Inlet (Figure 3). Discharge characteristics (volume, distance offshore, and depth) vary for each facility, and

most TP outfalls terminate close to shore, except for the Kimberly-Clark/City of Everett marine outfall in Port Gardner located 823 m offshore.

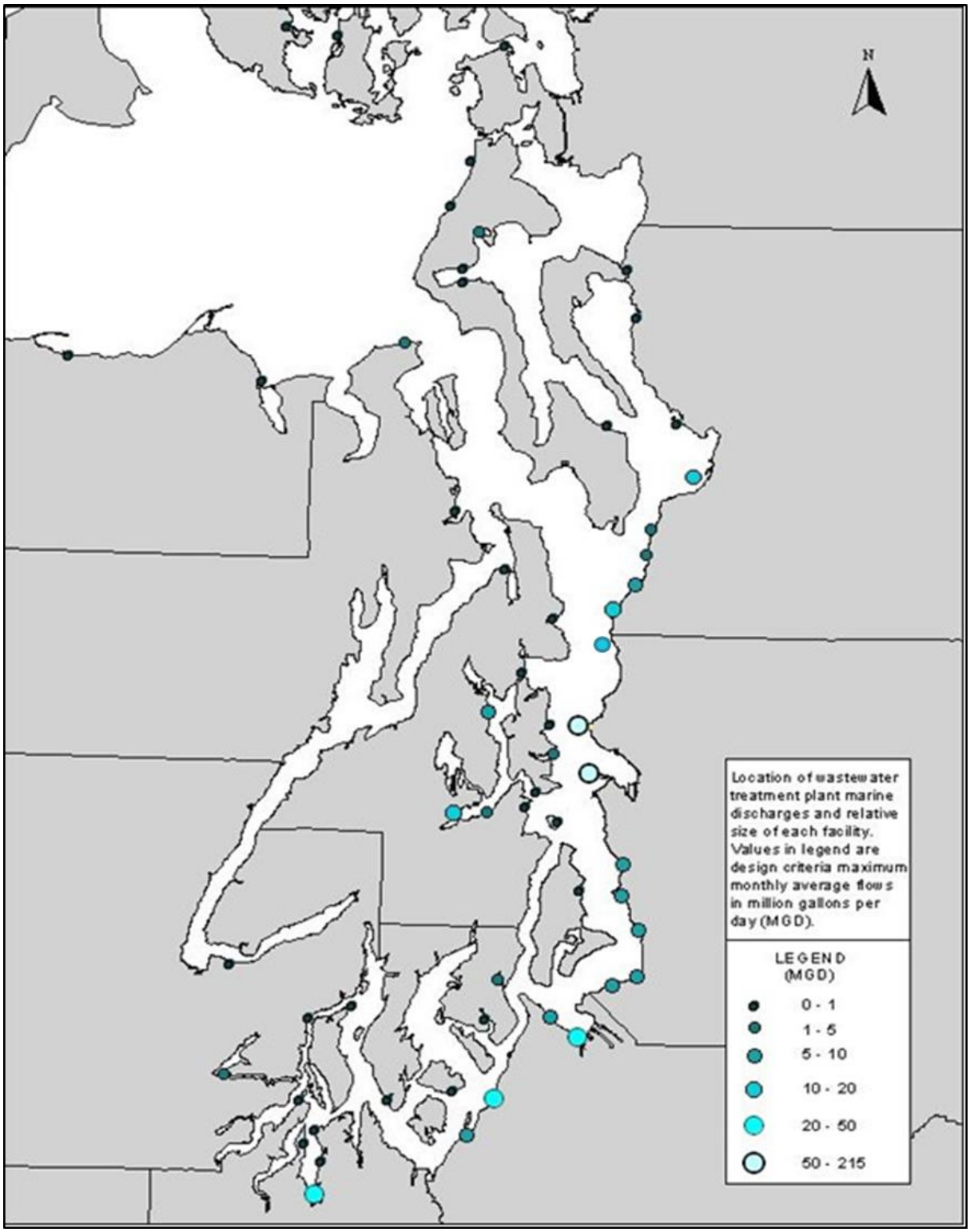

Figure 3. Puget Sound wastewater treatment plant marine discharge locations (King County, 2009a).

1.3.2 Combined Sewer Overflow Discharges

CSO discharges consist of untreated sewage and stormwater that is generated when the sewer pipes reach capacity during heavy rainfall events. CSOs provide relief points to prevent sewage and stormwater from backing up into homes and businesses. CSO discharges are typically 10-15% sewage and 85-90% stormwater. Between the late 1800s and 1940s in Seattle, engineers designed combined sewer systems to convey both sanitary sewage and stormwater runoff in a single pipe to the nearest receiving water body. In the early 1950s, most sewer systems were built as separated systems which conveyed sewage and stormwater runoff in separate pipes. In the late 1950s, treatment plants were built to treat sewage. Combined sewer systems still exist in portions of older cities in western King County, including Seattle (Figure 4). All CSOs within King County are in Seattle; this is the oldest part of the sewer system that is not separated. Wastewater and stormwater from other parts of King County are separated, and wastewater is conveyed to treatment plants prior to discharge. King County has a long-term CSO control plan to reduce frequency and volume of its CSOs to the required Washington State performance standard of no more than one untreated overflow event per year on average. Under the West Point TP NPDES permit, Ecology requires CSO overflow performance to be evaluated and achieved based on a 20-year average.

Figure 4. King County and City of Seattle CSO locations.

1.3.3 Stormwater Discharges

Stormwater runoff is rainwater that flows off surfaces such as paved streets, rooftops, parking lots, and lawns. Stormwater contains a variety of pollutants, dependent upon the runoff source. For example, runoff from parking lots and streets can contain hydrocarbons from combustible fuel, while runoff from lawns and grassy areas can contain pesticides and herbicides. In urban areas, stormwater is collected through storm drains and can be conveyed in different ways. Stormwater can be conveyed to various types of treatment systems before being discharged to a receiving water body or directly discharged through a stormwater outfall without receiving treatment. Figure 4 shows locations of CSOs within western King County. There are also many small stormwater-only outfalls that are too numerous to be shown on Figure 4.

In 1987, the CWA was amended to require certain industries and municipalities to obtain a NPDES permit for stormwater discharges. The EPA stormwater regulations for Washington State established two phases for the stormwater permitting process. Phase I permits first promulgated in 1990, cover stormwater discharges from certain industries, construction sites over five acres, and municipalities with a population over 100,000. King County and Seattle are covered under the Phase I municipal stormwater NPDES permit that requires implementation of a Stormwater Management Program, which includes a plan to reduce discharge of pollutants in stormwater, reduce receiving water impacts, and eliminate illegal discharges. Phase II regulations began in 1999 and expanded the stormwater permit requirements for municipalities located in urbanized areas and construction sites between one to five acres. The 2021 King County Stormwater Pollution Prevention Manual (King County, 2021) provides best management practices for managing stormwater on commercial, multi-family and residential properties and can be accessed at https://your.kingcounty.gov/dnrp/library/water-and-land/stormwater/stormwater-pollution-prevention-manual/2021-stormwater-pollution-prevention-manual.pdf.

2.0 MARINE MONITORING PROGRAM SAMPLING AREA

King County's Marine Monitoring Program sampling area is located within the Central Basin, extending south to Dumas Bay and north to Edwards Point. Elliott Bay, a large urban embayment which includes the Seattle waterfront, is located within the monitoring area. The eastern shoreline of Vashon Island and Quartermaster Harbor, an embayment between Vashon and Maury Islands, are also included in the monitoring area. Sampling sites monitored for some parameters are also located in the Duwamish River sub-estuary (Duwamish River) from East Waterway upstream to RM 6.5. The following sections present background information on the characteristics of the overall sampling area.

2.1.1 Sampling Area Characteristics

Puget Sound is a fjord-like estuary that extends approximately 230 kilometers (km) in a north-south direction bordered by the Olympic Mountains to the west and the Cascade Mountains to the east. Puget Sound consists of a series of underwater valleys and ridges (called basins) and submerged hills (called sills). Sills impede water flow in and out of the Sound and induce vertical mixing as water moves over the sill. The Sound consists of four major interconnected basins, including the Main (Admiralty Inlet and Central Basin), Whidbey, Southern, and Hood Canal Basins. The Whidbey Basin is not a basin in the geological sense; its southern boundary is an arbitrarily chosen line running from Possession Point on Whidbey Island across the channel to Picnic Point in southern Snohomish County.

Water from the Pacific Ocean enters the Sound primarily through Admiralty Inlet and secondarily through Deception Pass. The area where Possession Sound and Admiralty Inlet join with the Central Basin is referred to as the Triple Junction. The Main Basin, with depths > 280 m, is shielded at the northern entrance to the Sound by the Admiralty Inlet Sill which impedes exchange of deep waters. However, the Sound has near-oceanic salinity year-round and is supplemented with cold, nutrient-rich, low-oxygenated, deep oceanic water upwelled off the Washington coast during the late summer.

Puget Sound has an average depth of 106 m and contains approximately 168 billion cubic meters (m^3) of water. The average tidal range is 3.7 to 4.3 m and an average water volume exchange of 8 billion m^3 occurs with each tidal cycle (King County, 1994). A mixed semi-diurnal tide, characterized by two unequal high tides and two unequal low tides occurring each day, dominates the tidal pattern. These relatively large water exchange rates are conducive to maintaining overall favorable water quality conditions in Puget Sound.

Many complex factors influence water quality in Puget Sound, including currents; physical, biological, and chemical processes and human activities. Nearshore waters and sediments tend to exhibit more water quality problems due to their proximity to land and terrigenous pollutant sources. Bacteria levels in nearshore waters are consistently higher than in

offshore waters due to their proximity to sources such as storm drains, CSOs, freshwater inputs (creeks and streams), and urban wildlife. Sediment carried in runoff from land plays a much greater role in Puget Sound's water quality than in most marine areas. Being surrounded by hills, lakes, and rivers in an urbanized area with substantial rainfall gives the Sound a multitude of complex sediment sources. The predominant sediment sources are from river transport and bluff erosion. The twelve largest rivers entering Puget Sound contribute approximately 1.8 million m^3 of sediment annually (King County, 2001). Suspended sediment load from these rivers is highest during winter and early spring when heavy seasonal precipitation from storms erodes soil from the surrounding lowlands. Sediment chemistry results generally show the highest levels of organic chemicals are detected in nearshore areas of Elliott Bay, where urban runoff from storm drains, CSOs, industrial sources, and nonpoint sources is the greatest.

2.1.2 Freshwater Inputs

In an estuarine environment such as Puget Sound, freshwater flows from rivers and streams are important as they affect both physical and biological processes, as well as contaminant and nutrient inputs. Freshwater flows influence Puget Sound water quality and circulation as input volumes vary seasonally and affect water temperature, salinity, and density, factors that can lead to water column stratification. Water column stratification can affect biological populations by trapping nutrients and/or affecting vertical migration through the water column. Freshwater flow also affects the amount of nutrients and contaminants transported into marine waters. Freshwater input to rivers originates mainly from rainfall, but snowmelt also contributes a large input in late spring and early summer.

The two largest direct freshwater inputs into Central Basin marine waters are the Green/Duwamish River system and the Lake Washington Drainage Basin (Cedar River). The Green/Duwamish River flows into Elliott Bay, while drainage from the Lake Washington system flows into the Sound primarily through the Lake Washington Ship Canal. The Skagit, Stillaguamish, Snohomish, and Puyallup rivers also contribute substantial freshwater flows, particularly the Skagit River, and can affect marine waters within the Central Basin. The Puyallup River has the largest impact on marine waters in the southern portion of the Central Basin. Numerous smaller streams also discharge directly into nearshore Puget Sound waters. The annual average flow (2008 -2019) for eight rivers draining to Puget Sound is shown in Figure 5. The average combined monthly flow and seasonality for the same rivers and period is shown in Figure 6. Additional river flow data are in Section 3.5.3.

Freshwater inputs typically increase in late spring and summer from snow melt but are dependent upon location and hydrology of the drainage basin, as well as inter-annual variation. Typically, an increase in freshwater inputs occurs during late May to early July in the Skagit River and in May and June in the Puyallup River. Due to regulated flows in the Lake Washington Drainage Basin and the Green/Duwamish River, snow melt does not increase freshwater inputs in these systems to the extent that it does in other systems.

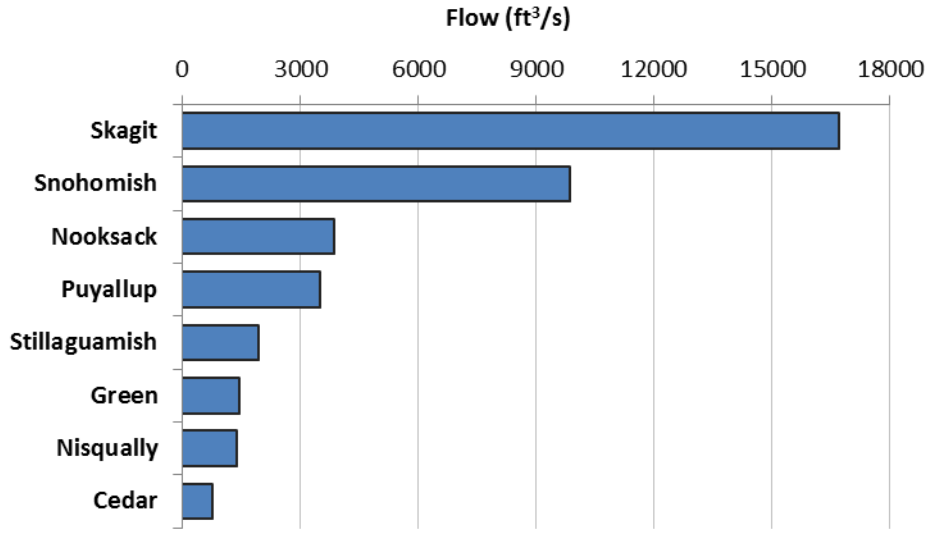

Figure 5. Average annual flow (cubic feet per second) (2008-2019) for eight major rivers draining to Puget Sound.

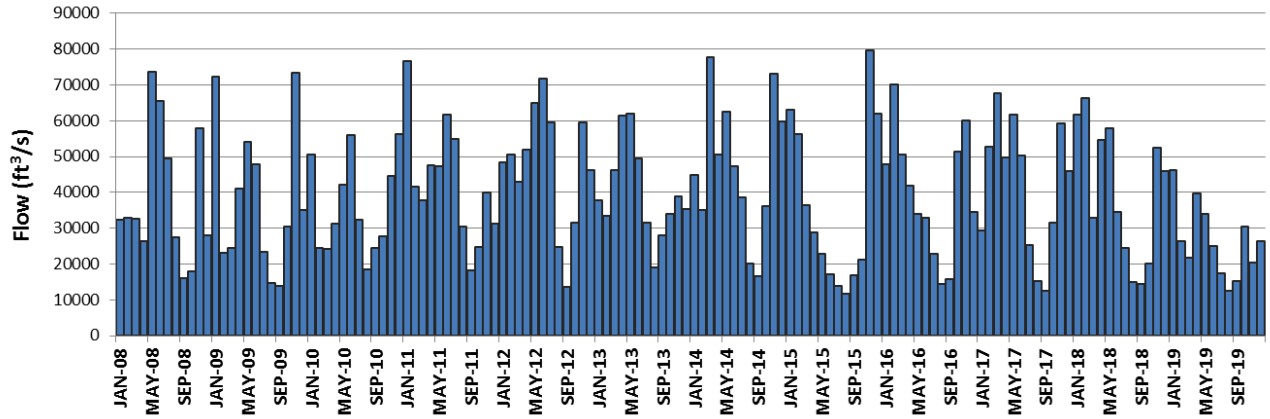

Figure 6. Average combined monthly flow for eight rivers (Skagit, Snohomish, Nooksack, Puyallup, Stillaguamish, Green, Nisqually, and Cedar) (2008-2019).

2.1.3 Oceanographic Characteristics

Water circulation in Puget Sound generally consists of a two-layered flow, with incoming, saltier oceanic water flowing along the bottom and a fresher, less dense water layer flowing out at the surface (Figure 7). As stated above, the largest single freshwater input into Puget Sound is the Skagit River, followed by the Snohomish and Stillaguamish rivers, all of which flow into the Whidbey Basin. The Nooksack River flows into Bellingham Bay in northern Puget Sound. The Puyallup and Nisqually rivers are the largest freshwater inputs into southern Puget Sound. The largest freshwater inputs into the Central Basin are the Duwamish River and the Lake Washington system. The freshwater inputs are driven by runoff from rainfall and summer snow melt. Salty, cold, dense waters enter Puget Sound at depth through Admiralty Inlet and a portion flows south in the Central Basin, while the other portion flows northeast through Possession Sound to the Whidbey Basin.

Water tends to flow faster on the eastern side of the Central Basin near Alki Point and Point Wells and along the western side near Point Monroe and north of Kingston, where major topographic features affect currents (Figure 7). The deeper, denser waters in the Central Basin often move 5 to 10 times faster than deeper currents in the Whidbey Basin due to vigorous mixing at the Tacoma Narrows (Ebbesmeyer and Cannon, 2001).

The circulation of inflowing and outflowing water is affected by the sills, particularly the shallow Admiralty Inlet and Tacoma Narrows sills, which induce vertical mixing of the two water layers. An exception to the two-layered flow in the Central Basin occurs in the southern portion around Vashon Island. In this area, net flow is mainly southward through East Passage, around the southern end of Vashon Island, and then north through Colvos Passage (Figure 7). This flow pattern is caused by the location of Vashon Island relative to outflowing water from the Tacoma Narrows. The outflow from Colvos Passage has a significant effect on surface circulation in the northern portion of the Central Basin (Ebbesmeyer and Cannon, 2001). Water moving northward through Colvos passage is directed across the channel towards Alki Point, where a portion then returns south in East Passage. The other portion flows north toward the Triple Junction, the area where waters from the Central Basin, Whidbey Basin, and Admiralty Inlet converge.

Winds can cause significant variations in circulation. Southerly winds augment the surface outflowing water and northerly winds can impede and sometimes reverse surface flow. Bottom water intrusions can also cause significant variations in circulation. Intrusions occur when dense Pacific Ocean saltwater crosses the Admiralty Inlet sill and replaces deep water in the Main Basin. Bottom water intrusions circulate down Puget Sound at speeds of about 20 centimeters per second (cm/s) near the Admiralty Inlet sill and 10 cm/s along the Central Basin (Ebbesmeyer and Cannon, 2001).

Northerly winds on the outer coast favor upwelling that brings deep Pacific Ocean water into Puget Sound. This upwelled ocean water is cold, salty, high in nutrients, and low in dissolved oxygen. The upwelled water is typically noticeable in the late summer to fall in the Central Basin and can affect water quality.

Residence time of water in the Main Basin is about 48 days, depending upon time of year (Babson, 2004).

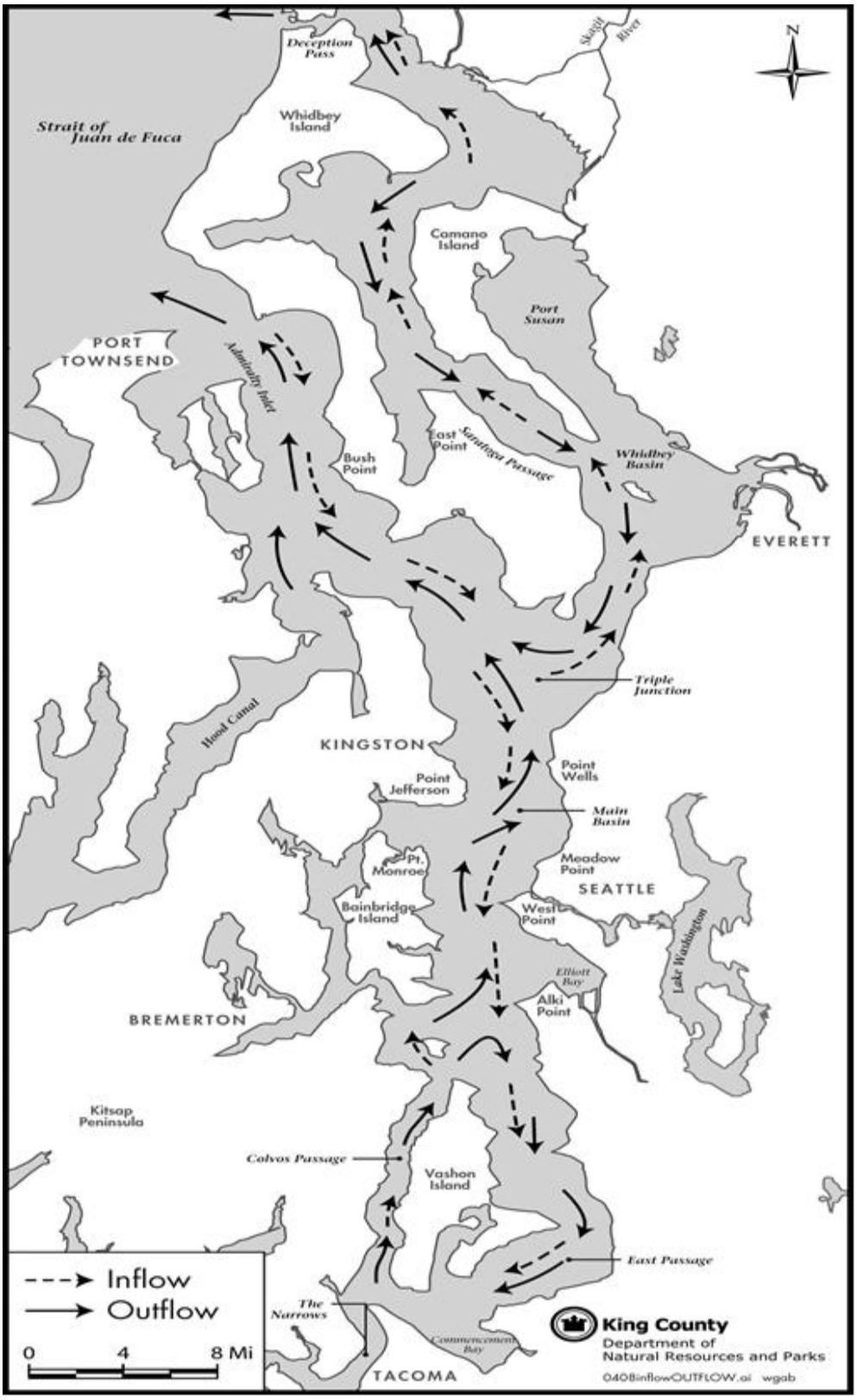

Figure 7. Generalized Puget Sound circulation (from Ebbesmeyer et al., 2002).

3.0 LARGE-SCALE AND REGIONAL CLIMATE AND WEATHER

Water quality and conditions in Puget Sound are influenced by many climate parameters, both near- and far-field. This section provides information for several key climate and weather patterns that were measured or observed between 2008 and 2019 that support interpretation of water quality results.

3.1 Large-scale Climate and Weather

Variations in circulation throughout the Pacific Ocean can have profound impacts on climate in the Puget Sound region. Ocean/atmosphere feedbacks throughout the Pacific alter wind, temperature, and precipitation patterns. Three quantitative measures of Pacific climate patterns are the El Niño/Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Aleutian Low pressure cell as measured by the North Pacific Index (NPI).

ENSO is a naturally occurring event in the equatorial regions of the Pacific Ocean caused by interactions between the tropical trade winds, sea surface temperatures, and ocean currents. These climate events typically occur on a 6 to 18-month time scale and vary in strength and duration. During an El Niño event, sea surface temperatures in the eastern equatorial Pacific are higher than usual, which co-occurs with an area of increased atmospheric convection over the central Pacific and a reduction or reversal of the tropical trade winds. These conditions usually result in warm, dry winters in the Pacific Northwest. La Niña events are typically characterized by the opposite conditions, though there is variation between individual ENSO events.

The PDO occurs over a longer timescale than ENSO, with a typical phase length of 20–30 years. Like ENSO, PDO phases are classified as warm (positive index value) or cool (negative) depending on the sea surface temperature anomalies along the North American Pacific coast. Positive index values are also associated with lower sea level pressure in the North Pacific, and the opposite for negative index values. Calculation of the PDO index attempts to account for the effects of global warming, since that likely has a significant impact on sea surface temperature when considering a multi-decadal time span.

The NPI corresponds to the intensity of the Aleutian Low, a semi-permanent low-pressure cell in the North Pacific. The strength and location of the Aleutian Low affects precipitation, wind, and other weather patterns in the Pacific Northwest. The NPI is calculated monthly as an area-weighted average of sea level pressure over 30–65°N and 160°E–140°W. The NPI anomaly, which normalizes the NPI to make the values more comparable to other climate indices, is calculated by first averaging the monthly NPI indices (in hPa) January–March of a given year along with November–December of the previous year. This 5-month average is then compared to the average from the historical baseline period (1929–1989). During late fall through winter, the Aleutian Low migrates to the southeast and typically

results in moist, mild conditions in the Pacific Northwest. The Aleutian Low retreats in the spring in conjunction with an expansion of a high-pressure cell further south. Both PDO and ENSO contribute to changes and variability in the NPI. When the Aleutian Low is intense, the NPI is low and the Pacific Northwest experiences warmer, drier winters. A weak Aleutian Low (i.e., high NPI) results in colder, wetter winters.

In the Pacific Northwest, prevailing winds during the winter are southerly, which drives surface seawater towards the coast. In summer, winds are northerly, which pushes surface seawater away from the coast. As surface water moves away from the coast, deeper water is transported to the surface in a process known as upwelling. This deep water is usually cold, oxygen-poor, and nutrient-rich, and supplies nutrients to Puget Sound. Ocean water is the primary source of nitrogen into the Sound (Mackas & Harrison, 1997). The intensity of upwelling is key to understanding the potential for biological production, particularly during the summer months when sunlight is abundant at the surface.

Upwelling varies substantially depending on wind conditions, which can be influenced by larger-scale climate patterns such as El Niño/La Niña. Upwelling indices indicate the strength of upwelling and are calculated using data such as wind speed, wind direction, and sea level air pressure. The spring transition is when conditions shift from downwelling to upwelling along the Pacific Coast between California and British Columbia. This transition causes important shifts in biological productivity and community structure in both the coastal regions and Puget Sound. In the fall, changes in prevailing winds lead to transition from upwelling to downwelling conditions.

3.2 Regional Climate and Weather

Direction and strength of winds within Puget Sound can affect overall estuarine circulation, with impacts on surface mixing and the direction of surface currents which can affect duration of phytoplankton blooms. Prevailing wind direction also impacts how water moves through Puget Sound.

Precipitation drives freshwater input into Puget Sound. High levels of precipitation lead to higher freshwater input flows, which introduces low-salinity and often high-nutrient (depending on watershed source) water into the Sound. Low summer precipitation is predicted to continue in the future, with reductions as high as 30% by the end of the 21st century (Kunkel et al., 2013). Conversely, the number of extremely high precipitation events are also expected to increase (Littell et al., 2009).

Freshwater inputs impact both physical and biological water properties in Puget Sound. Rivers in the Puget Sound region fall into three classifications based on their primary water source: snowmelt dominated, rainfall dominated, and transitional. Snowmelt dominated rivers experience high flows in spring and early summer, while rainfall dominated rivers experience high flows in winter when precipitation is greatest. Transitional rivers receive contributions from both melting snowpack and rainfall and experience peak flows during both spring and winter.

The six largest rivers that impact King County marine waters (Figure 8) are considered transitional rivers, with the Skagit River having the most snowmelt influence followed by the Snohomish and Puyallup rivers. Most of these rivers, except the Stillaguamish and Snohomish, have major dams and/or reservoirs that regulate flow to some extent.

Figure 8. Map of six rivers that impact King County marine waters.

Air temperature can be a useful indicator of local climate, since it is affected by large-scale climate patterns (e.g., El Niño/La Niña) and solar irradiance. Air temperature has impacts on precipitation, as well as water temperature, and thus biological production.

3.3 Data Sources, Collection and Analysis Methods

Much of the data used to assess large scale regional climate and weather is collected by other agencies. Except for the meteorologic data (wind speed/direction and air temperature) collected by the King County marine mooring at Dockton Park on Maury Island, all data described here were collected by other agencies. The following discussion describes the data collection and analysis methods used to calculate or summarize the climate and weather parameters/metrics described in this report.

Multiple methods are used to calculate ENSO status. The data presented here are based on values from the National Oceanographic and Atmospheric Administration (NOAA) Multivariate El Niño/Southern Oscillation Index (MEI), which was calculated using sea level pressure, sea surface temperature, zonal and meridional winds, and outgoing longwave radiation over 30°S–30°N and 100°E–70°W (Wolter and Timlin, 1993). MEI presents a more whole-system view of the atmospheric and oceanic conditions associated with ENSO events, contrasted with other indices that use only sea surface temperature. MEI values were calculated for 12 overlapping bi-monthly "seasons" (Jan.–Feb., Feb.–Mar., etc.) from 1979 to 2019. The time series presented in the results section below uses the first day of the second month of each "season" as the date.

Like ENSO, there are multiple methods to calculate PDO status. The PDO information presented here is based on values from the NOAA National Centers for Environmental Information (NCEI) PDO index from 1894 to 2019. This index is based on both reconstructed sea surface temperatures and the Mantua PDO index (Mantua, 1999). Monthly values were calculated.

For NPI, the most important variability occurs in Nov.–Mar. (Trenberth and Hurrell, 1994). Annual NPI values were estimated by averaging the values in those months for each year (Hurrell & NCAR), with the year being the calendar year of Jan.–Mar. Annual NPI anomaly values were calculated by subtracting annual NPI values from a baseline value of 1008.9 hPa, which is the 1925–1989 mean.

Satellite-derived sea surface temperature (SST) products are some of the most common ways to look at global or regional ocean temperatures. The *CoralTemp* SST estimate is produced by NOAA Coral Reef Watch (CRW) and was derived from several different SST estimates, which aim to correct for bias and gaps, such as from cloud cover (Skirving et al., 2020). SST estimates were calculated every day at 5 km resolution. Daily estimates were subtracted from a 1985–1990 plus 1993 monthly baseline to calculate SST anomaly (NOAA CRW).

Another way to assess sea temperature is to use observational data from Argo floats, which are autonomous profilers that collect data in the open ocean. As of 2007 there are more than 3000 Argo instruments collecting data in the global oceans. The Roemmich-Gilson Argo Climatology uses 33–100 Argo profile observations closest to a latitude-longitude

coordinate to estimate temperature at that location for a given month over a fixed vertical grid (Roemmich and Gilson, 2009). These monthly estimates were subtracted from a 2004–2018 baseline to calculate temperature anomaly. These data were collected and made freely available by the International Argo Program and the national programs that contribute to it (http://www.argo.ucsd.edu, http://argo.jcommops.org). The Argo Program is part of the Global Ocean Observing System.

Upwelling conditions are often represented as an index value, which is calculated based on geostrophic wind stress at a location of interest. NOAA Pacific Fisheries Environmental Group (PFEG) calculates upwelling indices at 15 different locations along the Pacific coast of North America. Calculations are performed with 6-hour and monthly surface pressure observations and interpolations (Schwing et al., 1996). Monthly index values for 48°N, 125°W (near La Push, WA) from 2008 to 2019 are presented in this report.

There are several ways, both biological and physical, to calculate the dates on which conditions shift between upwelling- and downwelling-favorable on the Pacific coast. The Pierce Barth method (Barth et al., 2007) presented here uses cumulative wind stress at Newport, OR (44°36'48" N, 124°4'0" W) to determine the date of the spring and fall transitions, which mark the beginning and end of the upwelling-favorable conditions. For each year, the length of the upwelling-favorable period is the difference between the spring and fall transition dates.

Wind speed and direction measurements are made every 10 minutes at the West Point Lighthouse (Figure 9) by NOAA National Data Buoy Center (NDBC). Total daily precipitation and daily maximum, minimum, and average air temperature measurements are made at Seattle-Tacoma International Airport (Figure 9) by NOAA (GHCND:USW00024233).

King County collects 15-minute water quality and meteorological data using a semi-permanent moored system attached to a dock at Dockton Park (Figure 9). This system collects data both in the water column (tidally variable depth) and on the dock. Presented in this report are data from the Dockton wind speed/direction and air temperature sensors, which are located on the dock. More information and downloadable data can be found on the mooring program website: https://green2.kingcounty.gov/marine-buoy/

River discharges (flow rates) near Puget Sound (Figure 8) are measured every 15 minutes by the United States Geologic Survey (USGS). These 15-minute rates are summed into monthly cumulative flow, measured in cubic feet. Rates for six stations are included in this report: 12200500, 12167000, 12150800, 12119000, 12113000, and 12101500.

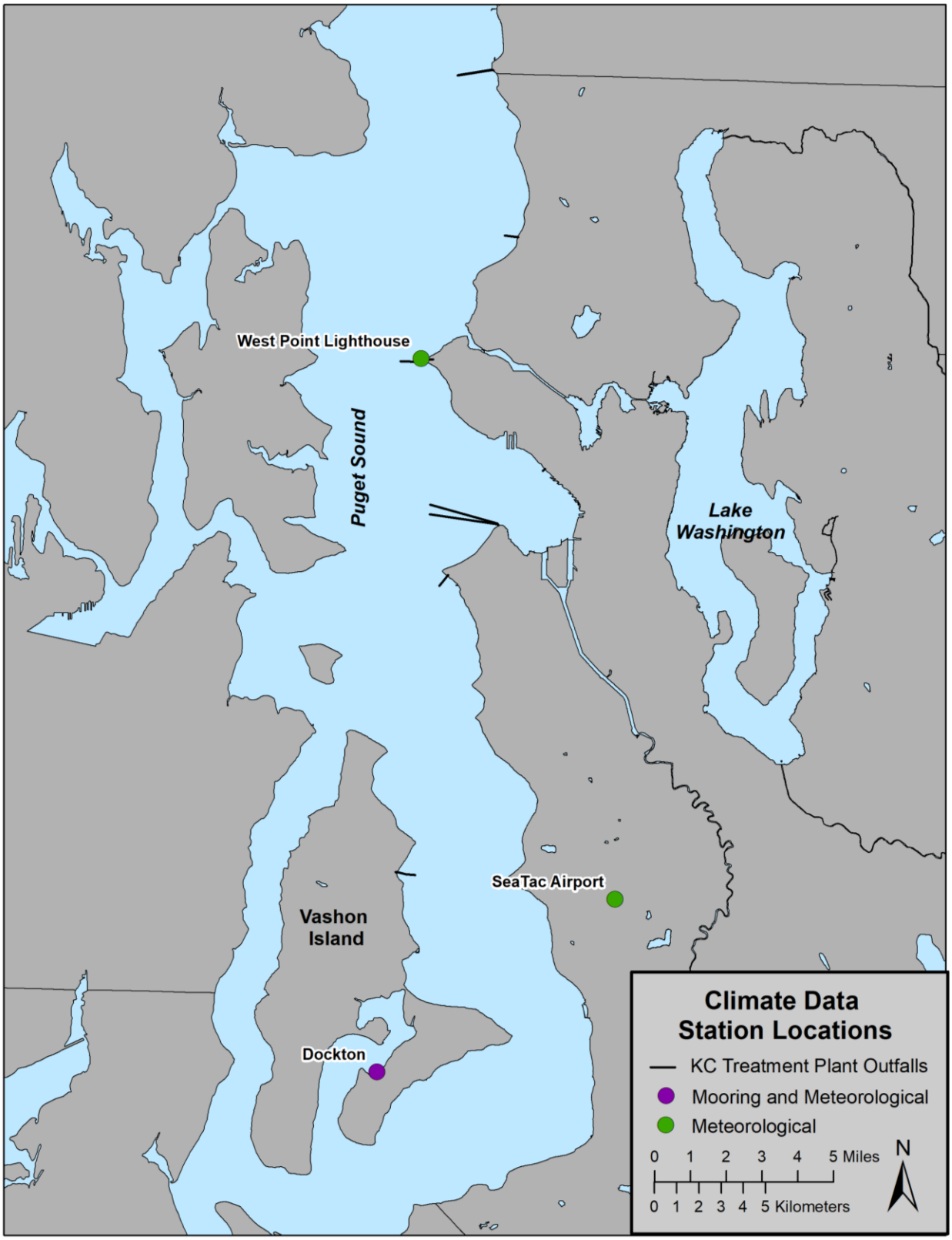

Figure 9. Map of meteorological data collection sites around Puget Sound.

3.4 Large-scale Climate Patterns

3.4.1 Pacific Ocean Circulation

The 2008–2019 period began in a La Niña event that lasted until 2009, followed by a brief El Niño and a longer, more intense La Niña from 2010 to 2014 (Figure 10). The next El Niño event was moderately intense and lasted until 2016, which was followed by a weak 2-year La Niña (2016–2018) and a weak El Niño in 2019.

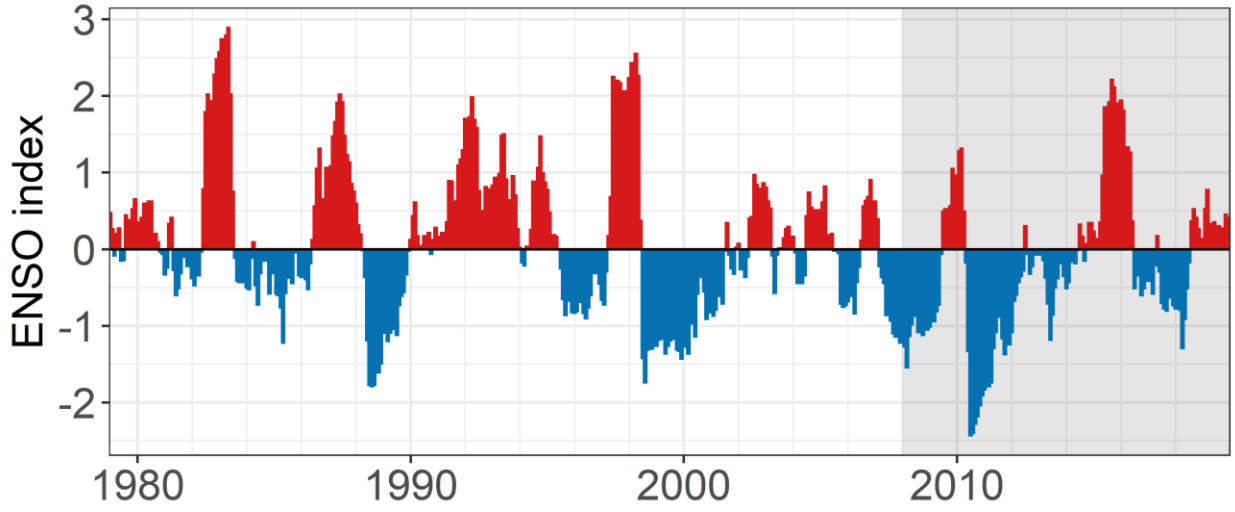

Figure 10. Monthly averages of the El Niño/Southern Oscillation (ENSO) Multivariate Index (MEI.v2), 1979–2019. The period covered in this report series (2008–2019) is shaded gray. Red bars indicate an El Niño (warm) phase, blue bars indicate a La Niña (cold) phase. Data available from NOAA: https://psl.noaa.gov/enso/mei

Early in the 2008–2019 period, the PDO index was strongly negative, indicating cooler-than-average sea surface temperatures along the Pacific coast (Figure 11). The PDO index was briefly and moderately positive from 2014 to mid-2017, and the following years have been weakly negative. The transition to positive PDO index values corresponded with the 2014–2016 marine heat wave.

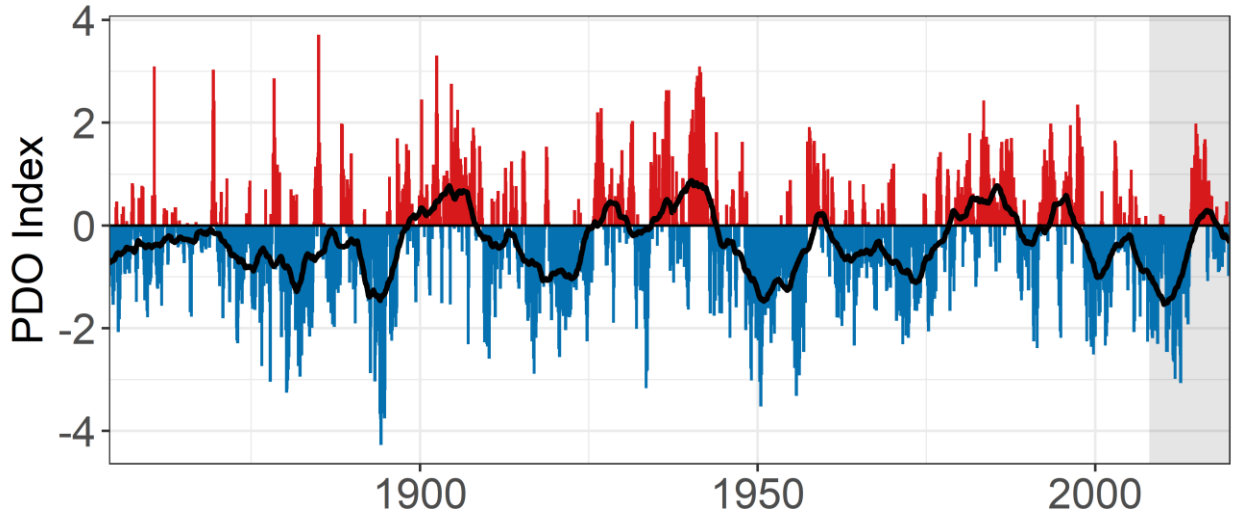

Figure 11. Monthly averages of the PDO index, 1854–2019. Thick black line represents 5-year moving average of PDO index. The period covered in this report series (2008–2019) is shaded gray. Red bars indicate a warm phase along the North American Pacific coast, blue bars indicate a cold phase. Data available from NOAA: https://www.ncdc.noaa.gov/teleconnections/pdo/

The Aleutian Low was generally weak (high NPI) during 2008–2019 (Figure 12), indicating colder and wetter winters, with brief positive excursions during 2010 and 2015–16. These conditions correspond to the generally low PDO index over this period along with the moderate-to-intense La Niña events.

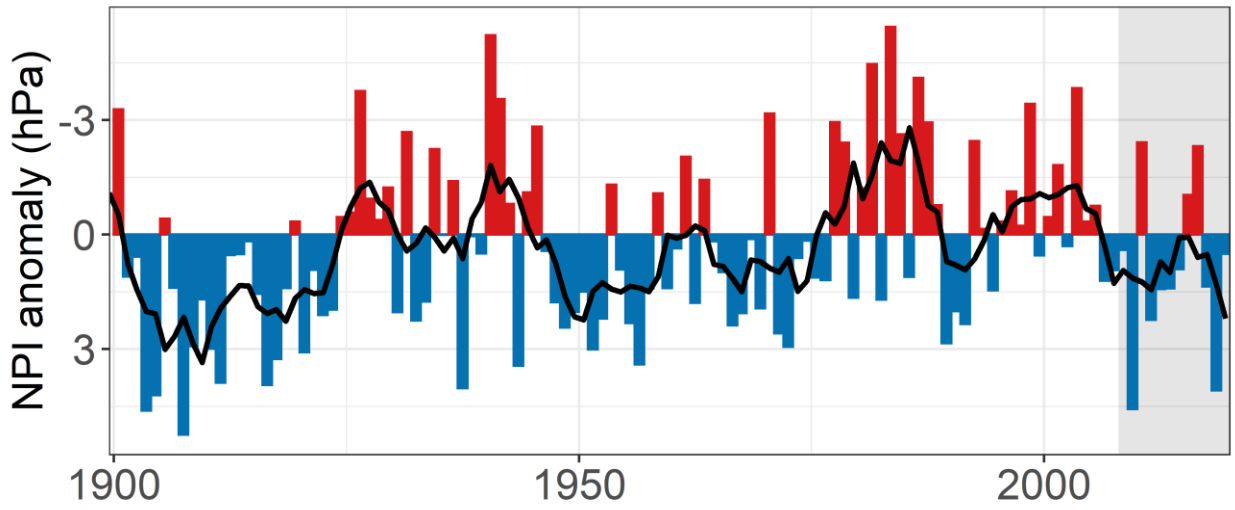

Figure 12. Annual average NPI anomalies, 1900–2019. Note reversed y-axis scale; negative values (red bars) indicate a more intense Aleutian Low. Positive values (blue bars) indicate a weaker Aleutian Low. Black line represents 5-year moving average of annual averages. The period covered in this report series (2008–2019) is shaded gray. Data available from UCAR: https://climatedataguide.ucar.edu/climate-data/north-pacific-np-index-trenberth-and-hurrell-monthly-and-winter

3.4.2 Marine Heat Waves

From winter of 2013–2014 through winter of 2014–2015, the northeast Pacific Ocean experienced one of the largest marine heat waves ever recorded. Referred to as "the Blob," this warm ocean water disrupted the marine ecosystem and had negative impacts on salmon and other fauna. These warm conditions were the result of a weak Aleutian Low, which yielded weak winds and minimal mixing, thereby reducing the amount of cooling in surface waters. The weak El Niño event and positive PDO index that correspond to this period are thought to have contributed to the atmospheric forcing patterns that caused this event (Di Lorenzo & Mantua, 2016). In Figure 13a, "the Blob" can be seen off the west coast of North America as a substantial positive sea surface temperature anomaly. In Figure 13b, a similar expansive region of positive sea surface temperature anomalies was seen in the summer of 2019, indicating another marine heat wave.

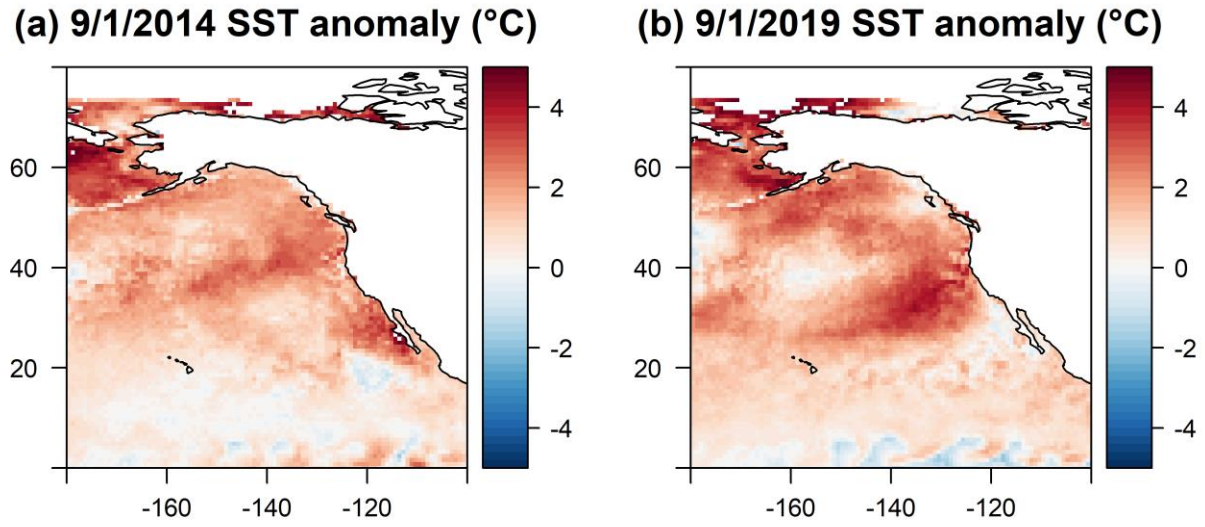

Figure 13. Daily mean high-resolution sea surface temperature (SST) anomalies from (a) August 1, 2014 and (b) August 1, 2019. Data available from NOAA Coral Reef Watch: https://coralreefwatch.noaa.gov/product/5km/

Though these marine heat waves are easily identified by satellites in surface waters, their signals can also be seen at depth. The surface warming signal from the 2013–2015 marine heat wave propagated to deeper waters and persisted even as surface waters cooled (Figure 14). In Puget Sound, warming from marine heat waves is retained over a long period, due to limited water mass mixing over the sills. The warming signal from the 2013–2015 marine heat wave was seen in the Puget Sound Central Basin from early fall 2014 through late summer 2016. Marine heat waves have increased in duration and frequency over the past century (Oliver et al., 2018) and scientists predict more increases as the ocean continues to warm.

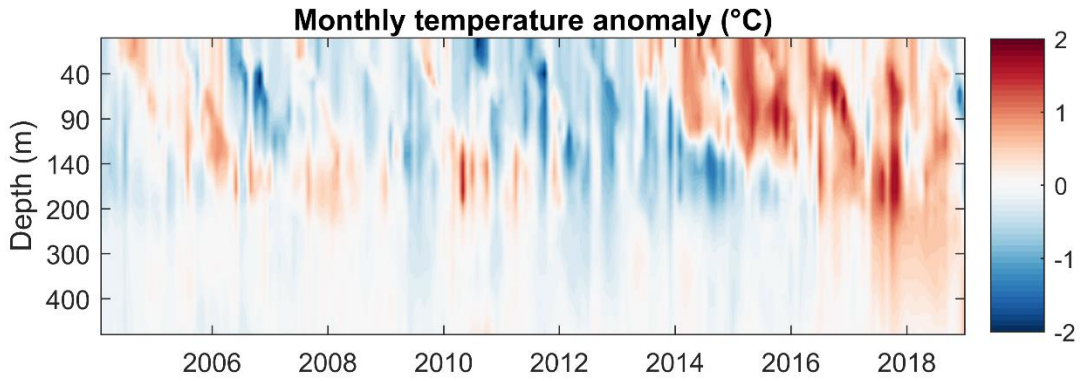

Figure 14. Monthly temperature anomalies from Argo float profiles off the Pacific coast (at 35°N and 135°W, 800 miles west of San Luis Obispo, CA), 2004–2019. Red colors indicate warmer temperatures than normal, and blue colors indicate cooler temperatures than normal. Data available from Argo: https://www.argo.ucsd.edu

3.5 Regional Climate Patterns

3.5.1 Upwelling and Winds

During 2008–2019, upwelling was generally strongest in the summer months, with downwelling (the opposite of upwelling; indicated by negative upwelling index values) occurring during the winter months (Figure 15). These patterns are typical. Summer upwelling was stronger during periods of El Niño and positive PDO index values (e.g., 2014–2016). Upwelling was weaker during periods of La Niña and negative PDO index values (e.g., 2010–2013).

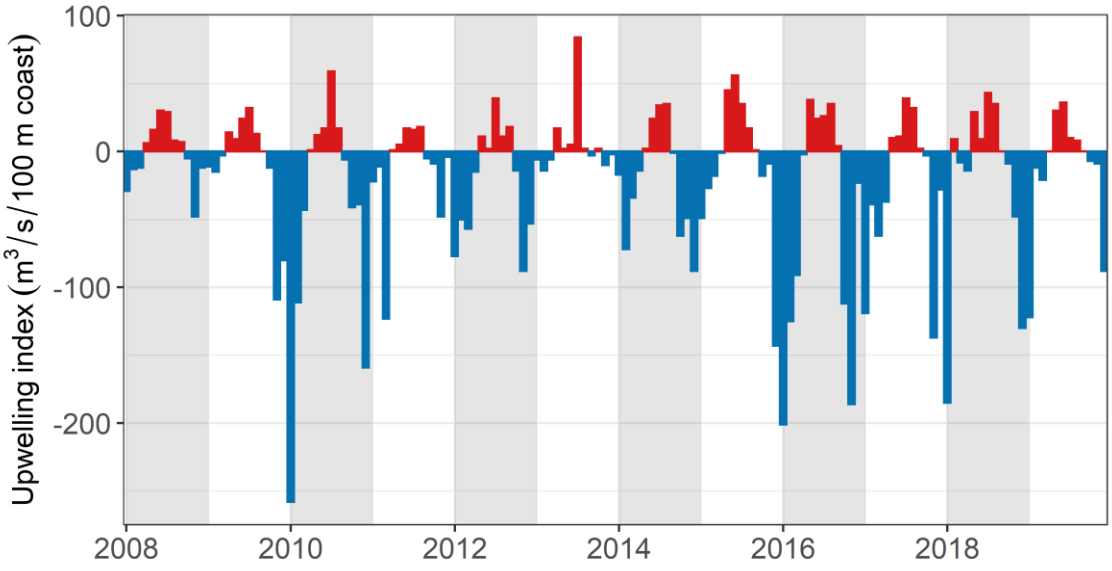

Figure 15. Monthly upwelling index at 48°N, 125°W (coastal WA near La Push), 2008–2019. Blue bars indicate negative upwelling index values, and red bars indicate positive upwelling index values. Data available from NOAA: https://oceanview.pfeg.noaa.gov/erddap/griddap

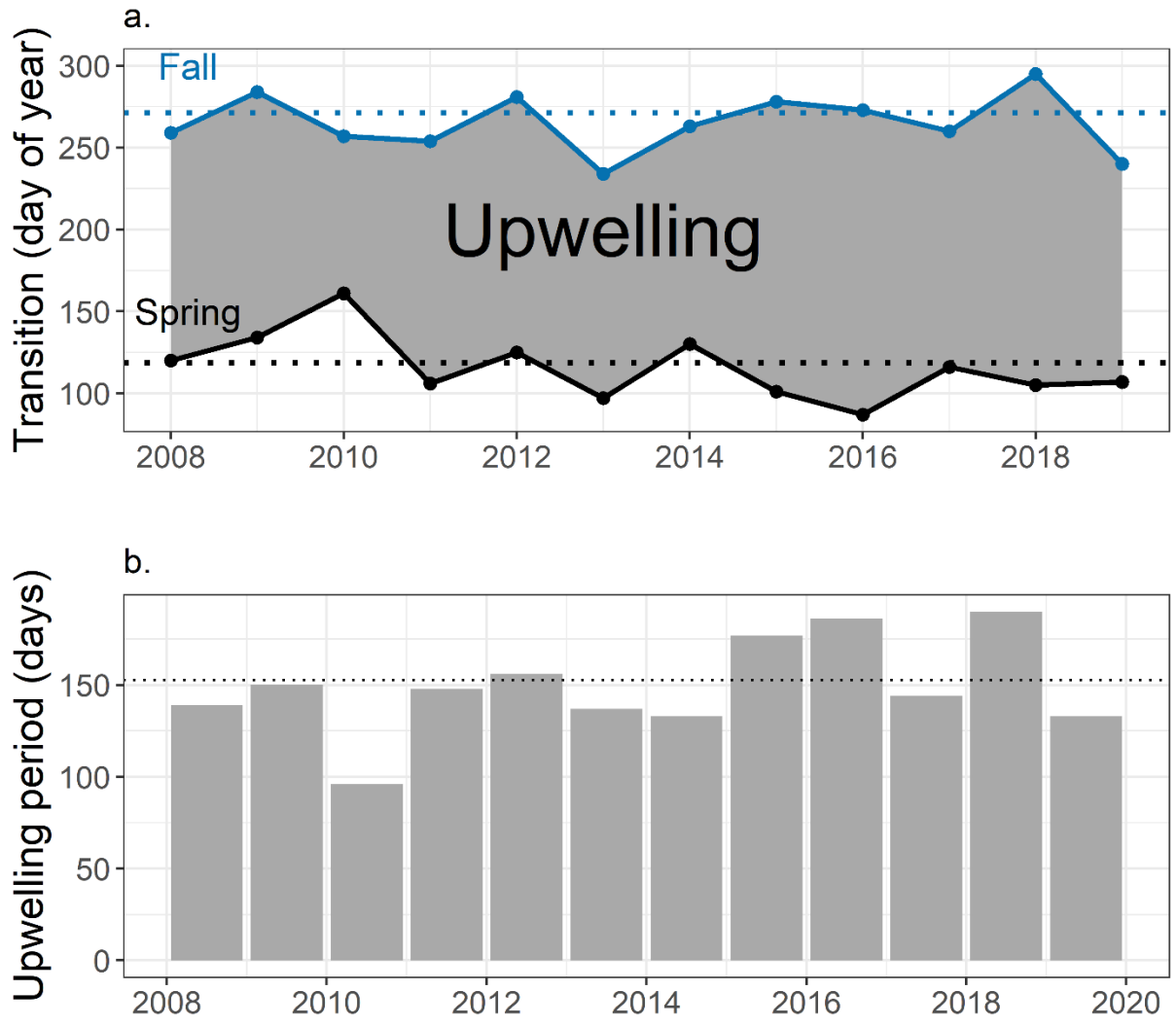

Figure 16. **a. Yearly spring upwelling (black) and fall downwelling (blue) transition dates and b. length of upwelling period between spring and fall transition, 2008–2019. Gray shading indicates period of upwelling. Dates calculated using the Pierce Barth method with wind stress data observed at Newport, OR (44°36'48"N, 124°4'0"W). Dotted lines indicate a. average transition dates and b. average upwelling period length over 1998–2013. Data available from UW: http://www.cbr.washington.edu/status/trans**

Between 2008 and 2019, the latest spring transitions occurred in 2009 (day 134; May 13–14) and 2010 (day 161; June 9–10). Late spring transitions result in lower surface nutrients and production in the coastal areas (Barth et al., 2007). These changes may also be observed in Puget Sound, though they are likely delayed by some lag period.

Between 2015 and 2019, estimated spring transition dates were earlier than the baseline (1998–2013) average (approximately day 119; April 28–29). The earliest transition occurred in 2016 (day 87; March 27–28). Between 2008 and 2019 there was a slight trend towards earlier transition dates, though this trend is not evident in the longer time series

data set (1985 to 2019). Earlier transitions to upwelling-favorable conditions may be associated with early phytoplankton blooms and higher overall ecosystem productivity.

Between 2008 and 2019, the latest fall transition occurred in 2018 (day 295; October 21–22) and the earliest occurred in 2013 (day 234; August 21–22) and 2019 (day 240; August 27–28). There was no span of more than 2 years when the fall transition occurred consistently before or after the baseline average (day 269; September 25–26). The shortest period of upwelling-favorable conditions occurred in 2010, with only 96 days between the spring and fall transitions, compared to a baseline average of 153 days (Figure 16b). The longest periods of upwelling occurred in 2018 (190 days) and 2016 (186 days).

Generally, winds at the West Point Lighthouse during 2008–2019 were strongest in fall and winter and weakest during summer (Figure 17). Variability between years was highest in fall and winter and lowest in summer. Average wind speed was unusually low in February 2010 and August 2014. The highest monthly wind speed was in November 2009—an outlier—though no notable windstorms occurred in the region that year. Unusually high winds also occurred in July 2008, July 2009, and August 2008.

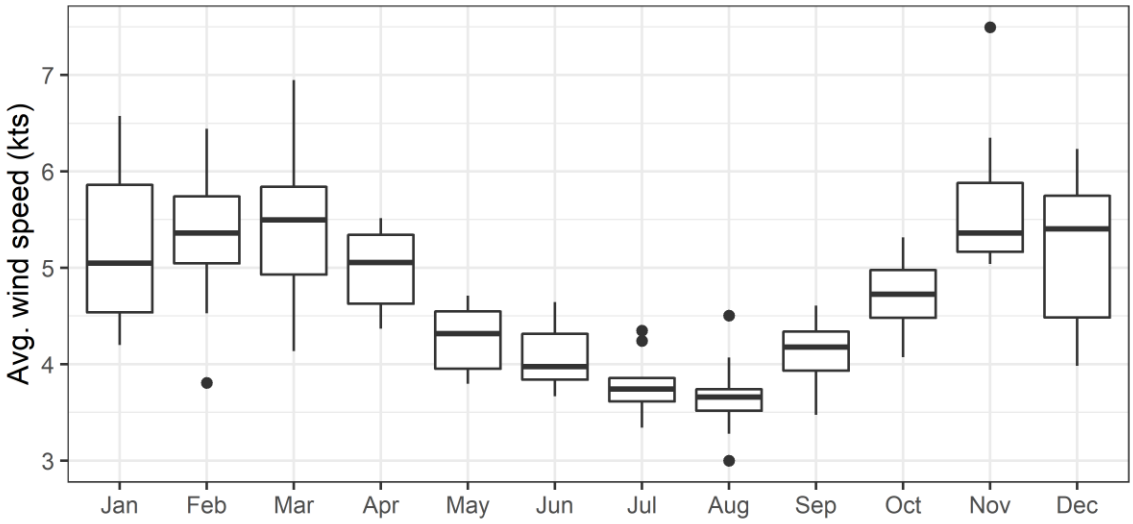

Figure 17. Boxplots of average monthly wind speeds at the West Point Lighthouse, 2008–2019. Thick black horizontal lines represent median average monthly wind speed (knots [kts]), and top and bottom edges of boxes indicate 25th and 75th percentile. Whiskers indicate the range, black dots represent outliers. Data available from NOAA: https://www.ndbc.noaa.gov/station_page.php?station=wpow1

Winds at the West Point Lighthouse and Dockton during 2008–2019 tended to come from either the south (S or SSW) or the north (NNE) (Figure 18). Wind speeds were higher at the West Point Lighthouse compared to Dockton. Moderate strength (>4 m/s) southerly winds were most common in November–April, with occasional stronger winds from the east. May–October had a balance of southerly winds and stronger northerly winds. Unusually early southerly winds in late summer 2016 led to the end of the phytoplankton growing season.

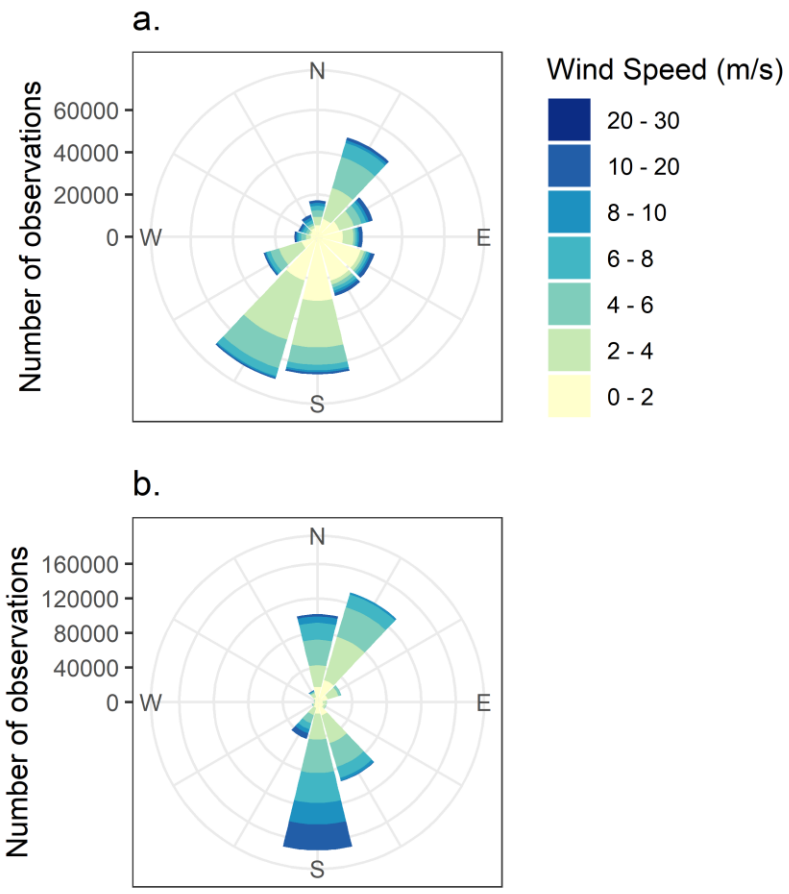

Figure 18. Wind rose of continuous wind measurements at a. Dockton mooring (15 min. data) in outer Quartermaster Harbor and b. West Point Lighthouse (10 min. data), 2008–2019. Each slice of figure represents 30° of wind direction (direction from which wind blows). Length of slice represents total observations, and color indicates wind speed associated with observations.

3.5.2 Precipitation

During 2008–2019, precipitation was generally highest during the fall and winter (Figure 19). Precipitation tapered off during spring and was lowest during the summer. About half the years had total precipitation above the 30-year average and half were below the average. The lowest total annual precipitation was observed in 2008, driven largely by low winter precipitation. The next lowest annual precipitation was observed in 2013, when there was unusually high precipitation during spring and summer but lower than usual precipitation during fall and winter. The lowest summer precipitation was observed in 2012, 2017, and 2018. Higher than normal precipitation occurred from 2014–2017, which coincided with significant flooding and landslides, including the 2014 Oso mudslide and 2017 West Point TP flooding event.

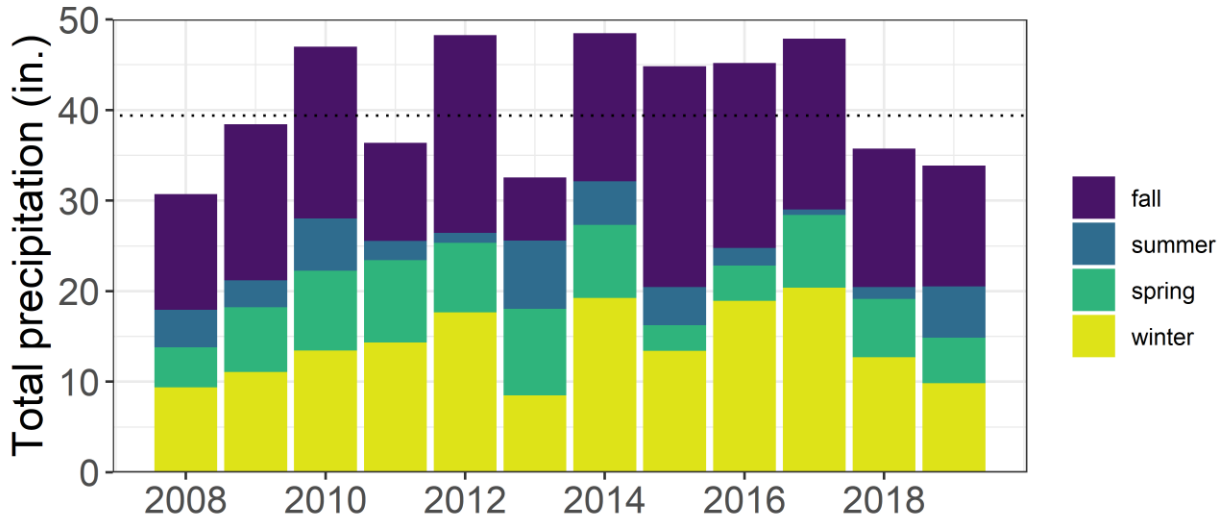

Figure 19. Seasonal precipitation at SeaTac Airport by year, 2008–2019. Horizontal dashed line represents 30-yr. average (1990–2019). Data available from NOAA: https://www.ncdc.noaa.gov/cdo-web

3.5.3 River Flow

All six major rivers experienced variable flows between 2008 and 2019 (Figure 20). Most noticeably, the lowest total annual flow in all six rivers occurred in 2019. Spring and summer flows in 2015 were low in all six rivers, but fall flows were high. Spring and summer flows were also low in 2016, particularly in the Stillaguamish, Cedar, and Green-Duwamish rivers.

The Skagit River, which discharges into Skagit Bay in the Whidbey Basin (north of the Central Basin; Figure 8), had the highest total annual flows. The Cedar and Green-Duwamish rivers, the major rivers that discharge within King County, had the lowest total annual flows of the six rivers. Years with high flow conditions were not consistent across all rivers, but several rivers had high flows in La Niña years (2011, 2012, 2014). Precipitation was particularly high in 2012 and 2014, and snowpack was high in 2011. Fall flows in most rivers were also high in 2015. Peak flows in most rivers occurred between December and May, with most in January and February. The Skagit River has 4 years with peak flows in June or July, driven by melting snowpack.

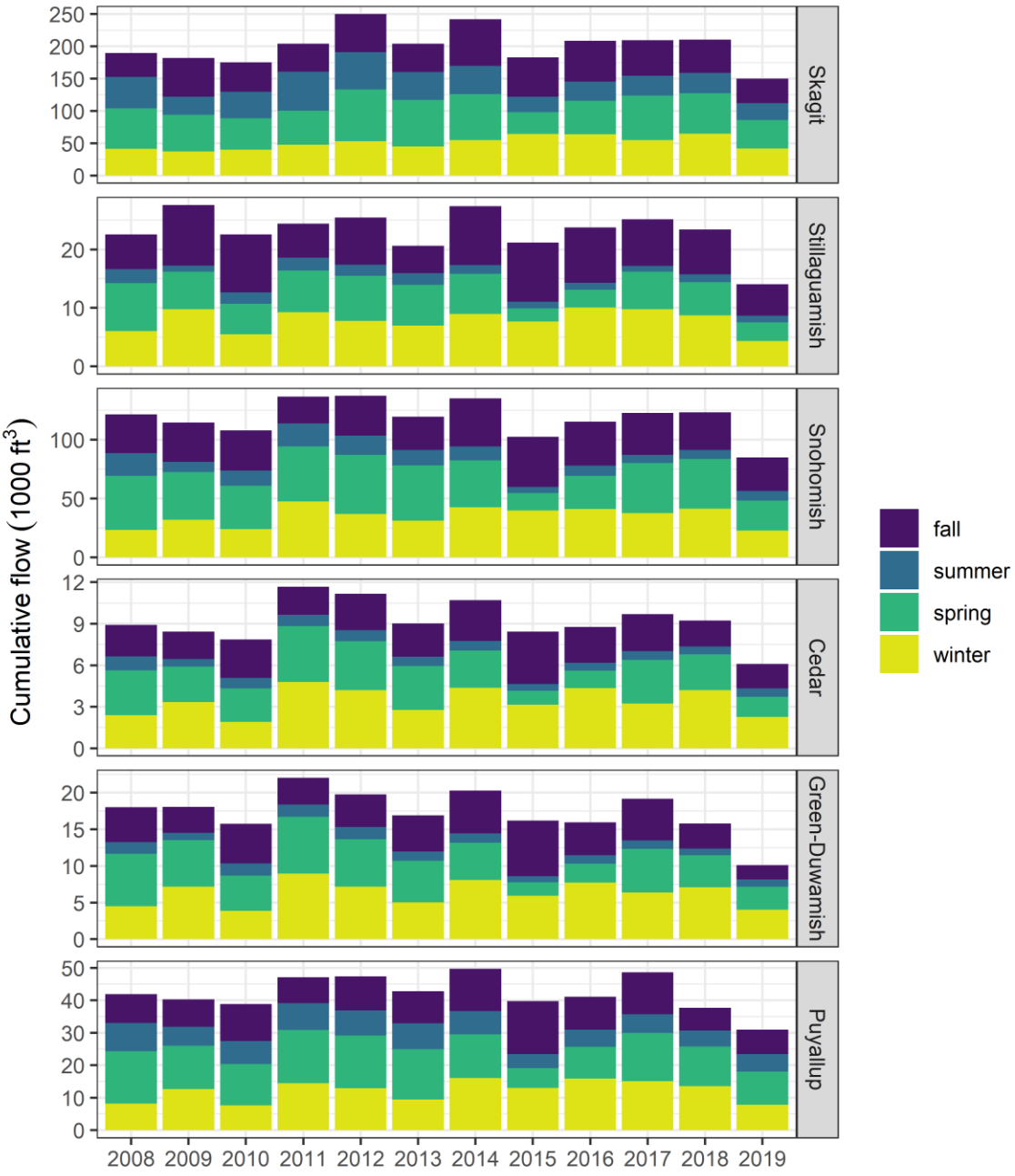

Figure 20. Seasonal cumulative flows for six Puget Sound rivers presented north (top) to south (bottom) by year, 2008–2019. Note differences in y-axis for each river. Data from USGS sites 12200500, 12167000, 12150800, 12119000, 12113000, and 12101500: https://waterdata.usgs.gov/nwis

3.5.4 Air Temperature

Air temperatures, both daily highs and lows, were highest in July and August at both SeaTac and Dockton in 2008–2019 (Figure 21). Highs at Dockton were lower than SeaTac at the summer peak, but similar during other months. The lowest daily high and low

temperatures occurred between December and February, depending on year. Daily low temperatures were more similar between SeaTac and Dockton compared to daily highs. The range of daily highs was larger than the range of daily lows.

The warmest year between 2008 and 2019 was 2015, which experienced both a warm winter and summer and coincided with the onset of El Niño. In 2015, the first calendar day at Dockton with an average temperature over 55 °F was January 25th. In contrast, the next earliest 55 °F day in a given year between 2008 and 2019 occurred in 2019 on March 17th. The monthly average temperature in 2015 was highest in July (66.9 °F) and was the highest average monthly temperature observed during 2008–2019. The most days (12) with an average daily temperature >70 °F also occurred in 2015. The next most 70+ °F days (5) occurred in 2010. The warm temperatures in 2015 occurred on the tail end of the marine heat wave (winter 2013–2014 through winter 2014–2015; see Section 3.4.2).

The coolest summer temperatures between 2008 and 2019 occurred during 2010–2013. These years coincided with an intense La Niña event and negative PDO index as discussed in Section 3.4.1.

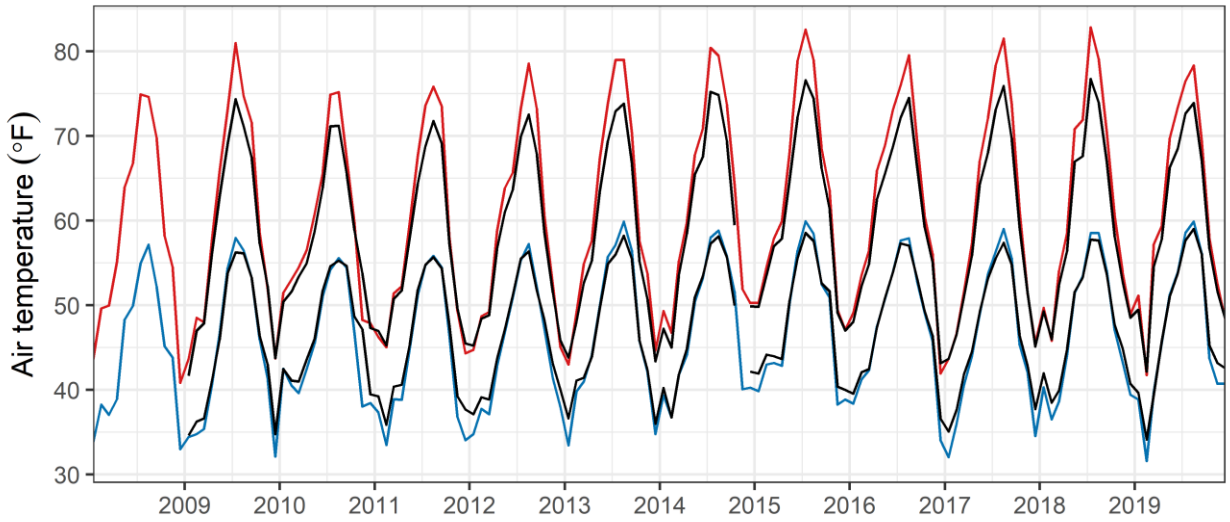

Figure 21. Average monthly high and low air temperature at SeaTac (red [high] and blue [low]) and Dockton Park (black [high and low]), 2008–2019.

3.6 Large-scale and Regional Climate and Weather Summary (2008–2019)

The highlights below summarize both large-scale and regional climate/weather patterns that occurred during the 2008–2019 monitoring period. Many of these climate and weather patterns/events affected water quality and biological parameters monitored during this timeframe and aid in interpreting data results.

- Regional weather phenomena like ENSO and PDO impact temperature, precipitation, and other local weather patterns in the Puget Sound region. The 2008–2019 period was characterized by La Niña, negative PDO, and weak Aleutian Low conditions that favor cold, wet conditions in the Pacific Northwest. Conditions were briefly reversed in 2014–2017.
- Two prominent marine heat waves occurred between 2008 and 2019. One began in the Pacific Ocean in winter of 2013–2014 and was observed in Puget Sound in early fall 2014 through late summer 2016. The second marine heat wave occurred in 2019. Marine heat waves are expected to increase in duration and frequency in the future.
- Coastal upwelling during spring and summer brings nutrients into Puget Sound, increasing productivity. The upwelling period was particularly short in 2010 and long in 2015, 2016, and 2018.
- Changes in wind speed and direction impact timing and duration of phytoplankton blooms. Winds are strongest in fall and winter and weakest in summer. Early onset of strong winds can shorten the growing season.
- Precipitation and freshwater inputs contribute to circulation patterns. The period from 2014 to 2017 was particularly rainy, especially in winter and fall. Higher than usual spring and summer rainfall occurred in 2010, 2013, and 2014.
- High river flows were observed in 2011, 2012, and 2014, which were all La Niña years. The lowest annual flows were observed in 2019, and low spring and summer flows in 2015–2016.

4.0 MARINE MONITORING PROGRAM

For over 50 years, King County has conducted extensive monitoring to assess water and sediment quality in King County marine waters within the Central Puget Sound. The food web (plankton) monitoring component was added in 2008. 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) wet weather treatment station (TS), and CSO marine outfalls (outfall monitoring).

As described above in Section 1.0, the main goals of the marine monitoring program are to identify areas with water quality problems, characterize water quality near outfalls, provide water quality information for management decisions, and evaluate the status and trends for a suite of parameters in marine waters within King County.

To meet these goals, the marine monitoring program works within a framework of the following objectives:

- Implement a long-term monitoring program to characterize water quality in King County and assess drivers and influencing factors (e.g., climate change, shifts in timing and magnitude of freshwater inputs, etc.).
- Ensure data are high quality and meet data quality assurance goals.
- Evaluate results using applicable state water and sediment standards and guidelines.
- Comply with NPDES sediment monitoring requirements.
- Collect sufficient data to determine both short and long-term water quality conditions around King County outfalls and in ambient waters.
- Determine physical and chemical dynamics that influence water quality.
- Determine lower trophic level (phytoplankton and zooplankton) and food web (including benthic infauna) dynamics in the Central Basin.
- Collect appropriate data to inform water quality management decisions.
- Support coordinated regional monitoring efforts.

Water quality may be affected by natural processes, as well as both point and nonpoint source pollution. Point source pollution enters the aquatic environment from a specific conveyance (e.g., outfall pipe) and can be generated by a variety of industrial and municipal facilities, such as wastewater treatment plants and manufacturing facilities. Nonpoint source pollution originates from any source that is not a point source and includes runoff or infiltration from streams, groundwater, stormwater, and atmospheric deposition.

Obtaining ambient monitoring data from receiving waters in areas not influenced by point sources is important to accurately evaluate overall receiving water conditions and to understand regional water quality.

The marine monitoring program assesses both nonpoint and point source pollution in nearshore and offshore environments. As described above, the stations monitored by the Marine Monitoring Program fall into one of two categories: outfall (point source) or ambient. Within these two categories, stations are classified as either offshore (depth > -3 m mean lower low water [MLLW]) or beach (+3 to -3 m MLLW).

The following sections provide an overview of the sampling locations for each component of the Marine Monitoring Program. The field and laboratory methods used to collect and analyze samples are also summarized here. A more detailed description of the methods for each of the program components can be found in sampling and analysis plans (King County; 2006, 2010, 2011, 2012, 2015, 2016, 2017, 2020).

Multiple sampling components are included in the Marine Monitoring Program (Table 3). Multiple matrices (e.g., water, sediment. plankton) were sampled at some stations. Matrices sampled at all offshore and beach monitoring locations are listed in Table 4 and Table 5. Details for each component are provided in Sections 4.1.1, 4.1.2, and 4.1.3 well as in each individual data summary report. The clam tissue monitoring component was discontinued in late 2010; however, 2008 – 2010 data are included in this report series.

Table 3. Summary of Marine Monitoring Program sampling components.

		Water		Sediment		Plankton	
		Offshore	Beach	Offshore	Beach	Phytoplankton	Zooplankton
Parameters	Physical	●	●	●	●		
	Biological	●	●	●		●	●
	Chemical	●	●	●	●		
	Meteorological	●					
Sampling Frequency	Continuous	●					
	Monthly	●	●				
	Bi-monthly	●				●	●
	2 or 5 years			●	●		
Sampling Depth	Entire water column	●					
	Specific depths	●	●	●	●	●	
	Other*						●

*Sampling depths are 0-30 and 0-maximum of 200 meters

Table 4. Sampling components at each offshore station.

Locator	Locator Description	Station Type	Water	Mooring	Phytoplankton	Zooplankton	Sediment/Benthic infauna
JSUR01	Brightwater TP outfall	outfall	◆		◆		◆*
KSBP01	Pt. Jefferson	ambient	◆		◆	◆	◆
KSRU03	outer Salmon Bay	ambient	◆				◆
CK200P	Carkeek Wet Weather TS outfall	outfall	◆				
KSSK02	West Point TP outfall	outfall	◆		◆		◆**
KSZY01	Elliott Bay-Piers 90/91	ambient					◆
LTAA02	Elliott Bay grain terminal	ambient					◆
LSCW02	outer Elliott Bay	ambient					◆
LTBC43	Elliott West Wet Weather TS outfall	outfall	◆				
LTCA02	mid-outer Elliott Bay	ambient					◆
LTDF01	Elliott Bay waterfront (near Pier 66)	ambient					◆
SeaQYSI	Seattle Aquarium	ambient		◆			
LTED04	central Elliott Bay	ambient	◆		◆		◆
LTGF01	Harbor Island (north end)	ambient					◆
LSHZ08	Seacrest Park (Cove 2)	ambient					◆
LSEP01	South Plant outfall	outfall	◆		◆		◆**
LSKQ06	Alki Wet Weather TS outfall	outfall	◆		◆		
LSML01	West Seattle	ambient					◆
PTWILLBUOY	off Pt. Williams	ambient		◆			
LSNT01	off Pt. Williams	ambient	◆		◆	◆	
LSVV01	Fauntleroy Cove	ambient	◆				◆
MSJN02	Vashon TP outfall	outfall	◆		◆		
MSWH01	inner Quartermaster Harbor	ambient	◆	◆			
NSAJ02	outer Quartermaster Harbor	ambient	◆	◆	◆		
MSVK01	inner Quartermaster Harbor	ambient					◆
NSEX01	East Passage	ambient	◆		◆	◆	◆
HNFD01	Duwamish River-East Waterway	ambient	◆				
LTKE03	Duwamish River	ambient	◆				
LTUM03	Duwamish River	ambient	◆				
LTXQ01	Duwamish River-Henderson WWTS	outfall	◆				

*10 stations around outfall

**8 stations around outfall

Table 5. Sampling components at each beach station.

Locator	Locator Description	Station Type	Water	Sediment	Clams *
ITEDWARDSPT	Edwards Point	ambient	◆	◆	◆
JSVW04	Richmond Beach	ambient	◆	◆	◆
ITCARKEEKP	Carkeek Park	ambient	◆	◆	
KSHZ03	Carkeek Park-Piper's Cr. Outflow	outfall	◆	◆	◆
KSLU03	Golden Gardens	ambient	◆	◆	◆
KSQU01	mouth Lk. Wash. Ship Canal	ambient	◆		
KSSN04	West Point-north	outfall	◆	◆	◆
KSSN05	West Point-south	outfall	◆	◆	◆
KSYV02	Magnolia CSO	outfall	◆	◆	
LTBD27	SAM Sculpture Park	ambient	◆		
LTEH02	Elliott Bay-ferry terminal	ambient	◆		
LSGY01	Seacrest Park	ambient	◆		
LSHV01	Alki Beach	ambient	◆		
LSKR01	Alki south	ambient	◆		
LSKS04	Alki south	outfall		◆	◆
LSKS01	Constellation Park	ambient	◆		
LSLT02	Mee-Kwa-Mooks Park	ambient	◆		
LSVW01	Fauntleroy Cove	ambient	◆	◆	
MTEC01	Seahurst Park	ambient	◆	◆	
MSJL01	Vashon outfall	outfall	◆	◆	◆
MTLD03	Normandy Park	outfall	◆	◆	◆
MSSM05	Tramp Harbor	ambient	◆		
MRUW01	Lisabuela Park	ambient	◆		
MTUJ01	Des Moines Park	ambient	◆		
MSXK01	Burton Acres	ambient	◆	◆	◆
MTXA01	Point Robinson	ambient	◆		
NTFK01	Redondo Beach	ambient	◆	◆	
NSJY01	Dumas Bay	ambient	◆	◆	
LTTL02	Duwamish River	ambient	◆		

*The clam monitoring component ended in December 2010.

4.1 Sampling Locations

The following section provides information on the outfall and ambient sampling locations for all matrices monitored. For the purposes of this report, each station is categorized as north, middle, Duwamish River, or south within the monitoring area and reference to the

"Central Basin" includes all offshore stations except Duwamish River sites. Reference to "mainstem" sites includes all offshore stations except Elliott Bay, the Duwamish River and the two Quartermaster Harbor stations.

4.1.1 Marine Water

The following sections describe the marine water sampling locations. Water samples are analyzed for a variety of parameters. Specific parameters measured at each station are described below in Section 4.2.

4.1.1.1 Offshore

Offshore water samples were collected (2008 - 2019) from both ambient and outfall stations. Samples were collected from 8 outfall (Table 6, Figure 22) and 10 ambient stations (Table 7, Figure 22).

Table 6. Outfall offshore water sampling locations.

Locator Name	Outfall Description
JSUR01	Brightwater TP outfall diffuser
CK200P	Carkeek Wet Weather TS outfall
KSSK02	West Point TP outfall diffuser
LTBC43	Elliott West Wet Weather TS outfall
LSEP01	South Plant outfall north diffuser
LSKQ06	Alki Wet Weather TS outfall
MSJN02	Vashon TP outfall
LTXQ01	Duwamish River near Henderson/MLK Wet Weather TS outfall

Table 7. Ambient offshore and Duwamish River water sampling locations.

Locator Name	Sampling Location Description
KSBP01	Pt Jefferson – represents northern Central Basin
LTED04	Inner Elliott Bay - represents Elliott Bay
LSNT01	Pt. Williams – represents middle Central Basin
LSVV01[1]	Fauntleroy Cove
MSWH01	Inner Quartermaster Harbor – represents shallow embayment
NSAJ02	Outer Quartermaster Harbor - represents shallow embayment
NSEX01	East Passage – represents southern Central Basin
LTUM03	Duwamish River - near 16th Ave South bridge
LTKE03	Duwamish River - near West Waterway
HNFD01	East Waterway of Duwamish Estuary

[1] Multiple stormwater outfalls and the Barton CSO outfall discharge in Fauntleroy Cove; however, LSVV01 is not located near a direct discharge point and is considered an ambient station.

The time period each offshore station has been monitored varies. Table 8 presents the first year of record, depth, and region for offshore monitoring stations.

Table 8. Offshore water monitoring station regions (from north to south), depths, and first year of record. *Denotes outfall stations.

Station	Monitoring Region	First year of record	Average maximum depth (m)
*JSUR01	North	2005	178
KSBP01	North	1998	262
*CK200P	North	2000	63
KSRU032	North	2007	14
*KSSK02	North	1998	65
*LTBC43	Middle – Elliott Bay	2005	17.5
LTED04	Middle – Elliott Bay	1998	85
*LSEP01	Middle	1999	185
HNFD01	Duwamish	1996	17
LTKE03	Duwamish	2005	12.5
*LSKQ06	Middle	1998	43
LSNT01	Middle	1998	205
LTUM03	Duwamish	2005	7.5
LSVV01	Middle	2007	12.5
*LTXQ01	Duwamish	2009	3**
*MSJN02	South	2005	63
MSWH01	South	2006	5.5
NSAJ02	South	2006	9
NSEX01	South	2003	173

**Depth is highly variable.

[2] KSRU03 only sampled 2007-2008 before being discontinued.

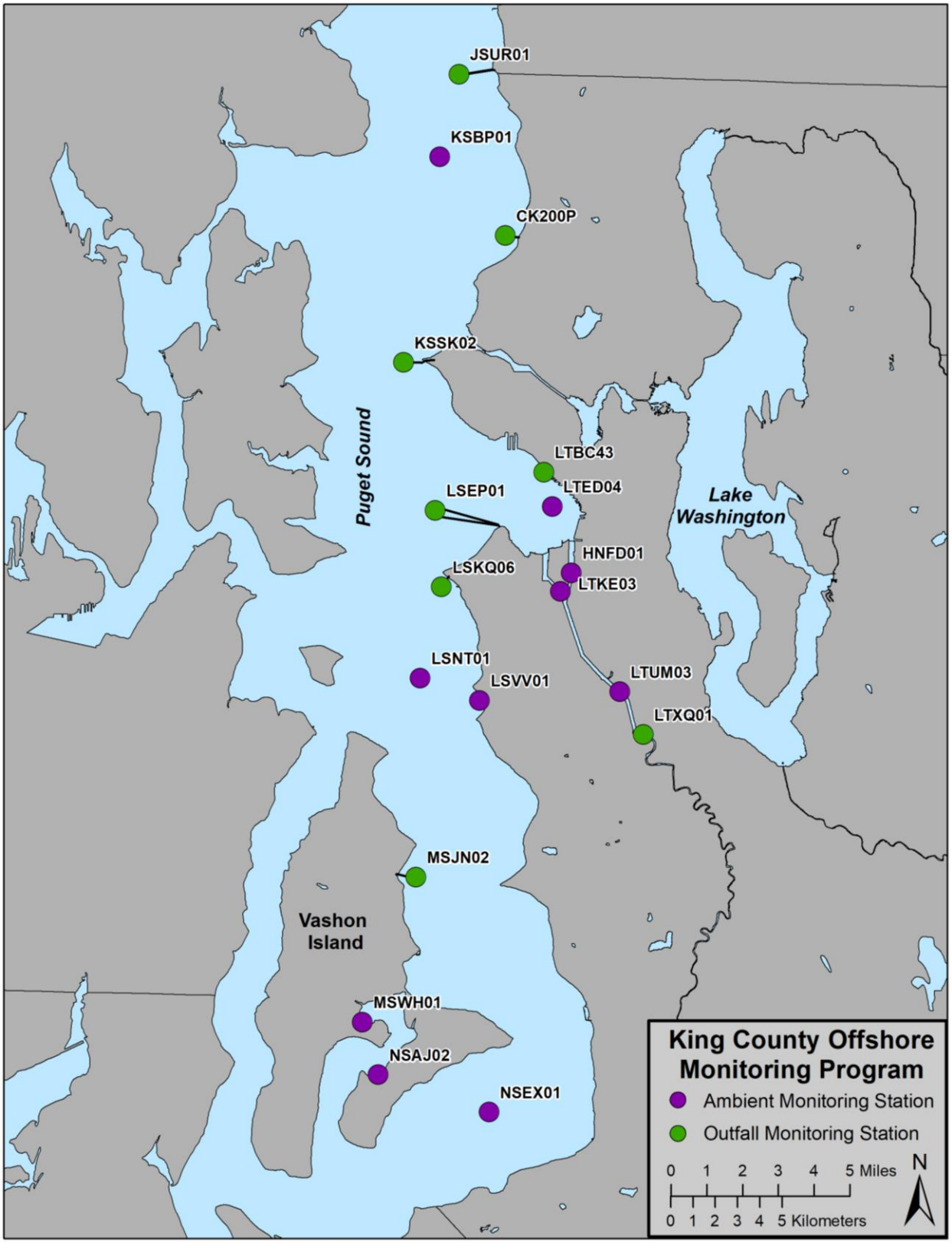

Figure 22. Offshore ambient and outfall water sampling locations.

4.1.1.2 Beach Outfall Water Sampling Locations

Water samples from eight outfall beach stations were collected monthly (2008 - 2019). Sampling locations were established along the shoreline in the vicinity of treatment plant outfalls, except for the Brightwater and South TP outfalls since they are more than 1,600 m offshore (Table 9 and Figure 23).

Table 9. Beach water outfall stations, regions, and first year of record.

Locator Name	Locator Description	Monitoring Region	First Year of Data Record
KSHZ03	Carkeek Wet Weather TS - near Piper's Creek outflow	North	1984
KSSN04	West Point TP - north side Discovery Park	North	1984
KSSN05	West Point TP - south side Discovery Park	North	1984
KSYV02	Magnolia CSO - Smith Cove	Middle	1985
LSKR01	Alki Wet Weather TS - north side Alki	Middle	1985
LSKS01	Alki Wet Weather TS - south side Alki	Middle	1984
MSJL01	Vashon TP - near Gorsuch Creek on Vashon Island	South	2002
MTLD03	Miller Creek TP[3] - Normandy Park	South	1998

4.1.1.3 Beach Ambient Water Sampling Locations

Water samples from 12 ambient beach stations were collected monthly (2008 -2019). Ambient beach sampling stations are located along the shoreline away from treatment plant outfalls to assess background conditions. However, stormwater outfalls are located about every 15 m along the shoreline within the City of Seattle and beach water quality may be affected by stormwater input. Ambient sites were chosen based on one of three criteria: continuation of a long-term dataset, a high-use public beach, or for spatial coverage (Table 10 and Figure 23). Eight additional ambient beach water stations were monitored between 2008 - 2010 (Table 10 and Figure 23). However, due to budget reductions monitoring at these sites was discontinued in 2011.

[3] The Miller Creek TP is operated by the Southwest Suburban Sewer District and secondary-treated effluent is discharged through a single port outfall off Normandy Park at a water depth of -61 m MLLW.

Table 10. Beach water ambient stations, regions, and first year of record. Stations shaded blue only sampled 2008 – 2010.

Locator Name	Location Description	Monitoring Region	First year of record
ITEDWARDSPT	Edwards Point,	North	2000
JSVW04	Richmond Beach/Pt. Wells	North	1984
ITCARKEEKP	Carkeek Park, north of Piper's Creek influence	North	2000
KSQU01	Lake Washington Ship Canal in Shilshole Bay outflow	North	1972
KSLU03	Golden Gardens	North	1984
LTBD27	SAM Sculpture Park	Middle – Elliott Bay	2007
LTEH02	Elliott Bay at Pier 48	Middle – Elliott Bay	1984
LSGY01	Seacrest Park	Middle – Elliott Bay	1997
LSHV01	Alki Beach	Middle	1985
LSLT02	Me-Kwa-Mooks Park in West Seattle	Middle	2007
LTTL02	Duwamish River Park in Duwamish River	Duwamish	2007
LSVW01	Fauntleroy Cove	Middle	1984
MRUW01	Lisabuela Park on Vashon Island	Middle	2007
MTEC01	Seahurst Park	South	1989
MSSM05	Tramp Harbor	South	1990
MTUJ01	Des Moines Creek Park	South	2007
MSXK01	Burton Acres Park	South – Quartermaster Harbor	2007
MTXA01	Point Robinson Park on Vashon Island.	South	2007
NTFK01	Redondo Beach	South	2007
NSJY01	Dumas Bay	South	2007

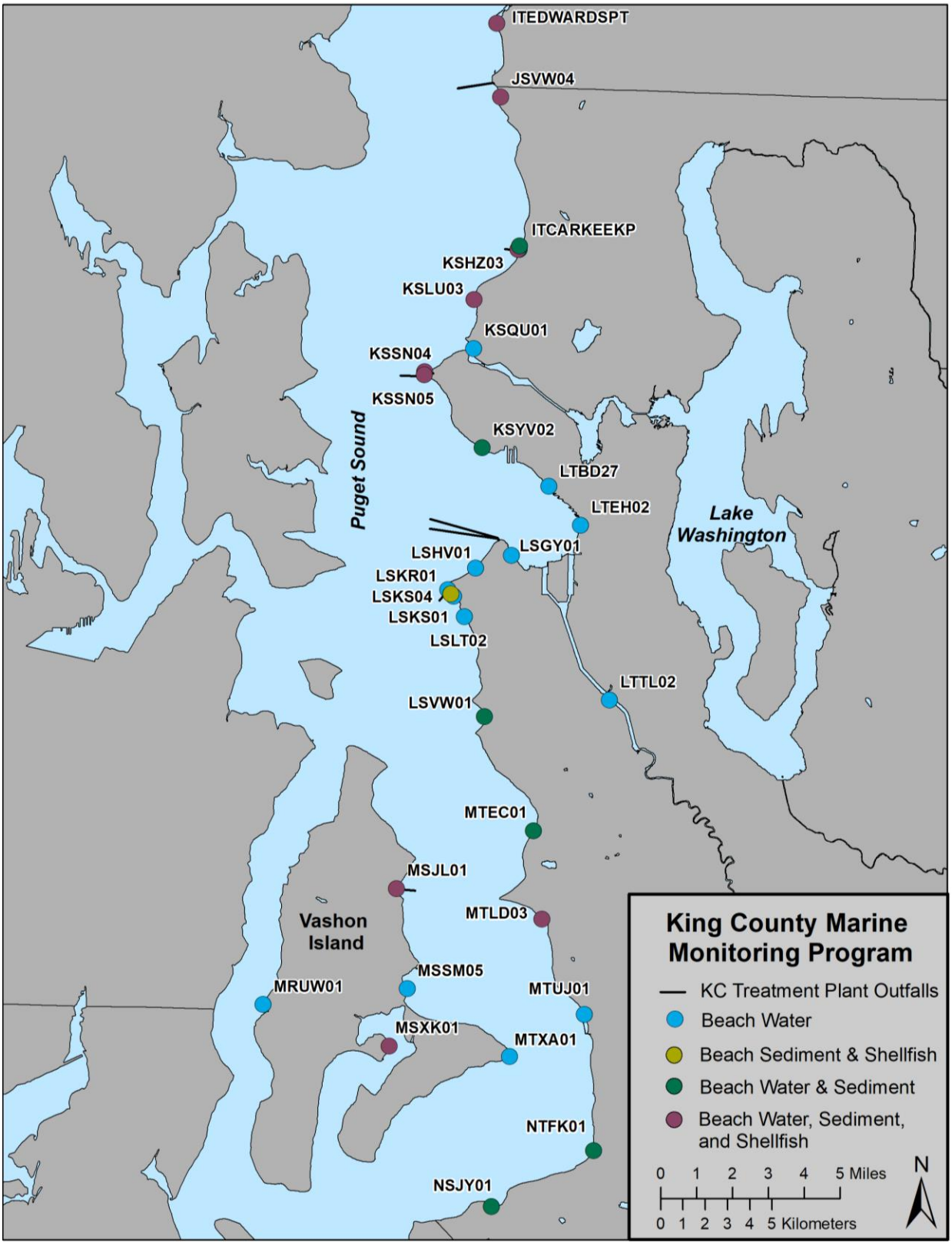

Figure 23. Beach sampling locations for all media; water, sediment and butter clams.

4.1.1.4 Moorings

Automated, high-frequency, water quality data collection systems, referred to as 'moorings', allow collection of continuous measurement of water quality and meteorological parameters. These systems allow characterization of variability over multiple time scales (e.g., daily, seasonal, annual, and inter-annual) not captured with traditional sampling methods.

Moorings were added to the monitoring program in 2008. Moorings are deployed at four sites (Table 11) and shown in Figure 24 relative to offshore water sampling locations. An additional mooring was deployed at the entrance to Quartermaster Harbor from February 2009 - December 2010 for a special study. Results of that study are presented in the *Quartermaster Harbor Water Quality Data Report: 2007-2011* (King County, 2014) and not included in this report.

Table 11. Mooring locations and first year of record.

Locator	Description	First Year of Record
SeaQYSI	Seattle Aquarium, off pump house	2008
NSAJ02	Dockton marina-outer Quartermaster Harbor	2009
MSWH01	Yacht Club marina-inner Quartermaster Harbor	2008, then discontinued, began again in 2011
PTWILLBuoy	Off Point Williams, Central Basin	2013

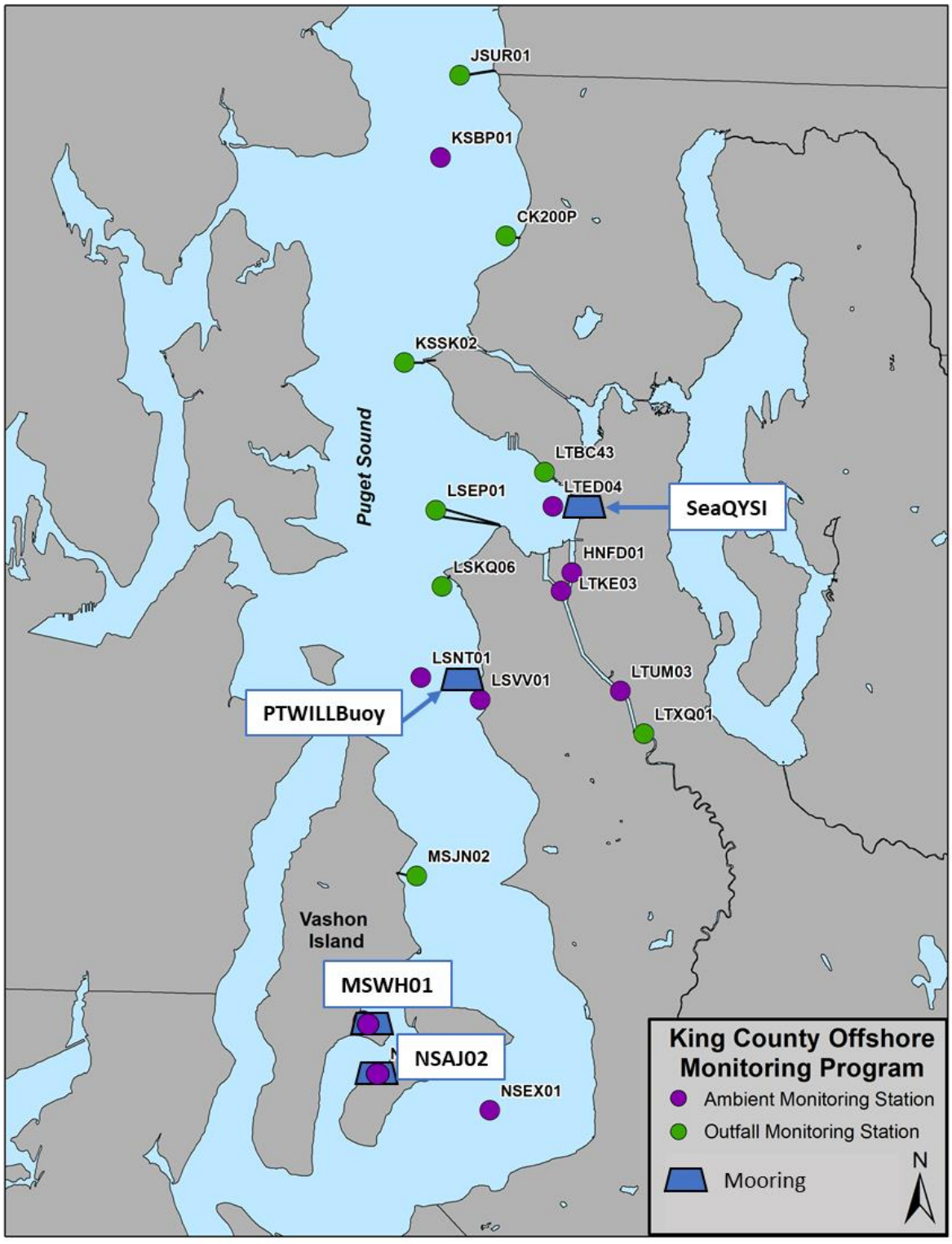

Figure 24. Mooring locations relative to offshore and Duwamish River water sampling locations.

4.1.2 Phytoplankton and Zooplankton

Eight offshore (three outfall and five ambient) locations were monitored for quantitative phytoplankton abundance and community structure (May 2014 – 2019) (Figure 25). Two additional outfall stations were added to the monitoring program in 2016 (Alki Wet weather TS [LSKQ06] and Vashon TP [MSJN02]) (Table 12 and Figure 25).

Semi-quantitative phytoplankton abundance and community structure were monitored at three offshore ambient stations (2008 - 2014) (Pt. Jefferson [KSBP01], East Passage [NSEX01], and inner [MSWH01] or outer Quartermaster Harbor [NSAJ02]) (Table 12). A program modification in 2009 included a site change from the inner Quartermaster Harbor station (MSWH01) to the outer station (NSAJ02).

Zooplankton monitoring was initiated in 2014. Zooplankton abundance and community structure was monitored at three offshore locations (2014 -2019) (Pt. Jefferson [KSBP01], Pt. Williams [LSNT01], and East Passage [NSEX01]) (Table 12 and Figure 25).

Table 12. Offshore plankton locations and first year of record.

Locator	Plankton type	Region	Station Type	First Year of Record
JSUR01	phytoplankton	North	outfall	2014
KSBP01	phytoplankton	North	ambient	2008
	zooplankton			2014
KSSK02	phytoplankton	North	outfall	2014
LTED04	phytoplankton	Middle – Elliott Bay	ambient	2014
LSEP01	phytoplankton	Middle	outfall	2014
LSKQ06	phytoplankton	Middle	outfall	2016
LSNT01	phytoplankton	Middle	ambient	2014
	zooplankton			2014
MSJN02	phytoplankton	South	outfall	2016
NSEX01	phytoplankton	South	ambient	2008
	zooplankton			2014
MSWH01	phytoplankton	South - inner Quartermaster Harbor	ambient	2008
NSAJ02	phytoplankton	South - outer Quartermaster Harbor	ambient	2009

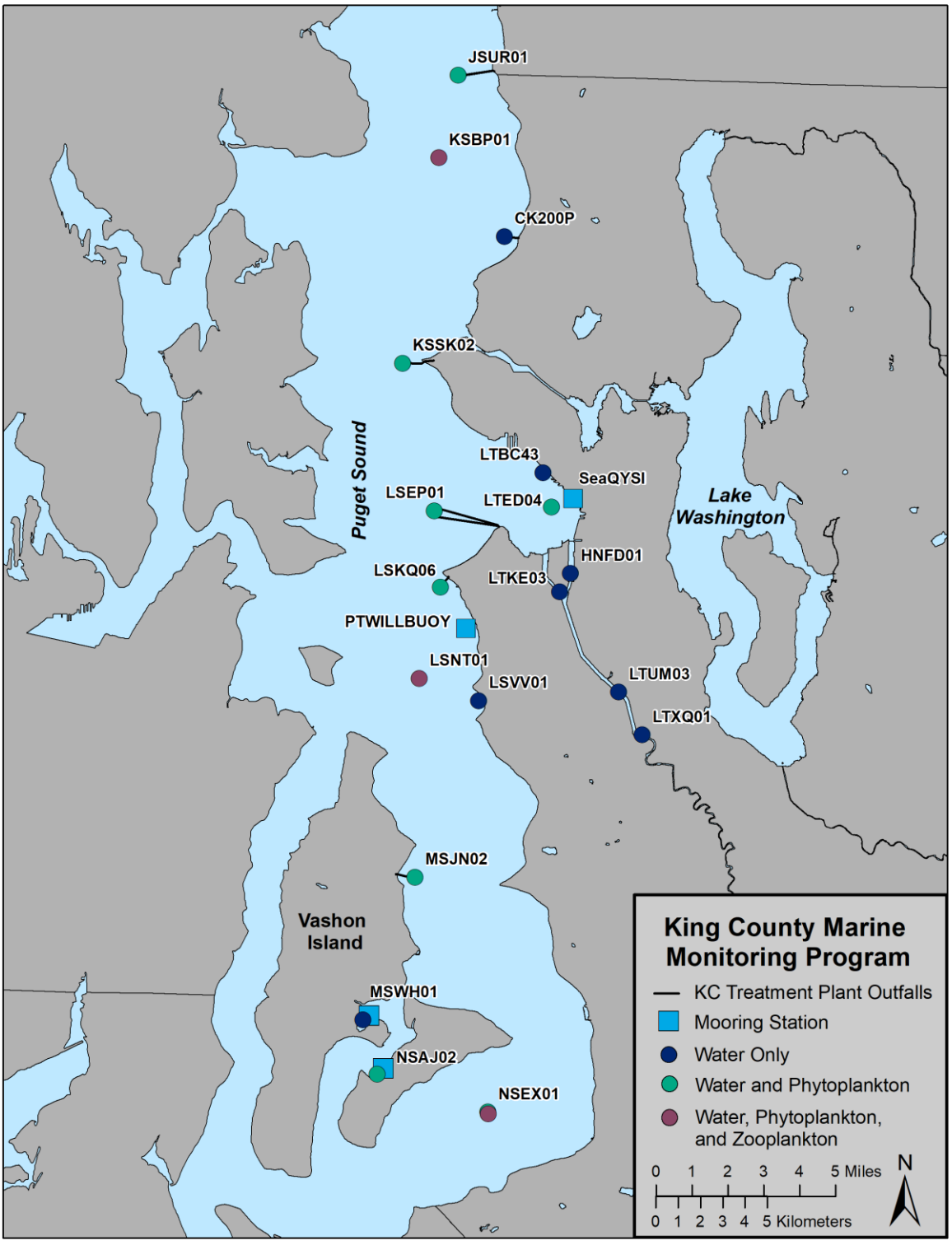

Figure 25. Offshore phytoplankton and zooplankton sampling sampling locations relative to other water sampling locations.

4.1.3 Sediment

The following sections describe sediment monitoring locations. Sediment samples were analyzed for metals, select organic compounds, and benthic community structure at some locations. Toxicity testing was conducted on sediments collected near some TP outfalls. The section below describes the specific parameters analyzed at each location.

4.1.3.1 Offshore (Subtidal) Sediments

Offshore (subtidal) outfall sediment samples were collected near the West Point, South , and Brightwater TP outfalls in 2011 and 2017[4] for NPDES permit compliance (Table 13). Sediments were not sampled near the Vashon TP outfall due to the rocky habitat surrounding the terminus of the outfall. Sediment stations are located along transects with respect to distance away from the discharge point of each outfall (Figure 26). Transects are placed in a north-to-south alignment as the currents are in a net north direction.

Table 13. Offshore outfall sediment station locators.

Brightwater TP	West Point TP	South TP
BWND800N	WP420NW	STP820NE
BWSD800N	WP430N	STP460N
BWND400N	WP215N	STP625NP
BWSD400N	WP410W	STP610MN
BWND600P	WP280W	STP570MS
BWSD600P	WP230P	STP625SP
BWND400S	WP430S	STP460S
BWSD400S	WPD215N	STP770SE
BWND800S		
BWSD800S		

The Elliott Bay offshore component of the monitoring program includes eight stations that were sampled every two years starting in 2007 (Table 14; Figure 26). Six sampling events have occurred between 2008 – 2019.

[4] A subset of stations located near the South Plant and West Point TP were resampled in 2018. Only a subset of Brightwater TP sites were sampled in 2017.

Table 14. Offshore Elliott Bay sediment locations and first year of record.

Locator	Description	First Year of Record
KSZY01	Piers 90/91 -area with heavy vessel traffic, including cruise ships	2007
LTAA02	Elliott Bay grain terminal	2007
LSCW02	outer Elliott Bay	1992
LTCA02	mid-outer Elliott Bay	1992
LTDF01	Seattle waterfront (near Pier 66)	1992
LTED04	Central Elliott Bay	1992
LTGF01	Harbor Island -north end, in heavy industrial area	2007
LSHZ08	Seacrest Park - Cove 2 used by recreational SCUBA divers	2007

Samples from six ambient (routine) offshore sediment monitoring stations were collected every five years (starting in 2007) (Figure 26). Three are Central Basin mainstem stations and three are located in embayments (Table 15).

Table 15. Offshore ambient sediment locations and first year of record.

Locator	Description	Location	First Year of Record
KSBP01	Point Jefferson	mainstem	1981
KSRU03	outer Salmon Bay	mainstem	2007
LSML01	West Seattle	mainstem	1985
LSVV01	Fauntleroy Cove	embayment	2007
MSVK01	inner Quartermaster Harbor	embayment	2007
NSEX01	East Passage	embayment	2007

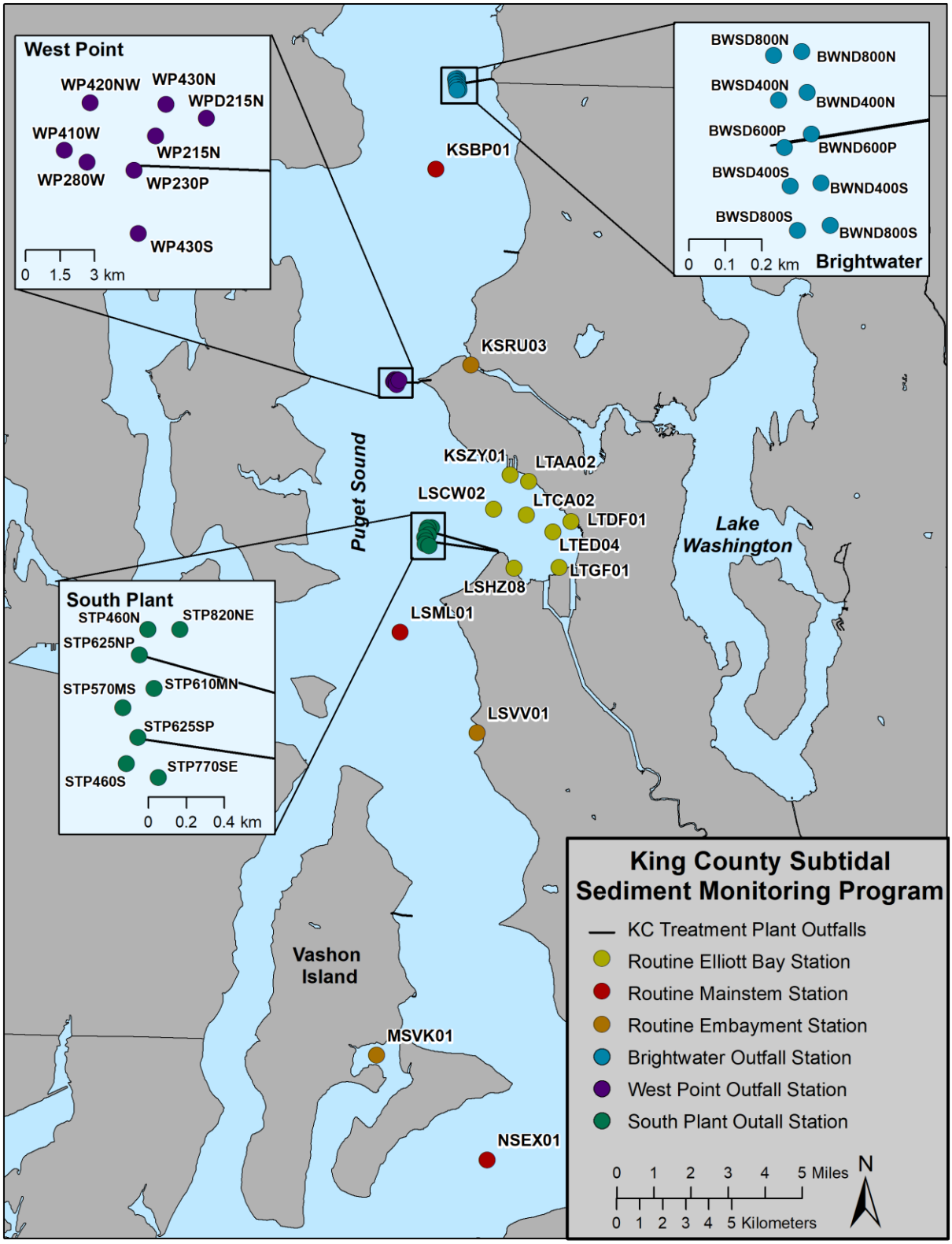

Figure 26. Offshore (subtidal) outfall, ambient (mainstem and embayment), and Elliott Bay sediment sampling locations.

Sediment samples were not collected in the Duwamish River as part of the Marine Monitoring Program. Two superfund sites are located in the lower Duwamish River and sediment monitoring and cleanup activities are conducted under the U.S. EPA Superfund Program.

4.1.3.2 Beach (Intertidal) Sediment

Beach (intertidal) sediments were sampled in 2010 and 2015. Samples were collected from seven outfall stations and nine ambient stations (Table 16 and Figure 23). Water samples were also collected at these stations except nearshore of the Alki TS outfall (LSKS04), Edwards Pt., (ITEDWARDSPT), and Seahurst Park (MTEC01).

Table 16. Beach sediment locations and first year of record.

Locator Name	Region	Location Description	Station Type	First Year of Record
ITEDWARDSPT	North	Edwards Pt.	ambient	2010
JSVW04	North	Richmond Beach/Pt. Wells	ambient	1988
ITCARKEEKP	North	Carkeek Park, north of Piper's Creek outflow	ambient	2010
KSHZ03	North	Carkeek Park - Piper's Creek outflow	outfall	1987
KSLU03	North	Golden Gardens Park	ambient	1987
KSSN04	North	West Point north beach	outfall	1987
KSSN05	North	West Point south beach	outfall	1987
KSYV02	Middle	Magnolia CSO	outfall	1985
LSKS04	Middle	Alki Point – South Side	outfall	2010
LSVW01	Middle	Fauntleroy Cove	ambient	1985
MTEC01	South	Seahurst Park	ambient	1997
MSJL01	South	Vashon Outfall beach	outfall	2002
MTLD03	South	Miller Creek TP/ Normandy Park	outfall	1999
MSXK01	South-Quartermaster Harbor	Burton Acres Park	ambient	2010
NTFK01	South	Redondo Beach	ambient	2010
NSJY01	South	Dumas Bay	ambient	2010

4.1.4 Clam Tissue

Butter clams (*Saxidomus giganteus)* from 10 beach stations (six outfall and four ambient)were sampled twice-annually (spring/March and summer/August) from 2008 - 2010 except Burton Acres Park (MSXK01) which was only sampled in 2010 (Table 17 and Figure 23). All summer clam samples were collected concurrently with beach sediment for chemical analysis.

The butter clam monitoring component of the monitoring program was discontinued after 2010 due to funding limitations.

Table 17. Clam tissue sampling locations and first year of record.

Locator Name	Region	Location Description	Station Type	First Year of Record
ITEDWARDSPT	North	Edwards Pt.	ambient	2006
JSVW04	North	Richmond Beach/Pt. Wells	ambient	1990
KSHZ03	North	Carkeek Park/ Piper's Creek outflow	outfall	1987*
KSLU03	North	Golden Gardens	ambient	1987*
KSSN04	North	West Point TP-north	outfall	1987*
KSSN05	North	West point TP-south	outfall	1987*
LSKS04	Middle	Alki Wet Weather TS outfall	outfall	2006
MSJL01	South	Vashon TP - near Gorsuch Creek on Vashon Island	outfall	2002
MSXK01	South-Quartermaster Harbor	Burton Acres Park	ambient	2010
MTLD03	South	Miller Creek TP/ Normandy Park	outfall	1998

*Clam tissue samples before 1998 included multiple species and are not directly comparable to butter clam results; therefore, those samples were not included in trend analysis.

4.2 Sampling and Analytical Methods

The following section provides a general summary of Marine Monitoring Program field and laboratory (analytical) methods as well as parameters measured for each matrix. Data analysis methods are specific to each matrix and/or parameter and are described in each individual monitoring component report listed in Section 1.0. More detail can be found in the sampling and analysis plans (SAPs) for the individual monitoring components referenced in the following sections.

4.2.1 Water

Field and laboratory methods for water samples are summarized below.

4.2.1.1 Water 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 KCEL Standard Operating Procedure (SOP) for each parameter.

In situ water column profiles for a suite of parameters were collected at all offshore stations (Figure 22) (except Quartermaster Harbor stations, MSWH01 and NSAJ02, and Duwamish River station LTXQ01). These data were collected by the KCEL from a research vessel using a SeaBird Electronics SBE 25 and 25 Plus SEALOGGER conductivity-temperature-depth (CTD) profiler with multiple parameter sensors. Measurements were collected and reported every 0.5 m for the entire profile (both down- and upcast) from near surface (~ 1-2 m) to within approximately 3-5 m of the sea floor at each station.

CTD parameters included:

- Chlorophyll fluorescence
- Dissolved oxygen
- Salinity
- Water temperature
- Density (calculated)
- Water and surface photosynthetically active radiation (PAR)
- Transmissivity
- Depth

Multiple five-liter Niskin bottles were mounted onto the rosette containing the CTD profiler for collecting water samples at specific depths on the upcast.

The two offshore Quartermaster Harbor stations (MSWH01 and NSAJ02) and Duwamish River station (LTXQ01) were sampled from docks and a bridge, respectively. Dissolved oxygen (DO) and temperature measurements at these sites were collected in situ using a YSI EXO instrument. Water samples were collected using a four-liter Scott bottle lowered by hand to the selected depth.

Samples for analysis of dissolved nutrients (except dissolved organic carbon), were filtered in the field using a 0.45 µm syringe filter. Following filtration, all samples were placed into appropriate sample containers and held on ice at 4°C until they were transported to the laboratory for analysis. Samples for dissolved organic carbon (DOC) were filtered in the laboratory. Samples for total nitrogen and total organic carbon analyses were unfiltered.

Transparency (water clarity) measurements were collected using a 12-inch diameter black and white Secchi disk. Secchi depths were recorded to the nearest 0.1 m. As readings may vary depending upon environmental conditions (e.g., waves and glare), readings were taken on the shaded and downwind side of the boat (or dock/bridge) to standardize results among individual field personnel and atmospheric conditions as much as possible.

Offshore water samples were collected monthly from 2008-2013 and twice monthly 2014-2019, except monthly in January and December. From 2008 - 2013, phytoplankton, chlorophyll *a*, and nutrient samples were collected twice monthly at Pt. Jefferson (KSBP01), East Passage (NSEX01), and outer Quartermaster Harbor (NSAJ02).

Beach water samples were collected monthly at approximately knee-depth by inverting sample containers just above the water surface, then sinking the bottle down to approximately three to six inches below the water surface. Water temperature was measured in the field using a calibrated digital thermometer.

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

Four automated in situ water quality data collection systems (moorings) were used to obtain measurements every 15 minutes for physical, chemical, and biological parameters (Table 18). Moorings were located at the Seattle Aquarium, inner and outer Quartermaster Harbor, and Pt. Williams (Figure 24). Meteorological measurements were also collected at the Pt. Williams and outer Quartermaster Harbor moorings. Detailed information regarding the range, accuracy, and precision of the mooring in situ sensors is provided at https://www.kingcounty.gov/services/environment/water-and-land/puget-sound-marine/marine-mooring/mooring-spec.aspx.

Table 18. Water and meteorological parameters collected by moorings.

			Water									Meteorological					
Locator	**Site description**	**Sensor depth (m)**	**Depth**	**chlorophyll fluorescence**	**Dissolved oxygen**	**Water temperature**	**Salinity**	**Density (calculated)**	**pH**	**Turbidity**	**Nitrate + nitrite-nitrogen**	**Air temperature**	**Rainfall**	**Relative % humidity**	**PAR**	**Pressure**	**Wind speed, direction**
PTWILLBUOY	Pt. Williams	1	●	●	●	●	●	●	●[1]	●	●	●		●	●		●
MSWH01	inner Quarter-master Harbor	1	●	●	●	●	●	●	●[1]								
NSAJ02	outer Quarter-master Harbor	variable[2]	●	●	●	●	●	●	●	●		●	●	●	●	●	●
SEAQYSI	Seattle Aquarium	1	●	●	●	●	●	●	●	●							
		10	●	●	●	●	●	●	●	●							

[1] Also includes high-resolution pH.
[2]Depth varies 5-9 m with tidal height.

4.2.1.2 Water Laboratory Parameters and Methods

Laboratory parameters measured in samples collected from offshore stations, as well as sample collection depths, are shown in Table 19. Total nitrogen samples were collected from the 1 m depth starting in 2010 at a subset of nine offshore stations, including three outfall stations (Brightwater, West Point and South Plant TPs). An additional total nitrogen sample was analyzed at a deeper depth at the West Point (KSSK02) and South Plant (LSEP01) TP outfalls and the outer Quartermaster Harbor station (NSAJ02).

Fecal coliform and *Enterococcus* bacteria were analyzed in samples collected from 1 m at all offshore stations. Bacteria samples were also collected from deeper depths at the six wastewater and wet weather TP outfall stations (Table 19). Depth of the additional bacteria sample varied for each location dependent upon the expected trapping depth of the effluent plume. Bacteria samples were also collected from a second deeper depth at all Duwamish River stations except LTXQ01. Collection depth for these samples was near-bottom and varied with tidal height.

Chlorophyll *a* and pheophytin (phytoplankton pigments) were measured in the upper 1-35 m of the water column where sufficient light penetrates to allow for photosynthesis. In 2017, an additional chlorophyll *a* and pheophytin sample was collected at a subset of seven stations at the depth of the chlorophyll maximum concentration as determined by the in situ fluorescence profile.

Laboratory parameters for all beach stations include:

- Ammonia-nitrogen
- Nitrite+nitrite-nitrogen
- Orthophosphate-phosphorus
- Fecal coliform bacteria
- Enterococci bacteria
- Salinity

Total nitrogen was also analyzed at a subset of six beach stations-Richmond Beach (JSVW04), Carkeek Park (KSHZ03), Fauntleroy Cove (LSVV01), Redondo (NTFK01), Dumas Bay Park (NSJY01), and Quartermaster Harbor (MSXK01). Prior to June 2010, total phosphorus was measured in both offshore and beach waters until the parameter changed to dissolved orthophosphate-phosphorus (orthophosphate).

Table 19. Laboratory parameters and depths analyzed for offshore waters.

		Parameter					
Locator	**Sample Depth (m)**	**Ammonia-N, Nitrate+nitrite-N, Orthophosphate-P[1], Silica**	**Total Nitrogen[1]**	**Total and dissolved organic -**	**Fecal coliform, Enterococcus bacteria**	**Chlorophyll *a*, Pheophytin****	**Total suspended solids**
JSUR01*	1	●	●		●	●	●
	15, 25, 35, 55	●				●	●
	100, 175	●			●		●
KSBP01	1	●	●		●	●	●
	15, 25, 35, 55, 100, 200	●					●
CK200P*	1, 35, 55	●			●	●	●
	15, 25	●				●	●
KSSK02*	1, 55	●	●		●	●	●
	15, 25, 35	●				●	●
LTBC43*	1, 15	●				●	●
LTED04	1	●	●		●	●	●
	15, 25, 35, 55, 75	●				●	●
LSEP01*	1, 100	●	●		●	●	●
	15, 25, 35, 55, 180	●				●	●
LSKQ06*	1, 15, 25, 35	●			●	●	●
LSNT01	1	●	●		●	●	●
	15, 25, 35, 55, 100, 180	●				●	●
LSVV01	1, 5	●			●	●	●
MSJN02	1, 15, 25, 35, 55	●				●	●
MSWH01	1	●	●		●	●	●
	variable[2]	●	●			●	●
NSAJ02	1	●	●		●	●	●
	variable[2]	●	●			●	●
NSEX01	1	●	●		●	●	●
	15, 25, 35, 55, 100, 170	●				●	●
LTKE03	1	●		●	●	●	●
	variable[2]	●		●		●	●
LTUM03	1	●		●	●	●	●
	variable[2]	●		●		●	●
HNFD01	1	●		●	●	●	●
	variable[2]	●		●		●	●
LTXQ01[3]*	1	●			●	●	

[1] Sample collection began in 2010.
[2] Sample collected one meter above the bottom (depth variable with tidal height).
[3] Silica not measured at LTXQ01
* Denotes outfall station.
** Chlorophyll a , pheophytin only measured 1, 15, 25, and 35m.

The following section provides a brief description of the laboratory methods used to analyze water samples. Additional details regarding analytical methods are presented in the *Marine Offshore and Beach Water Monitoring: Sampling and Analysis Plan* (King County, 2020). Table 20 provides analytical methods and detection limits for offshore and beach water parameters analyzed in the laboratory.

Table 20. Laboratory methods and detection limits for offshore and beach water parameters.

Parameter	Units	Method detection limit	Reported detection limit	Method
Fecal coliform	CFU/100 ml	1	--	SM9222-D
Enterococci	CFU/100 ml	1	--	SM9230-C
Ammonia-Nitrogen	mg/L	0.002	0.01	Kerouel & Aminot 1997
Nitrate+nitrite-Nitrogen	mg/L	0.01	0.04	SM4500-NO3-F-S
Total Nitrogen	mg/L	0.05	0.1	SM4500-N-C-S
Orthophosphosphate phosphorus	mg/L	0.005	0.01	SM4500-P-F-S
Silica	mg/L	0.05	0.1	Whitledge 1981
Chlorophyll *a*	ug/L	0.05	0.1	EPA 445.0
Pheophytin a	ug/L	0.1	0.2	EPA 445.0
Total Suspended Solids	mg/L	0.5	10	SM2540-D
Dissolved organic carbon	mg/L	0.5	1	SM 5310-B
Total organic carbon	mg/L	0.5	1	SM 5310-B
Salinity	PSU	2.0	3	SM2520-B
Dissolved Oxygen (Winkler)	mg/L	0.1	0.5	SM4500-O-C

PSU = practical salinity unit
mg/L = milligram per liter
CFU = colony forming unit
u/L = microgram per liter

Method detection limits (MDL) for several analytical parameters have changed over time. The following provides a summary of MDL changes during the monitoring period:

- Fecal coliform and Enterococci bacteria -- MDLs changed from 0 colony forming units(CFU)/100 milliliters (ml) in April 2009 to 1 CFU/100 mL
- Ammonia-nitrogen—MDL changed from 0.01 milligrams (mg)/L in 1997 to 0.005 mg/L in 2009 and then to 0.002 mg/L in August 2013
- Nitrate+nitrite-nitrogen—MDL changed from 0.02 mg/L in 1997 to 0.01 mg/L in 2009
- Chlorophyll *a*—MDL changed from 0.005 micrograms (µg)/L in 1997 to 0.01 µg/L in 1999 to 0.05 µg/L in May 2003

- Pheophytin a—MDL changed from 0.01µg/L in 1997 to 0.02 µg/L in 2001 to variable in September 2003.

4.2.2 Phytoplankton

The following section provide an overview of the field and laboratory methods used to collect and analyze phytoplankton samples. Samples for semi-quantitative phytoplankton abundance and community structure were collected from three ambient locations between 2008 - 2014. The type of analysis and number of sample locations changed in 2014. Quantitative analysis was conducted on samples from eight (three outfall and five ambient) locations collected from May 2014 – 2019. Two additional outfall sampling sites were added to the phytoplankton monitoring effort in 2016. . Detailed phytoplankton sample collection and laboratory methods are provided in the *Marine Phytoplankton Monitoring Program Sampling and Analysis Plan* (King County; 2008, 2016).

4.2.2.1 Phytoplankton Field Methods

Phytoplankton samples were collected at most sites from a research vessel concurrently with samples for other water parameters using a five-liter Niskin bottle mounted on the CTD rosette (see Section 4.2.1.1). Samples from Quartermaster Harbor were collected with a Scott bottle. Water from the Niskin and Scott bottles were transferred to 500-ml and 1-L containers and stored on ice until transported to the laboratory for processing.

Semi-quantitative phytoplankton samples were collected twice monthly April - October from 2008-2014 except in 2009 and 2010 when they were collected in April – September. Samples for quantitative analysis were collected twice monthly year-round, except monthly in January and December. Additional samples were collected from both the 1 m and chlorophyll maximum depths at two locations (Pt. Jefferson and East Passage) until February 2016. It was determined that the chlorophyll maximum samples did not add enough value to warrant additional sample collection; therefore the chlorophyll maximum sample collection was discontinued.

4.2.2.2 Phytoplankton Laboratory Methods

A complete phytoplankton taxonomic list (qualitative community structure) was generated by microscopy for all samples (2008 – 2019). Live (unpreserved) samples from the 1- liter (L) sample container were concentrated by reverse filtration and then analyzed using a compound microscope. Observations were limited to presence/absence of an organism in a live, concentrated sample, with identifications to the lowest possible taxonomic level.

Semi-quantitative phytoplankton abundance (relative abundance) was determined for samples collected 2008 -April 2014. Samples in the 1-L container were preserved in the laboratory with buffered formalin (final concentration 0.4%) within 24 hours of collection. Relative abundance was determined based on cell counts in concentrated preserved samples. Prior to analysis samples were concentrated by reverse filtration. A species/genus was categorized as ‘dominant’ when counts were dominant in >50% of nine or more microscope fields, ‘subdominant’ when counts were dominant in less than 50% but more

than 25% of the fields, or 'present' if observed but not dominant or subdominant. Starting in 2012, taxa were also categorized as 'present and common' if they were considered abundant in the live sample but did not qualify as dominant or subdominant in the preserved sample.

In May 2014, phytoplankton analysis protocol changed to a quantitative method using a FlowCAM instrument with live samples. The FlowCAM combines elements of flow cytometry and microscopy to determine quantitative abundance and biovolume down to the lowest practical taxonomic level, usally genus. Live samples in the 10-300 µm size range were analyzed Each whole water sample was separated into two size fractions for analysis: a <100 µm particle size-fraction and a 100-300 µm particle size-fraction for imaging with 10x and 4x objectives, respectively. The >300 µm fraction was retained for observation under a dissecting microscope and enumeration of the large dinoflagellate, *Noctiluca scintillans,* which is too large for the FlowCAM to adequately capture. Phytoplankton and other microplankton were identified to the lowest practical level (typically genus) or grouped into various unidentified categories. Some microzooplankton, such as ciliates and crustaceans, were also quantified to the furthest extent feasible.

A special study was conducted in 2015 and 2016 to evaluate the relationship between carbon biomass and FlowCAM generated biovolume by measuring particulate organic carbon (POC) and particulate organic nitrogen (PON). Samples for POC and PON analysis were collected from Niskin bottles along with phytoplankton samples. One-liter samples were collected twice monthly at eight stations from June - November 2015 and once in December 2015, and twice monthly from March - September 2016. POC samples were size fractionated using the FlowCAM method used to prepare routine phytoplankton samples. The particulates were then harvested by filtration, dried, and analyzed at the UC Davis Stable Isotope Facility. Details regarding the special study are provided in *Marine Conditions Report Series: 2008 – 2019: Phytoplankton* (King County, 2022).

4.2.3 Zooplankton.

The following sections provide an overview of the sampling and analytical methods used to collect and analyze zooplankton samples. Detailed zooplankton sample collection and laboratory methods are provided in the *Marine Zooplankton Monitoring Program Sampling and Analysis Plan* (King County, 2015a).

4.2.3.1 Zooplankton Field methods

Zooplankton samples were collected during daylight hours by the KCEL from a research vessel. Two types of sampling methods, vertical and oblique net tows, were used to collect zooplankton from two areas of the water column.

A vertical net tow was used to collect samples from the water column (200 m maximum depth) at three stations (Pt. Jefferson - KSBP01, Pt. Williams - LSNT01, and East Passage - NSEX01). The entire water column was sampled at Pt. Williams (LSNT01) and East Passage (NSEX01). However, due to the depth at Pt. Jefferson (KSBP01) (~275 m), approximately

75 m of the lower water column was not sampled. Results from these samples are used as an indicator of ecosystem and food web function.

The vertical net consists of a 60-cm diameter ring net with 200-µm mesh and a 15.2 cm length cod end that captures smaller zooplankton and early life stages. A TSK style flow meter was used to quantify the volume of water sampled. The vertical net was allowed to sink to 5 m above the bottom (to a maximum depth of 200 m) and then immediately brought to the surface at a rate of 30 m/min using the vessel's hydraulic winch. Vertical net samples were collected twice monthly April – October 2014, then twice monthly 2015 – 2019, except monthly in January and December.

Oblique net tows were used to sample the upper 30 m of the water column at two stations (Pt. Jefferson - KSBP01 and Pt. Williams - LSNT01) to focus primarily on prey items preferred by salmonids and other fish. The oblique samples were collected using 60-cm diameter paired ring (bongo) nets with 335-µm mesh and a 11.5 cm diameter by 30 cm length cod end, towed obliquely through the upper 30 m in a double-oblique (down and up) tow. One torpedo style flow meter was used in from 2014 to 2016 and a second meter was added in 2017 so that each net had a flow meter. A Sensus Ultra Dive Recorder was used to record a dive profile and tow depth for each tow. The net was deployed at the surface, allowed to sink down to 30 m, and brought back to the surface at 1.5-2 knots through the water with a wire angle of 45°. The oblique tow captures larger zooplankton that are strong swimmers and can evade the vertical tows. Oblique net samples were collected twice monthly April – October 2014 at Pt. Williams (LSNT01), then twice monthly 2015 – 2019, except monthly in January and December. Oblique samples were collected at Pt. Jefferson (KSBP01) starting in January 2016 and were collected during the same timeframe as the Pt. Williams (LSNT01) samples.

The nets were gently rinsed with seawater from the outside and the contents transferred to polypropelene jars. The contents from only one of the two bongo nets was transferred to a polypropelene jar. Organisms were immediately preserved using buffered formalin diluted in seawater to achieve a final concentration of approximately 5% formalin (pH 8.2). Preserved samples were delivered to Dr. Julie Keister's laboratory at the University of Washington for processing and analysis.

4.2.3.2 Zooplankton Laboratory Methods

Zooplankton samples were processed by first briefly examining the entire contents and removing rare and large organisms (e.g., large jellyfish), once documented. When abundance was very high, samples were subsampled with a Folsom plankton splitter. The whole or subsample was diluted to a known volume and two 10-mL aliquots were taken for analysis. A larger aliquot (10 – 40 ml) was taken to quantify the mid-size taxa not adequately subsampled by the smaller aliquots. All organisms in subsamples were identified, quantified and life stage of some taxa was determined using microscopy.

Organisms in vertical tow samples were identified to species level whenever possible for most taxonomic groups, including amphipods and copepods. Life stages of copepod and

crab larvae were also identified. Up to 30 individuals of aspecific taxa were measured using established length-weight relationships to estimate biomass, except length and weight of all larval fish were measured.

Broader taxonomic groups were identified in oblique tow samples and abundance and biomass were quantified. Zooplankton were identified to species level for some amphipods, large copepods, mysids, euphausiids, and decapod crabs. Life stages of some copepods, krill, and crabs were also identified and quantified in oblique tow samples. Up to 30 individuals of a specific taxa were measured to estimate biomass, except larval fish which were measured.

Species data for both tow types were aggregated into 40 broad taxonomic groups (e.g., copepods, hydrozoans, chaetognaths, krill adults, krill furcilia, etc.). Detailed laboratory methods and a list of zooplankton taxonomic groupings and life stages that were differentiated can be found in the most recent zooplankton annual report, *King County Zooplankton Monitoring Annual Report 2020* (Keister et al., 2021).

4.2.4 Sediment

The following sections provide an overview of the sampling and laboratory methods used to collect and analyze sediment samples. All sediment samples were collected in accordance with the Puget Sound Estuary Program (PSEP) *Recommended Guidelines for Sampling Marine Sediment, Water Column, and Tissue in Puget Sound* (PSEP, 1997). For more detail on individual sampling events please refer to the Sampling and Analysis Plans (SAP) for each sampling event:

- Beach (intertidal) sampling (King County, 2010a, 2015b)
- Offshore ambient sampling (King County, 2009b, 2011a, 2012, 2015c, 2017a, 2019).
- Offshore outfall sampling (King County, 2010b, 2010c, 2011b, 2011c, 2017b, 2017c)

4.2.4.1 Sediment Field Methods

All offshore sediment chemistry samples were collected using two stainless steel 0.1-m^2 modified van Veen grab samplers deployed in tandem off the research vessel. If sample acceptability criteria were met, the top 2 cm (Elliott Bay, mainstem, and embayment samples) or 10 cm (outfall samples) of sediment from a minimum of two subsamples (grabs) were composited, homogenized, placed in sample containers, and stored on ice until transport to the laboratory.

Beach sediments were collected at the +6.5 ft MLLW tidal elevation at each location. Chemistry samples were collected from the top 5 cm of sediment using hand-held 2-inch diameter stainless steel coring tubes. Once the required sample volume was obtained, sediments were homogenized in a stainless-steel bowl, transferred to sample containers, and stored on ice until transport to the laboratory.

Toxicity testing on some outfall samples was required to meet NPDES permit requirements. Composited and homogenized sediment were placed in additional jars for toxicity testing. Control and reference sediments for were collected from West Beach on Whidbey Island, WA or San Francisco Bay, CA depending on the test. Amphipods used for toxicity testing were collected from West Beach (West Point tests) or San Francisco Bay, CA (South Plant tests). All other test organisms were obtained from Aquatic Toxicology Support (Bremerton, WA).

Benthic infauna in offshore sediment samples were collected in triplicate, concurrent with chemistry samples, and consisted of the entire contents of a single van Veen grab. Sediments were rinsed through a 1 mm sieve using saltwater and organisms were preserved in buffered formalin in the field, then transferred to subcontracted personnel for later sorting, identification, and quantification. Benthic infauna samples were not collected from beach sediments.

4.2.4.2 Sediment Laboratory Methods

Parameters measured for the different sediment monitoring components varied slightly and are listed in Table 21.

Table 21. Parameters analyzed in sediment collected from beach, offshore outfall and ambient stations.

Parameter Type	Parameter(s)	Beach	Offshore Outfall	Offshore ambient
Conventionals	Total solids, grain size, TOC	✓	✓	✓
Nutrients	Ammonia, total sulfides		✓	✓
Metals*	SMS metals	✓	✓	✓
	Aluminum, iron, nickel	✓		✓
	Manganese, selenium	✓		
	Tin			✓
Organics*	PAHs	✓	✓	✓
	Phthalates	✓	✓	✓
	PCB Aroclors	✓	✓	✓
	SMS chlorinated semi-volatile organics	✓	✓	✓
	SMS misc. non-polar organics	✓	✓	✓
	SMS polar organics	✓	✓	✓
	Butyltins			✓
	Chlorinated pesticides			✓
	Total 4-nonylphenol and coprostanol		✓	✓
	PBDEs congeners	✓		✓
Toxicity	2 acute, 1 chronic test		✓**	
Benthic infauna	Taxa identification and abundance		✓**	✓**

*See individual SAPs for a full list of individual parameters analyzed (Section 4.2.4)

**Toxicity tests and benthic infauna analyzed for a subset of sampling events
SMS = Sediment Management Standards; TOC = total organic carbon

Chemistry

Total solids were measured by a gravimetric method and grain size/particle size distribution (PSD) was determined by a combination of sieve and hydrometer analyses. PSD results include both phi sizes and four broad classifications of clay, silt, sand, and gravel. The clay and silt fractions were also summed to report a result for percent fines. TOC analysis was conducted by a high-temperature combustion with infrared spectroscopy method.

Ammonia analysis used a potassium chloride extraction followed by fluorometric analysis of the extract. Total sulfide was analyzed by distillation following acidification and colorimetric analysis of the distillate.

All metals were analyzed using inductively coupled plasma (ICP) emission spectrometry except mercury, which was analyzed using cold-vapor atomic absorption spectrophotometry (CVAA).

Semi-volatile organics were extracted with an organic solvent and then analyzed by gas chromatography/mass spectrometry (GC/MS). Chlorinated pesticides and PCBs were extracted with organic solvents and then analyzed using a GC equipped with an electron capture detector (ECD). Butyltins and PBDEs were extracted with organic solvents and analyzed using GC/ MS in NCI (negative chemical ionization) SIM (selected ion monitoring) mode.

Modifications to analytical methods and detection limits have changed over time. Therefore, detailed information regarding analytical methods and detection limits for sediment parameters included in this report can be found in the SAPs for intertidal and subtidal sampling events.

Toxicity

Amphipod and larval echinoderm bioassays were used to assess acute toxicity, and the juvenile polychaete bioassay was used to assess chronic toxicity. All analyses were performed at KCEL.

The acute amphipod tests were run according to ASTM (1993) and the Puget Sound Estuary Program (PSEP) (1995). The amphipod *Rhepoxynius abronius* was used to test coarser-grained sediment (West Point). The amphipod *Ampelisca abdita* was used to test fine-grained sediments (South Plant).

The acute echinoderm larvae test was conducted using the sea urchin *Strongylocentrotus purpuratus* in initial 2011 West Point toxicity samples and the sand dollar *Dendraster excentricus* in repeated 2011 West Point and all 2018 toxicity samples. The tests were conducted, according to KCEL SOP 405, following protocols and procedures established by the PSEP (1995) and later modified in *SCUM II* (Ecology, 2017) for samples collected in

2018. Additionally, a second set of test chambers were prepared for side-by-side echinoderm larvae testing using a modified screen tube manipulation method described by Philips *et al.* (2003) on all but the initial 2011 samples. This method was used to isolate physical effects of the sediment on survival, such as turbidity.

Juvenile polychaete (*Neanthes* sp.) growth rate was used as a chronic toxicity test following methods outlined by the PSEP (1995).

Detailed methodologies including laboratory QA/QC procedures for each bioassay are available in SAPs for each individual sampling event referenced above (Section 4.2.4).

Benthic Community Structure

Benthic community (taxonomy) replicate samples (three replicate samples per site/event) were sorted and individuals were counted and identified to the lowest practical taxonomic unit (often to species). Abundance of each taxon was recorded, and wet weight (ww) biomass of each major taxonomic group (Crustacea, Mollusca, Polychaeta, and miscellaneous taxa) was measured.

For quality control purposes, a 20% aliquot of each sample was resorted to ensure 95% efficiency of all samples. Additionally, at least 5% of all replicate samples were re-identified by a separate taxonomist to ensure 95% taxonomic similarity. Discrepancies between analysts were discussed and data were reconciled prior to data being used.

All samples were analyzed by a contract laboratory; analysis included taxonomic identification and taxa abundance. Different contract laboratories were used over the monitoring period (Allan Fukuyama [2009-2015] and EcoAnalysts, Inc. [2017–2019]).

4.2.5 Clam Tissue

Butter clam *(Saxidomus giganteus*) tissues were collected at 10 ambient and outfall beach locations twice annually in spring (March) and summer (August) through 2010 when the sampling program was discontinued.

4.2.5.1 Butter Clam Field Methods

Butter clams were collected by hand digging with shovels in the vicinity of siphon holes. Five to 10 butter clams (shell length 60 to 120 mm) were collected at each station and composited into a single sample for analyses. Clams were placed into plastic bags and stored on ice until laboratory delivery.

4.2.5.2 Butter Clam Laboratory Methods

Butter clam samples were processed at the KCEL in accordance with PSEP *Recommended Guidelines for Sampling Marine Sediment, Water Column, and Tissue in Puget Sound* (PSEP, 1997). Before the clams were opened, shells were rinsed with deionized water to remove sand and other adhering material and length of each clam was recorded. Tissue from each

clam was removed with ceramic scalpels, composited with their liquor, and then homogenized in a sterilized blender equipped with stainless steel blades.

Butter clams were analyzed for the following parameters:

- Conventional parameters—total lipids, total solids, shell length
- Metals—aluminum, arsenic, beryllium, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel, selenium, silver, zinc
- Organic compounds—PBDEs.

Prior to 2008, BNAs, chlorinated pesticides, and PCBs were also measured in clam tissues. However, other than benzoic acid (a metabolic byproduct), these compounds were rarely detected and were discontinued from the monitoring program.

Except for mercury, all metals were analyzed using ICP or ICP-MS. Mercury was analyzed using CVAA spectroscopy. PBDEs were extracted with an organic solvent and analyzed by high-resolution GC-MS. Table 22 provides target MDLs for butter clam parameters.

Table 22. Butter clam target MDLs and analytical methods.

Parameter	Units	MDL	Method
Total solids	%	.005	gravimetric
Total lipids	%	.05	gravimetric
Arsenic, beryllium, lead, nickel, selenium	mg/Kg	0.0039	ICP-MS
Cadmium	mg/Kg	0.002	ICP-MS
Mercury	mg/Kg	0.00037	CVAA
Aluminum	mg/Kg	1	ICP
Chromium	mg/Kg	0.03	ICP
Copper, silver	mg/Kg	0.04	ICP
Iron, zinc	mg/Kg	0.05	ICP
PBDEs	µg/Kg	0.021 *	GC-MS

*MDL for DecaBDE-209 was 0.11 µg/Kg.

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