Chapter 4

A Temporal Analysis of Water Quality Variability at the Seattle Aquarium in Elliott Bay, Puget Sound, WA

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Additional information is available at the end of the chapter

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Abstract

The Seattle Aquarium is centrally located on Elliott Bay in Puget Sound, built on a pier along the central waterfront in Seattle, WA, USA. The Seattle Aquarium Water Quality Laboratory regularly measures water quality metrics on incoming saltwater pumped directly from Elliott Bay for use in the animal exhibits. This study provides a descriptive temporal analysis of variability in the incoming saltwater conducted from 2007 through 2016. Parameters measured on a weekly basis include ammonia (NH_3), nitrite (NO_2), pH and fecal coliform bacteria. Ammonia mean throughout the dataset was 0.02 mg/l (SE ± 0.0005), with clear seasonal trends of higher ammonia levels during the summer months (May, June and July) annually. Nitrite mean was 0.01 mg/l (SE ± 0.002), with clear seasonal trends of this nutrient with bi-annual peaks in spring and fall (May and September). Saltwater pH mean was 7.81 (SE ± 0.004), trending lower in winter and spring and higher in summer and fall. Fecal coliform bacteria mean over the 10-year period was 20 colony-forming units (CFU) per 100 ml of water. Overall, Elliott Bay water quality remained relatively stable from 2007 to 2016, and if remains unchanged, will continue to be a reliable source of saltwater with known water quality parameters for use in animal exhibits in the Seattle Aquarium.

Keywords: water quality, Puget Sound, Elliott Bay, Seattle Aquarium, ammonia, nitrite, pH, fecal coliform bacteria

1. Introduction

Water quality is fundamental for the health of aquatic organisms. Many characteristics can be used to define water quality and can be relatively easily quantified by biological, physical, chemical, and esthetic indicators. Clean, uncontaminated water is preferable if not required for sustaining all trophic levels from vegetation to apex predators, including human populations.

A reduction in relative water quality can cause cascading negative effects throughout the food web, thus disrupting stable ecosystem functioning. Urbanization and changes in land use can alter water quality by increasing runoff from point (stormwater overflow valves, drainage ditches and pipes) and non-point sources (those flowing over land). Uncontrolled or captured freshwater runoff not only increases the freshwater influx into the marine ecosystem, but can also pick up pollutants and contaminants along the way moving them into nearshore ecosystems [1]. Loss of critical nearshore habitats, such as wetlands that act as natural buffers and water filters, negatively impact larval fish survival, resulting in higher mortalities, smaller cohorts and ultimately less food for higher predators [2].

Seattle and the surrounding communities have been listed as one of the fastest growing cities in recent years. The population has grown tremendously since first settlements in the 1800s, and the landscape has changed dramatically from a mostly coniferous forest to an urban city. The 2016 population estimate was nearly 4 million in the greater Puget Sound region and has grown 2.2% annually since 2015 [3].

The Puget Sound is an estuarine inland sea with a shoreline of nearly 4000 km located in western Washington [4]. It is fed by 14 major rivers and is surrounded by the Cascade Mountains to the east and the Olympic Mountains to the west. Elliott Bay is located in central Puget Sound and is just west of the City of Seattle with its eastern border along Seattle's waterfront. The main freshwater source into Elliott Bay is the Duwamish River. This river enters at the north side of Harbor Island, a heavily industrial area, and the general current flows northward along the coastline of the City of Seattle's waterfront lowering the salinity to estuarine conditions [5]. Tidal changes vary between 3 and 4 m, and occur approximately every 12.4 hours. Each tidal change brings in or removes about 8 km^3 of water and causes turbulent mixing within the water column [6]. Coastal development has increased in the region, with more than 30% of the shoreline reinforced with artificial bulkheads, seawalls and other structures [7]. Historically, fishing and shellfish harvesting have been important to the quality of life for people living in Puget Sound. Healthy fish and shellfish populations rely on relatively clean water and intact, natural nearshore marine ecosystems. Thus, the increased urbanization of nearshore marine areas that has occurred in the Puget Sound region is thought to have negatively impacted fish and shellfish resources [8].

The Seattle Aquarium is centrally located on the east side of the Puget Sound, directly on Elliot Bay (**Figure 1**). It is owned by the City of Seattle Department of Parks and Recreation and managed by the non-profit Seattle Aquarium Society. It is the ninth largest aquarium in the United States by attendance and in 2016, welcomed more than 850,000 visitors. The aquarium is composed of two buildings located on Piers 59 and 60, along downtown Seattle's waterfront. The Aquarium is responsible for the care of over 30,000 animals (representing more than 350 species) in public exhibits and behind-the-scenes animal holding spaces. The exhibits are divided into four main sections: warm water tropical fish and invertebrates, local Pacific Northwest cold water fish and invertebrates, coastal birds, and marine mammals.

The Aquarium utilizes Puget Sound water for use in all of the saltwater exhibits. Incoming raw Puget Sound saltwater goes through multiple stages of processing before use, dependent on

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Figure 1. Location of study area, the Seattle Aquarium within Elliott Bay, Puget Sound, Washington.

exhibit (**Figure 2**). The warm water exhibits use incoming water that is sand filtered, mechanical cartridge filtered (Lifeguard Aquatics, Cerritos, CA), treated with ozone to remove organics (DEL Industries Infinity, San Luis Obispo, CA), filtered through activated carbon, UV sterilized (Emperor Aquatics, Inc., Pottstown, PA) and then finally heated to reach ambient tropical water temperature. The cold water or temperate exhibits use water that is sand filtered and depending on the exhibit, UV sterilized. Three bird habitats and two species-specific marine mammal exhibits (northern fur seals, *Callorhinus ursinus*, and northern sea otters, *Enhydra lutris kenyoni*) use only sand filtered seawater. The harbor seal, *Phoca vitulina richardsi*, exhibit uses

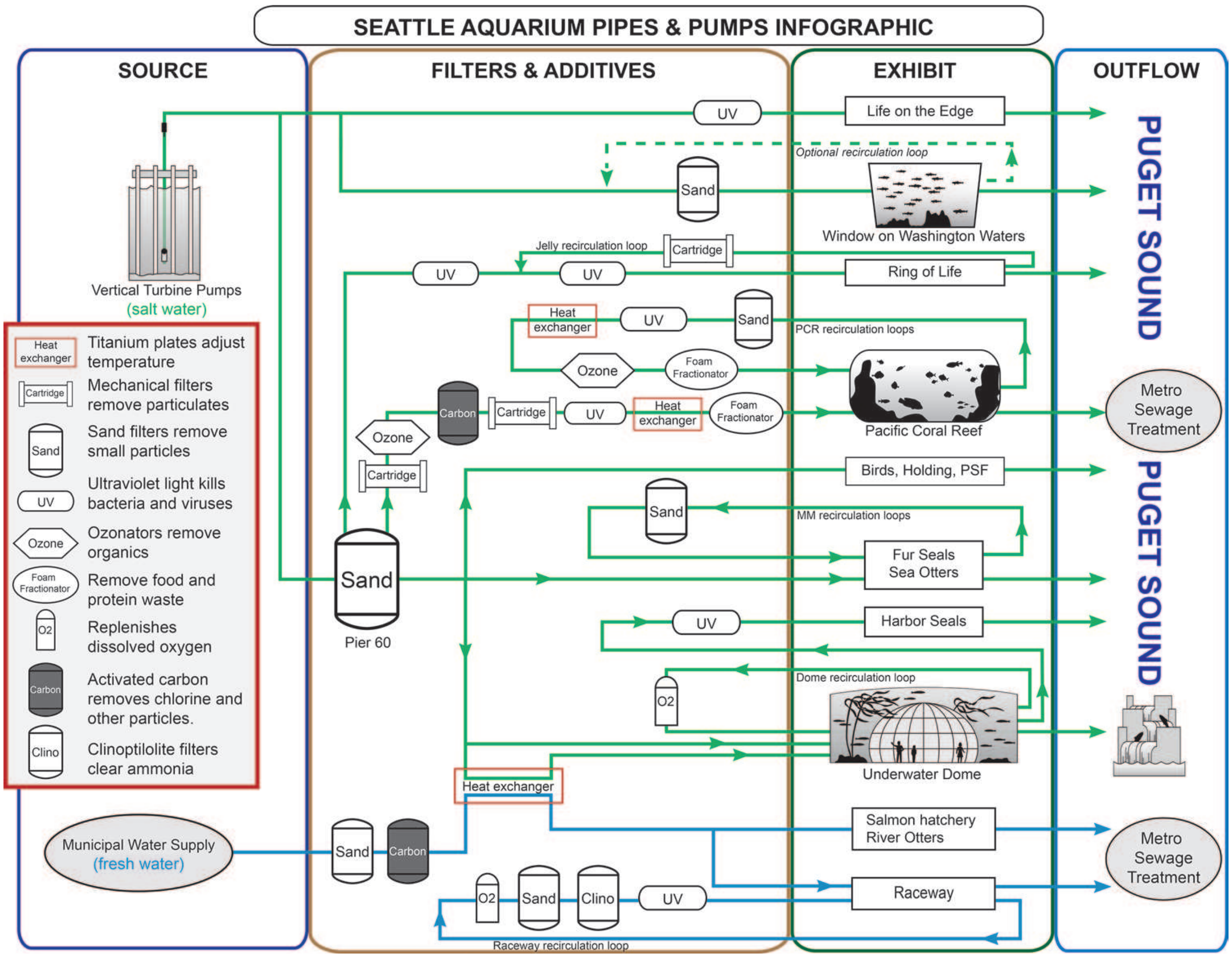

Figure 2. Pipes of pumps of the Seattle Aquarium. Incoming Puget Sound water is pumped though turbines (left) and eventually outflows to either King County metro sewage treatment or back to Puget Sound. (Source: Seattle Aquarium Engineering).

re-circulated water from the underwater dome, a temperate exhibit holding local fish, which uses Puget Sound water that is sand filtered and UV sterilized. After use in aquarium exhibits, most saltwater outflows back into Puget Sound untreated, with the exception of the water that was used in the tropical pacific coral reef exhibit which is pumped to King County Metro sewage for treatment.

The Seattle Aquarium Water Quality Laboratory has been measuring Elliot Bay water quality parameters since it opened in 1977. The principal objective for operating the laboratory is to consistently produce analytical data that accurately represents the chemical composition of the water samples. Since the aquarium is located in a highly populated and altered urban environment, it is critical to monitor the incoming water quality for use in exhibits. The results of these analyses are sent to aquarium biologists and aquarists who use this information to determine if any changes are needed (increase or decrease water flows, tank maintenance schedules, etc.) to protect and maintain aquatic animal health. Poor or inadequate water quality can weaken or sicken animals and lower disease resistance. Disease outbreaks typically occur following some form of stress to the aquatic animals, such as but not limited to changes in diet, food, tank mates, water chemistry, exposure to toxics or other environmental changes.

Water quality parameters regularly measured by the Aquarium Water Quality Laboratory and discussed here include ammonia (NH_3), nitrite (NO_2), potential of hydrogen (pH) and fecal coliform bacteria levels. Nutrients, such as NH_3 and NO_2, are key indicators of water quality. Aquatic plants require nutrients to grow and reproduce, but excessively high levels could pollute the water and cause eutrophication. This process can cause hypoxia, or very low oxygen levels, due to excessive decaying plant growth by bacteria. Potential of hydrogen (pH) is a measure of how acidic a solution is, represented by a scale from 0 to 14. Solutions with pH less than 7 are considered acidic and have a greater concentration of hydrogen ions, while those with pH higher than 7 are basic or alkaline with lower concentration of hydrogen ions. Most aquatic life have adapted to live between pH levels of 5 and 9. Fecal indicator bacteria (specifically coliform bacteria) are indicative of pollution from large amounts of human and other vertebrate sewage contamination of the water. This can result in spreading of disease and other pathogens associated with fecal contamination. Sources include leaky sewer systems, failing septic systems, pet waste, and wildlife waste. In Seattle, the Department of Health uses the Ten State Standard for beach closures. Revised in 2014, the standards are a guide for wastewater facilities to safeguard public health and protect water quality and include Indiana, Illinois, Iowa, Michigan, Minnesota, Missouri, New York, Ohio, Pennsylvania and Wisconsin [9]. King County beaches are closed to the public when coliforms exceed a geometric mean of 200 colony-forming units per 100 milliliters (CFU/100 ml) with no single sample exceeding 1000 CFU/100 ml. The Seattle Aquarium is required by the Department of Health to monitor fecal coliform bacteria in touch pools accessible to the public. In addition, the United States Department of Agriculture (USDA) requires the aquarium to monitor fecal indicator bacteria (fecal coliforms) in all marine mammal exhibits. Any sample from a marine mammal tank over 1000 CFU/100 ml is considered unacceptable and must be repeated three times every 48 hours. If the average of these samples is above 1000 CFU/100 ml then the facility must make a change to the exhibit to improve the water quality or risk losing their USDA exhibitors license permitting the facility to keep marine mammals.

Here we present the last 10 years (2007–2016) of water quality monitoring of incoming saltwater from Elliott Bay highlighting the temporal variability of these water quality parameters within Puget Sound.

2. Materials and methods

The Seattle Aquarium Water Quality Laboratory has been certified by the Washington State Department of Ecology to perform NH_3, NO_2, pH and fecal coliform analyses of water since 2014. The laboratory is inspected annually by Washington State employees and performs proficiency testing twice a year to maintain accreditation. All analytical procedures are completed according to approved standard, blank methods and include all quality assurance and quality control measures required by those methods. Quality control samples ensure that the tests performed adhere to a defined set of statistically-based criteria. These criteria are used to assess the accuracy of measurement data. Each analysis of a set of samples reported here included a check standard, blank and duplicate samples.

2.1. Water sample collection

The Seattle Aquarium has installed three intake pipes located underneath Pier 59, at 14 m below the surface of the pier (5-6 m depth in the water column, depending on tidal fluctuation). The rate of intake is 4500 gallons per minute through a 42-cm diameter pipe with 2 cm pore size screen to prevent large debris from entering. Samples reported here were raw Puget Sound saltwater collected pre-UV sterilization and filtering. Water samples were collected from a valve off the main pipe in clean plastic bottles, 2–3 times per week, from 2007 to 2016. Samples were brought back to the laboratory and are analyzed soon after collection.

2.2. Ammonia (NH_3) and nitrite (NO_2) standard method

Methods used for NH_3 and NO_2 analyses were colorimetric using a Hach (Loveland, CO) spectrophotometer to obtain absorbance values that were converted to mg/l using a conversion factor (obtained by linear regression analysis created when calibrating the spectrophotometer). Samples from 2007 through mid-2016 were analyzed on a Hach DR/5000 and the remaining samples to the end of 2016 were analyzed on a Hach DR/6000 model.

For NH_3 testing, the laboratory utilized a version of the phenol hypochlorite method outlined by Solórzano [10] and found in Standard Methods for the Examination of Water and Wastewater [11] method 4500-NH_3-F. Procedures also found in Standard Methods for the Examination of Water and Wastewater [11], were followed for NO_2 analysis (Method 4500-NO_2-B). Absorbance values for each of these tests were recorded and multiplied by a corresponding conversion factor for NH_3 and NO_2 final calculations. Duplicate deionized water blanks, a check standard (0.05 mg/l for both NH_3 and NO_2), and duplicate samples were analyzed at each session for each parameter tested. For standard preparations, an ammonia standard ampule (50 mg/l NH_3) made by Hach was utilized for years 2007 through 2013. In 2014, the laboratory switched to an ERA (Golden, CO) 1000 ± 06 mg/l NH_3 check standard which was diluted to 1.00 mg/l before use. The laboratory used a Sigma-Aldrich (St. Louis, MO) standard 1000 mg/l NO_2, also diluted to 1.0 mg/l for use, and was included for all years. Type II deionized water was used from 2007 through mid-2016 to make reagents and blanks and was produced in-house by a Barnstead Mega-Pure D1 System (Thermo Scientific, Waltham, MA). In July 2016, the laboratory switched to ultra-pure type I deionized water purchased from ChemWorld (Roswell, GA).

2.3. Potential of hydrogen (pH) method

Measurements of pH were determined using both hand-held and bench top meters. A one-point calibration was performed for the hand-held ISFET meter (Hach) using a 7.00 buffer solution prior to every analysis set. The bench top pH meter (Oakton 100 series, Vernon Hills, IL) was calibrated before each use with 4.00, 7.00, and 10.00 EMD buffer solutions. Additionally, a 6.00 + 0.05 Hach check standard buffer solution was measured to confirm the accuracy of calibration.

2.4. Fecal coliform method

The Millipore-Milliflex system (Millipore, St. Louis, MO) was used to measure fecal coliform levels. This membrane filtration system consisted of pre-made sample funnel sets for measuring

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100-ml water samples. The funnels fit on top of a Millipore Plus pump platform, where 100 ml of raw saltwater samples were filtered onto a built-in 0.45 μm filter membrane. After filtration, the funnel was snapped onto a cassette filled with 2 ml of fecal coliform nutrient media (mFC dehydrated broth base with rosolic acid, EMD Millipore). The funnel was then detached, and the labeled cassette was placed in an incubator at 44.5°C for 24 hours. This method, based on Section 9222D Thermotolerant (fecal) coliform membrane filter procedure, was outlined in Standard Methods for the Examination of Water and Wastewater [11].

3. Results

Ammonia (mg/l) values from 2007 to 2016 are shown in **Figure 3** (N = 808 samples). Ammonia mean was 0.02 mg/l (SE ± 0.0004) over the 10-year period. There were clear seasonal trends as ammonia peaked during the summer months (May, June and July) annually. Typical peak levels ranged from 0.05 to 0.06 mg/l. In the winter months, levels dropped to 0.01 mg/l. Annual mean was 0.02 mg/l for years 2007 through 2012 and for 2014. Years 2013, 2015 and 2016 were 0.01 mg/l on average. The maximum level (0.11 mg/l) was recorded in June 2014. The next highest measurement, taken in July 2007, was 0.09 mg/l. Summary descriptive statistics are listed in **Table 1**, and annual statistics are listed in **Table 2**.

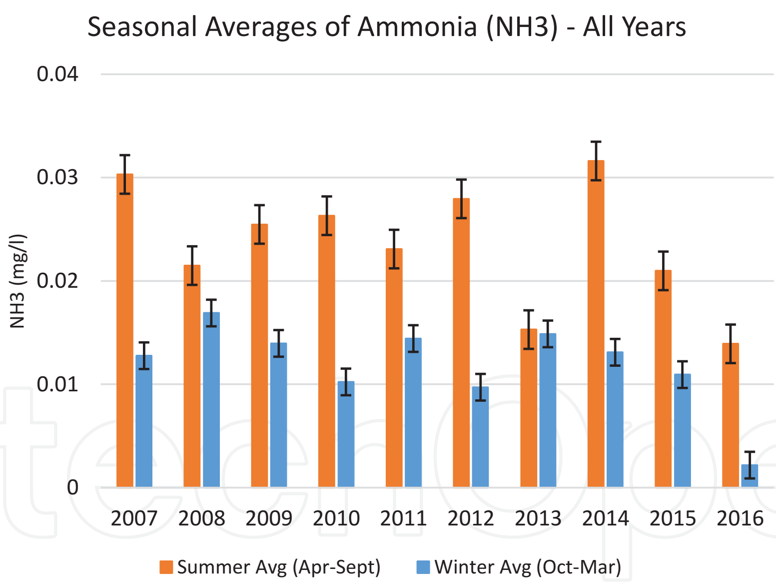

Figure 3. Ammonia (mg/l) in Puget Sound water samples from 2007 to 2016, measured in the Seattle Aquarium Water Quality Laboratory.

Nitrite (mg/l) values from 2007 to 2016 are shown in **Figure 4** (N = 811 samples). The nitrite mean was 0.00 mg/l (SE ± 0.0001) over the 10-year period. There were bi-annual, seasonal trends with peaks occurring during the late spring and fall months (April, May and September) and troughs during the winter months (December through February). The peaks were between 0.03 and 0.04 mg/l with low levels dropping to 0.00–0.01 mg/l. The annual mean was 0.00 mg/l for years 2007, 2008, 2011 through 2013, and 2016. For years 2009, 2010, 2014 and

2015, the annual mean was 0.01 mg/l. The maximum level (0.04 mg/l) for 2010 was recorded in September. The next two highest events were in September 2009 and September 2014 with 0.03 mg/l nitrite. Summary descriptive statistics are listed in **Table 1**, and annual statistics are listed in **Table 2**.

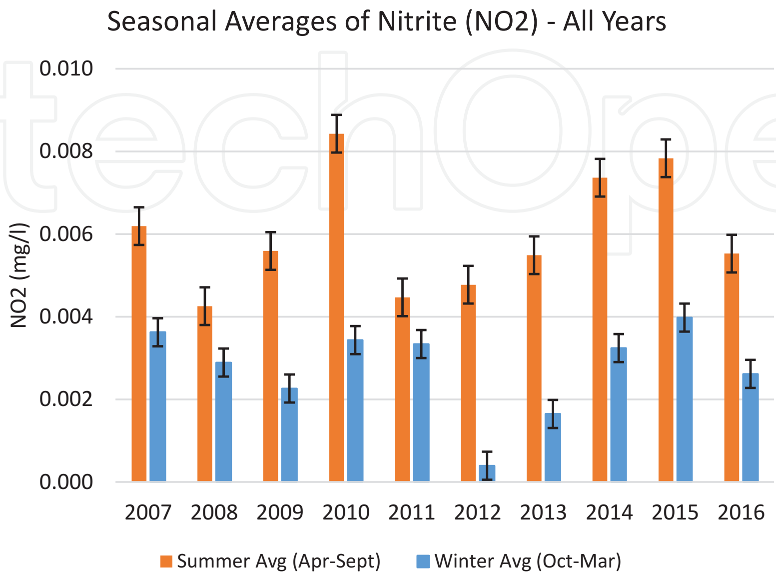

Figure 4. Nitrite (mg/l) in Puget Sound water samples from 2007 to 2016, measured in the Seattle Aquarium Water Quality Laboratory.

Water quality (2007–2016)				
	NO_2 (mg/l)	**NH_3 (mg/l)**	**pH**	**F. coliforms (CFU/100 ml)**
Mean	0.00	0.02	7.81	15
Standard error	0.00	0.00	0.00	2
Median	0.00	0.01	7.80	6
Mode	0.00	0.00	7.80	2
Standard deviation	0.00	0.01	0.11	42
Sample variance	0.00	0.00	0.01	1759
Kurtosis	13.93	5.49	0.40	91
Skewness	2.44	1.66	0.23	8
Range	0.04	0.11	0.75	584
Maximum	0.04	0.11	8.20	0
Minimum	0.00	0.00	7.45	584
Sum	3.71	14.10	6212	7616
Count	811	808	795	507

Table 1. Summary of descriptive statistics in water quality parameters, measured by the Seattle Aquarium Water Quality Laboratory, from Puget Sound water samples collected between 2007 and 2016. Parameters include nitrite (NO_2), ammonia (NH_3), pH and fecal coliforms.

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Water quality by year											
		2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Nitrite (NO_2) mg/l	Mean	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.00
	SE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Max	0.01	0.01	0.03	0.04	0.02	0.01	0.04	0.03	0.01	0.01
Ammonia (NH_3) mg/l	Mean	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.01
	SE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Min	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Max	0.09	0.05	0.06	0.05	0.06	0.05	0.03	0.11	0.05	0.04
pH	Mean	7.85	7.79	7.84	7.87	7.80	7.82	7.79	7.79	7.81	7.80
	SE	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Min	7.45	7.60	7.70	7.70	7.50	7.60	7.60	7.50	7.60	7.58
	Max	8.20	8.06	8.10	8.20	8.00	8.10	8.00	8.10	8.00	8.20
F. coliforms (CFU/100 ml)	Mean	31	7	24	13	9	17	14	15	13	5
	SE	12	1	9	5	2	5	3	4	6	1
	Min	0	0	0	0	0	0	0	0	0	0
	Max	584	31	418	240	60	174	102	172	315	69

Parameters include nitrite, ammonia, pH and fecal coliforms.

Table 2. Descriptive statistics in water quality parameters, measured by the Seattle Aquarium Water Quality Laboratory, from Puget Sound water samples per year.

Potential of hydrogen mean was 7.81 (SE ± 0.004) from 2007 to 2016 (**Figure 5**). The pH range varied from 7.45 to 8.20 (N = 795 samples). Linear regression with negative slope of 0.00002 indicated non-significant decrease over time (R^2 = 0.03). Annual mean values are listed in **Table 2** , and monthly mean values are shown in **Figure 6**. In general, pH means fluctuated slightly year to year, with lowest values of 7.79 in 2008, 2013 and 2014. Higher values were 7.84 in 2009, 7.85 in 2007 and 7.87 in 2010. Summary descriptive statistics are listed in **Table 1**, and annual statistics are listed in **Table 2**.

Fecal coliform mean was 15 (SE ± 2) colony-forming units per 100 ml of water (CFU/100 ml) over the 10-year period of 2007 through 2016 (N = 507) (**Figure 7**). Over all 10 years in weekly monitoring, the 200 CFU/100 geometric mean maximum was exceeded three times. The single sample maximum of 1000 CFU/100 ml for Seattle beach closure was never exceeded. The lowest annual mean value was 5 (SE ± 1) CFU/100 ml in 2016, and the highest annual mean value was 31 (SE ± 812) CFU/100 ml in 2007. Minimum count throughout all years was zero, and the highest single maximum count was 584 CFU/100 ml in January 2007. Summary descriptive statistics are listed in **Table 1**, and annual statistics are listed in **Table 2**.

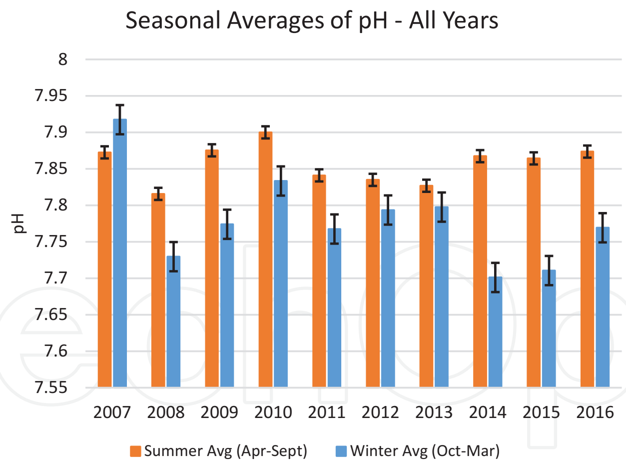

Figure 5. Puget Sound water sample pH values from 2007 to 2016, measured in the Seattle Aquarium Water Quality Laboratory.

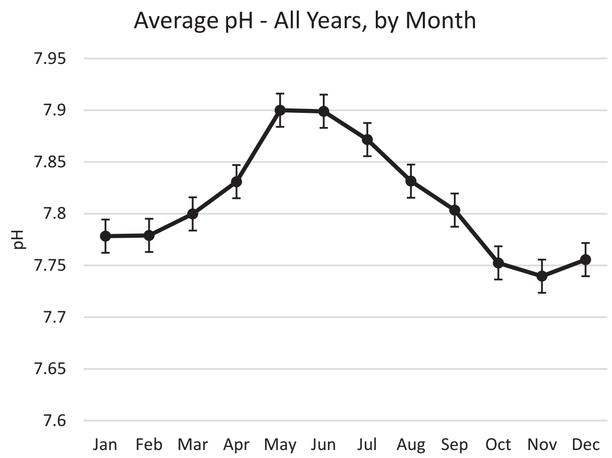

Figure 6. Monthly mean Puget Sound pH values from 2007 to 2016. Summer months increase to almost 8.0 (May and June) then drop to levels 7.75–7.8 in the fall and winter months.

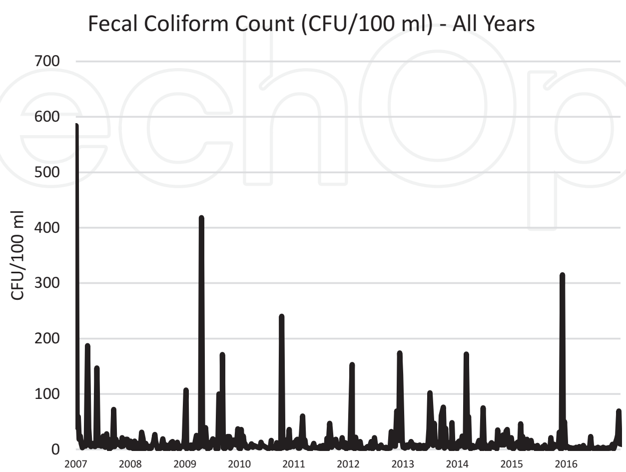

Figure 7. Fecal coliform (CFU/100 ml) levels in Puget Sound water samples from 2007 to 2016, measured in the Seattle Aquarium Water Quality Laboratory. Mean coliform count was 15 CFU/100 ml over the 10-year period.

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4. Discussion

Incoming seawater parameters measured in the Seattle Aquarium Water Quality Laboratory followed expected cyclic trends from 2007 to 2016 in Elliott Bay, WA. Seasonally, there were annual phytoplankton blooms in the spring and summer months in Puget Sound, causing an increase in NO_2 followed by a subsequent increase in NH_3 as the plankton degraded. These seasonal peaks are shown in **Figures 3** and **4**. In 2011, the Puget Sound Environmental Monitoring Program (PSEMP) reported higher than average precipitation from March through May, coupled with lower temperatures, delaying the spring phytoplankton bloom [12]. The PSEMP also measured lower NH_3 levels than usual that year, with the exception of June, July and August (over the entire Puget Sound area). Our data revealed high NH_3 values in May, which decreased over the next few months. That year, NO_2 values were high only in May and September. In 2012, PSEMP reported an unusually large fall bloom in September resulting in a spike in NH_3 levels in October [13]. Our data showed a similar pattern, with a high of 0.05 mg/l in NH_3 in October of 2012. In 2013, PSEMP reported a typical spring phytoplankton bloom occurring in early April, followed by an unusually large bloom in August and September resulting in an increase in ammonia [14]. Our data does not corroborate, with no seasonal changes occurring in the incoming water at the aquarium that year. Over the course of winter 2013–2014, an anomaly called the "Blob" began. The term "Blob" refers to the mass of warm surface water that formed in the northeastern Pacific Ocean. It occurred due to a rare atmospheric circulation pattern combined with a positive Pacific Decadal Oscillation (PDO), an extended El Nino Southern Oscillation-like condition and affected Pacific climate variables (based on sea surface temperatures north of 10°N) [12, 15]. As a result, Puget Sound was influenced by warmer than normal northeast Pacific Ocean surface waters [15]. This may have stimulated an early spring plankton bloom in Puget Sound resulting in a sharp increase in NH_3 toward the end of May through June of 2014 in our dataset. The blob anomaly continued in 2015, with resulting NH_3 levels rising through late June with the exception of an October peak following a large September phytoplankton bloom [16]. Our data shows an NH_3 peak in June and again in September, followed by a decrease in October. Overall, NH_3 levels measured underneath the Seattle Aquarium tend to trend with other data measured throughout the Puget Sound.

Several factors influence the pH of Elliot Bay, including rainfall, runoff and Duwamish River input. As less dense freshwater enters the Central Sound, it tends to flow along the surface as it leaves the mouth of the Duwamish and becomes more brackish as it mixes with the denser saltwater in the bay [17]. According to Ref. [17], the Central Puget Sound receives over 8000 cfs (cubic feet per second) of freshwater inflow from the combined Puyallup, Green-Duwamish, and Cedar-Lake Washington River Basins and stormwater runoff and wastewater discharges from the Seattle-Tacoma metropolitan area. Just in Elliot Bay, discharges from the Duwamish can be as high as 2000–4000 cfs, and in late January 2011, the discharge surpassed 10,000 cfs [18].

The pH results indicate a cyclical pattern based on season from 2007 to 2016, trending toward 7.6–7.8 in the winter–spring months and 7.8–8.0 in the summer-fall months. Precipitation (rainfall and snow) in this region is higher in the winter months followed by increased freshwater release as the snow pack melts during the spring months when temperatures begin to increase. There was a non-significant downward trend noted over the monitoring period; however, it would be difficult to link this slight decrease directly to ocean acidification. The instrumentation to better monitor minute pH changes has just become available in recent years. The instrumentation utilized by the Seattle Aquarium Water Quality Laboratory to measure pH produced one or two significant figures, and the use of a more sensitive machine may better track these trends.

Incoming freshwater into Puget Sound commonly occurs through a network of rivers, streams, creeks, sewage outflow and stormwater runoff through ditches and pipes (point source pollution sites). King County utilizes combined sewer systems designed to collect rainwater runoff, domestic sewage and industrial wastewater. The water is conditioned in water treatment plants and then discharged into the Puget Sound [19–23]. There are 84 outflow locations in the City of Seattle, and four are within 2000 ft of the aquarium (No. 069, 070, 071 and 072). During high rain events, the amount of water exceeds capacity for these systems to process in the treatment plants, and when this occurs, relief point pipes release untreated sewage and stormwater into Elliott Bay, called a combined sewer overflow (CSO). These events usually increase the fecal contamination of the nearshore saltwater. Annual mean Puget Sound fecal coliform counts by the Seattle Aquarium follow a similar trend to rainfall (inches) recorded by the City of Seattle in that coliform levels tend to increase as rainfall increases (**Figure 8**). However, coliforms and precipitation do not follow a similar pattern to CSO overflow volume from the nearest four outflow pipes to the aquarium. Thus, it seems that the overflow volume of outflow nearest to the Aquarium is not indicative of coliform level in the water under the Aquarium pier. Coliform values of raw incoming seawater were typically between zero and 20 CFU/100 ml and are below critical thresholds for animal health, and in 10 years of weekly

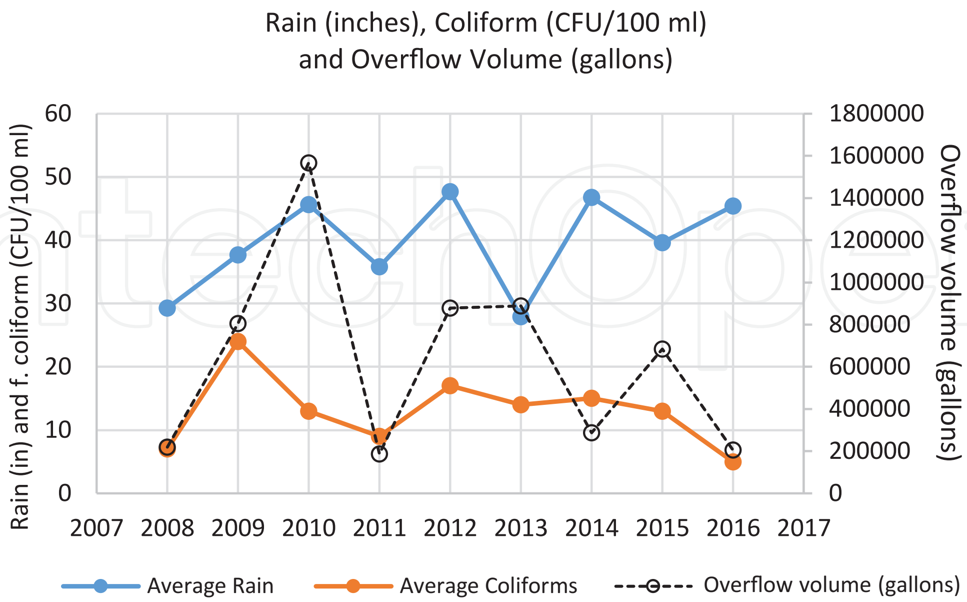

Figure 8. Mean annual rain (inches), coliform count (CFU/100 ml) and combined sewer outflow volume (gallons) from four of the nearest City of Seattle overflow locations. Coliform count and rain follow similar trends, as rain increases, coliform count also increases. Overflow volume does not seem to reflect any trends.

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monitoring, fecal coliform levels never exceeded the 1000 CFU/100 ml maximum for beach closure. All touch pool exhibit water at the aquarium is UV sterilized before accessible to the public, which is also monitored weekly, to protect guests.

The stability of the water quality parameters in the incoming saltwater for the aquarium's exhibits is encouraging, given the increasing concern about climate change, ocean acidification and increasing urbanization of the Puget Sound area. The Puget Sound is home to a variety of bird, fish, invertebrate and mammal species; many categorized as vulnerable, high risk or critical to extinction risk. Flagship species determined by the Puget Sound Partnership include Pacific herring, Pacific salmon and Southern resident killer whales [24–26]. Pacific herring are considered to be the most important component of pelagic prey fish in the Puget Sound food web and a known spawning ground is just north of the Aquarium in Elliott Bay [27]. Continued stability in water quality is necessary, as it affects almost every aspect of the Puget Sound ecosystem.

Long-term longitudinal time series are essential to tease out potential seasonal or annual patterns in data. Seattle Aquarium biologists and aquarists can use this data to predict when baseline levels may shift, and use that information to fine-tune exhibit husbandry and animal care. Ongoing data collection is needed monitoring Puget Sound water quality over large time scales, as water conditions change, as urbanization increases, and as we continue to alter our marine environment.

5. Conclusions

The Seattle Aquarium is the only waterfront facility monitoring multiple water quality parameters concurrently. The King County Department of Natural Resources and Parks has a mooring buoy at the end of the Aquarium pier to measure pH, among other metrics such as temperature, salinity etc. The King County Department of Health monitors fecal coliform levels throughout the Sound. The Puget Sound Environmental Monitoring Program is a conglomerate of researchers that measure ammonia and nitrite throughout the Sound. Due to the location of the Aquarium, lab staff can quickly and easily collect samples on a day-by-day basis to provide continuous monitoring. This research provides data on water quality that is unique to Elliott Bay within the downtown Seattle area. With this data, Aquarium staff can monitor the health of the nearby marine ecosystem, and the Aquarium can serve as a watch dog to any major changes in water quality. Any values that fall outside of normal ranges can be flagged, and the proper authorities can be notified. The Aquarium lab staff work closely with the Department of Ecology, the Port of Seattle, King County and other officials, and these partnerships are essential to keep this important research going.

One shortcoming of this research is the inability to pinpoint cause. Parameters can be measured, but locating a point pollution location or determining why or how quality changed is outside of the Seattle Aquarium laboratory capabilities. Typically, lab staff collects three samples a week, and the scale of the data is limited to this time frame. Water flushes in out and out of Elliott Bay continuously, and tides that occur twice daily also provide mixing. The Aquarium intake pipes are at depth, so surface water quality is not measured, which may differ from water quality at depth.

Elliott Bay and Puget Sound are unique study areas that are estuarine, highly populated, with directed in and out flow through the straits of Juan de Fuca and Georgia. This data can contribute to understanding how a body of water like this is affected by season, rainflow and tidal fluctuation. There is limited data on similar water systems, and by contributing to this area of research, other scientists may use this data as a comparison to quantify differences between areas.

The Aquarium will continue to monitor Puget Sound water quality on a weekly basis. As incoming water is used for exhibits and animals, it is necessary to confirm that the water provided for animal health and husbandry is the best available. With a long-term dataset, trends, patterns and outliers can be identified and analyzed. This research will help with continuing to keep the Puget Sound as clean as possible and supports the Seattle Aquarium's mission of Inspiring Conservation of the Marine Environment.

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