Sink or Swim:

Modeling anthropogenically released Pb and Cu in Puget Sound using the LiveOcean Regional Oceanographic Modelling System (ROMS)

Marissa Leatherman

University of Washington

School of Oceanography, Box 357940

Seattle, WA 98195-7940

male370@uw.edu

Plain Language Summary

Heavy metal pollution is both a global concern and a threat to the local communities it affects. The local communities in the Puget Sound area of Washington state create a lot of this pollution, which makes its way into local waterways through sewage, shipyard waste, and rivers. This area is home to many important species that humans rely on for food and heavy metal pollution puts these animals and the humans that consume them at great risk of metal poisoning. This study used a digital model of the Puget Sound area, called LiveOcean, to look at how lead and copper behave when added to the waters of Puget Sound. This was done to determine what factors influence how metals behave while in the water and to locate areas where these metals accumulate in Puget Sound. Based on their natural sinking behaviors, copper was modeled not to sink and lead was modeled to sink very quickly. These metals were released within the model from three locations where pollution is released by humans: the Puget Sound Naval Shipyard, the West Point Wastewater Treatment Plant, and the Puyallup River. Through modeling, we found that Puget Sound is a trap for trace metals because both copper and lead reached the bottom in high proportions. The fate of particles is highly dependent on their sinking behavior, the location from which they are released, and the season. With a more informed understanding of the behavior of trace metals in Puget Sound, we can put in place strategies to clean up human-caused pollution and minimize future health risks for the environment and the local human population.

Abstract

Trace metal pollution is a global concern and a threat to the local communities it affects. The human activity in the Puget Sound area of Washington state is a large source of these pollutants, with ambient pollution, wastewater treatment plants, shipyard waste, and rivers all flowing into the estuary. This area is home to many important organisms essential for subsistence and commercial fisheries, as well as keystone species vital for local ecosystem functioning. Trace metal pollution puts these organisms and the humans that consume them at great risk of trace metal poisoning. The LiveOcean Regional Ocean Modeling System (ROMS) was used to assess if Puget Sound acts as a trap for lead and copper, to determine what factors influence the behavior of trace metals, and to locate areas where trace metals accumulate in Puget Sound. Based on their natural behaviors, copper was modeled with no sinking rate and lead was modeled with a sinking rate of 40 m/day. Metals were released within the model from three trace metal point-source locations: the Puget Sound Naval Shipyard, the West Point Wastewater Treatment Plant, and the Puyallup River. The majority of both copper and lead reached the bottom of the water column at every release location and time. This supports the idea that Puget Sound is a sink for trace metals. Based on the differences in particle behavior between locations and months, the fate of particles is highly dependent on their sinking behavior, the location from which they are released, and the season. These findings neither support nor refute if the Main Basin is the key area of sequestration because, within the model, copper did not reach the bottom at higher rates here compared to the rest of Puget Sound. With a more informed understanding of the behavior of trace metals in Puget Sound, strategies can be implemented to mitigate anthropogenic pollution and minimize future health risks for the environment and the local human population.

Introduction

Environmental pollution is one of the largest and most daunting concerns of the 21st century (Ali and Khan 2017). Trace metal contamination is a form of environmental pollution that has effects on ecosystems that are long-lasting and far-reaching (Bernhard and Andreae 1984; Gawel et al. 2014). Trace metals are elements found in naturally low concentrations in the environment. Not all are inherently toxic, but an overabundance of them can have negative effects on the ecosystem in which they are released. Some of these elements, such as As, Cu, Zn, Cd, Cr, Pb, Hg, Se, and Ni, are commonly used in human industry and are very toxic in concentrations above their natural abundances (Duffus 2002). Without human influence, the processes that bring these elements to the Earth’s surface and into waterways occur on slow time scales (Taylor 1964). However, increased urbanization and industrialization have magnified the introduction of these elements (Vardhan et al. 2019). This allows for the accumulation of these substances in waterways and groundwater (Gu et al. 2020). Additionally, these trace metals are persistent and cumulative. Unless they are sequestered, they will continue to increase in concentration and bioaccumulate in organisms, contaminating food webs (Tchounwou et al. 2012; Ali et al. 2019).

Trace metals do not naturally degrade and require human intervention to clean-up (Masindi and Muedi 2018). Trace metal pollution can be cleaned using phytoremediation techniques, such as phytoextraction, phytovolatilization, rhizodegradation (Ali et al. 2013). These techniques use the bioaccumulating properties of plants and microorganisms to extract heavy metals from soils and water without the harmful by-products and expense of other chemical and physical remediation techniques. This is only achievable once sites of contamination are located and the extent of pollution at these sites is quantified. If released from point-sources (shipyards, wastewater treatment plants, etc), pollution can be controlled through regulation and on-site filtering techniques (Champ et al. 1999; Brandenberger et al. 2008). Point-source refers to a specific location that is a source of pollution, such as a smelter. However, historic pollutants and non-point sources continue to contribute to high trace metal concentrations in waterways (Paulson et al. 1989a; Brandenberger et al. 2008). Non-point source refers to ambient pollution contributed through runoff from urbanized areas, agriculture, and the atmosphere.

In marine organisms, exposure to trace metals is often fatal. These metals start accumulating in organisms as small as protozoans and bacteria (Fernandez-Leborans and Olalla Herrero 2000). For herbivorous and filter-feeding organisms, scavenged metals, such as Pb and Hg, pose the greatest threats, as these metals accumulate in sediments and are filtered or transferred through algae to organismal tissues (Jakimska et al. 2011). Except for select specialized organisms, trace metals within consumed organisms are incorporated into the tissues of the consumer. The risk for carnivorous animals is elevated, as they generally have higher levels of xenobiotic uptake due to their larger and more varied diets of higher trophic organisms. If exposure does not cause death, these metals bioaccumulate up the food chain (Fernandez-Leborans and Olalla Herrero 2000; Ali et al. 2019). The incorporation of these metals in tissue and bone causes cancer, decreased neurological functioning, organ failure, sterility, and death (Roemmich et al. 2002).

Humans, who both consume marine organisms and interact with marine waters and sediment, are not exempt from the dangers of trace metal accumulation and poisoning (Fleming et al. 2006). Studies of human bones from the West Coast of the United States from 1000 years ago show the mean body burden for lead is one-thousand times larger in the modern population than it was before the area was industrialized (Patterson et al. 1991). These studies speculate that all modern Americans face dysfunctions caused by Pb poisoning. This dramatic increase of lead and other trace metals in our bones over the past millennium is a result of industrialization and urbanization that have contaminated our water, air, and food sources (Paulson et al. 1989b). For humans that consume fish or any amount of marine mammal, trace metal contamination is a huge health risk with often fatal consequences (Johansen et al. 2000). If trace metal contamination is high, this can also deter consumers and fishermen from participating in the fishing industry, limiting available food, and impacting the economy.

Trace metal pollution is a global issue with immediate consequences to human and ecosystem health. In Puget Sound, scientists have published papers about trace metals since the early 1900s. The movement to quantify and qualify trace metals for the sake of public health gained traction in the 1970s, around the time the long-term effects of the Tacoma copper smelter and wastewater disposal became a public health concern (Bradford et al. 1975; Crecelius et al. 1975). Crecelius et al. (1975) looked at the historic impact of Sb, Ar, Hg, and other associated elements released from chemical plants and smelters using sediment cores. They were able to qualify the types of particles associated with contamination and discovered that atmospheric contamination from these sources was a large input of trace metals. Building off this work, Paulson et al. (1987) theorized, based on water sampling, the Puget Sound Main basin retains about 70% of the Pb added to it and about 40% of the Cu and Zn. These findings suggested that the Main Basin of Puget Sound is a sink for certain trace metals. Bradenburg et al. (2008) found that while policy implemented to reduce point-source trace metal pollution was effective, increasing urbanization and industrialization in the Puget Sound region is contributing trace metals from non-point source locations. These studies, and many more, show that inputs of trace metals into the Sound, both historic and current, are an ongoing problem. They also suggested that Puget Sound may be a sink for certain kinds of trace metals and that these metals are a risk to ecological and public health.

At the time that Puget Sound was proposed to be a sink for trace metals, modeling technology was not advanced enough to fully model the Sound and confirm or refute these hypotheses. This study proposed to test this hypothesis using a version of the Regional Ocean Modeling System (ROMS) (Haidvogel et al. 2000; Shchepetkin and McWilliams 2005). Unlike the technology used in the 1980s and 1990s, ROMS works in space, depth, and time, so particles modeled in ROMS are closer to actual particle flow than any kind of model historically used. This kind of model was used to model water and sediment quality issues in Southern California by UCLA with great success (The Coastal Center of the UCLA Institute of the Environment 2003).

The goal of this study was to use a Regional Ocean Modeling System (ROMS) to qualitatively describe the fate of lead and copper in Puget Sound. This study aimed to determine if Puget Sound acts as a trap for trace metal contaminants, if trace metals accumulate in the Main Basin, and to determine whether the behavior of the metal (scavenged vs bio-active, sinking vs remaining in the water column) is the primary determinant for the fate of the metal. I predicted that the majority of Pb released within the model would sink and remain in the Puget Sound and the majority of Cu released within the model would remain in the water column and eventually be flushed out of Puget Sound. Trace metals released into the modeled Puget Sound that do not reach the bottom were predicted to be flushed out into the Strait of Juan de Fuca. By investigating these questions, this study intended to locate areas where trace metals accumulate in Puget Sound and determine what factors influence the behavior of trace metals.

Methods

Data Collection

ROMS Modelling

The version of ROMS that was used for this experiment was the LiveOcean, version designation cas6_v3_lo8b. This model is run by Dr. Parker MacCready of the School of Oceanography at the University of Washington, Seattle. ROMS works in space, depth, and time simultaneously and accounts for factors such as tides, currents, and chemical properties of the modeled waterways. It does this using Reynolds averages, Boussuneq, incompressible equations of motion, and tracer concentration on a rotating, spherical grid (MacCready et al. 2021). The model assumes sediment is stationary, as on the timescales this project is working with, sediment is functionally fixed (Lavelle et al. 1986). It has been built off 15 years of region-specific research and is regularly tested against observational studies. For this study, information about the particles' sinking behavior, release conditions, and timing was given

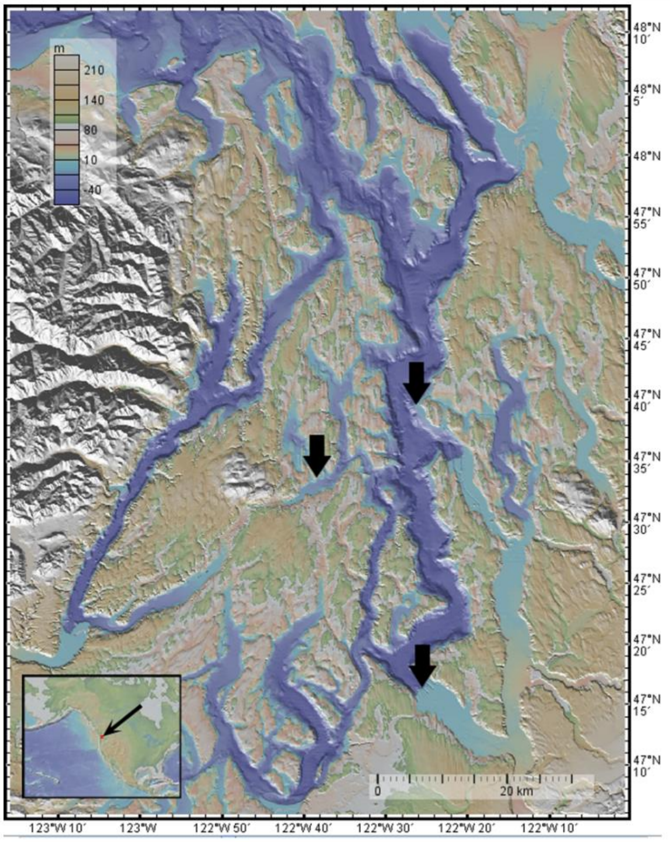

Figure 1. This map spans Puget Sound, from Olympia to the Admiralty Inlet. Different shades transitioning from brown to dark blue signify elevation. Black arrows show the locations where particles were released within the LiveOcean model. These locations are the West Point Wastewater Treatment Plant, the Puget Sound Naval Shipyard, and the Puyallup River, in order from most northernly to most southernly. Map made with GeoMapApp.

to Dr. MacCready, who ran the information provided through the model and provided data to then be analyzed. A total of 12 months were run separately with the conditions for each of these months following conditions for each month of 2018. This year was chosen because this is the most recent year to be fully tested against observational data. Months were then chosen for post-processing and analysis by looking at release location-specific weather conditions (e.g. rainfall) and hydrologic data from 2018.

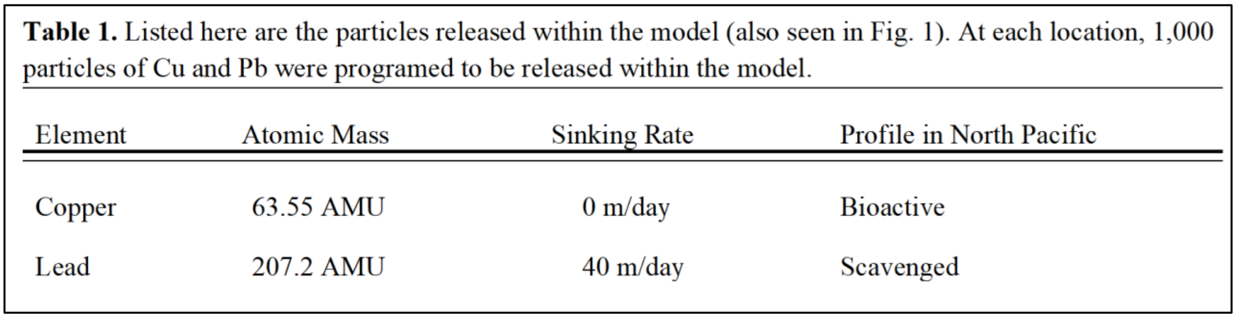

Table 1. Listed here are the particles released within the model (also seen in Fig. 1). At each location, 1,000 particles of Cu and Pb were programed to be released within the model.

Element	Atomic Mass	Sinking Rate	Profile in North Pacific
Copper	63.55 AMU	0 m/day	Bioactive
Lead	207.2 AMU	40 m/day	Scavenged

Particle Types and Release Information

Two types of particles were programmed into the model, one type to model lead and one type to model copper (Table 1). Lead is a heavy metal with an atomic mass of 207.2 AMU and a scavenged profile in the Northeastern Pacific (Paulson et al. 1988; Nozaki 1997). It is found at higher concentrations at the surface of the water column and decreases in concentration as a function of depth. This metal sticks to particles, follows their sinking patterns, and is sequestered in sediment. Copper has an atomic mass of 63.55 AMU and follows a bioactive profile in the Northeastern Pacific (Nozaki 1997). In small concentrations, it is an essential nutrient for most organisms, including humans. In oxic environments, it is found in smaller quantities at the surface of the water column and increases in concentration with depth. These metals were chosen because of their relative endmember behaviors, toxicity to humans and the environment, and abundance in anthropogenic waste. Copper particles were modeled without sinking behavior. Lead particles were modeled with sinking at a rate of 40 meters per day.

Table 2. Listed here are the locations where particles were released within the model (also seen in Fig. 1). At each location, 1,000 particles of Cu and Pb were programed to release at the depth and lat-longs shown below. Locations were chosen because of their high point-source contribution to trace metal pollution in Puget Sound.

Point-Source	Lat-Long	Depth	Largest Near-by City
Puget Sound Naval Shipyard	47.55, -122.64	12 m	Bremerton
Puyallup River	47.27, -122.43	31 m	Tacoma
West Point Wastewater Treatment Plant	47.667, -122.44	73 m	Seattle

These particles were released within the model from three locations: the affluent of the West Point Wastewater Treatment Plant, north of downtown Seattle, at 73 m deep, the Puget Sound Naval Shipyard in Bremerton at 12.6 km deep, and the Puyallup River mouth near Tacoma at 31.8 km deep (Table 2, Fig. 1). These three sites were chosen because all of them are point-sources for trace metal pollution in Puget Sound (Roemmich et al. 2002; Hope et al. 2012; Hines and Landis 2014; Seattle Public Utilities 2019). Depth was chosen to imitate the depth anthropogenically source trace metals would be released at each location (Roemmich et al. 2002; Hines and Landis 2014; Seattle Public Utilities 2019). For each modeled period and location, l,000 particles of each type were released. Other studies looking at Puget Sound have found that the release location of trace metals has less of a bearing on their destination than the physical characteristics of the metals (Crecelius et al. 1975; Bloom and Crecelius 1987). The size, mass, and chemical properties of the trace metal are thought to be the determining factors for the fate of trace metals in Puget Sound.

Data Analysis

Post-processing

Months were then chosen for post-processing and analysis by looking at release location-specific weather conditions and hydrologic data from 2018. For every location, the month of January was modeled to compare the behavior of particles released from each location within the same month. The West Point Wastewater Treatment Plant also had modeled releases for April and August, chosen because these were the months in Seattle of highest and lowest precipitation in 2018, respectively (https://water.weather.gov/precip/, *accessed 1/28/2021*). The Puget Sound Naval Shipyard had modeled releases for January and July, as these were the months of highest and lowest precipitation in Bremerton in 2018, respectively (https://water.weather.gov/precip/, *accessed 1/28/2021*). The Puyallup River had modeled releases for February and December because these were the months where river discharge was the highest and lowest, respectively (https://tinyurl.com/3vk7ayw5, *accessed 1/29/2021*).

Trace metal particle sticking and sequestration in sediment was incorporated in post-processing using Python in JupyterLab. Particle depth was determined using relative depth, where the sea surface is 0 and the bottom of the water column is -1. The coordinates of the first instance where particles reached a relative depth of -0.99 or less were taken as their final location. For particles that never reached a relative depth of -0.99 or less, the final coordinate points after 30 days were used as their final location (Dr. Parker MacCready, *personal communication, 10/4/2020*).

Analysis

Using the post-processed data, a series of calculations were performed to quantify the behavior of the modeled particles. The percentage of copper and lead that remained in the water column was determined by dividing the number of each particle that never reached less than -0.99 relative depth by the total number of each particle. As-the-crow-flies distance traveled was calculated using the cosine-Haversine formula (Robusto 1957) using the initial and final coordinates of each particle. As-the-crow-flies distance was used, rather than the total distance traveled in 30 days, because of time constraints that limited the creation of a more robust method for calculating distance. The relative final depth and as-the-crow-flies distance were then graphed separately for each particle using the matplotlib package. Maps were created for the final locations for each release location and month using the cartopy package.

Results

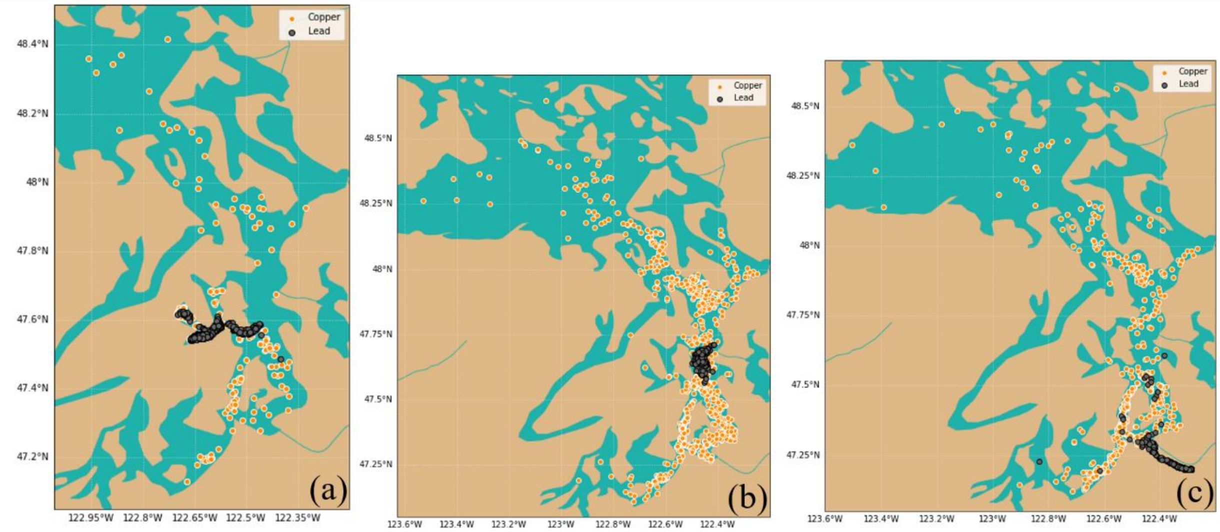

Figure 2. Theses maps show the location of copper and lead particles one month after release into the LiveOcean model. The release location for (a) was the Puget Sound Naval Shipyard in Bremerton, WA. The release point for (b) was the West Point Wastewater treatment plant underwater effluent. The release point for (c) was the mouth of the Puyallup River. The three maps used all depict the Puget Sound Area in Washington State. Land is depicted in brown; water is depicted in turquoise. Copper is shown in orange with a white border and lead is shown in grey with a black border. One-thousand particles of each element type were released at the same time and depth in the model and allowed to run for 30 days.

Comparison between Locations in January

Copper was found to have reached the relative bottom at different ratios from each release location within the same modeled month. When released from the Puget Sound Naval Shipyard, 2.8% of particles remained in the water column after 30 days. The average as-the-crow-flies distance traveled by a non-sinking particle was 7.2 km (Fig. 2; Fig. 3) with a standard deviation of 12.0 km and the average relative depth of particles after 30 days was -0.98 with a standard deviation of 0.10. When released from the West Point Wastewater Treatment Plant, 25.7% of particles remained in the water column after 30 days. The average as-the-crow-flies distance traveled by a copper particle was 29.7 km (Fig. 2) with a standard deviation of 19.6 km and the average relative depth of particles after 30 days was -0.82 with a standard deviation of 0.32. When

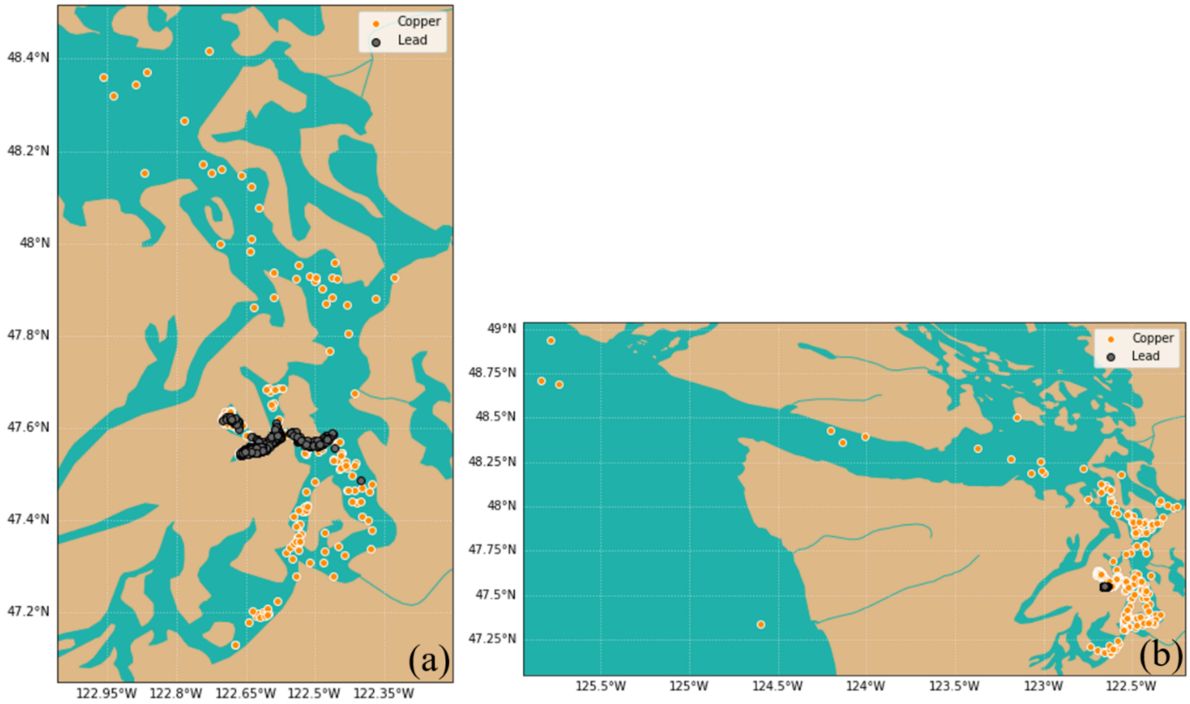

Figure 3. These maps show the location of copper and lead particles one month after release into the LiveOcean model. The release location for both graphs was the Puget Sound Naval Shipyard in Bremerton, Washington. Both maps depict the Puget Sound Area in Washington State. Land is depicted in brown; water is depicted in turquoise. Copper is shown in orange with a white border and lead is shown in grey with a black border. One-thousand particles of each element type were released at the same time and depth in the model and allowed to run for 30 days. (a) shows particles run in January 2018 and (b) shows particles run in July 2018.

released from the mouth of the Puyallup River, 11.6% of particles remained in the water column after 30 days. The average as-the-crow-flies distance traveled by a copper was 23.4 km (Fig. 2) with a standard deviation of 29.0 km and the average relative depth of particles after 30 days was -0.92 with a standard deviation of 0.23.

Lead was found to have reached the relative bottom at relatively similar ratios from each release location within the same modeled month. When released from the Puget Sound Naval Shipyard, 0% of particles remained in the water column after 30 days. The average as-the-crow-flies distance traveled by a lead particle was 3.6 km (Fig. 2; Fig. 3) with a standard deviation of 3.2 km and the average relative depth of particles after 30 days was -0.99 with a standard deviation of 0.003. When released from the West Point Wastewater Treatment Plant, 0% of particles remained in the water column after 30 days. The average as-the-crow-flies distance traveled by a lead particle was 2.0 km (Fig. 2) with a standard deviation of 1.2 km and the average relative depth of particles after 30 days was -1.00 with a standard deviation of 0.003. When released from the mouth of the Puyallup River, 1% of particles remained in the water column after 30 days. The average as-the-crow-flies distance traveled by a lead was 6.2 km (Fig. 2) with a standard deviation of 5.3 km and the average relative depth of particles after 30 days was -0.99 with a standard deviation of 0.01.

High and Low Hydrograph and Precipitation Months

For the Puget Sound Naval Shipyard, the month of highest precipitation in 2018 was January and is reported above. The month of lowest precipitation in 2018 was July. When released from the Naval shipyard in July, 8.2% of copper remained in the water column and 0% of lead remained in the water column after 30 days. Copper traveled as-the-crow flies an average of 12.5 km (Fig. 3) with a standard deviation of 21.3 km and lead traveled 1.0 km (Fig. 3) with a standard deviation of 0.3 km. The average relative depth after 30 days of copper was -0.94 with a standard deviation of 0.20 and the average relative depth after 30 days of lead was -0.99 with a standard deviation of 0.003.

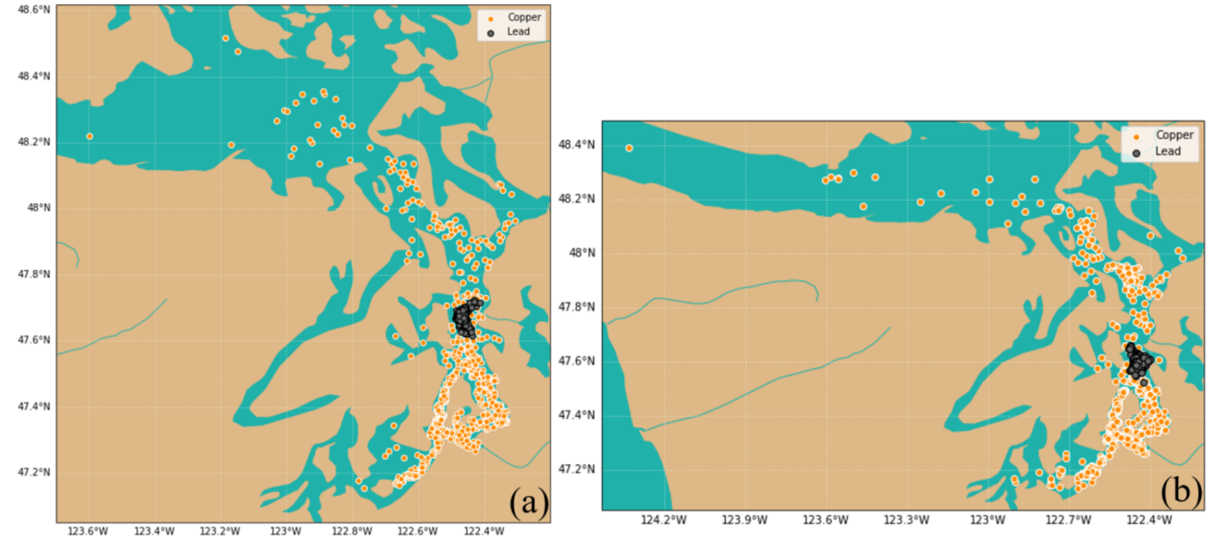

Figure 4. These maps show the location of copper and lead particles one month after release into the LiveOcean model. The release location for both graphs was the West Point Wastewater Treatment Plant in Seattle, Washington. Both maps depict the Puget Sound Area in Washington State. Land is depicted in brown; water is depicted in turquoise. Copper is shown in orange with a white border and lead is shown in grey with a black border. One-thousand particles of each element type were released at the same time and depth in the model and allowed to run for 30 days. (a) shows particles run in April 2018 and (b) shows particles run in August 2018.

For the West Point Wastewater Treatment Plant, the month of highest precipitation in 2018 was April. When released from the treatment plant in April, 32.1% of copper remained in the water column and 0% of lead remained in the water column after 30 days. Copper traveled as-the-crow flies an average of 30.5 km (Fig. 4) with a standard deviation of 15.8 km and lead traveled 1.8 km (Fig. 4) with a standard deviation of 1.1 km. The average relative depth after 30 days of copper was -0.80 with a standard deviation of 0.31 and the average relative depth after 30 days of lead was -1.00 with a standard deviation of 0.003. The month of lowest precipitation in 2018 was August. When released in August, 28.3% of copper remained in the water column and 0% of lead remained in the water column after 30 days. Copper traveled as-the-crow flies an average of 33.5

km (Fig. 4) with a standard deviation of 15.8 km and lead traveled 6.3 km (Fig. 4) with a standard deviation of 2.3 km. The average relative depth after 30 days of copper was -0.80 with a standard deviation of 0.33 and the average relative depth after 30 days of lead was -1.00 with a standard deviation of 0.003.

For the Puyallup River, the month of highest river discharge in 2018 was February. When released from the mouth of the Puyallup in February, 13.7% of copper remained in the water column and 1% of lead remained in the water column after 30 days. Copper traveled as-the-crow flies an average of 15.6 km (Fig. 5) with a standard deviation of 19.5 km and lead traveled 2.8 km (Fig. 5) with a standard deviation of 3.7 km. The average relative depth after 30 days of copper was -0.90 with a standard deviation of 0.25 and the average relative depth after 30 days of lead was -0.99 with a standard deviation of 0.018. The month of lowest river discharge in 2018 was

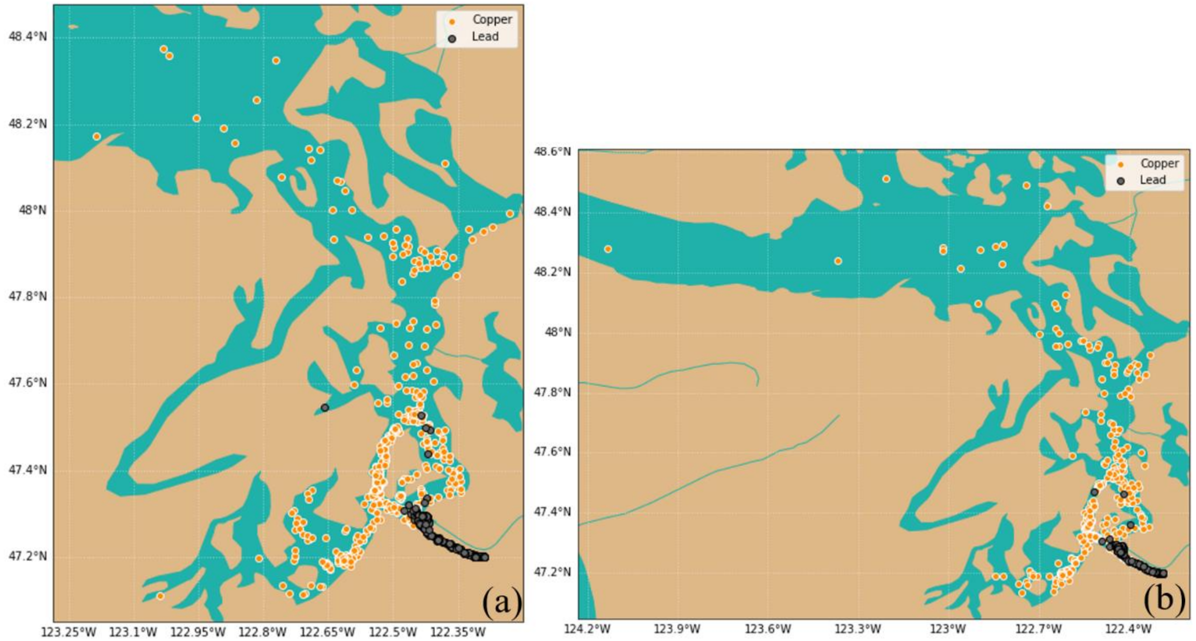

Figure 5. These maps show the location of copper and lead particles one month after release into the LiveOcean model. The release location for both graphs was the mouth of the Puyallup River in Seattle, Washington. Both maps depict the Puget Sound Area in Washington State. Land is depicted in brown; water is depicted in turquoise. Copper is shown in orange with a white border and lead is shown in grey with a black border. One-thousand particles of each element type were released at the same time and depth in the model and allowed to run for 30 days. (a) shows particles run in February 2018 and (b) shows particles run in October 2018.

October. When released in October, 10.8% of copper remained in the water column and 1% of lead remained in the water column after 30 days. Copper traveled as-the-crow flies an average of 11.6 km (Fig. 5) with a standard deviation of 20.6 km and lead traveled 2.3 km (Fig. 5) with a standard deviation of 3.8 km. The average relative depth after 30 days of copper was -0.92 with a standard deviation of 0.23 and the average relative depth after 30 days of lead was -0.99 with a standard deviation of 0.035.

Copper versus Lead Overall

Overall, copper particles traveled longer distances than lead particles. The average distance traveled, using every modeled copper particle, was 20.5 km (Fig. 6) with a standard deviation of 21.9 km. The furthest as-the crow flies distance traveled by a copper particle was 279.4 km and the shortest distance traveled was 55 m. The average distance traveled, using every modeled lead particle, was 3.2 km (Fig. 6) with a standard deviation of 3.6 km. The furthest as-the crow flies distance traveled by a lead particle was 37.6 km and the shortest distance traveled was 27 m.

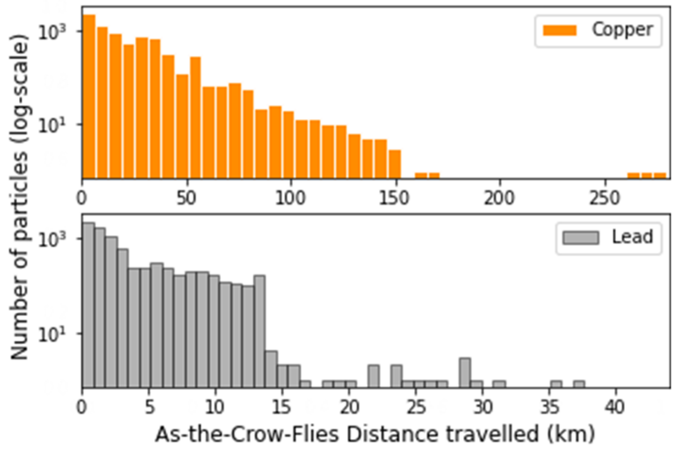

Figure 6. Histogram showing "as-the-crow-flies" distance traveled by each particle during the 30-day release period. Copper is shown in orange, lead is shown in grey. The x-axis shows distance in kilometers, and the y-axis shows the number of particles that traveled that distance, logarithmically scaled. This figure used all uses all 80,000 particles from all time periods and release locations used in this study.

Copper particles, on average, were found at shallower relative depths than lead after 30 days. The average relative depth using every modeled copper particle was -0.89 with a standard deviation of 0.26 (Fig. 7). The shallowest final relative depth was -0.0002 and the deepest was -1.00. The average relative depth using every modeled lead particle was -0.99 (Fig. 7) with a standard deviation of 0.014. The shallowest final relative depth was -0.24 and the deepest was -1.00.

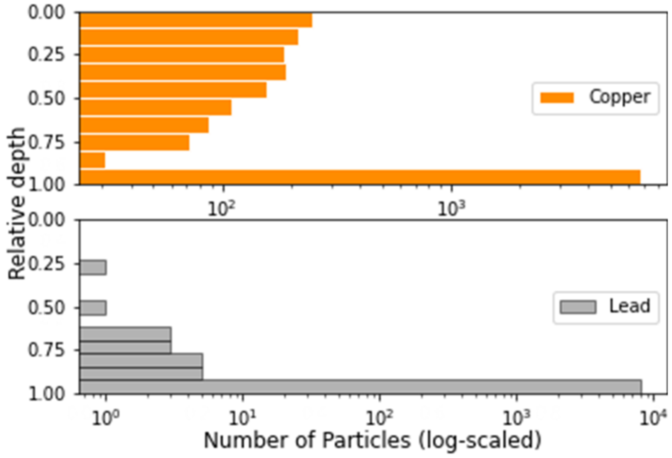

Figure 7. Histogram showing the distribution of copper and lead across the water column after the 30-day release period. Copper is shown in orange, lead is shown in grey. The y-axis is relative depth, calculated by finding the ratio of particle depth divided by the total depth of the water column. The x-axis is the number of particles found at that depth, on a logarithmic scale. This figure used all 80,000 particles from all time periods and release locations used in this study.

Discussion

Factors Influencing Behavioral Differences

Stratification is more distinct in the summer than in the winter in Puget Sound, and non-sinking particles are more affected by stratification than sinking particles (Uurasjärvi et al. 2021). It is possible the currents in the winter around Bremerton allowed lead to be more mobile after sinking, while stratification in the summer allowed copper particles to travel further as they became trapped in different stratified layers of the water column (Fig. 3). Release depth, which varied between locations (Table 2), was not directly related to distance traveled or ratio remaining within the water column for either particle type (Fig. 6; Fig 7). Other studies have shown that, in winter (including January), Puget Sound is less stratified than in the summer months (Moore et al. 2008).

However, the Puyallup River has been known to remain stratified for 70% of months, in comparison to the Main Basin, which is stratified for 25 – 50% of months. If stratification is occurring, the behavior of non-sinking particles is affected more than the sinking particle behavior, as non-sinking particles are known to get trapped in stratified layers (Uurasjärvi et al. 2021).

Studies have also shown that vertical advection peaks in the Main Basin in the late summer and is at its lowest in early winter (Babson et al. 2006). Horizontal advection (deep and shallow) in the Main Basin follows a similar trend. Near the Puyallup River, horizontal and vertical advection dip in early winter, but are fairly constant every other time of year (Babson et al. 2006). The differences in these trends tied with the differences in the effect of stratification between particle types support the idea that release location, sinking behavior, and season all affect at what ratio particles are sequestered and how far they travel if they are not.

Puget Sound: Trace Metal Trap?

Lead tended to pool within 3 km of where it was released, while copper generally pooled within 20 km of where it was released (Fig. 6). This is likely due to the difference in sinking behaviors, which have lead immediately sinking to the floor of the estuary while copper, without sinking, is more likely to be caught in a current or stratified layer and taken further from its release location (Fig. 5; Fig. 6). Other studies have found that the Puget Sound Main Basin is a sink for both lead and copper, and that lead is sequestered in the basin at higher rates than copper (Paulson et al. 1987). The findings from this study support that lead is sequestered at a higher rate but cannot conclusively report if the Main Basin is a sink for copper (Fig 4). Copper was more mobile than at other locations when released into the Main Basin and was the least mobile when released off the coast of Bremerton (Fig. 2). However, over 70% of copper reached the bottom of the water column within 30 days at every location and 100% of lead reached the bottom in every location but the Puyallup River (Fig. 7). These rates are higher than has been found in previous studies (Paulson et al. 1987, 1989b). This supports the theory that Puget Sound is a trap for trace metals but cannot conclusively support if the Main Basin is a sink for copper.

Implications and Broader Impacts

This study aimed to assess if Puget Sound acts as a trap for trace metal contaminants, to determine what factors influence the behavior of trace metals, and to locate areas where trace metals accumulate in Puget Sound. Based on the analysis conducted by this study, Puget Sound is a trap for trace metals. Our findings cannot support or refute if the Main Basin is the key area of sequestration. However, based on the differences in particle behavior between locations and months, the fate of particles is highly dependent on their sinking behavior, the location from which they are released, and the season. Copper is most likely to pool further from its release location, while lead is more likely to pool near where it has been released. However, there were limitations to this study that add uncertainty to these conclusions. Copper was modeled to not sink at all, while lead was modeled with a very high sinking rate. This does not fully reflect their chemical and physical behavior. Additionally, the LiveOcean model was not run with a biological component, and scavenging was incorporated in the post-processing of the data, so the behavior of the modeled particles does not fully reflect their natural behavior. Distance was calculated as-the-crow-flies, ignoring any movement that would lead to a particle returning to a location and ignoring vertical movement. This could give underestimates of many particle distances traveled.

Trace metals, if sequestered, remain in the sediment unless removed by human intervention (Masindi and Muedi 2018). Copper, as an essential nutrient, can be removed by organisms from the water column but is less likely to be removed once it reaches the sediment (Chow and Thompson 1952; Paulson et al. 1993; Arnold et al. 2005). If sequestered in sediment, these trace metals can be harmless, but activities like trawling and natural bioturbation can cause these metals to be reintroduced to the water column (Bloom and Crecelius 1987). Depending on the concentration of copper within Puget Sound and the chemistry of the water, copper can be essential or very harmful to the environment. Additionally, high levels of trace metals in sediments can be harmful to benthic organisms, such as shellfish (Bernhard and Andreae 1984; Jakimska et al. 2011). Urbanization and industrialization are increasing in the Puget Sound region (Brandenberger et al. 2008), and these are known to increase the rates of trace metal flux into waterways (Vardhan et al. 2019; Gu et al. 2020). If Puget Sound is a trap for trace metals, a higher flux of metals to the basins of this region could have a profound impact on the sediment and water chemistries within the region.

Future Improvements and Studies

Future studies could look further into how particle behavior can be more realistically modeled. This could be done by incorporating chemical and biological components to the mode and adding a variety of more realistic sinking behaviors depending on the chemical and physical conditions of the surrounding waters. These studies could also look more closely at how point-source and non-point source releases differ, focus more closely on areas where metals are accumulating, and calculate horizontal and vertical movement more precisely.

Conclusion

Trace metal pollution is a global issue with immediate consequences to human and ecosystem health. Within Puget Sound, trace metal contamination is an issue that becomes an increasing concern with the expansion of urbanization in the region. This study has concluded that Puget Sound is a sink from trace metals. This raises further questions about how to quantify the current levels of trace metal pollution and how to implement remediation techniques. Further studies are needed to verify these conclusions and to investigate the extent that this pollution may be affecting the chemistry and biology of the region. These studies could also use the methods of this paper to investigate other harmful trace metals, such as cadmium and mercury, and other pollutants such as microplastics and chemical pollutants. With a more informed understanding of the behavior of these pollutants in Puget Sound, we can implement strategies to mitigate anthropogenic pollution and minimize future health risks for the environment and the local human population.

Acknowledgments

First and foremost, I would like to thank my parents for helping me get my education at UW. I would also like to thank my advisor, Dr. Rick Keil, for helping me create this project and supporting me every step of the way. I would like to thank Dr. Parker MacCready for helping me use his model and teaching me how to use and interpret the data he provided. I would also like to thank Derya Gumustel for the use of her cartopy code that aided me in making my maps. Lastly, I would like to thank my quarantine buddies, Leland Wood and Kennedy Cameron, for keeping me sane enough during quarantine to complete this project.

References:

Ali, H., and E. Khan. 2017. Environmental chemistry in the twenty-first century. Environ. Chem. Lett. **15**: 329–346. doi:10.1007/s10311-016-0601-3

Ali, H., E. Khan, and I. Ilahi. 2019. Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. J. Chem. **2019**. doi:10.1155/2019/6730305

Ali, H., E. Khan, and M. A. Sajad. 2013. Phytoremediation of heavy metals-Concepts and applications. Chemosphere **91**: 869–881. doi:10.1016/j.chemosphere.2013.01.075

Arnold, W. R., R. C. Santore, and J. S. Cotsifas. 2005. Predicting copper toxicity in estuarine and marine waters using the Biotic Ligand Model. Mar. Pollut. Bull. **50**: 1634–1640. doi:10.1016/j.marpolbul.2005.06.035

Babson, A. L., M. Kawase, and P. MacCready. 2006. Seasonal and interannual variability in the circulation of Puget Sound, Washington: A box model study. Atmos. - Ocean **44**: 29–45. doi:10.3137/ao.440103

Bernhard, M., and M. O. Andreae. 1984. Transport of trace metals in marine food chains, p. 143–167. *In* Changing Metal Cycles and Human Health. Springer Berlin Heidelberg.

Bloom, N. S., and E. A. Crecelius. 1987. Distribution of silver, mercury, lead, copper and cadmium in central Puget Sound sediments. Mar. Chem. **21**: 377–390. doi:10.1016/0304-4203(87)90057-0

Bradford, G. R., A. L. Page, L. J. Lund, and W. Olmstead. 1975. Trace Element Concentrations of Sewage Treatment Plant Effluents and Sludges; Their Interactions with Soils and Uptake by Plants. J. Environ. Qual. **4**: 123–127. doi:10.2134/jeq1975.00472425000400010029x

Brandenberger, J. M., E. A. Crecelius, and P. Louchouarn. 2008. Historical inputs and natural recovery rates for heavy metals and organic biomarkers in Puget Sound during the 20th century. Environ. Sci. Technol. **42**: 6786–6790. doi:10.1021/es703099c

Champ, M. A., T. J. Fox, and A. J. Mearns. 1999. Treatment of Regulated Discharges from Shipyards and Drydocks. Proc. Ocean. 99 - Vol. 4.

Chow, T. J., and T. Thompson. 1952. The determination and distribution of copper in sea water: Part I - The spectrophotometric determination of copper in sea water.

Crecelius, E. A., M. H. Bothner, and R. Carpenter. 1975. Geochemistries of Arsenic, Antimony, Mercury, and Related Elements in Sediments of Puget Sound. Environ. Sci. Technol. **9**: 325–333. doi:10.1021/es60102a007

Duffus, J. H. 2002. “heavy metals” - A meaningless term? (IUPAC technical report). Pure Appl. Chem. **74**: 793–807. doi:10.1351/pac200274050793

Fernandez-Leborans, G., and Y. Olalla Herrero. 2000. Toxicity and bioaccumulation of lead and cadmium in marine protozoan communities. Ecotoxicol. Environ. Saf. **47**: 266–276. doi:10.1006/eesa.2000.1944

Fleming, L. E., K. Broad, A. Clement, and others. 2006. Oceans and human health: Emerging public health risks in the marine environment. Mar. Pollut. Bull. **53**: 545–560. doi:10.1016/j.marpolbul.2006.08.012

Gawel, J. E., J. A. Asplund, S. Burdick, M. Miller, S. M. Peterson, A. Tollefson, and K. Ziegler. 2014. Arsenic and lead distribution and mobility in lake sediments in the south-central Puget Sound watershed: The long-term impact of a metal smelter in Ruston, Washington, USA. Sci. Total Environ. **472**: 530–537. doi:10.1016/j.scitotenv.2013.11.004

Gu, C., Y. Zhang, Y. Peng, P. Leng, N. Zhu, Y. Qiao, Z. Li, and F. Li. 2020. Spatial Distribution and Health Risk Assessment of Dissolved Trace Elements in Groundwater in southern China.

Sci. Rep. **10**: 1–11. doi:10.1038/s41598-020-64267-y

Haidvogel, D. B., H. G. Arango, K. Hedstrom, A. Beckmann, P. Malanotte-Rizzoli, and A. F. Shchepetkin. 2000. Model evaluation experiments in the North Atlantic Basin: simulations in nonlinear terrain-following coordinates.

Hines, E. E., and W. G. Landis. 2014. Regional risk assessment of the Puyallup River Watershed and the evaluation of low impact development in meeting management goals. Integr. Environ. Assess. Manag. **10**: 269–278. doi:10.1002/ieam.1509

Hope, B. K., L. Pillsbury, and B. Boling. 2012. A state-wide survey in Oregon (USA) of trace metals and organic chemicals in municipal effluent. Sci. Total Environ. **417**–**418**: 263–272. doi:10.1016/j.scitotenv.2011.12.028

Jakimska, A., P. Konieczka, K. Skóra, and J. Namieśnik. 2011. Bioaccumulation of metals in tissues of marine animals, part II: Metal concentrations in animal tissues. Polish J. Environ. Stud. **20**: 1127–1146.

Johansen, P., T. Pars, and P. Bjerregaard. 2000. Lead, cadmium, mercury and selenium intake by Greenlanders from local marine food. Sci. Total Environ. **245**: 187–194. doi:10.1016/S0048-9697(99)00443-X

Lavelle, J. W., G. J. Massoth, and E. A. Crecelius. 1986. Accumulation rates of recent sediments in Puget Sound, Washington. Mar. Geol. **72**: 59–70. doi:10.1016/0025-3227(86)90099-X

MacCready, P., R. M. McCabe, S. A. Siedlecki, and others. 2021. Estuarine Circulation, Mixing, and Residence Times in the Salish Sea. J. Geophys. Res. Ocean. **126**. doi:10.1029/2020jc016738

Masindi, V., and K. L. Muedi. 2018. Environmental Contamination by Heavy Metals, *In* Heavy Metals. InTech.

Moore, S. K., N. J. Mantua, J. A. Newton, M. Kawase, M. J. Warner, and J. P. Kellogg. 2008. A descriptive analysis of temporal and spatial patterns of variability in Puget Sound oceanographic properties. Estuar. Coast. Shelf Sci. **80**: 545–554. doi:10.1016/j.ecss.2008.09.016

Nozaki, Y. 1997. A fresh look at element distribution in the North Pacific Ocean. Eos (Washington. DC). **78**: 221. doi:10.1029/97eo00148

Patterson, C., J. Ericson, M. Manea-Krichten, and H. Shirahata. 1991. Natural skeletal levels of lead in Homo sapiens sapiens uncontaminated by technological lead. Sci. Total Environ. **107**: 205–236. doi:10.1016/0048-9697(91)90260-L

Paulson, A. J., E. D. Cokelet, R. A. Feely, R. J. Stewart, and H. C. Curl. 1993. Modeling the Decrease in Dissolved Copper in Puget Sound during the Early 1980s. Environ. Sci. Technol. **27**: 2685–2691. doi:10.1021/es00049a006

Paulson, A. J., H. C. Curl, and R. A. Feely. 1989a. Estimates of trace metal inputs from non-point sources discharged into estuaries. Mar. Pollut. Bull. **20**: 549–555. doi:10.1016/0025-326X(89)90355-X

Paulson, A. J., R. A. Feely, H. C. Curl, E. A. Crecelius, and T. Geiselman. 1988. The impact of scavenging on trace metal budgets in Puget Sound. Geochim. Cosmochim. Acta **52**: 1765–1779. doi:10.1016/0016-7037(88)90002-6

Paulson, A. J., R. A. Feely, H. C. Curl, E. A. Crecelius, and G. P. Romberg. 1987. Sources and sinks of Pb, Cu, Zn, and Mn in the main basin of Puget Sound.

Paulson, A. J., R. A. Feely, H. C. Curl, and D. A. Tennant. 1989b. Estuarine transport of trace metals in a buoyant riverine plume. Estuar. Coast. Shelf Sci. **28**: 231–248. doi:10.1016/0272-7714(89)90015-2

Robusto, C. C. 1957. The Cosine-Haversine Formula. Am. Math. Mon. **64**: 38–40.

Roemmich, D. H., R. E. Davis, and S. C. Riser. 2002. A Partnership for Modeling the Marine Environment of Puget Sound, Washington - Puget Sound Naval Shipyard Report.

Seattle Public Utilities. 2019. Wastewater Collection System: 2019 Annual Report.

Shchepetkin, A. F., and J. C. McWilliams. 2005. The regional oceanic modeling system (ROMS): A split-explicit, free-surface, topography-following-coordinate oceanic model. Ocean Model. **9**: 347–404. doi:10.1016/j.ocemod.2004.08.002

Taylor, S. R. 1964. Abundance of chemical elements in the continental crust: a new table. Geochim. Cosmochim. Acta **28**: 1273–1285. doi:10.1016/0016-7037(64)90129-2

Tchounwou, P. B., C. G. Yedjou, A. K. Patlolla, and D. J. Sutton. 2012. Heavy metal toxicity and the environment. EXS **101**: 133–164. doi:10.1007/978-3-7643-8340-4_6

The Coastal Center of the UCLA Institute of the Environment. 2003. Application of the Regional Ocean Modeling System (ROMS) to Water and Sediment Quality Issues in the Southern California Bight. Program.

Uurasjärvi, E., M. Pääkkönen, O. Setälä, A. Koistinen, and M. Lehtiniemi. 2021. Microplastics accumulate to thin layers in the stratified Baltic Sea. Environ. Pollut. **268**. doi:10.1016/j.envpol.2020.115700

Vardhan, K. H., P. S. Kumar, and R. C. Panda. 2019. A review on heavy metal pollution, toxicity and remedial measures: Current trends and future perspectives. J. Mol. Liq. **290**: 111197. doi:10.1016/j.molliq.2019.111197