PNNL-39596

Mixing Zone Dilution Study for the Pacific Northwest National Laboratory Sequim Campus

April 2026

LT Premathilake
TP Khangaonkar

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99354

Acronyms and Abbreviations

CFR – Code of Federal Regulations
DOE – U.S. Department of Energy
EA – Environmental Assessment
EPA – U.S. Environmental Protection Agency
GUI – Graphical User Interface
gpm – Gallons per minute
MLLW – Mean Lower Low Water
NOAA – National Oceanic and Atmospheric Administration
NPDES – National Pollutant Discharge Elimination System
PNNL – Pacific Northwest National Laboratory
PSU – Practical Salinity Unit
SSCOFS – Salish Sea and Columbia River Operational Forecasting System
UM3 – Unified Mixing Model
WAC – Washington Administrative Code

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1.0 Introduction

The Pacific Northwest National Laboratory (PNNL) Sequim Campus, in Sequim, Washington, houses the only marine research facilities in the Department of Energy complex. The campus is uniquely positioned for marine-based research that is focused on helping the nation achieve sustainable energy, a sustaining environment, and coastal security. Nearly 15,000 square feet of research laboratories are connected to Sequim Bay, with a supply system that delivers 200 gallons of seawater per minute and returns it to Sequim Bay after treatment.

PNNL uses seawater and fresh water in research processes resulting in wastewater that is routed to the onsite treatment plant, where it is treated before being discharged to Sequim Bay. The wastewater treatment plant consists of ground cell settling chambers, bag filters, ultraviolet light and granulated activated carbon. The average discharge of wastewater to Sequim Bay is 16,000 gallons per day and discharges occur on an intermittent or batch flow basis when the ground cells reach capacity and are pumped through the treatment train.

In 1991, the Washington State Department of Ecology (Ecology) issued PNNL a National Pollutant Discharge Elimination System (NPDES) Permit (WA0040649). In 2025, the PNNL Sequim Campus was purchased by the U.S. Department of Energy (DOE), at which time jurisdiction for the NPDES program transferred from Ecology to U.S. EPA, Region 10.

The EPA is in the process of reissuing PNNL's NPDES permit in accordance with Title 40 of the Code of Federal Regulations, Part 122. Although EPA is not authorized to establish mixing zones in NPDES permits, EPA has indicated to PNNL that the new permit will include the mixing zones (acute and chronic) previously authorized by Ecology.

To establish the mixing zone boundaries as well as the dilution factors established at the edge of the mixing zones, EPA has instructed PNNL that modeling of the mixing zones and development of dilution factors is the responsibility of PNNL.

The specific objectives of the study are summarized as follows:

- Effluent Characterization - Characterize the effluent flow, temperature, and concentration using recent discharge monitoring data.
- Ambient Characterization – Characterize the local ambient conditions to determine the critical conditions for acute and chronic dilution calculations, additional mixing zone analysis, and compliance evaluation.
- Effluent Dilution Calculations – Revisit dilution of the effluent plume at the acute and chronic mixing zones using plume models and using updated effluent and ambient data.

2.0 Mixing Zone Description and Modeling

2.1 General Study Area

The study area for the mixing zone modeling is located close to the west shoreline of the inlet to Sequim Bay, WA (Figure 1). The inlet has an approximate depth of 12 m while the deepest areas inside the bay can reach about 40 m. The tidal currents in the inlet can be strong and can exceed 2 m/s which can significantly affect the dispersion of the effluents from the nearby Outfall 008.

Table 1. Location details of the outfall 008

Outfall No.	Location of Discharge	Discharge Description	Latitude	Longitude
008	Sequim Bay	Treated wastewater from the Marine Sciences Research Lab, PNNL	48.0788	-123.0436

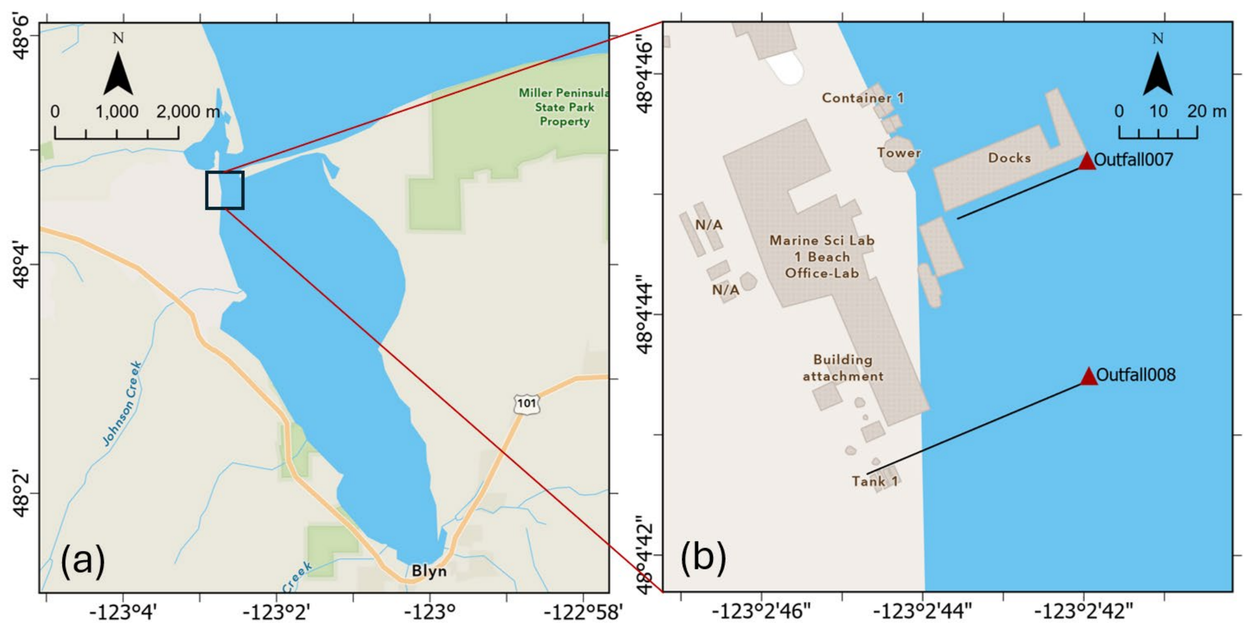

Figure 1. (a) Sequim Bay overview and outfall location (b) Zoomed-in view of the outfall location close to Marine Science Lab

2.2 Description of the Outfall and Diffuser

The outfall 008 diffuser consists of two flexible Red Valve Series 35 type ports. Each port has a variable opening area that operates based on the magnitude of the flow. Maximum opening areas of the ports are 0.0375 m^2 and 0.004 m^2. An average equivalent circular port diameter was estimated based on the maximum area of the openings. Although there are two ports installed on this outfall, the system is designed to activate only one port at a time during the operation. Diffuser configuration therefore corresponds to a single port design and is summarized in Table 2.

Table 2. A Summary of Diffuser Characteristics

Diffuser Characteristics	Parameter Value
Equivalent Port Diameter (m)	0.07
Port Vertical Angle (deg)	0.0
Port Horizontal Angle (deg)	22.0
Port Depth (m) – (from MLLW)	2.16
Port Elevation (m) – (from seabed)	1.04

2.3 Mixing Zone Description

According to the NPDES permit, the mixing zone dimensions of Outfall 008 are as follows:

1. The acute mixing zone extends 20 feet (6.1 m) from the last discharge port at both ends of the diffuser section and from the centerline of the diffuser section.

2. The chronic mixing zone extends 207 feet (63.1 m) from the outermost discharge at both ends of the diffuser section and from the centerline of the diffuser section.

Although the language is written for a multiport diffuser, since only one port is used at a time, the distances are interpreted as from end of pipe location of the single port in operation.

3.0 Effluent Characterization

3.1 Flow, Temperature and Salinity

The effluent flow from outfall 008 is intermittent and discharged as batches where each batch has an average volume of 12,000 gallons (Figure 2). Total daily volumes of the flow are monitored, and a 5-year-long data set has been compiled. Given the irregular nature of the intermittent flow from the outfall 008 (Figures 2 and 3), the critical effluent flow for the worst case scenario was selected as the maximum flow through the pump – 175 gpm, as per the guidelines provided by section 6.1.2 of Ecology (2018).

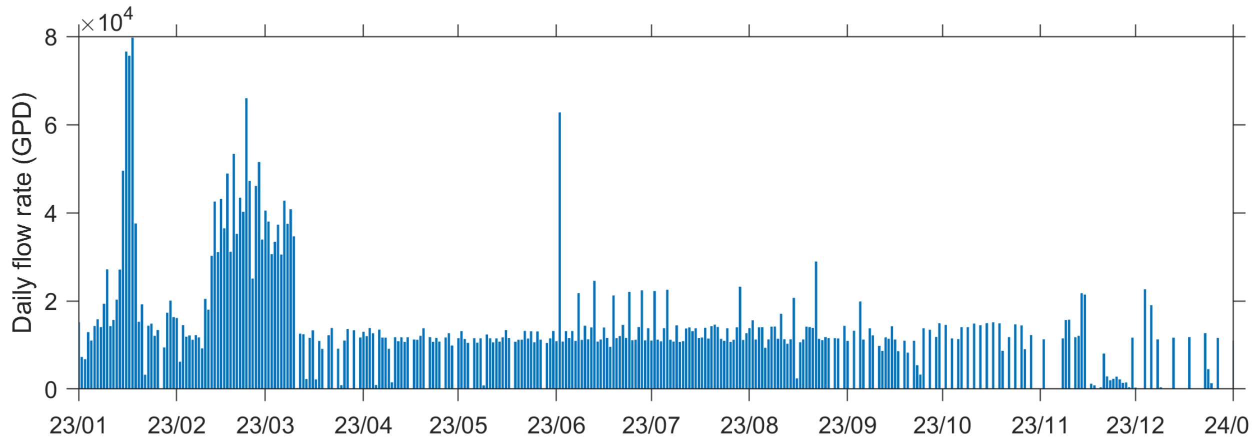

Figure 2. Measured daily effluent flows for the year 2023 which shows the intermittent nature of the discharge

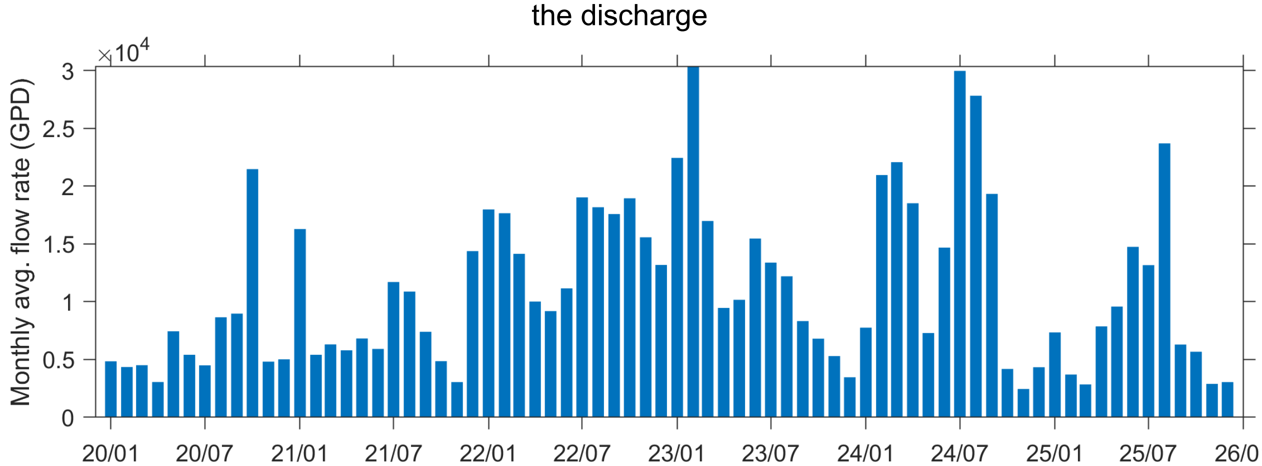

Figure 3. Monitored monthly average flow for the six years of data considered for this study

According to the guidelines, the dilutions computed with the effluent flow attributed to the worst-case scenario need to be elevated by a ratio of the maximum flow to the appropriate time-averaged flow for each criterion. Although the recommended time-averaged flow for acute criteria is one hour-averaged flow, we choose the factor to be 1 as a conservative approach due to the unavailability of required time resolution of the measured data (only daily flows are available) to estimate one-hour averaged flow. For the chronic criteria, the four-day averaged flow is recommended as per the guidelines (section 6.1.2 of Ecology, 2018). We first estimated the four-day running averages for the 5-year daily flow time series and the maximum of four-day running averages was calculated (12.21 gpm) as the applicable flow for estimating the dilution-upward factor for chronic criteria. The dilution-upward factors calculated for both acute and chronic criteria are summarized in Table 3.

Table 3. Dilution upward factors estimated for each mixing zone criteria

Water Quality Criteria	Dilution-upward factor
Acute Criteria (maximum *flow rate through the pump / maximum flow rate through the pump*)	1.0
Chronic Criteria (maximum flow rate through the pump / maximum of 4-day running average)	14.33

The temperature and salinity of the effluent are monitored monthly. Given that the bulk of the processed wastewater contains sea water from Sequim Bay, the temperature and salinity of the effluent reflect the ambient sea water conditions.

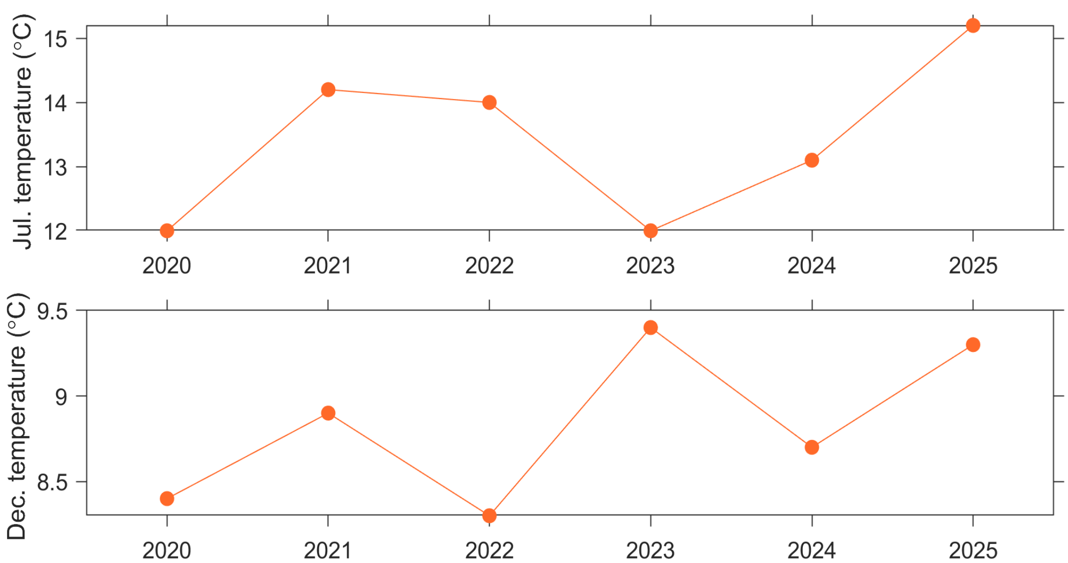

Figure 4. Measured monthly effluent temperatures for July (summer) and December (winter) months.

Therefore, the appropriate annually averaged monthly effluent temperature and salinity values that match the time associated with the critical ambient conditions (determined in section 4.2) were used for the model simulations (Figures 4 and 5). Table 4 summarizes the annually average effluent temperatures and salinities corresponding to the time periods when the critical ambient stratifications occur.

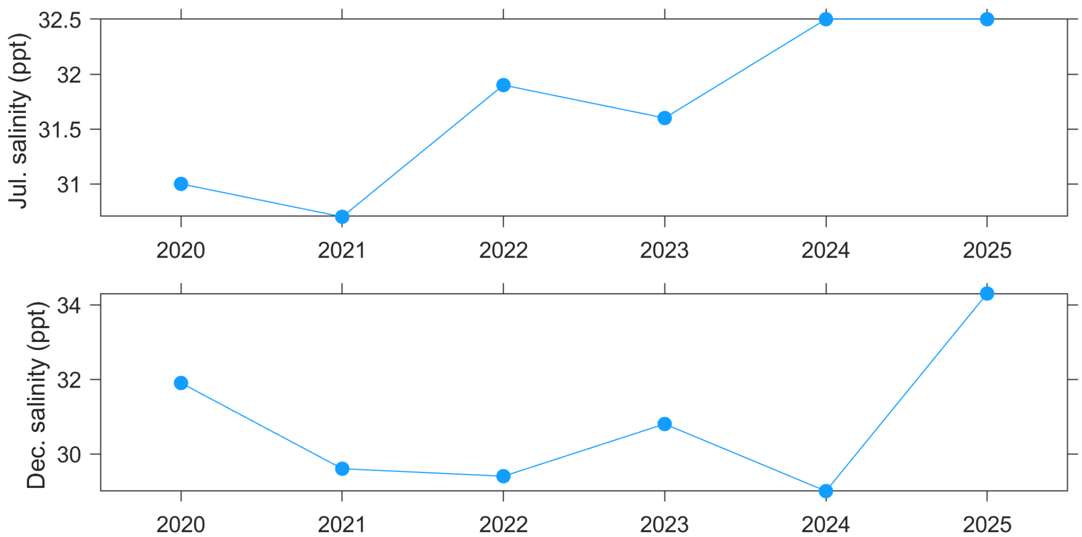

Figure 5. Measured monthly effluent salinities for July (summer) and December (winter) months.

Table 4. Annually averaged effluent temperature and salinities for the corresponding periods of critical stratification

	Effluent Temperature (C)	Effluent Salinity (PSU)
July (Summer)	13.42	31.7
December (Winter)	8.83	30.8

4.0 Ambient Characterization

4.1 Hydrodynamic Conditions in Sequim Bay

Sequim Bay is a shallow water body with maximum depths reaching 30-40 m and is connected to the Strait of Juan de Fuca via a narrow inlet in which the tidal currents can exceed 2 m/s. To obtain the critical ambient conditions for this mixing zone study, we used high resolution model solutions from the Salish Sea and Columbia River Operational Forecasting System (SSCOFS) originally developed by PNNL and which is now operated and maintained by National Oceanic and Atmospheric Administration (NOAA). The annual scale hydrodynamic characteristics at and near the outfall were analyzed to derive the critical stratification and velocity conditions for acute and chronic criteria.

4.2 Critical Stratification Conditions

According to the guidelines in Ecology (2018), the critical stratification condition is defined as the highest stratification that results in the least mixing of the effluent. The highest stratification was derived from the ambient depth-normalized densities estimated for the year 2024. As shown in Figure 6, the highest stratification at the outfall occurs during the winter months when a significant volume of freshwater flows into Sequim Bay creating a freshwater surface layer in the upper water column. The highest stratification driven by freshwater inflow occurred in the later part of December and the ambient temperature and salinity during this point of time were selected as the critical stratification conditions (Figure 7). In addition to the winter months, we also selected an additional critical stratification condition corresponding to the highest stratification during the summer months which occurs in July (Figure 8). The rationale behind this 2nd selection is as follows:

1. Although the summer timing does not represent the peak ambient stratification, it is crucial to consider the influence of high effluent temperature on dilution which occurs during the summer.

2. The hydrodynamic conditions in the summer (tides and currents) are lower in intensity compared to winter (e.g. absence of king tides and freshwater inflow driven currents).

Separate mixing zone modeling studies were conducted for both summer (July) and winter (December) stratification conditions to allow selection of critical dilution values.

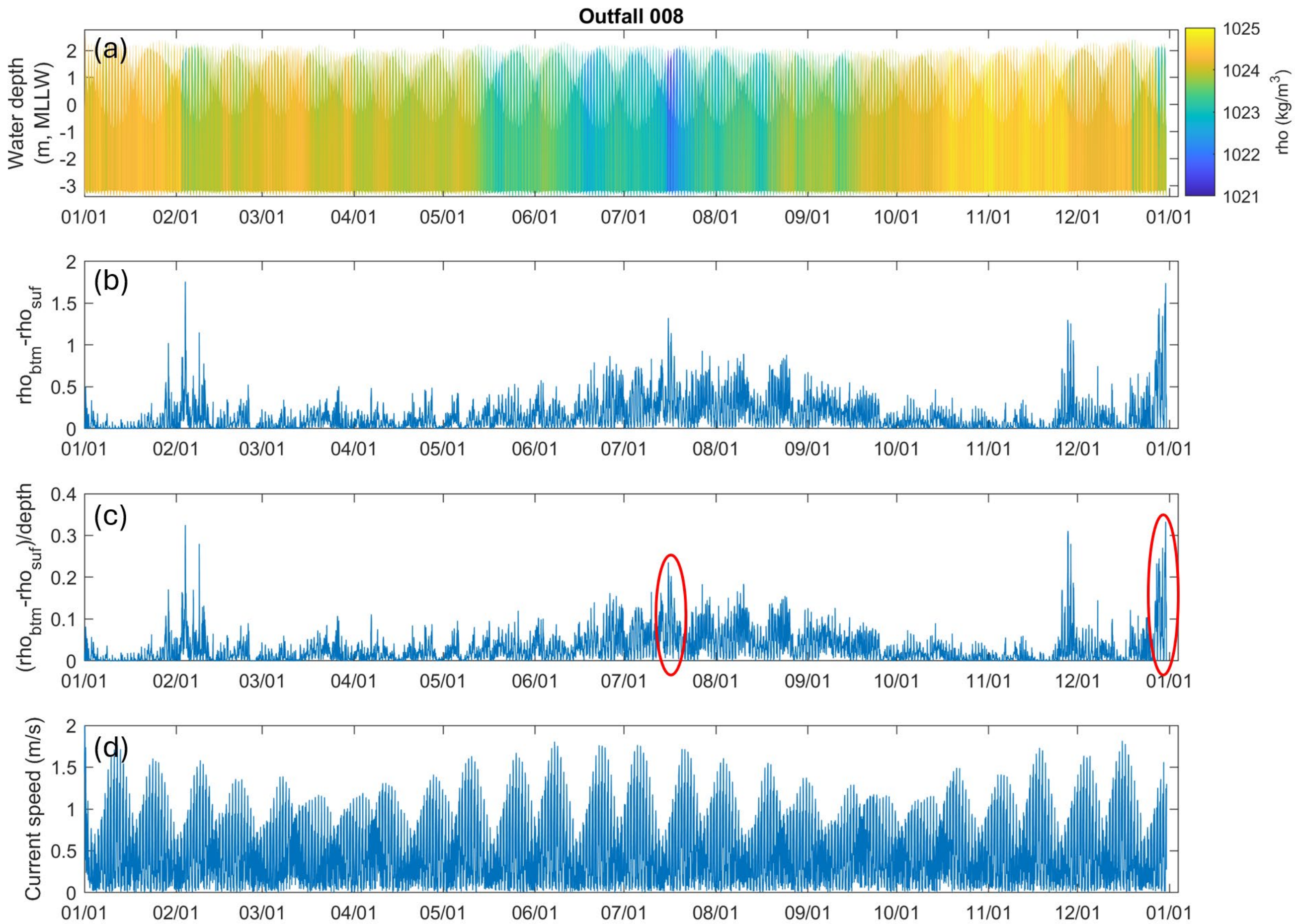

Figure 6. (a) Annual variation of ambient density with tides (b) Ambient density differential between top and bottom water layers (c) Normalized ambient density difference which indicates the level of ambient stratification (d) Velocity magnitudes of the surface water currents at outfall 008

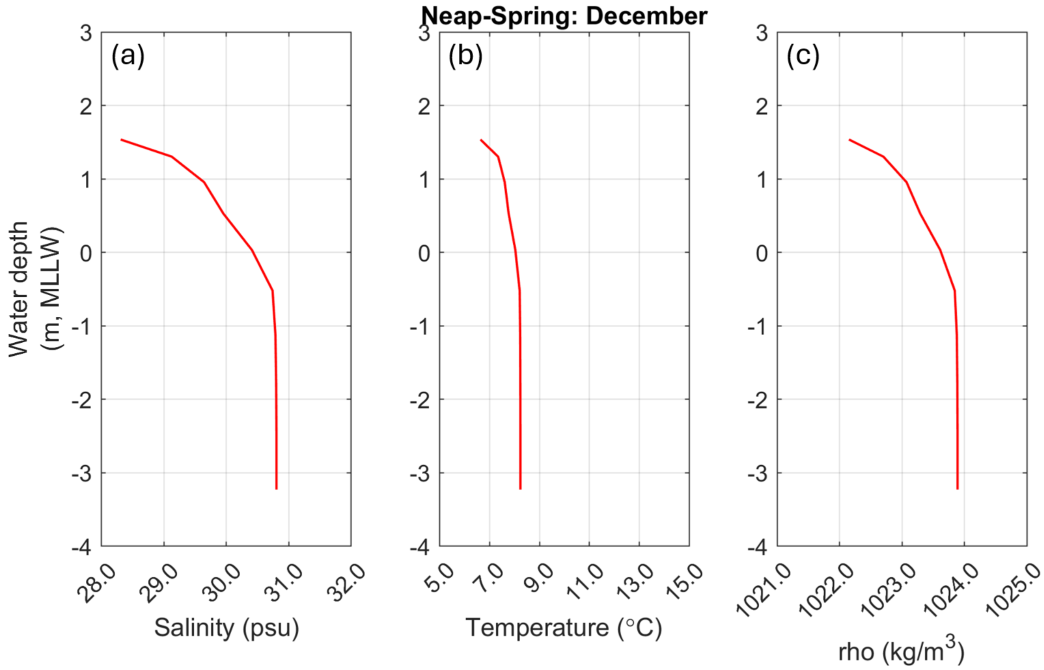

Figure 7. Highest winter ambient stratification (December 2024) (a) Salinity (b) Temperature (c) Density at outfall 008

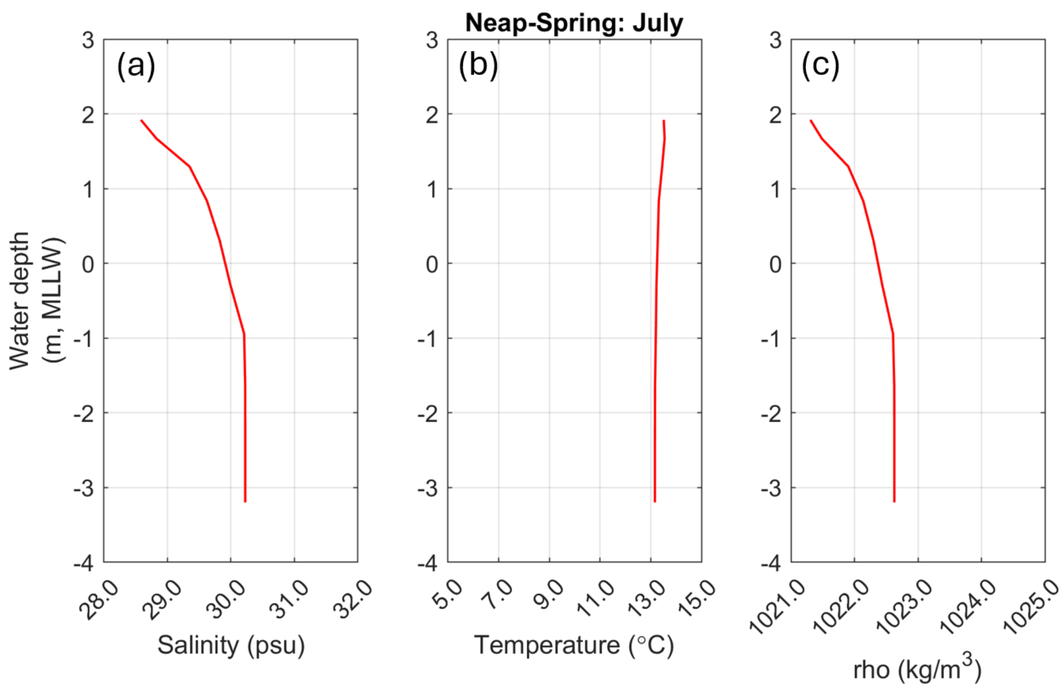

Figure 8. Highest summer ambient stratification (July 2024) (a) Salinity (b) Temperature (c) Density at outfall 008

4.3 Critical Ambient Currents Conditions

The critical ambient conditions for mixing zone studies in tidally driven marine waters are defined in section 6.2 of Ecology (2018). As per the guidelines, mixing zone modeling of acute criteria needs to be studied for 10th and 90th percentiles of cumulative frequency distribution which covers velocities over neap-spring tidal cycle (≈ 14 days) whereas the chronic criteria need to be studied with 50th percentile of the distribution (Figures 9 and 10). We extracted and preprocessed these velocity distributions for both selected periods in summer and winter months. Here, we have only shown summer conditions as a sample.

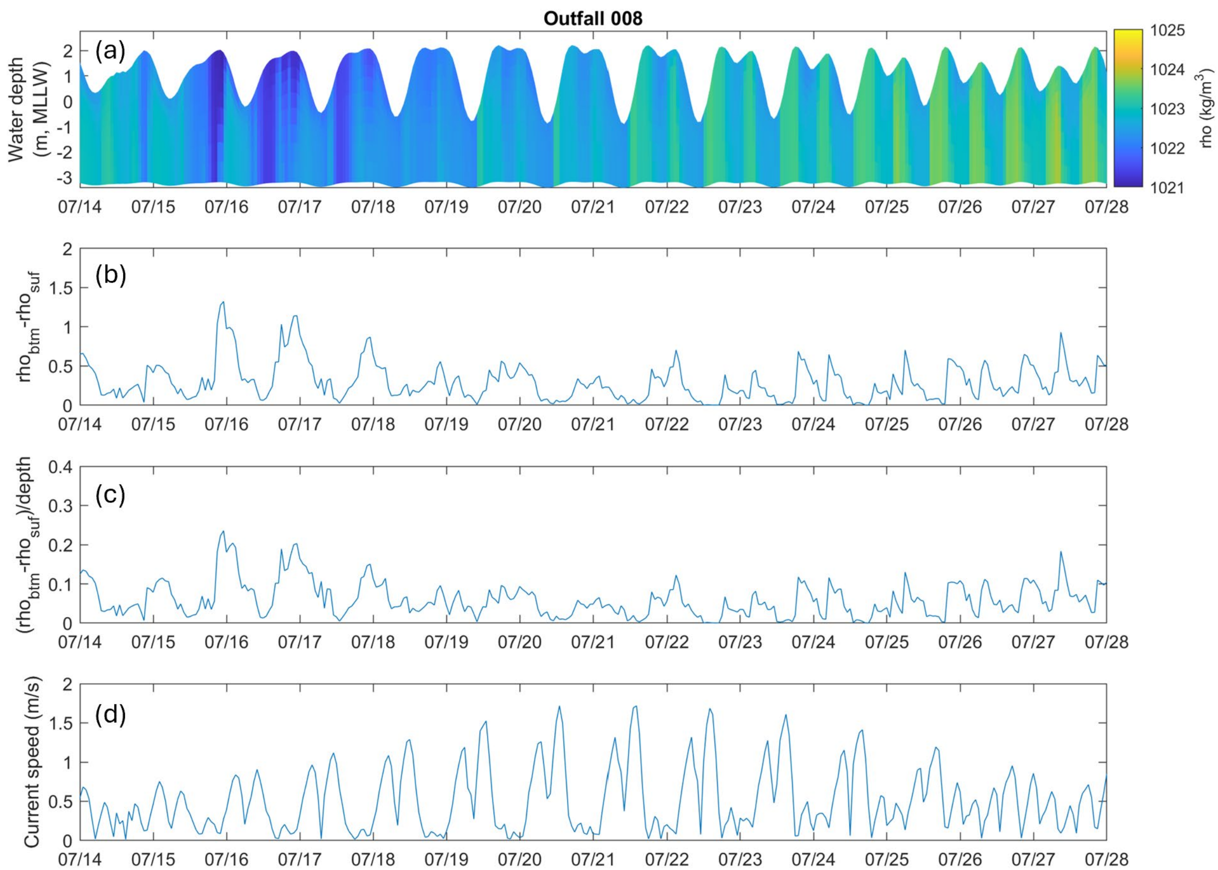

Figure 9. (a) The variation of ambient density with tides for July period when the ambient stratification is highest (b) Ambient density differential between top and bottom water layers (c) Normalized ambient density difference which indicates the level of ambient stratification (d) Velocity magnitudes of the surface water currents at outfall 008

A sample cumulative frequency distribution for surface water currents (surface layer) for July is shown in Figure (10). We developed such distributions for all 10 vertical layers of model data and extracted the ambient currents for each criteria for the corresponding period to create the ambient current distribution for the entire water column.

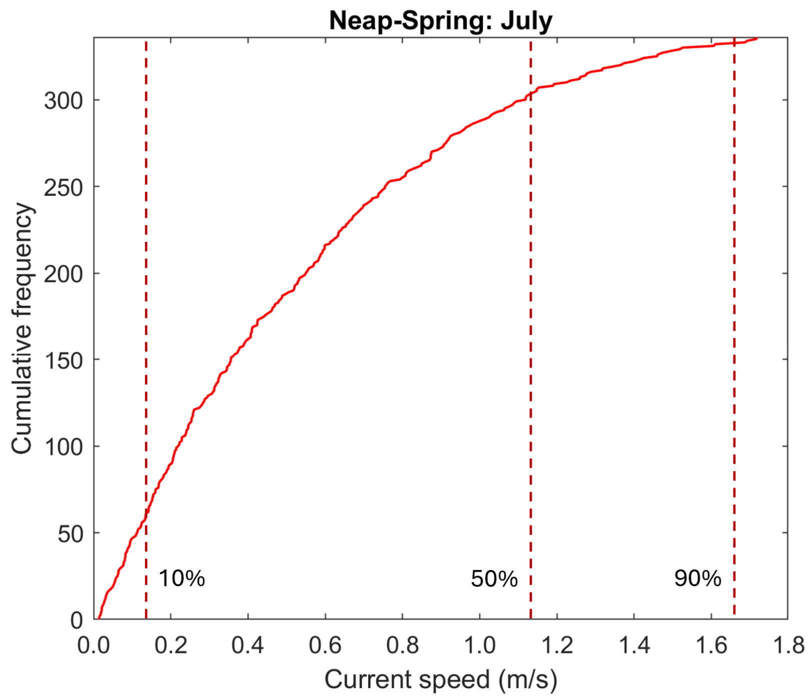

Figure 10. A sample cumulative frequency distribution for surface water currents over one neap-spring cycle for the month of July which includes the highest ambient stratification

4.4 Mixing Zone Modeling with PLUMES2.0

PLUMES2.0 (Khangaonkar et al., 2024) is a revived version of the Visual Plumes model that was developed by Dr. Walter Frick at USEPA. PLUMES2.0 and Visual Plumes are codes that compute initial and far-field dilution of buoyant discharges into receiving fresh or marine environments. PLUMES2.0 is a Fortran-based implementation of the UM3 code. Visual Plumes was a Windows-based guided user interface for UM3 that superseded the DOS-based PLUMES (Baumgartner et al.,1994) mixing zone modeling system. In PLUMES2.0, the initial dilution of the effluent, consisting of jet and buoyancy induced dynamic mixing of the effluent plume in the near-field is computed using the UM3 methodology. PLUMES2.0 then allows for analysis of plume fate following stabilization of the wastefield at the trapping depth when it is carried away by the ambient currents and further diluted by turbulence. This far-field transport of the wastefield and dilution is computed using Brooks laws (Brooks, 1960). Specifically, PLUMES2.0 includes (a) UM3 - initial dilution model, (b) Brooks' far-field model, and (c) an integrated GUI for better user experience. PLUMES2.0 (https://www.epa.gov/hydrowq/PLUMES2) development was funded by EPA and it has been added to the EPA suite of models that are recommended for modeling support for the NPDES permitting process. The latest version of PLUMES2.0v1 has been released with built-in calculations of carbonate chemistry and dissolved oxygen kinetics (Khangaonkar and Premathilake, 2025)

We applied PLUMES2.0 to model the mixing zone outfall 008, by setting up the model with inputs from diffuser characterization (section 2.1), effluent conditions (3.1), and ambient conditions with critical stratification (4.1). The following model scenarios were conducted for studying the mixing zone of outfall 008 using PLUMES2.0 for both December (winter) and July (summer).

(1) Acute criteria for 10% of the ambient current frequency distribution
(2) Acute criteria for 90% of the ambient current frequency distribution
(3) Chronic criteria for 50% of the ambient current frequency distribution
(4) Human health criteria (non-carcinogens) for 50% of the ambient current frequency distribution

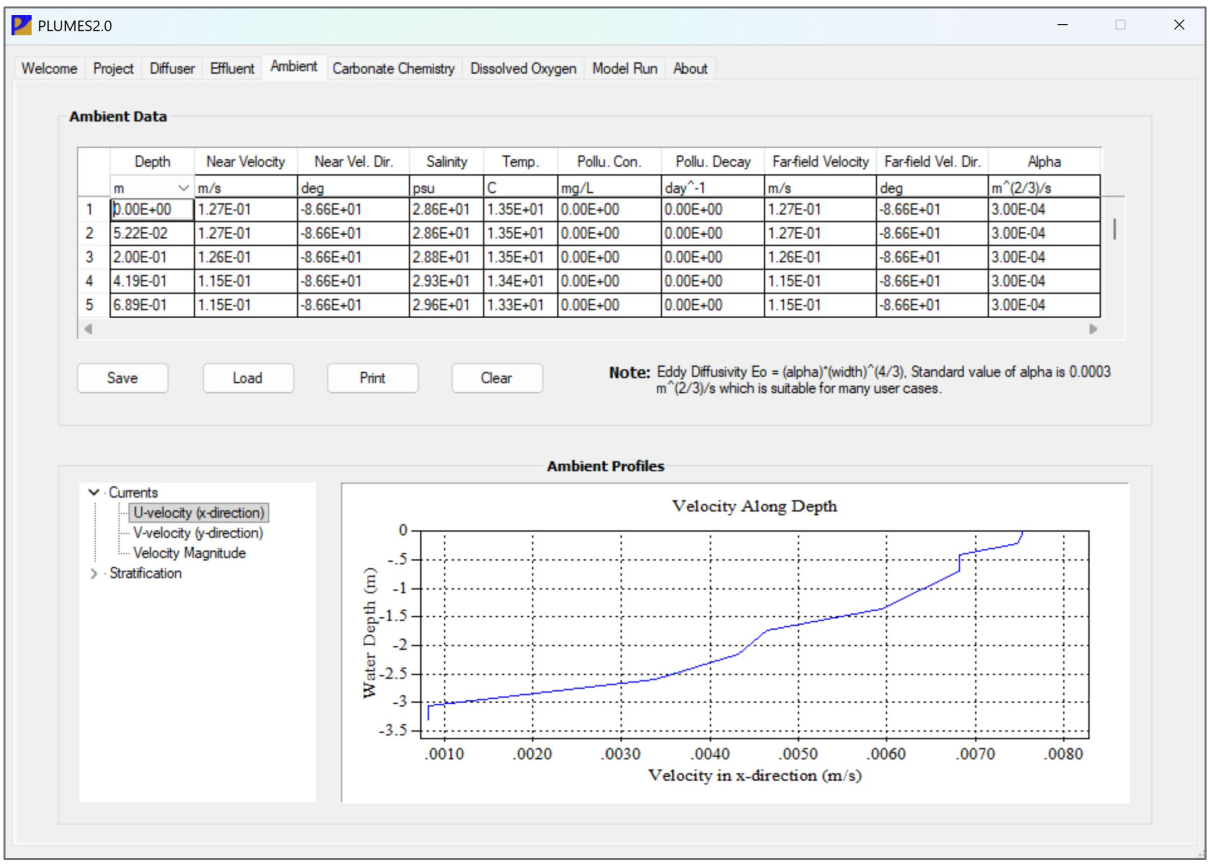

Figure 11. The ambient current inputs to PLUMES2.0 for July correspond to the scenario of acute criteria with 10th percentile of ambient current distribution

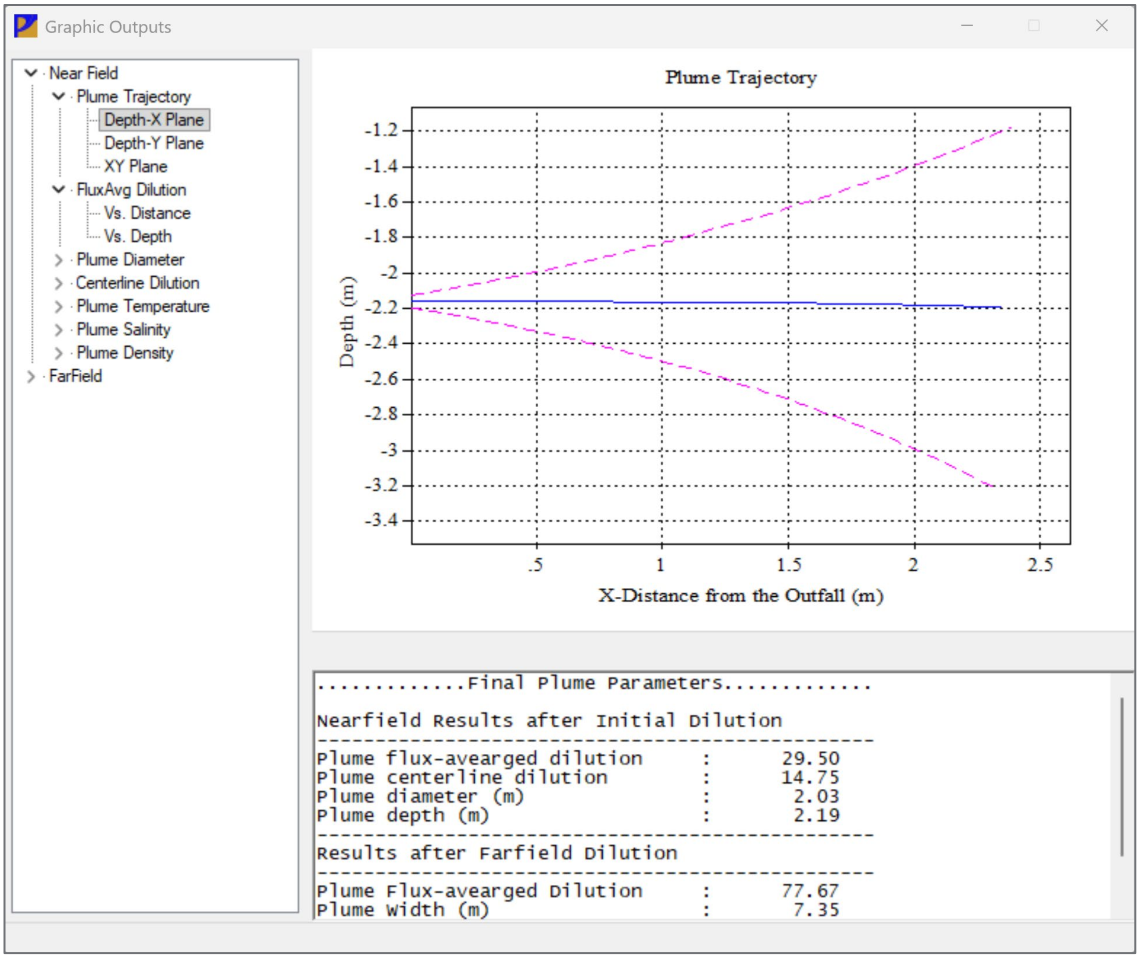

Figure 12. Model results from PLUMES2.0 for acute criteria (10th percentile currents) for July showing that the effluent plume hits the bottom before reaching the acute mixing zone

5.0 Results of Mixing Zone Study

The dilution calculations from the model scenarios are shown in Table 5. The flux average dilution numbers for both acute and chronic criteria at corresponding mixing zones are lower in July, under the summer conditions, compared to winter conditions in December. For both July and December, the effluent plumes simulated by the model for acute criteria with 10th percentile of the currents distribution hit bottom before reaching the acute mixing zone and transitioned to far-field (Figure 12). This is mainly due to stagnant ambient conditions contributing effluent plumes to expand as primarily momentum driven plume with rapidly expanding plume width. For the month of July, the plume hits the bottom at distance of 2.34 m with a flux average dilution of 29.0 and a centerline dilution of 14.75 while for December, the plume hits the bottom at distance of 2.29 m with a flux average dilution of 30.82 and a centerline dilution of 15.56. We further examined the acute case by allowing effluent plumes to evolve without limiting nearfield calculation at bottom hit criteria to study a potential occurrence of plume rise resulting in extended near-field development up/beyond acute criteria. However, the plumes continue with rapid expansion of plume width penetrating plume boundaries beyond the seabed creating unrealistic plume progression. This concluded that, terminating the plume's near-field calculation at bottom hit gives the best reasonable and realistically conservative estimates.

Table 5. Dilutions calculated at acute and chronic mixing zones (adjusted with dilution-upward factor)

Mixing zone criteria	Dilutions			
	Centerline Dilution		Flux Average Dilution	
	July (summer)	December (winter)	July (summer)	December (winter)
Acute (10th percentile of the ambient currents) at 6.1 m	**29.80**	31.37	29.80	31.37
Acute (90th percentile of the ambient currents) at 6.1 m	32.68	39.09	65.36	78.19
Chronic (50th percentile of the ambient currents) at 63.1 m			1727.19	**1713.58**

6.0 Summary

In summary, we conducted a plume modeling study to determine the dilutions at regulatory mixing zones for outfall 008 located at PNNL Sequim. This included an analysis of diffuser and effluent characteristics together with ambient conditions around the outfall. Table 5 summarized the main results for dilution numbers estimated in our study, showing the minimum dilution for acute criteria is 29.8 that occurred for July conditions and the minimum dilution for chronic criteria is 1713.58 under December conditions.

7.0 References

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