

MEMORANDUM

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Subject: Tracer simulations to investigate how waters move in Puget Sound and the Salish Sea to address questions related to the draft proposed No Discharge Zone petition

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1.0 Introduction

In 2014, the Department of Ecology released a Draft Petition to Designate the Waters of the Puget Sound as a No Discharge Zone (NDZ) (Herrera Environmental Consultants, 2014). A designated NDZ would prohibit the discharge of sewage (blackwater, toilet wastes) from boats. Currently, treated sewage can be discharged from boats anywhere in Puget Sound and untreated sewage can be discharged from a boat as long as it is more than three miles from shore.

Parts of Puget Sound are impaired by bacterial pollution that restricts shellfish harvest. Vessel sewage represents one of several pollutant sources the State is addressing. Marine sanitation devices used to treat boater waste onboard typically do not meet standards for water quality and public health protection.

Ecology received over 26,000 comments, with about 25,000 in support of the draft petition. Several comments related to whether or not discharges in particular areas could harm natural resources. During the process of evaluating NDZ feasibility, Ecology reviewed and considered a number of vessel pollutant studies and marine sanitation device performance data. In response to questions from a few commercial and recreational sector entities during the public comment period, the Water Quality Program requested that the Environmental Assessment Program perform a tracer study in an effort to further understand the complexities of the movement and the potential impact of vessel sewage discharges in the Puget Sound and the Salish Sea.

This memorandum summarizes results from computer modeling that simulates potential vessel discharges. Ecology and its partners at Pacific Northwest National Laboratory (PNNL) have developed a computer model that simulates how water circulates in Puget Sound and the Salish Sea (Khangaonkar et al., 2011; Yang et al., 2010). The water quality model was recently applied to understand how changes in human contributions, climate influences, and Pacific Ocean trends could affect dissolved oxygen (Roberts et al., 2014), but the model does not directly include bacteria or other pathogens. We simulated the release of contaminants at six locations in Puget Sound and the Salish Sea using a conservative tracer and evaluated areas influenced by those discharges. Because the model does not account for die-off or other loss mechanisms, these are addressed in a separate section of this memo. Ecology is using the information from this model as one of several sources of data and science to inform a final State petition to the Environmental Protection Agency.

2.0 Continuous Tracer Releases

2.1 Methods for Continuous Tracer Releases

The Salish Sea model simulates water circulation using FV-COM (Finite Volume Coastal Ocean Model), a three-dimensional hydrodynamic model (Figure 1). The model is forced by tides at the mouth of the Strait of Juan de Fuca, meteorological boundary conditions, and freshwater inputs from the US and Canada that induce estuarine circulation. The model was calibrated to water surface elevations and profiles for the year 2006.

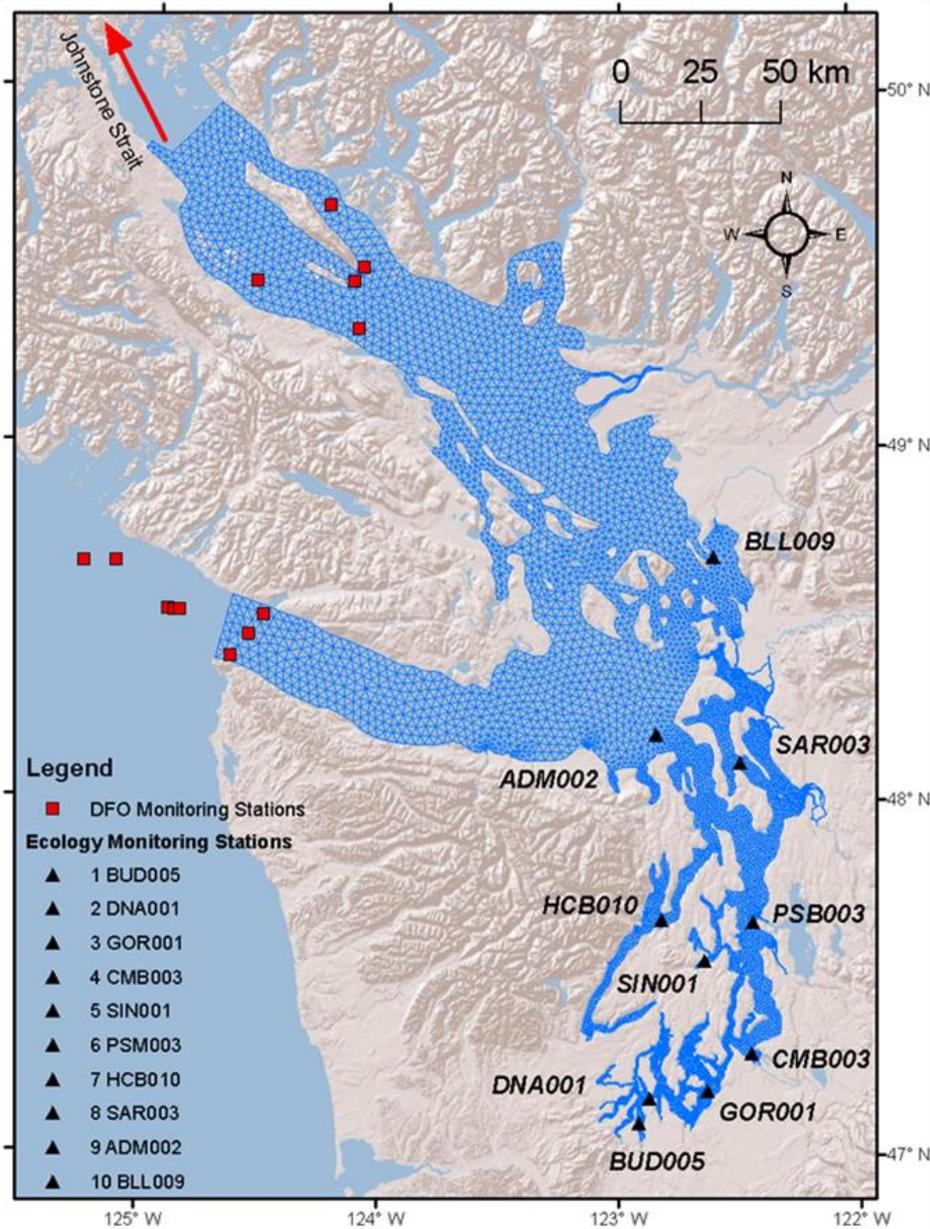


Figure 1. Salish Sea model domain and grid with calibration locations (DFO refers to Canada’s Department of Fisheries and Oceans). Source: Yang et al. (2010)

A fundamental question raised in the comments from the commercial vessel sector was whether or not vessel discharges to marine areas had the potential to impact sensitive areas near the shore. Circulation in marine waters includes complex patterns that vary with the location, tidal cycle, and winds, among other factors. Because there are no known comprehensive estimates of actual mobile vessel discharge volumes, locations, or discharge water quality, we evaluated the degree of connectivity between specific marine areas where vessels could discharge and nearby sensitive areas.

We simulated the continuous release of a conservative tracer at six distinct locations between June 1st and October 31st. This was done to evaluate connectivity between points of potential vessel discharge

and nearby sensitive areas, and to understand what tide and other environmental conditions posed the greatest threat with the least dilution between the hypothetical release locations and nearby sensitive areas. Other time periods may have more or less critical impacts.

A continuous release was used because we could not determine a priori what tidal or river flow conditions along with other factors like wind and ambient quality conditions would lead to the highest potential impacts. Vessels are not expected to release continuously. The objective is to evaluate patterns of water connectivity in terms of dilution factors rather than to quantify the impacts of a specific discharge.

The model has 10 layers, and the tracer was released in the surface layer where vessels would typically discharge. The calibrated model runs for five months to ensure that the model results are not just a response to initial conditions. The six locations were selected to represent high-use areas near potentially sensitive resources. These locations are where both recreational and commercial vessels frequently pass, such as along shipping routes, are at locations with proximity to shorelines or shellfish beds, are at distances greater than 3 miles from shore, or in locations where we wanted to better understand how circulation might affect the transport and dilution of potential discharges (Figure 2).

We used the FV-COM model sediment tracer functions to understand patterns of transport and physical dilution. The sediment particles are not subject to settling or die-off in the marine environment; Section 4 of this memo describes how die-off would influence concentrations. Tracers are released at a given location and over a specified time period. Resulting tracer concentrations are expressed as milligrams of sediment per liter of water. For this evaluation, we used 1 mg of sediment as equivalent to 1 fecal coliform unit; therefore, concentrations are expressed as particles per liter, or p/L.

Little information exists on actual fecal coliform concentrations in releases from vessels smaller than cruise ships. Untreated household wastewater contains concentrations of 10^4 to 10^8 fecal coliform bacteria per 100 mL (Rose et al., 1996). Boater waste could have higher or lower concentrations of pathogens and indicators such as fecal coliform. For example, boater waste would not have the dilution of non-toilet wastewater sources such as showers, laundry, and dishwashing that constitute a significant volume of wastewater from a household. Vessels with marine sanitation devices (MSDs) may release lower concentrations, while those without will release higher concentrations of fecal coliform bacteria. MSDs vary greatly in terms of the fecal coliform bacteria concentrations present in the waste that they discharge.

We selected an initial release concentration of 10^9 p/L. This is equivalent to a fecal coliform concentration of 10^8 organisms per 100 mL, since 1 liter contains 10 x 100 mL. We released 10^9 p/L at a rate of $0.005 \text{ m}^3/\text{s}$, or about 80 gal/minute of water, at the six locations in Figure 2. The flow rate was selected to represent a small amount of freshwater that would not substantially alter the estuarine circulation in the model. Results are expressed both as concentrations in p/L at nearby sensitive locations and as dilution factors by comparing concentrations with an initial concentration of 10^9 p/L.

The dilution factor is the ratio of an initial concentration to a final concentration that could represent a later date or a different location. For example, if an initial concentration of 1000 units per liter of water declines to 100, the dilution factor is $1000 / 100 = 10$. The dilution factor is a relative measure between two values and is unitless. An initial concentration of 100,000 that declines to 10,000 also represents a dilution factor of 10, as long as they are both in the same units.

Washington Administrative Code (WAC) 173-201A-210 describes the Washington State water quality standards for fecal coliform bacteria in marine waters. For marine waters where the protected use is primary contact recreation:

“Fecal coliform organism levels must not exceed a geometric mean value of 14 colonies/100 mL, with not more than 10 percent of all samples (or any single sample when less than ten sample points exist) obtained for calculating the geometric mean value exceeding 43 colonies /100 mL.”

The geometric mean is the nth root of the product of n numbers:

$$GM = \sqrt[n]{x_1 \cdot x_2 \cdot \dots \cdot x_n}$$

We compared peak concentrations against a value of 14 per 100 mL, equivalent to 140 p/L in the model units used for this analysis. This represents a conservative assumption, since the value applies to a geometric mean in the standard. To reduce initial concentrations of 10^9 p/L to 140 p/L would require dilution factors of at least 7.1×10^6 . If we compared against 43 per 100 mL, equivalent to 430 p/L, the minimum dilution factor needed would be 2.3×10^6 .

Model output was evaluated and is presented here in two main ways:

1. Plan view maps of surface layer tracer concentrations at the following intervals: 6 hrs, 1 day, 2 days and 3 days after the start of the tracer release.
2. 30-day time series plots between June 1st (start of tracer release) and July 1st at nearby sensitive areas for each discharge location for the following parameters:
 - a. Concentration in the surface layer.
 - b. Dilution factor in the surface layer (calculation described in more detail below).
 - c. Water surface elevation (a surrogate representation of tides).

Additionally, animations were also created to visualize the movement of the tracer over the first 20 days of the simulation for each of the six discharge locations. These animations can be at <http://www.ecy.wa.gov/programs/wq/nonpoint/CleanBoating/ndzwhatsteps.html>.

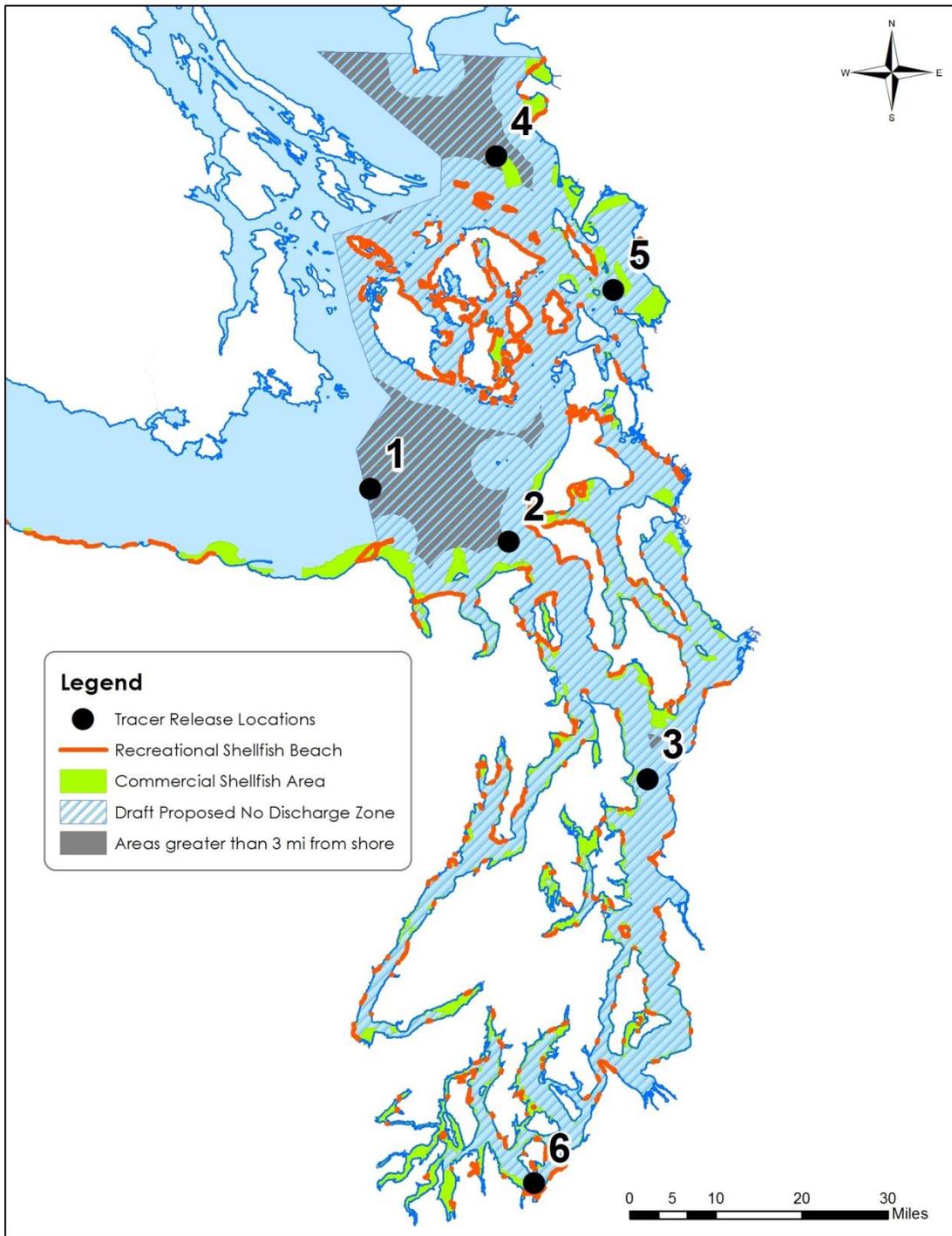


Figure 2. Map of Puget Sound showing the six locations where the conservative tracer was released in the computer model, as well as the extent of the draft proposed NDZ and shellfish areas.

2.2 Results of Continuous Tracer Releases

Table 1 summarizes results of the model tracer simulations, followed by corresponding plan-view maps identifying model locations and time-series of model output.

The tracer was released at each of the six locations and a total of sixteen sensitive areas were examined. It takes on the order of half a day to one day to arrive at sixteen sensitive locations. The first peak concentrations (defined in Table 1) at these sensitive areas are observed 1-4 days after dye release, depending on the location. In all cases, results show that discharge locations are connected via estuarine and tidal circulation to sensitive areas, and any waste discharged at these locations would eventually be diluted and transported to near-shore areas, including shellfish beds.

At all locations, the tracer disperses from the highest concentration at the point of release outward. Maximum observed concentrations are lower in regions where circulation is high (e.g. Location 1, in the Strait of Juan de Fuca) and higher where circulation is low (e.g. Location 6, in South Puget Sound). Observed tracer concentrations and dilution factors are also influenced by the magnitude of river inflows. For example, the Nooksack River and the Snohomish River both influence observed concentrations at nearby locations in Bellingham Bay and south of Hat Island, respectively, possibly by preventing surface transport to river delta regions.

Peak concentrations would be higher than the fecal coliform bacteria water quality standard of 140 p/L at all 16 locations and higher than 430 p/L at 14 locations during for some portion of the 120-day simulation period. On the graphics that follow, the dilution needed refers to the ratio of 10^9 p/L to 140 p/L, or 7.1×10^6 , based on the geometric mean for bacteria in the water quality standards. Results indicate that physical dilution alone would not decrease concentrations to ensure they would remain below either part of the marine fecal coliform bacteria water quality standard for the conditions tested. The following sections present more detailed results for each tracer release discharge location.

Table 1. Summary of model tracer simulation results for each of the six discharge locations and nearby sensitive areas where model output was evaluated.

	Model Node	Distance from tracer release to sensitive area	Travel time between start of tracer release and arrival of first concentration peak ¹	Max. tracer concentration at sensitive area during June ²	Min. dilution factor at sensitive area during June ³
Location 1 - edge of NDZ/in Strait of Juan de Fuca					
SJF, 5.2 mi west of release	390	5.29 mi	1.7 days	800 p/L	1.3 x 10 ⁶
Dungeness Spit	467	6.61 mi	1.5 days	300 p/L	3.3 x 10 ⁶
Location 2 - Admiralty Inlet					
North of Fort Worden State Park	965	2.57 mi	1.4 days	1950 p/L	5.1 x 10 ⁵
Location 3 - Central Puget Sound					
South end of Whidbey Island	3136	6.46 mi	1.3 days	1550 p/L	6.5 x 10 ⁵
Near Kingston	3462	1.92 mi	1.9 days	3200 p/L	3.1 x 10 ⁵
South of Hat Island	4147	15.48 mi	1.9 days	340 p/L	2.9 x 10 ⁶
Location 4 - North of San Juan Islands					
Shellfish bed south of release location	1447	1.85 mi	1.5 days	2560 p/L	3.9 x 10 ⁵
Inside Lummi Bay	1663	9.57 mi	2.2 days	690 p/L	1.5 x 10 ⁶
Near Birch Bay	1730	5.35 mi	1.9 days	860 p/L	1.2 x 10 ⁶
Location 5 - Entrance to Samish/Bellingham Bay					
Fidalgo Bay Aquatic Reserve	1922	9.51 mi	3.3 days	2200 p/L	4.6 x 10 ⁵
Samish Bay	2231	4.66 mi	2.0 days	2960 p/L	3.4 x 10 ⁵
Bellingham Bay	2238	10.19 mi	3.2 days	820 p/L	1.2 x 10 ⁶
Location 6 - South Puget Sound					
South of Fox Island	7226	8.36 mi	1.8 days	2090 p/L	4.8 x 10 ⁵
Pitt Passage	7696	7.43 mi	3.7 days	2830 p/L	3.5 x 10 ⁵
South side of Nisqually Reach	7964	6.25 mi	4.1 days	2280 p/L	4.4 x 10 ⁵
West side of Nisqually Delta	8107	1.93 mi	3.6 days	2600 p/L	3.8 x 10 ⁵

1. This represents the time between the start of the tracer release (on June 1st) and the arrival of the *first* peak of tracer concentration, where a peak was defined as the first maximum concentration in the times-series (where an increase in concentration was followed by a decrease in concentration). In all cases, this time is greater than the time it took for the tracer to first arrive at sensitive areas.
2. This is the maximum observed concentration over the first 30 days of the simulated 120-day tracer release.
3. This is the minimum dilution factor corresponding to the maximum observed concentration over the first 30 days of the simulated 120-day tracer release.

Location 1 – Edge of draft proposed NDZ in the Strait of Juan de Fuca

A continuous tracer release in the Strait of Juan de Fuca at the western edge of the draft proposed NDZ would flow east on an incoming tide and west on an outgoing tide, although the specific patterns reflect eddies and other features that move the tracer in patterns other than simply east and west (Figure 3). The cloud of dispersing tracer would sweep past the southern end of Dungeness Spit, with the diluted plume reaching shore in less than one day.

Figure 4 presents the time series of tracer concentrations and dilution factors from the initial release concentration for the month of June. Both are highly influenced by tidal circulation, represented by the water surface elevations. At times the plume reaches the two sensitive locations at tracer concentrations of 300 or 800 p/L. Concentrations drop when the tide reverses away from these areas. Dilution factors vary considerably.

Tracer concentrations at Dungeness Spit average 60 p/L, with a maximum of 300 p/L. Concentrations in the Strait of Juan de Fuca, just over 5 miles west of the discharge location (outside of the draft proposed NDZ) average 150 p/L, with a maximum concentration of 800 p/L in June. The conservative tracer concentration is greater than 140 or 430 p/L at both locations.

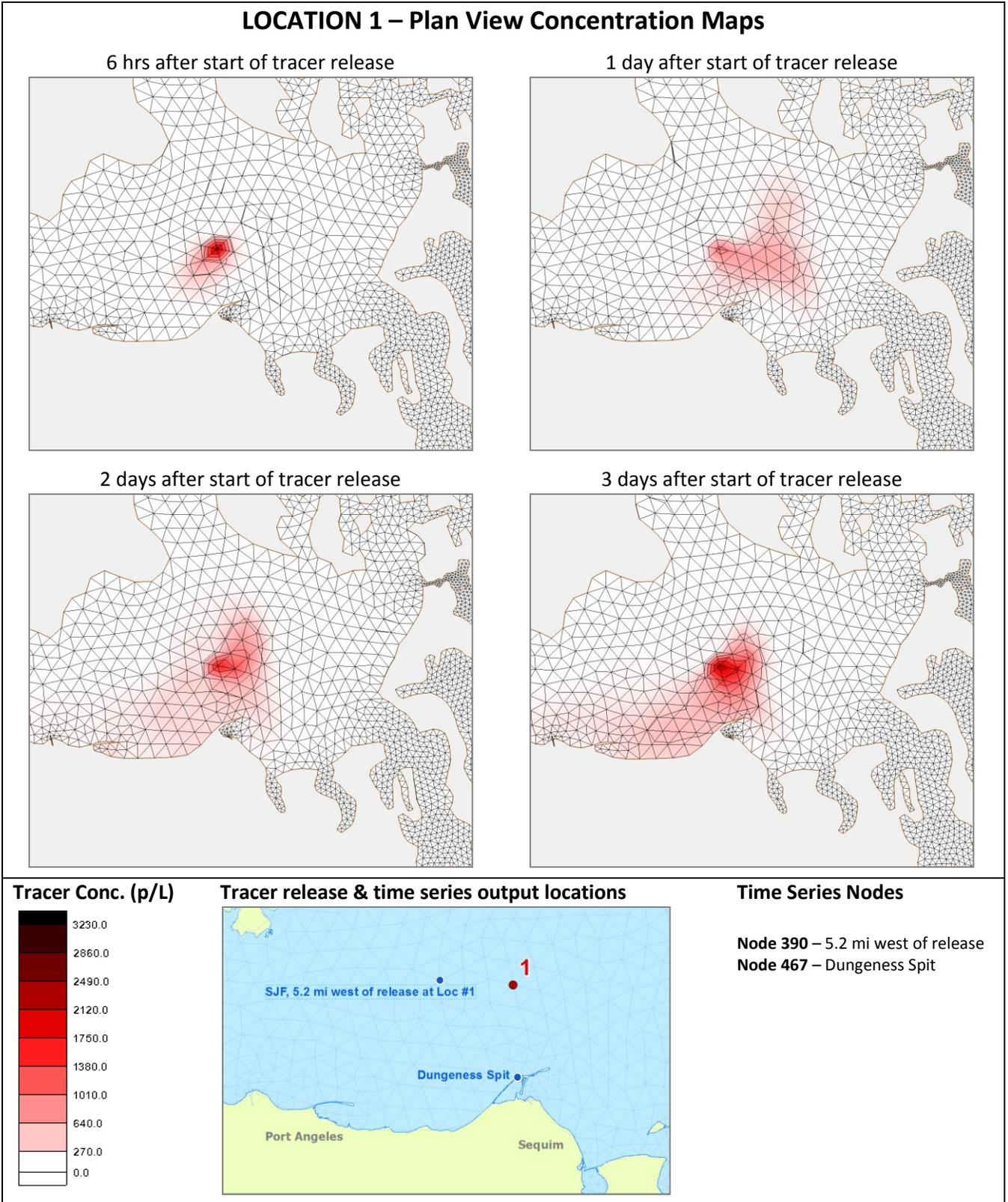


Figure 3. Horizontal dispersion of a tracer release at Location 1 illustrating surface layer tracer concentrations at different times after the start of the tracer release, and a map identifying model nodes where time series output was generated.

Results of Tracer Release at Location #1

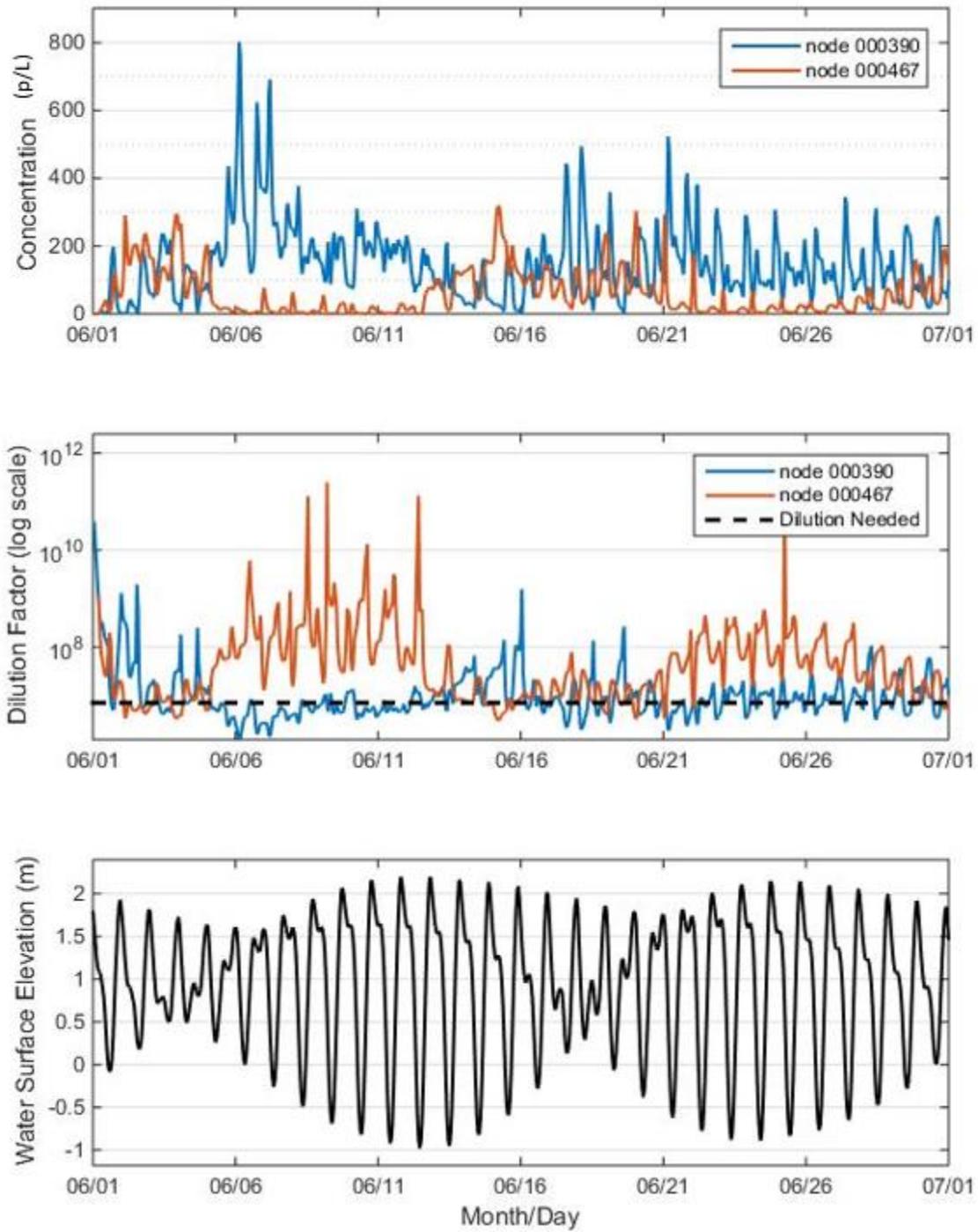


Figure 4. Time series of concentration and dilution factors resulting from a discharge at Location 1. Results are shown for a location in the Strait of Juan de Fuca (node #000390) and near Dungeness Spit (node #000467).

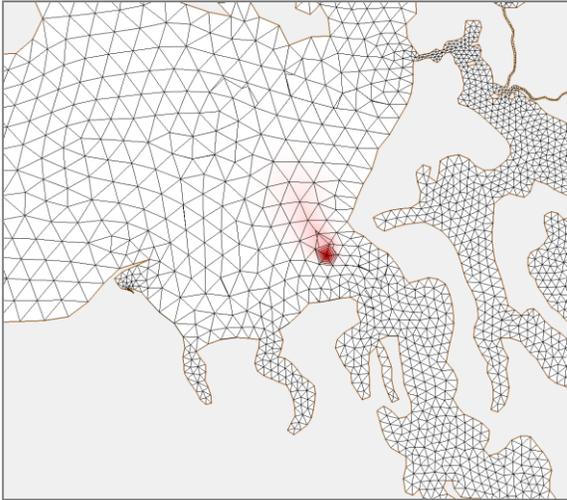
Location 2 – Admiralty Inlet

High velocities in Admiralty Inlet disperse the tracer quickly (Figure 5). Because surface waters, with lower salinity and warmer temperatures, exhibit a net-seaward transport over several tidal phases, tracer plumes generally travel away from Puget Sound. However, a tracer release in Admiralty Inlet primarily moves around in a clockwise pattern, and appears primarily to be transported out of Puget Sound along with the dominant direction of surface water export in this region. The cloud of dispersing tracer repeatedly sweeps past the shoreline north of Port Townsend in sync with the tides.

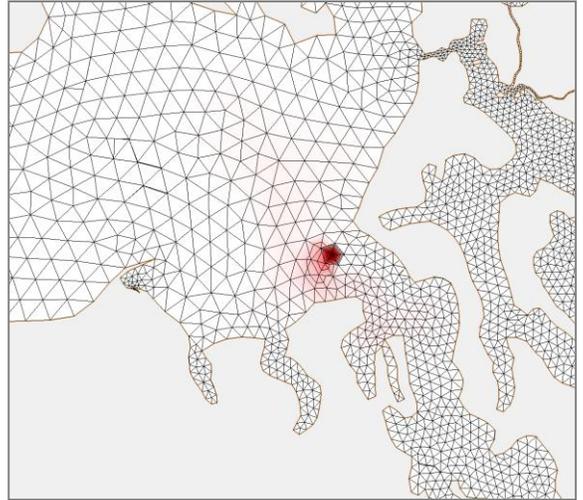
Concentrations near Port Townsend north of Fort Worden State average 230 p/L, with a maximum of 1950 p/L in June. Concentrations at the node would be greater than 140 or 430 p/L about once per tidal cycle.

LOCATION 2 – Plan View Concentration Maps

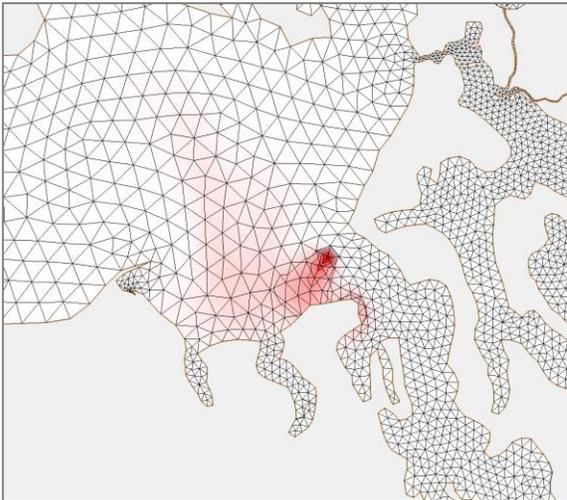
6 hrs after start of tracer release



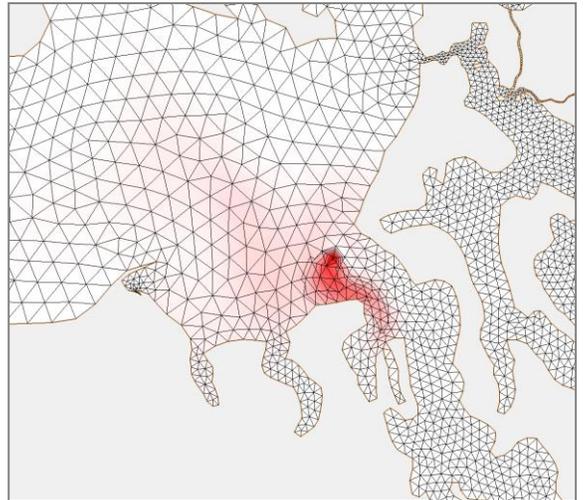
1 day after start of tracer release



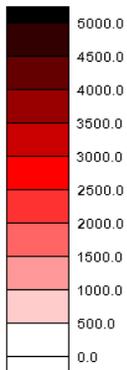
2 days after start of tracer release



3 days after start of tracer release



Tracer Conc. (p/L)



Tracer release & time series output locations



Time Series Nodes

Node 965 – N. of Fort Worden State Park

Figure 5. Horizontal dispersion of a tracer release at Location 2 illustrating surface layer tracer concentrations at different times after the start of the tracer release, and a map identifying model nodes where time series output was generated.

Results of Tracer Release at Location #2

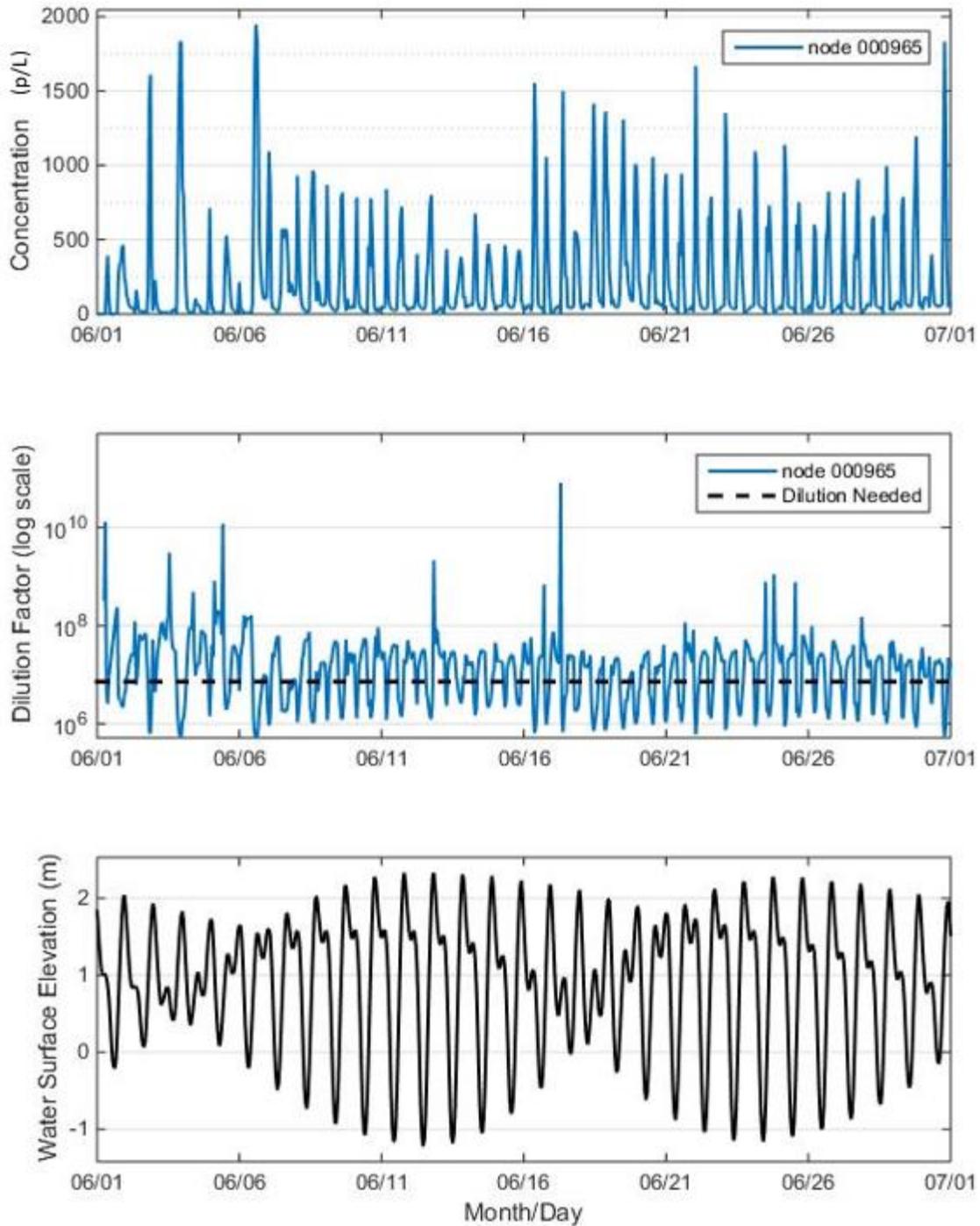


Figure 6. Time series of concentration and dilution factors resulting from a discharge at Location 2. Results are shown for a location in just north of Port Townsend/Fort Worden State Park (node #000965).

Location 3 – Central Puget Sound, south of Whidbey Island

A tracer release south of Whidbey Island in central Puget Sound pulses north and south with the tide direction, but appears to primarily hug the western shoreline for the conditions evaluated (Figure 7). This is likely because of the influence of the Snohomish River discharge to the northeast, which is the second-largest river flowing into Puget Sound in terms of discharge. The river flow keeps most of the tracer plume out of Possession Sound, but over 20 days, the tracer plume extends as far north as Admiralty Inlet and as far south as the southern end of Bainbridge Island.

Kingston area tracer concentrations reflect tidal circulation, and average 730 p/L with a maximum concentration of 3200 p/L. Concentrations are lower at sensitive areas near Whidbey Island and Hat Island due to the influence of the Snohomish River. River flow may contribute to the lower concentrations at Hat Island than the shellfish bed south of Whidbey (Figure 8). Physical dilution alone would disperse releases at Location 3 sufficiently to protect Hat Island. Higher concentrations near Kingston would be above 140 or 430 p/L most of June in this simulation.

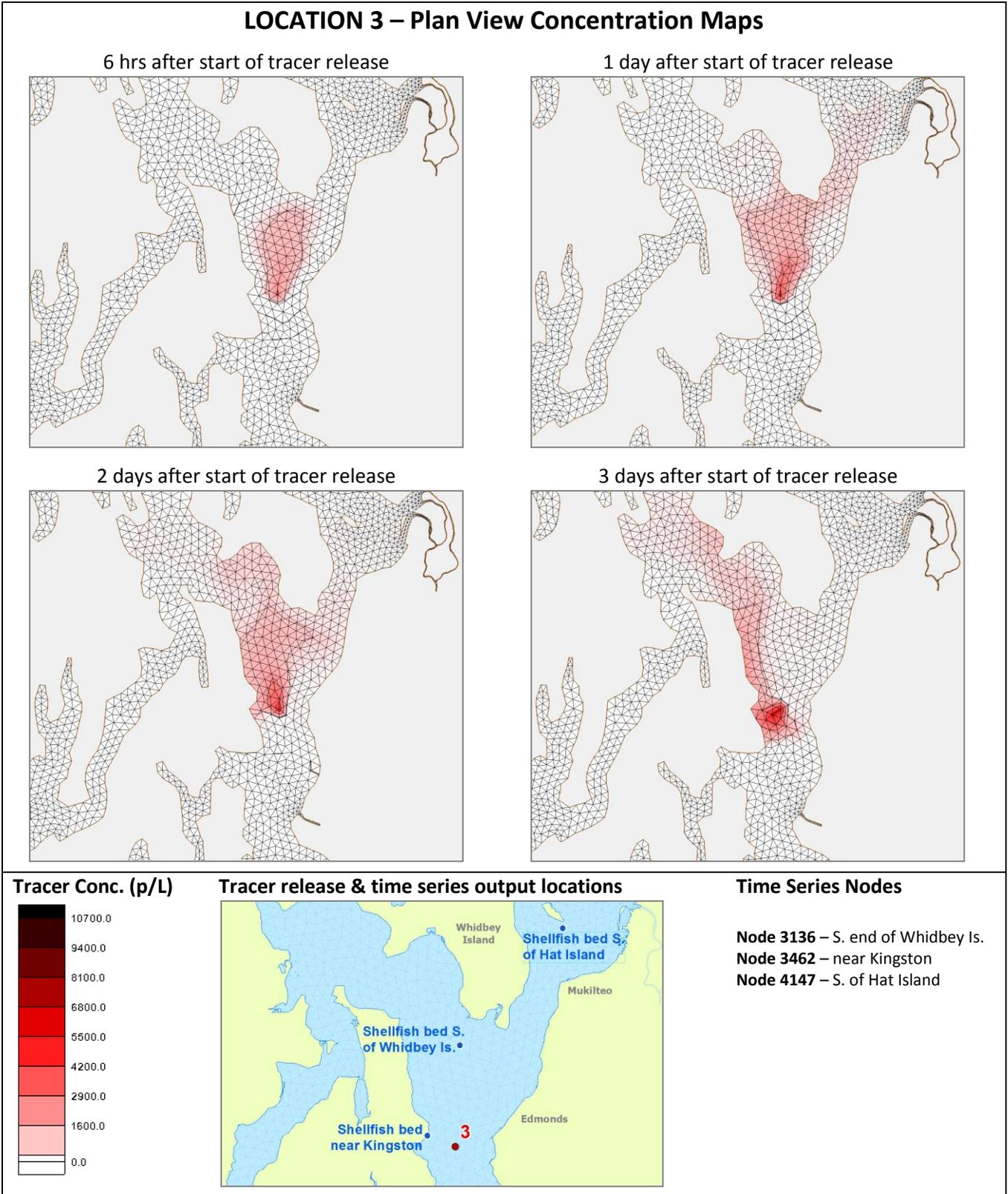


Figure 7. Horizontal dispersion of a tracer release at Location 3 illustrating surface layer tracer concentrations at different times after the start of the tracer release, and a map identifying model nodes where time series output was generated.

Results of Tracer Release at Location #3

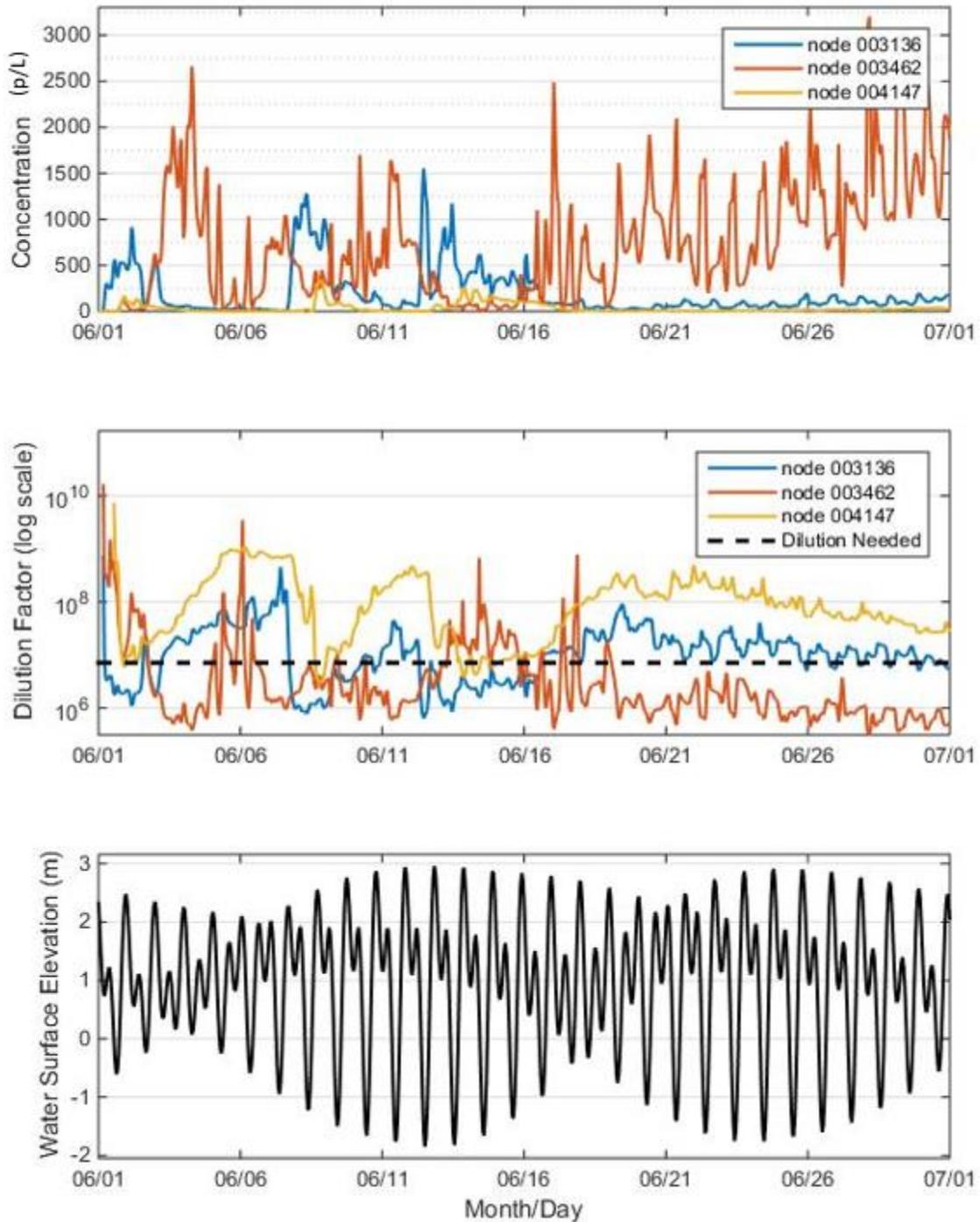


Figure 8. Time series of concentration and dilution factors resulting from a discharge at Location 3. Results are shown for three locations: south end of Whidbey Island (node #003136), near Kingston (node #003462), and the south end of Hat Island (node #004147).

Location 4 – North of San Juan Islands

A tracer release about 10 miles north of the San Juan Islands moves primarily in a southern direction due to the large influence of the Fraser River – the largest of the rivers discharging to the Salish Sea. The tracer plume primarily reaches the eastern shoreline north of Bellingham Bay, and the northern shores of the San Juan Islands (Figure 9).

Tracer concentrations are highest to the south of the release, near a shellfish bed north of the San Juan Islands. Tracer concentrations at the sensitive location vary with the tides, averaging 690 p/L with a maximum of 2560 p/L in June. Physical dilution at this location is as low as 3.9×10^5 through most of June (Figure 10). Concentrations near Lummi Bay and Birch Bay are lower, averaging 160 p/L and 90 p/L respectively, and influenced less by tides and more by Fraser River flow patterns. Concentrations exceed 140 and 430 p/L throughout the simulation at node 1447 and in mid-June for the other locations.

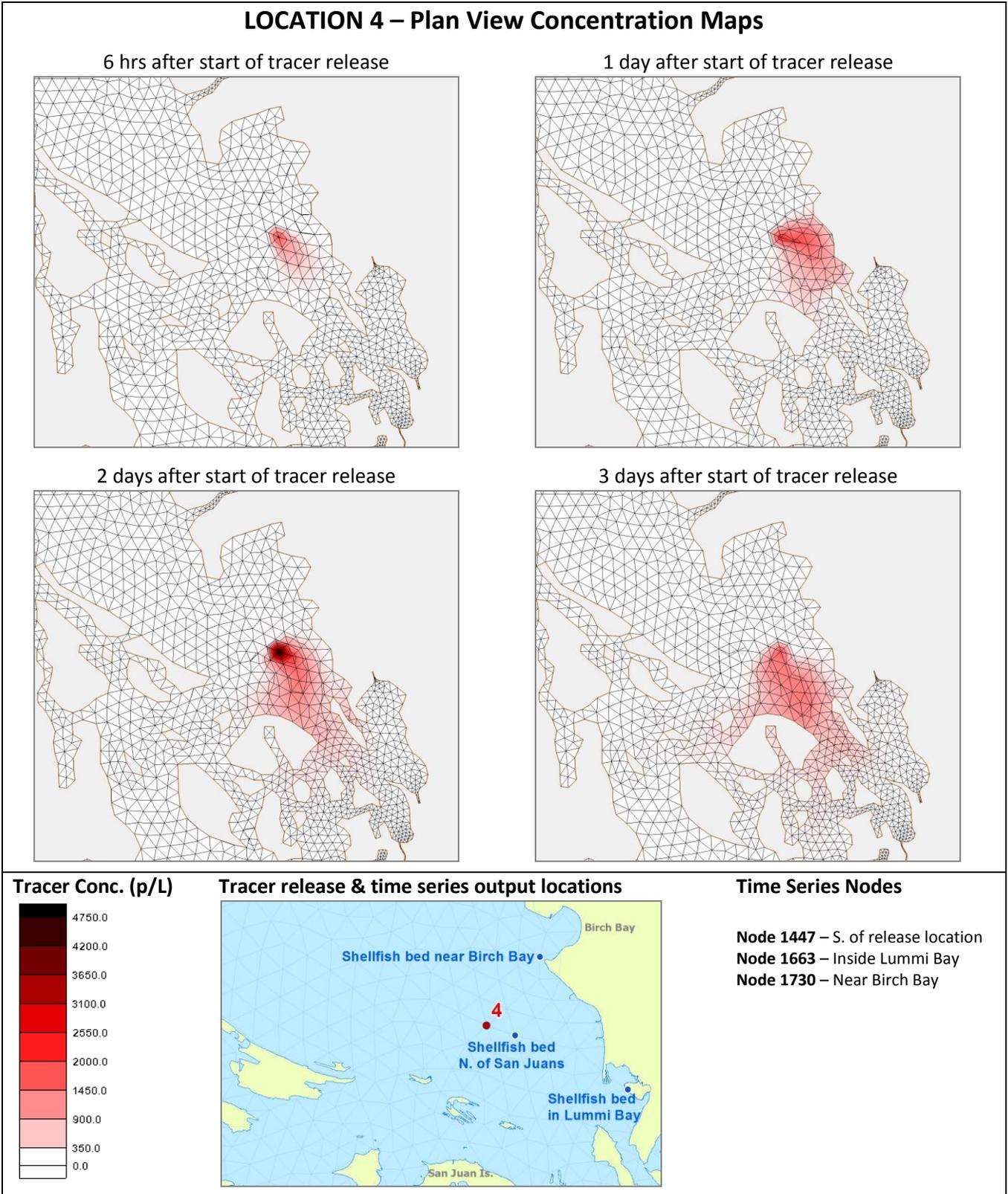


Figure 9. Horizontal dispersion of a tracer release at Location 4 illustrating surface layer tracer concentrations at different times after the start of the tracer release, and a map identifying model nodes where time series output was generated.

Results of Tracer Release at Location #4

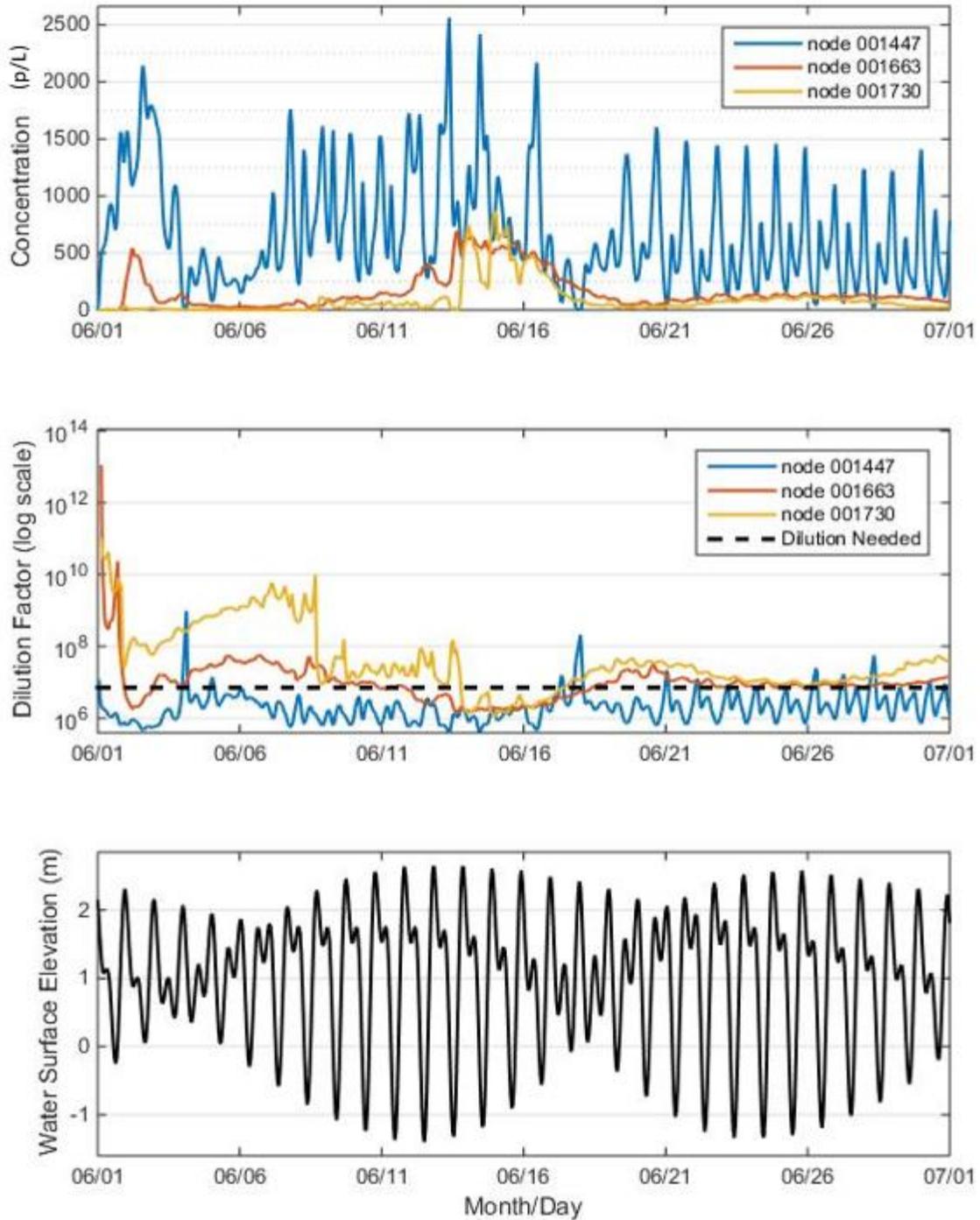


Figure 10. Time series of concentration and dilution factors resulting from a discharge at Location 4. Results are shown for three locations: just south of the discharge (node #001447), inside Lummi Bay (node #001663), and near Birch Bay (node #001730).

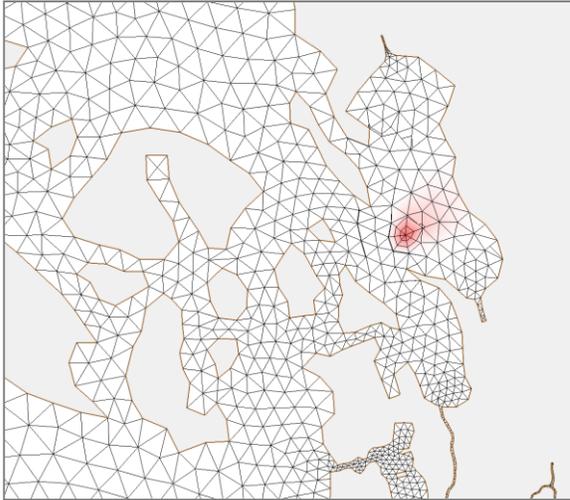
Location 5 – Entrance to Samish/Bellingham Bay

A tracer release at the entrance of Samish and Bellingham Bays is primarily pushed eastward and southward by the Nooksack River discharge in Bellingham Bay (Figure 11). The Fraser River discharge further north in Canada may also influence plume dispersion.

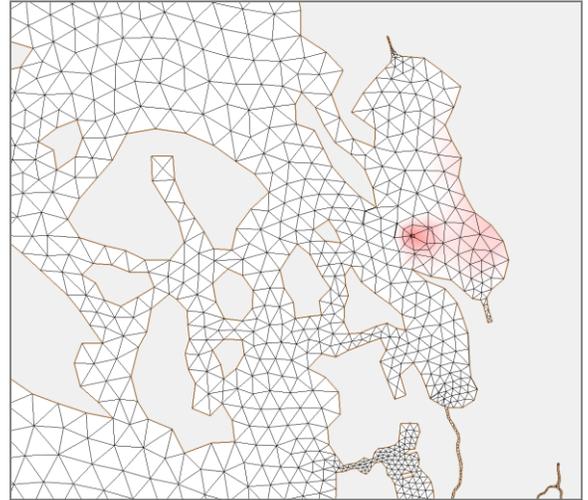
Tracer concentrations are generally high and dilution is low in Samish Bay and within the Fidalgo Bay Aquatic Reserve (Figure 12). Concentrations remain above 140 or 430 p/L throughout June. The peaks average 1030 p/L in Fidalgo Bay and Samish Bay (Figure 12). Concentrations in Bellingham Bay are lower, but still exceed 140 or 430 p/L in late June. Dilution in Bellingham Bay is slightly higher due to closer proximity to the Nooksack River discharge.

LOCATION 5 – Plan View Concentration Maps

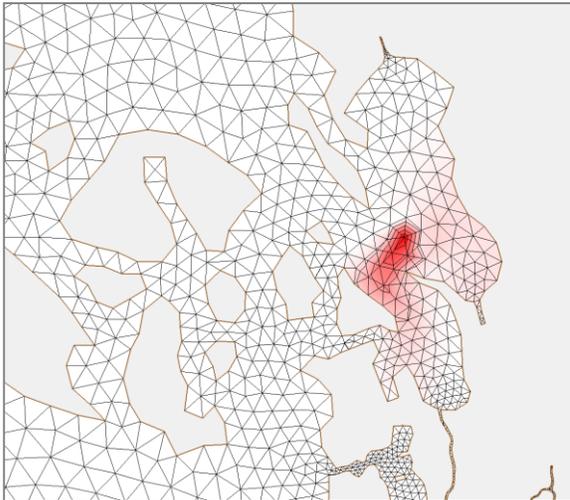
6 hrs after start of tracer release



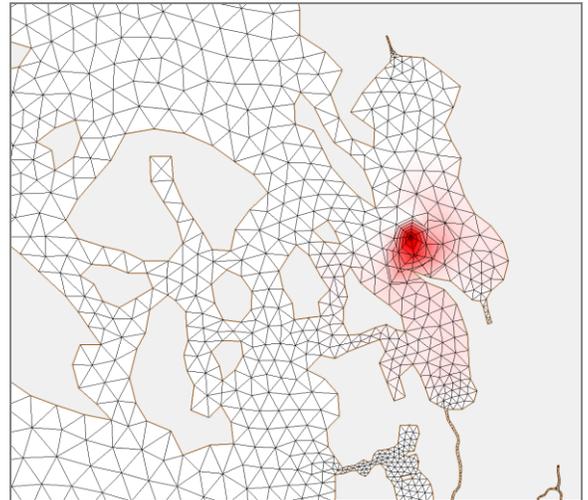
1 day after start of tracer release



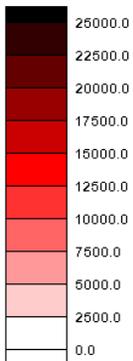
2 days after start of tracer release



3 days after start of tracer release



Tracer Conc. (p/L)



Tracer release & time series output locations



Time Series Nodes

- Node 1922** – Fidalgo Bay Aquatic Reserve
- Node 2231** – Samish Bay
- Node 2238** – Bellingham Bay

Figure 11. Horizontal dispersion of a tracer release at Location 5 illustrating surface layer tracer concentrations at different times after the start of the tracer release, and a map identifying model nodes where time series output was generated.

Results of Tracer Release at Location #5

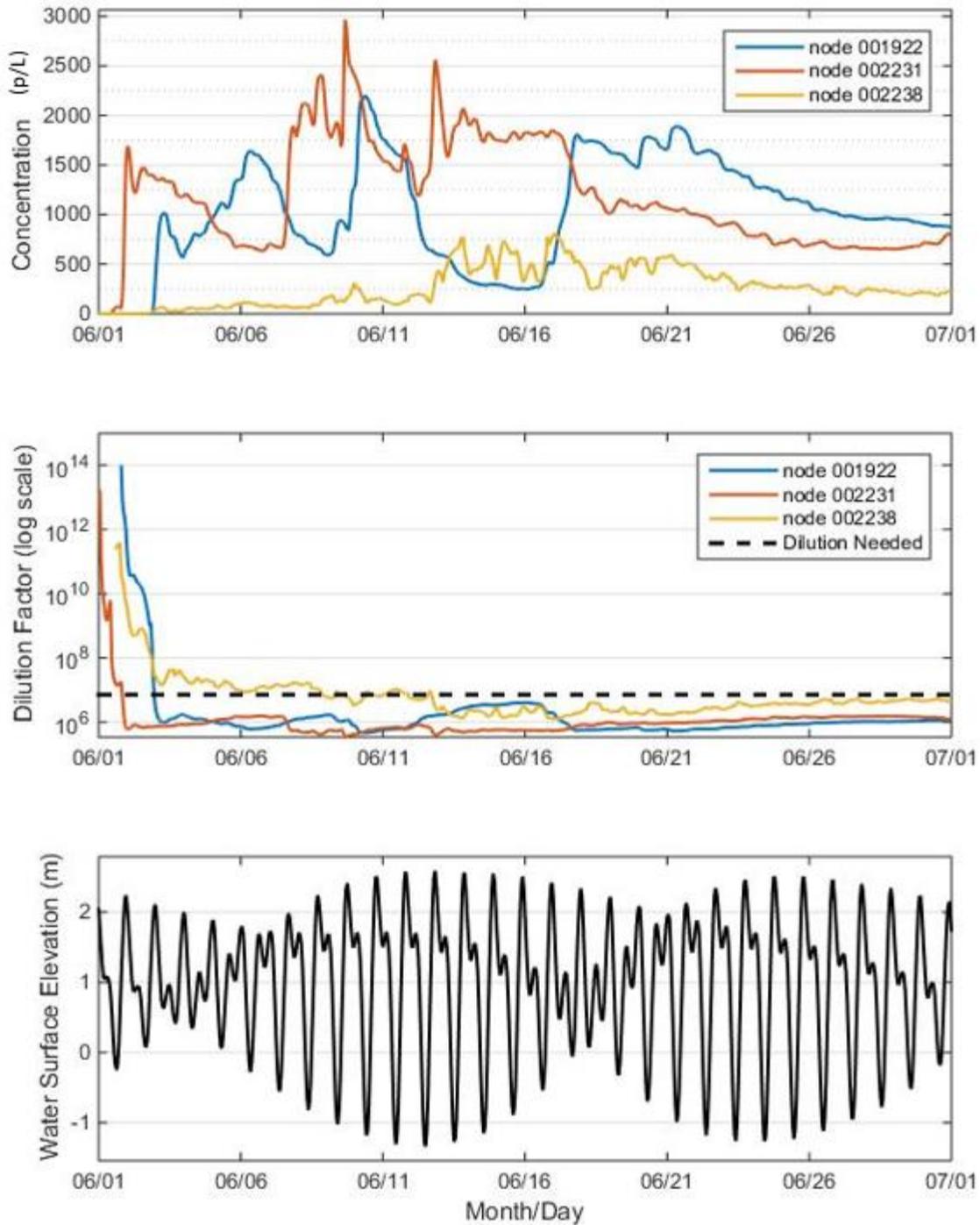


Figure 12. Time series of concentration and dilution factors resulting from a discharge at Location 5. Results are shown for three locations: within the Fidalgo Bay Aquatic Reserve (node #001922), inside Samish Bay (node #002231), and inside Bellingham Bay (node #002238).

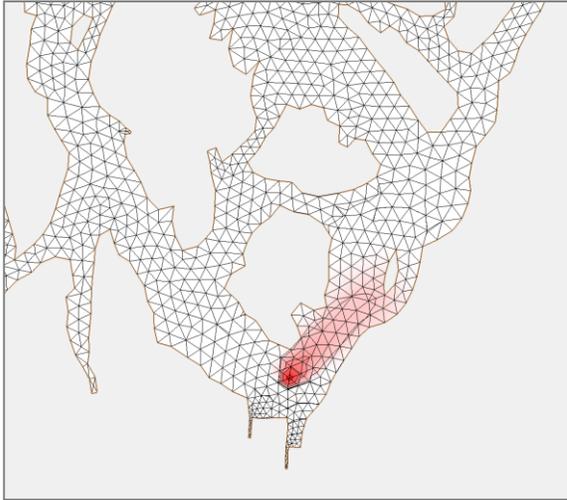
Location 6 – South Puget Sound, north of Nisqually Delta

A tracer release in South Puget Sound just north of the Nisqually Delta pulses in and out of the main passage of Puget Sound southeast of the Tacoma Narrows bridge. The plume also reaches the entrance of Carr Inlet and spreads southward into the Nisqually Delta and westward into the Nisqually Reach (Figure 13). South Puget Sound generally has lower circulation relative to the rest of Puget Sound, reflected in the high concentrations and low dilution observed at the selected sensitive areas. The rivers in South Puget Sound discharge lower flows than the larger watersheds to the North. The Nisqually River appears to push the plume away from the delta.

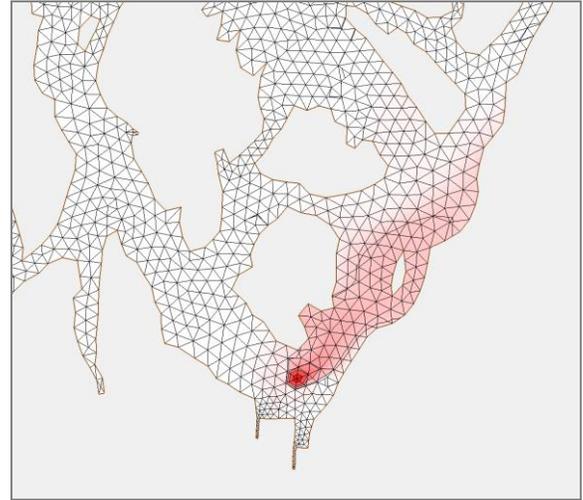
Tracer concentrations remain well above 140 or 430 p/L throughout June. Of the sensitive areas analyzed, concentrations are highest on the west side of the Nisqually Delta, averaging 840 p/L, and on the west side of the Nisqually Reach, averaging 380 p/L (Figure 14). Dilution is highest in the direction of the Nisqually Reach, and lowest in the west inlet of the Nisqually Delta and south of Fox Island.

LOCATION 6 – Plan View Concentration Maps

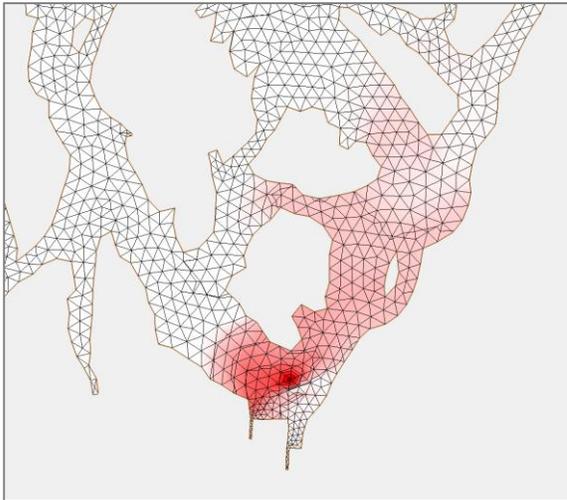
6 hrs after start of tracer release



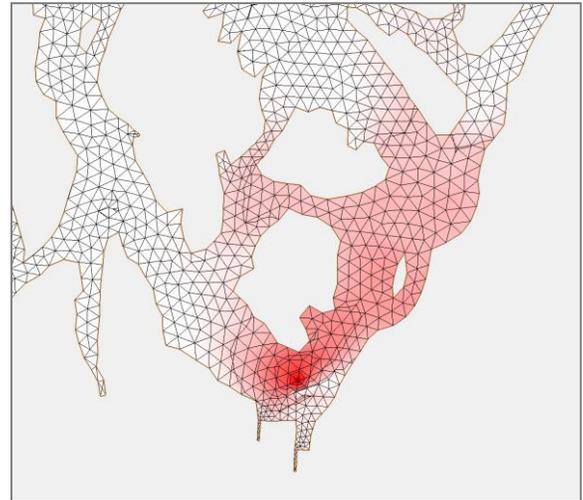
1 day after start of tracer release



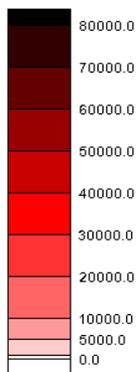
2 days after start of tracer release



3 days after start of tracer release



Tracer Conc. (p/L)



Tracer release & time series output locations



Time Series Nodes

- Node 7226** – S. of Fox Island
- Node 7696** – Pitt Passage
- Node 7964** – S. side of Nisqually Reach
- Node 8107** – W. side of Nisqually Delta

Figure 13. Horizontal dispersion of a tracer release at Location 6 illustrating surface layer tracer concentrations at different times after the start of the tracer release, and a map identifying model nodes where time series output was generated.

Results of Tracer Release at Location #6

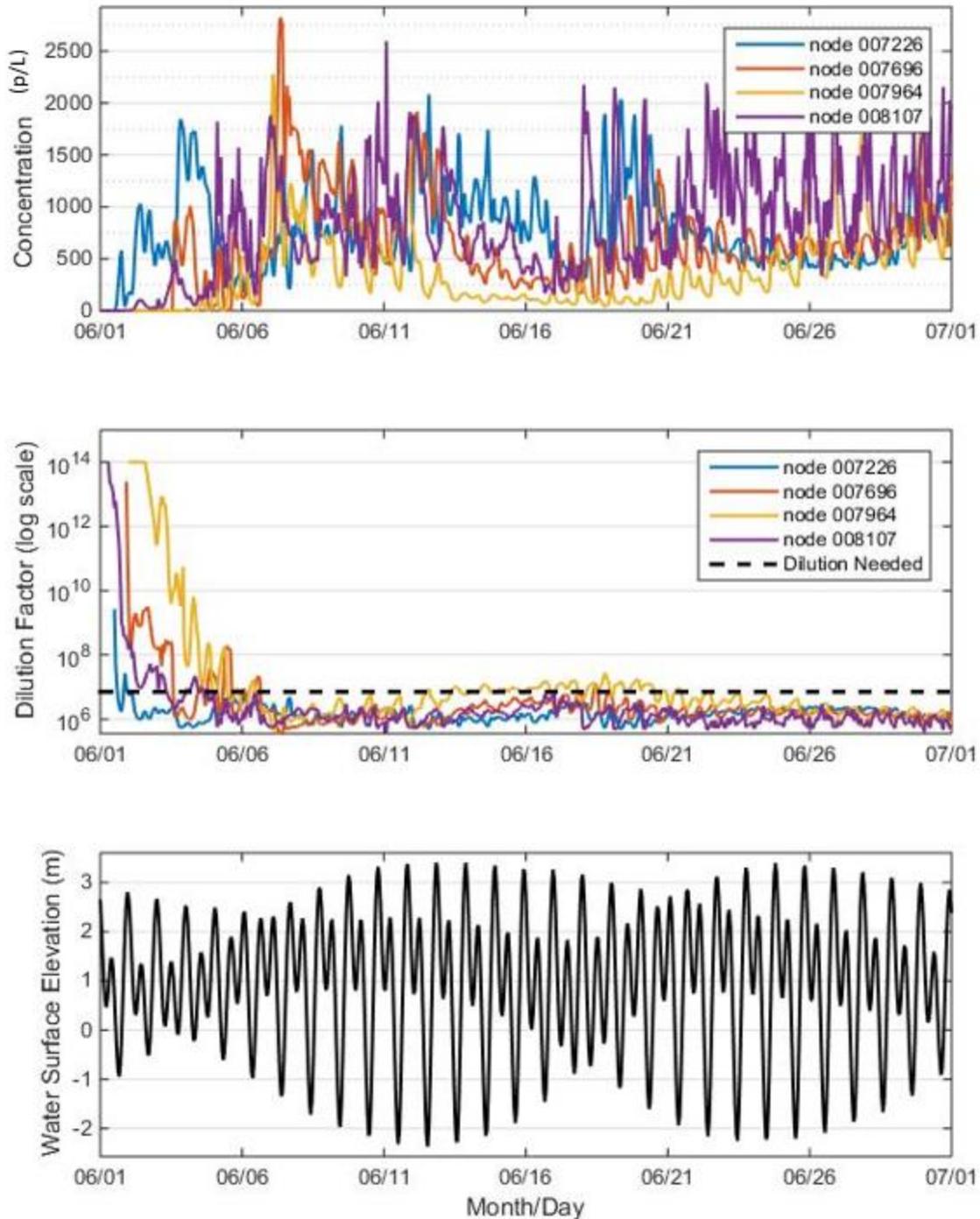


Figure 14. Time series of concentration and dilution factors resulting from a discharge at Location 6. Results are shown for four locations: south of Fox Island (node #007226), inside Pitt Passage (node #007696), south side of Nisqually Reach (node #007964), and the west side of the Nisqually Delta (node #008107).

2.3 Discussion of Continuous Tracer Releases

The continuous tracer releases were designed to evaluate connectivity between potential vessel discharge locations and nearby sensitive areas. Using the FVCOM model of the Salish Sea, we released a continuous virtual conservative tracer at six locations to evaluate whether discharges equivalent to raw sewage would have the potential to reach sensitive areas at levels that could impair natural resources. This was evaluated by considering dilution between the discharge location and sensitive areas.

Model simulations show the strong influence of tidal cycles on the movement of the tracer plume at all six locations. At some locations, freshwater river inflows into Puget Sound from rivers also influence the movement and dilution of the tracer plume. Physical dilution is greater in areas of Puget Sound and the Salish Sea that are known to have higher circulation and where large rivers affect circulation. Dilution is lower in areas of Puget Sound that have low circulation and are further away from the influence of the Pacific Ocean. For all six discharge locations evaluated, there are several periods when the physical dilution alone would not disperse fecal coliform bacteria concentrations typical of raw sewage enough to maintain concentrations below the marine fecal coliform bacteria water quality standard of 14 or 43 organisms per 100 mL at sensitive areas.

Several factors were considered in the development of these scenarios that could underestimate or overestimate influences:

- Continuous discharges were selected to evaluate patterns of water connectivity rather than to quantify the impacts of a specific discharge directly. Vessels are mobile sources, and a single vessel is not likely to discharge wastewater continuously in one location for extended periods. However, multiple vessels can congregate in single locations for extended periods. Because we could not determine a priori what tidal or river flow conditions would lead to the highest potential impacts, we used a continuous release to evaluate a more complete range of conditions. This identified locations and times where discharges could reach sensitive areas at levels of concern. Also, the continuous release means that our analysis is conservative in the sense that it is more protective. See below for pulse releases.
- In the model runs, the distances between the discharge locations and the sensitive areas were greater than 3 miles for 13 of the 16 cases examined. Vessels could discharge at locations that are physically closer to or coincident with sensitive areas. Other sensitive areas are closer to the six discharge locations selected for this analysis. Results from the six locations would likely underestimate the influences at these closer locations.
- Tracer releases were simulated with the actual winds that occurred on that date in 2006. However, these may not be the most critical conditions, which could underestimate potential impacts. Winds blowing from the release location toward the sensitive shore location could bring higher concentrations (lower dilution factors) to shore faster than these simulations indicate.
- In addition, factors other than wind could result in different patterns than those observed in 2006, including river flow and salinity/temperature profiles from the Pacific Ocean that could influence circulation. Periods of lower river flows could have higher concentrations reaching

sensitive areas, and 2006 conditions could underestimate impacts. Other conditions could produce lower connectivity.

- The model is not simulating actual pathogens, and does not include die-off. Therefore, results should not be used to predict exact concentrations of fecal coliform bacteria, but rather, to evaluate connectivity between potential discharge locations and sensitive near-shore areas where valuable shellfish resources are present. Neglecting die-off overestimates impacts. See Section 4 for additional considerations related to fecal coliform die off.
- Moving vessels could disperse releases faster than stationary vessels.

In summary, the conservative tracer runs indicated that water masses are highly connected. Transport to sensitive areas varies with the tides, river inflows, and wind conditions. Not enough physical dilution occurs to ensure that concentrations would remain below either the marine water quality standard for fecal coliform bacteria of 14 or 43 organisms per 100 mL for the sensitive locations and conditions evaluated. We cannot rule out the influence of vessel discharges at each of the six locations, even though most of the sensitive areas are at distances from the release locations at greater than 3 miles from shore. Discharges have the potential to reach nearby sensitive areas at concentrations that could impair natural resources.

3.0 Pulse Tracer Releases

The FVCOM hydrodynamic model of the Salish Sea is designed to answer larger-scale questions about circulation within Puget Sound and the Salish Sea, and has a relatively coarse grid for computational efficiency. When the model is used to evaluate a continuous discharge, it is effective in establishing connectivity between locations of potential vessel discharge, and potential dilution of that discharge by the time it reaches sensitive nearshore areas and shellfish beds. However, since vessels do not discharge continuously over long periods of time, we simulated a pulse release in the model to provide further perspective.

We selected Location 5, near the entrance to Samish Bay and Bellingham Bay, partly because continuous simulation results showed some of the highest concentrations of the tracer at sensitive areas. Samish Bay is also of particular interest for other pollution control efforts.

3.1 Methods of Pulse Releases

We evaluated whether a pulse release would disperse sufficiently such that we can rule out impacts from vessels >3 miles from sensitive areas. We released 3000 gallons, based on required tank volumes provided by the American Waterways Operators (Costanzo, 2014) to the Economic Evaluation summarized by Brauer and Michaud (2015) for tugs and similar vessels. Costanzo (2014) cites International Maritime Organization's International Convention for the Prevention of Pollution from Ships (MARPOL) rules. For a crew of 7 and 21 days, the minimum tank size was 2911 gallons (Costanzo, 2014). We used a duration of 1 hour for the release from a stationary vessel.

When the model calculates concentrations at each model node, it actually represents the concentration within a much larger area surrounding that node. More specifically, the concentration at a node represents the concentration in the surrounding ‘tracer control element’ or TCE. The TCE for the node at Location 5 in the FVCOM model is illustrated by the yellow area in Figure 15. Each node in the model is surrounded by triangular grid cells called ‘elements’. The edge of the TCE for each node is defined by drawing straight lines between the centroids of each triangular element and the midpoint between the edges of each triangular element, represented by the red lines in Figure 15.

The surface area of the TCE surrounding Location 5 is $3.11 \times 10^6 \text{ m}^2$ (1.2 mi^2), and the depth of the top layer of the model is about 0.86 m (the actual depth varies with the tides), resulting in a volume of $2.67 \times 10^6 \text{ m}^3$ into which the vessel effluent was discharged. This is similar to the volume of an Olympic-sized swimming pool ($2.5 \times 10^6 \text{ m}^3$). The model cannot resolve smaller volumes of water. For example, if purple dye was released in the middle of the pool at the surface, the best the model can do is instantaneously disperse the dye evenly over the entire swimming pool, from end to end and from surface to bottom. The model cannot calculate finer volumes or concentrations as the dye is spreading within the calculation element. This phenomenon is called numerical dispersion.

Numerical dispersion would artificially induce a dilution factor equivalent to the TCE volume divided by the volume of the release:

$$\frac{2.67 \times 10^6 \text{ m}^3}{3000 \text{ gal}} = 2.3 \times 10^5$$

In other words, a release of raw sewage (10^9 p/L) would artificially and instantaneously dilute to $4.3 \times 10^3 \text{ p/L}$ in the model, which overestimates dilution greatly compared with expected patterns in actual marine environments. Subsequent advection and dispersion would continue to decrease concentrations as the tracer reached adjacent model nodes.

The model cannot resolve a 3000-gal release directly. However, a fundamental question is how pulse releases behave compared with continuous releases. To investigate how a pulse release at Location 5 would move and disperse, we simulated a higher-concentration release that would produce concentrations on the order of 10^9 p/L throughout the TCE. This required a much higher tracer release concentration ($2.34 \times 10^{14} \text{ p/L}$) to keep the volume at 3000 gal, since adding more freshwater affects local estuarine circulation. The results were then scaled to alternative initial concentrations. The volume was released over an hour at a rate of $3.17 \times 10^{-3} \text{ m}^3/\text{s}$, which increased dilution over the theoretical instantaneous dilution.

The pulse was released 49 hours prior to the peak concentration, which is based on the time elapsed in the continuous release in Figure 16 between the start of the release and the first tracer peak at model node 2231 in Samish Bay (Table 1). The peak concentration in Samish Bay was associated with the lowest dilution factor in the continuous releases (Figure 16).

Two pulse releases were simulated in the model as follows:

1. **June 9th Pulse Release:** 3000 gallons of $2.34 \times 10^{14} \text{ p/L}$ dye tracer (sediment) released over one hour starting 3:00 pm
2. **July 5th Pulse Release:** 3000 gallons of $2.34 \times 10^{14} \text{ p/L}$ dye tracer (sediment) released over one hour starting 4:00 pm

All concentration results were evaluated for only the surface layer of the model.

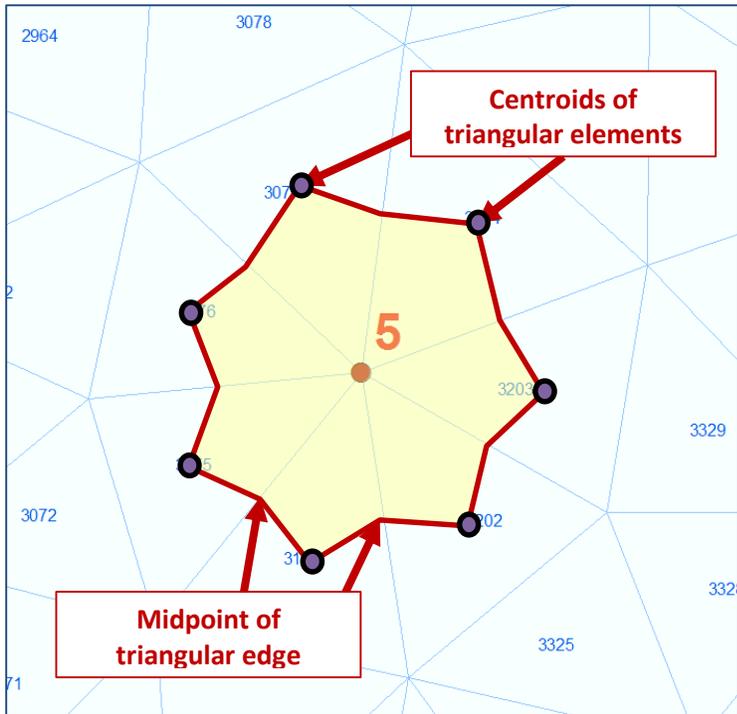


Figure 15. Illustration of the FVCOM triangular grid structure, and the tracer control element (TCE) associated with the node at Location 5.

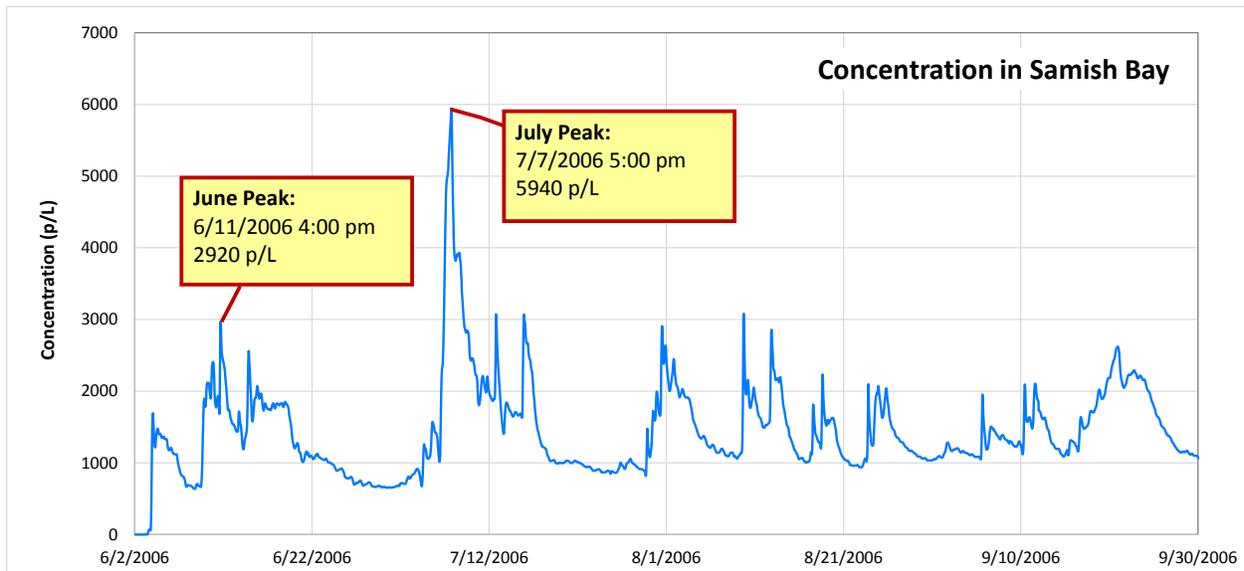


Figure 16. Tracer concentration in Samish bay as a result of continuous dye released at Location 5 between June-September 2006, with the two highest concentration peaks identified.

3.2 Results of Pulse Tracer Releases

Figure 17 presents the results of both the June 9 and July 5 pulse releases. The maximum concentration within the Location 5 TCE was 3.87×10^8 p/L in June and 3.15×10^8 p/L in July. This illustrates an initial dilution on the order of 10^5 within the TCE due to numerical dispersion, before the pulse begins to disperse and travel outward into surrounding grid elements. The concentration at the TCE quickly declined, although a small amount of dye returned to the node over several tidal cycles.

During the June pulse release, tracer reached a peak at the Fidalgo Bay node 20 hours after the release and at a peak concentration of 4.0×10^6 p/L resulting from the release concentration of 2.34×10^{14} p/L. This is equivalent to a dilution factor of 5.8×10^7 . Compared with the maximum concentration within Location 5 TCE, the peak concentration represents a dilution factor as low as 96 (Table 2) compared with the concentrations in the TCE. Similarly, the node in Samish Bay peaked at 3.4×10^6 p/L in 24 hours, representing a dilution factor of 114. The tracer reached Bellingham Bay at a peak of 2.9×10^5 p/L after 123 hours, representing a much higher dilution of 1.3×10^3 .

During the July pulse, the Samish Bay node peaked at 2.2×10^7 p/L after 18 hours for a dilution factor of 14 compared with the maximum concentration within the Location 5 TCE. Different river conditions likely protected the Fidalgo Bay node from receiving much tracer, with an equivalent dilution factor of 3.6×10^2 compared with the TCE concentration. The tracer reached Bellingham Bay after 209 hours at a much higher dilution.

Table 3 summarizes dilution factors and tracer concentrations for the June pulse; we did not evaluate the July results. First, in column A we calculated the maximum possible dilution that assumes instantaneous complete mixing in the TCE. In column B, we accounted for releasing the tracer over an hour instead of instantaneously, which produced a higher dilution factor than would occur for an instantaneous release. Third, we scaled the results to releasing sewage with (column C) and without (column D) accounting for the mixing within the TCE to bound the actual dilution. Beginning with a release concentration equivalent to residential sewage, we scaled the peak concentration at the node in Fidalgo Bay using the dilution factors in Column B to provide the lowest peak concentrations. We also calculated the highest peak concentrations without the initial mixing. Finally, we also evaluated the maximum concentration if the tracer had been released at a concentrations of 2×10^7 p/L. This value was the average effluent concentration from a marine sanitation device cited in an EPA study of cruise ships where the maximum values were as high as 2.4×10^8 p/L (U.S. EPA, 2008). Under this average initial concentration, results are presented with (Column E) and without (Column F) initial mixing.

For example, if the initial release concentration was 10^9 p/L, including instantaneous and complete mixing in the TCE, then the peak concentration in the TCE after mixing would decrease to 17 p/L. Applying a dilution factor of 96 and converting to organisms per 100 mL would result in a maximum of 0.02 organisms per 100 mL at Fidalgo Bay for the conditions modeled. Without the initial TCE dilution, the peak concentrations would be 10^6 organisms per 100 mL at the sensitive node before die-off. Adding in the effect of die-off would decrease peak concentrations at Fidalgo to 2.6×10^5 organisms per 100 mL. Using an alternative initial concentration of 2.0×10^7 p/L changes the peak concentration but not the result compared with either value of 14 or 43 organisms per 100 mL. The July pulse results (Table 2) scale similarly, although the Samish Bay node is more sensitive than the Fidalgo Bay node.

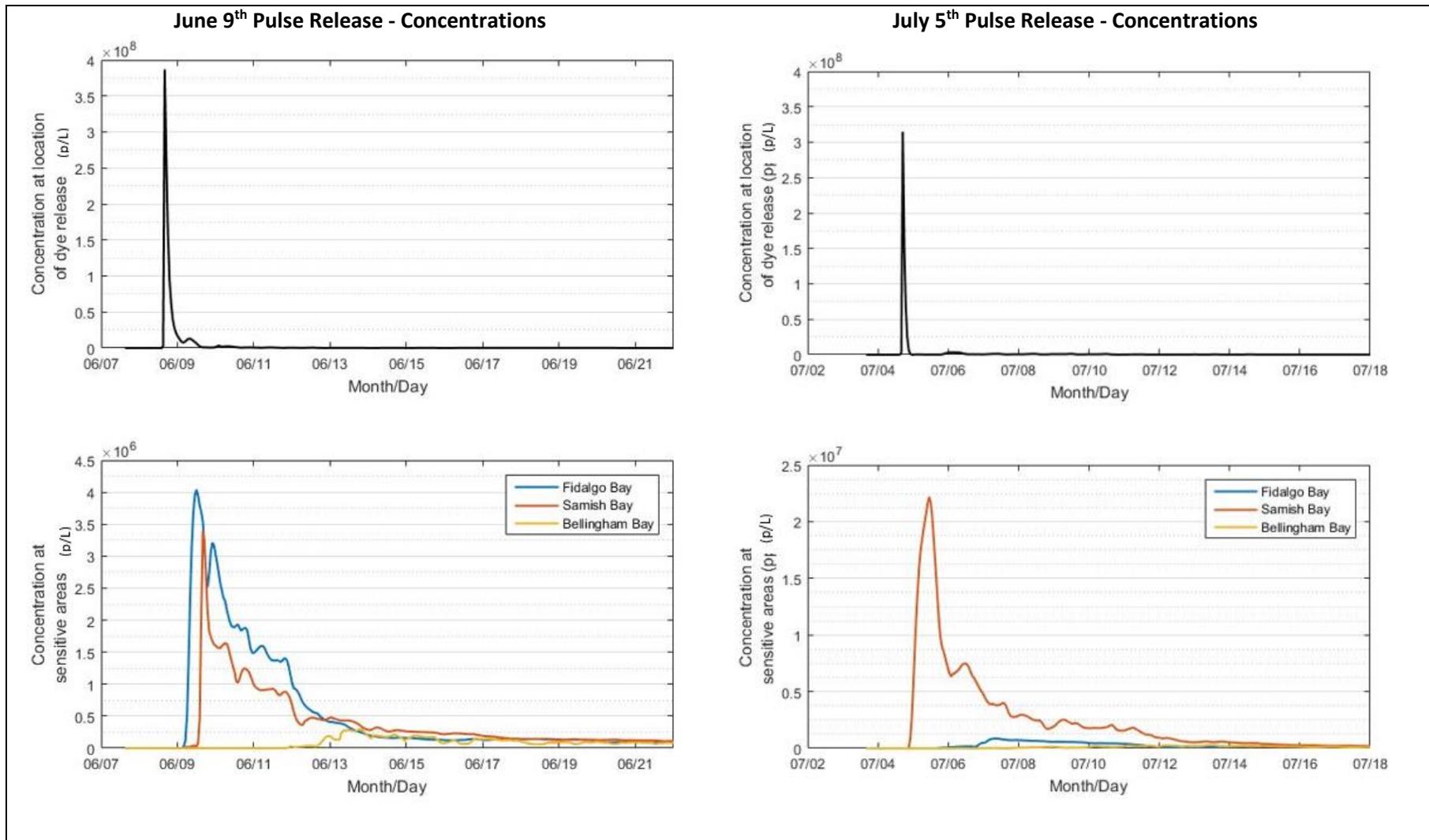


Figure 17. Timeseries of tracer concentrations in June and July at the location of the pulse release (top panel) and at sensitive areas (bottom panel).

Table 2. Summary of model results for a pulse release at Location 5, and evaluated at nearby sensitive areas.

June 9th Pulse Release				
	Peak pulse concentration at sensitive areas	Travel time of peak since pulse release	Min. dilution factor associated with peak concentration	Max. dilution factor associated with peak concentration
Fidalgo Bay	4.0 x 10 ⁶ p/L	20 hrs	95.8	5.8 x 10 ⁷
Samish Bay	3.4 x 10 ⁶ p/L	24 hrs	114	6.9 x 10 ⁷
Bellingham Bay	2.9 x 10 ⁶ p/L	123 hrs	1320	8.0 x 10 ⁸
July 5th Pulse Release				
	Peak pulse concentration at sensitive areas	Travel time of peak since pulse release	Min. dilution factor associated with peak concentration	Max. dilution factor associated with peak concentration
Fidalgo Bay	8.7 x 10 ⁵ p/L	63 hrs	363	2.7 x 10 ⁸
Samish Bay	2.2 x 10 ⁷ p/L	18 hrs	14.2	1.1 x 10 ⁷
Bellingham Bay	2.7 x 10 ⁵ p/L	209 hrs	1160	8.6 x 10 ⁸

Table 3. Summary of model results and scaling for alternative initial concentrations, with and without initial mixing in the model tracer control element (TCE).

	A - Salish model run with pulse release (theoretical instantaneous)	B - Salish model run with pulse release (release over 1 hr)	C - Scaled to residential sewage with complete mixing in TCE	D - Scaled to residential sewage with no mixing in TCE	E - Scaled to EPA vessel study with complete mixing in TCE	F - Scaled to EPA vessel study with no mixing in TCE
Initial release concentration (p/L)	2.34E+14	2.34E+14	1.0E+09	1.0E+09	2.0E+07	2.0E+07
Dilution by model in TCE	2.3E+05	5.8E+07	5.8E+07	1.0E+00	5.8E+07	1.0E+00
Concentration in release TCE (p/L)	1.0E+09	4.0E+06	17	1.0E+09	0.3	2.0E+07
Dilution between Loc 5 and Fidalgo Bay	96	96	96	96	96	96
Peak conc at Fidalgo Bay (p/L)	1.1E+07	4.2E+04	1.8E-01	1.0E+07	3.6E-03	2.1E+05
Convert to organisms per 100 mL	10	10	10	10	10	10
Peak conc at Fidalgo Bay (#/100 mL)	1,059,783	4,203	0.02	1,041,667	0.0004	20,833
< or > 14/100 mL (no die-off)			<14	>14	<14	>14
< or > 43/100 mL (no die-off)			<43	>43	<43	>43
Die-off factor	4	4	4	4	4	4
Peak conc at Fidalgo w/die-off (#/100 mL)	264,946	1,051	0.004	260,417	0.0001	5,208
< or > 14/100 mL (with die-off)			<14	>14	<14	>14
< or > 43/100 mL (with die-off)			<43	>43	<43	>43

3.3 Discussion of Pulse Releases

The Salish Sea model was used to evaluate how pulse releases behave. An infinite number of combinations exist in terms of pulse release locations, volumes, and concentrations; sensitive area locations where high fecal coliform concentrations would be problematic; ebbing or flooding tidal conditions and the lunar tidal cycle; river flow conditions; and wind and other meteorology. We selected one release location (Location 5), three model nodes at nearby sensitive areas, one volume consistent with the minimum tank volume in the Economic Analysis, and two dates for one-hour releases. The results are not exhaustive, and greater or lesser impacts may occur under different conditions.

The Location 5 pulse releases reached Fidalgo and Samish Bays as quickly as 18 to 24 hours. The time to peak concentration at Fidalgo Bay in the July release was several days, while travel time to Bellingham Bay was on the order of a week for both months considered. Many factors influence concentrations at the sensitive locations. Peak concentrations were lower when travel time increased at certain nodes. Peak concentrations declined over several days at each node, reflecting additional advection and dispersion. How the initial dilution within the TCE is considered influences the results. Concentrations peaked at nearby sensitive areas at levels representing dilution factors as low as 14 to 114 compared with peak concentrations in the TCE. Compared with the initial release concentrations, peak concentrations represent dilution factors of 10^7 to 10^8 . Factors such as initial concentration and whether or not die-off was included also influence concentrations.

The pulse release results provide high and low bounds for the peak concentrations that could occur due to physical dilution between release Location 5 and the nodes in the sensitive areas. Ignoring initial mixing and using the maximum concentration in the TCE to calculate dilution factors produces the smallest possible dilution. This would not be enough to protect sensitive locations from physical dilution alone. Assuming instantaneous and complete mixing across the TCE adds an additional dilution factor of 2.3×10^5 and produces the largest physical dilution, which would be sufficient to protect sensitive locations from physical dilution alone. The maximum possible dilution likely overestimates dilution and underestimates concentrations in sensitive locations. The minimum possible dilution likely underestimates dilution and overestimates concentrations in sensitive locations.

Factors that could overestimate the dilution factors and underestimate the peak concentrations at sensitive locations include:

- Instantaneous and complete mixing across an area equivalent to 1.2 mi^2 (TCE surface area) is highly unlikely in reality.
- The surface layer at Location 5 was assumed to be a constant 0.86 m, but a freshwater release would likely occupy a thinner layer than the full surface layer depth in the model. Concentrations would be higher in the thinner layer.
- Peak tracer concentrations occurred in advance of the 49-hour travel time predicted from the continuous release, and conditions more favorable to transport may have occurred if released later.
- Other sensitive locations are closer to Location 5 than the nodes modeled. The nodes in Fidalgo and Samish Bays were selected to be representative.
- Releases may occur closer to sensitive areas than from Location 5.

- Vessels may release holding tanks in less than an hour. Simulating a release with a duration of an hour allows some tracer to escape the node through advection and dispersion away from the release location. More rapid vessel releases would produce higher concentrations and less dilution than predicted for a one-hour duration release.
- Vessel releases may be more concentrated than residential wastewater because less gray water is produced.
- Vessels could discharge at larger volumes than the minimum tank size required under MARPOL.

Factors that could underestimate the dilution factors and overestimate the peak concentrations at sensitive locations include:

- Some initial dilution could occur, especially for moving vessels.
- Vessels could discharge at smaller volumes than the minimum tank size required under MARPOL.
- Vessel releases may be less concentrated if disinfection reduces tank concentrations.
- Die-off likely accounts for an additional dilution factor of 2 to 4 (see next section Table 3), although less die-off would occur with lower salinity in the surface layer.

The pulse release scenarios indicate that under certain conditions, the vessel discharges at Location 5 potentially impact sensitive locations.

4.0 Effects of Fecal Coliform Die-off

The continuous tracer analyses were performed assuming a conservative tracer that does not sink or die off. This neglects how pathogens respond to marine environments. Most pathogen die-off processes are represented as first-order decay rates, where the concentration at any time (t) is a function of the initial concentration (C_0) and a decay rate (k, with units of per time):

$$C(t) = C_0 e^{-kt}$$

The larger the first-order decay rate, the faster the die-off. Decay rates vary by organism as well as the environment they are subject to. Auer and Niehaus (1993) and Chigbu et al. (2005) summarize how different factors influence pathogen survival. These include ultraviolet light, salinity, and temperature in marine environments, which vary with time and over the Salish Sea model domain.

Sargeant et al. (2006) included local Puget Sound studies on fecal coliform die-off rates. These resulted in decay rates ranging from 1.4 to 2.0 d^{-1} . Figure 19 presents the theoretical percent survival of fecal coliform bacteria based on the range identified in Sargeant et al. (2006). Table 3 describes the percent survival and resulting concentrations based on an initial concentration of 10^9 p/L (equivalent to 10^8 organisms/100 mL in raw sewage) or 2000 organisms per 100 mL and a die-off rate of 1.4 d^{-1} .

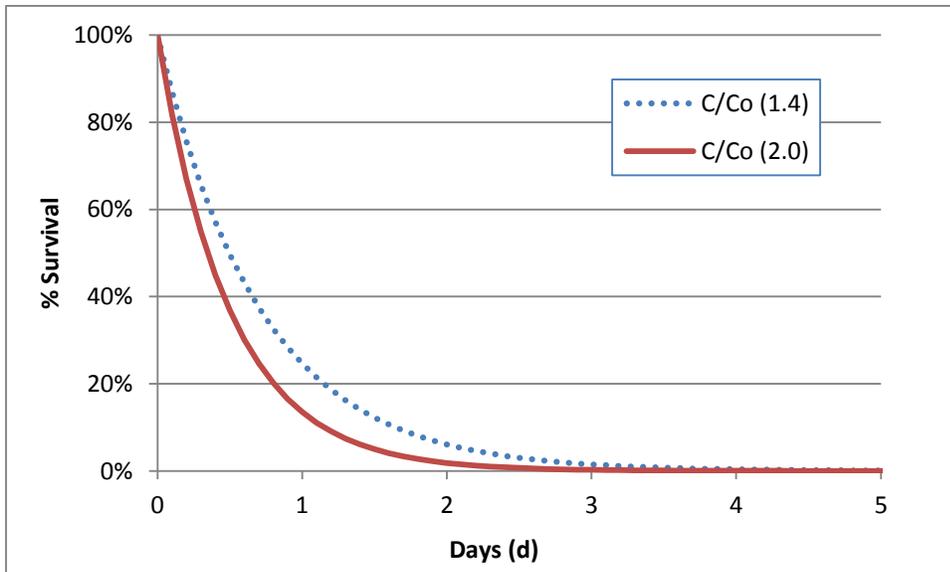


Figure 19. Fecal coliform bacteria percent survival as a function of days based on two first-order decay rates from Sargeant et al. (2006).

Table 3. Fecal coliform percent survival and surviving concentrations based on different initial concentrations and a die-off rate of 1.4 d^{-1} .

Days	C/C_0	C_0/C (dilution factor)	$C(t)$ for $C_0 = 10^8$ organisms/100 mL	$C(t)$ for $C_0 = 2000$ organisms/100 mL
0.5	50%	2.0	4.97×10^7	993
1	25%	4.0	2.47×10^7	493
1.5	12%	8.2	1.22×10^7	245
2	6%	16	6.08×10^6	122
3	1.5%	67	1.50×10^6	30
4	0.4%	270	3.70×10^5	7
5	0.1%	1100	9.12×10^4	2

During winter conditions, with less ultraviolet radiation and lower water temperatures, die-off reaches a seasonal minimum (Auer and Niehaus, 1993; Chigbu et al., 2005). Therefore, neglecting die-off may not significantly overestimate impacts during winter conditions. Nonetheless, after 72 hours, fecal coliform bacteria are expected to die off to 1.5% of the initial concentration (equivalent to a dilution factor of 67). The model indicates that the tracer released at each of the six locations took less than 72 hours to arrive at nearby sensitive areas. Therefore, neglecting die-off or decay factor in the model may be reasonably conservative.

5.0 Conclusions and Recommendations

Several analyses were designed to evaluate the potential for vessel discharges over 3 miles offshore to affect sensitive water bodies at levels that could be problematic in terms of fecal coliform bacteria concentrations. We used an existing model of the Salish Sea to release virtual conservative tracers as proxies for vessel releases at six representative locations. We found that vessel discharges at each of the

six locations have the potential to be transported to nearby sensitive areas at concentrations that could impair natural resources. The amount of physical dilution varies with the tide and other environmental influences, as well as release location and which sensitive areas were evaluated.

Raw sewage has much higher concentrations of fecal coliform bacteria than the marine water quality standard. Concentrations must decline many orders of magnitude through physical factors or die-off in order to meet the standard. Therefore, we developed this analysis to focus on dilution factors. For example, a dilution factor of 1000 is equivalent to 10^3 , which is a reduction of three orders of magnitude.

We evaluated the ratio of maximum concentration at the sensitive areas to the initial concentrations using several techniques to quantify the time-varying dilution. These represent physical processes alone, neglecting die-off, since the Salish Sea tracer model does not account for die-off directly. We evaluated the influence of die-off separately.

Continuous releases of conservative tracers in the model helped identify the range of dilution that would occur, and what environmental conditions would increase or decrease maximum concentrations at the sensitive areas. We identified which conditions produce the highest concentrations at select sensitive areas, which represent the lowest dilution from the release locations. Patterns of concentrations and dilution factors allowed us to evaluate potential connectivity between releases and nearby sensitive areas. Dilution alone does not prevent the arrival of virtual tracer at concentrations that could exceed values equivalent to either part of the fecal coliform bacteria water quality standard, based on initial releases equivalent to raw sewage.

Actual vessel discharges are likely pulse releases, but the actual volumes, release locations, and vessel discharge quality can vary in an infinite number of combinations. Once we identified that the release locations potentially could impact sensitive areas based on continuous releases, we evaluated pulse releases near Samish and Bellingham Bays in two different months. However, the horizontal and vertical model scale, or the smallest volume that can be resolved with the model, is much larger than the vessel release volumes. The model cannot directly evaluate volumes smaller than the minimum model calculation volume, yet how much dilution occurs at this stage strongly influences whether concentrations could be above or below values in the water quality standards. Crediting the discharges with complete and instantaneous mixing over 1.2 mi² and 2.8 ft deep could produce concentrations two to three orders of magnitude below either part of the standard. However, this is highly unlikely in reality and overestimates dilution. Not including initial mixing within the model volume could produce peak concentrations five orders of magnitude above either part of the standard. This likely underestimates dilution.

Using a conservative tracer focuses on physical processes of advection and dispersion. These account for time-varying dilution factors ranging from as low as 14 up to over 10^8 for the model runs evaluated. The higher the dilution, the lower the marine concentration would be. In the marine environment, fecal coliform and pathogens die off over time, with rates dependent on environmental factors such as salinity, temperature, and ultraviolet radiation. Separately we explored how die-off in marine environments would further reduce concentrations based on literature results. For travel times between 12 and 24 hours, fecal coliform die-off would be expected to reduce concentrations by a factor of 2 to 4 beyond physical processes. Die-off has much less of an effect on marine concentrations than physical processes. In addition, some marine sanitation devices partially disinfect to treat microorganisms including fecal coliform, but removal performance varies considerably. Disinfection through MSDs could

reduce the initial concentrations but for only those systems that are properly operated and maintained and effective.

The Salish Sea model provides insight to complex circulation patterns around sensitive waters. Additional analyses could evaluate alternative conditions when dilution could be higher or lower than this effort. We assessed only a single summer seasonal condition that may not have represented worst-case results. In particular, fecal coliform die-off reaches a seasonal minimum with lower temperature, ultraviolet radiation, and salinity in the winter months. Advection and dispersion were stronger influences than die-off for the conditions evaluated.

Should further evaluation be considered, we recommend a smaller-scale analysis using a plume model such as CORMIX. This would be similar to a mixing zone analysis that could evaluate spatial scales finer than in the FVCOM hydrodynamic model, which would reduce the effects of numerical dispersion.

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