

Model/data comparison of a sewage outfall in Puget Sound using ammonium as a tracer

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Summary

The Renton South Treatment Plant discharges treated sewage into Puget Sound. The discharge location of the effluent is 3 km northwest off of the Duwamish Head and it is on average comparable to 5% of the output of the Duwamish River. Monitoring the quality of the effluent in order to protect the water quality of the Puget Sound is important. The sewage (effluent) is thought to remain submerged at a depth of 100 to 150 m which is known to have high ammonium concentrations that allow detection of the outfall. Tracing the outfall with ammonium verified the plume location while a Visual Plumes (VP) computer model supplied by the Environmental Protection Agency (EPA) modeled the plume path, elevation and dilution of the effluent plume during an ebb tide. Ammonium data collected over the outfall was useful in comparison to water quality standards for ammonium. The field work occurred on the *R/V Thomas G. Thompson* 19 March 2007 to 20 March 2007. The CTD was used to measure conductivity, temperature and depth, which resulted in measurements such as the salinity in the vicinity of the outfall. Fluorometer data taken from seawater samples provided analysis of ammonium concentrations. The ammonium concentrations were found to be moderate. Furthermore, data from two acoustic Doppler current profilers (ADCP) measured currents. However, in contradiction to the predicted depth of 100-150 m, the data input to the computer model VP pictured an effluent plume submerged at a depth of 175-185 m. Alternatively, the ammonium analysis provided a maximum concentration near 150 m, a probable indicator of the effluent plume. Perhaps connecting the depths of maximum ammonium concentrations to an equal depth of the VP plume elevation is a candidate for future research.

Acknowledgements

I would like to thank everyone at the University of Washington's School of Oceanography who helped me with my field work along the way. I thank Professors Mark Holmes and Susan Hautala for their instruction. I also thank Leon Delwiche for his revisions. Grateful thanks go to Kathy Kroglund, Charles Stump, and Aaron Morrello for all of their help in the laboratory. Finally, thanks to all of the crew from the *R/V Thomas G. Thompson* who assisted in all of my operations.

Abstract

Modeling the effluent plume from the Renton Treatment Plant in addition to monitoring ammonium levels is one way to monitor the water quality of the Puget Sound. The modeling was made possible using a Visual Plume (VP) computer model supplied by the Environmental Protection Agency (EPA). The model tested whether or not the effluent, during an ebb tide, remained submerged at a reported depth of 100-150 m. As a result, the model predicts that the plume would be found at a greater depth from 175-185 m. Field work was done on 19 March 2007 to 20 March 2007 aboard the *R/V Thomas G. Thompson* to verify the predictions of the model. The data was gathered using a conductivity, temperature and depth (CTD) profiler, two acoustic Doppler current profilers (ADCP) and a fluorometer to measure ammonium. A decrease in salinity over the outfall was evident in addition to temperature and salinity anomalies. Fluorometric ammonium analysis revealed moderate concentrations of ammonium near the center of the outfall. The model displayed the northwards pathway of the plume accurately. Although the VP model did not display the plume at the predicted depth, the ammonium analysis indicated the effluent plume was at a depth near 150 m.

Introduction

The waste water of the Renton Treatment Plant is treated before it is released into the Puget Sound, but it is important to monitor the quality of the effluent in order to protect the water quality of the Puget Sound. A healthy Puget Sound is a goal supported by a state agency known as the Puget Sound Partnership (PSP) (<http://www.psat.wa.gov/partnership/psp.htm>). They strive to achieve goals such that human health is not threatened by changes in the ecosystem. That includes a Puget Sound that is healthy for “swimmers, fishermen and other human uses and enjoyment” (PSP). The Puget Sound Action Team (PSAT) reports that, “High ammonium concentrations are indicative of human sources of organic waste such as sewage.” An environmental indicators report from the PSAT lists concentrations of high or moderate ammonium levels that cause concern for marine water quality based on Ecology/PSAMP data from 1994-2000 (http://www.psat.wa.gov/Publications/pshealth2002/pshealth_2002.pdf), a coordination of the Washington State Department of Ecology and The Puget Sound Assessment and Monitoring Program. Testing the ammonium concentrations in and near the outfall during an

ebb tide monitors the water quality, traces the movement, and establishes the location of the plume. The hypothesis that the discharge water from the treatment plant remains submerged near a depth of 100-150 m (Ebbesmeyer et al. 1996) is tested with salinity data from the outfall plotted against background salinity of the Puget Sound water. The outfall releases mainly fresh water, and therefore it causes a salinity anomaly. The Visual Plume (VP) model, produced by the EPA, displays the plume released by the outfall. When constrained with observed salinity, temperature and ocean current data, the VP model predicts how far the outfall rises vertically to the surface (elevation), the pathway (direction), and the dilution of the outfall.

The South Treatment Plant treats wastewater for reclaim or discharge into the Puget Sound via the Transfer Effluent System (TES). After the effluent is disinfected with sodium hypochlorite, a compound that kills disease causing bacteria, the effluent travels down 19 km of transfer line. The transfer line enters Elliot Bay from Duwamish Head via two pipelines that extend 3 km along the bottom, to a depth of 185 m. The last 150 m of each pipe distribute the effluent through 168 ports that help diffuse the effluent into the marine water. When fresh water enters the seawater, its buoyancy has a tendency to rise through the water column. The outfall discharges an average $375,000 \text{ m}^3 \text{ day}^{-1}$, and that is about 5% of the Duwamish River output. The South Treatment plant checks water quality by maintaining Discharge Monitoring Reports (DMR). These reports include measurements of pH, temperature, chlorine and total nitrogen (ammonium, ammonia, NO_3 , and NO_2). They monitor parameters such as temperature to check that the effluent is below the limit of $15 \text{ }^\circ\text{C}$ so that the marine environment will not be adversely impacted.

The current in this region is complex, and few references discuss the character of the flow near the outfall. The assumption is that the outfall plume will advect with the estuarine flow with surface waters moving seawards, out of the estuary, and bottom waters moving landwards into the estuary (Ebbesmeyer et al. 1996), which is a common form of circulation. One study finds that sub tidal flow at 130 m depth near the outfall area is predominantly to the northwest (Baker et al. 1983). However, this contradicts the estuarine model and deserves further investigation. Near surface circulation patterns include northward moving water that is forced by flow from Colvos Passage. This water moves towards Admiralty Inlet where more than half of it diverges into East Passage (Fig. 1a), (Bretschneider et al. 1985). These tidal currents form residual eddies north and south of Alki Point (Ebbesmeyer et al. 1996). Water east of Colvos Passage continues

southwards in a clockwise circulation pattern towards East Passage in the vicinity of the outfall. However, ebb tide forcing from Colvos Passage moves surface currents northwards.

At one station in Elliot Bay (ELB015) (Fig. 1b), the South Treatment Plant reported on their Facts Sheet (http://www.ecy.wa.gov/programs/wq/permits/permit_pdfs/king_county_south_wtp/Final%20Permit/KingCountySouthWWTP_Factsheet.pdf) that dissolved ammonia-ammonium was equal to 0.016 mg L^{-1} , and this station is not centered on the outfall. The outfall water is known to have high ammonium concentrations, higher than the ELB015 reported concentrations.

Turner and Greg (1994) describe a study of the West Point Sewage outfall that provides a useful comparison to this project. They report three different methods of tracing plumes such as using Rhodamine dye, taking CTD measurements, and measuring backscatter. In the backscatter method, they found a scattering layer just above the diffuser of 10 m thick. They also found a distinct decrease in salinity centered above the diffuser from the CTD data plotted in a salinity contour. In other CTD data they compared upstream salinity and temperature plots with plume temperature and salinity, which showed a difference of about 0.3 PSU and an effluent temperature of $12.8 \text{ }^{\circ}\text{C}$ (Turner and Gregg 1994). Using a VP program to make a model of the effluent and diffuser will make a good comparison to that model done of the West Point plume.

Methods

The physical oceanography field work occurred on 19-20 March aboard the *R/V Thomas G. Thompson*. Most of the work involved CTD operations and took place from 6:00 pm to 10:00 pm, on 19 March, during an ebb tide. A Sea-Bird 911 CTD *Plus* (SBE 11 *Plus*) profiler sampling at 24 Hz was used to profile temperature and salinity. The CTD package includes sensors for temperature, conductivity, and sonar altimeter. The underwater sensors have aluminum housings that are mounted on a stainless steel frame. The frame also contains the rosette consisting of twenty-four Niskin bottles that take seawater samples. The data from the CTD has been averaged into 1 decibar bins, using the software provided by Seabird Electronics.

CTD profiling occurred in four operations (Table 1). The first CTD cast was made over the effluent outfall, and 18 Niskin water bottle samples were taken from the CTD's rosette, starting at a depth of 190 m and ascending every 10 m (Fig. 1b). The second CTD operation was executed in Tow-Yo, where the CTD is winched up and down while the ship steams (Fig. 1b).

The ship's speed during this operation was 1 knot. Two Niskin water bottle samples were taken near 150 m of depth, one from the downcast and one from the upcast for a total of 10. The third CTD operation was also executed in Tow-Yo (Fig. 1b). Two Niskin water bottle samples were also taken near 150 m of depth, one from the downcast and one from the upcast for a total of 9. The fourth CTD operation was executed as a background cast at a distance of 1.557 km from the effluent outfall (Fig. 1b). Niskin water bottle samples were taken at three depths, one from the bottom (190 m), two from 150 m and one near the surface (20 m). The ship's ADCP is a 75 kHz RD Instruments Ocean Surveyor, and it was used at CTD stations and during Tow-Yo to provide current information. In addition to the ship's ADCP, a 300 kHz RD Instruments Workhorse Sentinel was attached to the CTD. This lowered ADCP (LADCP) was intended to detect the plume from acoustic backscattering because of high turbidity at the diffuser and the contrast in temperature and salinity, of the effluent and surrounding seawater (Turner and Gregg 1994). The ship's ADCP provides current velocity and direction by using broad band water-profiling pings with 8 m bin lengths that registers good data below 2 bins (16 m). The data has been averaged into 5-minute intervals, and some of the filtering and processing is done by the University of Hawaii data acquisition system that allows the data to be imported into Matlab. The LADCP averages vertical and horizontal velocity into a vertical profile that is averaged into depth bins.

The change in concentration of ammonium was measured from seawater samples taken near the plume. The seawater samples from the CTD casts were collected in Nalgene bottles in preparation for fluorometric ammonium analysis. These samples were analyzed the next day, 20 March, for ammonium concentrations, using a Turner Designs, TD-700 Fluorometer. The method for the analysis consisted of mixing standards to obtain a standardized curve (Holmes et al. 1999). For a background reference in the standard, filtered Atlantic seawater with a salinity of 35 PSU was provided from a lab source. Then the samples were mixed with a reagent containing orthophthaldialdehyde (OPA) and left to sit for four hours. Finally each sample was placed in the fluorometer, and its fluorescence was used in a regression of the standard curve to provide the ammonium concentration. Further analysis was made of the remaining seawater samples by Kathy Krogslund to determine nutrients such as ammonium (NH_4), nitrate (NO_3), nitrite (NO_2), silicate ($\text{Si}(\text{OH})_4$) and phosphate (PO_4).

Data recorded from the first CTD cast, the LADCP, and the parameters of the effluent pipes were entered and run in the VP model. The VP is a Windows-based mixing zone modeling

application produced by the EPA, which is actually a three-dimensional flow model (Baumgartner et al. 1994). It contains dilution sub models that simulate merging submerged plumes into a stratified background flow. The visual plumes model is a standard model that is used to predict water quality (Shuman, R., pers. comm.). Using current speed, salinity, temperature, and density, the VP can find the sewage outfall's (plume) pathway, elevation, dilution from the source and the change in density with depth in comparison to the change in density of the background water (Frick et al. 2001). Salinity, temperature and density were taken from the CTD data file in Matlab from every 20 m and used in the VP model. The CTD data combined with outfall pipe parameters such as pipe diameter, length, and volume of discharge and temperature of discharge, enabled the model to run. Other parameters include the number of ports, area of ports, and the distance between ports. The model allows different scenarios to be played out by controlling these parameters such as the outfall's volume of discharge rate and the outfall's mixing zone boundary. All of the parameters except for discharge rate were taken from the South Treatment Plant's Facts Sheet (http://www.ecy.wa.gov/programs/wq/permits/permit_pdfs/king_county_south_wtp/Final%20Permit/KingCountySouthWWTP_Factsheet.pdf) and the discharge rate was estimated at $3,785 \text{ m}^3 \text{ d}^{-1}$.

In addition, the buoyancy frequency (Speer and Rona 1989), the diffusion coefficient of ammonium and the effluent ratio (dilution) show how the water is mixing. The buoyancy frequency is calculated from the CTD data where g is gravity, ρ_θ is potential density, ρ is the background density and z is the depth.

$$N = \left(-\frac{g}{\rho} \frac{\partial \rho_\theta}{\partial z} \right)^{1/2} \quad (1)$$

The turbulent mixing of ammonium is found with the diffusion equation by using the current speed from a current's profile of velocity. The eddy diffusion coefficient (k) is found using the eddy diffusion equation for k where N is the ammonium concentration, t is the time, x is the distance, and u is the horizontal current velocity.

$$\frac{\partial N}{\partial t} + u \frac{\partial N}{\partial x} = k \frac{\partial^2 N}{\partial x^2} \quad (2)$$

The effluent ratio is found by solving the equation (3) where PS is the ratio of effluent to the Puget Sound seawater, S_{PS} is the ambient Puget Sound water, S_m is the mixed outfall water and S_{eff} is the effluent water.

$$PS = \frac{(S_{PS} - S_m)}{(S_m - S_{eff})} \quad (3)$$

The effluent ratio is very small because of the rapid dilution of the effluent water. The effluent ratio can also be found by using temperature in the equation (4) where PS is again the ratio of effluent, θ_{PS} is the potential temperature of the ambient Puget Sound water, θ_m is the potential temperature of the mixed outfall water and θ_{eff} is the potential temperature of the effluent.

$$PS = \frac{(\theta_m - \theta_{PS})}{(\theta_{eff} - \theta_m)} \quad (4)$$

The effluent temperature can be found by using the effluent ratio from the third equation and then substituting the salinity with temperature in the fourth equation to solve for the effluent temperature, θ_{eff} .

Matlab was used to plot temperature, salinity and velocity data, and for calculations of temperature and salinity anomalies. The temperature and salinity anomaly are calculated as a difference in temperature (or salinity) at a given density relative to the background station.

Results

Salinity generally increased with depth while temperature decreased with depth. The range of salinity from the CTD operations equaled 1.35 PSU with a maximum salinity of 29.87 PSU and a minimum salinity of 28.52 PSU. The salinity plotted along the second Tow-Yo shows a slight decrease in salinity near the center of the outfall at the location 47.602° N, 160 m depth compared to 47.608° N, 160 m depth (Fig. 2a). Salinity anomaly along the second Tow-Yo is shown in Fig. 2b. An additional salinity anomaly plot shows a difference in salinity at the outfall from the background salinity where there is a positive salinity anomaly at 140-175 m (Fig. 3). The range of temperature from the CTD operations equaled 0.55 °C with a maximum temperature of 8.65 °C and a minimum temperature of 8.10 °C. The scatter plot of temperature anomaly with latitude vs. depth plot (Fig. 4a) shows the difference in temperature of the second Tow-Yo operation from the background. The temperature anomaly is associated with the salinity anomaly where the salinity and temperature change the density of the water in a nearly linear

relationship known as the equation of state, and thus their anomalies are linearly proportional to one another. Therefore, a positive salinity anomaly will be associated with a positive temperature anomaly. An additional plot of temperature anomaly from a vertical profile of the first CTD cast centrally located over the outfall, and the background CTD cast, indicates warmer waters from 130-155 m (Fig. 4b).

Velocities vectors are extracted from the ship's ADCP at 29 m and 149 m and were plotted with Matlab (Fig. 5a and 5b). They indicate a northeastward current near surface and a northwestward current at 149 m depth. Backscatter from the ADCP attached to the CTD did not provide a clear record as it was probably twisted around during the Tow-Yo; however, it did provide current profiles.

The ammonium concentrations were high near the outfall depth of 185 m and up to a depth of 150 m as expected (Fig. 6a). The ammonium plots from the Tow-Yos at a depth near 150 m also showed the highest concentrations near the outfall's location (Fig. 6b and 6c). The ammonium from the background showed a maximum concentration at mid depth near 150 m (Fig. 6d). The concentration of ammonium at 150 m in depth from the central location ($2.88 \mu\text{mol L}^{-1}$) minus the background location ($1.32 \mu\text{mol L}^{-1}$) was equal to $1.56 \mu\text{mol L}^{-1}$ ammonium. The highest ammonium concentration was 0.069 mg L^{-1} , which compared moderately to the Ecology/PSAT monitoring data, where ammonium that causes concern is high at $>0.14 \text{ mg L}^{-1}$ and ammonium that is moderate is 0.07 mg L^{-1} . Using ammonium concentrations from 150 m versus the salinity anomaly shows a slight relationship between ammonium concentrations and positive salinity differences (Fig. 7); this suggests that ammonium is connected to slightly higher salinity at depths of 150 m.

The CTD data from the outfall cast was used in the VP model with a port spacing of 91 cm. As a result the model displayed the plumes elevation, dilution, and pathway (Fig. 8a, b and c). The plume elevation rose to a depth of about 175 m, while the plume boundary rose to about 155 m. The dilution was rapid and the pathway extended northwards. A plot of the buoyancy frequency made at intervals of depth equal to 10 m showed a greater stratification in the outfall compared to the Background location (Fig. 9a and 9b). However, below 100 m the average buoyancy frequency of the outfall, 0.0044 s^{-1} , is slightly less than the average frequency of the background, 0.0045 s^{-1} , excluding the deepest frequency of the background, which is skewed from the rest. Directly over the outfall the partial derivative,

$$\frac{dN}{dt} \quad (5)$$

was much smaller than the equation (2) without the partial derivative. Therefore the time derivative could be neglected from the equation (2), and k could be determined from the two remaining terms in the equation (2). Using the velocity (u) from a current profile in the second Tow-Yo, the change in concentration with respect to distance was taken from an upcast just before the center of the Tow-Yo, and the following downcast which resulted in the maximum ammonium concentration. The second derivative was solved using the slope of the same two points divided by their distance which conceded $k=22.10 \text{ m}^2 \text{ s}^{-1}$. The effluent ratio was calculated from two up casts of the CTD Tow-Yo at locations near the outfall and an endpoint south of the outfall that showed a great contrast in salinity at 160 m. PS (3), using the two up casts from the salinity anomaly at the depth of 160m, is equal to 0.0022899. Using 0.0022899 for PS (4), the θ_{eff} is equal to 13.81 °C. Further analysis of seawater samples resulted in ratios of phosphorus, silica, and nitrogen, 1:22.2:5.5.

Discussion

The positive salinity anomaly is counterintuitive of the expected fresh water anomaly from the release of the effluent. Both salinity and temperature anomalies show a positive difference at 160 to 130 m depth. In both cases the stronger anomaly is toward the south end, while the anomaly toward the north is smaller. Currents at these depths are predominantly northwards with some change in an east to west component (Fig. 10). This may imply that there is an intruding water mass with higher salinity from another source, moving near the bottom of the outfall. An alternative explanation to the intruding water mass is that the effluent, which was warm, has mixed and become warm and salty in comparison to the background water. In another layer of water, in figure 3b at 100 m, there is a cold anomaly; which might be the result of plume water that gathered at slack tide and then advected during the ebb tide current into the background cast, creating a cold anomaly. In that case the plume rise height is reduced from the current of the ebb tide. With that speculation the depth of 150 m in Figure 7 supports that the ammonium concentrations are associated with slightly positive salinity anomalies. That would connect the weak positive salinity and temperature anomaly (Fig. 2b and Fig. 3a) near 150 m in the northern part of the second Tow-Yo to the effluent water. Consequently, the ebb tides are

moving predominantly northwards at the time of these anomalies, and the weak salinity anomaly near 150 m is being followed by the strong positive anomaly from the south end of the second Tow-Yo (Fig. 2b). The overall effect at any depth is that the effluent has been advected horizontally by the ebb tide.

A response to previous predictions such as the northwest current by Baker et al. (1983) at 130 m depth is shown as the slight change in direction near 140 m in Fig. 10. However, the 0.3 PSU difference in salinity from an estimated 500 m upstream of the outfall as reported by Turner and Greg does not match the difference of 0.068 PSU at a distance of 700 m upstream from the Renton outfall. Yet the temperature 13.8 °C of effluent taken from the ratio of effluent is near the 12.8 °C temperature of effluent in the Turner and Gregg study of the Westpoint outfall. Therefore the model is internally constrained to the previous model by the near comparison in temperature of the effluent but externally unconstrained in that the difference of salinity from upstream of the outfall is off by an order of magnitude.

In regard to the hypothesis that the effluent stays submerged at 100-150 m, there is a strong negative temperature and salinity anomaly in figures 2b and 4a; however, the VP model, in figure 8a shows that the plume is reaching a height of 160-175 m. Conversely, the ammonium indicates that the effluent plume would be around 150 m. Perhaps matching the plume elevation to the maximum ammonium concentrations is a subject for future study. Furthermore, the VP's dilution figure does not compare very well to the effluent ratio. The inverse of the effluent ratio 437, (0.0022899^{-1}), was taken from a distance of 700 m where the VP's dilution figure shows that a ratio of 450 is close to 50 m. In that respect a better plan may have been to survey just one of the diffusers locations, which would make for a more accurate model. A CTD transect taken closer to the north diffuser might result in a stronger difference in salinity, therefore making a better connection with the depth of the plume.

Conclusions

The water quality with respect to the ammonium turned out to be at acceptable levels, but the predicted plume depth was not achieved in the VP model. However, the ammonium, which is indicative of the effluent, did show maximum concentrations near 150 m. Furthermore the currents are mostly moving northwards so I believe that the effluent at the onset of the ebb tide probably advected northwards into the area of the CTD background cast, causing the negative

temperature anomaly seen in figure 4a at areas near 100 m depth. Likewise the positive salinity anomaly in figure 2b near 140 m could likely be an intruding water mass moving with the northwards current. That would also support how the weaker anomaly (Fig 2b) at the same depth is connected to ammonium concentrations (Fig. 7) because that water contains the ammonium signal from the effluent; additionally, the weak anomaly was followed by the strong salinity anomaly which was advected from the current. In conclusion, the ebb tide possibly reduces the elevation of the effluent and matching ammonium concentrations to the VP model plume height is a candidate for future research.

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Tables

Station	Latitude	Longitude
1 st CTD outfall	47° 36.05' N	122° 25.56' W
2 nd CTD Tow-Yo	47° 36.45' N	122° 25.21' W
3 rd CTD Tow-Yo	47° 35.85' N	122° 25.78' W
	47° 35.64' N	122° 25.20' W
4 th CTD background	47° 36.25' N	122° 25.75' W
	47° 36.89' N	122° 25.62' W

Table 1. Summary of CTD operations in Figure 3.

Figure Legends

Figure 1. **a** Picture of near surface circulation patterns above the outfall plume (Bretschneider et al., 1985). **b** Station in Elliot Bay where the South Treatment Plant listed ammonium-ammonia concentrations (King County, 2007); CTD cast locations and other CTD operations such as the ‘X’ shaped pathway of Tow-Yo.

Figure 2. **a** Scatter plot of salinity vs. depth from the second Tow-Yo. **b** Scatter plot of salinity anomaly with depth vs. latitude from the second Tow-Yo and the background CTD cast.

Figure 3. Salinity anomaly of the outfall (the first CTD) defined relative to the background (the fourth CTD).

Figure 4. **a** A scatter plot of temperature anomaly with depth vs. latitude of the second Tow-Yo. **b** Temperature anomaly of the outfall (the first CTD) defined relative to the background (the fourth CTD).

Figure 5. **a** Velocity vectors from the ship’s 75 kHz ADCP where data is collected in 5 minute averages and vectors are shown at 29 m of depth from the ship’s pathway as shown in figure 1b. **b** Velocity vectors at 149 m of depth from the ship’s pathway as shown in figure 1b.

Figure 6. **a** Ammonium vs. depth of the first CTD cast. **b** Ammonium at depth of 150m vs. distance from the start to the end of the first Tow-Yo where it moved southwards. **c** Ammonium at depth of 150m vs. distance from the start to the end of the second Tow-Yo where it moved northwards. **d** Ammonium vs. depth of the fourth (background) CTD cast (four samples taken at only three depths).

Figure 7. Salinity anomaly vs. ammonium concentrations at 150m.

Figure 8. **a** The VP model showing a plot of plume elevation using temperature, salinity and current speed from the first CTD cast for all VP plots. **b** VP model of predicted dilution. **c** VP model of the plume direction.

Figure 9. **a** Buoyancy frequency plotted with 10 m intervals at the outfall, the first CTD cast. **b** Buoyancy frequency at the background, the fourth CTD cast.

Figure 10. A velocity profile of V-(north/south) currents taken from the second Tow-Yo over the outfall with U-(west/east) current arrow heads and tails. A heads or arrow tip is eastwards current and a tails or arrow tail is westwards current.

Figures

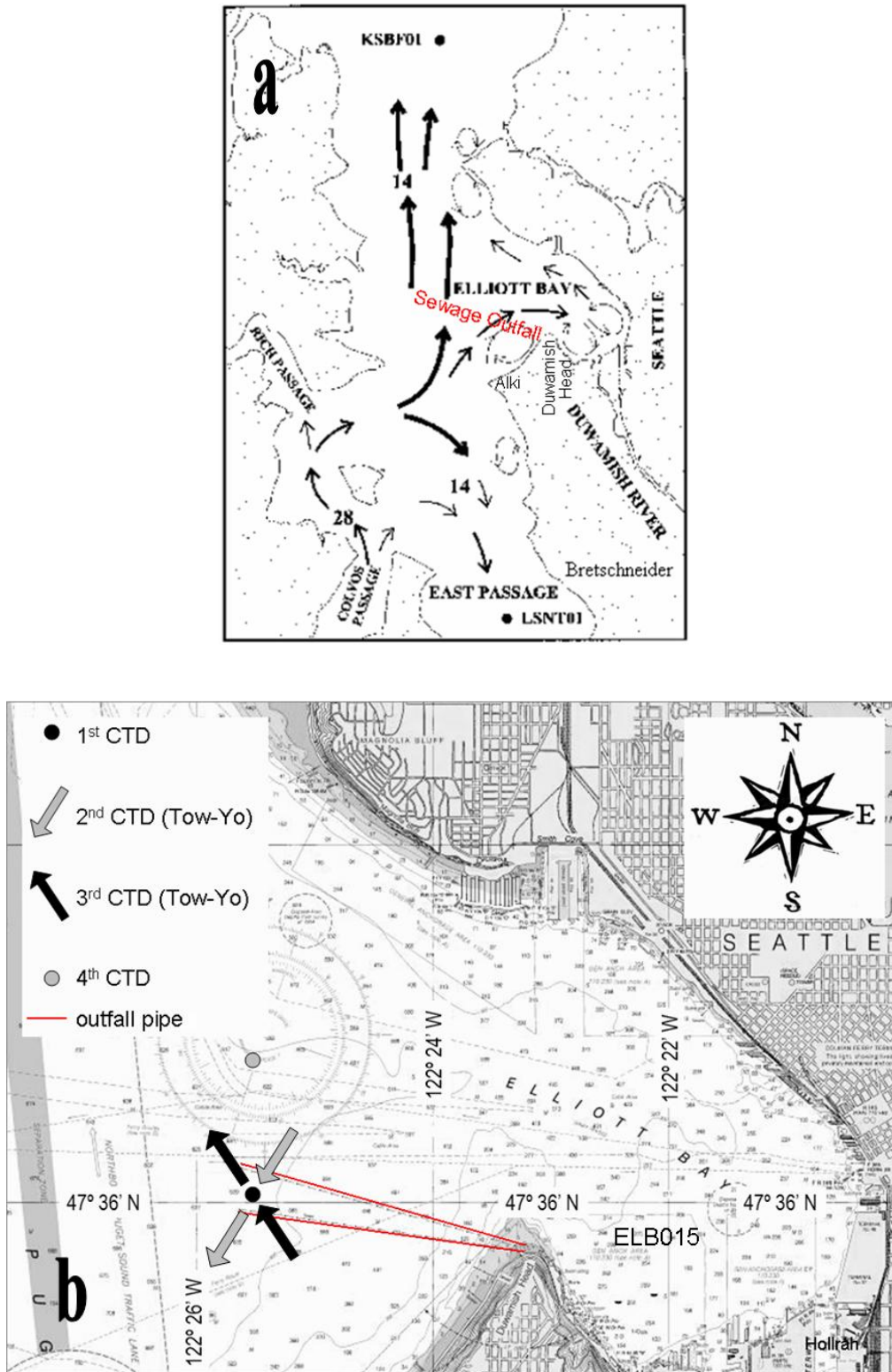


Figure 1.

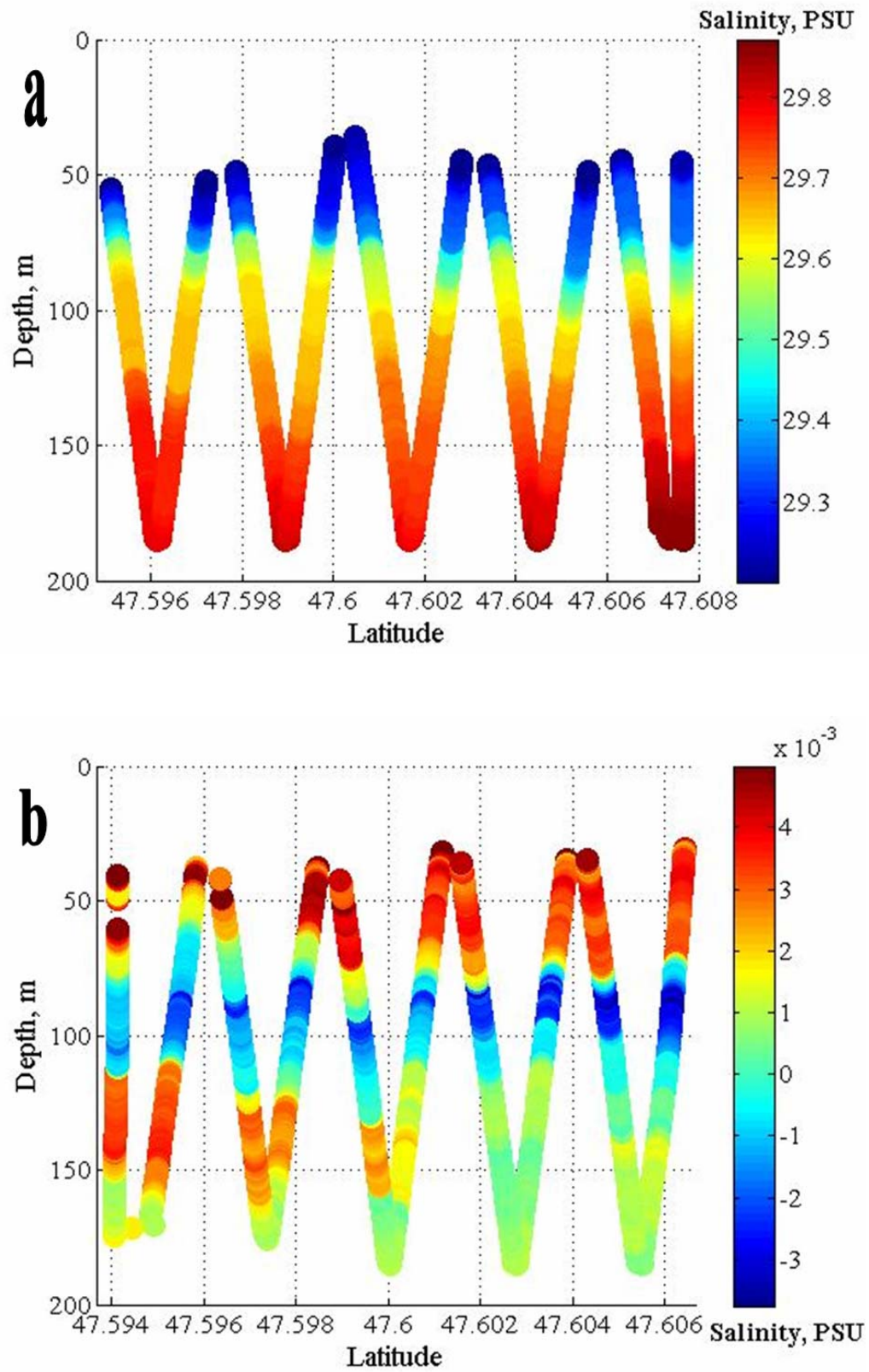


Figure 2.

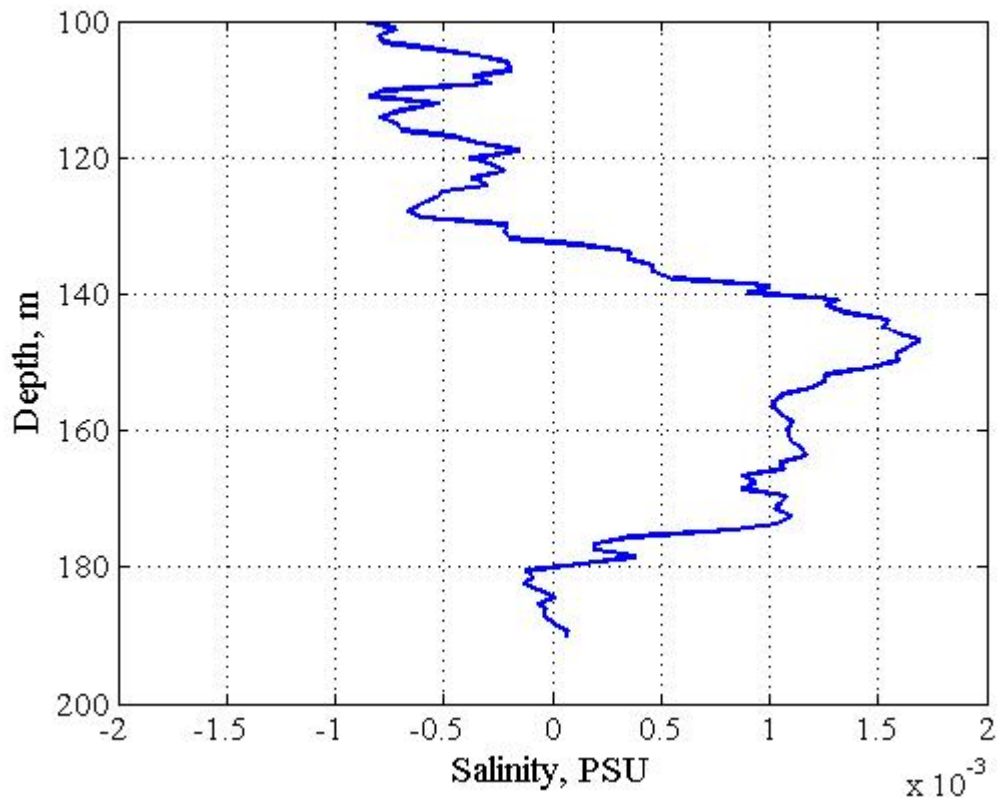


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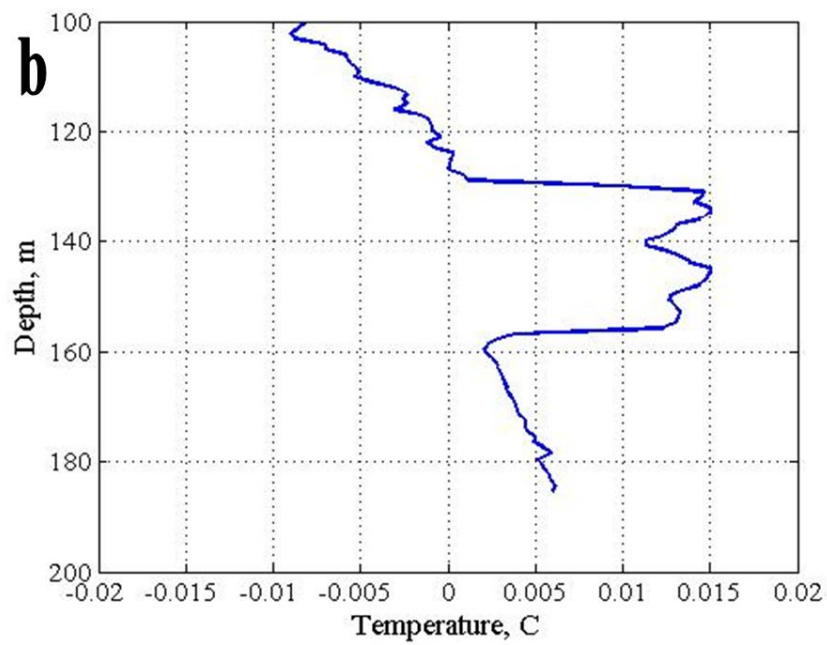
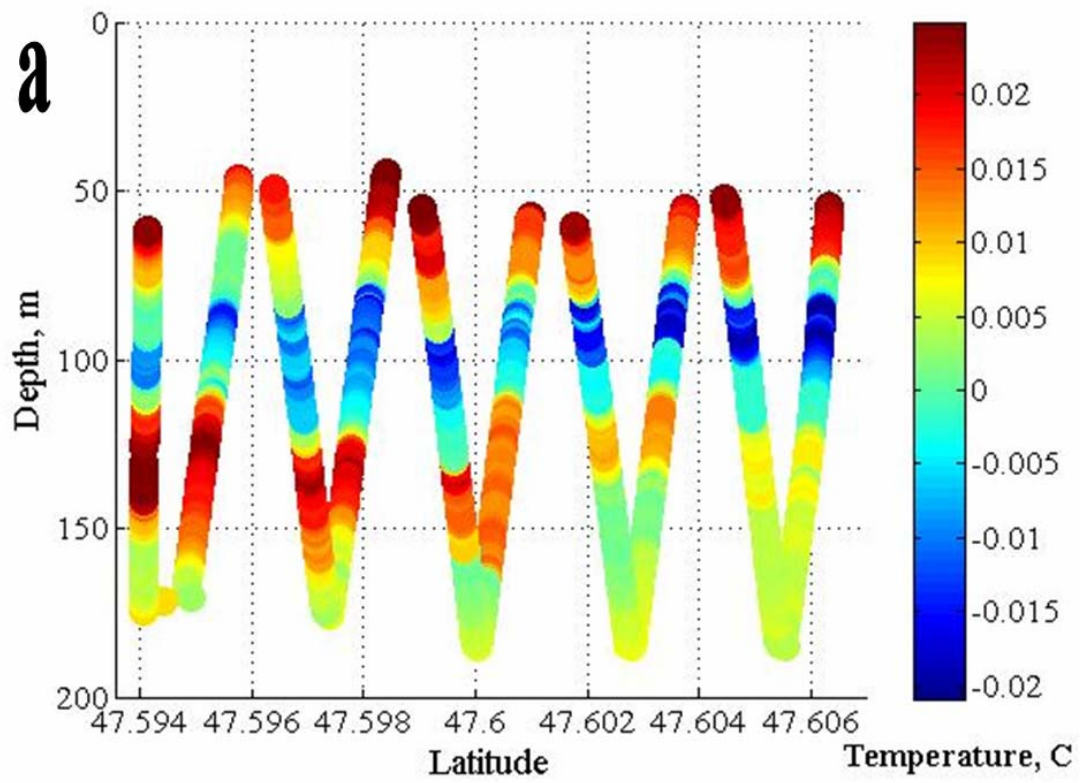


Figure 4.

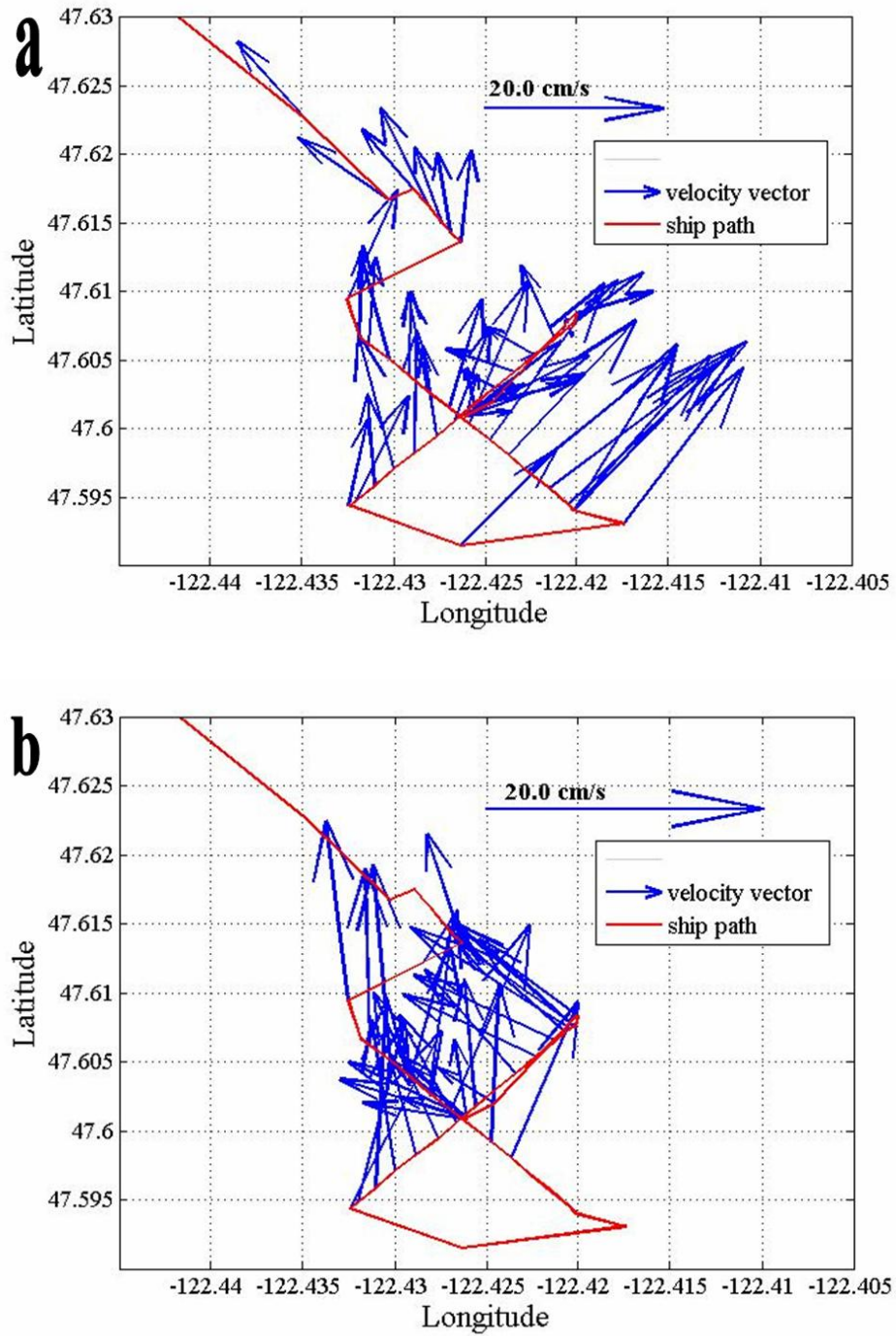


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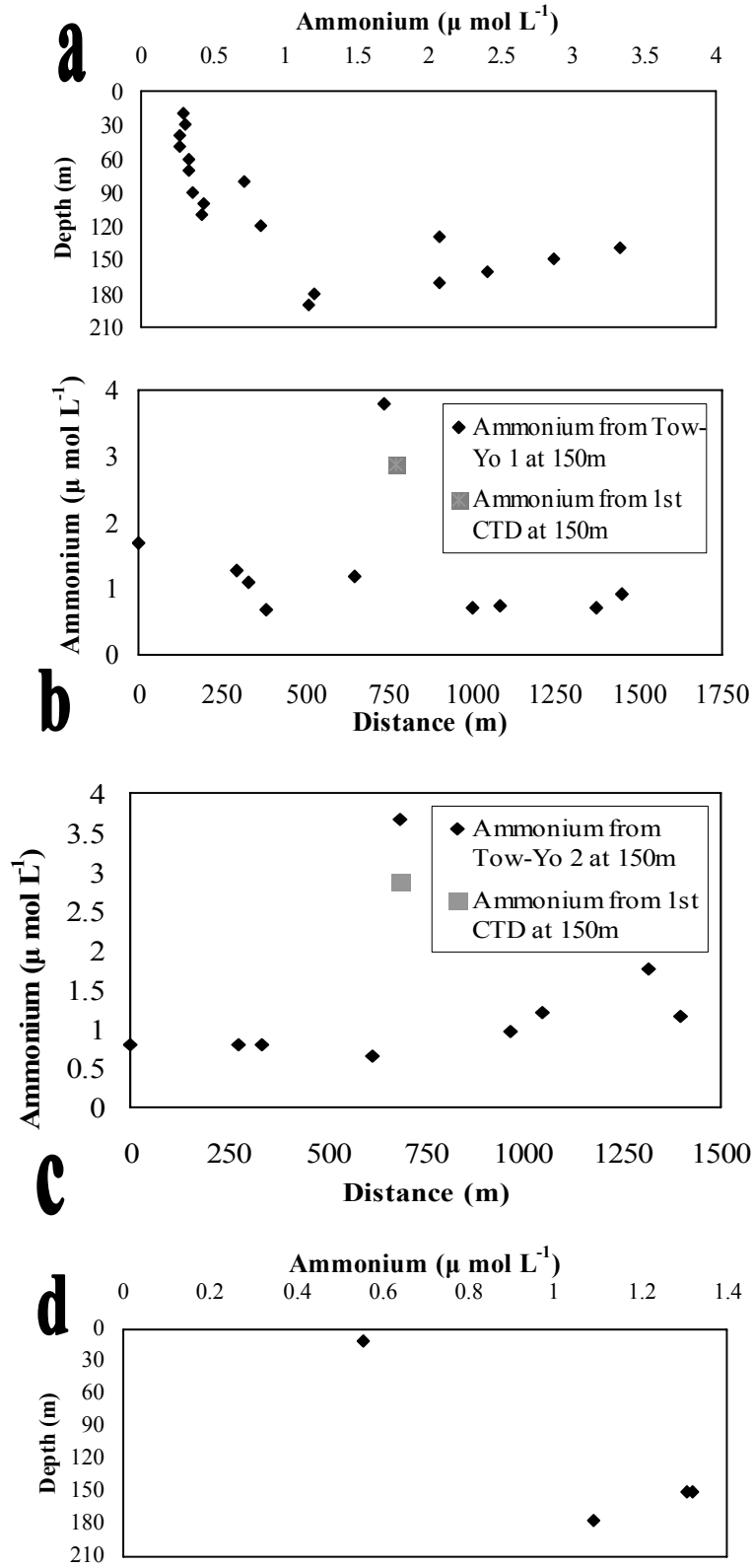


Figure 6.

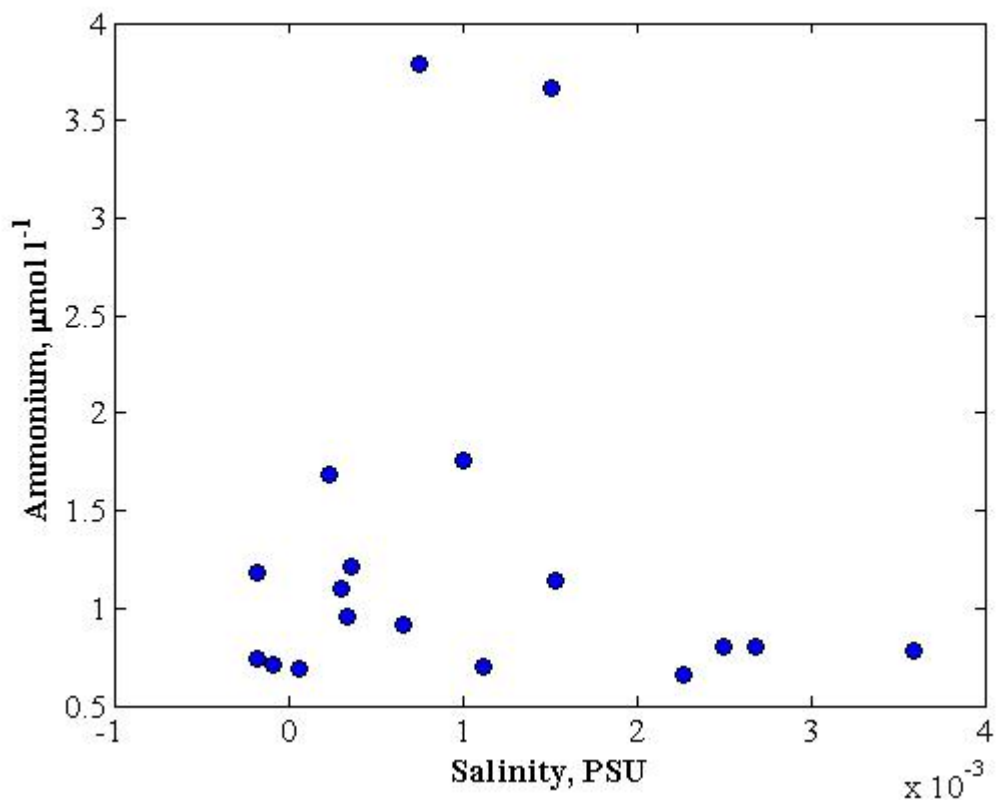


Figure 7.

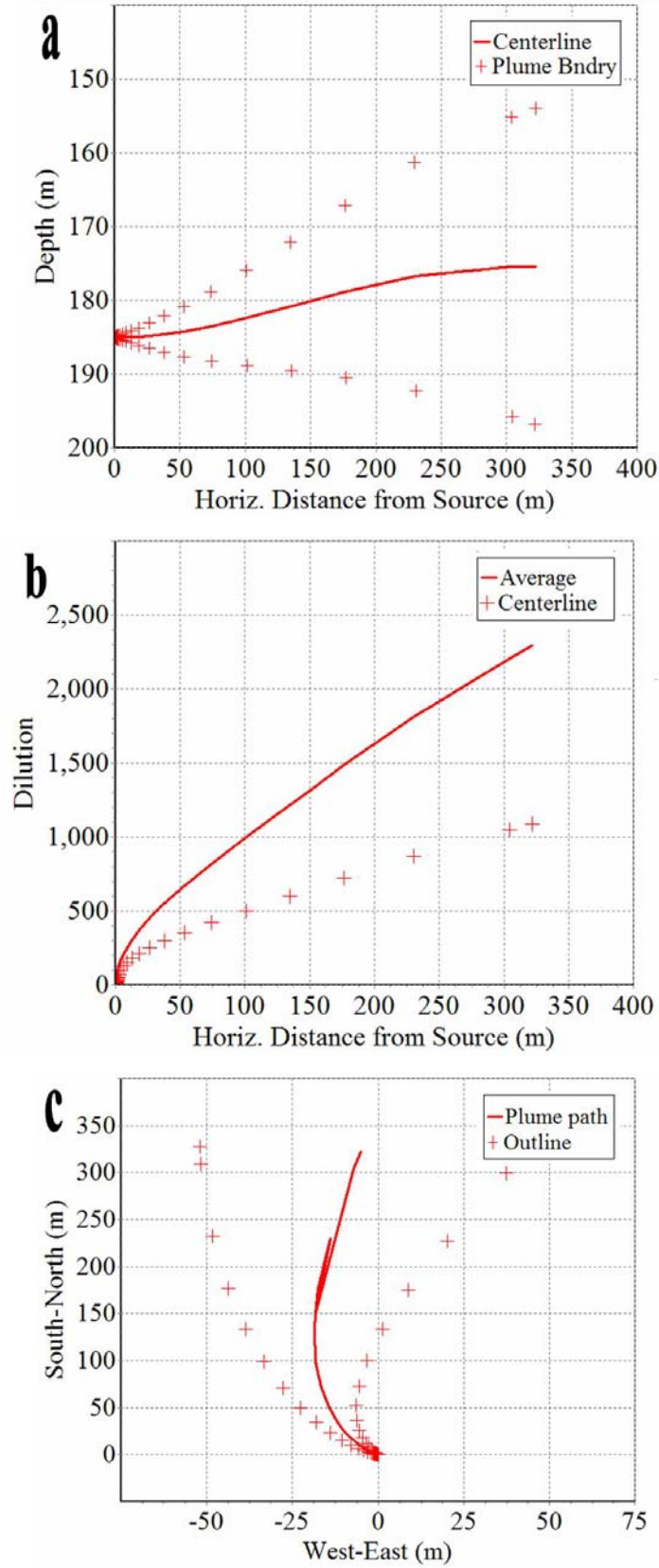


Figure 8.

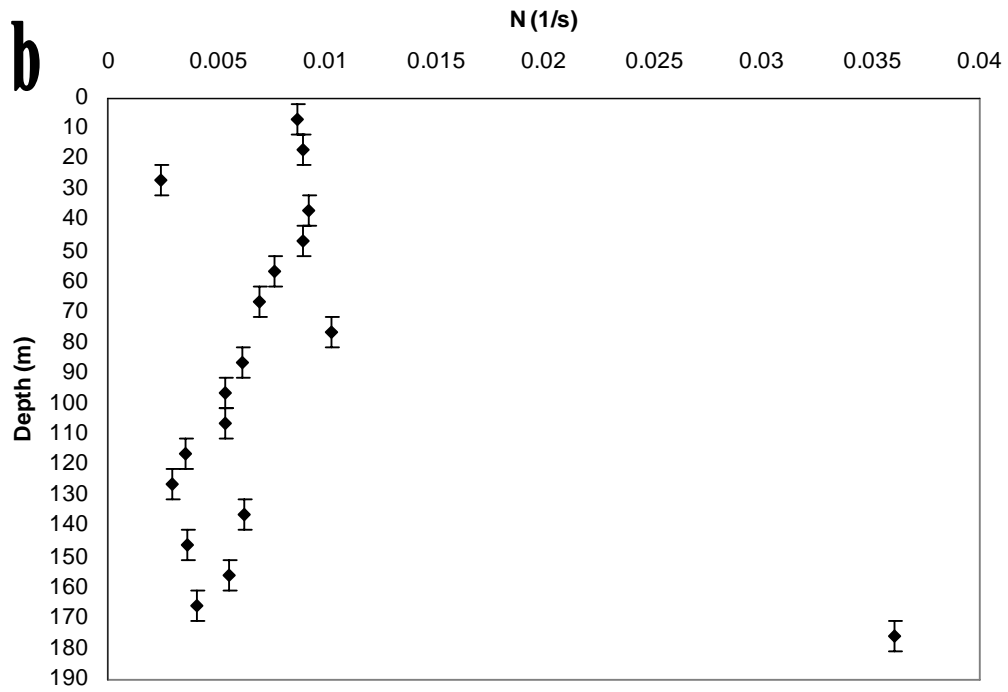
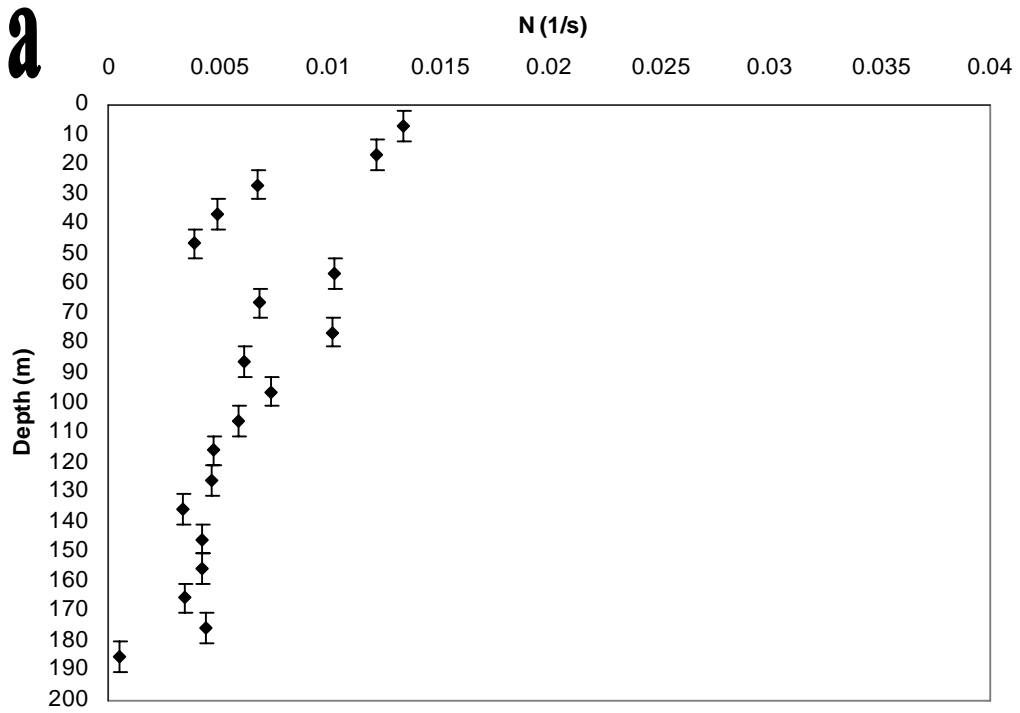


Figure 9.

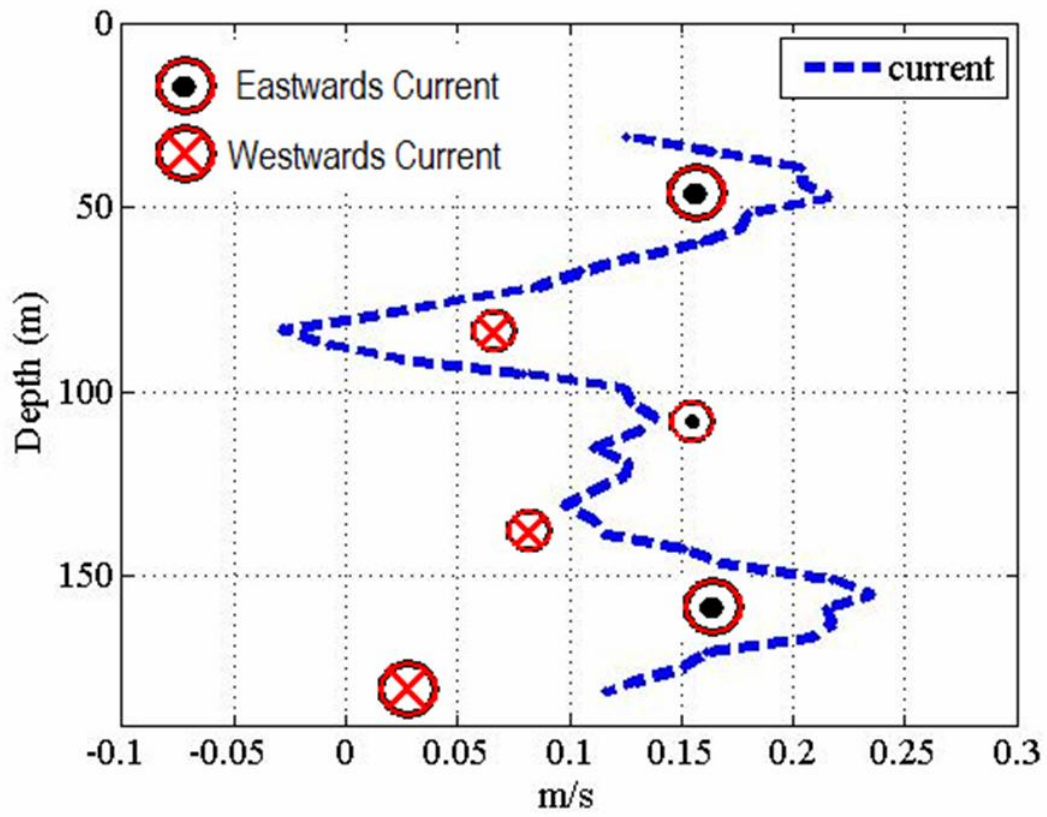


Figure 10.