A Department of Ecology Report

Saltwater Intrusion in Salmon Bay and Lake Union Sediments

Abstract

Saltwater intrudes into Salmon Bay as a result of operation of the Hiram Chittenden Locks, which connect the Lake Washington Ship Canal with Puget Sound. Depending on the levels of salinity present, sediments in certain areas may be classified as marine, low-salinity, or freshwater. These classifications can affect sediment cleanup decisions.

To evaluate the appropriate classification, sediment pore water salinity levels in Salmon Bay and Lake Union were determined using conductivity and temperature measurements. The results were then compared to sediment pore water definitions in the Washington State Sediment Management Standards (WAC 173-204-200). Pore water salinity results were also compared to the U.S. Army Corps of Engineers (USACOE) real-time water column monitoring data, to see if these data sets could be correlated for predicting pore water salinity levels.

Pore water salinity values ranged from 0.16 $^{o}/_{oo}$ (parts per thousand) to 13 $^{o}/_{oo}$. A little over 50% of the sediment samples collected had salinity values that would classify them as low salinity sediment (>0.5 to <25 $^{o}/_{oo}$). Under conditions present at the time of sampling, there was a trend towards lower salinity levels moving east from the locks.

Sediment pore water conductivity data were correlated with USACOE data for two of the transects, using multiple correlation equations. The models describe conditions at the time of the study. Small sample sizes and highly variable conductivity values result in models that may not be very reliable in predicting pore water salinity levels. Despite the limitations, the models do provide an approximation of sediment conductivity levels.

by Dave Rogowski
August 2000

Publication No. 00-03-032
Waterbody No. WA-08-9340

This report is available on the Department of Ecology home page on the
World Wide Web at http://www.ecy.wa.gov/biblio/0003032.html

For additional copies of this publication, please contact the Department of Ecology Publications Distribution Office and refer to publication number 00-03-032.

Address: PO Box 47600, Olympia WA 98504-7600

E-mail: ecypub@ecy.wa.gov

Phone: (360) 407-7472

Acknowledgements

The author would like to thank Rick Huey for sample collection and Dave VanRijn of the U.S. Army Corps of Engineers (USACOE) for providing monitoring instrument data and Hiram Chittenden Locks data.

Introduction

Lake Union, Portage Bay, and Lake Washington were historically unconnected to Salmon Bay and Puget Sound. These bodies of water, collectively called the Lake Washington Ship Canal, were connected with the construction of the Hiram Chittenden (Ballard) Locks and the dredging of two canals (Fremont Cut and Montlake Cut) to Lake Washington in 1914. These changes have had a great impact on Lake Washington and connecting waters. The water level in Lake Washington was lowered, and Salmon Bay was converted from a tidal saltwater inlet into a freshwater bay. As a result of the locks and their operation, saltwater seasonally intrudes into Salmon Bay and Lake Union.

This 1999 study was initiated to determine sediment salinity (pore water) values and the extent of the saltwater wedge in Salmon Bay (Figure 1). Depending on the concentration of the salinity in sediment pore water, sediments may be classified as marine, low-salinity, or freshwater sediments. How sediments are classified can affect cleanup efforts in the bay. In addition, an attempt was made to correlate sediment pore water conductivity data gathered with U.S. Army Corps of Engineers (USACOE) real time monitoring sensor data.

The USACOE is responsible for the operation and maintenance of the locks (USACOE, 1999). They are also responsible for keeping saltwater intrusion to a minimum. To minimize salt-water intrusion, the USACOE instituted the following measures.

- A basin was dredged and a drain was installed just above the large lock to collect saltwater. The heavier saltwater settles in this basin and is siphoned out through the drain using a mechanical pump.
- In 1966 a saltwater barrier was installed just downstream of the saltwater basin.

Despite these efforts, a saltwater wedge still intrudes into Salmon Bay.

The USACOE monitors salinity at various points along the Ship Canal (Lower Locks, Ballard Bridge, Fremont Bridge, Gas Works Park, and UW Bridge). Salinity is continuously monitored at depth and near the surface. Washington State Water Quality Standards (see description below) require that salinity within the ship canal is not to exceed 1 part per thousand (ppt) at all depths in the water column at the University Bridge. The primary goal of this requirement is to prevent saline water from passing east through the Montlake Cut into Lake Washington.

WAC 173–201A–130. Specific classifications-Freshwater. Specific fresh surface waters of the state of Washington are classified as follows:

(58) Lake Washington Ship Canal from Government Locks (river mile 1.0) to Lake Washington (river mile 8.6). Special condition - salinity shall not exceed one part per thousand (1.0 ppt) at any point or depth along a line that transects the ship canal at the University Bridge (river mile 6.1).

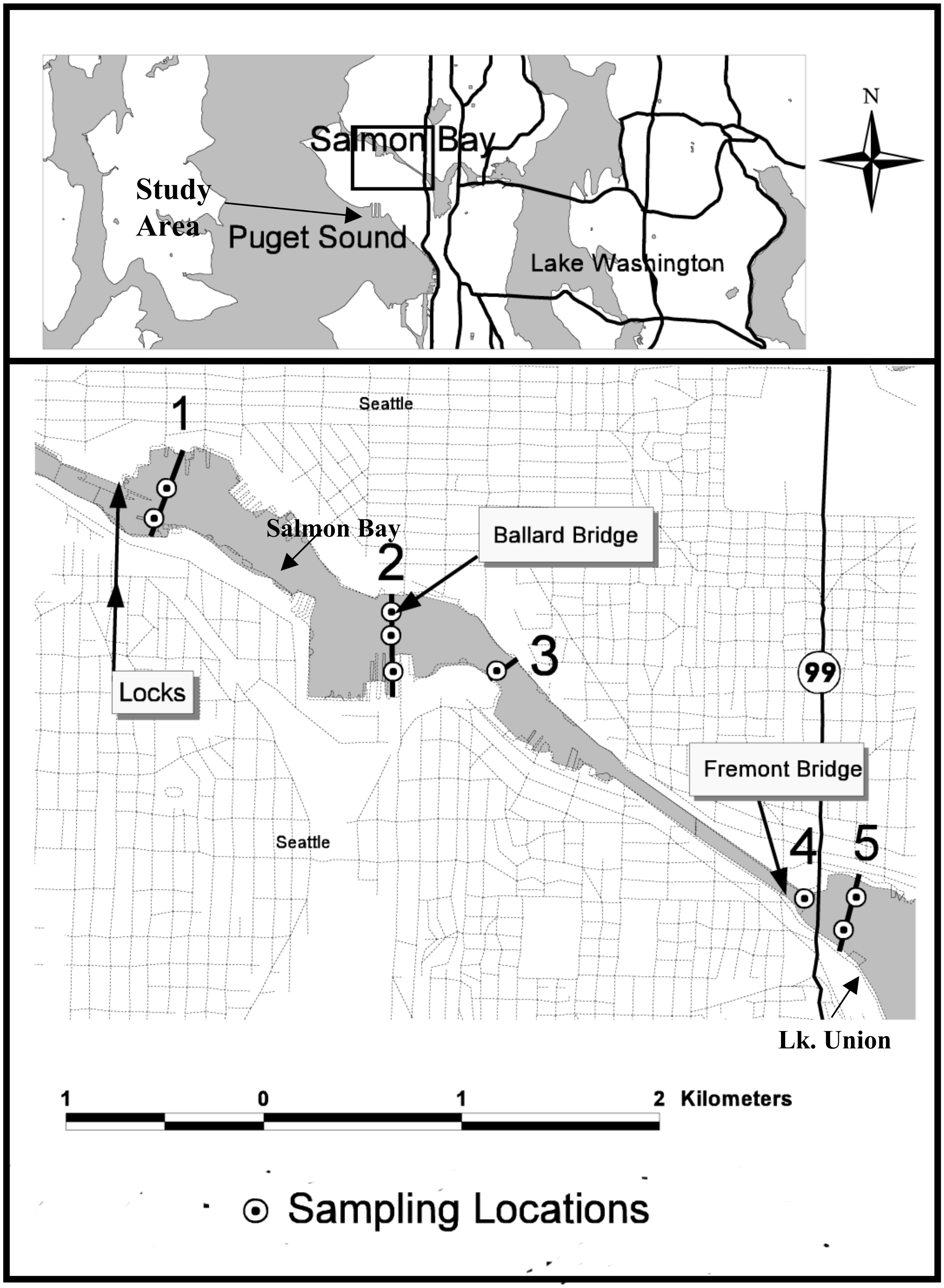

Figure 1. Salmon Bay sampling transects and station locations.

The extent of the salinity wedge depends on two main factors: how the locks are managed by the USACOE, and how much freshwater is flowing west through the system. When salinity levels get too high, the pump on the saltwater drain is turned on for an unspecified amount of time (Valentine, 1999).

Management considerations include lockages (boat traffic), use of the siphon, and maintaining water level in Lake Washington.

1. Saltwater intrusion is influenced by the frequency of lockages and whether the small or large locks are used. Also, large ships require lowering of the saltwater barrier on the bottom of the channel, allowing a greater intrusion of seawater.
2. Operation of the saltwater siphon is not on a set schedule, but is operated intermittently.
3. Water level maintenance affects the extent of the saltwater intrusion. The USACOE is restricted to maintaining a water level that never varies more than two feet annually. In the summer when there are lower flows, water level is maintained at a higher level than in the fall or winter when it is kept lower for flood control. During the summer, freshwater flow is generally not great enough to flush saltwater out of Salmon Bay. By October freshwater flows usually increase and flush saltwater out of Salmon Bay (Valentine, 1999).

The survey area is heavily urbanized and has been home to major industries over the last 100 years. Significant sediment contamination (heavy metals and organics) has been documented in Salmon Bay and Lake Union, primarily from historic sources (Cubbage, 1992, Serdar and Cubbage, 1996).

The Washington State Department of Ecology (Ecology) is the lead regulator for sediment quality issues in the state. As part of the interagency Lake Union Action Team, Ecology plays a lead role in planning for future sediment cleanups.

Saltwater is heavier than freshwater and tends to remain on the bottom. If sediments in a freshwater system are inundated with saltwater over time, sediment pore water may become saline. How sediments are classified can affect management of contaminated sediments and cleanup goals in Salmon Bay (Table 1). Sediment cleanup standards exist for Puget Sound marine waters. However, as of 1999 cleanup standards for low salinity or freshwater sediments have not been adopted.

Table 1. Pore water standards (WAC 173-204-200 definitions).

Sediment classification	Standards (ppt)
Marine	≥ 25
Low-salinity	>0.5 < 25
Freshwater	≤ 0.5

ppt: parts per thousand ($^{o}/_{oo}$)

Objectives

The objectives of this present study are as follows:

- Determine if a salinity wedge that intrudes into Salmon Bay/Lake Union results in changes in sediment pore water salinity. This information will be used to make determinations about classifying sediments in the area as marine, low-salinity, or freshwater.

- Identify and define marine, low-salinity, and freshwater sediment zones via measurements of sediment pore water in Salmon Bay.

- Determine if sediment pore water salinity data can be correlated with existing USACOE water column monitoring data, for predicting sediment pore water salinity levels.

Methods

Originally the sampling plan was designed to classify Salmon Bay by salinity zones. However due to the length of time required to collect sediment and extract pore water, the sampling scheme was reduced to collecting samples within a smaller number of transects. Sampling transects encompassed the area from the locks in Salmon Bay eastward to Lake Union (Figure 1). Five transects were established. Two to three sediment samples were collected per transect, with the exception of transect 4 which is a single sample point (Appendix A, B). Sampling dates were September 9, 13, and October 5, 27, 1999.

All samples were collected from a small vessel. Sediment samples were collected with a Petite Ponar® sampler (2.4 L). Overlying water was siphoned off with a peristaltic pump. Pore water was extracted from sediments with the use of a vacuum-operated pore water extractor (Winger and Lasier, 1991). The extractor was a syringe attached to aquarium tubing and a fused glass aquarium air stone. The air stone was inserted into the sediment sample; the syringe served as the vacuum extractor and initial collector for pore water. Pore water was then transferred to a pre-cleaned container for conductivity measurement.

Near-bottom water column samples were collected using a Van Dorn sampler. The Van Dorn sampler collected water from an interval of 30 to about 77 cm above the bottom. Conductivity was measured in a plastic container pre-rinsed three times with the water collected. Surface water measurements were made at approximately one foot below surface. Conductivity and temperature were measured in the field using either an Orion or a YSI conductivity meter.

Temperature readings for sediment pore water were made when conductivity readings were made. Temperature measurements were often made 15 to 20 minutes after sample collection, depending on how quickly pore-water extraction proceeded.

Sampling devices and containers were thoroughly rinsed with surface water at each site and between samples. Measuring instruments were rinsed with surface water, followed by de-ionized water and then a portion of the sample. Sample locations were determined using a Magellan ® GPS (Global Positioning System) receiver. Total water column depth was also measured at each sampling site.

Salinity was originally conceived as a measure of dissolved salts in a given mass of solution (American Public Health Association et al., 1995). The most common method of determining salinity is by measuring conductivity. Due to the low salinity values encountered and the inherent errors associated with low salinity measurements, conductivity was the analysis of choice. For determining salinity from conductivity values, the Practical Salinity Scale was used for values between 2-42. A correction factor provided in the Standard Methods for the Examination of Water and Wastewater was used for salinity values that fell below 2 (American Public Health Association et al., 1995).

Hourly conductivity readings from USACOE bottom sensors were obtained for October and November at the locks, Ballard Bridge, and the Fremont Bridge. USACOE conductivity values were extrapolated from the hourly readings, to obtain values to match the approximate time of sample collection.

Quality Control Procedures

Quality assurance and analytical methods were adequate to meet the stated objectives. Field instruments were calibrated prior to each day of sampling. Ten percent of the samples were replicate samples. Replicate samples were collected using the same procedures and collected to within approximately 1-2 meters of the original sample. The relative percent difference for samples with a replicate ranged from 0.00% to 40% (Appendix B).

The conductivity of the sediment pore water may be slightly less from what it actually is in situ. Sediment samples were brought up from the bottom through water that was generally at a lower conductivity than the underlying sediment. A screen and a rubber flap limited potential dilution; however, the extent of this potential bias is unknown.

Four separate sampling efforts were conducted. Ecology was unable to obtain sediment at all sampling locations. Heavy boat traffic often impeded sample collection. Debris lying on the bottom also prevented sample collection in certain areas. In areas where sediments were composed primarily of sand or gravel, the vacuum extraction method for pore water collection was ineffective. Pore water was not adequately retained in these samples to allow collection of pore water.

The preferred conductivity meter for analysis was the Orion 135. This instrument was unavailable for use during the first sampling run. Instead, a Yellow Springs instrument (YSI Model 3000) was used. The YSI requires a larger volume of water and is not as accurate as the Orion. In following sampling runs both instruments were used for comparison purposes. There was a significant difference between the two meters (log-transformed variables, T-test, $p < 0.0005$). The YSI consistently recorded a lower conductivity value than the Orion. A regression equation was used to create an estimate of comparable Orion values from YSI data for the first sampling run; these are the values reported in Appendix A.

Latitude and longitude measurements should be considered estimates, since differential correction was not employed.

Results

Pore water salinity values are summarized in Table 2. Complete sample results for surface, bottom water, and sediment pore-water conductivity and temperature are listed in Appendix D.

Table 2. Summary of pore water salinity levels (min. and max.) in Salmon Bay ($^{o}/_{oo}$).

Transect	1		2		3		4*	5	
Date (99)	Min	Max	Min	Max	Min	Max	Min	Min	Max
9/13	8.4	12	0.16	0.67	0.27	-	0.51	-	-
9/20	1.0	1.0	0.19	0.67	0.85	-	0.23	0.41	0.41
10/5	0.54	1.1	0.23	0.55	0.92	1.1	0.26	0.47	0.49
10/27	4.4	13	0.23	0.59	0.54	-	0.21	0.47	0.60

- Samples not collected.
* one sample point within transect.

Bottom water conductivity values were significantly correlated with sediment pore water and surface water conductivity (Table 3.). Pore water conductivity (log-transformed values) was also significantly correlated with depth ($r^2 = 0.45$, $p = 0.007$).

Table 3. Pearson correlation coefficients and Bonferroni adjusted probabilities of conductivity (logarithmic transformed) of samples from sediment pore water, surface water, and bottom water.

Correlation	r	Bonferroni adjusted probability
Log sediment vs. log bottom	0.685	**<0.0005**
Log sediment vs. log surface	0.367	0.090
Log surface vs. log bottom	0.632	**<0.0005**

Log: logarithmic transformed variable
r: Pearson correlation coefficients
Bold values are significantly correlated

Sediment pore water salinity values in transects 1 and 2 can be correlated to USACOE monitoring data (Appendix E). Transect 1 sediment conductivity (log transformed) values were significantly correlated with USACOE (log transformed) data at the Ballard Locks (r = 0.746, p = 0.033). Logarithmic transformations of Ecology and USACOE conductivity data were used along with other data, such as number of lockages in the previous six hours to construct multiple regression models.

A multiple linear regression (least square means) equation was generated to model conductivity levels in sediment pore water from USACOE data (Table 4). Two models were created for transect 1 depending on input data required and the accuracy of the model. The proportion of the total variation explained by the model is represented by r^2, the squared multiple correlation. The equation is considered statistically significant if the probability (p) is below 0.05.

Table 4. Sediment pore water conductivity models (multiple linear regression) based on available USACOE data.

Transect	n	Equation	r^2	*p*	*SE*
1	8	Sed-log = -10.893 + LL(3.971) - SMA(0.058) + Depth(0.026)	0.991 *	**0.001**	0.056
1	8	Sed-log = -3.137 + LL(1.857) - BB(0.002)	0.914 *	**0.001**	0.169
1	8	Sed-log = -2.702 + LL(1.553)	0.557	**0.033**	0.414
2	12	Sed-log = 3.882 + Depth(0.027) - LL(0.363)	0.635 *	**0.004**	0.157
3	5	Sed-log = 7.242 – LL(1.187) + BB(0.001)	0.857 *	0.071	0.094
4	4	Sed-log = -1.73 + LL(1.150) - BB(0.001)	0.818 *	0.246	0.122
5	6	Sed-log = 2.695 + SMA(0.021)	0.556	0.089	0.029

log = Logarithm.
Bold = Significant Difference at p<0.05.
LL = Ballard Locks lower conductivity value, log transformed variables, USACOE (water depth of 39 ft).
LG = Number of large lockages for the preceding 6 hours.
SMA = Number of lockages at the small lock for the preceding 6 hours.
BB = Ballard Bridge lower conductivity reading, USACOE (water depth of 30 ft).
* = Adjusted squared multiple correlation coefficient.
p = Probability.
SE = Standard Error.

Using the first equation as an example to determine approximate salinity of the pore water in transect 1, Ecology (1) entered the USACOE log transformed value for the bottom sensor at that time and multiplied by 3.791, (2) subtracted the number of small lockages in the preceding six hours times 0.058, (3) added the depth (feet) times 0.026, and (4) subtracted 10.983. The resulting value is the logarithmic conductivity value. The resulting log value was then back transferred to obtain an approximate conductivity value for that transect at the specified depth (between 36-46 feet).

Discussion

Salmon Bay was originally a saltwater tidal inlet that was converted to a freshwater system with the completion of the locks in 1916. Since the construction of the locks, saltwater has intruded into the freshwater Lake Washington Ship Canal system, at times reaching Lake Washington. In an attempt to control saltwater intrusion, the USACOE has instituted several measures, including dredging a basin and installation of a saltwater drain and barrier.

These corrective measures work to some extent, but do not completely control saltwater intrusion. Based on this study, sediments in Salmon Bay can be classified as low-salinity sediments (>0.5 to <26 $^{o}/_{oo}$). Over half (54%) of the sediment samples collected had a practical salinity at or above 0.5 $^{o}/_{oo}$ (Table 5). Nineteen sediment pore water samples exceeded a practical salinity of 0.5 $^{o}/_{oo}$. Sediment pore water salinity exceeded 0.5 $^{o}/_{oo}$ at least once during the four sampling dates in every transect.

Table 5. Sediment pore water samples that exceeded 0.5 $^{o}/_{oo}$ practical salinity standard for classification as low-salinity sediments.

Transect	Samples > 0.5 Salinity	Total Number of Samples	Percent > 0.5 Salinity
1	7	8	87
2	6	12	50
3	4	5	80
4	1	4	25
5	1	6	17
All	*19*	*35*	*54*

There are no time requirements for the classification of sediments as being marine, low-salinity, or freshwater. During the two months of this study, samples collected near the locks at transects 1 and 3 can be classified as low-salinity the majority of the time. Sediment samples from transects 4 and 5 are primarily freshwater.

A practical salinity of 0.5 $^{o}/_{oo}$ equates to approximately 790 umhos/cm at 13.8°C up to 930 umhos/cm at 21°C. All of the lower water conductivity sensor readings from the USACOE monitoring station located at the locks on the sampling days (Table 6) and for October and November were well above this value (Figure 2). Based on the conductivity values of the UASCOE lower lock sensor, one would think that all sediment samples collected from transect 1 between September and October would have had a salinity greater than 0.5 $^{o}/_{oo}$. However, one sediment sample collected on September 20 had a practical salinity below 0.5 $^{o}/_{oo}$ (Appendix D).

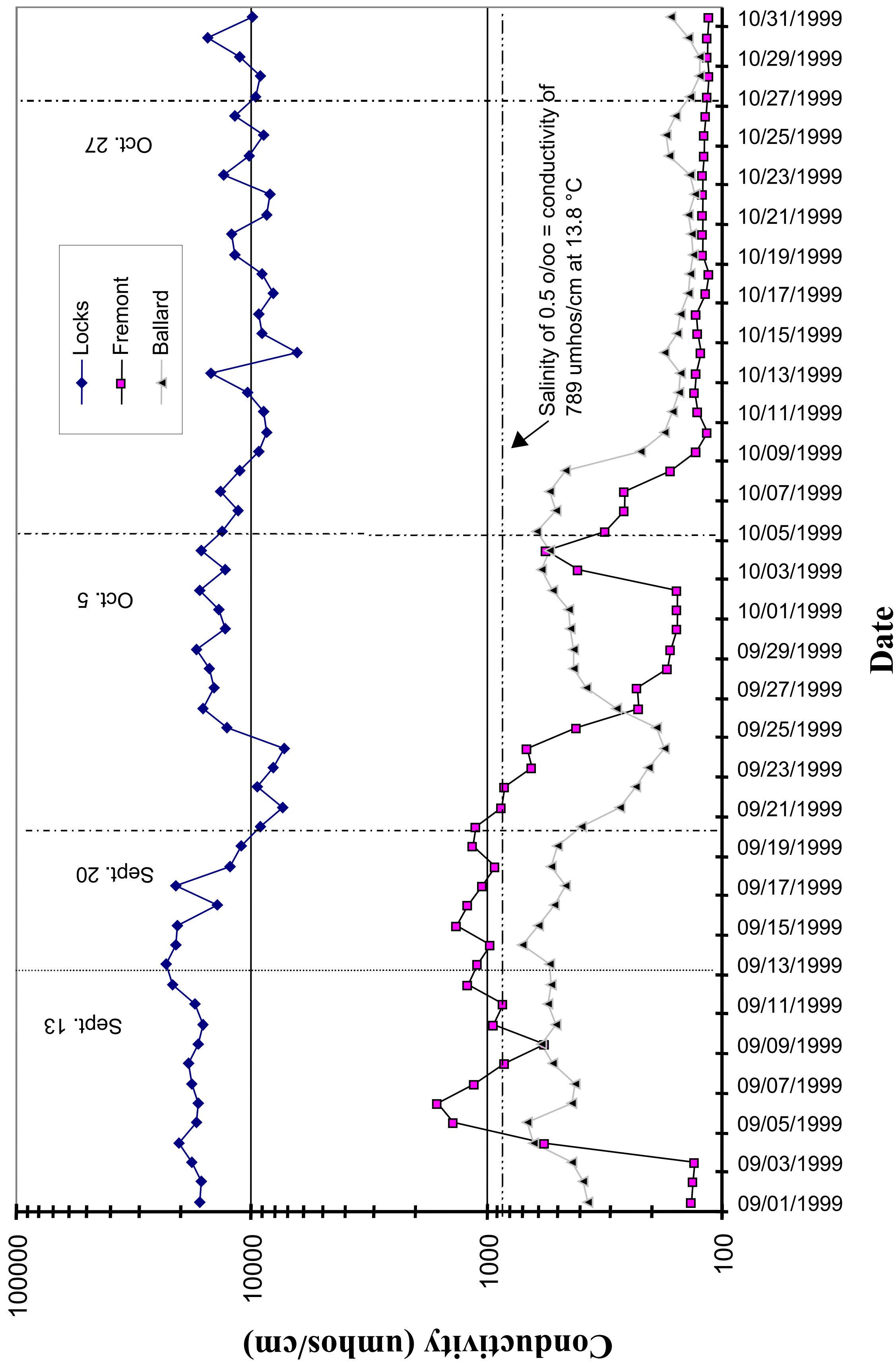

Figure 2. USACOE average daily conductivity readings in Salmon Bay from Sept. 1 to Oct. 31, 1999 at the Fremont and Ballard bridges and the locks.
Vertical lines represent sediment sampling days. The horizontal line represents a salinity of 0.5 $^{o}/_{oo}$ which is equivalent to a conductivity of 789 umhos/cm at a temperature of 13.8°C.

Table 6. Daily average conductivity values of hourly readings from USACOE bottom sensors (umhos/cm) and practical salinity of the four days of sampling.

Date	n	Locks		Ballard Bridge		Fremont Bridge	
		umhos/cm	Salinity ‰	umhos/cm	Salinity ‰	umhos/cm	Salinity ‰
Sept. 13	24	22,871	15	541	0.29	1,093	0.60
Sept. 20	24	9,175	5.9	395	0.22	1,107	0.63
Oct. 5	24	13,371	9.3	610	0.35	315	0.18
Oct. 27	24	9,571	7.1	137	0.08	116	0.072

The difference between the sediment pore water measurements and the water column measurements can be explained in part by the difference in hydrology of surface water and the interstitial flow in sediments. Interstitial flow is less responsive to change than to surface water. Sediment porosity or diffusion was not measured; consequently, it is not known how long it takes for sediment pore water salinity to equilibrate with overlying surface water.

Near the locks, conductivity of the water is constantly changing in conjunction with the opening and closing of the locks. This change is evident by the amount of variability present in the conductivity values closest to the locks (Figure 3). The variability of conductivity is greater at the locks than from those at sensors farther east. This was confirmed by looking at September and October data from the USACOE. An Analysis of Variance (ANOVA) of the coefficient of variation for the three USACOE sensors revealed a significant difference ($p<0.0005$) with the conductivity measured by the locks sensor having a greater coefficient of variation than either the Ballard Bridge ($p<0.0005$) or the Fremont Bridge ($p<0.0005$) sensors.

The two spikes in the graph (Figure 3) for the Fremont Bridge data, September 4 and October 3, are unusual and are believed to be a result of an initial change in the location of the sensor and of when its location was corrected (VanRijn, 1999).

Sediment pore water conductivity models

The model equations generated to describe conductivity levels in pore sediment from USACOE data are approximations, despite the apparent high *r* squared values (r^2). A high r^2 value represents the variability explained by the model. The r^2 values may be artificially high due to correlation of the variables used in building the model, i.e., the variables are not independent of each other (Zar, 1984). In addition, there was a large variation in conductivity depending on the depth of the sample and distance from the lock. Saline water has a higher density than freshwater; as a result, higher levels of salinity were found at sampling points with a greater depth. Model equations for transects 4 and 5 were not significant. It is believed that a change in location of the Fremont Bridge sensor affected the ability of the model to adequately model sediment pore water salinity.

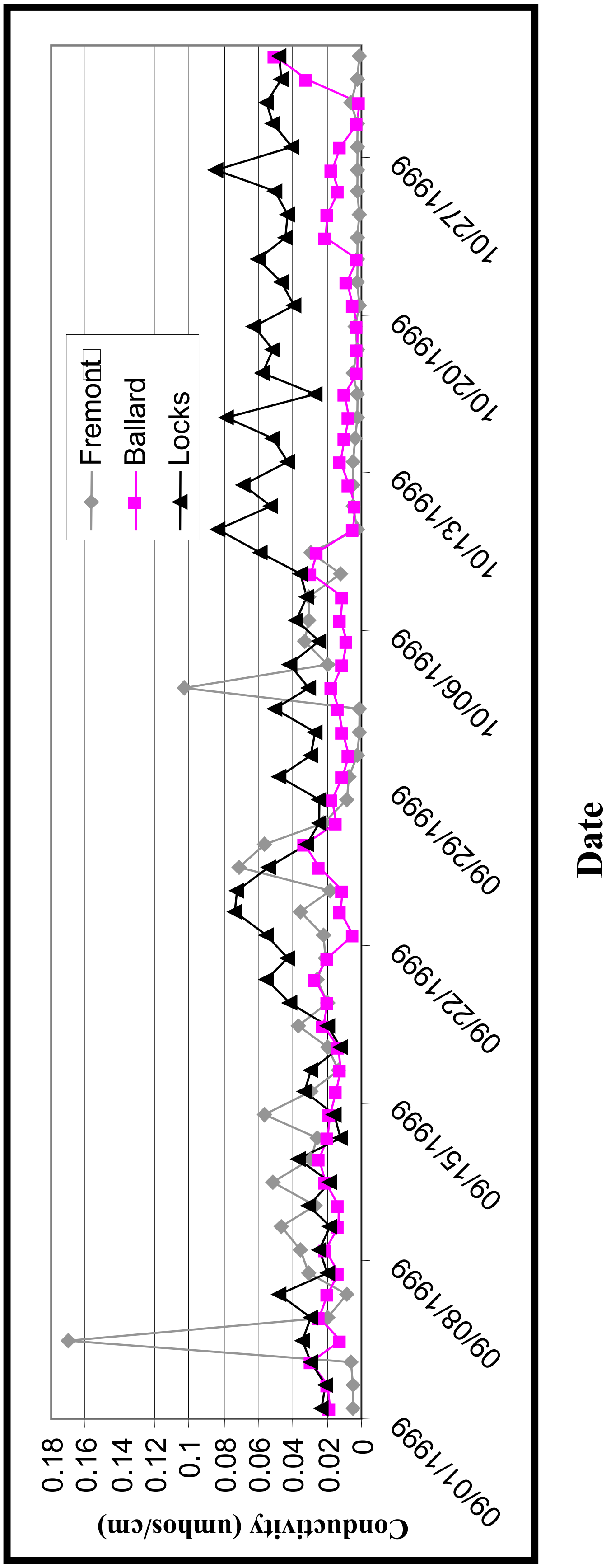

Figure 3. Coefficient of variability of USACOE hourly conductivity sensor readings in Salmon Bay for the four days of sampling in the fall of 1999.

This study was designed to investigate conditions when salinity would most likely be at a maximum in the area. Generally this occurs during late summer and early fall, when freshwater outflow is lowest and boat traffic through the locks is greatest.

Although some of the regression equations modeled measured sediment values fairly well, their predictive values are unknown. The regression equations developed were based on conditions that may not represent what is generally considered normal. 1999 was considered a relatively high-flow year, primarily due to above normal snowfall/rain (NOAA, 1999 a-b). In times of low flow, USACOE salinity readings are generally higher and remain that way for a longer period of time; as a result, it would be expected that sediment pore water salinity would also be higher.

Numerous variables impact saltwater intrusion and subsequent sediment salinity: water flow, lockages, tidal flow, use of the spillway, fish ladder operations, saltwater barrier, and use of the siphon. To take into account all of these variables, many additional samples would need to be collected over a number of years and conditions. This would allow for the use of a more accurate model based on a time-series analysis.

Release of ballast water from vessels transiting the waterway may also affect salinity. The quantity and quality of ballast water released is not known. Compared to the operation of the locks, released ballast water is probably a negligible saltwater load.

Salinity impact on bioavailability

There is some concern about the effects of salinity on bioavailability of contaminants in sediments. A review of the available literature revealed a few papers that directly addressed this topic. Differences in salinity can affect the speciation of metals. Increased salinity has been shown to result in an apparent increase in soluble cadmium levels and copper; however, the differences were not statistically significant (Gambrell et al., 1991). Increasing salinity results in a decrease in soluble levels of several organotins: tributyltin chloride, bis(tributyltin) oxide, triphenyltin chloride, and bis(triphenyltin) oxide (Inaba et al., 1995). Increased solubility of metals does not necessarily result in an increase in bioavailability.

There is evidence for a decrease in bioavailability of mercury compounds with increasing salinity in bacteria (Barkay et al., 1997). Differences in salinity affect the chemical mobility and bioavailability of sediment-bound heavy metals (As, Cd, Cr, Cu, Hg, Pb, Zn); however, surface properties of the substrates and the species of metal are more important than salinity level with regards to bioavailability in an algae and a hydroid (Calmano et al., 1992).

Redox potential and pH have a greater impact on the bioavailability of sediment contaminants than salinity. Anaerobic and low oxygen conditions can also affect contaminant bioavailability. There is evidence that portions of Salmon Bay sediments are anoxic. Although oxygen and pH were not measured, many of the sediment samples had the distinctive odor of rotten eggs, a characteristic of hydrogen sulfide and indicative of anoxic conditions. Anoxic conditions, increased salinity, and contamination individually and collectively can severely reduce habitat quality.

Conclusions

Saltwater intrudes into Salmon Bay through the Hiram Chittenden (Ballard) Locks. As a result, sediments in portions of Salmon Bay would be classified as low-salinity sediments for part of the year. 1999 was a relatively high-water year, with record rain and snowfall (NOAA 1999c). Consequently, saltwater intrusion was believed to be at a minimum. During a normal water flow year, it is anticipated that saltwater intrusion would have covered a larger area and been present at higher levels during the critical periods of the year. Generally, the closer sediments were to the locks, the higher the salinity levels. Based on the data collected, transects 1 and 3 would be classified as low-salinity, while transects 4 and 5 would be freshwater.

Sediment pore water conductivity can be correlated with existing USACOE bottom water column monitoring sensors at transects 1 and 2. Although the regression equations describe the data very well at these transects, their predictive ability is not known and may be severely limited to similar conditions of high water flow and time of year (October-November). The models described may also provide an artificially elevated *r* squared value, due to correlations of the variables used in the model. Despite these limitations, the model equations for transect 1 and 2 can provide a rough approximation of sediment conductivity and, consequently, sediment salinity.

Recommendations

Based on this study the following recommendations are made:

- Investigations into the toxicity of sediments in Salmon Bay should address salinity levels when conducting bioassays. Many organisms are intolerant of even low levels of salinity.

- Long-term sediment sampling and conductivity measurements can provide the required data for verification and refinement of the USACOE data based models.

References

American Public Health Association, American Water Works Foundation, and WaterEnvironment Federation. 1995. Standard Methods for the Examination of Water and Wastewater. Ed. A. E. Eaton, L. A. Cleason, and A. E. Greenberg. United Book Press Inc., Maryland.

Barkay, T., M. Gillman, and R.R. Turner. 1997. Effects of dissolved organic carbon and salinity on bioavailability of mercury. Applied and Environmental Microbiology, Vol. 63, No. 11, 4267-4271.

Calmano, W., W. Ahlf, and J.C. Bening. 1992. Chemical mobility and bioavailability of sediment-bound heavy metals influenced by salinity. Hydrobiologia, 235/236: 605-610.

Cubbage, J. 1992. Survey of contaminants in sediments in Lake Union and adjoining waters (Salmon Bay, Lake Washington Ship canal, and Portage Bay). Washington State Department of Ecology. Publication No. 92-e10. 72 pp.

Gambrell, R.P., J.B. Wiesepape, W.H. Patrick, Jr., and M.C. Duff. 1991. The effects of pH, Redox, and salinity on metal release from contaminated sediment. Water, Air, and Soil Pollution, 57-58: 359-367.

Inaba, K., H. Shiraishi, and Y. Soma. 1995. Effects of salinity, pH and temperature on aqueous solubility of four organotin compounds. Wat. Res., Vol. 29, No. 5, 1415-1417.

NOAA. 1999a. NOAA News: Mt. Baker Holds Snowfall Record, NOAA Reports. August 2, 1999. http://www.noaanews.noaa.gov/stories/s253.htm

NOAA. 1999 b. NOAA News: Turbulent Year in Weather Year-end Tip Sheet: Top Weather and NOAA/National Weather Service Stories. December 29, 1999. http://www.noaanews.noaa.gov/stories/s346.htm.

NOAA. 1999c. Climate of 1999 Annual Review - Preliminary Report National Climatic Data Center. December 13,1999. http://www.ncdc.noaa.gov/annual1999.html

Serdar, D. and J. Cubbage. 1996. Chemical Contaminants in Salmon Bay Sediments, Results of Phase II Sampling. Washington State Department of Ecology, Publication No. 96-343. 42 pp.

USACOE 1999. US Army Corps of Engineers web site accessed 8/18/1999. http://www.nws.usace.army.mil/opdiv/lwsc/index_n.html

Valentine, M. 1999. Personal communication. US Army Corps of Engineers, Seattle, WA.

VanRijn, D. 1999. Personal communication. US Army Corps of Engineers, Seattle, WA.

Winger, P.V. and P.J. Lasier. 1991. A vacuum-operated pore-water extractor for estuarine and freshwater sediments. Arch. Environ. Contam. Toxicol. 21. 321-324.

Zar, J. 1984. Biostatistical Analysis. Prentice Hall, NJ.

Appendix A. Written description of sampling transects and locations.

Transect	Location	Description
1	A	Near the Locks: South shore near NW corner of A1-Bldg, north at depth of approximately 41 feet. North shore landmark is the fire hose box on the waiting pier of the locks.
1	B	The fire hose box on the waiting pier of the locks, south side.
2	A	Underneath Ballard Bridge, located (east) across from fuel dock on south end of Salmon Bay.
2	B	Underneath Ballard Bridge tied up to eye hooks at the bridge pier that supports the south end of the drawbridge, west side.
2	C	On west side of Ballard Bridge at entrance to channel, tied up next to speed limit sign on north side of channel pilings.
3	A	Off center of middle channel closer to south side. South landmark is the NE corner of the Le Clercq Marine Construction building. North landmark is the east corner of the long concrete bulkhead.
3	B	Center of channel – deepest spot.
4		North side of the cut, east of Fremont Bridge, just east (20-30 feet) of pilings on north side of canal, just west of Aurora Bridge.
5	A	West end of Lake Union, approximately 50 yards off the Unocal dock (south shore) between the east end of the building from the north shore "Vic Franck" sign or dock-1.
5	B	Approximately ¾ across channel to the north in line with "Vic Franck" sign and Unocal front door.

Appendix B. Latitude and Longitude of samples (Datum = NAD 83).

Number	Run	Transect	Location	Latitude	Longitude
1	1	1	A	47 39.859	122 23.443
2	1	1	B	47 39.835	122 23.393
3	1	2	A	47 39.454	122 22.274
4	1	2	B	NA	NA
5	1	2	C	47 39.672	122 22.709
6	1	3	A	47 39.430	122 22.033
7	1	3	B	47 39.378	122 22.187
8	1	4	A	47 38.945	122 20.948
9	1	5	A	---	---
10	1	5	B	---	---
11	2	1	A	47 39.856	122 23.500
12	2	1	B	47 39.862	122 23.485
13	2	2	A	47 39.424	122 22.546
14	2	2	B	47 39.502	122 22.569
15	2	2	C	47 39.499	122 22.801
16	2	3	A	47 39.430	122 22.140
17	2	3	B	47 38.907	122 20.830
18	2	4	A	47 38.907	122 20.830
19	2	5	A	47 38.892	122 20.597
20	2	5	B	47 38.771	122 20.502
21	3	1	A	47 39.719	122 24.419
22	3	1	B	47 39.894	122 23.546
23	3	2	A	47 39.454	122 22.577
24	3	2	B	47 39.667	122 22.532
25	3	2	C	47 39.873	122 22.360
26	3	3	A	47 39.407	122 22.028
27	3	3	B	47 39.501	122 22.112
28	3	4	A	47 38.831	122 20.797
29	3	5	A	47 38.672	122.20.814
30	3	5	B	47 38.748	122 20.800
31	4	1	A	NA	NA
32	4	1	B	47 39.834	122 23.589
33	4	2	A	NA	NA
34	4	2	B	NA	NA
35	4	2	C	47 39.675	122 22.836
36	4	3	A	47 39.578	122 22.177
37	4	3	B	47 39.554	122 22.156
38	4	4	A	47 38.784	122 20.739
39	4	5	A	47 38.707	122 20.623
40	4	5	B	47 39.272	122 20.624

Positions reported in Degrees/Minutes

--- = Sample not collected

NA = Unable to get a GPS reading.

Appendix C. Replicate sediment pore water samples (umhos/cm).

Location	#	A	B	Average	RPD
surface	8	158	131	144	0.19
	18	123.2	123	123.2	0.000
	26	346	329	337.5	0.050
bottom	8	252	288	270	0.14
	18	159	201	180	0.24
	26	1604	1603	1604	0.00062
	31	865	971	918	0.12
	32	2270	1741	2005.5	0.26
	38	104.8	106	105.3	0.0095
sediment	8	1135	982	1059	0.14
	18	353	532	442.5	0.40
	22	920	863	891.5	0.064
	26	1318	1730	1524	0.27

RPD: Relative percent difference

Appendix D. Sample data collected in Salmon Bay, 1999.

Date	Time	Number	Run	Transect	Location	Depth (ft)	Surface conductivity (umhos/cm)	Surface temperature	Bottom conductivity (umhos/cm)	Bottom temperature	Sediment pore water conductivity (umhos/cm)	Sediment pore water temperature**	Sediment pore water salinity	Volume (1000 cu ft)	Lockages	Barrier	Drain	Small locks	Ballard Bridge conductivity (bottom sensor) (umhos/cm)	Large Locks conductivity (bottom Sensor) (umhos/cm)	Fremont conductivity (umhos/cm)	Small locks (#/6 hrs)
9/13	12:00	1	1	1	a	41.7	#548	19.2	#18520	20.1	#17332	18.7	**12**	4513	7		c	28	506	25300	1213	9
9/13	12:25	2	1	1	b	40.2	#467	19.0	#21829	20.0	#12735	19.1	**8.4**	4513	7		c	28	*496	*25600	*1229	10
9/13	13:00	3	1	2	a	11	#276	18.9	#334	17.8	#358	17.5	0.20	4978	8		c	28	487	25900	1244	9
9/13	13:30	4	1	2	b	7.2	#270	21.2	#275	18.9	#310	23.2	0.16	4978	8		c	28	*482	*26250	*1211	10
9/13	14:09	5	1	2	c	24.5	#278	21.2	#1135	20.8	#1320	24.0	**0.67**	4978	8		c	28	476	26600	1178	11
9/13	15:00	6	1	3	a	23.5	#288	20.2	#450	21.2	#531	23.1	0.27	4978	8		c	28	502	21900	1368	10
9/13	15:40	7	1	3	b	33	#288	.	#2727	19.9	.	.	.	4978	8		c	28	469	22800	1299	12
9/13	16:30	8	1	4	a	36	#144	20.1	#270	20.9	#1059	26.5	**0.51**	5568	9		c	28	*466	*23550	*1273	11
9/13	.	9	1	5	a	.	.	.	.	.	.	.	.	5568	9		c	28	.	.	.	.
9/13	.	10	1	5	b	.	.	.	.	.	.	.	.	5568	9		c	28	.	.	.	.
9/20	10:48	11	2	1	a	48	370	19.1	487	18.7	1021	18.9	**0.58**	785	1		o	29	396	4700	1171	7
9/20	11:05	12	2	1	b	37	358	19.1	1688	18.6	626	20.2	0.34	785	1		o	29	408	5000	1362	8
9/20	11:31	13	2	2	a	10.6	214	19.2	215	19.0	1072	19.2	0.60	1318	2		o	29	*407	*5150	*1201	8
9/20	11:48	14	2	2	b	6.6	207	19.1	211	19.0	342	18.9	0.19	1318	2		o	29	*407	*5200	*1120	9
9/20	12:02	15	2	2	c	25	208	19.2	527	19.1	1279	22.4	**0.67**	1797	3		o	29	406	5300	1039	9
9/20	12:16	16	2	3	a	30	181	19.2	450	19.3	1666	24.5	**0.85**	1797	3		o	29	*398	*5525	*1092	10
9/20	12:25	17	2	3	b	34	159	.	353	19.3	.	.	.	1797	3		o	29	*389	*5750	*1145	10
9/20	12:54	18	2	4	a	37	123	19.4	179.8	19.3	442.5	22.1	0.23	1797	3		o	29	372	6200	1251	9
9/20	13:20	19	2	5	a	42	123	19.4	1388	19.5	802	22.8	0.41	2576	4		o	29	*372	*6200	*1272	10
9/20	13:35	20	2	5	b	41	123	19.4	990	19.2	788	21.9	0.41	2965	4		o	29	372	6200	1293	11

** Temperature was taken after enough pore water was obtained, often 20 minutes after sediment collection.
* Conductivity value was interpolated from hourly data to the nearest 15-minute interval to correspond with the time of sample collection.
Bold values are averages of replicate samples.
• = Missing values.
Converted values from a YSI 33 instrument set to equal an Orion 135 instrument.

Appendix D (continued).

Date	Time	Sample	Run	Transect	Location	Depth (ft)	Surface conductivity (umhos/cm)	Surface temperature	Bottom conductivity (umhos/cm)	Bottom temperature	Sediment pore water conductivity (umhos/cm)	Sediment pore water temperature*	Sediment pore water Salinity	Volume (1000 cu ft)	Lockages	Barrier	Drain	Small locks	Ballard Bridge conductivity (bottom sensor) (umhos/cm)	Large Locks conductivity (bottom Sensor) (umhos/cm)	Fremont conductivity (umhos/cm)	Small locks (#/6 hrs)
10/5	10:46	21	3	1	a	46	489	16.9	1043	16.2	1733	16.5	**1.1**	2809	5		c	24	627	9200	318	7
10/5	10:58	22	3	1	b	36	482	16.9	475	16.6	891.5	16.1	**0.54**	2809	5		c	24	627	9200	318	8
10/5	11:23	23	3	2	a	11.4	355	17.0	357	16.8	891	15.0	**0.55**	3392	6		c	24	*602	*10400	*297	9
10/5	11:40	24	3	2	b	7.4	339	17.0	339	16.8	386	15.2	0.23	3392	6		c	24	*590	*11000	*276	9
10/5	11:53	25	3	2	c	23	325	17.0	467	16.8	792	15.2	0.48	3392	6		c	24	577	11600	255	9
10/5	12:25	26	3	3	a	31	338	17.1	1603.5	17.0	1524	16.9	**0.92**	3392	6		c	24	*593	*11850	*268.5	10
10/5	13:00	27	3	3	b	33	329	17.1	1603	17.0	1730	16.6	**1.1**	3795	7		c	24	609	12100	282	11
10/5	13:20	28	3	4	a	33	162	17.2	167	17.1	457	17.8	0.26	4116	8		c	24	*608	*12350	*271	11
10/5	13:38	29	3	5	a	41	168	17.2	544	17.1	809	17.6	0.47	4116	8		c	24	*607	*12600	*261	10
10/5	14:00	30	3	5	b	41	166	17.2	365	17.2	850	17.4	0.49	4756	9		c	24	605	12800	250	10
10/27	11:05	31	4	1	a	45	218	13.8	918	13.5	16240	12.8	**13**	2448	4		c	13	133	9800	116	3
10/27	11:30	32	4	1	b	36	210	13.8	2006	13.3	6010	12.8	**4.4**	2448	4		c	13	*133	*8400	*116	3
10/27	12:01	33	4	2	a	11	110	13.6	116.8	13.6	896	12.2	**0.59**	2448	4		c	13	133	7000	115	5
10/27	12:19	34	4	2	b	8.3	113	13.9	112.6	13.7	362	11.9	0.23	2916	5		c	13	*133	*7000	*115	6
10/27	12:37	35	4	2	c	22	108	13.8	136	13.7	1179	10.0	**0.84**	2916	5		c	13	*132	*7000	*116	6
10/27	12:53	36	4	3	a	33	106	14.0	107.9	13.6	.	.	.	2916	5		c	13	132	7000	116	6
10/27	13:15	37	4	3	b	30	106	.	108	13.9	761	9.4	**0.54**	2916	5		c	13	*132	*7000	*115	8
10/27	13:54	38	4	4	a	38	105	14.0	105.3	13.7	312	10.0	0.21	2916	5		c	13	133	5200	114	8
10/27	14:19	39	4	5	a	41	105	14.0	105.5	13.7	662	9.5	0.47	2916	5		c	13	*133	*5200	*115	7
10/27	15:00	40	4	5	b	41	105	14.0	105.3	13.8	838	9.2	**0.60**	2916	5		c	13	131	5600	115	9

** Temperature was taken after enough pore water was obtained, often 20 minutes after sediment collection.
* Conductivity value was interpolated from hourly data to the nearest 15-minute interval to correspond with the time of sample collection.
• = Missing values.
Bold values exceed salinity of 0.5.

Appendix E. USACOE hourly conductivity monitoring station readouts of the bottom sensor for the dates of sediment sampling (umhos/cm).

Time	Date	Ballard Bridge	Locks	Fremont Bridge
100	09/13/1999	589	22900	1431
200	09/13/1999	559	23400	754
300	09/13/1999	593	21300	1059
400	09/13/1999	569	20800	1209
500	09/13/1999	551	19000	1425
600	09/13/1999	483	18500	1050
700	09/13/1999	482	17200	1098
800	09/13/1999	515	21600	1086
900	09/13/1999	476	22100	1071
1000	09/13/1999	541	19600	1112
1100	09/13/1999	501	19800	1119
1200	09/13/1999	506	25300	1213
1300	09/13/1999	487	25900	1244
1400	09/13/1999	476	26600	1178
1500	09/13/1999	502	21900	1368
1600	09/13/1999	469	22800	1299
1700	09/13/1999	463	23300	1136
1800	09/13/1999	479	23800	972
1900	09/13/1999	555	24300	1047
2000	09/13/1999	561	24800	714
2100	09/13/1999	582	25300	943
2200	09/13/1999	606	26600	884
2300	09/13/1999	684	25500	960
2400	09/13/1999	744	26600	850
100	09/20/1999	529	7700	1197
200	09/20/1999	455	7900	994
300	09/20/1999	436	8900	778
400	09/20/1999	453	6600	868
500	09/20/1999	469	6000	1206
600	09/20/1999	485	5300	1181
700	09/20/1999	491	4600	775
800	09/20/1999	431	3900	927
900	09/20/1999	430	4000	1053
1000	09/20/1999	396	4700	1171
1100	09/20/1999	408	5000	1362
1200	09/20/1999	406	5300	1039
1300	09/20/1999	372	6200	1251
1400	09/20/1999	370	28100	1335
1500	09/20/1999	377	13500	1426
1600	09/20/1999	358	17900	1359
1700	09/20/1999	379	11300	1215
1800	09/20/1999	358	14400	1228
1900	09/20/1999	337	9900	1170
2000	09/20/1999	319	8300	1011

Appendix E (continued).

Time	Date	Ballard Bridge	Locks	Fremont Bridge
2100	09/20/1999	317	10300	843
2200	09/20/1999	308	10500	1053
2300	09/20/1999	309	12800	1251
2400	09/20/1999	298	7100	876
100	10/05/1999	585	21600	436
200	10/05/1999	610	18400	295
300	10/05/1999	657	15900	338
400	10/05/1999	670	15000	257
500	10/05/1999	698	13300	240
600	10/05/1999	654	10600	246
700	10/05/1999	650	12300	325
800	10/05/1999	647	9000	295
900	10/05/1999	563	11600	350
1000	10/05/1999	589	13500	344
1100	10/05/1999	627	9200	318
1200	10/05/1999	577	11600	255
1300	10/05/1999	609	12100	282
1400	10/05/1999	603	10100	250
1500	10/05/1999	611	12600	279
1600	10/05/1999	586	18000	341
1700	10/05/1999	567	15200	381
1800	10/05/1999	608	18200	305
1900	10/05/1999	604	16800	295
2000	10/05/1999	605	12800	250
2100	10/05/1999	607	11200	245
2200	10/05/1999	602	10600	404
2300	10/05/1999	558	10700	348
2400	10/05/1999	547	10600	477
100	10/27/1999	137	10400	115
200	10/27/1999	135	7900	116
300	10/27/1999	163	8000	115
400	10/27/1999	149	7200	116
500	10/27/1999	144	6300	117
600	10/27/1999	148	8400	117
700	10/27/1999	149	7200	115
800	10/27/1999	143	6500	114
900	10/27/1999	143	6100	115
1000	10/27/1999	137	7000	115
1100	10/27/1999	133	9800	116
1200	10/27/1999	133	7000	115
1300	10/27/1999	132	7000	116
1400	10/27/1999	133	5200	114
1500	10/27/1999	131	5600	115
1600	10/27/1999	130	14800	115