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Salinity Monitoring at the Lake Washington Ship Canal 2005: Data Review and Quality Assurance

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Introduction

Lake Washington is a large freshwater lake within the Seattle metropolitan area that historically drained to Puget Sound via the Black River and the Duwamish River. In 1916, the US Army Corps of Engineers, Seattle District (CENWS) constructed the Lake Washington Ship Canal (LWSC) to provide for both deep and shallow navigation between Puget Sound and Lake Washington as well as a means for the passage of anadromous fish to upstream spawning grounds. The LWSC connects these water bodies via the Hiram Chittenden Locks and two canals: the Montlake Cut between Lake Washington and Lake Union, and the Fremont Cut between Salmon Bay and Lake Union (Figure 1).

The Hiram Chittenden Locks, located at the entrance to Salmon Bay, separate Puget Sound (saltwater) from Lake Washington (freshwater). The locks consist of a double lock (small and large) and a fixed concrete gravity dam structure with six gated spillways, saltwater drain, guide walls, and a fish ladder. A result of operating the locks is a potential for saltwater intrusion into the LWSC, Lake Union, and Lake Washington, which can affect the freshwater environment. The CENWS operates the locks to minimize saltwater intrusion into Lake Union and Lake Washington. To assure that saltwater intrusion is kept to a minimum, the CENWS monitors salinity at various locations and depths throughout the LWSC.

Purpose and Scope

The Seattle District Corps of Engineers monitored salinity, conductivity, and temperature at four locations in the LWSC from March through November, 2005. The purpose of the monitoring program was to provide real-time salinity data to the U.S. Army Corps of Engineers (USCOE) to allow for management of the Hiram Chittenden Locks on the Lake Washington Ship Canal to minimize saltwater intrusion into Lake Washington. This report describes the salinity, conductivity, and temperature quality assurance (QA) results and associated data for the Lake Washington Ship Canal monitoring program.

Methods and Materials

Site Characterization

Operation of the Hiram Chittenden Locks raises vessels about 22 feet from tide level of Puget Sound's Shilshole Bay to the freshwater system of the Lake Washington Ship Canal at Salmon Bay. A consequence of each lockage is that denser saltwater flows from the bottom of the locks into the lighter freshwater in Salmon Bay. Lock operators attempt to reduce the amount of saltwater intrusion using the following operational methods:

- Small locks versus large locks – The large locks require about 25 times more lake water (86,000 m^3) than the small locks to fill and allow about 25 times more saltwater to enter the ship canal during each lockage. When water and flow levels are low, use of the large locks is limited.

- Saltwater drain – Located on the floor of the large lock, the saltwater drain plays a significant role in removing much of the saltwater from Salmon Bay, preventing an increase in saltwater concentrations of Lake Washington.

- Saltwater barrier – A barrier wall is raised during large lockages to block saltwater from entering Salmon Bay, thus reducing the amount of saltwater entering the system. The barrier is only lowered for deep draft vessels.

During the summer period of heavy boating use at the locks and low natural flushing, the saltwater drain cannot keep up with the amount of saltwater entering the freshwater system, and saltwater intrudes into the Fremont Cut, Lake Union, and the Montlake Cut, Figure 2. Because saltwater is denser than freshwater, if saltwater were allowed to enter Lake Washington it would create density stratification and possibly affect the sediment water ecosystem within the lake. To prevent impacting the ecosystem of Lake Washington, the Washington Department of Ecology (WDOE) has established a water quality standard for salinity at the University Bridge of 1 part-per-thousand (ppt). Judicious operation at the locks is necessary to meet water quality criteria while still maintaining the proper elevations in the freshwater system.

Data Collection

In 1992 the Corps installed seventeen sensors located at five different stations from the locks to the University Bridge (Figure 2). Sensor locations were near the large lock at the Locks (LLLW), near Ballard Bridge (BBLW), Fremont Bridge (FBLW), Gas Works Park (GWLW), and University Bridge (UBLW). However, in 2005, the Gas Works Park station was not operational because the CENWS was unable to renew the lease of the site and a delay was encountered in acquiring a new site. A lease has since been granted for a location approximately 500 feet south of the old site, and the sensors will be installed for the 2006 monitoring season.

Each station contains three to four sensors at various depths. The stations are operated each year from April to November and report salinity, conductivity, and temperature every hour. They are closely monitored, and lock operations are adjusted to control salt water entering the system. Monitoring station location details and dates of operation are summarized in Table 1 and shown in Figure 2.

Data Collection Methods

Data collection methods followed procedures set forth in the Lake Washington Ship Canal Water Quality Monitoring and Analysis Plan (USCOE 2004). Data collection methods used at all LWSC stations were similar and are summarized below. Instrumentation at the LWSC consisted of Hydrolab MiniSonde 4a water quality probes, Geomation 2380 data collection platforms (DCP), radio transmitters, and power sources. The water quality probes and DCPs were powered by 12-volt batteries that are charged by a 120-volt AC line. Measurements were made every hour and the data were transmitted via radio directly to the Seattle District's HEC-DSS water quality database. Data were then sent out from Seattle every hour via file transfer protocol (FTP) to the Corps of Engineers Northwestern Division (CENWD) in Portland, Oregon. The data were then stored in the Columbia River Operational Hydromet Management System (CROHMS) database.

Data Collection Locations

In 2005, the Corps installed thirteen sensors at four different stations from the Locks to the University Bridge, with the Gas Works Park (GWLW) station not operating during the 2005 sampling season (Figure 2). The probes were attached at various depths to a quarter-inch steel cable anchored to the lake bottom. The monitoring depths were specific to each site, with the deepest probe positioned about 1 foot off the bottom. As shown in Table 1, the Large Locks contained four sensors at depths of 18, 27, 36, and 42 feet. These sensors were located on the east end (Salmon Bay) of the lock wall between the small and large locks. Ballard Bridge sensors were located at the end of the westernmost dock at Fisherman's Terminal. Sensors were at depths of 11, 21, and 32 feet. Fremont Bridge sensors were located off the western end of Boatworld Marina, located just east of Fremont Bridge, on the southern side of the canal. Sensors were at 18, 31, and 40 feet depths. University Bridge sensors were in the middle of the channel attached to the middle support of the bridge. They were located at depths 8, 21, and 35 feet.

Data Completeness

Data completeness and quality for salinity, conductivity, and temperature data collected in 2005 are summarized in Table 2. The data were based upon the number of planned monitoring hours for each location. The percentage of real-time salinity, conductivity, and temperature monitoring data received was calculated from the number of missing hourly values versus the number of planned hourly values. The percent of real-time salinity, conductivity, and temperature data passing quality assurance represents the percent of data that was received as real-time data and passed the quality assurance review.

Once the real-time data were received and missing data were flagged, the following quality assurance review procedures occurred. First, tables of raw data were visually inspected for erroneous data resulting from DCP malfunctions or improper transmission of data value codes. Second, data tables were reviewed for sudden increases in temperature, conductivity, or salinity that could not be correlated to any hydrologic event and therefore may have been a result of mechanical problems. Third, a data checklist program was used to assist in identifying erroneous data. Values outside the data checklist program range of acceptable values (0 to 86°F for temperature and 0 to 30 ppt salinity) were flagged and reviewed to determine if the data were acceptable or an artifact of a DCP or instrument malfunction. Fourth, graphs of the data were also created and analyzed in order to identify unusual spikes in the data. These spikes were then further investigated in order to identify the causes of error. Suspect data were corrected if possible. For instance, data where drift occurred can be easily adjusted through software programs. Data that could not be corrected were flagged as rejected and deleted from the database.

As shown in Table 2, problems with receiving real-time hourly data were encountered at all monitoring stations. Missing data for all stations were largely due to DCP malfunctions and programming problems. The sensors at the Large Locks encountered the most data transmission problems throughout 2005 largely due to malfunctioning radio equipment. Rejected data at all stations were largely a result of DCP transmission of improper data value codes. Few data values were rejected. UBLW rejection ranged from 0.00%-0.02%. FBLW ranged from 0.00%-0.01%. BBLW was 0.00-0.40%, and LLLW was 0.00%-0.25% (Table 2).

Quality-Assurance Procedures

Data quality assurance and calibration procedures included calibration of instruments in the laboratory and in the field. Prior to deployment and field service visits, all field probes were calibrated in the laboratory according to manufacturer's instructions using the primary standard. All primary standards were National Institute of Science and Technology (NIST) traceable and maintained according to manufacturer's recommendations. Laboratory calibrations of the water quality probes' conductivity sensors were performed using primary standard calibration solutions representative of the expected conductivity for each station. If any measurement differed by more than 5 percent from the primary standard the probe was recalibrated. Laboratory calibrations of the temperature sensor were performed using a NIST traceable thermometer. If measurements differed by more than 0.4°F the probe was returned to the manufacturer for maintenance.

Every month, the currently operating field probes were checked with a laboratory-calibrated probe, which also operated as the secondary standard for the field probe. Prior to calibration, the currently operating field probe was raised from depth and placed in a 5-gallon bucket of ship canal water along with the secondary standard probe. If the field probe disagreed with the secondary probe by more than 5 percent for conductivity, the probe was recalibrated using the primary standard. If the field probe disagreed with the secondary probe by more than 0.4°F for temperature, the field probe was returned to the manufacturer for repair.

The comparisons of the field sensors and the secondary standards are presented in Figures 3 and 4. As shown in Figure 3, the majority of conductivity data were generally within 5 to 10 percent conductivity difference between the field sensor and the secondary standard. Similarly, the temperature sensor secondary standard and the field temperature sensor were generally within 0.4°F difference at all locations.

Water Quality Criteria

In July 2003, the Washington Department of Ecology (WDOE) proposed updating their 1997 water quality standards for temperature. The U.S. Environmental Protection Agency (EPA) announced in a letter dated March 23, 2006 that it formally disapproved parts of Washington State's 2003 water quality standards, including new temperature criteria and water quality site specific criteria including salinity concentrations in the Ship Canal. Therefore, WDOE continues to use the 1997 standards until EPA approval is received. The WDOE has classified the Ship Canal as 'Lake Class,' (WAC 173-201A-030 (5)). Bodies of water classified as Lake Class can have no measurable temperature changes from natural conditions. Further, a special salinity condition is assigned to the LWSC. It states that "…salinity shall not exceed one part per thousand (1.0 ppt) at any point or depth along the line that transects the ship canal at University Bridge…," (WAC 173-201A-130 (58)).

Results and Discussion

Temperature

Temporal patterns for water temperature collected at the Lake Washington Ship Canal's Large Locks, Ballard Bridge, Fremont Bridge, and University Bridge stations are presented in Figures 5, 6, 7, and 8, respectively. Temperatures ranged from 45°F to 75°F during the monitoring period. In general, early spring temperatures were fairly cool and ranged between 45°F and 50°F. After mid-April, temperatures showed a general increase due to seasonal changes, with the warmest temperatures measured near the surface in late July and early August. Temperatures then gradually decreased to the lower 50's by mid-November when the sensors were removed.

During the summer, strong vertical thermal gradients were evident only at the University Bridge and Freemont Bridge stations. The lack of a strong thermal gradient at the Large Locks and Ballard Bridge stations is likely due to their locations near the locks where a constant flushing of water from Lock operations reduces the formation of a thermocline. Temperatures at Fremont Bridge showed the greatest vertical gradient, with up to a 15°F difference between the bottom and top sensors during the summer. Because the Freemont Bridge station is located near Lake Union it is possible that the station is being impacted by the temperature stratification that occurs in Lake Union. The University Bridge station developed a thermal gradient, with about a 10°F temperature difference between top and bottom sensors from late spring through summer. Because the University Bridge station is located near the outlet of Lake Washington, it is likely impacted by temperature stratification that develops in Lake Washington.

Salinity

Hourly salinity data for the Lake Washington Ship Canal's Large Locks, Ballard Bridge, Fremont Bridge, and University Bridge are summarized in Figures 5, 6, 7, and 8, respectively. Salinity varied greatly among sensor locations, reflecting the movement of the saltwater wedge through the Ship Canal. The denser saltwater is also reflected by the bottom sensors showing the greatest salinity readings and the top sensors showing the lowest.

Salinity at the LLLW was lowest March-April, Figure 5. This is mainly due to natural flushing of the system. Since flows are still high, the saltwater drain can operate often, reducing salinity concentrations. Also of note at LLLW is that fewer lockages occur in early spring due to weather and are mainly for commercial traffic. Salinity ranged from less than 1 ppt to up to 17 ppt. The top sensor remained less than 1 ppt for the season. The bottom sensor ranged from 1-17 ppt, reaching 17 ppt during mid-August when little natural flushing occurs.

Ballard Bridge salinity concentrations remained less than 1 to 6 ppt throughout the year, Figure 6. The top and middle sensors were similar most of the year, while the bottom sensor showed the greatest range. Sensors at FBLW showed salinity concentrations of about 0.04 until June and then again from the end of October until the end of the monitoring season, Figure 7. Salinity was at its highest point for the first two weeks of June where the bottom sensor reached concentrations of about 2.0 ppt. Salinity for the bottom sensor was less than 1 ppt for the remainder of the season.

University Bridge's (UBLW), Figure 8, bottom sensor peaked at 0.25 ppt during 2005. All three sensors were at or less than 0.04 ppt for the majority of the year. From mid-June until September, most of the salinity variations for the bottom and middle sensors occurred due to the decrease in flows which would naturally flush the system. The red line indicates the WDOE salinity standard of 1.0 ppt at University Bridge. Salinity levels were in compliance for the 2005 monitoring season.

Conclusion

Evaluation of the Quality Assurance and monitoring results yielded the following conclusions:

- Data completeness for all stations ranged from 90.28%-95.26% for temperature, 90.22%-95.31% for conductivity, and 90.08%-95.31% for salinity. Missing data were largely due to radio transmitter malfunctions which prevented data from being sent to the District Office. Other missing data were due to DCP malfunctions and programming problems. The Large Locks and Ballard Bridge each had a sensor that malfunctioned and was returned to the manufacturer for repair. Rejected data were largely a result of DCP transmission of improper data value codes. Few data values were rejected. UBLW rejection ranged from 0.00%-0.02%. FBLW ranged from 0.00%-0.01%. BBLW was 0.00-0.40%, and LLLW was 0.00%-0.25%.

- In general, laboratory calibrations were good and within 0.32°F for temperature and 5% for specific conductance of the primary standard.

- In general, field calibration data for temperature were good and were within 0.36°F of the secondary standard. The bottom sensor at the Large Locks, LLLW-D, had the greatest outlier of a 1.4°F difference from the secondary standard. This outlier was from an older sensor initially installed at that location but was removed and replaced with a new, more reliable sensor shortly after. A slightly high reading at LLLW-A showed a 0.6°F difference. The sensor calibrated well the rest of the season. The difference may have been due to the calibration water heating up between the reading of the secondary standard and the reading of the field sensor.

- In general, field calibration data for conductivity were fair and were near 5.0% of the secondary standard. LLLW showed the greatest variance. These probes were calibrated using a conductivity standard of 8974 uS/cm. When recalibrated, they were placed in water that read around 150 uS/cm. This may account of the high percent difference recorded. When conductivity percent difference was greater than 5.0%, the sensors were recalibrated to account for drift that naturally occurs over time with these sensors. Sensors within 5.0% were also recalibrated to ensure accurate readings.

- University Bridge had no days exceeding the 1 part-per-thousand salinity criteria established by the Washington Department of Ecology.

References

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U.S. EPA. 1990. Recommended protocols for measuring conventional water quality variables and metals in fresh water of the Puget Sound region. Puget Sound Estuary Program U.S. Environmental Protection Agency, Region 10, Office of Puget Sound, Seattle, Washington.

U.S. EPA. 1996. Recommended protocols for measuring selected environmental variables in Puget Sound. U.S. Environmental Protection Agency, Region 10, Office of Puget Sound, Seattle, Washington.

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Tables

Table 1: Location and sensor information for LWSC monitoring, 2005.

Station Name	Site ID	Depth (ft)	Latitude	Longitude	2005 Sampling Period
Large Locks	LLLW-A	18	47°38'30.8" N	122°19'43.8" W	March 12 -November 13
	LLLW-B	27	47°38'30.8" N	122°19'43.8" W	March 12 -November 13
	LLLW-C	36	47°38'30.8" N	122°19'43.8" W	March 12 -November 13
	LLLW-D	42	47°38'30.8" N	122°19'43.8" W	March 12 -November 13
Ballard Bridge	BBLW-A	11	47°39'54.1" N	122°23'37.8" W	March 5 - November 13
	BBLW-B	21	47°39'54.1" N	122°23'37.8" W	March 5 - November 13
	BBLW-C	32	47°39'54.1" N	122°23'37.8" W	March 5 - November 13
Fremont Bridge	FBLW-A	18	47°38'44.2" N	122°20'41.3" W	March 5 - November 13
	FBLW-B	31	47°38'44.2" N	122°20'41.3" W	March 5 - November 13
	FBLW-C	40	47°38'44.2" N	122°20'41.3" W	March 5 - November 13
University Bridge	UBLW-A	8	47°39'11.7" N	122°19'06.6" W	March 5 - November 13
	UBLW-B	21	47°39'11.7" N	122°19'06.6" W	March 5 - November 13
	UBLW-C	35	47°39'11.7" N	122°19'06.6" W	March 5 - November 13

Table 2: Conductivity, salinity, and temperature data completeness for 2005.

Station Name/Site ID	Sensor Depth (ft)	Parameter	Planned monitoring hours	# of missing hourly values	% of real-time monitoring data received	% of real-time data received and passing QA
Large Locks (LLLW)						
LLLW-A	18	Conductivity	5928	485	91.82	91.80
		Salinity	5928	490	91.73	91.67
		Temperature	5928	495	91.65	91.65
LLLW-B	27	Conductivity	5928	572	90.35	90.33
		Salinity	5928	582	90.18	90.08
		Temperature	5928	576	90.28	90.28
LLLW-C	36	Conductivity	5928	378	93.62	93.51
		Salinity	5928	375	93.67	93.42
		Temperature	5928	370	93.76	93.76
LLLW-D	42	Conductivity	5928	571	90.37	90.22
		Salinity	5928	577	90.27	90.22
		Temperature	5928	559	90.57	90.57
Ballard Bridge (BBLW)						
BBLW-A	11	Conductivity	6096	299	95.10	95.08
		Salinity	6096	312	94.88	94.64
		Temperature	6096	306	94.98	94.98
BBLW-B	21	Conductivity	6096	379	93.78	93.75
		Salinity	6096	393	93.55	93.29
		Temperature	6096	388	93.64	93.64
BBLW-C	32	Conductivity	6096	321	94.73	94.65
		Salinity	6096	333	94.54	94.14
		Temperature	6096	323	94.70	94.70
Freemont Bridge (FBLW)						
FBLW-A	18	Conductivity	6096	291	95.23	95.23
		Salinity	6096	292	95.21	95.21
		Temperature	6096	293	95.19	95.19
FBLW-B	31	Conductivity	6096	303	95.03	95.03
		Salinity	6096	304	95.01	95.00
		Temperature	6096	294	95.18	95.18
FBLW-C	40	Conductivity	6096	300	95.08	95.08
		Salinity	6096	307	94.96	94.95
		Temperature	6096	303	95.03	95.03
University Bridge (UBLW)						
UBLW-A	6	Conductivity	6096	286	95.31	95.31
		Salinity	6096	286	95.31	95.31
		Temperature	6096	289	95.26	95.26
UBLW-B	21	Conductivity	6096	300	95.08	95.06
		Salinity	6096	298	95.11	95.10
		Temperature	6096	299	95.10	95.10
UBLW-C	35	Conductivity	6096	297	95.13	95.13
		Salinity	6096	300	95.08	95.08
		Temperature	6096	304	95.01	95.01

Figures

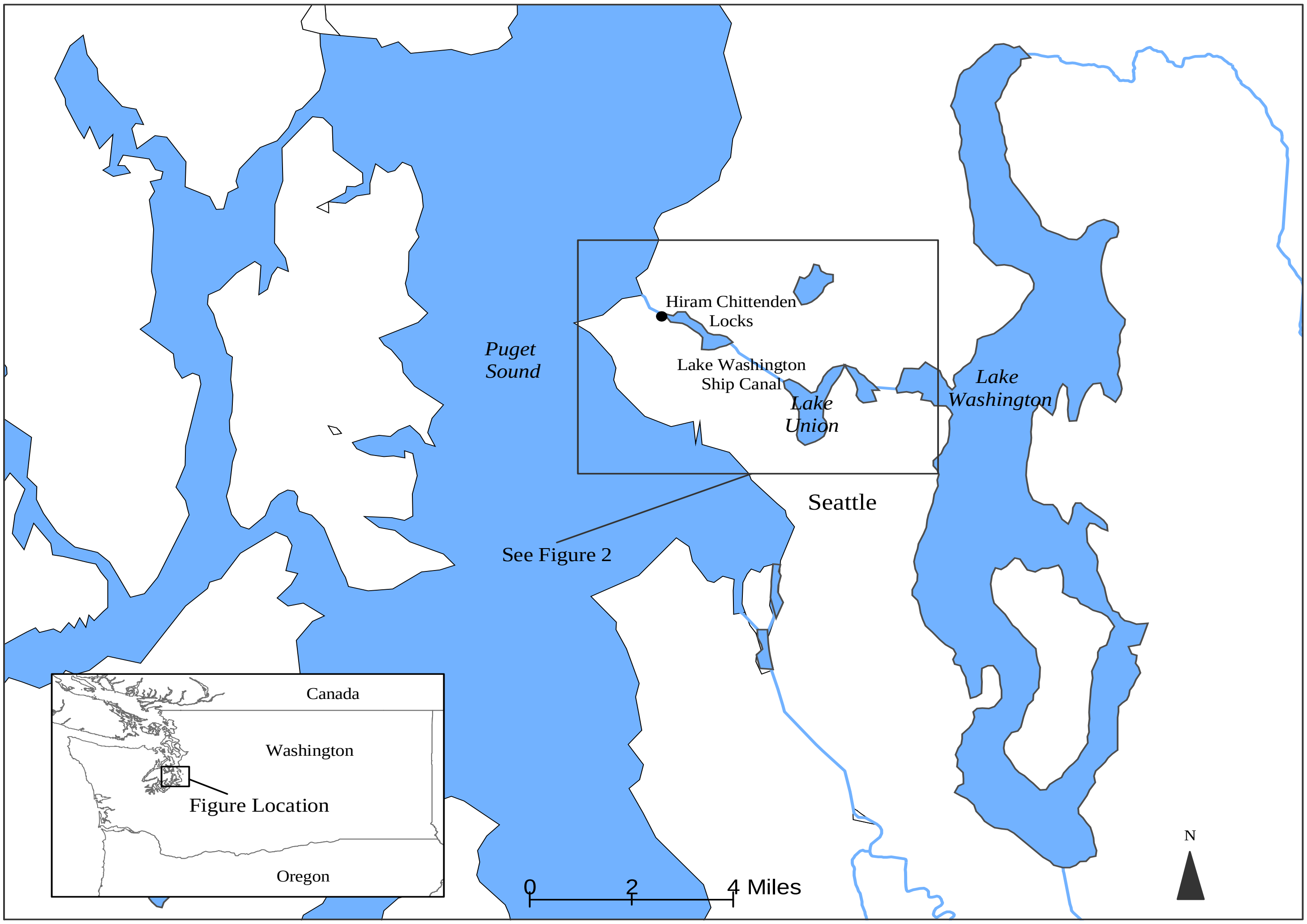

Figure 1: Overview of the Lake Washington Ship Canal.

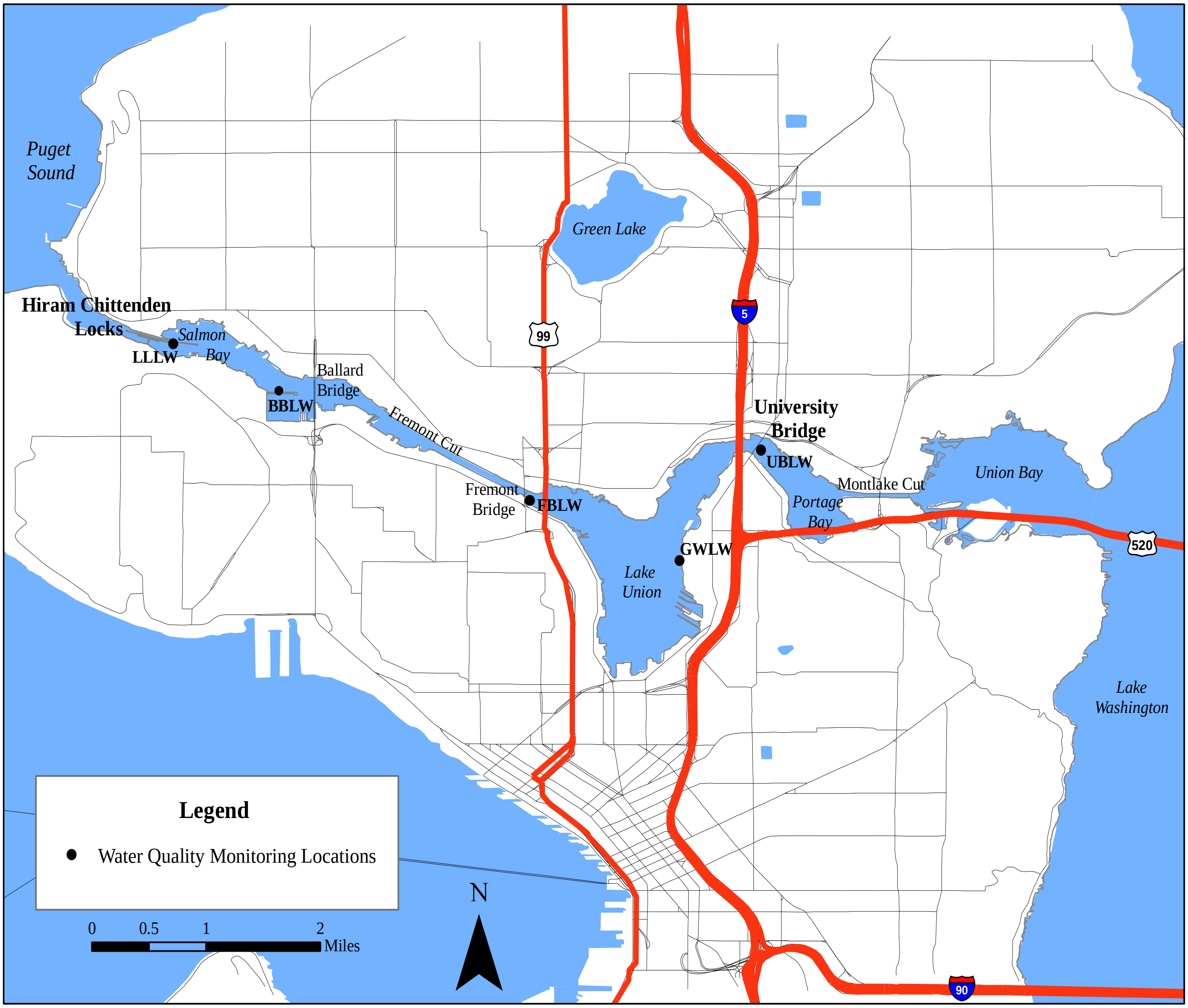

Figure 2: Station locations for LWSC salinity monitoring 2005

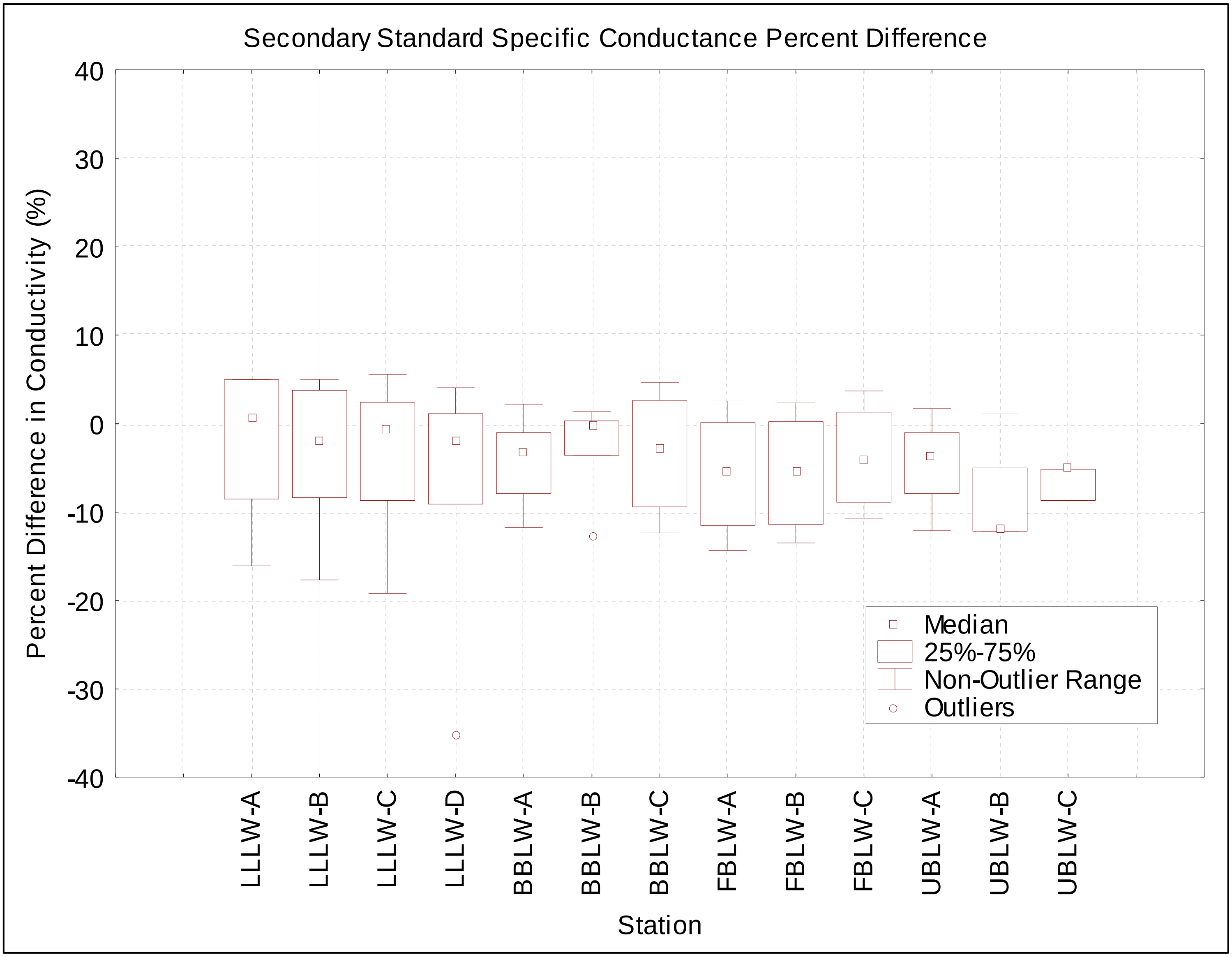

Figure 3: Percent difference between the secondary standard and the field conductivity.

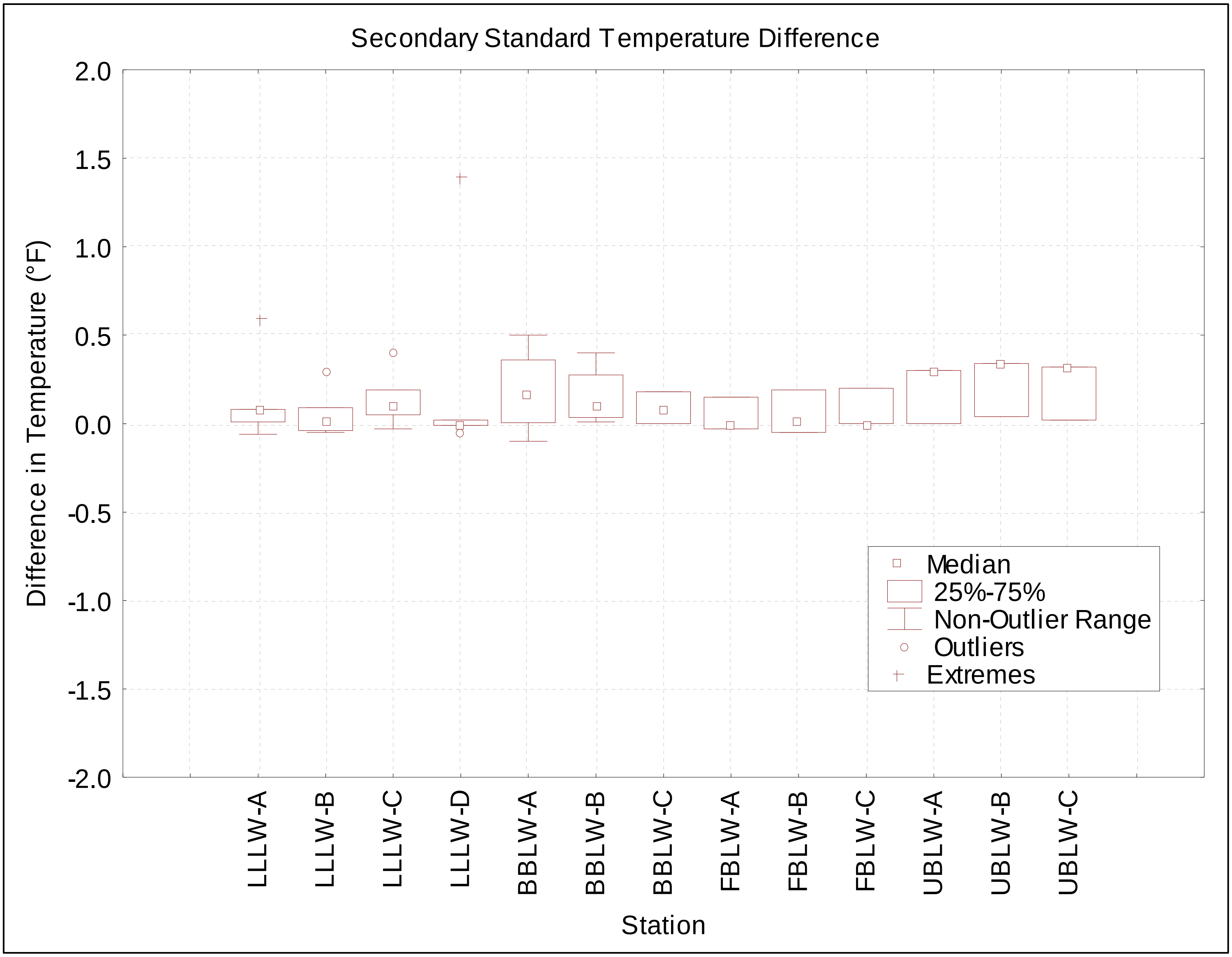

Figure 4: Difference between the secondary standard and the field temperature.

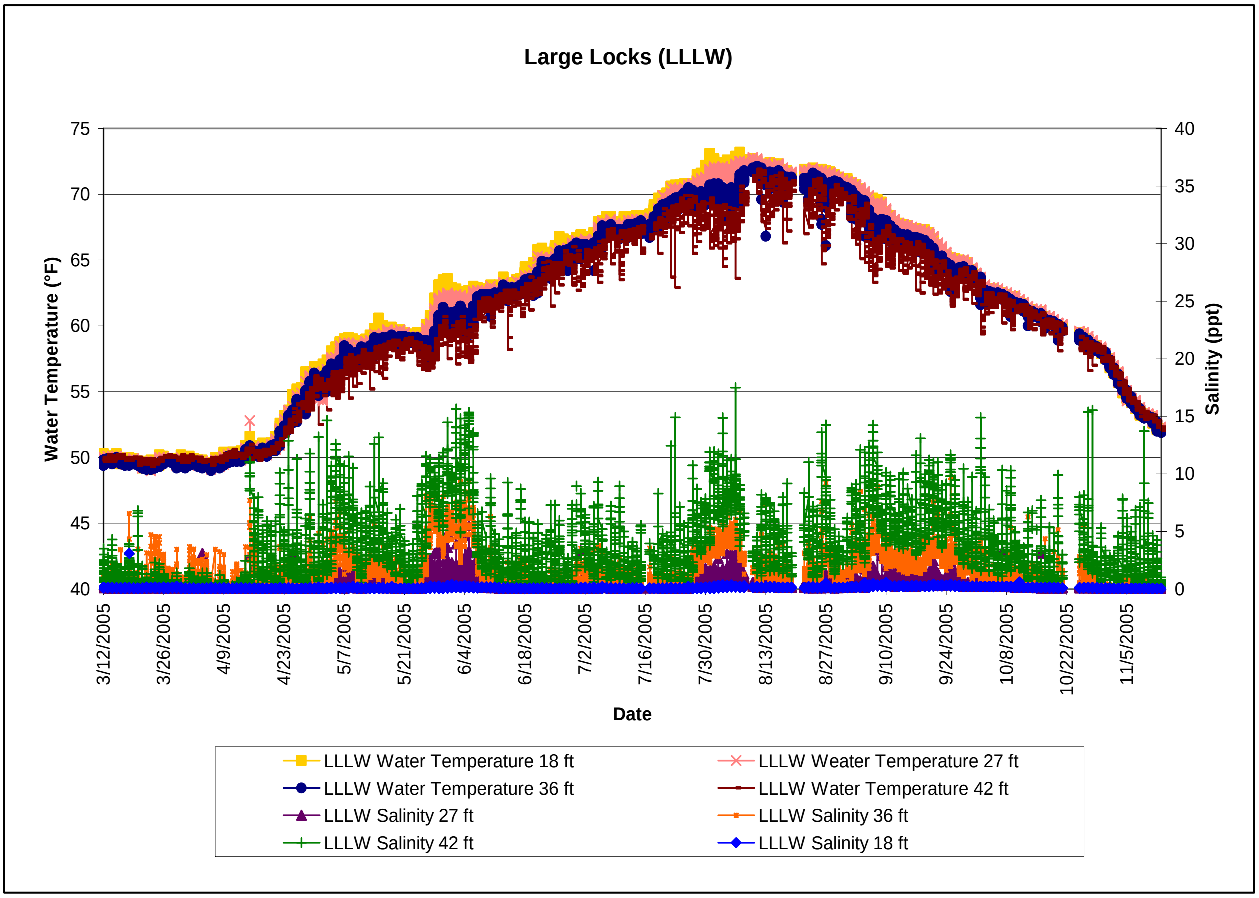

Figure 5: Temperature and salinity at Large Locks (LLLW) during the 2005 monitoring season.

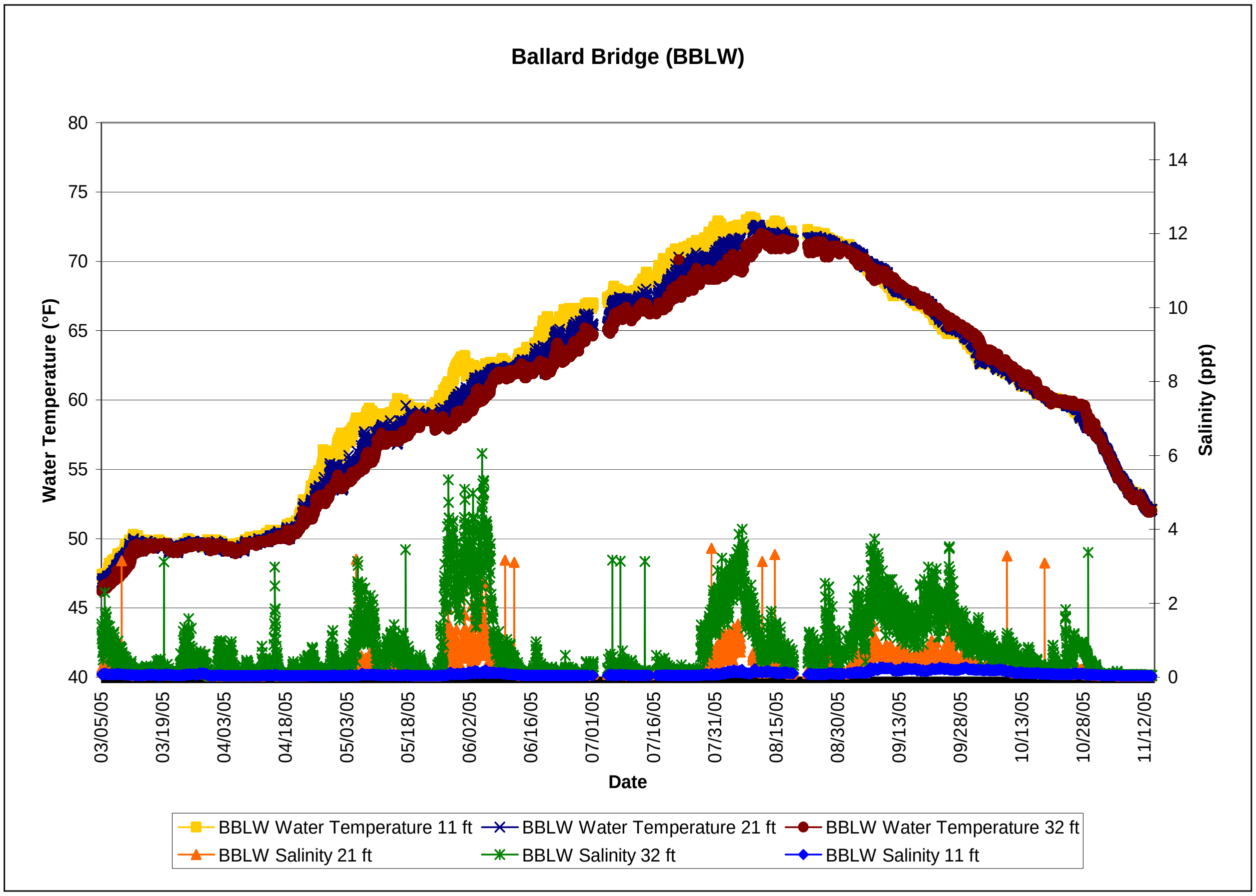

Figure 6: Temperature and salinity at Ballard Bridge (BBLW) during the 2005 monitoring season.

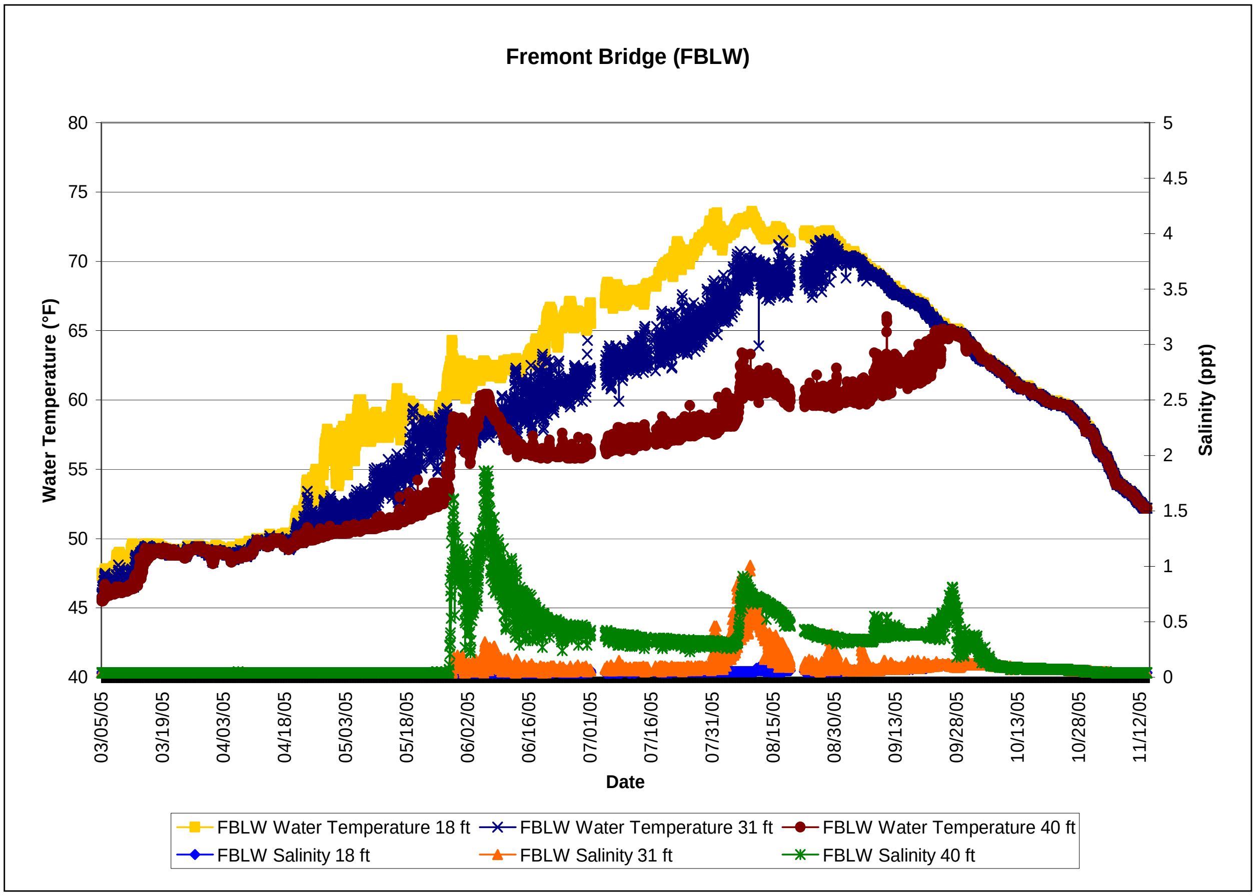

Figure 7: Temperature and salinity at Fremont Bridge (FBLW) during the 2005 monitoring season.

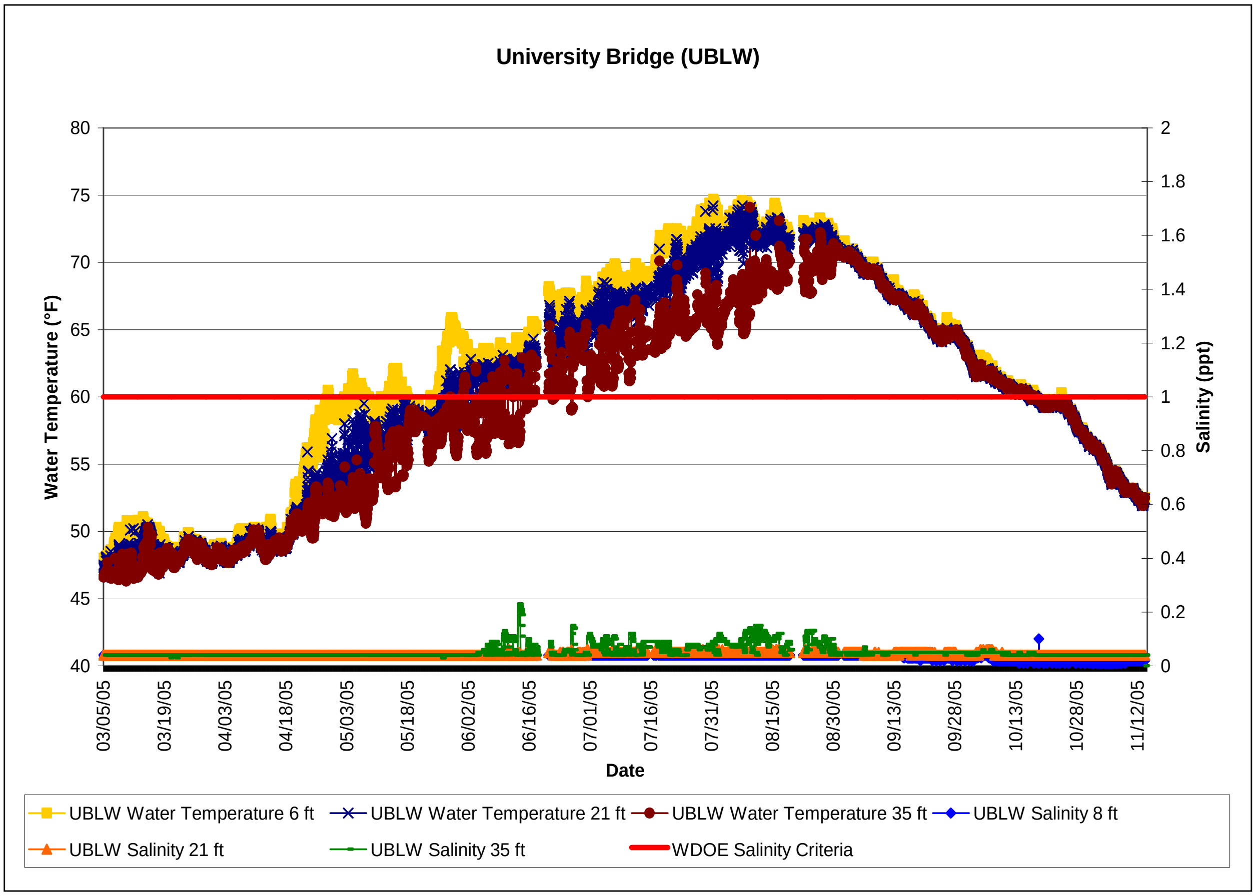

Figure 8: Temperature and salinity at University Bridge (UBLW) during the 2005 monitoring season.