Saltwater Intrusion and Infiltration into the King County Wastewater System

March 2011

King County

Department of
Natural Resources and Parks
Wastewater Treatment Division

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1.0. EXECUTIVE SUMMARY

Salt water is entering King County's combined sewer system that carries flows to the West Point Treatment Plant in Seattle. During high tides, the salt water enters through leaky gates, overflow weirs, groundwater infiltration, and local sewer connections in the industrial area along the Duwamish Waterway, the Downtown Seattle Waterfront, and the Salmon Bay area near the Ballard Locks.

About 3 to 6 million gallons of salt water enter the system each day, amounting to about 1 to 2 billion gallons each year. The salt water is not only causing severe and premature corrosion of equipment at the West Point plant but also substantially increasing flow to the plant and using valuable system capacity needed during critical overflow periods. Reduction in capacity both at the plant and in the conveyance system can contribute to combined sewer overflows in wet weather and sanitary sewer overflows in dry weather.

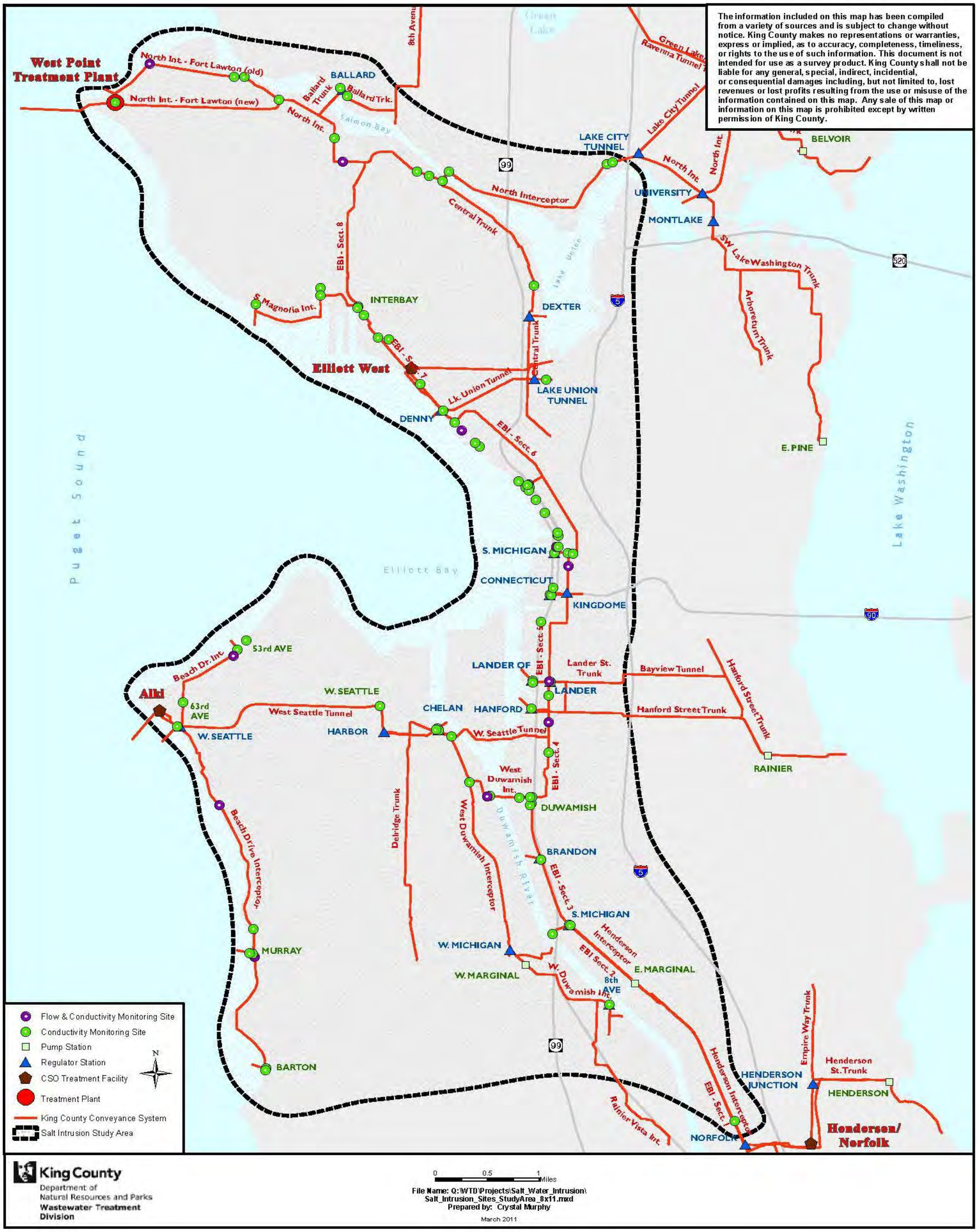
King County continues to incur the costs of rehabilitating corroded equipment and treating the salt water that enters the system. Repairing all damaged clarifiers at West Point after only seven years of service cost $1.2 million in 2003. Recent repair and replacement of gates at the plant cost almost $0.6 million. Many small repairs undertaken by operations staff go unreported as saltwater-related damage. The yearly cost of treating salt water entering the King County wastewater system has been estimated at $1.64 to $3.16 million.

Since 2003, King County's Wastewater Treatment Division (WTD) has been monitoring locations in the combined sewer system to determine the presence, magnitude, and sources of saltwater intrusion. The division undertook a more comprehensive study in 2007–2009. The following sections summarize the methods, conclusions, and recommendations of this study.

1.1 Study Methods and Conclusions

The study area extends as far south as Section 1 of the Elliott Bay Interceptor near the south end of the Boeing Field–King County International Airport and as far north as Ballard and the North Interceptor along the north side of Magnolia (see figure on next page). The study targeted areas near salt water that send flows to the West Point plant. Because conductivity near Elliott Bay along the Downtown Seattle Waterfront has consistently measured higher than in other areas, the monitoring focused on this area. Monitoring was conducted by taking grab samples; installing portable data loggers that measure salinity, conductivity, and temperature; and installing flow meters at selected sites. In all, 91 sites were monitored with the data loggers, including 27 Seattle Public Utility (SPU) sites.

The study found that saltwater intrusion is more endemic than anticipated at the start of the study. Despite King County and SPU modifications and repairs that significantly reduced saltwater intrusion and infiltration into the Elliott Bay Interceptor, the amount of salt water entering the West Point plant has remained about the same since initial monitoring in 2003. An estimated average of 5 to 6 mgd, or 7 to 10 percent, of the West Point influent is salt water. Maximum corrosion potential occurs at 7 percent salt water. The potential decreases either below or above this percentage. High conductivities in one portion of the study area are mitigated downstream as the wastewater volumes increase and dilute the salt water, only to become high again through intrusion at downstream locations.



Saltwater Intrusion Study Area

As in earlier studies, the major contributors are along the Elliott Bay Interceptor, particularly in the Downtown Seattle Waterfront and south of the waterfront near the East Duwamish Waterway. About half of the salt water entering West Point enters in the waterfront area. Most of this salt water enters the system through SPU outfalls and other structures on the waterfront, with connections to the Elliott Bay Interceptor. SPU plans to restructure much of its waterfront facilities either through the seawall replacement project, estimated to be completed around 2014, or its CSO control program.

The relationship between flow, tide, and conductivity found during this study is consistent with findings from previous monitoring. A noticeable spike in conductivity occurs during or after tides greater than 11 feet, with some smaller spikes associated with tides over 10 feet. The higher the volume of flow in the pipe, the lower the spike in conductivity. Temperatures confirmed that colder sea water is entering the system during these high tides.

1.2 Recommendations

The recommended approach to remedy the problem is to implement a comprehensive program to identify current and future saltwater intrusion sites and take measures to stop these sources of intrusion. This work will require coordination with SPU to learn more about their system and their plans to address intrusion into the County‘s system from SPU facilities, especially along the downtown waterfront. It will also require coordination with other King County programs and projects, such as the CSO Control Program and efforts to plan for effects of climate change. The following recommendations can be folded into the program or, in the absence of such a program, could be undertaken as individual projects.

One recommendation—a carryover from a 2003 study of corrosion at the West Point Treatment Plant—is to investigate the extent of the corrosion and damage to the return-activated sludge, medium-pressure gas, and primary effluent piping at the plant. In addition, the 2003 report recommended the evaluation, installation, or upgrading, as appropriate, of cathodic protection throughout the plant‘s piping network, including buried steel process piping.

Recommendations resulting from this 2007−2009 study are as follows:

- Inspect all King County gates near Puget Sound, Elliott Bay, and the Duwamish River for saltwater intrusion, and identify and address the causes.
- Make the following repairs to problems indentified at three locations during this study:
  - Reseat the gate and install a bulkhead at the Hanford Regulator Station outfall.
  - Reseat the gate and install a bulkhead at the King Street Regulator Station outfall.
  - Install a new seal on the overflow flap gate at the Lander Street Regulator Station.
- In coordination with SPU, investigate five areas to determine the location of local lines, gates, lift stations, and connections to the County‘s system. Concentrated conductivity monitoring should accompany the investigations. The locations are as follows:
  - The vicinity of the 8th Avenue South Regulator Station
  - Near the Duwamish Pump Station
  - The Port of Seattle Pier 91 property near Interbay Pump Station

- The Ballard area near Shilshoe Bay that feeds into an SPU line that runs south under the Lake Washington Ship Canal
- The North Interceptor prior to where the pipeline enters the West Point plant

2.0. INTRODUCTION

Salt water is entering King County's combined sewer system that carries flows to the West Point Treatment Plant in Seattle. During high tides, the salt water enters through leaky gates, overflow weirs, groundwater infiltration, and local sewer connections in the industrial area along the Duwamish Waterway, the Downtown Seattle Waterfront, and the Salmon Bay area near the Ballard Locks.

About 3 to 6 million gallons of salt water enter the system each day, amounting to about 1 to 2 billion gallons each year. The salt water is not only causing severe and premature corrosion of equipment at the West Point plant but also substantially increasing flow to the plant and using valuable system capacity needed during critical overflow periods. Reduction in capacity both at the plant and in the conveyance system can contribute to combined sewer overflows in wet weather and sanitary sewer overflows in dry weather.

King County continues to incur the costs of rehabilitating corroded equipment and treating the salt water that enters the system. Repairing all damaged clarifiers at West Point after only seven years of service cost $1.2 million in 2003. Recent repair and replacement of gates at the plant cost almost $0.6 million. Many small repairs undertaken by operations staff go unreported as saltwater-related damage. The yearly cost of treating salt water entering the King County wastewater system has been estimated at $1.64 to $3.16 million.

Since 2003, King County's Wastewater Treatment Division (WTD) has been monitoring locations in the combined sewer system to determine the presence, magnitude, and sources of saltwater intrusion. The division undertook a more comprehensive study in 2007–2009. This report presents the methods, results, conclusions, and recommendations of this study.

This chapter discusses the relationship of salt water and corrosion, the relationship of saltwater intrusion and tides, and the history of saltwater monitoring at WTD facilities.

2.1 Relationship of Salt Water and Corrosion

WTD monitors salinity in wastewater flows by measuring either the chloride ion content or the conductivity of the flows (ability to conduct electricity). The conductivity of sea water depends on the number of dissolved ions per volume (salinity) and the mobility of the ions (temperature and pressure). The basic unit of conductivity is the Siemens (S). Standardized measurements are expressed in specific conductivity units. For this study, WTD uses mS/cm (milli-Siemens per centimeter). Earlier studies described below used ųS/cm (micro-Siemens per centimeter). Conductivity is affected by temperature: the warmer the water, the higher the conductivity. All meters have either fixed or adjustable automatic temperature compensation referenced to a standard temperature, usually 25°C (77°F). Conductivity in a conveyance facility will decrease as increasing volumes of wastewater dilute the salt water in the flow.

The average conductivity of Puget Sound is about 32 mS/cm. The Duwamish River is considered an estuary in its lower reaches as it enters Puget Sound. During high-tide stages and periods of low freshwater inflow, saltwater inflow has been documented as extending as far upstream as the

Foster Bridge (River Mile 8.7).[1] At the river's mouth at the northern end of Harbor Island, a salinity level similar to that of Elliott Bay is typical for the entire water column; salinity decreases toward the upriver portion of the estuary.

The background conductivity for normal wastewater is 0.65 mS/cm. Conductivity readings over about 2 mS/cm clearly indicate an influence of salt water in the system. Wastewater flows entering the South Treatment Plant show an average peak conductivity of 0.590 mS/cm; flows entering the West Point Treatment Plant show an average peak conductivity of 3.2 mS/cm. Given the average conductivity of Puget Sound and an average peak conductivity at any location, the percentage of salt water at that location can be calculated. For example, an average peak conductivity of 3.2 mS/cm indicates that the flow is about 10 percent salt water. The percentage of salt water entering West Point ranges from 5 to 10 percent. Maximum corrosion potential occurs at 7 percent salt water. The potential decreases either below or above this percentage.

The salt water contributes to total dissolved solids, which must be removed in the treatment process; sulfates, which enhance hydrogen sulfide generation; and chlorides, which accelerate corrosion and may inhibit the flocculation process and, thus, increase the demand for polymers at West Point.

2.2 Relationship of Saltwater Intrusion and Tides

Seattle is a large metropolitan city in a low-lying coastal area with over 350 miles of existing conveyance system pipes. Each of the three identified areas of saltwater intrusion—the industrial area along the Duwamish Waterway, the Downtown Seattle Waterfront, and near the Ballard Locks—has hundreds of potential contributing sites and connections. These areas contain approximately 45 to 50 miles of pipe, or roughly 15 percent of King County's total conveyance system, in addition to a multitude of other wastewater or stormwater lines—owned by the City of Seattle, Port of Seattle, or private concerns—that may directly connect to the county system.

Both city and county combined sewer systems include outfalls with gates installed at elevations that allow predicted flows during heavy rainfall to overcome the pressure of the water in the receiving water body and leave the system without allowing water to enter. If these flows cannot leave the system through outfalls, the combined flows can back up in the conveyance pipes and exit through the lowest points in the system—storm drains, homes, and businesses.

Upstream of the outfalls, the elevations of weirs and gates that channel the flows to treatment plants were designed on the basis of tidal elevations experienced during the twentieth century, mostly in the 1960s. From the observed NOAA mean sea level trend at the Seattle Tide Gauge, sea level rose approximately 4 inches from 1950 to 2000.[2] Forecasted sea level rise resulting from climate change could exert increased hydraulic pressure at these structures, resulting in greater saltwater intrusion, reduced capacity, and upstream flooding.

The elevations of outfalls, gates, and weirs on the Downtown Seattle Waterfront range from 11.3 to 11.96 feet. Previous saltwater monitoring efforts found sharp rises in conductivity in relation

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[1] A river mile is a measure of distance in miles along a river from its mouth. River mile numbers begin at zero and increase farther upstream.

[2] NOAA = National Oceanographic and Atmospheric Administration.

to high tides over about 11 feet. Such high tides occur in Elliott Bay approximately 250 times a year.

2.3 History of Saltwater Monitoring at WTD Facilities

In 1998, the laboratory at West Point noted high levels of conductivity in the plant. Inspections conducted by WTD‘s Facilities Inspection unit noted saltwater intrusion into the conveyance system but did not recognize the significance of its role in corroding West Point equipment. At that time, coatings applied to some West Point equipment failed within the first 2 years of service. The suction duct piping in the clarifiers was severely corroded. The galvanizing on the equipment had an expected useful service life of at least 10 years. A number of plant gates, expected to last around 30 years, also showed severe corrosion within 2 years of service. The corrosion appeared to be galvanic, suggesting the presence of a highly corrosive electrolyte, most likely salt water. Similar equipment at South plant, brought online in 1961, did not show the same corrosion.

In 2002 and 2003, saltwater intrusion was suspected as the cause of localized corrosion, including a 1-inch-diameter hole in return-activated sludge piping at West Point. A study in 2003 found additional corrosion, including corrosion in the primary effluent piping (Appendix A).[3] The study also identified (1) a correlation between high tides over 11 feet, spikes in conductivity, and increases in flow volume at West Point, (2) acceleration in the rate of pitting corrosion in the primary effluent piping following high tides, and (3) elevated rates of corrosion in the clarifiers that correlated with high tides, a correlation not found at South plant. The study concluded that ―it is reasonable to assume that all steel surfaces, coated or not, that come in contact with the West Point process stream are suffering accelerated corrosion and the a high chloride influx is largely responsible" and that ―even with significant reduction in chloride ion contamination, it will be necessary to implement active corrosion control in much of the West Point facility through galvanizing and coating or cathodic protection."

During the study, conductivity was measured for about two months (May 23–July 20, 2003) in West Point influent. Tidal and flow data were graphed along with conductivity readings. For example, peaks in conductivity in West Point influent in the week of July 6–12 ranged between 2.5 and 3.2 mS/cm, indicating that between 8.4 and 10 percent of the flows entering the plant was salt water (Figure 1). Most of the peaks occurred at night when flows were low. Salt water at these low-flow peak conductivity times was about 10 percent of the 62 mgd entering the facility, or about 6.2 mgd of salt water. During the day when flows were higher, conductivity peaked at 1.5 mS/cm. Salt water was about 4.7 percent of the about 100 mgd entering the facility, or about 4.7 mgd of saltwater intrusion.

Concurrently, WTD‘s Facilities Inspection unit conducted conductivity, tidal, and temperature monitoring to identify sources of saltwater intrusion in the conveyance system (Appendix B). The investigation found that salt water enters the combined sewer system from many locations. The main areas targeted for monitoring were the Elliott Bay Interceptor along the Duwamish

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[3] King County, 2003, *West Point Treatment Plant Corrosion Control Investigation,* prepared by Tinnea & Associates.

Waterway, Salmon Bay, and through the Seattle Public Utilities (SPU) overflow gates along the downtown waterfront.

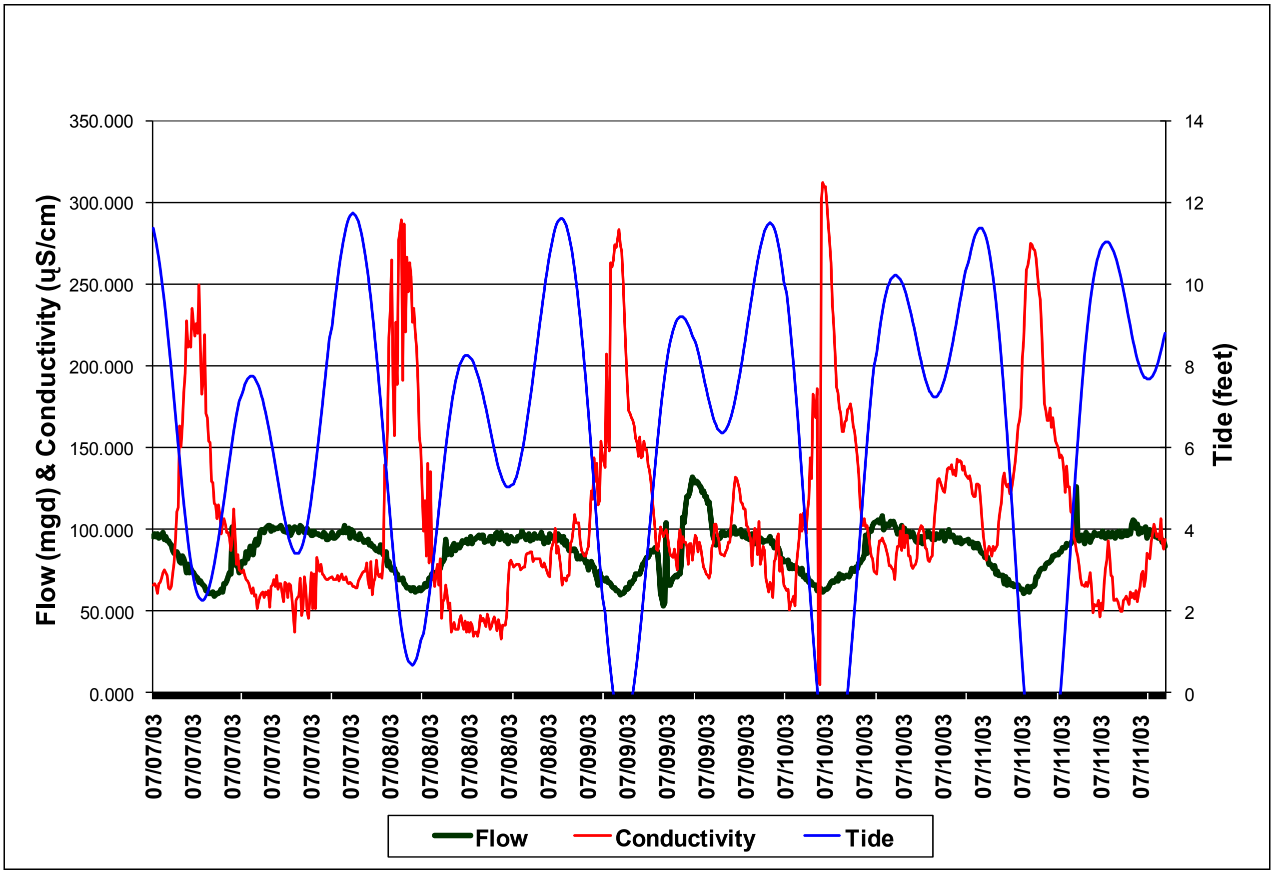

Figure 1. Conductivity, Tide, and Flows (mgd) in West Point Treatment Plant Influent (July 7–11, 2003)

The monitoring was done in two phases. Initial monitoring found that most salt water was entering in the Duwamish Waterway and downtown waterfront areas where the Elliott Bay Interceptor carries the flow north to the Interbay Pump Station in South Magnolia. The highest conductivities were in flows from the Downtown Seattle Waterfront (15 to 31 mS/cm, indicating about 48−98 percent salt water) and in flows from Harbor Island (20.6 mS/cm). Conductivities were below 2 mS/cm in flows originating in West Seattle and those collected by the South Magnolia Trunk. Sporadic conductivity was found downstream of the North Interceptor Bifurcation Structure in North Magnolia near the Ballard Locks where flows split into two pipelines before entering West Point.

After the initial monitoring, four sites were selected for additional monitoring because of their high conductivities. All four sites were at SPU manholes: three manholes along the downtown waterfront and one in West Seattle that receives flow from Harbor Island. Peak conductivities in flow from Harbor Island were around 5 mS/cm, most likely occurring from infiltration into pipes of salt water absorbed by the dredge material on the island.

Peak conductivities at the downtown waterfront sites averaged 25 mS/cm. Rapid increases in conductivity and subsequent decreases in temperature correlated with high tides (all high tides

above 11 feet, with apparent but less dramatic effects from high tides as low as 9 feet). Results of monitoring conductivity and temperature at King County's Adit Structure on the downtown waterfront, for example, demonstrates that rapid increases in conductivity and subsequent decreases in temperature correlate with high tides (Figure 2). The flow-conductivity correlation at the Adit Structure was apparent with tides as low as 10 feet. The correlations point to an intrusion of cooler salt water from Elliott Bay.

At the time, it was estimated that about 4 to 6 million gallons of salt water entered the county system each day, the equivalent of 1.46 to 2.19 billion gallons per year. The study concluded that most of the salt water was entering through SPU overflow gates along the downtown waterfront.

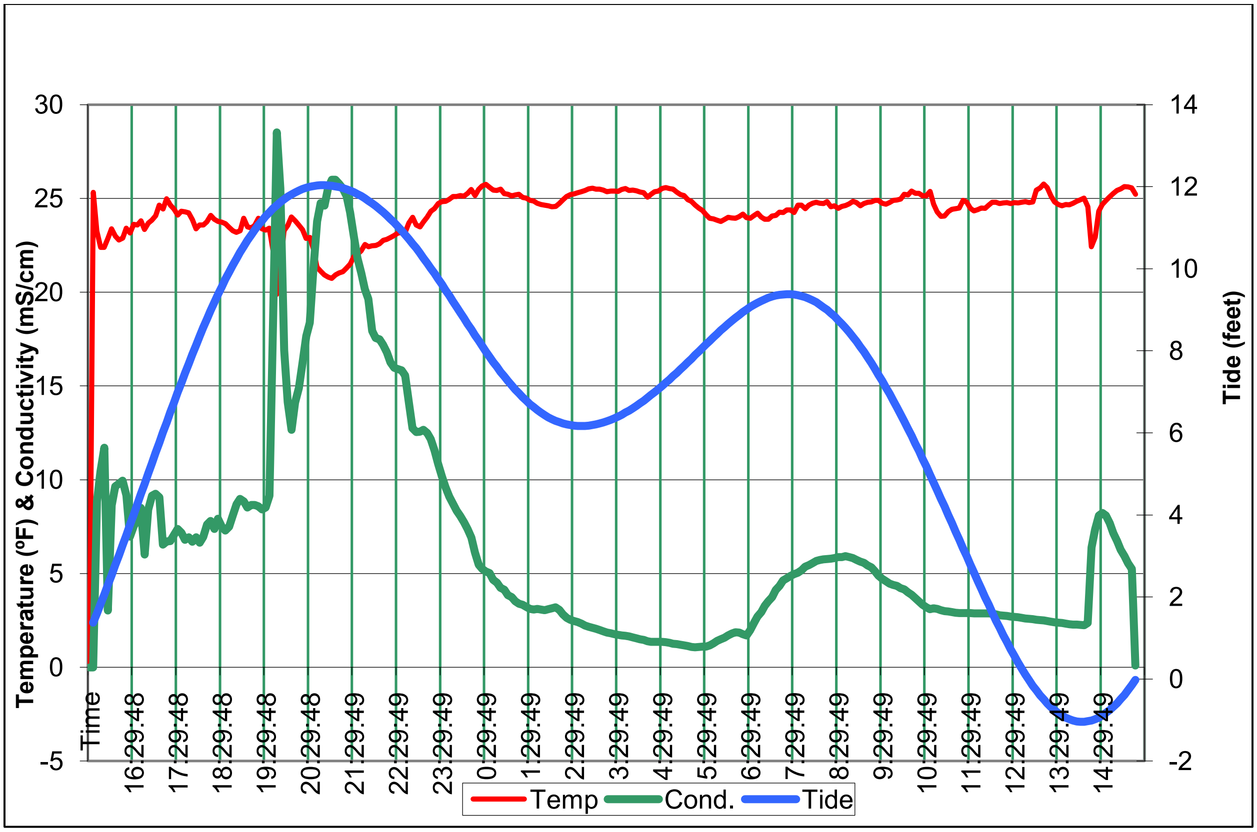

Figure 2. Relationship of Tide, Temperature, and Conductivity at the King County Adit Structure in the Downtown Seattle Waterfront (July 16–17, 2003)

In addition to monitoring efforts, measures were taken in 2003 and 2004 to protect West Point equipment from corrosion and to reduce saltwater intrusion into the conveyance system:

- WTD added zinc coatings and sacrificial anodes to the 13 clarifiers at West Point, at a cost of $1.2 million (2003 dollars) per clarifier.
- SPU raised the level of its downtown waterfront weirs by 6 inches as a short-term remedy for saltwater intrusion. This strategy reduced the amount of salt water entering from that area by about 25 percent.

- The Port of Seattle sliplined local lines in the Harbor Island conveyance system. This project reduced the percentage of salt water pumped by a local fill-and-draw station to the county's West Duwamish Interceptor from 60 to 9 percent.

In 2004, Facilities Inspection started to collect and analyze grab samples for the presence of chloride ions as a part of its summer hydrogen sulfide (H_2S) monitoring program. Results of this routine monitoring also suggest that salt water is entering the Elliot Bay Interceptor and accumulating at the Interbay Pump Station.

In 2006, staff at West Point requested that a more comprehensive study be undertaken because plant influent was experiencing high conductivity spikes. The study began in late 2006, with most monitoring done in 2007−2009. The remainder of this report presents the methodology, results, conclusions, and recommendations of this study.

3.0. METHODOLOGY

This study relied on results of previous monitoring to determine when, where, and how to further characterize the nature and extent of saltwater intrusion into King County's wastewater system.

Monitoring took place from spring 2007 through fall 2009. Sites were monitored during periods when high tides were between 10.80 and 12.95 feet (maximum verified high tide).[4] Earlier monitoring noted a significant drop in conductivity levels with tides under 11.20 feet. A few conductivity measurements were taken during low tides for purposes of comparison.

Figure 3 shows the study area. The area extends as far south as Section 1 of the Elliott Bay Interceptor near the south end of the Boeing Field–King County International Airport and as far north as Ballard and the North Interceptor along the north side of Magnolia. Monitoring targeted areas near salt water that send flows to the West Point Treatment Plant. Because conductivity near Elliott Bay along the Downtown Seattle Waterfront has consistently measured higher than in other areas, the monitoring focused on this area. Areas north and south were also monitored, particularly areas to the south near the Duwamish Waterway where high levels of conductivity were recorded in the past, areas in West Seattle including pump stations that send flow to South plant, and areas to the north to determine whether areas such as Ballard were contributing salt water to the system and to measure saltwater levels as flows move toward West Point.

Monitoring was conducted by taking grab samples; installing Sondi 665 portable data loggers that measure salinity, conductivity, and temperature; and installing flow meters at selected sites:

- Grab samples were taken first to identify general locations for further monitoring. The samples were taken during times of high tides and, if possible, at times of little or no precipitation. Hand-held conductivity meters were used to measure the level of salinity in the samples.
- The Sondi data loggers were installed in areas where grab samples showed a conductivity level of 1.0 mS/cm or greater. These data loggers are very accurate, capable of measuring conductivity in parts per million. They allow for 24-hour monitoring that can capture a full 12-hour high-tide cycle. Because there were only six data loggers, all six were installed for 4–5 days in one area and then moved to another. Some areas of interest were monitored more than once. The sampling frequency was set to correspond with real time tide data provided every five minutes from NOAA's website. Additional grab samples were taken to identify specific locations for Sondi loggers and to verify Sondi readings in some areas. In all, 91 sites were monitored with Sondi loggers, including 27 SPU sites.
- From November 2008 through June 2009, Flo-Dar flow meters were installed at 12 high-conductivity sites concurrently with data loggers to measure total flow and instantaneous changes in flow, and to provide conductivity and flow data for both low and high tides. The flow meters were programmed to read every five minutes to synchronize with the Sondi and NOAA data. The flow monitoring conducted for this study was part of the staff training program for WTD's decennial flow monitoring effort.
- Flow volumes at pump stations and at West Point were obtained from records.

[4] Since completion of the monitoring, a record high tide was of 13.95 feet occurred in January 2010.

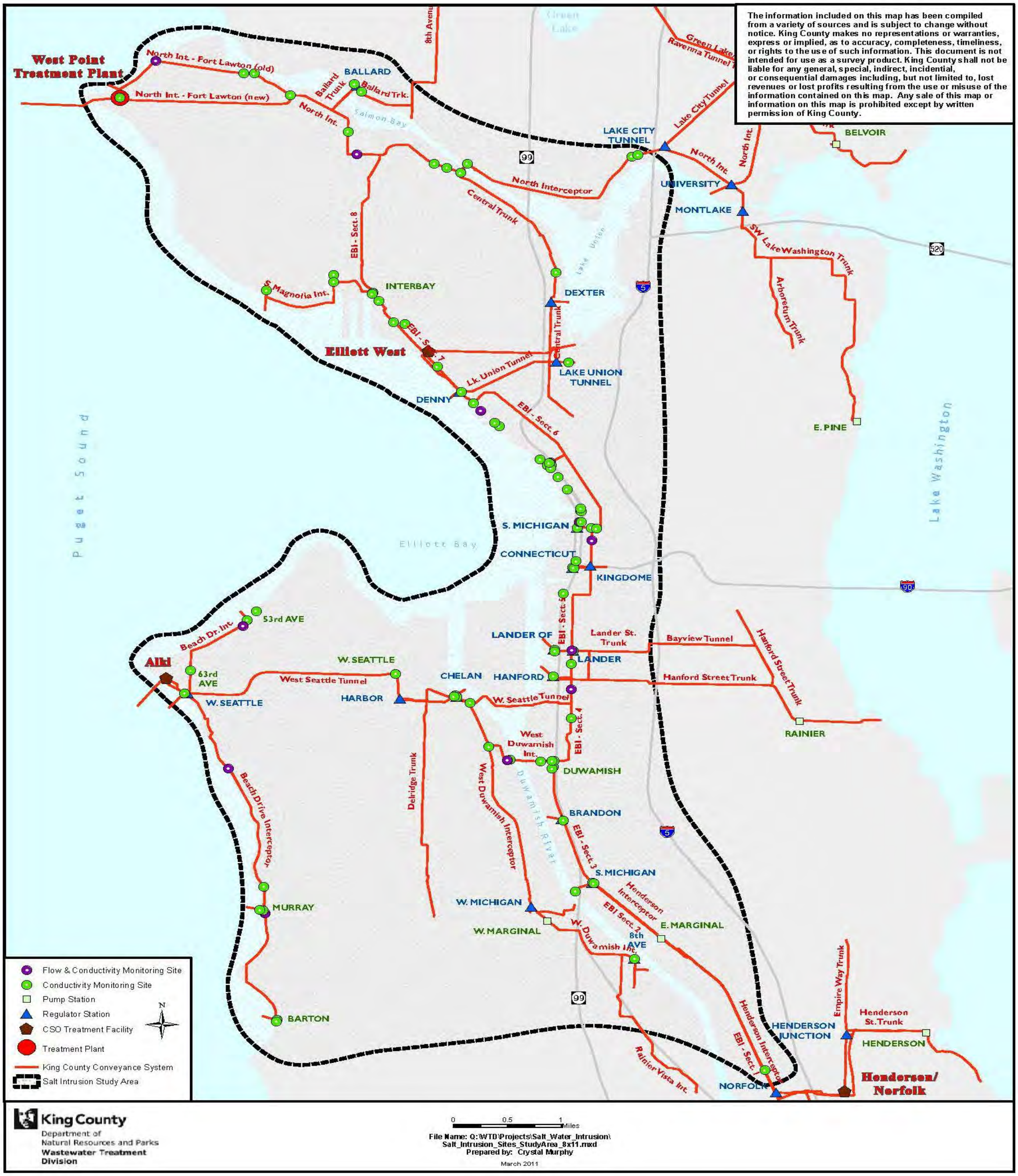

Figure 3. Study Area and Monitoring Sites for the 2007−2009 Salt Water Intrusion Study

Conductivity, tides, and flow (where available) were graphed over time to identify places that clearly showed strong correlations and high conductivity peaks. The percentage of the salinity in the wastewater flow was estimated where flow data were available. Rainfall data were not included in the analysis because it would have added another level of complexity to already complex calculations and synchronizations. Each parameter is measured differently: conductivity in mS/cm, flow in million gallons per day (mgd), tides in feet, and rain in hundredths of inches. The frequency of measurements also varies.

The scope of the study was limited by budget, staff, equipment, and other factors. Most manholes are located in industrial areas and can be on private property. Gaining permission from property owners, other utilities, and the Port of Seattle does not guarantee access because manholes can be blocked by fencing, covered by machinery and cars, or buried under soil. Tracking salt water that ebbs and flows with tides, not knowing the existence or location of pipes and connections owned by others, and synchronizing flow, conductivity, and tidal data posed further challenges. During the monitoring period, investigations were conducted of suspect facilities and repairs were made to some of the obvious places of saltwater intrusion. However, it was not possible to follow-up on every known and unknown source of conductivity.

4.0. RESULTS

This chapter presents the results of the 2007−2009 monitoring for saltwater intrusion. The results are given in terms of average peak conductivity. Reporting only peak conductivities could be misleading because conductivity levels vary with flow levels. The peak conductivities at a monitoring site were averaged for all monitoring episodes in each year, both from grab samples and Sondi data logging. Annual averages were then averaged to arrive at the average peak conductivity. Annual average peak conductivities are discussed, where appropriate, to illustrate changes in conductivity from year to year, particularly in instances where repairs were made during the study period to reduce saltwater intrusion. Results of earlier monitoring conducted at a few sites in 2006 were included in the peak conductivity averages.

Some sites were monitored only once during the three-year period, while others were monitored a few or several times depending on the findings. The first year of monitoring (2007) focused mostly on sites in the Upper Duwamish River and North subareas to define the extent of the study area. Figure 4 shows how conductivity in flows during one day in 2007 moving north from the area west of the Duwamish River, through the Downtown Seattle Waterfront, and to West Point via the Interbay Pump Station correlate with tides over 11 feet. The peak in conductivity at Interbay occurs later, indicating the time it takes for the flows with salt water intrusion at high tide to reach the station. The chapter includes other graphs depicting the relationship of flow, tide, and conductivity at representative sites where flow was measured to depict what is happening inside pipes during high and low tides.

The chapter is organized according to five subareas of the study area (Figure 5): Upper Duwamish River, Lower Duwamish River, West Seattle, Downtown Seattle Waterfront, and Interbay–West Point.

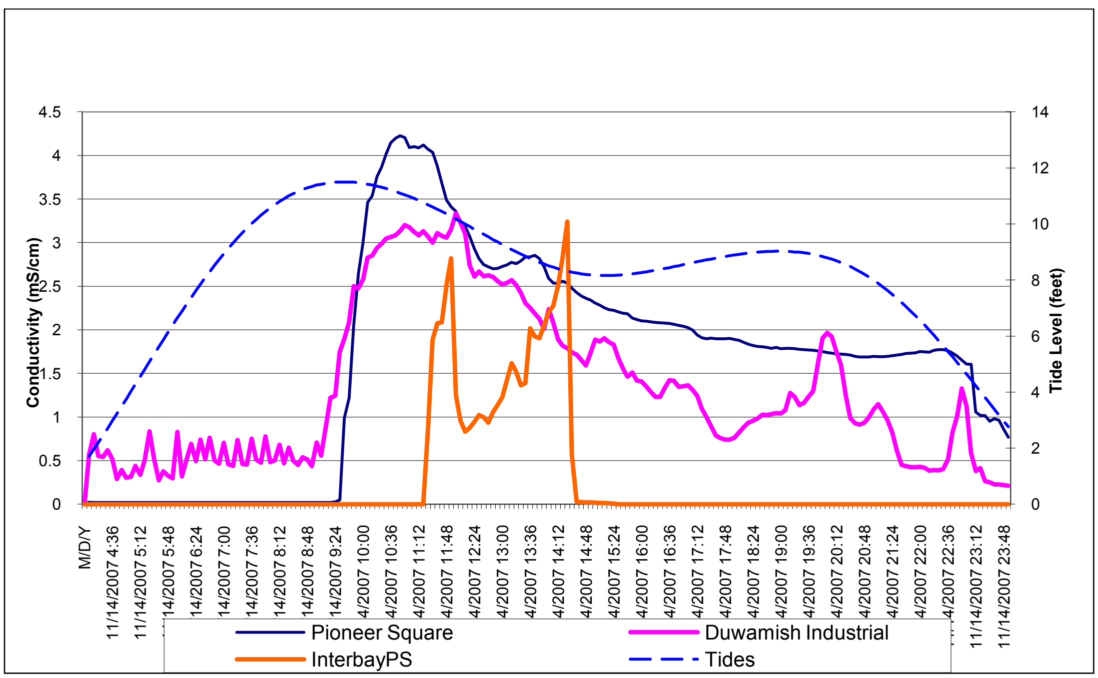

Figure 4. Relationship of Tide and Conductivity in Study Area, November 14, 2007

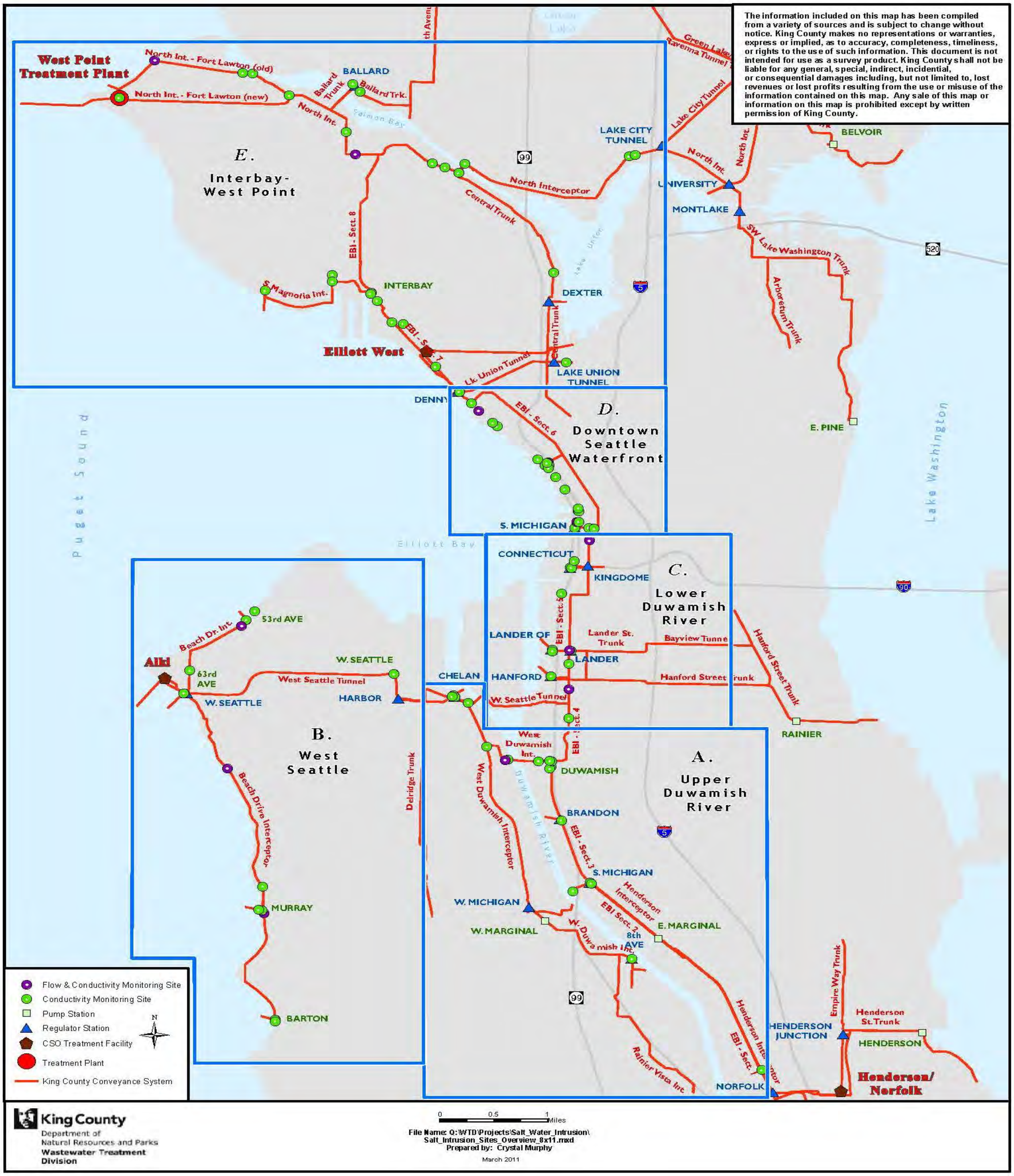

Figure 5. Subareas of the Study Area

Table 1shows the average annual peak conductivities and the average of the annual averages for each site monitored. The text that follows describes these results.

Table 1. Average Peak Conductivities

Site Name	KC or SEA Site	Flow, Conductivity, or Both	Average Peak Conductivity (mS/cm)				
			Average Peak	2009	2008	2007	2006
Upper Duwamish Subarea							
8th Ave Regulator Station	KC	Conductivity	5.03	5.25	4.84	n/a	n/a
Chelan Regulator Station	KC	Conductivity	1.66	1.87	1.459	n/a	n/a
Delridge EB7-1	KC	Conductivity	0.62	0.75	0.484	n/a	n/a
Delridge W14-118	KC	Conductivity	2.06	n/a	2.057	n/a	n/a
Duwamish Pump Station	KC	Conductivity	4.78	3.42	4.94	5.98	n/a
EBI Section 1 W10-19	KC	Conductivity	0.60	n/a	0.56	0.64	n/a
EBI Section 3 MH 6	KC	Conductivity	3.62	n/a	3.62	n/a	n/a
EBI Section 3 MH 13	KC	Conductivity	8.87	4.40	5.59	10.55	14.95
EBI Section 3 MH 13A	KC	Conductivity	1.06	0.88	0.95	1.35	1.26
EBI Section 3 W10L-01	KC	Conductivity	4.18	n/a	4.26	4.12	n/a
EBI Section 3 W10L-02	KC	Conductivity	3.27	1.71	n/a	4.84	n/a
S. Michigan Outfall	KC	Conductivity	16.78	1.76	9.09	27.1	29.20
Sea 56-195	KC	Conductivity	27.84	27.84	n/a	n/a	n/a
Siphon Inlet Structure	KC	Conductivity	20.80	n/a	n/a	20.80	n/a
W. Duwamish Int W14-101	KC	**Both**	18.78	n/a	n/a	18.78	n/a
W.Duwamish Int W114-101AA	KC	Conductivity	4.73	1.52	7.93	n/a	n/a
W. Duwamish Int W14-101C	KC	Conductivity	3.45	2.24	4.66	n/a	n/a
W. Duwamish Int W14-113	KC	Conductivity	1.64	n/a	1.64	n/a	n/a
W. Duwamish Int W14-118	KC	Conductivity	2.29	n/a	2.29	n/a	n/a
W. Duwamish Int W14-201	KC	Conductivity	2.38	n/a	2.38	n/a	n/a
West Seattle Subarea							
53rd Pump Station Wetwell	KC	Conductivity	1.50	1.66	1.36	n/a	n/a
63rd Pump Station Wetwell	KC	Conductivity	1.76	1.47	2.05	n/a	n/a
Barton Pump Station Wetwell	KC	Conductivity	2.69	3.09	3.50	1.53	n/a
Beach Drive South B-05	KC	**Both**	1.20	1.01	1.30	n/a	n/a
Beach Drive North F-1	KC	Conductivity	5.05	1.66	8.45	n/a	n/a
Beach Drive M-1	KC	Conductivity	2.05	2.02	2.01	n/a	n/a
Beach Drive South M-18	KC	**Both**	1.62	n/a	1.62	n/a	n/a
Murray Pump Station Wetwell	KC	Conductivity	2.71	3.39	2.04	n/a	n/a
Sea 47-127 (30") 54th	SEA	**Both**	0.45	0.45	n/a	n/a	n/a
Sea 47-164 (42") Bonair	SEA	Conductivity	1.26	0.92	1.59	n/a	n/a
SPU P.S. # 76 (Murray Pump Station)	SEA	Conductivity	0.82	n/a	0.82	n/a	n/a
SPU P.S. # 70 (Barton Pump Station)	SEA	Conductivity	2.73	n/a	2.73	n/a	n/a
West Seattle Pump Station	KC	Conductivity	2.84	0.94	3.427	n/a	n/a

Site Name	KC or SEA Site	Flow, Conductivity, or Both	Average Peak Conductivity (mS/cm)				
			Average Peak	2009	2008	2007	2006
Lower Duwamish Subarea							
Connecticut Regulator Station	KC	Conductivity	0.79	1.021	0.55	n/a	n/a
EBI Section 4 MH W10-149	KC	**Both**	6.11	4.934	7.07	6.33	n/a
EBI Section 4 MH W10-151	KC	Conductivity	4.92	n/a	n/a	4.92	n/a
EBI Section 5 MH W10-135	KC	**Flow**	7.68	n/a	7.68	n/a	n/a
EBI Section 5 MH W10-144	KC	**Both**	11.18	12.24	10.583	n/a	n/a
EBI Section 5 MH W10-146	KC	Conductivity	11.539	n/a	11.539	n/a	n/a
Hanford Regulator Station	KC	Conductivity	4.11	2.773	5.44	n/a	n/a
Lander Regulator Station	KC	Conductivity	22.04	n/a	22.04	n/a	n/a
Sea 43-93	SEA	Conductivity	3.93	3.93	n/a	n/a	n/a
Sea 43-96	SEA	Conductivity	14.96	14.96	n/a	n/a	n/a
Sea 50-55	SEA	Conductivity	1.10	n/a	1.10	n/a	n/a
Sea 50-184	SEA	Conductivity	32.01	n/a	32.01	n/a	n/a
Sea 50-186	SEA	Conductivity	31.02	n/a	31.02	n/a	n/a
Seattle Downtown Waterfront Subarea							
Adit structure	KC	**Both**	24.38	20.233	28.54	n/a	n/a
EBI Section 5 MH W10-133	KC	Conductivity	5.47	5.024	6.628	4.77	n/a
EBI Section 7 MH W10-130	KC	Conductivity	6.22	n/a	6.22	n/a	n/a
EBI Section 7 W10-129	KC	Conductivity	7.90	n/a	7.90	n/a	n/a
King Street Regulator Station	KC	Conductivity	8.08	8.517	7.64	n/a	n/a
King Street W10-201	KC	Conductivity	2.13	n/a	2.13	n/a	n/a
SEA 39-008	SEA	**Both**	4.87	5.544	1.98	n/a	n/a
Sea 39-53	SEA	Conductivity	0.66	0.66	n/a	n/a	n/a
Sea 39-257	SEA	Conductivity	20.01	16.80	23.21	n/a	n/a
Sea 39-300 (Aquarium)	SEA	Conductivity	19.27	15.51	23.02	n/a	n/a
Sea 39-374	SEA	Conductivity	1.45	1.45	n/a	n/a	n/a
Sea 39-376	SEA	Conductivity	0.77	0.77	n/a	n/a	n/a
Sea 39-382 (downstream Madison CSO)	SEA	Conductivity	1.03	1.03	n/a	n/a	n/a
Sea 39-482 (Adit)	SEA	Conductivity	19.95	19.85	20.40	n/a	n/a
Sea 43-28	SEA	Conductivity	0.78	0.62	0.94	n/a	n/a
Sea 43-41 (Jackson St)	SEA	**Both**	20.60	20.602	n/a	n/a	n/a
Sea 43-49	SEA	Conductivity	11.20	11.20	n/a	n/a	n/a
University Street Diversion Structure	SEA	Conductivity	1.24	0.704	1.39	n/a	n/a
Vine Street Diversion Structure	SEA	Conductivity	2.52	2.535	2.52	n/a	n/a
Washington Street Diversion Structure	SEA	Conductivity	14.65	16.312	12.98	n/a	n/a
Washington Street W10-210A	SEA	Conductivity	10.63	10.63	n/a	n/a	n/a

Site Name	KC or SEA Site	Flow, Conductivity, or Both	Average Peak Conductivity (mS/cm)				
			Average Peak	2009	2008	2007	2006
Interbay−West Point Subarea							
Ballard LU-18-02	KC	Conductivity	0.49	0.44	0.51	0.59	0.49
Central LU12-2	KC	Conductivity	0.63	n/a	0.63	n/a	n/a
Central LU15-8	KC	Conductivity	0.70	n/a	0.70	n/a	n/a
EBI Section 7 W10-118	KC	Conductivity	6.89	n/a	3.37	10.41	n/a
EBI Section 7 W10-122	KC	Conductivity	1.39	n/a	1.39	n/a	n/a
EBI Section 7 W10-127	KC	Conductivity	5.61	4.96	6.22	n/a	n/a
Interbay Pump Station	KC	Conductivity	6.01	n/a	8.78	3.24	n/a
Lk Un LU20-2	KC	Conductivity	0.48	n/a	0.48	n/a	n/a
N. Int MH B20-03	KC	**Both**	2.66	n/a	2.66	n/a	n/a
N. Int MH B21-03	KC	Conductivity	2.25	n/a	2.253	n/a	n/a
N. Int MH B21-10A	KC	Conductivity	4.59	4.585	n/a	n/a	n/a
N. Int MH B21-13	KC	Conductivity	5.25	n/a	5.245	n/a	n/a
N. Int MH B21-13A	KC	Conductivity	1.37	1.33	1.4	n/a	n/a
N. Int MH B21-15A	KC	**Both**	7.27	11.24	3.3	n/a	n/a
N. Int MH N23-1A	KC	Conductivity	0.56	n/a	0.56	n/a	n/a
N. Int MH N23-19	KC	Conductivity	0.45	n/a	0.45	n/a	n/a
N. Int MH N23-20	KC	Conductivity	0.45	n/a	0.45	n/a	n/a
N. Int MH N25-2	KC	Conductivity	0.41	n/a	0.41	n/a	n/a
N. Int MH N25-3	KC	Conductivity	0.51	n/a	0.51	n/a	n/a
Sea 11-243	SEA	Conductivity	0.43	0.43	n/a	n/a	n/a
Sea 39-1	SEA	Conductivity	10.16	8.66	11.66	n/a	n/a
Sea 34-109	SEA	Conductivity	0.72	0.72	n/a	n/a	n/a
S. Magnolia W10-78-A	KC	Conductivity	0.69	0.85	0.53	n/a	n/a
S. Magnolia W10-89	KC	Conductivity	0.71	0.67	0.75	n/a	n/a
S. Magnolia W10-117	KC	Conductivity	10.5	n/a	10.50	n/a	n/a
West Point Treatment Plant	KC	Conductivity	3.20	n/a	3.2	n/a	n/a

4.1 Upper Duwamish River Subarea

As shown in Figure 6, the southernmost conductivity monitoring sites near the Duwamish River were about 5.5 and 4 miles upstream from the mouth of the river on its east and west sides, respectively. Most of the monitoring in the Upper Duwamish area was done from manholes on Sections 1, 2, and 3 of the Elliot Bay Interceptor (EBI) that run along the east side of the river and on the West Duwamish Interceptor (WDI) that runs along the west side. Both interceptors convey flow to the Duwamish Pump Station, east of the river about 1.5 miles upstream of its mouth.

The Duwamish Pump Station receives flows from the south via Section 3 of the Elliott Bay Interceptor. EBI Section 3 extends about 1.5 miles from south of the South Michigan Street Regulator Station north to the pump station. The South Michigan Street Regulator feeds flows to

EBI Section 3. EBI Sections 1 and 2 send flows from the south to EBI Section 3. The Duwamish Pump Station receives flows from the west via the WDI.

The WDI carries flows north from points along the west side of the river starting at 8th Avenue South Regulator Station and south from the Chelan Regulator Station just west of Harbor Island. The interceptor sends flows from both directions to the Duwamish Siphon, which carries the flows under the river to the pump station. The siphon is a two-barrel inverted siphon with an overflow flap gate located at its inlet and outlet. It connects a large area of West Marginal Way in South Seattle, the Delridge neighborhood, and a large area of Harbor Island and West Seattle.

At the start of the study, large continuous spikes of conductivity were noted at the Duwamish Pump Station influent gate. Further investigation found that flows from the EBI and WDI entering the pump station contained salt water in different quantities at different times. EBI Sections 2 and 3 south of the station contained salt water at tides lower then 11.2 feet. This flow arrived earlier than flow with salt water in the WDI coming from the west.

4.1.1 Moving North to Duwamish Pump Station via EBI Sections 1, 2, and 3

A total of seven locations on EBI Sections 1, 2, and 3 between the Norfolk Regulator Station and Duwamish Pump Station were monitored for conductivity. No flow monitoring was done along this stretch of pipe. Sampling locations and results are as follows:

- **EBI Sections 1, 2, and 3 south of the South Michigan Regulator Station.** Two manholes were monitored on the EBI south of the South Michigan Regulator Station:
    - One manhole (W10-19) was monitored on EBI Section 1 near East Marginal Way South north of the Norfolk Regulator Station. This southernmost location on the east side of the Duwamish River about 5.5 miles upstream of the mouth of the river showed a peak conductivity of less than 1 mS/cm (0.6 mS/cm). This low conductivity may be due, in part, to replacement of the gates at the upstream Norfolk Regulator Station about 10 years ago. Because of the low conductivity, this location was not monitored again and no locations were monitored farther south. No sites were monitored north of this manhole on Section 1 nor on the entire length of Section 2 because flows in these sections are low. Even if conductivity in these sections proved to be high, the influence on the upstream system would be minimal given the low flows.
    - One manhole (MH 13A) was monitored along EBI Section 3, just upstream (south) of the regulator station at the intersection of South Michigan Street and East Marginal Way where EBI Sections 2 and 3 meet. Average peak conductivity at this site was also low (1.06 mS/cm).
- **South Michigan Street Outfall Station.** Average peak conductivity just west of the South Michigan Street Regulator Station was 16.78 mS/cm.
- **EBI Section 3, north of the South Michigan Street Regulator Station to Duwamish Pump Station.** Four manholes were monitored on EBI Section 3 between the South Michigan Street Regulator Station and the Duwamish Pump Station, as described below.

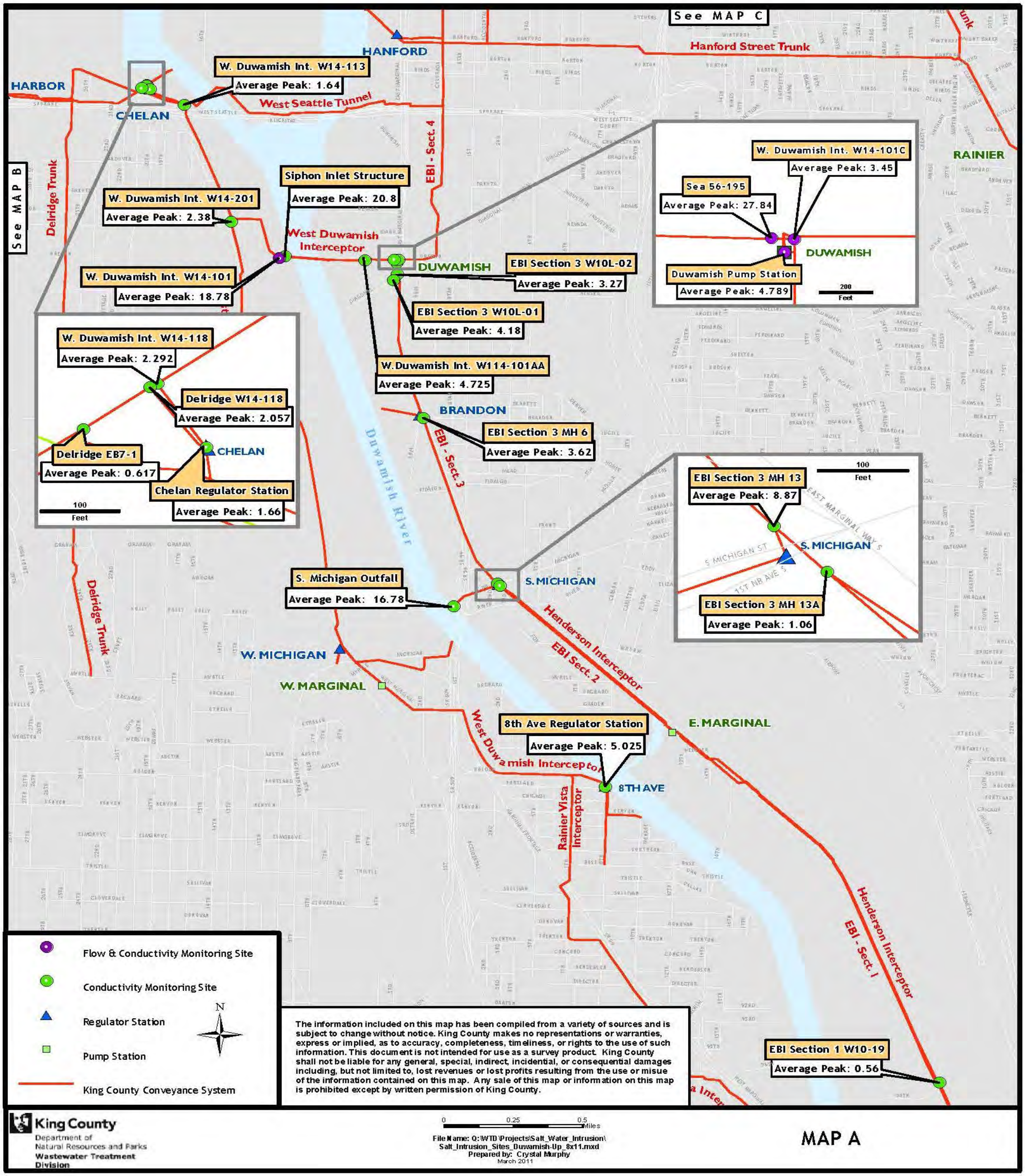

Figure 6. Upper Duwamish River Subarea

— A manhole (MH 13) where flows from the Michigan Street Regulator Station enter the EBI showed an average peak conductivity of 8.87 mS/cm.

— A manhole (MH 6) about 1 mile downstream (north) near the Brandon Regulator Station showed an average peak conductivity of 3.62 mS/cm. Salt water was seen entering through the station's outfall gate.

— One manhole (W10L-01) about one-half mile downstream and close to the Duwamish Pump Station showed an average peak conductivity of 4.18 mS/cm.

— Another manhole (W10L-02) closer to the Duwamish Pump Station showed an average peak conductivity of 3.27 mS/cm.

The average peak conductivity of 1.06 mS/cm just south of the South Michigan Street Regulator Station at the junction of EBI Sections 2 and 3 indicates that very little salt water is entering the EBI before flows from the South Michigan Regulator Station enter EBI Section 3 north of the station. The average conductivity was much higher at the South Michigan Regulator Station outfall line (12.65 mS/cm). During most high tides, the South Michigan outfall gate is submerged (Figure 7). Investigation found that the gate was missing and a leaky bulkhead had been put in place. The gate was replaced in 2008. Average peak conductivity readings at the outfall after gate replacement dropped about 65 percent from previous readings but were still high (from 29.20 mS/cm in 2006 to 9.09 mS/cm in 2008). Peak conductivity readings at the manhole where flow from the South Michigan Regulator Station enters EBI Section 3 (MH 13) dropped from 14.95 mS/cm in 2006 to 5.59 mS/cm in 2008.

Further investigation found that several large cracks and fill-portholes inside of the outfall structure were leaking during high tides.[5] These leaks were sealed via grout injection in 2009 through a work-order contract. After completion of these repairs, the average peak conductivity at the outfall dropped to 1.76 mS/cm, almost 95 percent lower than the average peak conductivity measured in 2007 (Figure 8). (The 2009 average peak conductivity shown in Figure 8 for MH 13 is similar to that of 2008 because the monitoring was done before grout injection.)

Old South Michigan outfall gate bulkhead	New outfall gate completely submerged

Figure 7. South Michigan Outfall Gate Before and After Installation

[5] A fill-porthole is a hole on the concrete form where concrete can be injected.

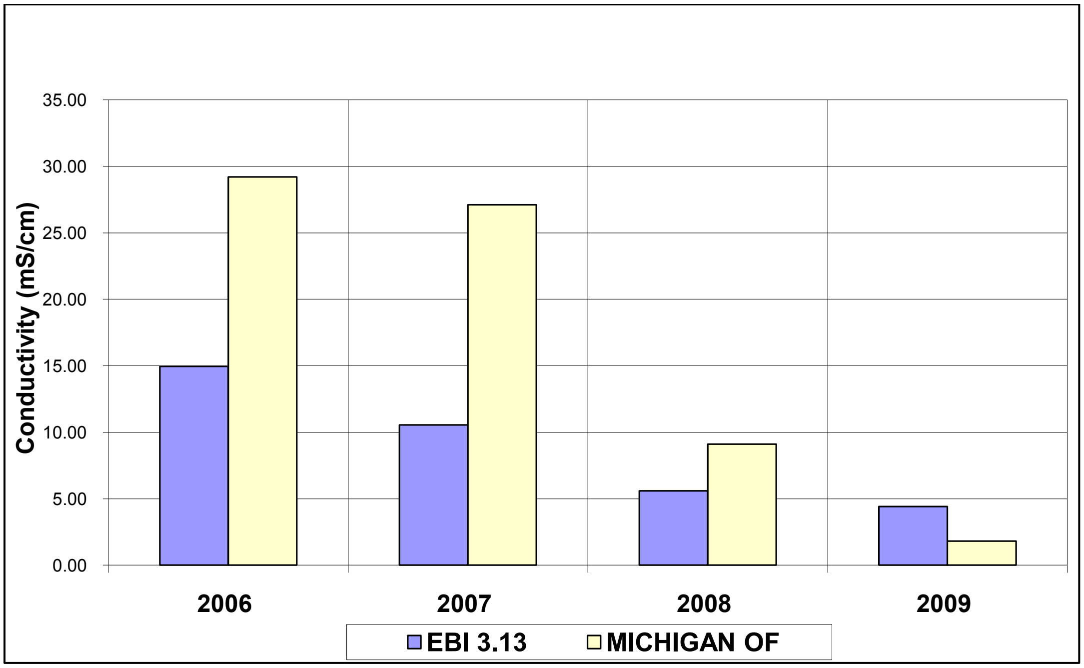

Figure 8. Decrease in Conductivity at Outfall and Downstream Manhole after Gate Replacement and Grouting at South Michigan Outfall

4.1.2 Moving Along the WDI and East to Duwamish Pump Station via the Duwamish Siphon

A total of 12 locations on pipes and structures that carry flow from the west to the Duwamish Pump Station via the Duwamish Siphon were monitored for conductivity. Results of the conductivity monitoring are described below.

- **WDI upstream (south) of the Duwamish Siphon.** One location was monitored on the WDI south of the Duwamish Siphon, a manhole at the 8th Avenue South Regulator Station in West Seattle just north of the start of the WDI and about 4 miles upstream of the mouth of the Duwamish River. The site showed an average peak conductivity of 5.03 mS/cm. The average peak conductivity in 2008 and in 2009 were similar (4.84 and 5.25 mS/cm, respectively), indicating the ongoing presence of an agent that increases conductivity. Results of recent flow monitoring at the manhole found flows to be consistently low, with no increase during high tides. Thus, it appears that salt water is not entering the system in this area and that other agents, perhaps from industrial discharges, are at play. Further work needs to be done, in coordination with King County‘s Industrial Waste Program, to determine the cause of high conductivity at this location.

  No other conductivity monitoring was done on this stretch of pipeline because the pipeline is farther from the river than the EBI. Moreover, there is only one overflow structure (West Michigan Regulator Pump Station outfall) between the 8th Avenue South Regulator Station and the Duwamish Siphon and this structure has an overflow weir.

- **At and near Chelan Regulator Station.** Two manholes (Delridge EB7-1 and W14-118) on the Delridge Trunk, which conveys flows from a small portion of West Seattle to the WDI just before the Chelan Regulator Station, showed average peak conductivities of 0.62 and 2.06 mS/cm. Average peak conductivities at the station and at one manhole (WDI W14-118) on the WDI just downstream of the station were 1.66 and 2.29 mS/cm, respectively. The causes for the higher conductivities entering and leaving the Chelan Regulator Station were not investigated. Recent visual inspection, however, did reveal salt water entering through the station‘s outfall.
- **WDI downstream (south) of Chelan Regulator Station and north of the Duwamish Siphon.** Two locations were monitored between the Chelan Regulator Station and the inlet to the Duwamish Siphon. One manhole (W14-113) just southeast of the station showed an average peak conductivity of 1.64 mS/cm. Flows from Harbor Island enter the system at this point. The other manhole (W14-201) just north of the siphon inlet, where the north and the south legs of the WDI meet, showed a higher average peak conductivity of 2.38 mS/cm.
- **Duwamish Siphon Inlet Structure.** One manhole (W14-101) on the WDI just upstream of the siphon inlet structure on the west side of the river near Terminal 105 registered an average peak conductivity of 18.78 mS/cm. This location was also monitored for flow using the flow meter at the structure‘s overflow. Monitoring at the inlet structure itself showed an average peak conductivity of 20.8 mS/cm.
- **WDI east of river and the Duwamish Siphon.** Two manholes were monitored on the WDI close to where the interceptor meets the Duwamish Pump Station. The manhole (W114-101AA) farthest from the station showed an average conductivity of 4.72 mS/cm (at the outlet to the Duwamish Siphon). The manhole (W14-101C) closest to the station had an average peak conductivity of 3.45 mS/cm. Another manhole (SEA 56-195), an SPU manhole located where a city line meets the WDI, showed an average peak conductivity of 27.84 mS/cm. Because the flow in the SPU pipe is low, this high conductivity would not have a great impact on the county system.
- **Duwamish Pump Station.** Peak conductivities at the Duwamish Pump Station influent gate averaged 4.78 mS/cm. The averages for individual years steadily decreased from 5.98 mS/cm in 2007 to 4.94 mS/cm in 2008 to 3.42 mS/cm in 2009. These decreases may have been the result of the gate replacement at the South Michigan Street Regulator Station and the plugging of the pipe west of Duwamish (see below).

Even though the Port of Seattle sliplined almost all of its pipes on Harbor Island and stopped the intrusion of large amounts of salt water into the WDI via the Port‘s trunk line under the West Seattle freeway just downstream of the Chelan Regulator Station, average peak conductivity at the Duwamish Siphon Inlet Structure (20.80 mS/cm) indicated that salt water was continuing to enter the WDI close to the siphon inlet. Further monitoring found high conductivity (18.78 mS/cm) at the manhole just prior to the inlet structure near Terminal 105 and that the manhole contained a local connection.

Investigation found that an abandoned SPU line tied in from the west from Herring‘s House Park, a new park built in the vicinity of Kellogg Island at River Mile 2 of the Duwamish Waterway. This connection carried averages of 1.0 to 2.0 mgd of salt water. A CCTV inspection found that the line was broken in several places and was crushed at the end. Smoke testing

located the breaks in a newly restored estuary habitat at Terminal 107 Park, next to Herring‘s House Park (Figure 9). The cracks are in an area that is submerged by tidal flows of several feet two times a day. With SPU‘s assistance, the Facilities Inspection unit installed a mechanical plug at the nearest manhole to the estuary to stop the saltwater intrusion at this location. The work was completed in 2009. The two WDI manholes that were monitored downstream of the Duwamish Siphon near the Duwamish Pump Station registered lower peak conductivities in 2009 than in 2008 before the plugging. Conductivity at the manhole closest to the siphon outlet was reduced from 7.93 mS/cm in 2008 to 1.52 mS/cm in 2009. The manhole closest to the pump station showed a reduction from 4.66 mS/cm in 2008 to 2.24 mS/cm in 2009.

Smoke testing reveals broken pipe at Terminal 107 Park

The broken pipe is plugged in the next manhole downstream

Figure 9. Discovery and Plugging of Broken Pipe in Terminal 107 Park

4.2 West Seattle Subarea

The Beach Drive Interceptor in the western and northern portions of West Seattle sends flows to the 63rd Avenue Pump Station south of Alki Point, which then sends flows to the West Seattle Tunnel that leads to the West Seattle Pump Station just west of the West Duwamish Waterway (Figure 10). The tunnel continues east from the pump station under Harbor Island and connects to EBI Section 4 north of the Duwamish Pump Station. The tunnel and pump station are part of a complex system that stores excess flows during heavy rains for later transport to the EBI. If storage capacity is exceeded, flows may be sent to the Alki CSO Treatment Plant for storage and possible treatment.

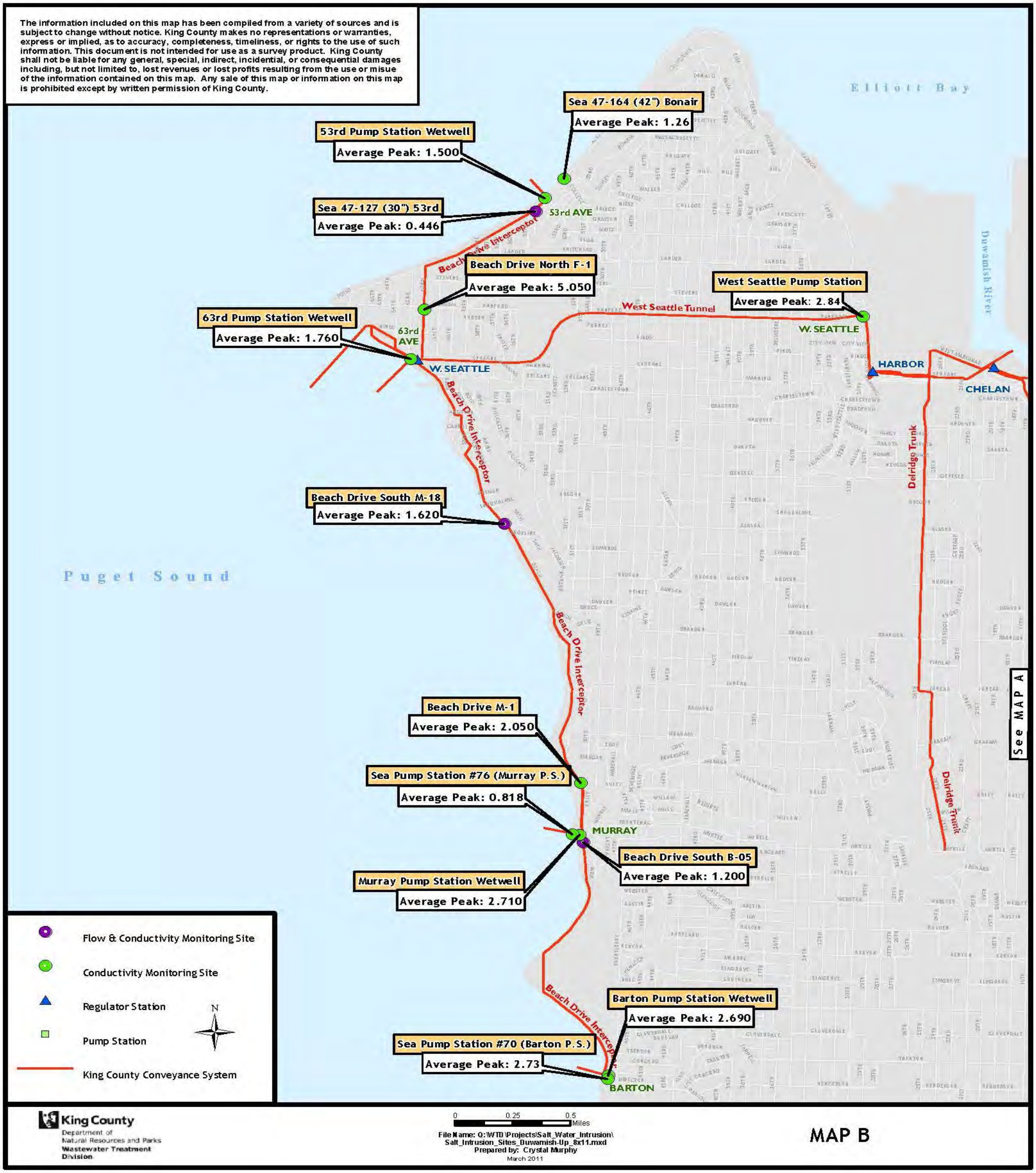

Figure 10. West Seattle Subarea

4.2.1 Moving North via Beach Drive Interceptor to 63rd Avenue Pump Station

Seven locations were monitored for conductivity along the western leg of the Beach Drive Interceptor, starting with its southern terminus at the Barton Pump Station:

- **At and near Barton Pump Station.** Two locations were monitored in this area:
    - The Barton Pump Station wet well had an average peak conductivity of 2.70 mS/cm. The most recent annual averages were 3.50 and 3.09 mS/cm for 2008 and 2009, respectively. The lower average of 1.53 mS/cm in 2007 could have resulted from a greater influx of stormwater during this wet year. A flap gate was installed at the station in May 2010, which allows only outflow of wastewater from the overflow. Recent monitoring (not part of this study) found that this installation has reduced the amount of salt water intrusion at this site. The elevation of the outflow weir will be raised in 2012, which should further reduce saltwater intrusion.
    - The average peak conductivity at SPU Pump Station 7 near the Barton Pump Station was 2.73 mS/cm.
- **At and near Murray Avenue Pump Station.** Three locations were monitored at and near the Murray Avenue Pump Station. The locations showed average peak conductivities as follows: 2.71 mS/cm at the Murray wet well, 1.20 mS/cm just south of Murray (B-05) (also monitored for flow), and 0.82 mS/cm at the wet well of SPU Pump Station 76 west of Murray.
- **Between Murray and 63rd Avenue Pump Stations.** The average peak conductivities at the two locations monitored in this stretch of the Beach Drive Interceptor were 2.05 mS/cm at a manhole (M-1) about 0.25 mile north of Murray and 1.6 mS/cm at an overflow point (M-18) farther north (also monitored for flow).

4.2.2 Moving South via Beach Drive Interceptor to 63rd Avenue Pump Station

Four locations were monitored between the northern terminus of the Beach Drive Interceptor and the 63rd Avenue Pump Station.

- **At and near 53rd Avenue Pump Station.** Three locations were monitored in the vicinity of the 53rd Avenue Pump Station. Average peak conductivities were as follows: 1.5 mS/cm at the pump station wet well, 1.26 mS/cm at a location on an SPU pipe downstream of the station (SEA 47-164), and 0.45 mS/cm at another SPU pipe upstream of the station (SEA 47-127) (also monitored for flow). The pump station upgrade, which included raising the overflow weir and replacing the gate, was completed early in 2010.
- **Between 53rd and 63rd Avenue Pump Stations.** One manhole (F-1) about 0.25 mile north of the 63rd Avenue Pump Station on Beach Drive North showed an average peak conductivity of 5.05 mS/cm. In 2008, the average of the peak conductivity at this site was high (8.45 mS/cm). After noting the high conductivity in 2008, staff investigated the cause and found that the new gate at the 53rd Avenue Pump Station had been installed

incorrectly and salt water was entering the system until the gate was reinstalled. The 2009 average was much lower (1.66 mS/cm).

4.2.3 Moving East from the 63rd Avenue Pump Station via the West Seattle Tunnel to West Seattle Pump Station

- There is no access to the West Seattle Tunnel either west or east of the West Seattle Pump Station. Average peak conductivities were 1.76 mS/cm at the 63rd Avenue Pump Station at the east end of the tunnel and 2.84 mS/cm at the West Seattle Pump Station. Average peak conductivities at the West Seattle Pump Station for each year of monitoring (2008 and 2009) were 3.43 and 0.94 mS/cm, respectively. The high reading in 2008 may have occurred during the period when the improperly installed gate at the 53rd Street Pump Station was allowing salt water to enter the system.

4.3 Lower Duwamish Subarea

Flows from the West Seattle and Duwamish Pump Stations travel north via EBI Sections 4 and 5 on the east side of the East Waterway of the Duwamish River to the King Street Regulator Station in the Pioneer Square area just north of Qwest Field and south of downtown (Figure 11). Pipelines convey wastewater from local sewers to the Hanford, Lander, and former Connecticut Regulator Stations, which direct the flows to the EBI.

4.3.1 Moving North to Hanford Street Regulator Station via EBI Section 4

- **Between Duwamish Pump Station and Hanford Street Regulator Station.** Two manholes on EBI Section 4 were monitored. One manhole (W10-151), west of the south end of Harbor Island upstream of where the West Seattle Tunnel meets the EBI, had an average peak conductivity of 4.92 mS/cm. The other manhole (W10-149), about 0.5 mile north just downstream (north) of where the West Seattle Tunnel meets the EBI and upstream (south) of the intersection of the pipeline that leads from the Hanford Street Regulator Station with the EBI, had an average peak conductivity of 6.11 mS/cm. This location was also monitored for flow.
- **Hanford Street Regulator Station.** The average peak conductivity of this station was 4.11 mS/cm. Inspections indicate that the regulator‘s outfall gate located in Terminal 25 is leaking. The gate is currently closed, but sewer flows deadhead against the gate. The leaking gate allows salt water to enter directly into the sewer through the outfall pipe.

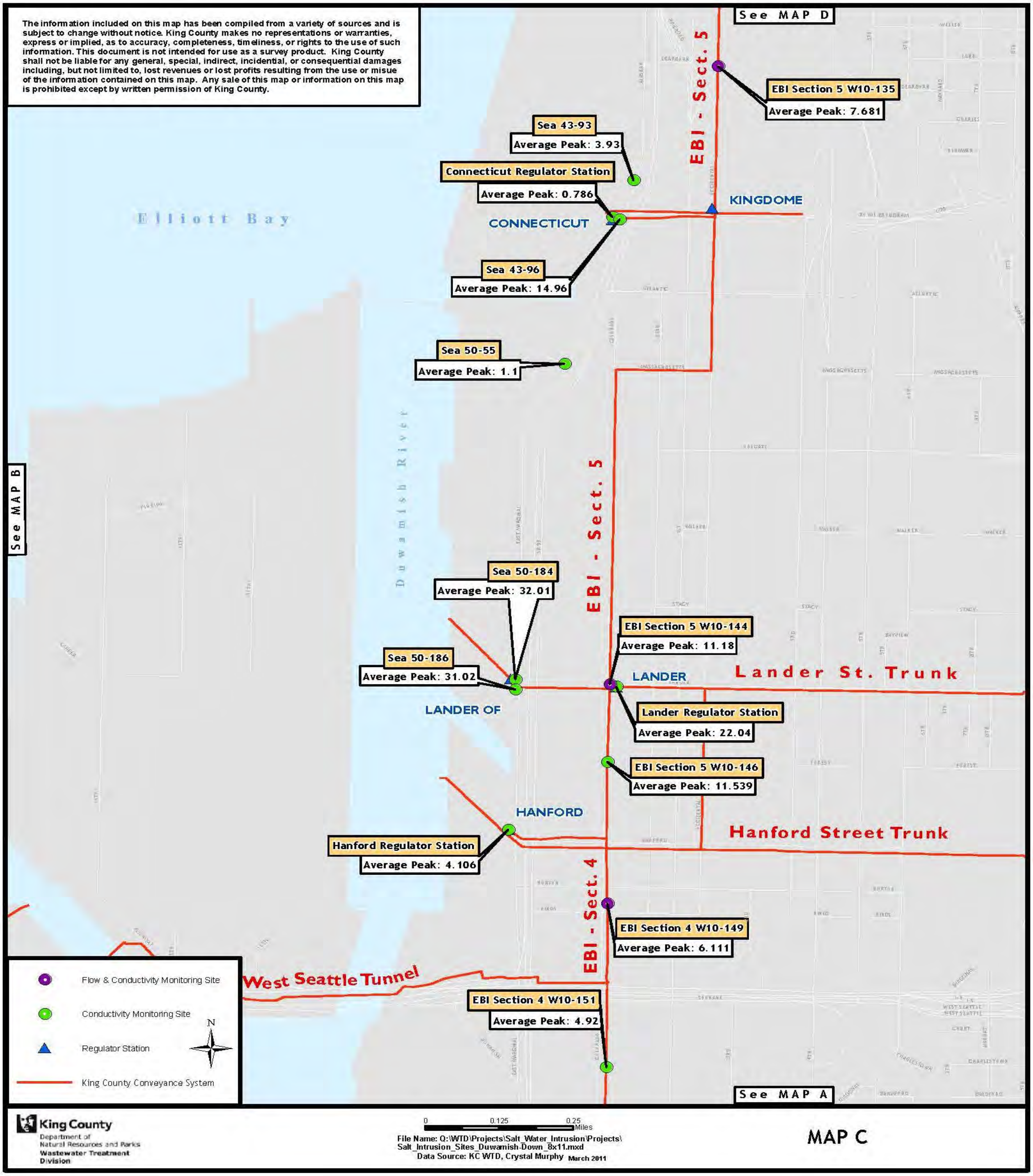

Figure 11. Lower Duwamish River Subarea

4.3.2 EBI Section 5, Including Flows From the Lander Street Outfall, Lander Street Regulator, and Former Connecticut Regulator Stations

Ten locations were monitored on EBI Section 5 leading to the King Street Regulator Station. Three locations were at regulator stations and five were at SPU manholes where local lines connect to the King County system. The locations, moving north, are as follows:

- **Between Hanford Street and Lander Street Outfall/Lander Street Regulator Stations**. One manhole (W10-146) halfway between the two stations was monitored. Average peak conductivity was 11.54 mS/cm.
- **At and near Lander Street Outfall and Lander Street Regulator Stations.** Two SPU manholes (SEA 50-186 and SEA 50-184) were monitored near the Lander Street Outfall Station. Average peak conductivities at these manholes were 31.02 and 32.01 mS/cm. The Lander Street Regulator Station and a location (W10-144) on EBI Section 5 just downstream of the station (also monitored for flow) showed average peak conductivities of 22.04 and 11.18 mS/cm, respectively. All measurements were taken in 2008. Figure 12 shows the relationship between tide, flow, and conductivity at this downstream location. Both flow and conductivity increase with high tides over 11 feet.

  Salt water is entering the overflow structure inside the Lander Street Regulator Station through a defective flap and low flow diversion gates (FG-01 and SG-02, shown in Figure 13) and then spilling into the conveyance system just prior to the first downstream manhole on EBI Section 5. The salt water enters the outfall line at high tides and then into the 90-inch-diameter Lander Street Storm Drain that runs through the station. The gate in the Lander Street Outfall Station is permanently open, allowing water to flow in both directions (Figure 15). The bypass gate, designed to move the first flush of stormwater into the EBI, is permanently closed. The height of the interconnect pipe between the storm drain and the regulator station overflow is only 1.26 feet. This pipe and the overflow structure fill daily with salt water (Figure 15). Barnacles can be found inside the storm drain and on the outer walls of the Lander Street Regulator Station.
- **From Lander Street Regulator Station to former Connecticut Regulator Station.** Other than the location just outside the Lander Street Regulator Station, the stretch of EBI Section 5 between this station and the former Connecticut Regulator Station was not monitored, primarily because of access issues. An SPU manhole (SEA 50-55) west of EBI Section 5 about 0.5 mile south of the former Connecticut Regulator Station showed an average peak conductivity of 1.10 mS/cm. The average peak conductivities at another SPU location (SEA 43-96) just east of Connecticut and at a King County manhole at the station itself were 14.96 and 0.79 mS/cm, respectively. Saltwater was observed entering through the station‘s outfall pipe.
- **Between Connecticut and King Street Regulator Stations.** An SPU location (SEA 43-93) just north of the former Connecticut Regulator Station and about 0.25 mile west of EBI Section 5 showed an average peak conductivity of 3.93 mS/cm. Another location (W10-135) on EBI Section 5 about 0.5 north of the Kingdome Regulator Station showed an average peak conductivity of 7.68 mS/cm; this location was also monitored for flow.

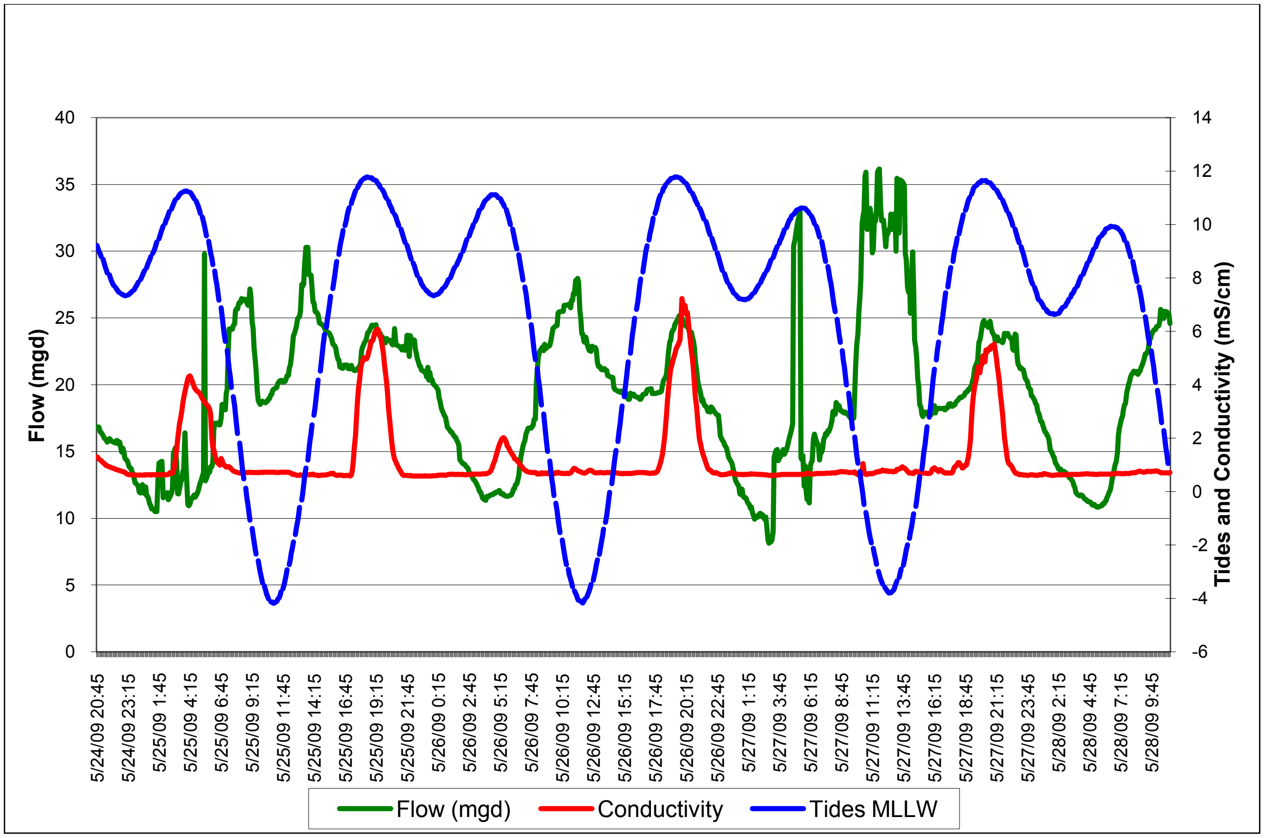

Figure 12. The Immediate Impact of High Tides Just Downstream from the Lander Street Regulator Station, May 24–28, 2009

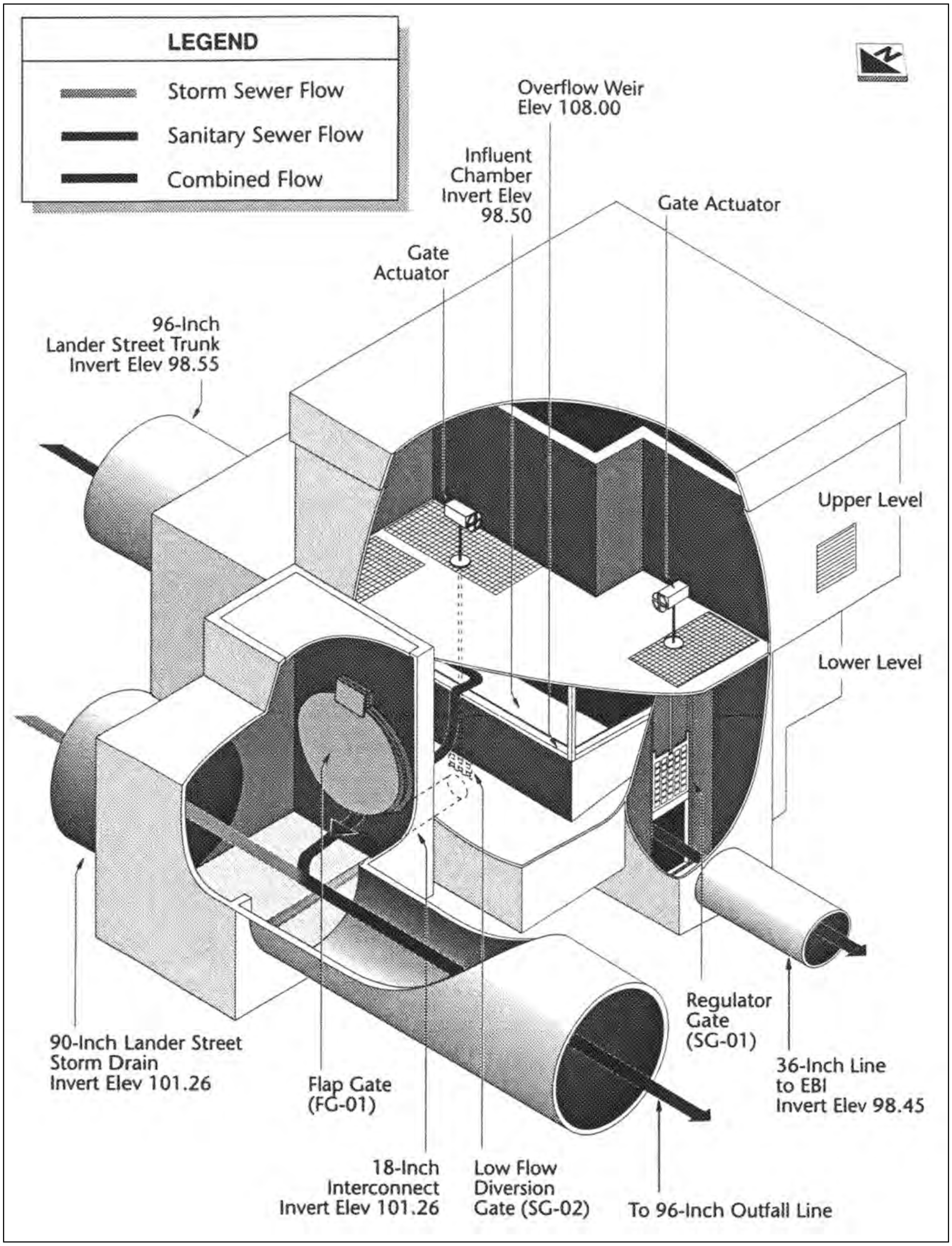

Figure 13. Gates in the Lander Street Regulator Station

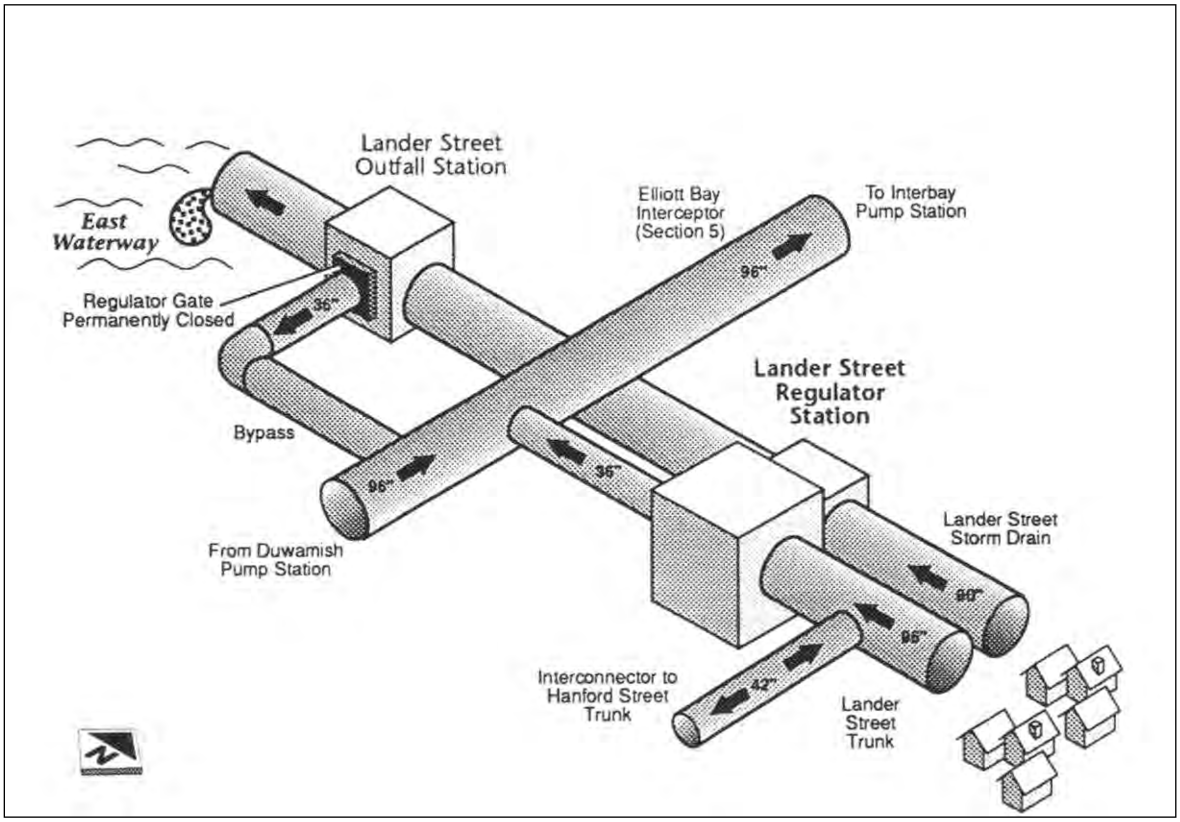

Figure 14. Flow Through Lander Street Regulator and Outfall Stations

Salt water leaking through the Lander Street Regulator Station flap gate

As the tide rises, the overflow structure fills and spills into EBI 5.

Figure 15. Salt Water Entering and Leaving the Lander Street Regulator Station

4.4 Downtown Seattle Waterfront Subarea

A total of 21 locations were monitored along the Downtown Seattle Waterfront on or near EBI Sections 5, 6,and 7 starting at the King Street Regulator Station and extending to the Denny Way Regulator Station (Figure 16). These locations receive flow from the downtown and Pioneer Square areas.

Only six of the locations were at King County facilities because EBI Section 6 is in a tunnel with only one access point. Three sites were on the south end of this stretch near the King Street Regulator Station and before the start of EBI Section 6; one site was at the Adit Structure on the waterfront that feeds wastewater to about the mid-point of EBI Section 6; and two sites were at the north end near the Denny Way Regulator Station and after the start of EBI Section 7.

The other 15 sites were at SPU manholes and structures on local lines that connect to the EBI. Instead of trying to monitor all suspect waterfront manholes, the locations were narrowed to single lines that collect flows from other local lines before entering the EBI. The last local manhole on each line was monitored to verify the amounts of salt water entering from the waterfront. Both flow and conductivity were measured at these sites. Much of the flow data, however, was invalid because the local lines surcharged with flows during high tides.

4.4.1 Moving North From King Street Regulator Station to Adit Structure

- **At and near the King Street Regulator Station.** Conductivities were monitored at a manhole (W10-133) on EBI Section 5 east of the regulator station and one at the station itself. Average peak conductivities were 5.47 and 8.08 mS/cm, respectively. Another manhole (W10-201) between these two locations on the line that runs between the regulator and the EBI showed an average peak conductivity of 2.13 mS/cm.

  The King Street Regulator Station‘s gate and overflow weir are located at the end of King Street on Alaskan Way. Worn gate seals are allowing salt water to enter directly into the conveyance system.
- **At Jackson Street.** SPU manholes (SEA 043-41 and SEA 43-28) on two SPU sewer lines had average peak conductivities of 20.60 mS/cm and 0.78 mS/cm. Both manholes were on Jackson Street under the viaduct. SEA 043-41, which is just to the west of SEA 43-28, receives flows from SPU‘s Washington Street Overflow Gate (elevation 6.3 feet). These flows collect and enter the King Street Regulator Station before entering EBI Section 5. During high tides, 70 percent of the line from the overflow gate would fill with salt water and then would peak the flow meter at 1.2 mgd, when the line became surcharged.
- **Near Washington Street.** Three SPU facilities near Washington Street under the viaduct were monitored. Two manholes (SEA 43-49 and SEA W10-210A) registered average peak conductivities of 11.20 and 10.63 mS/cm. The average peak conductivity at SPU‘s Washington Street Diversion Structure was 14.65 mS/cm. During monitoring, salt water was seen entering through the structure‘s overflow gate (Figure 17).

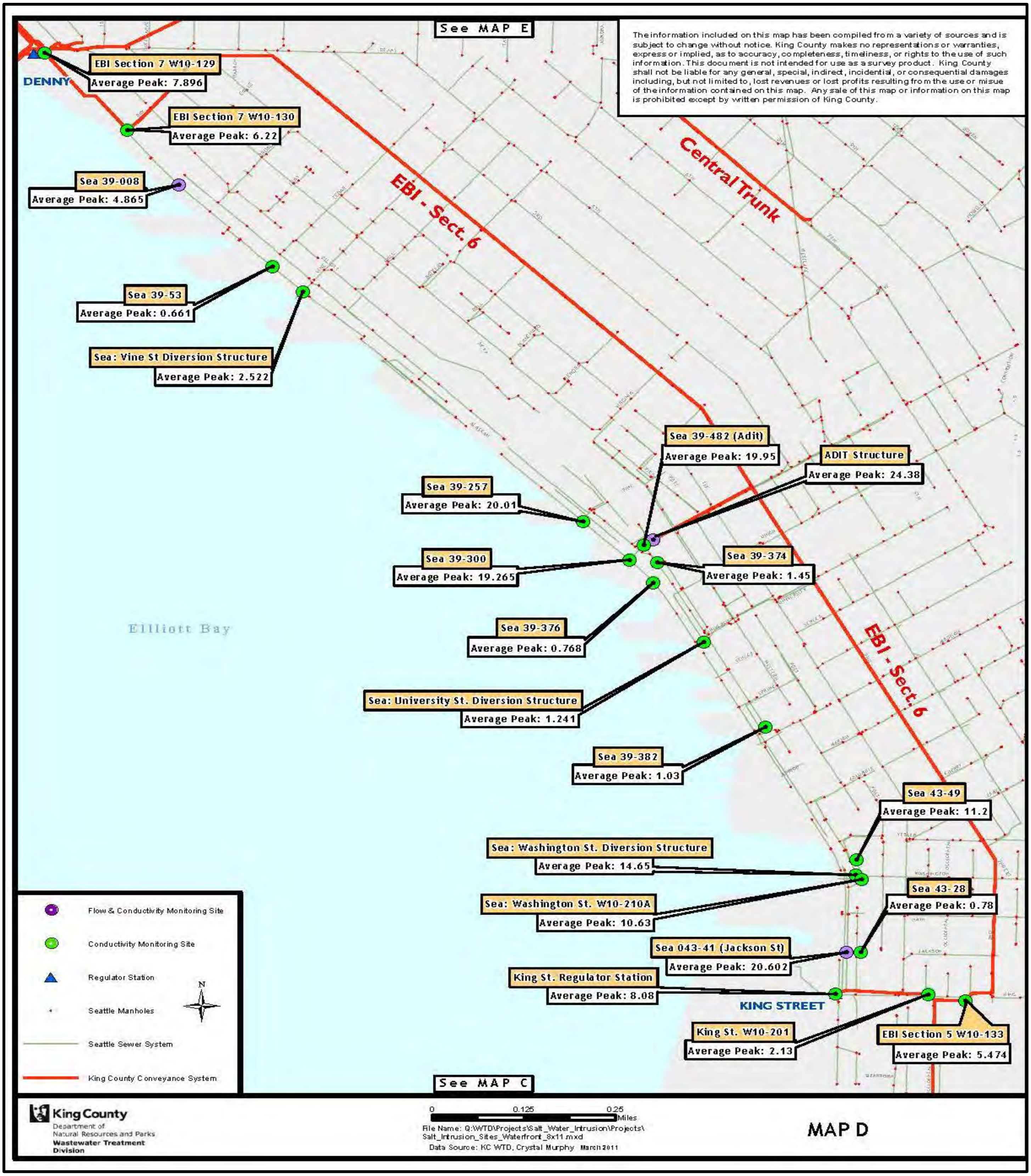

Figure 16. Downtown Seattle Waterfront

- **Between Washington Street and Adit Structure.** One SPU manhole (SEA 39-382) under the viaduct at Madison Street showed an average peak conductivity of 1.03 mS/cm. SPU‘s University Street Diversion Structure at the foot of University Street showed an average peak conductivity of 1.24 mS/cm.

Figure 17. Salt Water Entering SPU‘s Washington Street Diversion Structure Overflow Gate on the Downtown Seattle Waterfront

4.4.2 At or Near Adit Structure

- **Along the waterfront.** Average peak conductivities at three SPU manholes (SEA 39-376, 39-300, and 39-257), moving north, along the waterfront in the vicinity of the Adit Structure were 0.77, 19.26, and 20.01 mS/cm.
- **Near the Adit Structure.** Average peak conductivities at two SPU manholes (SEA 39-374 and SEA 39-482) were 1.45 and 19.95 mS/cm. SEA 39-482 is just west of the Adit Structure.
- **At the Adit Structure.** The King County Adit Structure, near the Pike Street Hillclimb, collects wastewater from almost all of the central waterfront basins before sending them into EBI Section 6. The structure receives flows from SPU‘s University Street Overflow Gate (elevation 6.7 feet) and the Madison Street Overflow Gate (elevation 8.3 feet). It showed an average peak conductivity of 24.38 mS/cm. Flow was monitored at the structure. The flows entering the Adit structure were usually 60 to 90 percent salt water during high tides; the structure would surcharge at times and invalidate the flow data. The average inflow of salt water was about 1.0 mgd; the peak flow was 1.9 mgd. Figure 18 shows the relationships of flow, tide, and conductivity at the Adit Structure.

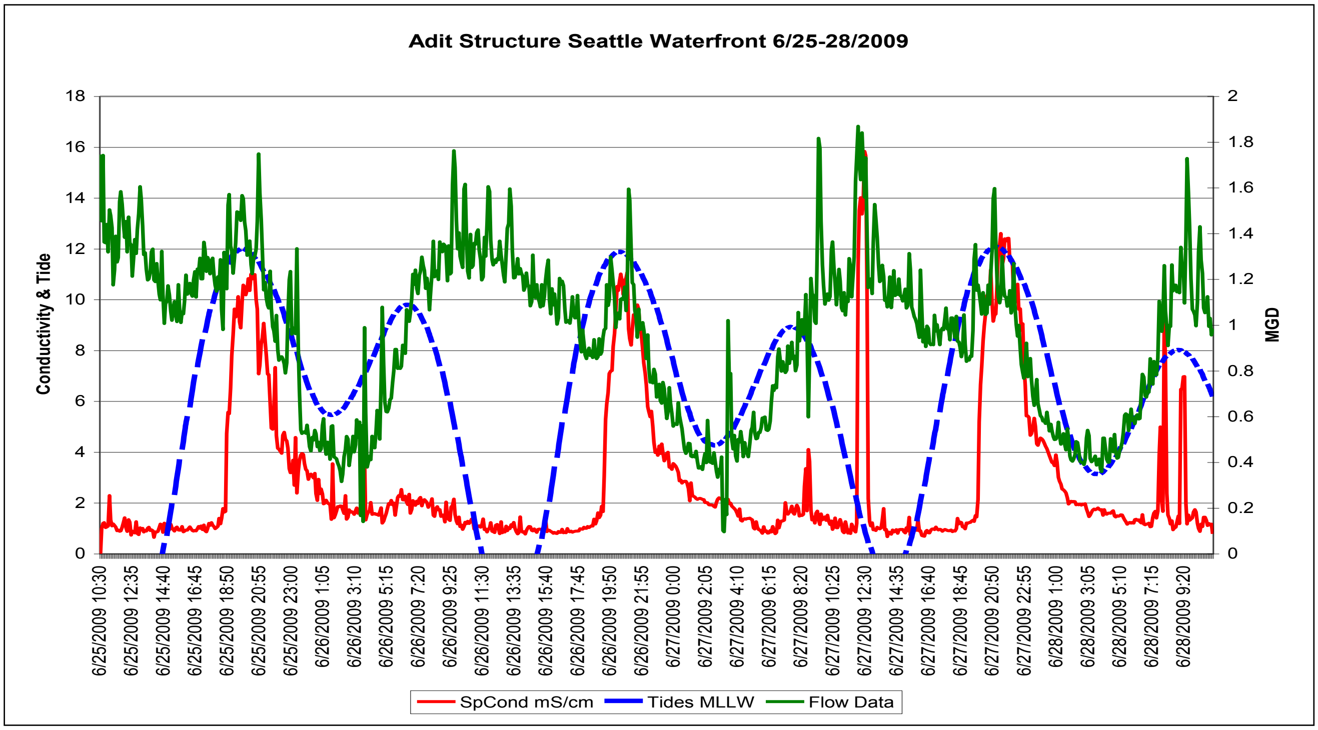

Figure 18. Relationship of Flow, Tide, and Conductivity at Downtown Adit Structure, June 25−28, 2009

4.4.3 Moving North From Adit Structure to Denny Way Regulator Station

- **SPU facilities on the waterfront.** Starting at Vine Street, about 0.5 mile northwest of the Adit Structure, three SPU structures on the waterfront were monitored. The Vine Street Diversion Structure showed an average peak conductivity of 2.52 mS/cm. One manhole (SEA 39-53) around 300 feet northwest showed an average peak conductivity of 0.66 mS/cm.

  Another manhole (SEA 39-008) in the Seattle Art Museum's Olympic Sculpture Park just west of the railroad tracks and near Myrtle Edwards Park showed an average peak conductivity of 4.86 mS/cm. This manhole receives flows from SPU's Vine Street Overflow Gate (elevation 4.7 feet) before entering EBI 7. Figure 19 shows salt water entering through this gate. During monitoring, the 24-inch-diameter line started with little or no flows and then quickly surcharged during most high tides, peaking the flow meter at 0.63 mgd. Figure 20 illustrates the impact of tides at this location, which is representative of other locations along the Downtown Seattle Waterfront. Because of surcharging and fluctuating flows, conductivity, flow, and tides are not as synchronized as in other locations.

- **At or near Denny Way Regulator Station.** Two manholes on EBI Section 7 were monitored in this area: one southeast of the Denny Way Regulator Station (W10-130) and one at the station (W10-129). Average peak conductivities were 6.22 and 7.90 mS/cm, respectively.

Figure 19. Salt Water Entering at SPU's Vine Street Overflow Gate on the Downtown Seattle Waterfront

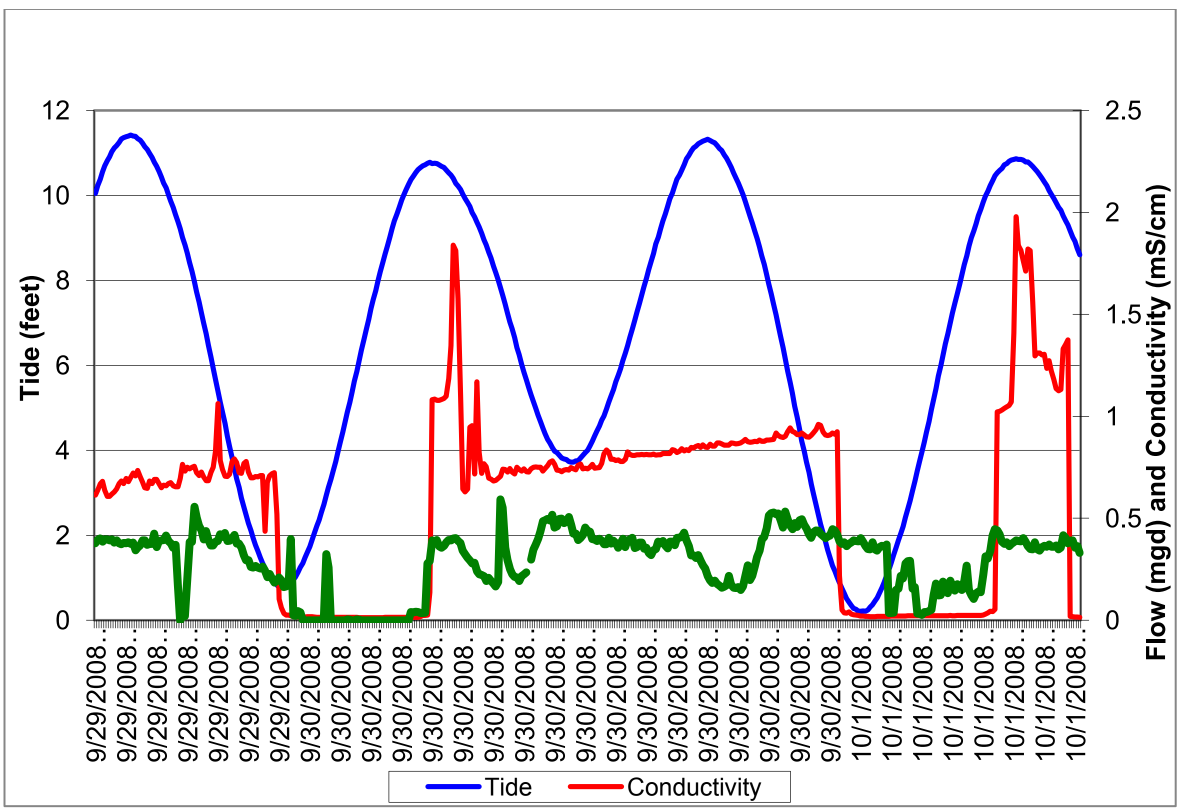

Figure 20. Relationship of Flow, Tide, and Conductivity at the SPU Manhole that Receives Flows from SPU's Vine Street Overflow Gate, September 29−October 1, 2008

4.5 Interbay–West Point Subarea

The Interbay Pump Station in south Magnolia collects flows from the south along the south side of Magnolia via EBI Section 7 north of the Denny Way Regulator Station and from the west via the South Magnolia Trunk (Figure 21). The pump station sends the flows north to the North Interceptor, which runs west from the north sides of Lake Union and the Lake Washington Ship Canal, crosses the canal, and runs along the south side of the canal to West Point. The North Interception also collects flows from the Ballard area via the Ballard Siphon, which also crosses the canal, and from the Central Lake Union Trunk that runs north and west along the west side of Lake Union and the south side of the canal to meet the North Interceptor after it crosses the canal.

Twenty-four sites were monitored in this area—eleven are on the North Interceptor, four are on EBI Section 7 and at the Interbay Pump Station, three are SPU manholes, one is at West Point, and the remaining five are on King County trunks.

4.5.1 Moving Northwest to Interbay Pump Station via EBI Section 7 and East via South Magnolia Trunk

- **EBI Section 7.** Three manholes (W10-127, W10-122, and W10-118) on EBI Section 7 between the Denny Way Regulator Station and the Interbay Pump Station were monitored. Moving from north to south, the average peak conductivities at these manholes were 5.61, 1.39, and 6.89 mS/cm. The low conductivity of 1.39 mS/cm at W10-122 is likely an anomaly. The conductivity at this site was measured only once. This one-time monitoring may have taken place during high flows, which would have diluted the salt water in the pipe. One SPU manhole (SEA 34-109) near EBI Section 7 showed an average peak conductivity of 0.71 mS/cm.
- **South Magnolia Trunk.** Three manholes were monitored on the South Magnolia Trunk that leads east from the South Magnolia Pump Overflow Structure to the Interbay Pump Station. An SPU manhole on a line that feeds into the trunk was also monitored. Average peak conductivities at the two manholes (W10-78-A and W10-89) upstream of the SPU connection were low (0.69 and 0.71 mS/cm); average peak conductivities at the SPU manhole (SEA 39-1), north of the trunk and less than 0.5 mile upstream of the Interbay Pump Station, and the manhole (W10-117) downstream of the connection near the station were of 10.16 and 10.50 mS/cm, respectively. The South Magnolia Trunk is a pressurized pipeline, which makes it difficult to install and monitor the data loggers.

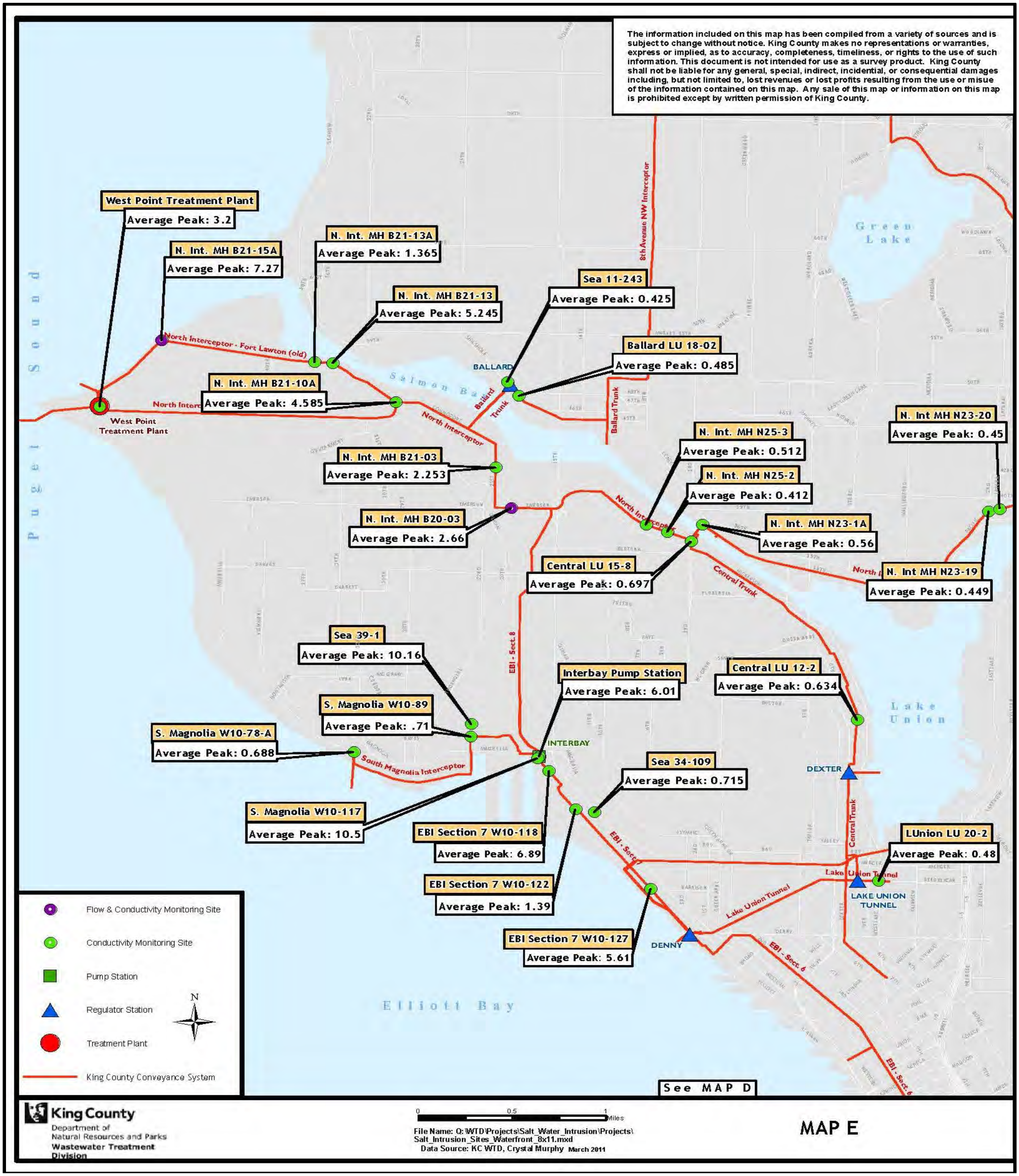

Figure 21. Interbay−West Point Subarea

- **Interbay Pump Station.** The average peak conductivity at the Interbay Pump Station was 6.01 mS/cm. Figure 22 shows a peak of 3.24 mS/cm and a flow of 42 mgd recorded on November 14, 2007, at the station. Given that the conductivity of Elliott Bay is around 32 mS/cm, the percentage of salt water in the wastewater flows at this peak would be almost 10 percent and the average volume of saltwater would be 4.2 mgd. The average conductivity over the three-hour period shown in Figure 22 is 2.0 mS/cm (6 percent solution of salt water) and the average pump flow is 40 mgd, which amounts to an estimated 2.5 mgd of salt water pumped through the station.

  A peak of 8.78 mS/cm in 2008 and a peak of 12.96 mS/cm in 2009 occurred during monitoring at the Interbay Pump Station. A conductivity of 8.78 mS/cm indicates 27 percent salt water in flows at Interbay, which equates to 10.8 mgd of salt water in a 40-mgd daily average flow during the high tide cycle. The salt water is coming both from EBI 7 and the South Magnolia Trunk.

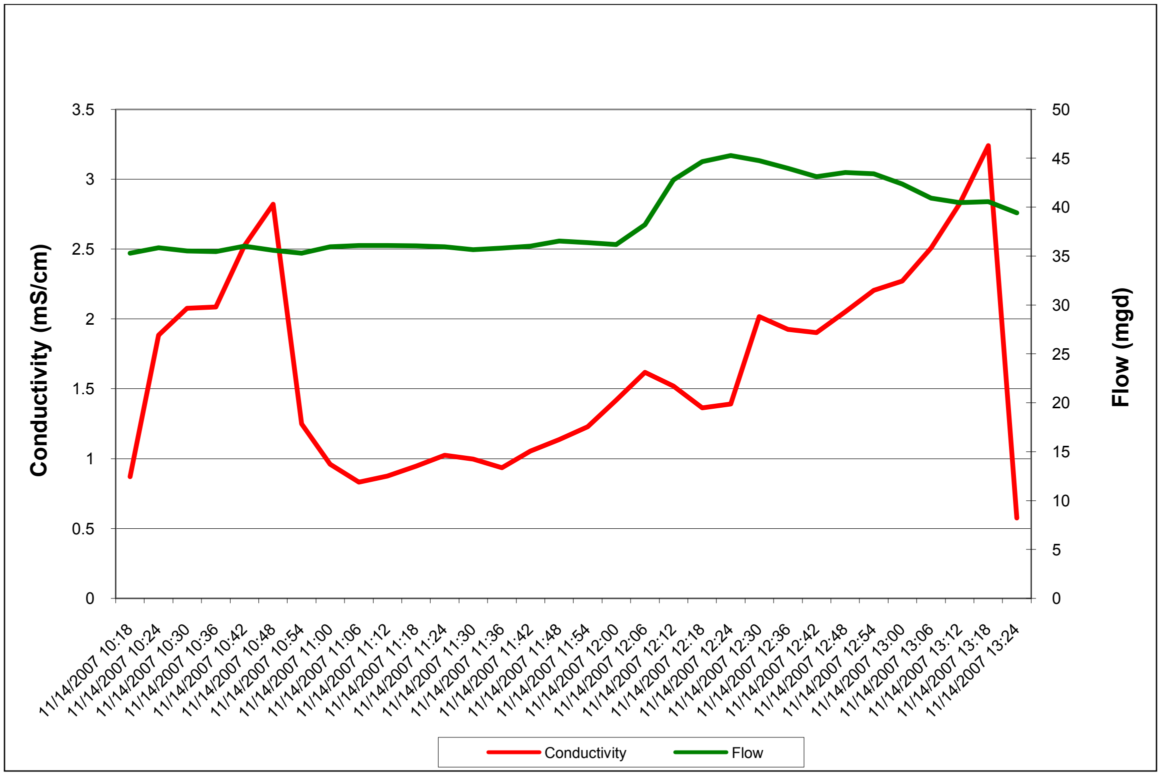

Figure 22. Relationship of Flow and Conductivity at Interbay Pump Station, November 14, 2007

4.5.2 Moving Northwest to North Interceptor via Central Trunk

- Three manholes were monitored on the Central Trunk in the Lake Union area before intersecting with the North Interceptor: one south of the lake (LU 20-2), one west of the lake (LU 12-2), and one on the south side of the ship canal near the North Interceptor (LU 15-8). All three locations are near fresh water and showed average peak conductivities below 1.0 mS/cm.

4.5.3 Moving West via North Interceptor on North Side of Lake Union and Lake Washington Ship Canal

- Three manholes were monitored on the North Interceptor before it crosses the ship canal west of Lake Union through the Fremont Siphon—two at the northeast tip of the lake (N23-19 and N23-20) and one north of the ship canal at the point of the crossing (N23-1A). As with the Lake Union trunks, these manholes are near fresh water and registered average peak conductivities below 1.0 mS/cm.

4.5.4 Ballard Trunk North of Ballard Siphon

- A manhole (LU 18-02) on the Ballard Trunk on the north end of Salmon Bay before the trunk crosses the ship canal through the Ballard Siphon and an SPU manhole (SEA 11-243) on a line that connects to the trunk, both near fresh water north of the ship canal and east of the Ballard Locks, showed average peak conductivities below 1.0 mS/cm.

4.5.5 Moving Northwest to West Point via North Interceptor on South Side of Lake Washington Ship Canal

- **East of Ballard Locks.** Average peak conductivities measured at two manholes (N25-2 and N25-3) on the North Interceptor just west of where the interceptor crosses the ship canal were below 1.0 mS/cm. These contrast with average peak conductivities at manholes on the interceptor after the point where flows from the Interbay Pump Station have entered. Average peak conductivities at these three manholes (B20-03, B21-03, and B21-10A), moving east to west, were 2.66, 2.25, and 4.58 mS/cm. Flows were monitored at Manhole B20-03. At Manhole B21-10A, the North Interceptor splits into the two parallel Fort Lawton Tunnels that bring flow to West Point.
- **West of Ballard Locks.** Three manholes were monitored on the North Interceptor (north Fort Lawton Tunnel west of the Ballard Locks before the interceptor enters West Point. Average peak conductivities of two locations just west of the locks (B21-13 and B21-13A) were 5.45 and 1.36 mS/cm. The average peak conductivity at the last manhole prior to West Point (B21-15A) was higher: 7.27 mS/cm. Figure 23 shows the relationship between flow, tide, and conductivity for a 48-hour period (June 24–26, 2009) at this site. Although the high flows and conductivity lag behind high tides by 4 to 6 hours, the data clearly show the rise in conductivity following tides over 11 feet. The high conductivity at the end of the period highlights the impact of salt water during low flow and dry season periods when conductivity is more concentrated and flow is lower.
- **West Point Treatment Plant.** The average peak conductivity at a manhole immediately before flow from the North Interceptor enters the plant was 3.2 mS/cm.

Local lift stations along Shilshole and Salmon Bays may be pumping salt water during high tides into the North Interceptor just prior to West Point. These small lift stations, located in low-lying coastal areas, pump salt water into the system in locations between manholes. The mid-pipe connections make tracking the location of salt water intrusion difficult. WTD does not know the locations of the lift stations and mid-pipe connections. It would be resource intensive to determine these locations and to conduct monitoring when high tides occur and flows are low so that conductivity spikes are more visible and easier to synchronize with tidal data.

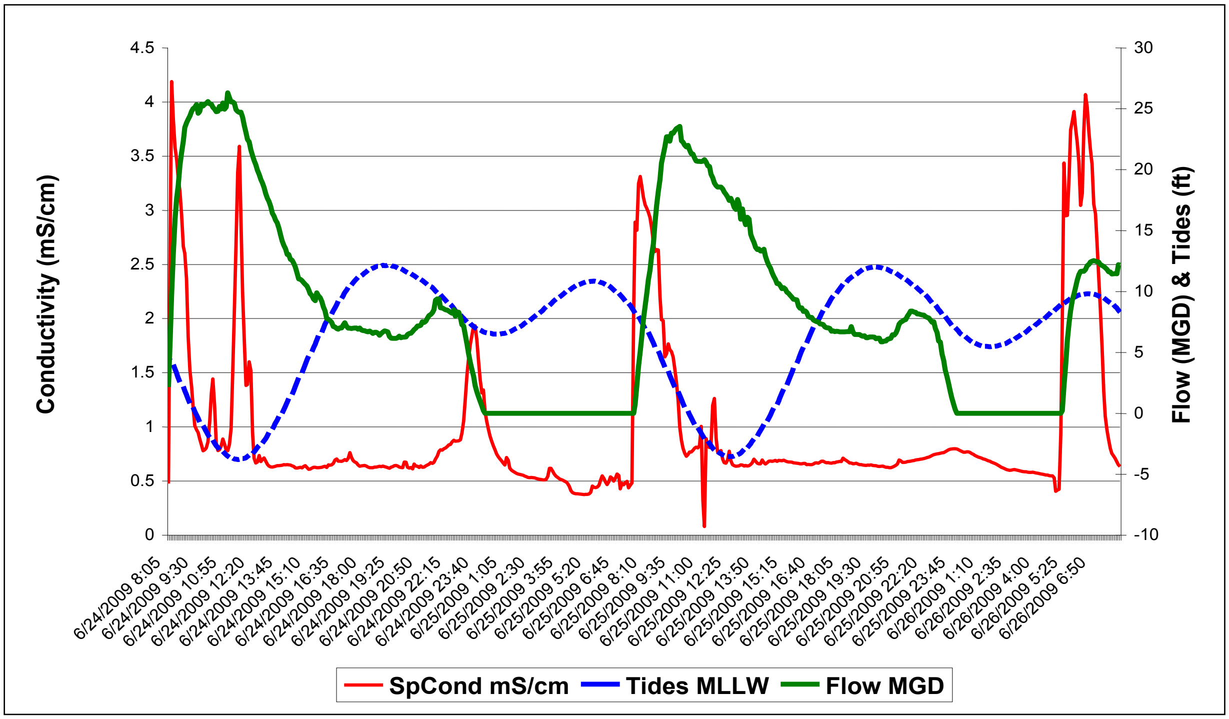

Figure 23. Relationship of Flow, Tide, and Conductivity in North Interceptor Flows Prior to Entering West Point, June 24−26, 2009

5.0. CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the results of the 2007−2009 conductivity monitoring of King County's combined sewer system and makes preliminary conclusions based on the findings. This discussion is followed by recommendations for investigations and repairs at the West Point Treatment Plant and the combined conveyance system that sends flows to West Point.

5.1 Findings and Conclusions

Saltwater intrusion is more endemic than anticipated at the start of the study. Despite repairs that significantly reduced saltwater intrusion and infiltration in the Upper Duwamish Subarea, the amount of salt water entering the West Point Treatment Plant has remained about the same since initial monitoring in 2003. An estimated average of 5 to 6 mgd, or 7 to 10 percent, of the West Point influent is salt water (Figure 24). High conductivities in one portion of the study area are mitigated downstream as the wastewater volumes increase and dilute the salt water, only to become high again through saltwater intrusion at downstream locations. Figure 25 shows the average peak conductivity at the last site monitored in each subarea before the flows move to the next subarea. (The last manhole in the Interbay−West Point Subarea is at the West Point plant.)

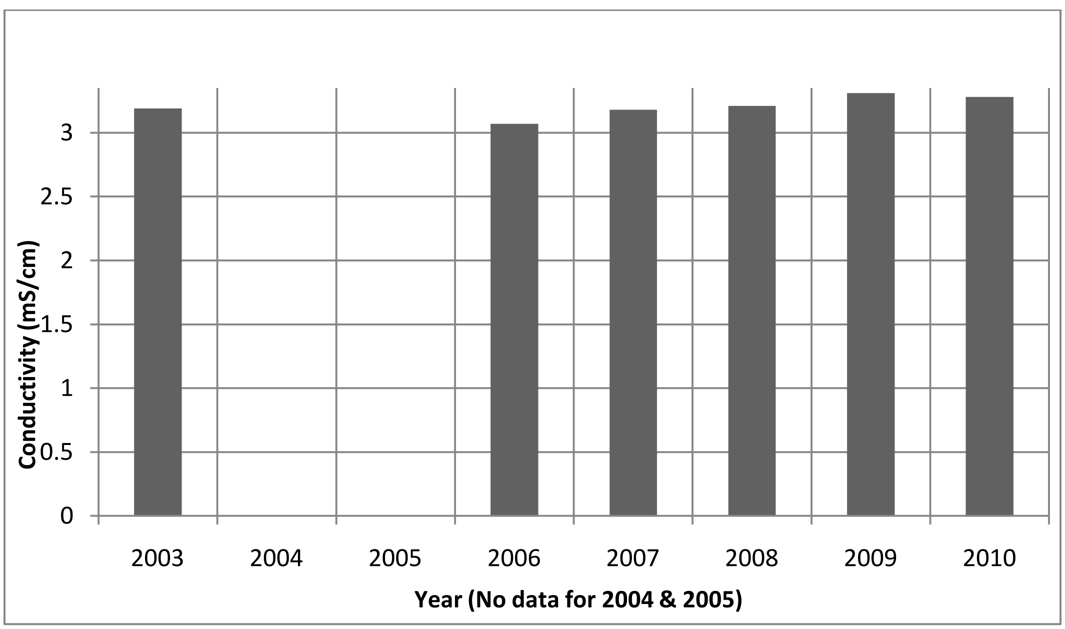

Figure 24. Average Peak Conductivities at West Point, 2003−2010

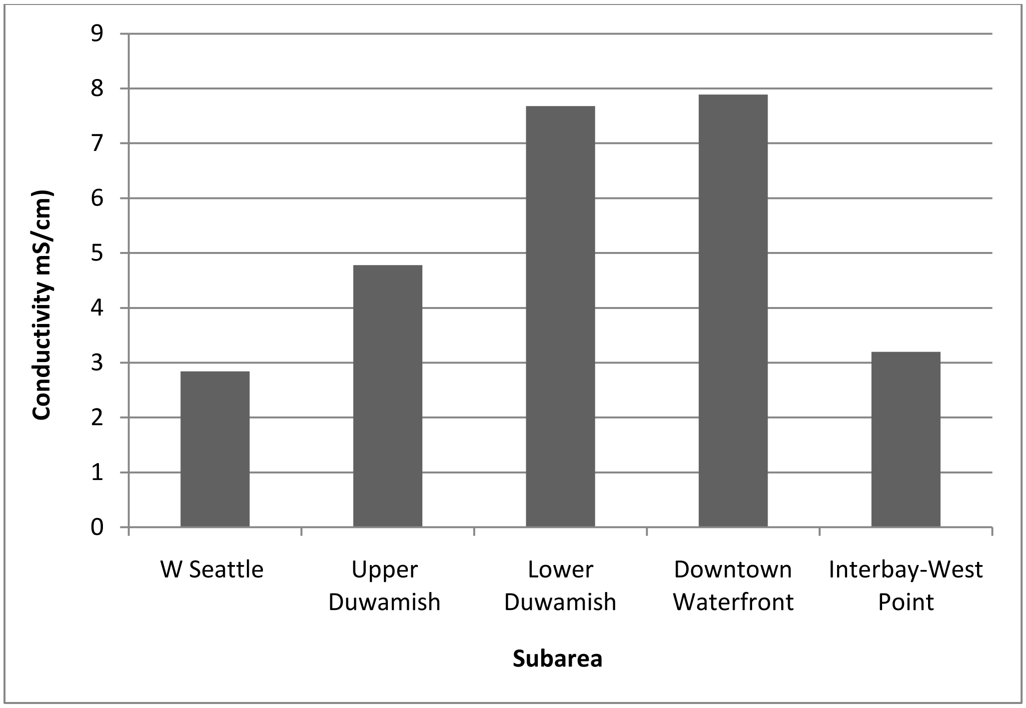

Figure 25. Average Peak Conductivities at Last Monitoring Site in Each Subarea

As in earlier studies, the major contributors are along the EBI, particularly in the Lower Duwamish River and Downtown Seattle Waterfront subareas. Completion of recommended repairs to the Hanford, Lander, and King Street Regulator Station gates (see below) should help reduce saltwater intrusion in these areas. About half of the salt water entering West Point enters in the waterfront area. Most of this salt water enters the system through SPU outfalls and other structures on the waterfront. SPU plans to restructure much of its waterfront facilities either through the seawall replacement project, estimated to be completed around 2014, or its CSO control program.

The relationship between flow, tide, and conductivity found during this study is consistent with findings from previous monitoring—a noticeable spike in conductivity occurs during or after tides greater than 11 feet, with some smaller spikes associated with tides over 10 feet. The point at which conductivity spikes occur depends on the site‘s proximity to the source of saltwater intrusion. For example, spikes and increases in flow occur simultaneously with high tides at the Adit Structure on the waterfront, while spikes at West Point occur 4 to 6 hours after the high tides. The timing of spikes at pump stations depends on wet well levels and pumping operations. The magnitude of the spikes depends on the amount of flow—the lower the flows, the higher the spikes. Temperatures confirmed that colder sea water is entering the system during high tides.

This saltwater intrusion is already posing problems for the combined system. Forecasted higher sea levels will further affect the ability of the conveyance system to operate as designed. Potential impacts to the conveyance system include the following:

- Inflow of salt water into the system, causing damage to facilities and taking up needed capacity
- Increased pressure, resulting in reduced capacity and upstream flooding

- Increased power consumption and costs to convey and treat saltwater inflow
- Increased hydrogen sulfide generation in pump stations, especially Interbay Pump Station

WTD will identify facilities most likely to experience saltwater intrusion and recommend design and adaptive operational strategies, implementation schedules, and approaches as part of a project to analyze the hydraulic impacts of sea-level rise.

The following text summarizes findings in each subarea and draws tentative conclusions based on the findings. The conclusions should be viewed in light of the limitations of the study. The study area covers a large geographical area, the existence and locations of many SPU and private sewer facilities are unknown or inaccessible, and the extent of the problem was greater than anticipated. One person conducted the entire study with only six Sondi data loggers and limited access to flow meters. Some sites were monitored only once, either because the conductivities were too low to warrant further monitoring, the meters failed, or time did not allow for additional monitoring. Concentrated monitoring in targeted areas, as recommended below, will help verify these findings and conclusions.

Upper Duwamish River Subarea

Average peak conductivity at the Duwamish Pump Station that collects flows from all portions of the Upper Duwamish River Subarea has dropped from 5.98 mS/cm in 2007 to 3.42 mS/cm in 2009, likely from repairing the South Michigan outfall and plugging the leaky pipe near the Duwamish Siphon Inlet. Areas that are still contributing salt water to the station are in the vicinity of the Chelan Regulator Station, EBI Section 3 south of the station, and local lines near the station. Salt water does not appear to be entering the EBI south of EBI Section 3 on the east side of the river nor the WDI south of the Duwamish Inlet Structure on the west side of the river, although only limited monitoring was conducted in these areas.

West Seattle Subarea

The West Seattle Subarea does not appear to be contributing much salt water to the system. Most average peak conductivities were below 2 mS/cm. Higher conductivities at and near the Barton and Murray Pump Stations decrease through dilution as the flows move north to the 63rd Avenue Pump Station, and higher conductivities north of the station decreased after the gate to the 53rd Avenue Pump Station was reinstalled. The most recent annual average peak conductivity (2009) at the West Seattle Pump Station, the last site monitored before West Seattle flows enter the EBI, was below 1 mS/cm.

Lower Duwamish River Subarea

Conductivities were higher in the Lower Duwamish River Subarea than in the Upper Duwamish River Subarea. Conductivities appear to be higher in EBI Section 4 after flows from West Seattle enter the pipeline. Average peak conductivity in 2007 at the manhole on EBI Section 4 downstream of the junction with the West Seattle Tunnel was about 1.5 mS/cm higher than at the manhole in the Upper Duwamish River Subarea upstream of the junction. Further investigation is needed to confirm this finding because the upstream manhole was monitored only in 2007. Average peak conductivities decreased over time downstream of the junction (from 6.33 mS/cm in 2007 to 4.93 mS/cm in 2009.

Investigations found that salt water is entering through King County‘s Hanford and Lander Regulator Stations. The highest conductivities in the subarea occurred near and at the Lander Street Outfall and Regulator Stations. The regulator station registered an average peak

conductivity of 22.04 mS/cm. It appears that salt water is entering not only through the Lander outfall gate but also through SPU lines in the area. Two SPU manholes near the Lander Outfall Station registered average peak conductivities of over 30 mS/cm.

The average peak conductivity at the northernmost site monitored in this area, on EBI Section 5, was 7.68 mS/cm, indicating dilution of salt water as volumes increase moving north from Lander. Conductivity at three SPU manhole south of this manhole near the Connecticut Regulator Station ranged from 1.1 to 14.96 mS/cm.

Downtown Seattle Waterfront Subarea

The dilution of salt water continues northward, as indicated by a lower average peak conductivity (5.4 mS/cm) at the southernmost site monitored on EBI Section 5 in the Downtown Seattle Waterfront Subarea. However, average peak conductivities were higher (7.90 mS/cm) at the northernmost site monitored in this subarea on EBI Section 7 near the Denny Regulator Station.

King County has only two overflow facilities on the Downtown Seattle Waterfront because EBI Section 6 is a tunnel with only one mid-pipe connection at the county‘s Adit Structure. At one of these overflow facilities, the King Street Regulator Station, salt water is entering through the station‘s outfall gate (8.08 mS/cm at the station); the other facility, the Denny Way Regulator Station, underwent extensive work in 2004, including a new outfall, to control CSOs at the site.

The highest conductivities noted in this subarea were at SPU facilities near or south of the Adit Structure with lines that connect to the EBI via the structure. Average peak conductivities were around 20 mS/cm at four of these SPU facilities and 24 mS/cm at the Adit Structure. During monitoring, salt water was seen entering at SPU‘s Washington Street (almost 15 mS/cm) and Vine Street (2.5 mS/cm) Diversion Structures.

Interbay−West Point Subarea

Most sites in the Interbay−West Point Subarea were monitored only once, and conductivities varied widely at some sites that were monitored more often. For example, the average peak conductivity at Interbay Pump Station was 3.24 mS/cm in 2007 and 6 mS/cm in 2009, and at the last manhole monitored on the North Interceptor before West Point, conductivity was 3.3 mS/cm in 2008 and 11.24 mS/cm in 2009.

Conductivities appeared to hover around 5 mS/cm in EBI Section 7 before flows enter the Interbay Pump Station. Contrary to findings of earlier monitoring, flows from the South Magnolia Trunk are carrying salt water to the station, most likely through connection of local lines on the Pier 91 site.

Average peak conductivities were low in the east and northeastern portion of the subarea. Conductivities at all sites on the Central Trunk and the North Interceptor north and south of the Ship Canal around the Fremont Siphon were below 1 mS/cm. Conductivities in flows from these areas after they move south and west and then combine with flows in EBI Section 8 from the Interbay Pump Station were around 2.5 mS/cm, increasing as the flows move west to West Point. The sources of salt water intrusion in the area just east and north of Discovery Park are unknown, but SPU lift stations in the area may be a factor.

5.2 Recommendations

The infiltration and intrusion of salt water into King County's conveyance system and West Point Treatment Plant are corroding equipment at the plant, considerably shortening the lifespan of this equipment, and increasing the volume of wastewater to be conveyed and treated. The yearly cost of treating salt water entering the system has been estimated at $1.64 to $3.16 million, not to mention the cost to repair and replace damaged equipment. Similar equipment at South Treatment Plant is not experiencing such corrosion.

The recommended approach to remedy the problem is to implement a comprehensive program to identify current and future saltwater intrusion sites and take measures to stop these sources of intrusion. This work will require coordination with SPU to learn more about their system and their plans to address intrusion into the County's system from SPU facilities, especially along the downtown waterfront. It will also require coordination with other King County programs and projects, such as the CSO Control Program and efforts to plan for effects of climate change.

The following recommendations can be folded into the program or, in the absence of such a program, could be undertaken as individual projects.

5.2.1 West Point Investigations and Repairs

As recommended in the Tinnea & Associates (2003) study, investigation of the extent of the corrosion and damage to the return activated sludge (RAS) piping at the West Point plant should be conducted (Appendix A). There are 8,000 linear feet of RAS piping at West Point. The three elbow sections of RAS piping that were examined are above ground. Most of the RAS piping is extremely difficult to access because it is buried underground and encased in concrete. The majority of the buried pipes measure between 48 and 60 inches in diameter. The Tinnea & Associates study recommended an examination of all the pipes and subsequent rehabilitation of any pipes affected by pitting. The original cost of purchasing and installing the RAS piping was $16.5 million in 1989. Any potential replacement should include the additional cost of removing old buried pipe and the disruption of plant operations. If only the pipe elbows and severely corroded piping were replaced and the remaining 75 percent is untouched, repair costs are estimated at $4.1 to $4.9 million.

In addition, the 2003 report recommended the inspection of medium-pressure gas and primary effluent pipes at the plant and the evaluation, installation, or upgrading, as appropriate, of cathodic protection throughout the plant's piping network, including buried steel process piping. No cost estimates have been prepared for this work.

5.2.2 Conveyance System Investigations and Repairs

Outfall Gates

All King County gates near Puget Sound, Elliott Bay, and the Duwamish River should be inspected for saltwater intrusion and the causes identified and addressed either through repair or replacement. Such an inspection at the Chelan Regulator Station outfall gate, for example, could help determine whether the outfall is the source of conductivity noted near the station.

Below are recommended repairs to three gates in the Lower Duwamish and Downtown Seattle Waterfront subareas that were investigated during this study. Salt water was also seen

entering through the Brandon and Connecticut Regulator Station outfall gates, but the causes for the intrusion have yet to be identified.

- **Hanford Regulator Station.** The station's outfall gate located in Terminal 25 needs to be reseated. The leaking gate allows salt water to enter directly into the EBI through the outfall pipe. In addition, a bulkhead should be installed between the outfall gate and sewer flows. After the bulkhead has been sealed, the wastewater should be pumped out of the outfall so that the gate can be opened at low tide. Cost estimates range from $130,000 to $170,000.
- **King Street Regulator Station.** Worn outfall gate seals are allowing salt water to enter directly into the conveyance system. The gate and overflow weir are located at the end of King Street on Alaskan Way. A bulkhead should be installed between the outfall gate and the wastewater flows. After the bulkhead has been sealed, the wastewater should be pumped out of the outfall so that the gate can be opened at low tide. Cost estimates range from $130,000 to $170,000.
- **Lander Street Regulator Station.** A new seal should be installed on the large overflow flap gate FG-01. Salt water is entering the overflow structure through the defective gate and then spilling into the conveyance system prior to EBI Section 4. This work will have to be done during low tides because the height of the interconnecting pipe off the Lander 90-inch-diameter storm drain is only 1.26 feet. Cost estimates range from $30,000 to $50,000.

Additional Monitoring

It is recommended that King County, in coordination with SPU, investigate five areas to determine the location of local lines, gates, lift stations, and connections to the county's system. Concentrated conductivity monitoring should accompany the investigations. The locations are as follows:

- The vicinity of the 8th Avenue South Regulator Station
- Near the Duwamish Pump Station
- The Port of Seattle Pier 91 property near Interbay Pump Station
- The Ballard area near Shilshoe Bay that feeds into an SPU line that runs south under the Lake Washington Ship Canal
- The North Interceptor prior to where the pipeline enters the West Point plant

APPENDIX A

West Point Treatment Plant Corrosion Control Investigation

WEST POINT TREATMENT PLANT

CORROSION CONTROL INVESTIGATION

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EXECUTIVE SUMMARY

Three 30-inch diameter mild steel pipe elbows at the West Point Treatment Plant located near Discovery Park in Seattle have suffered serious corrosion damage. The problem is in the form of pits that tend to concentrate along weld seams present in the elbows. Some of these pits were of sufficient depth to penetrate the pipe wall and cause leaks.

To date the damaged piping has been observed on the return activated sludge (RAS) process line. This stream is part of the secondary treatment process at the facility. Other property associated with the plant has suffered accelerated corrosion damage including steel rake arms and aluminum and steel hardware used in secondary clarifiers.

It is noteworthy that the very similar secondary treatment facility at the South Treatment Plant, located in Renton, has not suffered similar damage. The damaged West Point equipment has been in service about seven years. The undamaged Renton has been in service for over 40 years. Just below, the photo to the left shows a heavily corroded secondary clarifier rake arm at West Point. The photo to the right shows a rake arm and piping at Renton exhibiting only minor "rust blushing."

West Point Clarifier

Renton Clarifier

The principal identified factor that differentiates these two facilities is that saltwater contamination of the West Point process stream occurs whenever the tide level exceeds approximately 11 feet. This seawater contamination includes corrosive chloride ions that accelerate steel corrosion in the plant.

It is likely that the corrosion damage is systemic throughout the facility and would be expected to be a problem for most metals that are in contact with the process stream. The damage does not appear limited to the RAS line. The most direct means to control future corrosion at the West Point Treatment Plant would be to reduce raw sewage influent chloride ion content to the levels that are seen at the South Treatment Plant. Even with significant reduction in chloride ion contamination, it will also be necessary to implement active corrosion control in much of the West Point facility through galvanizing and coating or cathodic protection.

WEST POINT TREATMENT PLANT

CORROSION CONTROL INVESTIGATION

INTRODUCTION

The West Point Treatment Plant is an integral part of King County's regional wastewater treatment system. Each day it treats approximately 125 million gallons of wastewater. In December of 2002, a 30-inch diameter elbow on one of the return activated sludge (RAS) lines began leaking and had to be removed from service for repair. An inspection of the elbow by King County and Tinnea & Associates personnel identified pitting corrosion as the cause of the elbow failure.

King County requested that Tinnea & Associates perform testing and analysis of the corrosion failure at the West Point facility. This work was to include a comparative component that included inspection and testing at the Renton Treatment Plant. To assist us in this project we were joined by the US Department of Energy's Albany Research Center. We also received assistance from InterCORR, the manufacturer of the FieldCET™ electrochemical noise monitoring equipment. Authorization to proceed with this work was provided by Work Order Authorization 03 to the on-call corrosion consultant agreement E13025E.

This report provides the findings of that investigative work including a discussion of the corrosion mechanism and recommendations for future corrosion control and monitoring. Also included are graphic presentations of the test data and a discussion of the several test methods employed. An overview of corrosion basics and a detailed discussion of the electrochemical testing techniques employed during this work are attached as appendices.

Tinnea & Associates extend our sincere thanks to Bob Isaac and Sarah White, of the Wastewater Treatment Division of the King County Department of Natural Resources and Parks, for their invaluable assistance, guidance and input during this work. We also extend our appreciation to Bernie Covino, of the US Department of Energy, for his help in selecting the appropriate testing regimen, installation of the test equipment and evaluation of the results. Finally, we thank Dawn Eden and Russell Kane from InterCORR for their assistance in proper use and interpretation of electrochemical noise test data.

THE REPORT

This report is broken down into several distinct sections. First was the cover Executive Summary. Following is the main report that discusses the several inspections conducted, the corrosion testing, makes estimates for future corrosion activity and provides recommendations for further work and corrosion control. The corrosion test data are included as attachments. Included as appendices are an extended discussion of corrosion fundamentals and a discussion of the electrochemical testing performed.

INSPECTION

OVERVIEW

In December of 2002, Tinnea & Associates joined King County Staff in an inspection of a failed 30-inch diameter steel pipe elbow at the West Point Treatment Plant. The elbow had suffered a leak and was removed for inspection and repair. The elbow was located in a gallery immediately adjacent to a RAS aeration tank. The pipe failure was the result of pitting corrosion. A letter report dated January 10, 2003 that discussed the findings of that inspection was prepared and provided to the County.

The Seattle inspection firm, Professional Service Industries, Inc. (PSI), was retained by the County to conduct an extensive ultrasonic thickness (UT) inspection of the piping in the aeration galleries. The PSI inspection did not identify any addition pitting.

Figure 1

In early February of 2003, King County Staff removed an additional elbow for inspection. Generally, the epoxy coating was in good shape. However, some pits were present and coating blisters were observed.

After a meeting between King County Staff and Tinnea & Associates personnel, it was decided to perform on-line corrosion testing and monitoring of the West Point Treatment Plant. Given the somewhat random nature of pitting corrosion and the fact that microbiological activity may play a role, it was decided the testing should employ several distinct methodologies during concurrent periods. It was also decided to perform some parallel testing at the Renton Treatment Facility as a control.

Figure 1 shows an elbow that was removed in May of 2003 from the RAS line of the West Point facility. Of the three elbows inspected, this showed the least damage. There were, however, pits and coating blisters present.

Later in May, the corrosion test equipment was installed, and monitoring was initiated. Monitoring continued through early July of 2003.

This report presents the findings from those inspections and test measurements. It includes a discussion of the likely cause of the corrosion failures and the likelihood of future corrosion related problems. Recommendations are made for future work and methods to control the corrosion problem.

PIPE CONDITION INSPECTIONS

COATING SYSTEM

The interior of the West Point piping in question was coated with a premium coal tar epoxy. In a system of this kind, the coating provides a physical barrier between the underlying steel and the process stream. By keeping potentially corrosive agents from the metal surface, it is expected that the corrosion rate will be reduced.

During the inspections of the removed RAS elbows, the condition of the coating was observed. Some incidental mechanical probing was also performed. For all elbows inspected the following conditions were observed:

- In general the coating was in good condition and, in most areas, adheres very tightly to the underlying steel surface
- The weld seams appeared smooth and the areas adjacent to the welds appeared free from weld slag and splatter.
- Pitting was noted
    - The pits favored locations on, or near, weld seams
    - Some pits were located at a distance from the weld seams
    - Pitting was noted at the inner edge of the elbow flange
    - Some of the pits had penetrated the pipe wall
- Coating blisters were noted
    - Some blisters occurred over pits
    - Some blisters occurred without any underlying pits

PIPE CONDITION

The pipe elbows are carbon steel, electric fusion welded from ASTM A283, Grade C, ASTM A285, Grade C, or ASTM A570, Grade C plate of ¼-inch thickness. The elbows were to be fabricated in accordance with the requirements of AWWA C200.

Excepting the pits, the pipe appeared in excellent condition. In all inspections of the pipe, serious pitting was observed. During one inspection the pH in the wells of several pits was measured. It ranged from 6.0 to 6.1. The typical pH of the RAS line is about 6.5. Unfortunately, the pipe interior had been washed prior to inspection, so the pH measured may be somewhat higher than was the in situ case.

Figure 2 *Photo Sarah White*

Figure 2 shows the penetrating pit that led to the December 2002 inspection. The orange in the background is from an amber lighting system present in the area. The orange in the center of the pit is reflecting from the floor behind and is not rust-colored liquid in the pit. Note that the full thickness penetration is adjacent to coating showing no sign of distress.

Figure 3

Figure 3 shows pitting and blisters along a weld seam. Several of the blisters contained little or no corrosion product. The coating adjacent to this damage appeared to be in excellent condition. The coal tar epoxy tightly adhered to the underlying steel. There were no obvious signs of weld splatter or other clear construction-fabrication defect. During several inspections the coating was examined with 10x magnification. No clear signs of wear, impingement or other operations-based damage were observed.

Figure 4

Figure 4 shows a flange of one of the inspected elbows. Note the pitting damage at the flange-pipe transition. The deepest pit penetration was 0.16". The pipe-flange face appeared to be in good condition. Potential, resistance and high frequency insulation tests were preformed on-line and all joints appeared to be electrically continuous.

ON-LINE CORROSION MONITORING

BASIS FOR TESTING PROTOCOL

During the winter of 2002-2003, Tinnea & Associates had many conversations with staff from King County and the US Department of Energy's Albany Research Center (ARC). The pitting behavior observed during the pipe condition inspections and possible contributing factors were discussed. From these conversations a consensus evolved that any testing protocol needed to address several issues. Further, it was understood that of the available corrosion testing methods for any one of the possible corrosion-contributing factors, certain test methods were more likely to be successful than others. These possible contributors are discussed below. Appendix 2 includes a comparative discussion of several of the corrosion testing techniques employed for this work.

TEST PROCEDURES

Three main test approaches were selected. Two provide information on the general corrosion rate. One of these methods was linear polarization resistance (LPR) testing. LPR test systems would be installed on a secondary clarifier at both the West Point and Renton Treatment Plants. The second general corrosion test device was an electrical resistance (ER) probe to be installed on the RAS line of the West Point Plant that runs from the secondary clarifier with the LPR system to the aeration line. Two electrochemical noise (EN) probes would be installed to provide information on localized (pitting) corrosion in addition to general corrosion information. One EN probe would be installed on each of adjacent primary effluent (PE) and RAS lines. To augment the corrosion testing, data from existing on-line equipment would provide information on process stream chemistry.

STRAY CURRENT

Stray current was considered as a possibility. The elbows connect to the aeration tanks and main piping runs through bolted flange joints. If the joints were not electrically continuous, stray current could be a problem unique to the joints. As mentioned above, electrical continuity was checked during several inspections. All of the joints appeared electrically continuous. Continuity would tend to eliminate stray current from being specific to the joints. It was still possible that stray current could be a problem, but that it was systemic, rather than specific to the elbows.

To evaluate stray current as a systemic problem, attention would be paid to on-line corrosion probes showing spikes in corrosion activity that could be associated with plant operations, such as motors starting or stopping.

CHLORIDE IONS

The West Point Treatment Plant secondary treatment system went on line in 1996 and suffered pitting failure of one of its RAS lines within seven years. The South Treatment Plant secondary system went on line in 1961 and has not had a similar failure. One major difference between the two facilities it that West Point's raw sewage influent includes a seawater influx during some high tides. Chloride ions can be extremely corrosive toward mild and low alloy steels.

Parallel corrosion tests would be conducted at the West Point and South Treatment Plants. This would provide comparative information. In addition, attention would be given to variations in West Point corrosion activity that could be associated with tide level variation. Finally, the monitoring of plant influent conductivity and PE flow will be coupled with grab samples from the RAS and PE lines taken for chemical analysis.

PITTING

Pitting corrosion is a particularly insidious form of corrosion. Although the corrosion results in a small or modest metal loss, the damage can penetrate deep into the metal. In the case of pipes, a pinhole is usually too big. Given this situation, pitting can lead to catastrophic failure.

Another factor about pitting that can compound the problem is that it is an inherently random process. In Figure 3 and the accompanying text, it can be seen, and was noted, that the pits concentrated along the weld seams. They do, but they do so in a random fashion. The same is true in non-weld areas. The pits appear in a random fashion, it just that the frequency is higher along the welds.

This probabilistic nature of pitting explains why the PSI inspection did not detect any pits, yet each elbow removed has shown pitting. For example, consider a situation where pits average ½-inch in diameter with a density in non-welded areas of one pit for every five square feet. A typical UT gauge has a test head that also is about ½-inch in diameter, so the pit and sampler footprint are about the same size. If you break five square feet into half-inch squares you will have a total of 2880 squares. For any measurement taken you have a 1 in 2880 chance of success. The inspector must take a lot of readings to have favorable odds of finding a single pit.

Pitting of the mild steel in the West Point Plant occurs, in part, because of the excellent coating system. As such we can, at least in terms of pit initiation, look as the process as one of general corrosion on a highly localized basis.

EN equipment was selected to evaluate changes and fluctuation in pitting or similar localized corrosion conditions. The LPR and ER results would compliment the EN testing.

MICROBIOLOGICALLY INFLUENCED CORROSION (MIC)

MIC was assumed to be factor in the corrosion process. How MIC may have affected observed corrosion can be complex. EN can afford indications of MIC.

EQUIPMENT INSTALLATIONS

LPR PROBES

The LPR equipment was fabricated for installation in the influent wells of secondary clarifiers. For durability and to avoid corrosion interference, the bodies of the probes were fabricated from heavy duty PVC conduit. The upper portion of the probes was strapped to walkway railings with fence clamps. The probes were positioned so the lower portion would be continuously submerged.

Figure 5 shows the end of one of the probes after general cleaning at the end of the test period. These probes employ three electrodes. The electrodes are fabricated from steel that matched the type used to fabricate the pipe. In LPR one electrode is the working electrode, the WE; one electrode is the counter electrode, the CE; and one electrode is the reference electrode, the RE. A direct current is applied in steps between the WE and the CE. For each step the voltage, or potential, is measured between the WE and the RE. For this work, two Gamry RPX-1 Corrosion Rate Transmitters were employed. The RPX-1 transmitters were connected to data loggers through a 4-20 mA current loop and a 12 volt deep cycle battery. Figure 6 shows the PVC test probe strapped to the railing, near the photo centerline, at Renton. The logging equipment and battery are in the background. Figure 7 shows the installation from the opposite direction, with the RPX-1 and battery in the foreground and the probe to the back.

Figure 5

Figure 6

Figure 7

The installation at West Point was virtually identical. At both locations the probes functioned well, and the plastic enclosures and use of moisture-resistant electrical connections avoided any rain-related electrical short circuits or similar weather related problems. By simply replacing the three steel electrodes, the test equipment can be easily re-installed to repeat the work, or provide extended monitoring.

RETRACTABLE HOT TAP PROBES

As the clarifiers are open vessels, installation of test equipment there was not difficult. The EN and ER probes were installed in pipes. It was decided that the installations should allow for probe installation and replacement without requiring shutdown of the line. Retractable, hot-tap devices from Metal Samples, Inc. were selected for installation.

The EN probes employed three steel electrodes identical to those used in the LPR probe. There, much of the similarity ends. Figure 8 shows the probe head to the left and mounting body to the right. The mounting body is threaded onto a short NPT pipe nipple mounted to a ball valve. Figure 9 shows the probe extended and the ball valve closed. Figure 10 shows the PE and RAS EN probes installed. Figure 11 shows the EN monitoring equipment being installed. Figure 12 shows the FieldCET™ EN equipment installed with test leads and the laptop computer controller.

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

The ER probe contains a thin-walled tube that makes a loop within a protective metal guard. Figure 13 shows the working end of the ER probe prior to installation. You can see the tube loop through the holes in the stainless steel guard. Each end of the loop is connected to a pole of a sensitive resistance meter. As the tube corrodes its metal cross-sectional area reduces and the electrical resistance measured by the meter increases. A simple formula converts the resistance readings to corrosion rate. Figure 14 shows the ER probe installed and the Metal Samples MS 3500E resistance probe data logger.

Figure 13

Figure 14

INTERMITTENT MONITORING

All of the equipment had the ability to store data for the duration of the testing period. However, prudence dictated that the equipment was checked on a regular basis. In fact a very small leak started from the packing gland of the upper EN probe, dripped down its safety chain, and dripped on the connector of the lower probe. This caused a short circuit and was the cause of the interruption in EN data during the period May 26 through May 29.

Intermittent monitoring also allowed the data being collected to be shared with the workers at ARC and with the staffs of InterCORR and Metal Samples. As there was no pre-existing database to work from, many of the set-up choices were based on experience. Intermittent monitoring afforded the opportunity, if needed, to make adjustments and not miss events we could not control, e.g., some the year's highest tides.

CORROSION TEST RESULTS

CONDUCTIVITY AND FLOW

Data for the influent conductivity and primary effluent flow are included as an attachment, sheets A-1 through A-9. The data is presented as graphs that also include a graph of the tide level and annotation of daily rainfall at SeaTac Airport.

The relationship between tide level and conductivity is clear for all eight weeks included. On days when highest tides are less than about 11 feet, the effect on influent conductivity is small. For example, the week of May 25 and June 22, sheets A-2 and A-6, have relatively low high tides and show limited variation in influent conductivity. The weeks of June 8 and July 6, sheets A-4 and A-8, have higher high tides, and a clear relationship may be seen between the tides and the influent conductivity.

Rainfall can have an impact on conductivity. This is because some storm water flows from combined sewers to the process plant. The rainfall amount that appears just below the clouds is from just one location. County-wide precipitation can vary considerably. For example, look at the week of June 15, sheet A-5. On the 20th and 21st the influent conductivity appears less than what would be expected looking at the tide. Note the large flow peaks on those two days. Following the major conductivity peaks on the 20th and 21st, note that the baseline influent conductivity has also dropped. This is a good example of a case where rainfall dilutes the system influent.

ELECTROCHEMICAL NOISE

Charts showing the EN data are attached as sheets B-1 through B-18. It was possible to keep all the RAS data on consistent scales for the test duration. Unfortunately, that was not possible for the PE corrosion rate data. When reviewing the information, keep track of the changing mils per year (mpy) scale.

The EN data included on these sheets are the corrosion rate, determined through LPR testing, and the pitting factor. The pitting factor is a number from 0 to 1 and refers to the risk for localized corrosion. Following is an approximate guide to its use:

Pitting Factor	Form of Corrosion
0 – 0.1	General Corrosion
0.1 – 0.2	Tendency towards localized corrosion or pitting
>0.2	Localized Corrosion / Pitting Regime

Table 1: Pitting Factor: Corrosion Form

As was the case with the conductivity and flow data, the tide level is included on the charts. Each of these charts covers a calendar week. By breaking the data down on a week time interval, some details are observable that are not easy to see on a plot that covers the full duration of the testing.

PE LINE

For the PE line, the pitting factor remained low throughout the test period. These values typically indicate general corrosion. Through week 4 the PE corrosion rate data shows a response to tidal influence (see sheets B1, B3, B5, B7 and B9). That is, there are spikes in the corrosion rate that follow peaks in tide elevation in a periodic manner. During the week of June 8, these peaks in corrosion rate trailed the peak highest tide elevation by an average of 8:54 hours ± 26 minutes. The corresponding raw sewage influent conductivity peak trailed the peak highest tide elevation by 5:48 hours ± 19 minutes.

Table 2 shows a full test duration plot of the PE line LPR-based corrosion rate and pitting factor. Note the marked drop in the pitting factor and concurrent upswing in the corrosion rate.

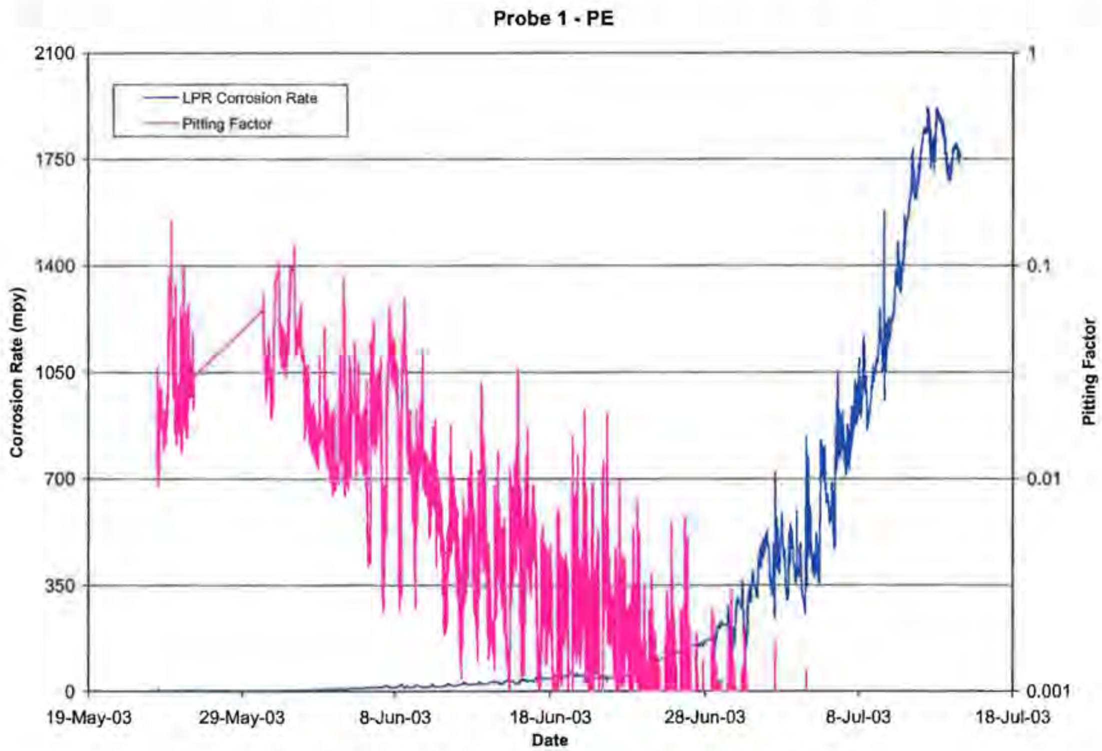

Table 2: PE Line Corrosion Rate and Pitting Factor

The predicted LPR-based corrosion reaches 1800 mpy! This was accompanied by a significant drop in an electrochemical value known as the B value down to 0.5 mV. An expected B value would be about 25 mV, or about 50 times that calculated from EN. The EN corrosion rates were much lower than the LPR-based rates. Also, the electrode potential noise was low. All of this activity occurred on a single probe. This wide composite of activity may be indicative of microbe activity from sulfate reducing bacteria (SRB) and sulfide bridging. Iron sulfides on a steel surface can be involved in cathodic depolarization. The actual corrosion rates, determined gravimetrically at the end of the test, were much lower.

RAS LINE

Table 3 shows a full test duration plot of the LPR-based corrosion rate and pitting factor for the RAS line. The LPR corrosion rate was low, 0.1 to 0.2 mpy, throughout most of the test period. There was a 2 hour spike on June 4 where the LPR-based corrosion rate went to about 10 mpy. Typically the pitting factor remained in the transition zone, where pitting would be unlikely. However, the pitting factor shows periodic spikes into the lower end of the range characteristic of pitting. The cycling averages around 5.5 hours, but varies a good deal. To fully evaluate this behavior would require additional work.

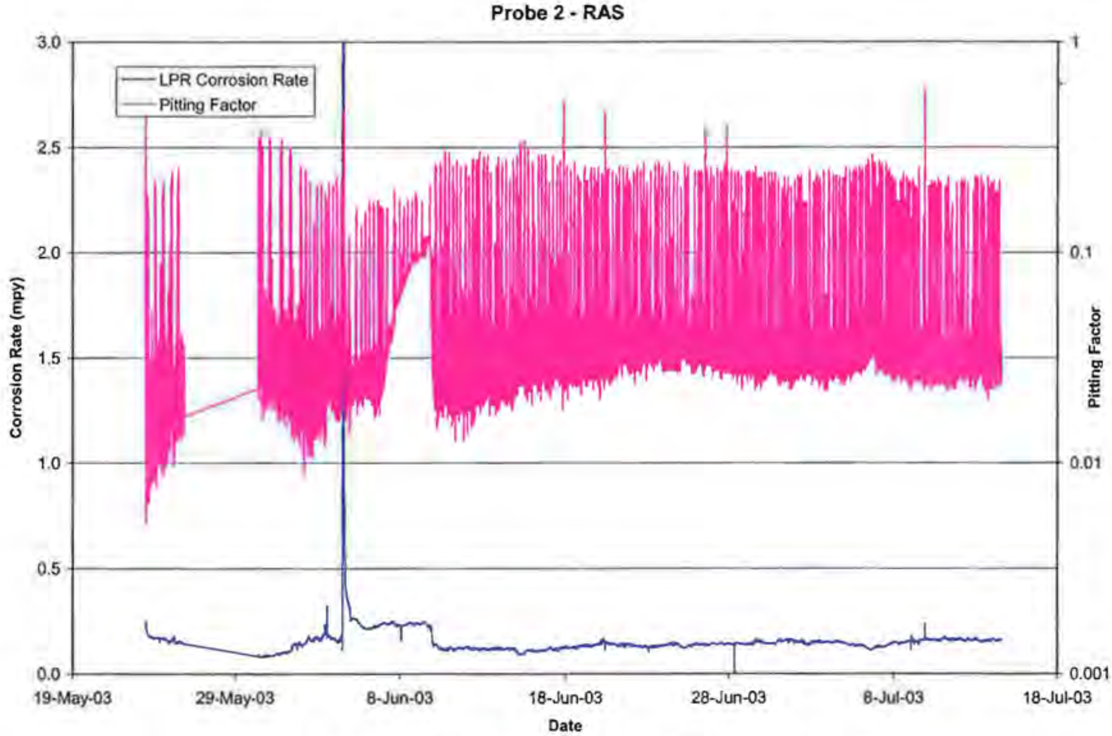

Table 3: RAS Line Corrosion Rate and Pitting Factor

ELECTRICAL RESISTANCE

The ER probe data is shown in the charts C1 through C4. The data shows a relatively consistent corrosion rate of 57 mpy. Although the most sensitive ER probe was selected for use, the response time of the probe is not sufficiently short to pick-up process chemistry variations in real time, and what is observed is an averaged result. When removed, the thin-walled tube in the ER probe was fully corroded and did not show any indication that localized pitting had generated a spuriously high measured corrosion rate. A corrosion rate sustained at that level would penetrate a ¼-inch steel wall in 4.4 years. If we assume the system was in operation from 6.5 years before the failure in December of 2002, the calculated corrosion rate would be 38 mpy. The results obtained with the ER probe are within this general time range.

LINEAR POLARIZATION RESISTANCE

The single function LPR devices installed in West Point and Renton clarifiers both showed similar average corrosion rates. The major difference between the two data sets is the cyclic nature of corrosion activity at West Point. Tables 4 and 5 present the data for the two treatment plants for the same period in late June. Note how the West Point polarization resistance, Rp, cycles trailing peaks in high tide. The data from Renton is a bit more noisy and

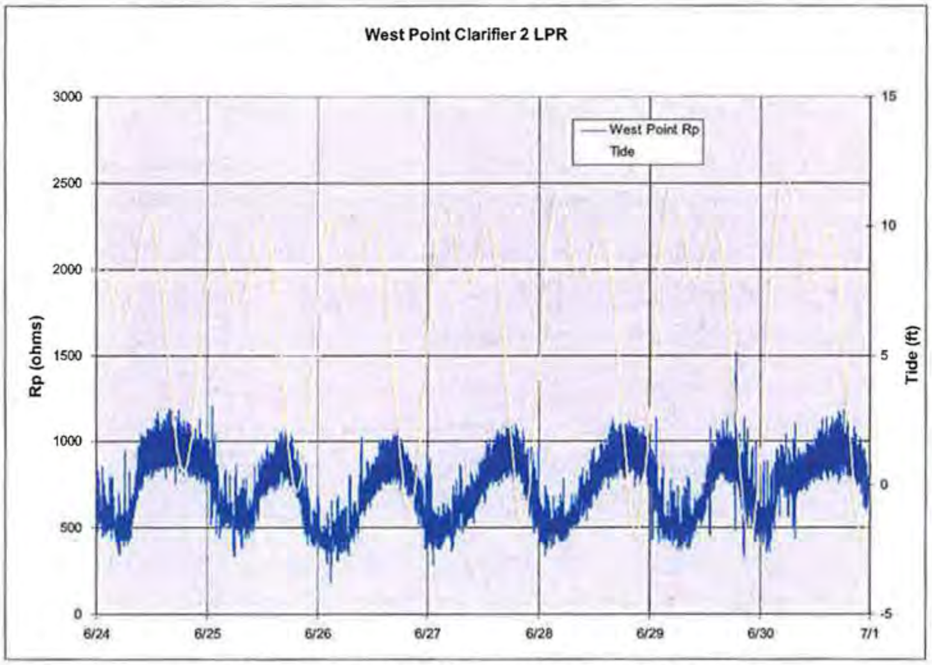

Table 4: West Point Secondary Clarifier LPR

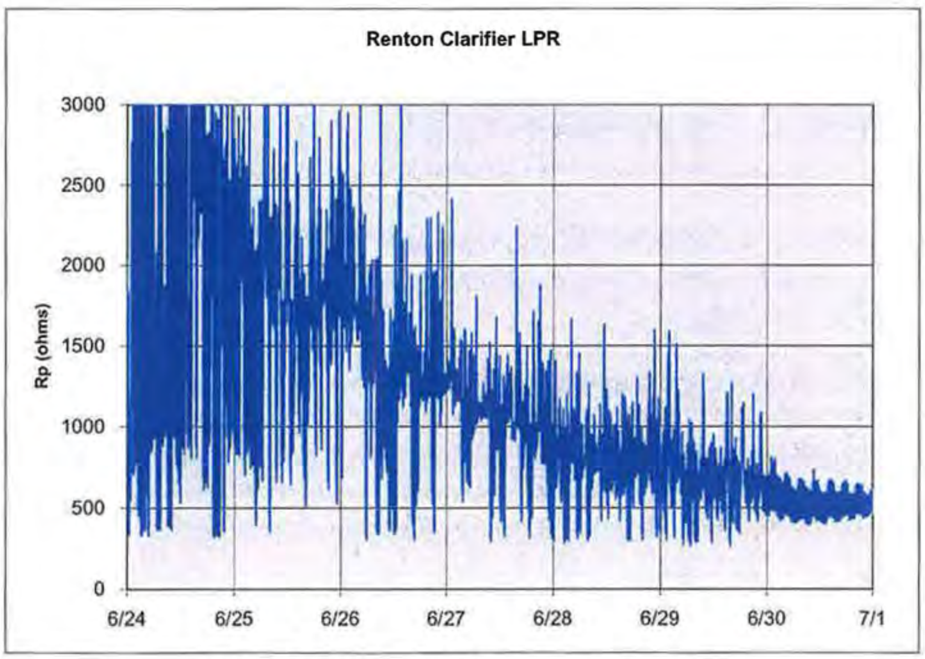

Table 5: Renton Secondary Clarifier LPR

eventually stabilized at around 500 ohms. When the Renton probe was removed shortly after the period shown in Table 5, it was discovered the probe had become fouled and that may be responsible for the decay in Rp and reduction of scatter.

If a B value of 26 mV is assumed, the West Point LPR data shows an average corrosion rate of just under 19 mpy with peaks going to just under 80 mpy. When employing the same assumptions for the Renton data, the average corrosion rate was about 15 mpy and a maximum about half of that at West Point.

ON-LINE GRAB SAMPLES

The Staff at the West Point Treatment Plant obtained grab samples from the PE and RAS lines during the course of this corrosion investigation. The results from some of that testing appears in Table 6. Chloride concentrations greater than 500 ppm (mg/l) are corrosive. Chloride concentrations greater than 1000 ppm are in the range of what are known as saline solutions.

		RAS						PE						Raw Sewage		
		Chloride		Dissolved				Chloride		Dissolved						
Date	Time	Test 1 (mg/l)	Test 2 (mg/l)	Oxygen (mg/l)	Sulfide (mg/l)	pH	Conductivity (mmhos)	Test 1 (mg/l)	Test 2 (mg/l)	Oxygen (mg/l)	Sulfide (mg/l)	pH	Conductivity (mmhos)	Chloride (mg/l)	pH	Conductivity (mmhos)
17-Apr	700	385	340			6.55	1.07									
	1655	505	520			6.54	1.55									
19-Jun	515	285	270	0.0	1.0	6.65	1115	500	485	1.7	0.0	7.10	2160			
17-Jul	200													1295		2690
	502							>170	566	0.1	0.3	6.99	2510			
	1058	385	384	0.0	0.6	6.6	1571									
24-Jul	755													285	7.04	1020
	802	175		0.0	<0.56	6.65	960									
	810							182		0.4	0.1	7.07	1250			

Notes: 1. RAS chloride 1 & 2 are duplicates run on the same sample; same for PE 1 and 2.
2. 17 Jul: 1st PE chloride result (>170) imprecise due to titration overrun, use 2nd result only.
3. 17 Jul: PE sulfide test run on unfiltered sample.

CONCLUSIONS

Following are conclusions than may be drawn from this investigation:

- RAS line piping at the West Point Treatment Plant has failed from corrosion
- PE piping has not yet shown corrosion failure
- Piping at the South Treatment Plant has not suffered similar failures
- No indications of stray current were observed
- The corrosion occurring at West Point is localized corrosion known as pitting
  - Pitting is occurring at holidays in the coal tar epoxy coating
  - Pitting is more concentrated along weld seams
  - Pitting is being aggravated by tide-related chloride ion influx
  - Microbiological influences may also aggravate this corrosion process
- There is blistering of the West Point RAS line interior coating

    - The blistering of the coating is from cathodic disbondment
    - Adjacent pitting activity may accelerate the disbondment process
- It is unlikely that the corrosion damage is limited to the RAS elbows
    - Straight sections of the RAS gallery and buried manifold piping likely are suffering from similar corrosion activity
    - The PE piping is also likely suffering from similar pitting damage
    - From this work, and work performed to correct corrosion damage to rake arms and other secondary clarifiers, it is reasonable to assume that all steel surfaces, coated or not, that come in contact with the West Point process stream are suffering accelerated corrosion; and the high chloride influx is largely responsible.

RECOMMENDATIONS

The recommendations to correct the corrosive conditions at West Point fall into several categories. Some are made to reduce the corrosiveness of the environment. Others are maintenance related, and some are of a preventive maintenance variety.

These recommendations are based on reducing the West Point corrosion. They do not include, nor were they based upon, a thorough cost analysis. For any work of this scale, cost considerations clearly need to be incorporated. Further, some of the recommendations may be beyond the County's area of control.

1) Stop or greatly reduce the tide-related chloride ion influx. Clearly, a significant quantity of seawater enters the West Point Treatment Plant process stream when tides elevations exceed about 11 feet. Chloride ions are extremely corrosive. Given that some of the piping, like the RAS line, run at no or very low oxygen content, and given the inherent microbiological nature of the process stream, many stainless steels would be susceptible to serious pitting with the current chloride ion levels. Given the performance of the piping at the South Treatment Plant, matching that stream's chloride ion content would be a best situation target.

2) Remove, inspect and repair all of the RAS line weld-fabricated elbows that have not been inspected as part of this overall work.

    a. Assume some welding work will be required

    b. While the elbows are removed attempt to inspect adjacent straight, non-welded pipe

    c. During elbow inspection make an inventory of observed pits

        i. Identify the pits by diameter size: small (<0.125"), medium (0.125-0.250") and large (>0.25")

        ii. Identify the pits by depth: shallow (<0.125"), deep (0.125-0.250"), very deep (>0.250")

iii. Identify pits by location; along the flange, along a weld seam, other

iv. The piping inventory should be used to develop a risk model for use in defining the probability of serious damage already existing in areas that are more difficult to access

3) Remove, inspect and repair any similar PE line weld-fabricated elbows. This inspection should follow the protocol outlined above in 2.a through 2.c

4) Install galvanic cathodic protection (CP) throughout the piping network

   a. Given the possibility over-protection may be a problem with magnesium anodes and pure zinc anodes may have biological issues, it is recommended that the anodes be an aluminum-zinc-indium alloy

   b. Given the likelihood of sulfate reducing bacteria, protection of carbon steel may require cathodic polarization shift of 200-300 mV

   c. To avoid being tangled with debris, surface-mounted button anodes should be used

      i. To evaluate the placement and spacing of the anodes, a section of pipe similar to those to be protected should be fabricated (including premium epoxy coating)

      ii. This test section would be suspended from a secondary clarifier walkway at or near the influent well to avoid conflict with rake arm travel

      iii. An anode, or anodes, would be located near the center of the pipe

      iv. Pits could be fabricated by drilling holes in the pipe wall at varying distances from the anode

      v. Micro reference electrodes would be fitted into each pit to monitor polarization

      vi. Monitoring of the system would be done over a period of time to include a good range of system conductivity variation required to define both anode placement and consumption rate

      vii. Final CP system design would derive from a review of pipe steel polarization as a function of distance from the anode

5) Given that internal corrosion damage has occurred, the cathodic protection of all buried steel process piping should be evaluated, upgraded or installed, as is appropriate

6) Prepare an inventory of non-piping metal structures within the Facility and evaluate corrosion implications and control for that property

WEST POINT TREATMENT PLANT

CORROSION FUNDAMENTALS

INTRODUCTION

When a metal suffers from general corrosion, the metal loss is spread relatively uniformly across the exposed surface. Most metals exist in their natural state as oxides, sulfides, carbonates or similar compounds that are often comparable to corrosion products. Iron, present in steel, starts as iron ore that is very similar to rust.

Refining metals typically requires applying a great deal of energy to the ore to convert it to a metal. When these metals are exposed to many environments, they will return to their natural state through the corrosion process. Figures 1a and 1b show this rust to metal to rust cycle.

Figure 1a - Refining

Metals vary in their resistance to corrosion. Among pure metals, gold is often found in metal form in nature. It and similar metals like platinum and silver are called noble metals and are corrosion-resistant.

Some metals, like copper, are sometimes found free in nature and other times found as ore. Other metals are never found as natural metals.

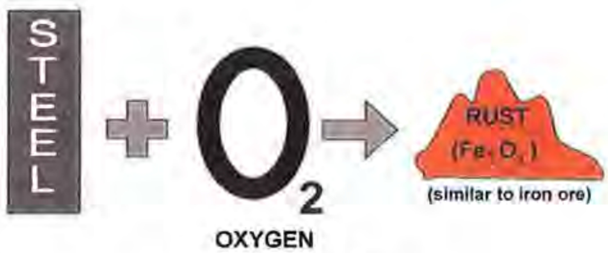

Figure 1b - Rust

CORROSION PRODUCTS

Corrosion products come in many varieties. In Figure 1b, steel is shown reacting with oxygen to form an iron oxide we know as rust. Metals can react with other compounds to form other types of corrosion products. For example, copper reacts with carbon dioxide to form a carbonate. These are green in color and form the beautiful patina we see on copper and its alloys. The corrosion products often contain water as well.

OXIDE LAYERS

When a metal corrodes, the corrosion products form on the surface. Some of these corrosion products are soft materials that are loosely held to the metal surface. Common red rust on steel is of this type. When the corrosion product sloughs-off, the metal surface is exposed to

the environment and continued corrosion is not impeded by something on the surface of the metal.

Some metals form oxides on their surfaces that are tightly held. These layers protect the underlying metal like a high performance paint. Chrome is an example. A thin, clear, tightly adhering oxide protects the underlying metal. This is why chrome bumpers stay shiny. Some very reactive metals, like aluminum, form a very tightly-held oxide layer. We typically consider aluminum to be a non-reactive metal since it has good corrosion resistance. However, the solid fuel in the two rockets strapped to each side of the space shuttle is powdered aluminum. Given the right circumstance aluminum corrodes quite quickly.

Depending on the environment, some metals' corrosion products are protective and some are not. When copper corrodes, the resulting corrosion products include the brown oxide of the common penny to the green and black patinas on statues. Some of these protect, as in the case of the penny. Other times they do not. This was the case with the Statue of Liberty where some of the black patinas did not protect and an extensive restoration was required.

Metals are often alloyed to take advantage of protective corrosion products. In stainless steel, iron provides the strength. Nickel, chromium and molybdenum are added to provide protective corrosion layers to make a steel that stains less.

CORROSION MECHANISMS

GENERAL CORROSION

The corrosion rate for any metal depends on the environment to which it is exposed. Table 1 shows the corrosion rate for mild steel in several environments.

Environment	Corrosion Rate (mpy)
Atmospheric[1]	
Industrial	1-2
Marine	5-40
Submerged - tropical[2]	
Freshwater – year 16	1.8
Saltwater – year 16	2.9

Table 1: Corrosion Rates for Mild Steel.

Temperature, humidity and pollutants all influence atmospheric corrosion. Corrosion of metals immersed in liquids will vary with what the liquid is and what is dissolved in it. Chloride ions, present in seawater, are very corrosive towards steel. This is why, if all other conditions are similar, long-term steel corrosion loss is greater in seawater than it is in

[1] Metals Handbook, ASM, Vol. 1, 9th Ed. p. 720

[2] Ibid, p. 742

freshwater. Generally, acidic conditions, with low pH, are more aggressive to steel than alkaline environments, with a high pH. Finally, corrosion is a process similar to burning. In most cases, oxygen availability plays a significant factor in setting the corrosion rate.

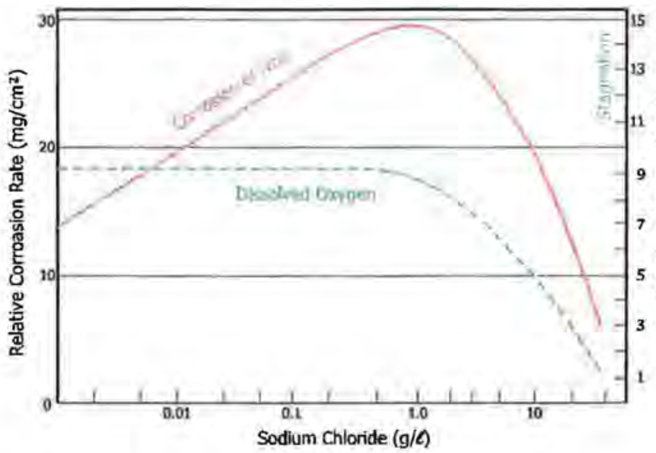

Figure 2

Figure 2 shows how chloride ion concentration and oxygen content affect iron's corrosion rate[3]. Note that after the sodium chloride content reaches approximately 0.8 g/l the dissolved oxygen concentration drops. It is shortly past this point that the corrosion rate for iron, too, begins to fall. This graph is for neutral seawater. If the solution was more acidic or basic, the corrosion rates would change. For more acidic conditions, lower pH, the rates will increase. Conversely, an increase in pH would reduce the rate.

GALVANIC CORROSION

ENERGY HILL

As mentioned earlier, metals are found at different points on the energy hill. Figure 3 shows several metals on the "energy hill."

Note that the noble metals, like gold, are at the top of the hill. Zinc and aluminum are at the bottom of the hill. Steel and copper fall in the middle.

Figure 3

Figure 2 shows the affect of chloride ions and oxygen availability on the corrosion rate of steel. Here in Figure 3, note the different positions held by steel depending on its environmental exposure.

To map hills, a surveyor adds elevation to the two-dimensional data points of northing and easting. The typical units measured are expressed in feet or meters; miles or kilometers. The elevation is given with respect to sea level, the elevation zero. The elevation of a mountain is above sea level, so is positive. The depth of an ocean is below sea level, and is then negative.

[3] Fink, F.W., "Corrosion of Metals in Seawater," U.S. Dept. Interior Office of Saline Water, Report No. 46, (1960).

POTENTIALS AND POTENTIAL DIFFERENCES

In corrosion the elevation of our energy hill in Figure 3 is typically measured in volts. To see where a particular metal is on the energy hill, corrosion engineers measure the metal against a reference cell. For these measurements the reference cell is zero and the metal is some voltage above or below that value. The voltage between a metal and a reference electrode is often referred to as a potential or corrosion potential.

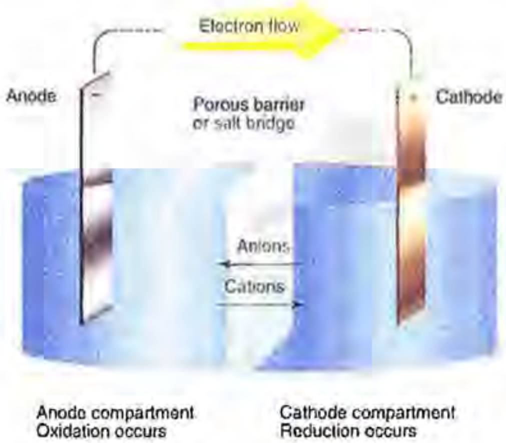

Figure 4

If a steel rod is placed in a glass of saltwater and oxygen is available the steel will corrode. The idea of defining separate anodes and cathodes is not necessary. They can be present together on a single grain of metal. In this example of general corrosion the metal is oxidized and the oxygen is reduced.

If two different metals are connected, two dissimilar metals, a galvanic cell is created. Figure 4 shows a galvanic cell. The anode is the more electronegative of the pair and is where corrosion occurs, through a process known as oxidation. The cathode is the more electropositive of the pair and is where reduction occurs.

Corrosion, however, thrives on differences. If the two dissimilar metals shown in Figure 4 were copper and steel the steel will corrode but at a rate much faster than when it was not coupled with the copper. In the copper-steel couple, the copper is the cathode and the steel is the anode. At the anode, metal dissolves into solution. At the cathode, oxygen is consumed. Electrons pass in the metallic path between the copper and steel to balance the anodic and cathodic reactions.

If instead of copper, you connected zinc to the steel and submerged those two in seawater, the steel would not corrode! In this couple, the zinc is the anode and the steel is the cathode. This is the basis for an approach to control corrosion called cathodic protection. Zinc anodes are installed on steel ship hulls to control corrosion. Steel nails are coated with zinc, a process called galvanizing, to control corrosion.

LOCALIZED CORROSION

With general corrosion, damage is equated to the total amount of metal lost. This may be expressed in terms of thickness lost, for example an expression in mils-per-year; or the mass lost, such as grams/meter^2.

In localized corrosion, loss is typically measured in a penetration rate. A pipe that is still structurally sound, but is leaking because of a pit, is considered failed. The problem with such a pit is not the volume of metal lost, as would be small. The problem was that the loss

was not spread over the entire structure, as in the general corrosion. Rather, the loss was suffered on a small, localized area and hence the term, *localized corrosion*.

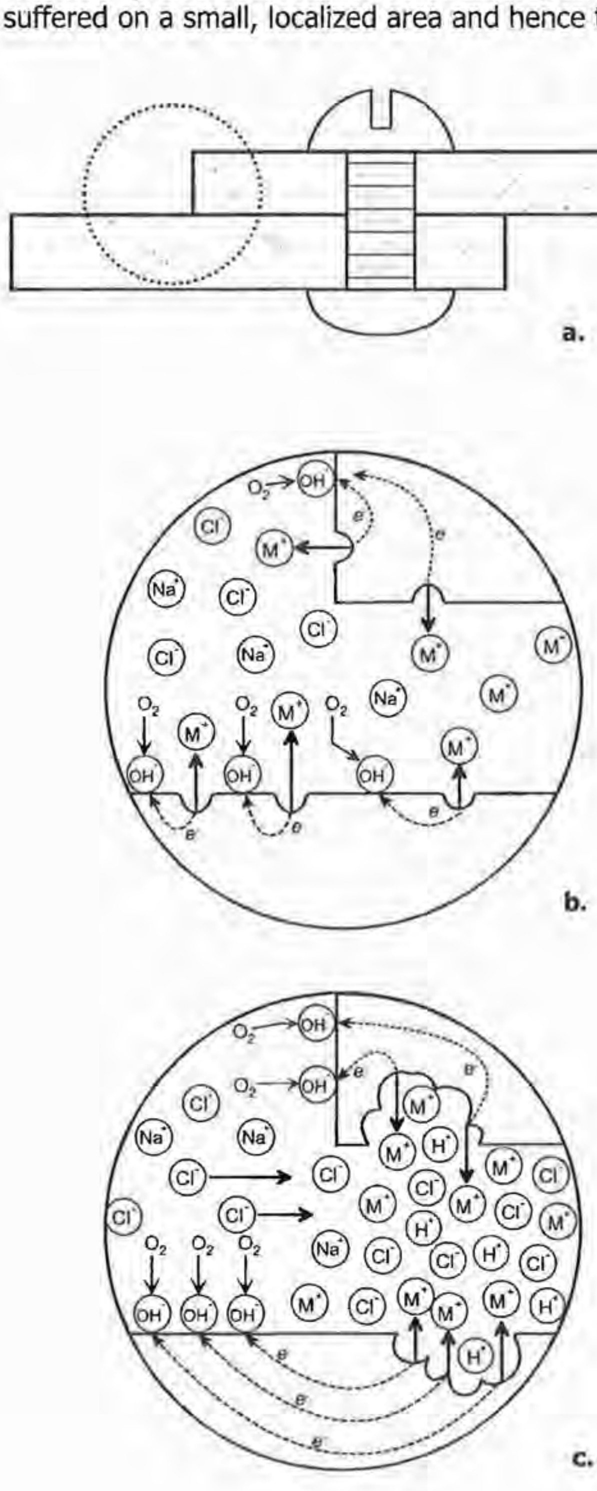

Figure 5

CONCENTRATION CELL

Environmental differences can accelerate corrosion. A typical case is one where one area of a structure has a higher oxygen concentration than another. The area with the higher oxygen concentration will be cathodic to the area with the lower oxygen concentration. The area with limited oxygen will become the anode. As stated before, the anode is where metal dissolves, or corrodes.

For corrosion to proceed, it is not necessary to have distinct anodes and cathodes. In general corrosion, distinguishing anodes from cathodes is difficult at best, and is not necessary to describe the process. In localized corrosion, however, the anodes and cathodes often times are separated, and a better understanding of the processes involved is achieved by discussing the two processes driving the corrosion cell.

CREVICE CORROSION

Crevice corrosion is a type of corrosion attack associated with small volumes of stagnant water often found near holes, gaskets, lap joints, bolts, rivets and even under deposits and other crevice-like areas[4]. The crevice must, at once, be wide enough to allow the transport of corrosion process reactants to and from the corrosion site, yet sufficiently narrow to maintain stagnation in the crevice area (see Figure 5a).

[4] Fontana, M.G. and Greene, N.D., Corrosion Engineering, 2nd Ed., McGraw-Hill, New York, 1978, p.39

Crevices can result from mechanical gaps as shown in Figure 5. They can also occur under disbonded coatings, under insoluble deposits and under microbiological colonies.

Initially the mechanism follows the same process of general corrosion:

Oxidation (anode) $$2M \rightarrow 2M^{+} + 2e^{-} \quad (1)$$

Reduction (cathode) $$\tfrac{1}{2}O_2 + H_2O + 2e^{-} \rightarrow 2OH^{-} \quad (2)$$

As the reaction proceeds, the oxygen within the crevice becomes exhausted. By itself, this is not a problem. As the reaction continues, positive ions will continue to form in the crevice. Because of the absence of oxygen, no negatively charged ions are being produced in the crevice. This will lead to a net positive charge in the crevice solution. Figure 5b shows this early stage for a crevice in a neutral saline solution.

To correct this charge imbalance, negatively charged ions, called anions, migrate into the crevice towards the anode (see Figure 5c). In the figure, chloride ions are shown migrating as they are more mobile than hydroxide ions. The chloride ions can form soluble complexes with iron corrosion products. This helps move the corroded iron away from the reaction site and thereby reduces the development of any protective oxide.

HYDROLYSIS

Note in Figure 5c that some hydrogen ions, H^{+}, are shown. pH is a measurement of hydrogen ion concentration. As the concentration of these ions increases, the pH becomes smaller and the solution more acidic. Iron and steel are more susceptible to corrosion in an acidic environment. The hydrogen ions are formed by the reaction called hydrolysis, or "water breaking." The general form is:

Hydrolysis $$M^{z+} + H_2O \rightarrow M(OH)^{z-1} + H^{+} \quad (3)$$

The metal M reacts with water to form a hydroxide. Also formed is a hydrogen ion.

PITTING

Pitting follows a corrosion process similar to that of the crevice. Pitting is an highly localized form of corrosion that can generate holes in the metal[5]. Pits typically are associated with a breach in a coating that is protecting the metal. That coating can be a protective oxide layer or a barrier coating.

When mild steel corrodes, the process is generally uniform. This form is followed because mild steel often does not form a protective corrosion product on its surface. When stainless steel corrodes, it is usually in the form of pits. This pitting occurs because stainless steel typically does form a protective oxide layer on its surface. If mild steel is coated, however, situations can occur where the corrosion takes the form of pits rather than uniform loss.

[5] Fontana, M.G. and Greene, N.D., Corrosion Engineering, 2nd Ed., McGraw-Hill, New York, 1978, p.48

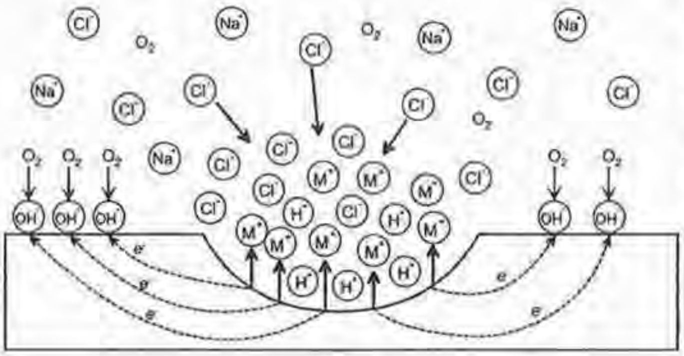

Figure 6

Figure 6 shows the morphology of a typical pit. Note the similarity to the crevice corrosion situation in Figure 5. The areas to the left and right of the pit are cathodic areas. The pit itself is the anode. Again, an excess of positively charged metal ions is balanced by the influx of negatively charged chloride ions. For mild steel, the presence of chloride ions improves the solubility of corrosion products and hydrolysis. The increase in hydrogen ions makes the pit acidic and accelerates corrosion.

COATING SYSTEMS

Coatings are applied to steel to reduce corrosion. Coating systems vary in how this protection is achieved. NACE International, the largest corrosion engineering society, defines a coating system as:

> *The complete number and types of coats applied to a substrate in a predetermined order. (When used in a broader sense, surface preparation, pretreatments, dry film thickness, and manner of application are included.)*

COATING APPLICATION

The performance of any coating is directly related to the quality of the surface preparation. If the surface to be coated is irregular, the coating thickness will tend to be thinner at surface high spots and thicker in valleys. Typically, coatings perform better with some irregularity, called an anchor profile. Surface preparation, such as abrasive blast, often includes a specified anchor profile to afford the coating some "tooth" that improves adherence and long-term performance.

Weld seams introduce a variation in profile. Proper welding technique produces a relatively smooth bead. Slag and splatter from welding can leave the surface adjacent to the weld quite rough and irregular. Construction documents often specify cleaning and removal of slag, splatter and other irregularities before applying the coating system. Even with industry standard welding and surface preparation, it is not unusual that coatings will be thinner along a weld seam.

METAL AND INORGANIC COATINGS

Coatings of metallic and inorganic materials are used to provide corrosion protection. Sometimes these coatings provide sacrificial protection. Hot-dip galvanizing is an example. In other cases, these coatings provide a barrier against corrosive agents and environments. An example of this type of protection is chrome plating on an automobile bumper.

ORGANIC COATINGS

Organic coatings provide a thin barrier between a potentially corrosive environment and the underlying metal. These coatings include water based latex and urethanes, epoxies, vinyl esters and asphaltic based materials. They can incorporate inorganic materials, such as the case with zinc-rich primers.

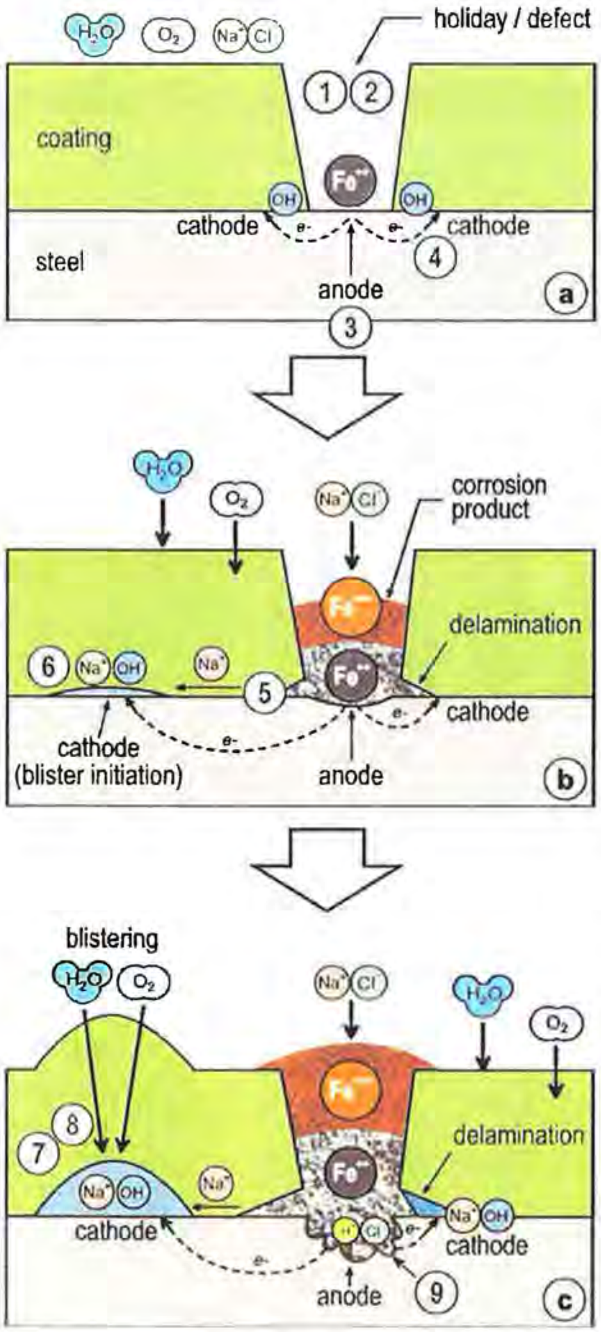

Figure 7

COATING DEGRADATION

Even with proper surface preparation and application, it is not possible to obtain a perfect coating. Small pinholes, known as holidays, will occur. Scratches can also occur, both during construction and during operation. Abrasive material in a process stream can cause wear. Any of these defects can be a path from the environment to the underlying metal.

FAILURE AT A DEFECT

Figure 7 shows coating degradation that occurs as the result of a coating defect. This figure and discussion follows a model developed by staff at the National Institute of Standards and Technology (NIST)[6].

In Figure 7a, step 1 is the formation of the coating defect and step 2 is the transport of water and other reactants, such as oxygen and chloride ions, to the metal surface. Steps 3 and 4 are the formation of the anode (corrosion site) and cathode(s).

In Figure 7b, note that the cathodic reaction is not benign. Here the sodium ion is part of a hydrolysis reaction:

$$\tfrac{1}{2}O_2 + H_2O + 2e^- + 2Na^+ \quad 2(Na^+OH^-) \qquad 4$$

This leads to delamination of the coating.

Sodium ions diffuse along the metal-coating interface, step 5, and initiate blisters at a distance, step 6. This alkaline solution then creates an osmotic pressure gradient (7) the main force behind step 8, blister growth.

[6] Nguyen, T. et al," Unified Model for the Degradation of Coatings on Steel in a Neutral Environment." Journal of Protective Coatings, 68, No. 855, pg 45-56 (1996)

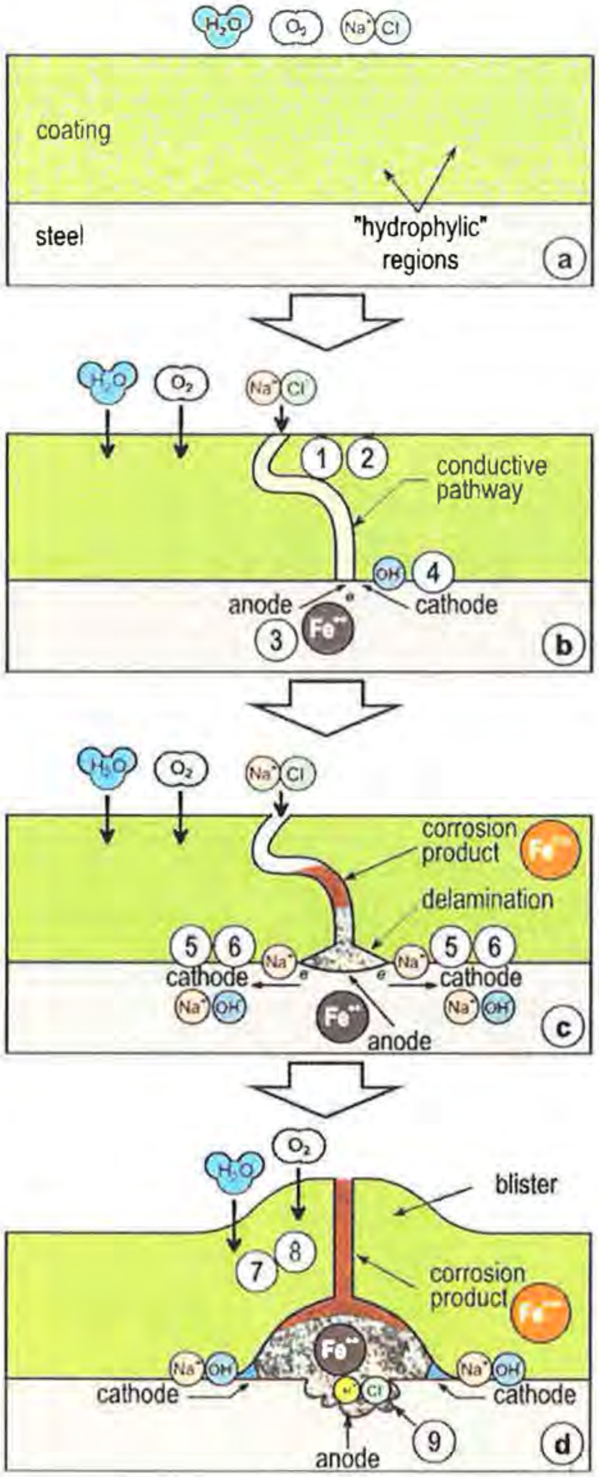

Figure 8

FAILURE WITHOUT A DEFECT

Figure 8 shows the NIST model for coating degradation without a defect. In 8a, the hydrophilic regions are areas with low molecular weight materials that have relatively little cross-linking. As such they can take up water and ions and are subject to hydrolysis. Films made of epoxy, phenolic and phthalate resins show these types of areas.

The hydrolysis and dissolution of the hydrophilic regions eventually lead to the formation of pathways through the coating to the steel surface, see step 1, Figure 8b. As in the case of coatings with a defect, water and reactants reach the steel, step 2; leading to the formation of anodes and cathodes, steps 3 and 4 respectively.

In Figure 8c, again the small and mobile sodium ion diffuses along the steel-coating interface in step 5. Through hydrolysis, step 6, alkaline solutions develop. This leads to delamination of coating adjacent to the conductive pathway.

In Figure 8d, step 7, the alkaline pools generate osmotic pressure gradients that transport water to the reaction site. This inflow of water and expansion due to the formation of corrosion products causes swelling and blister formation in step 8.

HYDROLYSIS

For both, step 9 shows pits forming as the result of hydrolysis. This reaction is aggravated by the presence of chloride ions. As mentioned previously, iron will form soluble complexes with chlorides. This aids in the removal of reaction products from the active site. Hydrolysis also will reduce the local pH.

MICROBIOLOGICALLY INFLUENCED CORROSION (MIC)

Microbes are ubiquitous. Bacteria, fungi, protozoa and algae have all been identified as effecting corrosion. In a wastewater treatment facility, clearly much of the process piping system is exposed to microbes. MIC occurs when microbes influence corrosion[7].

MIC does not generate its own class of corrosion. Rather, the housekeeping and metabolites from microorganisms influence corrosion. The microbes can be planktonic, that is they are dispersed and free to move in or with the process media. The microbes can also be stationary as part of a biological film or sessile colony.

MECHANISMS

Typically MIC occurs with other corrosion mechanisms[7]. Biofims show a preference for rough surfaces and anodic and cathodic sites[8]. Even under lab conditions bacteria do not form biofilms that are uniform[9]. These factors coupled with microbiological issues make MIC an extremely complex phenomenon[8].

Even with that warning, it is helpful to have some understanding of the mechanisms that might be expected in a biologically active environment like a wastewater treatment facility. Following is a brief discussion of several of these mechanisms[10]:

Cathodic Depolarization

This is the classic MIC mechanism and it continues to hold sway as the most important influence on steel and iron although lab work would indicate otherwise. Sulfate reducing bacteria (SRB) would be the culprit.

Formation of an Occluded Concentration Cell

This is where microbes establish colonies on a structure surface. As mentioned before, these colonies may preferentially locate at preexisting rough or anodic sites. The microbes often produce sticky polymers that trap metals and chlorides. Through the metabolism of iron, manganese and oxygen these colonies can aggravate anodic conditions. Through the production of acidic metabolites, the colonies can reduce the pH under the deposit that will accelerate corrosion. Corrosion in these locations can take the form of pits or crevices. Local geometry often will dictate the form.

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[7] Pope, D.H., Morris, A.M., "Some Experiences with Microbiologically Influenced Corrosion of Pipelines" *Materials Performance*, 34, 5 (1995): p. 23

[8] Little, B. and Wagner, P., "Myths Related to Microbiological Influenced Corrosion," *Materials Performance*, 46, 6 (1997): p.40

[9] Little, B. and Ray, R., "A Perspective on Corrosion Inhibition by Biofilms," *Corrosion*, 58, 5 (2002): p. 426

[10] Pope, D.H., Morris, A.M., "Some Experiences with Microbiologically Influenced Corrosion of Pipelines" *Materials Performance*, 34, 5 (1995): p. 24

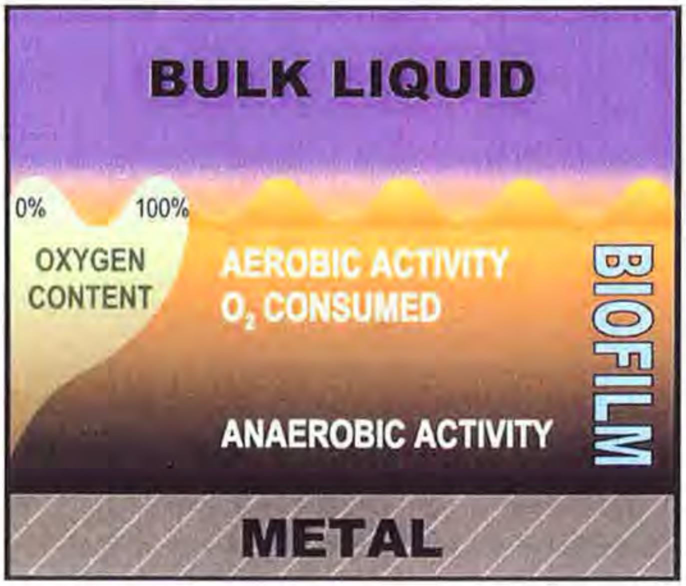


Figure 9

Figure 9 shows a simplified schematic of a biofilm. To the left in the figure is a stylized graph of the oxygen concentration in the biofilm. Note that the concentration is highest near the surface and drops with depth. At the bulk liquid interface, note that the dominate metabolic pathway is aerobic while at the metal surface it is anaerobic. Traditional pitting activity, as is shown in Figures 6-8, can provide iron in solution that iron bacteria can metabolize. As with chloride complexes, this process helps move reaction products from the active site and accelerates corrosion.

WEST POINT TREATMENT PLANT

ELECTROCHEMICAL NOISE

ELECTROCHEMICAL NOISE (EN)

Electrochemical Noise measurements refer to the fluctuations in current or potential that occur on the surface of a metal at the free corrosion potential. Electrochemical Noise arises due to relatively short-term variations in corrosion current and potential, which occur due to the changes in anodic and cathodic areas. The technique was originally developed to detect non-uniform or localized metal loss, such as pitting, crevice corrosion, cavitation damage etc, but may also be used for general corrosion.

A BRIEF HISTORY OF EN TECHNOLOGY

When the technique was first developed (~20 years ago) raw EN current and potential timeseries data (sometimes called Current & Potential Logging) was obtained using complex and expensive computer-controlled instrumentation. This instrumentation worked in a laboratory environment, but was of little practical use for field monitoring. The raw EN data was stored on magnetic disk for time-consuming analysis, and calculation of corrosion rate, often at a later date.

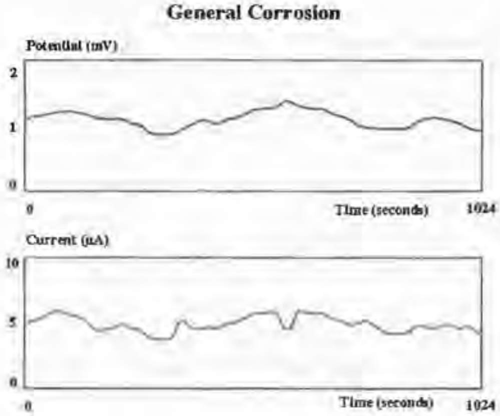
Since both the acquisition and analysis of raw EN data was difficult (and costly in time), the EN technique was regarded by many in the corrosion field as little more than a 'squiggly-line' technological curiosity. This hindered the use and widespread acceptance of EN-based online corrosion monitoring technology, in troubleshooting and proactive corrosion control applications, for many years.

However, for completeness and in order to give an insight into the background of the technique, a number of schematized raw EN timeseries data traces representing a range of typical corrosion conditions are briefly considered below.

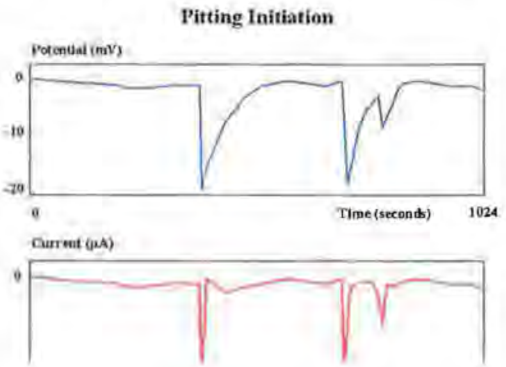
GENERAL CORROSION

When general corrosion is occurring on the metal surface, the electrochemical noise has a smooth appearance and also a smooth statistical distribution. This is because there are a relatively large number of small anodic and cathodic sites distributed evenly across the metal surface.

General Corrosion



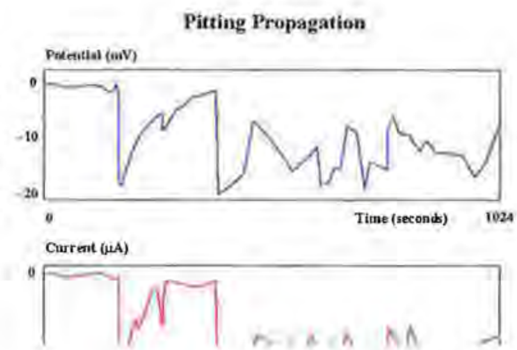
PITTING INITIATION



When a small number of pits begin to form on the metal surface (initiation), but few of these pits continue to grow (known as propagation), the traces start to have occasional 'glitches'. These glitches are associated with a small number of short-lived pits, and change the otherwise smooth statistical distribution of the data. The potential glitches can vary in amplitude, from a few milliVolts to hundreds of milliVolts, depending on the metal or alloy being studied.

PITTING PROPAGATION

When the average pit lifetime increases then the number of propagating pits present on the metal surface, at any moment in time, also increases. This results in an increase in the amplitude of both the potential and current noise traces, and further changes in the statistical distribution of the data.



MODERN EN TECHNOLOGY

Today, the EN technique has moved on from the study of these raw timeseries data, which required time-consuming post-acquisition analysis to be carried out by skilled corrosion scientists or electrochemists. In fact, with improved analysis these data series are not available as outputs from **FieldCET™** and hence cannot be stored or displayed in the InterCorr software package.

Advanced statistical data analysis techniques have been integrated into the **FieldCET™** unit allowing the data to be processed continuously online, and the corrosion rates to be output directly in mils-per-year (or millimeters per year) to the online corrosion monitoring displays.

STATISTICAL DATA ANALYSIS

For general corrosion it is possible to relate the Potential Noise and Current Noise mathematically and calculate the Noise Resistance (the polarization resistance derived from EN) for the system. This can then be related to the general (uniform) corrosion rate.

Further statistical analysis is made on the EN data, and statistical parameters known as skewness and kurtosis (measures of the symmetry of the current and potential fluctuations) are calculated. These parameters can be used to identify localized corrosion and produce an estimate of the rate at which it occurs.

The electrochemical noise arising from general corrosion has a relatively smooth (Gaussian) statistical distribution with little, or no, skewness, since the anodic and cathodic processes are relatively uniformly distributed across the metal surface. By comparison, localized attack is not uniform and in the short term will show symptoms of a skewed statistical distribution. Similarly the kurtosis may be used to identify periods of "glitchy" behavior which arises during, for example, pitting. This tends to lead to high values of kurtosis indicating a very "peaky" statistical distribution in comparison to general corrosion where the kurtosis value is relatively low.

The Noise Resistance, R_n is defined as the ratio of the standard deviation of the electrochemical noise potential signals to the standard deviation of the electrochemical noise current signals. These signals are generated spontaneously by corroding electrodes in the probe.

$$R_n = V_n / I_n$$

The general corrosion current (I_{corr}) is obtained from the Stern-Geary approximation.

$$I_{corr} = \beta / R_n,$$

Where β = Stern-Geary constant (see section below).

LIMITATIONS OF THE TECHNIQUE:

- EN will not work in very low conductivity environments unless probe design is optimized in terms of electrode area and separation (typically large electrode area, close together). For example alternator stator cooling water - extremely pure water with close to theoretical resistivity. Measuring stress corrosion crack activity occurring within a compact tension specimen is problematical because it is difficult to get the counter electrode close to the active surface.
- EN measurements are complicated when a lot of redox reactions are occurring in the environment, e.g. stainless steel in the alkaline permanganate solutions typically used in nuclear decontamination. This is also true of other electrochemical techniques such as AC impedance or LPR. Often all that can be measured is high noise from the relatively fast redox reactions occurring on the surface.
- At very low corrosion rates (low levels of potential and current noise), instrumentation noise becomes a factor and artificially high corrosion rates may be indicated.

ENVIRONMENTS IN WHICH EN TECHNIQUE PERFORMS WELL:

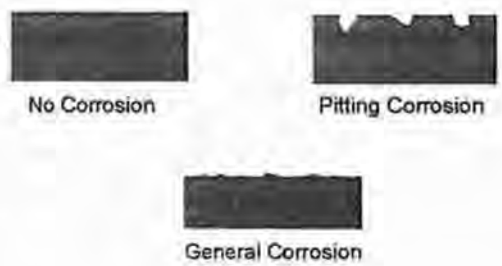
- Mixed phase
- Hydrocarbon/water condensate
- Aqueous/conductive
- Low Conductivity environments (Solution Resistance R_s>10,000 ohms)

SUMMARY OF EN

- Measures spontaneous fluctuations in potential and current at free corrosion potential
- Calculate Noise Resistance, $R_n = V_n/I_n$
- Assess if corrosion is general or localized
- General Corrosion Rate $\propto$ Icorr
- Sensitivity typically 0.001-0.01 mm/year (0.04-0.4 mpy)

PITTING FACTOR

Diagrammatic Representation of Pitting



The Pitting Factor (PF) is derived from the electrochemical noise data, and the harmonic data. It refers to the risk of localized attack (pitting) on the metal surface, and is always examined together with corrosion rate.

The calculation for Pitting Factor (PF) is as follows:

PF =

(ECN) / (A*IHM)

Where: ECN = Electrochemical Current Noise
A = Electrode Surface Area
IHM = Corrosion Current from Harmonic Distortion Analysis

Pitting is a form of localized attack that results in holes in the metal. Pits can be close together or isolated, and pits may be large or small in diameter. Pitting is the most destructive form of corrosion because it causes metal to fail with only a small percent weight loss, and it is often difficult to detect. Pitting is particularly dangerous because it is localized and failures can occur with extreme suddenness.

The Pitting Factor is a value between 0 and 1. As the value approaches 1, the system will be in a pitting regime rather than a regime of general corrosion. When the Pitting Factor is greater than or equal to 0.1 then pitting may occur on the metal surface. As a rough guide the following may be assumed:

Pitting Factor	Form of Corrosion
0 – 0.1	General Corrosion
0.1 – 0.2	Tendency towards localized corrosion or pitting
>0.2	Localized Corrosion / Pitting Regime

These numbers are for rough indications only and will depend on the individual system. If in doubt, a corrosion engineer should be consulted for advice.

HARMONIC DISTORTION ANALYSIS (HDA)

Harmonic distortion is a measure of the non-linear current distortion arising during the LPR measurement. The data is analyzed (using Fast Fourier Transform analysis) to provide a measure of the corrosion current, and to provide an on-line estimate of the corrosion rate calculation (Stern-Geary) constant.

Harmonic analysis measurements will become unstable under pitting corrosion conditions (or other localized attack). However, this phenomenon together with an increase in the Pitting Factor can be used to alert the operator to pitting of the metal surface. General corrosion rate estimates will tend to be inaccurate under pitting conditions.

LIMITATIONS OF THE TECHNIQUE:

- Harmonic analysis measurements become unstable under pitting corrosion conditions (localized attack).

ENVIRONMENTS IN WHICH TECHNIQUE PERFORMS WELL:

- Aqueous/conductive

SUMMARY OF HDA

- Polarize metal/solution interface with low voltage(~25 mV) sine wave signal of frequency ω, measure current response at frequencies 1ω, 2ω, and 3ω
- Calculate Icorr, and Tafel coefficients
- General Corrosion Rate $\propto$ Icorr
- Sensitivity typically 0.001-0.01 mm/year (0.04-0.4 mpy)

STERN-GEARY CONSTANT (B VALUE)

The Stern-Geary Constant, also know as the B value, is the Corrosion Rate constant used in the following formula:

$$\textbf{Corrosion Rate, mpy} = \frac{\mathbf{B} \times \mathbf{N} \times \mathbf{365.25} \times \mathbf{24} \times \mathbf{3600} \times \mathbf{10} \times \mathbf{39.37}}{\mathbf{R_n} \times \mathbf{96500} \times \mathbf{2} \times \rho \times \mathbf{A}}$$

Where:

R_n (or R_p) = Electrochemical noise (Polarization) Resistance
ρ = Alloy density (g/cm^3)
A = Electrode area (cm^2)
N = Atomic weight
B = Stern-Geary constant (mV)

The Stern-Geary Constant is calculated from the Harmonic Distortion Analysis data. As can be seen from the equation above, the corrosion rate is directly proportional to the Stern-Geary constant. Therefore, it is essential that an accurate value be employed in order to obtain an accurate corrosion rate.

A value of 30mV is generally regarded as the engineering standard value for the Stern-Geary constant. However, in reality this value will change with process composition and with different metals or alloys.

All other commercial instruments using electrochemical measurements assume a constant, unvarying value for B. Their instrumental factor will not change with changes in the corrosive environment, as occurs when a process upset causes a corrosion excursion in a plant.

LINEAR POLARIZATION RESISTANCE (LPR)

Stern and Geary noted that the voltage-current response of a corroding electrode is almost linear over a small range of potentials either side of the free corrosion potential. The **FieldCET™** LPR implementation involves the in-phase measurement of the current response to a small amplitude (~25mV) sinusoidal polarization of the electrodes under potentiostatic control. The polarization resistance, $R_{p,}$ is then calculated from 100 pairs of data points using Fourier transform techniques. This approach results in a high instrumental resolution and also has the benefit of giving the device extremely good rejection of external sources of interference e.g. from plant equipment.

LIMITATIONS OF THE TECHNIQUE:

- Corrosion rates values are calculated from LPR but the scientific basis of the technique assumes a steady state condition in which all estimates relate to the likelihood of uniform or general corrosion. Thus, the LPR technique is incapable of providing localized corrosion information.
- Tests performed in low conductivity electrolytes can give erroneous results if the electrolyte resistance is not considered when using two electrode probes.

- LPR results should always be compared with another corrosion rate measurement to ensure accuracy of the technique and suitability for a particular environment
- LPR can under-estimate low corrosion rates.

ENVIRONMENTS IN WHICH TECHNIQUE PERFORMS WELL:

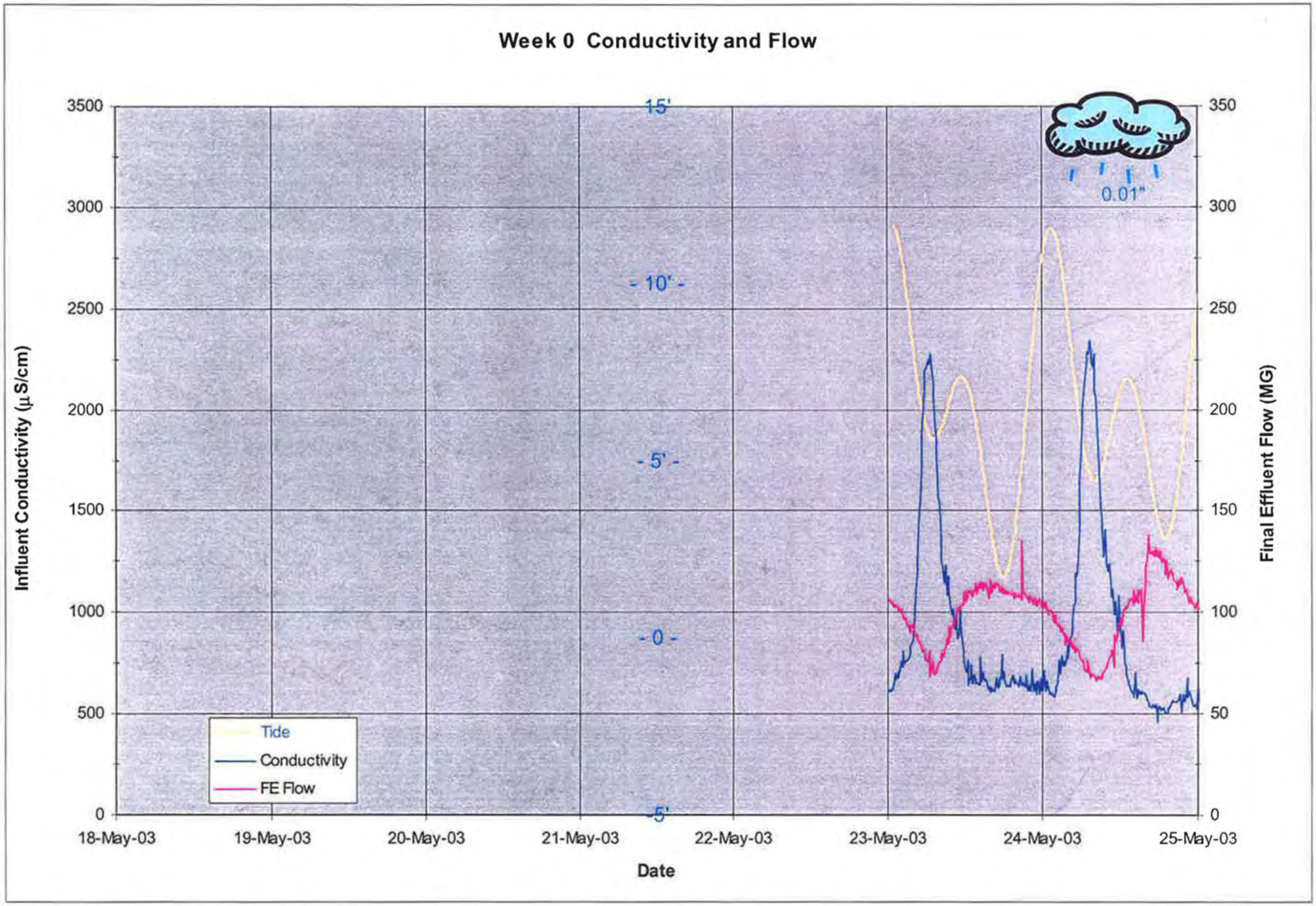
- Aqueous/conductive

SUMMARY OF LPR

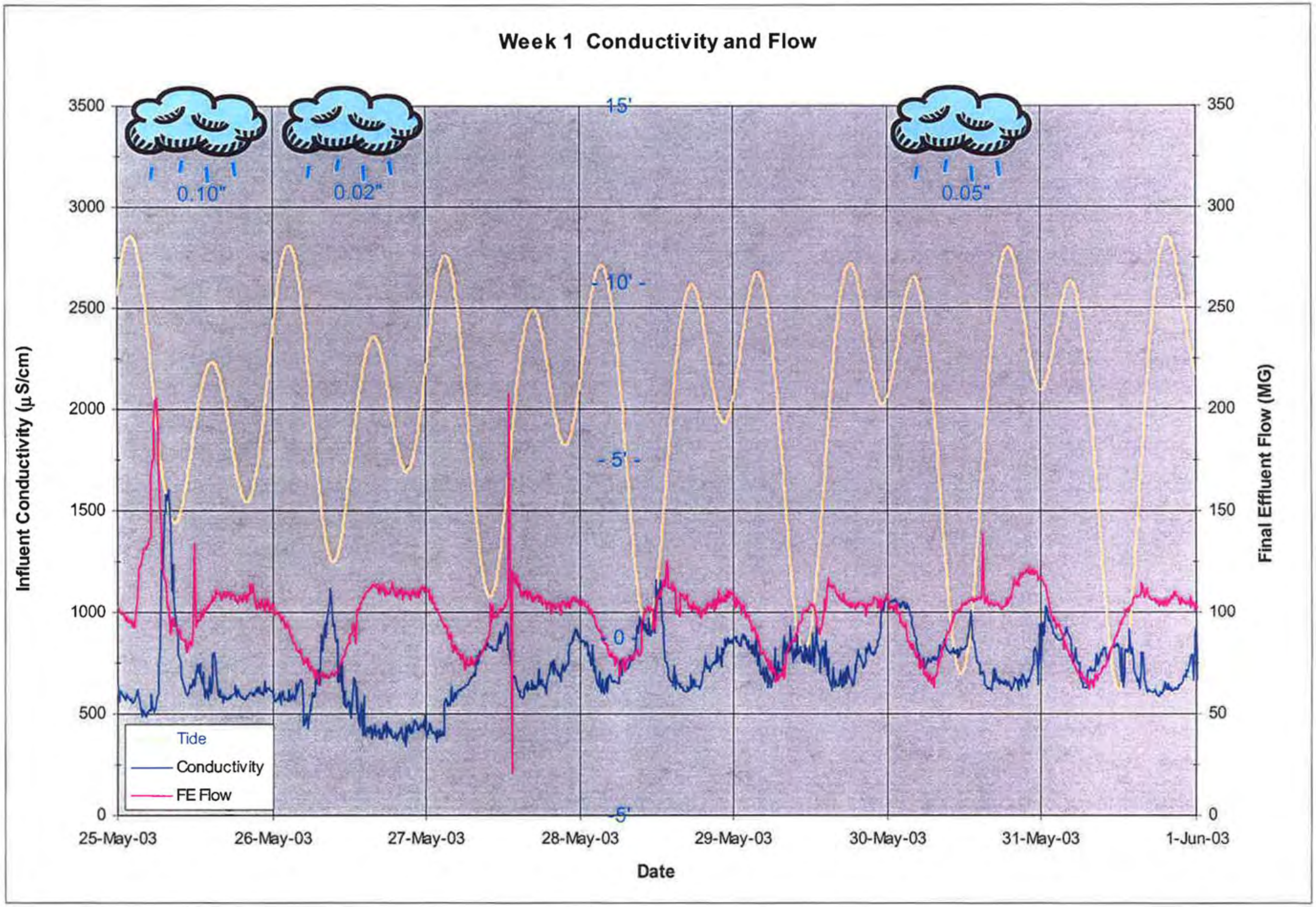
- Polarize metal/solution interface with low voltage (~25 mV) signal, measure current response
- Polarization resistance $Rp = \Delta V/ \Delta I$
- General Corrosion Rate $\propto 1/Rp$
- Sensitivity typically 0.001-0.01 mm/year (0.04-0.4 mpy)

COMPARISON OF ELECTROCHEMICAL MONITORING TECHNIQUES

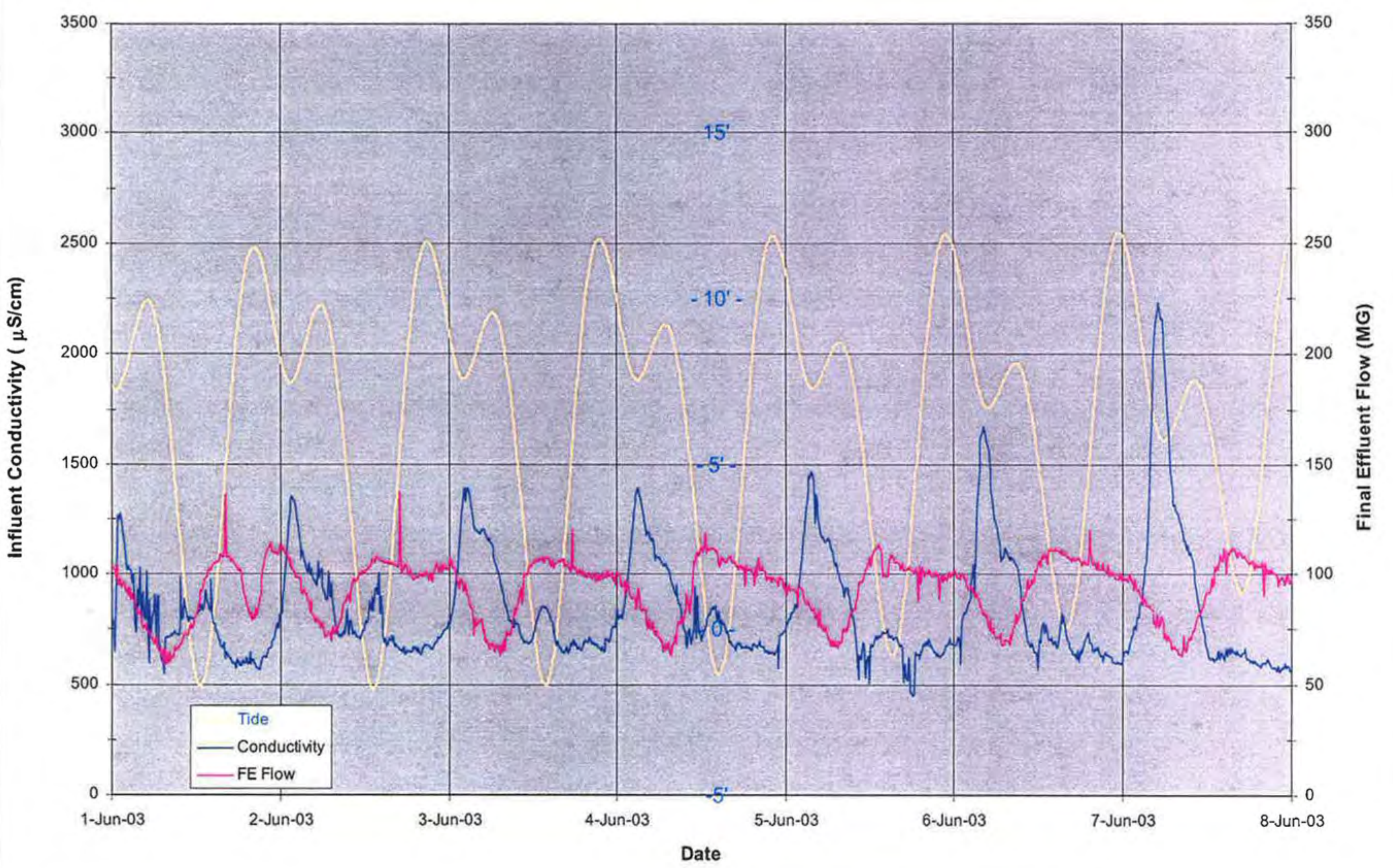
	LPR	HDA	EN
Can Identify General Corrosion?	Yes	Yes	Yes
Can Identify Localized Corrosion?	No	Unknown	Yes
Sensitivity	0.001-0.01 mm/year (0.04-0.4 mpy)	0.001-0.01 mm/year (0.04-0.4 mpy)	0.001-0.01 mm/year (0.04-0.4 mpy)
Response time @40mpy	2-10 minutes	2-10 minutes	5-10 minutes
Response time @0.4mpy	2-10 minutes	2-10 minutes	5-10 minutes
Electrode surface area	Low rates >=5cm^2 High rates <=1cm^2	Low rates >=5cm^2 High rates <=1cm^2	Low rates >=5cm^2 High rates <=1cm^2

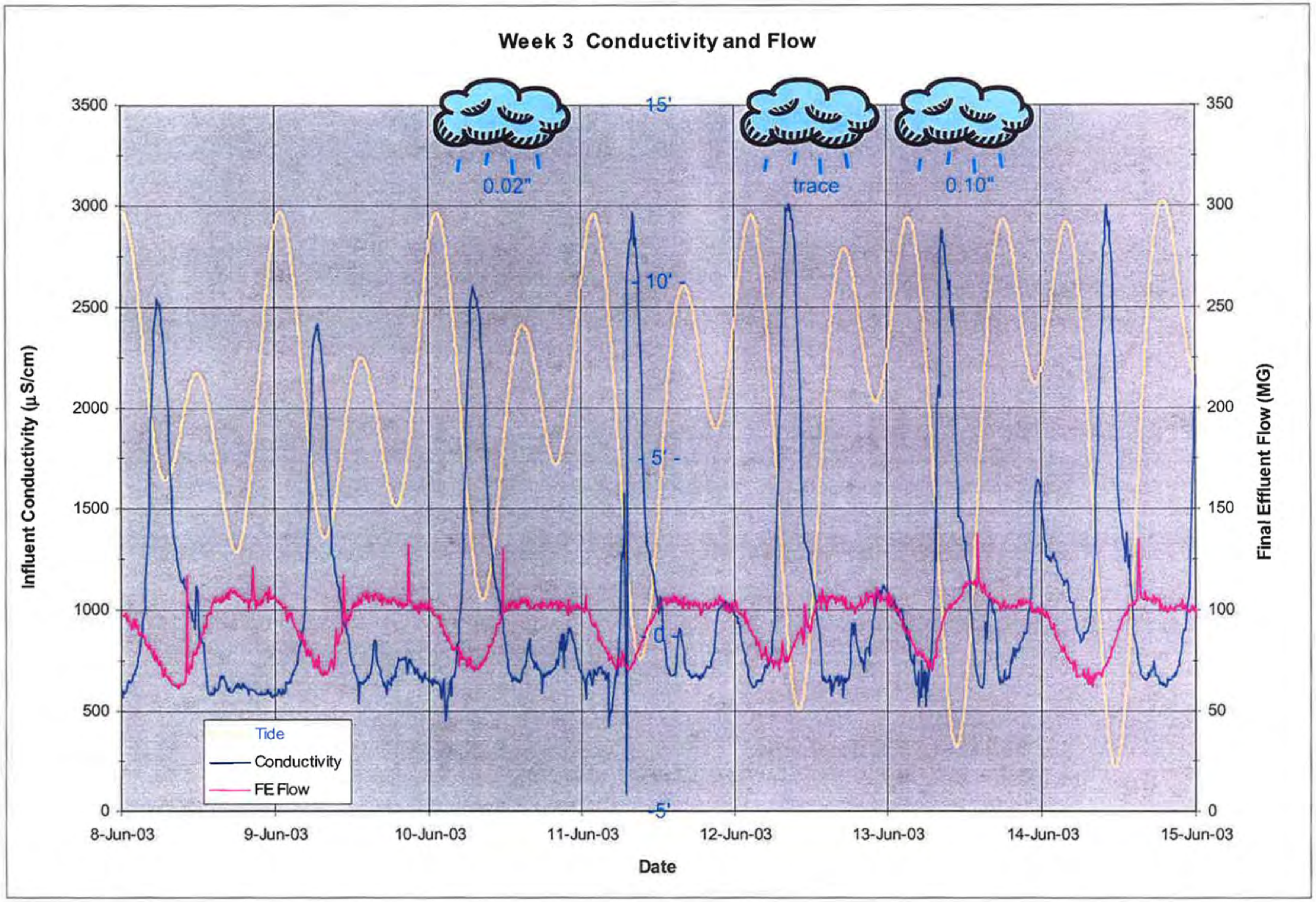


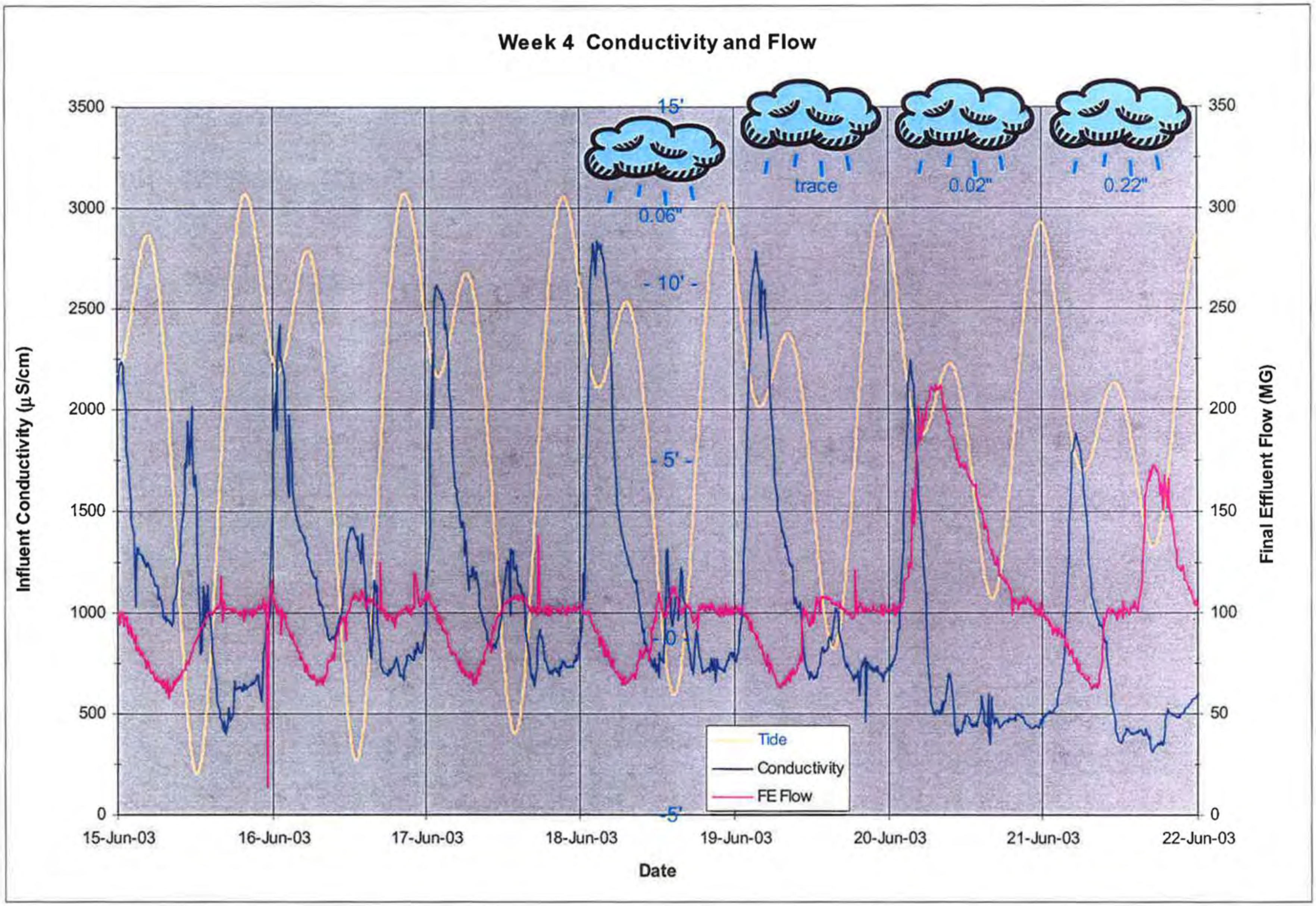
Week 0 Conductivity and Flow
3500
3000
2500
2000
1500
1000
500
0
Influent Conductivity (µS/cm)
350
300
250
200
150
100
50
0
Final Effluent Flow (MG)
15'
- 10' -
- 5' -
- 0 -
-5'
0.01"
Tide
Conductivity
FE Flow
18-May-03
19-May-03
20-May-03
21-May-03
22-May-03
23-May-03
24-May-03
25-May-03
Date

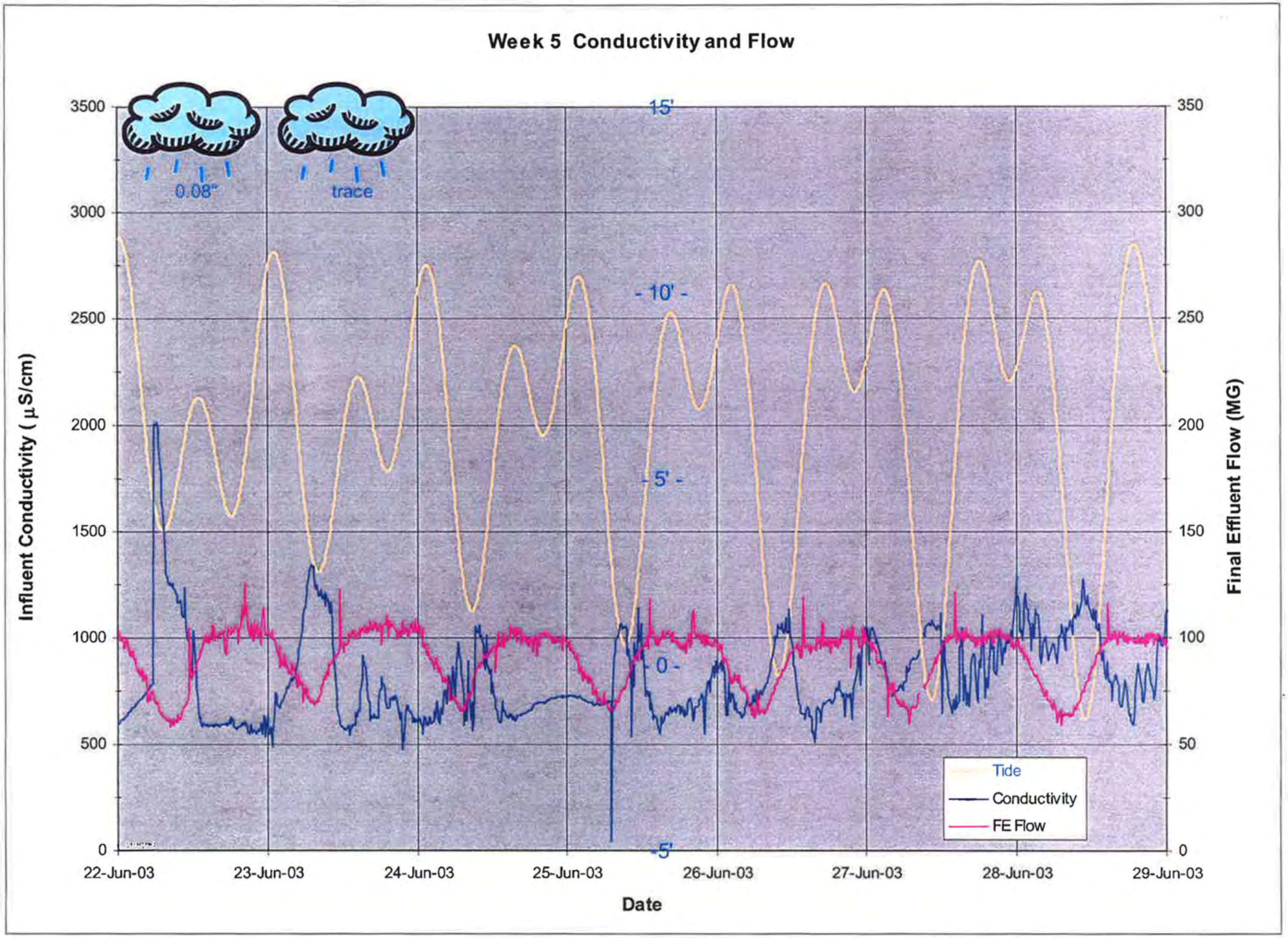

Week 1 Conductivity and Flow
Influent Conductivity (µS/cm)
3500
3000
2500
2000
1500
1000
500
0
Final Effluent Flow (MG)
350
300
250
200
150
100
50
0
15'
10'
5'
0
-5'
0.10"
0.02"
0.05"
25-May-03
26-May-03
27-May-03
28-May-03
29-May-03
30-May-03
31-May-03
1-Jun-03
Date
Tide
Conductivity
FE Flow

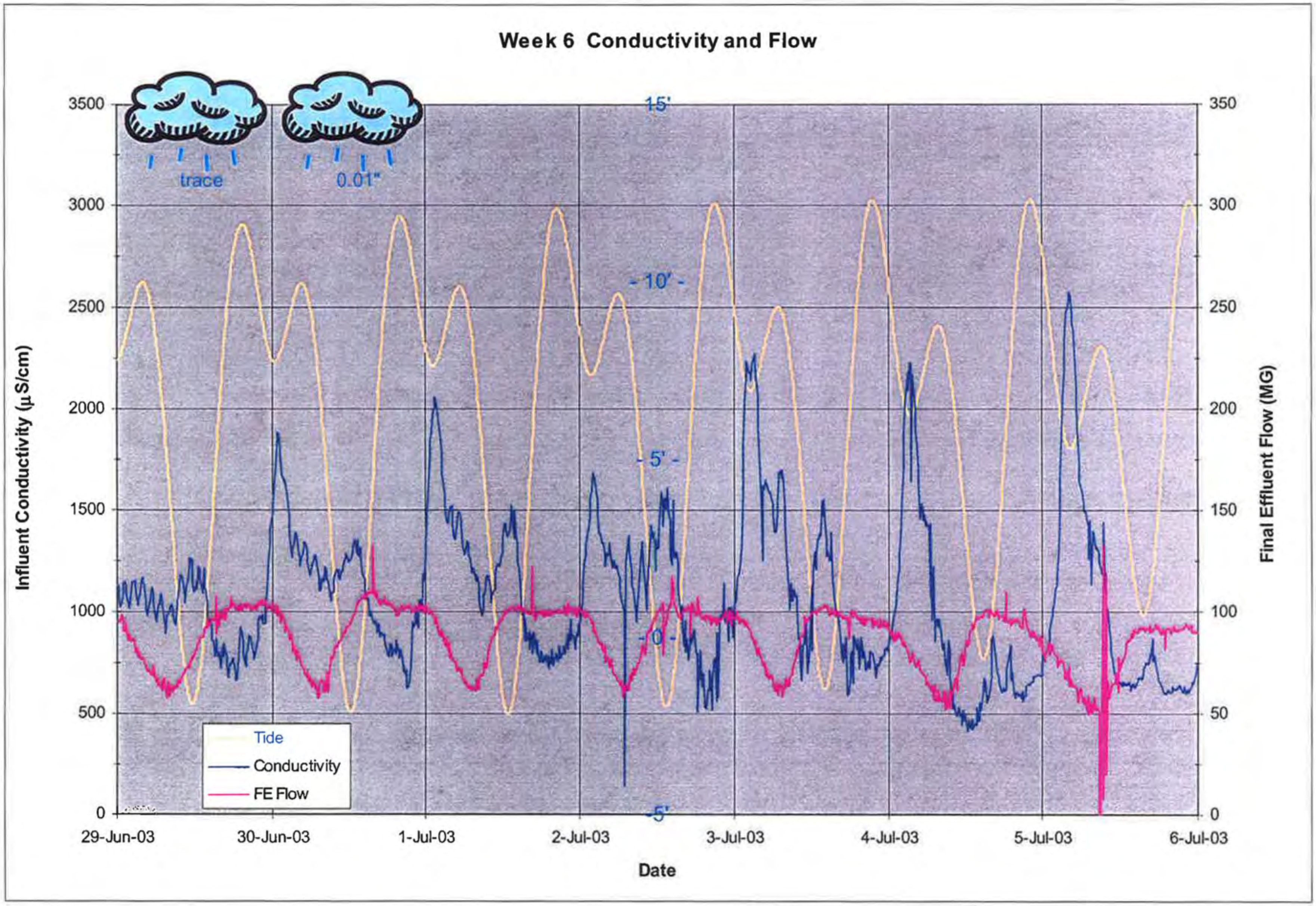
Week 2 Conductivity and Flow

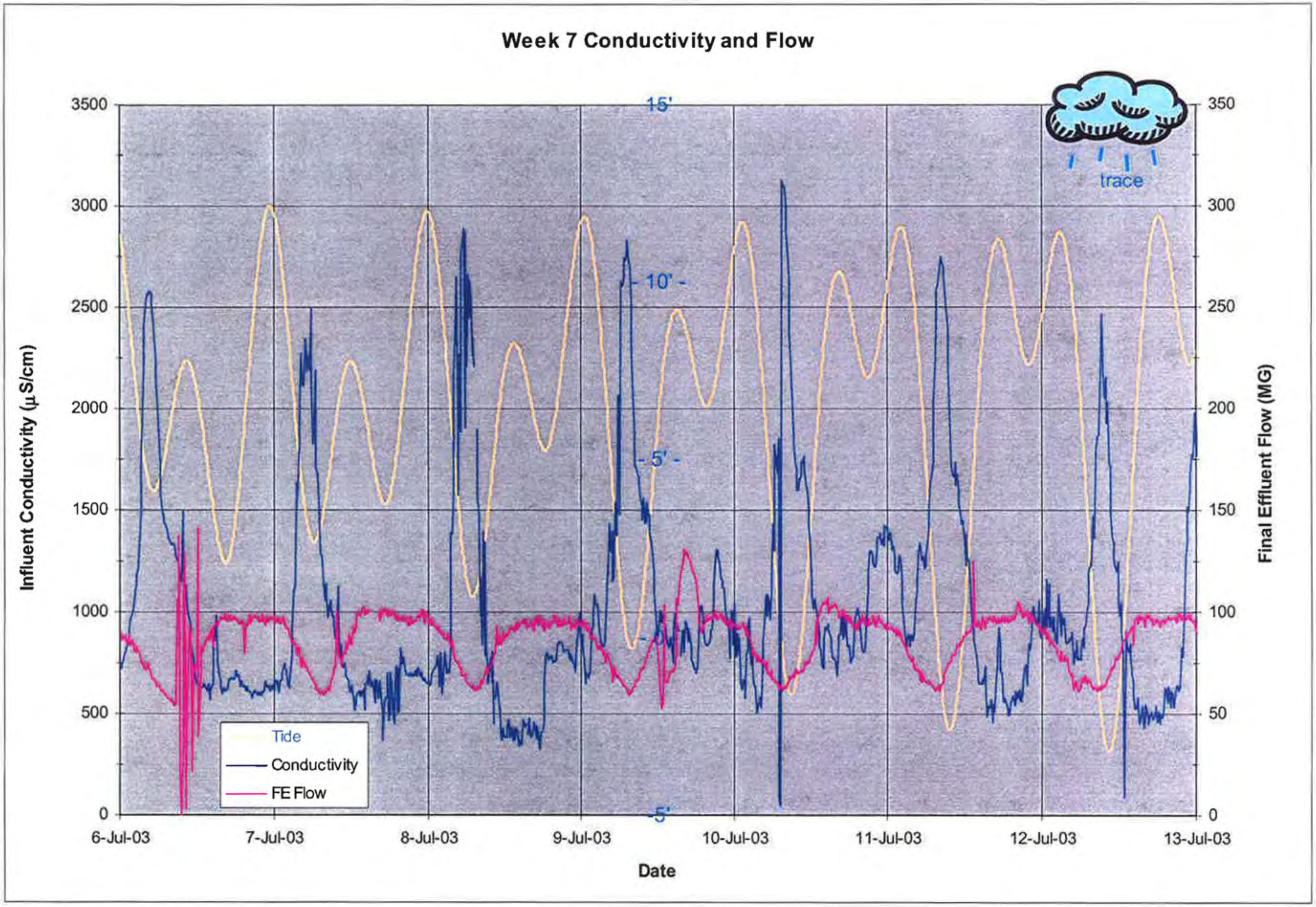


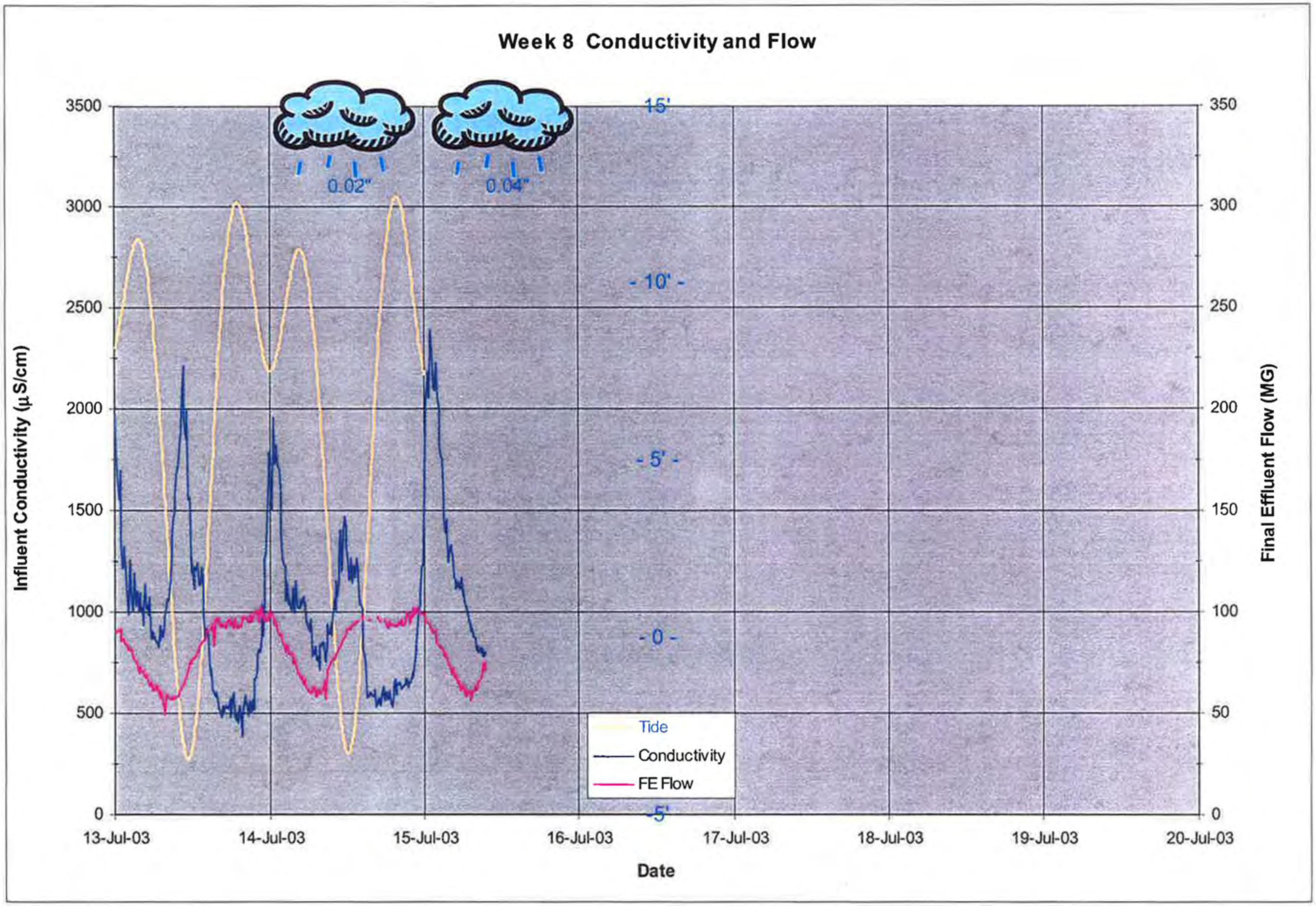

Week 3 Conductivity and Flow
0.02"
trace
0.10"
15'
10'
5'
0
-5'
Influent Conductivity (μS/cm)
3500
3000
2500
2000
1500
1000
500
0
Final Effluent Flow (MG)
350
300
250
200
150
100
50
0
8-Jun-03
9-Jun-03
10-Jun-03
11-Jun-03
12-Jun-03
13-Jun-03
14-Jun-03
15-Jun-03
Date
Tide
Conductivity
FE Flow

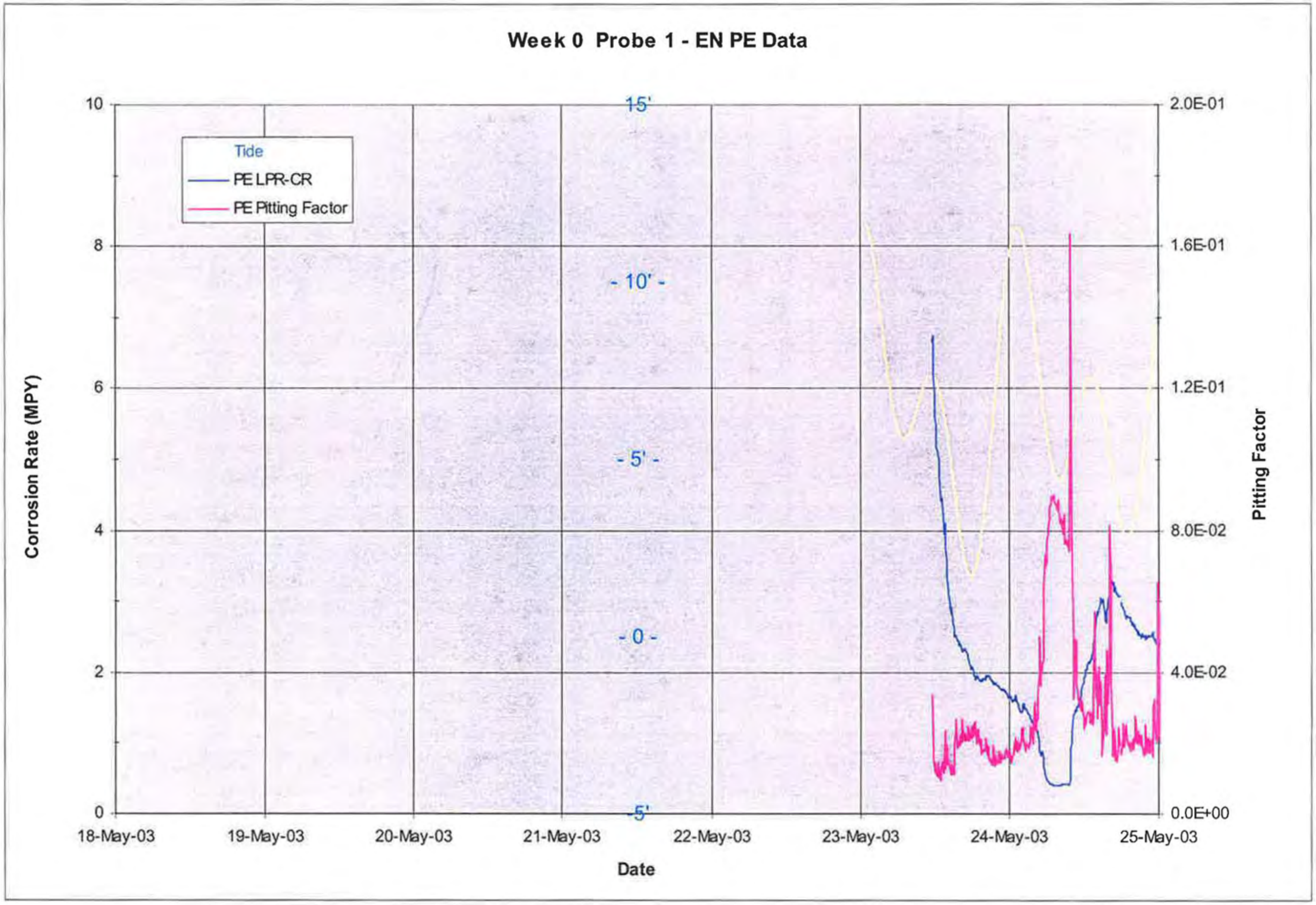

Week 4 Conductivity and Flow
Influent Conductivity (µS/cm)
Final Effluent Flow (MG)
Date
15-Jun-03
16-Jun-03
17-Jun-03
18-Jun-03
19-Jun-03
20-Jun-03
21-Jun-03
22-Jun-03
0.06"
trace
0.02"
0.22"
15'
10'
5'
0
-5'
Tide
Conductivity
FE Flow

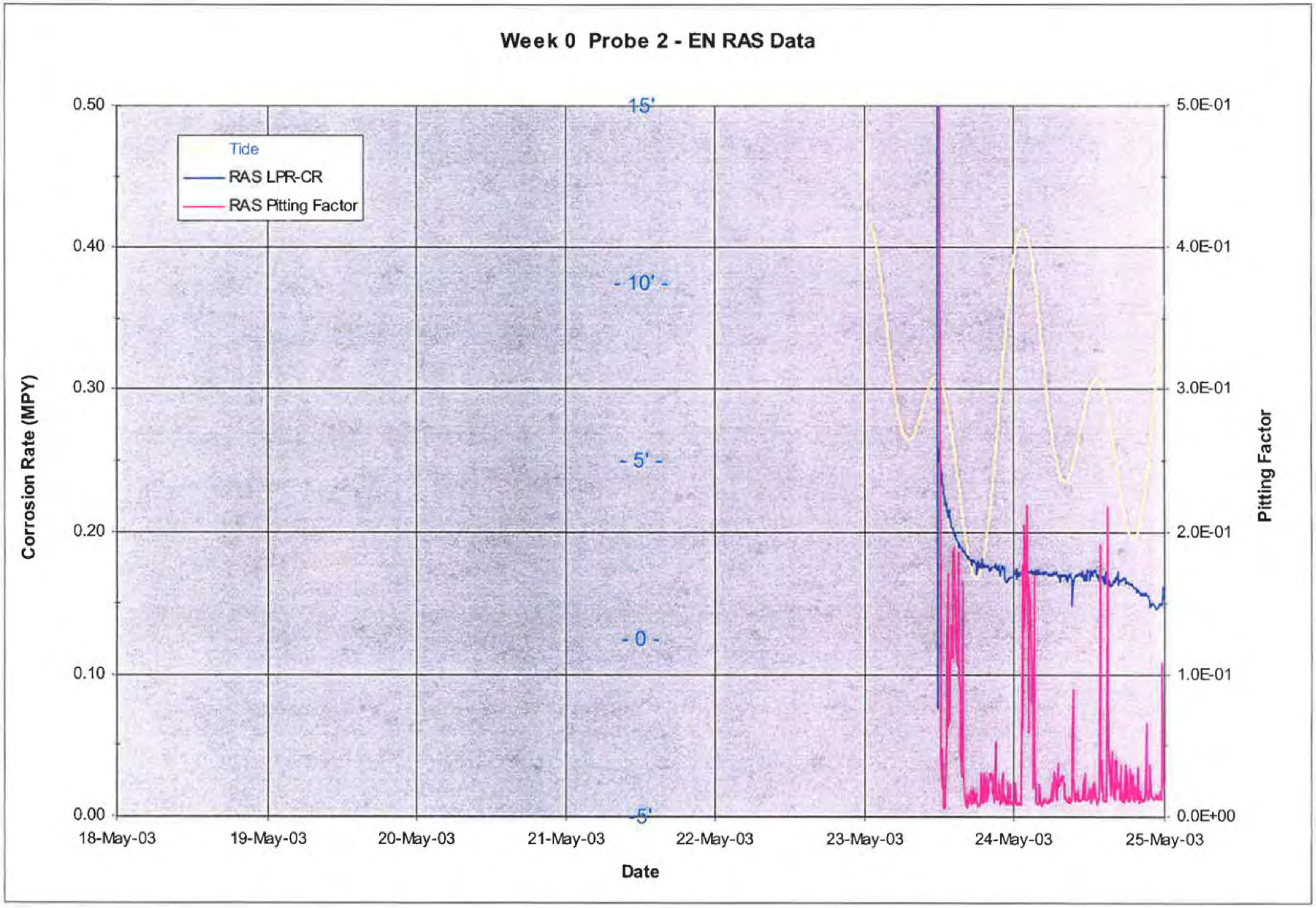

Week 5 Conductivity and Flow
0.08"
trace
15'
- 10' -
- 5' -
- 0 -
-5'
Influent Conductivity (µS/cm)
Final Effluent Flow (MG)
3500
3000
2500
2000
1500
1000
500
0
350
300
250
200
150
100
50
0
22-Jun-03
23-Jun-03
24-Jun-03
25-Jun-03
26-Jun-03
27-Jun-03
28-Jun-03
29-Jun-03
Date
Tide
Conductivity
FE Flow

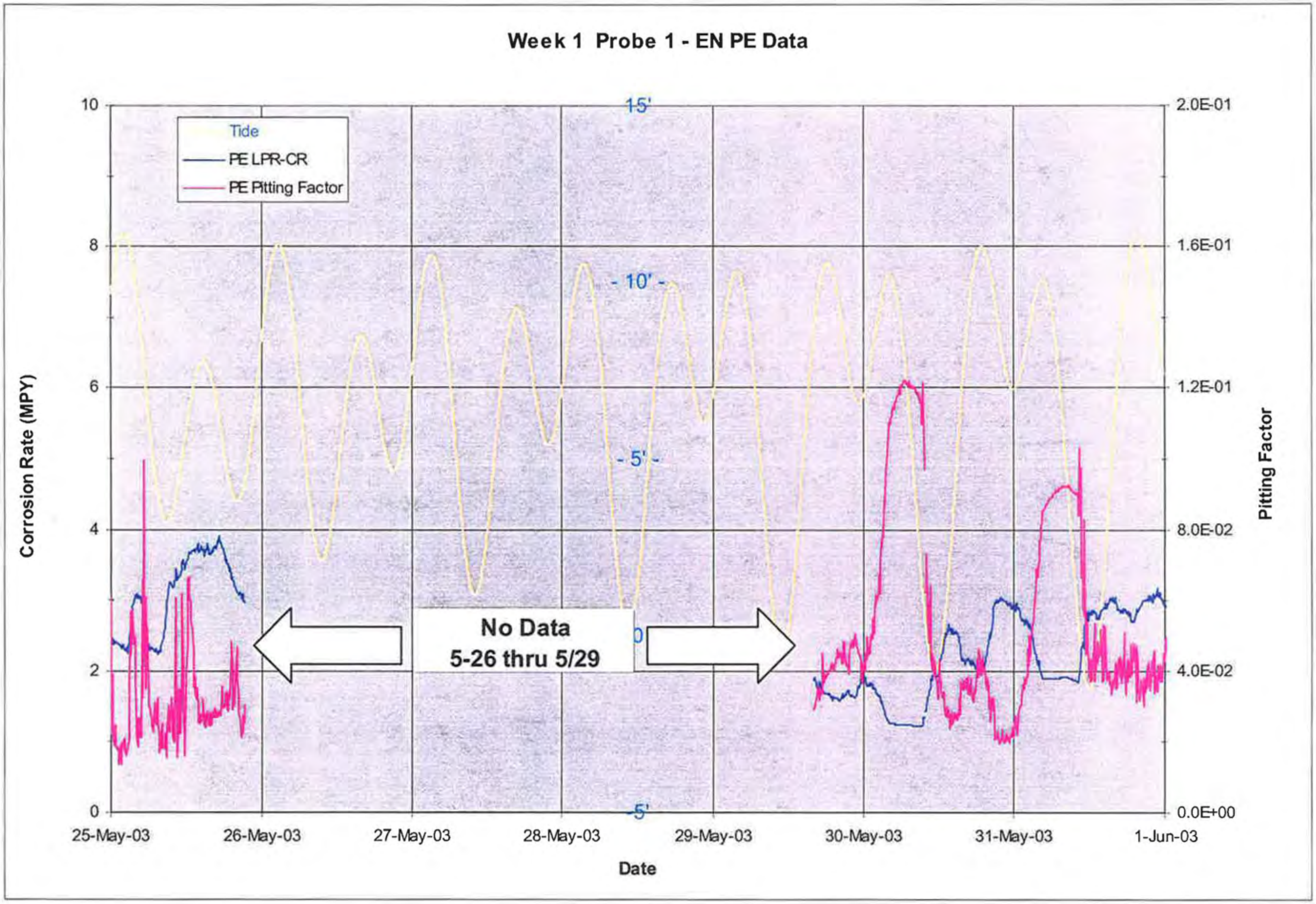

Week 6 Conductivity and Flow
trace
0.01"
15'
- 10' -
- 5' -
- 0 -
-5'
Influent Conductivity (µ S/cm)
3500
3000
2500
2000
1500
1000
500
0
Final Effluent Flow (MG)
350
300
250
200
150
100
50
0
29-Jun-03
30-Jun-03
1-Jul-03
2-Jul-03
3-Jul-03
4-Jul-03
5-Jul-03
6-Jul-03
Date
Tide
Conductivity
FE Flow

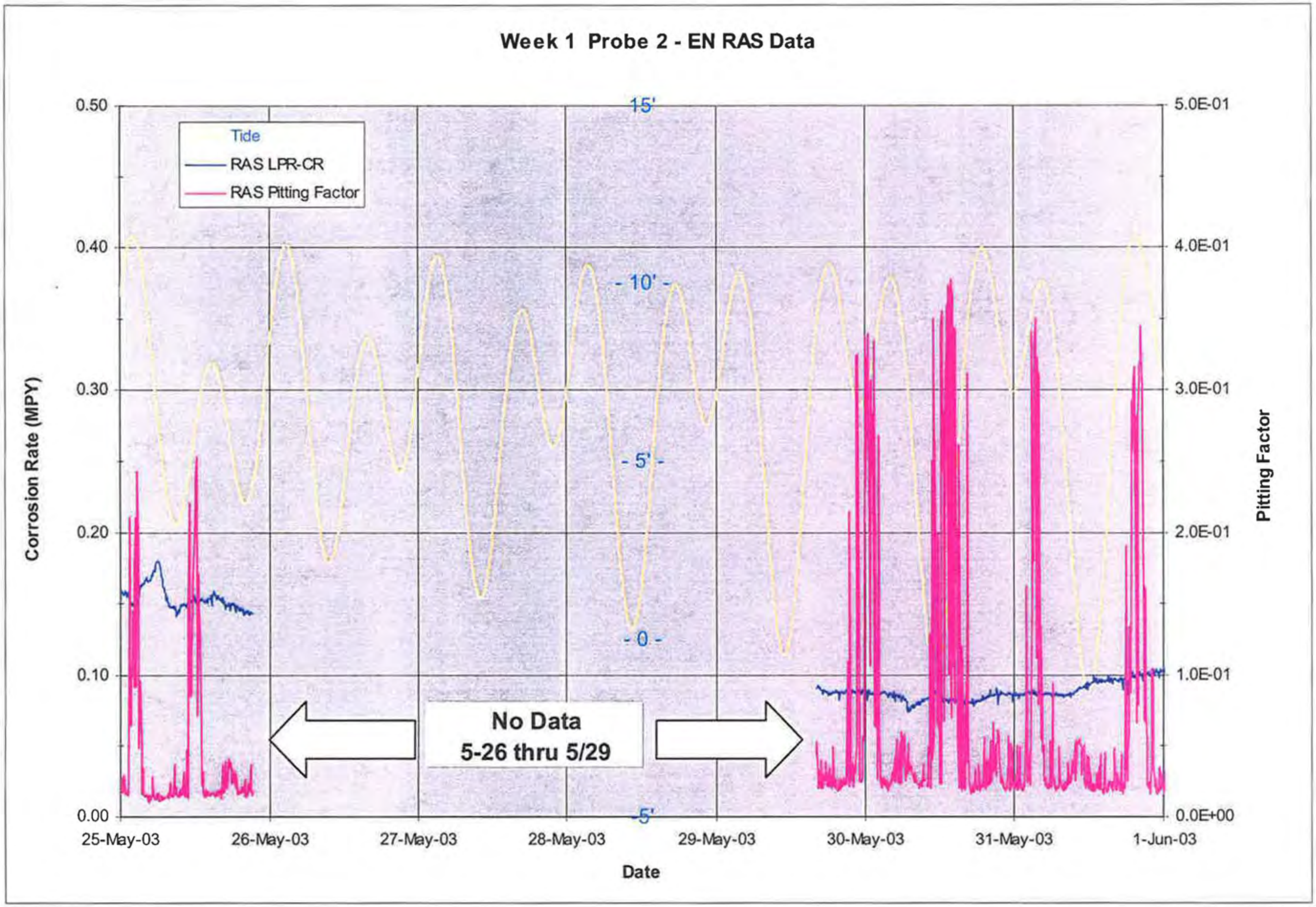

Week 7 Conductivity and Flow
Influent Conductivity (μS/cm)
Final Effluent Flow (MG)
Date
0
500
1000
1500
2000
2500
3000
3500
0
50
100
150
200
250
300
350
6-Jul-03
7-Jul-03
8-Jul-03
9-Jul-03
10-Jul-03
11-Jul-03
12-Jul-03
13-Jul-03
15'
10'
5'
-5'
trace
Tide
Conductivity
FE Flow

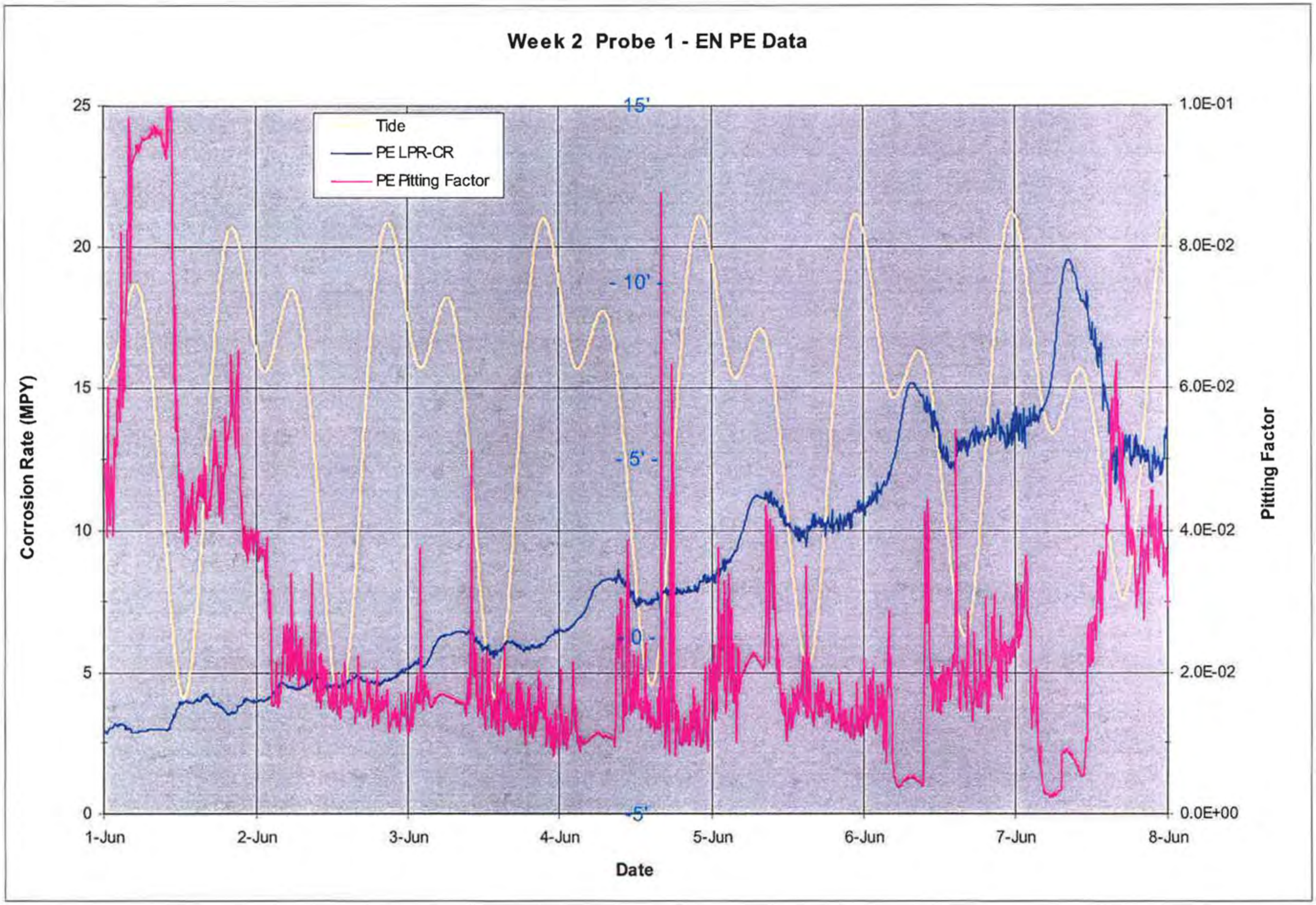

Week 8 Conductivity and Flow
0.02"
0.04"
15'
- 10' -
- 5' -
- 0 -
-5'
Influent Conductivity (µ S/cm)
3500
3000
2500
2000
1500
1000
500
0
Final Effluent Flow (MG)
350
300
250
200
150
100
50
0
13-Jul-03
14-Jul-03
15-Jul-03
16-Jul-03
17-Jul-03
18-Jul-03
19-Jul-03
20-Jul-03
Date
Tide
Conductivity
FE Flow

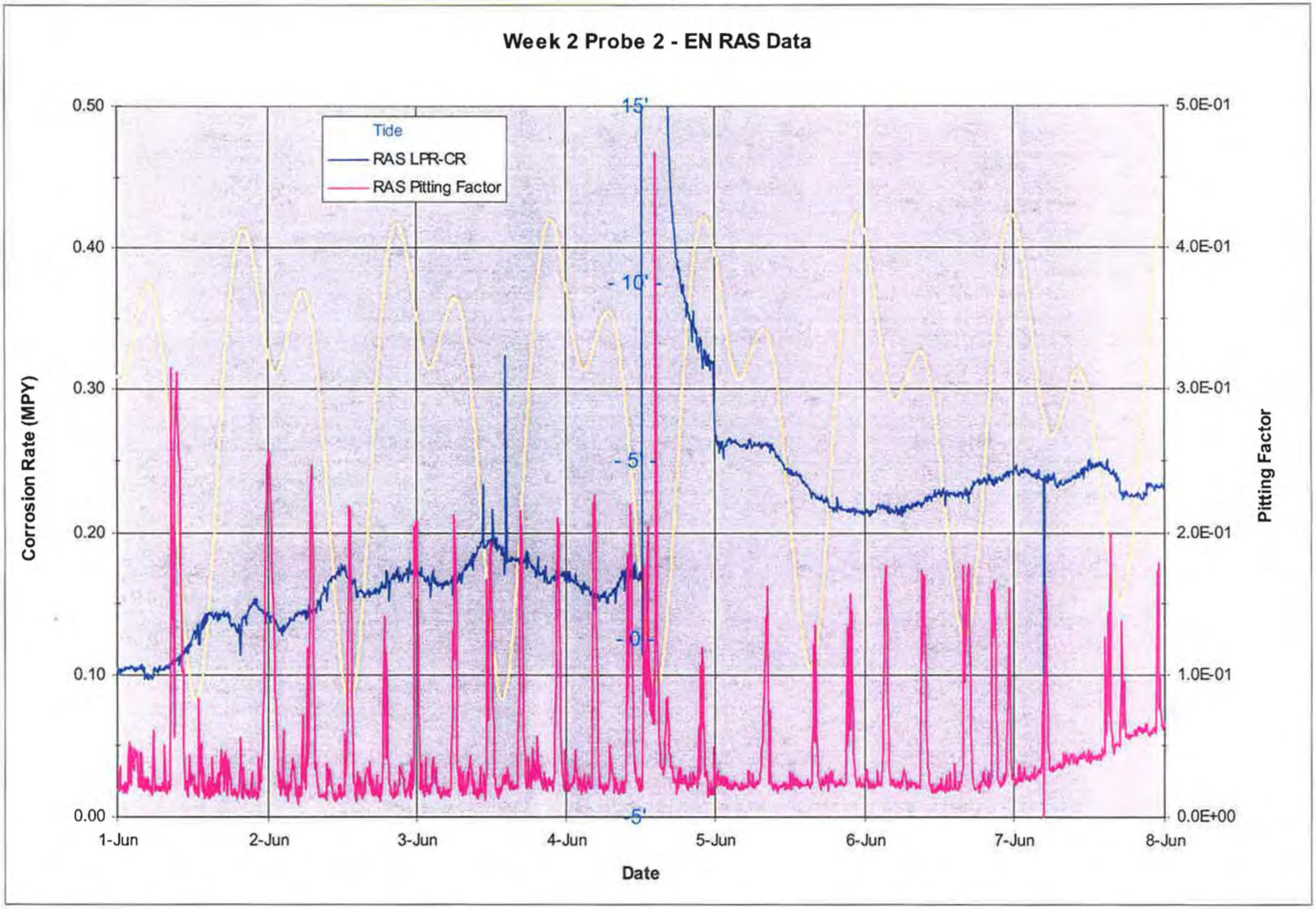

Week 0 Probe 1 - EN PE Data
Tide
PE LPR-CR
PE Pitting Factor
Corrosion Rate (MPY)
Pitting Factor
Date
10
8
6
4
2
0
2.0E-01
1.6E-01
1.2E-01
8.0E-02
4.0E-02
0.0E+00
15'
- 10' -
- 5' -
- 0 -
-5'
18-May-03
19-May-03
20-May-03
21-May-03
22-May-03
23-May-03
24-May-03
25-May-03

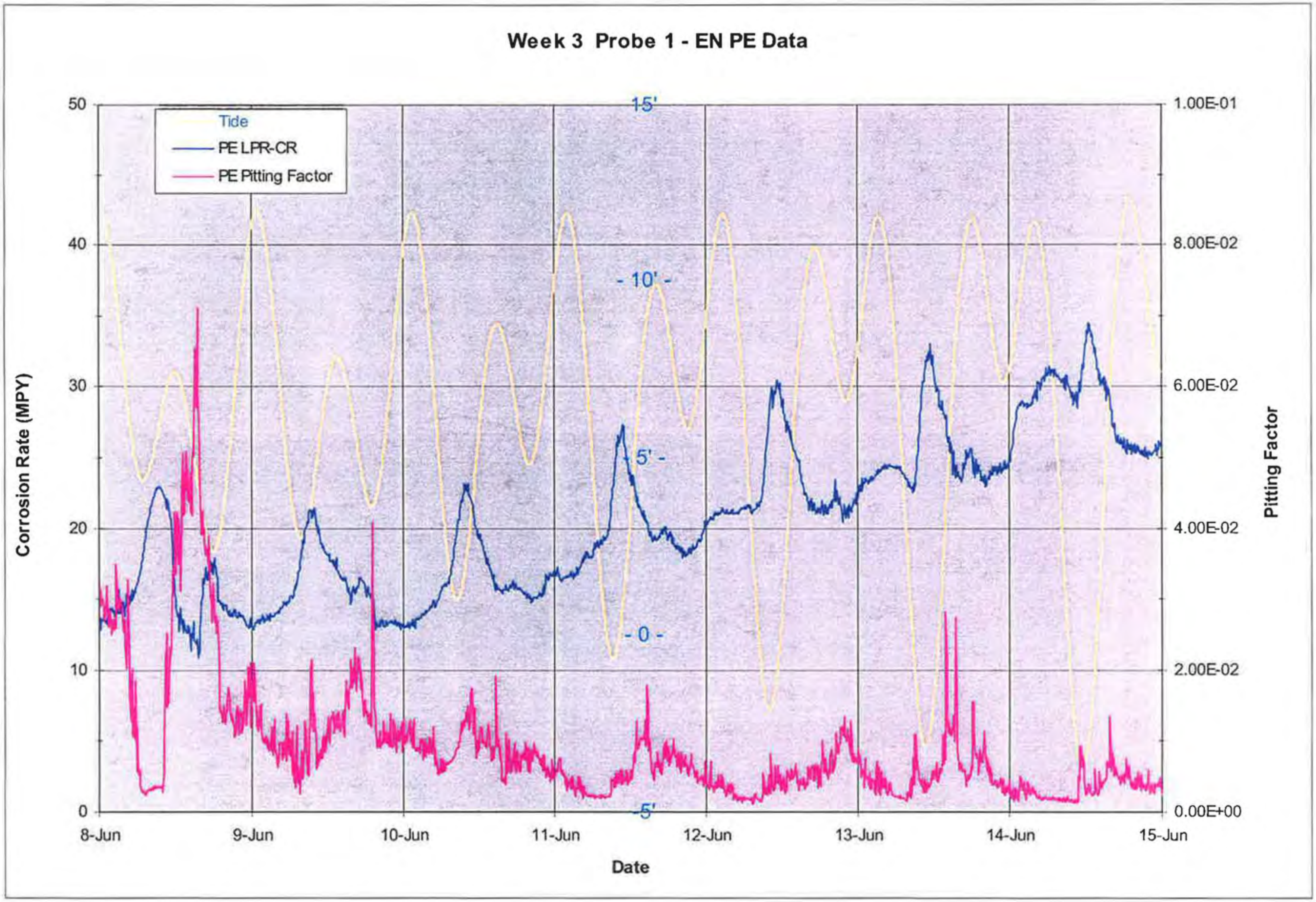

Week 0 Probe 2 - EN RAS Data
Tide
RAS LPR-CR
RAS Pitting Factor
15'
- 10' -
- 5' -
- 0 -
-5'
Corrosion Rate (MPY)
0.50
0.40
0.30
0.20
0.10
0.00
Pitting Factor
5.0E-01
4.0E-01
3.0E-01
2.0E-01
1.0E-01
0.0E+00
18-May-03
19-May-03
20-May-03
21-May-03
22-May-03
23-May-03
24-May-03
25-May-03
Date

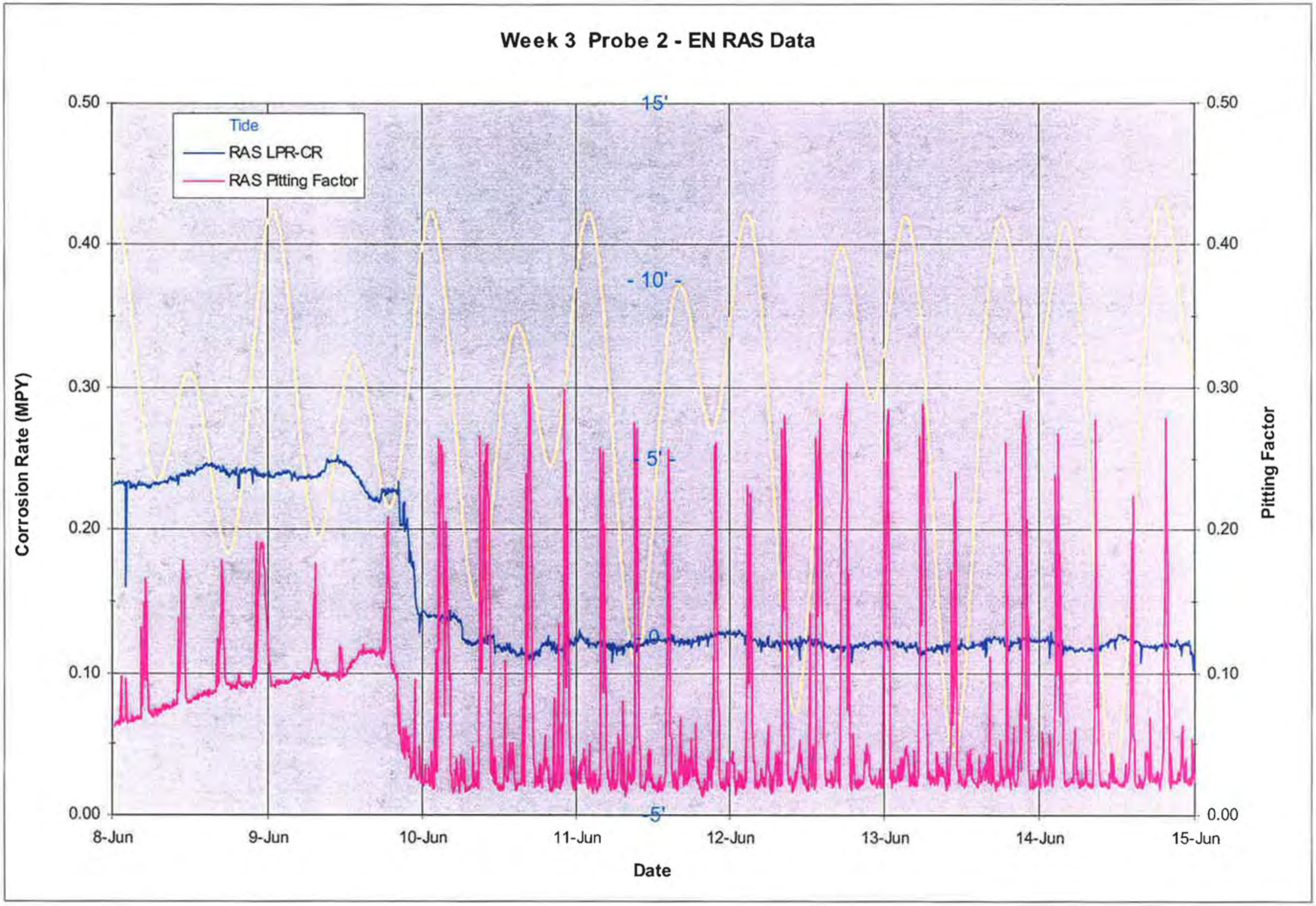

Week 1 Probe 1 - EN PE Data
Tide
PE LPR-CR
PE Pitting Factor
Corrosion Rate (MPY)
Pitting Factor
Date
0
2
4
6
8
10
0.0E+00
4.0E-02
8.0E-02
1.2E-01
1.6E-01
2.0E-01
15'
- 10' -
- 5' -
0
-5'
No Data
5-26 thru 5/29
25-May-03
26-May-03
27-May-03
28-May-03
29-May-03
30-May-03
31-May-03
1-Jun-03

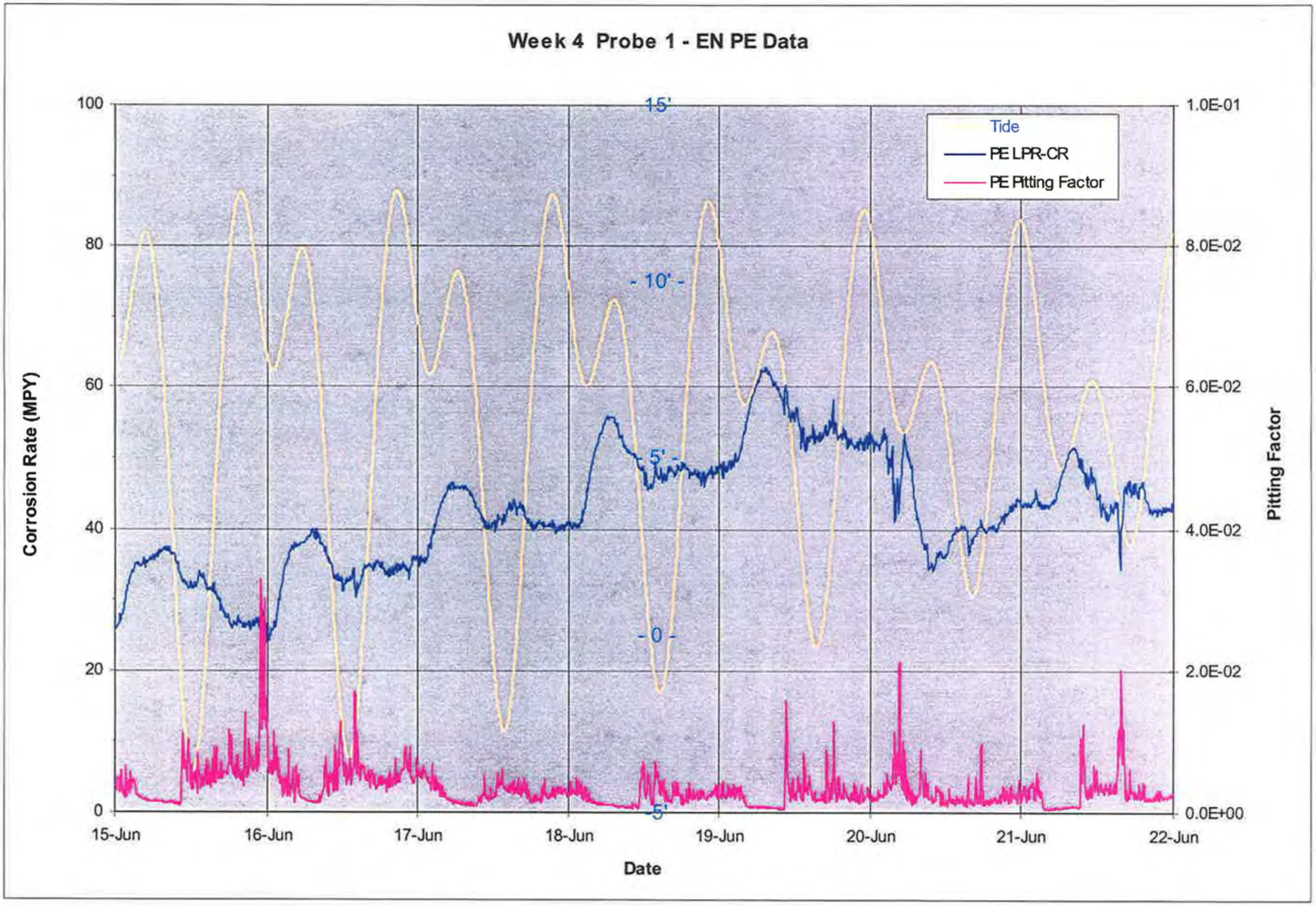

Week 1 Probe 2 - EN RAS Data
Tide
RAS LPR-CR
RAS Pitting Factor
Corrosion Rate (MPY)
0.50
0.40
0.30
0.20
0.10
0.00
Pitting Factor
5.0E-01
4.0E-01
3.0E-01
2.0E-01
1.0E-01
0.0E+00
15'
- 10' -
- 5' -
- 0 -
-5'
No Data
5-26 thru 5/29
25-May-03
26-May-03
27-May-03
28-May-03
29-May-03
30-May-03
31-May-03
1-Jun-03
Date

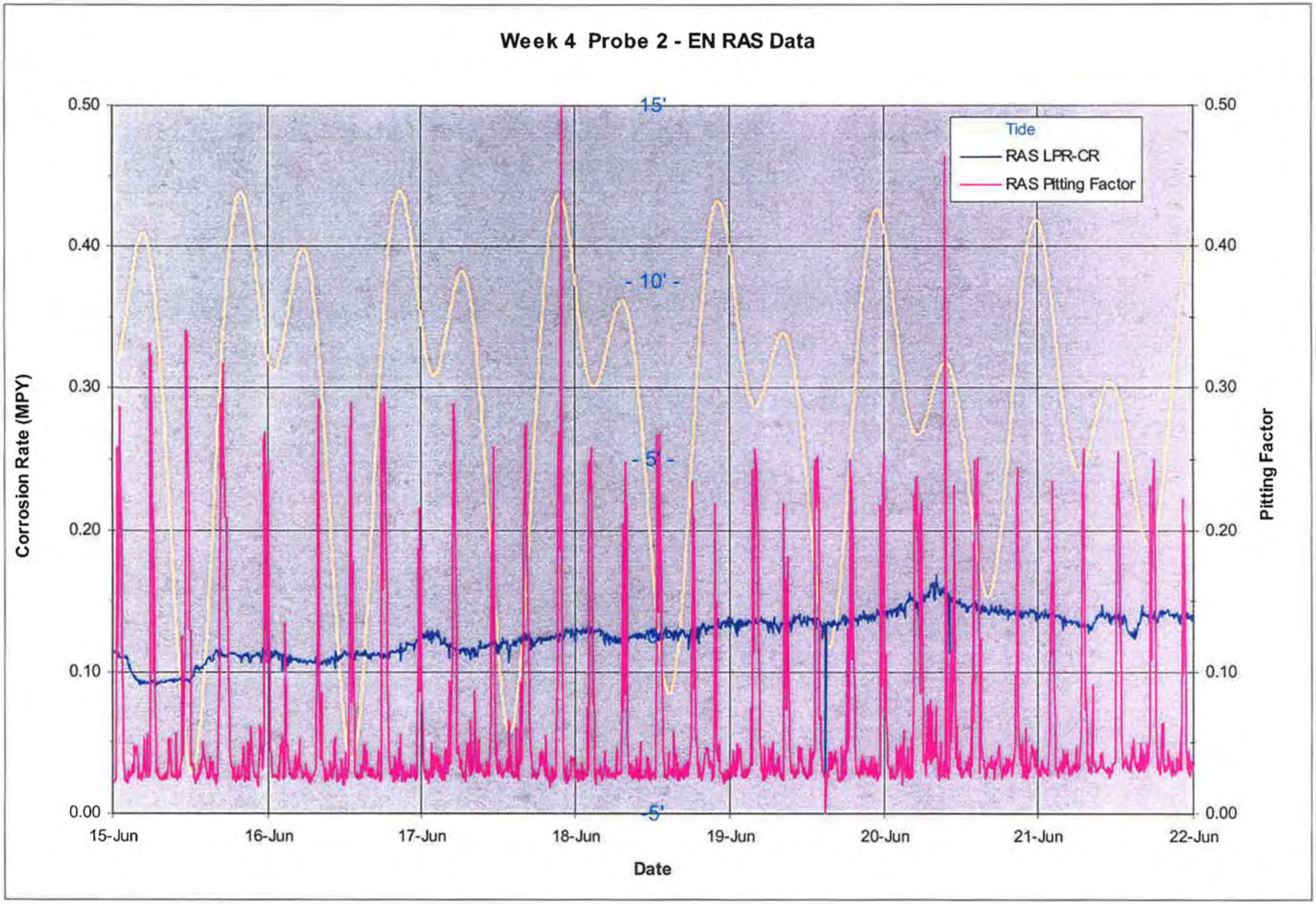

Week 2 Probe 1 - EN PE Data
Tide
PE LPR-CR
PE Pitting Factor
Corrosion Rate (MPY)
Pitting Factor
Date
25
20
15
10
5
0
15'
10'
5'
0
-5'
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
0.0E+00
1-Jun
2-Jun
3-Jun
4-Jun
5-Jun
6-Jun
7-Jun
8-Jun

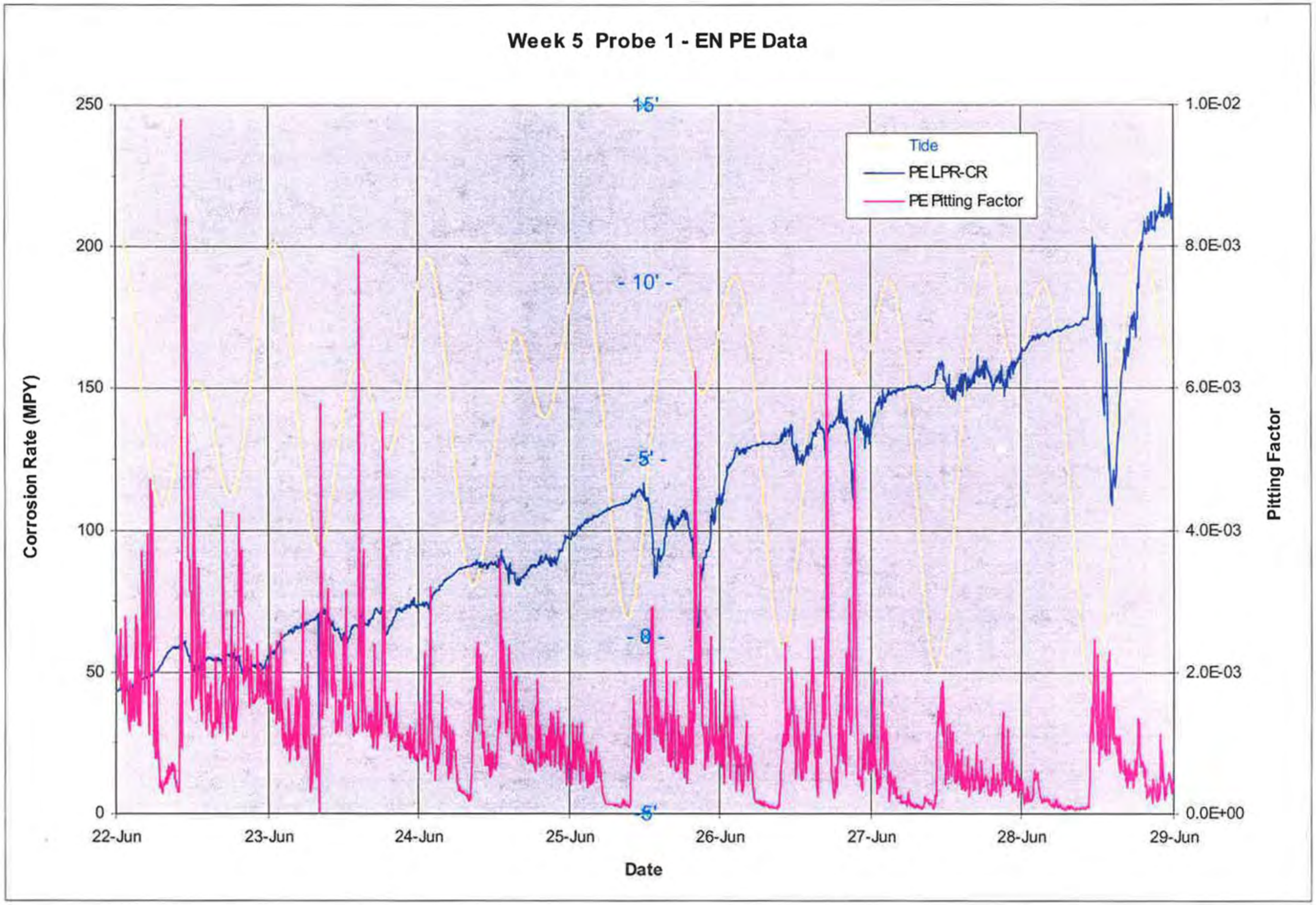

Week 2 Probe 2 - EN RAS Data
Tide
RAS LPR-CR
RAS Pitting Factor
Corrosion Rate (MPY)
0.50
0.40
0.30
0.20
0.10
0.00
Pitting Factor
5.0E-01
4.0E-01
3.0E-01
2.0E-01
1.0E-01
0.0E+00
15'
10'
5'
0'
-5'
1-Jun
2-Jun
3-Jun
4-Jun
5-Jun
6-Jun
7-Jun
8-Jun
Date

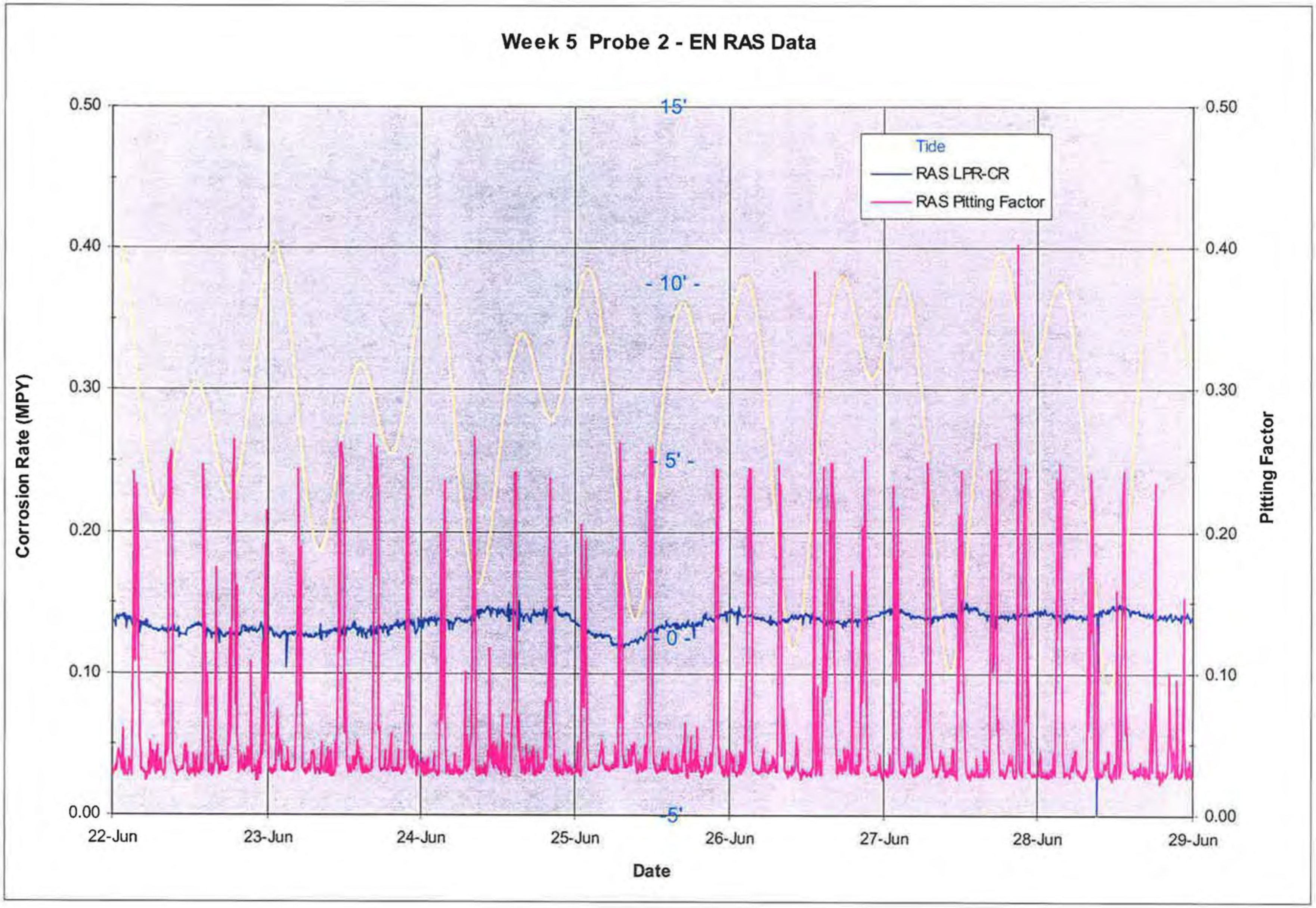

Week 3 Probe 1 - EN PE Data
Tide
PE LPR-CR
PE Pitting Factor
Corrosion Rate (MPY)
Pitting Factor
Date
50
40
30
20
10
0
1.00E-01
8.00E-02
6.00E-02
4.00E-02
2.00E-02
0.00E+00
15'
10'
5'
0
-5'
8-Jun
9-Jun
10-Jun
11-Jun
12-Jun
13-Jun
14-Jun
15-Jun

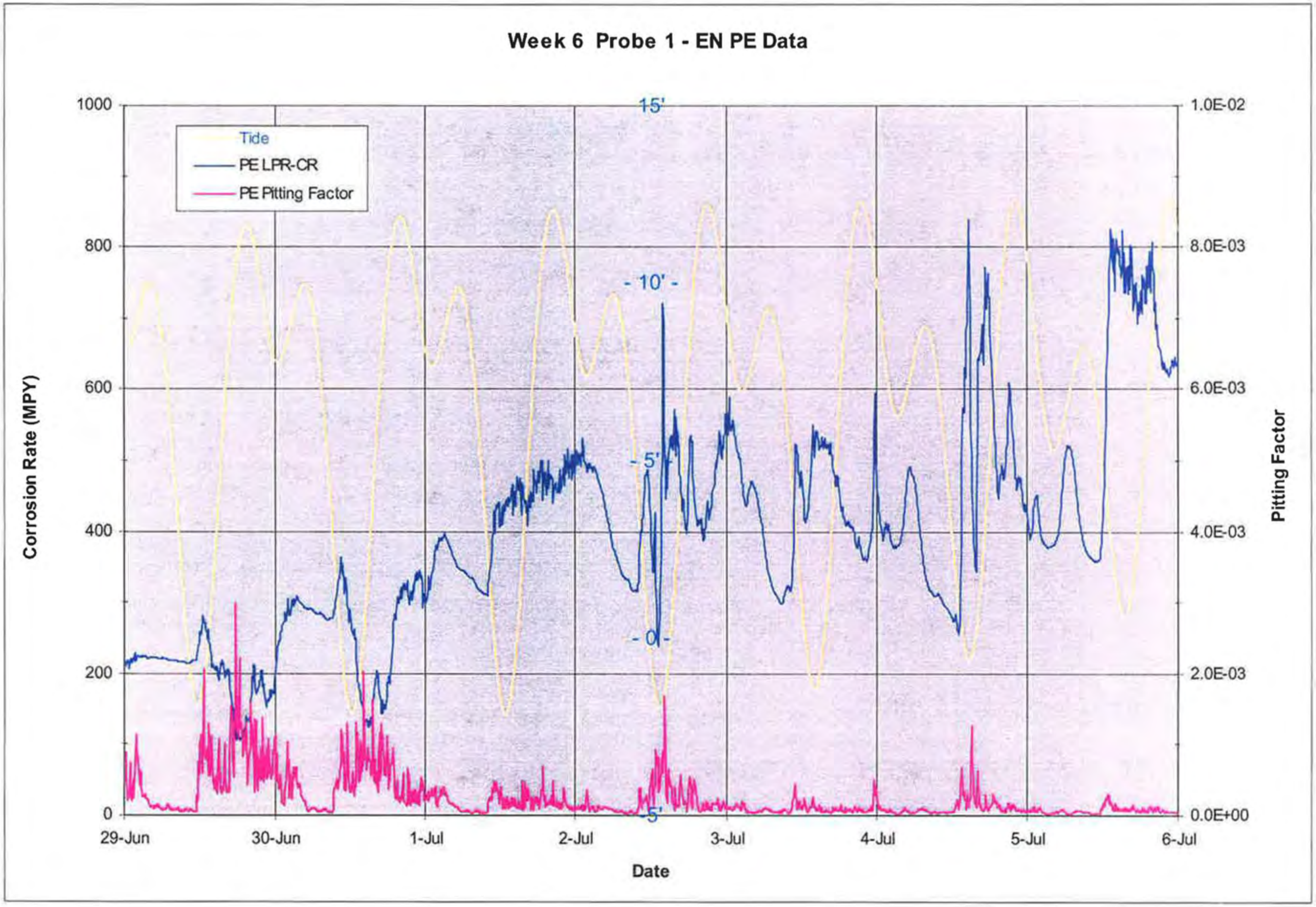

Week 3 Probe 2 - EN RAS Data
Tide
RAS LPR-CR
RAS Pitting Factor
15'
- 10' -
- 5' -
0
-5'
0.50
0.40
0.30
0.20
0.10
0.00
Corrosion Rate (MPY)
Pitting Factor
8-Jun
9-Jun
10-Jun
11-Jun
12-Jun
13-Jun
14-Jun
15-Jun
Date


Week 4 Probe 1 - EN PE Data
Tide
PE LPR-CR
PE Pitting Factor
Corrosion Rate (MPY)
Pitting Factor
Date
100
80
60
40
20
0
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
0.0E+00
15'
- 10' -
- 5' -
- 0 -
-5'
15-Jun
16-Jun
17-Jun
18-Jun
19-Jun
20-Jun
21-Jun
22-Jun

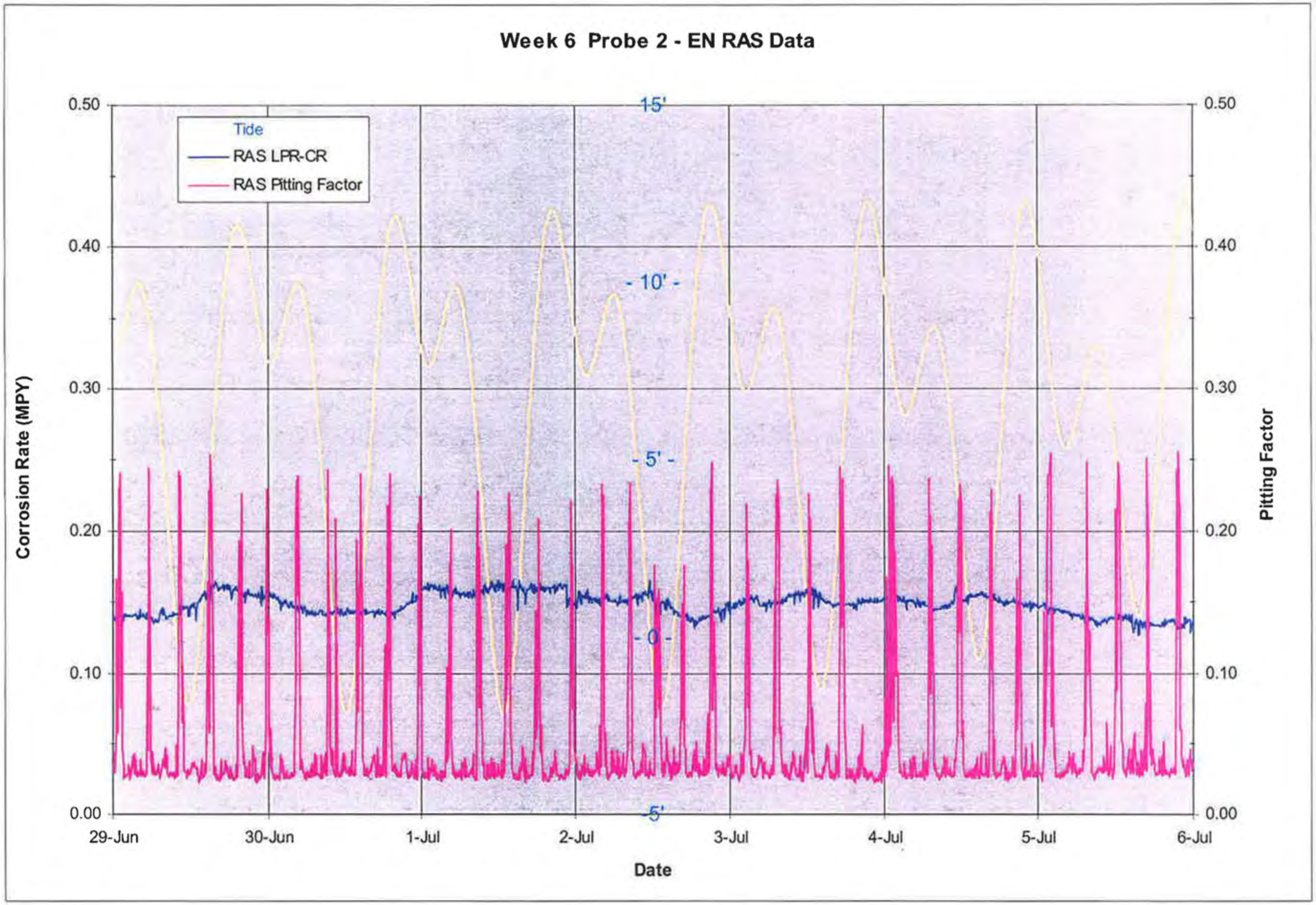

Week 4 Probe 2 - EN RAS Data
Tide
RAS LPR-CR
RAS Pitting Factor
Corrosion Rate (MPY)
Pitting Factor
Date
0.00
0.10
0.20
0.30
0.40
0.50
15'
- 10' -
- 5' -
-5'
15-Jun
16-Jun
17-Jun
18-Jun
19-Jun
20-Jun
21-Jun
22-Jun

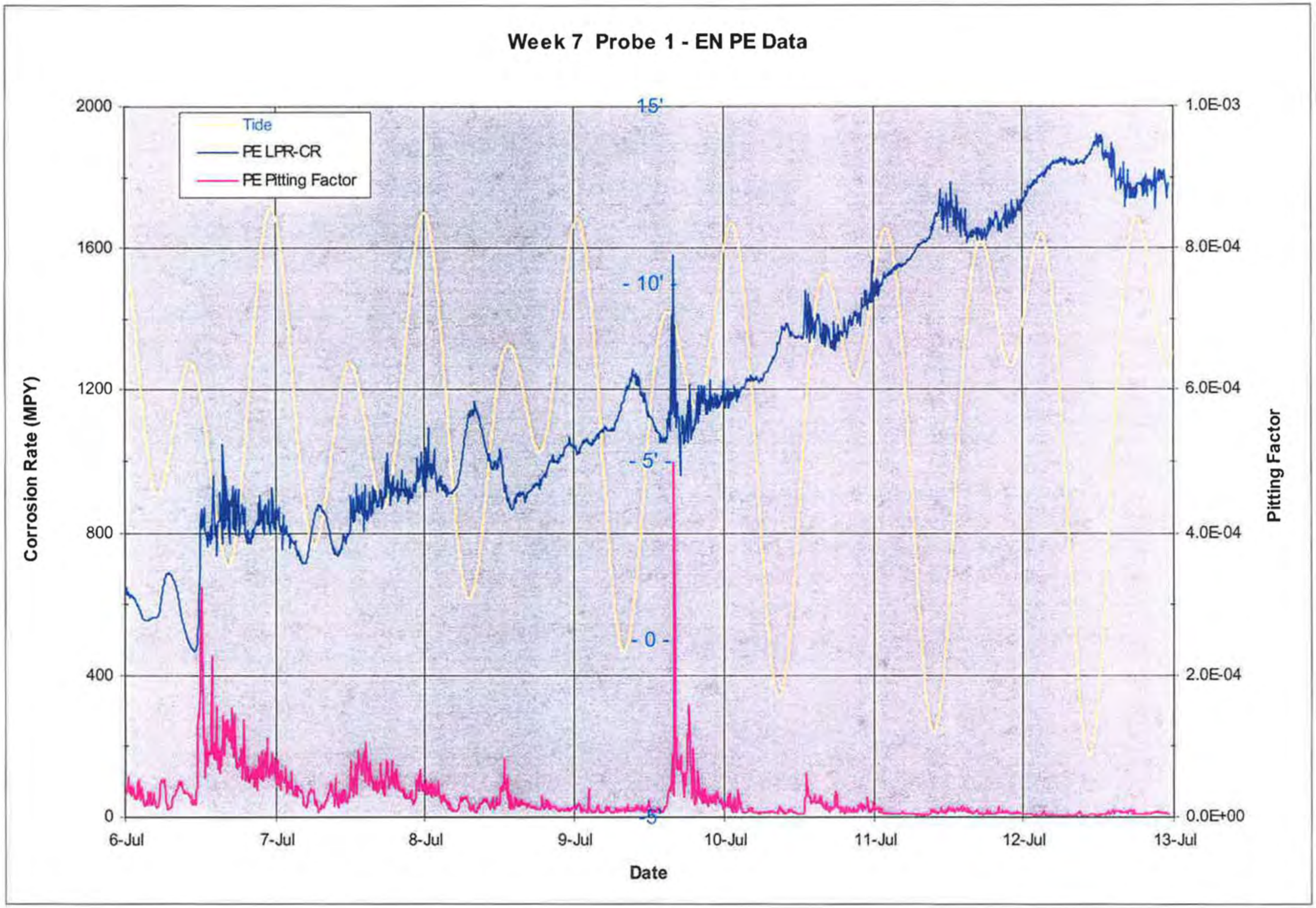

Week 5 Probe 1 - EN PE Data
Tide
PE LPR-CR
PE Pitting Factor
Corrosion Rate (MPY)
Pitting Factor
Date
250
200
150
100
50
0
1.0E-02
8.0E-03
6.0E-03
4.0E-03
2.0E-03
0.0E+00
15'
10'
5'
0
-5'
22-Jun
23-Jun
24-Jun
25-Jun
26-Jun
27-Jun
28-Jun
29-Jun

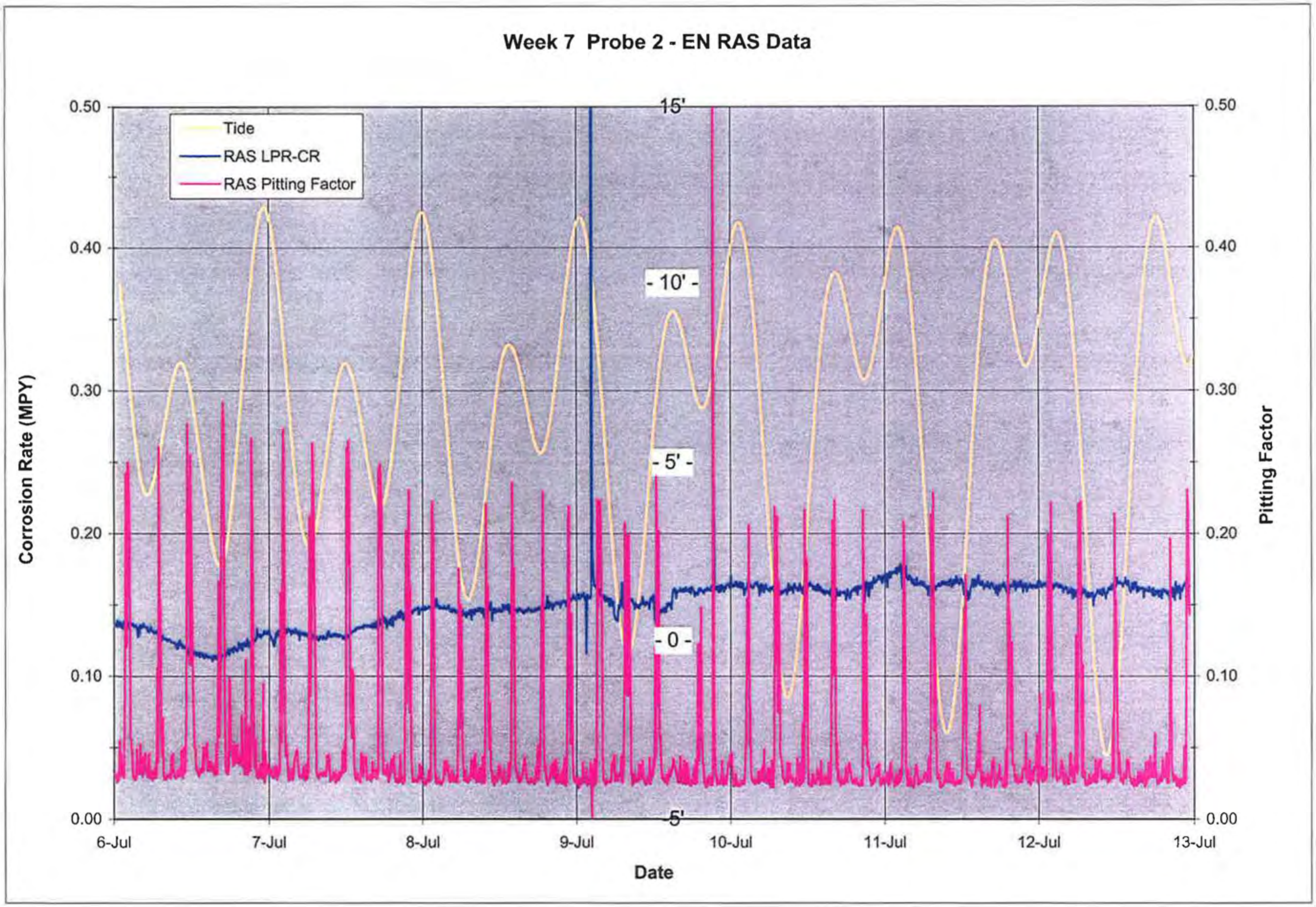

Week 5 Probe 2 - EN RAS Data
Corrosion Rate (MPY)
Pitting Factor
Date
0.50
0.40
0.30
0.20
0.10
0.00
15'
10'
5'
0
-5'
Tide
RAS LPR-CR
RAS Pitting Factor
22-Jun
23-Jun
24-Jun
25-Jun
26-Jun
27-Jun
28-Jun
29-Jun

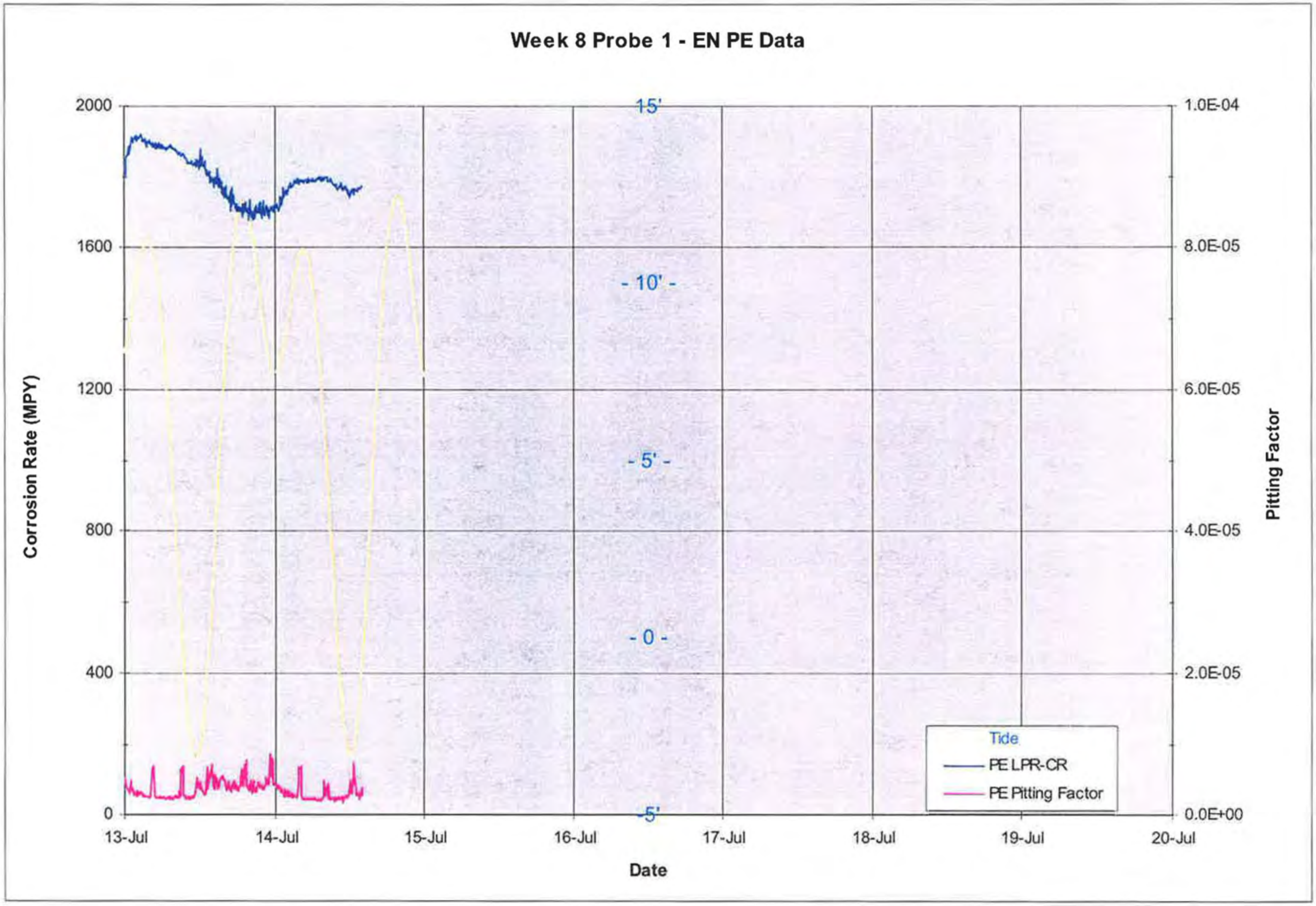


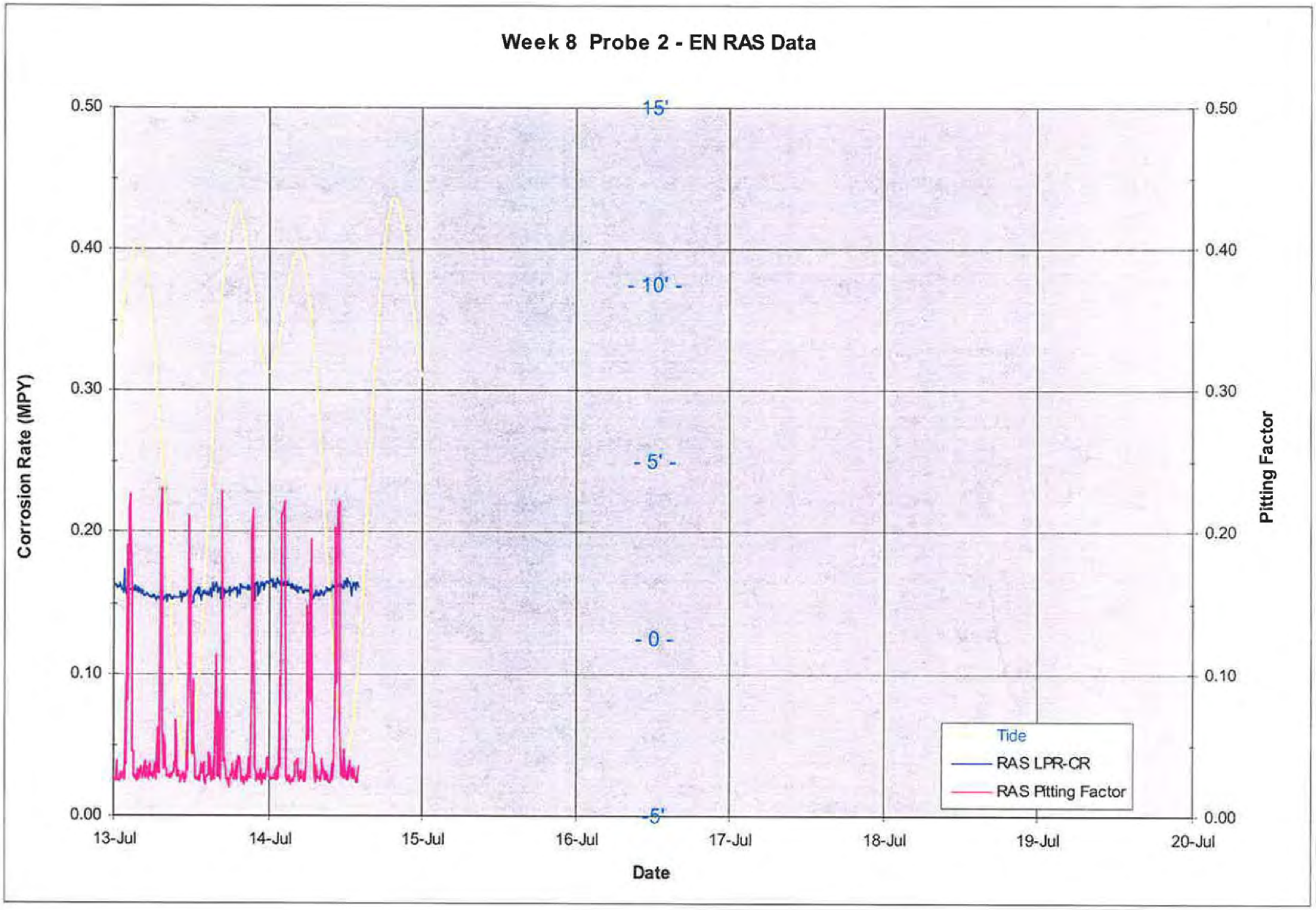
Week 6 Probe 1 - EN PE Data
Tide
PE LPR-CR
PE Pitting Factor
Corrosion Rate (MPY)
Pitting Factor
Date
1000
800
600
400
200
0
1.0E-02
8.0E-03
6.0E-03
4.0E-03
2.0E-03
0.0E+00
15'
- 10' -
- 5'
- 0 -
-5'
29-Jun
30-Jun
1-Jul
2-Jul
3-Jul
4-Jul
5-Jul
6-Jul

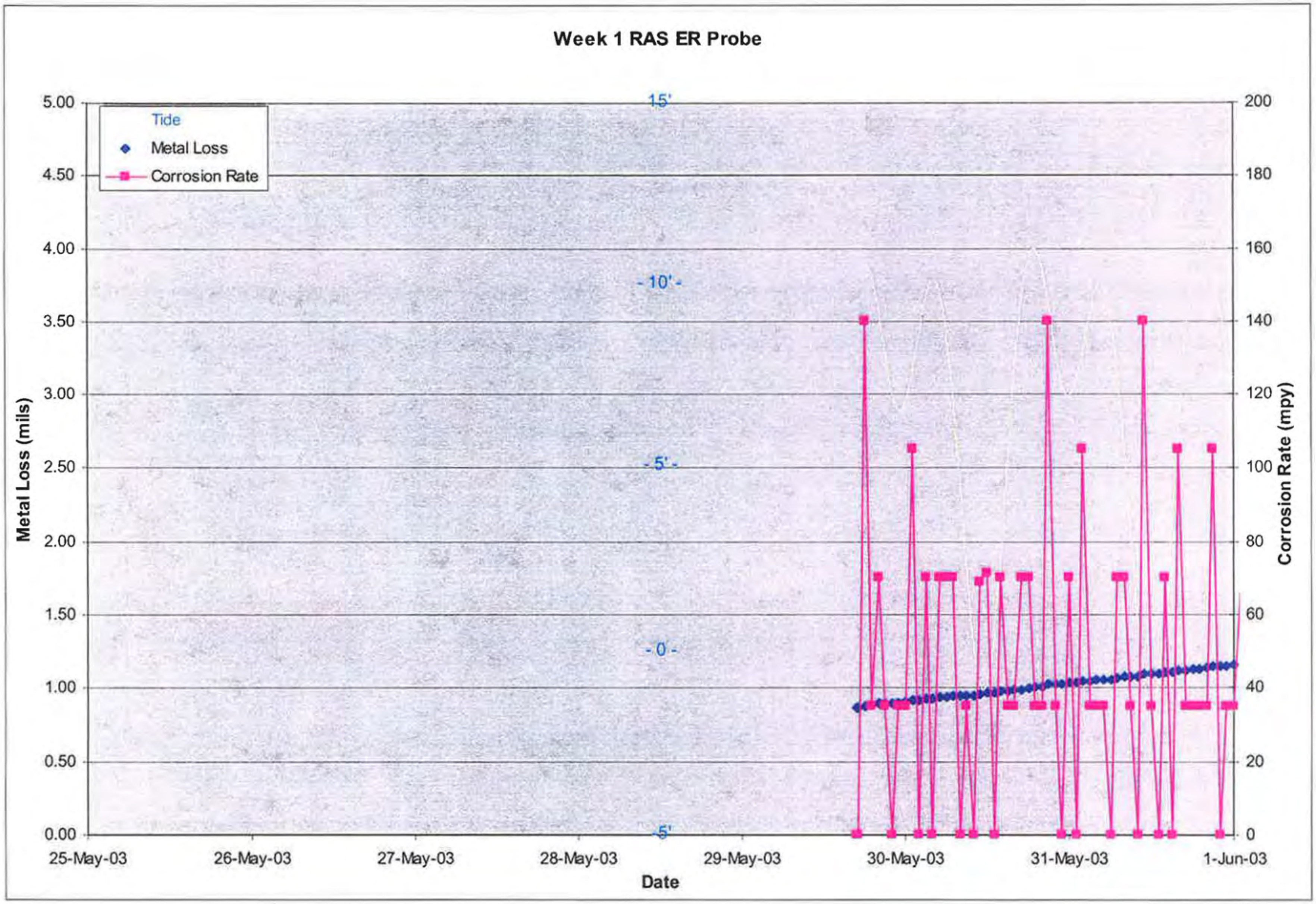

Week 6 Probe 2 - EN RAS Data
Tide
RAS LPR-CR
RAS Pitting Factor
15'
- 10' -
- 5' -
- 0 -
-5'
0.50
0.40
0.30
0.20
0.10
0.00
Corrosion Rate (MPY)
Pitting Factor
29-Jun
30-Jun
1-Jul
2-Jul
3-Jul
4-Jul
5-Jul
6-Jul
Date

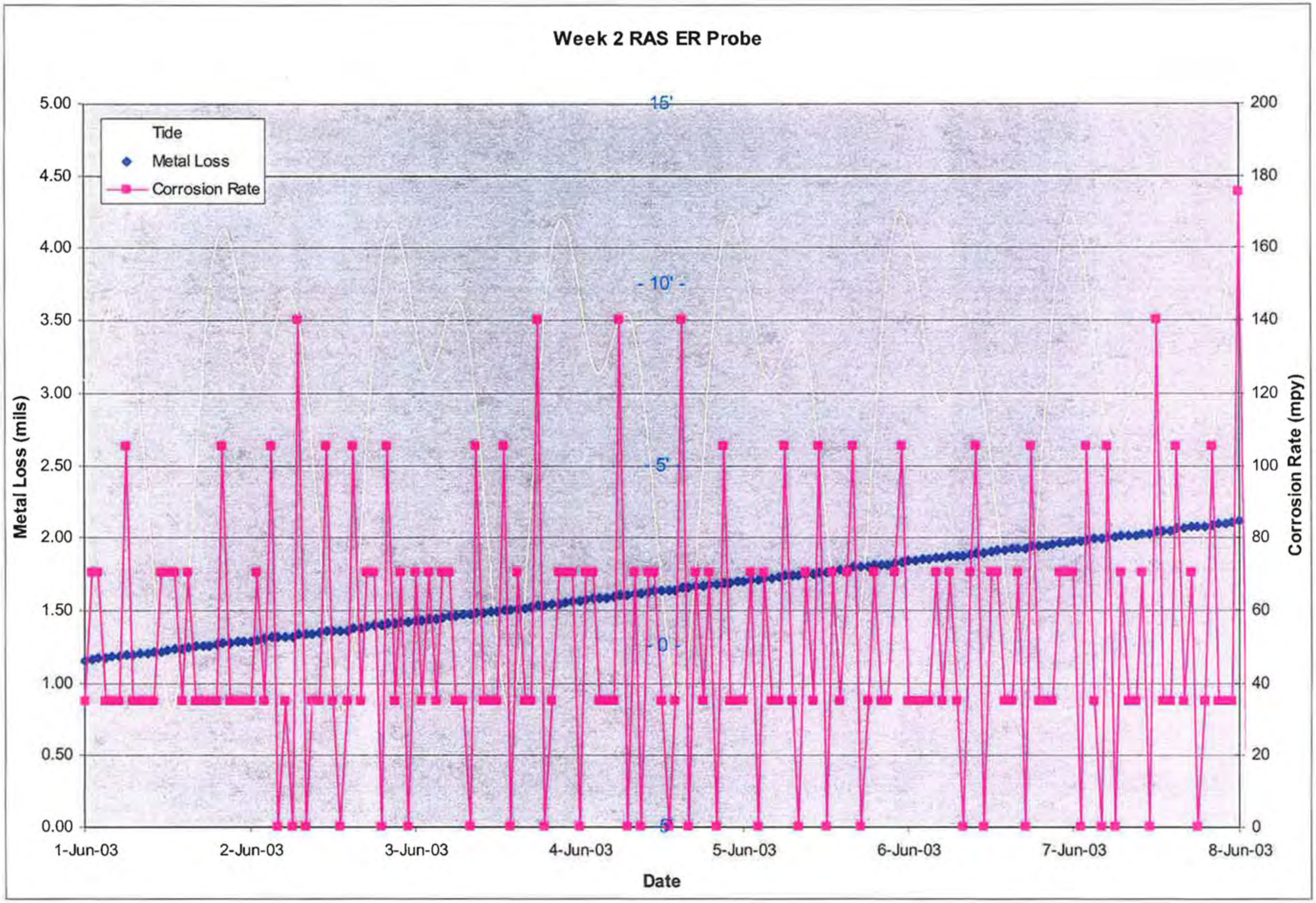

Week 7 Probe 1 - EN PE Data
Tide
PE LPR-CR
PE Pitting Factor
Corrosion Rate (MPY)
Pitting Factor
Date
2000
1600
1200
800
400
0
1.0E-03
8.0E-04
6.0E-04
4.0E-04
2.0E-04
0.0E+00
15'
- 10' -
- 5' -
- 0 -
-5'
6-Jul
7-Jul
8-Jul
9-Jul
10-Jul
11-Jul
12-Jul
13-Jul


Week 7 Probe 2 - EN RAS Data
Tide
RAS LPR-CR
RAS Pitting Factor
Corrosion Rate (MPY)
Pitting Factor
0.50
0.40
0.30
0.20
0.10
0.00
15'
- 10' -
- 5' -
- 0 -
-5'
6-Jul
7-Jul
8-Jul
9-Jul
10-Jul
11-Jul
12-Jul
13-Jul
Date

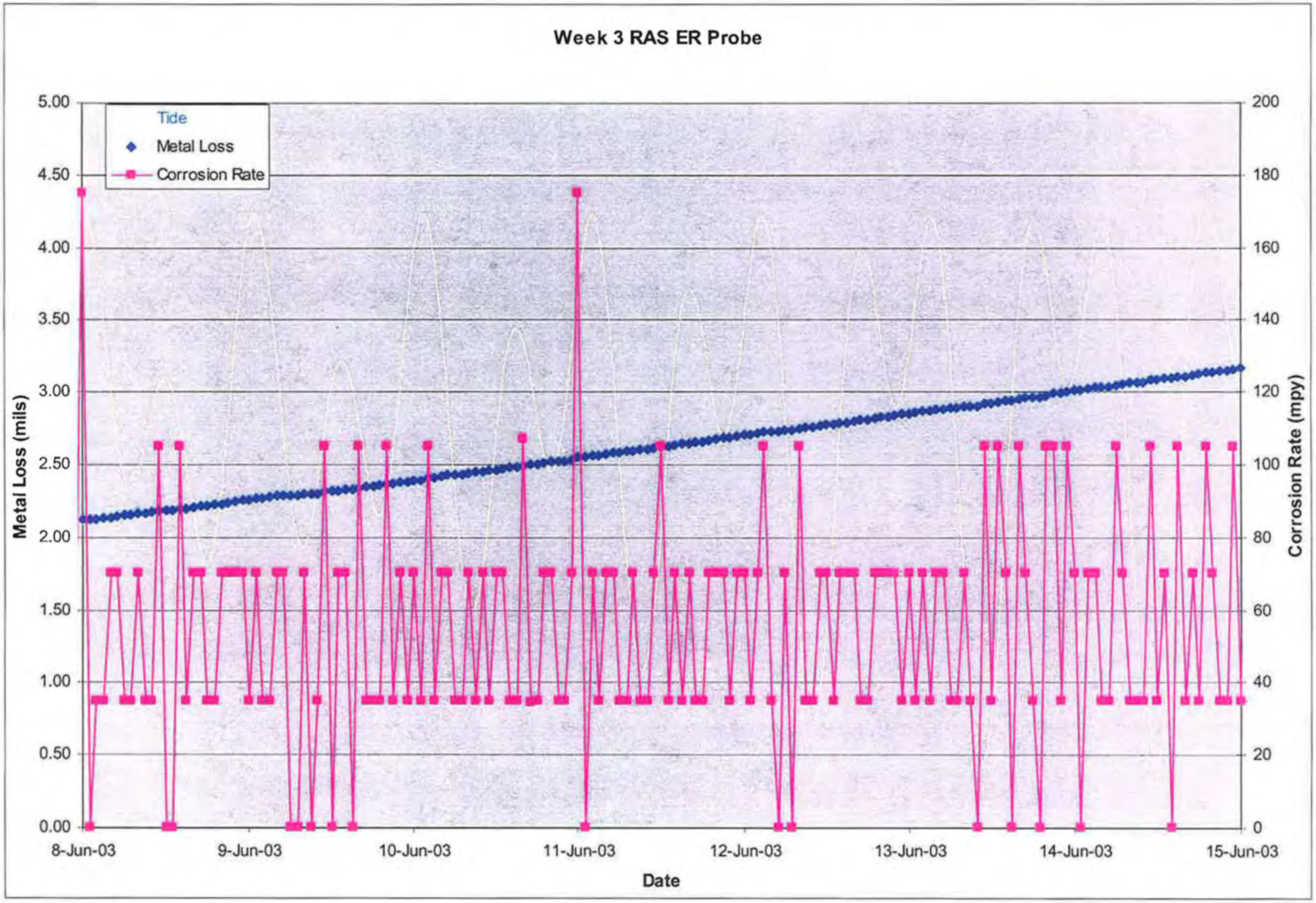

Week 8 Probe 1 - EN PE Data
Corrosion Rate (MPY)
2000
1600
1200
800
400
0
Pitting Factor
1.0E-04
8.0E-05
6.0E-05
4.0E-05
2.0E-05
0.0E+00
15'
- 10' -
- 5' -
- 0 -
-5'
13-Jul
14-Jul
15-Jul
16-Jul
17-Jul
18-Jul
19-Jul
20-Jul
Date
Tide
PE LPR-CR
PE Pitting Factor

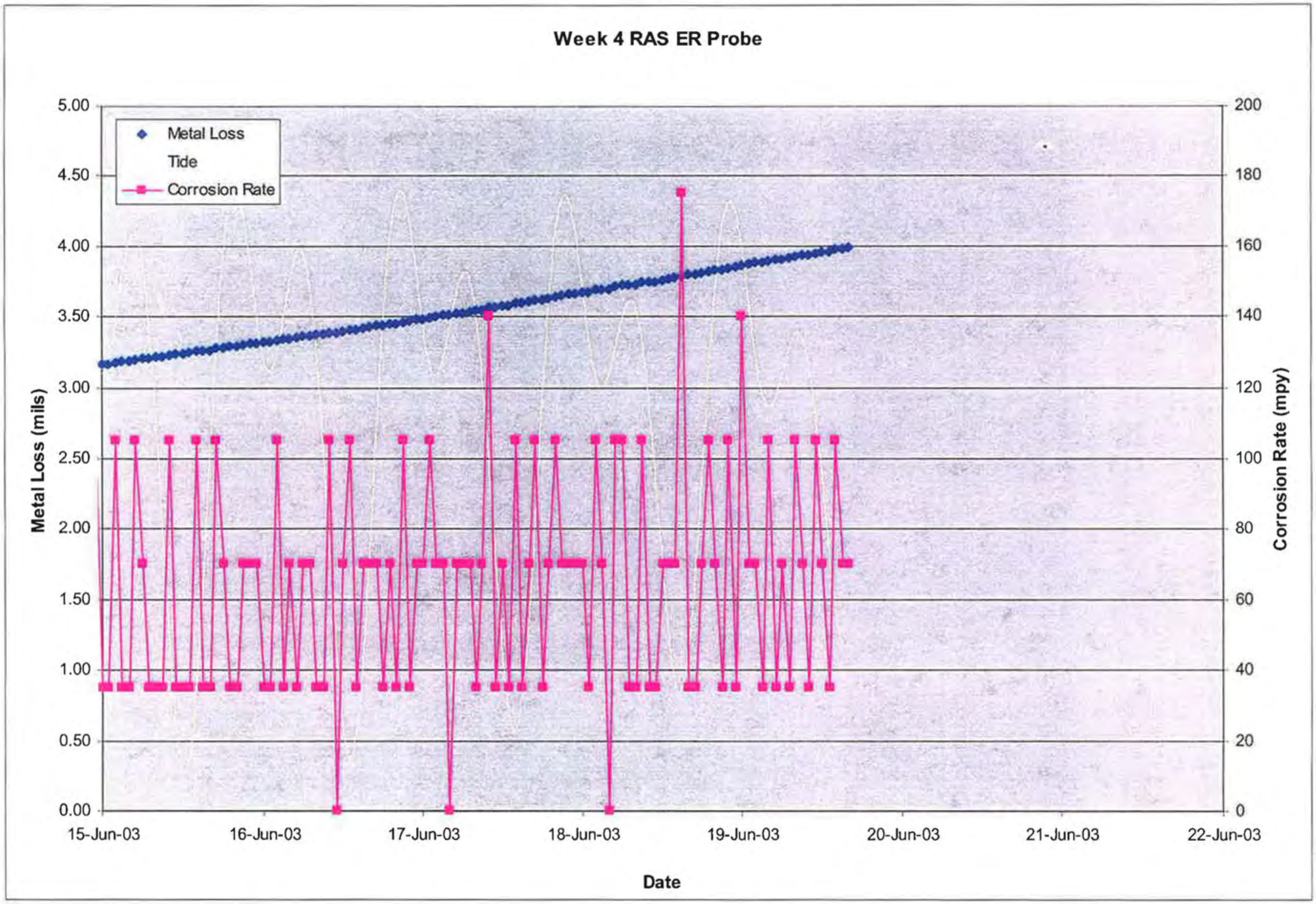

Week 8 Probe 2 - EN RAS Data
Corrosion Rate (MPY)
0.50
0.40
0.30
0.20
0.10
0.00
Pitting Factor
0.50
0.40
0.30
0.20
0.10
0.00
15'
- 10' -
- 5' -
- 0 -
-5'
13-Jul
14-Jul
15-Jul
16-Jul
17-Jul
18-Jul
19-Jul
20-Jul
Date
Tide
RAS LPR-CR
RAS Pitting Factor


Week 1 RAS ER Probe
Tide
Metal Loss
Corrosion Rate
Metal Loss (mils)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Corrosion Rate (mpy)
200
180
160
140
120
100
80
60
40
20
0
15'
- 10' -
- 5' -
- 0' -
-5'
25-May-03
26-May-03
27-May-03
28-May-03
29-May-03
30-May-03
31-May-03
1-Jun-03
Date



Week 2 RAS ER Probe
Tide
Metal Loss
Corrosion Rate
15'
10'
5'
0
5'
Metal Loss (mils)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Corrosion Rate (mpy)
200
180
160
140
120
100
80
60
40
20
0
1-Jun-03
2-Jun-03
3-Jun-03
4-Jun-03
5-Jun-03
6-Jun-03
7-Jun-03
8-Jun-03
Date


Week 3 RAS ER Probe
Tide
Metal Loss
Corrosion Rate
Metal Loss (mils)
Corrosion Rate (mpy)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
200
180
160
140
120
100
80
60
40
20
0
8-Jun-03
9-Jun-03
10-Jun-03
11-Jun-03
12-Jun-03
13-Jun-03
14-Jun-03
15-Jun-03
Date



Week 4 RAS ER Probe
Metal Loss
Tide
Corrosion Rate
Metal Loss (mils)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Corrosion Rate (mpy)
200
180
160
140
120
100
80
60
40
20
0
15-Jun-03
16-Jun-03
17-Jun-03
18-Jun-03
19-Jun-03
20-Jun-03
21-Jun-03
22-Jun-03
Date

APPENDIX B

Saltwater Intrusion into the King County Sewer System

Saltwater Intrusion into the King County Sewer System

Prepared by
King County Department of Natural Resources and Parks
Wastewater Treatment Division
Facilities Inspection Unit

December 16, 2003

Summary

Saltwater is flowing into the King County sewer system from Harbor Island and through City of Seattle overflow gates that are located along the Seattle waterfront. This claim is based on studies conducted by the King County Wastewater Treatment Division, and by a third party consultant, to ascertain why equipment at King County's West Point Treatment Plant is suffering severe corrosion. The saltwater inflow causes not only severe corrosion of equipment at the West Point Treatment Plant but also substantial increases in flow to the plant. Increased flows can reduce capacity in the conveyance system and contribute to CSO's in wet weather and SSO's in dry weather periods. Costs for repair and replacement of equipment total approximately $7,075,000; costs to treat saltwater flows total between $1,022,000 and $1,533,000 per year.

History of corrosion at the West Point Treatment Plant

King County has experienced severe corrosion in its West Point Treatment Plant over the past six years and has been aware of high levels of conductivity in the treatment plant influent since 1998. Corroded equipment includes gates and return-activated sludge (RAS) pipes, as well as suction duct and piping in all of the plant's thirteen clarifiers. This equipment, which was part of a major plant expansion, came online in 1996 and has failed far short of its expected service life, as discussed below. Similar equipment at the South Treatment Plant, brought online in 1961, does not exhibit the problems found at West Point.

The lab at the West Point Treatment Plant reported increased conductivity in the plant influent to King County's Industrial Waste Program and Facilities Inspection Unit in 1998. The Facilities Inspection Unit undertook some investigation at this time; the saltwater intrusion was observed but its significance was not realized.

The coatings applied to some equipment in the West Point Treatment Plant failed within the first two years of use. The suction duct and piping in the clarifiers were severely corroded already in 1998. The corroded equipment had been galvanized, and the galvanizing had an expected service life of at least ten years. A number of the plant's gates, expected to last no less than thirty years, also showed severe corrosion within two years of service. Because zinc coatings on equipment deteriorated especially rapidly, the corrosion appeared to be galvanic, suggesting the presence of a highly corrosive electrolyte, most likely saltwater. See the executive summary of the attached report from Tinnea and Associates, the third party consultant to King County, for a photograph of the corroded suction duct in a West Point clarifier (the suction duct is referred to as the "rake arm" in the report).

King County became aware of corrosion in the RAS pipes in December of 2002, when plant personnel discovered a hole measuring approximately 1 inch in diameter in an elbow section of a 30-inch diameter pipe. Tinnea and Associates identified pitting in the RAS pipes. Such localized corrosion existed not only in the elbow section that had developed a hole but also in the two additional sections that King County was able to take offline for purposes of inspection. As with the corrosion in the clarifiers, saltwater infiltration was suspected since high concentrations of chlorides in the flow could initiate pitting.

Cause of corrosion

A corrosion study conducted by Tinnea and Associates provides strong evidence that the rapid deterioration at West Point is due to high levels of chlorides in the flow. Furthermore, Tinnea and Associates identified high rates of corrosion not only in the clarifiers and RAS piping, which were known to be corroded, but also in the primary effluent (PE) piping. Refer to the report from Tinnea and Associates for a detailed discussion of results and for an account of the methodology and testing equipment used in the study. Major findings of the study are as follows.

- Spikes in conductivity and increases in the volume of flow to the West Point Treatment Plant correlate with tides over 11 feet, indicating that saltwater infiltrates the wastewater treatment system during high tides. See the discussion of *Conductivity and flow* in the section on *Corrosion test results* in the report from Tinnea and Associates, as well as the appended graph that is referenced in their report.
- Results obtained for the PE piping show spikes in the rate of pitting corrosion following high tides. See the discussion of *Electrochemical noise* in the section on *Corrosion test results* in the report from Tinnea and Associates.
- Results obtained for the RAS piping predict that the existing corrosion rate would penetrate the ¼-inch pipe wall in 4.4 years. See the discussion of *Electrical resistance* in the section on *Corrosion test results* in the report from Tinnea and Associates.
- Elevations in the corrosion rate in the clarifiers at West Point correlate with high tides. A control study at the South Treatment Plant showed that such correlation does not occur at that plant. Although the methods of oxygenation differ between the treatment plants, aeration blowers at South Plant and High Purity Oxygen (HPO) at West Point, the control comparison was for corrosion rates due to chloride concentration. See the discussion of *Linear polarization resistance* in the section on *Corrosion test results* in the report from Tinnea and Associates.

Sources of saltwater infiltration

In an effort to understand where the chlorides are coming from, the King County Wastewater Treatment Division completed a study of conductivity levels at sites that were considered to be potential sources of saltwater infiltration because of their proximity to the Puget Sound, Elliott Bay, or the Duwamish Waterway. Of all the sites sampled, very high levels were found at four sites, all of which receive flows from facilities owned by the City of Seattle. Like the study by Tinnea and Associates, the King County study shows that spikes in conductivity correlate with high tides. Data collected by King County also show a correlation between high tides and decreases in the temperature of flows.

Methodology

King County conducted an initial study to identify sites with high conductivity levels and then installed data loggers at those sites in order to monitor conductivity and temperature over a longer, continuous period of time.

In the initial study, staff used handheld conductivity meters to measure the amount of saltwater in sewer samples from King County interceptors, trunks, and local lines. Conductivity (μS/cm) is the standard test for the presence of chloride contaminants, including saltwater. Samples were taken during peak tides that measured between 11.8 and 12.8 feet and that occurred at times when no precipitation was present to dilute the samples. Staff used a process of elimination similar to that used to identify illegal industrial waste discharges.

In the follow-up study, King County installed Sondi 665 portable data loggers at the sites found to have high chloride concentrations. Two Sondi 665 data loggers, which have conductivity and temperature capabilities, were installed for two days at each location and were programmed to record conductivity and temperature every five minutes. Data was gathered during the week of June 14-21, 2003, when peak tides ranged between 12 and 12.4 feet.

Initial sampling and findings

King County staff took conductivity readings at sites that receive flows from areas considered to be potential sources of saltwater infiltration. These areas are the West Seattle flow area, the south Magnolia trunk, the Elliott Bay interceptor, the Seattle waterfront, and Harbor Island. The sampling sites are indicated on the attached map.

Results obtained from the samples were assessed in relation to the conductivity of normal sewage and that of Puget Sound saltwater. The background conductivity reading for normal sewage is around 650 μS/cm, while water in the Puget Sound registers 31,500 μS/cm. Conductivity readings over 2,000 μS/cm clearly indicate an influence of saltwater into the sewer system.

Conductivity was typically below 500 μS/cm in samples from the West Seattle flow area, eliminating this area as a cause for concern. The area includes flows from three pump stations close to the Puget Sound. Staff measured wet well concentrations at the Murray and 63rd (53rd?)Avenue Pump Stations, which flow to the West Seattle Pump Station.

Conductivity of 1,200 μS/cm was recorded at the south Magnolia trunk, eliminating this area as a cause for concern. The south Magnolia trunk is located close to the shoreline and has one King County overflow gate; flow was sampled prior to the Interbay Pump Station.

Conductivity of 2,400 μS/cm was recorded along the Elliott Bay interceptor, upstream of the Duwamish Pump Station, indicating that the area is not a primary contributor of saltwater to the sewer flow but that the flow does contain some saltwater. King County has four overflow gates along the Elliott Bay interceptor upstream from the Duwamish Pump Station. Conductivity readings were also taken upstream and downstream of the North Interceptor Bypass structure, near the Ballard Locks, where results showed no saltwater infiltration.

Conductivity ranging from 15,000 to 31,000 μS/cm was recorded in flows from the Seattle waterfront, indicating that flows from this area contain about 48-98 percent saltwater. At the Seattle waterfront, samples were taken from three manhole sites that receive potential flows from four City of Seattle overflow gates: the Jackson Street site, which receives flow from the Washington Street overflow gate; the Trolley Barn site, which receives flow from the Vine Street overflow gate; and the Adit Structure, which receives flows from the University Street and Madison Street overflow gates. Manhole numbers and specific locations for these sites are listed in the section on *Monitoring*, below.

High conductivity was recorded in the flow from Harbor Island not only after high tides but also during low tides. Conductivity of 20,600 μS/cm was recorded at high tide, indicating that high tide flow from this area contains about 65 percent saltwater. Furthermore, conductivity of 6,500 μS/cm was recorded at low tide, revealing a continuous infiltration of saltwater. This finding points to a problem with infiltration of saltwater absorbed by the dredge material on which the manmade island is built. Flow from Harbor Island was sampled at a West Seattle manhole (C/SEA MH 333), the first manhole to receive the entire flow from Harbor Island. After passing by this manhole, the flow goes through the Delridge trunk across the Duwamish Waterway and then to the Elliott Bay interceptor.

Monitoring

Four sites were selected for more extensive monitoring because high tide conductivity readings at these sites ranged from 15,000 to 31,000 μS/cm, indicating that saltwater comprises a large percentage of the flows from these locations. These sites receive the flows from Harbor Island and the Seattle waterfront. The attached photographs show tidewater leaking through the four City of Seattle overflow gates; the clarity of the water in the two vortex photographs indicates that the flows are comprised mostly of seawater.

The specific locations of the sites selected for more extensive monitoring are as follows.

- Jackson Street (C/SEA MH 041), which receives potential flow from the Washington Street overflow gate (C/SEA MH 047, elevation 6.3 feet).
- Trolley Barn just west of the railroad tracks and near Myrtle Edwards Park (C/SEA MH 008), which receives potential flow from the Vine Street overflow gate (C/SEA MH 058, elevation 4.7 feet).
- Adit Structure near the Pike Street hill climb (C/SEA MH 482), which receives potential flow from the University Street overflow gate (C/SEA MH 455, elevation 6.7 feet) and the Madison Street overflow gate (C/SEA MH 393, elevation 8.3 feet).
- West Seattle (C/SEA MH 333, elevation 6.9 feet), which is the first manhole receiving the entire flow from Harbor Island.

Results from monitoring of conductivity and temperature at the Seattle waterfront sites demonstrate that rapid increases in conductivity and subsequent decreases in temperature correlate with high tides (the correlation is apparent with tides varying from 9 to 11 feet, as well as with any tides above 11 feet). Both correlations point to an intrusion of water from Elliott Bay. The attached graphs show the readings obtained for temperature and conductivity. (Because data for the Adit Structure was obtained on two non-consecutive days, results for this site appear on two separate pages.)

Results from monitoring of conductivity and temperature of Harbor Island flow demonstrate that increases in conductivity correlate with high tides, while temperatures were constant. No overflow gate exists that can impact Harbor Island flow, but high tides appear to raise the saltwater level in the island dredge material. High conductivity readings show a five-hour lag between peaks, caused by the cycling of the two draw and fill pump stations that effectively purge the accumulated saltwater into the King County system. The lag is apparent in the attached graph for the Harbor Island flow, which shows a step-like increase in conductivity. The temperature of the cooler Bay water that enters the Harbor Island dredge material during high tides likely has time to balance out with existing water in the fill prior to infiltrating into the network of sewer lines throughout the island.

Costs and implications

As the result of saltwater intrusion into the King County wastewater treatment system, the County has incurred, and continues to incur, the costs of rehabilitating corroded equipment and treating the saltwater that enters the system. In addition, further investigation of the extent of the damage to the RAS and PE pipes is necessary. Below is a general discussion of the costs associated with repairs, as well as the cost of treating the saltwater that is infiltrating the King County system. A summary follows at the end of the discussion.

To repair the clarifiers, King County has taken them out of service to rehabilitate the corroded equipment with zinc coatings and sacrificial anodes. Ten of the clarifiers have been rehabilitated to date, and King County has a contract in place for the remaining three. The cost incurred for the thirteen clarifiers is $1,200,000.

King County will replace one gate in the next six months and will schedule repairs and replacements for the remaining five gates. The cost incurred for replacing one gate is $350,000.

Damage is expected throughout the 8,000 linear feet of RAS piping at the West Point Treatment Plant, but the extent of this damage is currently unknown, as is the extent of damage to the PE piping. While the three elbow sections of RAS piping examined were installed above ground, most of the RAS piping is extremely difficult to access because it is buried underground and encased in concrete. The pipes range in size from 18 to 60 inches in diameter, with most of the buried pipes measuring between 48 and 60 inches in diameter. Tinnea and Associates recommend an examination of all the pipes and subsequent rehabilitation of any pipes affected by pitting. The original cost of purchasing and installing the RAS piping was $16,500,000. Replacing RAS piping would, of course, also incur the cost of removing old pipe. Repairing or replacing the buried RAS piping would, furthermore, require that King County shut down the West Point Treatment Plant while completing the necessary work.

Tides over 11 feet occur in Elliott Bay approximately 250 times per year, resulting in a total of about 4 to 6 million gallons of tidewater entering the County sewer system each day, the equivalent of 1.46 to 2.19 billion gallons of tidewater per year. The yearly cost of treating tidewater entering the King County wastewater system is estimated at $1,022,000 to $1,533,000. This figure is based on the assumption of a cost of $700 per million gallons of sewage treated.

King County staff recognizes the argument that the only costs for this increased flow is the actual pumping costs. However, this does represent actual increased flows at the plant. The saltwater contributes Total Dissolved Solids (TDS) which must be removed, sulfates that contribute to hydrogen sulfide generation, and chlorides, which accelerate corrosion and may inhibit the flocculation process needed for secondary treatment. Inhibiting flocculation increases the use of polymers at the treatment plant, therefore the cost of treatment.

Increased flows affect the capacity of the conveyance system. Limiting the capacity of the conveyance system increases the frequency of Combined Sewer Overflows (CSO's) during wet weather periods and contributes to Sanitary Sewer Overflows (SSO's) during dry weather flow periods.

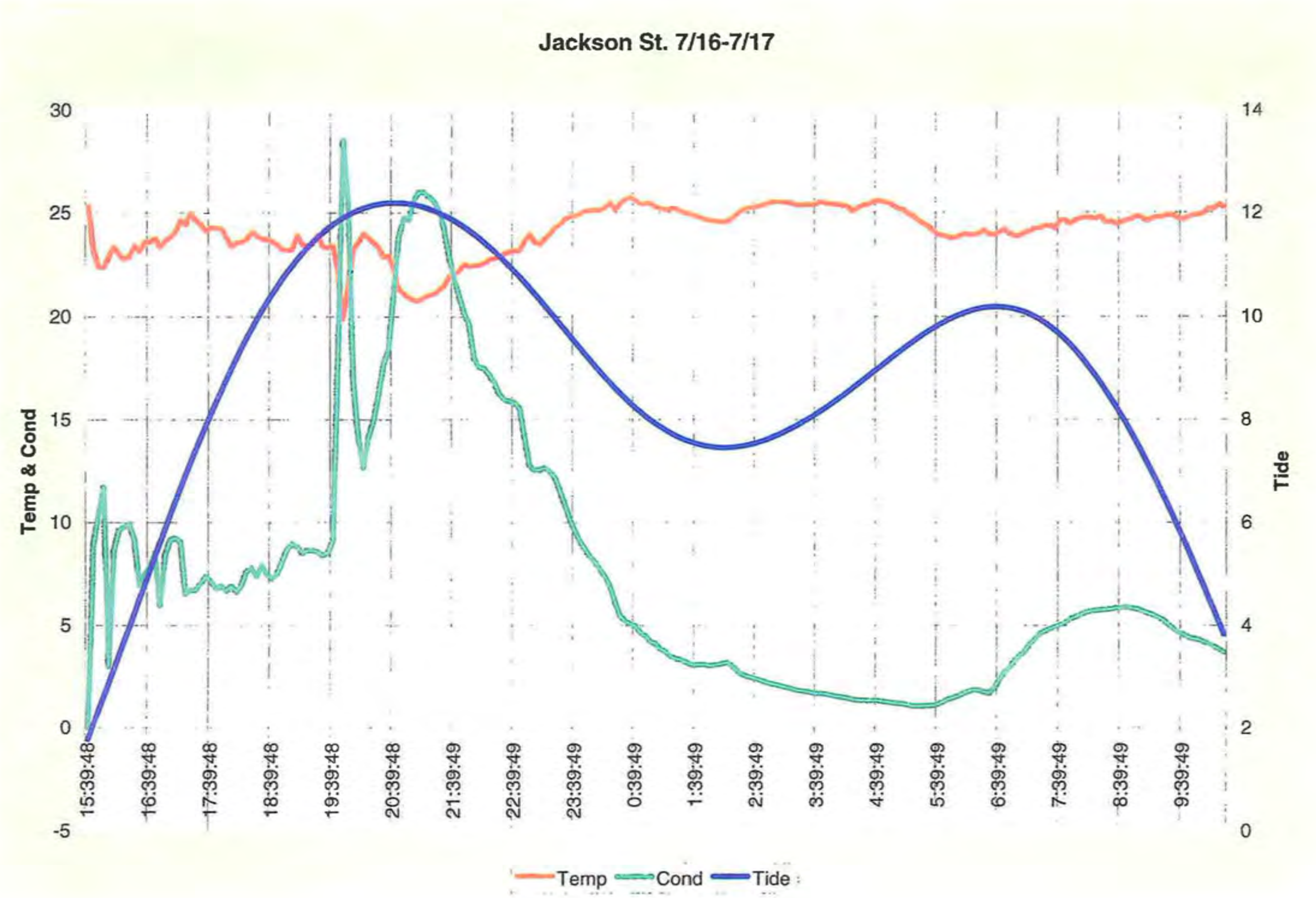
Below is a cost summary. The summary includes neither potential replacement of PE piping nor costs incurred for facilities beyond the West Point Treatment Plant, such as corrosion repair of the Elliott Bay interceptor or gate replacements elsewhere in the conveyance system.

Cost summary

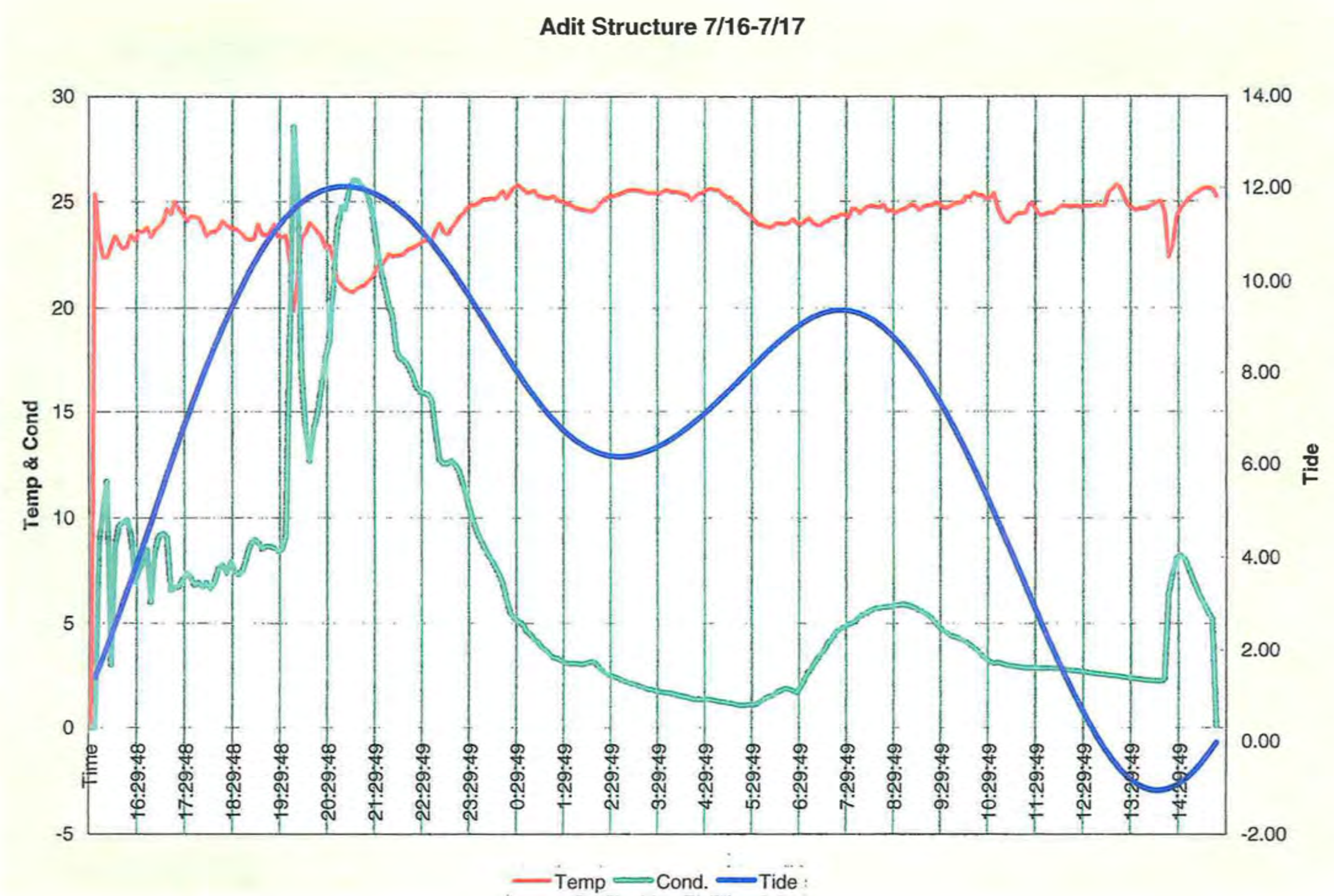
Item	Cost
Rehabilitate 13 clarifiers at 20% of expected service life (2 years instead of 10), based on full cost of $1,500,000	$1,200,000
Replace 6 gates at 15% of expected service life (5 years instead of 30), based on full cost of $2,100,000 (6 gates each at $350,000)	$1,750,000
Replace RAS piping at 15% of expected service life (5 years instead of 30), based on full cost of entire system at $16,500,000 and a conservative estimate that 25% of piping must be replaced	$4,125,000
Total for known one-time costs	**$7,075,000**
Treat 1.46-2.19 billion gallons of tidewater per year	between $1,022,000 and $1,533,000 per year
Total for yearly costs	**between $1,022,000 and $1,533,000**

Recommendations

The King County Wastewater Treatment Division recommends that the City of Seattle repair or replace leaking sewer pipes on Harbor Island and defective overflow gates along the Seattle waterfront. This recommendation is supported by the conclusion of Tinnea and Associates, the third party consultant retained by King County, that the most direct way to control corrosion at the West Point Treatment Plant is to greatly reduce the chloride concentrations in the wastewater flow to the plant.



Jackson St. 7/16-7/17
Temp & Cond
Tide
30
25
20
15
10
5
0
-5
14
12
10
8
6
4
2
0
15:39:48
16:39:48
17:39:48
18:39:48
19:39:48
20:39:48
21:39:49
22:39:49
23:39:49
0:39:49
1:39:49
2:39:49
3:39:49
4:39:49
5:39:49
6:39:49
7:39:49
8:39:49
9:39:49
Temp
Cond
Tide


Adit Structure 7/16-7/17
Temp & Cond
Tide
30
25
20
15
10
5
0
-5
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
Time
16:29:48
17:29:48
18:29:48
19:29:48
20:29:48
21:29:49
22:29:49
23:29:49
0:29:49
1:29:49
2:29:49
3:29:49
4:29:49
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6:29:49
7:29:49
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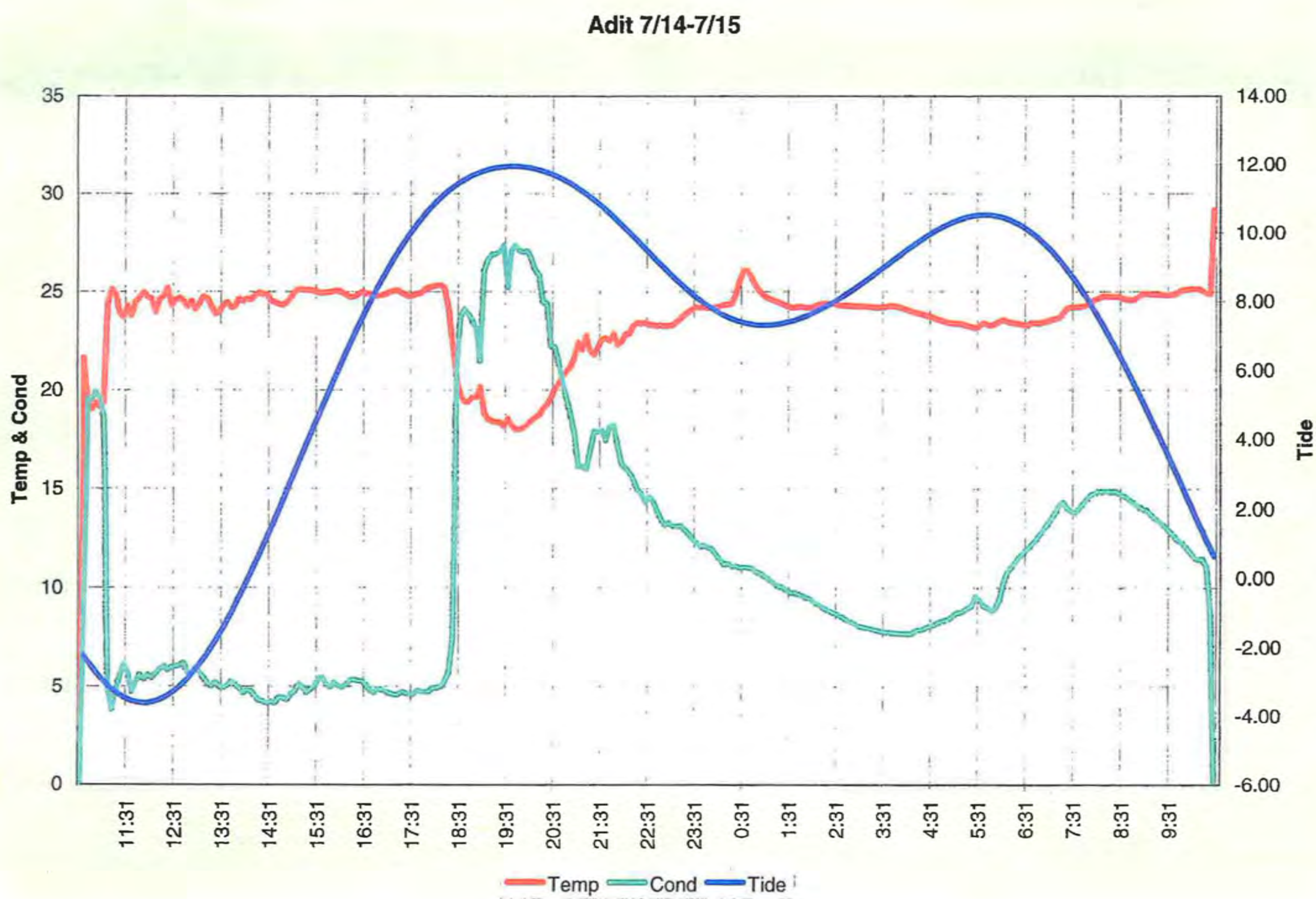
14:29:49
Temp
Cond.
Tide


Adit 7/14-7/15
Temp & Cond
Tide
35
30
25
20
15
10
5
0
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
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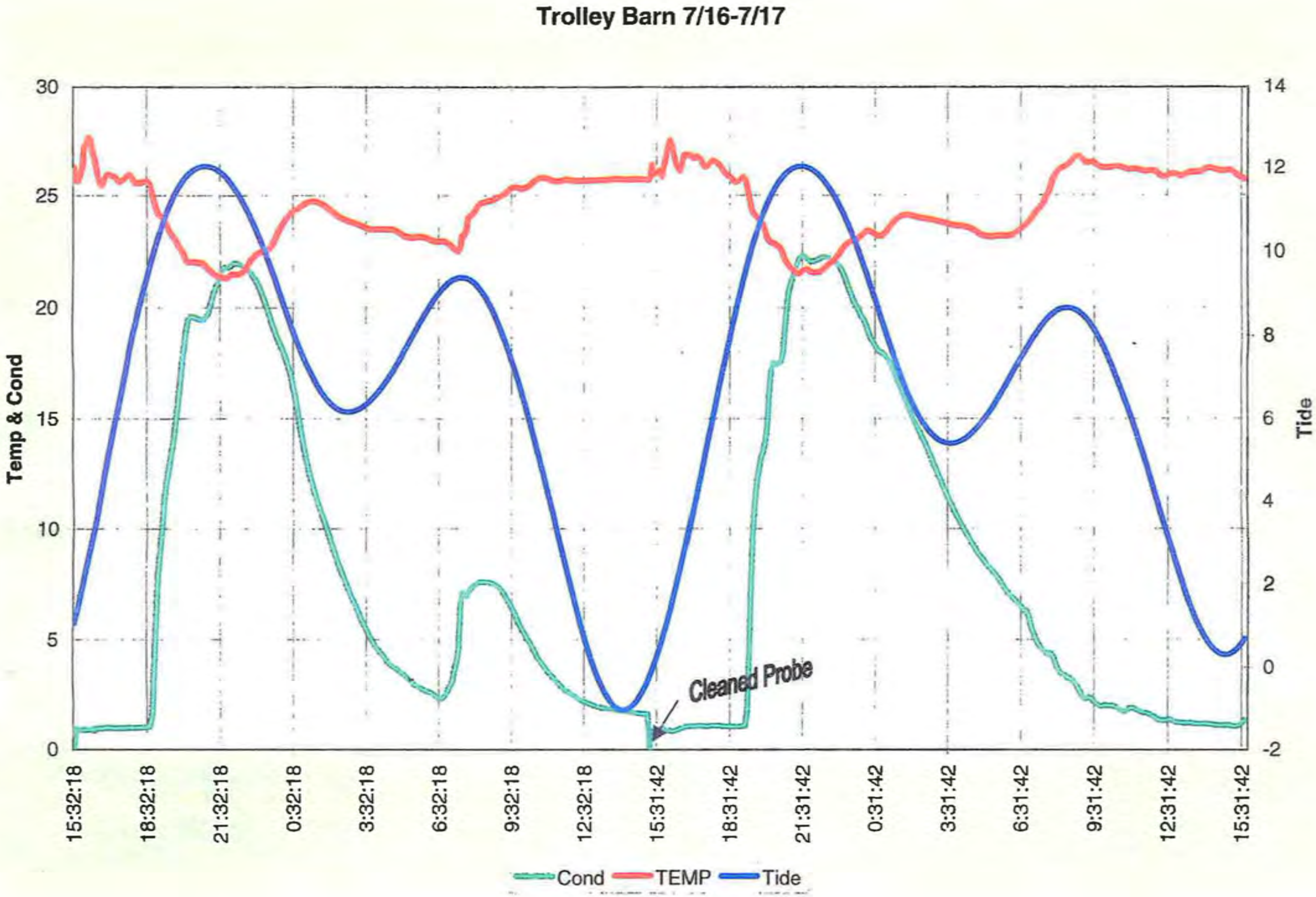
22:31
23:31
0:31
1:31
2:31
3:31
4:31
5:31
6:31
7:31
8:31
9:31
Temp
Cond
Tide



Trolley Barn 7/16-7/17
Temp & Cond
Tide
30
25
20
15
10
5
0
14
12
10
8
6
4
2
0
-2
15:32:18
18:32:18
21:32:18
0:32:18
3:32:18
6:32:18
9:32:18
12:32:18
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18:31:42
21:31:42
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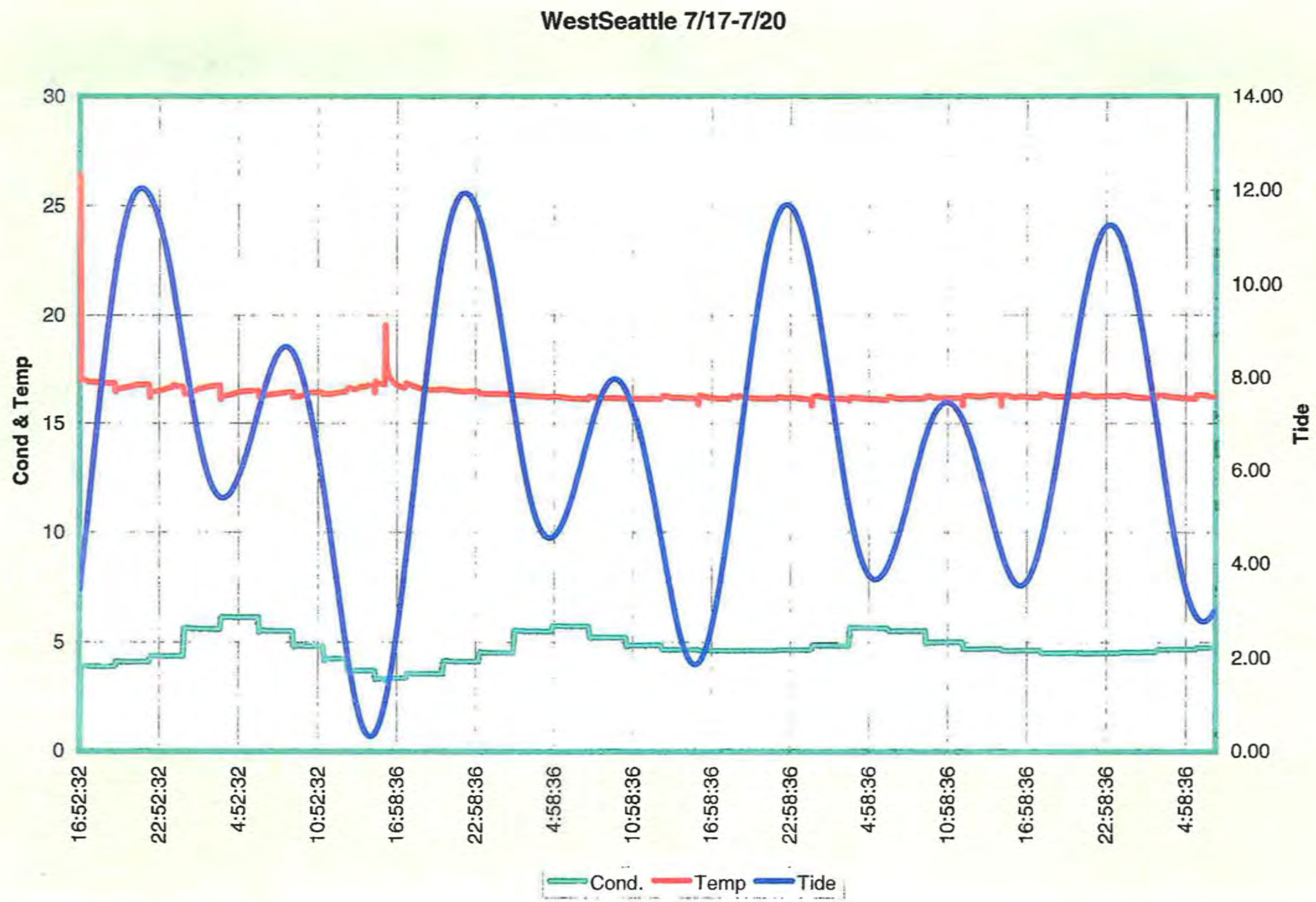
6:31:42
9:31:42
12:31:42
15:31:42
Cleaned Probe
Cond
TEMP
Tide


WestSeattle 7/17-7/20
Cond & Temp
Tide
30
25
20
15
10
5
0
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
16:52:32
22:52:32
4:52:32
10:52:32
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4:58:36
10:58:36
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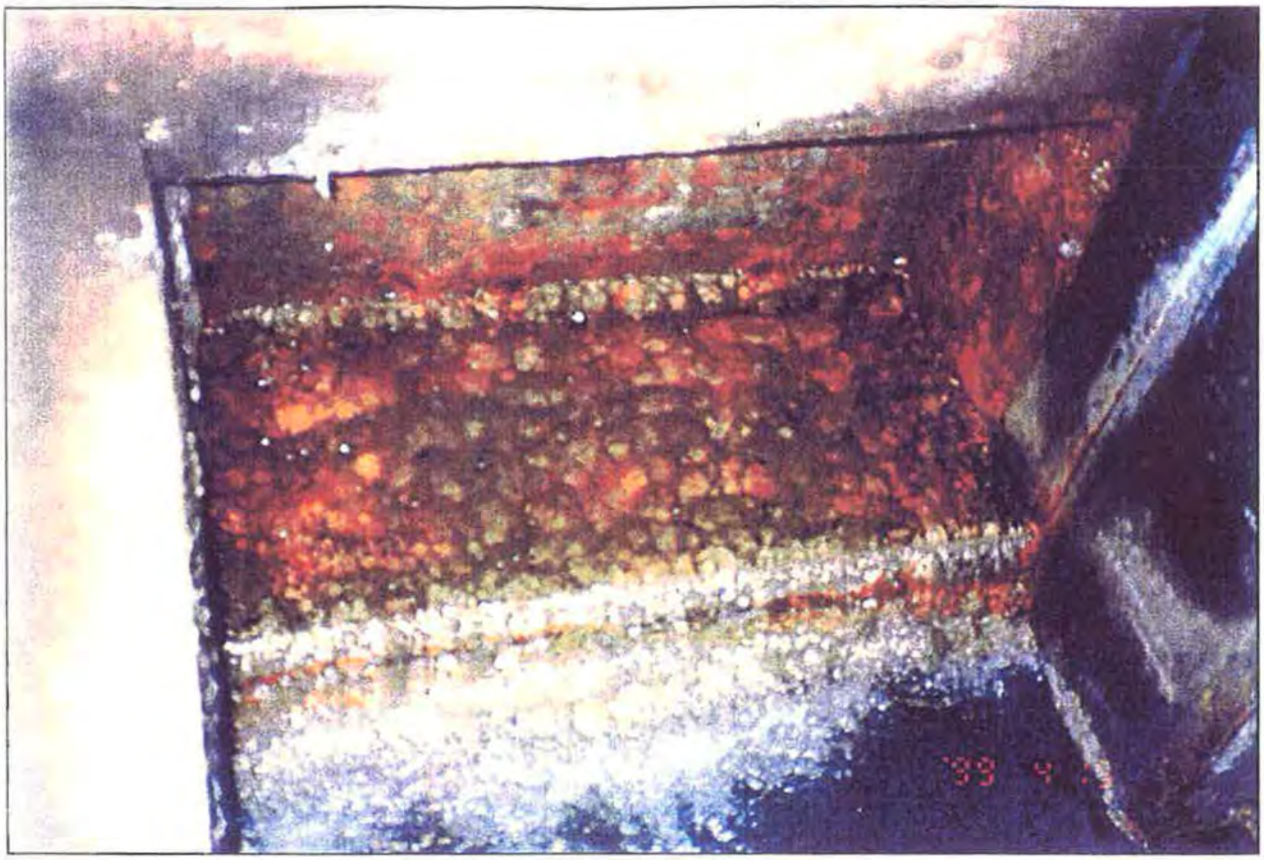
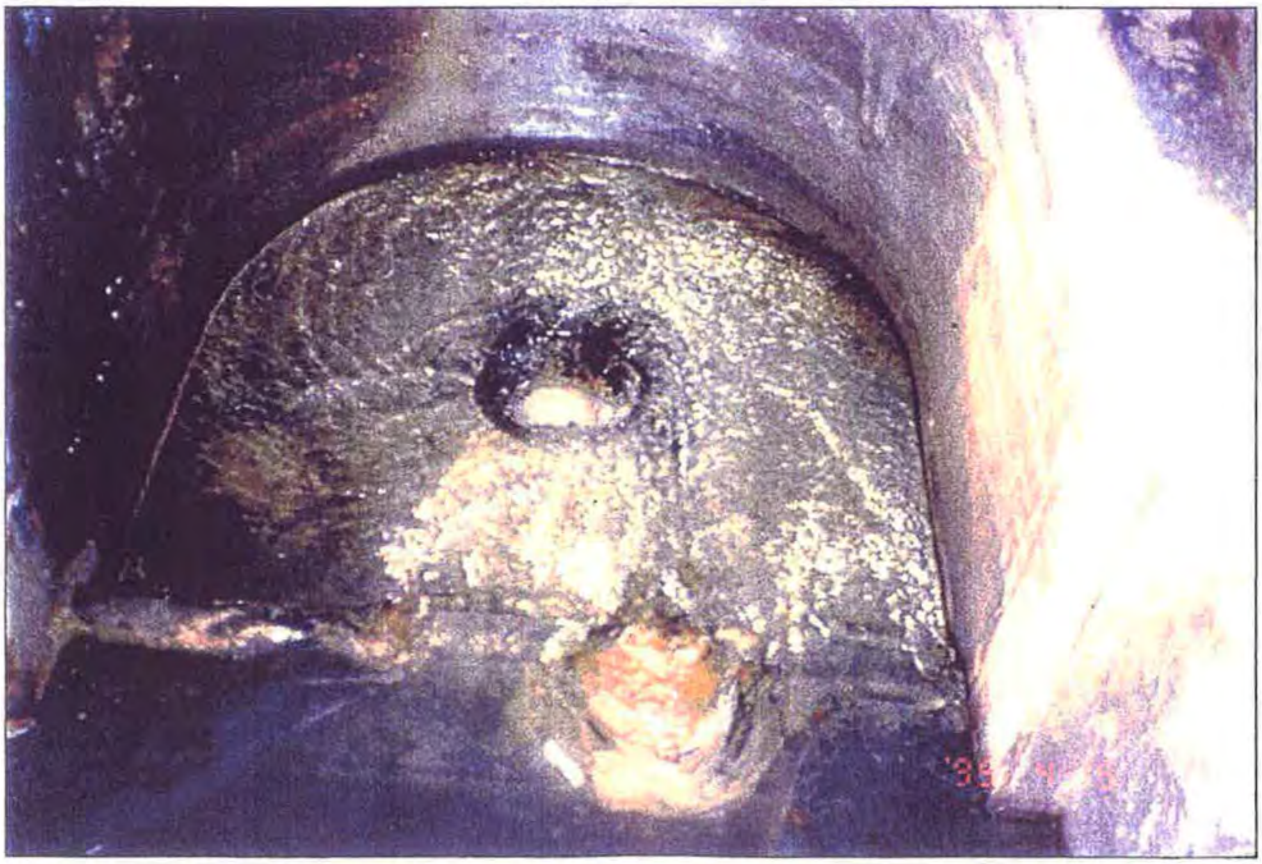
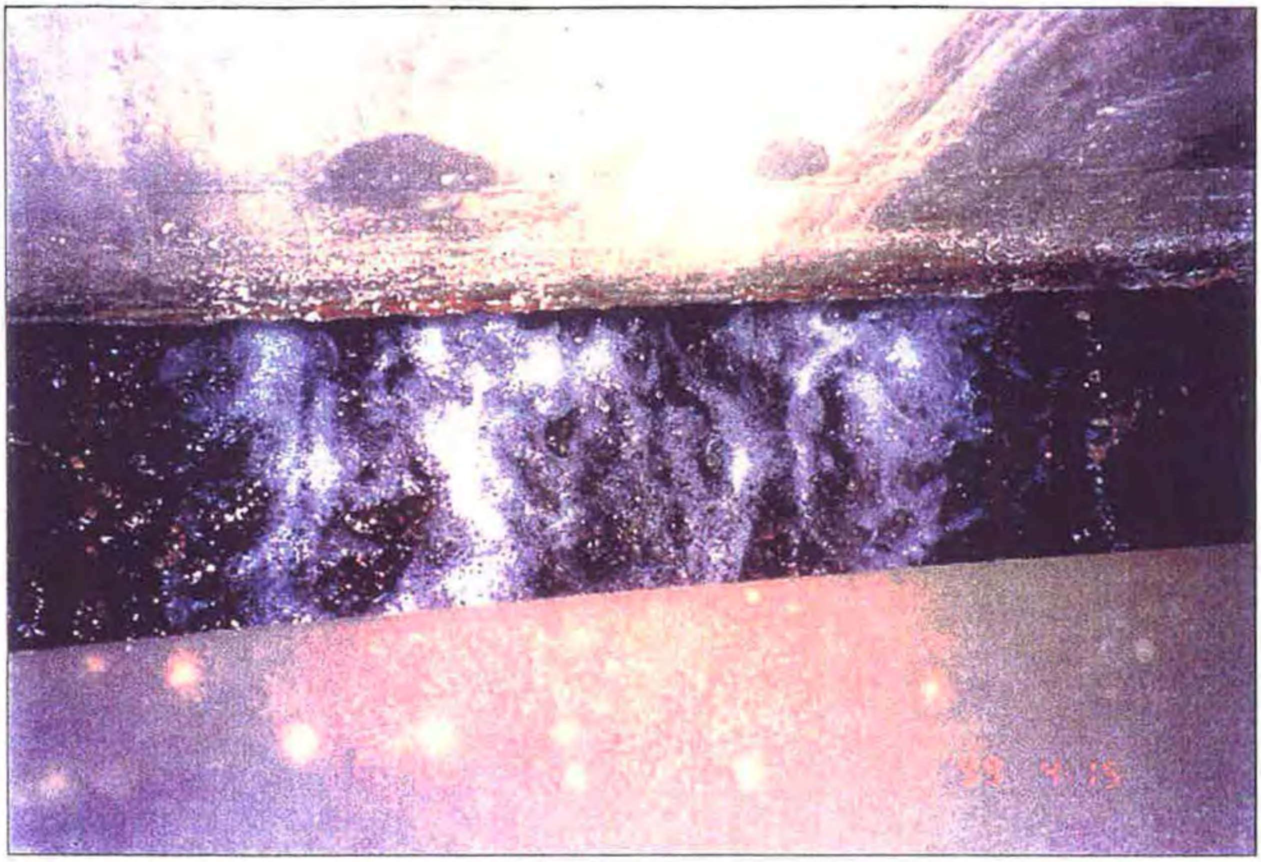
Cond.
Temp
Tide



University Street Gate



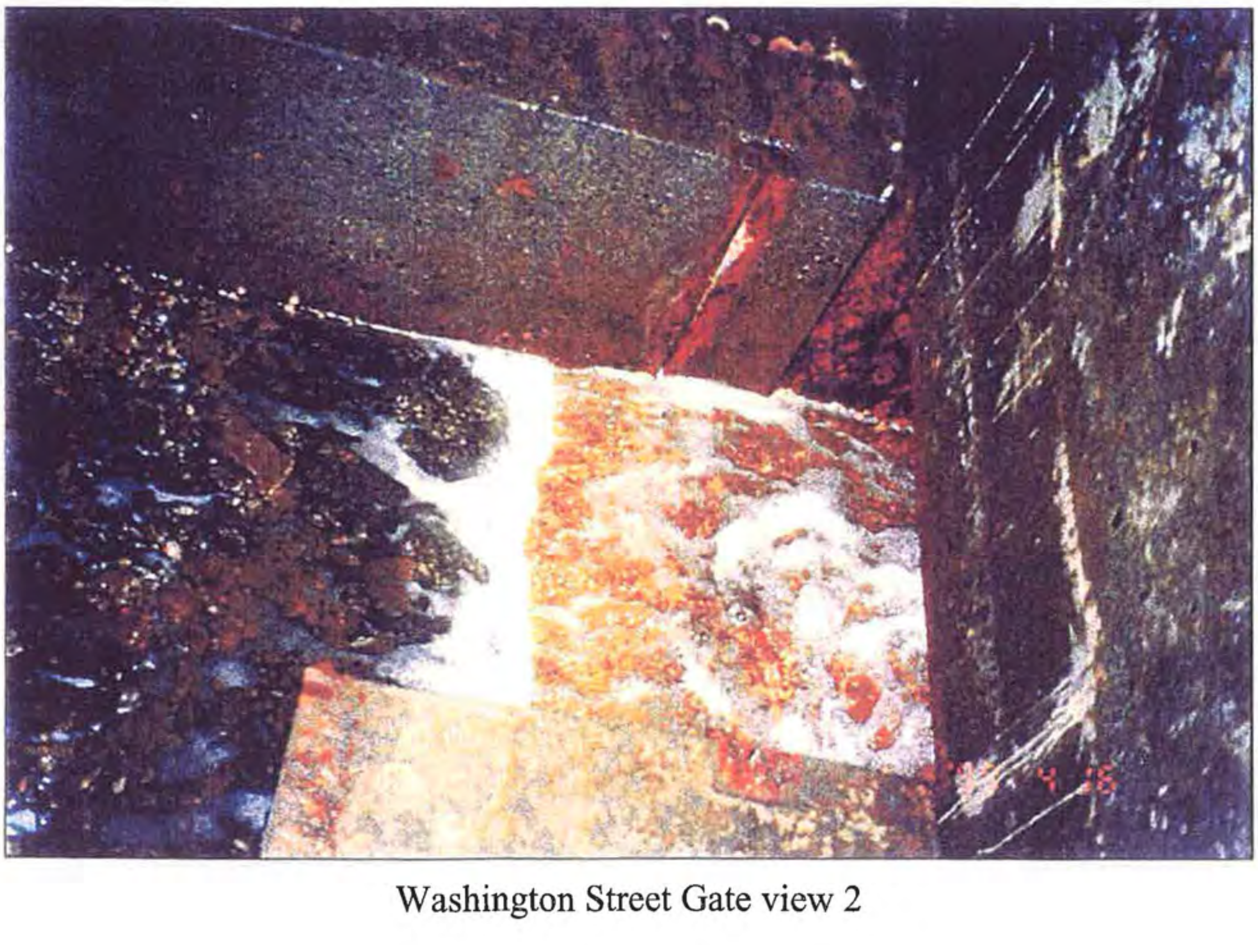
University Street Vortex



Vine Street Leaking Gate

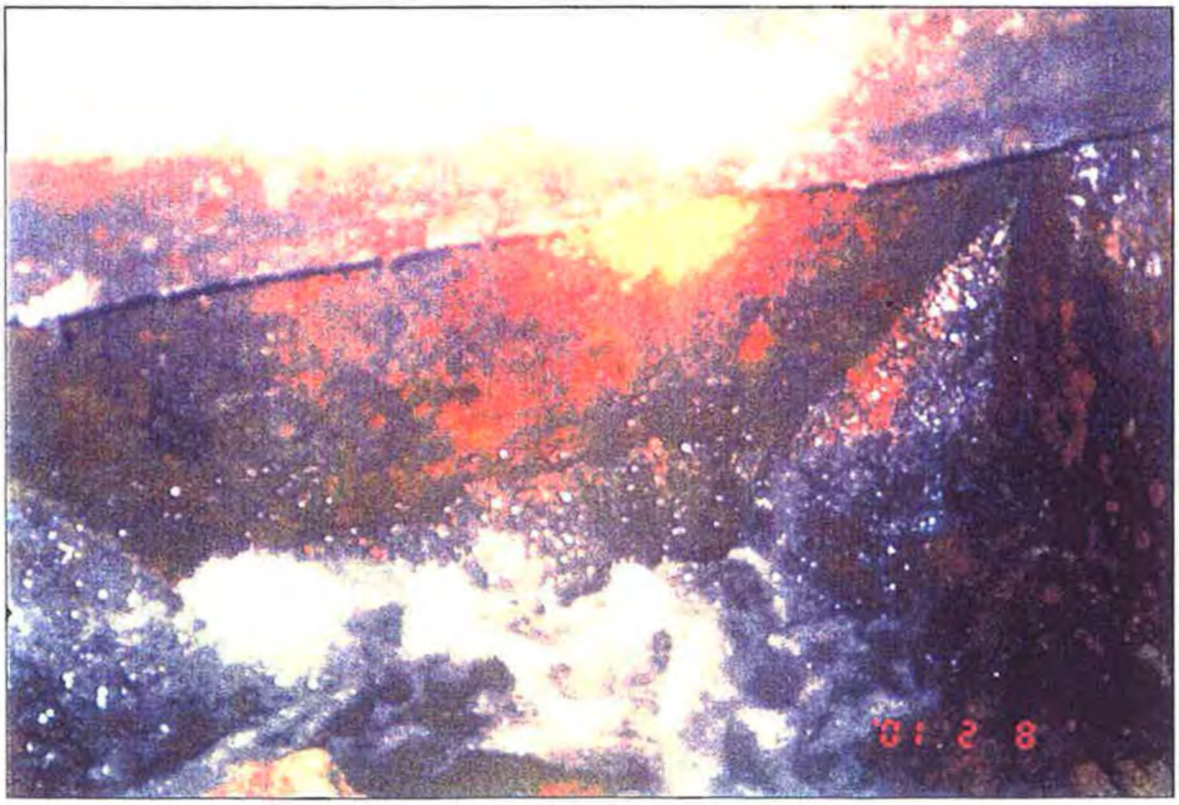
Vine Street Vortex

Washington Street Gate view 1

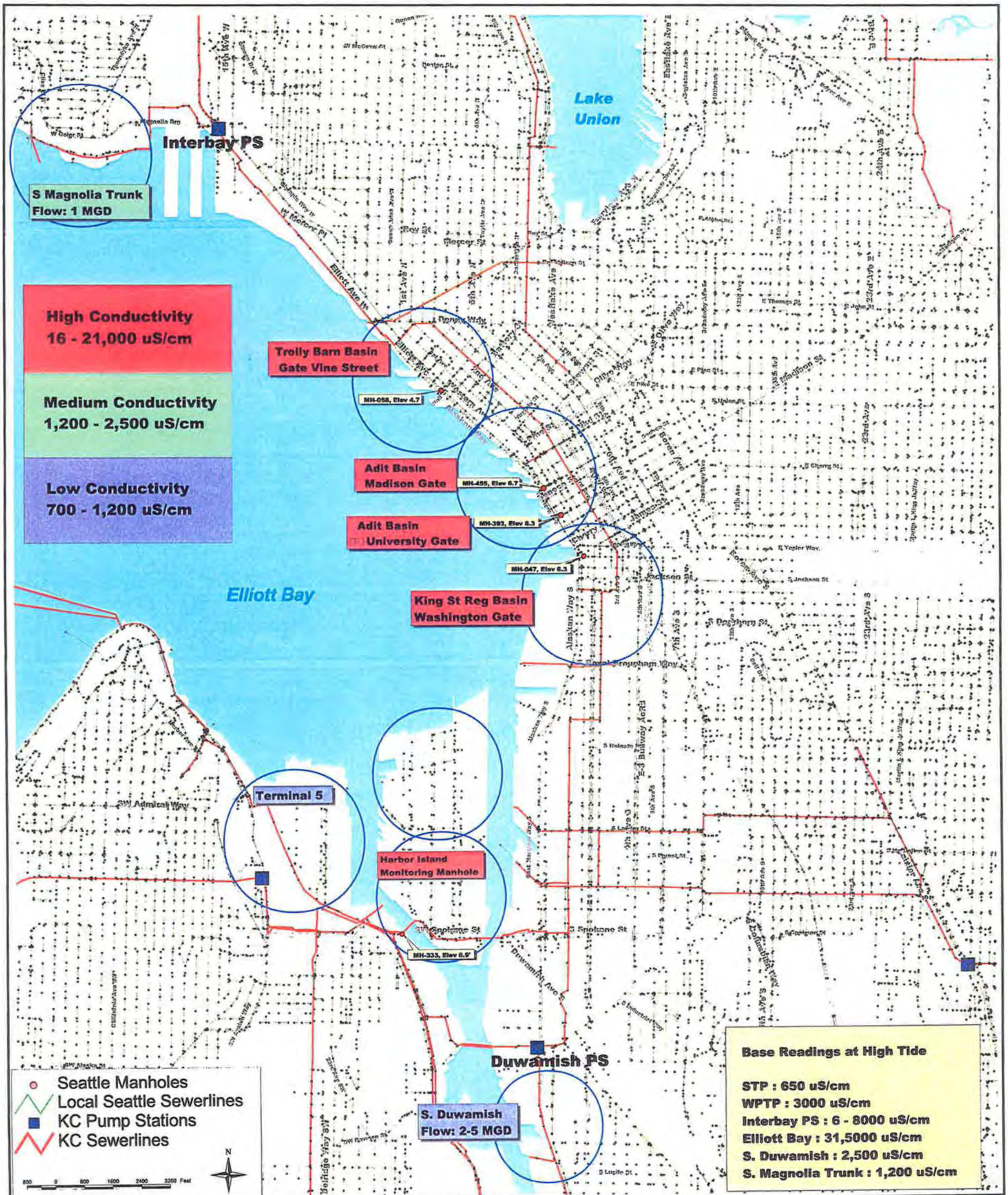


Washington Street Gate view 2

Madison Street view 1



Madison Street view 2



King County
Department of
Natural Resources and Parks
Wastewater Treatment Division

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Seattle Sewer System

Along Downtown Waterfront