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LESSONS LEARNED: ELECTROCOAGULATION TREATMENT OF DREDGE RETURN WATER TO ACUTE AND CHRONIC WATER QUALITY CRITERIA FOR DISSOLVED METALS, TOTAL PCBS, PH, AND TURBIDITY

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ABSTRACT

Building demolition in 2011 at a former airplane manufacturing plant located on the Duwamish Waterway in Seattle allowed for removal of sediment affected by polychlorinated biphenyls (PCBs), hydrocarbons, and heavy metals from the adjacent Duwamish Waterway. Amec Foster Wheeler and DOF designed the final remedy, which included dredging ~160,000 cubic yards (120,000 cubic meters) of contaminated sediments and restoring habitat. Over one-half mile of shoreline was restored to its natural habitat, which also created a resting area for migratory fish. DOF developed dredging design and construction best management practices that were highly instrumented and precise in order to reduce dredge material residuals, re-suspension, and release. For example, using barge-mounted excavators with boom and environmental buckets guided by GPS minimized the release of contaminants during dredging.

Dredge return water treatment criteria required by U.S. EPA and Washington State Department of Ecology were very stringent, with part per trillion requirements for total PCBs and part per billion requirements for dissolved heavy metals. To meet the strict discharge criteria, the team used electrocoagulation as the primary treatment. The Dredge Return Water System (DRWS) was designed to meet the highly variable conditions of the site (tidal fluctuations, salt water/fresh water changes), changes in dredging technique (mechanical, hydraulic), and limitations in project footprint, timeline, and transport.

Over 70 million gallons (265 million liters) of water were successfully treated to meet discharge criteria in the three construction seasons between January 2013 and March 2015. The dredging project was highly successful with very little turbidity or residuals generated and no exceedances of water quality criteria at the DRWS discharge. Lessons were learned about flow rate and buffer capacity requirements, the value of equipment robustness and redundancy, and how to treat water ranging from 15 percent solids to nearly pure rainwater with one combined system.

Keywords: sediment, contaminated, hydraulic, mechanical, GPS

INTRODUCTION

This project used electrocoagulation to process dredge return water generated by the mechanical and hydraulic dredging of sediment affected by polychlorinated biphenyls (PCBs) from the Duwamish Waterway. It was part of an Early Action by The Boeing Company at the upstream end of the Lower Duwamish Waterway Superfund site. The project was completed over three discrete construction seasons (CS) beginning in 2013. This was an innovative use of electrocoagulation technology, which was selected because typical water treatment methods for solid separation including chemical flocculants or coagulants were not allowable by regulatory agencies within the required project timeline and could not meet metals criteria for discharge water.

Project Location

The project site is located on the Lower Duwamish Waterway, a man-made, channelized waterway on the south end of Seattle that flow north and eventually enters the Puget Sound in Elliott Bay (Figure 1).

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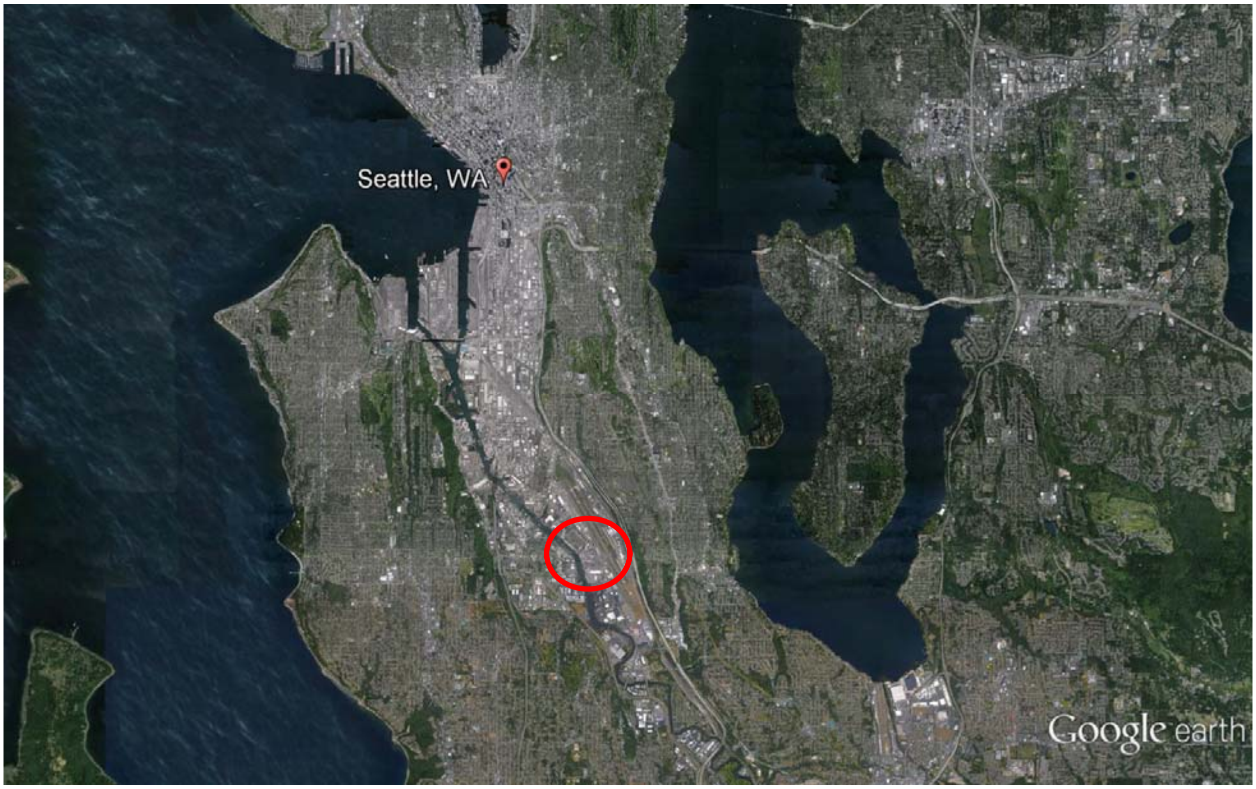

Figure 1. Site location.

The project was completed by The Boeing Company as a remedial action on the shoreline and in the Lower Duwamish Waterway around the Boeing Plant 2 site. The Boeing Plant 2 sediment and shoreline bank remedial action was conducted pursuant to an Administrative Order on Consent under the Resource Conservation and Recovery Act (RCRA). The Boeing Plant 2 site is also designated as an Early Action site within the Lower Duwamish Waterway Superfund site.

Boeing can trace its nearly 100-year history back to the banks of the Lower Duwamish Waterway. In 1936, the federal government ordered 13 of Boeing's new B-17 Flying Fortress, the nation's first four-engine bomber. Due to the lack of space at Boeing's original manufacturing plant, the company purchased 28 acres (113,000 square meters) along the Lower Duwamish Waterway and constructed an assembly building to accommodate the government's growing need for military aircraft.

By the end of World War II, Plant 2 had expanded to almost 1.7 million square feet (.16 million square meters). To protect Plant 2 from any foreign surveillance, the U.S. Army Corps of Engineers camouflaged the building's roof to resemble a hillside neighborhood dotted with homes and trees. From the air, Plant 2 seemed to disappear into the residential communities surrounding it.

In addition to supplying the military with nearly 7,000 B-17s, Plant 2 provided thousands of Washington men and women with manufacturing and industrial jobs. As more men left the assembly lines for the front lines, Boeing began recruiting women, who were known as Rosie the Riveters and built an average of 12 B-17s a day.

In December 2011, the aging Plant 2 facility was demolished to clear the way for Boeing's cleanup and habitat restoration efforts along the Lower Duwamish Waterway. Over 85 percent of the building materials were recycled or reused, including steel and wood beams, copper wiring, and concrete.

Duwamish Waterway

The Duwamish Waterway is an urban, industrial waterway created by channelizing the Green River in the early 20th century. The waterway has historically been used to support a variety of industrial businesses including aircraft manufacturing, chemical and petroleum processing, metal recycling, cement kilns, ship building, commercial fishing and shipping. In addition to a number of industrial uses and properties along the waterway, there are also residential neighborhoods, marinas, parks and other public spaces. The Duwamish waterway is a mix of freshwater (flowing from south to north) and salt water (which encroaches and recedes based on the tides.)

The northern end of the Duwamish Waterway is connected to Elliott Bay and is tidally influenced. The typical tide range at the site is approximately 8 feet (2.5 meter) with maximum range of -3.5 feet to +12 feet mean lower low water (MLLW). During higher tides, the salt wedge in the Duwamish Waterway is typically upstream of the project site, resulting in fresh river water overlying the marine water. This creates complications for the processing of dredge return water; the salinity of the dredge return water varies with the tide and river discharge, and the varying salinity changes the conductivity of the dredge return water and its salt content.

In addition to tidal influences, water levels and currents also varied because river flow was mainly controlled for the most part by upstream dams. In addition, all dredging was performed during the wetter fall and winter months, resulting in precipitation and snowmelt causing significant variation in river flow and background turbidity.

Project Approach

Based on extensive sampling, Amec Foster Wheeler Environment & Infrastructure, Inc. (Amec Foster Wheeler) developed a detailed characterization of the contaminated sediments, and a three-dimensional map of the contaminated sediments. Dalton, Olmsted & Fuglevand, Inc. (DOF) then developed dredging design and construction best management practices that were highly instrumented and precise in order to minimize cross-contamination and the amount of dredging necessary to remove the contaminated sediments. Sediments were generally loaded to a barge and then dewatered as much as practicable by pumping water to the Dredge Return Water System (DRWS) for treatment. The dewatered sediment barge was then brought to a transload facility for stabilization and loading to rail cars for disposal at the appropriately permitted landfill.

The work was performed during three discrete construction seasons, controlled by a number of factors including allowable in-water work seasons and Tribal fishing on the waterway. Construction season 1 (CS1) was from January to March 2013, CS2 was from January to March 2014, and CS3 was from October 2014 to March 2015. During the course of the project, a new bridge spanning the site was constructed to replace an old bridge that was demolished. This created challenges in executing the dredging, including phasing of the dredge work and dredging under the newly constructed bridge during CS3.

Dredge Material

The dredge material removed from the Duwamish Waterway consisted primarily of the “recent depositional” material and a smaller portion of the underlying “native” material, as well as debris that was co-mingled with the sediment and water that was captured in the dredging bucket. The grain size of recent depositional material trends from sandy silt to silty sand with gravels in places. Additional gravel was also encountered in specific areas, particularly near the bridge.

The constituents of concern primarily include PCBs, along with polycyclic aromatic hydrocarbons (PAHs), metals, and other organic compounds. The majority of dredge material generated by the project contained PCBs at less than 50 parts per million and qualified for RCRA Subtitle D Landfill disposal. Approximately 300 cubic yards (230 cubic meters) of dredged material from the Early Removal Area (ERA) areas required disposal at a RCRA Subtitle C Landfill and was managed as a separate waste stream.

Dredge cut thickness was up to 15 feet (4.6 meters) in some locations, with dredging performed to a maximum depth of approximately -35 MLLW, which required frequent movement of the dredge to avoid grounding or to reach the deepest cuts near the navigation channel. Dredging work areas were on both sides of the bridge, as shown on Figure 2.

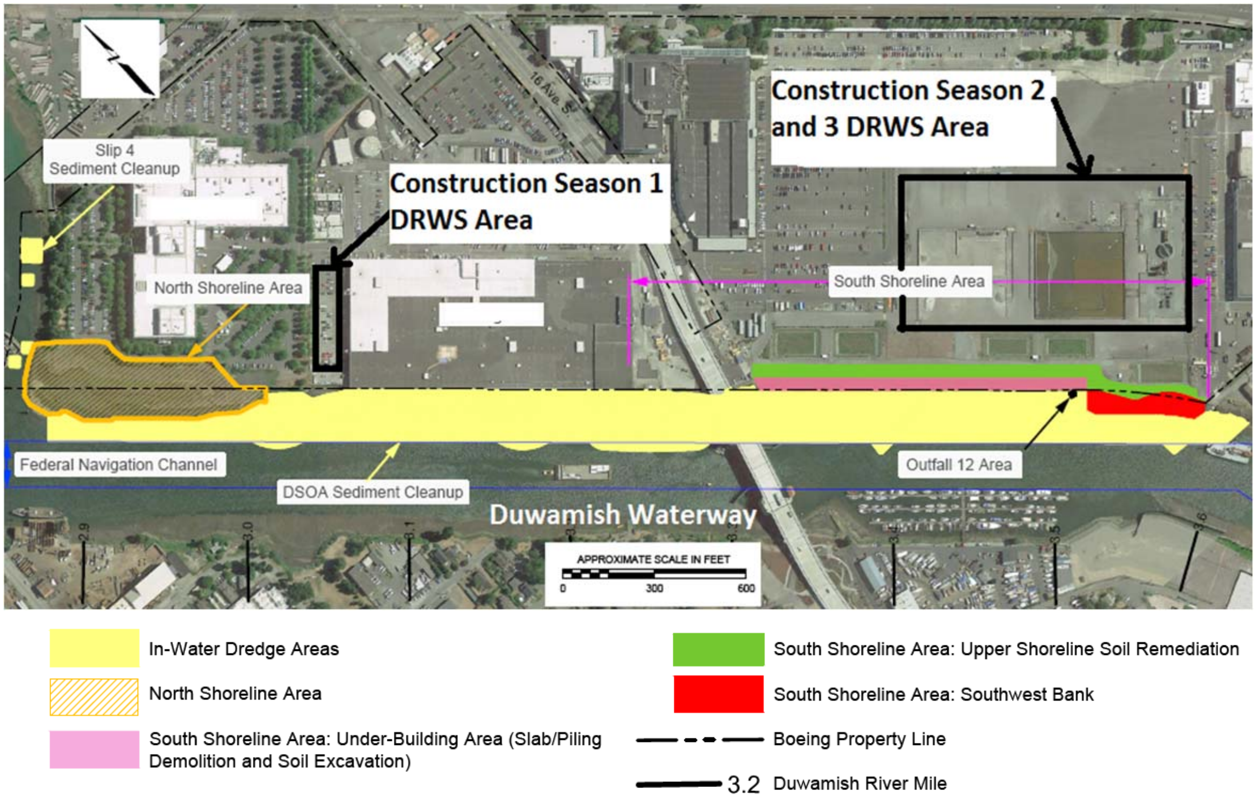

Figure 2. Dredging work areas.

Mechanical Dredging

With the exception of a small amount of diver-supported hydraulic dredging performed in the immediate vicinity of the recently completed South Park Bridge, all of the dredging was performed by precision mechanical dredge including the use of a fully instrumented excavator with a 4-cubic-yard (3-cubic-meter) Young's re-handling clamshell bucket, modified for use as a dredging bucket. The Young's bucket has a relatively level cut over approximately 70 percent of its open footprint and, based on observation, tends to remove material closer to its in situ water content with less mixing and remolding with the overlying water.

During the mechanical dredging work, all materials removed from the waterway by the dredge were placed into sealed, water tight bin barges (Figure 3). As each dredge bucket cycle was performed, 4 cubic yards (3 cubic meters) of water and dredge material, in varying proportions, were placed into the barge. During the initial dredge passes in areas of thicker cuts and softer material, higher fill factors on the order of 75 to 80 percent were typical. Over-penetration of the bucket into the sediment or overfilling of the bucket was avoided to the extent practicable, in order to reduce water quality impacts and residual formation. During final pass dredging, which typically involved removing only the last few inches of sediment (which was usually a stiffer, silty sand material), fill factors on the order of 25 to 50 percent were typical. For any given cycle time, the rate at which water accumulates in the barge is a function of the fill factor — the lower the fill factor, the greater the rate of water accumulation in the barge. As a result, the quantity of total suspended solids and water produced was quite variable from moment to moment, over the course of an individual shift and also over the course of several days.

Figure 3. Loaded sediment barge alongside water barge prior to pump-off.

Water that accumulated within the dredge barge was then pumped to the upland water processing system. This was sometimes done concurrently with the dredging and at other times after a barge was loaded. Water was pumped from the barges to the shore based processing system using a submersible pump positioned within the sediment barge by a small crane (Figure 4). The water was pumped through a 6-inch (15-centimeter) diameter floating high density polyethylene (HDPE) single-wall pipeline to the shore.

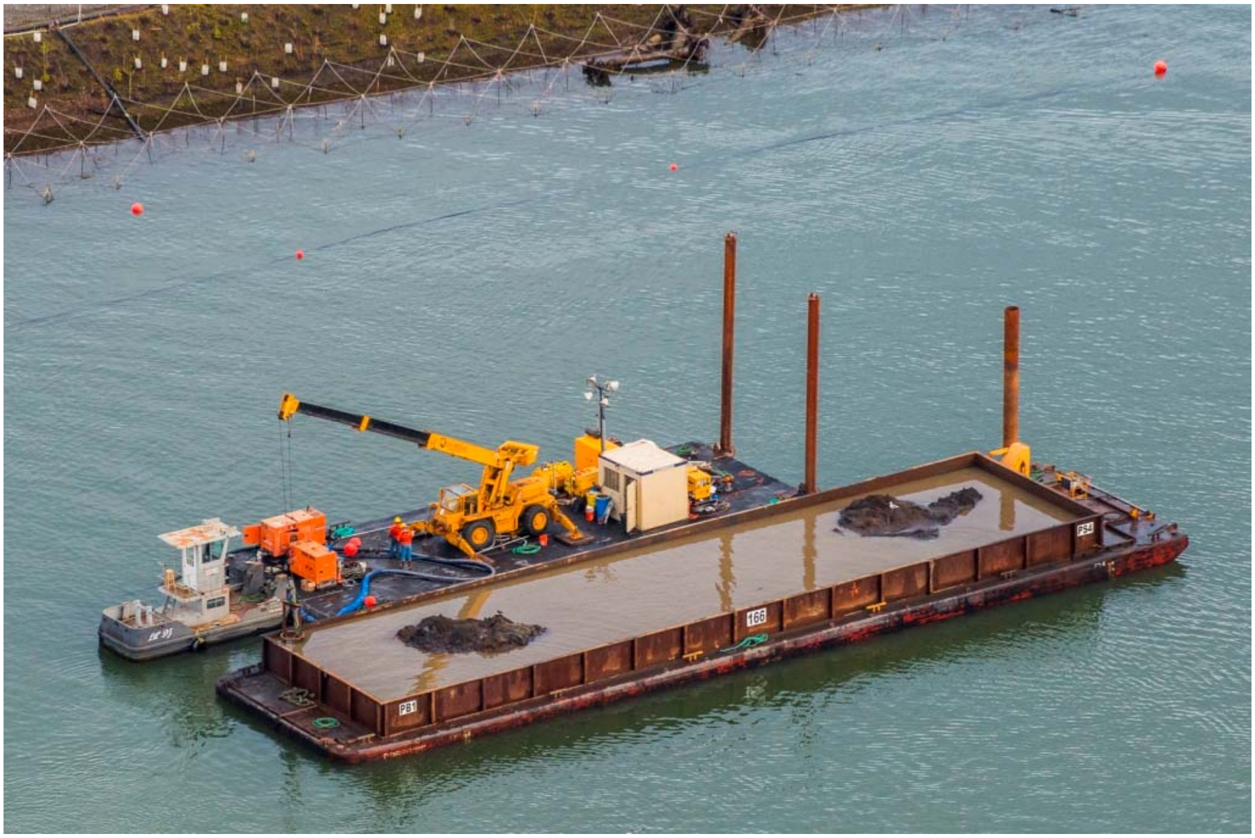

Figure 4. Close-up of a loaded sediment barge alongside water barge prior to pump-off.

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Hydraulic Dredging

During CS3, diver-operated hydraulic dredging was performed underneath the newly constructed South Park Bridge to removed affected sediment within that part of the Duwamish Sediment Other Area (DSOA). Divers used a 6-inch pump to hydraulically remove dredge material, including gravel, from the area under the bridge. The dredge material was then pumped directly to the DRWS for treatment. The slurry content during hydraulic dredging ranged from 5 to 15 percent. Roughly 600 cubic yards (460 cubic meters) was dredged from the waterway using this method, with 100 percent of the solids managed at the DRWS and no solids sent to the transload facility directly by barge. Diver dredging was typically performed one shift (10 hours) per day, five or six days per week.

Early Removal Area Dredging

ERA sediments were mechanically dredged and placed on a sediment barge. However, in order to minimize risk during transfer, these sediments were then mixed with additional water and pumped to the DRWS for treatment. The slurry content during ERA dredging ranged from 5 to 10 percent. Roughly 300 cubic yards (230 cubic meters) was dredged from the waterway using this method with 100 percent of the solids managed at the DRWS and no solids sent to the transload facility.

Dredge Return Water Production

During the mechanical dredging process, as dredge material and water were placed within the barge, a submersible pump was suspended within the bin barge and operated to remove ponded water to the extent practicable. This pump had a maximum flow rate of approximately 1,200 gallons per minute (gpm) (4,500 liters per minute [lpm]). However, the pump only operated at this maximum rate for limited durations, typically to remove the final ponded water as a barge approached capacity. The ponded water was pumped through a floating pipeline to shore, where the water was treated prior to discharge back to the Duwamish Waterway.

During dredging operations, an empty barge was positioned alongside the dredge. The mechanical dredge loaded the barge. As sediment and water were placed into the barge, free water ponded until a suitable depth was achieved for pumping operations to begin. Once pumping was started, the flow rate was matched to dredge water production by the mechanical dredge. This typically ranged from 200 to 600 gpm (760 to 2300 lpm). The rate of water production varied within this range for hours or days at a time or varied barge by barge as the dredge moved through different cuts. For example, a typical pattern would be water was produced at a rate of ~ 200 gpm (760 lpm) for four hours, stopped completely for a half hour, then resumed at 600 gpm (2,300 lpm) for the next four hours as the dredged moved through various portions of the site, with varying cut thicknesses or dredge passes being performed. Typically, as the sediment barge neared capacity, the dredge return water pump-off rate increased to allow a final pump-off of water prior to releasing the barge from the dredge. Pumping then stopped for a period of time—typically 10 to 40 minutes—while a full sediment barge was swapped for an empty one, at which time dredging and pumping resumed.

At other times during the mechanical dredging work, the water could not be pumped off concurrently with barge loading, so instead the barge was loaded to capacity during dredging and the loaded barge then moved to the water barge for pump-off (while a second barge was positioned at the dredge). The water from the loaded barge would then be pumped off to the DRWS at the higher end of the pump's flow rate. Once dewatered, the barge would be sent back to the dredge for additional loading, followed by an additional pump-off before being sent to the transload facility for offloading.

Original Water Treatment Design

At time of project bidding and award, it was anticipated that a DRWS (including a typical mixing zone) would be permitted and that dredge return water processing protocols that have been followed on similar projects in Puget Sound would meet regulatory requirements. Such a system was anticipated to use chemical polymers (coagulants and flocculants) as needed to support water processing. Geotubes were planned to be used to separate the flocculated/coagulated solids prior to discharge of the processed water back to the Duwamish Waterway.

Changes to Regulatory Requirements

During project permitting (post-project award, but prior to mobilization), the Washington State Department of Ecology (Ecology) determined that a mixing zone was not applicable to the project, that water quality criteria would need to be met prior to discharge of dredge return water, and that if chemical flocculants or coagulants were to be used, a complete set of toxicity tests (six months of lab studies on populations of fish, plants, and other biota to measure toxicity) would be required before Ecology could approve their use. Such testing time would have required delaying the start of the project by a year until the next in-water construction season.

As a result, the water quality criteria (Tables 1 and 2) would have to be met in the discharge pipe from the DRWS. When these additional water quality criteria were required by Ecology at the end of 2012, the design of the DRWS for CS1 changed considerably. The major limitations (in addition to the limited time to make changes), included:

- Very few flocculation/coagulation chemicals that met all Ecology requirements for direct discharge to surface water bodies;
- Very few readily-available treatment technologies that could treat for both dissolved metals and dissolved PCBs;
- South Park Bridge construction (details discussed below); and
- Almost no electrical availability, so electricity was primarily provided by diesel generators.

Table 1. Discharge water quality standards-conventional parameters.

Parameter	Excellent Quality – Water Quality Standards
Temperature	>16°C (or within 0.3°C of 16°C; 1-day maximum), no incremental increase of more than 0.3°C (7-DADMax) <16°C (or more than 0.3°C below 16°C [<15.7°C]) incremental temperature increases resulting from individual point source activities must not, at any time, exceed 12/(T-2) as measured at the edge of a mixing zone boundary, where T = highest ambient background in the vicinity (°C)
Dissolved oxygen	>6.0 mg/L at compliance boundary
Turbidity	If background <50 NTU, <5 NTU above if background >50 NTU, <10% increase
pH	Within range of 7.0 to 8.5, with human-caused variation <0.5 units

Abbreviations:
7-DADMax = 7-day average of daily maximum temperatures
C = degrees Celsius
mg/L = milligrams per liter
NTU = Nephelometric turbidity units

Table 2. Discharge water quality standards-chemical parameters.

	Acute Water Quality Standards [1]		Chronic Water Quality Standards [1]		Proposed Reporting Limit
	Criterion	Criterion Basis	Criterion	Criterion Basis	
Metals (µg/L) [2]					
Cadmium	40	1-hour average water column concentration	8.8	4-day average water column concentration	0.1
Total Chromium [3]	1,100	1-hour average water column concentration	50	4-day average water column concentration	0.5
Copper	4.8	1-hour average water column concentration	3.1	4-day average water column concentration	0.5
Lead	210	1-hour average water column concentration	8.1	4-day average water column concentration	0.1
Mercury	1.8	1-hour average water column concentration	0.025	4-day average water column concentration	0.02
Silver	1.9	Instantaneous average water column concentration	1.9 [4]	Instantaneous average water column concentration [5]	0.2
Zinc	90	1-hour average water column concentration	81	4-day average water column concentration	4.0
PCBs (µg/L)					
Total PCBs [6]	10	24-hour average water column concentration	0.03	24-hour average water column concentration	0.01

Notes:

1. Lowest of National Recommended Water Quality Criteria: Aquatic Life Criteria. U.S. Environmental Protection Agency, http://water.epa.gov/scitech/swguidance/ standards/criteria/current/index.cfm or Water Quality Standards for Surface Waters of the State of Washington
2. Acute and chronic criteria for metals (except for mercury) are based on the dissolved fraction. The chronic criterion for mercury is based on total recoverable and the acute criterion is based on the dissolved fraction.
3. Acute and chronic criteria for chromium is for the hexavalent form. Hexavalent chromium is not one of the chemicals of concern at the Boeing Plant 2 site; therefore total chromium will be reported.
4. There is no chronic criterion for silver; the acute criterion of 1.9 µg/L will be used as the chronic criterion.
5. There is no chronic criterion for silver; the acute criterion basis is used.
6. Criteria for total PCBs based on total recoverable fraction (EPA 2002).

Abbreviations

µg/L = micrograms per liter

EPA = Environmental Protection Agency

PCBs = polychlorinated biphenyls

Schedule

Several limiting factors complicated the scheduling of work at the site. The foremost was the requirement of all in-water work to be performed in the "fish window" (between August 1 and February 15) in order to protect endangered species of migrating fish. With additional regulatory approvals, short extensions to in-water working periods was possible, but otherwise no in-water work outside this window was possible. With that in mind, the proposed construction schedule was for three seasons of dredging, from August to February in 2013, 2014, and 2015.

Several additional factors led to changes in the schedule. These complicating factors included the South Park Bridge construction (Figure 5) and three neighboring dredging projects.

Figure 5. South Park bridge demolition and construction.

The site was bisected by the South Park Bridge (Figure 5), which was under construction from before the project started until July 1, 2014. Work was performed on both the north and south sides of the South Park Bridge at various phases of the project, as described below. While the bridge was under construction, barge and tug traffic through the bridge construction area was severely limited and no piping (either on land or water) was allowed through the bridge construction area. These restrictions made detailed coordination for large on water vessels through the bridge necessary, and restricted the possible location(s) of the DRWS.

As a result, in-water work, including removal of material from the Duwamish Waterway, was limited each year to an in-water construction season as described below.

- Construction Season 1 (CS1) extended from January 2, 2013 to March 8, 2013. Work was performed on the north side of the South Park Bridge.
- CS2 was delayed until January 2, 2014 but extended to March 8, 2014. Work was initially planned to occur on both the north and south sides of the South Park Bridge, requiring two dredge return water processing systems on both sides of bridge. However, the dredging plan was re-arranged to avoid conflicts, and only one system was necessary for CS2, and was located on the south shoreline.
- CS3 was delayed until September 24, 2014 but extended until March 6, 2015. Work was performed on both the north and south sides of the South Park Bridge, as well as under the bridge. Diver-operated hydraulic dredging was performed under the newly constructed South Park Bridge.

ELECTROCOAGULATION

Electrocoagulation

The electrocoagulation treatment process uses electrical current to bind undesirable molecules of chemicals in water to each other and to the materials in the reactor. It also breaks emulsions by binding the negative end of polar anionic surfactants to the positive charge on the iron complexes created in the electrical environment. Undesirable contaminants are removed from the reacted fluid by flotation, settling, skimming, or filtering. The reactor is constructed with steel plates, and is specifically designed for removal of dissolved metals, emulsified oils and colloidal solids. The amount of energy required for treatment depends on the level of ions and contaminants in the fluid being processed. A typical electrochemical reactor is shown in Figure 6.

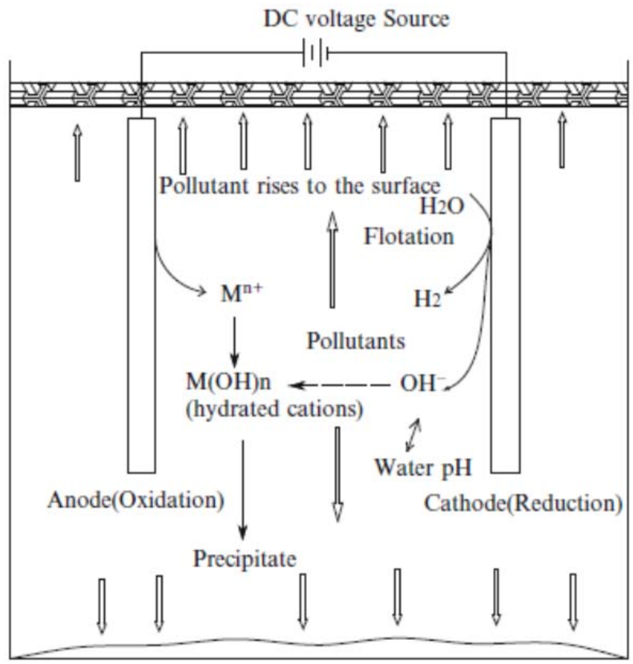

Figure 6. Electrocoagulation reactor (Liu et al., 2010).

The electrodes in the reactors were iron. The anode and cathode were both iron plates. The electrodes were connected in a bipolar configuration. Iron ions enter the water due to electrochemical reactions at the anode surface:

$$\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2e \qquad (1)$$

On the cathode surface, hydrogen gas (H_2) and OH ions are released into the water (Liu et al., 2010).

$$2\mathrm{H}^{+} + 2e \rightarrow H_2 \qquad (2)$$

where

Iron (Fe), electron (*e*)
Hydrogen (H)

Reactor Design

The electrode metal, spacing, orientation, and accessibility affect6 the overall treatment performance. The metal electrode can be changed to promote specific chemical reactions and change the metal hydroxide floc formed for removing contaminants from the water. The electrode spacing affects the ability of solids to pass between electrodes and the ability of solids to accumulate and block water flow through the reactor. The plates can be oriented vertically or horizontally in the reactor. A reactor with horizontal plates has a tendency to collect settling solids. Vertically oriented plates allow settling solids to pass between the plates and accumulate in the bottom of the reactor. Free and emulsified oils are described as a “sticky” solid and can accumulate in the reactor. In some instances, these “sticky” materials need to be removed mechanically to open the flow path through the reactor and resume treatment. The accessibility of the reactor plates defines the amount of effort required to clean the reactors. Some reactor designs are totally enclosed, which limits access to the reactor during operation. Many enclosed reactors must be removed from service to allow access for mechanically removing debris from the plates. An open reactor design can allow access for mechanically cleaning the plates during system operation. Several design choices are available for configuring an electrochemical cell. These choices can limit the ability of the reactor to treat water with suspended solids and emulsified oils. Additionally, all reactors will become plugged with solids; thus, the ability to easily access and remove the solids are critical design considerations for maximizing treatment time vs. down time.

An electrical power supply is a critical component of an electrochemical treatment system. Electricity is delivered from an alternating current (AC) or direct current (DC) source, based on the manufacturer. Additionally, the current and voltage are critical items to consider when working around an electrochemical reactor. The current dictates the size of conductor required to transmit the power; therefore, a conductor to transmit 3,000 amps is relatively large. Transformers to provide this level of power must have adequate airflow and cooling to allow for round the clock operations.

Occupational Safety and Health Administration (OSHA) standards allow direct access to DC power lines transmitting current with less than 50 volts of force. Some electrochemical reactors have large copper transmission cables which appear to imply a safety risk. For example, a DC power supply may provide 3,000 amps of current with 18 volts of force required for the current to flow through the transmission cables to the electrochemical reactor. That system meets the OSHA standards for voltage and while the amperage is high, the cables are safe for the operator to touch because a person (or their clothing, even when wet) is not conductive enough to be the preferred path for the current (assuming the system is properly grounded). The main safety concern for EC systems are tools or other metal objects, because crossing the positive and negative cables (or plates) can cause a direct short and explosive arcing at that amperage. Common safety SOPs include signs and training to ensure no metal tools are brought near the reactors and the removal of all jewelry that could come in contact with exposed conductors.

The electrochemical reactions in the electrochemical reactor generated both the ferrous iron and hydroxide ions for formation of the iron hydroxide floc needed for water treatment. The rectifiers in the Kaselco treatment system provided the DC power to the reactors. The electrical current was adjusted to generate the flocculant needed for removal of the contaminants. The ferrous hydroxide floc is generally referred to as a “green floc” and is visible in the middle sample in Figure 7. After aeration, the ferrous hydroxide oxidized to ferric hydroxide, which is visually represented by a red/orange color.

Figure 7. Water samples: untreated (left), post Kaselco electrocoagulation treatment (middle), post clarification (right).

Bench Test Results

Bench scale testing was performed to determine the appropriate cartridge for treating specific waters. Water samples representing river water, settled sludge, and Tri-Flo discharge were used to conduct bench scale testing. Bench tests were performed on four samples, river water, river water with 5 percent sludge, river water with 25 percent sludge and Tri-Flo discharge. The lowest metal concentrations and greatest clarity water were achieved using reactors with all iron electrodes.

DREDGE RETURN WATER SYSTEM OPERATIONS

CS1 DRWS Overview

Despite all of the challenges noted above, a DRWS was assembled in time for CS1 based on a Water Tectonics 300 gpm (1,100 lpm) treatment system (Figure 8, Table 3). The DRWS constructed for CS1 successfully treated water to meet the water quality criteria, but was one of the factors that increased the non-effective working time of the dredge (Table 4). The high variability of percent solids coming in the dredge return water and the high variability in the density of solids (sands, silts, clays, woody debris) provided a unique challenge in maintaining a consistent DRWS flow rate due to plugging of piping and equipment. In addition, this variability resulted in inconsistent flocculation from the electrocoagulation system, requiring a large amount of recirculation time prior to discharge.

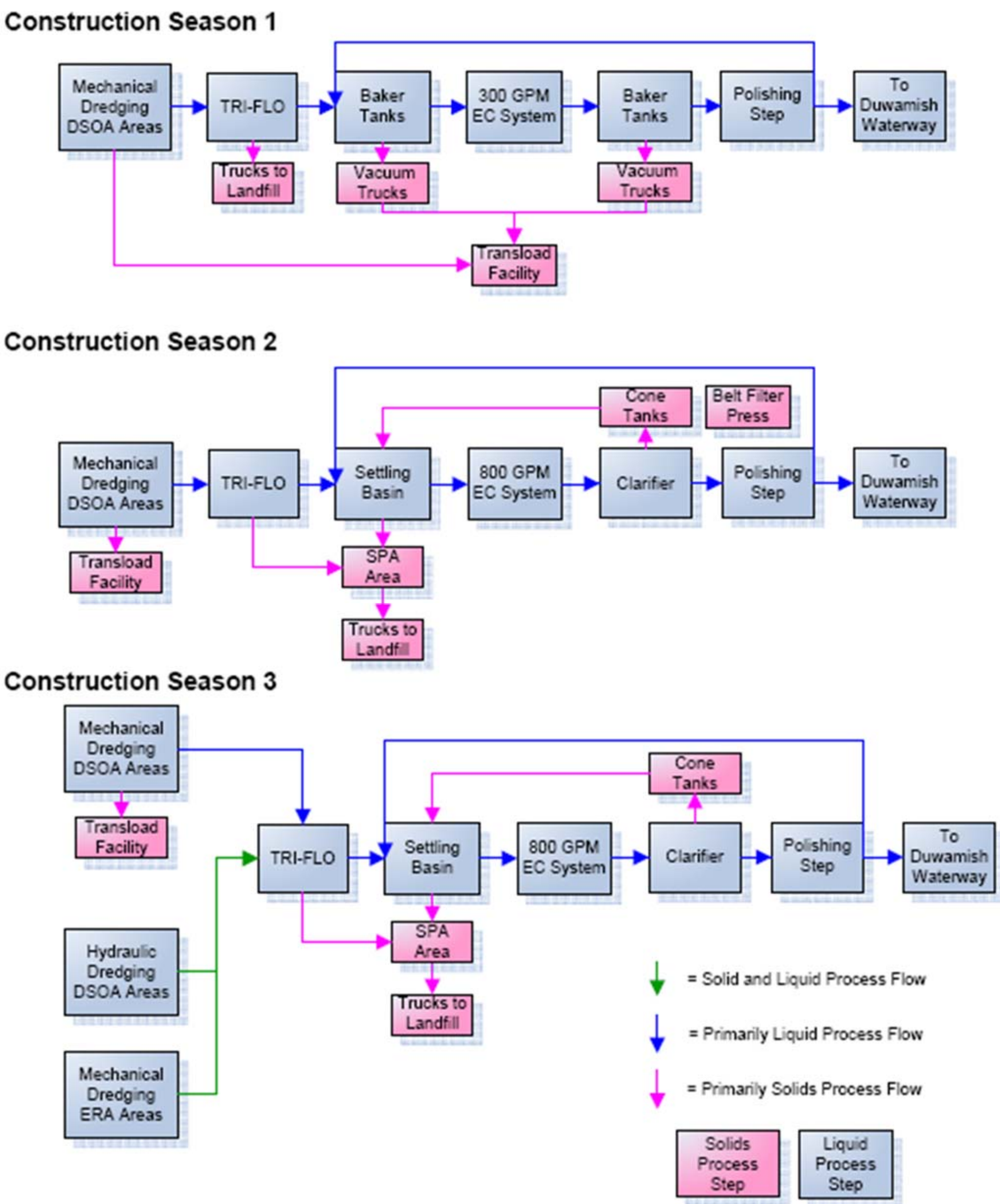

Figure 8. Dredge return water system process flow diagram for each construction season.

Table 3. DRWS components by construction season.

Dredge Return Water System Variation	**Dredge Return Water Process Steps**										
	Major Changes to Operations	**Step 1 Dredging**	**Step 2 Bulk Solids Removal**	**Step 3 Surge Capacity**	**Step 4 Fine Solids Coagulation /Floculation**	**Step 5 Solids Separation**	**Step 6 Holding Tanks**	**Step 7**	**Step 8**	**Step 9**	**Step 10**
Original Proposed System	Not applicable	Mechanical dredging to barge	Liquids to rock box Bulk solids to transload facility	3 Baker Tanks 20,000 gallons (76,000 liters) each	Chemical Precipitation	Geotube	Sump 125,000 gallon (473,00 0 liters)	Discharge	Geotube Dewatered at season completion	Solids trucked to landfill	
Const. Season 1	Addition of stringent water quality criteria and end of pipe discharge requirements	Mechanical dredging to barge	Liquids to Tri-Flo	6 Baker Tanks 20,000 gallons (76,000 liters) each	300 gpm (1,100 lpm) Electro-coagulation	4 Baker Tanks 20,000 gallons (76,000 liters) each		Automatic turbidity and pH check	400 gpm (1,500 lpm) polish step	Water Quality Check	Recirculation Discharge
			Bulk solids to transload facility	Vacuum Trucks Solids to transload				Vacuum trucks solids to transload facility			
Const. Season 2	Move to south shoreline, availability of larger area for DRWS and fixed electrical power	Mechanical dredging to barge	Liquids to Tri-Flo	Settling Basin 2 million gallons (7.6 million liters)	800 gpm (3,000 lpm) - coagulation	Clarifier 132,000 gallons (500,000 liters)	1 Baker Tank 20,000 (76,000 liters) gallons	Automatic turbidity check and pH adjustment	800 gpm (3,000 lpm) polish step	Water quality check (automatic pH recirculation)	Recirculation Discharge
			Bulk solids to transload facility	Solids to SPA			Cone Tanks	Solids to SPA	Solids trucked to landfill		
Const. Season 3	Three different types of dredging methods, 5 months of operations	Mechanical dredging to barge	Liquids to Tri-Flo Bulk solids to transload facility	Settling Basin 2 million gallons (7.6 million liters) Solids to SPA	800 gpm (3,000 lpm) - coagulation	Clarifier 132,000 gallons (500,000 liters)	1 Baker Tank 20,000 (76,000 liters) gallons	Automatic turbidity check and pH adjustment	800 gpm (3,000 lpm) polish step	Water quality check (auto turbidity and pH recirculation)	Recirculation Discharge
		Hydraulic dredging to barge	Solids and liquids to Tri-Flo				Cone Tanks	Solids to SPA	Solids trucked to landfill		
		ERA dredging to barge	solids and Liquids to Tri-Flo								

Abbreviations:
DRWS = Dredge Return Water System
ERA = Early Removal Area
gmp = gallons per minute
lpm = liters per minute SPA = sediment processing area

The solids handling was also less than ideal, as it required confined space entry for operators to vacuum out the sludge from the Baker Tanks. In addition to the extra health and safety requirements, the process was highly inefficient and costly, since the solids at the bottom of the tanks had to be liquefied for vacuuming and then re-solidified at the transload facility by addition of cement kiln dust (making the final disposal weight much higher as it included water and cement kiln dust weight on top of the sediment weight.) The most successful portion of the DRWS was the final water treatment step—the polish step (sand filters, bag filters, and granular activated carbon units)—and as a result, the polish step was retained for all three construction seasons (with only an upgrade in size to match higher flow rates.)

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At the end of CS1, Amec Foster Wheeler sampled and characterized the water and solids from different stages in the DRWS in order to design improvements for CS2. The goal was to reduce non-effective working time of the dredge and to eliminate confined space entry as part of routine operations. As such, the DRWS was redesigned with a specific focus on solids handling. A national search for additional water treatment technology and vendors was spearheaded by Amec Foster Wheeler and DOF beginning in March 2013, with the goal of having a new system installed and operational by August 1, 2013.

Table 4. DRWS effectiveness summary.

		Typical DRWS labor		NEWT due to DRWS		Conventional Parameter exceedances at end of discharge pipe	Chemical Parameter exceedances at end of discharge pipe	GAC Sample Results Indicating Breakthrough	Detected Leaks at Settling Basin
Name	Type of work	Hours	Days/week	Hours	Shifts				
Construction Season 1	Mechanical DSOA Dredging	24	7	156	16	0	0	0	NA
Construction Season 2	Mechanical DSOA Dredging	10	6	0	0	0	0	0	0
Construction Season 3	Mechanical DSOA Dredging	10	6	0	0	0	0	0	0
	Hydraulic Dredging	20	6	0	0	0	0	0	0
	Mechanical ERA Dredging	18	6	0	0	0	0	0	0

Abbreviations:
DRWS = Dredge Return Water System
DSOA = Duwamish sediment other area
GAC = granular activated carbon
NA = not applicable
NEWT = non-effective working time

CS2 DRWS Overview

As noted above, the beginning of CS2 was delayed until January 2014. Since south shoreline construction had been completed by the start of CS2, Boeing was able to provide much more space (more than 10 acres) and fixed electrical power for the DRWS on the south shoreline (Figure 2). As a result, major changes for CS2 included the addition of a 2-million-gallon (7.6 million liters) settling basin, a 130,000-gallon (500,000-liter) clarifier, two 27,000-gallon (100,000-liter) cone tanks, and a new 800-gpm (3,000-lpm) electrocoagulation system (including aeration system) provided by KASELCO, a subsidiary of Bakercorp (Figure 8 and Table 3). Dredge return water was pumped to the Tri-Flo unit for bulk solids removal, then to the settling basin, and then through the electrocoagulation system, clarifier, and polishing steps (Table 3). A unique feature of the KASELCO electrocoagulation system is that each system has a series of reactors with interchangeable cartridges. The basic components of an electrochemical treatment system include power supply, electrodes, and a vessel containing the reactor that is designed to allow easy access for plate cleaning and has built in solids collection and handling systems. The interchangeable cartridge allows the reactor to be changed in the treatment electrochemical cell without changing the treatment. In addition, the electrocoagulation system provided was based on dual 400-gpm (1,500-lpm) electrocoagulation systems with three reactors in each system. This arrangement allowed for superior control and redundancy, as each reactor cell was independently controlled and set to optimize performance, while minimizing electrical costs. The dual 400-gpm (1,500-lpm) units allowed for maintenance on half the system, while still treating water at up to 400 gpm (1,500 lpm) with the other half of the system. The system used aeration to turn black influent water into orange floc and eventually into clean water (Figure 9.)

Figure 9. Water samples from the CS2 DRWS.

Solids handling was greatly simplified, with the majority of the solids being mechanically removed by excavator from the first leg of the setting basin. These solids were then transported by dump truck to the sediment processing area and allowed to dewater further. Stabilizer (Zapzorb ™) was added if any further stabilization was needed and the solids were then loaded to trucks for offsite disposal.

Sludge with approximately 1 percent solids was pumped from the bottom of the clarifier to the cone tanks for further thickening (ranging from 5 percent to 15 percent solids). The thickened cone tank sludge was then pumped back to the head of the settling basin, where it was removed with the sediment from the first leg of the settling basin. The CS2 DRWS also initially included a belt filter press, but startup testing found the flocculated particles too soft for the belt filter press to be effective.

These improved solid handling measures in CS2 led to the elimination of confined space entry and use of vacuum trucks as part of routine DRWS operations. The increased holding capacity (more than 10 times the CS1 capacity) and higher maximum flow rate (from 300 gpm [1,100 lpm] in CS1 to 800 gpm [3,000 lpm] in CS2) provided ample buffering capacity to keep up with the dredge and resulted in no non-effective working time caused by the DRWS for CS2. As with CS1, the DRWS for CS2 successfully treated water to meet the water quality criteria (Table 4), even with more than 1.5 times the total discharge volume (Table 5).

The one major drawback of the DRWS for CS2 was the large surface area (including containment areas for the sediment processing area, settling basin, and DRWS) resulted in the generation of millions of gallons of stormwater for treatment (Figure 10). This additional water was pumped into the settling basin for treatment by the DRWS, which had major impacts on turbidity and salinity of water to be treated.

Figure 10. CS3 dredge return water system.

Table 5. Summary of operational data for water treatment.

Construction Season	Timing for In Water Work		Dredged Materials		Stormwater	Dredge Return Water		Maximum Flow Rate
			Volume	Weight		Processed	Discharged	
	Start	End	Cubic Yard (cubic meter)	Ton (metric ton)	Million gallons (million liters)	million gallons (million liters)	million gallons (million liters)	gpm (lpm)
Construction Season 1	1/2/13	3/8/13	36,000 (27,500)	46,500 (42,200)	0.03 (0.11)	8.1 (31)	6.3 (24)	300 (1,100)
Construction Season 2	1/2/14	3/8/14	48,500 (37,100)	67,000 (60,800)	4.7 (17.8)	17.7 (67)	9.3 (35)	800 (3,000)
Construction Season 3	9/24/14	3/6/15	75,300 (57,600)	124,300 (112, 800)	7.7 (29.2)	45.4 (172)	28.6 (108)	800 (3,000)
Totals			159,800 (122,200)	237,800 (215,700)	12.4 (47.0)	71.2 (270)	44.2 (167)	Not applicable

CS3 DRWS overview

The DRWS began water treatment for CS3 on September 24, 2014 and completed water treatment on March 6, 2015. Two main phases of operation occurred, DSOA dredging and ERA Dredging (for areas with PCB concentrations greater than 50 ppm). The DSOA dredging included both mechanical dredging and hydraulic dredging. The dredge return water processing for CS3 was operated on the south shoreline (Figure 2). No major changes to the DRWS occurred between CS2 and CS3. Minor improvements for higher flow rates and better treatment efficiency were installed and maintenance was performed on the Tri-Flo and other components in the offseason (Table 3, Figure 8).

- Pulleys on the post treatment tank discharge pump were changed out to increase the pressure head of the pump, effectively increasing overall throughput.
- Small bubble diffusers and electrically powered blowers were installed in the defoam tank for improved aeration over CS2.
- A variable frequency drive was installed for the clarifier rake to allow for adjustment of rake speeds internal to the clarifier.
- Modifications were made to the influent piping of the clarifier to improve energy dissipation in the stilling well and to reduce breaking of flocculated particles.
- A turbidimeter was added at the pH recycle valve (after the activated carbon units, but before the final water quality monitoring point). This addition increased quality control for water discharged by the system as the system would automatically change to recirculation mode if any spikes in turbidity were detected.

The biggest differences for CS3 related to the fact that three different dredging processes were followed—mechanical dredging in the DSOA with solids going to the transload facility, mechanical dredging in the ERA with solids slurried and pumped to the DRWS, and hydraulic dredging in the DSOA (Figure 8, Table 3). In order to keep up with the additional solids handling and higher flow rate (1,200 gpm, [4,500 lpm]) on the influent to the DRWS, additional hours of operation were necessary to stay ahead of the dredge production (Table 4.) The DRWS for CS3 was able to successfully treat water to meet the water quality criteria (Tables 4), even with handling a much larger amount of water and solids (Table 5).

LESSONS LEARNED

Water Treatment

The water treatment system in CS2 and CS3 effectively removed the contaminants from the water with no non-effective working time for the dredge (Table 4). Water treated on a given day varied greatly based on dredging operation and rainfall Table 6.

Table 6. Summary of operational data for water treatment during CS2 and CS3.

	Construction Season 2		Construction Season 3	
	Electrocoagulation Treatment	Discharge	Electrocoagulation Treatment	Discharge
Average daily flow gallons (liters)	189,000 (717,000)	142,000 (539,000)	405,000 (1,500,000)	254,000 (961,000)
Maximum daily flow gallons (liters)	660,000 (2,500,000)	416,000 (1,600,000)	1,028,000 (3,900,000)	757,000 (2,900,000)
Average ration (discharge/treated)		0.54		0.60
Maximum ration (discharge/treated)		0.91		0.90
Average daily operation (hours)	7.6		10.3	
Maximum daily operation (hours)	24		24	
Total operation (hours)	452		1,152	

Operational costs for electrocoagulation treatment differ from chemical treatment due to the use of electricity and metal plates (electrodes) for generating the metal hydroxide flocculant. During CS3, electrical consumption for electrocoagulation treatment operation averaged 3.95 kilowatt hours per 1,000 gallons treated. Assuming an electrical rate of $0.09 per kilowatt hour, the electricity cost $0.36 per 1,000 gallons ($0.10 per 1,000 liters) treated. The iron plates used in the reactors during CS 2 and CS3 totaled 121,000 pounds (55,000 kilograms). Assuming a 50 percent electrode utilization rate, the iron dosage rate to the water was approximately 100 milligrams per liter. Assuming an iron plate cost of $0.40 per pound, the metal cost was $0.77 per 1,000 gallons ($0.20 per 1,000 liters) treated.

Size of Retention

The large (nearly 2 million gallons [7.6 million liters] total with an 800,000-gallon [3-million-liter] working capacity) settling basin was added to the treatment train for CS2 and CS3. This large volume effectively provided a few days of buffer, such that the DRWS could be shut down for minor maintenance and repairs without immediately affecting the dredge EWT. The retention basin was divided into a serpentine flow path using floating water curtains (Figure 10). This extended flow length increased the efficiency of the basin for removing suspended solids. As a result, the turbidity of the water at the inlet of the treatment system was often less than 30 Nephelometric turbidity units. Additionally, the rainfall volume collected by the large retention basin and sumps draining the surrounding paved working area was equivalent to approximately four times the rainfall falling on the basin. Therefore, while the larger retention basin provided needed buffering capacity, the size reduced solids on intake and salinity of the water significantly. This cleaner water ultimately led to significantly lighter floc in the clarifier, which reduced system flow rates to 400 gpm (1,500 lpm). In order to increase DRWS flow to the maximum amount, a dirty water line was added to be able to add more solids to the intake and produce a heaver floc to optimize settling at the clarifier.

Belt Filter Press

A belt filter press was proposed as a means to further solidify sludge from the cone tanks and/or clarifier. While the sludge leaving the cone tanks was approximately 10–15 percent solids, the particulates were only loosely bound in iron hydroxide precipitates. Thus, pressure and rough handling only lead to floc particulate breaking up. In order to stiffen the sludge from the cone tanks, a bench test was performed using one of the few approved polymers. The polymer was ineffective at producing a more robust floc and the belt filter press was never used.

Radio Frequency interference

The DRWS included pH and turbidity sensors to automatically trigger the system into recirculation mode should field instruments measure out-of-range conditions. However, initial pH readings varied wildly and calibrations did not hold steady even just a few minutes after calibration. pH probes were replaced with higher end models, electrical cables were checked for proper grounding and shielding, and this improved pH readings somewhat. However, further testing found that radio signals were causing voltage discrepancies for the pH sensors. Marine radios used during calibration caused large variances, but small variances (10 percent drift) occurred throughout the site. The instruments with longer communication lines were more strongly affected than those closer to the control trailer. Once instrumentation that used millivolt signaling was replaced with milliamp-based equipment and marine radios were removed from the DRWS standard operating procedures, readings stabilized.

Robustness and Redundancy

A large lesson learned from CS1 was that the variability of dredge return water was hard on equipment, either clogging it or wearing parts down. As part of the bid requirements for CS2 and CS3, an emphasis was placed on robustness of design and equipment. This meant not only having high quality equipment, but having spare parts on site to allow for easy change out of equipment. The size of the settling basin allowed for up to a few days of down time, but not enough time for parts to be manufactured and shipped to the site (even on rush). Spare pumps, transformers, instruments, impellers, screens, were kept on site in addition to standard spare parts such as belts, washers, and disposable items such as bag filters, etc.

CONCLUSIONS

Over 40 million gallons (150 million liters) of water were successfully treated to meet water quality criteria and discharged to the Duwamish Waterway. The DRWS was significantly modified based on the lessons learned and data collected during the first construction season. The Triflo/retention basin combination removed a significant portion of the suspended sediments from the water. The electrocoagulation treatment reactor generated iron hydroxide floc for removal of the remaining fine particulate and dissolved contaminants from the water. Overall, the dredging project was highly successful, with very little turbidity or residuals generated and no exceedances of the water quality criteria set at part per trillion requirements for total PCBs and part per billion requirements for dissolved heavy metals. The project demonstrated several key factors for conducting dredging projects in environmentally sensitive areas: a barge-mounted excavator with boom and environmental bucket guided by GPS can mechanically dredge a waterway with minimal releases of turbidity during dredging; and a DRWS can use electrocoagulation, clarification, filtration and absorption equipment to remove contaminants with no other chemical inputs.

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