

TIDALLY INFLUENCED CONTAINMENT BERM FUNCTIONING AS A LEACHATE TREATMENT CELL - PUGET SOUND EXPERIENCE IN CONFINED DISPOSAL OF CONTAMINATED SEDIMENTS

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ABSTRACT

Studies by the Port of Seattle over the last decade, on both proposed and operating nearshore confined disposal sites for contaminated sediments have delineated most of the factors controlling contaminant loss. Our experience includes the results of early models, updated with monitoring data, from a site that was monitored and studied extensively for six years following construction. The results from this site were used in modeling proposed designs for another site. These included the use of a two dimensional fully integrated hydrodynamic and transport model. This model included tidal fluctuations, density dependent flow and allowed for distinct biogeochemical zones. This allowed us to account for colloidal release with changing salinity as well as varying regimes of adsorption to predict contaminant movement and biogeochemical attenuation. The modeling studies have shown that the hydraulic flow parameters are less important in influencing contaminant loss than adsorption and biodegradation when contaminated leachate is moving from the anaerobic to aerobic areas of a well flushed and oxygenated berm. The studies also show how strongly the net flow is modified by the density structure, and the need to consider both the net and tidal flows in designing a monitoring program.

The relative influence of dilution versus biogeochemical attenuation within the berm was determined from the monitoring data using conservative tracers for a number of contaminants. In addition, the long-term potential for clogging and loss of attenuation capacity was evaluated. These studies demonstrate the high degree of efficiency of a tidally-influenced berm to act as a natural biogeochemical treatment filter. This work points the way to tremendous cost savings in allowing natural processes powered by tidal flushing to effectively treat contaminants released from a nearshore contaminated sediment disposal site.

KEYWORDS

Adsorption; attenuation; biogeochemical; confined disposal; contaminated sediments; density-driven flow; transport; treatment.

INTRODUCTION

In Puget Sound, as elsewhere around the world, using dredged material as fill in various port developments is not a new concept. The types of sites built and studied by the Port of Seattle are primarily the deep nearshore fills, where berms are constructed out from the shoreline and contaminated dredged material is placed inside to such a depth that the material is kept within the saturated zone. For over a decade, the Port of Seattle has been engaged in research and monitoring of nearshore contaminated dredged material disposal sites. These studies have been prompted by state and federal regulatory agency concerns over potential long-term environmental impacts from contaminated dredged material disposal, and the Port's interest in understanding contaminant mobility and transport processes to optimize the containment performance of future sites. In this paper we present some of the major findings from these studies.

TERMINAL 91 NEARSHORE FILL MONITORING AND MODELING

In 1984, the Port of Seattle proposed the Terminal 91 Nearshore fill (Figure 1). By then, there was increased regulatory awareness and concern regarding contaminated fills. There was also increased knowledge from previous studies by the Port at a tidally-influenced upland fill site and other published reports. The Port was confident that this was an environmentally reasonable approach. It appeared that if the dredged materials remained in their original saturated and anaerobic state, the contaminants would remain associated with the sediments particles and be retained within the fill. The majority of the dredged material for the fill would come from the Port's redevelopment of an old petroleum handling and storage facility into a modern container terminal. The sediments contained moderate levels of the standard urban harbor contaminants, with maximum concentrations in the tens of ppm for total PAHs, in the hundreds for metals and up to 6 ppm for PCBs.

The Port's proposal was for a deep nearshore fill to be built by constructing two berms spaced about 120 meters apart extending across the slip between the solid fill Piers 90 and 91. Each berm contained clean structural fill with sandy gravel cores and riprapped slopes. Approximately 100,000 m³ of contaminated dredged materials would be clamshelled, barged into the site through a gap in one of berms which was kept closed with a surface to bottom silt curtain, and bottom dumped. The dredged material would be entirely contained below the saturated zone, and capped with uncontaminated sand and gravel then paved with asphalt. A stormwater drainage system would be installed. A system of monitoring wells installed as part of the design to collect data and analyze how the facility would perform over time (Figure 1). There would be no liners, low permeability barriers, or leachate control systems. The design would retain the sediments, but the initial dewatering and regional groundwater could move through the dredged material and berms.

[Figure 1]

When the Terminal 91 project was first proposed, the regulatory agencies said the Port lacked sufficient data on long-term contaminant mobility from tidally-influenced nearshore disposal sites to evaluate the project and recommended enclosing the site with a slurry wall. The agency concerns were: 1) what was the immediate impact of any leachate loss on the water quality and sediments; and 2) what was the long-term loss. In a series of meetings between the Port and the agencies, ideas and approaches to resolving the issue and filling data gaps were debated. Major input during these discussions came from US EPA Region 10, the Washington State Department of Ecology, and the U.S. Army Corps of Engineers.

The negotiated solution was to predict, monitor, and remedy (if necessary), the performance of the disposal site. The Port needed first to assure the agencies that the containment system would provide adequate environmental protection based on existing water quality criteria. Next, to evaluate the level of long-term environmental protection the facility would provide, the agencies requested a prediction of the percent loss of the total amount of contaminants in the fill over time. The regulatory agencies were concerned that leaching would be exacerbated by the hydraulic pumping action of the tides which needed to be addressed in the predictions.

The Port proposed a modeling approach to predict the long-term contaminant mobility from the facility. In this modeling approach leachate predictions were made using a numerical hydraulic model run separately from an analytical solute transport model. The hydraulic model was run over a number of tidal cycles to simulate tidal flushing within the system. The maximum tidal velocities (2 to 4 m/day) were used to estimate a tidal dispersion coefficient based on the range of dispersivities measured for similar materials (0.1 to 10 m) which was then used as input to the one-dimensional analytical transport model (Javandel et al., 1984). Steady-state hydraulic simulations were used to determine the long-term advective velocity through the fill. The tidal dispersion coefficient accounted for the accelerated transport due to tidal pumping. Modeling assumptions used were consistently conservative in a direction which would produce worst-case results. Both metals and organic contaminants were modeled.

The model predictions showed that no water quality violations would be observed at the berm-seawater interface and that only a very small fraction (less than 1 percent) of the contaminants would be lost in 100 years. The model also showed that the majority of tidal flow within the berm occurred in the intertidal zone with the maximum flow out of the berm occurring at the end of the ebbing tide.

The modeling results were used to determine locations and sampling depths of the monitoring wells in a five-year monitoring program which began in 1986. The monitoring program collected data to demonstrate site performance, to verify model predictions, and to provide additional data that would help us understand the processes influencing contaminant mobility and transport from these sites in order to optimize the containment performance of future facilities. Monitoring well locations were chosen to best monitor the performance of the system in terms of hydraulic flow and contaminant concentrations. Wells were placed in the berms, in the contaminated dredge fill, in the cap material and in an upgradient groundwater flow direction (see Figure 1).

One of the main goals of the monitoring program was to demonstrate facility performance. The monitoring data demonstrated that the facility met all regulatory requirements and performance criteria established by the permitting agencies. While some levels for a few metals including nickel were elevated in the south berm wells, it was shown that these metals came from the clean structural fill in the berm and not from the contaminated dredged material.

A second goal of the monitoring program was to better understand tidal mixing within the berm. Total dissolved organic carbon (DOC) was demonstrated to be conservative given its residence time within the berm and to be an adequate tracer of tidal mixing. The effects of tidal mixing and dispersion can be seen in Figure 2 which shows concentrations of DOC over a tidal cycle at three locations within the facility. The inner berm face data is from well W-6 which was completed in the fill at the berm/fill interface; the berm data is from well W-4B located in the center of the berm; and the outer berm face data is from Station 14 (see Figure 3). The two wells are at the same elevation of about one meter below mean lower-low water. The berm time series shows rising DOC concentrations associated with falling tides with a spike at the outer berm face at the end of the lower-low ebb. Rising tides produce lower DOC concentrations within the berm as fresh seawater advances into the berm.

The DOC data (Figure 2) was also used to calibrate the tidal dispersion coefficient which was used in a follow-up modeling study updating the earlier model using actual as-built measurements and the measured monitoring results. The new calibrated dispersion coefficient (about 20 m²/day) was within the range of coefficients used in the previous modeling. The updated model's predicted leach rates and concentrations were lower than originally predicted. However, the percentage of contaminant mass leached from the fill during 100 years of operation were predicted to be higher in than previously modeled, although generally less than one percent of the total. This higher percentage leached resulted from greater flow rates through the as-built facility.

A third goal of the monitoring program was to understand the biogeochemical processes acting within the berm to reduce concentrations. Figure 3 illustrates the impact of the major biogeochemical processes occurring within the berm on the berm chemistry. It shows the concentrations of seven reactive inorganic species at four locations within the facility normalized to their largest value for convenient display. The locations are the same inner and outer berm face and berm locations as in Figure 2 with the addition of a dredge fill location (well W-5B).

[Figure 2]

Figure 3 shows that oxygen, nitrate and sulfate are introduced into the berm at the outer berm face through tidal action. Oxygen is consumed by the time it reaches the inner berm face. Sulfate is partially reduced near the inner berm face as the oxygen becomes depleted as evidenced by the large increase in sulfide. Nitrate is produced in the outer portions of the berm via nitrification and consumed in the inner berm via denitrification where the oxygen becomes depleted. The reduced species iron (II) and ammonia are highest in the dredge fill and are rapidly depleted as they enter the berm, while manganese (II) is lost inside the berm.

This figure clearly shows that oxygen is being utilized within the berm. Most of oxygen in the inner portion of the berm is probably being consumed in iron (II) and sulfide oxidation and nitrification of the ammonia. In the outer berm, oxygen is primarily being consumed in aerobic respiration of organic carbon with a smaller amount used in nitrification to produce the peak of nitrate concentrations. In the inner portions of the berm, organic matter is being oxidized by anaerobic bacterial respiration via sulfate reduction and denitrification. Therefore, the introduction of fresh oxygen, sulfate, and nitrate with each incoming tide enhances the rate of aerobic and anaerobic biodegradation of the organic contaminants throughout the berm.

In addition to the bacterial mediated organic matter oxidation, iron (II) oxidation to iron (III) also occurs within the berm. This is an important process because iron (III) is relatively insoluble and precipitates out of solution as ferric oxides and hydroxides (oxyhydroxides). The precipitating ferric oxyhydroxides are captured on the surface of the berm material and remain there. Although not shown in Figure 3, total unfiltered iron is undetected at < 0.01 mg/L in the berm dropping from over 11 mg/L in the fill indicating that the iron has been lost from solution.

The precipitating oxyhydroxides then coprecipitate other metals and are captured in the berm material and continue to act as an efficient surface-active sorption substrate for capturing additional metals over time (Davies-

Colley et al. 1984). Furthermore, the production of sulfide near the berm/fill interface through sulfate reduction (Figure 3) enhances precipitation of the highly insoluble metal sulfides at or near the berm/fill interface.

[Figure 3]

In addition to coprecipitating and adsorbing metals from solution, as the Fe (III) oxyhydroxides precipitate, they will also enmesh some dissolved and colloidal organics along with them. This is because ferric iron (Fe(III)) is strongly complexed by some natural organics such as humics which contain phenolic and carboxyl groups. These compounds become enmeshed in the rapidly forming precipitate (Hahn and Stumm, 1970). The natural organic matter will also adsorb to the Fe (III) oxyhydroxides (Gu et al., 1994) which will then adsorb other hydrophobic contaminants (Murphy et al. 1990).

[Figure 4]

The Terminal 91 project has shown that the berm is not just a passive physical barrier to particle transport, but is an active biogeochemical environment in which fresh oxygenated seawater containing oxygen, sulfate and

nitrate penetrates far into the berm with each incoming tide. This initiates a number of important biological and geochemical reactions which have the ultimate effect of treating contaminants inside the berm.

TREATMENT VERSUS DILUTION

The major flow path for the outgoing tidal flow from the hydraulic modeling of the Terminal 91 fill is represented schematically in cross-section on Figure 4 along with locations of the sampling wells and sampling station 14. Well W-6, the berm/fill well, is located in the dredge fill material below the cap and at the berm/fill interface. Based on the flowpaths, we expect Well W-6 to represent the source and type of water that is flowing from the fill through the upper portions of the south berm on the outgoing tide.

Treatment (or loss) can be distinguished from dilution along the flow path shown in Figure 4 by application of a conservative mixing diagram (e.g. see Officer, 1979). The method assumes you have two water types with one-dimensional steady-state mixing over some distance. Each water type is characterized by a different concentration of a conservative tracer such as salt or chloride. Other constituents which may or may not behave conservatively are measured along with the conservative tracer and plotted versus the conservative tracer.

The amount of gain or loss through the mixing area is calculated by taking a best-fit line to the data near the end of the mixing area, which in our case would be near the seawater station. The assumption is that at this point, most or all of the gains or losses have occurred and we are conservatively mixing. This regression line is extrapolated back to the "upstream" conservative end-member concentration, which in our case would be the concentration of the conservative constituent at Well W-6. The extrapolated concentration of the non-conservative constituent at the upstream end-member concentration is the "apparent" non-conservative end-member concentration (c_0^*) which the seawater is apparently mixing with. The actual measured concentration of the non-conservative Well W-6 end-member is c_0 , and the background seawater concentration is c_{sw} . The ratio of $(c_0 - c_0^*) / (c_0 - c_{sw})$ is taken as an estimate of the fractional loss or gain within the mixing zone. We define fractional loss as the percent reduction due to treatment occurring in the inner portion of the berm between Well W-6 and Well W-4B.

[Figure 5]

Figure 5 shows an example conservative mixing plot for the average arsenic concentration versus average boron

concentrations for all of the Terminal 91 monitoring surveys. Boron was chosen over DOC as the conservative tracer across all the surveys because there were some inconsistencies in the DOC data in a few surveys. Table 1 gives the calculated percent gain or loss due to treatment for iron, manganese, arsenic, ammonia-N, and naphthalene. These constituents were chosen because they showed concentration levels consistently above detection limits in Well W-6 throughout the surveys and in the case of iron and manganese, should also indicate the extent of precipitation of iron and manganese hydrous oxides occurring within the berm.

Table 1. Treatment Results from the Conservative Mixing Plots

Contaminant	Concentration			Percent Loss
	Seawater	Well W-6	Apparent Well W-6 End-member	
Iron (mg/L)	0.031	.27	0.027	100%
Manganese (mg/L)	0.0078	18	0.41	98%
Arsenic (µg/L)	1.10	4.3	0.64	100%
Naphthalene (µg/L)	0.11	2.7	0.99	>66%
Total Ammonia-N (mg/L)	0.032	3.0	0.10	98%

The results in Table 1 show that the contaminants analyzed had estimated losses in the region between Well W-6 at the berm/fill interface and Well W-4B in the middle berm of between greater than 66% to 100%. It is important to note that the estimated >66% percent loss for naphthalene is driven by a detection limit value for Well W-4B, and could easily exceed 90% if the concentration were half the detection limit. It is also important to note that this analysis does not account for additional losses which may be occurring in the outer berm between Well W-4B and there berm/seawater interface.

Dilution can be estimated from either the DOC or boron data. Estimates of the total dilution factor from Well W-6 to the berm face range from 17:1 to 20:1 using this data. The dilution in the inner portion of the berm ranges from 3.1:1 to 3.6:1 which indicates that the majority of the dilution occurs in the outer portion of the berm between Well W-4B and the berm face. The dilution factors within the berm suggest that dilution of a contaminant at Well W-6 with ambient seawater would lower the concentration from Well W-6 by up to 95% upon reaching the berm face. This percent reduction is comparable to the reduction due to treatment.

SOUTHWEST HARBOR NEARSHORE FILL FEASIBILITY STUDY

This project was initiated by the Port of Seattle in 1992 as the contaminated sediment cleanup alternatives portion of a Remedial Investigation/Feasibility Study and EIS for the large Southwest Harbor Cleanup and Redevelopment Project (SHCRP). Two of the sediment cleanup alternatives investigated were a nearshore confined disposal facility which would create new upland, and a much smaller submerged nearshore confined fill rising to just below the intertidal zone. Both of these alternatives had the potential to serve as a multi-user confined disposal site for other contaminated sediment cleanups.

Since SHCRP could potentially serve as a multi-user site, it received extensive peer review throughout the project from US EPA, USGS, US Army Corps of Engineers, and state agencies along with the Port. It was agreed that because site conditions affecting system performance would be different than in the Terminal 91 project, and because computer resources and more sophisticated models were available which could include additional processes, a more sophisticated model would be used. This more sophisticated approach would help differentiate between predictions of unacceptable concentrations resulting from overly conservative modeling assumptions, and predictions that more realistically represent actual system performance. This would allow for more control and flexibility in the design to maximize the use of the most contaminated sediments and make

the best use of this valuable resource.

The model chosen was a modified version of PORFLOW (Runchal and Sagar, 1992) which could directly include variably saturated density-dependent flow and the tidal boundary conditions for both flow and solutes, as well as some of the biogeochemical processes. Simulations were conducted using three inorganic contaminants (copper, lead, arsenic) and three polycyclic aromatic hydrocarbons (naphthalene, fluoranthene, indeno(1,2,3-cd)pyrene) which were chosen based on the known level of contamination in sediments likely to be dredged, their toxicity, mobility and persistence. The major biogeochemical processes included were: first order biodegradation for the organics using anaerobic rate constants which are conservatively much less than aerobic rates; adsorption constants for inorganic contaminants based on geochemical models using amorphous ferric oxides in the berm and cap and organic carbon equilibrium partitioning for the organics; and a salinity-dependent source term to simulate leaching and colloidal release from the dredged fill based on laboratory column and sequential batch leach tests using upland groundwater and modified USACOE Waterways Experiment Station protocols.

Major conclusions from the modeling are: the model shows that the flow is strongly influenced by the density difference along the freshwater/saltwater interface; fresh upland groundwater flow is directed upward as it approaches the more dense saltwater which enhances the outward flow in the intertidal zone where greater than 95% of flux of contaminants occurs; flow paths through the fill are also influenced by the hydraulic conductivities of the surrounding upland soils and aquatic sediments; and the model is much more sensitive to the inorganic K_d s in the berm, the salinity-dependent source term, and the biodegradation rates than to the hydraulic flow parameters.

Modeling results showed that concentrations derived from the fill at the berm or cap face did not pose a human health or environmental risk, and that the net mass loss from each of the alternatives was less one percent after a 100 year period. Based on this work, the site is presently being considered as a candidate for an area-wide multi-user confined sediment disposal facility.

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FIGURE CAPTIONS

Figure 1. Terminal 91 project site and sampling locations.

Figure 2. DOC from Terminal 91 tidal survey.

Figure 3. Inorganic redox species from Terminal 91.

Figure 4. Terminal 91 sampling well orientation and generalized flow path through active upper berm.

Figure 5. Conservative mixing plot of arsenic vs. boron.

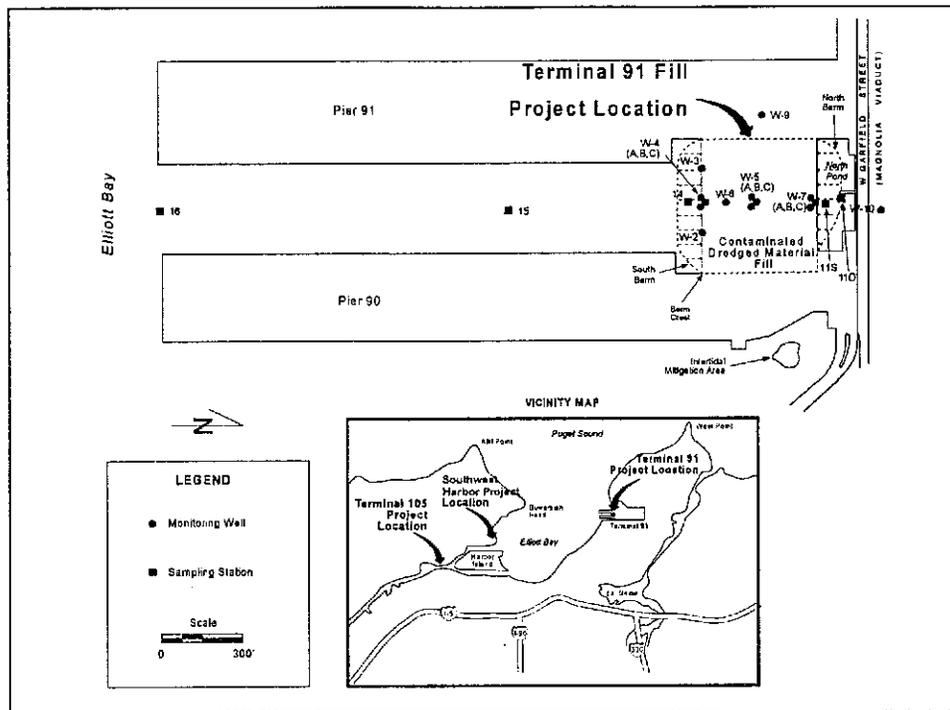


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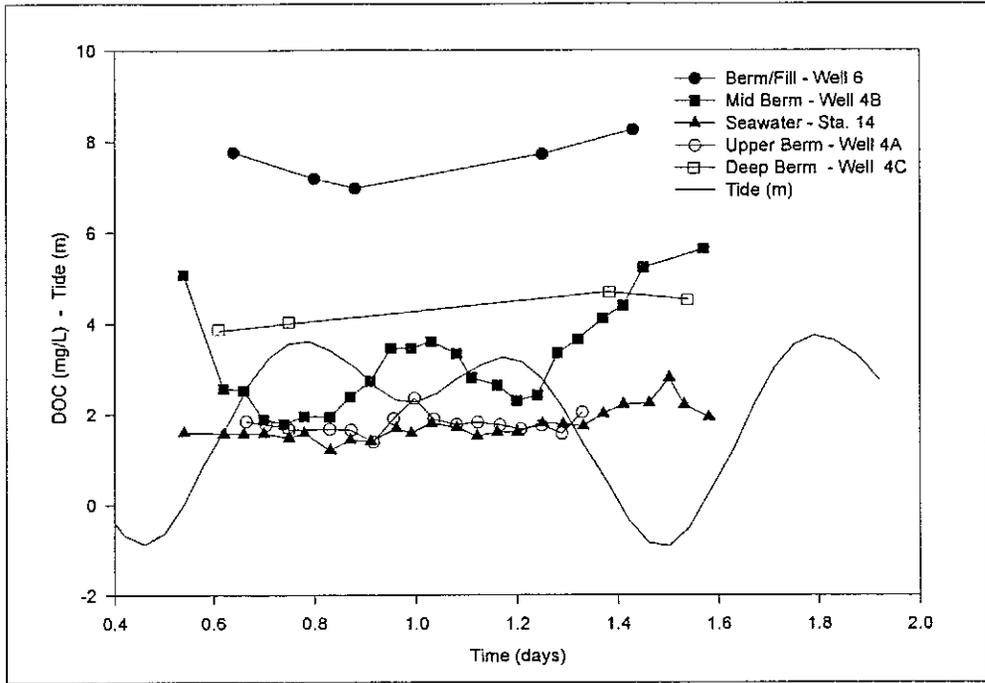


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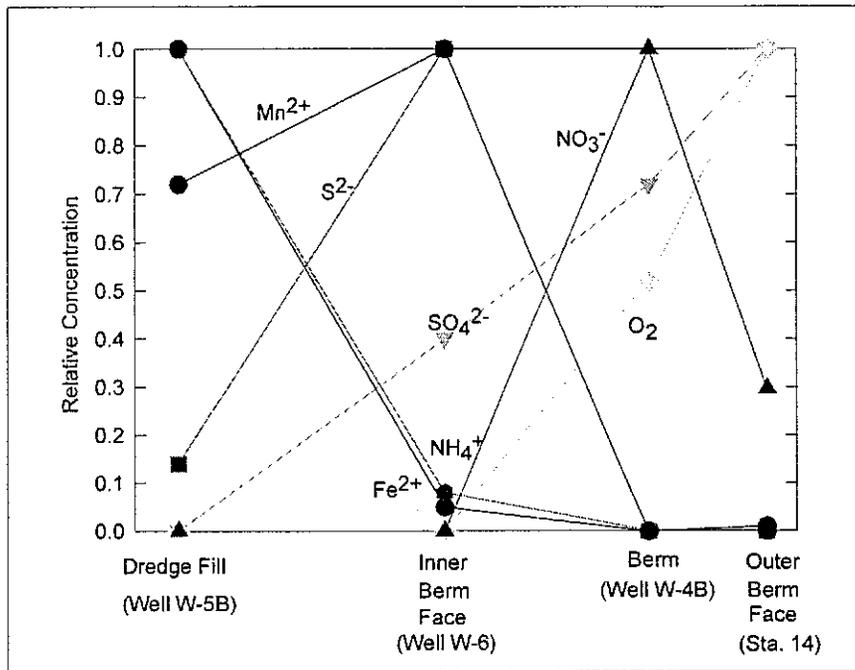


Figure 3. Inorganic redox species from Terminal 91.

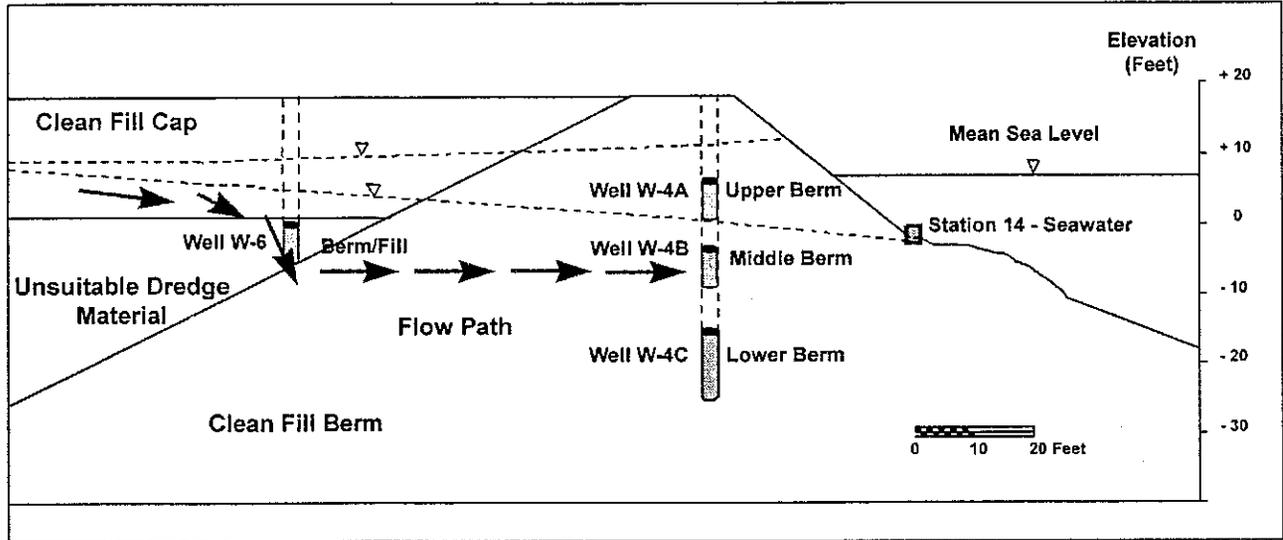


Figure 4. Terminal 91 sampling well orientation and generalized flow path through active upper berm.

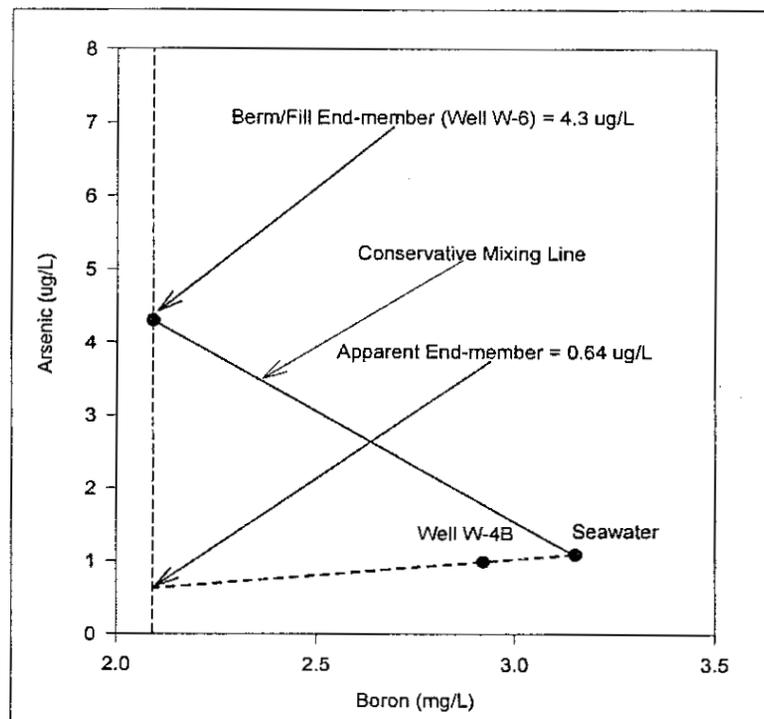


Figure 5. Conservative mixing plot of arsenic vs. boron.