7.0 CONTAMINANT FATE AND TRANSPORT

This section describes the fate and transport of contaminants in soil, groundwater, sediment, and soil vapor at the Haley Site. The text is organized according to the following topics:

- Phase distribution of contaminants
- LNAPL mobility
- Fate and transport processes affecting IHSs

7.1. Phase Distribution of Contaminants

As discussed in previous sections of this report, contaminants related to the Haley Site are primarily associated with the wood-treating solution historically used at the Haley facility. This solution reportedly consisted of P-9 carrier oil with PCP; samples of oil from the Haley UST contained approximately 6 percent PCP. Contamination exists in several physical states (phases) and environmental media at the Site. It exists as a distinct layer of LNAPL; in the aqueous/dissolved phase in groundwater; in the adsorbed phase in soil, debris and sediment; and in the vapor phase in soil. The nature and extent of contamination in these various phases/media are described in Section 6.0.

7.1.1. LNAPL

A detailed description of the nature and extent of LNAPL is presented in Section 6.2. As previously explained, LNAPL in the Haley upland is associated primarily with releases of diesel-range carrier oil historically used for wood treatment at the Haley facility. Over time, these oil releases created a petroleum smear zone throughout much of the upland (Figure 6-1). The greatest mass of LNAPL occurs in the LNAPL Plume behind the sheet pile barrier, in the tidally-influenced zone of the Haley upland. Measurable LNAPL in monitoring wells also is intermittently present in several other upland areas, as described in Section 6.2. At times, LNAPL has been observed in the form of petroleum sheens in the intertidal zone west of the shoreline bank.

Section 6.2.3 and Table 6-2 present a summary of analytical results for samples of UST oil (carrier oil), oil from the beach oil seep observed in 2000, and LNAPL from monitoring wells and a test pit. A comparison of the chemical composition of UST oil samples to the composition of LNAPL samples provides insight into some of the past natural processes and/or industrial practices that may have affected the distribution of LNAPL and associated contaminants at the Site.

The chemical analyses indicated that the UST oil samples consisted of wood-treating (carrier) oil containing approximately 6 percent PCP and a small fraction of dioxin/furan impurities. The composition of LNAPL samples differed from UST oil samples in some cases, as described below. One possible explanation for the observed differences is that the composition of the Haley facility carrier oil may have changed somewhat over the years. In addition, releases of petroleum products other than carrier oil may have occurred at the Haley facility or the former lumber mill on the Haley and Cornwall properties, resulting in different types of petroleum in the LNAPL mixture. Fate and transport processes also likely differed in subsurface environmental media than in the UST.

- Dioxin/furan concentrations in the beach oil seep sample and the LNAPL sample obtained from well TL-MW-3 were as much as 20 times higher than in the UST oil sample analyzed for dioxins/furans. This may be due to the partitioning/mass transfer of dioxins/furans from the adsorbed phase in soil back into LNAPL.
- The concentration of PCP detected in the beach oil seep sample (2,100 ppb, or 0.00021 percent) was significantly less than what would be expected for dispersed or degraded carrier oil originally containing approximately 6 percent PCP. PCP was not detected in the two LNAPL samples analyzed for this constituent; however, similar to the PCP concentration detected in the beach oil seep sample, the PCP reporting limits for the LNAPL samples were four to five orders of magnitude less than the PCP concentrations reported in the UST oil samples. PCP would be expected to partition over time from LNAPL to organic soils, and to a lesser degree to groundwater as the LNAPL weathers or degrades over time. PCP concentrations detected in several soil samples collected from the petroleum smear zone (Figure 6-29) were one to two orders of magnitude higher than the PCP concentration detected in the beach oil seep sample.
- Naphthalene was detected in an UST oil sample and two of the three LNAPL samples analyzed for this constituent. The naphthalene concentrations in the LNAPL samples were approximately 1.5 to 2 times greater than the concentration detected in the UST oil sample.

The expected partitioning of LNAPL components from the oil phase to the aqueous (dissolved) phase in groundwater can generally be predicted if the component concentrations are known in the original petroleum product source(s) and in LNAPL that is in equilibrium with water. However, in the case of the LNAPL at the Haley Site, such partitioning predictions are difficult because more than one type of petroleum product may have been released historically and the carrier oil used over the years also may have varied somewhat. The comparison of analytical results for the Haley LNAPL and UST oil samples suggests that other processes besides simple dissolution may have affected composition of the LNAPL samples.

7.1.2. Aqueous Phase

The primary source of contaminants at the Haley Site was historical releases of carrier oil and, to a lesser degree, other petroleum products during past industrial operations. The petroleum releases migrated laterally on the groundwater table as LNAPL. The dissolution of contaminants from LNAPL into the aqueous phase (i.e., into groundwater) is a primary contaminant transport mechanism at the Haley Site.

The dissolution of contaminants from LNAPL into the aqueous phase is governed by the aqueous solubility of the respective LNAPL constituents. The effective solubility of an individual LNAPL constituent in groundwater is equal to the aqueous solubility of the pure constituent times the mole fraction of the constituent in the LNAPL. Using this relationship, the theoretical aqueous-phase concentrations of LNAPL constituents in groundwater that is in contact with the LNAPL can be calculated.

The transport of aqueous-phase contaminants is affected by several processes, including advection, dispersion, destructive attenuation, adsorption, and volatilization. Advection and dispersion are the primary transport mechanisms for aqueous-phase contaminants in groundwater. Advection transports contaminants via groundwater flow driven by hydraulic (pressure) gradients. Dispersion

causes the spreading of aqueous-phase contaminants in groundwater via molecular diffusion, physical deflection of groundwater by solid particles as it flows through interconnected pore spaces, and chemical retardation (advective transport slowed by adsorption of dissolved contaminants to organic matter).

Destructive attenuation processes affecting aqueous-phase contaminants include biological degradation and abiotic (non-biological) destruction or transformation. Most of the groundwater IHSs at the Haley Site, particularly petroleum hydrocarbons, can be biologically degraded to varying degrees under favorable aerobic conditions. However, aerobic biodegradation occurs at significant rates only when sufficient quantities of dissolved oxygen are present in groundwater. Dissolved oxygen is depleted in shallow groundwater beneath the Haley Site, most likely due to the presence of organic-rich soil, wood debris and LNAPL in the saturated zone. Field parameter measurements during groundwater sampling have indicated relatively low dissolved oxygen concentrations (Appendix K, Table K-1), generally ranging from less than 1 mg/L to 2 mg/L[10]. Likewise, field measurements of redox (-30 to -354 millivolts) indicate a slightly to moderately reducing environment in the saturated zone, which is generally not conducive to significant aerobic biodegradation under natural conditions.

Aqueous-phase contaminants in groundwater experience attenuation near the shoreline as a result of physical (tidal) mixing, prior to the point at which groundwater discharges to surface water. The mixing of groundwater and surface water near the shoreline can be a significant component of natural attenuation of contaminants in groundwater prior to discharge to marine sediment and water (Aspect 2012). Tidal influences not only reduce contaminant concentrations as a result of physical mixing, but also enhance oxygen concentrations, which can increase biological and chemical attenuation processes in groundwater near the shoreline. The effect of tidal mixing on dissolved-phase contaminants in groundwater has been demonstrated at the adjacent Cornwall Landfill (Landau 2013) and GP West sites (Aspect and Anchor 2013). At these sites, contaminant concentrations in groundwater samples collected from beneath the sediment surface in the intertidal zone were found to be considerably lower than in upland monitoring wells adjacent to the shoreline.

Attenuation factors (AFs) were calculated for the GP West site by two different methods: using empirical groundwater data, and by developing a shoreline groundwater attenuation model (Aspect 2012). Empirical data showed that dissolved-phase contaminant concentrations in groundwater samples collected from the intertidal zone were less than adjacent upland groundwater concentrations by factors ranging from 54 to 290. These AFs were derived by dividing contaminant concentrations in shoreline (upland) monitoring wells by contaminant concentrations in intertidal zone groundwater samples. The empirical data at the GP West site is anticipated to underestimate the amount of attenuation that actually occurs because the intertidal zone groundwater samples were collected from several feet below the sediment surface; these groundwater samples, therefore, do not reflect the additional attenuation that occurs along the remaining flow path toward the point of discharge to surface water. The shoreline groundwater attenuation model for the GP West site was used to estimate attenuation of contaminants in groundwater prior to reaching the biologically active zone in sediment. The model output estimated an AF of 76 at the point where high tide

[10] July 2012 dissolved oxygen measurements of 7 mg/L and 8 mg/L appear anomalous and are likely the result of equipment malfunction.

intersects the shoreline. The modeled AFs quickly increased with increasing horizontal distance from the shoreline, as follows: 3,900 at 35 feet, 8,800 at 64 feet, and 64,000 at 94 feet from the shoreline. These modeling results also are anticipated to underestimate attenuation because the modeling approach accounts only for physical mixing of groundwater and surface water near the shoreline; biological and chemical attenuation processes are not accounted for, and would be expected to provide additional attenuation not predicted by the model.

The amount of tidal attenuation at a specific waterfront site likely varies throughout the tidal cycle as the sea water/groundwater ratio changes in response to tidal fluctuations. In addition, the amount of attenuation caused by tidal mixing likely varies between sites as a result of site-specific conditions. Site-specific variables that could influence attenuation include the geometry and hydraulic characteristics of hydrostratigraphic units, nearshore hydraulic gradients, profile of the beach, and contaminant concentrations in soil and sediment along the groundwater flow path. As a result, attenuation along the Haley shoreline may not be similar to that observed or modeled at the GP West and Cornwall sites.

7.1.3. Adsorbed Phase

For the purposes of this report, adsorption refers to the process of dissolved contaminants partitioning out of groundwater and adhering to the surface of soil or sediment particles. In the case of organic compounds such as the Haley Site IHSs, the adsorption process involves the uptake of the compound by the organic fraction of the soil or sediment. The distribution coefficient, K_d, of an organic compound is the ratio of the compound's adsorbed-phase concentration in soil (or sediment) to its dissolved-phase concentration in groundwater. The distribution coefficient is directly proportional to the fraction of organic material in the soil (or sediment) and an empirically-based organic carbon-water partitioning coefficient, K_{OC}. The compound-specific K_{OC} values used to estimate distribution coefficients provide a general indication of the tendency of a compound to preferentially partition to soil/sediment (higher K_{OC} values) or to groundwater (lower K_{OC} values). Accordingly, K_{OC} values provide an indication of a compound's relative aqueous-phase mobility; compounds with higher K_{OC} values have a greater tendency to sorb to soil or sediment, and are therefore less mobile in the aqueous-phase than compounds with lower K_{OC} values.

The mass of adsorbed-phase organic contaminants present in soil or sediment that is in equilibrium with groundwater containing dissolved contaminants is highly dependent on the fraction of organic material present in the solid matrix and the type of organics present. At the Haley Site, soil and sediment generally contain a significant fraction of organics; some exploration locations were found to have very high percentages of wood or other organic debris. Consequently, relatively higher adsorbed-phase contaminant concentrations in soil and sediment, and lower aqueous-phase concentrations and mobility in groundwater, would be expected at the Haley Site in comparison to sites with less organic material in soil and sediment.

7.1.4. Vapor Phase

Organic contaminants can volatilize directly from LNAPL as well as from soil and groundwater. For LNAPL in equilibrium with soil vapor, the relationship between the concentration of an individual volatile compound in the LNAPL and its concentration in soil vapor is similar to that described in Section 7.1.2 for LNAPL in equilibrium with groundwater. The concentration of a particular organic compound in soil vapor is proportional to the compound's concentration in LNAPL and its equilibrium

vapor pressure. This relationship is described by Raoult's Law. The higher the equilibrium vapor pressure of a compound, the higher its concentration in soil vapor.

The equilibrium relationship between the concentration of a volatile organic compound in soil vapor that is in contact with groundwater containing the same compound in the dissolved (aqueous) phase is described by Henry's Law. Similar to Raoult's Law for LNAPL volatilization, Henry's Law states that the concentration of a particular organic compound in soil vapor is proportional to the compound's dissolved concentration in groundwater. The proportionality constant is known as the Henry's Law constant and is empirically derived.

Soil vapor sampling results for the Haley Site are presented in Section 6.5. The results suggest that some of the Site-related contaminants (i.e., BETX compounds and light aliphatic hydrocarbons) are volatile enough to transport to soil vapor and reach concentrations exceeding established MTCA screening levels under equilibrium conditions. However, several soil, groundwater and/or sediment IHSs, particularly the heavier PAHs and dioxins/furans, are not sufficiently volatile to partition from LNAPL, groundwater, or soil-to-soil vapor. The majority of the petroleum hydrocarbons associated with the Haley Site do not have a significant volatile fraction.

7.2. LNAPL Mobility

The term "LNAPL" used in this RI report refers to nonaqueous-phase hydrocarbon having a density less than water that is either: (1) present at residual saturation concentrations and immobile, or (2) present at concentrations greater than residual saturation, and potentially mobile. LNAPL present at residual saturation concentrations is immobile and typically occurs in the subsurface soil as discontinuous blobs, ganglia, and/or a coating on subsurface materials. LNAPL throughout the greater portion of the smear zone is immobile. LNAPL that exceeds residual saturation is considered "free LNAPL," synonymous with the often used term "free product." Free LNAPL in the subsurface is hydraulically connected in void spaces, and is capable of migrating (into a well, for example) if sufficient pressure gradients and transport pathways exist. Free LNAPL at the Haley Site is currently present only in wells near the shoreline in the area identified as the LNAPL Plume (Figure 6-1). Not all free LNAPL is mobile; the term "mobile LNAPL" refers to free LNAPL that is mobile in the environment under prevailing hydraulic conditions (ASTM 2009), as explained in more detail below.

As noted above, mobile LNAPL migration requires a gradient and a pathway. This is in contrast to LNAPL that cannot move from one point to another because of the lack of a gradient or due to a barrier to migration. Barriers are common in heterogeneous soil as the result of lateral fining of soils as small changes to soil texture (e.g., increased silt content) that can form a capillary barrier to migration. Barriers can also be manmade such as the sheet pile barrier along a portion of the Haley shoreline. LNAPL mobility at the Haley Site was evaluated based on a review of relevant existing Site conditions (Section 7.2.1) and LNAPL recoverability test data (Section 7.2.2). Conclusions regarding LNAPL mobility at the Site are presented in Section 7.2.3.

7.2.1. Potential LNAPL Mobility

Potential LNAPL mobility was evaluated by reviewing: (1) data regarding LNAPL spatial extent, LNAPL elevation and thickness in monitoring wells, and LNAPL recovery (Section 7.2.1.1.); (2) LNAPL gradients (Section 7.2.1.2); and (3) digital imaging and petrophysical testing of soil cores from the LNAPL Plume area (Section 7.2.1.3).

In general, LNAPL migrates most rapidly during or shortly after a release, when the pressure gradient driving migration (the "driving head") is greatest. The driving head dissipates with time after the release, resulting in progressively decreasing LNAPL migration. The LNAPL eventually becomes immobile when there is insufficient LNAPL to occupy interconnected pore space. As mobile LNAPL migrates, the volume of free LNAPL continually decreases as LNAPL becomes trapped as isolated droplets in the soil pore space. Unless continually supplied from an ongoing release, LNAPL plumes are spatially self-limiting. This is especially true in a tidally-influenced environment. Tidal fluctuation spreads LNAPL vertically, typically producing a thick smear zone, resulting in the LNAPL spreading less in areal extent than it would otherwise in the absence of tidal fluctuation. In addition, tidally-driven groundwater table fluctuations can restrict the ability of LNAPL to coalesce and migrate as a continuous plume (API 2004).

Mobile LNAPL generally exists near release areas and areas of LNAPL mounding, or along preferential transport pathways; the preferential pathways are often zones with larger interconnected pores (e.g., coarser zones). LNAPL can become trapped or confined by natural barriers or man-made barriers such as the Haley sheet pile barrier, or by frequent groundwater table fluctuations such as those caused by tides. Given the heterogeneous nature of Site soils, which reflects historical tideland filling practices at the Site, other subsurface barriers (besides the sheet pile barrier) may exist in some locations that further limit or prevent LNAPL mobility.

The Site history presented in Section 2.0 describes oil seeps and sheens that have infrequently emerged in the intertidal zone since the mid-1980s. Although tidally-influenced groundwater table fluctuations likely limit LNAPL mobility at the Site, LNAPL migration may have contributed to the incidence of these seeps and sheens. However, since the 2001 construction of the existing sheet pile barrier and removal of some intertidal sediment, seeps immediately downgradient (west) of the sheet pile barrier have been eliminated.

7.2.1.1. LNAPL OBSERVATIONS

The distribution of LNAPL at the Site is described in Section 6.2 and depicted in Figure 6-1. The relatively small quantities of LNAPL recovered to date (Section 6.2), despite considerable efforts to recover LNAPL, suggest that LNAPL is immobile in most areas. This is particularly true in the monitoring wells inland from the shoreline (e.g., CL-MW-1H, CL-MW-6, CL-MW-103, HS-MW-4, HS-MW-7 and HS-MW-8; Figure 6-1) where the presence of LNAPL is intermittent and accumulation thicknesses are relatively small (Table 6-1b). Given the duration since wood treatment operations ceased and the low groundwater gradients in the inland areas, observations suggest that the LNAPL in these areas is immobile.

Areas where LNAPL is potentially mobile include the LNAPL Plume area behind the sheet pile barrier, where the greatest thicknesses of LNAPL are consistently present (e.g., well TL-MW-2); the area immediately west of the sheet pile barrier (well TL-MW-6); and the area south of the sheet pile barrier, in the vicinity of wells TL-MW-10 and TL-MW-12. However, LNAPL thickness data for wells behind the sheet pile barrier suggest that even within the LNAPL Plume, LNAPL is immobile in most locations. In 2012, the measured LNAPL thickness in most monitoring wells behind the sheet pile barrier was less than 1 foot, which is less than the "critical thickness" for LNAPL mobility of a diesel product in a sandy matrix (i.e., 1 to 2 feet) (ITRC, 2013). Only three wells had LNAPL thicknesses greater than 1 foot: TL-MW-2 had approximately 3 to 6 feet of LNAPL (Table 4-1 and Figure 6-2); TL-MW-3 had just over 1 foot of LNAPL in August 2012 (Table 4-1); and TL-MW-8 had just over 1 foot of LNAPL in

May 2012 (Table 4-1). All three of these wells are located near the southern end of the sheet pile barrier. The presence of LNAPL in wells TL-MW-6, TL-MW-10 and TL-MW-12 is intermittent and measured thicknesses are relatively small (Table 4-1), suggesting that the LNAPL in the vicinity of these wells is immobile.

7.2.1.2. LNAPL GRADIENTS

Site-wide monitoring of depth to LNAPL and LNAPL thickness in monitoring wells suggests that the greatest LNAPL gradients (driving heads), if present, would exist in the LNAPL Plume area. LNAPL gradients (ITRC 2013) were calculated for September 2011, December 2011 and May 2012 based on the air/LNAPL interface elevations in three wells in a relative triangulated position (TL-MW-2 and TL-MW-3 behind the sheet pile wall and inland well HS-MW-8). Apparent LNAPL gradients ranged from approximately 0.01 to 0.03 feet/foot. These values are similar to or slightly greater than the hydraulic gradient. In areas of the Haley upland where the LNAPL layer on the groundwater table is much thinner, the driving head for LNAPL mobility appears to be limited by the horizontal groundwater gradient (approximately an average of 0.016 feet/foot; Section 4.0).

7.2.1.3. DIGITAL IMAGING AND PETROPHYSICAL TESTING

Digital imaging (visible and UV light photography) and petrophysical testing were performed on soil cores obtained from two of the 2012 supplemental investigation borings (Appendix J). Continuous soil cores were collected from the petroleum smear zone at locations TL-MW-14 and TL-MW-15 in the LNAPL Plume area. This was a deviation from the 2012 Work Plan; the reason for the deviation is explained in Appendix E. The TL-MW-14 soil core was representative of the Upland Fill unit, and the TL-MW-15 soil core was representative of the Wood Fill unit.

Exhibits J-1 and J-2 in Appendix J provide side-by-side visible light and UV light photographs of the soil cores which document the variable petroleum impacts within the core interval. The UV light photographs document the UV fluorescence of hydrocarbons present in the same core intervals shown in the visible light photographs; the relative intensity of the fluorescence allows the most heavily-impacted portion of each core interval to be identified. By comparing the visible and UV light photographs, the degree of petroleum impacts can be correlated with the lithologies present in the cores. This information was used in the RI to select samples for FPM testing.

The UV photography suggests that the petroleum smear zone extends from approximately 7.5 to 12 feet bgs at TL-MW-14, and from approximately 9 to 12 feet bgs at TL-MW-15. At both locations, the smear zone thickness interpreted from UV photography was less than the thickness estimated from field screening of soil samples obtained during drilling (Figure 6-4). A possible explanation for this discrepancy is that UV fluorescence may be a less sensitive screening method for detecting hydrocarbons than the water sheen test method used in the field.

The UV fluorescence of the soil core from TL-MW-14 was strongest at the approximate depth of the groundwater table (7.5 to 8.0 feet bgs); fluorescence between 8.0 and 10.5 feet bgs was less intense yet pervasive, while only scattered zones of speckled fluorescence occurred below that (Appendix J, Table J-1 and Exhibit J-1). Based on these observations and comparison to lithologies, soil at four different depths in the TL-MW-14 borehole was selected for petrophysical testing (Appendix J, Table J-1). The soil at the two shallowest depths (7.75 and 8.2 feet bgs) consisted of poorly-graded gravel with sand and silt. The soil at 10.2 feet bgs consisted of silty sand with gravel and occasional wood

fragments, whereas soil at 11.65 feet bgs consisted of poorly-graded sand with gravel and silt and occasional wood and shell fragments.

In the soil core from TL-MW-15, a zone of pervasive fluorescence was observed from approximately 9.0 to 11.6 feet bgs (Appendix J, Table J-1 and Exhibit J-2). Soil at two depths (9.6 and 10.95 feet bgs) in the TL-MW-15 borehole was selected for petrophysical testing (Appendix J, Table J-1); these two samples consisted primarily of wood debris.

The petrophysical testing consisted of free product mobility (FPM) testing, and was performed by PTS Laboratories, Inc. of Santa Fe Springs, California (Appendix J, Exhibit J-4). FPM testing involves centrifuging portions of the undisturbed sample cores either in air or after first immersing the sample under water. After centrifuging, the percent saturation of LNAPL and water in the samples is measured. The centrifuging is done at various "centrifuge pressures" (spin velocities) intended to simulate conditions ranging from gravity drainage up to approximately 1,000 times the force of gravity. The two samples collected above and near the groundwater table (TL-MW-14 at 7.75 and 8.2 feet bgs) were centrifuged in air to evaluate LNAPL mobility in unsaturated soil above the groundwater table. The remaining four samples were centrifuged after immersing in water, to evaluate LNAPL mobility in saturated soil below the groundwater table. In addition to centrifuging, the FPM testing also included measurement of sample bulk density, grain density and total porosity (Appendix J). The FPM test results are summarized in the table below.

Location	Sample Depth (feet bgs)	Fluid Measured	FPM Test Results for Soil Core Samples			
			Percent Saturation (% of Pore Volume)			
			Initial	250 rpm	500 rpm	1,000 rpm
TL-MW-14	7.75	Water	61.4	51.9	19.0	13.2
		LNAPL	8.9	8.9	8.9	8.1 (Note 1)
	8.2	Water	64.1	45.5	20.1	12.9
		LNAPL	3.1	3.1	3.1	2.9 (Note 1)
	10.2	Water	37.0	41.6	47.1	55.4
		LNAPL	9.0	9.0	9.0	9.0
	11.6	Water	47.3	52.2	61.9	72.4
		LNAPL	13.9	13.9	13.9	13.9
TL-MW-15	9.6	Water	23.4	31.3	41.1	51.6
		LNAPL	15.9	15.9	15.9	15.9
	10.95	Water	36.1	44.3	54.1	65.2
		LNAPL	4.0	4.0	4.0	4.0

Note 1: Indicative of a small amount of LNAPL displacement, but only at the greatest pressures (corresponding to 1,000 rpm).
rpm = revolutions per minute

As shown in the above table, LNAPL was not displaced (i.e., the LNAPL percent saturation did not change relative to initial conditions) in any of the soil core samples at centrifuge pressures of 250 and 500 revolutions per minute (rpm). These results suggest that LNAPL at the locations and depths sampled is immobile. At the maximum centrifuge pressure tested (corresponding to

1,000 rpm), a minor amount of LNAPL was displaced (i.e., the LNAPL percent saturation decreased) in two of the samples from location TL-MW-14 (7.75 and 8.2 feet bgs). In both cases, the amount of LNAPL displaced was small and not indicative of mobile LNAPL.

Two soil samples (TL-MW-14 at 11 feet bgs and TL-MW-15 at 11 feet bgs) from locations and depths generally corresponding to two samples tested by FPM methods, were analyzed for TPH (Table 6-4). TPH concentrations in these two samples were 17,770 mg/kg (TL-MW-14 at 11 feet) and 6,110 mg/kg (TL-MW-15 at 11 feet bgs). The sample obtained from 11.6 feet bgs at TL-MW-14 had the second highest initial LNAPL percent saturation of the six samples submitted for petrophysical testing. No reduction in the LNAPL percent saturation was observed in either of these two samples at any of the centrifuge pressures tested. These results suggest that the residual saturation concentration for LNAPL at the Site may be greater than 17,770 mg/kg.

7.2.2. LNAPL Recoverability

LNAPL recoverability can be evaluating by measuring LNAPL transmissivity, similar to standard groundwater transmissivity. LNAPL transmissivity refers to the volume of LNAPL that will discharge into a well (or trench) and therefore relates to LNAPL mobility. LNAPL transmissivity measures the "ability" for LNAPL migration, which is not the same as confirming that LNAPL is actually migrating. LNAPL bail-down tests were used to evaluate LNAPL transmissivity.

LNAPL bail-down tests were performed in four 2-inch diameter wells that historically had relatively greater thicknesses of LNAPL: TL-MW-2, TL-MW-4, TL-MW-5A and TL-MW-6. Test data (Appendix I) are summarized as follows:

Well	Maximum Groundwater Table Decline From Bail-Down (ft)	Initial Thickness of LNAPL Before Bail-Down (ft)	LNAPL Thickness After Testing (Same Day) (ft) (% Recovered)	LNAPL Thickness After Testing (7 Days After Test) (ft) (% Recovered)
TL-MW-2	0.39	2.07	1.35 (65%)	1.92 (93%)
TL-MW-4	0.86	1.01	0.44 (44%)	0.49 (48%)
TL-MW-5A	0.34	1.08	0.39 (36%)	0.48 (44%)
TL-MW-6	0.23	0.99	0.47 (47%)	0.65 (66%)

LNAPL bail-down data collected from monitoring well TL-MW-2 met the Work Plan requirements (GeoEngineers 2012a) for data evaluation for unconfined conditions (Appendix I). LNAPL bail-down data collected for TL-MW-4, TL-MW-5A and TLMW-6 could not be further analyzed because of the apparent very low LNAPL transmissivities, in combination with the lack of a stable water table due to tidal fluctuation during the test.

Data from the TL-MW-2 LNAPL bail-down tests were analyzed using two methods developed by Huntley (Huntley 2000) and Kirkman (Kirkman 2012) (Appendix I). Both methods are based on the Bouwer and Rice slug test analysis method (Bouwer and Rice 1976, 1989), modified to address LNAPL. The estimated LNAPL transmissivity values were 2.96 ft^2/day (Huntley method) and 2.11 ft^2/day (Kirkman method).

LNAPL transmissivity estimates from TL-MW-2 appear to be reasonable when compared to site conditions and are representative of low to moderate LNAPL transmissivity. Results for TL-MW-2 suggest there is additional recoverable LNAPL at this location.

7.2.3. LNAPL Mobility Summary

The various lines of evidence evaluated for the RI regarding LNAPL mobility suggest that LNAPL is immobile throughout most of the site, but is potentially mobile behind the sheet pile wall in the area of TL-MW-2 and possibly south of the sheet pile wall (TL-MW-10 and TL-MW-12). Most of the remaining LNAPL mass is trapped (immobile) in the petroleum smear zone generally between the seasonal high and low elevations of the groundwater table. Based on multiple lines of evidence, the area of the Site where mobile LNAPL would be most likely to exist is the LNAPL Plume area behind the sheet pile barrier. The sheet pile barrier has impeded LNAPL migration to Bellingham Bay since it was completed in 2001.

Petroleum sheens that have historically been observed in the intertidal zone west and south of the sheet pile barrier likely were caused by the erosion of nearshore smear-zone soils containing LNAPL, or by occasional limited migration of LNAPL through upland soils to intertidal sediments. As noted previously, the sheet pile barrier has been effective in preventing significant migration of LNAPL to Bellingham Bay. The migration of LNAPL beneath the upland margin also is likely limited by tidally-driven groundwater table fluctuations.

7.3. Fate and Transport Processes Affecting IHSs

This section describes chemical, physical, and biological processes affecting the fate and transport of the IHSs identified at the Haley Site.

7.3.1. Petroleum Hydrocarbons

Petroleum hydrocarbons associated primarily with the carrier oil used for wood treating represent the greatest mass and spatial extent of the IHSs. Diesel- and heavy oil-range hydrocarbons are present: (1) as a distinct LNAPL layer, (2) as discontinuous, immobile globules at low levels of pore saturation in equilibrium with pore water and soil vapor (immobile LNAPL), (3) in the adsorbed phase in soil and sediment below concentrations indicative of LNAPL, and (4) in the aqueous phase in groundwater. Generally, diesel- and heavy oil-range hydrocarbons have relatively low solubilities, so the majority of the petroleum hydrocarbon mass at the Site is expected to exist as dispersed, immobile LNAPL in smear-zone soils. However, diesel-range hydrocarbon mixtures have an average solubility of approximately 5 mg/L, and therefore can dissolve and migrate in groundwater beyond the limits of LNAPL and adsorbed-phase impacts. In addition, tidally-driven groundwater table fluctuations cause repeated flooding and draining of the smear zone near the shoreline, leading to increased rates of dissolution to groundwater.

Aqueous-phase petroleum hydrocarbons in groundwater can biodegrade under aerobic conditions. However, as described above in Section 7.1.2, dissolved oxygen concentrations and redox values in groundwater at the Haley Site suggest that conditions in the saturated zone are unfavorable for significant aerobic biodegradation. Degradation of wood waste and other non-petroleum organics present in the saturated zone is likely utilizing dissolved oxygen, leaving reducing conditions that inhibit the natural attenuation of petroleum hydrocarbons.

In the subsurface, the more volatile constituents of an LNAPL such as carrier oil partition to soil vapor, and the more soluble constituents partition to groundwater. Through this process, the LNAPL can lose enough mass of volatile/soluble constituents over time that it becomes more viscous, and hence less mobile. Considering the many years that have elapsed since the petroleum releases occurred at the Haley Site, this LNAPL transformation has likely contributed to decreased LNAPL mobility at the Site.

7.3.2. Polycyclic Aromatic Hydrocarbons

Generally, PAHs are hydrophobic and have low vapor pressures, resulting in limited mass transfer to soil vapor and groundwater. Accordingly, most of the PAH mass at the Site is expected to occur in the distinct LNAPL layer and the adsorbed phase in soil. However, LPAHs, including the soil and groundwater IHSs 1-methylnaphthalene and 2-methylnaphthalene, have significantly higher volatility, solubility, and mobility than HPAHs such as acenaphthene and benzo(a)anthracene (also IHSs). The higher solubility and mobility (lower K_{OC}) of the methylnaphthenes, combined with the relatively high concentration (nearly 1 percent) of 2-methylnaphthalene in the carrier oil (based on UST oil sample data; Table 6-2), have resulted in the widespread distribution of methylnaphthalenes in Site groundwater at concentrations that are orders of magnitude greater than other PAHs.

7.3.3. Pentachlorophenol

PCP is slightly soluble in water (solubility of approximately 20 mg/L), similar to the LPAHs. However, as indicated by its high K_{OC}, PCP generally is not highly mobile in the aqueous phase due to its high affinity for organic matter in soil and sediment. Because PCP is an ionizing organic compound, its aqueous-phase mobility is highly dependent on groundwater pH; as pH increases, PCP mobility increases (Kaiser and Valdmanis 1981). Kaiser and Valdmanis studied the partitioning of PCP between octanol and water at various pH values, which demonstrated that acidic (low pH) environments result in higher octanol/water partition coefficients (log K_{OW} of 4.5 to 5) while highly alkaline conditions of pH between 9 and 12 result in a significant reduction of the partition coefficient (log K_{OW} of approximately 1.5). In the pH range typical of groundwater at the Haley Site, approximately 5.5 to 6.5, the log K_{OW} for PCP ranges from approximately 3.5 to 4, corresponding to a K_{OC} range of between 2,000 to 6,300 L/kg (Kaiser and Valdmanis 1981).

Other literature sources suggest the PCP K_{OC} values corresponding to the pH range of Site groundwater may be even higher. The EPA Technical Fact Sheet for PCP (EPA 2010) lists the K_{OC} for PCP as 1,000 L/kg for soil, 3,000 to 4,000 L/kg for sediment, and as high as 25,000 L/kg for low pH conditions. Schellenberg et al. evaluated adsorption of PCP and concluded that the average K_{OC} for PCP in sediment and aquifer materials is 32,900 L/kg, and that the adsorption of PCP is highly dependent on the organic content of the adsorbent (Schellenberg et al. 1984). However, the default, conservative K_{OC} value listed in Table 747-2 of the MTCA Cleanup Regulation is 592 L/kg, for neutral pH groundwater. This default value was used to develop the PCP soil screening levels protective of groundwater and surface water that are presented in this report. Because the cited literature sources suggest that the MTCA default K_{OC} value overestimates the extent to which PCP partitions to groundwater, the PCP soil screening levels presented in this report (based on protection of groundwater) are likely overly conservative. This appears to be confirmed by the limited number of PCP exceedances in groundwater relative to the exceedances in soil.

PCP has a low vapor pressure and Henry's Law constant. As a result, volatilization of PCP from LNAPL and groundwater is expected to be minor, and not a significant mass transfer mechanism.

PCP is susceptible to biodegradation under aerobic conditions. However, as described above for petroleum hydrocarbons, conditions in the saturated zone at the Haley Site do not appear to be favorable for aerobic biodegradation.

7.3.4. Dioxins/Furans

Dioxins/furans are highly stable in the environment due to low volatility, low solubility, and a strong tendency to adsorb to organics in soil. Dioxins/furans have been detected in groundwater at the Site, but at extremely low concentrations (on the order of less than 1,000 pg/L TEQ). Dioxins/furans have also been detected in soil and sediment at the Site.

The solubility of individual dioxin/furan congeners ranges by several orders of magnitude from approximately 74 pg/L (OCDD) to 420,000 pg/L (TCDF group average). Solubilities generally decrease as the number of chlorine atoms, and thus molecular weight of the congener, increase (EPA 2003b). Congeners in the tetrachlorinated homolog groups (TCDF and TCDD) have higher solubilities than more chlorinated homologs. Only one tetrachlorinated congener was detected in groundwater at the Site (2,3,7,8-TCDF in monitoring well TL-MW-11). The dioxin/furan congeners detected at the highest concentrations in groundwater at the Site, heptachlorinated and octachlorinated dioxins and/or furans, represent the lower range of congener solubility, and the highest level of chlorine saturation (seven to eight chlorine atoms). Generally, the frequency of detection, as well as the detected concentrations, of individual congeners increased with higher chlorine saturation and decreased solubility. In fact, the congener OCDD which was detected at significantly higher concentrations than other detected congeners, was consistently detected in the groundwater samples at concentrations that are several orders of magnitude greater than its reported solubility of 74 pg/L. This behavior is indicative of groundwater samples containing entrained particulates with strongly sorbed dioxins/furans. The variability of the concentrations is impacted more by the turbidity of the groundwater sample than dissolved concentrations in the groundwater (Section 6.4.5).

While dioxins/furans are extremely hydrophobic and generally stable when adsorbed to organics in soil and sediment, they are capable of mobilizing in the presence of cosolvents that may exist in groundwater or mobile LNAPL. Some of the more mobile compounds characteristic of wood-treating sites, including 2-methylnaphthalene, have been shown to mobilize dioxins/furans by cosolvent processes (Puri et al. 1990). Dioxins/furans adsorbed to sediments can be transported by natural or anthropogenic erosion processes, such as wave erosion or anchor drag (Section 7.3.5).

7.3.5. Processes Affecting Sediment

Physical and biological processes such as soil erosion and sediment deposition, bioturbation and biodegradation and physical disturbances affecting the marine environment have the potential to transport or attenuate adsorbed-phase contaminants in soil and sediment at the Haley Site as further described below.

7.3.5.1. SOIL EROSION AND SEDIMENT DEPOSITION

The marine sediments in the intertidal and subtidal zones at the Haley Site are typical of nearshore marine environments where wave energy and surface water flow regimes vary based on weather

patterns, local currents, tidal range, shoreline configuration, bottom slopes, water depths and nearby boat traffic. Although not directly exposed to the prevailing winds and weather from the south and north/northeast, the shoreline is influenced by wave action and storms in Bellingham Bay. Historically, substantial portions of the marine areas of the Haley Site were covered with piers and wharves that limited shoreline erosion. These structures began to degrade in the late 1940s; the wharf structures either were removed or degraded into the water, with wooden piling supports remaining in many places. The Haley shoreline has since been subjected to relatively high-energy wave action and long-shore currents, which over time have created an intertidal zone dominated by coarse-grained sediment including boulders, cobbles and gravel. The Haley shoreline bank has historically eroded inland at rates up to 6 inches per year (Section 4.1.4.3). The erosion protection measures completed in 2001 following construction of the sheet pile barrier significantly reduced shoreline erosion in the area of the LNAPL Plume.

The Nooksack River is the main source of sediment to Bellingham Bay (Section 4.6.1). Although the majority of the coarse-grained sediments discharged to the Bay are deposited on the river's delta, silts and clays are transported throughout the Bay, contributing to the predominantly fine-grained texture of the subtidal sediments offshore of the Haley Site. Studies conducted by Ecology (Hart Crowser 2009b) at the Cornwall site estimated a deposition rate of approximately 1.1 cm/year in the subtidal portion of the Cornwall site (Section 4.1.6.5); this estimate is relevant for the neighboring Haley Site. Estimated sediment deposition rates for inner Bellingham Bay based on Whatcom Waterway studies range from 1.52 to 1.77 cm/year (RETEC 2006). This ongoing deposition of uncontaminated sediment, derived largely from the Nooksack River, has likely contributed to the natural recovery of sediments in the subtidal portion of the Haley Site.

7.3.5.2. BIOTURBATION AND BIODEGRADATION

Bioturbation is the process by which benthic organisms regularly rework the near-surface sediment column as a result of tube-building, burrowing, feeding, respiration or other behaviors. These activities in the "biologically active zone" physically mix the sediments, thereby increasing the exchange of sediment porewater with the overlying water column and extending the depth to which dissolved oxygen and other microbial nutrients in seawater penetrate the sediment. In Bellingham Bay, the biologically active zone has been defined as the upper 12 cm of sediment, although some larger organisms may burrow deeper (up to 3 feet below mudline). As a result of the increased sediment porewater exchange and deeper penetration of microbial nutrients, bioturbation can reduce contaminant concentrations in the uppermost sediment column by accelerating biodegradation. Additionally, bioturbation can expose sediment contaminants to ultraviolet (UV) radiation (in relatively shallow water), which also can accelerate contaminant degradation; PAHs, in particular, can be degraded by UV light.

7.3.5.3. PHYSICAL DISTURBANCE

Physical disturbances can also rework surface sediment, exposing subsurface sediment or mixing surface with subsurface sediment. Physical disturbances in the vicinity of the Haley Site are likely intermittent, and may be anthropogenic (e.g., anchor drag) or biological (e.g., flat-fish feeding). The portion of the sediment column that may be physically disturbed can range from several inches to several feet below mudline, depending on the source of the disturbance. Several studies investigating one or more of these processes have been conducted in Bellingham Bay; the most recent study was associated with the Whatcom Waterway cleanup project (RETEC 2006). Propeller wash and anchor drag also can cause larger-scale disturbances where large vessels are allowed to

anchor, as in Whatcom Waterway (RETEC 2006). The nearshore area of the Haley Site is unlikely to experience this scale of physical disturbance, as water depths are shallow and are not part of the Port's navigational lanes or anchorage areas.

8.0 CONCEPTUAL SITE MODEL

A CSM was developed for the Haley Site during the 2007 RI/FS. The CSM summarized potential contaminant sources and release mechanisms, transport processes, and exposure routes by which receptors may be affected by Site contaminants. The Haley CSM has been refined based on results of supplemental upland and sediment investigation activities. The revised CSM is discussed in this section, which is organized as follows:

- Section 8.1 – Potential contaminant sources
- Section 8.2 – Nature and extent of contamination
- Section 8.3 – Contaminant transport mechanisms
- Section 8.4 – Potential exposure pathways and receptors
- Section 8.5 – Brief review of cleanup actions to date that addressed certain historical sources and pathways identified in the CSM

8.1. Potential Contaminant Sources

8.1.1. Historical Industrial Sources

More than a century of industrial waterfront activities have affected environmental conditions at the Haley Site (Section 2.2 and 2.3). The most prevalent impacts at the Haley Site were caused by past wood treatment including treated wood storage activities, as discussed further below. Several other waterfront activities were associated with contaminant sources that may have also impacted the upland and nearshore aquatic environments at the Site such as the historical lumber mill activities, much of which occurred on overwater structures supported by wooden pilings. Tideland filling and municipal landfill operations also introduced potential contaminant sources to the present-day upland and marine environments. Former tidelands that comprise the present-day Haley upland were filled with lumber mill-derived wood debris, apparent construction debris, dredged marine sediment, and landfill waste. Stormwater runoff from the Haley and Cornwall uplands and a municipal stormwater outfall also potentially introduced contamination to Site sediment.

The adjacent Cornwall Landfill and Whatcom Waterway sites overlap upland and/or in-water portions of the Haley Site (Sections 2.5 and 2.6). The primary contaminant sources associated with the Cornwall site include wood debris placed as tideland fill before landfill operations, municipal wastes placed during landfill operations (Landau 2013), and possible past releases on upland property after landfill closure (e.g., reported oil dumping; Section 2.2.7). Contaminant sources associated with the Whatcom Waterway site are related to discharges from historical pulp and paper mill activities on upland properties adjacent to the Whatcom Waterway north of the Haley Site. Specific contaminants associated with these adjacent MTCA sites and the areas of overlap with the Haley Site are described below.

The most prevalent environmental impacts on the Haley Site are related to the release of wood treatment constituents contained in P-9 carrier oil. The presence of these constituents in soil, groundwater and sediment overlap upland portions of the Cornwall site, and in-water portions of the Cornwall and Whatcom Waterway sites. Investigation results suggest that P-9 carrier oil (Section 6.2.1)

was released in the wood treatment area at the location of above-ground equipment (e.g., retort, tram and ASTs) and underground equipment (e.g., UST, surge tank and piping) (Figure 2-4). Wood treatment chemicals also were apparently released in areas where treated wood was stored. This includes the drying sheds and drip pads adjacent to the shoreline, and the area between the former drying sheds and the eastern property boundary. Wood-treating constituents also were released to soil and groundwater via the former wastewater seepage pit. Subsequent to the release of these contaminants at the former Haley facility, wood treatment constituents migrated to other locations and media by several transport mechanisms, as discussed in Section 8.3.

While portions of the Haley Site are underlain by fill that contains wood waste, the impacts related to former wood treatment activities encompass the areas of wood waste fill. Furthermore, future remedial actions directed at wood treatment chemicals are anticipated to address any potential impacts associated with the wood waste.

8.1.2. Primary Contaminants Associated with Cornwall, Haley, and Whatcom Waterway Sites

The geographic footprints of contaminants associated with the Haley and Cornwall sites overlap in both the upland and in sediment. Municipal waste associated with the former Cornwall Landfill is present beneath the southwestern portion of the Haley upland; similarly, petroleum hydrocarbons and petroleum-related constituents associated with the Haley Site extend onto the northeastern portion of the Cornwall upland (Section 6.3.2) (Figures 6-9 and 6-10). Upland Cornwall constituents include PCBs, refuse and wood waste, metals, dioxins/furans in stabilized sediment stockpiles, SVOCs, manganese, ammonia and fecal coliform (Landau 2013). Upland Haley constituents primarily consist of petroleum hydrocarbons, PAHs, PCP and dioxins/furans.

Contaminants associated with the Cornwall and Haley sites also overlap in Bellingham Bay sediment (Section 6.6.1). Cornwall-related sediment contaminants include metals, PCBs and SVOCs (phthalates). Haley-related contaminants in sediment primarily consist of petroleum hydrocarbons, PAHs, PCP, and dioxins/furans. Marine portions of the Haley Site also overlap with the Whatcom Waterway site. The key contaminants associated with the Whatcom Waterway site are mercury, 4-methylphenol and phenol, which were associated with historical pulp and paper mill activities. Former pulp and paper mill activities also released dioxins/furans to Bellingham Bay sediment, although mercury is the focus of the Whatcom Waterway cleanup.

8.2. Nature and Extent of Contamination

8.2.1. Upland Impacts

Multiple constituents are present in Site soil and groundwater at concentrations exceeding screening levels (Sections 6.1 through 6.5). Specific IHSs were selected to focus the Haley RI/FS on those constituents that pose the greatest risk and encompass the geographic footprint of all constituents detected above screening levels at the Site (Section 5.2). IHSs for soil include: TPH (expressed as the sum of diesel- and heavy oil-range hydrocarbons); two noncarcinogenic PAHs (1- and 2-methylnaphthalene); total cPAHs and the individual cPAH benzo(a)anthracene; PCP; and dioxins/furans (Section 6.3). These same constituents, excluding TPH and including acenaphthene, were selected as IHSs for groundwater (Section 6.4). The occurrence of the individual IHSs is discussed in previous sections of this report. This section focuses on the collective extent of the Haley-related soil and groundwater IHSs relative to their respective screening levels. IHSs were

detected at concentrations less than screening levels over a broader geographic area than what is reflected in this discussion and the associated figures.

The estimated upland extent of soil and groundwater exceedances associated with the Haley Site is shown in Figure 8-1. This discussion pertains to all soil and groundwater IHSs excluding dioxins/furans, which are discussed separately below. Groundwater screening level exceedances are bound to the north. Most soil screening level exceedances are also bound to the north excluding a few constituents at certain depths. The potential need for additional data at the northern end of the Site will be considered during remedial design.

The estimated extent of petroleum-impacted soil to the south, on the northern portion of the Cornwall property, is based on a combination of chemical analytical data and qualitative field screening results. These field screening results indicate that a petroleum smear zone is present in the north-central and northeastern portion of the Cornwall upland (Sections 6.2 and 6.3). Landfill refuse is present west of this smear zone. The refuse was not sampled, and therefore, the western extent of the petroleum smear zone is not defined by soil analytical results. Comprehensive groundwater data, however, provide a means to assess the nature and extent of contamination beneath the northern portion of the Cornwall property.

Groundwater analytical data suggest that petroleum-related constituents contiguous with the Haley Site do not exceed screening levels on Cornwall much farther south than inland monitoring well CL-MW-101. Only one constituent (1-methylnaphthalene) substantially exceeds the groundwater screening level (EF=6) in monitoring well CL-MW-101 (Section 6.4.1). Two other constituents (acenaphthene and fluorene) only marginally exceed the groundwater screening level in this well (EF=1.3 and EF=1.03, respectively). Although petroleum-related constituents are present at detectable concentrations in the Cornwall shoreline monitoring wells (MW-11S through MW-16S), all detected concentrations are less than screening levels; diesel- and oil-related petroleum constituents were not detected in the Cornwall intertidal zone seep samples (Landau 2013). This suggests that all petroleum-related constituents in groundwater beneath Cornwall, regardless of source or migration pathway, attenuate to values that are protective of sediment and surface water before reaching Bellingham Bay.

The eastern extent of Haley-related soil and groundwater screening level exceedances is not defined by analytical results; however, the eastern extent is anticipated to be very limited because bedrock beneath the upland rises sharply to the east and forms the bluff immediately east of the railroad tracks (Section 4.2). The combination of shallow bedrock and an unknown thickness of railroad ballast suggests that the lateral extent and thickness of saturated upland fill east of the property boundary are very limited (Figures 4-3, 4-5 and 4-6). In addition, groundwater in the upland fill unit, if present beneath the narrow railroad corridor, would have a westerly gradient. Collectively, these conditions suggest that any impacts east of the Haley property boundary are likely limited in extent.

The lateral extent of dioxins/furans in Haley soil is not fully defined based on the existing analytical data. Further evaluation of the extent of Haley-related dioxins/furans in soil will require a concurrent evaluation of background dioxin/furan concentrations that are present as a result of urban and industrial sources unrelated to the former Haley facility. Dioxins/furans in groundwater, although detectable at the northernmost (HS-MW-15) and southernmost (CL-MW-101) sampling locations, are

present at very low concentrations and likely exist as an artifact of the sampling process rather than being representative of actual groundwater conditions at those locations (Section 6.4.5).

The extent of soil vapor screening level exceedances for indoor air is variable but appears to be geographically consistent with the smear zone and LNAPL Plume on the Haley upland, presumably where lighter fractions of petroleum hydrocarbons are present (Section 6.5).

The cumulative body of soil and groundwater chemical analytical data for upland portions of the Haley and Cornwall sites, combined with qualitative field screening results, provides the necessary information to support the evaluation of remedial alternatives at each site, including the area where the sites overlap.

8.2.2. Sediment Impacts

Multiple constituents exceeding screening levels were identified in intertidal and shallow subtidal zone sediment adjacent to the upland portion of the Site (Section 6.6). Constituent concentrations exceeding screening levels extend below the mudline to depths up to 12 feet (one location in the intertidal zone); however, exceedances most commonly occur between 2 and 6 feet below mudline in the intertidal zone, and between 4 and 6 feet in the shallow subtidal zone.

Constituents exceeding screening levels in sediment include TPH, dioxins/furans, individual PAHs, cPAHs, chlorinated phenols, dibenzofuran and n-nitrosodiphenylamine. Exceedances of dibenzofuran and n-nitrosodiphenylamine were infrequent, and sediment IHS concentrations exceeding screening levels co-occurred in the samples with exceedances of dibenzofuran and n-nitrosodiphenylamine. Mercury and phthalates also are present in sediment at concentrations above screening levels, but are not related to sources associated with the Haley Site.

Dioxins/furan concentrations in Site sediment decrease with distance from the shoreline and approach concentrations similar to other urbanized areas of Bellingham Bay in subtidal surface sediments. The limit of Site-related dioxins/furans in the subtidal area will be evaluated by additional subtidal surface sediment sampling.

Sediment bioassay (toxicity) testing indicates that toxic impacts to benthic invertebrates in surface sediment do not extend beyond the shallow subtidal zone (-15 feet NAVD88). The southern and northern extent of contamination in surface sediment in the intertidal zone is not fully defined; additional data will be collected to refine the extent of contamination along the shoreline prior to remedial design.

Areas of the Site where contaminant concentrations in surface sediment exceed established chemical and biological screening criteria are shown in Figure 8-1. Subsurface sediment impacts will be considered during evaluation of remedial alternatives in the FS.

The lateral extent of sediment impacts shown in Figure 8-1 does not account for potential risks to human health posed by the presence of bioaccumulative compounds. Potential Site-related sediment impacts associated with bioaccumulative constituents (i.e., PCP, cPAHs and dioxins/furans) are evaluated in the FS. Cleanup levels for bioaccumulative compounds will likely expand the area over which in-water remedial actions will be evaluated; additional sediment data will be collected to evaluate the lateral limits of screening level exceedances for these compounds.

The remedy in this expanded area is anticipated to include monitored natural attenuation, and may involve a larger PLP group.

8.3. Contaminant Transport Mechanisms

Historical research and investigation data suggest that releases of P-9 carrier oil occurred in the wood treatment area and areas where treated wood was stored. These releases impacted soil beneath most of the former Haley facility. Process wastewater also was released in the seepage pit. Contaminants associated with these primary releases subsequently migrated to other locations and environmental media by secondary release mechanisms and transport processes (Figure 8-2).

The investigation data indicate that some of the historical carrier oil releases migrated downward vertically and collected on the groundwater table as LNAPL (Section 6.2). LNAPL then migrated on the groundwater table in a general downgradient direction toward the shoreline. This horizontal migration of LNAPL, combined with vertical groundwater table fluctuations in response to seasonal and tidal influences, produced the petroleum smear zone (Figure 8-1).

LNAPL accumulated near the shoreline as a result of tidally-driven groundwater table fluctuations (Section 6.2). LNAPL at the shoreline has intermittently migrated to the upper intertidal zone in the form of oil seeps. Erosion of the shoreline bank was the likely cause of the oil seep observed in 2000; this led to the installation of the sheet pile barrier (Section 2.4.8). The sheet pile barrier prevents westward migration of the LNAPL plume. South of the sheet pile wall along the shoreline, the potential for LNAPL migration is limited due to the natural “hydraulic barrier” effect of tidally-driven groundwater table fluctuations. Farther inland, residual LNAPL that occurs locally appears to be immobile (Section 7.2.3).

Petroleum releases in the upland have impacted the majority of the fill prism beneath the Site. Contaminants in the fill have leached to groundwater to produce an upland plume of aqueous-phase (dissolved) constituents. The aqueous-phase plume extends to the Haley shoreline. Dissolved-phase contaminant concentrations in groundwater are anticipated to substantially decrease as a result of tidal mixing beneath and near the intertidal zone (Section 7.1.2). At the nearby GP West site, empirical data indicate that tidal mixing reduces contaminant concentrations in groundwater by a factor of 54 or more before the groundwater reaches the biologically active zone in surface sediment. The magnitude of tidal attenuation, however, varies at waterfront sites based on site-specific conditions. The elevated contaminant concentrations in sediment at the Haley Site would tend to reduce the effects that tidal mixing would otherwise have on chemical attenuation.

Contaminated sediment in the upper intertidal zone has been impacted by the migration of LNAPL and/or aqueous-phase contaminants from the upland (Section 6.8). This migration has been more prominent in the shallow part of the upland fill aquifer based on the greater number of screening level exceedances in shallow versus deep monitoring wells near the shoreline. LNAPL and dissolved-phase contaminants likely migrated to sediment as surface and shallow subsurface flow in the intertidal zone, primarily during receding tides. Deeper groundwater impacts near the shoreline, although present, do not appear to have caused screening level exceedances in sediment at correlative depths. Sediment impacts in the upper intertidal zone associated with this transport pathway are generally limited to depths of 0 to 6 feet below mudline.

Sediment impacts in lower (0 to –4 feet NAVD88) portions of the intertidal zone and in the shallow subtidal zone (-4 to -15 feet NAVD88) are likely the result of erosion and deposition of contaminated upland fill and upper intertidal zone sediment (Section 6.8). Other sources that are not Site-related (e.g., other historical waterfront and overwater activities, treated pilings, and urban background sources) may have also contributed to sediment impacts in these tidal zones.

Haley sediment was also likely impacted by stormwater discharges from the Site (Section 4.1.3). P-9 carrier oil and associated wood treatment chemicals were potentially transported to the marine environment as a result of both overland flow and discharge from the Haley facility stormwater system when the facility was active. Stormwater from the former wood treatment area discharged at the southernmost outfall on the Haley shoreline (Figure 2-4). Stormwater also was captured in other portions of the Site and likely discharged from the 8-inch-diameter concrete outfall located farther north (Figure 2-4), although the specific orientation and function of this portion of the former Haley stormwater system are not known. These former Haley facility stormwater drains do not currently discharge water from the Site.

Several marine processes have potentially altered the distribution of Site-related contaminants in sediment (Section 7.3.5). Contaminated surface sediment is subject to re-suspension and transport by wave, current, and tidal energy. This process can erode impacted sediment in the upper intertidal zone and transport it to deeper-water depositional areas in the lower intertidal and subtidal zones. Other studies have indicated that clean sediment discharged from the Nooksack River is also transported and deposited in the lower intertidal and subtidal zones of the Site, leading to natural recovery of sediment in these zones. The combined effects of clean sediment deposition and bioturbation tend to reduce contaminant concentrations in the shallow sediment profile over time.

8.4. Potential Exposure Pathways and Receptors

To be considered complete, a contaminant exposure pathway must have: (1) an identified source of contamination, (2) a release/transport mechanism from the source, and (3) contact with a receptor. This section summarizes exposure pathways that are potentially complete at the present time or may be in the future based on investigations at the Haley Site.

Potentially complete exposure pathways by which people could be exposed to Haley contaminants under current conditions include:

- Direct contact (incidental ingestion and dermal contact) with contaminated soil.
- Direct contact (incidental ingestion and dermal contact) with contaminated sediment during beach recreation (wading, fishing, clamming, etc.).
- Direct contact with contaminated groundwater or LNAPL that may discharge to the intertidal or shallow subtidal zones.
- Indirect contact via consumption of aquatic organisms that have been exposed to contaminated sediment, groundwater, or LNAPL (i.e., bioaccumulation).

Although direct contact with contaminated sediment is a potentially complete pathway under current conditions, it is expected that this pathway will be eliminated by future remedies implemented to address risks to aquatic organisms (Section 5.1.1.3).

The vapor intrusion pathway (migration of contaminated soil vapor to indoor air, followed by inhalation of indoor air) is not considered a complete pathway under current conditions because there are no buildings on the Haley and Cornwall upland. However, vapor intrusion represents a potential future risk if buildings are constructed on the Site in the future.

Potentially complete exposure pathways by which ecological receptors could be exposed to Haley contaminants include:

- Direct contact with contaminated soil by terrestrial wildlife, plants and soil biota.
- Direct contact with contaminated marine sediment and/or discharging groundwater or LNAPL by aquatic organisms.
- Indirect contact (by higher tropic level organisms) via consumption of aquatic organisms that have been exposed to contaminated sediment, groundwater, or LNAPL (i.e., bioaccumulation).

The ecological exposure pathways listed above were evaluated in this RI. Within certain areas of the Site, people, terrestrial receptors, and aquatic receptors are potentially at risk from exposure to Site media contaminated with wood-treating constituents. The extent of the area presenting potential direct contact or inhalation risks is shown in Figure 8-1. Potential risks from bioaccumulative effects, including risks associated with PCP, cPAHs and dioxins/furans in sediment, are further addressed in the FS.

8.5. Cleanup Actions Completed To Date

Limited cleanup actions have previously been completed at the Haley and Cornwall sites to remove and/or contain contaminant sources (Section 2.4.8 and 2.5). Most of these actions focused on mitigating releases to the aquatic environment.

8.5.1. Haley Site

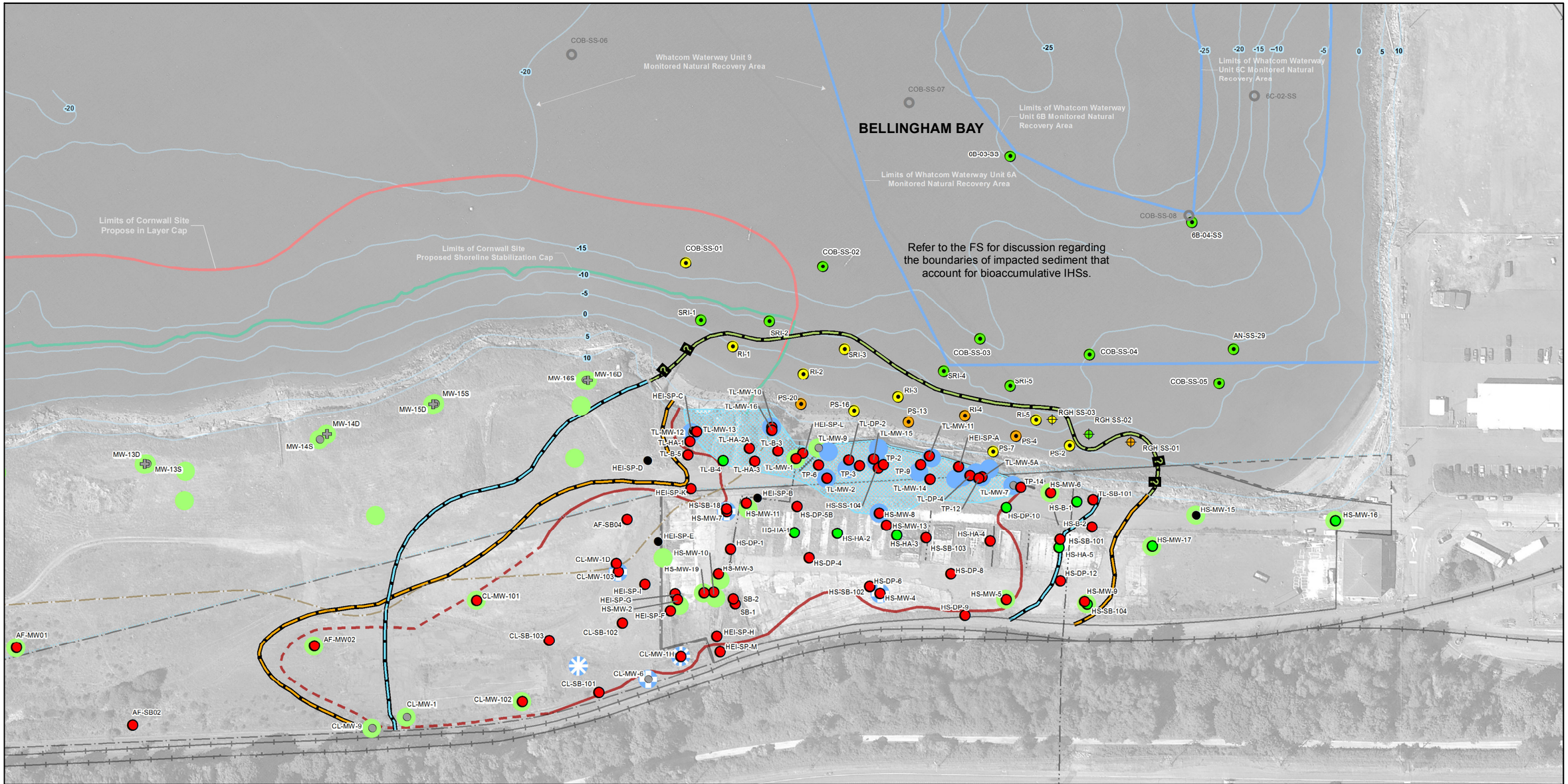
The earliest documented cleanup action at the Haley Site consisted of the removal of approximately 80 tons of PCP-contaminated soil/sludge from the wastewater seepage pit on the southern end of the former Haley facility (Section 2.4.8.1). A more extensive cleanup action was conducted along the Haley waterfront in 2000 and 2001. A sheet pile barrier was constructed adjacent to the shoreline to contain LNAPL (Section 2.8.2). Approximately 100 cubic yards of petroleum-impacted sediment was also removed from the intertidal zone at that time, and LNAPL recovery began. Approximately 760 gallons of LNAPL have been recovered from the Site (Section 6.2.4). In 2001, additional erosion control materials were placed along the shoreline west of the sheet pile barrier, significantly reducing the erosion of shoreline bank soils (Section 4.1.4.2).

Petroleum sheens have been infrequently observed on surface water adjacent to the Haley shoreline since the 2000 and 2001 cleanup actions. These sheens were observed in the intertidal zone south of the existing sheet pile barrier. Containment booms were used to contain the sheens and absorbent materials were used to capture the sheens to the extent possible. The City performed an interim action at the Site in 2013 in an intertidal area where petroleum sheen was most recently observed in 2012/2013 (Figure 3-1, GeoEngineers 2013a). The interim action consisted of placing an amended cap at the location where the sheen appeared to emerge from sediment.

8.5.2. Cornwall Site

A soil layer of varying thickness was placed on top of the refuse after landfill closure in the late 1960s. In 2011 and 2012, approximately 47,000 cubic yards of dredged sediment was stockpiled on the landfill property and a landfill gas control system was installed as an interim action (Section 2.5). The dredged sediment will be beneficially reused as part of an engineered cap that will be constructed during the final cleanup action.

Various episodes of *ad hoc* shoreline stabilization were conducted by placing armoring along the marine margin of the closed landfill.



W True North S N E Project North

0 50 100 Feet

Reference: Aerial from Google Earth, August 2011.
Contour elevation displayed is referenced to NAVD88 vertical datum.

Notes:
1. The locations of all features shown are approximate.
2. This drawing is for information purposes. It is intended to assist in showing features discussed in an attached document.
3. Refer to Figure 6-1 for identification of property lines and other upland features.
GeoEngineers, Inc. cannot guarantee the accuracy and content of electronic files. The master file is stored by GeoEngineers, Inc. and will serve as the official record of this communication.

- Existing Deep Monitoring Well
- Existing Shallow Monitoring Well
- City Owned Property, Former R.G. Haley International
- Cornwall Property
- Port of Bellingham Property
- Inner Harbor Line
- Sheet Pile Wall
- Storm Drain
- Cornwall Approximate Landward Boundary of Landfill Refuse
- Estimated extent of petroleum smear zone immobile LNAPL except where shown

Soil Sample Results

- One or more soil samples exceed screening levels
- All soil samples analyzed less than screening levels
- Non-detect, PQL > screening level

Note: Symbol and color are shown for any exploration with soil sample IHS analytical result regardless of sample depth or date sampled. Gray (no color) used where no data for this analyte.

- Current Measurable LNAPL in Well
- Current Trace LNAPL in Well
- Historical LNAPL (Not Currently Present)
- LNAPL Never Observed
- Potentially Mobile LNAPL at Shoreline

Sediment Sample Results

- Exceeds CSL/2LAET Chemical or Biological Criterion for One or More Site Contaminants
- Exceeds SCO/LAET Chemical or Biological Criterion for One or More Site Contaminants
- Meets SMS Benthic Criteria for Site Contaminants
- Estimated boundary of all soil screening level exceedances
- Estimated boundary of all groundwater screening level exceedances
- Estimated boundary of sediment exceedances for SMS benthic chemical and/or toxicity criteria

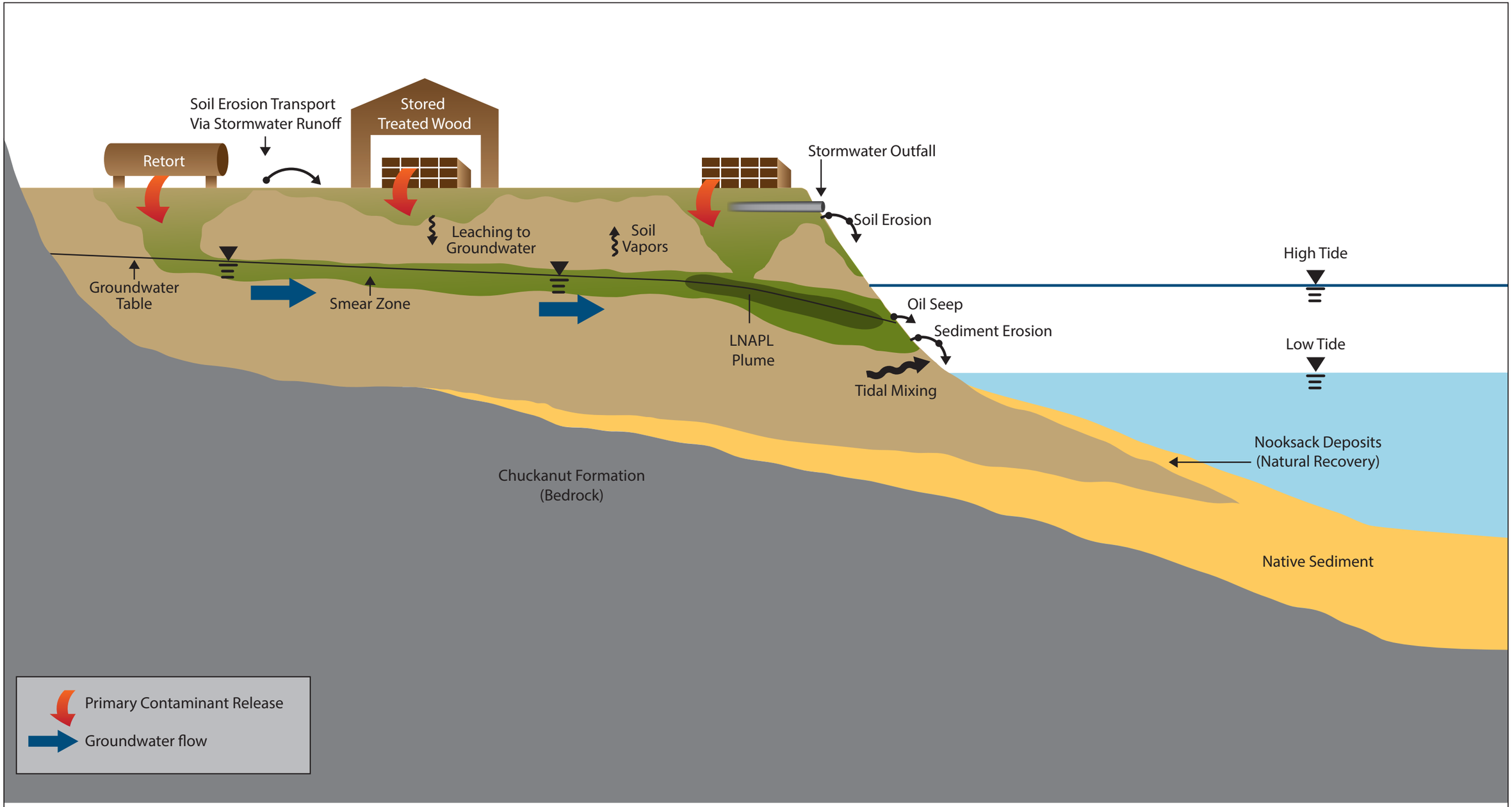
Estimated Footprint of Haley Contaminants

R.G. Haley Site
Bellingham, Washington

GeoEngineers

Figure 8-1

Path: \\sea\projects\0\0356114\GIS\MXDs\Fig_8-1_Total_Impact.mxd Map Revised: 17 August 2015 cgonzales



Notes

1. The locations of all features shown are approximate.
2. This drawing is for information purposes. It is intended to assist in showing features discussed in an attached document. GeoEngineers, Inc. cannot guarantee the accuracy and content of electronic files. The master file is stored by GeoEngineers, Inc. and will serve as the official record of this communication.

Conceptual Site Model

R.G. Haley Site
Bellingham, Washington

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Figure 8-2

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