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**COMPREHENSIVE LONG-TERM ENVIRONMENTAL
ACTION NAVY
CLEAN II**

**TECHNICAL MEMORANDUM No. 3:
CONTAMINANT MIGRATION ANALYSIS
TO SUPPORT THE DEVELOPMENT OF
CLEANUP GOALS FOR THE
NAVY EXCHANGE GAS STATION (SITE 3)
NAVAL TRAINING CENTER
SAN DIEGO, CALIFORNIA
CTO-0064/0189**

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ACRONYMS/ABBREVIATIONS

BTEX	benzene, toluene, ethylbenzene, and xylenes
BNI	Bechtel National, Inc.
Cal/EPA	California Environmental Protection Agency
CAP	corrective action plan
cm ² /s	squared centimeters per second
ft/day	feet per day
ft ² /day	square feet per day
ft/year	feet per year
g/cm ³	grams per cubic centimeter
g/mol	grams per mole
g/m ³	grams per cubic meter
in/yr	inches per year
kg/L	kilograms per liter
kPa	kilopascal
µg/L	micrograms per liter
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
mg/m ² /hr	milligrams per square meter per hour
mg/m ³	milligrams per cubic meter
mL/g	milliliter per gram
NEX	Navy Exchange
PRG	U.S. EPA Region IX preliminary remediation goal
RWQCB	(California) Regional Water Quality Control Board
SAM	Site Assessment and Mitigation
SWDIV	Southwest Division Naval Facilities Engineering Command
TPH	total petroleum hydrocarbons
U.S. EPA	United States Environmental Protection Agency

Section 1 INTRODUCTION

This technical memorandum presents the methodology and the results of the contaminant migration analysis in support of the development of cleanup goals for benzene, toluene, ethylbenzene, and xylenes (BTEX) present in the soil and groundwater at the Navy Exchange (NEX) Gas Station Site 3. The proposed cleanup goals are based on the protection of human health and the environment. The approach presented in this document was cooperatively developed by the U.S. Navy and the County of San Diego Department of Health Services, Site Assessment and Mitigation (SAM) Division during the 19 January 1995 meeting held at the Southwest Division Naval Facilities Engineering Command (SWDIV).

The approach presented here meets the requirements for the development of applicable cleanup levels under a corrective action plan (CAP) as defined in Section 5.C.4 of the 1994 County of San Diego Department of Health Services, Department of Environmental Health SAM Division Manual.

Groundwater in the station area has been classified by the Regional Water Quality Control Board (RWQCB), San Diego Region, as being unsuitable for beneficial uses. Therefore, BTEX in groundwater does not present a direct threat to future property users but could pose a threat to biota in the San Diego Bay. This document describes the analysis of BTEX migration through the groundwater pathway. The analysis addresses dissolved BTEX migration originating from a potential free-product pool underneath the NEX Gas Station and from the vadose soils. It also addresses vapor phase migration. The analysis is based on site-specific data presented in the May 1995 Extended Site Assessment Report for the NEX Gas Station (BNI 1995a). Where applicable, conservative, bounding assumptions are made for both the values of different physical parameters used in the analysis and for the definition of potential contamination sources.

Section 2 **GROUNDWATER PATHWAY**

Because groundwater beneath Site 3 is classified unsuitable for beneficial use by the RWQCB, San Diego Region, the evaluation of potential impacts of groundwater contamination focuses on potential threats to the marine environment at the point of discharge in San Diego Bay of groundwater flowing underneath Site 3. This section describes the methods used to evaluate contaminant migration in the groundwater from the NEX Gas Station to the San Diego Bay. A groundwater transport model is used to assess the potential for migration of BTEX from the NEX Gas Station Site 3 to the bay. The estimated discharge concentrations are compared with the applicable water quality standards for bays and estuaries to assess and back-calculate the acceptable levels of BTEX concentration in the soils for protection of the bay from contaminants that could migrate from the vadose zone soils to the groundwater and eventually to the bay.

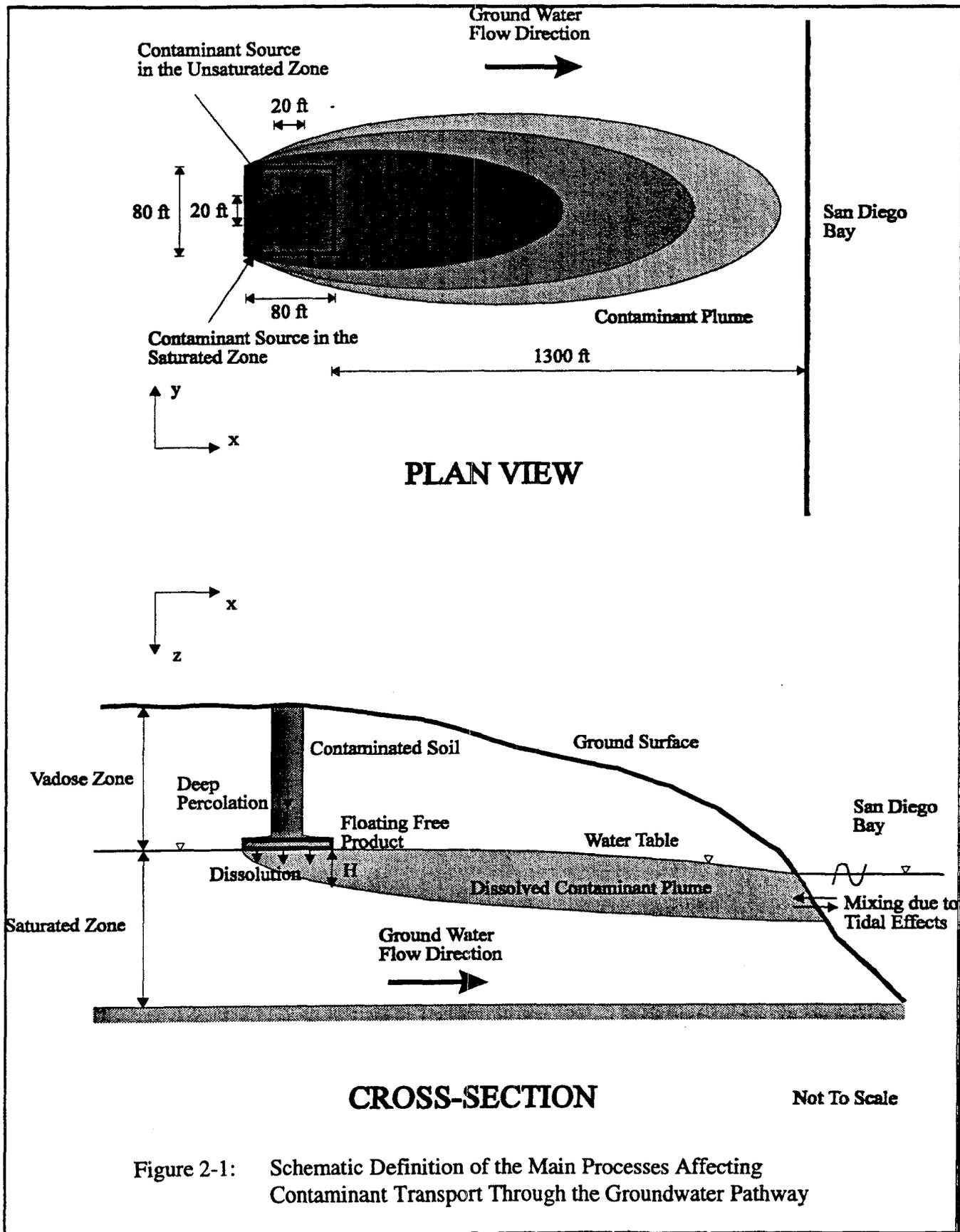
2.1 DISSOLVED-PHASE MIGRATION THROUGH GROUNDWATER

The groundwater transport model, which assesses the potential for migration of dissolved BTEX from the NEX Gas Station (Site 3) to the bay, provides estimates of migration times and BTEX concentrations at the point of groundwater discharge to the San Diego Bay. The model is used to analyze the migration of contaminants already in the groundwater under the site as well as the contribution of contaminants in the vadose zone that may eventually move to the saturated zone.

2.1.1 Conceptual Transport Model and Basic Assumptions

The conceptual model used to describe BTEX migration through the groundwater pathway applies worst-case assumptions to obtain conservative estimates of migration rates maximizing the potential contribution of contaminants from past spills or leaks at the site. Specific assumptions for contaminant migration through the vadose and saturated zones are detailed below.

- In the vadose zone, BTEX exists in all three phases: adsorbed to the soils, dissolved in the water, and in the vapor phase. To maximize the contribution of vadose zone contaminants to the groundwater, the vapor phase is neglected in the groundwater calculations, and it is assumed that all compounds are distributed only between the solid and water phases based on equilibrium partitioning. Also, as a conservative assumption, loss of BTEX due to volatilization is neglected.
- Data from preliminary investigations and information on the regional hydrogeology suggest that the hydraulic gradient between Site 3 and the bay is uniform, and the materials in the shallow zone are fairly homogeneous. Therefore, it can be assumed that groundwater flow between Site 3 and the bay is one-dimensional and uniform. The direction of groundwater flow is to the south, and the nearest discharge point to the San Diego Bay is Commercial Basin located about 1,300 feet south of the NEX Gas Station. A schematic of this process is presented as Figure 2-1.



Section 2 Groundwater Pathway

- The migration of contaminants through the vadose zone is instantaneous (i.e., no credit is taken for the travel time through the vadose zone to the water table). A schematic of this process is presented as Figure 2-2.
- Infiltrating water from the ground surface moves contaminants from the vadose zone to the groundwater, based on equilibrium partitioning, slowly depleting the mass of contaminants in the vadose zone. This process continues until all vadose zone contamination has migrated to the saturated zone. A schematic of this process is presented as Figure 2-2.
- It is assumed that the concentration distribution of BTEX in the vadose zone is uniform from the ground surface to the water table.
- Contaminant migration through the saturated zone is limited to the upper 10 feet of the aquifer. This is a conservative assumption because limiting the vertical dispersion of contaminants to within the upper 10 feet of the aquifer produces higher concentrations.
- A groundwater contaminant plume may have been formed several years ago and may have already moved toward the bay at some distance from the NEX Gas Station. To maximize the potential contribution of such a plume, it was assumed that dissolved BTEX compounds were dissolving from a hypothetical free-product pool under the NEX Gas Station and were contaminating the groundwater over the last 20 years.
- Soil cleanup levels are estimated on the basis that the combined concentration from the mass of each contaminant already in the groundwater and the mass that may move to the groundwater in the future from the vadose zone soils should not exceed the applicable California Enclosed Bays and Estuaries Plan standards.
- It is assumed that all free-product will be removed (i.e., that there is no remaining source of dissolved contaminants in the groundwater).
- The migration and distribution of dissolved contaminants in the groundwater is affected by advection, molecular diffusion, hydrodynamic dispersion, adsorption, and biodegradation. The parameters determining the rate of these processes are selected in a manner that provides conservative (i.e., high) estimates of concentration in the groundwater discharge to the bay.
- The groundwater system is influenced by tides in San Diego Bay. The effect of tidal water level fluctuations depends on the distance from the bay. Tidal fluctuations contribute to vertical dispersion and mixing near the bay. Also, the flow of a volume of water in and out of the shoreline sediments during each tidal cycle contributes to reduction of contaminant concentrations prior to the discharge of groundwater into the bay.
- As a conservative assumption, no credit is taken for the dilution of groundwater discharges because of mixing with the bay waters. The dilution factor of groundwater discharges in the bay may be significant, causing a reduction of several orders of magnitude in contaminant concentrations in the discharging groundwater. Ignoring this dilution factor produces conservative estimates of acceptable soil concentrations.

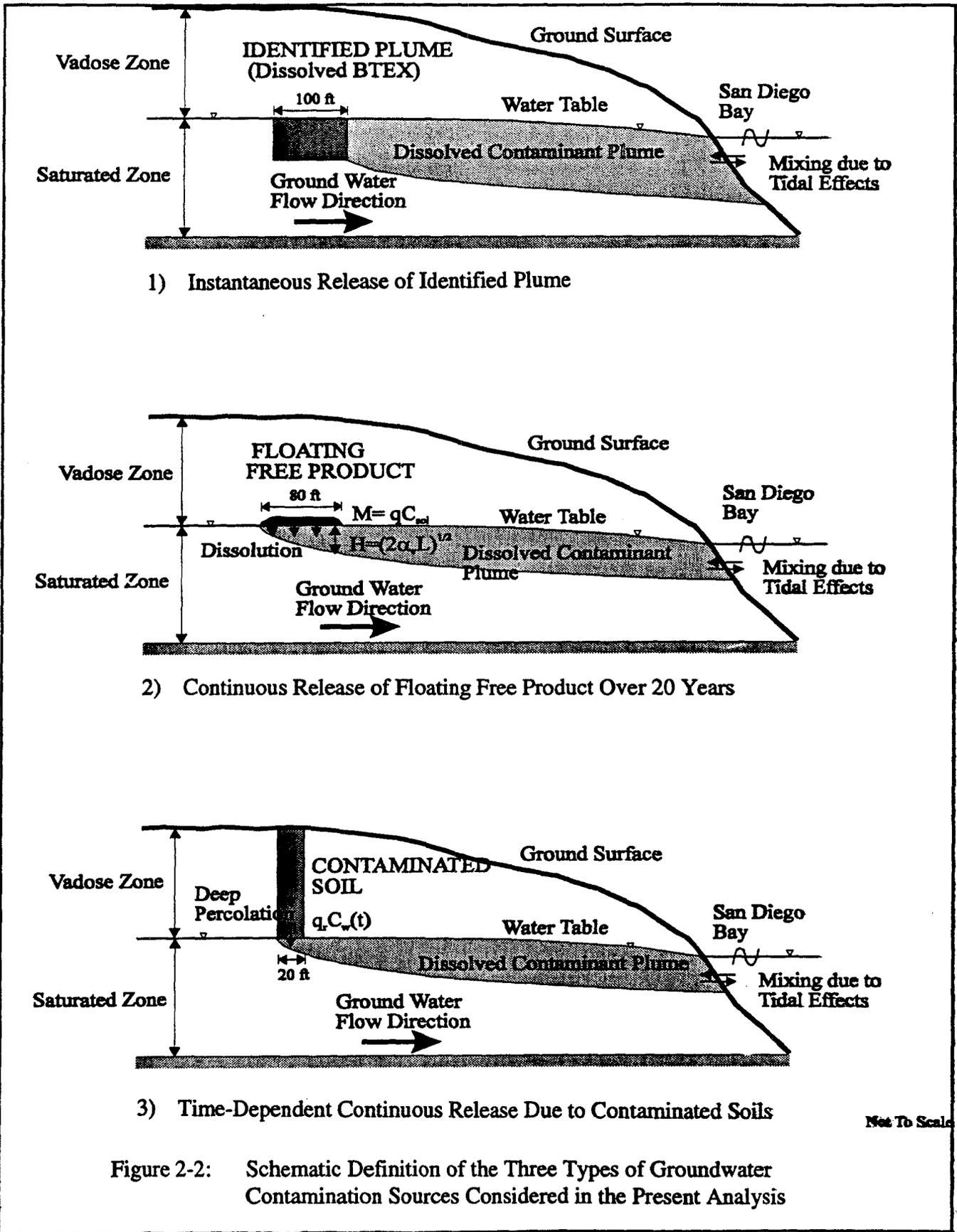


Figure 2-2: Schematic Definition of the Three Types of Groundwater Contamination Sources Considered in the Present Analysis

Section 2 Groundwater Pathway

2.1.2 Analytical Methods

The migration rate of contaminants through the vadose zone and the saturated zone is estimated using analytic solutions of the transport equation under the assumptions discussed in Section 2.1.1. The following describes the mathematical expressions and physical parameter values used for this purpose.

2.1.2.1 TRANSPORT THROUGH THE SATURATED ZONE

Migration through the saturated zone is described by the transport equation, which accounts for one-dimensional advection in the direction of the flow, three-dimensional diffusion and dispersion, retardation, and first-order decay due to biodegradation. The values of the physical parameters used are given in Table 2-1.

Dispersion

Dispersivity is generally accepted to be proportional to a length scale characteristic of the transport problem under consideration (e.g., the distance from the source). Longitudinal dispersivity values of 5 to 10 percent of the distance from the source are often used (e.g., Gelhar 1985). To obtain conservative (i.e., high) concentration estimates, a dispersivity value equal to 5 percent of the distance from the source to the discharge point in San Diego Bay was used. This corresponds to the low end of values reported in the literature. For a distance to the bay, $L = 1,300$ feet, the longitudinal dispersivity α_L is equal to $0.05 L = 65$ feet. The transverse dispersivity is assumed to be equal to 10 percent of the longitudinal dispersivity (equal to 6.5 feet). The vertical dispersivity is assumed to be equal to 1 foot (equal to less than 2 percent of the longitudinal dispersivity). The vertical dispersivity used in the analysis is also of the order of magnitude of the expected range of tidal fluctuations of the water table near the bay, which would contribute to vertical mixing in the groundwater. As part of a sensitivity analysis, a lower vertical dispersivity value (0.1 feet) was also used.

Biodegradation

The May 1995 work plan for this activity (BNI 1995b) stated that the analysis would be performed under the conservative assumption of no biodegradation for BTEX. A literature search on this topic suggested that the assumption of no biodegradation would have been unrealistic. No technical reference was found suggesting that BTEX would not biodegrade. Therefore, it was decided to account for biodegradation, but in conservative manner (i.e., using lower than the average of reported biodegradation rates).

Reported rates of intrinsic biodegradation of BTEX vary over a wide range of values. Many studies have described biodegradation as a first-order decay process with half lives from few weeks to few years, depending on chemical, and biological conditions (see Baedecker 1994; Wilson et al. 1994; Stauffer et al. 1994; MacFarlane et al. 1994). Based on several reviewed studies, it was assumed that the half-life of benzene is 5 years and

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**Table 2-1
 Physical Parameter Values Used in the Analysis**

Parameter/Mathematical Term	Value	Source
Distance from the shore (L)	1,300 ft ^a	Figure 1-1, page 1-3, in BNI 1995a
Hydraulic conductivity (K_h)	10 ft/day ^b	Conservative assumption to maximize migration velocity
Hydraulic gradient (i)	0.0025	Figure 3-6, page 3-15, in BNI 1995a
Total porosity (n)	0.3	Assumed
Effective porosity (n_e)	0.3	$n_e = n$
Bulk density (dry) (ρ_d)	1.82 kg/L ^c	$\rho_d = (1-n) \rho_s$ where ρ_s density of solids (2.6 kg/L)
Bulk density (saturated) (ρ_b)	2.12 kg/L	$\rho_b = (1-n) \rho_s + n \rho_w$ where ρ_w density of water (1 kg/L)
Aquifer thickness (B)	10 ft	Assumed dissolved BTEX transport limited to the uppermost layer of the saturated zone
Storage coefficient (S)	0.03	Estimated from pumping test (see page 3-12, in BNI 1995a)
Darcy velocity (U_D)	0.025 ft/day	Estimated from rows 2 and 3
Migration velocity (U)	30 ft/yr ^d	
Dispersivity		
Longitudinal (a_L)	65 ft	Estimated as $a_L = 0.05L$ (Gelhar 1985)
Transverse (horizontal) (a_T)	6.5 ft	Estimated as $a_T = 0.1 a_L$
Vertical (a_V)	1 ft	Assumed to account for mixing effect of ~1-ft tidal fluctuation near the shoreline
Organic carbon content (f_{oc})	0.025%	Measured from samples from the site collected in December 1994 through January 1995
Mixing factor in the sediments due to tides (F_T)	5	Conservative assumption lower than its theoretical value estimated below
for $B = 10$ feet; $S = 0.03$	30.9	Estimated as described in Section 2.1.2.3

Notes:

- ^a ft – feet
- ^b ft/day – feet per day
- ^c kg/L – kilograms per liter
- ^d ft/yr – feet per year

Section 2 Groundwater Pathway

the half-life of toluene, ethylbenzene, and xylenes is 2 years. These values are conservative (i.e., close to the longest reported half-lives for each compound reported in the literature). Examples of BTEX biodegradation half-lives reported in the literature are given in Appendix A.

Retardation

Retardation due to adsorption of BTEX compounds to the soils is accounted for by assuming equilibrium partitioning between the solid and dissolved phases. The partition coefficient, k_d , for each BTEX compound is estimated as $k_d = k_{oc}f_{oc}$, where k_{oc} is the organic carbon water partition coefficient for each contaminant and f_{oc} is the organic carbon content of the soil. The f_{oc} value was estimated from four soil samples from the site analyzed for organic carbon. The k_{oc} values for BTEX used are given in Table 2-2. The average of the four samples gave an f_{oc} value equal to 0.00025. The retardation factor, R , is estimated as $R = 1 + \rho_b k_d/n$, where ρ_b is the dry bulk density of the soil assumed to be equal to 1.8 grams per cubic centimeter (g/cm^3), and n is the porosity assumed to be equal to 0.30. The estimated retardation factors for the four BTEX compounds are given in Table 2-2.

The analytic solution of the transport equation is obtained with the aid of the computer code AT123D (Yeh 1981), which implements analytical solutions for one-, two- and three-dimensional transport of dissolved chemicals in a homogeneous aquifer with uniform, one-dimensional, steady-state flow. AT123D accounts for retardation, first-order decay, longitudinal, horizontal, and vertical transverse dispersion. AT123D includes the solution of several problems for different configurations of the source and different aquifer boundary conditions. The code is in the public domain and is available from different sources. The version of AT123D was used for this study (IGWMC 1993).

2.1.2.2 SOURCE OF DISSOLVED BTEX IN THE SATURATED ZONE

Three different sources of groundwater contamination are considered besides the contribution of contaminants from the vadose zone soils. First, a source of existing contaminants in the groundwater is considered in a portion of the aquifer underneath the NEX Gas Station, based on the BTEX concentrations detected during the site investigation (BNI 1995a).

Second, as part of the sensitivity analysis, to account for the effect of potential existing groundwater contamination that might have been caused by past spills and leaks at the NEX Gas Station and might have already moved off-site, it is assumed that an active source of dissolved BTEX existed at the site over the last 20 years. To provide conservative (i.e., high) estimates of the contribution of such a source, it is assumed that a pool of free-product (gasoline) existed at the water table. It is also assumed that BTEX compounds could freely dissolve from the lower surface of the floating free-product pool, providing a source of groundwater contamination.

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Table 2-2
Values of Physical Properties of BTEX Used

Property	Units	Benzene	Toluene	Ethylbenzene	Xylenes	Reference
Organic carbon partition coefficient, k_{oc}	mL/g ^a	65	331	846	937	Fetter 1993
Distribution coefficient, k_d	mL/g					
for $f_{oc} = 0.025\%$		0.016	0.083	0.211	0.234	
for $f_{oc} = 0.05\%$		0.033	0.165	0.423	0.468	
Retardation factor, R						
for $f_{oc} = 0.025\%$		1.11	1.56	2.42	2.58	
for $f_{oc} = 0.05\%$		1.22	2.11	3.85	4.15	
Percent mass		3	5	2	7	
Pure-phase solubility	mg/L ^b	1,780	537	167	162 ^c	
Effective solubility for gasoline-saturated conditions	mg/L	64.8	27.6	3	10.1	Lyman et al. 1992
Half-life	years	5	2	2	2	

Notes:

- ^a mL/g – milliliter per gram
- ^b mg/L – milligrams per liter
- ^c m-xylene

Also as part of the sensitivity analysis, an off-site source was considered to account for the potential incremental concentrations in groundwater discharging to the Commercial Basin due to the plume originating from the former Chevron Gas Station located at the corner of Nimitz Boulevard and Rosecrans Street, or from other off-site sources.

The three groundwater contamination sources are defined as follows:

Representation of the Identified Plumes During the Site Investigation

The BTEX plumes identified during the site investigation are conservatively approximated by an area 100 by 100 feet. It is assumed that within this area and over the upper 10 feet of the aquifer, each contaminant exists at the level of the highest concentration detected at the site. These concentrations are 30 milligrams per liter (mg/L) for benzene, 38 mg/L for toluene, 4.1 mg/L for ethylbenzene, and 16 mg/L for xylenes (see also Section 2.3). The area used to represent the existing contamination plume is conservatively assumed to be larger than the area contained within the interpreted contours for each contaminant.

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Free-Product Source

The areal extent of the free-product source is assumed to be 80 by 80 feet. The zone of contaminated groundwater at the effective solubility level for each compound grows underneath the free-product pool in the direction of the flow due to dispersion. The depth of this zone at the downgradient end of the free-product pool can be estimated as $H = (2\alpha_v L)^{1/2}$ where α_v is the vertical dispersivity and L is the length of the source (Woodward-Clyde 1988, Appendix C, pages 3-4). The vertical dispersivity at the source is assumed to be 0.1 feet. For a source 20-foot-long, the estimated depth of the source is 2 feet, and for an 80-foot-long source, the depth is 4 feet.

It is assumed that the BTEX concentration is equal to the effective solubility of each compound for gasoline-saturated water. The values used are for the typical gasoline composition presented in Lyman et al. (1992) (i.e., 64.8 mg/L for benzene, 27.1 mg/L for toluene, 3 mg/L for ethylbenzene, and 10.1 mg/L for m-xylene).

Off-Site Source

The contribution of potential off-site sources is accounted for by assuming that a plume identical to that identified at the NEX Gas Station exists 200 feet west of the centerline of the NEX plume. This plume is conservatively represented by a zone 100 by 100 feet and 10 feet deep, where the concentration of each contaminant is equal to the highest groundwater concentration detected at the NEX Gas Station (i.e., equal to 30 mg/L for benzene, 38 mg/L for toluene, 4.1 mg/L for ethylbenzene, and 16 mg/L for xylenes).

2.1.2.3 TIDAL MIXING IN SEDIMENTS NEAR THE DISCHARGE TO THE BAY

Tidal fluctuations in the bay cause a volume of water to flow in and out of the aquifer during each tidal cycle. Water flowing into the aquifer during the flood tide mixes with the aquifer flow and discharges into the ocean during the ebb tide, diluting the aquifer flow prior to its discharge in the bay. The tidal-mixing factor depends on the characteristics of the tide and the hydraulic characteristics of the groundwater system. For a homogenous aquifer with one-dimensional flow discharging in the ocean, the tidal-mixing factor in the sediments can be estimated from the solution for a coastal aquifer presented by Todd (1959). The tidal-mixing factor in the sediments, F_T , for the general case of a tide with multiple harmonics is:

$$F_T = 1 + \frac{1}{i_h} \sqrt{\frac{2S}{\pi T}} \frac{1}{P_1} (h_1 \sqrt{P_1} + h_2 \sqrt{P_2} + \dots + h_n \sqrt{P_n})$$

where:

P_1, P_2, \dots, P_n , and h_1, h_2, \dots, h_n are the periods and amplitudes of tidal components 1, 2 ... n (e.g., semidiurnal, diurnal, fortnightly),

S is the storage coefficient,

T is the transmissivity of the aquifer, and

i_h is the hydraulic gradient.

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The derivation of this expression for the tidal-mixing factor in the sediments is given in Appendix B.

Using $S = 0.03$, $T = 100$ square feet per day (ft^2/day) (corresponding to a hydraulic conductivity of 10 feet per day [ft/day] and an aquifer thickness of 10 feet) and accounting for the diurnal and semidiurnal tide gives a tidal-mixing factor in the sediments of approximately 30. As a conservative assumption, in all present simulations the tidal-mixing factor in the sediments is assumed to be equal to 5, which is lower than this estimated value.

2.1.2.4 TRANSPORT THROUGH THE VADOSE ZONE

It is assumed that the concentration in the soil, C_s , is uniform over the entire thickness of the vadose zone and that the concentration in the water moving through the vadose zone, C_w , can be estimated based on equilibrium partitioning. Accounting for depletion due to flushing of the vadose zone soils by percolating water, the concentration in the vadose zone soil and water can be expressed as:

$$C_s(t) = C_{so} e^{-\lambda t}$$

$$C_w(t) = \frac{\rho_s(1-n) + \rho_w \theta}{k_d \rho_s(1-n) + \theta} C_{so} e^{-\lambda t}$$

where:

- C_{so} is the initial soil concentration,
- $C_s(t)$ and $C_w(t)$ are the soil and groundwater concentrations respectively at time t ,
- ρ_s is the density of the solid matrix,
- n is the porosity,
- q is net infiltration (recharge) rate,
- λ is the first-order decay constant for biodegradation, and
- θ is the moisture content.

The recharge rate determines the time required to move the contaminants from the soils to the groundwater. The most conservative estimates of contaminant contribution to the groundwater would be under the assumption that all vadose zone contaminants are completely dissolved in the pore water (i.e., readily available to move to the saturated zone). This condition gives the shortest migration time for all vadose zone contaminants to reach the groundwater, which minimizes concentration reduction due to biodegradation. The recharge rate q is assumed to be 1 inch per year (in/yr), equal to a little over 10 percent of the mean annual precipitation of 8.7 in/yr (Station Number 722906, North Island NAS, from National Climatic Data Center 1992).

Section 2 Groundwater Pathway

2.1.3 Verification and Partial Validation of the Transport Model

Model verification of the computer code that implements a model is the process designed to assure that the computer code correctly solves the mathematical equations of the model. The AT123D code was verified for the type of transport problem that was used at the NEX Gas Station by independently solving the same problem and comparing the solution. The verification of AT123D is documented in the BNI calculation 22214-064-GWM-2.

The term model validation indicates the process of confirming that the model correctly represents and predicts the simulated physical processes. The extent of model validation depends on the availability of historic data that would allow comparison of model predictions with observed behavior. The AT123D model was partially validated by comparing its predictions with historic data for a plume originating from the Chevron Gas Station located at the corner of Nimitz Boulevard and Rosecrans Street, near the NEX Gas Station. Hydrogeologic conditions at the Chevron Gas Station are similar to those at the NEX Gas Station. The Chevron plume has been monitored longer and appears to be moving off-site. Figure 2-3 shows the lateral benzene concentration distribution 100 feet downgradient from an assumed free-product source providing dissolved benzene over a period of 20 years. Concentration profiles are presented for two sizes of free-product source (20 by 20 feet and 80 by 80 feet), and at 20 years after the introduction of the free-product source. A comparison of Figure 2-3 with the interpreted concentration contours for the Chevron benzene plume shown in Figure 1-4 of the May 1995 Extended Site Assessment Report for the NEX Gas Station (BNI 1995a) suggests that the model predicts reasonably well the order of magnitude of concentrations and the lateral spread of this plume.

2.2 WATER QUALITY STANDARDS

The estimation of soil cleanup goals is based on the condition that BTEX concentrations in groundwater discharges to San Diego Bay will not exceed the levels listed in the proposed California Enclosed Bays and Estuaries Plan (Cal/EPA 1993). However, the California Environmental Protection Agency (Cal/EPA) plan does not provide a standard for xylenes and in the absence of a standard for xylenes, the United States Environmental Protection Agency (U.S. EPA) marine ambient water quality criteria have been used (U.S. EPA 1985). Table 2-3 lists the standard used for each compound.

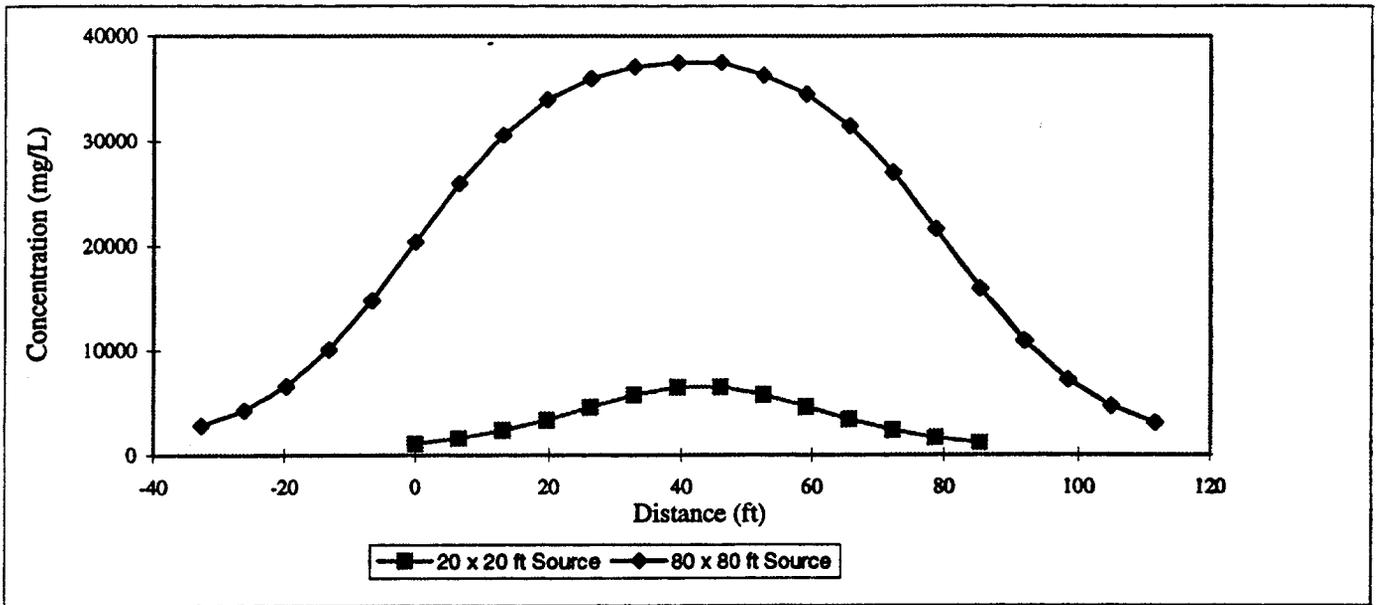


Figure 2-3: Lateral Benzene Concentration Distribution at 100 ft Downgradient from an Assumed Free Product Source Providing Dissolved Benzene Over a Period of 20 Years. (Concentration Profiles are Presented for Two Sizes of Free Product Source [20 by 20 ft and 80 by 80 ft])

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**Table 2-3
 Water Quality Standards**

Compound	µg/L*	MAXIMUM CONCENTRATION
		Source
Benzene	21	Proposed California Enclosed Bays and Estuaries Plan
Toluene	300,000	Proposed California Enclosed Bays and Estuaries Plan
Ethylbenzene	29,000	Proposed California Enclosed Bays and Estuaries Plan
Xylenes	2,200	U.S. EPA ambient water quality criteria

*µg/L – micrograms per liter

2.3 ESTIMATED GROUNDWATER DISCHARGE CONCENTRATIONS

The method and assumptions described in Section 2.1 are used to estimate the maximum BTEX concentration at the point of groundwater discharge to the bay for the following cases of groundwater contamination:

- the identified groundwater contamination plume at the NEX Gas Station during the BNI investigation;
- a plume caused by contaminants originating from the vadose zone soils and moving to the water table by percolating water; and
- combination of the two cases above.

The present BTEX plume is approximated by a rectangular area 100 by 100 feet, 10 feet deep, with a BTEX concentration equal to the maximum concentration for each compound detected at the NEX Gas Station. The highest detected BTEX concentrations and the concentrations assumed to represent the existing plume are given in Table 2-4. This representation of the plume is conservative because it introduces in the aquifer a larger BTEX mass than what has actually been observed.

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**Table 2-4
 Assumed Concentrations of Identified Contamination**

Case	CONCENTRATION			
	Benzene	Toluene	Ethylbenzene	Xylenes
Maximum groundwater concentration, mg/L ^a (December 1991)	30	38	4	16
Maximum groundwater concentration, mg/L (December 1994)	12	16	4.1	16
Assumed groundwater concentration, mg/L	30	38	4.1	16
Maximum average vadose zone concentration, mg/kg ^b (December 1994)	37.5	312.5	102.9	623
Assumed soil concentration, mg/kg	40	300	100	600

Notes:

- ^a mg/L – milligrams per liter
- ^b mg/kg – milligrams per kilogram

2.3.1 Migration of the Identified NEX Plume

Figure 2-4 shows the estimated concentration at the discharge point of the Bay caused by this plume as function of time. The concentrations shown on Figure 2-4 are along the centerline of the plume. All estimated concentrations are lower than the respective water quality standards.

2.3.2 Contribution of Contaminants from Vadose Soils

The impact of soil contamination on groundwater discharges to San Diego Bay is accounted for by considering a 20- by 20-foot area of contaminated soils. It is assumed that the concentration of contaminants in the soils within this area is equal to the highest soil concentrations measured at the NEX Gas Station. The assumed BTEX concentrations are approximately equal to the highest of the depth-averaged vadose zone soil concentrations measured in 1991 and 1994. These concentrations are the average of measured concentrations in samples from MW-6 between 6 and 6.5 feet, and between 11 and 11.5 feet. Figure 2-5 shows the estimated concentration at the discharge point of the Bay caused by contaminants from the 20 by 20 feet area of contaminated soils.

2.3.3 Combination of Soil and Groundwater BTEX Sources

The peak concentrations for the cases presented in Sections 2.3.1 and 2.3.2 are summarized in Table 2-5. As can be seen from Table 2-5, adding the discharge concentrations of these cases would produce BTEX concentrations below the bay water quality criteria.

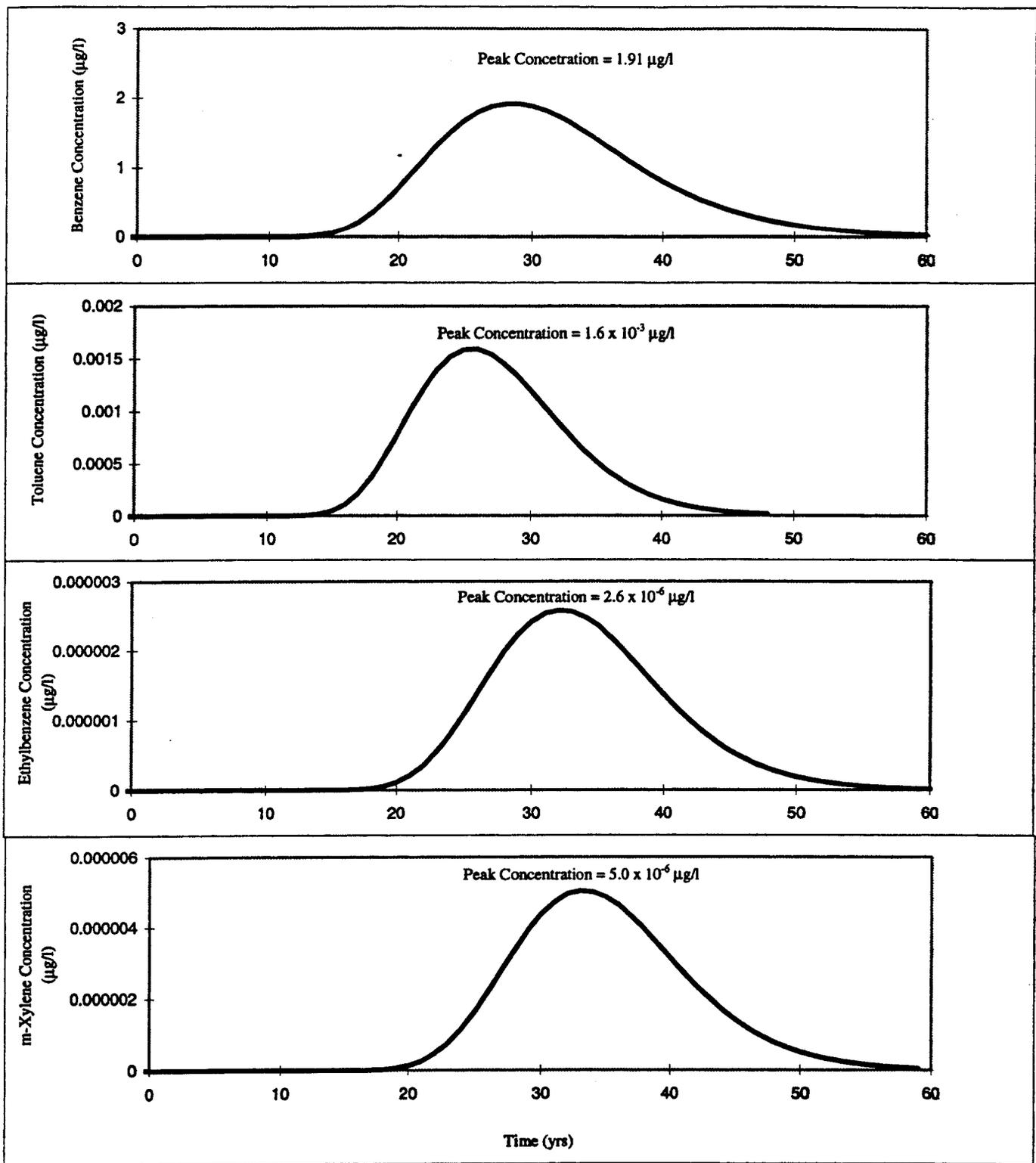


Figure 2-4: Maximum BTEX Concentration in Groundwater Discharging in San Diego Bay due to the Identified Plume at the NEX Gas Station. (The Concentrations are Given as a Function of Time For a Discharge Point at 1,300 ft from the NEX Gas Station.)

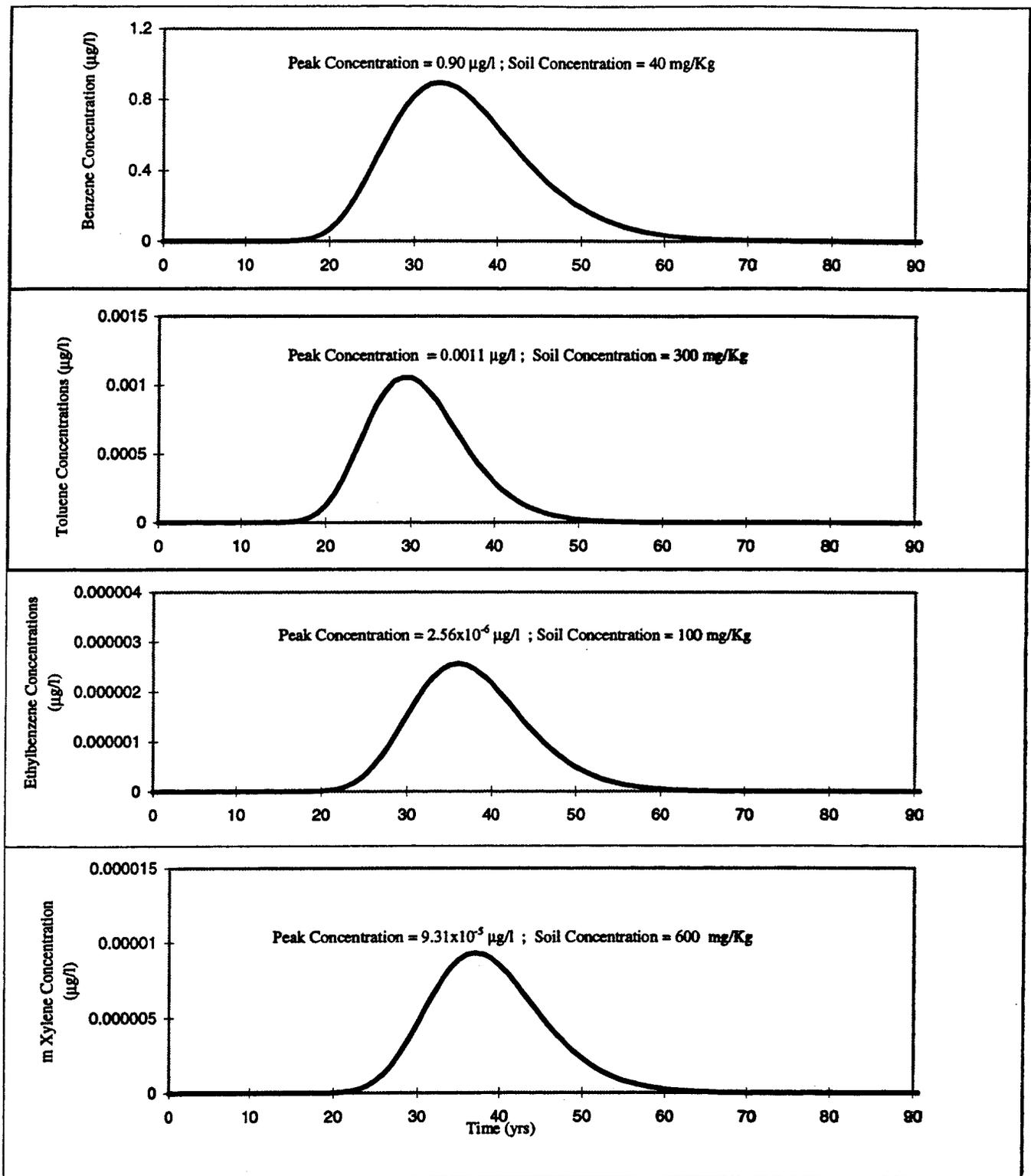


Figure 2-5: Maximum BTEX Concentration in Groundwater Discharging in San Diego Bay due to a 20 by 20 ft Area of Contaminated Soils at the NEX Gas Station. (The Concentrations are Given as a Function of Time For a Discharge Point at 1,300 ft from the NEX Gas Station.)

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**Table 2-5
 Maximum Groundwater Discharge Concentration**

Case	PEAK DISCHARGE CONCENTRATION (µg/L*)			
	Benzene	Toluene	Ethylbenzene	Xylenes
1a Identified NEX plume represented as a 100- by 100-foot plume 10 feet deep with uniform concentration per Table 2-4	1.91	0.0016	2.6 x 10 ⁻⁶	5.0 x 10 ⁻⁶
1b 20- by 20-foot vadose zone soils at the maximum measured concentration	0.90	0.0011	2.6 x 10 ⁻⁶	93.1 x 10 ⁻⁶
Water Quality Goal	21	300,000	29,000	2,200

*µg/L - micrograms per liter

It is assumed that higher concentrations in the contaminated soils would produce higher groundwater concentrations. The worst-case combination would consist of the identified plume and BTEX contribution from soils contaminated at a higher concentration level such that the resulting concentrations in the groundwater discharge to the bay are equal to the water quality criteria. For example, in this case benzene concentrations in the soils could be 21 times higher than those used in the case discussed in Section 2.3.2 and still produce total discharge concentrations within the water quality standards. In this case, the peak discharge concentration would be 1.91 + 21 x 0.9 = 21 micrograms per liter (µg/L). This implies that the benzene concentration in the soil could be as high as 21 times the value of 40 milligrams per kilogram (mg/kg) (per Table 2-4), which produces a concentration of 0.9 µg/L (i.e., it can be equal to 21 x 40 = 840 mg/kg). The relationship between soil concentration and pore water concentration is:

$$C_s = \frac{k_d \rho_s (1-n) + \theta}{\rho_s (1-n) + \rho_w \theta} C_w$$

Using the partition coefficient, porosity and moisture content values discussed in Section 2.2, and $C_s = 840$ mg/kg, gives a pore water concentration in the vadose zone soils C_w equal to 8,480 mg/L (i.e., greater than even the pure-phase solubility of benzene). This suggests that to have such high concentration, benzene must exist in the form of free-product. Because a basic assumption in the present study is that all free-product (in both the saturated and the vadose zone) will be removed, the solubility of each compound provides an upper bound for its concentration in the pore water, which can be used to calculate the corresponding bounding concentration for the soils.

Section 2 Groundwater Pathway

The solubility of each compound is estimated for an average composition of hydrocarbon contamination in the soils. Based on the average of eight groundwater samples collected at the NEX Gas Station (BNI 1995a), benzene represents approximately 15 percent of total petroleum hydrocarbons (TPH), toluene 18 percent, ethylbenzene 8 percent, and xylenes 26 percent. Assuming that these samples are representative of the composition of TPH contamination in the NEX Gas Station soils and that the molecular weight of the other petroleum hydrocarbons is approximately 100, the average value of the mole fraction of benzene in these samples is estimated to be 0.18, toluene 0.18, ethylbenzene 0.07, and xylenes 0.22. The effective solubility of benzene is then estimated to be 326 mg/L, toluene 98 mg/L, ethylbenzene 12 mg/L, and xylenes 36 mg/L. The maximum soil concentration for each compound without exceeding the effective solubility can then be estimated using the partition coefficient, porosity and moisture content values discussed in Section 2.2, and the relationship between soil and groundwater concentration for equilibrium partitioning. The estimated soil concentrations are given in Table 2-6. An upper bound for the soil concentration of each compound can be obtained based on the pure compound solubility. These values are also given in Table 2-6. The estimated soil concentration in each case depends on the partitioning between the solid matrix and the water. Table 2-6 gives estimates of soil concentrations corresponding to pore water concentrations equal to the effective and pure compound solubility, for different values of the content of organic carbon, which affects the partition coefficient k_d . Besides the data-based value of 0.025 percent, soil concentration estimates are given for organic carbon content equal to 0, 0.1, and 1 percent.

The proposed soil cleanup goals are the lowest of the estimated values for each compound in Tables 2-6 and 2-7, and the proposed values satisfy the following two conditions:

- groundwater discharge concentrations in San Diego Bay will always be lower than the water quality criteria; and
- no free-product (nonaqueous-phase liquid) will be left in the groundwater or in the vadose zone.

2.4 SENSITIVITY ANALYSIS

The values used in the contaminant migration analysis are conservative (i.e., they have been selected to maximize the estimated concentrations in the groundwater discharge to the bay and give low soil cleanup criteria). To assess the sensitivity of the estimated soil cleanup levels, calculations were made for different values of the parameters having the greatest effect on the estimated soil concentrations. The parameters and values used in the sensitivity analysis are detailed below.

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Table 2-6
Maximum Soil Concentrations Consistent with Pore Water
Concentrations That Do Not Exceed BTEX Solubility

Description	Benzene	Toluene	Ethylbenzene	Xylenes	Total
Estimated average mole fraction in weathered gasoline, based on eight on-site samples (BNI 1995a)	0.18	0.08	0.07	0.22	N/A
Effective solubility in weathered gasoline, mg/L ^a	326	98	12	36	N/A
Pure-phase solubility, mg/L	1,780	537	167	162	N/A
Total soil concentration for $f_{oc} = 0$ Corresponding to effective solubility, mg/kg ^b	32	10	1	4	47
Corresponding to pure-phase solubility, mg/kg	176	53	17	16	262
Total soil concentration for $f_{oc} = 0.025\%$ Corresponding to effective solubility, mg/kg	42	24	6	19	91
Corresponding to pure-phase solubility, mg/kg	229	134	81	85	529
Total soil concentration for $f_{oc} = 0.1\%$ Corresponding to effective solubility, mg/kg	71	68	20	65	224
Corresponding to pure-phase solubility, mg/kg	387	377	274	292	1,329
Total soil concentration for $f_{oc} = 1\%$ Corresponding to effective solubility, mg/kg	418	598	187	616	1,819
Corresponding to pure-phase solubility, mg/kg	2,282	3,288	2,588	2,779	10,937

Notes:

^a mg/L – milligrams per liter

^b mg/kg – milligrams per kilogram

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**Table 2-7
 Maximum Soil Concentrations That Do Not Violate California
 Enclosed Bays and Estuaries Plan Water Quality Standards**

Description	MAXIMUM SOIL CONCENTRATION (mg/kg ^a)			
	Benzene	Toluene	Ethylbenzene	Xylene
Identified groundwater plume + Contaminated soils (20 by 20 feet)	848	b	b	b

Notes:

^a mg/kg – milligrams per kilogram

^b The estimated concentration for the protection of the bay can be as high as that corresponding to saturation of the soil with free-product (~125 grams per kilogram for 30-percent porosity and pure-product density of 0.867 grams per milliliter). In this case, soil cleanup goals for this compound will be based on the requirement that no free-product is left at the site, rather than on ecological protection of the San Diego Bay.

- **Retardation due to adsorption.** As an extreme assumption, it is assumed that $k_d = 0$ for all BTEX.
- **Biodegradation rate.** As an extreme assumption, it is assumed that the half-life of benzene is 10 years and that the half-life of toluene, ethylbenzene and xylenes is 5 years. These values are longer than all half-lives for BTEX that were found in the literature.
- **Size of the source area.** To maximize the contribution of contaminants in the soil, it is assumed that the contaminated area is 80 by 80 feet. As in the “base” case, it is assumed that the contaminant concentrations are uniform from the ground surface to the water table.
- **Past contamination of the groundwater.** To account for the effect of potential groundwater contamination already in place due to past spills and leaks at the NEX Gas Station, it is assumed that a hypothetical active source of dissolved BTEX was contaminating the groundwater over the last 20 years. The characteristics of this source are described in Section 2.1.2.2.
- **Off-site sources.** To account for the potential additive effect of BTEX contamination from the NEX Gas Station and other off-site sources, it is assumed that a plume identical to that identified at the NEX Gas Station exists 200 feet west of the centerline of the NEX plume. The size and concentration of each compound in this plume are described in Section 2.1.2.2. In this case, the concentration at the point of groundwater discharge to San Diego Bay is estimated as the sum of the concentration from the plumes. Because of lateral dispersion, this concentration is less than twice the concentration of a single plume.

Section 2 Groundwater Pathway

In each case, only one parameter is varied and the values of all other parameters are kept equal to those used in the base case. The estimated groundwater discharge concentrations from the sensitivity analysis along with the concentrations for the base case are given in Table 2-8. Figure 2-6 shows the estimated concentration at the discharge point of the bay caused by an 80- by 80-foot free-product source as a function of time (Table 2-8, Case 5). Figure 2-7 shows the lateral distribution of concentrations for the case of an off-site source located 200 feet west of the NEX Gas Station. The concentration profiles shown in Figure 2-7 are at the time of maximum groundwater concentration at the point of discharge to San Diego Bay. All estimated concentrations in the discharge to the bay are lower than the respective water quality standards. The maximum acceptable soil concentrations based on the groundwater concentrations estimated for the sensitivity analysis cases are given in Table 2-9.

2.5 SOIL CLEANUP GOALS

Comparing the concentrations for each compound given in Tables 2-6, 2-7, and 2-9 suggests that the most conservative, controlling condition for setting soil cleanup goals is the requirement that all free-product is removed and that soil cleanup goals be based on the effective solubility of each compound. The total concentration of each compound in a soil sample without its pore water concentration exceeding its solubility, which would suggest the presence of free-product, depends on the mole fraction of the compound and its partitioning between the solid and the liquid phase. Using the concentrations estimated in Table 2-6 for the average measured organic carbon content of 0.025 percent ($f_{oc} = 0.025\%$), the following concentrations could be used as soil cleanup goals: 42 mg/kg for benzene, 24 mg/kg for toluene, 6 mg/kg for ethylbenzene, and 19 mg/kg for xylenes.

It is stressed that these concentrations are derived from the condition that no free-product is left in place. Much higher cleanup goals are derived from the migration analysis which estimates concentrations in the groundwater discharge to the San Diego Bay and their comparison with levels protective of human health and the environment. The development of a condition for determining whether or not free-product exists in the soils based on the concentration of individual compounds depends on parameters (e.g., organic carbon content in the soils and the compound fraction mole composition of weathered gasoline at the site) that, prior to testing, are not known precisely, and can be estimated only within a range. For example, if the content of organic carbon in the soils, or the mole fraction of individual compounds are higher, then higher soil concentrations could be tolerated. Therefore, it is recommended that cleanup efforts focus on the broader goal of removing all free-product in soil and groundwater, rather than on meeting these specific concentrations.

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**Table 2-8
 Maximum Groundwater Discharge Concentration (sensitivity analysis)**

Case	PEAK DISCHARGE CONCENTRATION (µg/L*)				
	Benzene	Toluene	Ethylbenzene	Xylenes	
Base Case					
1a	Identified NEX plume represented as a 100- by 100-foot plume 10 feet deep with uniform concentration per Table 2-4	1.91	0.0016	2.6 x 10 ⁻⁶	5.0 x 10 ⁻⁶
1b	20- by 20-foot vadose zone soils at the maximum measured concentration	0.90	0.0011	2.6 x 10 ⁻⁶	93.1 x 10 ⁻⁶
Lower Biodegradation Rates					
2a	Same as (1a) but with longer half-lives (benzene: 10 years; toluene, ethylbenzene, and xylenes: 5 years)	14.5	0.55	0.0047	0.013
2b	Same as (1b) but with longer half-lives (benzene: 10 years; toluene, ethylbenzene, and xylenes: 5 years)	5.24	1.10	0.0200	0.100
No Retardation					
3	Same as (1a) but with $k_d = 0$	2.82	0.04	0.004	0.015
Larger Area of Contaminated Vadose Zone Soils					
4	Same as (1b) but for an 80- by 80-foot area of contaminated vadose zone soils	14.4	0.018	41 x 10 ⁻⁶	0.00015
Free-Product Source Providing Dissolved Benzene, Toluene, Ethylbenzene, and Xylenes over the Last 20 Years					
5	80- by 80-foot free-product pool	6.62	0.0013	2.4 x 10 ⁻⁶	4.2 x 10 ⁻⁶
Off-Site Sources					
6	100- by 100- by 10-foot plume 200 feet west of the NEX Gas Station	2.24	0.0017	2.7 x 10 ⁻⁶	5.3 x 10 ⁻⁶
Water quality goal		21	300,000	29,000	2,200

*µg/L – micrograms per liter

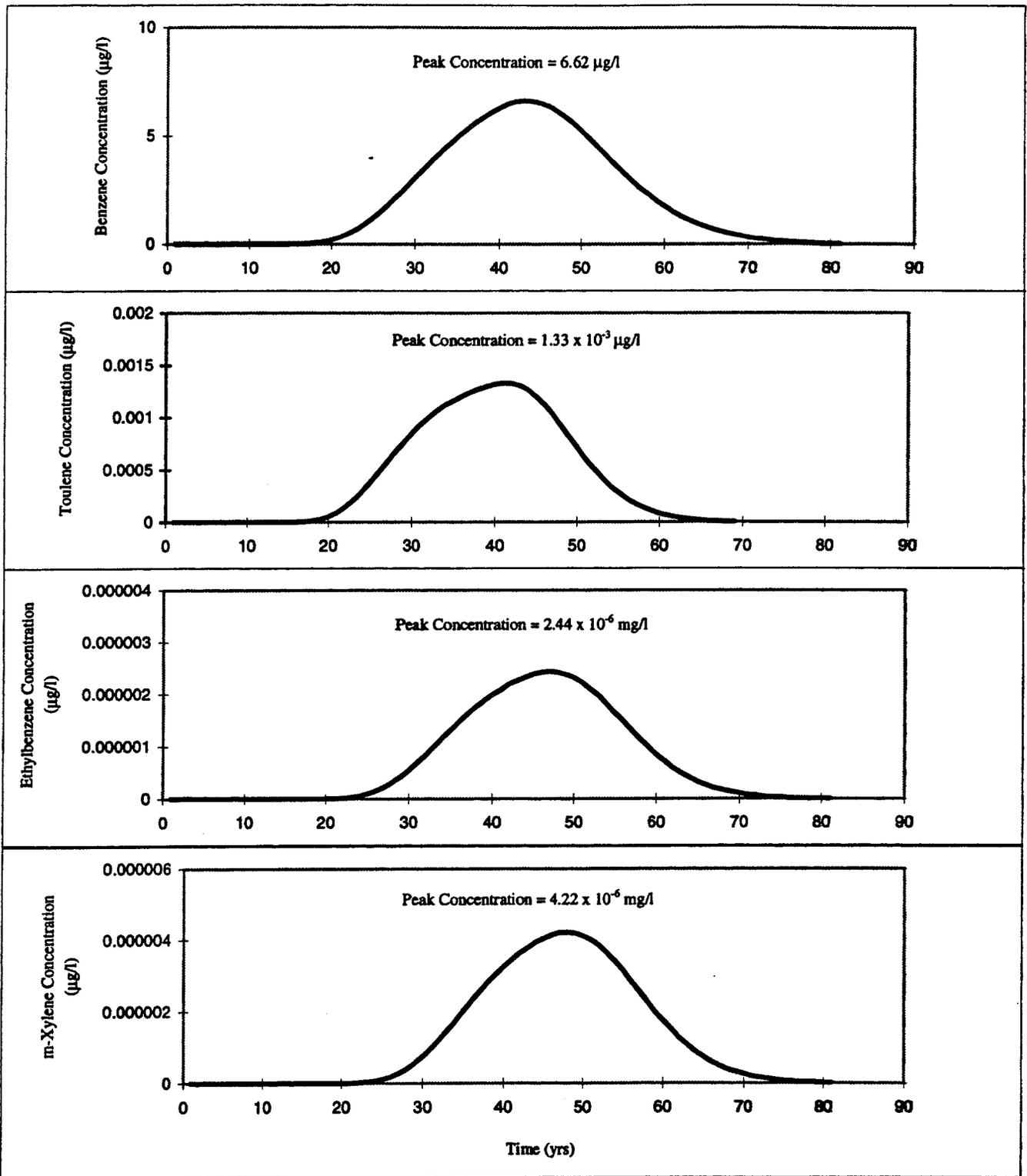


Figure 2-6: Maximum BTEX Concentration in Groundwater Discharging in San Diego Bay due to a Hypothetical 80 by 80 ft Free Product Source Providing Dissolved BTEX Underneath the NEX Gas Station. (The Concentrations are Given as a Function of Time For a Discharge Point at 1,300 ft from the NEX Gas Station.)

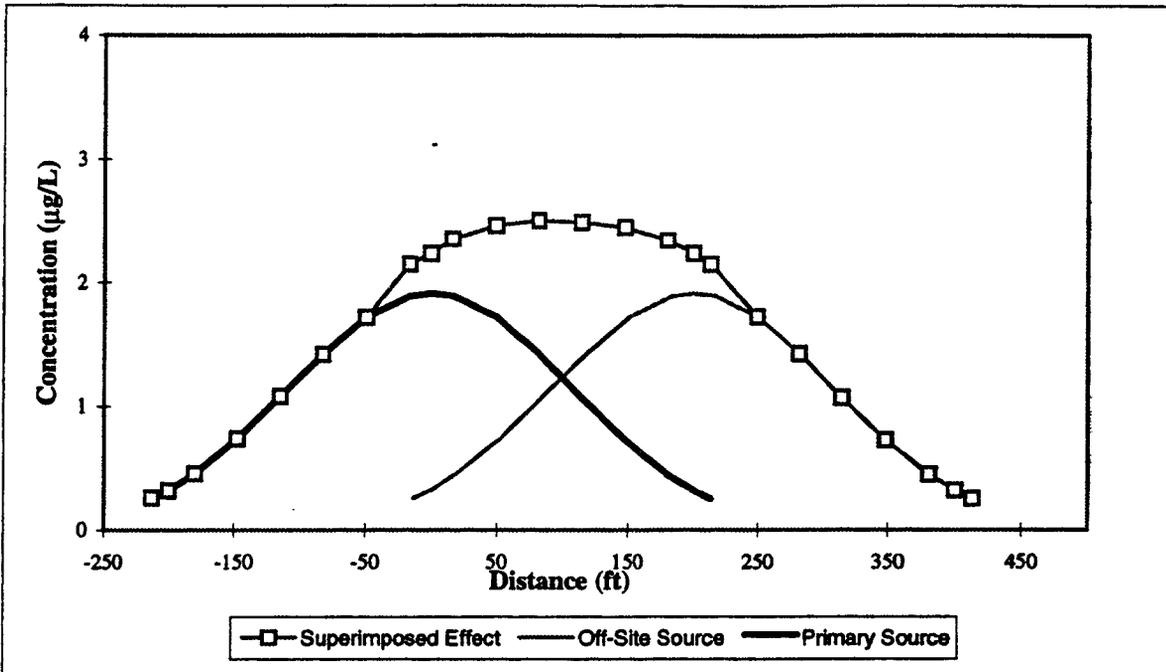


Figure 2-7: Lateral Distribution of Concentration at the Point of Discharge to San Diego Bay and the Time of Maximum Concentration Illustrating the Combined Effect of the NEX Gas Station Plume and an Off-Site Plume 200 ft West of the NEX Gas Station.

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Table 2-9
Maximum Soil Concentrations That Do Not Violate California
Enclosed Bays and Estuaries Plan Water Quality Standards
(sensitivity analysis)

Case	MAXIMUM SOIL CONCENTRATION (mg/kg ^a)			
	Benzene	Toluene	Ethylbenzene	Xylenes
Base Case	848	b	b	b
Lower Biodegradation Rates				
Longer half-lives (benzene: 10 years; toluene, ethylbenzene, and xylenes: 5 years)	288	b	b	14,778
No Retardation				
$k_d = 0$	808	b	b	b
Larger Area of Contaminated Vadose Zone Soils				
80- by 80-foot area of contaminated soils	58	b	b	b
Free-Product Source Providing Dissolved Benzene, Toluene, Ethylbenzene, and Xylenes over the Last 20 Years				
80- by 80-foot free-product pool over 20 years + contaminated vadose zone soils	639	b	b	b
Off-Site Sources				
100- by 100- by 10-foot plume 200 feet west of the NEX Gas Station	838	b	b	b

Notes:

- ^a mg/kg – milligrams per kilogram
- ^b Estimated concentration for the protection of the bay can be as high as that corresponding to saturation of the soil with free-product (~125 grams per kilogram for 30-percent porosity and pure-product density of 0.867 grams per milliliter). In this case, soil cleanup goals for this compound will be based on the requirement that no free-product is left at the site, rather than on ecological protection of the San Diego Bay.

Section 3

VAPOR PATHWAY

This section describes the two-step approach that was used to estimate the human health impacts that could occur to current and future property users at Site 3. The concentration of BTEX in air and the associated risk are approximated based on a vapor-transport analysis for certain adverse conditions.

A two-step process described below is used to identify: the emission rate or flux rate of BTEX in soil, and the concentration of BTEX in outdoor air. A diffusion model is used to obtain a gaseous flux value between the vadose zone and the ground surface. The modeled flux value is based upon the assumption that vapor-phase migration through the vadose zone is one-dimensional and does not vary in time (i.e., it is steady-state). The source of the migrating compounds in the vapor phase is volatile contaminants adsorbed in the soil and dissolved in the vadose zone water. It is assumed that the contribution of vapors emanating from volatilization of chemical compounds from the water table is small, compared with the contribution of chemicals in the soil, and can be neglected.

BTEX compounds are assumed to migrate upward through a concentration gradient that is defined as the ratio of the difference between the initial vapor concentration in impacted soil and the vapor concentration at the soil surface. A conservative assumption that a clean layer of soil, rather than concrete, is present at the ground surface is used to develop a concentration gradient for evaluating outdoor air concentrations. Currently, nearly 100 percent of the site is covered by asphalt pavement or cement structures.

The flux results of the Fickian model are used in a "box" model to calculate outdoor air concentrations. For the outdoor air model, bare soil is assumed to exist over the entire site; no surface barriers to diffusion, such as pavements, building foundations, or ponded water, are included.

The two-step process described above entails first identifying the concentration of BTEX in soil in order to calculate a soil-gas concentration. For conservative modeling purposes, the highest concentrations of BTEX identified in the analytical results are used to calculate soil-gas concentrations. The approach proposed in the SAM Manual (DEH 1995) is used to estimate gas emission rates.

3.1 ANALYSIS OF THE VAPOR PATHWAY

A two-phased approach was used to analyze the vapor pathway at Site 3 as described below.

3.1.1 Emission Rates from the Soil

The SAM Manual describes a simple procedure for calculating the effective flux or rate at which the volatile compound is transported to the atmosphere. This procedure is based on the assumption that the concentration gradient between the highest measured concentration and the ground surface or floor is linear. Based on this assumption the flux rate per unit surface area can be calculated using the following equation (DEH 1995):

Section 3 Vapor Pathway

$$F = \frac{D_e C_{sg}}{B}$$

where:

F is the effective flux,
 D_e is the effective diffusion coefficient in the soil,
 C_{sg} is the concentration in soil gas, and
 B is the distance between the contamination and surface.

The effective diffusion coefficient can be estimated as (Lyman et al. 1992, page 28):

$$D_e = \frac{(n - \theta)^{10/3}}{n^2} D_a$$

where:

D_a is the diffusion coefficient in the air,
 θ is the volumetric moisture content, and
 n is the porosity.

The concentration of a chemical in soil gas, C_{sg} , (milligrams per cubic meter [mg/m^3]) can be estimated from the following equation (DEH 1995):

$$C_{sg} = \frac{p_v M f}{RT}$$

where:

p_v is the vapor pressure of chemical,
 M is the molecular weight,
 f is the mole fraction of the compound,
 R is the universal gas constant, and
 T is temperature.

3.1.2 Outdoor Concentrations

The second step in the vapor pathway evaluation is calculation of the ambient air concentration via the "box" model. For outdoor air, the following equation is used (DEH 1995):

$$C_o = \frac{FL_u}{Wh}$$

where:

C_o is the concentration in air,
 L_u is the upwind length of contamination,
 W is wind speed, and
 h is the height of the assumed box.

Section 3 Vapor Pathway

3.2 ESTIMATED OUTDOOR CONCENTRATIONS

Outdoor concentrations are estimated for a gasoline source located 10 feet below the ground surface (B = 10 feet), and small "box" defined as approximately 3 by 3 feet (1 by 1 meter). Air concentrations are calculated for the 1945-1990 mean annual wind speed of 8 miles per hour (Station Number 722906, North Island NAS, from National Climatic Data Center 1992). The mole fraction of each compound is equal to that of the liquid phase gasoline. The parameters used in these calculations and the estimated outdoor concentrations are given in Table 3-1.

The estimated outdoor concentrations are significantly lower than the U.S. EPA Region IX preliminary remediation goals (PRGs) for ambient air (U.S. EPA 1995). Therefore, even if there is a source of pure gasoline at the water table, the ambient air BTEX concentrations would be too low to pose any threat to human health.

**Table 3-1
 Parameter Values Used in the Vapor-Phase Calculations
 and Estimated Outdoor Concentrations**

Parameter	Unit	Benzene	Toluene	Ethylbenzene	Xylenes
Diffusion coefficient in the air ^a , D_a	cm ² /s ^b	0.0905	0.0824	0.0733	0.0668
Effective diffusion coefficient, D_e	cm ² /s	0.000467	0.000425	0.000378	0.000345
Vapor pressure ^a , p_v	kPa ^c	10.033	2.91	0.94	0.82
Molecular weight, M	g/mol ^d	78.11	92.14	106.17	106.17
Mole fraction, f		0.0364	0.0515	0.0179	0.0625
Soil gas concentration, C_{sg}	g/m ^{3e}	11.71	5.676	0.737	2.239
Effective flux, F	mg/m ² /hr ^f	0.646	0.285	0.033	0.091
Estimated outdoor concentration	mg/m ^{3g}	0.050	0.022	0.0026	0.0071
U.S. EPA Region IX PRGs ^h (U.S. EPA 1995)	mg/m ³	0.23 ca ⁱ	400 nc ^j	1,100 nc	730 nc

Notes:

- ^a from Table 1-1B from Lyman et al. (1992) for a temperature of 20 degrees Celsius
- ^b cm²/s – square centimeters per second
- ^c kPa – kilopascal
- ^d g/mol – grams per mole
- ^e g/m³ – grams per cubic meter
- ^f mg/m²/hr – milligrams per square meter per hour
- ^g mg/m³ – milligrams per cubic meter
- ^h PRG – preliminary remediation goal
- ⁱ ca – carcinogen
- ^j nc – noncarcinogen

Section 4

CONCLUSIONS

A conservative "bounding case" analysis was performed to evaluate the potential ecological impact of dissolved BTEX migrating from the NEX Gas Station toward the San Diego Bay, and to evaluate the potential impact on human health of BTEX vapor emissions originating from contaminated groundwater and soils. The analysis was conservative because it used:

- higher values of site contaminant concentrations than those measured during the site investigation;
- hydraulic conductivity higher by more than one order of magnitude than measured;
- low biodegradation and retardation rates; and
- low tidal-mixing factor in the sediments.

The analysis was based on the assumption that all free-product in the groundwater or the vadose zone will be removed (i.e., in the future there will be no BTEX sources other than the vadose zone soils).

The migration analysis suggests that the detected contamination does not pose an ecological risk in San Diego Bay or risk to the health of future occupants and users of the site. Specifically, contaminated groundwater from the site discharging in San Diego Bay would not cause exceedance of the proposed California Bays and Estuaries Plan standards. Also, the ambient air concentrations in vapor emissions from the site are lower than the U.S. EPA Region IX PRGs. Therefore, no remedial action is required, beyond the removal of any free-product found in the groundwater and the vadose zone.

The analysis was extended to determine cleanup goals in the event that future investigations reveal higher soil concentrations at the site. The cleanup goals are defined as the highest soil concentrations that could be left in place without violating the water quality criteria for the protection of the bay; without having free-product (nonaqueous-phase liquids) in the soils; and without posing any risk to human health due to vapor emissions. The computed maximum concentrations for satisfying these conditions suggest that the controlling condition for setting soil cleanup goals is the requirement that all free-product is removed. The total concentration of each compound in a soil sample without its concentration in the pore water exceeding its solubility (which would suggest the presence of free-product) depends on the mole fraction of the compound and its partitioning between the solid and the liquid phase.

Based on site-specific conditions and conservative assumptions, the estimated concentrations beyond which the presence of free-product will be likely are **42 mg/kg for benzene, 24 mg/kg for toluene, 6 mg/kg for ethylbenzene, and 19 mg/kg for xylenes**. These concentrations could be used as soil cleanup goals. These concentrations are derived from the condition that no free-product is left in place. Much higher cleanup goals are derived from the migration analysis, which estimates concentrations in the groundwater discharge to the San Diego Bay and their comparison with levels protective of human health and the environment. Because of the uncertainty in the parameters that affect the relationship between the concentration of individual compounds and whether or not free-product exists in the soils (e.g., organic carbon content in the

Section 4 Conclusions

soils, and the mole the composition of weathered gasoline at the site), it is recommended that cleanup efforts focus on the broader goal of removing all free-product in soil and groundwater, rather than on meeting these specific concentrations.

Section 5 REFERENCES

- Baedecker, M.J. 1994. Field and laboratory results: Getting the whole picture, in *Symposium on Intrinsic Biodegradation of Ground Water*. Denver, Colorado. 30 August - 1 September. EPA/540/R-94/515.
- Bechtel National, Inc. 1995a. Comprehensive Long-Term Environmental Action Navy, CLEAN II: Draft Extended Site Assessment Report for the NEX Gas Station at Naval Training Center, San Diego, California, prepared for Southwest Division Naval Facilities Engineering Command. May.
- . 1995b. Comprehensive Long-Term Environmental Action Navy, CLEAN II, Technical Memorandum #1: Approach for the Development of Cleanup Goals at the NEX Gas Station at Naval Training Center, San Diego, California, prepared for Southwest Division Naval Facilities Engineering Command. May.
- BNI. See Bechtel National, Inc.
- Cal/EPA. See California Environmental Protection Agency.
- California Environmental Protection Agency State Water Resources Control Board. 1993. California Enclosed Bays and Estuaries. May.
- County of San Diego, Department of Environmental Health. 1995. Site Assessment and Mitigation Manual. San Diego, California: Site Assessment and Mitigation Division.
- DEH. See County of San Diego, Department of Environmental Health.
- Fetter, C.W. 1993. *Contaminant Hydrogeology*. New York: McMillan Publishing Co.
- Gelhar, L.W., A. Mantoglou, C. Welty, and K.R. Rehfeldt. 1985. A Review of Field-Scale Physical Solute Transport Processes in Saturated and Unsaturated Porous Media. Electric Power Institute. Report no. EPRI-EA-4190.
- IGWMC. 1993. AT123D, Analytical Transient One-, Two- and Three-Dimensional Simulation of Waste Transport in the Aquifer System. Developed by G.T. Yeh, code version 1.22. Distributed by the International Ground Water Modeling Center, Colorado School of Mines, Golden, Colorado.
- Lyman, W.J., P.J. Reidy, and B. Levy. 1992. *Mobility and Degradation of Organic Contaminants in Subsurface Environments*. Chelsea, Michigan: C.K. Smoley, Inc.
- MacFarlane, I.D., E.J. Bouwer, and P.J.S. Colberg. 1994. Demonstrating the feasibility of intrinsic biodegradation at a former manufactured gas plant, in *Symposium on Intrinsic Biodegradation of Ground Water*. Denver, Colorado. 30 August - 1 September. EPA/540/R-94/515.
- National Climatic Data Center. 1992. International Station Meteorological Climate Summary, Version 2.0. Federal Climate Complex, Asheville, North Carolina. June.
- Southwest Division Naval Facilities Engineering Command. 1995. Minutes to cleanup level determination meeting (CTO-0064). 19 January.

Section 5 References

- Stauffer, T.B., C.B. Antworth, J.M. Boggs, and W.G. MacIntyre. 1994. A natural gradient tracer experiment in a heterogeneous aquifer with measured *in situ* biodegradation rates: A case of natural attenuation. In *Symposium on Intrinsic Biodegradation of Ground Water*. Denver, Colorado. 30 August - 1 September. EPA/540/R-94/515.
- SWDIV. See Southwest Division Naval Facilities Engineering Command.
- Todd, D.K. 1959. *Groundwater Hydrology*. New York: John Wiley & Sons.
- United States Environmental Protection Agency. 1985. Quality Criteria for Water. Office of Water Regulations and Standards. Washington D.C.: Report no. EPA440/-5-86-001.
- . 1995. Region IX Preliminary Remediation Goals (PRGs) Second Half 1995. United States Environmental Protection Agency, Region IX. San Francisco. 1 September.
- U.S. EPA. See United States Environmental Protection Agency.
- Wilson, J.T., T.H. Wiedemeier, J.E. Hansen, and R.N. Miller. 1994. Intrinsic bioremediation of JP-4 jet fuel. In *Symposium on Intrinsic Biodegradation of Ground Water*. Denver, Colorado. 30 August - 1 September. EPA/540/R-94/515.
- Woodward-Clyde. 1988. Background Document for the Unsaturated Zone Flow and Transport Module of EPACML. Prepared for U.S. EPA, Office of Solid Waste, Washington D.C.
- Yeh, G.T. 1981. AT123D, Analytical Transient One-, Two- and Three-Dimensional Simulation of Waste Transport in the Aquifer System. ORNL-5602. Oak Ridge, Tennessee: Oak Ridge National Laboratory.

Additional Source

- Borden, R.C. 1995. Comparison of Laboratory and Field Intrinsic Bioremediation Rates - Why Don't They Match? AGU Spring Meeting, Baltimore, Maryland., published in EOS. 25 April.

APPENDIX A

EXAMPLES OF REPORTED BTEX BIODEGRADATION RATES

Appendix A Examples of Reported BTEX Biodegradation Rates

The following table summarizes reported BTEX biodegradation rates found in a review of the recent technical literature. All references are listed in Section 5.

Reference	Site Location	HALF-LIFE, YEARS			
		Benzene	Toluene	Ethylbenzene	Xylenes
MacFarlane et al. 1994	Baltimore, MD	2.00	1.81	2.4	2.34
Stauffer et al. 1994	Columbus Air Force Base, MS	0.29			0.13 ^a
Wilson et al. 1994	Eglin Air Force Base, FL		0.04	0.06	0.09 ^a
Borden et al. 1995	North Carolina			0.83	
	North Carolina	9.50	0.90		0.90 ^b

Notes:

- ^a p-xylene
- ^b o-xylene

APPENDIX B

TIDAL DILUTION FACTOR EQUATION

Appendix B Tidal Dilution Factor Equation

The response of a one-dimensional confined aquifer to a tidal fluctuation can be expressed as (Todd 1959, page 243):

$$h = h_o e^{-\beta x} \sin\left(\frac{2\pi}{P}t - \beta x\right) \quad (1)$$

where:

- h_o = the amplitude of the tide,
- P = the tidal period,
- x = distance from the discharge point,
- $\beta = \sqrt{\frac{\pi S}{PT}}$,
- S = storage coefficient, and
- T = aquifer transmissivity.

The tidal component of the Darcy velocity, q_T is obtained from (1):

$$q_T = -K \frac{\partial h_T}{\partial x} = Kh_o \beta \sqrt{2} e^{-\beta x} \sin\left(\frac{2\pi}{P}t - \beta x + \frac{\pi}{4}\right) \quad (2)$$

The flow q_o in or out of the aquifer at $x = 0$ is:

$$q_o = Kh_o \beta \sqrt{2} \sin\left(\frac{2\pi}{P}t + \frac{\pi}{4}\right) \quad (3)$$

The volume of the flow into the aquifer per unit area during one tidal cycle is:

$$V_T = \int_{\frac{3}{8}P}^{\frac{7}{8}P} q_o dt = \int_{\frac{3}{8}P}^{\frac{7}{8}P} Kh_o \beta \sqrt{2} \sin\left(\frac{2\pi}{P}t + \frac{\pi}{4}\right) dt = h_o T \beta \sqrt{2} \frac{P}{\pi} \quad (4)$$

The volume of net discharge into the ocean due to regional aquifer flow over one tidal cycle is:

$$V_A = T i_h P \quad (5)$$

where:

i_h is the hydraulic gradient in the aquifer for mean sea water level conditions.

The tidal mixing factor in the sediments F_T due to tidal effects for a single tidal component is equal to:

$$F_T = \frac{V_A + V_T}{V_A} = \frac{i_h \pi + h_o \beta \sqrt{2}}{i_h \pi} \quad (6)$$

Appendix B Tidal Dilution Factor Equation

In the case that the tidal forcing consists of several harmonic components with periods P_1, P_2, \dots, P_n , and amplitudes h_1, h_2, \dots, h_n , with corresponding aquifer constants $\beta_1, \beta_2, \dots, \beta_n$, the tidal mixing factor is:

$$F_T = 1 + \frac{\sqrt{2}}{i_h \pi} \left(\beta_1 h_1 + \frac{P_2}{P_1} \beta_2 h_2 + \dots + \frac{P_n}{P_1} \beta_n h_n \right) \quad (7)$$

or,

$$F_T = 1 + \frac{1}{i_h} \sqrt{\frac{2S}{\pi T}} \frac{1}{P_1} (h_1 \sqrt{P_1} + h_2 \sqrt{P_2} + \dots + h_n \sqrt{P_n}) \quad (8)$$