

**ASSESSMENT AND CALCULATION OF BTEX PERMEATION
THROUGH HDPE WATER PIPE**

FINAL REPORT

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1.0 INTRODUCTION

The water industry in Europe has extensively used HDPE (High Density Polyethylene) pipe for drinking water supply and distribution systems for many decades. In the US and Canada, the adoption of HDPE water pipe continues to increase in municipal and utility applications. Compared to other pipe materials such as steel, ductile iron, concrete and PVC, HDPE pipes have many advantages such as flexibility, corrosion and biological resistance, fatigue (Jana 2012) and seismic resistance (Eldinger and Davis 2012) and availability of various types of joints, such as a leak free fusible joints and mechanical joints and provides the lowest life cycle costs (CSIRO 2008).

As indicated in the AWWA pipe standards (such as AWWA C110, C200, C905, C906, and etc), underground pipelines can be contaminated by various chemical organic substances during service. Hydrocarbon permeation occurs by external contamination sources existing around the water pipe systems. Subsequently the contaminants diffuse through the pipe wall and joints into the water carried in the pipe. AWWA Standards include similar Permeation Requirements for pipes and gaskets and refer the user to consult with the manufacturer regarding permeation of pipe walls, jointing materials, etc., before selecting materials for use in such areas. As such, the Plastics Pipe Institute contracted with the Purdue School of Engineering at IUPUI to develop this report to assist the users with these applications.

BTEX is an acronym for four hydrocarbon compounds, including Benzene, Toluene, Ethylbenzene, and Xylenes. BTEX is known to be highly volatile organic compounds and is the main source of ground contamination caused by petroleum related contamination such as Fuel tank leakage. Because of their small molecular size and high solubility in water, BTEX has the

potential to permeate through pipes and gasket joints under certain conditions as will be discussed later in this report. Hydrocarbon permeation occurs through polymeric gasket joints and other plastic piping materials. Water quality is compromised only when the permanent contamination amount exceeds safe limits.

Research has been performed to measure diffusion and permeation coefficients for PE products, such as a PE film, which is mainly used as a landfill barrier (Joo et al. 2004 and 2005, Park et al. 1996, Sangam and Rowe 2001, Park and Nibras 1993). Research for PE pipe material permeation was most recently published in 2008 by AWWA Research Foundation (AWWA RF, currently Water RF); this AWWA RF report provides BTEX diffusion coefficients and permeation rates for a 1-inch diameter Iron Pipe Size (IPS) HDPE water pipe in various lab settings (Ong et al. 2008). However, Ong et al (2008) only tested a thin wall 1- inch diameter HDPE pipe that is primarily used for service connection in many water systems. Distribution and transmission pipe are thicker. Thus, using 1-inch diameter pipe permeation rates to predict the performance of thicker distribution and transmission pipes can over-estimate the rate of permeation. In addition, the previous Water RF research was limited to the 1” service tube; testing was not conducted for the wider selections of HDPE pipe sizes used in water supply and distribution pipelines in various geotechnical and operating conditions from actual job sites. This presents a technical challenge to most engineers. A practical application of previous AWWA RF findings evidently requires numerous engineering assumptions and extensive understanding of chemical permeation and BTEX transport mechanisms prior to selecting HDPE as a valid water pipeline material designed for a potentially BTEX contaminated site. This report provides a step-by-step BTEX permeation estimation methodology and suggests guidelines for incorporating jobsite geotechnical and design variables including bulk concentration of BTEX in soil, ground

temperature, groundwater saturation, flow velocity, water stagnation, pipe thickness, and soil characteristics. The methodology in this report will be used to perform example calculations based on existing regulatory limits and common design practices.

2.0 BTEX DEFINITIONS AND PROPERTIES

Hydrocarbon (organic) compounds are major environmental contamination sources in groundwater. BTEX is acronym for a group of hydrocarbon organic compounds including Benzene, Ethylbenzene, Toluene, and three isomers of Xylene referring to total Xylene. BTEX is defined as “*Volatile, monocyclic aromatic compounds present in coal tar, petroleum products, and various organic chemical product formulations*” (Cohen and Mercer, 1993) and “*the most soluble of the major gasoline compounds and, therefore, are common indicators of gasoline contamination*” (Wilson and Moore, 1998). Generally, gasoline consists of BTEX (approximately 18 percent by weight) and other hydrocarbons (approximately 82 percent by weight). Figure 1 shows percentages of each BTEX component weight out of 18 percent BTEX by weight (Christensen and Elton, 1996).

**BTEX Components in Regular Gasoline
(Percent by Weight)**

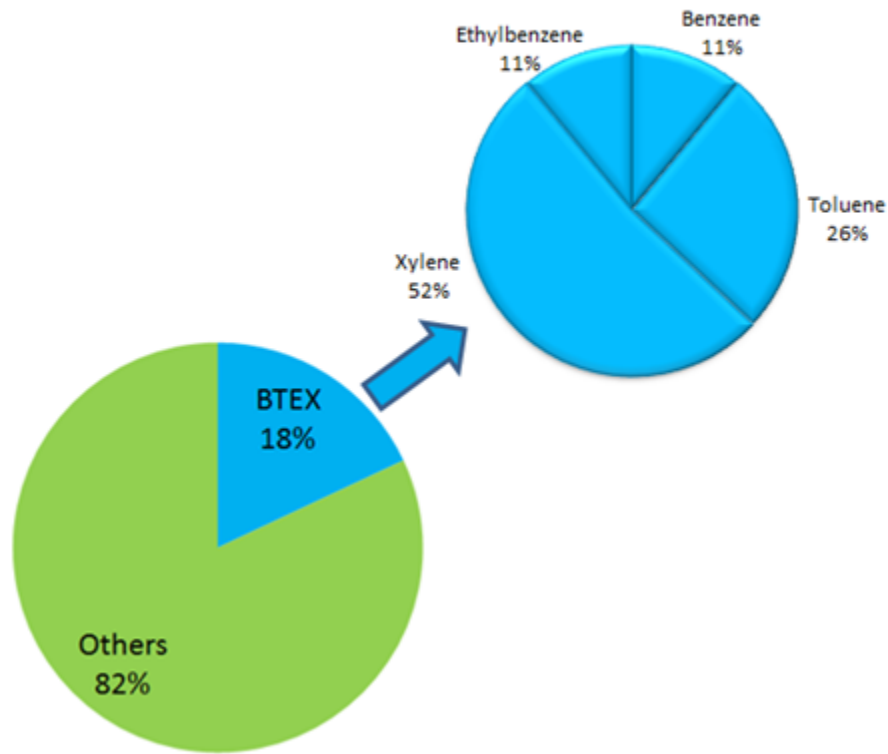


Figure 1. BTEX Components in Gasoline (Christensen and Elton, 1996)

When BTEX transports through the ground, it is mixed with existing ground water. The actual mixture of each BTEX compound in the groundwater is different because of different levels of solubility. The recent AWWA RF report (Ong et al. 2008) demonstrated a solubility test and measurement. A mixture of 350 mL (mililiter) of gasoline with 3.5 liters of deionized water in a 4 liter glass bottle was agitated by a magnetic stirrer for 48 hours to prepare BTEX solution samples. Table 1 shows aqueous gasoline solutions prepared by Ong et al. (2008). Three diluted aqueous solutions of varying concentrations in Table 1 were obtained by diluting the 100% dissolved BTEX concentration with deionized water at a ratio of 1:1, 1:9, 1:99, respectively. These solutions are used as bulk concentration (C_{bulk}) to estimate BTEX permeation rate

(P_m). The actual concentration of BTEX contaminants in contaminated ground water may be significantly different when it is compared to the percent of weight in regular gasoline shown in Figure 1. Table 1 indicates that Benzene has the highest solubility. In other words, Benzene dissolved in the water to the highest degree amongst the other organic compounds and it can be dispersed as contaminated groundwater moves through underground soil layers.

Table 1. Bulk Concentration of contaminant in the Groundwater (Soil Pore Water) (C_{bulk})

Aqueous Gasoline Solutions	Total BTEX	Benzene	Toluene	Others
100 %	136.6 mg/L (0.1366 mg/cm ³)	67.5 mg/L (0.0675 mg/cm ³)	56.2 mg/L (0.0562 mg/cm ³)	12.9 mg/L (0.0129 mg/cm ³)
50 %	63.9 mg/L (0.0639 mg/cm ³)	31.2 mg/L (0.0312 mg/cm ³)	26.3 mg/L (0.0263 mg/cm ³)	6.4mg/L (0.0064 mg/cm ³)
10 %	12.6 mg/L (0.0126 mg/cm ³)	6 mg/L (0.006 mg/cm ³)	5.2 mg/L (0.0052 mg/cm ³)	1.4 mg/L (0.0014 mg/cm ³)
1 %	1.2 mg/L (0.0012 mg/cm ³)	0.6 mg/L (0.0006 mg/cm ³)	0.5 mg/L (0.0005 mg/cm ³)	0.1 mg/L (0.0001 mg/cm ³)

Note: Data from Ong et al (2008).

Table 2 presents the BTEX chemical and physical properties. The molecular weight is calculated by multiplying the atomic weight of each element in a chemical formula by the number of atoms in the formula, then adding all of these products together (Convert units 2011). The soil organic carbon-water partitioning coefficient (K_{OC}) is an important property to estimate the mobility of BTEX compounds (Guo et al. 2004). K_{OC} is a ratio of the mass of a chemical, including BTEX, absorbed in the soil in the equilibrium BTEX concentration solution. According to the general rule of K_{OC} , the lower the K_{OC} values, the higher the mobility of BTEX through groundwater-saturated soil. The soil type and properties must be taken into consideration to estimate the

mobility of BTEX in the soil (Yang et al. 1995). The absorption of BTEX compounds in soil particles are significantly governed by specific types and properties of soils. However, Koc values in various soil types for BTEX compounds have not been known for engineer's practice. Vapor pressure is the pressure of the gas in equilibrium compared to a liquid or solid status at a given temperature. BTEX is a highly volatile organic compound. Thus, it tends to evaporate in atmosphere relatively easier than other hydrocarbons. In other words, the higher the vapor pressure, the more volatilization from the liquid or dissolved status from the contaminated ground.

Table 2. Chemical and Physical Properties of BTEX Compounds

Parameters	Benzene	Toluene	Ethylbenzene	Xylenes
Formula	C ₆ H ₆	C ₆ H ₅ CH ₃	C ₆ H ₅ CH ₂ CH ₃	C ₆ H ₄ (CH ₃) ₂
Molar weight (g/mol)	78.12	92.15	106.18	106.18
Density (g/ml)	0.88	0.87	0.87	0.87 ^a
Soil organic carbon-water partitioning coefficient (K_{OC})	97	242	622	570 ^a
Vapor Pressure^b				
A	17.1	6.63	2.86	2.48
B	0.0547	0.0473	0.0445	0.0442

Note: Data from Weast et al. (1990), Carey and Sundberg (1990), and Fetter (1998).

a: Average Values;

b: At a given temperature (T), vapor pressure (P)=exp(-0.05223 a/T +b).

3.0 REGULATIONS AND HEALTH EFFECTS

The US EPA has established National Primary Drinking Water Regulations (NPDWR) controlling the Maximum Containment Levels (MCLs) for the nation's drinking water systems in

a wide range of microorganisms, disinfectants, disinfection byproducts, inorganic and organic chemicals, and radio nuclides (EPA 2009). NPDWR currently applies to approximately 170,000 public water systems, including 54,000 community water systems and 89,000 transient non-community water systems, in the United States. Post-treatment contamination of the distribution system may affect public health risks if the contamination exceeds MCLs for more than a year. Special groups may be particularly sensitive to the effects of certain chemicals (Quevauviller and Thompson 2006).

Table 3 presents the latest NPDWR for BTEX. Benzene is the only BTEX compounds classified as a human genotoxic and carcinogen substance. Other BTEX compounds are neither carcinogen nor regulated contaminants in Canada and the European Union as shown in Table 4. Public health goals, referring to the Maximum Contaminant Level Goals (MCLG), are also established by USEPA, yet it is not currently mandated by federal regulations. Potential health effects from long-term exposure above MCLs are presented in Table 3. Canada and the European Union (EU) do not regulate Ethylbenzene, Toluene, and total Xylene in their drinking water quality standards.

In most instances, drinking water contamination reports have been made by ordinary customers, who detected odor and taste change (USEPA 2002). Table 5 presents odor and taste thresholds for BTEX compounds. Water customers can easily detect Ethylbenzene, and Xylene before consumption because of strong odor. A Benzene contamination level less than 0.5mg/L is almost impossible to detect by an ordinary human being. Benzene is identified as a carcinogen whereas Toluene, Xylene, and Ethylbenzene are not as shown in Table 4. Thus, Benzene permeation is the foremost issue and Benzene permeation estimation should take more consideration than the three other volatile hydrocarbons.

Table 3. National Primary Drinking Water Regulations for Organic Chemical (BTEX)

Contaminant	MCL (mg/L)	Public Health Goal (MCLG) (mg/L)	Potential Health Effects from Long-term Exposure above the MCL	Common Sources of Contaminant in Drinking Water
Benzene	0.005	0	Anemia, Increased risk of cancer	Discharge from factories Leaching from gas storage tanks and landfills
Toluene	1	1	Nervous system, Liver or kidney problems	Discharge from petroleum factories
Ethylbenzene	0.7	0.7	Liver or kidney problems	Discharge from petroleum refineries
Xylenes (total)	10	10	Nervous system damage	Discharge from petroleum factories Discharge from chemical factories

Data: EPA (2009) National Primary Drinking Water Regulations

Table 4. Comparison of Drinking Water Standards

	Canada	World Health Organization (WHO)	EU	USEPA	Human Carcinogenicity*
	MAC (mg/L)	Guideline Value (mg/L)	Parametric Value (mg/L)	MCL (mg/L)	
Benzene	0.005	0.01	0.001	0.005	Genotoxic and carcinogen
Ethylbenzene	N/A	0.3	N/A	0.7	No
Toluene	N/A	0.7	N/A	1.0	No
Xylenes (total)	N/A	0.5	N/A	10.0	No

Data: SDWF (2011)

N/A: not regulated contaminants or insufficient data to prove adverse health effect

*: Human carcinogenicity is referenced from Stern and Lagos (2008), USEPA (2000, 2002, 2005), and American Cancer Society.

Table 5. Taste and Odor Thresholds for Pure Compounds Compared to MCLs

Contaminant	MCL (mg/L)	Taste Threshold (mg/L)	Odor Threshold (mg/L)	Detect Before Risk
Benzene	0.005	0.5 – 4.5	2.0	No
Toluene	1	No Data	2.9*	No Data
Ethylbenzene	0.7	0.029	0.029	Yes
Xylenes (total)	10	No Data	2.2	Yes

Data: EPA (2002). Permeation and Leaching

*: Data from J.E. Amooore and E. Hautala (1983)

4.0 BTEX TRANSPORT MECHANISMS

As discussed in previous sections, BTEX is one of the main groundwater contamination sources due to several reasons including: 1) wide use of petroleum products such as gasoline, 2) BTEX makes up a significant percentage of petroleum products, and 3) BTEX’s high solubility in ground water. There are four major BTEX transport mechanisms distributing BTEX through the ground; 1) volatilization, 2) dissolution, 3) sorption, and 4) biodegradation (Christensen and Elton, 1996). As the BTEX transport mechanisms progress, the concentration level of BTEX will be reduced over time.

4.1 Volatilization

BTEX, a group of volatile organic compounds, vaporizes into atmosphere when it is exposed to the ground surface. Vapor pressure properties presented in Table 2 are obtained from the pure BTEX components. Higher vapor pressures indicate that BTEX molecules will evaporate out of

BTEX solutions quickly from contaminated groundwater or absorbed in soil particles. However, volatilization can be limited if the urban built environment is covered by an impermeable surface restraining the vaporization process into the atmosphere. In addition, an impermeable surface prohibits BTEX spill from entering into ground. Vegetation on the surface may increase volatilization.

4.2 Dissolution

BTEX has relatively high solubility when mixed with water. Each component of BTEX has different degrees of dissolution. Dissolved BTEX concentration is expressed as a percentage of aqueous saturation in Table 1. Benzene shows the highest solubility in groundwater amongst Benzene, Toluene, Ethylbenzene, and total Xylene. According to Yang et al. (1995), BTEX moves with groundwater in response to natural hydraulic gradients, eventually migrating over large boundary areas, and diluting in groundwater. Ong et al (2008) demonstrated that the permeation rates of BTEX through PE pipes were strongly dependent on the BTEX bulk concentration outside of the pipe. Bulk solutions in various BTEX concentration levels were made as shown in Table 1. The aqueous saturation degree of contaminated groundwater around the buried PE water pipe is a significant factor to estimate the quantity of BTEX permeation. The amount of Benzene permeation increases where the ground is fully saturated and an HDPE water pipe exterior is completely exposed to 100% dissolved BTEX contaminated ground water. The external bulk concentration of BTEX reduces as contaminated groundwater dilutes the aqueous concentration dispersing BTEX into the surrounding groundwater. Underground water saturation, influence zone, and time can be significant factors. However, those two factors are site-specific conditions and only measured from the site.

4.3 Sorption

Sorption is defined as the attachment of the organic contaminants to the soil surface or matrix (Christensen and Elton, 1996). From the geotechnical engineering perspective, the sorption process takes place when the soil is unsaturated. The unsaturated soil zone is defined as the soil layers between the ground water table and the surface. Thus, this sorption process holds BTEX compounds in soil structure and inhibits their movement through soil particles. Sorption is controlled by many factors, including properties of organic contaminants and soil. Higher polarity and solubility attribute to increase organic contaminants, for example, Benzene is to be absorbed easily in soil and increases affinity between soil matrix and organic compounds (Zytner 1994 and Ong et al. 2008). When the quantity of BTEX is not sufficient to reach the underground HDPE pipes and/or groundwater is unsaturated, sorption traps organic contaminants and slows groundwater migration.

Most distribution mains and service connections are typically buried in unsaturated soil zone within 10 ft from ground surface. This unsaturated soil zone develops negative suction pressure and typically increases the water content close to the groundwater table (Fredlund and Rahardjo 1993). However, the groundwater table level fluctuates by precipitation, percolation, topography, and soil properties such as hydraulic conductivity and particle sizes of the soil. The degree of groundwater saturation is a significant factor in determining if BTEX dissolves in groundwater or absorbs in soil. AWWA RF report (Ong et al. 2008) only covers dry soil and 100% aqueous condition for their permeation experiments.

4.4 Biodegradation

Many organic compounds can be degraded by natural microbial activity. The microbial degradation (biodegradation) of BTEX is a predominant mechanism for the natural remediation process. According to Kim et al. (2003), the availability of BTEX during microbial degradation process is often limited due to sorption and entrapment in the soil structure. Zang and Bouwer (1997) tested microbial degradation for Benzene and Toluene. They found that the rate of biodegradation decreased with the increasing hydrophobicity, soil to water ratio, soil particle size, and soil organic carbon content. The effect of biodegradation is greatly inconsistent and affected by the concentration of microbial population and BTEX concentration (Kim et al. 2003). The biodegradation process certainly attenuates the BTEX contamination level in soil and groundwater. It is an extremely complex biochemical process to generalize into a permeation calculation. The biodegradation factors include, but are not limited to, existence of oxygen, type of bacteria, existence of hydrogen peroxide, and soil properties (Kim et al. 2006).

4.5 Summary

All four mechanisms are considered as passive natural remediation processes. Volatilization, sorption, and biodegradation may cause a significant degree of BTEX contamination attenuation. However, those three mechanisms are difficult to control as independent factors in permeation estimating formulas because of the complicated interaction between all existing natural conditions and site-specific properties. When evaluating BTEX permeation for HDPE pipe, engineers should take into consideration that the long-term attenuation process occurs naturally; this long-term process reduces the bulk concentrations of contaminants (C_{bulk}). C_{bulk} is the most

important factor for the BTEX permeation calculation methodology presented in the following section.

5.0 BTEX PERMEATION CALCULATION METHODOLOGY

5.1 Steady State Permeation Coefficient Equation

Fick’s laws of diffusion provide a concept of diffusive flux from high concentration to low concentration. Fick’s law governs mass transfer at the molecular diffusion level using a diffusion coefficient (Yahya 2006). Ong et al. (2008) conducted literature reviews and several tests to measure diffusion coefficients in different levels of BTEX concentration. They used a 1-inch diameter HDPE (IPS and DR9) pipe, which has an average wall thickness of 0.146 inches, to measure diffusion coefficients. The diffusion coefficients were confirmed and were similar to previous studies by Vonk (1985) and Joo et al (2004). Permeation rates (P_m) were estimated from cumulative mass flux and showed that the permeation rates were strongly dependent on the bulk concentration of contaminants as shown in Equations 2 and 3. Equation 1 provides a formula of concentration of the contaminants that permeated through an HDPE pipe. Equation 1 assumes that contaminants permeate at a steady state and diffuse across the pipe once the contaminants permeate through the pipe wall. Figure 2 demonstrates a flow diagram for BTEX contamination calculation process using six variable conditions.

$$C_{pw} = \frac{M}{V} = \frac{P_m \times \pi \times x \times OD}{\frac{1}{4} \times \pi \times ID^2} \text{-----} (1)$$

Where: C_{pw} = daily concentration of contaminant in pipe-water ($\mu\text{g}/\text{cm}^3/\text{day}$),

M = total mass of permeated contaminant (μg),

V = volume of water in the pipe (cm^3),

P_m = steady permeation rate of the contaminant ($\mu\text{g}/\text{cm}^2/\text{day}$),

ID = inside diameter of pipe (cm), and

OD = outside diameter of pipe (cm).

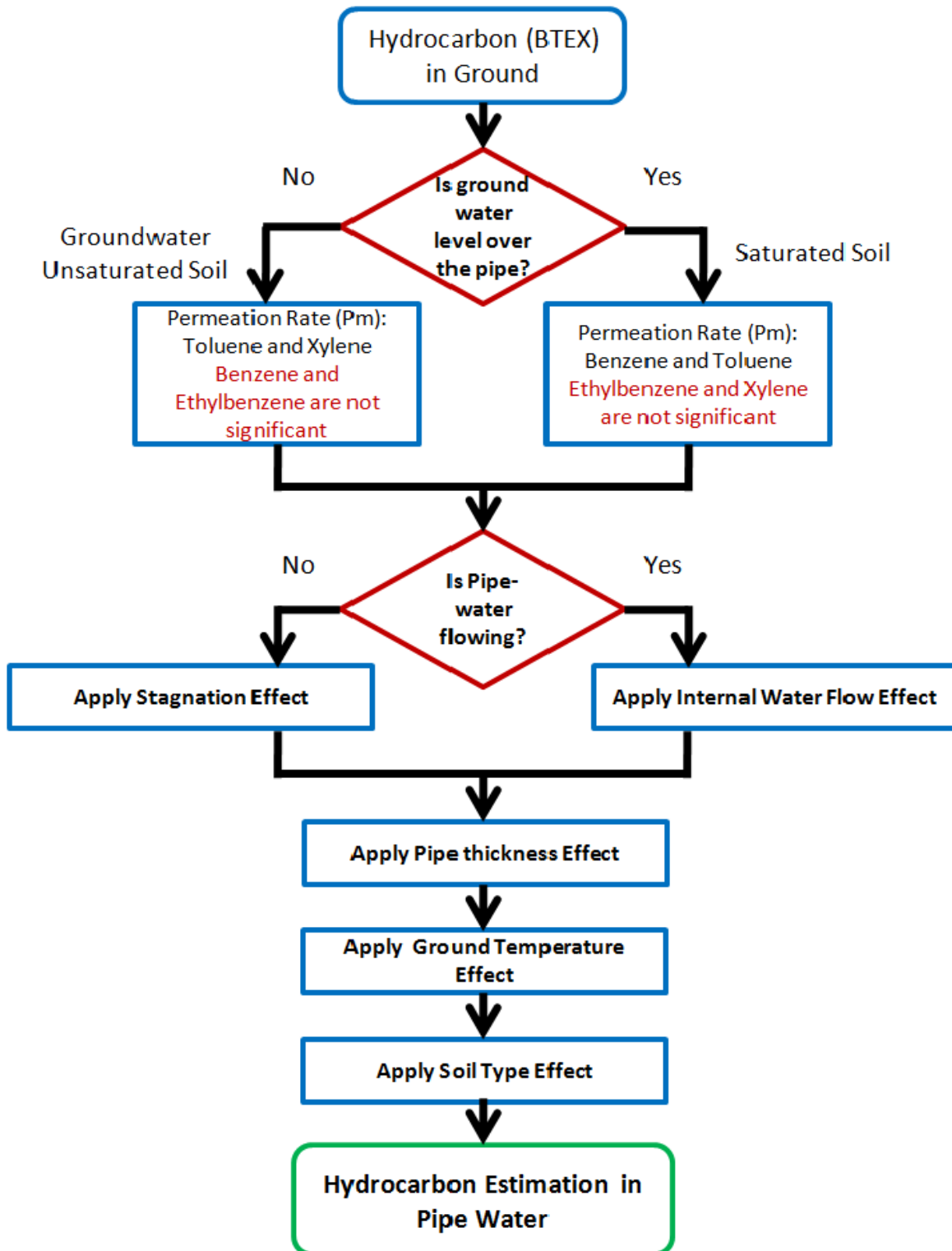


Figure 2. IUPUI Flow Diagram for BTEX Contamination Calculation Process

5.2 Condition Variables - Saturated and Unsaturated Ground Water

According to Ong et al. (2008), degree of groundwater saturation is a significant factor to control the permeation rate because of high solubility of BTEX contaminant in the saturated groundwater. For example, if the dissolved bulk concentrations of contaminants are 100% saturated in the groundwater and an entire pipe exterior surface area is exposed, the Benzene permeation rate would be at its maximum.

The AWWA RF report tested a 1-inch diameter HDPE water pipe in the theoretically worst-case condition and submerged the pipe submerged in various dissolution levels of BTEX mixed water. Benzene and Toluene were detected in the pipe-water. Ethylbenzene and total Xylene are only detected at insignificantly low level. These results can be explained by the higher solubility of Benzene in water and the higher mass fraction of Toluene in BTEX as shown in Table 1. Ong et al. (2008) proposed permeation rates for Benzene and Toluene under 100% saturated groundwater condition as shown in Equations 2 and 3. Although Ethylbenzene and Xylene permeation are negligible, Ethyl benzene and Xylene may be estimated at approximately 10% of the Benzene permeation rate for design convenience. This approach will remind engineers in practice to consider potential Ethylbenzene and Xylene presence in the pipe-water.

$$\text{Benzene: } P_m (\mu\text{g}/\text{cm}^2/\text{day}) = 0.0079 * C_{\text{bulk}}^{1.1323}, \text{ where } C_{\text{bulk}} = \text{mg}/\text{L} \text{ ----- (2)}$$

$$\text{Toluene: } P_m (\mu\text{g}/\text{cm}^2/\text{day}) = 0.0087 * C_{\text{bulk}}^{1.1444}, \text{ where } C_{\text{bulk}} = \text{mg}/\text{L} \text{ ----- (3)}$$

$$\text{Ethylbenzene: } P_m (\mu\text{g}/\text{cm}^2/\text{day}) = 0.00079 * C_{\text{bulk}}^{1.1323}, \text{ where } C_{\text{bulk}} = \text{mg}/\text{L} \text{ ----- (4)}$$

$$\text{Xylene (total): } P_m (\mu\text{g}/\text{cm}^2/\text{day}) = 0.00079 * C_{\text{bulk}}^{1.1323}, \text{ where } C_{\text{bulk}} = \text{mg}/\text{L} \text{ ----- (5)}$$

*Note: $C_{\text{bulk}} = \text{mg}/\text{cm}^3$ shall be converted to mg/L to use this equation by multiplying 1000

*Note: Ethylbenzene and Xylene compounds, including m-Xylene and o+p- Xylene, are not notably detected in the pipe-water

Soil porosity and water content have an effect on the BTEX contaminants transport through the soil structure, thus porosity and water content significantly affect the permeation through the HDPE pipe. Benzene permeates HDPE water pipe at a much lower rate in an unsaturated groundwater condition as compared to a 100% groundwater saturation condition described earlier. Permeation rate in unsaturated groundwater condition changes as groundwater and BTEX contamination level changes due to sorption in soil particles and volatilization. Ong et al. (2008) propose permeation rates for Toluene and Xylene under an unsaturated groundwater condition as shown in Equations 7 and 9. Tests were conducted to add bulk concentrations(C_{bulk}) of dissolved BTEX in dry soil. Ong et al. (2008) did not provide permeation rates for Benzene and Ethylbenzene because of insignificantly low permeation level. Although Benzene and Ethylbenzene permeation are negligible, Benzene and Ethylbenzene may be estimated at approximately 10% of Toluene permeation rate for design convenience. This is same approach used for Ethylbenzene and Xylene in 100% groundwater saturated condition.

$$\text{Benzene: } Pm (\mu\text{g}/\text{cm}^2/\text{day}) = 0.00002 * C_{bulk}^{1.6054}, \text{ where } C_{bulk} = \text{mg}/\text{kg} \text{ in dry soil} \text{----- (6)}$$

$$\text{Toluene: } Pm (\mu\text{g}/\text{cm}^2/\text{day}) = 0.0002 * C_{bulk}^{1.6054}, \text{ where } C_{bulk} = \text{mg}/\text{kg} \text{ in dry soil} \text{----- (7)}$$

$$\text{Ethylbenzene: } Pm (\mu\text{g}/\text{cm}^2/\text{day}) = 0.00002 * C_{bulk}^{1.6054}, \text{ where } C_{bulk} = \text{mg}/\text{kg} \text{ in dry soil} \text{----- (8)}$$

$$\text{Xylene (total): } Pm (\mu\text{g}/\text{cm}^2/\text{day}) = 0.000003 * C_{bulk}^{2.2594}, \text{ where } C_{bulk} = \text{mg}/\text{kg} \text{ in dry soil} \text{----- (9)}$$

*Note: Unit for C_{bulk} is mg/kg for unsaturated conditions.

Bulk concentrations of contaminants (C_{bulk}) are expressed in two different units for saturated and unsaturated groundwater conditions. Saturated groundwater condition assumes that HDPE pipe is submerged in aqueous gasoline dissolved solutions. C_{bulk} is expressed in terms of *mg per liter* (*mg/L*). Unsaturated pore water conditions, assumes that HDPE pipe, is surrounded by contaminated soil. Thus, C_{bulk} is expressed in mg per kilogram in dry soil. It is critical to consider the groundwater table in order to determine which bulk concentration of contaminant and permeation rate should be used. The summary of permeation rates is presented in Table 6.

Table 6. Permeation Rates in Saturated and Unsaturated Ground Conditions

Contaminant	Saturated Groundwater Zone		Unsaturated Groundwater Zone	
	Equation	Unit	Equation	Unit
Benzene ($\mu\text{g}/\text{cm}^2/\text{day}$)	$0.0079 * C_{\text{bulk}}^{1.1323}$	$C_{\text{bulk}} = \text{mg/L}$	$0.00002 * C_{\text{bulk}}^{1.6054}$	$C_{\text{bulk}} = \text{mg/kg}$
Toluene ($\mu\text{g}/\text{cm}^2/\text{day}$)	$0.0087 * C_{\text{bulk}}^{1.1444}$	$C_{\text{bulk}} = \text{mg/L}$	$0.0002 * C_{\text{bulk}}^{1.6054}$	$C_{\text{bulk}} = \text{mg/kg}$
Ethylbenzene ($\mu\text{g}/\text{cm}^2/\text{day}$)	$0.00079 * C_{\text{bulk}}^{1.1323}$	$C_{\text{bulk}} = \text{mg/L}$	$0.00002 * C_{\text{bulk}}^{1.6054}$	$C_{\text{bulk}} = \text{mg/kg}$
Xylenes (total) ($\mu\text{g}/\text{cm}^2/\text{day}$)	$0.00079 * C_{\text{bulk}}^{1.1323}$	$C_{\text{bulk}} = \text{mg/L}$	$0.000003 * C_{\text{bulk}}^{2.2594}$	$C_{\text{bulk}} = \text{mg/kg}$

* Data: Ong et al. (2008).

5.3 Condition Variables – Stagnation Effect in Contaminated Ground

The water distribution system, are normally categorized in two types of pipeline network. One type is a gridiron network and another type is a dead-end network (Nathanson 2008). In case of a dead-end network, the water may stagnate much longer than a gridiron network system because of poor water circulation at the dead-end. Another location of possible stagnation happens at the service line, connecting the water main to the water meter, in the case the water is not used by a

service customer for a significant period. The stagnation effect in the pipe degrades pipe-water quality as exposure time and the area increases in BTEX contamination.

Equation 10 predicts the concentration of BTEX in the pipe as a function of C_{bulk} to account for the different BTEX permeation rates after a period of stagnation in BTEX contamination. This equation uses a stagnation factor as shown in Equation 11. Ong et al. (2008) presented this equation for the 100% groundwater saturated zone in the AWWA RF report. This equation can be applied in an unsaturated groundwater condition as well because the stagnation factor is simply a function of the exposed length and time in total length. Stagnation factor shall not be used for zero stagnation time ($t=0$) because the zero time in Equation 11 yields the value of the concentration of contaminant into zero. Zero stagnation time indicates that the water flows in the pipe and is diluted by amount of water carried in the pipe as described in the next section. Stagnation effect and internal water flow effect discussed in the next section should not be simultaneously included in a permeation calculation because stagnation and water flow cannot coexist in a same pipe section during the same period. In other words, the calculation users are only allowed to use either the stagnation effect or the internal water flow effect during a permeation calculation. Therefore, long-term permeation estimation may require multiple and cumulative calculations to consider several different flow conditions.

$$C_{pw_Stagnation} = \frac{M}{V} = \frac{P_m \times \pi \times OD \times L_c \times t}{\frac{1}{4} \times \pi \times ID^2 \times L_T} = \frac{4 \times f(C_{bulk}) \times OD \times L_c \times t}{ID^2 \times L_T} = C_{pw} \times StagnationFactor \text{-----} (10)$$

$$Stagnation\ Factor = \frac{L_c \times t}{L_T} \text{-----} (11)$$

Where:

$C_{pw_Stagnation}$ = concentration of containment in pipe-water after a period of stagnation ($\mu\text{g}/\text{cm}^3$),

M = total mass of permeated contaminant (μg),

V = volume of water in the pipe (cm^3),

P_m = steady permeation rate of the contaminant ($\mu\text{g}/\text{cm}^2/\text{day}$); P_m is shown as a function of C_{bulk} or $f(C_{\text{bulk}})$ to account for permeation rate for different BTEX

t = period of stagnation (days),

L_c = length of contaminated pipe (cm),

L_T = total length of pipe (cm),

ID = inside diameter of pipe (cm), and

OD = outside diameter of pipe (cm).

5.4 Condition Variables – Internal Water Flow Effect in Contaminated Ground

The water flow rate in the pipe affects the concentration of contaminants. The flow velocity is a variable factor to estimate the amount of BTEX residuals in a given time and length. The flow velocity fluctuates by the water consumption and the pressure throughout a water distribution system. The flow velocity in the water pipe directly increases as the water pressure increases to meet higher water demands through same size of pipe. The peak hourly demand is the highest point of water consumption per day, thus the concentration of contaminants changes by hourly demand of water supply. According to AWWA RF manual (2000), the minimum unidirectional flow velocity to remove biofilm and loose deposits is 5 ft/sec and a velocity of 12 ft/sec to remove sand from siphons. Jana Lab (2012) published a survey that documented a 6.7 ft/sec for average maximum design normal flow and 11.6 ft/sec for average maximum design fire flow. Thus, flow velocity 5 ft/sec is chosen as a normal flow value for the permeation estimation calculations.

To take into account the flow velocity effect uniformly in pipe-water contamination, flow velocity is, assumed to be, steady during period (t) in Equation 12. The Equation 12 is derived

from integration of Equation 13 into Equation 1. The unit of flow velocity is *cm/day*. Flow velocity is usually expressed in terms of meter per second or feet per second. A conversion factor is used as multiplying conversion factor (2,633,472) in *ft/s* to get *cm/day*, for example, 3 – 5 *ft/s* is equal to 7,900,416 – 13,167,360 *cm/day*. Flow factor (Equation 13) and stagnation factor (Equation 11) should be used in entirely separated calculation process as shown in Figure 2.

$$C_{pw_Flow} = \frac{M}{V} = \frac{P_m \times \pi \times OD \times L_c \times t}{q \times t} = \frac{4 \times f(C_{bulk}) \times OD \times L_c}{ID^2 \times v} = C_{pw} \times FlowFactor \quad \text{----- (12)}$$

$$Flow\ Factor = \frac{L_c}{v} \text{----- (13)}$$

Where:

C_{pw_Flow} = concentration of containment in pipe-water at a flow rate ($\mu\text{g}/\text{cm}^3$),

M = total mass of permeated contaminant (μg),

V = volume of water in the pipe (cm^3),

P_m = steady permeation rate of the contaminant ($\mu\text{g}/\text{cm}^2/\text{day}$),

t = period of stagnation (days),

L_c = length of contaminated pipe (cm),

OD = outside diameter of pipe (cm),

q = water flow rate (cm^3/day), and

v = average water flow velocity (cm/day).

5.5 Condition Variables – PE Pipe Thickness Effect in Contaminated Ground

The permeation rates are the results of empirical tests using 1” IPS, SDR 9, standard size HDPE pipe for a water distribution system. Small size pipes are more vulnerable to permeation than larger size pipes. Table 7 shows pipe wall thickness correction factors from the AWWA RF report (Ong et al. 2008). 1” IPS SDR 9 pipe has a correction factor as one,

which is a baseline for other thickness correction factors. The minimum wall thickness of 1-inch IPS SDR9 HDPE pipe is 0.146” and is relatively thinner than most Ductile Iron Pipe (DIP) sizing HDPE pipes used for water distribution systems. For instance, an 8” DIPS DR17 HDPE pipe has a minimum wall thickness of 0.532”.

HDPE pipe used for water supply (transmission) mains are larger and thicker than most distribution mains or service connection lines. Large diameter HDPE pipe with several inches of wall thickness (low DR) is commonly used for water supply systems such as a 24” DIPS DR11 HDPE pipe has a minimum wall thickness of 2.345”. This wall thickness allows only 5 percent of the permeation of a 1” IPS DR9 pipe as indicated in Table 7. Equation 14 is utilized to apply the thickness factor for the permeation estimation. Figure 3 shows a regression model based on various pipe wall thickness and correction factors plotted against Ong’s data. Thickness correction factor in Equation (15) is derived from the regression model in Figure 3.

$$C_{pw_Thickness} = \frac{M}{V} = \gamma \times \frac{4 \times f(C_{bulk}) \times OD}{ID^2} \text{-----} (14)$$

$$Thickness\ Correction\ Factor\ (dimentionless) = \gamma = 0.1219 \times t^{-1.001} \text{-----} (15)$$

Where:

γ = thickness correction factor (dimensionless), and

t_p = pipe thickness (inch)

Table 7. Pipe Wall Thickness Correction Factor (γ)

HDPE Pipe Wall Thickness (inch)	Correction Factor (dimensionless)
0.069	1.769
0.097	1.258
0.122	1.000
0.123	0.992
0.154	0.793
0.155	0.787
0.202	0.604
0.235	0.519
0.238	0.513
0.307	0.401
0.598	0.204
0.861	0.142
1.128	0.108
1.384	0.088
1.645	0.074
1.908	0.064
2.171	0.056
2.432	0.050
2.695	0.045
3.218	0.038

* Data: Ong et al. (2008)

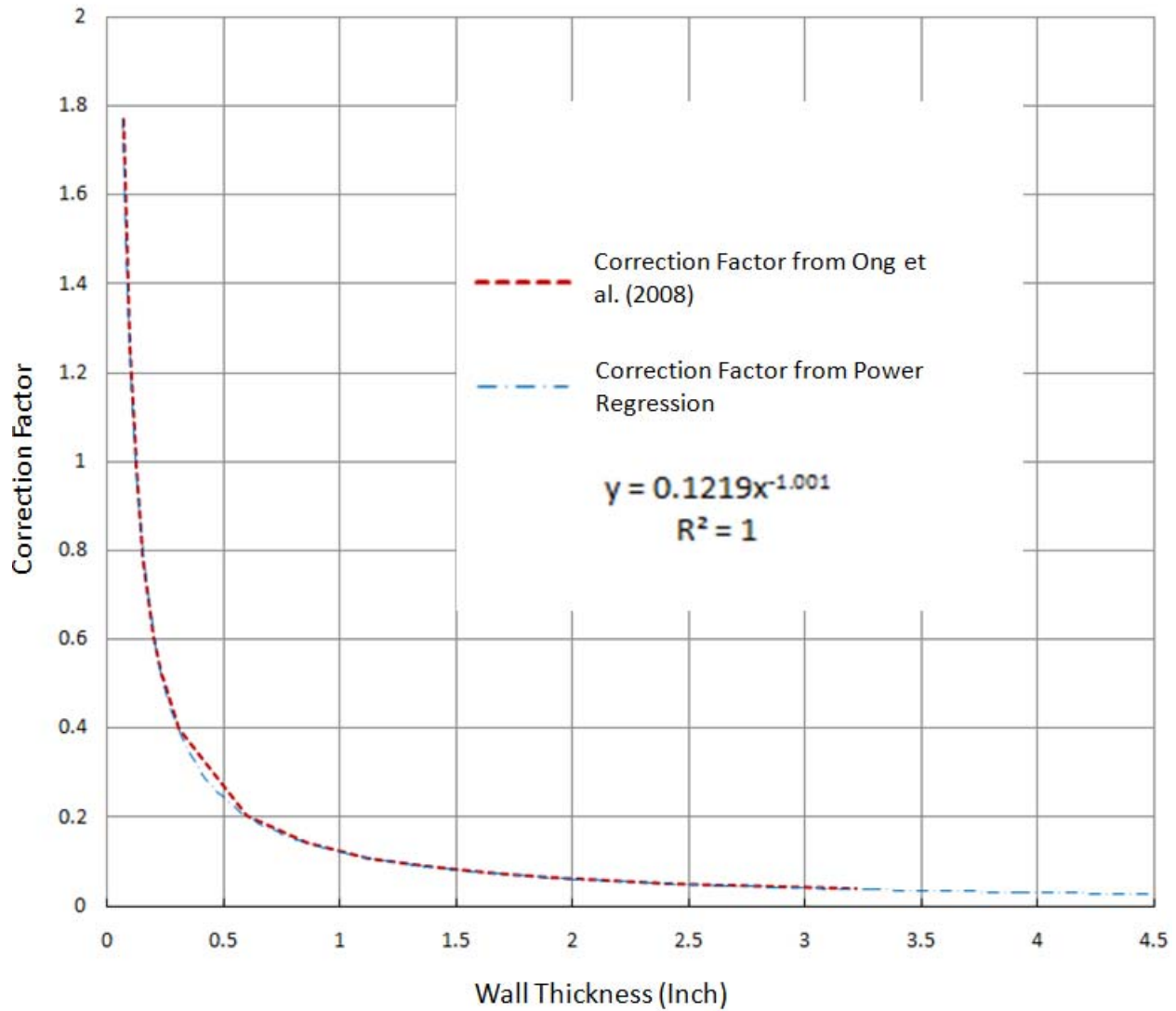


Figure 3. Regression Model for Permeation Correction Factor by Thickness of PE Pipe

5.6 Condition Variables –Different Ground Temperatures

Diffusion coefficients tend to increase as temperature increases. All tests shown in the AWWA RF report were conducted at ambient room temperature at approximately 23 °C (73.4 °F) (Ong et al. 2008). The ground temperature depends on many factors including soil properties such as thermal conductivity, degree of groundwater saturation, presence of a geothermal source, and the

atmosphere temperature. Water distribution pipes are buried under minimum required cover depth regulated by design standards. Although ground temperature tends to be more stable than atmosphere temperature, it still affects permeation rates. according to a water temperature survey in the United States, average temperature of water in water distribution systems is approximately 14 °C (57 °F) and average temperatures range is between 3°C (39 °F) and 29 °C (84 °F) (Jana Lab 2010). There is no reference data regarding BTEX permeation rate changes versus the ground temperature changes. However, it is obvious that the magnitude of permeation may be over estimated if the ground temperature is lower than the baseline temperature at 23 °C. Joo et al. (2004) recommended that the effects of temperature on diffusion coefficients should be considered for practical applications.

USEPA (2011) provides a web tool for site assessment using the Hayduk and Laudie (HL) method for estimating the diffusivity of BTEX in water as shown in Equation (16).

$$D_{BW} = \frac{13.26 \times 10^{-5}}{n_w^{1.14} \times V_B^{0.589}} \text{----- (16)}$$

Where:

D_{BW} = the diffusion coefficient of compound B in water (cm²/s),

n_w = the temperature corrected viscosity of water, and

V_B = the LaBas molar volume increments.

Diffusion coefficients upon various temperatures as shown in Table 8 are acquired from the USEPA web tool and use 5°C incremental ranging from 5°C to 30°C. The results of diffusion coefficients consistently and gradually increase as temperature increases. Fick's first law for mass flux of organic compounds gives the proportionality between diffusion coefficients and

concentration of contaminants. The permeation rate is empirically correlated to the diffusion coefficient. Therefore, the permeation rate may drop nearly 25% at 15 °C as compared to ambient temperature baseline at 25°C. The calculation process in section 6 applies temperature factors from BTEX linear regression models in Figures 4, 5, 6, and 7. The regression model is based on the Table 8 data and indicates the percentage change of the diffusion coefficients from the baseline temperature of 25°C.

Table 8. Diffusion Coefficient per Temperature Change in Water

Benzene		
°C	Estimated Diffusion Coefficient in Water (cm ² /sec)	Change of Diffusion Coefficient in Percent (25°C Diffusion Coefficient is used as a baseline value)
5	0.00000560	-46 %
10	0.00000560	-46 %
15	0.00000777	-25 %
20	0.00000899	-13 %
25	0.00001030	0 %
30	0.00001170	14 %
Ethylbenzene		
5	0.00000447	-46 %
10	0.00000531	-35 %
15	0.00000621	-25 %
20	0.00000719	-13 %
25	0.00000823	0 %
30	0.00000933	13 %
Toluene		
5	0.00000495	-46 %
10	0.00000588	-35 %
15	0.00000688	-24 %
20	0.00000796	-13 %
25	0.00000910	0 %
30	0.00001030	13 %
Xylene (o, p, m- Xylene)		
5	0.00000447	-46 %
10	0.00000531	-35 %
15	0.00000621	-25 %
20	0.00000719	-13 %
25	0.00000823	0 %
30	0.00000933	13 %

Benzene

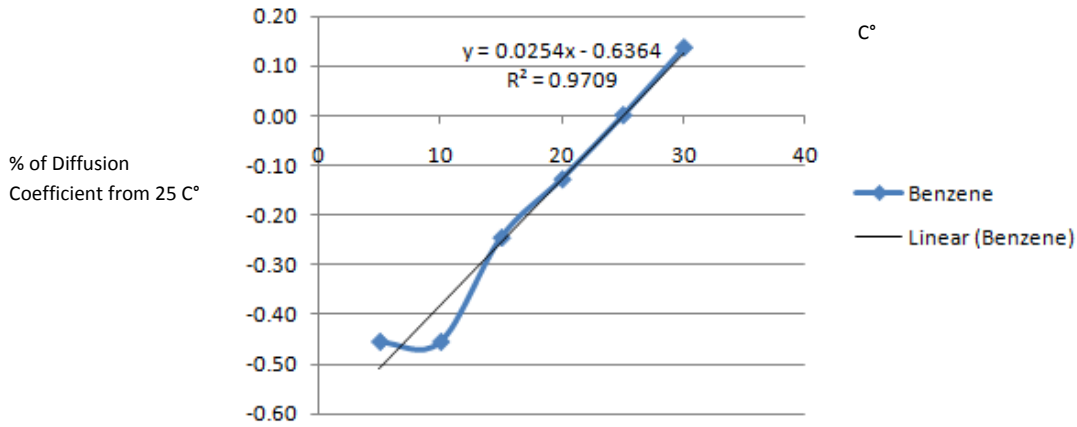


Figure 4. Linear Regression for Benzene Diffusion Coefficient vs. Temperature

Toluene

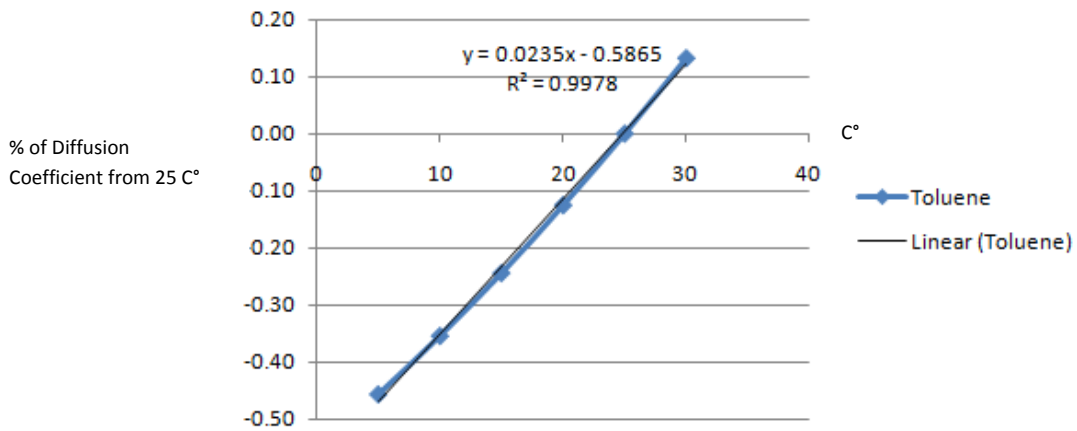


Figure 5. Linear Regression for Toluene Diffusion Coefficient vs. Temperature

Ethylbenzene

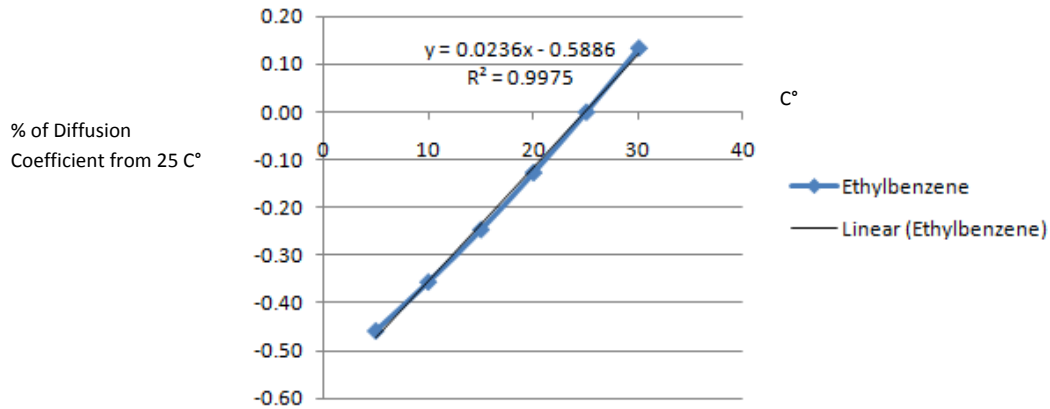


Figure 6. Linear Regression for Ethylbenzene Diffusion Coefficient vs. Temperature

Xylene (o, p, m- Xylene)

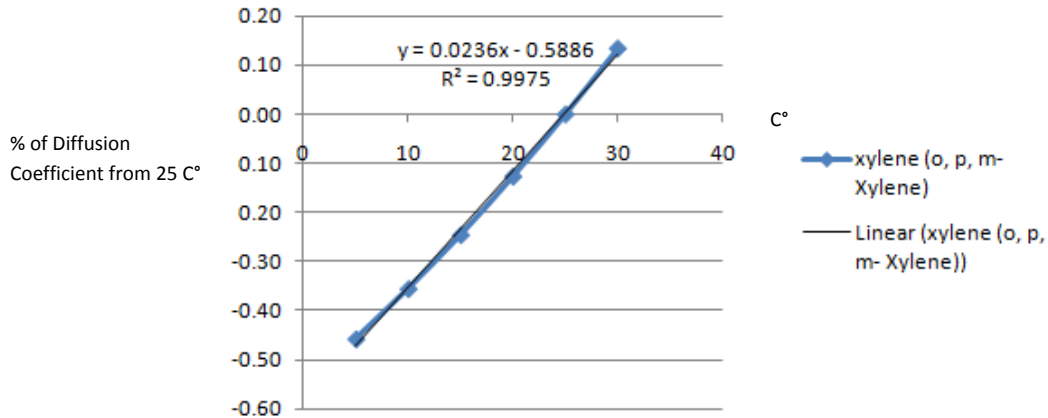


Figure 7. Linear Regression for Xylene (total) Diffusion Coefficient vs. Temperature

5.7 Condition Variables – Ground Soil Type

As shown in the AWWA RF report, BTEX is dissipating quickly through the soil particles. Organic soil and fine soil particles show a higher sorption rate and a significant amount of the BTEX rapidly volatilizes into the air after spillage. Understanding soil properties such as the

coefficient of permeability, also known as the hydraulic conductivity, are very important to estimate the BTEX transport through groundwater in underground soil structures. The typical value of the permeability coefficient of clean gravel is a million times larger than that of typical clay (Das 1985). The groundwater permeability concept is based on 100% groundwater saturation through porous soil media. (The void space between soil particles is completely filled with groundwater.) The permeation rates shown in Equations 2, 3, 4 and 5 are obtained from 100% saturated groundwater condition.

The permeation rates in unsaturated groundwater zone are significantly affected by soil type. Various soil types in BTEX contaminated sites will have significantly different degrees of sorption and capillary force. Ong et al (2008) used only three soil types; 1) silica sand, 2) sand-top soil mixture, and 3) organic top soil. Civil engineering practice uses standard soil classification systems in accordance with ASTM and AASHTO. BTEX permeation rates shall be tested in accordance with standard soil classification systems such as the unified soil classification system to be used as reference data for all other types of soils. The AWWA RF report shows approximately four (4) times the cumulative mass of total BTEX permeation between silica sand and organic top soil. The organic content of the silica sand was 0 percent while the organic top soil had an organic content of 5 percent. An HDPE pipe buried in soil high in organic matter may have a significantly lower permeation rate. The soil type factor is added in the permeation estimation calculation in section 6. The author recommends using the soil factors less than 1 when soil contains organic matter and fine particles.

6.0 BTEX PERMEATION CALCULATION

Figure 2 is a flow chart for the calculation of BTEX permeation through HDPE pipe. There are two decision (branching) points in the flow chart: (1) Is the ground water level above the pipe? (2) Is water flowing in the pipe? Thus, four possible BTEX permeation scenarios can occur as follows:

1. Pipe below the groundwater level, referred to as the groundwater saturated case, and water flowing inside the pipe → see results in Table 10
2. Pipe above the groundwater level in dry, unsaturated soil, referred to as the groundwater unsaturated case, and water flowing inside the pipe → see results in Table 11
3. Pipe below the groundwater level and water stagnate inside the pipe → see results in Table 12
4. Pipe above the groundwater level and water stagnate inside the pipe → see results in Table 13

An example calculation is given below for each of the four permeation scenarios. Table 9 shows the input parameters used for the four examples. The bulk concentrations for BTEX organic contaminants are randomly selected to be 50% aqueous BTEX solution, which is equal to 50 percent bulk concentration, dissolved in the saturated groundwater. Other input parameters such as 100 percent bulk concentration can be simulated using the same permeation estimation methodology shown in Figures 8 and 9. The BTEX concentration in dry soil is based on the residential surface soil regulatory guidance values (RGVs). State environmental agencies in the

United States have different contamination level thresholds that require regulatory action. Jennings (2009) conducted statistical analysis for BTEX RGVs data. Fifty (50) percent probability values are used for concentration level in Table 9.

Other input values for the calculation include stagnation period (Tables 11 and 13), flow velocity (Tables 10 and 12), length of contaminated pipe and total length of pipe, and pipe dimension, as shown in Table 9. Tables 10, 11, 12, and 13 present permeation calculation results. Appendices 1, 2, 3 and 4 show the step-by-step procedures of the four categorized permeation calculations. The result cell indicates one of four categories depending on estimated BTEX permeation in pipe-water. Four categories in the result cell are:

- 1) ***“Negligible Contamination”***: permeated BTEX contamination is less than 20 percent.
- 2) ***“Allowable”***: permeated BTEX contamination ranges between 20 percent and 100 percent MCLs.
- 3) ***“Consider other options”***: permeated BTEX contamination exceeds 100 percent MCLs.
- 4) ***“Invalid Calculation _ Use other parameters”***: consider other input parameters.

Table 9. Input Parameters for BTEX Permeation Calculations

Input Parameters	Groundwater Saturated Soil and BTEX 50% Saturated Solution(see results in Table 10 and 11)		Groundwater Unsaturated Soil	
	Benzene	31.2 ^a	C _{bulk} = mg/L	1.0 ^c
Toluene	26.3 ^a	C _{bulk} = mg/L	100.0 ^c	C _{bulk} = mg/kg
Ethylbenzene	3.2 ^b	C _{bulk} = mg/L	100.0 ^c	C _{bulk} = mg/kg
Xylenes (total)	3.2 ^b	C _{bulk} = mg/L	200.0 ^c	C _{bulk} = mg/kg
Stagnation	1 day (24 hours)		1 day (24 hours)	
Flow Velocity	1.524 m/s (5ft/s)		1.524 m/s (5ft/s)	
Length of contaminated pipe (L _C)	100 ft		100 ft	
Total length of pipe (L _T)	1,000ft		1,000 ft	
Ground Temperature	15 °C (59 °F)		15 °C (59 °F)	
Soil Factor	0.9		0.9	
HDPE Pipe Size	16 inch, DIPS, 200 psi, DR 9, (1.933” Thickness)		16 inch, DIPS, 200 psi, DR 9, (1.933” Thickness)	

Note: ^a Data from Table 1,

^bEstimated as 50% of others (mixture of Ethylbenzene and Total Xylenes) in Table 1,

^c50% probability value from Jennings (2009)

Table 10. BTEX Permeation Calculation Results Scenario 1 –Groundwater Saturated and Pipe-water Flows

Estimated BTEX Concentration	Maximum Contaminants Levels (MCLs) and Other Categories	BTEX Permeation in Pipe Water (mg/L) (Scientific Expression on Right)	Result for Saturated Groundwater Condition *Assumption for Results: Negligible contamination is assumed to be less than 20% of MCLs.
MCLs cited from National Primary Drinking Water Regulations (EPA 2009)	Benzene MCLs: 0.005mg/L (Allowable Contamination Range: 0.001 - 0.005 mg/L) (Negligible Contamination: less than 0.001 mg/L) (Consider Other Options: Exceeding MCLs)	7.71E-06	Negligible Contamination
	Toluene MCLs: 1.0 mg/L (Allowable Contamination Range: 0.2 - 1.0 mg/L) (Negligible Contamination: less than 0.2 mg/L) (Consider Other Options: Exceeding MCLs)	7.28E-06	Negligible Contamination
	Ethylbenzene MCLs: 0.7 mg/L (Allowable Contamination Range: 0.14 - 0.7 mg/L) (Negligible Contamination: less than 0.14 mg/L) (Consider Other Options: Exceeding MCLs)	5.85E-08	Negligible Contamination
	Xylene MCLs: 10.0 mg/L (Allowable Contamination Range: 2.0 - 10.0 mg/L) (Negligible Contamination: less than 2.0 mg/L) (Consider Other Options: Exceeding MCLs)	5.85E-08	Negligible Contamination

Table 11. BTEX Permeation Calculation Results Scenario 2 –Groundwater Saturated and Pipe-water Stagnates

Estimated BTEX Concentration	Maximum Contaminants Levels (MCLs) and Other Categories	BTEX Permeation in Pipe Water (mg/L) (Scientific Expression on Right)	Result for Saturated Groundwater Condition *Assumption for Results: Negligible contamination is assumed to be less than 20% of MCLs.
MCLs cited from National Primary Drinking Water Regulations (EPA 2009)	Benzene MCLs: 0.005mg/L (Allowable Contamination Range: 0.001 - 0.005 mg/L) (Negligible Contamination: less than 0.001 mg/L) (Consider Other Options: Exceeding MCLs)	3.33E-03	Allowable
	Toluene MCLs: 1.0 mg/L (Allowable Contamination Range: 0.2 - 1.0 mg/L) (Negligible Contamination: less than 0.2 mg/L) (Consider Other Options: Exceeding MCLs)	3.15E-03	Negligible Contamination
	Ethylbenzene MCLs: 0.7 mg/L (Allowable Contamination Range: 0.14 - 0.7 mg/L) (Negligible Contamination: less than 0.14 mg/L) (Consider Other Options: Exceeding MCLs)	2.53E-05	Negligible Contamination
	Xylene MCLs: 10.0 mg/L (Allowable Contamination Range: 2.0 - 10.0 mg/L) (Negligible Contamination: less than 2.0 mg/L) (Consider Other Options: Exceeding MCLs)	2.53E-05	Negligible Contamination

Table 12. BTEX Permeation Calculation Results Scenario 3 –Groundwater Unsaturated and Pipe-water Flows

Estimated BTEX Concentration	Maximum Contaminants Levels (MCLs) and Other Categories	BTEX Permeation in Pipe Water (mg/L) (Scientific Expression on Right)	Result for Saturated Groundwater Condition *Assumption for Results: Negligible contamination is assumed to be less than 20% of MCLs.
MCLs cited from National Primary Drinking Water Regulations (EPA 2009)	Benzene MCLs: 0.005mg/L (Allowable Contamination Range: 0.001 - 0.005 mg/L) (Negligible Contamination: less than 0.001 mg/L) (Consider Other Options: Exceeding MCLs)	3.97E-10	Negligible Contamination
	Toluene MCLs: 1.0 mg/L (Allowable Contamination Range: 0.2 - 1.0 mg/L) (Negligible Contamination: less than 0.2 mg/L) (Consider Other Options: Exceeding MCLs)	6.63E-06	Negligible Contamination
	Ethylbenzene MCLs: 0.7 mg/L (Allowable Contamination Range: 0.14 - 0.7 mg/L) (Negligible Contamination: less than 0.14 mg/L) (Consider Other Options: Exceeding MCLs)	6.65E-07	Negligible Contamination
	Xylene MCLs: 10.0 mg/L (Allowable Contamination Range: 2.0 - 10.0 mg/L) (Negligible Contamination: less than 2.0 mg/L) (Consider Other Options: Exceeding MCLs)	9.67E-06	Negligible Contamination

Table 13. BTEX Permeation Calculation Results Scenario 4 –Groundwater Unsaturated and Pipe-water Stagnates

Estimated BTEX Concentration	Maximum Contaminants Levels (MCLs) and Other Categories	BTEX Permeation in Pipe Water (mg/L) (Scientific Expression on Right)	Result for Saturated Groundwater Condition *Assumption for Results: Negligible contamination is assumed to be less than 20% of MCLs.
MCLs cited from National Primary Drinking Water Regulations (EPA 2009)	Benzene MCLs: 0.005mg/L (Allowable Contamination Range: 0.001 - 0.005 mg/L) (Negligible Contamination: less than 0.001 mg/L) (Consider Other Options: Exceeding MCLs)	1.71E-07	Allowable
	Toluene MCLs: 1.0 mg/L (Allowable Contamination Range: 0.2 - 1.0 mg/L) (Negligible Contamination: less than 0.2 mg/L) (Consider Other Options: Exceeding MCLs)	2.86E-03	Negligible Contamination
	Ethylbenzene MCLs: 0.7 mg/L (Allowable Contamination Range: 0.14 - 0.7 mg/L) (Negligible Contamination: less than 0.14 mg/L) (Consider Other Options: Exceeding MCLs)	2.87E-04	Negligible Contamination
	Xylene MCLs: 10.0 mg/L (Allowable Contamination Range: 2.0 - 10.0 mg/L) (Negligible Contamination: less than 2.0 mg/L) (Consider Other Options: Exceeding MCLs)	4.18E-03	Negligible Contamination

7.0 FUTURE RESEARCH

A BTEX permeation calculation methodology for water industry’s use is presented in this report. Further research and testing may require simulating real field environments. The small-scale experiments using a glass jar and 1” HDPE pipe shown in the AWWA RF report may not adequately demonstrate a real field full-scale permeation process. A real-field test for permeation rates in a 6 inch or 8 inch distribution pipe would be helpful. Another theoretical approach using conventional geotechnical concept may strengthen the concept based on Fick’s law. Geotechnical consideration may include, but not limited to, groundwater migration, permeability of soil, pore-water pressure, and backfill conditions in trench. Design consideration may include type of water pipeline, for example, transmission main, distribution main, and service connection. Several design manuals approve only metallic pipe materials as non-permeable pipe materials in the organic contaminated site including BTEX contamination (Indy Water 2009, Hartlepool

Water 2011, and WRAS 2002). However, specific guidance regarding the contamination threshold and magnitude, and effective boundary is not addressed in water design manuals. Research for engineering methodology to determine the boundary limits of the contaminated site and BTEX permeation field-testing data collection will improve the existing permeation calculation methodology presented in this report.

8.0 CONCLUSIONS

This report presents an engineering methodology for calculating the BTEX permeation through HDPE water pipe. The report also includes various aspects of BTEX transport mechanisms, health effects and regulations, and properties of BTEX associated with permeation process. The AWWA RF report proposes a BTEX permeation methodology based on several lab experiments. Although this report works mostly within the existing permeation calculation methodology in the AWWA RF report, it reinforces various engineering variables and aspects to incorporate into the BTEX permeation calculation methodology so this proposed calculation can be used in engineering practice.

This report also shows that conclusions drawn about permeation through 1" HDPE pipe in the AWWA RF report may be overly conservative for larger diameter HDPE pipes because of the significance of pipe wall thickness in reducing permeation. For instance, 24"DIPS DR11 pipe has a minimum wall thickness of 2.345". The permeation rate through this wall is about one-twentieth of that of the 1" test pipe. The dilution by water flow in HDPE pipes can be considered due to significant BTEX contamination reduction.

The BTEX permeation calculation methodology is demonstrated using plausible input parameters to simulate the calculation process through four examples in Figures 8, 9, 10, and 11

using six variables. Units in the examples are converted into common engineering expressions in order to avoid any unit-conversion mistake. The calculation provides numerical and verbal expression results. Verbal expression helps the user understand magnitude of permeation estimation in the pipe-water. The BTEX permeation methodology is fully expanded throughout the report to develop a computerized BTEX permeation calculator. The example calculations show that the presence of BTEX contamination in soil along an HDPE water pipe does not necessarily mean that the drinking water in the pipe will exceed regulatory limits. This report may assist engineers and others when they need to make an engineering decision for water pipe material selection.

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Appendix 1. BTEX Permeation Calculation Example 1 –Groundwater Saturated and Pipe-water Flows

INPUT Parameters (Groundwater Saturated + Pipe water Flows)					
C _{bulk, water}	: Bulk concentration of contaminant in the soil pore water	=	INPUT VALUE	UNIT	REMARKS
Benzene	Dissolved Benzene Concentration in Ground Water	=	31.2	mg/L	Soil around pipe is 100% saturated with groundwater.
Toluene	Dissolved Toluene Concentration in Ground Water	=	26.3	mg/L	
Ethylbenzene	Dissolved Ethylbenzene Concentration in Ground Water	=	3.2	mg/L	
Xylene (total)	Dissolved Xylene (total) Concentration in Ground Water	=	3.2	mg/L	
L _c	: Length of contaminated pipe	=	100	ft	Length of pipe directly exposed to BTEX
L _T	: Total Length of the pipe	=	1000	ft	Total length in a single water main pipeline within a pressure zone.
v	: Average water flow velocity (No stagnation in Pipe-water)	=	5.00	ft/sec	Consult your local water utility company to get average flow velocity.
L _{tc}	: Wall Thickness of HDPE water pipe	=	1.933	inch	Use PPI sizing table.
T	: Ground Temperature	=	59	°F	Average ground temperature is 59°F (15°C)
S	: Soil Type Factor	=	0.9	Dimensionless	Higher content % of organic Soil attenuates contamination (value recommends b/w 0.7-1.0 (pure sand))

BTEX Contaminant Concentration Estimation in Groundwater Saturated Soil				
Steady State Permeation Equation	$C_{pw} = \frac{M}{V} = \frac{P_m \times \pi \times OD}{\frac{1}{4} \times \pi \times ID^2}$		This steady state permeation calculation is a baseline value from 1 inch SDR 9 IPS HDPE pipe.	
P _m	: Steady permeation rate of the contaminant	=		
Benzene	P _m = 0.0079 C _{bulk} ^{1.1323}	=	0.3886	µg/cm ² /day
Toluene	P _m = 0.0087 C _{bulk} ^{1.1444}	=	0.3669	µg/cm ² /day
Ethylbenzene	Insignificant concentration in water pipe (P _m is assumed)	=	0.0029	µg/cm ² /day Assumption: 10% of Benzene P_m
Xylene (total)	Insignificant concentration in water pipe (P _m is assumed)	=	0.0029	µg/cm ² /day Assumption: 10% of Benzene P_m
C _{bulk}	: Bulk concentration of contaminant in the soil pore water	=		INPUT
Benzene	Dissolved Benzene Concentration in Ground Water	=	31.2	mg/L = (ppm) 31200 µg/L
Toluene	Dissolved Toluene Concentration in Ground Water	=	26.3	mg/L = (ppm) 26300 µg/L
Ethylbenzene	Dissolved Ethylbenzene Concentration in Ground Water	=	3.2	mg/L = (ppm) 3200 µg/L
Xylene (total)	Dissolved Xylene (total) Concentration in Ground Water	=	3.2	mg/L = (ppm) 3200 µg/L
C _{pw}	: Concentration of Contaminant in Pipe-Water Estimation	=		
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.7888	µg/cm ³ /Day
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.7448	µg/cm ³ /Day
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.0060	µg/cm ³ /Day
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.0060	µg/cm ³ /Day

Applying Flow Velocity in Pipe Effect				
	$Flow\ Factor = \frac{L_c}{v}$		0.000231	Dimensionless (no unit)
v	: Average water flow velocity	=	13170732	cm/day 5.00 ft/sec
L _c	: Length of contaminated pipe (see #2 for L _c)	=	3048	cm 100 foot
C _{pw}	: Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect	=		
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.0001825	µg/cm ³ 0.18255 ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.0001724	µg/cm ³ 0.17236 ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.0000014	µg/cm ³ 0.00139 ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.0000014	µg/cm ³ 0.00139 ppb

Applying Pipe Wall Thickness Effect				
	$Thickness\ Factor = 0.1219 \cdot L_{tc}^{-1.001}$		0.0630210	Dimensionless (no unit)
L _{tc}	: Wall Thickness of contaminated pipe	=	1.933	Inch
C _{pw}	: Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect	=		
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.0000115	µg/cm ³ 0.01150 ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.0000109	µg/cm ³ 0.01086 ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.0000001	µg/cm ³ 0.00009 ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.0000001	µg/cm ³ 0.00009 ppb

Applying Ground Temperature Effect	Temperature Factor at approximately 25°C as a baseline is 1.0	It is assumed that diffusion coefficient is directly proportional to permeation.	INPUT
	Benzene Temperature Factor = $1 + (0.0254 T - 0.6364)$	0.7446 Dimensionless (no unit)	15 °C
	Ethylbenzene Temperature Factor = $1 + (0.0236 T - 0.5886)$	0.7654 Dimensionless (no unit)	15 °C
	Toluene Temperature Factor = $1 + (0.0235 T - 0.5865)$	0.7675 Dimensionless (no unit)	15 °C
	Xylene Temperature Factor = $1 + (0.0236 T - 0.5886)$	0.7654 Dimensionless (no unit)	15 °C
C_{pw} : Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect			
Benzene	Dissolved Benzene Concentration in Pipe-Water	= 0.0000086 µg/cm ³	0.00857 ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	= 0.0000081 µg/cm ³	0.00809 ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	= 0.0000001 µg/cm ³	0.00007 ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	= 0.0000001 µg/cm ³	0.00007 ppb

Applying Soil Type Effect	Sorption and biodegradation attenuation in bulk concentration by organic content in soil	0.9 Dimensionless (no unit)	INPUT
			0.9
C_{pw} : Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect			
Benzene	Dissolved Benzene Concentration in Pipe-Water	= 0.00000771 µg/cm ³	0.00771 ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	= 0.00000728 µg/cm ³	0.00728 ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	= 0.00000006 µg/cm ³	0.00006 ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	= 0.00000006 µg/cm ³	0.00006 ppb

Estimated BTEX Concentration	Maximum Contaminants Levels (MCLs) and Other Categories	BTEX Permeation in Pipe Water (mg/L) (Scientific Expression on Right)		Result for Saturated Groundwater Condition *Assumption for Results: Negligible contamination is assumed to be less than 20% of MCLs.
MCLs cited from National Primary Drinking Water Regulations (EPA 2009)	Benzene MCLs: 0.005mg/L (Allowable Contamination Range: 0.001 - 0.005 mg/L) (Negligible Contamination: less than 0.001 mg/L) (Consider Other Options: Exceeding MCLs)	0.00001	7.71E-06	Negligible Contamination
	Toluene MCLs: 1.0 mg/L (Allowable Contamination Range: 0.2 - 1.0 mg/L) (Negligible Contamination: less than 0.2 mg/L) (Consider Other Options: Exceeding MCLs)	0.00001	7.28E-06	Negligible Contamination
	Ethylbenzene MCLs: 0.7 mg/L (Allowable Contamination Range: 0.14 - 0.7 mg/L) (Negligible Contamination: less than 0.14 mg/L) (Consider Other Options: Exceeding MCLs)	0.00000	5.85E-08	Negligible Contamination
	Xylene MCLs: 10.0 mg/L (Allowable Contamination Range: 2.0 - 10.0 mg/L) (Negligible Contamination: less than 2.0 mg/L) (Consider Other Options: Exceeding MCLs)	0.00000	5.85E-08	Negligible Contamination

Appendix 2. BTEX Permeation Calculation Example 2 –Groundwater Saturated and Pipe-water Stagnates

INPUT Parameters (Groundwater Saturated + Pipe water Stagnates)					
C _{bulk, water}	: Bulk concentration of contaminant in the soil pore water	=	INPUT VALUE	UNIT	REMARKS
Benzene	Dissolved Benzene Concentration in Ground Water	=	31.2	mg/L	Soil around pipe is 100% saturated with groundwater.
Toluene	Dissolved Toluene Concentration in Ground Water	=	26.3	mg/L	
Ethylbenzene	Dissolved Ethylbenzene Concentration in Ground Water	=	3.2	mg/L	
Xylene (total)	Dissolved Xylene (total) Concentration in Ground Water	=	3.2	mg/L	
t	: Period of stagnation (No Pipe-water flow)	=	1	days	Length of pipe directly exposed to BTEX
L _c	: Length of contaminated pipe	=	100	ft	Only length of pipe directly located BTEX exposure.
L _T	: Total Length of the pipe	=	1000	ft	Total length in a single water main pipeline within a pressure zone.
L _{tc}	: Wall Thickness of HDPE water pipe	=	1.933	inch	Use PPI sizing table.
T	: Ground Temperature	=	59	°F	Average ground temperature is 59°F (15°C)
S	: Soil Type Factor	=	0.9	Dimensionless	Higher content % of organic Soil attenuates contamination (value recommends b/w 0.7-1.0 (pure sand))

BTEX Contaminant Concentration Estimation in Groundwater Saturated Soil				
Steady State Permeation Equation	$C_{pw} = \frac{M}{V} = \frac{P_m \times \pi \times OD}{\frac{1}{4} \times \pi \times ID^2}$		This steady state permeation calculation is a baseline value from 1 inch SDR 9 IPS HDPE pipe.	
P _m	: Steady permeation rate of the contaminant	=		
Benzene	P _m = 0.0079 C _{bulk} ^{1.1323}	=	0.3886	µg/cm ² /day
Toluene	P _m = 0.0087 C _{bulk} ^{1.1444}	=	0.3669	µg/cm ² /day
Ethylbenzene	Insignificant concentration in water pipe (P _m is assumed)	=	0.0029	µg/cm ² /day Assumption: 10% of Benzene P_m
Xylene (total)	Insignificant concentration in water pipe (P _m is assumed)	=	0.0029	µg/cm ² /day Assumption: 10% of Benzene P_m
C _{bulk}	: Bulk concentration of contaminant in the soil pore water	=		INPUT
Benzene	Dissolved Benzene Concentration in Ground Water	=	31.2 mg/L = (ppm)	31200 µg/L
Toluene	Dissolved Toluene Concentration in Ground Water	=	26.3 mg/L = (ppm)	26300 µg/L
Ethylbenzene	Dissolved Ethylbenzene Concentration in Ground Water	=	3.2 mg/L = (ppm)	3200 µg/L
Xylene (total)	Dissolved Xylene (total) Concentration in Ground Water	=	3.2 mg/L = (ppm)	3200 µg/L
C _{pw}	: Concentration of Contaminant in Pipe-Water Estimation	=		
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.7888	µg/cm ³ /Day
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.7448	µg/cm ³ /Day
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.0060	µg/cm ³ /Day
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.0060	µg/cm ³ /Day

Applying Stagnation Effect				
Stagnation Factor	$\frac{L_c L_c \times t}{v L_T}$		0.1 Dimensionless (no unit)	
t	: Period of stagnation	=	1	days
L _c	: Length of contaminated pipe	=	3048	cm
L _T	: Total Length of the pipe	=	30480	cm
C _{pw}	: Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect	=		
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.07888	µg/cm ³ 78.8801 ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.07448	µg/cm ³ 74.4776 ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.00060	µg/cm ³ 0.5986 ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.00060	µg/cm ³ 0.5986 ppb

Applying Pipe Wall Thickness Effect	Thickness Factor = $0.1219 \cdot L_w^{-1.001}$	0.0630210	Dimensionless (no unit)	INPUT	
	L_w : Wall Thickness of contaminated pipe	=		1.933	Inch
C_{pw}	: Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect				
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.0049711 $\mu\text{g}/\text{cm}^3$	4.97111	ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.0046937 $\mu\text{g}/\text{cm}^3$	4.69366	ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.0000377 $\mu\text{g}/\text{cm}^3$	0.03772	ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.0000377 $\mu\text{g}/\text{cm}^3$	0.03772	ppb

Applying Ground Temperature Effect	Temperature Factor at approximately 25°C as a baseline is 1.0	It is assumed that diffusion coefficient is directly proportional to permeation.		INPUT	
	Benzene Temperature Factor = $1 + (0.0254 T - 0.6364)$	0.7446	Dimensionless (no unit)	15	°C
	Ethylbenzene Temperature Factor = $1 + (0.0236 T - 0.5886)$	0.7654	Dimensionless (no unit)	15	°C
	Toluene Temperature Factor = $1 + (0.0235 T - 0.5865)$	0.7675	Dimensionless (no unit)	15	°C
	Xylene Temperature Factor = $1 + (0.0236 T - 0.5886)$	0.7654	Dimensionless (no unit)	15	°C
C_{pw}	: Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect				
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.0037015 $\mu\text{g}/\text{cm}^3$	3.70149	ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.0034949 $\mu\text{g}/\text{cm}^3$	3.49490	ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.0000281 $\mu\text{g}/\text{cm}^3$	0.02809	ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.0000281 $\mu\text{g}/\text{cm}^3$	0.02809	ppb

Applying Soil Type Effect	Sorption and biodegradation attenuation in bulk concentration by organic content in soil	0.9	Dimensionless (no unit)	INPUT	
				0.9	
C_{pw}	: Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect				
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.00333134 $\mu\text{g}/\text{cm}^3$	3.33134	ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.00314541 $\mu\text{g}/\text{cm}^3$	3.14541	ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.00002528 $\mu\text{g}/\text{cm}^3$	0.02528	ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.00002528 $\mu\text{g}/\text{cm}^3$	0.02528	ppb

Estimated BTEX Concentration	Maximum Contaminants Levels (MCLs) and Other Categories	BTEX Permeation in Pipe Water (mg/L) (Scientific Expression on Right)		Result for Saturated Groundwater Condition *Assumption for Results: Negligible contamination is assumed to be less than 20% of MCLs.
MCLs cited from National Primary Drinking Water Regulations (EPA 2009)	Benzene MCLs: 0.005mg/L (Allowable Contamination Range: 0.001 - 0.005 mg/L) (Negligible Contamination: less than 0.001 mg/L) (Consider Other Options: Exceeding MCLs)	0.00333	3.33E-03	Allowable
	Toluene MCLs: 1.0 mg/L (Allowable Contamination Range: 0.2 - 1.0 mg/L) (Negligible Contamination: less than 0.2 mg/L) (Consider Other Options: Exceeding MCLs)	0.00315	3.15E-03	Negligible Contamination
	Ethylbenzene MCLs: 0.7 mg/L (Allowable Contamination Range: 0.14 - 0.7 mg/L) (Negligible Contamination: less than 0.14 mg/L) (Consider Other Options: Exceeding MCLs)	0.00003	2.53E-05	Negligible Contamination
	Xylene MCLs: 10.0 mg/L (Allowable Contamination Range: 2.0 - 10.0 mg/L) (Negligible Contamination: less than 2.0 mg/L) (Consider Other Options: Exceeding MCLs)	0.00003	2.53E-05	Negligible Contamination

Appendix 3. BTEX Permeation Calculation Example 3 –Groundwater Unsaturated and Pipe-water Flows

INPUT Parameters (Groundwater Unsaturated + Pipe water Flows)				
$C_{\text{bulk_dry soil}}$: Bulk concentration of contaminant in dry soil	=		
Benzene	Benzene Concentration in Dry Soil	=	1	mg/kg
Toluene	Toluene Concentration in in Dry Soil	=	100	mg/kg
Ethylbenzene	Ethylbenzene Concentration in Dry Soil	=	100	mg/kg
Xylene (total)	Xylene (total) Concentration in Dry Soil	=	200	mg/kg
L_C	: Length of contaminated pipe	=	100	ft
L_T	: Total Length of the pipe	=	1000	ft
v	: Average water flow velocity (No stagnation in Pipe-water)	=	5.00	ft/sec
L_{tc}	: Wall Thickness of HDPE water pipe	=	1.933	inch
T	: Ground Temperature	=	59	°F
S	: Soil Type Factor	=	0.9	Dimensionless

Soil around pipe is not saturated with groundwater.

Length of pipe directly exposed to BTEX

Total length in a single water main pipeline within a pressure zone.

Consult your local water utility company to get average flow velocity.

Use PPI sizing table.

Average ground temperature is 59°F (15°C)

Higher content % of organic Soil attenuates contamination (value recommends b/w 0.7-1.0 (pure sand))

BTEX Contaminant Concentration Estimation in Groundwater Unsaturated Soil				
Steady State Permeation Equation	$C_{pw} = \frac{M}{V} = \frac{P_m \times \pi \times OD}{\frac{1}{4} \times \pi \times ID^2}$	This steady state permeation calculation is a baseline value from 1 inch SDR 9 IPS HDPE pipe.		
P_m	: Steady permeation rate of the contaminant			
Benzene	Insignificant concentration in water pipe (P_m is assumed)	=	0.00002 $\mu\text{g}/\text{cm}^2/\text{day}$	Assumption: 10% of Toluene P_m
Toluene	$P_m = 0.0002 C_{\text{bulk}}^{1.6024}$	=	0.32496 $\mu\text{g}/\text{cm}^2/\text{day}$	
Ethylbenzene	Insignificant concentration in water pipe (P_m is assumed)	=	0.03250 $\mu\text{g}/\text{cm}^2/\text{day}$	Assumption: 10% of Toluene P_m
Xylene (total)	$P_m = 0.000003 C_{\text{bulk}}^{2.2594}$	=	0.47432 $\mu\text{g}/\text{cm}^2/\text{day}$	
C_{bulk}	: Bulk concentration of contaminant in dry soil	INPUT		
Benzene	Benzene Concentration in Dry Soil	=	1.00 mg/kg dry soil	1000.00 $\mu\text{g}/\text{kg}$
Toluene	Toluene Concentration in in Dry Soil	=	100.00 mg/kg dry soil	100000.00 $\mu\text{g}/\text{kg}$
Ethylbenzene	Ethylbenzene Concentration in Dry Soil	=	100.00 mg/kg dry soil	100000.00 $\mu\text{g}/\text{kg}$
Xylene (total)	Xylene (total) Concentration in Dry Soil	=	200.00 mg/kg dry soil	200000.00 $\mu\text{g}/\text{kg}$
Pipe Dimensions	1 inch SDR 9 IPS pipe (baseline) Ong et al (2008)			
ID	: inside diameter of pipe	=	2.57 cm	1.01 inch
OD	: outside diameter of the pipe	=	3.34 cm	1.32 inch
C_{pw}	: Concentration of Contaminant in Pipe-Water Estimation			
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.000041 $\mu\text{g}/\text{cm}^3/\text{Day}$	
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.659689 $\mu\text{g}/\text{cm}^3/\text{Day}$	
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.065969 $\mu\text{g}/\text{cm}^3/\text{Day}$	
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.962892 $\mu\text{g}/\text{cm}^3/\text{Day}$	

Applying Flow Velocity in Pipe Effect	$Flow\ Factor = \frac{L_c}{v}$	=	0.000231 Dimensionless (no unit)	INPUT
v	: Average water flow velocity	=	13170732 cm/day	5.00 ft/sec
L_c	: Length of contaminated pipe (see #2 for L_c)	=	3048 cm	100 foot
C_{pw}	: Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect			
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.0000000 $\mu\text{g}/\text{cm}^3$	0.00001 ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.0001527 $\mu\text{g}/\text{cm}^3$	0.15267 ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.0000153 $\mu\text{g}/\text{cm}^3$	0.01527 ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.0002228 $\mu\text{g}/\text{cm}^3$	0.22283 ppb

Applying Pipe Wall Thickness Effect	Thickness Factor = $0.1219 \cdot L_{tc}^{-1.001}$	0.0630210	Dimensionless (no unit)	INPUT
	L_{tc} : Wall Thickness of contaminated pipe	=		1.933 Inch
C_{pw}	: Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect			
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.0000000 $\mu\text{g}/\text{cm}^3$	0.0000 ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.0000096 $\mu\text{g}/\text{cm}^3$	0.0096 ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.0000010 $\mu\text{g}/\text{cm}^3$	0.0010 ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.0000140 $\mu\text{g}/\text{cm}^3$	0.0140 ppb

Applying Ground Temperature Effect	Temperature Factor at approximately 25°C as a baseline is 1.0	It is assumed that diffusion coefficient is directly proportional to permeation.		INPUT
Benzene	Temperature Factor = $1 + (0.0254 T - 0.6364)$	0.7446	Dimensionless (no unit)	15 °C
Ethylbenzene	Temperature Factor = $1 + (0.0236 T - 0.5886)$	0.7654	Dimensionless (no unit)	15 °C
Toluene	Temperature Factor = $1 + (0.0235 T - 0.5865)$	0.7675	Dimensionless (no unit)	15 °C
Xylene	Temperature Factor = $1 + (0.0236 T - 0.5886)$	0.7654	Dimensionless (no unit)	15 °C
C_{pw}	: Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect			
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.0000000 $\mu\text{g}/\text{cm}^3$	0.00000 ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.0000074 $\mu\text{g}/\text{cm}^3$	0.00736 ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.0000007 $\mu\text{g}/\text{cm}^3$	0.00074 ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.0000107 $\mu\text{g}/\text{cm}^3$	0.01075 ppb

Applying Soil Type Effect	Sorption and biodegradation attenuation in bulk concentration by organic content in soil	0.9	Dimensionless (no unit)	INPUT
				0.9
C_{pw}	: Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect			
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.0000000 $\mu\text{g}/\text{cm}^3$	0.00000 ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.0000066 $\mu\text{g}/\text{cm}^3$	0.00663 ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.0000007 $\mu\text{g}/\text{cm}^3$	0.00066 ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.0000097 $\mu\text{g}/\text{cm}^3$	0.00967 ppb

Estimated BTEX Concentration	Maximum Contaminants Levels (MCLs) and Other Categories	BTEX Permeation in Pipe Water (mg/L) (Scientific Expression on Right)		Result for Unsaturated Groundwater Condition *Assumption for Results: Negligible contamination is assumed to be less than 20% of MCLs.
MCLs cited from National Primary Drinking Water Regulations (EPA 2009)	Benzene MCLs: 0.005mg/L (Allowable Contamination Range: 0.001 - 0.005 mg/L) (Negligible Contamination: less than 0.001 mg/L) (Consider Other Options: Exceeding MCLs)	0.0000000	3.97E-10	Negligible Contamination
	Toluene MCLs: 1.0 mg/L (Allowable Contamination Range: 0.2 - 1.0 mg/L) (Negligible Contamination: less than 0.2 mg/L) (Consider Other Options: Exceeding MCLs)	0.0000066	6.63E-06	Negligible Contamination
	Ethylbenzene MCLs: 0.7 mg/L (Allowable Contamination Range: 0.14 - 0.7 mg/L) (Negligible Contamination: less than 0.14 mg/L) (Consider Other Options: Exceeding MCLs)	0.0000007	6.65E-07	Negligible Contamination
	Xylene MCLs: 10.0 mg/L (Allowable Contamination Range: 2.0 - 10.0 mg/L) (Negligible Contamination: less than 2.0 mg/L) (Consider Other Options: Exceeding MCLs)	0.0000097	9.67E-06	Negligible Contamination

Appendix 4.BTEX Permeation Calculation Example 4 –Groundwater Unsaturated and Pipe-water Stagnates

INPUT Parameters (Groundwater Unsaturated + Pipe water Stagnates)				
$C_{\text{bulk, dry soil}}$: Bulk concentration of contaminant in dry soil	=		
Benzene	Benzene Concentration in Dry Soil	=	1	mg/kg
Toluene	Toluene Concentration in in Dry Soil	=	100	mg/kg
Ethylbenzene	Ethylbenzene Concentration in Dry Soil	=	100	mg/kg
Xylene (total)	Xylene (total) Concentration in Dry Soil	=	200	mg/kg
t	: Period of stagnation (No Pipe-water flow)	=	1	days
L_c	: Length of contaminated pipe	=	100	ft
L_T	: Total Length of the pipe	=	1000	ft
L_{tc}	: Wall Thickness of HDPE water pipe	=	1.933	inch
T	: Ground Temperature	=	59	°F
S	: Soil Type Factor	=	0.9	Dimensionless

Soil around pipe is not saturated with groundwater.
 Only days of water stagnation under BTEX contaminated area.
 Only length of pipe directly located BTEX exposure.
 Total length in a single water main pipeline within a pressure zone.
 Use PPI sizing table.
 Average ground temperature is 59°F (15°C)
 Higher content % of organic Soil attenuates contamination (value recommends b/w 0.7-1.0 (pure sand))

BTEX Contaminant Concentration Estimation in Groundwater Unsaturated Soil				
Steady State Permeation Equation	$C_{pw} = \frac{M}{V} = \frac{P_m \times \pi \times OD}{\frac{1}{4} \times \pi \times ID^2}$	This steady state permeation calculation is a baseline value from 1 inch SDR 9 IPS HDPE pipe.		
P_m	: Steady permeation rate of the contaminant	=		
Benzene	Insignificant concentration in water pipe (P_m is assumed)	=	0.00002 $\mu\text{g}/\text{cm}^2/\text{day}$	Assumption: 10% of Toluene P_m
Toluene	$P_m = 0.0002 C_{\text{bulk}}^{1.6024}$	=	0.32496 $\mu\text{g}/\text{cm}^2/\text{day}$	
Ethylbenzene	Insignificant concentration in water pipe (P_m is assumed)	=	0.03250 $\mu\text{g}/\text{cm}^2/\text{day}$	Assumption: 10% of Toluene P_m
Xylene (total)	$P_m = 0.000003 C_{\text{bulk}}^{2.2294}$	=	0.47432 $\mu\text{g}/\text{cm}^2/\text{day}$	
C_{bulk}	: Bulk concentration of contaminant in dry soil	=		INPUT
Benzene	Benzene Concentration in Dry Soil	=	1.00 mg/kg dry soil	1000.00 $\mu\text{g}/\text{kg}$
Toluene	Toluene Concentration in in Dry Soil	=	100.00 mg/kg dry soil	100000.00 $\mu\text{g}/\text{kg}$
Ethylbenzene	Ethylbenzene Concentration in Dry Soil	=	100.00 mg/kg dry soil	100000.00 $\mu\text{g}/\text{kg}$
Xylene (total)	Xylene (total) Concentration in Dry Soil	=	200.00 mg/kg dry soil	200000.00 $\mu\text{g}/\text{kg}$
Pipe Dimensions	1 inch SDR 9 IPS pipe (baseline) Ong et al (2008)	=		
ID	: inside diameter of pipe	=	2.57 cm	1.01 inch
OD	: outside diameter of the pipe	=	3.34 cm	1.32 inch
C_{pw}	: Concentration of Contaminant in Pipe-Water Estimation	=		
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.000041 $\mu\text{g}/\text{cm}^3/\text{Day}$	
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.659689 $\mu\text{g}/\text{cm}^3/\text{Day}$	
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.065969 $\mu\text{g}/\text{cm}^3/\text{Day}$	
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.962892 $\mu\text{g}/\text{cm}^3/\text{Day}$	

Applying Stagnation Effect				
	$\text{Stagnation Factor} = \frac{L_c \times t}{L_T}$		0.1 Dimensionless (no unit)	INPUT
t	: Period of stagnation	=	1 days	24.00 hours
L_c	: Length of contaminated pipe	=	3048 cm	100.00 foot
L_T	: Total Length of the pipe	=	30480 cm	1000.00 foot
C_{pw}	: Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect	=		
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.0000041 $\mu\text{g}/\text{cm}^3$	0.0041 ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.0659689 $\mu\text{g}/\text{cm}^3$	65.9689 ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.0065969 $\mu\text{g}/\text{cm}^3$	6.5969 ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.0962892 $\mu\text{g}/\text{cm}^3$	96.2892 ppb

Applying Pipe Wall Thickness Effect	Thickness Factor = $0.1219 \cdot L_{tc}^{-1.001}$	0.0630210	Dimensionless (no unit)	INPUT
	L_{tc} : Wall Thickness of contaminated pipe	=		1.933 Inch
C_{pw}	: Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect			
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.0000003 $\mu\text{g}/\text{cm}^3$	0.0003 ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.0041574 $\mu\text{g}/\text{cm}^3$	4.1574 ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.0004157 $\mu\text{g}/\text{cm}^3$	0.4157 ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.0060682 $\mu\text{g}/\text{cm}^3$	6.0682 ppb

Applying Ground Temperature Effect	Temperature Factor at approximately 25°C as a baseline is 1.0	It is assumed that diffusion coefficient is directly proportional to permeation.		INPUT
Benzene	Temperature Factor = $1 + (0.0254 T - 0.6364)$	0.7446	Dimensionless (no unit)	15 °C
Ethylbenzene	Temperature Factor = $1 + (0.0236 T - 0.5886)$	0.7654	Dimensionless (no unit)	15 °C
Toluene	Temperature Factor = $1 + (0.0235 T - 0.5865)$	0.7675	Dimensionless (no unit)	15 °C
Xylene	Temperature Factor = $1 + (0.0236 T - 0.5886)$	0.7654	Dimensionless (no unit)	15 °C
C_{pw}	: Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect			
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.0000002 $\mu\text{g}/\text{cm}^3$	0.00019 ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.0031821 $\mu\text{g}/\text{cm}^3$	3.18210 ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.0003191 $\mu\text{g}/\text{cm}^3$	0.31908 ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.0046446 $\mu\text{g}/\text{cm}^3$	4.64464 ppb

Applying Soil Type Effect	Sorption and biodegradation attenuation in bulk concentration by organic content in soil	0.9	Dimensionless (no unit)	INPUT
				0.9
C_{pw}	: Concentration of Contaminant in Pipe-Water Estimation Including Stagnation Effect			
Benzene	Dissolved Benzene Concentration in Pipe-Water	=	0.0000002 $\mu\text{g}/\text{cm}^3$	0.00017 ppb
Toluene	Dissolved Toluene Concentration in Pipe-Water	=	0.0028639 $\mu\text{g}/\text{cm}^3$	2.86389 ppb
Ethylbenzene	Dissolved Ethylbenzene Concentration in Pipe-Water	=	0.0002872 $\mu\text{g}/\text{cm}^3$	0.28717 ppb
Xylene (total)	Dissolved Xylene (total) Concentration in Pipe-Water	=	0.0041802 $\mu\text{g}/\text{cm}^3$	4.18017 ppb

Estimated BTEX Concentration	Maximum Contaminants Levels (MCLs) and Other Categories	BTEX Permeation in Pipe Water (mg/L) (Scientific Expression on Right)		Result for Unsaturated Groundwater Condition *Assumption for Results: Negligible contamination is assumed to be less than 20% of MCLs.
MCLs cited from National Primary Drinking Water Regulations (EPA 2009)	Benzene MCLs: 0.005mg/L (Allowable Contamination Range: 0.001 - 0.005 mg/L) (Negligible Contamination: less than 0.001 mg/L) (Consider Other Options: Exceeding MCLs)	0.0000002	1.71E-07	Negligible Contamination
	Toluene MCLs: 1.0 mg/L (Allowable Contamination Range: 0.2 - 1.0 mg/L) (Negligible Contamination: less than 0.2 mg/L) (Consider Other Options: Exceeding MCLs)	0.0028639	2.86E-03	Negligible Contamination
	Ethylbenzene MCLs: 0.7 mg/L (Allowable Contamination Range: 0.14 - 0.7 mg/L) (Negligible Contamination: less than 0.14 mg/L) (Consider Other Options: Exceeding MCLs)	0.0002872	2.87E-04	Negligible Contamination
	Xylene MCLs: 10.0 mg/L (Allowable Contamination Range: 2.0 - 10.0 mg/L) (Negligible Contamination: less than 2.0 mg/L) (Consider Other Options: Exceeding MCLs)	0.0041802	4.18E-03	Negligible Contamination