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SUSTAINABLE RISK MANAGEMENT IN A FUTURE RESIDENTIAL AREA WITH CVOC CONTAMINATED GROUNDWATER

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Sustainable risk management in a future residential area with CVOC contaminated groundwater

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Abstract

The aim of this thesis was to present an overview on the remediation techniques and risk management methods that can be introduced in areas where groundwater is contaminated with chlorinated volatile organic compounds (CVOC). These compounds can often be found in old industrial areas with a history of dry-cleaning or metal industry. In the first chapters of the thesis the characteristics and use of the main degreasing agent, tetrachloroethene (PCE), are presented. Following chapters offer a glance at the ways the PCE behaves in the subsurface and groundwater.

Because of the characteristics of the compounds, any site with CVOC contamination should be investigated carefully considering different pathways of migration and exposure. The investigations should include not only chemical analysis of the soil samples but also determination of the physical features of the soil. Thus, together with comprehensive groundwater investigations, the magnitude of the plume will be conceived more accurately. Nowadays, there are several ways to treat the contaminated groundwater. The thesis presents five remediation methods known to be effective in the degradation of CVOCs, also, the principle of monitored natural attenuation will be described.

CVOC compounds pose a significant human exposure risk, because they can migrate through the unsaturated zone upwards to the lowest floors of buildings. Therefore, also soil gas investigations play an essential role when selecting the most suitable groundwater remediation method(s) and determining the magnitude of the measures. Soil gas investigations will set the baseline for risk management measures that need to be introduced below the building foundation. Sometimes available, indoor air investigations in the old buildings can be of great help as they would suggest the level of vapour intrusion that would occur if no remedial measures or vapour mitigation methods were to be introduced.

Later, the thesis presents a case study located in Tampere, Finland. Over 70 years of manufacturing at the site resulted, among other contaminants, in CVOC contamination on soil and groundwater. The extent of contamination posed challenges for site redevelopment. Remedial measures included excavating contaminated soil, and in June 2019 a groundwater remediation was initiated. Targeting the remedial measures into areas with the highest concentrations is estimated to eliminate the long-term risks of exposure and to lower the overall amount of CVOCs to levels that will allow future site development without additional engineering controls. Passive ventilation and crawl spaces are designed to control natural radon gas intrusion in the area. Additionally, active venting will be initiated if CVOC concentrations during the monitoring exceed the action limits set for the site.

The case study provides an example of how the remediation community and developers face the challenge of enabling property reuse while extensive remedial activities are being conducted. Furthermore, the thesis suggests a set of risk management methods to be linked with sustainable building design to redevelop brownfields while minimising the energy expenditures and emissions associated with remedial actions.

Keywords

CVOC, groundwater, soil gas, sustainability, risk management, residential area, vapour intrusion

Tiivistelmä

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Julkaisun nimi

Kestävä riskinhallinta tulevalla asuinalueella, jolla on CVOC-yhdisteillä pilaantunutta pohjavettä

Tutkinto

Insinööri (YAMK)

Tiivistelmä

Opinnäytetyön tavoitteena oli esittää yleiskatsaus puhdistustekniikoista ja riskinhallintamenetelmistä, joita voidaan käyttää alueilla, joilla pohjavesi on pilaantunut klooratuilla haihtuvilla orgaanisilla yhdisteillä (CVOC). Kyseisiä yhdisteitä löytyy usein vanhoilta teollisuusalueilta, joilla on ollut kuivapesutoimintaa tai metalliteollisuutta. Opinnäytetyön ensimmäisissä luvuissa on esitetty tyypillisesti käytetyn rasvanpoistoaineen, tetrakloorieteenin (PCE), ominaisuudet ja käyttö. Seuraavissa luvuissa kerrotaan, miten PCE käyttäytyy maaperään päästessään ja myöhemmin pohjavedessä.

CVOC-yhdisteillä pilaantuneissa kohteissa tehtävät tutkimukset on suunniteltava poikkeuksellisen huolellisesti ottaen huomioon erilaiset kulkeutumis- ja altistumisreitit. Tutkimuksissa tulisi huomioida maaperän kemiallisten analyysien lisäksi myös maaperän fysikaaliset ominaisuudet. Näin, yhdessä kattavien pohjavesitutkimusten kanssa, pilaantuneisuuden laajuudesta saadaan parempi käsitys. Markkinoilla on nykyään tarjolla useita erilaisia tapoja käsitellä pilaantunutta pohjavettä. Opinnäytetyössä esitellään viisi puhdistusmenetelmää, joiden tiedetään olevan tehokkaita CVOC-yhdisteiden hajottamisessa. Näiden lisäksi kuvataan luonnollisen hajoamisen ja seurannan periaate.

CVOC-yhdisteet aiheuttavat merkittävän terveysriskin, koska ne voivat kulkeutua vajovesivyöhykkeen läpi nousten rakennusten alimpiin kerroksiin. Tästä syystä myös huokosilmatutkimuksilla on keskeinen rooli valittaessa kohteeseen sopivinta pohjaveden puhdistusmenetelmää tai menetelmien yhdistelmää, ja määritellessä niiden laajuutta. Lisäksi huokosilmatutkimukset asettavat vaatimustason riskinhallintatoimenpiteille, joita on tarpeen toteuttaa rakennusten alapohjissa. Joskus kohteiden vanhoista rakennuksista on saatavilla hyödyllisiä sisäilmatutkimustietoja, joiden avulla voidaan arvioida haitta-aineiden kulkeutumista sisäilmaan ja millaiset olosuhteet kohteessa olisi, jos pohjavettä ei puhdistettaisi tai alapohjan ilman haitta-aineiden aiheuttamia riskejä hallittaisi.

Jälkimmäisessä osassa opinnäytetyössä esitellään Tampereella sijaitseva esimerkkikohde, jossa yli 70 vuotta jatkunut teollinen toiminta aiheutti laaja-mittaisen maaperän ja pohjaveden pilaantumisen muun muassa CVOC-yhdisteillä aiheuttaen samalla haasteita kohteen suunnitellulle kehitykselle. Kohteen kunnostustoimenpiteisiin sisältyi pilaantuneen maaperän kunnostaminen massanvaihdolla vuosien 2013–2017 aikana, ja kesäkuussa 2019 alueella aloitetaan pohjaveden puhdistaminen. Puhdistustyöt kohdistetaan osa-alueille, joilla on havaittu korkeimpia pitoisuuksia, millä pyritään poistamaan pohjavedestä aiheutuvat altistumisriskit pitkällä aikavälillä ja alentamaan CVOC-yhdisteiden kokonaismäärä tasolle, joka mahdollistaa alueen kehittämisen ilman normaalista poikkeavia rakenteellisia ratkaisuja. Alueen rakennuksissa toteutetaan maaperän luonnollisen radonkaasun kulkeutumisen hallitsemiseksi passiiviset tuuletusjärjestelmät sekä ryömintätilat. Mikäli tarkkailun aikana rakennusten alapuolisessa ilmassa havaitaan asetetut rajat ylittäviä haitta-ainepitoisuuksia, voidaan kohteessa ottaa käyttöön myös aktiivinen tuuletus.

Kohde toimii esimerkkinä siitä, miten kunnostuksista vastaavat tahot ja alueiden kehittäjät voivat toimia mahdollistaakseen pilaantuneen kiinteistön uusiokäytön samalla, kun alueella toteutetaan laajamittaisia kunnostustoimenpiteitä. Lisäksi tarkastellaan, miten haihtuvien haitta-aineiden riskienhallintamenetelmät voidaan yhdistää kestävään rakentamiseen ja miten uudelleenkehitettäviä brownfield-kohteita voidaan suunnitella minimoimalla mittaviin kunnostustoimenpiteisiin liittyvät energiakustannukset ja päästöt.

Asiasanat

CVOC, pohjavesi, huokosilma, kestävyys, riskinhallinta, asuinalue, maaperän huokosilman tunkeutuminen rakennukseen

CONTENTS

ABBREVIATIONS / GLOSSARY

Activated carbon	A form of carbon with a high adsorptive capacity for gases, vapours and colloidal solids
AFCEE	The Air Force Center for Engineering and the Environment
Aquifer	A layer of rock or soil that is able to hold or transmit water
ARD	Anaerobic reductive dehalogenation
BNP	Bimetallic nanoscale particles
Brownfield	Real property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant
BTEX	Benzene, toluene, ethylbenzene and xylenes
Chlorinated solvent	Organic solvent containing chlorine atoms: examples include methylene chloride, tetrachloroethene and 1,1,1 trichloroethene used as cleaning agents
COC	Constituents of concern
COD	Chemical oxygen demand
CSM	Conceptual site model
CVOC	Chlorinated volatile organic compound
DCE	Dichloroethene
Degreasing	Removal of grease, oil or other lubricant-type materials by immersion in an effective solvent
DNAPL	Dense non-aqueous phase liquid
DO	Dissolved oxygen
ERD	Enhanced reductive dechlorination
EZVI	Emulsified zero-valent iron
Groundwater	Subsurface water contributing to the water table, an aquifer or a confined aquifer
HDPE	High-density polyethylene (a thermoplastic polymer)

Hot spot	Area of high concentration of contaminant(s)
HRC	Hydrogen release compound
HVAC	Heating, ventilation and air conditioning
In situ	Latin for "in place", signifying that an action occurs at the site (here: remediation of the contamination)
Institutional controls	Legal or administrative actions that help minimise the potential for human exposure to contamination by ensuring appropriate land or resource use. Examples include restrictive covenants, zoning restrictions, and special building permit requirements.
ISCO	In situ chemical oxidation
ISCR	In situ chemical reduction
ISTT	In situ thermal treatment
ITRC	Interstate technology regulatory council
LDPE	Low-density polyethylene
Leakage air	Uncontrolled ventilation due to the leakages in the exterior of the building. This document refers in particular to leaks through the bottom of the building (vapour intrusion)
LNAPL	Light non-aqueous phase liquid
MAMSL	Metres above mean sea level
MNA	Monitored natural attenuation
Mitigation	Engineering approaches to preventing vapor intrusion to a building
MTBE	Methyl tert-butyl ether
N2000	Vertical coordinate reference system used in Finland
PCE	Tetrachlorothene (also tetrachlorothylene or perchloroethylene)
PSD	Particle-size distribution
Radon piping	Typically, an under-floor piping, which is primarily designed to prevent radon from entering the building's indoor air

RAO	Remedial action objective
ROI	Radius of influence
Remediation	Process of addressing contamination by removing, dispersing, destroying, reducing or mitigating the contamination of a parcel of land or water
RT card archive	A versatile information service for sustainable construction. It includes RT guidelines and general quality guidelines that define good construction practices, key laws and regulations, and product information for the construction industry.
Soil gas (soil vapour)	Air in the voids of the soil and vapours emitted from volatile and semivolatile organic compounds at contaminated sites
Sub-slab	Beneath the foundation of a building
SVOC	Semivolatile organic compounds
TCA	Tolerable concentration in air
TCE	Trichloroethene
Vapour intrusion	The migration of chemical vapours from contaminated soil and groundwater into overlying buildings
VC	Vinyl chloride (also vinyl chloride monomer (VCM) or chloroethene)
VOC	Volatile organic compound
Water table	The level below which the ground is saturated with groundwater
ZVI	Zero-valent iron (nZVI / mZVI = nano- and micro-scaled ZVI)

1 INTRODUCTION

Habitation usually spreads to new areas either by taking over unbuilt land or by transforming formerly constructed areas into new use. The continuous trend of urbanisation brings more and more people to cities which requires cities to change and rearrange their structure. In most of the cases, supplemental construction is a cost-effective way to develop the city as there often is a readily available infrastructure and service network in the vicinity. Sometimes, the former activities can cause challenges for the new development. This is the case especially in old industrial areas.

Especially in the 20th century certain industrial activities, such as dry-cleaners, industrial textile treatment and metal surface cleaning / degreasing, used chlorinated solvents (including chlorinated ethenes, CVOCs) in their processes. Their chlorine-containing chemical structure helps them to efficiently dissolve organic materials like fats and greases and to serve as raw materials or intermediates in the production of other chemicals. (WHPP 2013.)

Chlorinated ethenes are among the most common contaminants at industrial sites. Globally, spills, discarding onto the ground and careless storing of the solvents have led to numerous cases with both soil and groundwater contamination during the past decades. The toxic substances complicate the development process and pose a potential threat to future building occupants. (Siegel 2016.)

Chlorinated ethenes, which will be focused on in this thesis, include the mother product tetrachloroethene (PCE) and its degradation products trichloroethene (TCE), dichloroethene (DCE) and vinyl chloride (VC). Because of their physical and chemical properties these compounds are mobile in both vadose and saturated zone.

Chlorinated ethenes may be transported beneath residences as a separate phase, dissolved in groundwater or as a vapour in soil gas. Once these contaminants are present near or beneath buildings, they may move as a vapour through soil gas and intrude into the residence. These compounds are environmentally persistent and pose serious health threats due to their toxic and sometimes carcinogenic effects. (Henschler 1994; Volpe et al. 2007.)

Vapour intrusion is an area of active research as scientists and practitioners try to understand and predict human exposure to harmful vapours emanating from the subsurface (Provoost et al. 2010). Vapour intrusion potentially is a significant hurdle to redeveloping brownfield properties. Prior to approving redevelopment plans, regulatory agencies place a high burden of proof on the responsible parties that vapour intrusion will not pose significant health risks, a requirement that triggers costly and time-consuming investigations (Lowe et al. 2009).

While subsurface clean-up is the long-term solution to the threat of vapour intrusion, reducing subsurface contamination to safe levels can take years. The more immediate, routine protection against vapour intrusion is known as mitigation, largely based upon decades of experience protecting building occupants from the intrusion of naturally occurring radon. Common solutions include systems that depressurise the subsurface and plastic- or rubberlike vapour barriers, which can be implemented in existing and new buildings. If implemented properly the technical response to the vapour intrusion threat, particularly in new structures, is protective, reliable, and cost-effective. (Siegel 2016.)

A wider array of approaches and technical options is typically available to mitigate or avoid vapour intrusion at new buildings, compared to existing buildings. These options potentially include the choice of building location and opportunities to modify the building design and construction (e.g., building designs that separate living and work spaces from the threat of soil gas intrusion). (Siegel 2016.)

Regulatory agencies recognise engineering controls on building systems as a mitigation measure for vapour intrusion pathways; however, these controls are sometimes not viewed as permanent measures for reducing vapour intrusion risks. Given the historical mindset of clean-up programmes, remediation of soil and groundwater often is viewed as the final measures for controlling vapour intrusion as opposed to engineering controls. A regulatory bias against vapour-resistant construction as a remedial measure for controlling vapour intrusion potentially delays redevelopment decisions at these sites. (Lowe et al. 2009.)

Because mitigation is often designed into new buildings, implementing it has usually become the responsibility of building developers. Thus, vapour mitigation has often become a brownfields issue, even at many sites where subsurface remediation has been carried out according to environmental legislation and under regulatory oversight. (Adapted by Siegel 2016.)

The purpose of this thesis is to present a thorough process of how to identify and manage the ecological and health risks that may exist in areas with CVOC contaminated groundwater. The thesis will present an overview of the important site investigations that should be carried out at a site where CVOCs are suspected. To manage the risks at such site the thesis will list the best practices to remediate the contaminated groundwater and also different ways to mitigate the migration of volatile compounds above the saturated zone.

The thesis presents a former industrial area located in Tampere, Finland as a case study. The selected site is undergoing a profound change from a lengthy history with a diverse workshop and assembly industry into residential use. The thesis will describe the best measures and investigation techniques which were implemented during the project. In the end of the thesis, there are also suggestions for more sustainable risk management approach for the site which could have been introduced.

2 THEORETICAL FRAMEWORK

2.1 Chlorinated volatile organic compounds (CVOC)

Chlorinated solvents, including chlorinated volatile organic compounds (CVOC or CVOCs), are chemical compounds containing chlorine that have been widely used in various industries. They are divided in three groups (methanes, ethanes, ethenes) based on their structures, and include common groundwater contaminants such as carbon tetrachloride (CT), tetra- or perchloroethene (PCE), trichloroethene (TCE), dichloroethene (DCE, mainly two geometric isomers cis-1,2-dichloroethene and trans-1,2-dichloroethene) and vinyl chloride (VC). Chlorinated solvents tend to be colourless liquids at room temperatures, heavier than water, volatile, sparingly soluble, and moderately hydrophobic. (EnviroWiki, Chlorinated solvents 2018.)

The primary compounds that will be scrutinised in this thesis are tetrachloroethene (PCE) and its degradation products (TCE, DCE and VC).

2.1.1 Production and use of tetrachloroethene (PCE)

Manufacturing processes

Tetrachloroethene was first prepared in 1821 by Michael Faraday using thermal decomposition of hexachloroethane (Doherty 2000). For many years, the most important process for producing tetrachloroethene was from acetylene via trichloroethylene, but because of the increasing price of acetylene feedstock in the 1970s, newer processes involving direct chlorination or oxychlorination of other hydrocarbons were introduced. (ATSDR 1997a.)

Production volume

Production of tetrachloroethene in Japan, western Europe and the USA reached its peak in the 1980s (Linak et al. 1992). In 1992, the annual capacity was 10,000 tonnes in Austria, 30,000 tonnes in Belgium, 62,000 tonnes in France, 100,000 tonnes each in Germany and in Italy, 21,000 tonnes in Spain, 130,000 tonnes in the United Kingdom, 96,000 tonnes in Japan and 223,000 tonnes in the USA (Linak et al. 1992). In 2007, the USA was the largest consumer of tetrachloroethene (43% of demand), followed by western Europe (19%), China (10%) and Japan (9%). (Glauser & Ishikawa 2008.)

Use

Tetrachloroethene is widely used for a range of industrial and commercial purposes, including degreasing and dry cleaning, and in a host of mixing and thinning solutions. The chlorine-containing chemical structure helps to efficiently dissolve organic substances like fats and grease and also serves as a raw material in the production of other chemicals. (NSW 2011.)

In the 1950s, about 80% of tetrachloroethene was used in dry-cleaning, and 15% in metal-cleaning and vapour degreasing (Doherty 2000). By the 1980s, the pattern was changing as a result of the establishment of environmental regulations and improved technology, and about 50% of tetrachloroethene was used for dry-cleaning, 28% for chemical intermediates (mostly for production of fluorocarbons), and 10–15% for metal cleaning and degreasing (Linak et al. 1992; Doherty 2000). The relative proportions used for dry-cleaning and chemical production have continued to shift, with more than 50% being used as intermediates and 15% for dry-cleaning in the 1990s (ATSDR 1997). Currently the most common use of tetrachloroethene is as a feedstock for producing fluorocarbons (Glauser & Ishikawa 2008).

2.1.2 Dry-cleaning industry

Since the 1950s, tetrachloroethene has been the most commonly used dry-cleaning solvent (Doherty 2000a). Tetrachloroethene is ideally suited for dry-cleaning as it is non-flammable and a good degreaser that does not saturate the fabric fibres, thus avoiding swelling and shrinking of the fabric (Linak et al. 1992; NICNAS 2001).

By the 1960s, almost all dry-cleaning facilities in the USA used tetrachloroethene, and this continued until the 1990s (Doherty 2000). In 2007, tetrachloroethene was used by about 70% of dry-cleaners in the USA (State Coalition for Remediation of Drycleaners 2009). It is currently used by two thirds of dry-cleaners in Denmark, and 90% of dry-cleaners in France (ECSA 2012).

Technological changes in dry-cleaning machines are well documented for the USA (Earnest 2002), Europe (von Grote et al. 2003; Johansen et al. 2005), and Australia (NICNAS 2001). Before the 1960s, most machines were transfer types for which the clothes (which had been immersed in tetrachloroethene) were moved manually from the washer to the dryer. In the 1960s, dry-to-dry machines that did not require manual transfer were invented. In addition, the newer machines were equipped with carbon absorbers and did not vent into the atmosphere. Improvements in recycling dry-cleaning solvents in closed machines have meant that more than 95% of tetrachloroethene is recovered in these modern machines. However, in practice, the replacement of the transfer machines took about two decades. In a study in

New Jersey communities in 1984, dry-to-dry machines were present in 75% of the facilities included (Garetano & Gochfeld 2000).

Alternatives to PCE, including 1-bromopropane, carbon dioxide, hydrocarbon solvents, and propylene glycol ether, have been developed in response to restrictions on the use of tetrachloroethylene in the dry-cleaning industry. (IARC 2014.)

2.1.3 Metal-degreasing in the automotive and metal industries

Tetrachloroethene is used as a degreasing agent in vapour and liquid forms. It dissolves many organic compounds (including pitches and waxes) and inorganic compounds, and can be used to clean metal parts. Tetrachloroethene is used as a solvent in aerosol products for cleaning tyres, brakes, engines, carburettors and wire; in 2004, such uses accounted for 12 % of the total use of tetrachloroethene in the USA (TURI 2006). These aerosol automotive products may be used by the public, as well as by professionals. (IARC 2014.)

Tetrachloroethene has been used in cleaning products for electrical equipment; these products can be applied by spraying, brushing or dipping (NICNAS 2001).

2.1.4 Other industrial applications

i. Chemical intermediates

Currently the most common use of tetrachloroethene is as a feedstock for the production of chlorofluorocarbons and hydrofluorocarbons. Under the Montreal Protocol on Substances that Deplete the Ozone Layer of the 1990s, production of chlorofluorocarbons is being phased out by 2030 due to their contribution to ozone depletion. (Doherty 2000a.)

ii. Textile industry

In textile processing, tetrachloroethene is used as a solvent to remove oils from fabrics after knitting and weaving operations, and as a carrier solvent for scouring, sizing and desizing, and for fabric finishes and water repellents. Tetrachloroethene is able to dissolve fats, greases, waxes, and oils without harming natural or synthetic fibres. (IARC 1995.)

iii. Printing industry

Flexographic printing is a method that is similar to letterpress printing but uses flexible plates. Tetrachloroethene is used to clean unpolymerized coatings from the flexible film. The cleaning is performed in automated enclosed machinery (NICNAS 2001). Tetrachloroethene has also been used in printing inks. (IARC 2014.)

iv. Miscellaneous

There are several other uses of tetrachloroethene (NICNAS 2001), including for testing in the coal industry; as a source of chlorine in the catalytic reforming process in petroleum refineries; to clean prints and negatives of cinema film; in typewriter correction fluid; in carpet stain-removal products; and as an anthelminthic agent (O'Neil et al. 2006).

2.2 Properties of the chlorinated ethenes

Chlorinated ethenes (also referred to as chlorinated ethylenes) possess two carbon centres, but unlike chlorinated ethanes, these carbon atoms are joined by a carbon-carbon double bond.

Chlorinated ethenes and many of their transformation products are colourless liquids at room temperature. They are heavier than water with densities greater than 1 gram per cubic centimetre (g/cm^3) which means they can penetrate deeply into an aquifer. They are relatively volatile compounds with relatively high Henry's Law constants (K_H), a measure of the strength of partitioning from water into air). Generally, when K_H for a compound exceeds 0.2 atmosphere/mole fraction (atm/M), they can readily be removed from water by air stripping it. Most chlorinated solvents can be classified as sparingly soluble in water, with aqueous solubilities generally on the order of 10s to 100s of mg/L. (EnviroWiki 2018.)

Under favourable groundwater microbial and hydro-geochemical conditions, attenuation of PCE occurs in the form of its transformation products. Researchers first demonstrated the potential for anaerobic biotransformation of halogenated aliphatic compound in 1981. Subsequent studies have shown that these compounds can bio-transform under a variety of environmental conditions in the absence of oxygen. The mechanism by which PCE transformation can occur is called "reductive dechlorination": the micro-organisms usually serve as catalysts for the reactions that progressively remove chlorine atoms from PCE, that reduce PCE to TCE, which in turn can be reduced anaerobically to 1,1-DCE or cis 1,2-DCE or trans 1,2-DCE, eventually converted to VC and ethane. Microbes can convert ethane to methane, carbon dioxide and hydrogen chloride (harmless compounds). (Massabó et al. 2008.)

Flow chart in Figure 1 shows the dechlorination scheme of PCE.

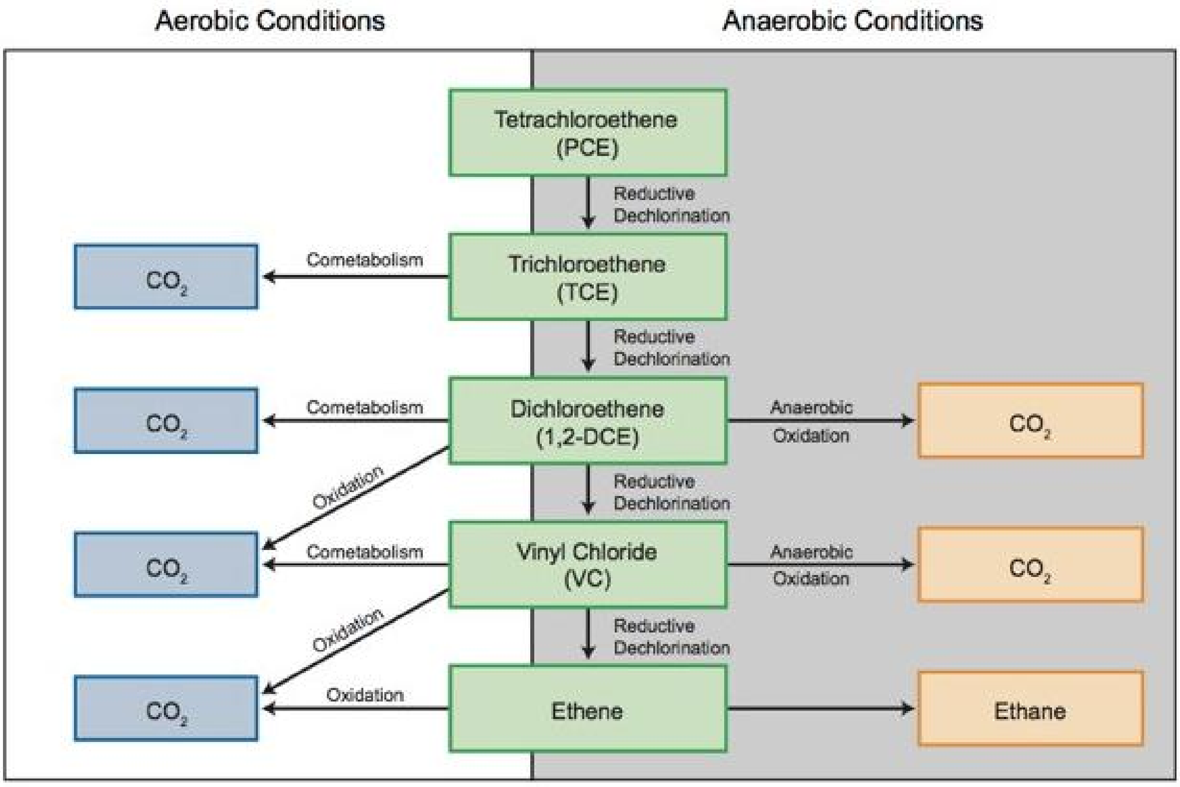


FIGURE 1. Dechlorination scheme of tetrachloroethene (PCE) (Innovative Environmental Technologies Inc. 2019)

2.3 Overview of chlorinated ethene behaviour in the subsurface

These compounds are environmentally persistent and many pose serious health threats due to their toxic and sometimes carcinogenic effects (Henschler 1994; Volpe et al. 2007). Chlorinated solvents have a density greater than water and the separate non-aqueous phase liquid (NAPL) that forms, is referred to as a dense non-aqueous phase liquid (DNAPL) (WDNR 2014). A major problem associated with the contamination of groundwater systems by these compounds (PCE and TCE) stems from the formation of DNAPLs which are formed as the compounds sink through permeable groundwater aquifers until a non-permeable zone is reached. The typical resulting distribution of the DNAPL is highly complex and non-uniform. Entrapped DNAPL mass tends to dissolve slowly into the flowing groundwater, serving as a long-term source of groundwater contamination. (Aulenta et al. 2006; Matteucci et al. 2015.)

Although chlorinated solvents are not very soluble in water, their solubility is typically orders of magnitude greater than their established drinking water standards (EnviroWiki2018).

Because of the highly volatile nature of these compounds, the unsaturated zone plays an important role in the movement and fate of chlorinated solvents in the subsurface. Volatilisation from the upper part of the water table into the unsaturated zone, and from soil moisture and soil particles in the unsaturated zone to the atmosphere, may result in losses of chlorinated solvents from the subsurface system. Sorption onto soil surfaces, chemical partitioning into soil organic matter, biodegradation, and/or chemical degradation also may reduce the concentrations of infiltrating contaminants before they reach the water table. However, contaminants sorbed onto sediments may act as a reservoir of chlorinated solvents that may be released to the groundwater during percolation of recharge water or during periods of high water table. (U.S. Geological survey 1987)

2.3.1 Physical behaviour of NAPLs, DNAPLs and LNAPLs

Understanding the physical behaviour of chlorinated ethenes in the subsurface will help guide site investigation strategies and define exposure pathways. Chlorinated ethenes can enter the subsurface as a separate non-aqueous phase liquid (NAPL), in solution (e.g., dissolved in water), and/or as a vapour phase. According to the guidance by Wisconsin Department of Natural Resources it is important to determine how the chlorinated ethenes have entered the subsurface (e.g., whether the release was on-going, episodic, or a one-time event). This knowledge will guide the site investigation and possible subsequent remediation. (WDNR 2014.)

DNAPL released to the environment can migrate through the soil where it coats soil particles and is held in soil and aquifer pores as residual NAPL. Residual NAPL (which can be either dense or light phase) is held in soil or aquifer material under capillary forces, it will not flow under the force of gravity and will not drain into a well. (WDNR 2014.)

Because it is denser than water, DNAPL that reaches the groundwater can move below the water table and, if enough DNAPL is released, moves to great depths below the surface forming “pools” of free phase liquid on low permeability surfaces as “free” or “mobile” NAPL. Free or mobile NAPL occurs at saturations high enough to move under the force of gravity and will drain into a well. (WDNR 2014.)

The residual and mobile DNAPL serve as long-term sources of groundwater contamination. Groundwater plumes emanating from DNAPL can exist throughout the vertical extent of the aquifer. However, small releases of DNAPL can remain in the unsaturated soils and never reach groundwater. Additionally, according to WDNR, chlorinated ethenes in soils are a source of vapour contamination that can migrate to enclosed spaces (such as basements) and serve as a source of contamination to shallow groundwater. (WDNR 2014.)

The ability of soils to hold DNAPL is dependent on the properties of the DNAPL and the subsurface media. The saturation of a DNAPL in soil (i.e., the volume fraction of pore space occupied by the liquid) is difficult to directly measure but is dependent on interfacial tension between water and the DNAPL, the wettability of the media, capillary pressure, relative permeability of the formation, and the solubility, volatility, density, and viscosity of the NAPL. (Mercer & Cohen 1990). The interaction of DNAPL and soils can lead to DNAPL spreading along the water table leading to significant contaminant mass at the soil-water table interface, even though DNAPL is denser than water. WDNR explains that this happens because interfacial tension and capillary pressures cause a DNAPL pressure head to build up at the groundwater table until the DNAPL is able to penetrate the groundwater table. (WDNR 2014.)

Solvent mixtures that are less dense than water can also contain chlorinated compounds. These are referred to as light non-aqueous phase liquids (LNAPL). For example, a petroleum solvent that contains a proportion (e.g., 25 %) of trichloroethene (TCE) can have a density less than water. A release of LNAPL tends to move through the soil, with significant amounts being held in the soil. If enough solvent mixture is released, the LNAPL will “float” on the water table and will tend to create a shallow groundwater plume near the source. Further downgradient from the source, the dissolved contaminant plume may move to deeper levels in the subsurface due to infiltration of clean water above the plume, to hydraulic gradients, and/or to site stratigraphy. (WDNR 2014.)

WDNR guide explains that also aqueous mixtures can contain chlorinated hydrocarbons. As contaminated water, such as landfill leachate, enters the subsurface, it moves through the soil or unsaturated zone and, if there is enough volume, enters the groundwater. Aqueous phase contaminants are less likely to cause significant vapour plumes in the soil. The hydraulics of the flow system and the retardation characteristics of the contaminants will determine movement of dissolved phase contaminants in the groundwater. (WDNR 2014.)

WDNR points out that vapour migration within unsaturated soils and bedrock can be a source of shallow groundwater contamination in any direction from the original source area. Soil gas monitoring is useful in identifying these source zones. McCarthy & Johnson (1993) explain that the relationship between contaminant concentrations in the soil gas and concentrations in the groundwater is not straightforward and is strongly dependent on soil moisture content. In addition, chlorinated compounds in shallow groundwater (even at concentrations that approach groundwater enforcement standards) can volatilise and present a threat of vapour intrusion to indoor air. (WDNR 2014.)

Whether vapours will off-gas from a shallow groundwater plume is dependent on the depth of the capillary fringe and the amount of unsaturated pore space available for vapour migration. Depending upon site conditions, soil gas monitoring may be useful to identify shallow groundwater contaminant plumes. (WDNR 2014.)

Figures 2 and 3 illustrate the concepts of chlorinated compound movement in the subsurface.

WDNR guide emphasises that all site investigations should assess the source(s) of the chlorinated compounds, including an estimate of the volume of contaminant in the source zone of the release. The source, history and location of the release, the characteristics of the release, the subsurface characteristics and the fate of the contaminants after the release will largely determine the subsurface distribution of the contaminants. (WDNR 2014.)

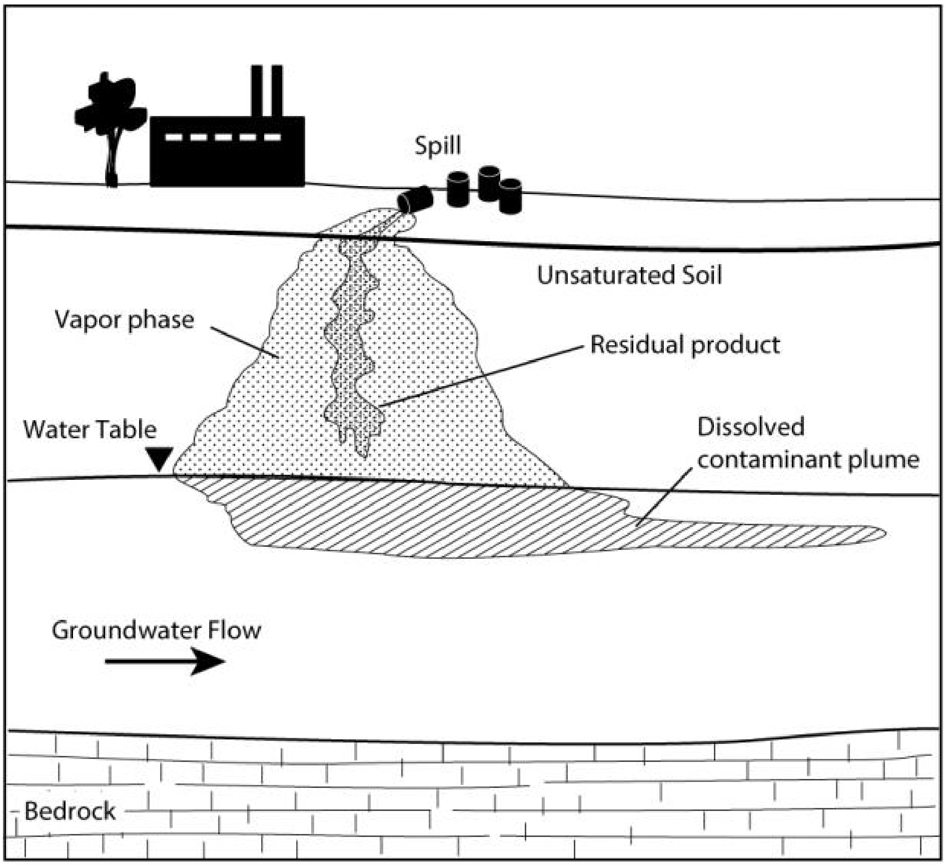


FIGURE 2. Release of a small volume of chlorinated solvent. The spill does not exceed the retention capacity of the soils. The residual product is entrained on the soil particles and DNAPL never reaches the groundwater table. Primary sources of contamination to the groundwater are soil vapour migration and surface water infiltrating through the contamination. (Graphic after Schwille 1988; WDNR 2014.)

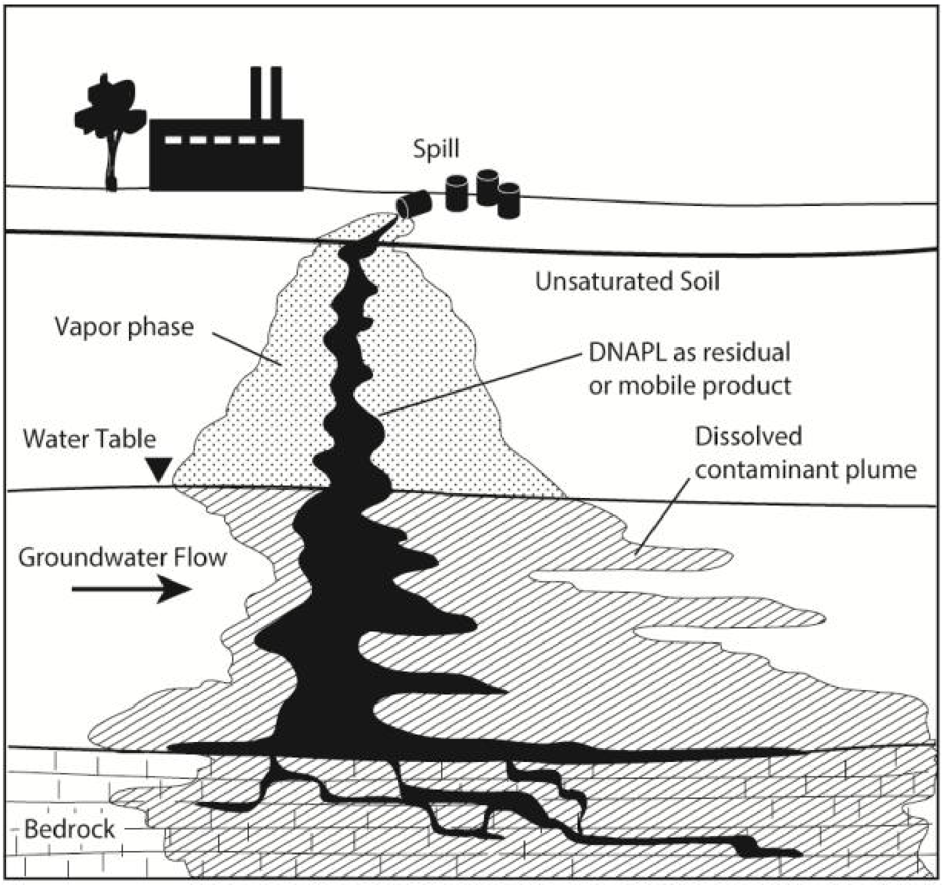


FIGURE 3. Release of a large volume of chlorinated solvent. The spill exceeds the retention capacity of the soils and underlying aquifer materials. The chlorinated solvent moves through the soil and groundwater as a DNAPL. In this illustration, the DNAPL forms "pools" along less permeable bedrock surfaces. (Graphic after Schwille 1988; WDNR2014.)

2.3.2 Degradation processes affecting chlorinated hydrocarbons

The guidance by the WDNR explains that when a chlorinated contaminant enters the subsurface, the contaminant will partition among four possible compartments: soil-air, soil-water, soil-matrix and NAPL (when the soil pores are saturated with solvent). Contaminant moving from these phases (but mainly the dissolved fraction) will subsequently contaminate groundwater. WDNR reminds that the contaminant concentration and mass in all the contaminant phases should to be understood to effectively and efficiently address the contamination. Natural attenuation processes occur in all media (with perhaps the exception of NAPL), but the most studied processes are those occurring in groundwater. Physical processes, including sorption on soil grains, volatilisation, dilution in groundwater, etc. that serve to reduce contaminant concentration all play a part in natural attenuation processes. The primary naturally occurring degradative processes affecting chlorinated ethenes include anaerobic and aerobic biotic processes and abiotic destruction depending on the compound in question. However, for purposes of remediating the environment and meeting regulatory goals, mass loss of chlorinated compounds from the subsurface occurs primarily through biotic and abiotic destruction. (WDNR 2014.)

Reductive dechlorination

The degradation of chlorinated compounds with 3 or 4 chlorine atoms are subject primarily to reductive dechlorination. WDNR explains that reductive dechlorination is a microbially mediated process in which the chlorinated compound serves as an electron acceptor and a chlorine atom is removed sequentially from the core carbon molecule (e.g., ethene, ethane or methane). Reductive dechlorination occurs under strongly reducing conditions and requires carbon as a food source for the microbes. Less chlorinated compounds (those with 1 or 2 chlorine atoms) are also subject to reductive dechlorination but the degradation rates are usually slower than for the more highly chlorinated compounds. Complete reductive dechlorination produces ethene, ethane, or methane and CO_2. (WDNR 2014.)

According to WDNR, reductive dechlorination often results in partial dechlorination that can lead to accumulation of intermediates such as cis-DCE and VC. VC is a known human carcinogen and, as such, has a groundwater enforcement standard that is 25 times lower than either PCE or TCE (in the U.S.). Due to the increased toxicity of the degradation product it is critical to understand the subsurface processes affecting degradation and transport of chlorinated hydrocarbons. WDNR guide emphasises that the selected remedy must adequately protect human health and result in the clean-up of parent contaminants and their breakdown products. (WDNR 2014.)

Oxidative destruction

Ethenes serve as an electron donor (food source) when microbes oxidise the contaminants. Microbes have not been found to oxidise PCE. Oxidation can occur under both aerobic and anaerobic conditions, with oxygen (an aerobic process) or nitrate, iron, sulphate, methane (anaerobic processes) serving as the electron acceptor. The less chlorinated compounds, such as cis-DCE and VC are also subject to oxidation. Enhanced bioremediation systems can stimulate the oxidation of TCE, which occurs fortuitously (i.e., the microbe receives no benefit from the degradation). However, it is not likely that TCE is microbially oxidised under natural conditions. (WDNR 2014.)

Abiotic destruction

Abiotic degradation involves chemical reactions in soil and water that do not require the mediation of microbes. WDNR explains that the primary naturally occurring abiotic processes are hydrolysis and elimination (a.k.a. dehydrohalogenation). Abiotic degradation is usually a slow process but plays an important role in some of the chlorinated ethenes. (WDNR 2014.)

2.4 Site investigations

A site investigation is planned with some understanding of the site geology, the source of the release and the likely physical, chemical, and biological processes affecting the chlorinated contaminants in the subsurface. According to WDNR the results of the site investigation should provide an initial understanding of the plume behaviour, subsurface heterogeneity, likely attenuation processes, the 3-D extent of the plume, subsurface distribution of contaminants, hydrogeological control, and an initial estimate of contaminant decay rates.

Understanding the history and behaviour of the plume includes gathering information about the volume, physical and chemical characteristics of the contaminants released and the approximate date, location and condition (surface spill, underground leak, etc.) of the release. Typically, the site history includes the following: ownership and land use of the property; location of above and below ground structures (including utilities); and all other site-specific information that will help identify potential impacts of the contaminant release and guide the site investigation. (WDNR 2014.)

Furthermore, the site investigations lay the basis for selecting a solution that will lead either to the remediation of the contamination or to successful risk management method. (WDNR 2014.)

2.4.1 Identifying groundwater contamination

The site investigation will involve a number of field activities at the contaminated site as well as gathering as much existing information about the site as possible. Usually several permanent monitoring wells (water table and optionally piezometers) are installed during the site investigations. These wells may or may not subsequently be used during the long-term monitoring phase as the future redevelopment can be difficult to predict. (WDNR 2014.)

2.4.2 Developing the conceptual site model

Developing a conceptual site model (CSM) is an important first step for assessing contaminated sites and the potential for vapour intrusion.

Briefly, a CSM is a picture and narrative of the site contamination:

- how it got there,
- whether or not it is migrating or degrading,
- its distribution across the site,
- who might be exposed to it, and
- what risk-reduction strategies are most feasible

According to the primer from U.S. EPA’s Office of Solid Waste and Emergency Response, CSM development begins during the phase I environmental site assessment with collection and evaluation of site history and reconnaissance information. During subsequent site characterisation activities, the CSM can be augmented, as necessary, with site-specific information on source areas, contaminant properties, stratigraphy, hydrogeology, exposure pathways, and potential receptors (EPA 2008a). ITRC (2007) explains that a CSM typically contains information on soils, geology, hydrogeology, the relative amount of heterogeneity, groundwater quality data, regional groundwater flow direction, well records, boring logs, and surficial features suggestive of whether the area is in a groundwater recharge or discharge area, ground cover and surface water bodies. (ITCR 2007.)

EPA (2008a) further explains that building a thorough CSM may involve a combination of techniques and tools to understand the subsurface, but specifically, investigations for vapour intrusion often include collecting samples of soil, groundwater, soil gas, and/or indoor air. According to the primer, gathering sufficient information for a CSM is essential for assessing vapour intrusion and determining remediation and mitigation approaches. Developing a CSM by using this information helps focus attention on areas where uncertainties in site information exist, and direct further information gathering and sampling efforts to where they may be needed most. Reducing these uncertainties and developing a robust CSM can provide more reliable results when implementing the appropriate approaches to assessing vapour intrusion, or the predictive computer models. (EPA 2008a.)

Sample collection and analysis as well as other site assessment activities which are used to develop the CSM can be expensive. However, the expense of thorough, upfront characterisation is often offset by the ability to plan for proper mitigation. (EPA 2008a.)

2.4.3 Monitoring wells

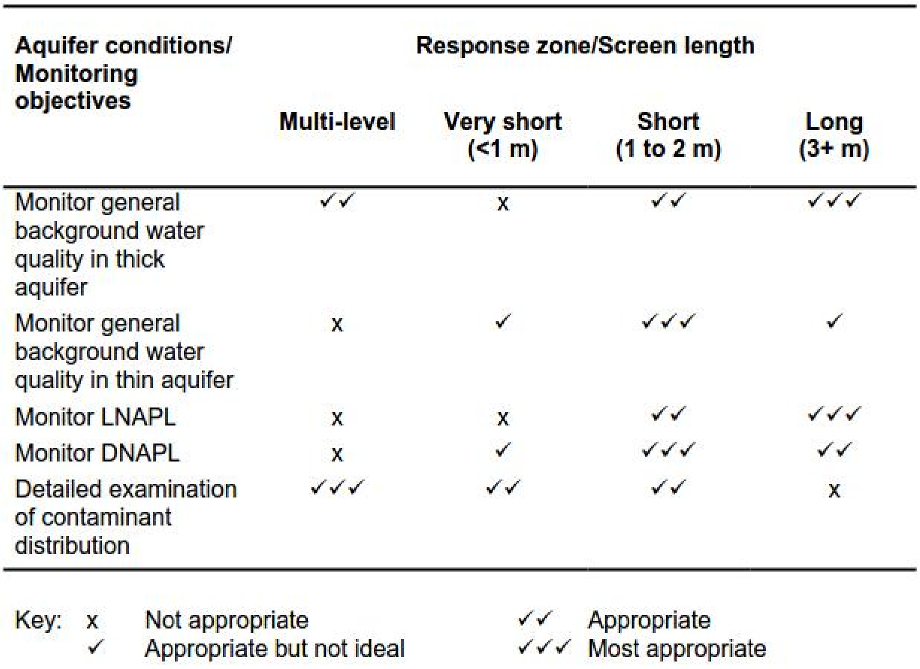
During the drilling of monitoring wells (aka observation wells), samples of aquifer and confining unit material will be collected. Samples will be analysed for sorbed organic compounds. Additional laboratory analyses of the samples may include, for example, particle-size analyses, porosity, permeability, organic-matter content, clay mineralogy, and content of selected elements. After a review of the available hydrogeologic data, also aquifer tests may be performed. Existing hydrogeologic data can be used to develop a preliminary three-dimensional flow model for the area. (U.S. Geological Survey 1987.)

Response zone depth and length in monitoring wells

The response zone is the section of installation that is open to the aquifer and includes the filter pack and the well screen. The well screen allows contact between the filter pack and the casing via a series of slots or other openings. EA explains that the filter pack may be longer than the well screen and the filter pack’s (response zone) length is often constrained by sealing (such as bentonite) in the annulus of the borehole. (Environment Agency 2006.)

The depth of the drilled borehole and the length and location of the well screen will be determined by the depth to the aquifer required to be monitored, the type of compounds to be monitored and the depth to the groundwater table. Boreholes may be over-drilled to provide stratigraphical information on deeper strata, and then backfilled to the required installation depth. Table 1 provides a summary of suggested screen lengths. (Environment Agency 2006.)

TABLE 1. Guide to monitoring interval selection (Environment Agency 2006)



Aquifer conditions/ Monitoring objectives	**Response zone/Screen length**			
	Multi-level	**Very short (<1 m)**	**Short (1 to 2 m)**	**Long (3+ m)**
Monitor general background water quality in thick aquifer	✓✓	x	✓✓	✓✓✓
Monitor general background water quality in thin aquifer	x	✓	✓✓✓	✓
Monitor LNAPL	x	x	✓✓	✓✓✓
Monitor DNAPL	x	✓	✓✓✓	✓✓
Detailed examination of contaminant distribution	✓✓✓	✓✓	✓✓	x

Key:				
	x	Not appropriate	✓✓	Appropriate
	✓	Appropriate but not ideal	✓✓✓	Most appropriate

The EA guidance reminds that the screen installations should be designed to minimise the risk of interference with groundwater flow regimes (long screens can induce vertical flow within an aquifer) and to allow the collection of a sample that meets the requirements of the monitoring objectives. In general, the screen should be the minimum length required to meet the objectives whilst ensuring that mixing and sample dilution within the borehole does not affect the sample results or the interpretation of those results. (Environment Agency 2006.)

The screen should be located such that at least part of it remains within the saturated zone during the period of monitoring, considering the likely annual fluctuation in the groundwater table. (Environment Agency 2006.)

The guidance explains that in layered aquifer systems, the response zone should be of an appropriate length to prevent connection between different aquifer layers within the system. This means that it should be no greater in length than the thickness of the strata being monitored. In thick granular aquifers the benefits of a short response zone are limited, given that mixing and sample dilution will occur within the aquifer itself. EA also reminds that long response zones should be installed with caution as vertical gradients may still exist. (Environment Agency 2006.)

Screen location and length are important considerations when monitoring the presence of free-phase NAPLs. For monitoring of light NAPLs (LNAPLS) which float on the water table, it is necessary to monitor across the zone of fluctuation of the water table. For monitoring of dense NAPLS (DNAPLS) which will sink in groundwater until they reach a layer through which they cannot pass, EA points out that the lowest part of the open screen should coincide with, or be slightly lower than, the base of the aquifer unit. (Environment Agency 2006.)

Appropriate response zone lengths are determined by a number of factors, such as background sampling, discrete horizons and multi-level monitoring. For background sampling, a long response zone drawing water from all parts of the aquifer may be appropriate, provided that this will not connect separate aquifer systems or induce vertical flows. For discrete horizons, where geological conditions or contaminants may cause vertical variations in groundwater quality, short response zones are likely to be more appropriate. (Environment Agency 2006.)

Where detailed information on the vertical distribution of water quality is required, the guidance suggests that users should consider installing more than one monitoring zone within a single borehole. Because of the difficulties of achieving an adequate seal, EA explains that no more than two monitoring locations should be installed in a single borehole using separate installations. Thus, where more sampling points are required, a proprietary multi-level installation is needed. An alternative is to install a series of closely-spaced boreholes to different depths at a single location. (Environment Agency 2006.)

Monitoring dissolved contaminants in plumes requires an appreciation of the likely characteristics of the plume and its behaviour in the aquifer. Plumes will be elongated in the direction of groundwater flow and will undergo longitudinal, lateral and vertical dispersion. They also tend to ‘plunge’ as additional recharge is added to the aquifer downgradient of the plume source area. In locating the groundwater monitoring points, users also need to consider the rate of contaminant movement, which will be affected by advection, dispersion, retardation and degradation. (Environment Agency 2006.)

Casing material

The guidance from Environment Agency recommends choosing HDPE plastic as the casing material for sites with chlorinated solvents, because it stands not only the presence of free-phase contaminants but also acidic, alkaline and high salinity conditions. (Environment Agency 2006). Also in Finland, HDPE is usually used as the casing and screen material.

Filter packs

A filter pack is required to prevent the influx of fine aggregate into the borehole and to stabilise the flow to the sampling point. Turbid samples (samples with high suspended solids) can affect analysis. Silt entering the borehole can clog the screened section.

The filter pack should be matched to the aquifer and to the size of the screen openings (usually referred to as slot size). An appropriately designed filter pack and screen will prevent or limit the entry of fine material into the well. Accurate filter design requires a particle size distribution (PSD), preferably from sieve analysis, but an estimate of the PSD can also be made from visual inspection for the target formation. (Environment Agency 2006.)

Sealing and backfilling the borehole

The annular space from the top of the filter pack to ground level (or other monitoring zones in multiple installations) should be backfilled with a material that will:

- prevent interconnection of aquifer units;
- prevent preferential flow of contaminants or recharge
- support and protect the casing

This is achieved by placing a seal immediately above the filter zone and then backfilling the remaining annular space with a low permeability grout. The choice of material depends upon the geological and hydrogeological setting, the risk of contaminant mobilisation along the borehole and the available budget. In general, seals are made from bentonite and grouts. To prevent these materials entering the screened section of the borehole-grout contamination is a common problem with installations - a seal should always be placed on top of the filter pack. (Environment Agency 2006.)

Seals

A bentonite seal of 1.0 to 1.5 m above the secondary filter pack (sand bridge) is recommended in accordance with UK and US guidance (Aller et al. 1989, US Army 1998 and Environment Agency 2003). The seal can be formed either from granular, pelleted or slurred bentonite. In installations above the water table granular bentonite is recommended. For sub-water table installations, the use of bentonite pellets is more appropriate because they sink to the top of the filter pack are. Where backfilling is via a tremie pipe, the bentonite must be capable of being added to the borehole via the pipe. (Environment Agency 2006.)

Bentonite is used as sealing material in most situations. However, in the presence of free-phase NAPLs there is a potential for degradation and failure of the seal. EA reminds that when drilling in a location with the possible presence of free-phase chlorinated solvents, over-deepening of the borehole and subsequent backfilling with bentonite should only be undertaken with great care. (Environment Agency 2006.)

The EA guide explains that backfill techniques using bentonite below a monitoring installation should not be used where the bentonite provides a seal between different aquifer layers and where DNAPL may be present in the upper layers. An alternative to a bentonite seal in the presence of chlorinated solvents is a permanently installed packer constructed from material resistant to DNAPL. (Environment Agency 2006.)

The material used to backfill the annulus of the borehole between the seal and ground level is referred to as grout. A number of materials can be used, but the most common is a combination of bentonite and cement. EA goes on to explain that all grout seals should be mechanically rather than manually mixed, they should consist of a thick, lump-free fluid suitable for pumping and should be placed by tremie methods. (Environment Agency 2006.)

2.4.4 Sampling and analysis

Collecting samples for chemical analysis is the primary way in which a conceptual site model (CSM) is augmented and refined with site-specific data. Sampling not only helps evaluate the amount of contamination present beneath or inside a building, but it can help environmental practitioners to identify the source and extent of the contamination, possible receptors, and the levels of risks. The sampling tools and analytical techniques selected for an investigation will largely depend on the current CSM. (EPA 2008a.)

Table 2 (on page 26) summarises the advantages and disadvantages of the various options for sampling: groundwater, bulk soil, soil gas, sub-slab soil gas, and indoor air. The following subsections briefly describe some of the tools available for collecting these samples.

Groundwater sampling

Groundwater sampling helps indicate whether a source in the unsaturated zone is contaminating groundwater, which may result in vapour intrusion occurrences downgradient of the source. Additionally, EPA points out that groundwater sampling results may help to estimate the vapour concentrations expected inside a building due to vapour intrusion. (EPA 2008a.)

Prior to sampling, according to ITCR, monitoring wells should be purged to remove stagnant water from the well because it is not representative of aquifer conditions. Wells should purged either by removing at least three casing volumes prior to sampling or by purging with low-flow techniques as described below. ITRC reminds that wells should not be purged dry because this practice would drain the filter pack and may lead to volatilisation losses during recovery. If adequate purging cannot be conducted without significant drawdown because of low permeability of the soil, use of passive diffusion samplers should be considered, because they do not require purging. (ITCR 2014.)

Low-flow purging and sampling is a widely approved method for obtaining high quality samples from groundwaters that are contaminated with CVOCs. Low-flow sampling involves extracting groundwater at rates comparable to ambient groundwater flow (typically less than 500 ml/min), so that the drawdown of the water level is minimised, and the mixing of stagnant water with water from the screened intake area in a well is reduced. (ITCR 2014.)

Stabilisation of parameters (pH, dissolved oxygen (DO), conductivity, temperature, etc.) and turbidity of the purged water are monitored before a sample is taken, thus low-flow methods facilitate equilibrium with the surrounding formation and produce samples that are truly representative of the formation water. (Solinst Canada 2019.)

Passive diffusion bag (PDB)

Passive diffusion bag (PDB) sampling is a cost-effective alternative to low-flow purge and sample techniques for collecting concentrations of a variety of volatile organic compounds (VOCs) in groundwater at monitoring wells. According to ITRC (2002), using PDB samplers can result in significant cost savings at sites where VOCs are the constituents of concern and particularly where long-term monitoring of groundwater is required. PDB sampling can also provide inexpensive and precise vertical contaminant concentration profiles that can be used to optimise remedial systems. (ITRC 2002.)

A PDB sampler is a low-density polyethylene bag filled with deionised water, which acts as a semipermeable membrane and is suspended in a well to passively collect groundwater samples. PDB samplers rely on the free movement of groundwater from the aquifer or water -bearing zone through the well screen. VOCs in groundwater will diffuse across the bag material until constituent concentrations within the bag reach equilibrium with concentrations in the surrounding groundwater. (ITRC 2002.)

Field and lab testing have shown that PDB samplers are effective for a number of VOCs, including chlorinated aliphatic compounds and petroleum hydrocarbons. ITRC points out that if natural attenuation monitoring is required, a combination of sampling techniques could be considered. For example, annual monitoring of natural attenuation parameters can be performed using a traditional sampling method, while quarterly monitoring of VOCs can be accomplished using diffusion sampling technology. (ITRC 2002.)

ITRC reminds that PDB samplers can be used in most formations, but they are not currently recommended for use in low-permeability formations because the flow of water through the well screen is restricted if the rate of VOC change in the well (by volatilisation) is less than the rate that the VOCs are replaced by movement into the well screen. In this case, the VOC concentrations in the well water may not be representative of the VOC concentrations in the formation. PDB sampling relies on self-purging of wells to maintain concentrations within a well that are representative of the surrounding aquifer conditions. (ITRC 2002.)

PDB samplers should be left in place for a minimum of two weeks prior to sample collection to ensure that the deionised water in the diffusion bag has reached equilibrium with the surrounding groundwater. Under low-flow conditions, the PDB should be left in place longer prior to sample collection. (ITRC 2002.)

Statistical variability between different sampling techniques

It is practically impossible not to introduce statistical variability when you switch sampling methods. According to ITRC, PDB samplers may not be appropriate for sites that are complying monitoring and using statistics to demonstrate a decreasing trend. However, if there is already a strong decreasing trend established in the data, switching methodologies would be less critical because there is good evidence that the plume concentrations are decreasing. If good correlation with existing results was obtained, the decision to switch methodologies is not scientifically complex. In a more complicated case where data do not correlate well, additional work will be required to document why there is poor correlation (e.g., vertical profiling, bore-hole flow testing, review of hydrogeology and well construction information). It should be noted that some of the questions regarding PDB-sample data correlation and use, such as vertical placement of the sampler, can also apply to low-flow samples. ITRC points outs that PDB samplers have the potential to generate detailed data that may not always agree with the existing database of samples that have undergone some degree of mixing during pumping. The significance of these new data, in terms of contaminant fate, transport, and site management, is a site-specific consideration. (ITRC 2002.)

Additionally, in the market, there are also other suitable sampling methods such as disposable or reusable bailers and multilevel monitoring systems. A bailer is a portable grab sampler typically used for retrieving groundwater samples from monitoring wells.

Multilevel groundwater monitoring systems are engineered technologies installed in single boreholes above and/or below the water table to obtain data from different depth intervals. The technologies may consist of various pipes, liners, access ports, sampling pumps, pressure sensors, and sealing mechanisms that are installed temporarily or permanently in boreholes drilled into unconsolidated sediments or bedrock. An essential design element of all MLS systems is that they must prevent hydraulic connection of the various monitored intervals within the wellbore. (Einarson 2006.)

Soil gas sampling

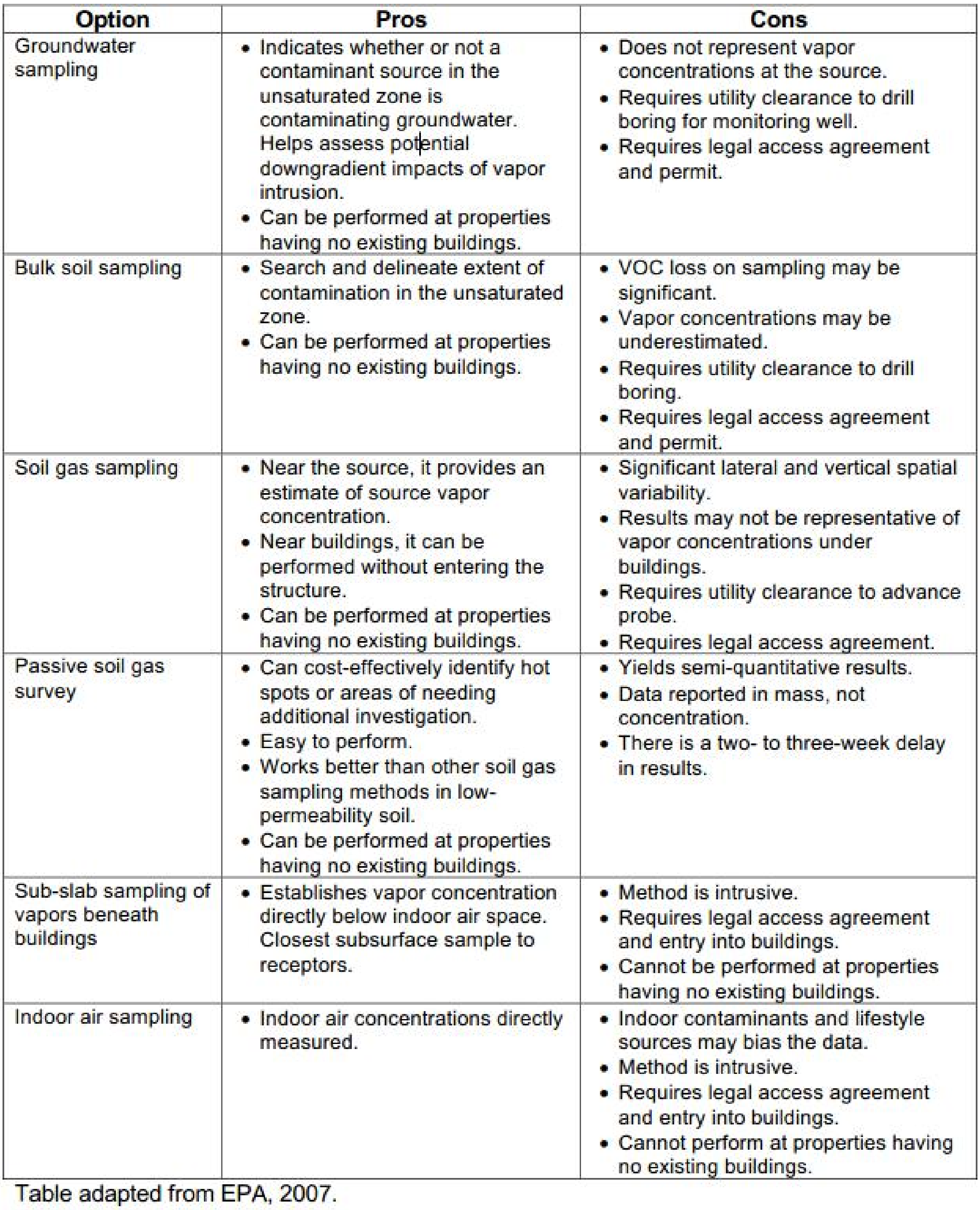
Like groundwater samples, soil gas samples can be used to estimate expected indoor air concentrations. Soil gas sampling and analysis results tend to be most reliable where the contaminant concentrations are high and soils are more permeable (i.e. they allow for freer movement of soil gas). Soil gas sampling is limited to the unsaturated zone above the water table and cannot be performed at sites directly underlain by bedrock or having less than 1.5 metres of soil depth. (EPA 2008a.)

Soil gas samples which are collected near a known source of contamination best represent source vapour concentrations. To collect soil gas samples which would most closely represent the vapour intrusion to a building requires collecting them from close to the building. However, the EPA primer reminds that sampling too close to the building could potentially lead to inaccurate results. Vertical profiling (taking samples at several depths in one location) is recommended to get a sense of vertical distribution of vapours near the building, although sampling at shallow depths (< 1.5 m) is to be avoided due to possible influence of ambient air on the sample. For buildings which are constructed slab-on-grade, deep enough soil gas samples should be collected to minimise any bias due to ambient air that might occur by sampling too close to the ground surface. (EPA 2008a.)

EPA (2008a) points out that because of the complex distribution of contaminants and soil layers beneath a site, soil gas concentrations may vary widely across a property. Because soil gas samples are often collected outside the foundation of the building, they may not accurately represent the contaminant concentrations present under the building as a result of the capping effect.

Table 2 shows the typical sampling options for the assessment of vapour intrusion.

TABLE 2. Sampling options for the assessment of vapour intrusion (EPA 2008a)



Option	Pros	Cons
Groundwater sampling	• Indicates whether or not a contaminant source in the unsaturated zone is contaminating groundwater. Helps assess potential downgradient impacts of vapor intrusion. • Can be performed at properties having no existing buildings.	• Does not represent vapor concentrations at the source. • Requires utility clearance to drill boring for monitoring well. • Requires legal access agreement and permit.
Bulk soil sampling	• Search and delineate extent of contamination in the unsaturated zone. • Can be performed at properties having no existing buildings.	• VOC loss on sampling may be significant. • Vapor concentrations may be underestimated. • Requires utility clearance to drill boring. • Requires legal access agreement and permit.
Soil gas sampling	• Near the source, it provides an estimate of source vapor concentration. • Near buildings, it can be performed without entering the structure. • Can be performed at properties having no existing buildings.	• Significant lateral and vertical spatial variability. • Results may not be representative of vapor concentrations under buildings. • Requires utility clearance to advance probe. • Requires legal access agreement.
Passive soil gas survey	• Can cost-effectively identify hot spots or areas of needing additional investigation. • Easy to perform. • Works better than other soil gas sampling methods in low-permeability soil. • Can be performed at properties having no existing buildings.	• Yields semi-quantitative results. • Data reported in mass, not concentration. • There is a two- to three-week delay in results.
Sub-slab sampling of vapors beneath buildings	• Establishes vapor concentration directly below indoor air space. Closest subsurface sample to receptors.	• Method is intrusive. • Requires legal access agreement and entry into buildings. • Cannot be performed at properties having no existing buildings.
Indoor air sampling	• Indoor air concentrations directly measured.	• Indoor contaminants and lifestyle sources may bias the data. • Method is intrusive. • Requires legal access agreement and entry into buildings. • Cannot perform at properties having no existing buildings.

Table adapted from EPA, 2007.

EPA reminds that properties which will be developed, but have no existing buildings present an additional challenge because soil gas samples collected from an open field will underpredict concentrations that gather under buildings due to the capping effect. (EPA 2008a.)

Soil gas probes are the primary tools for collecting soil gas samples. In areas where subslab sampling is impractical, probes can be installed adjacent to a structure at an angle to sample underneath a building. Care should also be taken to avoid significant disturbance of the soil when installing probes. (EPA 2008a.)

Passive soil gas survey

EPA's brownfield technology primer presents a passive soil gas survey which is another method that can be used to evaluate soil gas for vapour intrusion. These surveys are often used to direct other sampling. Passive soil gas samplers consist of an adsorbent material in a container or a tube that is placed in a small-diameter boring in the unsaturated zone, typically at a depth of less than one metre. The sampler is left underground for a set period of time before the adsorbed material is retrieved and analysed for masses of contaminants. (EPA 2008a.)

Passive soil samplers estimate the total mass of each contaminant (essentially the total amount measured in micrograms) accumulated over the time they are left underground, typically one to two weeks depending on the level of contamination at the site. This approach does not yield concentrations of soil gas contaminants (the amount per a given volume). Therefore, it should be noted that the results are not directly comparable to those from soil gas probes. (after EPA 2008a.)

Because the adsorbent material irreversibly accumulates contaminants and over a longer period of time than active sampling, short-term variations in soil gas movement have less of an impact on detecting contaminants. Additionally, smaller amounts of contaminants can be detected. (EPA 2008a.)

Use of passive soil gas samplers can help confirm the presence of contaminants in soil gas. The EPA primer reminds that the absence of contaminants detected in a sampler does not necessarily mean a complete absence of contaminants in the soil gas, soil gas distribution in the subsurface typically is not uniform and the sampler may not be located in an optimal area to capture the gases. (EPA 2008a.)

However, by deploying the samplers at once (often in a grid pattern over the area of concern) and by comparing contaminant masses measured across a property, passive soil gas sampling can augment a CSM by helping to identify the location of sources, "hot spots" (areas of high concentrations) and preferential pathways. Unlike soil gas probes, passive soil gas sampler can also be used to detect some SVOCs. (EPA 2008a.)

Sub-slab samples

Sub-slab samples are samples of soil gas collected just beneath the building foundation, whether a basement floor or slab-on-grade. Soil gas probes designed specifically for sub-slab sampling are used to collect samples. (EPA 2008a.)

The EPA primer encourages taking the sub-slab samples beneath areas of the slab where there are no cracks or openings nearby. Avoiding cracks and openings is important for calculating the attenuation factor that is used in predictive models and vapour intrusion guidance. The attenuation factor is a measure of how soil and building properties limit the intrusion of CVOCs into overlying buildings. It is defined as the concentration of the contaminant in the indoor air divided by the concentration of the contaminant in soil gas or groundwater. Avoiding the cracks and openings may not be easy because they are often not obvious, and furniture, appliances, utilities, etc. may limit access to certain desired sampling points. In addition, care must be taken to avoid structural damage as well as drilling holes through reinforcing bars, utilities, etc. (EPA 2008a.)

Sub-slab samples better represent potential vapour intrusion concentrations and potential risk than soil gas samples collected outside the building foundation. Additionally, investigators can use sub-slab samples to distinguish the contribution of vapour intrusion to indoor concentrations, because sub-slab samples are usually not biased by possible indoor air contaminants. However, EPA states that the primary obstacle to obtaining sub-slab samples, is that they require access to the building and drilling holes in the foundation, which may not be allowed by the building owner. (EPA 2008a.)

ITRC's guideline includes a rule of thumb that if sub-slab concentrations are 1,000 to 10,000 times greater than the target indoor levels, the probability of unacceptable vapour intrusion is so high that proactive mitigation needs to be introduced without further characterisation. This scenario may not be valid for all sites, but it helps the property owner to decide whether to continue to further site characterisation or to start investing in mitigation. (After ITRC 2007.)

Indoor air sampling

Where possible, EPA encourages collecting samples of the indoor air to aid in the assessment of vapour intrusion. Deciding where and when to collect samples is important as indoor air and ambient air samples tend to exhibit considerable degree of variability over time. Concentrations of vapours can vary from building to building on the same block by a couple of orders of magnitude. Additionally, concentrations may rise and fall seasonally, with higher concentrations during cold months when windows and doors are shut and heating systems on. During warmer months, when windows and doors are often open, possible vapours are ventilated to the outdoors. (EPA 2008a.)

Concentrations within a building are typically higher in the lower level near the sub-slab. Therefore, EPA recommends collecting indoor air samples in basements, if present, or on the first floor. EPA goes on to remind that elevated concentrations may also be present in upper stories as a result of air circulation by heating, venting, and air-conditioning (HVAC) systems, or if conduits such as bathroom pipes connect the lower and upper levels. (EPA 2008a.)

Presence of contaminant vapours from background sources may complicate the evaluation of indoor air concentrations. Such background sources can be present in most households and office buildings, such as cleaning products, hobby supplies, paints and solvents, carpet, cigarette smoke, dry-cleaned clothing and a host of other common items. Thus, an inventory should be conducted before indoor air sampling to identify potential indoor sources of VOCs and SVOCs that may affect the evaluation. To minimise the impact of background sources, the ITRC guide recommends conducting a building survey and removing obvious sources of indoor air vapours from the building before the sampling. ITRC (2007) reminds that all indoor sources may not be apparent. For example, less obvious indoor sources such as non-functioning vapour traps on waste lines to sewer may contribute to indoor air contamination (ITRC 2007.)

In addition to indoor source identification and removal, indoor air measurements should be considered in conjunction with sub-slab measurements to help distinguish vapour intrusion from background sources within the building. Primary source of vapours may be identified by the different ratios of contaminant concentrations in the sub-slab and the indoor air. According to EPA (2008a), sampling of the outdoor air should also be considered in conjunction with indoor air sampling in order to assess the contribution of possible outdoor sources of air pollution, such as a nearby petrol station, highway, or industries. (EPA 2008a.)

Samplers and devices used to collect indoor air samples are often the same that are also used to collect soil gas samples from soil vapour probes (e.g. wells) and sub-slab probes. (EPA 2008a.)

2.4.5 Hydrogeologic and geochemical framework

i. Groundwater and soil contaminant and geochemical parameter distributions

Data from the site investigation can be used to quantify the mass of contamination in the soil and saturated material. Redox conditions of the soil and groundwater should be determined. Soil gas samples can also be used to screen for contaminant concentration, oxygen, carbon dioxide and the presence of methane in soil. Groundwater should be sampled and analysed for contaminants, their degradation products, terminal electron acceptors and other parameters that identify conditions of plume development. (WDNR 2014.)

ii. Regional hydrogeology including regional drinking water aquifers and confining units

The contaminated site should be tied into the regional hydrogeologic setting to determine the overall risk the site poses to receptors and the likely paths of contaminant movement if contaminants enter the regional flow system. (WDNR 2014.)

iii. Site-specific hydrogeology includes:

a) local drinking water aquifers

b) location of private and public water supply wells & use of these wells

c) lithology

d) site stratigraphy, including identification of transmissive vs. non-transmissive units (i.e., site heterogeneity)

e) grain size distribution

f) hydraulic conductivity of each lithologic unit based on grain size, pump tests or monitoring well testing

g) 3-D understanding of groundwater hydraulics (e.g., groundwater flow fields, horizontal & vertical hydraulic gradients, water table & potentiometric surface maps over several seasons.).

h) preferential flow paths

i) bedrock fracture frequency and orientation

j) location and type of surface water bodies

k) groundwater recharge & discharge areas (WDNR 2014.)

2.4.6 Definition of potential receptors and exposure pathways

Potential receptors include water supply wells, contaminant discharges to surface waters and vapour migration to enclosed spaces.

The site investigation should determine whether any exposure pathway is “complete”, that is an actual (versus potential) threat exists to human health or the environment. The remedy and/or the other risk management method(s) chosen for the site must address all completed exposure pathways. (WDNR 2014.)

i. Water supply wells

According to WDNR, all public water supply wells and high capacity wells should be identified within 1.5 kilometres and private water supply wells within 300–400 metres of the contaminated site. Identifying public water supply wells within 1.5 kilometres of the contaminated site is recommended because of the persistence and ability of chlorinated contaminants to migrate long distances in groundwater. Public water supply and high capacity wells induce groundwater gradients that can affect contaminant movement. In addition, many high capacity wells operate seasonally and can cause seasonal shifts in groundwater flow direction and/or gradient. WDNR emphasises that impacts to water supplies must be immediately reported to the well users and environmental authorities. Action (such as providing an alternative water supply) must be taken if any contaminant exceeds safe drinking water standards for private, community or municipal wells. (WDNR 2014.)

ii. Surface waters

All surface water bodies should be identified within 1.5 kilometres of the contaminated source area. Additionally, all surface water discharge locations need to be identified and the effect of the surface water discharge on contaminant movement assessed. WDNR continues that if contaminated groundwater is discharging to surface water, the impact of the discharge must be evaluated. (WDNR 2014.)

iii. Soil gas migration

WDNR states that vapour intrusion from chlorinated contaminants migrating through soils is a significant concern when buildings are located near source areas or located at the water table in groundwater plumes. Chlorinated hydrocarbons do not readily degrade in the vadose zone and contaminants can travel significant distances through soils to enter buildings. The vapour pathway may present a risk even in situations where groundwater enforcement standards are not exceeded. If soil gas sampling, groundwater concentrations or sub-slab vapour concentrations below buildings indicate that contaminant vapours may be migrating into a structure, WDNR points out that passive or active venting of the structure may be necessary. An example of a venting system is a sub-slab depressurisation, which has proven to be effective in reducing radon gas levels in homes. (WDNR 2014.)

2.4.7 Predictions of contaminant fate and transport

For complicated sites with chlorinated contaminants (highly heterogeneous sites or sites exhibiting strong transient flow or sites with high contaminant levels) WDNR recommends that a fate and transport model will be developed after the site investigations (National Research Council 2000). A fate and transport model can be very useful in assessing alternative conceptual models for the site and for understanding complex flow or complex contaminant characteristics. (WDNR 2014.)

A contaminant fate and transport model will benefit the assessment of a contaminated site by:

- predicting contaminant flow paths;
- assessing the expected extent of a contaminant plume;
- testing alternate hypothesis for plume movement and attenuation;
- aiding in placement of long-term monitoring wells;
- refining the site conceptual model;
- assessing the strength of the contaminant source;
- predicting contaminant concentrations in time and space along the plume;
- predicting plume life and estimating a time to clean-up using various remediation strategies;
- providing a baseline to compare results of long-term monitoring; and
- contingency planning. The model can assess active remedial options for containing or controlling the contaminant plume, if this is necessary. (WDNR 2014.)

The complexity of the fate and transport model will be determined by the complexity of the contaminated site. Models range from fairly simple, one dimensional screening models to complex 3-D models. (WDNR 2014.)

For less complicated sites, statistical, graphical, and mass budget analysis may suffice for assessing site data. WDNR guide emphasises that whatever methods are used to assess data, the results should be verified by long-term monitoring. (WDNR 2014.)

2.4.8 Site investigation report

The goal of a site investigation is to identify the subsurface distribution of contaminants, assess contaminant fate and transport and to lay the basis for selecting a remedy that will lead to the clean-up of the contamination and/or selecting a risk management method which mitigates the detected exposure routes. (WDNR 2014.)

Site investigation reports for chlorinated contaminants should include detailed assessment of the geology and hydrogeology of the site as well as mapping and identifying patterns of contaminant degradation and geochemical parameters. (WDNR 2014.)

WDNR guidance urges to emphasise particularly the following points in the site investigation report:

1) A description of the site conceptual model, summarising the information the conceptual model is based upon.
2) A description of the source and estimate of the mass of contamination in the source zone. Identify areas of residual and/or free NAPL, if applicable.
3) Water table and piezometric surface maps with an assessment of change in groundwater flow direction, horizontal and vertical gradients, and velocity for each date of measurement.
4) Detailed geologic and hydrogeologic cross-sections with enough cross-sections to depict each soil boring and monitoring well at the site. At a minimum, cross-sections should be constructed along the centre line of plume and perpendicular to the centre line across the source area and across the dissolved plume, showing the following:
    a. screen length and depth
    b. geology with groundwater flow paths indicated
    c. contaminant concentrations at each well screen interval or boring and mapped isoconcentrations for each compound
5) Identify preferential flow paths for contaminant movement (in DNAPL, subsurface air and groundwater).
6) Preliminary assessment of natural attenuation processes occurring at the contaminated site using appropriate assessment tools.

7) If available, results of a fate and transport model will help to evaluate the history and behaviour of the groundwater plume and to predict future contaminant concentrations at specific monitoring points in the well network. If a fate and transport model has not been used for the site, the results of other assessments such as graphical analysis, decay rate calculations and mass budgets from the initial site investigation data can be used to make predictions of expected contaminant movement and concentrations in the future.

At the end of the site investigation, all the information necessary for screening a site to select a remedy should exist. WDNR summarises that the plume behaviour can be assessed once a proper monitoring well network is in place. Data collected from the monitoring network is then used to assess degradation conditions throughout the plume and to extract degradation rates. (WDNR 2014.)

2.5 Sustainable risk management

The primary objective of risk management for contaminated land is to ensure that no harmful substances are present in the soil or groundwater of the region health or environmental risks. Potential drawbacks to the environment and health of contaminants are identified and described in the risk assessment. Based on the risk assessment, the soil contamination and remediation needs are assessed and, if necessary, determined from the soil and groundwater. Risk management measures for risk reduction are typically carried out through remediation measures for emission sources or routes of contamination. (The Prime Minister’s Office 2017.)

In practice, the decision on a risk management solution and the choice of measures are influenced by a number of factors that cannot be addressed by the environmental and health risk assessment of contaminants. For example, land use and construction plans in the area are governed by decisions such as estimates of the impact of the measures to be selected on the value of the area, for construction or other future use. On the other hand, risk management measures, such as remediation, always have adverse effects that should be minimised in operational planning. Stakeholder views on the objectives of risk management and its various implementation options may differ fundamentally from each other. (The Prime Minister’s Office 2017.)

Sustainable risk management refers to the design and implementation of risk management measures that aim to maximise the overall benefits of operations by maximising its impact on the environment, people's living conditions and comfort, as well as the economy (Figure

4). The sustainability of risk management can be influenced both by the choice of remediation methods in a single site and by means of land use planning and construction at regional level. The earlier the design process takes into account the principles of sustainable development, the more opportunities there are for influencing decision-making and operational benefits. (The Prime Minister’s Office 2017.)

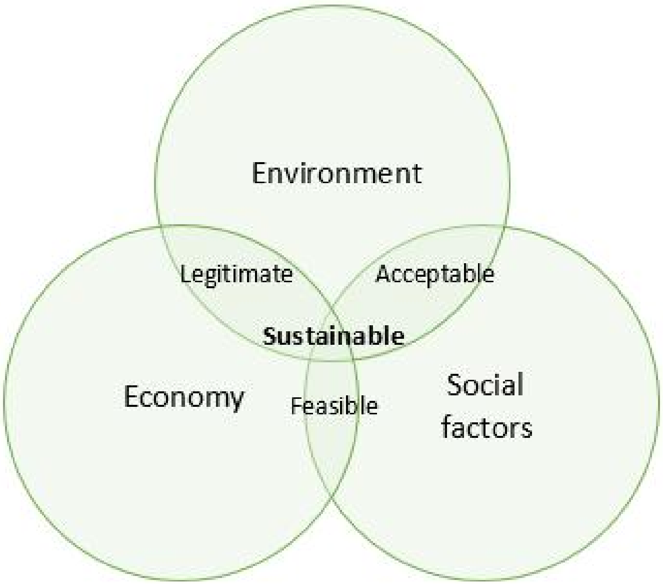


FIGURE 4. Sustainable risk management has environmental, social and economic impacts balanced with each other (The Prime Minister’s Office 2017)

2.5.1 Risk management planning and implementation

Risk management planning and implementation should ensure the following objectives:

Protecting human health and the environment

Measures must always lead to a sufficient reduction in health and environmental risks. On the other hand, the acceptability of risks and the adequate risk reduction must be commensurate with other principles of sustainable development, so that decision-making and implementation support the appropriate use of land and resources. (The Prime Minister’s Office 2017.)

Multidimensional and justified review of sustainability

Ensuring the overall sustainability of a project requires a coherent and multidimensional approach to sustainability. Decisions and factors affecting it must be clearly documented. (The Prime Minister’s Office 2017.)

Stakeholder involvement in decision-making

Implementing sustainability in a project requires consultation with key stakeholders in the project or region and the opportunity to present their own views. The information relevant to the project must be accessible to all and understandable. (The Prime Minister’s Office 2017.)

The careful selection, design and implementation of the project methods

make possible to find a result where the benefits of the project outweigh the disadvantages, and where the work is carried out safely by its implementers. Also the local community and environment are considered. (The Prime Minister’s Office 2017.)

The technical feasibility and suitability of the remediation methods for the site largely determine what kind of methods can be used. Therefore, the sustainability of remediation methods should only be considered after a preliminary technical assessment. The technical assessment will identify possible remediation options that will focus on sustainability assessment. As part of sustainable risk management, the technical assessment of remediation methods must also be open and justified so that potential sustainable remediation solutions are not limited outside the sustainability analysis. (The Prime Minister’s Office 2017.)

2.6 Groundwater remediation methods for CVOCs

After a site investigation is finished, WDNR guidance explains that a remedy selection process will then be completed for every site contaminated with chlorinated hydrocarbons. Data collected during the site investigations are used to identify, evaluate and select a remedial action (or actions) that will result in a timely and cost-effective site clean-up. The range of options available for a specific site will be used to determine initial screening of likely remedial technologies should determine. (WDNR 2014.)

The screened options will then be evaluated for technical and economic feasibility. The technical feasibility of each option is evaluated considering long-term and short-term effectiveness, implementability, and restoration time frame. Economic feasibility, instead, is evaluated by estimating the costs associated with each remedial option and then comparing the costs to what can be technically achieved by each option. (WDNR 2014.)

WDNR reminds that the remedy (or remedies) selected must meet the criteria of environmental laws and standards for soils, groundwater, surface water and wetlands, air discharge, as well as solid and hazardous waste laws. (WDNR 2014.)

The remediation of chlorinated ethenes is possible through both abiotic and biotic pathways. Depending on the pre-existing geochemical conditions, either an aerobic or anaerobic design is created for the specific type of chlorinated contamination. (IET 2019.)

2.6.1 Monitored natural attenuation (MNA)

Chlorinated hydrocarbons can degrade under a variety of environmental conditions, also naturally. The processes most important to natural attenuation are reductive dechlorination (where the chlorinated compound serves as an electron acceptor) and oxidation (where the chlorinated compound serves as an electron donor). (WDNR 2014.)

Environmental conditions that support natural attenuation processes for chlorinated compounds (particularly reductive dechlorination) include:

- Microorganisms capable of degrading the contaminants
- Oxidation-reduction (redox) capacity of the groundwater
- Sufficient electron donors (e.g., a carbon source)
- Absence of competing electron acceptors (WDNR 2014.)

The guidance from WDNR explicates that natural attenuation refers to any naturally occurring physical, chemical or biological process that degrades contaminants or limits their movement in the subsurface. Natural attenuation processes include dilution, dispersion, sorption, precipitation, volatilisation, biotic and abiotic degradation and transformation (Figure 5). (WDNR 2014.)

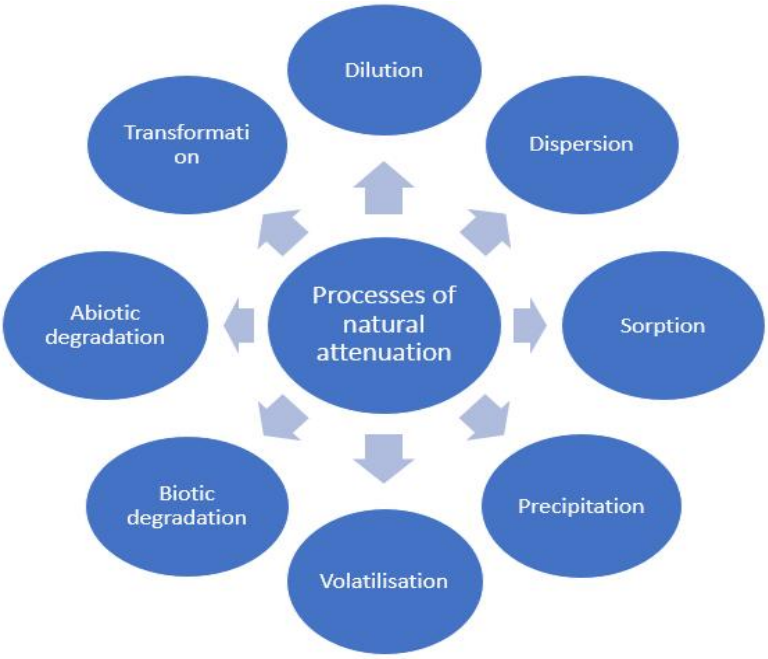


FIGURE 5. Processes of natural attenuation

The processes that reduce mass of contaminants in the environment and are most effective and acceptable for meeting environmental standards and reducing risk to people and the environment, are degradation (biotic and abiotic) and immobilisation. However, it is often quite difficult to distinguish in the field the contributions from the various natural attenuation processes to the observed changes in contaminant concentration. (WDNR 2014.)

According to EPA (2001), monitored natural attenuation (MNA) has been termed a “knowledge-based remedy in which a proper engineering analysis informs the understanding, monitoring, predicting, and documenting of the natural processes, rather than manipulating them”. As such, WDNR reminds that MNA takes place only after a contaminated site has been investigated, site data analysed, source control measures completed, and attenuation processes understood. MNA requires an adequate, long-term monitoring programme that confirms that natural attenuation processes will protect public health, welfare and the environment until clean-up standards are met. (WDNR 2014.)

MNA has most commonly been applied to petroleum contaminants. Field and laboratory experience over the last two decades has established that benzene, toluene, ethylbenzene, and xylene (BTEX) are likely to degrade in the natural environment under both aerobic and anaerobic conditions. Chlorinated ethenes degrade through different pathways and under different conditions than petroleum. (WDNR 2014.)

Reviews of monitored natural attenuation conducted by the National Research Council (2000) and EPA’s Science Advisory Board (2001) have concluded that MNA may serve as an effective remedy for chlorinated contaminants at some limited number of contaminated groundwater sites. However, every contaminated site presents its own challenges and MNA should never be assumed to be effective. Chlorinated contaminants present unique challenges to determining their fate in the environment. Availability of a carbon source along with the proper geochemical and microbial conditions necessary for degradation determine whether chlorinated contaminants will degrade naturally. (WDNR 2014.)

WDNR states that the effectiveness of MNA is based on fully defining the plume, documenting conditions for natural attenuation throughout the plume, and long-term monitoring data that documents natural attenuation processes (effective until standards are met). (WDNR 2014.)

Most sites contaminated with chlorinated hydrocarbons will require active remediation for source reduction and perhaps for plume control. MNA is more likely to be successful when used as one part of a comprehensive site clean-up, rather than as a sole remedy, at most chlorinated hydrocarbon sites. (WDNR 2014.)

2.6.2 In situ bioremediation (ISB) / anaerobic bioremediation

In situ bioremediation (ISB) of chlorinated ethenes involves the stimulation of microorganisms to convert chloroethene contaminants to less harmful compounds. ISB of especially DNAPL source zones is practiced by many throughout the industry and is sometimes referred to by other names, including ERD, enhanced anaerobic bioremediation (EISB), and anaerobic reductive dechlorination (ARD).

In anaerobic conditions, microorganisms will ultimately metabolise organic contaminants to methane, limited amounts of carbon dioxide, and trace amounts of hydrogen gas. In anaerobic reactions, bacteria gain energy and grow as an atom on a contaminant element is replaced with hydrogen (AFCEE). Anaerobic metabolism encompasses many processes including fermentation, methanogenesis, reductive dechlorination, sulphate- and iron-reducing activities, and denitrification. Depending on the contaminant of concern, a subset of these activities may occur. EPA (2006a) explains that in anaerobic metabolism, nitrate, sulphate, carbon dioxide, oxidised metals, or organic compounds, such as chlorinated hydrocarbons, may replace oxygen as the electron acceptor. Hydrogen used in the reaction typically is supplied indirectly through the fermentation of organic substrates (EPA 2000).

In general, anaerobic conditions are used to degrade highly halogenated contaminants, though some petroleum hydrocarbons may also be biodegraded anaerobically. The halogenated compound, typically a chlorinated solvent such as tetrachloroethene (PCE), trichloroethene (TCE), 1,1,1-trichloroethane (TCA), carbon tetrachloride (CT), chloroform (CF), and methylene chloride or one of their degradation products dichloroethene (DCE), vinyl chloride (VC), dichloroethane (DCA), and chloroethane serves as the electron acceptor, while hydrogen serves as the direct electron donor (EPA 2000). Chlorinated solvents can exist and migrate in multiple phases depending on how they were released and the site conditions present. These include a vapour phase in unsaturated soils, a dissolved phase in groundwater, and non-aqueous phase liquids (NAPL) in the subsurface. Most chlorinated solvents are denser than water and hydrophobic. (ITRC 1999.)

During anaerobic biodegradation of chlorinated compounds, sequential removal of chloride ions is generally observed. Figure 6 demonstrates the dechlorination of PCE to TCE to cis-DCE or trans-DCE to VC to the final degradation product, ethene. In this reaction, hydrogen, the electron donor, is oxidised while the chlorinated ethene, the electron acceptor, is reduced. Hydrogen is generally the most important electron donor for anaerobic dechlorination. (Parsons 2004; EPA 2019a.)

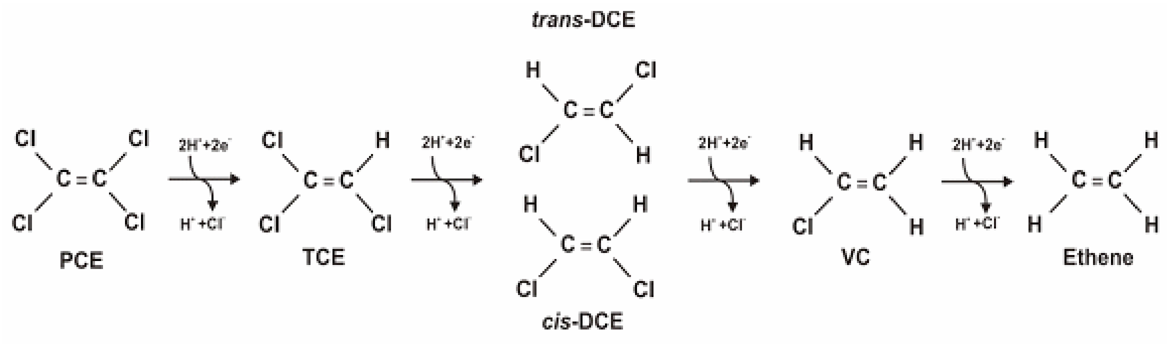


FIGURE 6. Dechlorination of PCE (Parsons 2004)

The anaerobic reductive dechlorination of the more highly chlorinated (more oxidised) chlorinated hydrocarbons, such as PCE and TCE, occurs more readily than the dechlorination of chlorinated hydrocarbons that already are somewhat reduced (less oxidised), such as DCE and VC. Therefore, it is important to determine as part of the planning stage that Dehalococcoides or other species capable of completely reducing PCE or TCE to ethene are present and are of sufficient quantity to ensure the process does not stop at DCE/VC and allow their build up in the subsurface. If necessary, the site can be bioaugmented with Dehalococcoides ethenogenes cultures to enable or accelerate degradation to ethene. (EPA 2019a.)

Most applications of anaerobic bioremediation occur in situ rather than ex situ. The most frequently used in situ bioremediation technique is enhanced reductive dechlorination that consists of the addition of organic substrates (electron donors) to ensure highly reducing conditions and to provide the hydrogen needed by dechlorinating organisms (ITRC 2005), which can be used for dissolved phase contaminants, DNAPL, and DNAPL source zones. In some cases, the addition of selected organisms (bioaugmentation) can be used as well (ITRC 2008). Figure 7 provides an example of the distinct zones that are established after the addition of an organic substrate to the source area.

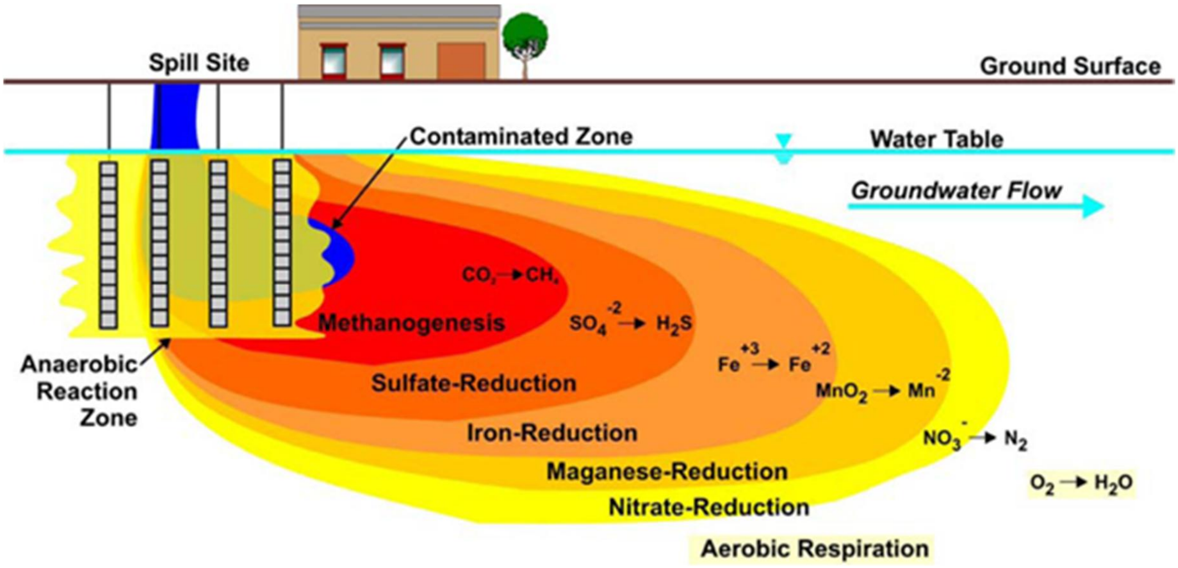


FIGURE 7. Anaerobic microbes use electron acceptors in preferential order: nitrate, manganese, ferric iron oxyhydroxides, sulphate, and carbon dioxide (Parsons 2004).

Most chlorinated solvents are DNAPLs and their properties make investigation and remediation difficult. According to EPA (2019a), in situ bioremediation does not work directly on free-phase DNAPL but relies on degradation and solubilisation processes that occur near the water-DNAPL interface, instead. In situ bioremediation technology and injection of electron donors can enhance the dissolution and desorption of non-aqueous-phase contaminants to the aqueous phase in which they can be degraded by the microbial population. (EPA 2019a.)

2.6.3 In situ chemical oxidation (ISCO)

In situ chemical oxidation (ISCO), a form of advanced oxidation processes and advanced oxidation technology, is an environmental remediation technique used for soil and/or groundwater remediation to reduce the concentrations of targeted environmental contaminants to acceptable levels. EPA (2012a) explains that ISCO is accomplished by injecting or otherwise introducing strong chemical oxidisers directly into the contaminated medium (soil or groundwater) to destroy chemical contaminants in place. It can be used to remediate a variety of organic compounds, including some that are resistant to natural degradation. (EPA 2012a.)

Chemical oxidation is one half of a redox reaction, which results in the loss of electrons. One of the reactants in the reaction becomes oxidised, or loses electrons, while the other reactant becomes reduced, or gains electrons. (EPA 2012a.)

The remediation of certain organic substances, such as chlorinated solvents (PCE, TCE), and gasoline-related compounds (BTEX and MTBE) by ISCO is possible. Some other contaminants can be made less toxic through chemical oxidation. (MEC^x 2019.)

A wide range of groundwater contaminants react either moderately or highly with the ISCO method, and ISCO can also be used in a variety of different situations (e.g. unsaturated vs saturated ground, above ground or underground, etc.), so it is a popular method to use. (EPA 2006b.)

To treat soil and groundwater in situ, the oxidants are typically injected underground by pumping them into wells (Figure 8). The wells are installed at different depths in the source area to reach as much dissolved and undissolved contamination as possible. Once the oxidant is pumped down the wells, it spreads into the surrounding soil and groundwater, where it mixes and reacts with contaminants. (EPA 2012a.)

To improve mixing, EPA (2012a) explains that the groundwater and oxidants may be recirculated between wells. This involves pumping oxidants down one well and then pumping the groundwater mixed with oxidants out another well. After the mixture is pumped out, more oxidant is added, and it is pumped back (recirculated) down the first well. Recirculation helps treat a larger area faster. Another option is to inject and mix oxidants using mechanical augers or excavation equipment. This may be particularly helpful for clayey soil. (EPA 2012a.)

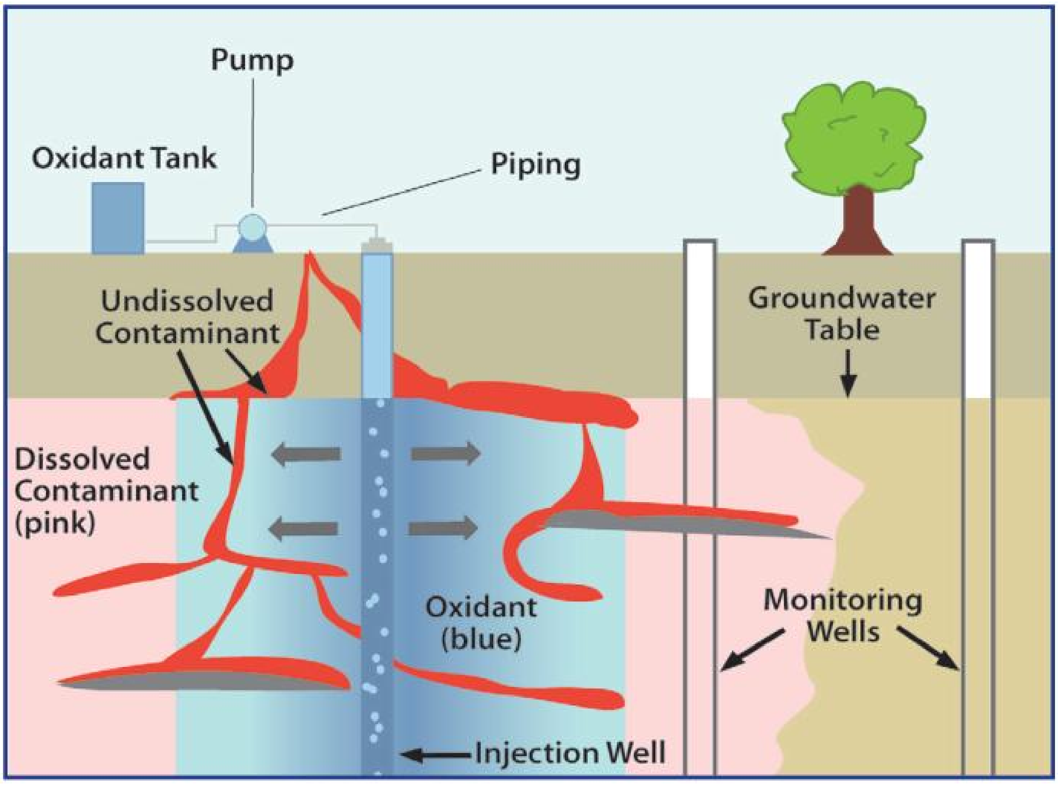


FIGURE 8. The principle of ISCO (EPA 2012a)

The four major oxidants used for ISCO are permanganate, persulfate, hydrogen peroxide and ozone. The first three oxidants are typically injected as liquids. Although ozone is a strong oxidant, it is a gas, which can be more difficult to use. As a result, it is used less often. (EPA 2012a.)

Catalysts are sometimes used with certain oxidants. A catalyst is a substance that increases the speed of a chemical reaction. For instance, if hydrogen peroxide is added with an iron catalyst, the mixture becomes more reactive and destroys more contaminants than hydrogen peroxide does alone. (EPA 2012a.)

Following treatment, if contaminant concentrations begin to climb back up or "rebound," a second or third injection may be needed. Concentrations will rebound if the injected oxidants did not reach all of the contamination, or if the oxidant is used up before all the contamination is treated. It may take several weeks to months for the contamination to reach monitoring wells and to determine if rebound is occurring. (EPA 2012a.)

2.6.4 In situ chemical reduction (ISCR)

In situ chemical reduction, or ISCR, uses chemicals called "reducing agents" to help change contaminants into less toxic or less mobile forms. ISCR can clean up several types of contaminants dissolved in groundwater. According to EPA (2012b) it can also be used to clean up DNAPLs, which do not dissolve easily in groundwater and can be a source of contamination for a long time. ISCR is most often used to clean up the metal chromium and the industrial solvent trichloroethene, or TCE, which is a DNAPL. (EPA 2012b.)

In essence, chemical reduction is the mirror process of in situ chemical oxidation (ISCO), a technique commonly used to treat environmental contaminants in soil and groundwater. (Regenesis 2019.)

When reducing agents are added to contaminated soil and groundwater, a chemical reaction occurs that changes contaminants into other forms. Common reducing agents include zero valent metals, which are metals in their pure form. The most common metal used in ISCR is zero valent iron (ZVI). ZVI must be ground up into small granules for use in ISCR. In some cases, micro- or nano-scale (extremely small) particles are used. (EPA 2012b.)

Figure 9 shows the two main ways of bringing reducing agents into contact with contaminated soil and groundwater: construction of a permeable reactive barrier (PRB) and direct injection (EPA 2012b.)

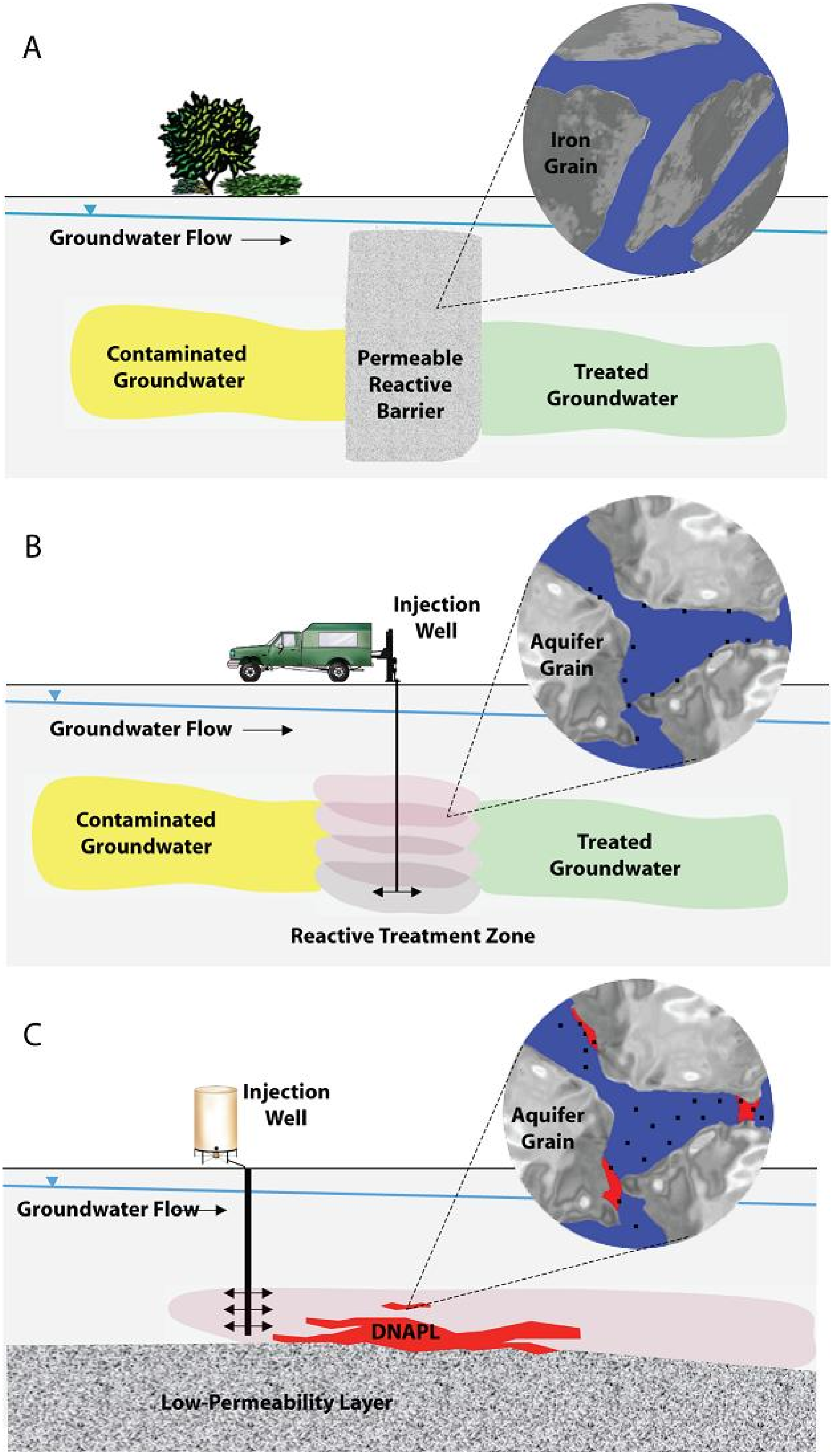


FIGURE 9. Schematic diagramme of two methods of groundwater remediation using nanoscale iron. Both B and C use injection. (Tratnyek research group 2005)

Permeable reactive barriers (PRBs) are one of the technologies widely accepted as an alternative to the ‘pump and treat’ (P&T) for sustainable in situ remediation of contaminated groundwater. The concept of the technology involves the emplacement of a permeable barrier containing reactive materials, such as granular ZVI, across the flow path of the contaminated groundwater to intercept and treat the contaminants as the plume flows through it under the influence of the natural hydraulic gradient. (Obiri-Nyarko et al. 2014)

Direct injection involves mixing the reducing agent with water (or sometimes vegetable oil) to create a slurry, which is pumped down holes drilled directly into the contaminated soil and groundwater. This method is often used to treat highly contaminated source areas, including DNAPLs. Nano-scale ZVI is usually used when injecting iron underground, but micro-scale ZVI is also used. (EPA 2012b)

Due to the high specific surface area, nano- and micro-sized ZVI-particles (nZVI & mZVi) are more reactive than granular materials. Moreover, nZVI- and mZVI-particles can be readily injected into the soil matrix, thus allowing for active treatment of source and plume areas, even at greater depth. (CityChlor 2013)

Nowadays there are many different types of ZVI-materials available on the market. ZVI-particles can be differentiated based on size (nano (1 µm)) and on constitution:

- Catalysed bimetallic ZVI-particles consist of zerovalent iron/metal and a catalyst (Pt, Pd) thus generating more reactive materials which cause higher degradation rates (CityChlor 2013).
- Supported ZVI-particles consist of ZVI-particles attached on a non-metallic carrier material, which mostly serves to create higher stability and mobility of the ZVI suspension (CityChlor 2013).
- Emulsified ZVI-particles (EZVI) are developed to directly treat the free phase of chlorinated solvents (DNAPL). The ZVI-particles are surrounded by a biodegradable oil-based hydrophobic membrane (CityChlor 2013).
- S-MicroZVI™ is an ISCR reagent that promotes the destruction of many organic pollutants and is most commonly used with chlorinated hydrocarbons. It is engineered to provide an optimal source of micro-scale ZVI that is both easy to use and delivers enhanced reactivity with the target contaminants via multiple pathways. S-MicroZVI can destroy many chlorinated contaminants through a direct chemical reaction. S-MicroZVI will also stimulate anaerobic biological degradation by rapidly creating a reducing environment that is favourable for reductive dechlorination. S-MicroZVI is composed of colloidal, sulfidated ZVI particles suspended in glycerol

> using proprietary environmentally acceptable dispersants. The passivation technique of sulfidation, completed using proprietary processing methods, provides unparalleled reactivity with chlorinated hydrocarbons like PCE and TCE and increases its stability and longevity by minimising undesirable side reactions. (Regenesis 2019b.)

Since the remediation with injectable ZVI-particles is based on direct contact between the ZVI-particle and the contaminant, the mobility and stability of the ZVI-particle in the soil is of crucial importance for the effectiveness of the remediation. Based on mathematical models and previous experiments, the mobility of non-modified nZVI-particles in the soil is limited to a few centimetres. The limited mobility is mainly due to aggregation of ZVI-particles (electromagnetic forces), ZVI-soil particle interactions and geochemical conditions. (CityChlor 2013.)

Mobility of ZVI-particles can be increased by

- surface modifications of ZVI-particles to prevent aggregation;
- the implementation of high injection velocities;
- mechanical modifications of the subsurface via fracturing (pneumatic or hydraulic) or dilatation (pressure pulse technology). (CityChlor 2013.)

Figure 10 shows how the ZVI particle size impacts the ease of injection (Regenesis 2019b).

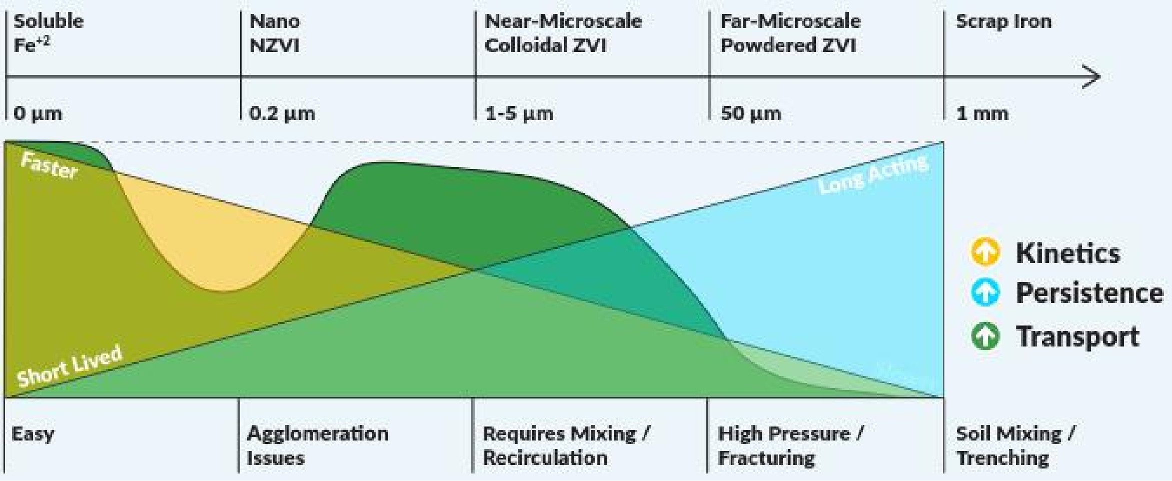


FIGURE 10. ZVI particle size impacts the ease of injection (Regenesis 2019b)

Modification examples include adding coatings such as polyelectrolyte or triblock polymers (Saleh et al. 2007; Hydutsky et al. 2007; He et al. 2007) to improve mobility, or encasing in emulsified vegetable oil droplets (Quinn et al. 2005) to improve stability and to improve reactivity by improving contact with the contaminant (see EZVI section below). Some nanoscale materials are made with catalysts (see Bimetallic nanoscale particles section below) that enhance the intrinsic reactivity of the surface sites (Tratnyek and Johnson 2006). It should be noted that modifications to enhance mobility may result in reduced reactivity (Phenrat et al. 2009). (EPA 2019b.)

Bimetallic nanoscale particles (BNP)

BNPs have been used to remediate contaminants in soil and groundwater. BNPs consist of particles of elemental iron or other metals in conjunction with a metal catalyst, such as platinum, gold, nickel, and palladium. EPA (2019b) explains that the combination of metals increases the kinetics of the oxidation-reduction (redox) reaction, thereby catalysing the reaction. Palladium and iron BNPs are commercially available and currently the most common. In bench-scale tests, according to Zhang & Elliot (2006), BNPs of iron combined with palladium achieved contaminant degradation two orders of magnitude greater than microscale iron particles alone: these particles were 99.9 percent iron and less than 0.1 percent palladium. Nutt et al. (2005) note that palladium can catalyse the direct reduction of TCE to ethane without producing other intermediate by-products such as VC. BNPs are generally incorporated into a slurry for injection and can be injected by gravity or by pressure feed (Gill 2006). (EPA 2019b.)

Emulsified zero-valent iron (EZVI)

EZVI has been specifically developed for the treatment of free phases of chlorinated solvents (DNAPLs) (Quinn et al. 2003). EZVI consists of nano- or microscale ZVI surrounded by an emulsion membrane that facilitates treatment of chlorinated hydrocarbons. The exterior emulsion membrane is made from food-grade surfactant and biodegradable oil and the inside of the droplets contain water and the ZVI particles. Figure 11 illustrates the structure of an EZVI particle. The exterior emulsion membranes are hydrophobic, similar to the properties of dense nonaqueous phase liquid (DNAPL) contaminants such as TCE. EZVI particles (or "droplets") therefore mix directly with DNAPL. When the emulsion droplets come into contact with a TCE DNAPL, the TCE partitions into the oil membrane and then diffuses into the interior of the emulsion droplet, where it comes into contact with the ZVI and is degraded. O’Hara et al. explain that a concentration gradient is established by migration of the TCE molecules into the interior aqueous phase of the emulsion droplet and by migration of the by-products out of the droplet and into the surrounding water phase, further driving the degradation reactions. (O'Hara et al. 2006.)

The vegetable oil can also provide "food" (electron donors) to microorganisms and enhance biological activity, which in turn contributes to the destruction of the contaminant (Quinn et al. 2005). In addition, EZVI can be especially effective when DNAPL is present because DNAPL tends to be miscible in vegetable oil. When DNAPL contacts EZVI, the DNAPL can mix with the EZVI, after which the contaminants are in close proximity with the ZVI and can be effectively degraded. (EPA/CLU-IN 2019.)

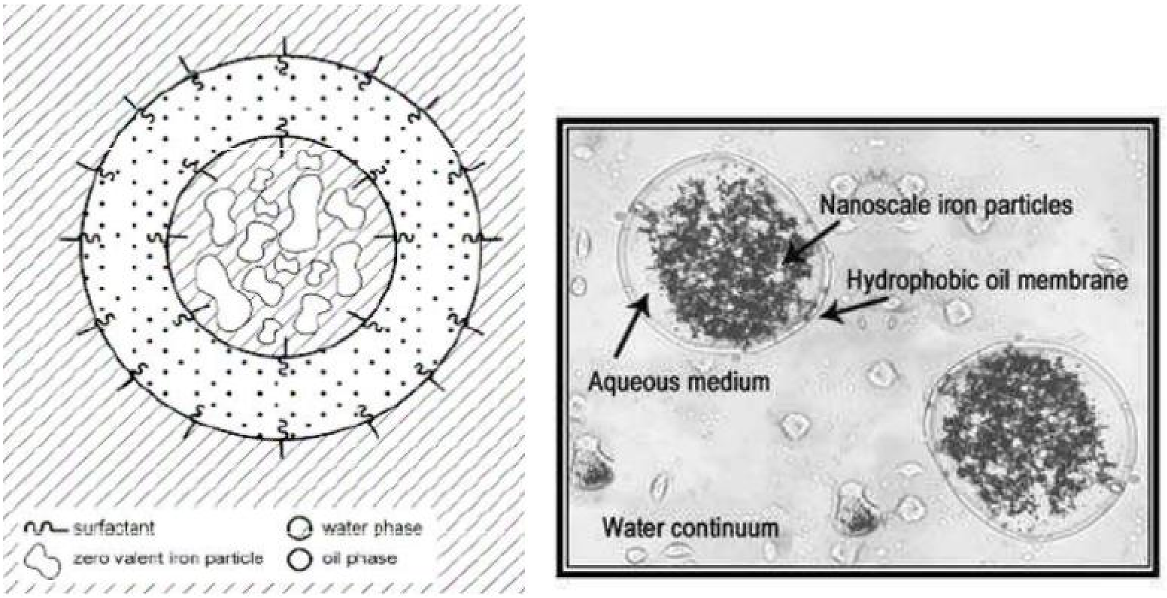


FIGURE 11. Graphic representation of EZVI particles (left) & microscopic view of EZVI particles (right) (CityChlor 2013)

For the past 20 years, nanoscale metallic iron (nZVI) has been investigated as a new tool for the treatment of contaminated water and soil. The technology has reached commercial status in many countries worldwide, however is yet to gain universal acceptance.

Key factors for a lack of universal acceptance include:

- concerns over the long-term fate,
- transformation and ecotoxicity of nZVI in environmental systems and,
- a lack of comparable studies for different nZVI materials and deployment strategies.

It is highlighted that few investigations to date have examined systems directly analogous to the chemistry, biology and architecture of the terrestrial environment. Such emerging studies have highlighted new concerns, including the prospect for remobilisation of heavy metals and radionuclides over extended periods. The fundamental importance of being able to accurately predict the long-term physical, chemical and biological fate of contaminated sites following nZVI treatment is emphasised and, as part of this, a universal empirical testing framework for nZVI is suggested. (Crane & Scott 2012.)

2.6.5 Air sparging (AS)

In situ air sparging is a means by which to enhance the rate of mass removal from contaminated saturated-zone systems. Air sparging (AS) involves injecting air into the target contaminated zone, with the expectation that volatile and semivolatile contaminants will undergo mass transfer (volatilisation) from the groundwater to the air bubbles (Figure 12). Because of buoyancy, the air bubbles generally move upward toward the vadose zone, where a soil-venting system (soil vapour extraction, SVE) is usually employed to capture the contaminated air stream. (EPA 2012c.)

Recent laboratory and pilot-scale research has shown that the effectiveness of air sparging is often limited by a number of factors in practice. One major constraint is the impact of "channelling" on air movement during sparging. Studies have shown that air injected into water-saturated porous media often moves in discrete channels that comprise only a fraction of the entire cross section of the zone, rather than passing through the entire medium as bubbles (as proposed in theory). This channelling phenomenon greatly reduces the "stripping efficiency" of air sparging. (EPA 2012c.)

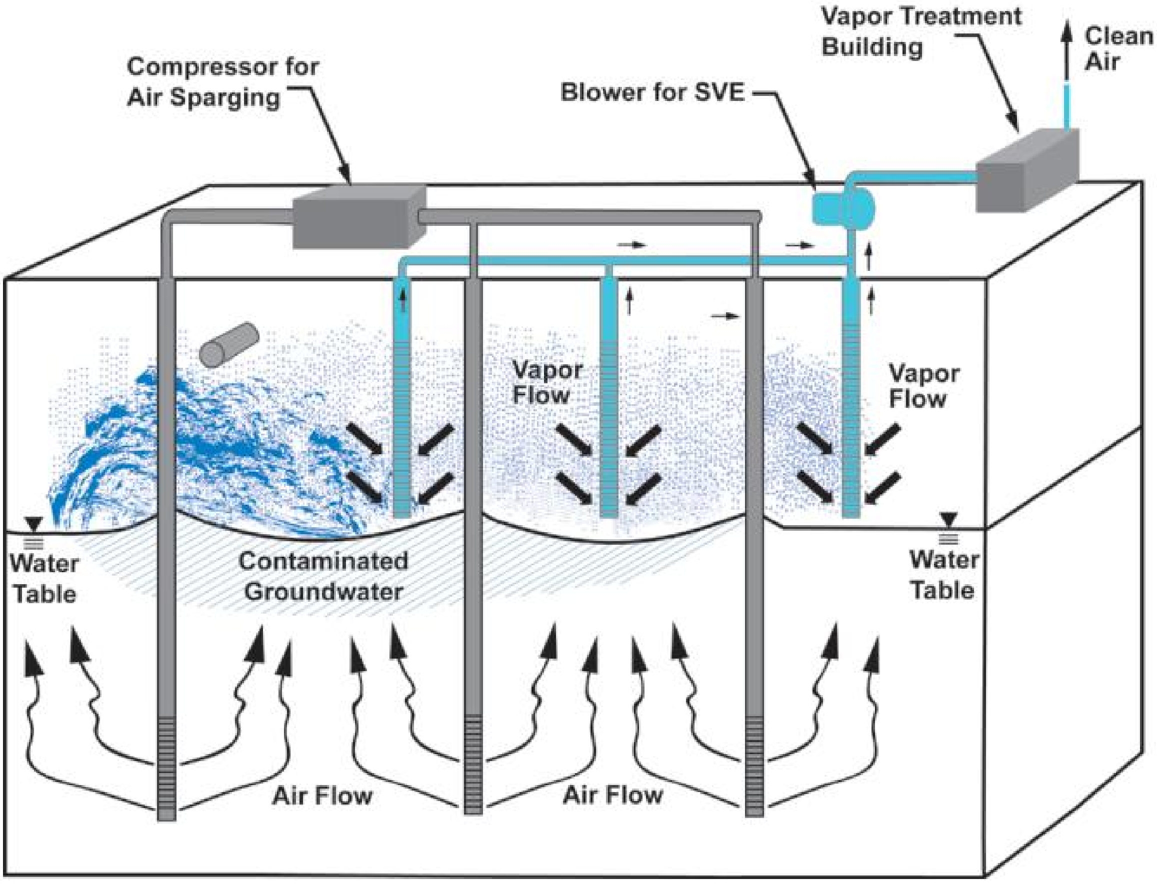


FIGURE 12. Illustration of a combined AS and SVE system (EPA 2012c)

Another significant limitation to air sparging applications is the presence of low-permeability zones overlying the target zone. As previously noted, air-sparging systems are designed to operate in tandem with a soil-venting system, so that the contaminated air can be collected and treated. Brusseau & Maier (2004) explain that the presence of a low-permeability zone overlying the target zone can prevent the air from passing into the vadose zone, preventing capture by the soil-venting system. In such cases, the air-sparging operation may act to spread the contaminant. Although limited by such constraints, air sparging may be of potential use for specific conditions, such as for targeting localized zones of contamination. (Brusseau & Maier 2004.)

2.6.6 In situ thermal treatment (ISTT)

In Situ Thermal Treatment (ISTT) is particularly suitable for sites with significant contaminant mass (variously described as source zone(s), free product, non-aqueous phase liquid (NAPL), or hot spots) (EPA 2015).

ISTT has been used in a variety of settings:

- Beneath operating industrial facilities/commercial buildings
- Beneath inhabited residential structures
- Beneath the water table
- At considerable depth below ground surface (>30 m)
- In low permeability strata
- In fractured rock (EPA 2015)

In situ thermal treatment methods move or “mobilise” harmful chemicals in soil and groundwater using heat. The chemicals move through soil and groundwater toward wells, where they are collected and piped to the ground surface to be treated using other remediation methods (Figure 13). Some chemicals are destroyed underground during the heating process. Thermal treatment is described as “in situ” because the heat is applied underground directly to the contaminated area. It can be particularly useful for NAPLs, which do not dissolve readily in groundwater and can be a source of groundwater contamination for a long time if not treated. Examples of NAPLs include solvents, petroleum, and creosote (a wood preservative). (EPA 2012d.)

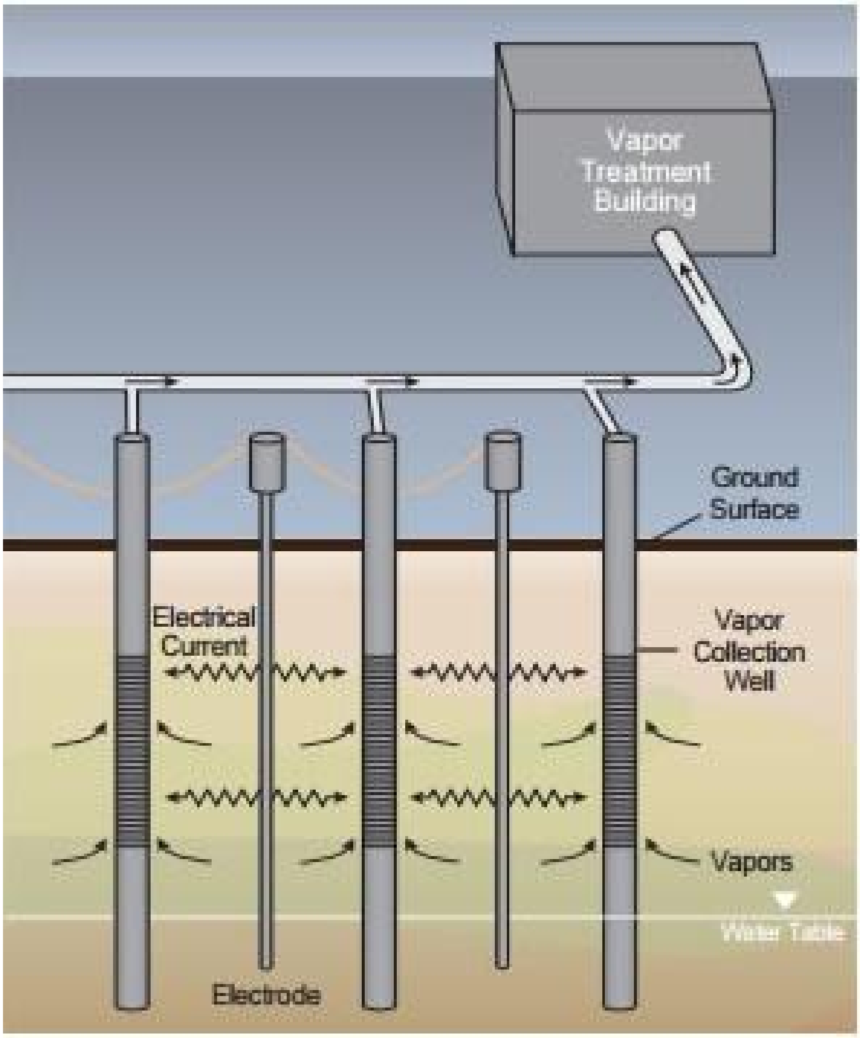


FIGURE 13. Principle of in situ thermal treatment system (EPA 2012d)

According to EPA (2015), treatment volume is a primary factor in the cost of ISTT. Conceptual site model (CSM) refinement efforts that more accurately define the volume requiring thermal treatment are a good investment. (EPA 2015.)

If ISTT is to be the primary or only remediation technology, it is desirable to match the ISTT system footprint to the source zone(s) to be treated. At sites with groundwater plume restoration objectives, failure to adequately treat the source(s) will hamper or frustrate achievement of remedial action objectives (RAOs). If untreated source material is upgradient, treated source areas are likely to be re-contaminated. Target treatment zones may be defined as volumes of known or suspected NAPL and/or may be circumscribed by a concentration isopleth. (EPA 2015.)

2.7 Vapour intrusion

2.7.1 Principle

Vapour intrusion is defined as the migration of volatile contaminants from the subsurface into overlying buildings. Volatile contaminants from buried wastes and/or contaminated groundwater or soil can migrate through subsurface soils and into indoor air spaces of overlying buildings. The vapour intrusion risk pathway may be important for buildings with or without a basement. (EPA 2008b.)

According to EPA (2008b), most vapour intrusion cases occur when contaminants from either the soil or groundwater enter the soil gas at the water table or in the vadose (unsaturated) zone. The contaminated soil gas then migrates under the influences of advective flow or diffusion until they escape into the atmosphere or enter the zone of influence of a building. The term “advective flow” here refers to bulk flow driven by pressure or density differences. (EPA 2008b.)

Volatile chemicals can enter the vapour phase via partitioning across the groundwater/soil gas interface (a process which at equilibrium can be described by Henry’s Law). Volatile compounds can also enter soil gas via volatilisation from a free phase contaminant or adsorbed contaminant. Contaminants may undergo transformation in the subsurface, and the flux of contaminants may vary seasonally or otherwise due to changes in soil moisture, height of the water table, barometric pressure, and other factors. Once in soil gas, deep in the soil and absent any natural or anthropogenic preferential flow conditions, diffusion dominates the soil vapour transport process; but near the building, advective flow is the dominant mechanism. (EPA 2008b.)

The building’s zone of influence arises from two primary effects:

1) The building constitutes a barrier to the free upward migration of the contaminants, so they tend to accumulate under the building.
2) The building interacts with the soil through pressure differences that are induced between the interior of the building and the soil.

A basic conceptual model of subsurface contaminant movement into the sub-slab space involves the migration of volatile contaminants upward from a contaminated soil or groundwater source, through the unsaturated zone, to the engineered fill material which usually underlies a building slab. In this sub-slab space, the distribution of contaminants is dependent on a number of factors, including the distance from and geometry of the source area, geological influences on vapour migration, and foundation design. (EPA 2008b.)

2.7.2 Pathway

Sub-slab vapours may also follow preferential pathways such as utility corridors instead of collecting uniformly under the slab or above the source (NJDEP 2005). Sub-slab vapours can then migrate into the overlying structure. Vapour migration into residences is generally thought to be at its maximum during the cold season, when there is a significant difference in temperature between ambient and indoors. (EPA 2008b.)

When the pressure in the lowest portion of the building (i.e., basement, crawl space or ground floor) is lower than the pressure in the soil below the building soil gas advectively flows into the building through cracks or openings. This negative pressure in the building is often due to the stack effect (buoyancy of warmer indoor air), barometric pressure changes or the interaction of the building with winds. According to EPA (2008b), this advective flow of contaminated soil gas is the primary mechanism by which soil vapour intrudes into buildings. It is much more important than direct diffusion through pores. Only after advective flow through macroscale cracks has been substantially reduced (by reducing driving forces and closing entry routes) does diffusion through concrete slab pores become the dominant entry mechanism. EPA (2008b) goes on to explain that typically, this situation occurs only in buildings in which the foundation has been specifically engineered to prevent entry of soil gases through cracks. Diffusion constitutes a significant risk pathway only if the concentration in the sub-slab soil gas is very high or the slab is unusually thin and porous. Unparged cinder block walls are, however, a separate case. Cinder blocks are intentionally designed to be lighter than concrete blocks and are more porous. Advective flow through cinder block walls is therefore likely. (EPA 2008b.)

Below are listed the most typical vapour intrusion pathways:

- Poured concrete joints such as control joints and the floor-wall interface
- Fieldstone, concrete block, and brick mortar joints
- The interstitial space between inner and outer courses in above-grade brick courses
- Utility penetrations (sewer, water, gas, storm water, buried electrical)
- Sumps and interior perimeter drains
- Crawl spaces
- Dirt floors and incomplete concrete floor slabs
- Cracked concrete floor slabs (Ash et al. 2010)

The stack effect is a process that induces a negative pressure in the interior of the building as warm air rises and escapes through the top of the building. In turn this process draws replacement air in through the openings in the lower portion of the building; some of these openings will draw in soil gas. The stack effect is less strong in the summer time in buildings with a cooling system running. EPA (2008b) reminds that although this simplified view of the stack effect would suggest that the flow would reverse directions in the summer, empirical observations indicate that the driving forces across the slab still are in the direction of vapour intrusion during the summer, at least on average over 24 hours. The phenomenon of summertime soil gas entry is probably aided by the fact that the temperature in the sub-slab remains lower than the indoor air temperature during summer. (EPA 2008b.)

Negative pressures in a building can also be enhanced by mechanical systems such as heating and cooling systems, exhaust fans (including those built into stoves or grills), clothes dryers, central vacuums and combustion devices, especially fireplaces. EPA (2008b) points out that since bathroom, kitchen, or utility room ventilation fans remove large volumes of air from those rooms, the rooms may depressurise if the doors are shut. This depressurisation could cause at least brief periods of high vapour intrusion if the kitchen, bath, or utility room is on the lowest floor (in contact with the soil). The exposure period in these cases can be short. Building exhaust fans, if operated for a long period of time, can cause significant depressurisation in whole buildings, especially if there is no system providing an inflow of outside air. (EPA 2008b.)

In order to have a potential vapour intrusion problem, there must be:

- Contaminants in the soil gas
- Entry routes for soil gas to enter the inhabited building or the potential for future inhabited buildings
- Driving forces (pressure gradients or diffusion gradients) to draw the contaminants into the building. (Geyer 2006)

A method for removing any one of these three conditions would constitute mitigation. Removal of the source is the definitive long-term solution. EPA (2008b) notes that many remediation technologies, or passive methods such as natural attenuation, might require years or even decades. Moreover, there may be natural sources of contaminants such as radon or methane that cannot be effectively removed. Consequently, it is necessary to utilise one or a combination of the other two conditions to create intermediate mitigation methods to protect the public health. (EPA 2008b.)

The primary options are to prevent entry of the contaminants into the building or remove the contaminants after they have entered (EPA 2008b.)

Vapour intrusion has been recognised as a potential exposure pathway at contaminated sites for decades, however, before the year 2000, few regulatory guidance documents provided comprehensive recommendations for field investigation of this pathway. Following the discovery of vapour intrusion problems at a small number of sites in the late 1990s and early 2000s, this exposure pathway has received more attention in regulatory guidance and among the regulated community. As a result, our understanding of the vapour intrusion pathway has evolved rapidly since 2000. (McHugh et al. 2017.)

Lines of evidence

The attribution of chemicals in indoor air to vapour intrusion can become a relatively complex and difficult task. ITRC reminds that it is important to use multiple lines of evidence to reach decisions based on professional judgment. (ITRC 2007.)

The following are some lines of evidence, listed in no particular order:

- soil gas spatial concentrations, including sub-slab and exterior (some distance outside the perimeter of the foundations) soil gas data with some level of vertical profiling, if appropriate
- groundwater spatial data, with vertical profiling, if appropriate
- background sources (internal and external)
- building construction and current conditions
- sub-slab (or crawl space) soil gas data
- indoor air data
- concurrent outdoor air data
- constituent ratios

Other lines of evidence may be available depending on the site-specific circumstances. Conversely, regulatory frameworks of individual states may limit the ability to use some or all of these lines. (ITRC 2007.)

Figure 14 depicts the migration of vapours in soil gas from contaminated soil and groundwater into buildings. Vapours in soil gas are shown to enter buildings through cracks in the foundation and openings for utility lines. Atmospheric conditions and building ventilation are shown to influence soil gas intrusion.

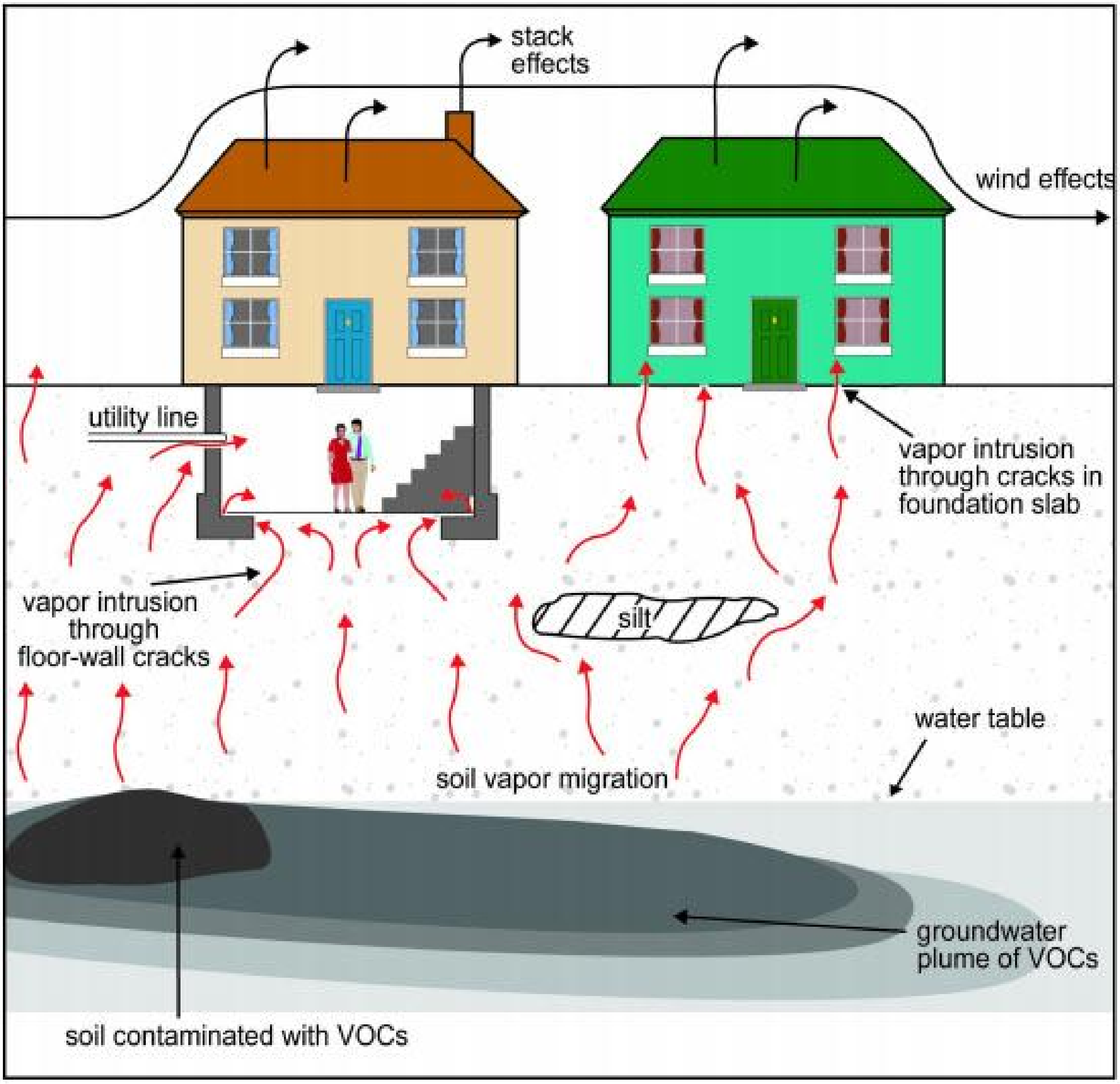


FIGURE 14. Migration of soil vapours to indoor air (EPA 2017)

2.8 Risk management above the groundwater table

2.8.1 Land use planning and strategies for new construction

At new construction sites it can possible to plan a redevelopment according to the conceptual site model (CSM). EPA (2008a) explains that, for example, new building construction could be targeted to the portions of the site that are least prone to vapour intrusion, such as those areas furthest from the contaminant source or upgradient of a groundwater plume. (EPA 2008a.)

Future-use exposure scenarios may involve the evaluation of municipal zoning criteria (commercial, residential) and zoning exceptions (e.g., commercial zones that allow residential, multifamily residential, second-story residential). ITRC (2007) states that the use of institutional controls (e.g., deed restrictions, environmental covenants) can be appropriate to ensure that a contaminated property is safe and healthy for future residential use. Institutional controls could include land use restrictions, future building design requirements to address the potential for vapour intrusion, notification requirements for land owners/developers, or stipulations for further investigation of the vapour intrusion pathway during evaluation of specific future use scenarios. (ITRC 2007.)

In addition, construction could incorporate strategies that minimise vapour intrusion induced by stack and wind effects and ventilate vapours. Such strategies include using a raised building design or including an open-air parking facility on the lower level of the building. Plans for new buildings could also proactively consider the potential for vapour intrusion by incorporating mitigation strategies into construction. (EPA 2008a.)

According to EPA (2008a) buildings should be designed and constructed to minimise potential entry pathways for vapours and minimise the pressure differences that draw them in. Examples of design elements that can be evaluated include lift shafts (and drains), utility corridors and penetrations, and basement sumps. HVAC systems in new buildings can be designed to limit entry pathways and conduits, and/or create positive pressure inside the building. EPA (2008a) points out that incorporating vapour intrusion mitigation strategies into new construction provides more options for mitigation and can save costs in the long run. For example, radon mitigation systems, which are normally required in high-radon areas in Finland too, could be introduced to mitigate vapour intrusion. Another possibility is placing aggregate beneath the foundation slab and installing passive ventilation systems which can facilitate incorporation of further post-construction mitigation systems. (After EPA 2008a.)

2.8.2 Mitigation of vapour intrusion

Whether existing structures will be renovated or new buildings constructed, vapour intrusion can be mitigated at brownfield sites. Eliminating the source of contamination can be more protective of human health and the environment than mitigation alone, but it may not be technically feasible, cost-effective, or well-suited to site redevelopment. EPA (2008a) reminds that depending on the nature of contamination present, source elimination may involve a combination of activities, such as excavating contaminated soil for treatment and disposal, pumping and treating groundwater plumes, or soil vapour extraction to remove vapours. Additionally, several remediation technologies available to treat soil and groundwater in situ, which avoids the hazard and added expense of handling and disposing large volumes of waste. (EPA 2008a.)

However, eliminating the source of contamination is unlikely to immediately protect building occupants from vapour intrusion. Because remedial activities can take years to be completed, institutional controls may be required to prevent or limit development of certain parcels until the risks have been sufficiently reduced via remediation. Furthermore, EPA (2008a) points out that mitigation may be necessary. For example, existing buildings may need to be retrofitted with vapour mitigation systems, and new construction may require design elements that incorporate the mitigation of vapour intrusion. Next sections offer a glance on both passive and active mitigation methods for vapour intrusion. (EPA 2008a.)

According to Ash et al. (2010), under certain conditions and with the appropriate design, passive systems can be successful in mitigating the vapour intrusion pathway and have the advantage of being greener and more sustainable over the long term. Active systems, such as sub-slab depressurisation systems utilised for radon mitigation, are being used increasingly to mitigate vapour intrusion pathways. While active systems can be effective, they are not the only option, and in some cases may not be the preferred approach. (Ash et al. 2010.)

There are numerous potential vapour intrusion pathways including:

- Poured concrete joints such as control joints and the floor-wall interface
- Fieldstone, concrete block, and brick mortar joints
- The interstitial space between inner and outer courses in above-grade brick courses
- Utility penetrations (sewer, water, gas, storm water, buried electrical)
- Sumps and interior perimeter drains
- Crawl spaces
- Dirt floors and incomplete concrete floor slabs
- Cracked concrete floor slabs (Ash et al. 2010)

Building control remedies are typically required at vapour intrusion sites (in both existing and new buildings) until long-term, sitewide remedies reduce soil and/or groundwater concentrations to acceptable levels. (ITRC 2007.)

Building control technologies

Several building control technologies that can reduce or eliminate the potential for vapour intrusion impacts in new and existing buildings are identified below. A brief summary of each technology is provided, along with some of the advantages and disadvantages of each system. In addition, a typical range of installed costs for each technology is provided. Because vapour intrusion controls are often added to older buildings, the potential need for and additional costs of lead paint and asbestos abatement should be considered on a case-by-case basis. In some cases, excessive costs associated with these issues could affect technology selection. (ITRC 2007.)

Table 3 summarises the typical attributes of each technology. It should be noted that the ranges of installed costs are based on ITRC information from 2007 and have not been updated.

TABLE 3. Comparison of mitigation methods (ITRC 2007)

Technology	**Typical applications**	**Challenges**	**Range of installed costs***
Passive barrier	• New construction • Crawl spaces • Often combined with passive or active venting, sealing openings in the slab, drains, etc.	• Preventing tears, holes • May not suffice as a stand-alone technology • Some states (in the U.S.) do not accept • Ensuring caulking seals cracks in floors, etc.	• 4–40 €/m^2 • Thinner, less-expensive barriers likely to be inadequate
Passive venting	• New construction • Low soil gas flux sites • Should be convertible to active system if necessary	• Relies on advective flow of air due to wind and heat stack effects • Air flows and suction typically far less than achieved by fans	• 6–40 €/m^2
Sub-slab depressurisation (SSD)	• New and existing structures • Sumps, drain tiles, and block wall foundations may also be depressurised if present	• Low permeability and wet soils may limit performance • Otherwise, highly effective systems	• 8–40 €/m^2 • Residential systems typically in the 8–16 €/m^2 range
Submembrane depressurisation	• Existing structures • Crawl spaces	• Sealing to foundation wall, pipe penetrations • Membranes may be damaged by occupants or trades people accessing crawl space	• 8–48 €/m^2 • Residential systems typically in the 12–16 €/m^2 range
Sub-slab pressurisation	• Same as SSD • Most applicable to highly permeable soils	• Higher energy costs and less effective than SSD • Potential for short-circuiting through cracks	• 8–40 €/m^2
Building pressurisation	• Large commercial structures, new or existing • Sensitive receptors	• Requires regular air balancing and maintenance • May not maintain positive pressure when building is unoccupied	• 8–120 €/m^2 • Heavily dependent on size and complexity of structure

Indoor air treatment	• Specialised cases only	• Typically generates a waste disposal stream • Effective capture of air contaminants may be difficult • Energy-intensive, with significant operation, maintenance, and monitoring burden	• 11,000–18,500 € per application not atypical • Actual costs heavily dependent upon type of technology employed
Sealing the building envelope	• Cracks and holes in existing buildings	• Access to perforations • Permanence	• Highly dependent on the extent of sealing required

* Costs per square metre based on building footprint

2.8.3 Passive mitigation methods

The general aim of passive mitigation methods is to prevent vapour intrusion by blocking entries through the building foundation. EPA (2008a) points out that it is usually simpler and more cost-effective to prevent the entry of soil vapour than remove soil vapours using active approaches. However, active mitigation methods are generally more effective at meeting regulatory standards for the vapour intrusion pathway. Selection of approach will depend on site circumstances, including the amount of contaminant reduction in the vapour required. The primary passive approaches are to seal cracks, install a passive barrier, and install a passive venting system. (EPA 2008a.)

Sealing cracks

According to EPA (2008a), cracks and openings in the building foundation are the primary routes of vapour entry. Thus, sealing cracks in the floors and walls as well as gaps around utility conduits is an important first step in preventing vapour intrusion. Sealing cracks and gaps can be necessary when the practise is used with other mitigation strategies, such as sub-slab depressurisation to ensure efficiency. Similarly, any gaps around utilities, sumps, and lift shafts need to be properly sealed. (EPA 2008a.)

In existing buildings, cracks may be difficult to find, and as buildings age, more cracks tend to appear, and seals tend to fail. Buildings that are in seismically active areas may be particularly prone to additional cracking and compromising of existing seals. On the other hand, walls made of porous cinder blocks may also allow vapour entry. (EPA 2008a.)

According to EPA (1988) studies of radon gas, a thorough job of sealing cracks and openings typically only results in a 50–70 percent reduction in radon entry. As a result, the EPA does not recommend radon mitigation merely by sealing cracks because this approach has not been shown to lower levels significantly or consistently (EPA 2003). Thus, additional mitigation also may be needed to prevent vapour intrusion. (EPA 2008a.)

Passive barriers

ITRC (2007) explains that passive barriers are materials or structures installed below a building to block the entry of vapours. Barriers are usually installed during construction, but, if needed, they can be installed in existing buildings with a crawl space. Typically, a passive barrier comprises a sheet of polyethylene plastic or equivalent geomembrane installed beneath a slab-on-grade foundation and sealed to the foundation walls or footings. ITRC (2007) points out that passive barriers are only effective if they are not compromised by holes, tears, or a poor seal around the foundation. Therefore, their integrity must be tested after installation. It should also be noted that, passive barriers without an underlying venting layer are not likely to be effective unless the subsurface conditions are conducive to natural venting. (ITRC 2007.)

A passive barrier can also be applied in liquid form. An example of such is a technology called “Liquid boot”. It is a spray-applied, water-based membrane which does not contain any volatile organic compounds (VOCs). With superior chemical resistance properties, it seals vapour intrusion pathways, preventing contaminated soil vapours from penetrating the slab. Liquid boot spray can be used in underslab and below-grade vertical wall applications to minimise gas and vapour intrusion into buildings. (Minerals Technologies 2019.)

Passive venting

In areas where vapour intrusion may be anticipated in new buildings, passive venting systems may be introduced to control vapour intrusion. These systems are often combined with passive barriers. Typically, perforated collection pipes, such as radon systems, are installed in a layer of permeable sand or gravel to direct vapours to the edges of the foundation. EPA (2008a) explains that such collection pipes are often connected to a main header point that runs up through the building’s inner wall and exhausts above the roofline. If the permeable layer is vented directly to the atmosphere, no exhaust pipes are needed. (After EPA 2008a.)

Because passive systems rely on wind currents to induce vapour flow through the pipes, they can be ineffective at removing vapours on days that are not windy. On the other hand, if the wind blows towards the exhaust pipe at the roof-line level, it may blow vapours back down to the sub-slab region. Thus, active systems which use electric fans to induce vapour flow, are more consistently effective at mitigating vapour intrusion. However, passive venting systems can often easily be converted to an active depressurisation system when needed. (EPA, 2008a)

2.8.4 Active mitigation methods

With active approaches to mitigate vapour intrusion, the primary idea is to remove the driving force behind vapour migration, which is the higher pressure that exists in the sub-slab area relative to indoors. Potential vapour flow is neutralised or reversed by lowering the pressure beneath the sub-slab or passive barrier or inducing a higher pressure in the building. (EPA 2008a.)

Depressurisation

There are several types of depressurisation systems, including sub-slab depressurisation, sub-membrane depressurisation, block-wall suction, and drain-tile suction. In most cases, according to Mosley (2005), mitigation of residential structures requires a sub-slab depressurisation system, which can be installed in buildings with basements or slab-on-grade construction. They are similar to passive venting systems, except that they include a fan to induce a level of sub-slab depressurisation that compensates for the depressurisation of the building. In practice, the purpose of these systems is to sweep contaminated soil vapour, or natural radon gas, from the sub-foundation (Figure 15). The fans should normally operate quietly without disruption to building occupants. Depressurisation systems offer the added benefit of reducing radon concentrations, moisture, and mould. (Mosley 2005; EPA 2008a.)

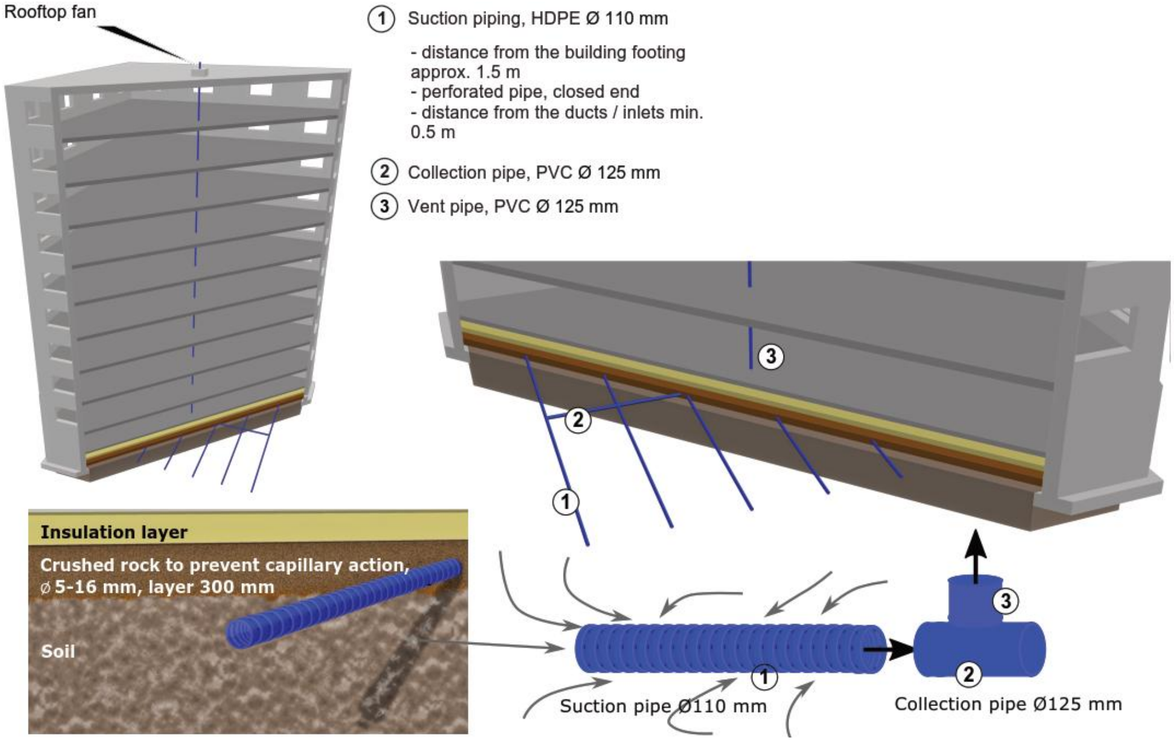


FIGURE 15. Schematic of an active sub-slab depressurisation system. The system provides a pathway for the vapours to vent to the outside air, instead of migrating into the building (Ramboll 2018)

In existing buildings, holes are drilled into the sub-slab for installation of vertical PVC pipes (usually 110 mm of diameter). The optimum location for the pipes would be near the centre of the sub-slab. However, this location is often inconvenient to building occupants. Therefore, EPA (2008a) suggests that pipes are installed at the perimeter of a room but, at the same time, they should not be too close to the building footing to avoid short circuiting of ambient air down the exterior wall. The pipes are usually connected by manifold and equipped with a fan to draw vapours up the pipe, or stack. The stack is typically vented to the outdoors at the top of the building. EPA (2008a) reminds that although the location of the stack vent is usually at the discretion of the owner, consideration should be given to position of the vent so that there are no windows, decks, or other location near where air can be inhaled or drawn back into the building or neighbouring buildings. Additional suction points may be needed, if the soil beneath the building is not very permeable or if the gravel subbase is discontinuous. After installation of the system, a demonstration of a negative pressure under the entire slab can be used to confirm the performance. (EPA 2008a.)

Submembrane depressurisation systems are similar to sub-slab depressurisation systems except that they are installed below the passive barrier during construction, or can be retrofitted in buildings with crawl spaces. The vertical pipes penetrating the passive barrier should be well-sealed. The principle of block-wall suction systems is to remove vapours that accumulate in basement walls constructed of hollow blocks whereas drain-tile suction systems apply suction to existing water drainage systems that circle a building, in order to remove vapours. (EPA 2008a.)

Sub-slab soil pressurisation

A sub-slab soil pressurisation system is similar to a depressurisation system except that the fan is reversed to pressurise the sub-slab region and divert the air flow away from the foundation. EPA (2008a) points outs that this practise should only be used for high permeability soil and if other options fail. It is generally not recommended because it can exacerbate vapour intrusion in some situations. (EPA 2008a.)

Building pressurisation

Building pressurisation involves adjusting the heating, ventilation, and air conditioning (HVAC) system of a building or installing a new system to maintain a positive pressure indoors relative to the sub-slab area. This approach is more commonly used in large commercial buildings and can be the most cost-effective if there is already positive pressure maintained by the existing HVAC system (ITRC 2007). However, increasing the pressure will result in larger energy costs, particularly if significant heating and cooling is required, and having to replace an HVAC system will be significantly more expensive. (EPA 2008a.)

According to EPA (2008a), modifications to an HVAC system should be designed to avoid condensation of water resulting from excessive humidity. Excess moisture can foster the growth of mould, which has significant negative impacts on indoor air quality and potentially the health of building occupants. Conversely, in cold climates HVAC modifications might sometimes lead to uncomfortably low levels of humidity. (EPA 2008a.)

2.8.5 Crawl space

A crawl space is a type of basement in which one cannot stand up. The height may be as little as 30 cm, and the surface is often soil. Crawl spaces offer a convenient access to pipes, substructures and a variety of other areas that may be difficult or expensive to access otherwise. Care must be taken in designing crawl spaces as water from the damp ground, water vapour (entering from crawl space vents), and moisture seeping through porous concrete can create a perfect environment for mould to form on any surface in the crawl space, especially cardboard boxes, wood floors and surfaces, drywall and some types of insulation. (Wikipedia 2019.)

Health and safety issues must be considered when installing a crawl space. As air warms in a home, it rises and leaves through the upper regions of the house, much in the same way that air moves through a chimney. This phenomenon, called the "stack effect", might cause the home to suck air up from the crawl space into the main area of the home. Mould spores, decomposition odours, and faecal material from dust mites in the crawl space can come up with the air, aggravating asthma and other breathing problems, and creating a variety of health concerns. (Medical College of Wisconsin 2005.)

It is usually desirable to finish a crawl space with a plastic vapour barrier that will not support mould growth or allow humidity from the earth into the crawl space. This helps insulate the crawl space and discourages the habitation of insects and vermin by breaking the ecological chain in which insects feed off the mould and vermin feed on the insects, as well as creating a physical inorganic barrier that deters entrance into the space. Vapour barriers can end at the wall or be run up the wall and fastened to provide even more protection against moisture infiltration. Almost unheard of as late as the 1990s, vapour barriers are becoming increasingly popular in recent years. In fact, the more general area of conditioned vs. unconditioned crawl spaces has seen much research over the last decade. (Wikipedia 2019.)

Alternatively, some find it desirable to create a "breathing home" with ample air flow, rather than "finish" a crawl space. There are contrary opinions as to what is healthier with many suggesting that vapour barriers simply create a new space where mould can flourish, trapping moisture below it and still creating a problem inside the home. (Wikipedia 2019.)

In areas with humid summers, during the summer months, the air vented into a crawl space will be humid, and as it enters the crawl space, which has been cooled naturally by the earth, the relative humidity of the air will rise. In those cases, crawl space vents can even increase the humidity level of a crawl space and lead to condensation on cool surfaces within, such as metal and wood. (Advanced Energy 2005.)

In the winter, crawl space vents should be shut off entirely, to keep out the cold winter air which can cool hot water pipes, furnaces, and water heaters stored within. During rainy weather, crawl space vents bring wet air into the crawl space, which will not dry the space effectively. (Advanced Energy 2005.)

2.8.6 Soil vapour extraction (SVE)

Soil vapour extraction (SVE) is a physical treatment process for in situ remediation of volatile contaminants in vadose zone (unsaturated) soils (EPA 2012). SVE (also referred to as in situ soil venting or vacuum extraction) is based on mass transfer of contaminant from the solid (sorbed) and liquid (aqueous or non-aqueous) phases into the gas phase, with subsequent collection of the gas phase contamination at extraction wells. Extracted contaminant mass in the gas phase (and any condensed liquid phase) is treated in aboveground systems. (Hutzler et al. 1990.)

In essence, SVE is the vadose zone equivalent of the pump-and-treat technology for groundwater remediation. SVE is particularly amenable to contaminants with higher Henry's Law constants, including various chlorinated solvents and hydrocarbons. SVE is a well-demonstrated, mature remediation technology and has been identified by the U.S. Environmental Protection Agency (EPA) as presumptive remedy. (EPA 1993.)

3 CASE STUDY

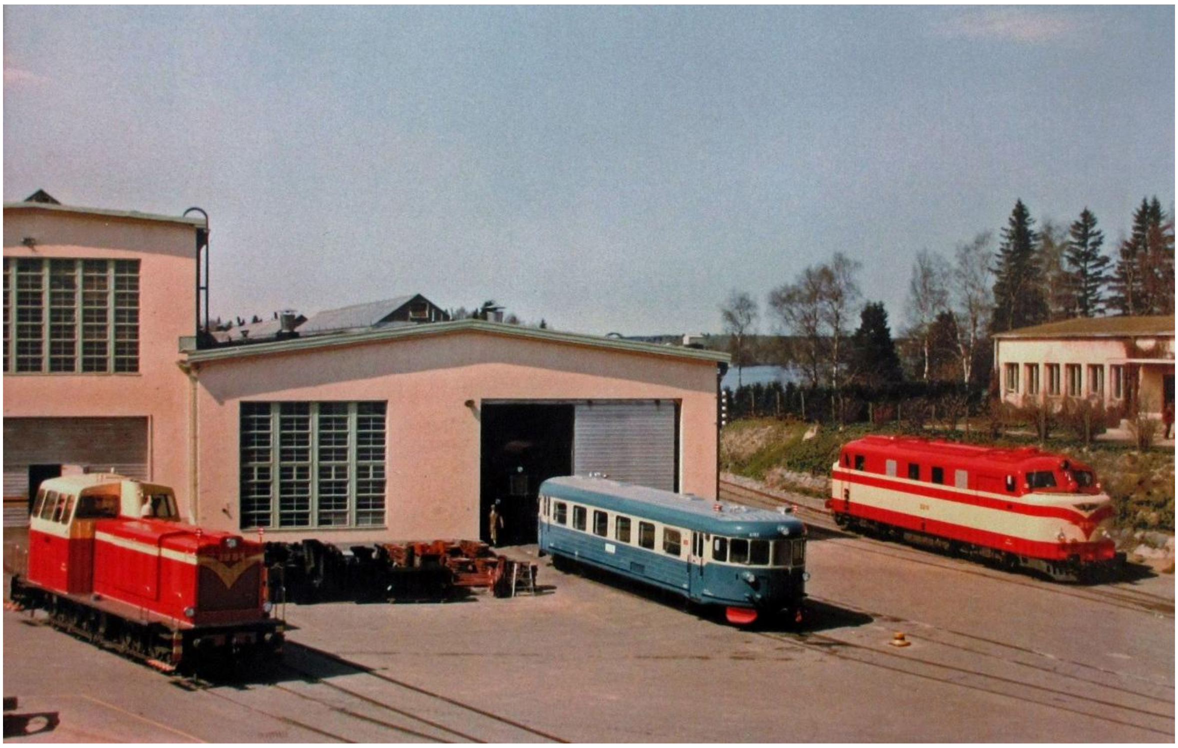
3.1 Site description

3.1.1 History

The case study site is a redevelopment site, which is an old industrial area in the southern part of Tampere, Finland. There were various industrial operations since 1936 until 2013. In the beginning an aeroplane manufacturing facility (no 1 in Picture 1) operated in the area. Over the following decades diverse workshop and assembly industry has been in operation including the manufacturing of trains, trams, metros, straddle carriers, lifts etc. Industrial activities included the use of oils, metal cleansers and coating chemicals, paints and metal machining fluids. Additionally, there has been fuel storing and distribution, as well as heating oil storing.

PICTURE 1. Aerial photo of the area from the south in 1985 (scanned from a framed picture on a wall)

After the industrial operations in the area in question ceased in 2013 four large industrial buildings, one office building and a diner / office building (no 28 in Picture 1) were decommissioned and demolished between 2014 and 2016. The only old building that remained in the area is the administration building (no 26 in Picture 1) which dates back to 1936–38.



PICTURE 2. Train garage in the eastern part of the area in 1960 (Author unknown)

Large-scale demolition of old industrial buildings was followed by extensive soil remediation using mass exchange and numerous soil, groundwater, soil gas and indoor air investigations. In addition to investigations, historical source areas and the extent of VOC contamination related to former production activities were identified from manufacturing operational information and visual observations.

Ramboll Finland Oy has been conducting the investigations as an environmental consultant since the beginning. Investigations showed that the soil was, in many places, contaminated with petroleum hydrocarbons, heavy metals, volatile organic compounds (VOCs) and community and industrial wastes. In all, between 2013–2017, over 200,000 tonnes of contaminated soil were removed from the area and delivered for further treatment at a specialised soil treatment facility. Soil remediation was carried out in two phases:

Between May 2013 and February 2014, a large-scale excavation was carried out in southern parts of the area, in blocks 1909–1912 of the current master plan area, where an old dumping site was partially removed. After the old diner / office was demolished the rest of the area was remediated between 2015–2016. From the southern blocks the remediation works were moved towards the northerly section and by November 2017 the soil had been remediated also in the rest the area (blocks 1900–1907).

Also, groundwater investigations were started soon after the industrial operations ceased in 2013, and organic contaminants, mainly chlorinated ethenes (CVOCs) were detected in groundwater as well. Tetrachloroethene (PCE) was used as a metal degreasing agent in the area, and based on the soil investigations and remediation it was widely used. PCE most probably ended up down in the groundwater through processing and storage basins but also via the sewerage system.

The vadose zone to a depth of approximately 4–5 m was highly impacted with chlorinated VOCs and petroleum hydrocarbons over the past decades. Deeper soils were impacted with a “smear zone” created by fluctuations in the water table. Contamination levels in groundwater are higher than groundwater quality criteria (for classified groundwater areas) throughout the site.

Vinyl chloride has been detected as the most harmful substance in the area because it is known to be carcinogenic and very transmissible in soil and groundwater. It mainly causes health hazard. (IARC 2012.)

3.1.2 Current state of the area and future use

The area is in the current, approved city plan (Figure 16), mainly designated for the residential, commercial and office block areas. The plan symbol is AL-1.

The area is being transformed into residential use and construction of the new city plan area started in the south-eastern part of the region in September 2015. The area to the north of the planning area is defined as a block of service buildings in the current plan.

In addition, the areas at the southern, western and northern edges of the area are zoned as a park and beach park, with VP and VP-2 designations. The block 1903 in the north-western part of the area is zoned as a community maintenance area with the plan designation ET-3.

The industrial area used to be paved during its operating years. All structures above and below ground level that may have created a soil contamination risk have been removed.

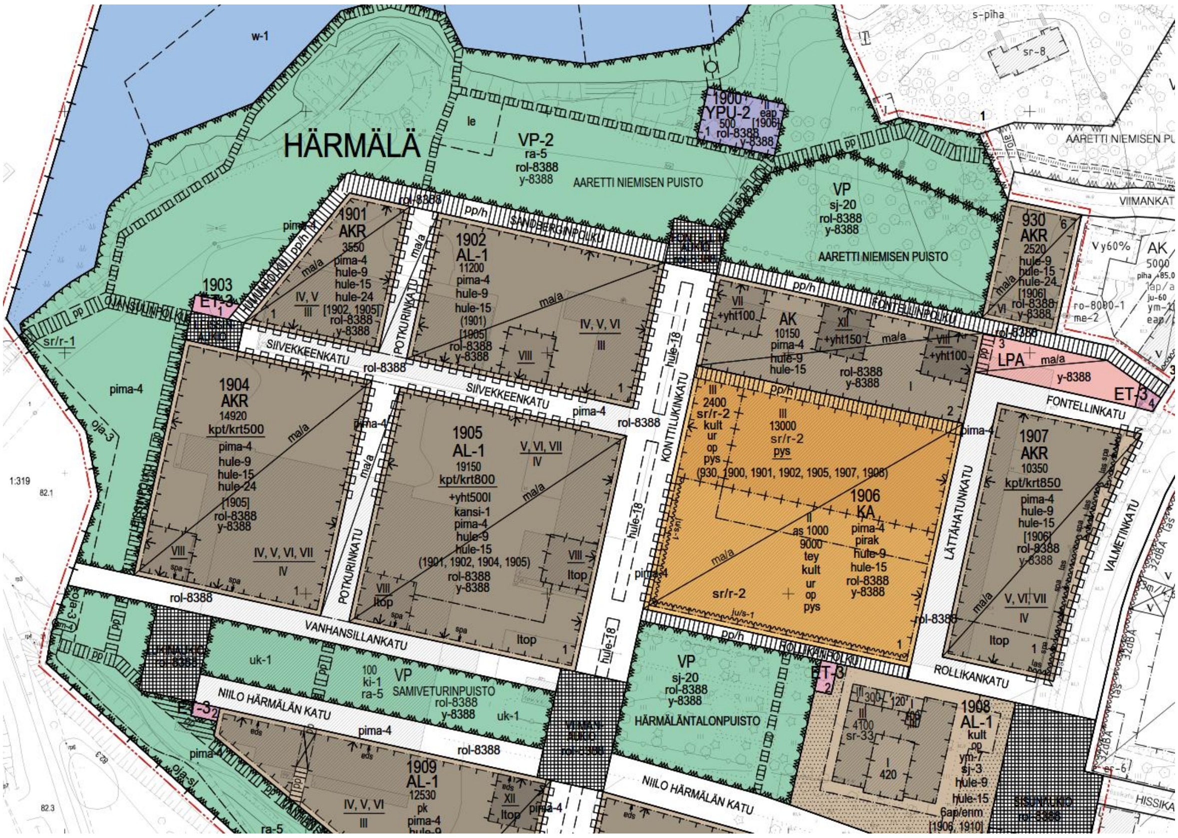


FIGURE 16. An excerpt from the Master Plan (no 8388) and its blocks 1900–1908 (the City of Tampere)

3.1.3 Soil properties

Ground level in the area is mostly +81.5…+82.5 (N2000, MAMSL). In most of the parts the ground level leans towards the south and Härmälänoja ditch. Western and northern sides of the area end in steep banks slanting down to Lake Pyhäjärvi. In asphalted areas the structure layers have been about 1 to 3 metres thick.

Soil investigations (drillings, groundwater well installations and test pits) have shown that below the upmost fill layer there has been a 2–5 metres thick layer of silt clay (Picture 3). Below this layer there is a silt moraine and a gravel moraine layer before reaching the bedrock. According to the investigations the silt clay layer is at its thinnest in the northern part of the area and thickest in the southern part of the area.

PICTURE 3. In many parts of the area the contaminated soil was excavated until below the groundwater table and delivered for further processing at external reception sites specialised in contaminated soil treatment (Ramboll/Parviainen, 7 Sep 2015)

The southern third of the area differs essentially from the northern parts. The southern part was originally a wetland whose soil consisted of peat (top) and fat clay (bottom). These layers used to be 10–15 metres thick as the bedrock sank deeper correspondingly.

Excavation pits have mainly been filled with the non-contaminated silt moraine previously dug from the area. In structural courses of parks and streets, where applicable, there has also been used crushed recycled concrete from the demolished industrial buildings.

3.1.4 Bedrock properties

The bedrock lies at its highest (+84.42, N2000) in the northern part of the area next to Lake Pyhäjärvi where it rises approximately 2 metres above the surrounding ground level and is bare. The deepest point has been detected in the southern part of the area, next to Härmälänoja ditch at 19.90 metres from ground level (groundwater well PVP3; bottom level +57.36; N2000; bedrock confirmed). In addition to rising towards the north, bedrock also rises towards Valmetinkatu Street on the eastern side of the old administrational building.

3.1.5 Groundwater properties

The area is not situated in a classified groundwater area and there is no domestic use of groundwater in the area. The nearest classified groundwater area is on the opposite side of Lake Pyhäjärvi about 3.5 kilometres to the north. The class I groundwater area is called Epilänharju-Villilä (no 0483702).

The level of groundwater has been measured at its highest in the area of the former aeroplane manufacturing facility (block 1906). The groundwater level in this area is approximately +79 (N2000) whereas the mean level in the surrounding area would be approximately +78. In the same area the ground is also the most fragmented and rocky. According to soil properties and graduated water samplings the most conductive layers for groundwater are generally speaking from a depth of 4–5 metres down to the bedrock.

Judging by hundreds of groundwater table measurements it has been estimated that the groundwater has three prominent flow directions inside the area. Based on the measurements and bedrock modelling, the main flow direction of the three seems to be to the west. The two other flow directions seem to be partially northwards and towards the north-east through a narrow crack in the bedrock. It is very likely that all groundwater finally discharges either into Härmälänoja ditch or to Lake Pyhäjärvi.

Groundwater levels have been measured at numerous stages during the contaminated soil remediation process and groundwater investigations. The impact of open excavation pits and water pumping in the pits were notable in the measurements so, at times, the flow pattern in the area has been disturbed.

Removal of the paved surfaces (buildings, asphalt surfaces) during the demolition works and soil remediation has significantly changed the rainwater infiltration circumstances of the area. Currently, with no stormwater drainage system available, all rainwater infiltrates to the ground and forms new groundwater. A large number of measurements of groundwater level starting from late 2014 until the present show that there has been approximately a 20–40 cm rise in the water table. The current situation, however, is temporary as in the future the stormwater will be collected systematically in the whole area. According to the planning ordinance set in the area no stormwater should be infiltrated into the ground, but rather retained and directed to Härmälänoja ditch or Lake Pyhäjärvi.

Thousands of cubic metres of contaminated water were pumped from the excavation pits to make soil remediation possible in some areas. Water at ground level +76…+78 was presumably a mixture of rainwater and groundwater. The water was initially pumped to a large buffer basin from where it was directed to Härmälänoja ditch through oil separators and active carbon filtering. Despite the great amount of water pumped, the later groundwater samples have shown that pumping away the contaminated water did not notably lower the concentrations of CVOCs in groundwater, as the monitoring data stretches to both sides of the pumping period.

3.1.6 Surface waters

In the south-west the area is bounded by Härmälänoja ditch which discharges into Lake Pyhäjärvi. Respectively, western and northern parts of the area are bounded by the lake. The mean water level of the lake is +77.4 (N2000).

3.2 Investigations

3.2.1 Groundwater investigations

Monitoring wells

Monitoring wells have been installed in different stages around the area. Some of the wells were also destroyed or removed during the demolition of the old buildings and earthworks. Altogether, there have been 80 groundwater monitoring points installed to date. Additionally, almost since the beginning of investigations a double well principle has been carried out in order to be able to identify the possible phases or stratified concentrations more reliably. Deep wells have been given a supplemental letter A after the well number whereas shallow wells have been marked with a letter B. Exceptions in this practise have been the areas where the saturated zone (bedrock – groundwater table) has been too shallow for successful stratified sampling.

Wells have been placed in various environments inside the area. For example, some of the wells aim to present source areas and some serve as sentinel wells in the outside perimeters.

Sampling

Quality of the groundwater has been examined broadly using both active and passive sampling methods. Active sampling has been carried out by purging the wells 1–2 days before taking the samples. Purging was done to remove stagnant casing water from the well that is not representative of aquifer conditions. The actual samples have been taken with tube-shaped grab samplers called bailers, which can take one litre of sample per one immersion.

Alongside the active method, also passive diffusion samples have been taken by using a LDPE bag sampler that is filled with de-ionised water. Passive diffusion bag (PDB) samplers have been kept in the well for seven days during which the organic contaminants penetrate the film resulting the concentrations to balance during the selected sampling period. In the bottom of the bags stainless steel nuts were used to add weigh on the sampler in order to make it sink faster in the water column. Picture 4 shows a typical sampler setting used.

PICTURE 4. PDB sampler which has been used at the site, well PVP1A (Ramboll/Parviainen, 28 July 2016)

Results from the groundwater investigations

Investigations have shown that groundwater in the area is mainly oxygen-free and slightly reductive. The pH of the water is neutral or slightly acid. Ferrum concentrations are relatively high, 2–9 mg/l, which is typical of oxygen-poor groundwater. Heavy metal concentrations in the groundwater are low.

There have been various organic contaminants detected in the groundwater, but the primary constituents of concern (COCs) at the site have been chlorinated ethenes. Tetrachloroethene (PCE) has previously been used as degreasing agent in the area. PCE is heavier than water and it has very low viscosity. Because of these characteristics, it has quickly descended to groundwater and further downwards after being spilled into the ground or having leaked from tanks and basins.

During the past decades, the degradation of PCE has naturally started in the groundwater which is indicated by the fact that the VC concentrations in the area have been clearly higher than the concentrations of TCE or PCE. The natural degradation processes of PCE and TCE are normally rather slow and, according to the investigations, it seems that it has stopped when it has reached the form of VC. Generally speaking, the highest concentrations of all CVOCs have been detected in the bottom groundwater wells, on top of bedrock.

The highest concentration of PCE have been recorded in a shallow groundwater well PVP61B (3,200 µg/l; July 28, 2017). The well was located next to an identified source of contamination (the so called lift factory, building no. 28 in Picture 1), and it was later removed during the soil remediation. The highest concentration of TCE (3,300 µg/l; passive sample: June 13–20, 2018) has been detected in the sample which was taken from the well PVP37. Monitoring well PVP37 is located next to another source of contamination, an old collection well.

Degradation products, DCE and especially VC, have been detected more generally in the area. The highest concentration of DCE has been detected in well PVP63A (2,120 µg/l; Jan 16, 2019).

The highest VC concentrations in groundwater have been detected in monitoring well “PVP2A” where the maximum concentration has been 1,900 µg/l (passive sample: March 14–April 11, 2016). The all-time median concentration is 480 µg/l whereas the mean concentration is 633 µg/l. In Table 4, there has been listed concentrations of vinyl chloride in selected monitoring wells from the east to the west. As shown in the table, the highest VC concentrations have usually been observed in the bottom of the aquifer which suggests that the breakdown process from PCE/TCE/DCE has occurred there.

Considering the whole area, concentrations of other contaminants (e.g. oil compounds, BTEX compounds) have usually been low or below the laboratory detection limit.

TABLE 4. Concentrations of vinyl chloride in the groundwater from east to west (Ramboll)

Groundwater monitoring well (from east to west)	Median, all time	Median, 01/2017-01/2018	Mean, all time	Mean, 01/2017-01/2018	Maximum, all time	Last concentration (01/2018)
	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l
PVP13A	49	46	59	34	300	57
PVP13B	0.7	0.3	0.3	1.4	7.0	<0.1
PVP34 (bottom)	10	4.0	44	70	310	310
PVP34 (top)	9.0	3.0	41	66	300	300
PVP65A*	630	630	703	703	900	630
PVP65B*	1.4	1.4	1.4	1.4	2.0	2.0
PVP62A*	550	550	503	503	640	640
PVP62B*	170	170	190	190	280	120
PVP63A*	120	120	107	107	130	130
PVP63B*	15	15	15	15	22	7.0
PVP2A	480	480	633	575	1,900	600
PVP2B	87	47	137	113	650	460
PVP10A	420	380	427	388	790	290
PVP10B	0.8	2.0	3.0	2.0	24	<0.1
PVP20 (bottom)	200	200	196	190	260	120
PVP20 (top)	180	150	178	167	270	100
PVP39 (bottom)	100	87	118	83	310	8.0
PVP39 (top)	110	56	99	59	220	5.0
* only three sampling events						

Groundwater contamination

Based on the investigations, VC has spread the widest from the CVOCs that have been detected in the area, because of its high solubility in groundwater (U.S. National Library of Medicine 2019). Not only due to its solubility but also because VC is lighter than water, it has most commonly been detected throughout the saturated zone whereas the heavier PCE and TCE have been seen in more limited areas and depths.

Elevated VC concentrations have been detected over an area of 10.8 hectares, from which approximately 5–6 hectares is the area where the VC concentration exceeds 50 µg/l.

Based on the investigations, the plume is confined to the east of Valmetinkatu Street, where the rise of the bedrock surface appears to be partly a natural barrier to the spread of contaminants.

According to studies, there is likely to be a hydraulic link between eastern and western sides of Valmetinkatu Street. However, on the eastern side of Valmetinkatu Street, there has been a different distribution of the ethenes during the monitoring, i.e. the PCE and TCE concentrations used have been clearly detected more than the degradation products (1,2-DCE and VC). Similarly, a significantly higher percentage of degradation products on the western side has been observed over the entire sampling history.

The bedrock surface has also been found to rise in the northern direction, which limits the spread of contaminants except for the area of monitoring wells PVP17 and PVP37, where it has been observed, on the basis of drillings, that there is a gap towards the north and Lake Pyhäjärvi.

In the southern part of the area, the bedrock is much deeper than in the north. Soils in the southern region are also substantially different from those in the northern region. Drilling investigations revealed a dense layer of peat / clay (PVP3, PVP4, PVP31, PVP32 and PVP33) reaching a depth of about 9 to 10 metres, under which the groundwater is clearly under pressure. Most of the studies conducted in the southern region have not detected any harmful substances.

In the western part, the CVOC contaminated groundwater plume has been found to extend to Härmälänoja ditch and, on the other hand, to the shore of Lake Pyhäjärvi (PVP39).

On the basis of a wide network of monitoring wells and investigations conducted, it is estimated that the prevalence of chlorinated hydrocarbons in groundwater in the area has been reliably determined.

Calculations derived from overall average concentrations of CVOCs have resulted that the remaining amount of CVOCs in the groundwater varies between 32 to 87 kilogrammes. Table 5 shows an example of the calculation with different soil porosities. Average depth of the saturated zone is 7–8 metres.

TABLE 5. Example: Calculations of amounts of CVOCs in groundwater with different soil porosities (based on average concentrations in year 2018 monitoring results) (Ramboll)

Compound	**Amount, kg (based on year 2018)**		
	Porosity 0.15	Porosity 0.20	Porosity 0.30
PCE	1.5	2.0	3.0
TCE	8.5	11	17
1,2-DCE	16	21	32
VC	18	24	35
Overall	**44**	**58**	**87**

3.2.2 Soil gas investigations

Monitoring wells

Also soil gas monitoring wells have been installed at different stages around the area and many wells have been removed during the demolition of old buildings and earthworks. Altogether, there have been approximately 60 soil gas monitoring points installed to date. As with groundwater wells, a double well principle has been carried out in order to be able to identify the possible phases or stratified concentrations more reliably. Deep wells were installed until just above the groundwater table, with a 1- or 2-metre screen section in the bottom. Shallow wells were installed next to the deep ones adjusting the screen section approximately one metre below the ground level. Any gaps or openings at the ground level were sealed as well as possible to prevent the sample from diluting with ambient air.

Sampling

At the site, also soil gas sampling has been carried out using both active and passive sampling. Every monitoring event has been initiated with passive sampling. Sampling tubes have been installed to diffuse inside the monitoring wells for seven days. Tubes are set to hang in the midsection of the screened well. At the site, Tenax TA tubes with diffusion caps were used (Picture 5).

PICTURE 5. Diffusion sample tube (Ramboll/Kangasniemi, 13 Feb 2017)

A wide selection of organic compounds was analysed from the passive (diffusion) samples. From the target compounds vinyl chloride is an exception because, presumably, there is no established passive sampling method for it. The adsorbent of the Tenax tubes does not retain VC.

Active samples have been taken immediately after the diffuse sampling. During active sampling the air (soil gas) is pumped through the sampling tubes (Tenax TA). Respectively an active carbon tube (Dräger type B/G) is used to take a VC sample. Before taking the sample, the air in the monitoring well has been purged twice the volume it holds. During the change of the sampling tubes and pumping equipment, the wells and hoses were kept as sealed as possible to prevent samples from being diluted by ambient air.

Picture 6 shows an active soil gas sampling event.

PICTURE 6. Active sampling with a Tenax tube attached to a sampling hose (Ramboll/Kangasniemi, 21 Feb 2017)

With Tenax TA sorbent tubes, a flow rate of 100 ml/min and sample volume of 1 L were used. Respectively, with active carbon tubes a flow rate of 250 ml/min and sample volume of 10 L were used. The sampling tubes, flow rates and sample volumes were selected according to the instructions from the laboratory used (Eurofins).

Test structure for detecting CVOCs in sub-slab venting system

In Tampere area, because of naturally high radon concentrations, planning regulations urge developers to introduce radon mitigation system in any construction projects. Often, radon gas intrusion is prevented by installing a ventilation pipe system under the buildings.

In order to imitate the circumstances where soil gas would gather under a residential building, a concrete slab (3,100 x 5,160 x 200 mm) was placed in an area from where contaminated soil had been previously excavated and where there had been detected high (> 100 µg/l) concentrations of VC in the groundwater. The slab was placed approximately one metre above the mean level of groundwater to correspond with a basement slab of a future high-rise. Under the slab there was installed a ventilation piping with a central feedthrough from where the soil gas samples were taken. The installation was surrounded by similar crushed rock material to what is typically used under building foundations. The 300 mm crushed rock layer was set on top of the silty moraine fill that had been used as a primary fill layer in the excavation pit.

Results from the test structure are not comparable with the actual structures that are being, or will be introduced in the area, because the temperature and pressure circumstances are not equal with the ones in real buildings. Despite the differences in circumstances, it was estimated that the soil gas samples taken from the test structure would be more comparable with real-life setting than traditional soil gas monitoring wells, as they would collect the soil gas from a larger area than vertical wells. The volume of the ventilation pipe system was also significantly larger than in vertical wells because of the diameter and the pipe length used in the installation. Ventilation pipes are normally 110 mm of diameter, whereas the diameters of vertical monitoring wells vary between 30 to 50 mm. The test structure was removed from the ground in December 2018 as earthworks related to the redevelopment of the area would have caused it to be buried underground and possible hindered the future piling. A collage of photos taken from the test structure is shown in Picture 7.

PICTURE 7. Photos of a soil gas venting test structure where a concrete slab with sub-slab ventilation was placed near groundwater table (Ramboll/Parviainen 2016)

Underground horizontal test setting

Additionally, two horizontal sieved pipe systems were placed (“horizontal sieve 1 and 2”) underground in areas with >50 µgVC/L concentrations in the groundwater. From both test areas CVOC contaminated soil had previously been excavated until the depth of the groundwater table. Both pipe systems were approximately 30 metres long and lay approximately 0.5 metres above the mean groundwater level. The collection pipe was attached to a solid feedthrough pipe which was directed above the ground level for soil gas sampling. Diameter of the pipe material (PE plastic) was 110 mm. Test setting no 1 was placed on top of crushed rock, which was used as a fill material starting from below the water table (Picture 8). Test setting no 2 was installed respectively in the former excavation pit but on top a silty moraine fill so per se the possible CVOC concentrations evaporating from the groundwater would likely be smaller than the ones measured from the system no 1.

PICTURE 8. A photo taken during the installation of the horizontal soil gas test setting no 1 (Ramboll/Sillanpää, 28 June 2017)

Sub-slab soil gas sampling

Soil gas samples (HI2–3) have also been taken from the old administration building where two drill holes were made in the lowest-lying parts of the building. Diffusion sampling tubes were put to hang in the drill hole while attached to a cap that had seals on it to keep the tube from exposing to ambient air (Pictures 9 and 10).

From the same rooms, also indoor air samples (SI2–3) were taken.

PICTURE 9. Photo of sub-slab soil gas sampling tube attached to a sealed cap (Ramboll/Kangasniemi, 29 Sep 2017)

PICTURE 10. Photo of sub-slab soil gas sampling event (point HI3) where the only visible part indoors during the diffusion is the sealed cap (Ramboll/Kangasniemi, 29 Sep 2017)

Results from the soil gas investigations

Constantly highest concentrations of PCE and TCE have been detected in monitoring well HKP45 (five monitoring rounds: PCE: 540…2,000 µg/m^3; TCE 670…3,300 µg/m^3), which is located next to a metal degreasing department of an old aeroplane factory. The well is located approximately 20 metres north from the groundwater well PVP2A where the highest VC concentrations have been detected.

Also, in the wells HKP6 (Feb 3, 2016: PCE 610 µg/m^3; TCE: 6,900 µg/m^3) and HKP12 (Feb 3, 2016: PCE 120 µg/m^3; TCE: 1,700 µg/m^3) there has been elevated concentrations detected at times. A few times, PCE concentrations have exceeded the detection limit of the analytical method (>150…>1,000 µg/m^3) in wells HKP38 and HKP39. In turn, in wells HKP41A&B and HKP43 concentrations of TCE have also exceeded the detection limit (>1,000…>1,200 µg/m^3).

The highest DCE concentration has been detected (Oct 19, 2017: >1,710 µg/m^3) in well HKP43. What is typical for the degradation process, it mainly consists of cis-1,2-dichloroethene (>1,200 µg/m^3), but also 1,1-dichloroethene (140 µg/m^3) and trans-1,2-dichloroethene (370 µg/m^3) have been detected.

VC concentrations have mainly fallen below the detection limit of analytical methods (<0,35…<2 µg/m^3), with some exceptions. In the area there is a well, HKP32A, where elevated VC concentrations have been detected since the beginning of its monitoring in early

2017. VC concentrations have varied between 0.33 and 130 µg/m^3. The highest concentration, 340 µg/m^3, in the area was detected in monitoring well HKP17 on October 1, 2017. The detected concentration has been exceptional for the well, because in most of the samples taken before and after it the concentrations have fallen below the detection limit of the analytical method. However, in the same well there have been elevated concentrations of PCE, TCE and DCE detected (PCE: <0.5...150 µg/m^3; TCE: <0.6…340 µg/m^3; DCE: 0…569 µg/m^3). In soil gas monitoring well HKP43 there has been VC detected in two sampling events (Oct 19, 2017: 34 µg/m^3 and Nov 28, 2018: 4.1 µg/m^3).

A few ethene analyses that were executed proved that also ethene has been formed naturally in the area, which is a sign of the PCE degradation process advancing until the end.

Figure 17 shows concentrations of contaminants in various locations.

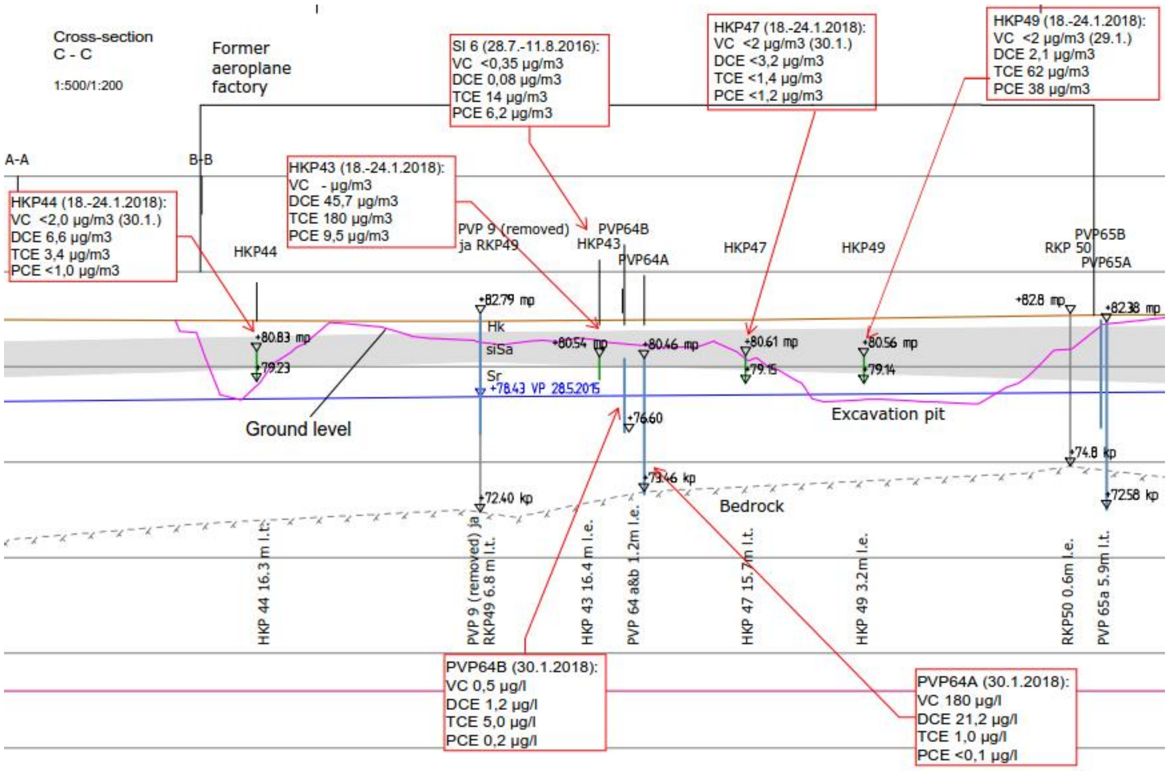


FIGURE 17. A cross-section set near the source of contamination and text boxes showing CVOC concentrations in selected monitoring points (groundwater, soil gas and indoor air) (Ramboll 2018).

Sub-slab test structure

In all, from the sub-slab test structure there were 12 sampling rounds taken from 2017 until late 2018. Often both active and passive sampling methods were used. PCE concentrations varied between 0.38 and 2.5 µg/m^3, but no trend could be drawn from the results. TCE concentrations varied between <0.11 and 22 µg/m^3, the latter being an order of magnitude higher than the rest of the results. To date, no clear reason has been identified for the peak detected in June 2018, as the vicinity of the test structure has remained uninterrupted.

From the DCE compounds trans-1,2-DCE was detected twice (0.21 and 0.34 µg/m^3) in 2017. VC concentrations fell below the detection limit (<2.0 µg/m^3) of the analytical method used.

From the two horizontal soil gas test settings higher CVOC concentrations were detected in setting no. 1, as expected due to the more pervious fill material under it. The highest PCE concentration was detected in the first sample, 130 µg/m^3, taken on Sep 4, 2017. Also other CVOC concentrations were at their highest in the same sampling event: TCE 300 µg/m^3, DCE 129 µg/m^3 and VC 9.9 µg/m^3.

In setting no. 2, which was lying on top of the silty moraine fill, the CVOC concentrations remained low or below the detection limit of the analytical method (PCE: <1.0 µg/m^3; TCE: 7.1 µg/m^3; DCE: 3.8 µg/m^3; VC: <2.0 µg/m^3).

Maximum concentrations of other significant compounds are listed below:

Benzene:	420 µg/m^3	(HKP1, Feb 2016)
Toluene:	4,900 µg/m^3	(HKP1, Feb 2016)
Ethyl benzene:	790 µg/m^3	(HKP3, Feb 2016)
Xylenes:	3,060 µg/m^3	(HKP3, Feb 2016)
Trimethylbenzenes:	210 µg/m^3	(HKP31, passive sample: May 23 – June 1, 2017)

While interpreting the results from soil gas investigations, it should be noted that they cannot be compared with indoor air concentrations, nor with the guidelines set for indoor air.

3.2.3 Indoor air investigations

Monitoring points

From the old administration building and the aeroplane factory several indoor air samples have been taken since 2015. In the administration building, samples have been taken from the lowest-lying parts of the building (sampling points SI1–4). During the time when the old aeroplane factory was still in place, until late 2016, the indoor samples were taken from the pipe and cable channels underneath the factory floor (sampling points SI5–10; altitude: +80.5…+81, N2000). In all, three sampling events were executed in the old factory before its demolition.

Pipe and cable channels were at some places dirty and, for example, transformer oil was found which might have influenced some petroleum hydrocarbon concentrations. Channels were chosen as sampling points to exaggerate the vapour intrusion conditions inside the building (worst case). According to primary data gathered from the site, in the south-east corner of the factory there was a suspected source of contamination with old concrete metal treatment basins. Originally, the factory was planned to be preserved and modified to serve as a community centre for the people living in the area. During that planning phase most of the source of contamination (old contaminated structures and surrounding soil) was removed by excavating inside the building. The source area was confirmed and limited via soil and air investigations during the excavation, as high CVOC concentrations were detected in both soil and indoor air. At that time, it was not possible to remove all contaminated soils from the hall due to stability issues.

After the major part of the contaminated soil was removed from factory hall, an indoor sampling point “SI11” was placed in the bottom of the excavation pit (Picture 13). It located in a central spot in the open pit, approximately 2.5 metres lower than the original floor slab level (+80, N2000). Remaining, still contaminated, soil in the excavation pit was solid silt lying approximately 0,5–1.0 metres above the groundwater table.

Later, after the demolition of the factory, in 2017, a massive contaminated soil remediation was carried out in the area and 49,800 tonnes of soil was excavated, covering 37 % of the blocks’ 1906–07 area. In many parts the excavations reached the groundwater table, also in the source area.

At the moment, only two indoor air sampling points (SI2–3) are in use. They are located in the old administration building: SI2 in a storage (heat distribution centre, Picture 11) and SI3 in the old phone centre (also a civil defence shelter) which is the lowest-lying part of the building. In the room, there are also sub-slab soil gas sampling points HI2 and HI3.

PICTURE 11. Indoor air sampling point SI2 in the administration building (Ramboll/Parviainen, 28 July 2016)

PICTURE 12. Indoor air sampling point SI10 in an old pipe channel (Ramboll/Parviainen, 28 July 2016)

PICTURE 13. Indoor air sampling point SI11 in the open excavation pit inside the old factory. The silty soil under the sampling tube was still highly contaminated. (Ramboll/Parviainen, 28 July 2016)

Sampling

Sampling has been carried out using the same equipment and methods as with soil gas sampling. Samples have been taken with an active method, i.e. pumping. Samples for VC analysis has been taken with active carbon tubes (Dräger type B/G) and other test substances in the Carbopack-B tubes. The Tenax TA tube does not reach a sufficiently low limit of determination for benzene.

The most significant variation in the practise is the placement of the sampling tubes. Diffusion tubes have been placed on top of a hard surface instead of using a monitoring well. Samples have been taken using a 14-day diffusion period. VC samples have been taken in the active carbon tubes by pumping 60 L of air with a flow rate of 1 L/min.

The instruments and methods used for indoor air sampling have been determined by the laboratory.

Results from the indoor air investigations

During the indoor air monitoring elevated CVOC concentrations were detected only in the samples which were taken from the old factory, and especially from the sampling points (SI10 and SI11) near the source of contamination. WHO guidelines for indoor air quality

(2000/2010) and TCA values have been used to assess the concentrations detected in the monitoring. From the most part WHO and TCA guidelines correspond with each other.

Guidelines for carcinogenic contaminants have been set, so that the additional risk of cancer may not be greater than 10^{-5} (1 observed cancer case per 100,000 people). For VC, which is classified as a carcinogenic compound, WHO has set a value of 1.0 µg/m^3 in its guide from 2000. However, in Finland a lower CR_{inhal} value of 0.36 µg/m^3 has been used, which is presented in guide no 6 by the Environmental Administration (YM 2014). Use of the lower guideline value improves certainty of the risk assessment.

Table 6 shows all-time average concentrations of chlorinated ethenes in indoor air sampling points. Monitoring points SI1 and SI4 were removed from the programme after the functions in the rooms changed significantly and representative samples could not be taken anymore. Monitoring points SI5–SI11, on the other hand, were removed from the programme after the old aeroplane factory was demolished in late 2016.

TABLE 6. Concentrations of chlorinated ethenes in indoor air (average)

		Average concentration (µg/m^3)			
Reference / sampling point	Number of samples	PCE	TCE	ΣDCE	VC
WHO guideline		**250**	**23**	**-**	**1.0**
TCA, tolerable concentration in air		**250**	**23**	**30**	**0.36**
Administration building					
SI1	3	1.9	3.2	0.09	<0.35
SI2	9	6.2	8.1	0.33	<0.35
SI3	9	5.7	6.5	0.21	<0.35
SI4	3	0.5	1.0	<0.15	<0.35
Aeroplane factory					
SI5	3	22	**31**	0.39	<0.35
SI6	3	8.3	18	0.08	<0.35
SI7	3	8.2	19	0.14	<0.35

SI8	3	6.5	16	<0.15	<0.35
SI9	3	6.4	15	0.24	<0.35
SI10	3	57	**93**	1.21	<0.35
SI11	2	70	**70**	1.12	**0.66**

In three of the sampling points (SI5, SI10 and SI11) in the aeroplane factory both the WHO guideline (23 µg/m^3) and the TCA value (23 µg/m^3) for TCE were exceeded. Additionally, also benzene and total VOC concentrations exceeded the TCA values in some samples. Generally speaking, 40–50 % of the VOCs were identified compounds.

Point SI11 has been the only sampling point during the monitoring where the VC concentration has exceeded the detection limit of the analytical method (0.35 µg/m^3). The observed concentration, 0.66 µg/m^3, was still rather low. As stated earlier, the rest of the contaminated soil from that time was later excavated from the source area.

3.3 Assessment of the need for groundwater remediation

Large-scale soil remediation was carried out in the area, and because of that there will not be chlorinated solvents leaking to the groundwater anymore. The area has undergone extensive research also on groundwater and soil gas, and three clear emission sources were identified in certain parts, where the PCE and TCE concentrations in groundwater or soil gas were higher than in the other parts of the area. One emission source was located within the former aeroplane factory (no 1 in Picture 1) and its southwest corner. Another clear source of emission was found in the area of a former lift factory (no 28 in Picture 1). A third emission source, and likely lesser than the other two, was in the northern part of area (a former sewer collection well). Contaminated soil was excavated until the level of the groundwater table or under in all three emission source areas, after which unspoiled fill material was backfilled.

There are significant differences in the conditions of the emission source areas. The highest levels of PCE and TCE in groundwater have been detected in the lift factory area, whereas decomposition has progressed in the aeroplane factory area, with DCEs and VC being found in groundwater.

Investigations suggest that, by volume, a majority of the chlorinated ethenes of the site lie in the groundwater (81–100 %). Judging by numerous soil, groundwater and soil gas investigations executed in the area, a connection between contaminated soil and elevated concentrations of CVOCs in soil gas has been identified. In the areas where the contaminated soil has been removed and replaced by applicable, unspoiled fill material, the CVOC concentrations in soil gas have been considerably lower than in uncorrupted (undug) areas.

The assessment was made by calculating the highest safe concentrations in the soil gas and groundwater, so that the indoor air concentration in the ground floor would not exceed the reference of long-term exposure (TCA) nor the short-term exposure reference values (HTP8h / 10) in cellars and parking spaces (STM 2018; Talotekniikkateollisuus 2019). The computational review was carried out using environmental management guidelines to assess the migration of contaminants from groundwater to soil gas and from soil gas under the buildings to indoor air. Where necessary, the formulas were supplemented with the instructions of the Dutch RIVM and the U.S. EPA.

In the calculation model used, the analysis was based on the diffusion of contaminants in the soil. From the soil to the building, the calculation model included the leakage air through the sub-base.

Vinyl chloride (VC) has been identified as the most harmful compound in the area because of its prevalence in the groundwater and toxicity for human. VC is a human carcinogen and the critical concern with regard to environmental exposures to VC is the risk of malignancy. No safe level has been indicated. (IARC 2012.)

From the ecological perspective, the most significant processes occur in the topmost layers of the ground. These layers were mainly removed from the area during the soil remediation, and they will also be disturbed as the redevelopment proceeds. The area will become a dense urban area, where there will likely not be any natural habitats left. Thus, contaminated groundwater is not estimated to pose any risk for the future urban environment and its ecology.

According to the site-specific risk assessment targeted in environmental and health risks, there has not been a need for groundwater remediation in the area. Site-specific assessment was based on direct evidence (confirmatory sampling of sub-slab air, soil gas, pipe & cable channel air concentrations and indoor air concentrations in old administration building). Also the planned structural features of the future buildings will ensure that no further action with respect to vapour intrusion should be needed.

However, because there are still rather high concentrations of CVOCs in the groundwater, and close to the sources of contamination there are still elevated concentrations of PCE and TCE which will degrade, it cannot be stated absolutely that the risk level would decrease as a whole in the future. In some parts of the area, there have been higher soil gas concentrations detected than previously during the monitoring. There are also uncertainties related to the future migration of the contaminants. Therefore, a selection of risk management methods will be introduced in the area.

3.3.1 Determination of the highest safe concentrations in the soil gas and at the top of the aquifer

Chlorinated compounds pose a theoretical health risk in the area via vapour intrusion, which could induce the contaminants to migrate to respiratory air. According to the groundwater and soil gas investigations, which have been carried out since late 2014, it cannot be clearly concluded at which state the degradation process of the target compounds is at the moment. Due to degradation of PCE and TCE concentrations of DCE and VC in the groundwater and soil gas might still rise temporarily.

Because the maximum concentration levels may not have been reached yet in the groundwater and soil gas and to manage the long-term risks, a calculatory risk assessment was introduced to determine the highest safe concentrations in the topmost layer of groundwater and soil gas in selected depths from the ground level (Figure 18). The top of the aquifer is essential in determination of the highest safe concentrations in groundwater, because from there the volatile CVOC compounds migrate upwards the unsaturated zone and soil gas.

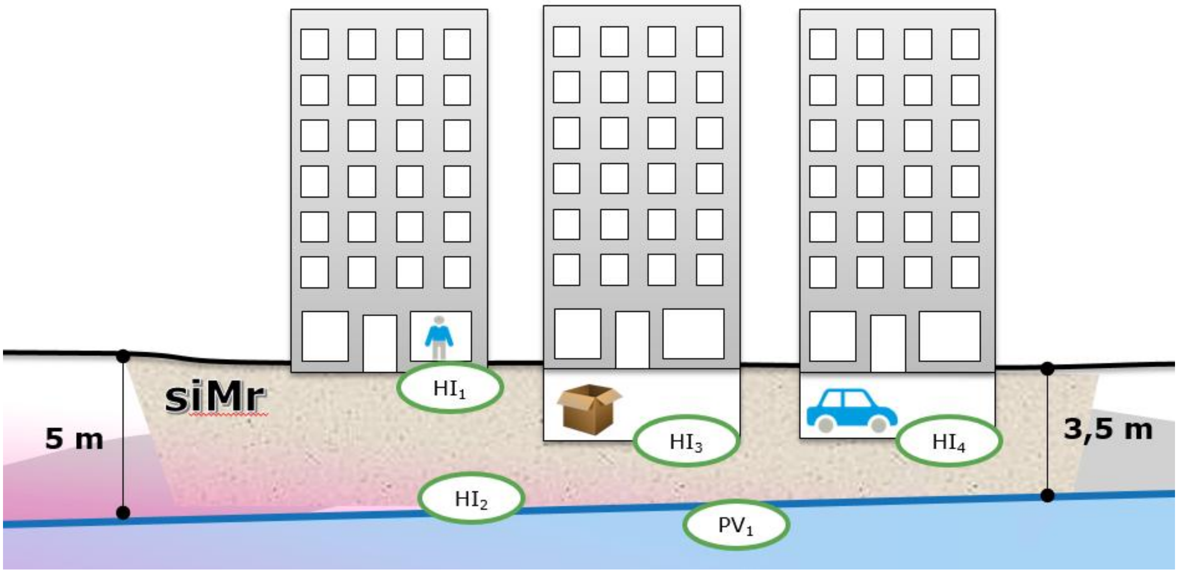


FIGURE 18. Conceptual site model (CSM) showing the targeted situations for calculatory determination of the highest safe groundwater and soil gas concentrations (Ramboll 2019)

Table 7 shows target situations topped by housing and other spaces.

TABLE 7. Target situations topped by housing and other spaces (Ramboll 2018)

Target situations topped immediately by housing	
HI_1	Safe concentration underneath the building foundation (5 cm below)
HI_2	Safe concentration in 3 m depth from the building foundation
Target situations topped by other spaces (e.g. storage, parking facility)	
HI_3	Safe concentration underneath a space which is in use other than housing or parking facility (5 cm below)
HI_4	Safe concentration underneath a parking facility (5 cm below)

In late 2018, Ramboll carried out a calculatory risk assessment for the area to determine the safe concentrations for the five different situations described in the CSM above. Maximum concentrations for each CVOC compound are presented in Table 8 below.

In Table 8 the calculatory safe concentrations (HI_1 and HI_2) of soil gas at different depths based on health risks are presented. In addition, comparisons between detected and safe concentrations are presented.

TABLE 8. Calculatory safe concentrations of soil gas (HI_1 and HI_2) (Ramboll 2018)

Compound	**HI_1** Safe concentration in soil gas underneath the foundation (-5 cm)	Detected maximum concentration in shallow wells	Comparison: detected / safe concentration	**HI_2** Safe concentration in soil gas in 3 m depth	Detected maximum concentration in other wells	Comparison: detected / safe concentration
	µg/m^3	µg/m^3	%	µg/m^3	µg/m^3	%
PCE	240,000	31	0.013	5,700,000	2,000	0.035
TCE	21,000	350	1.7	480,000	6,900	1.4
DCE	26,000	340	1.3	540,000	1,710	0.32
VC	1,800	<2	0.11	38,000	340	0.89

The maximum concentrations of TCE (1.7 %) and DCE (1.3 %) have been found to be the closest to the highest safe concentrations.

In Table 9 there the calculatory safe concentrations (HI_3 and HI_4) of soil gas in different situations based on health risks are presented. The spaces below are basements, storages and parking halls, where people do not spend longer periods of time nor visit regularly. In addition, comparisons between detected and safe concentrations are presented. Human exposure in these spaces is lesser, so safe soil gas concentration levels under these spaces are higher. Additionally, ventilation in parking halls is usually more efficient than in other spaces.

TABLE 9. Calculatory safe concentrations of soil gas (HI_3 and HI_4) (Ramboll 2018)

Compound	**HI_3** Safe concentration in soil gas under the cellar (-5 cm)	**HI_4** Safe concentration in soil gas under the parking facility
	µg/m^3	µg/m^3
PCE	6,800,000	11,000,000
TCE	4,700,000	7,800,000
DCE	71,000,000	110,000,000
VC	230,000	390,000

The distribution of soil gas and groundwater is illustrated by the substance specific constant Henry's Law. In general, the constants of Henry's Law are defined by laboratory tests or computation based on solubility and vapour pressure, and they do not reliably represent the distribution of the contaminant under the conditions of the site.

The distribution between groundwater and soil gas can also be considered on the basis of the observed concentration ratios. However, at least for the time being, the results of the measurements in the well pairs have varied so greatly, that it is difficult to reliably assess the relationship based on the measurements so far. In addition, the remediation measures have affected the concentrations of contaminants in soil gas and groundwater.

Table 10 shows the calculatory safe concentrations at the top of the aquifer.

TABLE 10. Calculatory safe concentrations at the top of the aquifer (PV_1) (Ramboll 2018)

Compound	**PV_1** Safe concentration at the top of the aquifer	Detected maximum concentration at the top of the aquifer	Comparison: detected / safe concentration
	µg/L	µg/L	%
PCE	6,100	3,200 (PVP61B)	52
TCE	1,700	100 (PVP1B)	5,9
DCE	660	707 (PVP62B)	**107**
VC	61	650 (PVP2B)	**1,065**

Investigations have shown that high groundwater concentrations of PCE and TCE refer to the vicinity of the source of contamination, which was also the case with monitoring wells

PVP1B and PVP61B. PVP1B locates close to a former sewer collection well, which has leaked to its environment. PVP61B, instead, located south from the so-called lift factory area where there was a submerged metal treatment basin in the ground, which had leaked in the past as well.

The next chapters will describe the groundwater remediation methods that have been considered in the area to achieve a significant decrease in the volume of CVOCs in the short term, and the structural solutions which will be introduced to manage the risk of CVOC vapour intrusion in the long term and thus ensure safe indoor air.

3.4 Groundwater remediation

3.4.1 Groundwater remediation pilots

In order to find out what type of remedial method or methods would be the most suitable for the area, three pilot projects were introduced in August 2016. The three contractors, Doranova Oy, Fortum Environmental Construction Oy and Nordic Envicon Oy, were given independent pilot areas. The following chapters describe briefly each pilot project and their success.

Doranova

Doranova's pilot area and input wells were located in the area of the former source of contamination (lift factory). Doranova's remediation plan was based on the recycling of groundwater from the DPIE wells installed in the area and its treatment with their DoAct® CORE equipment. The technique used by Doranova was based on anaerobic reductive dehalogenation (ARD). DoAct® CORE is Doranova Oy's own, patented and remotely controlled modular soil and groundwater remediation system. In addition to a pilot project in the field, Doranova also carried out a laboratory pilot. The remediation pilot was based on exploring the usability of three different HRC chemicals in the area.

Doranova stated in their final report that based on the results of the laboratory pilot, as well as the results of the remediation pilot, the soil and the groundwater of the area contain the microbes that contribute to the decomposition of chlorinated ethylene to non-hazardous end-products under non-oxidative conditions. In addition, based on the results of the laboratory pilot, it was found that using hydrogen donor chemicals the formation of oxygen-free conditions in groundwater can be accelerated and the microbial dehalogenation process supported.

On the basis of the results obtained in terms of yield and injection, the groundwater of the area was well suited for remediation with anaerobic reductive dehalogenation.

From the results of the remediation piloting, Doranova concluded that using their DPIE recycling wells and hydrogen donor chemicals, the remediation method presented, ARD, would work technically also on a large scale.

The method employs hydrogen donor chemicals to enhance anaerobic dehalogenation and contribute to the formation of oxygen-free conditions in groundwater. Hydrogen donor chemicals used acted as expected in groundwater in the area, and Doranova estimated that their use could be continued, if necessary, by injecting both fast- and slow-acting hydrogen donor emulsions into the groundwater in different parts of the area, depending on the proportions of CVOCs in question.

Fortum Environmental Construction

According to the groundwater investigations Fortum's pilot area located in the southern part of the VC contaminated groundwater area. Fortum's remediation pilot was based on three adjacent reactive walls using different reagents (EHC® / ELS®). The injection sites were 10 m x 10 m and two of the areas were anaerobic and one aerobic.

Area 1

The effects on the physico-chemical properties of groundwater were relatively small based on measurements. The dissolved oxygen content immediately increased after injection and oxygen was available during treatment. Concentrations were relatively low due to competing oxygen demand (COD). Chemical oxidation worked well on the site. Concentrations of chlorinated solvents decreased in the observation wells EK3 and EK6 during PermeOx® treatment. Immediately after the injection, the peak of cis-1,2-DCE was observed, which is a typical finding based on the mixing effect of the injection and possibly also on the degradation of PCE and TCE.

Based on the results, the decomposition of chlorinated solvents began shortly after injection. PCE and TCE were sparingly soluble in their own phase, and therefore did not appear in detectable concentrations in groundwater samples. DCE began to decompose further to form VC. VC also decomposed well during the treatment period. Fortum stated in their pilot report that the treatment time of one year was suitable for chemical oxidation, and the result would probably not have changed significantly even if the test had been extended for longer.

Area 2

The effects of injection were minor compared to the groundwater variables. However, reductive dehalogenation worked well. Also, in EHC®-L treatment, the concentration of cis-1,2-DCE increased immediately after injection. However, the increase in concentrations was more moderate compared to the oxidation treatment. Approximately 2-3 months after injection, the DCE concentration started to decrease and the concentration of VC formed in the decomposition reaction increased. The concentration of VC was finally lowered, about 4-5 months after injection. In terms of processing time, Fortum concluded that the year is not necessarily long enough for EHC®-L treatment, but with longer processing times, even lower residual concentrations could be achieved.

Area 3

The degradation profile of chlorinated hydrocarbons appeared to be similar to that of areas 1 and 2, i.e. DCE and VC were the first to decompose. No specific concentration peak was observed, but the DCE concentration started to decrease immediately after injection. The VC decomposition during the one-year pilot period was partial based on the concentration profile.

The decomposition was slower by the EHC method than by the EHC®-L method or by the oxidation-based PermeOx® method. The manufacturer's estimate of the duration of the refurbishment was 2 years, when the pilot took only one year. Based on the results, it appeared that the decomposition was unfinished at least in the case of VC and that the longer treatment time would have resulted in a lower final concentration.

Fortum’s conclusion from their pilot period was that the results were encouraging. Residual concentrations were generally low. In addition, the degradation profiles were logical and can be explained by the operating principles of the refurbishment technologies used. In region 1 and 2 cis-1,2-DCE and VC degradation appeared to be most effective. In area 3, the results were less clear, but the EHC is also a slower method, so it was assumed that the degradation of the contaminants would continue after one year of the pilot period.

The elevated levels of VC and cis-1,2-DCE at the beginning of the pilot period were explained by the poor water permeability of the soil. During the injection of the reagents, cracks opened in the soil under the influence of high pressure, which facilitated the passage of water for some time. On the other hand, the increase in concentration was also explained by the fact that DCE and VC are degradation products of heavier chlorinated hydrocarbons (PCE and TCE). The interpretation of the results was challenged by inadequate knowledge of groundwater flows and a limited number of sampling points.

For large-scale remediation, Fortum recommended that the various methods used in the pilot tests combined in a rational way. EHC treatment was recommended near the emission sources, which would more effectively disrupt heavily chlorinated hydrocarbons. In addition, zones with the remainder of VC and DCE concentrations should be designed on the downstream side. This was shown to be implemented by EHC-L or PermeOx treatment. The EHC-L treatment was supported by the fact that the required conditions are the same as in EHC processing. The suitability of PermeOx in conjunction with the EHC would be limited by the need to change the circumstances from one extremity to another (from a reducing oxidising agent).

Nordic Envicon

The Nordic Envicon area was selected near the long-term monitoring well PVP39 and near the shore of Lake Pyhäjärvi for two reasons. Firstly, high levels of VC and DCE (> 1000 µg / l) were found in the area. Secondly, the purpose of the reactive wall chosen by Nordic Envicon was to reduce the CVOC load discharging to Lake Pyhäjärvi already in the pilot phase. Based on previous studies, the contaminants in the area were discharged into the lake just at the well PVP39.

Anaerobic reductive dechlorination (ARD) was used to remedy the contaminated saturated zone, in which reductive conditions favourable to biodegradation were generated in the groundwater. The treatment method is biological and the formation of conditions favourable to anaerobic declination in the injection area typically takes a few months. The growth of the bacterial population involved in the disintegration process is slow, which means that significant reductions in contaminants and mass pruning can be expected, depending on the conditions from 0.5 to 1 year after injection.

The method which was used has been developed by the Nordic Envicon partner Regenesis. The chemical composition that improves the degradation conditions is injected into the soil through drill holes. The effect of the injection has been found to last 4-5 years. Remediation chemicals and products were injected directly into the soil using specially designed high-pressure injection equipment (RGS Nordic).

The remediation was carried out by feeding the treatment solution to the entire groundwater layer so that a permeable reactive wall (ARD) was formed in the bottom of the aquifer, where the decomposition of chloroethenes and vinyl chloride is biological. The application of the treatment solution to the soil was done by a specially developed direct push injection method, where the injection tip was first pushed down to the bedrock, after which the treatment agent was injected in the desired amounts to the desired layer by gradually lifting the injection tip upwards. The injection was stopped when the injection tip reached the groundwater table.

The reactive ARD wall was dimensioned on the basis of existing source data. The length of the wall was determined to be 20 m, which resulted in five injection points. The treatment chemical recipe and dosing were determined on the basis of soil and groundwater data and contaminant concentrations. The injection, that was executed by RGS Nordic, was successful, and the saturated zone received the planned amount of treatment solution.

Because the injection solution spread better than expected, the well PVP50, which was originally intended for water monitoring, could not be used directly for this purpose, as it was located within the reactive wall area. Significant ethene levels began to occur about half a year after injection, which meant that an effective ARD wall had been formed and that the chloroethene decomposition chain had progressed until the end.

Remediation worked effectively. The PCE and TCE levels fell below the limit of the analytical method. The DCE concentration in the reference well PVP39 was reduced from the level of 1100 µg/l to 25 µg/l in 2017, and later, in 2018, after the pilot period to 2 µg/l. The VC content followed a typical trend - rose at the start of the pilot test and went down towards the end. Before the pilot period the VC concentration varied between 70 and 310 µg/l, and by June 2018 the concentration had dropped to as low as 2 µg/l.

Nordic Envicon concluded that the remediation method would also suit the full-scale remediation of area.

General views

Generally speaking, the remediation pilots achieved the desired and good results. However, due to the small size of the pilot areas and the wide range of VC contamination in groundwater, complete decomposition of polychlorinated ethenes was not fully reliable. Pilots also found the formation of ethene, but VC was detected at the end of the one-year follow-up period, so the groundwater remediation period would be significantly longer under these conditions. It is possible that CVOCs and especially VC spread into the pilot areas from the contaminated groundwater surrounding the pilot areas.

3.4.2 Groundwater remediation goals

The purpose of the large-scale remediation is to eliminate the highest contaminant concentrations in the groundwater and at the same time reduce the total amount of contaminants. The natural degradation of chloroethenes, which has progressed in the groundwater in past decades, has stopped in VC. Decomposition can be triggered by the addition of substances to groundwater and is expected to continue after the end of the active remediation phase.

Since VC can theoretically cause the greatest health risk, the general goal of the remediation is to reduce the amount of VC in the long term.

i. if the subarea contains PCE and / or TCE, the aim is to reduce the amounts of both compounds (while DCE and VC concentrations may rise temporarily)

ii. if the major component of the subarea is VC and / or DCE, the aim is to reduce the amounts of both compounds (and at the same time VC may rise temporarily)

3.4.3 Targeted risk management methods

The case study area comprises approximately 10.8 ha, where the concentrations of contaminants have been detected or for which it is estimated that the harmful substances may be introduced. According to the risk assessment for the area, there is currently no health or environmental risk in the area. The goal setting for sustainable risk management of contaminated land (by the Finnish Ministry of Environment) was used to define the risk management objectives and measures in the area.

In accordance with the principles of sustainable risk management, Ramboll presented the following principles, which were considered in the goal setting and targeting the measures to optimise the positive effects of risk management measures.

The set of objectives for risk management is based on the following three principles:

1) Reducing the overall volume of contaminants (risk removal)

- Targeting the areas with the highest concentrations

2) Restriction of contamination (reduction of risk)

- Minimise the migration of contaminants towards the foundations of future buildings

3) Prevention of exposure to contaminants (risk acceptance)

- Residual risk management with building engineering solutions

In addition to these three principles of risk management, the following land use targets were considered in the design:

4) Future land use and construction schedule (economic dimension),

5) The effect of remediation operations on the comfort of living in the area (social dimension), and

6) Long-term benefits of the measures (social dimension)

Based on the objectives set for risk management, three subareas (1, 2 and 3) were identified in the project area to justify the implementation of remedial measures (see Figure 19). In addition to the risk management objectives, the selection of areas also took into account the history of the contaminants in the regions, as well as the hydrogeological characteristics such as the soil layers and the groundwater flow directions and velocities. The groundwater remediation planning was carried out by experts from Ramboll Finland Oy, Vahanen Environment Oy and Pöyry Finland Oy.

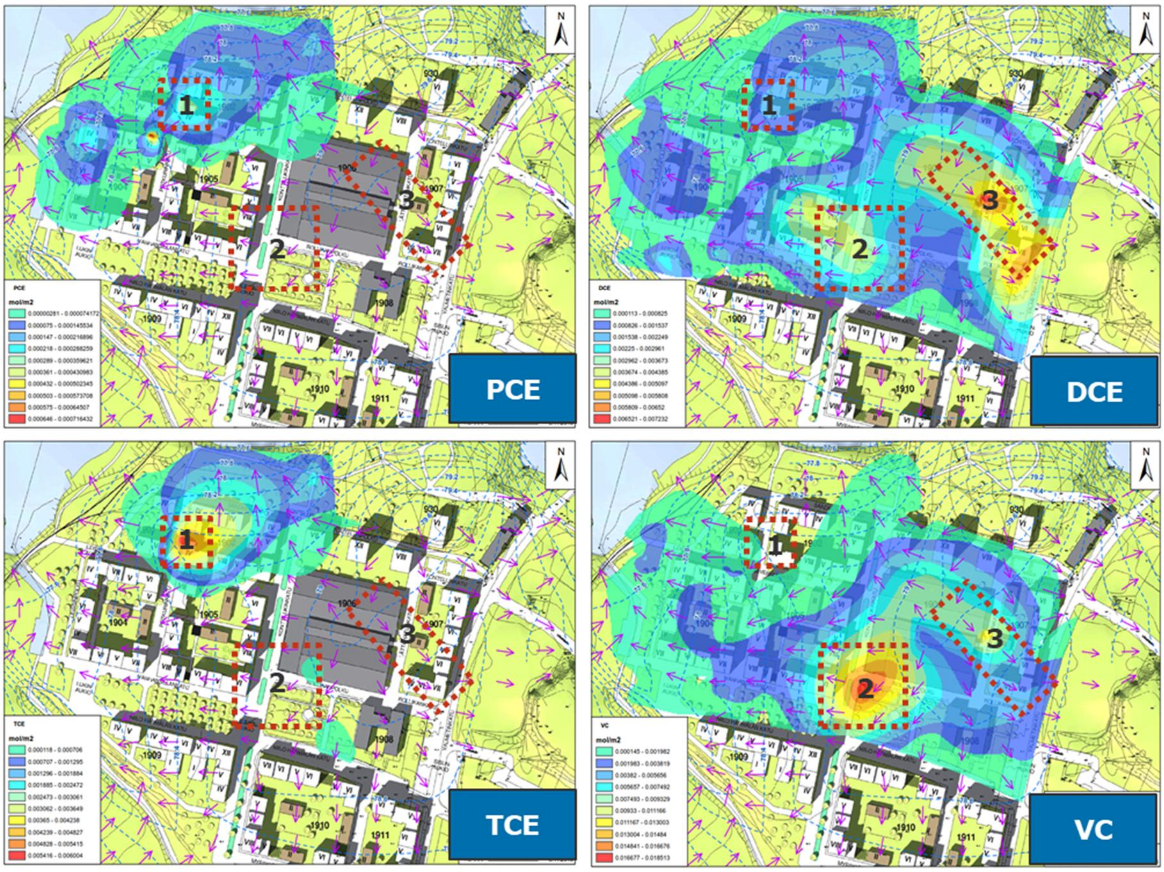


FIGURE 19. Selected areas for remediations defined in accordance with the principles of sustainable risk management (Pöyry 2018)

The three areas selected for clean-up operations only comprise limited parts of the entire project area but targeting these areas will allow for a reduction in harm and potential risks.

The selection of areas supports the objectives of sustainable risk management:

1) The selected remediation areas cover a significant part (70–90%) of the contaminant mass in the project area, which is limited to a total area of approximately 1.5 ha
2) Groundwater flow directions are taken into account
3) Remediation areas prioritise future land use and the in situ method will not hinder the redevelopment of the area

4) Injections are scheduled according to the planned construction

Selection of remediation areas reduces the long-term risk of the area and thus facilitates possible changes in the future regarding zoning, ownership, environmental conditions, etc.

Remediation area 1

The main contaminants in the remediation area are PCE and TCE. In addition, there is very little VC in the area. The groundwater layer in the area is about 4 m thick and has a water conductivity of > 5 cm/d.

The remediation method in the area is abiotic degradation with zero-valent iron (ZVI) and anaerobic reductive dehalogenation. ZVI enables rapid decomposition of PCE and TCE, while biological dehalogenation allows for rapid degradation of DCE and VC.

Remediation is to be carried out in a limited area of 1,600 m^2 in blocks 1901 and 1902 and in the adjacent street area. Remediation is accomplished by injecting a combination of both fast and slow carbon donors (electron donor) into the soil as an injection mixture. Additionally, nutrients and microbes may be used. The area is also fed a ZVI solution. Products suitable for injection have been tested in pilot phase 2016–2017. Detailed injection rates and frequency are determined in the detailed design plan.

Remediation area 2

The main contaminants in the remediation area are VC and DCE. Mother products PCE or TCE have not been established. In the remediation area, the groundwater layer is about 13 m thick and has a water conductivity >10 cm/d.

The remediation method in the region is anaerobic reductive dehalogenation. The method allows rapid decomposition of DCE and VC.

Remediation is to be carried out in a limited area of 8,000 m^2 in the blocks 1905 and 1906 and in Härmälänpuisto Park and adjacent street areas. Remediation is accomplished by feeding into the soil a combination of fast and slow carbon donors (electron donor) and possibly nutrients and microbes. Products suitable for injection have been tested in pilot phase 2016–2017. Detailed injection rates and frequency are determined in the detailed design plan.

Remediation area 3

The main contaminant in the remediation area is DCE, in addition a slight VC concentration has been detected. Mother products PCE or TCE have not been detected. In the remediation area, the groundwater layer is about 6 m thick and the conductivity <5 cm/d. The remediation method in the region is anaerobic reductive dehalogenation (ARD). The method allows rapid decomposition of DCE and VC.

Remediation is to be carried out in a limited area of 5,000 m^2 in the blocks 1906 and 1907 and in adjacent street areas. Purification is accomplished by feeding into the soil a combination of fast and slow carbon donors (electron donor) and possibly nutrients and microbes. Products suitable for injection have been tested in pilot phase 2016–2017. Detailed injection rates and frequency are determined in the detailed design plan.

Regional objectives:

Area 1:	A descending trend in PCE and TCE concentrations over three years
Areas 2 and 3:	DCE decreases over three years and reliable decrease in VC concentration

The objective is therefore to reduce the amounts of contaminants - not primarily concentrations. Targeting remediation in the highest concentration areas will reduce particularly long-term risks. Figures 20 and 21 show the estimated concentration development of chlorinated compounds in areas 1 to 3 during remediation.

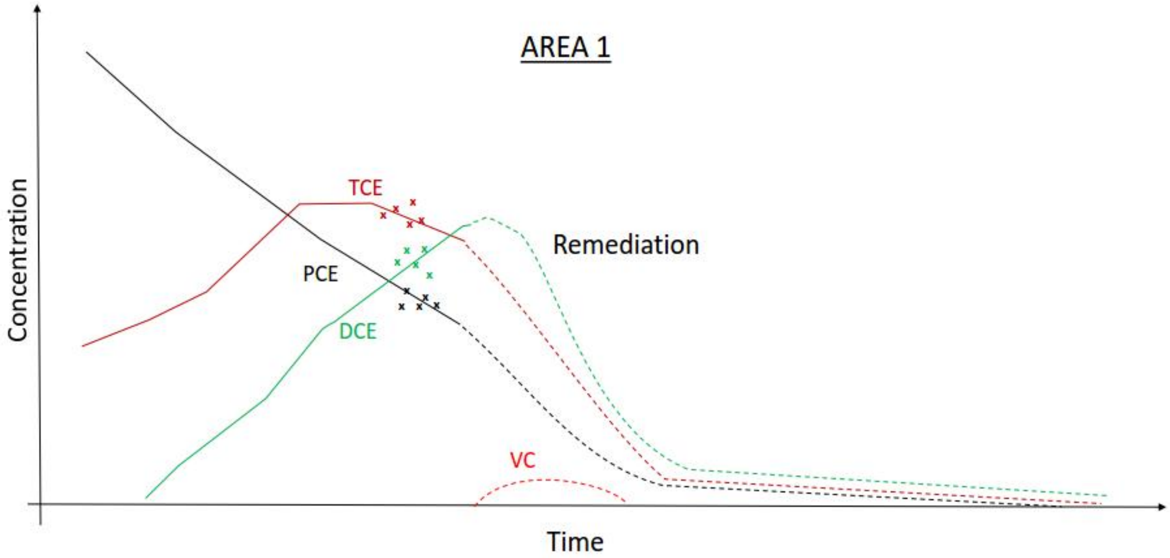


FIGURE 20. Estimated development of concentrations during remediation in area 1 (Ramboll 2019)

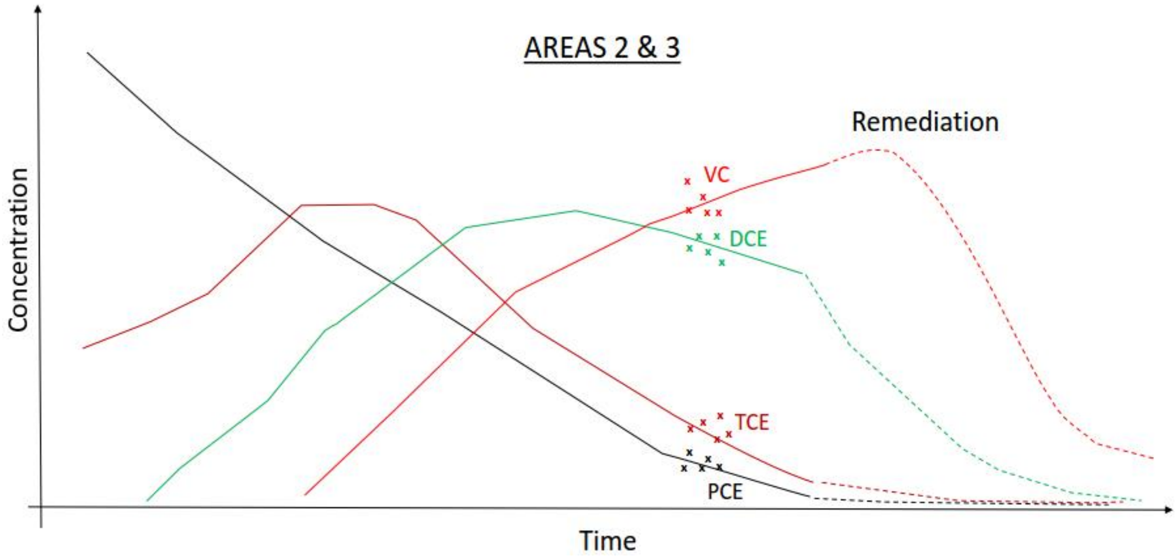


FIGURE 21. Estimated development of concentrations during remediation in areas 2 and 3 (Ramboll 2019)

3.4.4 Description of the selected remediation methods

Remediation is carried out using anaerobic reductive dechlorination (ARD) which is estimated to be the most sustainable remediation method for risk management purposes and, to a limited extent, chemical reduction (ISCR) on zero-valent iron (ZVI).

Anaerobic reductive dechlorination (ARD)

Anaerobic reductive dechlorination is a biological remediation method in which non-oxidative microbes utilise chlorinated compounds as electron receivers as part of their metabolism. As a result of these microbiological reactions, the chlorine atoms of the target compound are replaced by hydrogen atoms, allowing the method, for example, to decompose tetra- and trichloroethene into dichloroethene, further into vinyl chloride and ultimately ethene. Several anaerobic dechlorinating microbes are capable of biodegradation of PCE and TCE, but only few are known to degrade cis-1,2-DCE and VC. They belong to the Dehalococcoides family which are highly specialised from their metabolism.

In ARD remediation, favourable conditions in soil and / or groundwater are created by adding oxygen-consuming and hydrogen-producing reagents (so-called electron donor) such as alcohols, lactic acids, black treacle (molasses) or vegetable oil. The purpose of the electron donor is to ensure a suitable microbial reducing environment (oxygen <1 mg/L, redox <-150 mV) and sufficient protons (H_2, electron recipient) in the remediation area. Also, nutrients and trace elements such as nitrogen (N) and phosphorus (P) can be added to accelerate microbial activity and enhance microbial growth. If necessary, bacteria and enzymes can also be injected into the soil and / or groundwater to enhance the natural biodegradation.

ARD remediation is carried out on site in situ. In in situ remediation, the injection mixture is applied at the required concentration to the entire treatment area, also considering the vertical alignment of the remediation. The purpose is to create suitable conditions for the entire treatment area and to ensure the sufficiency of the protons.

In the case study area, there are soil layers which conduct water poorly and to which chloroethenes are bound. Due to poor water conductivity, the injection of the mixture into the soil is primarily carried out using direct injection or possibly also through different wells and pipelines where this method is estimated to succeed.

Direct injection is carried out by injecting solutions into the soil under high pressure with specially designed drill bits for drilling machines (Picture 14). The method allows injection solutions to be spread wider in the groundwater also in poorly conducting soil. Depending on the dimensioning, it is possible to achieve a long-lasting remedial effect by using a single injection using both slow and rapidly disintegrating organic additives.

PICTURE 14. Ongoing ARD injection (left, Nordic Envicon 08/2016). Principle of mass injection (right). Radius of influence (ROI, blue circle) can be 2–3 m while the injection borings locate 4–6 m from each other

Typically, method-specific analyses to be monitored in the ARD method are as follows: contaminants with the decomposition products, TOC, DOC, nitrate nitrogen, phosphorus, sulphate, chloride, soluble iron and manganese, dissolved oxygen, pH, redox potential and conductivity.

Chemical reduction (ISCR) with zero-valent iron (ZVI)

Chemical reduction is a remediation method in which the addition of reducing agents to the soil or water will chemically disintegrate bound or soluble contaminants, reduce their toxicity, alter solubility or susceptibility to other remediation methods. Chemical reduction is primarily used to decompose chlorine-containing compounds and reduce metal toxicity.

The most widely used chemical reducing agents are zero-valent irons (ZVI) and polysulphides, the first of which is a widely applied and well-known catalyst in the degradation process of chlorinated compounds. For example, in chemical reduction, PCE, TCE and cis-1,2-DCEs can be disintegrated directly into ethene using so-called abiotic beta-elimination, where vinyl chloride is not produced as an intermediate. In addition to beta-elimination, the chemical degradation of chloroethenes occurs biotically, whereby the reaction proceeds stepwise from PCE to ethene (see Figure 22).

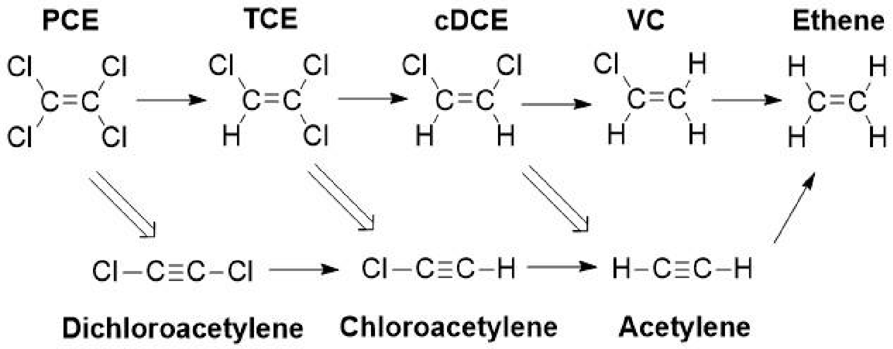


FIGURE 22. Decomposition of PCE through biotic (above) and abiotic (below) beta-elimination pathway to ethene (Regenesis 2019)

Remediation by chemical reduction requires strong oxygen-free and reducing conditions in the soil and water of the area (<1 mg/L, redox <-200 mV). In the soil or groundwater, suitable conditions for the remediation can be created by adding oxygen-consuming and hydrogen-producing reagents (so-called electron donor), such as alcohols, lactic acids, black treacles (molasses) or vegetable oil. The zero-valent iron (ZVI) used as a chemical reducing agent is generally added in a solution in which its particle size and surface activity are adjusted to allow appropriate spreading and to prevent aggregation and unintentional response.

The chemical reduction is carried out in situ. In in situ remediation, the injection mixture is applied at an appropriate concentration to the entire treatment area, also considering the vertical alignment of the remediation. The purpose is primarily to ensure contact between the ZVI and the contaminant. Placing the injection mixture in the soil can be accomplished by using different wells and pipelines, using direct injection into the soil, or combinations of the previous.

The method is known to be compatible with anaerobic reductive dehalogenation (ARD), which is why the methods are often applied as a treatment chain in which the primary contaminant is removed in the first stage and residual concentrations are treated biologically.

Typically, method-specific analysis to be monitored in connection with the ISCR-ZVI method are as follows:

- contaminants with decomposition products,
- used reducing agent if possible,
- chloride,
- dissolved oxygen,
- pH,
- redox potential and
- conductivity

Environmental effects of remediation and their prevention

The remediation is carried out in such a way that the methods used do not pose a risk to the environment or health. Prior to the commencement of work, a separate in situ cleaning work safety document and a safety and quality plan by the main contractor will be prepared for the work. The remediation work is estimated to not impair the environmental quality of the area.

3.5 Selected building practices in the area

3.5.1 Finnish Building Regulations

According to regulation 2.1.3 of Finnish Building Regulations Part D2, "The achievement of a healthy, safe and comfortable indoor climate must be ensured when… 2) defining the air tightness of the building envelope, subfloor and openings, and the air-tightness of interspace structures" (YM 2011). According to the instructions of the Finnish Association of Civil Engineers (RIL 107-2012), the base floor must always be sealed so that the radon, microbes and other contaminants do not enter the indoor air to an adverse extent (RIL 2012). All buildings are known to have either ventilated crawl spaces or radon ventilation, with the option of adding a roof-top fan. However, the review has noted that temporary air leaks in the building are possible as the building ages and the seals possibly deteriorate.

3.5.2 Mitigation of vapour intrusion

Risks can be managed by ensuring that concentrations below the future buildings - in the soil gas - remain at a safe level. In an area where groundwater contamination has been detected, normal structural solutions are presented as priority risk management measures. When the living quarters are on the lowest-lying floor of the building, ventilation and removal of the possible contaminants are taken care of by either ventilated crawl spaces or a radon ventilation systems (radon pipings).

Ventilated crawl spaces

The prefabricated, ventilated crawl spaces must be airtight so that the ground humidity and any gaseous contaminants do not have access to indoor air through the replacement air from leaks. Kosteudenhallinta.fi (website: humidity control) recommends having a height of at least 1.2 m above ground level for maintenance work (otherwise 0.8 m is recommended). The bottom beams and base walls can divide the crawl space and impede ventilation.

The crawl space ventilation is designed to keep the crawl space dry. The air in the crawl space should change between 0.5 and 1 times per hour. Ventilation can be arranged using wind pressure differences, and the gravity chimney effect by leading the outlet pipe to the roof or, if necessary, mechanically.

Depending on the area of the building site, the reference values for cavity vents according to RIL 107-2012 are 0.5–1.0. It should be noted that louvres covering / venting the vent hole reduces air flow and should be taken into account with reduction factors.

Building solutions can be placed in a crawl space, making checking and servicing work easier. The crawl space is normally accessed through the base floor or plinth through a special service door, so any remedial action does not require opening the bottom floor. (www.kosteudenhallinta.fi, adapted.)

Parking facilities

According to the master plan, the parking will be carried out either in underground parking facilities or under superstructures, as indicated in the formula. Non-structural parking is only permitted in blocks 1908 and 1914 and in block 1906 (block with parking area) according to the plan symbols of the blocks. Driving to the parking facilities takes place through the buildings or under the yard decks, not through openings.

According to Annex 2 of the Finnish Building Code Part D2 (indoor climate and ventilation of buildings), the ventilation of the parking garage must be arranged in such a way that air pollutants do not cause harm to the users of shelters. (YM 2011)

If the parking facilities is in the context of the rest of the building, its ventilation must be arranged in such a way that it is depressurised compared to other spaces. The supply air of the parking hall can be transfer air. The inlet and outlet holes are positioned to ensure adequate ventilation of various parts of the space. The holes are positioned so that the air does not spread unnecessarily from areas with high contamination levels. Also, there should be no points in the parking facilities, where the concentrations of air pollutants may exceed the permissible values. For example, local exhausts or transfer air fans can be used to prevent this. (YM 2011)

Exhaust airflow for mechanical ventilation in spaces, where an average of one run per parking place occurs during the 8-hour period of the most busy 8 hours, is at least 0.9 $(dm^3/s) / m^2$. Examples of these are parking spaces for residential buildings. (YM 2011)

Radon piping

The sub-base ventilation system ensures the control of indoor radon concentration if there are air leaks in the substructures. The radon ventilation system also effectively removes other potential gaseous contaminants, such as chlorinated solvents. The guidance from Finnish Radiation and Nuclear Safety Authority (STUK) explains that the purpose of the ventilation system is to ventilate the soil air in the sub-surface drainage layer and to create underpressure in the foundation. Then the amount of air flowing into the house and the radon concentration decrease.

In a Finnish study of 111 houses in 2013, passive (freely ventilated) radon piping was observed to reduce the radon concentration by 41 % on average (Holmgren & Arvela 2013). Therefore, it is important to lead the end of the exhaust duct above the roof already during the construction phase, keeping the end open. This also helps to avoid the need for alterations in the completed building, which would be the case if the exhaust pipe were installed afterwards. The reduction of radon level in the passive pipe system is based on ventilation. It is induced by the temperature difference between the soil and outdoor air and the effect of wind.

If, after completion of the building, a STUK test is carried out in accordance with the instructions, the heating and ventilation must be fully finished and in normal use in order to obtain a reliable result. Whenever possible, the timing of the sampling cycle will be matched with the time of commissioning of the building.

If, despite the preventive measures introduced in the construction phase, the concentrations of the pollutants exceed the concentrations determined as harmful on the basis of the risk assessment, the need to install mechanical ventilation into the piping will be examined later. The RT card provides more detailed instructions for dimensioning the exhaust fan and airflow. Connecting the fan to the radon piping typically reduces the radon concentration by 60–95% (cf. free-air piping).

Furthermore, radon piping has advantageous moisture-related effects. Ventilation caused by the piping removes moisture from soil material located under the slab and near ground-supported walls.

The installation of the radon piping is based on the solutions according to the RT reference card (RT 81-11099). Abnormal installations may result in a poorly functioning solution. The suction ductwork may be designed as looped or branched. The piping is placed at least 200 mm below the thermal insulation. In this way, a greater vacuum is achieved in the ductwork and no harmful air is sucked into the suction duct through the thermal insulation. (STUK 2018)

Potential lowering of groundwater

Some new building subfloors will possibly be equipped with 24-hour and year-round base water pumping stations to lower groundwater level in the block areas. The operation of the pumping stations is estimated to cause minor changes in groundwater flow in the area. The quality of the pumped water is assured by a separate sampling plan after the construction plans are completed and the specifications of the pumping systems are more detailed.

Based on the amount of water and the concentrations of the contaminants, it will be assessed whether the water can be discharged into Lake Pyhäjärvi or to the sewer and whether the water needs to be treated before the discharge. This assessment can only be made after knowing which buildings may be equipped with water lowering stations and the amount of water to be pumped.

3.6 Follow-up and monitoring

Groundwater, surface water, soil gas and indoor air are monitored at the site. The purpose of the monitoring is to ensure that the boundary conditions found to be safe by the risk assessment are met, and that any health or environmental risks that may result from groundwater contamination can be managed by taking measures as required by the contingency plan.

During the active phase of the remediation there will be monitoring of concentrations for at least PCE, TCE, DCE and VC (CVOCs), both in the remediation area and at the edges of the groundwater plume.

Changes in the chemical quality of groundwater and soil gas in the site are not particularly rapid, so monitoring will continue for years to come. On the other hand, the partial groundwater remediation that will be initiated in 2019 may cause sudden changes in the CVOC levels, and thus, more frequent monitoring is likely carried out in the following weeks after the remedial injections. Monitoring will be reported annually, and an updated monitoring programme will be presented to environmental and health officials based on these results.

Monitoring will be carried on as long as groundwater CVOC concentration is above target of the remediation, or it can be proved that the amount of CVOC in soil gas does not exceed the highest safe levels.

3.6.1 Groundwater

The sampling points have been and will be selected so that the effect of groundwater remediation can be monitored by following the development of concentration levels of the most harmful substances. Also, sentinel wells have been installed to monitor the potential for wider migration, such as to the east of Valmetinkatu Street or to the west towards Lake Pyhäjärvi.

The monitoring wells have been installed in various ways depending on the location, soil types, thickness of the aquifer and contaminant proportions. Some wells reach the bedrock level so that the sieve section caters for the entire water column. In the area, there are also parallel A and B wells, of which the A wells reach the bedrock, whereas the B wells are targeted to serve investigations of the topmost layers of the aquifer (about 2 metres below the groundwater table).

CVOCs and BTEX compounds are analysed from the groundwater samples in an accredited laboratory. Also other parameters may be examined related to regional remediation activities.

3.6.2 Soil gas

Any time engineering controls, such as mitigation systems, are implemented to protect the occupants of buildings, new or existing, from vapour intrusion, it is essential that a long-term management plan be developed and carried out. For new structures, the most immediate requirement is that mitigation systems be inspected and pressure differentials be measured. (Siegel 2016)

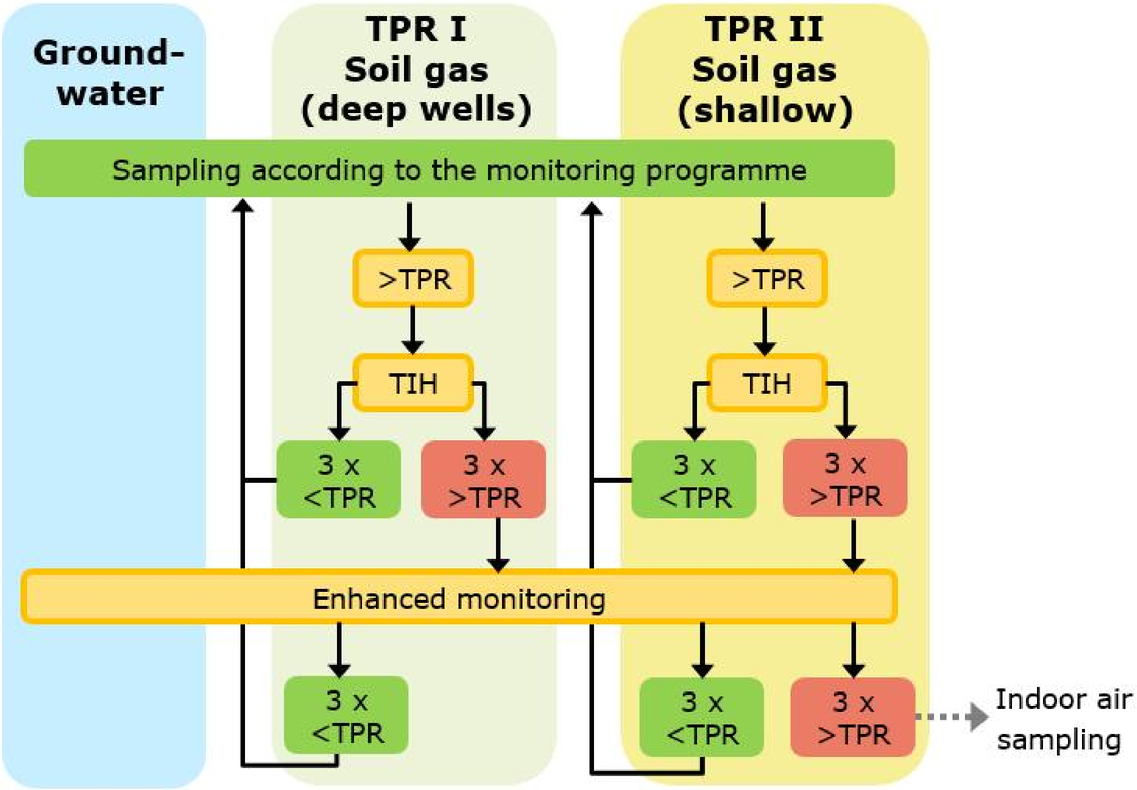
For the moment, soil gas samples have been taken from the field-mounted monitoring wells. Three of the sampling points have been specially planned horizontal sieve structures (imitation of radon ventilation) and the rest vertically mounted wells. As the construction progresses in the area, the monitoring points will be placed in ventilated crawl spaces of the buildings and in radon ventilation systems. The exact locations of the points and the arrangement of the sampling will be determined as the planning progresses with the construction companies. The needs for building-specific sampling will be assessed based on the results of long-term monitoring, unless a decision is made to stop monitoring before this.

The action limits for soil gas monitoring are given in section 3.7. The action limits are used to interpret the results of the soil gas samples and to define further actions.

The soil gas action limits apply as follows:

- If the concentrations of the contaminants in the soil gas are below the stated action limits, the monitoring is continued as usual.
- If the concentration of any of the contaminants exceeds the action limit, two replicate samples shall be taken at monthly intervals. Repeat samples are taken from the same well(s) from which the observation was made, and on a case-by-case basis, from three adjacent wells (within 50 m radius).
- If the action limit (TPR I) in the deep soil gas well is exceeded in three consecutive sampling events, the samples will also be taken from the groundwater and shallow soil gas wells, underground crawl spaces or radon piping.
- If the action limit (TPR II) in the shallow soil gas well is exceeded in three consecutive sampling operations, the samples are also taken from the groundwater and deeper soil gas wells. If the area already has buildings for residential use, indoor air concentrations will also be investigated in a specifically chosen space in the lowest-lying floor of the building close to the place where the action limit was exceeded.
- If some of the results are above and some below the action limit, sampling is continued every month until three consecutive consistent results are obtained.

The progress of the contingency plan in the soil gas is shown in Figure 23.



TPR = Action limit (concentration)
TIH = Densified (monthly) sampling from one matrix
Enhanced = Monthly samples from groundwater and soil gas from monitoring wells and sub-base points available
3 X <TPR = Three consecutive samples where the concentrations falls below action limits
3 X >TPR = Three consecutive samples where the concentrations falls below action limits

FIGURE 23. Progress of the soil gas sampling according to the contingency plan (Ramboll 2018)

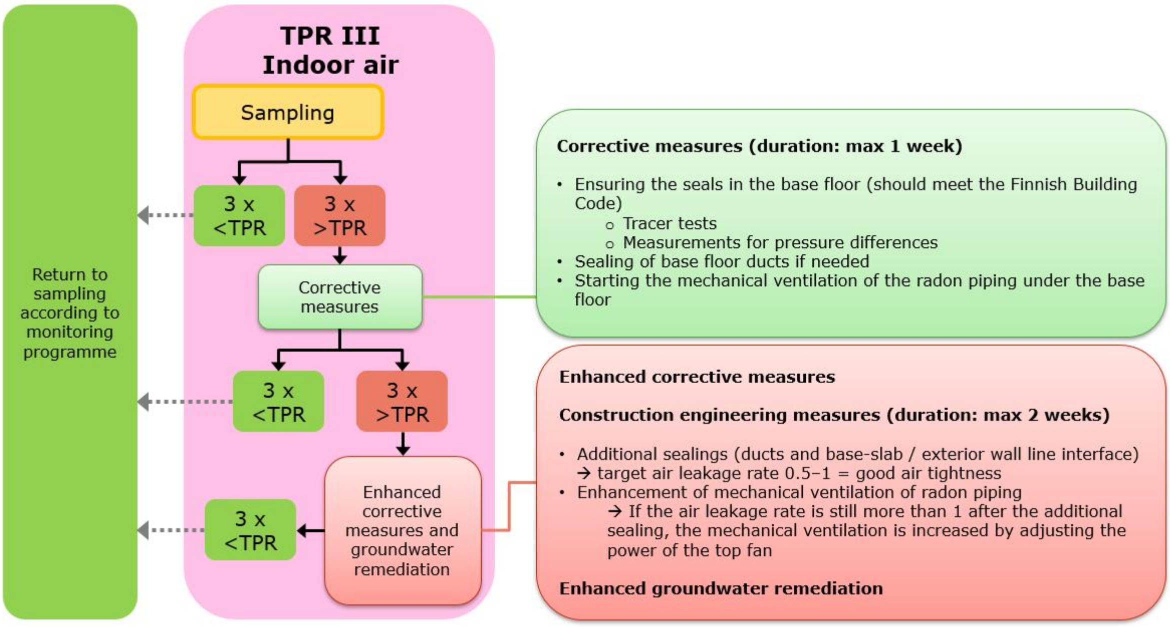
3.6.3 Transition to indoor air sampling

If the action limit TPR II of the soil gas sample is exceeded in three consecutive samples, the samples are also drawn from the groundwater and from deeper soil gas wells available. If there are already residential buildings in the area, the concentrations of indoor air will also be investigated from an appropriate space of the lowest-lying floor of the building, closest to the detection of the action limit.

The progress of indoor air sampling and corrective actions is shown in Figure 24. The estimated time for completion / start-up of corrective actions is shown in the figure.

If the indoor air limits (TPR III) are exceeded three times in succession, corrective measures are performed (Figure 25). If, after corrective actions, the indoor air limits are exceeded three times in succession, enhanced corrective measures are taken (Figure 26), in addition to which groundwater remediation is enhanced. Continued sampling is carried out until the indoor air concentration has fallen below the action limits in three consecutive measurements.

Since the action limits are defined on the basis of long-term exposure (lifetime exposure), short-term dwelling in a stressed environment does not cause any health hazards.



Corrective measures (duration: max 1 week)

- Ensuring the seals in the base floor (should meet the Finnish Building Code)
    - Tracer tests
    - Measurements for pressure differences
- Sealing of base floor ducts if needed
- Starting the mechanical ventilation of the radon piping under the base floor

Enhanced corrective measures

Construction engineering measures (duration: max 2 weeks)

- Additional sealings (ducts and base-slab / exterior wall line interface)
  → target air leakage rate 0.5–1 = good air tightness
- Enhancement of mechanical ventilation of radon piping
  → If the air leakage rate is still more than 1 after the additional sealing, the mechanical ventilation is increased by adjusting the power of the top fan

Enhanced groundwater remediation

FIGURE 24. Progress of the contingency plan in indoor air sampling (Ramboll 2018)

3.6.4 Indoor air

Administration building

The monitoring of the indoor air and the air below the floor will be continued in the lowest-lying rooms of the preserved administration building in block 1908. The sample points are located in the current heat distribution room (SI2 and HI2) and in the former telephone switchboard room (SI3 and HI3). In the case of alterations to possible buildings, the need for sampling and the possibility of re-evaluation will be reviewed. Concentration levels have been low in the indoor air of the building, and it can already be concluded that concentrations of chlorinated solvents in the indoor air of this building have not resulted in health hazards. Therefore, it is estimated that continuing monitoring over a longer period is not necessary.

Passive samples have been taken using a 7-day diffusion period and Tenax TA tubes. The VC sample has been pumped into the activated carbon sampler at the end of the diffusion time. In the room to be examined, the collectors are placed at a height of about 1 metre. The sub-slab samples are taken from holes that have been drilled in the bottom plate, or in the former telephone switchboard room, through the wooden floor.

Indoor air samples according to the contingency plan

It is not necessary to monitor the indoor air quality of future buildings in the area unless there are detected overshootings in three consecutive samples in shallow soil gas wells or in the crawl spaces of the buildings / radon pipings.

Indoor air sampling points are determined on a case-by-case basis. Samples are taken from the lowest-lying rooms and, as far as possible, from a space where no contaminants can be collected from sources other than groundwater and soil gas, such as stored chemicals, building materials, or automotive exhaust gases. In the case of indoor air sampling, the so-called blank sample is taken from the outdoor air during the same sampling event.

The sampling technique is the same as stated earlier in this document.

In exceptional circumstances, indoor air sampling will be prepared if the action limit (TPR II) for ground level air is exceeded in three consecutive samples. For indoor air sampling, the measures apply to buildings where the lowest-lying floor has residential or commercial premises. If the lowest-lying residential or commercial space is above the ground floor, or if there is a basement, garage, technical room or similar under the premises, no indoor air samples will be taken.

However, in all buildings, the possibility to perform sampling is reserved and, on a case-by-case basis, the need for sampling can also be assessed in buildings where the lowest-lying floors are not in residential or commercial use. Background concentrations in parking facilities should be taken into account in the design and implementation of the sampling and interpretation of the results.

The action limits for indoor air (TPR III) are TCA values and are applied as follows:

- If the target concentrations in the indoor air fall below the TPR III in the first sampling event, two follow-up samples will be taken with a compressed schedule along with the groundwater and soil gas samples.
- If the target concentrations in the indoor air fall below the action limit at three successive sampling events, the monitoring will be stopped in the building in question.
- If the target concentrations in the indoor air exceed the action limit, two successive samples will be taken monthly.

Based on the results of the sampling, measures are taken in accordance with the contingency plan.

3.6.5 Surface water

The water body receiving the potential load from the contaminated groundwater is Lake Pyhäjärvi. Concentrations of contaminants are highest in the middle of the area, and low concentrations have been found in the peripheral monitoring wells. Surface water samples have not yet been found to exceed quality standards.

Surface water loads are monitored at two points in Lake Pyhäjärvi, approximately 3 metres from the shore. Surface water samples are taken during normal monitoring rounds.

Surface water samples are analysed for chlorinated solvents in an accredited laboratory.

3.7 Action limits set for soil gas and indoor air monitoring

The action limits are the concentrations of contaminants in soil gas and indoor air, which are used to help interpret the monitoring results.

There is no action limit for groundwater, as the measured concentration of soil gas near the ground is a real indication if contaminants have evaporated from groundwater or soil into the soil gas. Contaminants in the indoor air can only be transported from the soil through the soil gas.

The action limits for the concentrations of soil gas contaminants were calculated using the same calculation method as in the risk assessment prepared for the area (YM, 2014).

Concentration levels were generated by looking at how high the concentrations of the monitored compounds can be in the soil gas at different depths without exceeding the maximum allowable air concentrations (TCA values) in the indoor air of the buildings.

For airborne chlorinated compounds, action limits (TPR I–III, Table 10) were set based on the safe concentrations estimated in the risk assessment.

- at a depth of 3 metres below ground level (TPR I), and
- just below ground level (TPR II)

Before the completion of the new buildings, the ground level soil gas concentration (TPR II) is measured from the most suitable shallow soil gas wells, at a depth of about one metre from the ground. When the buildings are completed, the ground level concentrations are measured separately from the crawl spaces of the buildings or radon pipelines, which are considered representative of the selected sites. The building-specific need for measurements is determined on the basis of an overall assessment of the completed buildings.

Long-term monitoring in the area is taken into account when assessing the need for measurements.

TABLE 10. Action limits in soil gas and indoor air (Ramboll 2018)

	Action limits		
	TPR I Soil gas / Deep (3 m), μg/m^3	**TPR II Soil gas / Ground level, μg/m^3**	**TPR III Indoor air (TCA value), μg/m^3**
PCE	5,700,000	240,000	250
TCE	480,000	21,000	23
DCEs	540,000	26,000	30
VC	38,000	1,800	2.0

Some uncertainties are known to be associated with calculating action limits. For example, the calculation assumes that some leakage of air from the void volume of the soil is always flowing through the bottom of the building, although in new buildings this should not be the case. Therefore, in new buildings, the risk of contamination intruding into indoor air is considerably lower than that of old buildings.

The TCA reference values are based on long-term exposure for years or decades, so the short-term exceedance of TPR III does not pose a health risk. The proposed action limits for soil gas are estimated to be suitable for the target, and no harmful concentrations can be formed in the indoor air, even if the structural solutions would malfunction.

The maximum air intake limit (TPR III) is the maximum permitted air intake (TCA).

3.8 Contingency plan

The process according to the contingency plan is carried out when the buildings are in a suitable condition for their use and if the results of groundwater and soil gas sampling observed during long-term monitoring so require. If the process according to the contingency plan requires indoor air sampling, samples will be taken from the buildings on which the lowest floor has residential or commercial premises.

If the lowest residential or commercial space is above the ground floor, or if there is a basement, garage, technical room or similar under the premises, indoor air samples will not be taken as a rule. Samples are also not taken from the living quarters above those premises. However, in all buildings, the possibility of sampling is reserved and, on a case-by-case basis, the need for sampling can also be assessed in buildings where the lowest floors are not in residential or commercial use. However, the background concentrations in the parking hall should be taken into account in the design and implementation of sampling.

Buildings to be included in the monitoring plan under the contingency plan are defined as groundwater remediation is monitored based on available groundwater and soil gas results. However, in buildings, a sampling point should be installed in connection with the underground radon ventilation piping or in the crawl space, from which it is possible to measure the concentrations of pollutants in the air under the building and the amount and speed of the air flow in the piping. All the aforementioned buildings must also be equipped so that the mechanical ventilation of the radon piping can be used if necessary.

3.8.1 Corrective measures

If the action limits are exceeded in the indoor air for three consecutive measurements, corrective measures of the first round are carried out. These include ensuring that the construction seals and pressure ratios are in compliance with building regulations. If the pressure difference between the interior of the building and the sub-slab is found to be such that the leakage air can be transported inside, the lead-throughs are sealed and pressure levels corrected, so that impurities do no enter the indoor air from under the building. The first-round corrective actions are shown in Figure 25.

Corrective measures (duration: max 1 week)

- Base floor tightness assurance (at least in accordance with building regulations)
    - Tracer tests
    - Pressure differential measurements
- If necessary, sealing of the bottom lead-throughs
- Installation and start-up of the mechanical ventilation of the radon piping under the base floor

FIGURE 25. First-round corrective measures (Ramboll 2018)

If, after the first round of remedial measures, the action limits are exceeded in three consecutive measurements, enhanced corrective measures are taken to improve the sealing of the building and the ventilation of the base. The enhanced corrective measures are shown in Figure 26.

Enhanced corrective measures

Engineering measures (duration: max 2 weeks)

- Additional seals (lead-throughs and structural connections for bottom slab and outer wall)
  → target air leakage rate 0.5–1 = good air tightness
- Enhancement of the mechanical radon ventilation
  → If the air leakage rate is still more than 1 after the additional sealing, the mechanical ventilation is increased by adjusting the power of the top fan

Enhanced groundwater remediation

FIGURE 26. Corrective measures for the second round (Ramboll 2018)

4 CONCLUSIONS

The thesis has described the characteristics of sites where there has been contamination with chlorinated hydrocarbons detected. Later, the steps which need to be taken to gain a proper understanding of the risks of such sites, and what solutions and remedies are available to address these problems, were explained.

The former industrial area, which was used as a case study, has since 2013 undergone a wide range of environmental studies aimed at identifying the area's suitability for residential use and, on the other hand, if the industrial history has caused environmental risks. During the massive soil remediation work carried out from 2013 to 2017 most of the contaminated soil situated above the groundwater table was removed from the area. As the polluting activities in the area have ceased and the soil has been remediated, there is no reason to assume that there will be significantly higher levels of harmful contaminants in the future.

After the soil remediation, the most significant health risk left in the area has been caused by the groundwater contamination with chlorinated hydrocarbons. Degradation product of VC (ethene) has also been found in the groundwater of the site, indicating that biodegradation into harmless compounds also occurs without active remediation measures. VC and DCEs have been found to be present in groundwater at levels exceeding the calculatory harmful levels. Concentrations of DCEs and VC may rise in the short term, but long-term levels are expected to be at a safe level. To control the low health risk caused by DCEs and VC, groundwater remediation is being initiated in three subareas at the site in June 2019. As a result from these targeted remedial activities, a significant decrease in the overall amount of CVOCs is expected.

During the early groundwater monitoring, at a few places in the western shoreline (<50 m away from the shore), vinyl chloride and dichloroethenes were found in concentrations at levels which could have been harmful to aquatic organisms. The groundwater is presumed to discharge into Lake Pyhäjärvi through this area. However, the groundwater investigations have shown that the pilot remediation (permeable reactive barrier, ARD), that was carried out from 2016 until 2017, led to CVOC concentrations decreasing significantly in this area. In 2018 both DCE and VC concentrations had already dropped to below 10 µg/l from being 100–1,100 µg/l for DCE and 70–310 µg/l before the pilot period. Therefore, it appears that the environmental risk posed to aquatic organisms has now been controlled by restraining the CVOCs from discharging into the lake.

Based on numerous studies of groundwater and soil gas, followed by the site-specific risk assessment, chlorinated hydrocarbons do not migrate from groundwater to soil gas in harmful amounts. Since the CVOC concentrations in soil gas are generally at a safe level, no harmful amounts of such contaminants can either intrude into the indoor air of future buildings.

Concentrations found in the site's soil gas after soil remediation measures are several orders of magnitude lower than the levels for health risk of most of the contaminants examined. Nevertheless, soil gas will be monitored and the tightness of the new structures of the new buildings will be checked, for example, by means of marker tests.

The next section will suggest some aspects and measures which could have resulted even in more successful and sustainable approach in the area.

4.1 Suggestions

4.1.1 Addressing the potential issue of groundwater lowering

When viewed vertically, the site has been planned with narrow margins with respect to the groundwater. Where there will be basements or parking facilities underground, the distance between the contaminated groundwater and the building base will likely be very little. This being the case, groundwater lowering might be needed. Any groundwater pumped from the areas where there have been detected high concentrations of CVOCs will have to be examined before it can be discharged e.g. into the stormwater sewer. If the water still contains elevated concentrations of CVOCs, it must be treated, and such treatment units are expensive and troublesome if they need to be integrated with newly-built residential buildings and their yards afterwards.

By more carefully considering the ground level altitude, already during the master planning stage it would have been possible to eliminate the possible issue with the groundwater level. The possibility to use more filling materials from the site would have been also an economically and environmentally good solution, as less materials would have been transported away from the site. Also, the demolition debris (concrete crush) from the old buildings could have been used more widely in the area.

4.1.2 Architecture and building regulations

The extent of CVOCs in the groundwater in the area posed uncertainties in site redevelopment. Alongside the partial groundwater remediation, to control the risk of vapour intrusion, all the future buildings will have either ventilated crawl spaces, radon ventilation systems or parking facilities under them. However, the vapour intrusion pathway being addressed already at an earlier stage of the development process could have enabled an even more sustainable approach for the site by controlling the risks from contaminated soil and groundwater with an emphasis on the architecture.

The first step from this point of view would have been the systematic locating of the residential housing on the floors above the ground floor. By placing only non-sensitive premises such as parking facilities, storage areas and commercial premises on the lowest-lying floors the potential health risks of the site could have been controlled, because no long-term exposure would be possible.

Secondly, the vapour intrusion pathway could have been considered more carefully in the building regulations that were set for the area. The scrutinised regulations could have demanded enhanced vapour mitigation measures as a proactive approach. Such design could include, for example, an increased amount of crawl spaces, additional radon piping per building's sub-foundation, rooftop fans and passive vapour barriers.

To be successful, a technical and regulatory guidance by ITRC recommends that agencies conducting or overseeing vapour intrusion investigations need to develop a strong community outreach programme to educate and reassure the local community about vapour intrusion in a meaningful, sensitive, and effective manner. Unlike any other contaminant pathway, vapour intrusion merits effective education of the affected community regarding the risk of soil gas migrating from the subsurface. (ITRC 2007.)

Introducing the enhanced mitigation measures would have eliminated the existing, marginal risks in the area and might have resulted in the groundwater not being remediated at all.

4.1.3 Enhanced vapour intrusion mitigation

The methods for controlling vapour intrusion fall into three categories:

1) remediation of soil and groundwater with the methods used historically in clean-up programmes;

2) institutional controls; and

3) engineering controls on buildings, including sub-slab depressurisation systems typically used for radon mitigation and vapour barriers (ITRC 2007).

Regulatory guidance documents routinely state that the final remedy for vapour intrusion involves clean-up of contaminated soil or groundwater since vapour intrusion falls within the clean-up programmes and engineering controls ("building-side solutions") are not typically viewed as permanent solutions. (Lowe et al. 2009.)

Regulatory programme requirements to clean up affected soil or groundwater have the unintended consequence of creating barriers for many potential solutions to vapour intrusion problems. Final remedies that use technologies designed to reduce contamination volume, toxicity, and mobility often have the unintended consequence of creating a reluctance to apply remedies that rely on institutional or engineering controls to eliminate the exposure pathway. (Lowe et al. 2009.)

Green building design

The architecture, engineering, and construction community has been dealing with similar issues for years when constructing buildings that are subject to moisture vapour intrusion with subsequent mould growth. Integrated (that is, green) building design techniques above and beyond vapour barriers, that are used to prevent moisture vapour intrusion should also be considered for mitigating soil gas vapour intrusion over the life of the building.

Examples of green building-integrated design solutions to minimise soil gas vapour intrusion include

1) ventilation and climate controls that maintain positive building pressure relative to the sub-slab;
2) automated building controls that control pressurisation;
3) air and vapour barriers, which are the combination of interconnected materials, flexible sealed joints, and other components of the building envelope that help control building pressurisation and air infiltration; and
4) building commissioning and re-commissioning to verify building performance at start-up and throughout the life of the building.

According to Lowe (2009) integrated building design methods (including sub-slab barriers) hold the promise to provide an alternative or supplemental mitigation option, accelerating property redevelopment, and offering a sustainable solution to vapour intrusion. Overcoming regulatory hurdles is a key factor in gaining acceptance of building-side techniques as permanent solutions to vapour intrusion concerns. (Lowe et al. 2009.)

Improved vapour ventilation system

To improve the vapour ventilation system described in this paper, a more sophisticated system with a venting layer beneath and a monitoring layer above a vapour barrier could be introduced at the site.

Such solution could both verify the effectiveness of the barrier without collecting indoor air samples, and provide a contingency plan that would address exceedances of action levels potentially detected in the sub-slab monitoring layer

Passive vapour barrier

Under certain conditions and with the appropriate design, passive systems can be successful in mitigating the vapour intrusion pathway and have the advantage of being sustainable over the long term. A successful passive vapour intrusion control system is likely to require more extensive construction efforts, because the system requires comprehensive sealing of all vapour intrusion pathways. According to Ash (2010) these efforts are likely to result in higher initial capital costs and short-term disruption to building users, but these elements may be offset by lower long-term operation and maintenance efforts and avoidance of aesthetic and other impacts on property owners that, for example, may be inherent in continuous operation of an external fan-based system. (Ash et al. 2010.)

These reduced operation and maintenance requirements and impacts are also likely to make passive systems preferable to the building owners, particularly in residential applications. Documenting the effectiveness of these systems is likely to rely initially on indoor air sampling, but long-term monitoring can be limited to confirming that the systems remain intact. (Ash et al. 2010.)

New construction is an excellent opportunity to install a passive system, since it can be easily incorporated into the design process and may even serve other purposes such as water vapour control and waterproofing. A passive system may be more effective in cases where low permeability soil is located beneath the floor slab. In Finland, buildings are often located on soils with low permeability such as glacial till or silt and clay deposits, and do not exhibit a layer of granular material that would permit effective soil gas migration. If a building foundation is constructed on low permeability material, then the likelihood of creating an adequate vacuum field under the slab using an active system is diminished. (adapted from Ash et al. 2010.)

Shallow water table conditions can also pose challenges to active systems if the vadose zone beneath the slab is relatively thin and dissolved phase contamination is present close to the slab elevation. In active systems, the sumps or sub-slab piping may be inundated with water causing low air flow and a spike in vacuum. The spike in vacuum can cause water to flow into pipes, possibly necessitating shut down of the system. (Ash et al. 2010.)

In many parts of the site there have not been alarming concentrations of CVOCs in the soil gas detected. On the other hand, the government decree guideline values for CVOC compounds in soil are very low. For example, for VC the upper guideline value equals the normal detection limit from the environmental laboratories. Because of the strict guidelines and because no structural risk management measures were considered or approved, a large-scale soil remediation via excavation was carried out. During 2013–2017 over 200,000 tonnes of contaminated soil was removed from the site and transported to reception sites specialised in the types of soils observed. From an environmental point of view, especially the treatment of the CVOC contaminated soils caused a significant burden measured in the amount of CO_2 emissions, because the trucks needed to take hundreds of loads of soil over 100 km away.

Introducing sustainable solutions, such as passive vapour barriers, to architectural planning could have resulted in great savings economically and would have been environmentally friendly when no excavation or less excavation would have been needed in certain parts of area. The same principle could have also been used with the old aeroplane factory, which was demolished in late 2016. After the demolition and removal of the demolition waste 54,400 tonnes of contaminated soils were excavated and removed from the site. Excavation areas comprised 37 % of the overall surface area of the blocks 1906 and 1907. Removing the contaminated soil partially from the subsurface of the factory, introducing targeted in situ remediation methods in the remaining vadose and saturated zone, and introducing vapour barriers could have allowed the old – architecturally distinctive – factory being preserved.

The groundwater remediation, sub-foundation vapour mitigation, monitoring, and contingency plan described in this paper provide an example of how the remediation community, regulators, and developers can work together to advance property reuse. From a technology perspective, there is a need to shift the regulatory paradigm away from soil and groundwater remediation being viewed as the only final measure for controlling vapour intrusion to one that also recognises engineering controls on buildings as a permanent solution. (After Lowe et al. 2009.)

REFERENCES

Advanced Energy (Dastur, Davis). 2005. Closed Crawl Spaces Do Double Duty. [Accessed 9 May 2019]. Available at: https://web.archive.org/web/20090124142036/http://advancedenergy.org/buildings/knowledge_library/crawl_spaces/pdfs/Home%20Energy%20January%202005_low%20res2.pdf

Agency for Toxic Substances and Disease Registry (ATSDR) 1997a. Toxicological Profile for Trichloroethylene (update). Atlanta, GA: Agency for Toxic Substances and Disease Registry, US Department of Health and Human Services, Public Health Service.

Aller, L. , Bennett, T. W., Hackett, G., Petty R. J., Lehr J. H., Sedoris, H., Nielsen, D. M. and Denne, J. E. 1989. Handbook of Suggested Practices for the Design and Installation of Ground Water Monitoring Wells. US EPA Report No. 600/4-89/034. National Water Well Association.

Ash, Ensign, Simons (GEI Consultants). 2010. Sustainable Vapor Intrusion Controls – Designing an Effective Passive System. [Accessed 9 May 2019]. Available at: https://clu-in.org/download/contaminantfocus/vi/Sustainable%20vapor%20intrusion%20controls%20passive.pdf

Brusseau, Maier. 2004. Environmental Monitoring and Characterization, Air Sparging. [Accessed 9 May 2019]. Available at: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/air-sparging

CityChlor (an interreg IVB-NWE project between partners from Flanders, Germany, France and the Netherlands). 2013. In Situ Chemical Reduction Using Zero Valent Iron Injection - A Technique for the Remediation of Source Zones. [Accessed 9 May 2019]. Available at: http://www.citychlor.eu/sites/default/files/in_situ_chemical_reduction_using_zero_valent_iron_injection.pdf

Clark, L. 1988. The Field Guide to Water Wells and Boreholes. Geological Society of London and Open University Press.

Crane, Scott. 2012. Nanoscale zero-valent iron: Future prospects for an emerging water treatment technology. [Accessed 9 May 2019]. Available at: https://www.sciencedirect.com/science/article/pii/S0304389411014531

Doherty RE. 2000. A history of the production and use of carbon tetrachloride, tetrachloroethylene, trichloroethylene and 1,1,1-trichloroethane in the United States, Part 1 Historical background: carbon tetrachloride and tetrachloroethylene. J Environmental Forensics, 1:69–81

Driscoll, F. G. 1986. Groundwater and Wells (Second Edition). Johnson Filtration Systems Inc.

Earnest GS. 2002. A control technology evaluation of state-of-the-art, perchloroethylene dry-cleaning machines. Appl Occup Environ Hyg, 17: 352–359. doi:10.1080/10473220252864950 PMID:12018399

Einarson, Murray D. 2006. Multi-level Groundwater Monitoring. [Accessed 9 May 2019]. Available at: http://documents.wrwc.us/files/2368-00037.pdf

Environment Agency. 2003. Guidance on the Monitoring of Landfill Leachate, Groundwater and Surface Water. Landfill Technical Guidance Note 02.

Environment Agency. 2006. Guidance on the Design and Installation of Groundwater Quality Monitoring Points (Science Report SC020093). [Accessed 9 May 2019]. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/290727/scho0106bkct-e-e.pdf

EnviroWiki, Chlorinated Solvents, website [last edited on 25 July 2018. [Accessed 9 May 2019]. Available at: https://www.enviro.wiki/index.php?title=Chlorinated_Solvents

European Chlorinated Solvent Association (ECSA). 2012. All about "Per" in a nutshell. [Accessed 22 October 2013]. Originally available at: https://www.eurochlor.org/media/61344/05-infosheet-publicper-dry-cleaning.pdf

Garetano G & Gochfeld M. 2000. Factors Influencing Tetrachloroethylene Concentrations in Residences Above Dry-cleaning Establishments. Arch Environ Health, 55: 59–68. doi:10.1080/00039890009603387 PMID:10735522

Gill, H.S. 2006. Bimetallic Nanoscale Particles. PARS Environmental Inc. Power Point Presentation. Originally available at: http://www.itrcweb.org/Documents/sedimentsgillslides.pdf (N/A 15 May 2019)

Glauser J, Ishikawa Y. 2008. Chemical Industries Newsletter. Chemical Economics Handbook Marketing, Research Report: C2 Chlorinated Solvents. SRI Consulting. [Accessed 24 July 2013]. Originally available at: http://chemical.ihs.com/nl/Public/2008Aug.pdf.

Henschler D. 1994. Toxicity of Chlorinated Organic Compounds: Effects of the Introduction of Chlorine in Organic Molecules. Angew. Chem. 33 1920–1935. 10.1002/anie.199419201 [Cross Ref]

Holmgren, Arvela. 2013. Vapaasti tuulettuvan radonputkiston vaikutus sisäilman radonpitoisuuteen – kenttätutkimuksia. Sisäilmastoseminaari 13 March 2013, Helsinki. Presentation.

Hutzler, Murphy, and Gierke. 1990. State of Technology Review: Soil Vapor Extraction Systems." EPA/600/S2-89/024, U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, Ohio.

Innovative Environmental Technologies, Inc. 2019. Chlorinated VOC. [Accessed 9 May 2019]. Available at: http://www.iet-inc.net/services/target-compounds/

International Agency for Research on Cancer (IARC). 1995. Dry cleaning, some chlorinated solvents and other industrial chemicals. IARC Monogr Eval Carcinog Risks Hum, 63: 1–551. PMID:9139130

International Agency for Research on Cancer. 2012. Vinyl Chloride, IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Volume 100F. [Accessed 15 May 2019]. Available at: https://monographs.iarc.fr/wp-content/uploads/2018/06/mono100F-31.pdf

International Agency for Research on Cancer. 2014. Evaluation of carcinogenic risks to humans. [Accessed 9 May 2019]. Available at: https://monographs.iarc.fr/wp-content/uploads/2018/06/mono106-002.pdf

The Interstate Technology & Regulatory Council (ITRC). 2002. ITRC Diffusion Sampler Team. [Accessed 9 May 2019]. Available at: https://www.itrcweb.org/Documents/PDBFAQs2.pdf

The Interstate Technology & Regulatory Council (ITRC). 2005. Technology Overview: Overview of In Situ Bioremediation of Chlorinated Ethene DNAPL Source Zones. [Accessed 9 May 2019]. Available at: https://www.itrcweb.org/Guidance/GetDocument?documentID=10

The Interstate Technology & Regulatory Council (ITRC). 2007. Technical and Regulatory Guidance, Vapor Intrusion Pathway: A Practical Guideline. [Accessed 9 May 2019]. Available at: https://www.itrcweb.org/documents/vi-1.pdf

The Interstate Technology & Regulatory Council, Bioremediation of DNAPLs Team. 2008. In Situ Bioremediation of Chlorinated Ethene: DNAPL Source Zones. [Accessed 9 May 2019]. Available at: https://www.itrcweb.org/Guidance/GetDocument?documentID=12

The Interstate Technology & Regulatory Council (ITRC), Petroleum Vapor Intrusion Team. 2014. Petroleum Vapor Intrusion Fundamentals of Screening, Investigation, and Management. [Accessed 9 May 2019]. Available at: https://www.itrcweb.org/PetroleumVI-Guidance/Content/Resources/PVIPDF.pdf

Johansen K, Tinnerberg H, Lynge E. 2005. Use of History Science Methods in Exposure Assessment for Occupational Health Studies. Occup Environ Med, 62: 434–441. doi:10.1136/oem.2004.016493 PMID:15961618

Kosteudenhallinta.fi (Ympäristöministeriö, Rakennusteollisuus, Mittaviiva Oy, Tampereen Teknillinen Yliopisto). 2019. Ryömintätilalliset eli tuulettuvat alapohjat. [Accessed 12 May 2019]. Available at: http://www.kosteudenhallinta.fi/index.php/fi/rakenteet/alapohjat/ryoemintatilalliset-eli-tuulettuvat-alapohjat

Linak E, Leder A, Yoshida Y. 1992. Chlorinated Solvents. In: Chemical Economies Handbook. Menlo Park, CA, USA: SRI International, 632.3000–632.3001.

Lowe, Raphael, Lund, Casselberry. 2009; Accelerating the Redevelopment of a Vapor-impacted Property Based on Data-informed Verification of Vapor Barrier Technology. [Accessed 9 May 2019]. Available at: https://clu-in.org/download/contaminantfocus/vi/Accelerating%20Redevelopment.pdf

Massabò, Catania, Piazza, Paladino. 2008. Groundwater Risk Assessment of PCE at a Contaminated Site. [Accessed 9 May 2019]. Available at: https://www.researchgate.net/publication/288765648_Groundwater_risk_assessment_of_PCE_at_a_contaminated_site

Matteucci, Ercole, del Gallo. 2015. A Study of Chlorinated Solvent Contamination of the Aquifers of an Industrial Area in Central Italy: a Possibility of Bioremediation. [Accessed 9 May 2019]. Available at: http://europepmc.org/articles/pmc4556989

McCarthy, K.A. and R.L. Johnson. 1993. Transport of Volatile Organic Compounds Across the Capillary Fringe. Water Resources Research. 29(6)1675-1683.

McCaulou D. R. and Huling S. G. 1999. Compatibility Of Bentonite And DNAPLS. Ground Water Monitoring And Remediation Vol. 19, No 2 Pp. 78 - 86.

McHugh, Loll, Eklund. 2017. Recent Advances in Vapor Intrusion Site Investigations. [Accessed 9 May 2019]. Available at: https://www.sciencedirect.com/science/article/pii/S0301479717301196

Medical College of Wisconsin. 2005. Mold Allergies. Healthlink.mcw.edu. 2013-07-22. Archived from the original on 2009-01-22. Retrieved 2013-11-02.

Mendoza, C.A. and T.A. McAlary. 1990. Modeling of ground-water contamination caused by organic solvent vapors. Ground Water. 28(2) 199-206.

Mercer, J.W. and R.M. Cohen. 1990. A Review of Immiscible Fluids in the Subsurface: Properties, Models, Characterization and Remediation. Journal of Contaminant Hydrology. 6 (1990) 107 – 163.

Minerals Technologies Inc. 2019. LIQUID BOOT® Vapor Intrusion Barrier Systems. [Accessed 9 May 2019]. Available at: https://www.mineralstech.com/business-segments/performance-materials/cetco/products/environmental-products/vapor-intrusion-barrier-systems

Mosley. 2005. Engineering Design Considerations for Mitigation of Vapor Intrusion. Presented at the conference of national association of remedial project managers, Phoenix, AZ. May 24.

National Industrial Chemicals Notification and Assessment Scheme (NICNAS). 2001. Tetrachloroethylene. Priority Existing Chemical Assessment Report No. 15. Australian Government, National Industrial Chemicals Notification and Assessment Scheme. [Accessed 24 July 2013]. Originally available at: https://www.nicnas.gov.au/__data/assets/pdf_file/0020/4376/PEC_15_Tetrachloroethylene_Full_Report_PDF.pdf.

New Jersey Department of Environmental Protection (NJDEP). 2005. Vapor Intrusion Guidance. Trenton, NJ: Site Remediation and Waste Management Program (SRWMP) and the Division of Science, Research and Technology (DSRT)

NSW, Office of Environment and Heritage. 2011. Management of Chlorinated Solvents. [Accessed 9 May 2019]. Available at: https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/licensing/110642chlorinatedsolvents.pdf

Nutt, M.O., J.B. Hughes, and M.S. Wong. 2005. Designing Pd-on-Au Bimetallic Nanoparticles for Trichloroethylene Hydrodechlorination. Environmental Science & Technology. 39(5):1346-1353.

O'Hara, S., T. Krug, J. Quinn, C. Clausen, and C. Geige. 2006. Field and Laboratory Evaluation of the Treatment of DNAPL Source Zones Using Emulsified Zero-valent Iron. Remediation Journal. Spring 2006.

O’Neil MJ, Heckelman PE, Roman CB. 2006. The Merck Index.14th Ed. Whitehouse Station, NJ, USA: Merck & Co., Monograph Number 09639

Obiri-Nyarko, Grajales-Mesa, Malina. 2014. An Overview of Permeable Reactive Barriers for In Situ Sustainable Groundwater Remediation. [Accessed 9 May 2019]. Available at: https://www.sciencedirect.com/science/article/pii/S0045653514004731

Parsons. 2004. Principles and Practices of Enhanced Anaerobic Bioremediation of Chlorinated Solvents. [Accessed 20 May 2019]. Available at: https://frtr.gov/costperformance/pdf/remediation/principles_and_practices_bioremediation.pdf

Phenrat, T., Y. Liu, R. Tilton, and G.V. Lowry. 2009. Adsorbed Polyelectrolyte Coatings Decrease Fe0 Nanoparticle Reactivity with TCE in Water: Conceptual Model and Mechanisms. Environmental Science & Technology. 43(5): 1507-1514.

Prime Minister´s Office (Pyy, Tikkanen, Reinikainen, Nihtilä and Sorvari). 2017. Sustainable risk management practices of contaminated land. [Accessed 9 May 2019]. Available at:

https://tietokayttoon.fi/documents/10616/3866814/25_Pilaantuneiden+maa-alueiden+kest%C3%A4v%C3%A4t+riskinhallintakeinot_.pdf/f88082c5-6994-4aa6-b138-7776e62be6b0/25_Pilaantuneiden+maa-alueiden+kest%C3%A4v%C3%A4t+riskinhallintakeinot_.pdf.pdf?version=1.0

Provoost, Tillman, Weaver. 2010. Vapour Intrusion into Buildings – A Literature Review. [Accessed 9 May 2019]. Available at: https://www.researchgate.net/publication/253235097_Vapour_intrusion_into_buildings_-_A_literature_review

Pöyry Finland Oy. 2018. Figure 19. Selected areas for remediations defined in accordance with the principles of sustainable risk management.

Quinn, J., C. Geiger, C. Clausen, K. Brooks, and C. Coon, S. O'Hara, T. Krug, D. Major, W.-S. Yoon, A. Gavaskar, and T. Holdsworth. 2005. Field Demonstration of DNAPL Dehalogenation Using Emulsified Zero-valent Iron. Environmental Science & Technology. 39(5):1309-1318.

The Radiation and Nuclear Safety Authority (STUK). 2018. Installation of Radon Piping, website [last edited on 19 April 2018; accessed 9 May 2019].

Regenesis. 2019a. In Situ Chemical Oxidation, website. [Accessed 9 May 2019]. Available at: https://regenesis.com/eur/site-remediation-solutions/in-situ-chemical-oxidation-isco/

Regenesis. 2019b. S-MicroZVI, website. [Accessed 9 May 2019].
Available at: https://regenesis.com/en/remediation-products/zero-valent-iron-new/;
Available at: https://regenesis.com/wp-content/uploads/2019/02/S-MicroZVI_SpecSheet-7.pdf

Saleh, N., K. Sirk, Y. Liu, T. Phenrat, B. Dufour, K. Matyjaszewski, R. Tilton, and G. Lowry, 2007. Surface Modifications Enhance Nano-iron Transport and NAPL Targeting in Saturated Porous Media. Environmental Engineering Science. 24(1):45-57.

Siegel, Lenny. 2016. A Stakeholder's Guide to New Construction at Vapor Intrusion Sites. [Accessed 9 May 2019]. Available at: http://www.cpeo.org/pubs/SGNC.pdf

Solinst Canada Ltd. 2019. Low Flow Groundwater Sampling, website. [Accessed 9 May 2019]. Available at: https://www.solinst.com/products/groundwater-samplers/407-bladder-pumps/user-tips/low-flow-sampling.php

Sosiaali- ja terveysministeriö, STM (Ministry of Social Affairs and Health). 2018. HTP values 2018: Concentrations known to be harmful. [Accessed 20 May 2019]. Available at: http://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/160967/STM_09_2018_HTParvot_2018_web.pdf

State Coalition for Remediation of Drycleaners. 2009. Chemicals Used in Drycleaning Operations. Available at: https://drycleancoalition.org/chemicals/%20ChemicalsUsedInDrycleaningOperations.pdf

Suomen Rakennusinsinöörien Liitto, RIL (Finnish Association of Civil Engineers). 2012. RIL 107-2012. [Accessed 20 May 2019]. ISBN 978-951-758-545-3

Talotekniikkateollisuus. 2019. Sisäilman laatu, website. [Accessed 20 May 2019]. Available at: https://www.talotekniikkainfo.fi/sisailmasto-ja-ilmanvaihto-opas/5-ss-sisailman-laatu

Toxics Use Reduction Institute (TURI). 2006. Perchloroethylene. In: Five Chemical Alternatives Assessment Study.

Tratnyek Research Group. 2005. Own work (figure). [Accessed 9 May 2019]. Available at: https://upload.wikimedia.org/wikipedia/commons/7/73/Iron_Wall_Types.png

Tratnyek, P.G., and R.L. Johnson. 2006. Nanotechnologies for environmental cleanup. Nanotoday. 1(2). Available at: http://dx.doi.org/10.1016/S1748-0132(06)70048-2.

U.S. Environmental Protection Agency. 2001. Monitored Natural Attenuation: USEPA research program – an EPA Science Advisory Board Review. EPA-SAB-EEC-01-004.

U.S. Environmental Protection Agency. 2006a. Engineering Forum Issue Paper: In Situ Treatment Technologies for Contaminated Soil. EPA 542/F-06/013.

U.S. Environmental Protection Agency. 2007. Subsurface Characterization for Vapor Intrusion: Vadose Zone Sources. Presentation by Gary Newhart, EPA, at the NARPM annual training conference. Baltimore, MD. May 22, 2007.

U.S. Environmental Protection Agency. 2017. What Is Vapor Intrusion?, website. [Accessed 9 May 2019]. Available at: https://www.epa.gov/vaporintrusion/what-vapor-intrusion

U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory. 2006b. Engineering Issue: In Situ Chemical Oxidation. [Accessed 15 May 2019]. Available at: https://clu-in.org/download/contaminantfocus/pcb/ISCO-600R06072.pdf

U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory. October 2008 (EPA 2008b). Engineering Issue: Indoor Air Vapor Intrusion Mitigation Approaches. [Accessed 9 May 2019]. Available at: https://clu-in.org/download/char/600r08115.pdf

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. 1993. Presumptive Remedies: Site Characterization and Technology Selection for CERCLA Sites with Volatile Organic Compounds in Soils. [Accessed 15 May 2019]. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi/P1009SO4.PDF?Dockey=P1009SO4.PDF

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. 2000. Engineered Approaches to In Situ Bioremediation of Chlorinated Solvents. [Accessed 15 May 2019]. Available at: https://clu-in.org/download/remed/engappinsitbio.pdf

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Brownfields and Land Revitalization Technology Support Center. March 2008 (EPA 2008a). Brownfields Technology Primer: Vapor Intrusion Considerations for Redevelopment. [Accessed 9 May 2019].
Available at: https://semspub.epa.gov/work/HQ/160663.pdf
Available at: https://sewagesludgeactionnetwork.com/sites/default/files/BTSC_Vapor_Intrusion_Considerations_for_Redevelopment_EPA_542-R-08-001.pdf

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. 2012 (EPA 2012a). A Citizen's Guide to In Situ Chemical oxidation. [Accessed 9 May 2019]. Available at: https://clu-in.org/download/Citizens/a_citizens_guide_to_in_situ_chemical_oxidation.pdf

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. 2012 (EPA 2012b). A Citizen's Guide to In Situ Chemical Reduction. [Accessed 9 May

2019]. Available at: https://clu-in.org/download/Citizens/a_citizens_guide_to_in_situ_chemical_reduction.pdf

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. 2012 (EPA 2012c). A Citizen's Guide to Soil Vapor Extraction and Air Sparging. [Accessed 9 May 2019]. Available at: https://clu-in.org/download/Citizens/a_citizens_guide_to_soil_vapor_extraction_and_air_sparging.pdf

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. 2012 (EPA 2012d). A Citizen's Guide to In Situ Thermal Treatment. [Accessed 9 May 2019]. Available at: https://clu-in.org/download/Citizens/a_citizens_guide_to_in_situ_thermal_treatment.pdf

U.S. Environmental Protection Agency, Office of Superfund Remediation and Technology Innovation (OSRTI). 2015. Engineering Paper, In Situ Thermal Treatment Technologies: Lessons Learned. [Accessed 9 May 2019]. Available at: https://www.epa.gov/sites/production/files/2015-06/documents/istt_ll_issue_paper.pdf

U.S. Environmental Protection Agency, Office of Superfund Remediation and Technology Innovation (OSRTI). 2019 (EPA 2019a). Bioremediation, website. [Accessed 9 May 2019]. Available at: https://clu-in.org/techfocus/default.focus/sec/Bioremediation/cat/Anaerobic_Bioremediation_(Direct)/

U.S. Environmental Protection Agency, Office of Superfund Remediation and Technology Innovation (OSRTI). 2019 (EPA 2019b). Nanotechnology, website. [Accessed 20 May 2019]. Available at: https://clu-in.org/techfocus/default.focus/sec/nanotechnology:_applications_for_environmental_remediation/cat/application/

U.S. Geological Survey. 1987. Movement and Fate of Chlorinated Solvents in Groundwater. [Accessed 9 May 2019]. Available at: https://pubs.usgs.gov/of/1987/0395/report.pdf

U.S. National Library of Medicine, National Center for Biotechnology Information. 2019. Vinyl Chloride. Website. [Accessed 15 May 2019]. Available at: https://pubchem.ncbi.nlm.nih.gov/compound/Vinyl-chloride

von Grote J, Hürlimann C, Scheringer M, Hungerbühler K. 2003. Reduction of Occupational Exposure to Perchloroethylene and Trichloroethylene in Metal Degreasing over the last 30 years: Influences of Technology Innovation and Legislation. Journal of exposure analysis and environmental epidemiology 13: 325–340. doi:10.1038/sj.jea.7500288 PMID:12973361

Wikipedia, Underground Crawl Space, website. [Last edited on 9 May 2019; accessed 9 May 2019]. Available at: https://en.wikipedia.org/wiki/Basement

Wisconsin Department of Natural Resources (WDNR). 2014. Understanding Chlorinated Hydrocarbon Behavior in Groundwater: Guidance on the Investigation, Assessment and Limitations of Monitored Natural Attenuation. [Accessed 9 May 2019]. Available at: https://dnr.wi.gov/files/PDF/pubs/rr/RR699.pdf

The Worker Health Protection Program (WHPP). 2013. Chlorinated solvents, website. [Accessed 9 May 2019]. Available at: http://www.worker-health.org/chlorinatedsolvents.html

Ympäristöministeriö (The Ministry of Environment), Rakennetun ympäristön osasto. 2011. D2 Suomen rakentamismääräyskokoelma (The National Building Code of Finland). [Accessed 12 May 2019]. Available at: https://www.finlex.fi/data/normit/37187-D2-2012_Suomi.pdf

Ympäristöministeriö (The Ministry of the Environment). 2014. Ympäristöhallinnon ohjeita 6/2014. Pilaantuneen maa-alueen riskinarviointi ja kestävä riskinhallinta. [Accessed 19 May 2019].

Available at: https://helda.helsinki.fi/bitstream/handle/10138/136564/OH_6_2014.pdf

Zhang, W-X., and D.W. Elliot. 2006. Applications of Iron Nanoparticles for Groundwater Remediation. 16(2).