

# 5 1,2,3-Trichloropropane (TCP)

## 5.1 Introduction

### 5.1.1 Chemical Overview

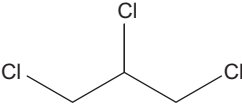
1,2,3-Trichloropropane (hereinafter referred to as TCP) is a chlorinated hydrocarbon that was historically used as an industrial solvent and a degreasing agent. Currently, however, TCP is utilized as an intermediate in the production of polymer cross-linking agents, pesticides, and glycerol. In its pure form, TCP is a colorless to yellow liquid with limited solubility in water, a strong chloroform-like odor, moderate volatility, and high flammability. Additional chemical properties may be found in [Table 5.1](#). Produced in large quantities as an epichlorohydrin production byproduct, TCP is a synthetic compound that does not occur naturally in the environment. In the agrochemical industry, TCP is formed via the manufacture of dichloropropene-derived nematicides (pesticides used to kill parasitic nematodes), and it is also present as an impurity in these soil fumigants. As a result, application of these products has produced significant atmosphere, soil, and groundwater contamination, which in turn can induce various health problems in wildlife and humans. The toxicological effects of TCP depend on dose and duration, but can range from kidney and liver damage to tumors and cancers. Approximately 50 000 metric tons (110 million pounds) of 1,2,3-trichloropropane are produced worldwide each year ([WHO, 2003](#)). In 2002, total US production was estimated at between 453 to 4530 metric tons (1–10 million pounds).

### 5.1.2 Environmental Transport, Distribution, and Transformation

In general, TCP is released into the environment where it is found primarily in air (85%) and, to a lesser extent, in water (11%) ([Mackay et al., 1993](#)). Due to its moderate volatility, TCP escapes aqueous solution relatively quickly with a 56-minute water-stripping half-life ([Dilling, 1977](#)). The substance evaporates rapidly from surface water and surface soil where it concentrates in the atmosphere. In soil, the half-life of TCP from abiotic loss (mostly evaporation) was shown to be 2.2–3.5 days ([Andersen et al., 1991](#)). Thus when TCP is co-injected with fumigants into soil, it is able to volatilize and transport from the soil into the surrounding air reasonably quickly. High atmospheric concentrations of TCP can result in a variety of possible health effects which will be detailed in later sections.

Additionally, TCP is subject to leaching and groundwater infiltration. Its low soil sorption coefficient ( $K_{OC}$ ) and relatively low vapor pressure ([Table 5.1](#))

**Table 5.1** Chemical Properties of 1,2,3-Trichloropropane (WHO, 2003; EPA, 2009)

Property	Value
Chemical structure	
CAS registry number	96-18-4
Chemical formula	C <sub>3</sub> H <sub>5</sub> Cl <sub>3</sub>
Physical state	Liquid
Color	Clear to yellow
Odor	Sweet, strong
Molecular weight (g/mol)	147.43
Density (g/cm <sup>3</sup> )	1.38 (at 20°C)
Solubility in water (mg/L)	1750 (at 25°C)
Miscible organic solvents	Ethyl alcohol, chloroform, ethyl ether, benzene
Vapor pressure (mm Hg)	3.1–3.69 (at 25°C)
Henry's Law constant (atm·m <sup>3</sup> /mol)	3.43 × 10 <sup>-4</sup> (at 25°C)
Organic carbon absorption coefficient (Log K <sub>OC</sub> )	1.98
Octanol-water partition coefficient (Log K <sub>OW</sub> )	2.27 (measured) – 2.54 (calculated)
Melting point (°C)	-14.7
Boiling point (°C)	156
Conversion factors	1 ppm = 6.1 mg/m <sup>3</sup> at 20°C, 1 atm 1 mg/m <sup>3</sup> = 0.16 ppm

demonstrate high soil mobility. As such, the substance is able to leach from deeper soil into the groundwater where it slowly breaks down. Due to little evaporation from groundwater, TCP is extremely persistent in groundwater and has a calculated hydrolysis half-life of 44–74 years (Ellington et al., 1987). Moreover, a number of aerobic biodegradation and biotransformation studies using a variety of bacterial strains indicate that TCP is not readily biodegradable (0% biological oxygen demand during 28 day incubation) (WHO, 2003). Furthermore, TCP is a Dense Nonaqueous Phase Liquid (DNAPL), one of a group of organic substances that are relatively insoluble in water and denser than water (EPA, 2010); thus TCP will often sink to the bottom of an aquifer, making remediation difficult. Due to these factors, soil and groundwater contamination by TCP are serious issues that will persist if not managed properly.

## 5.2 Toxicology and Health Risks

### 5.2.1 Exposure

The general public may be exposed to TCP through inhalation of ambient air, consumption of contaminated food or water, and dermal contact. TCP can enter the environment while it is being produced, where it is used to produce other

substances, or where it is released in the waste created during production. Exposure in the workplace also poses an occupational risk and can occur from both accidental spills and normal operations. Furthermore, those living near areas at high risk for TCP – such as hazardous waste disposal sites – may be exposed to TCP (from breathing air or drinking water) if the site does not handle and store the chemical properly.

### **5.2.2 Cancer Effects**

TCP is recognized by the State of California as a human carcinogen (SWRCB, 2009). In 1992, it was added to the list of carcinogens in the Safe Drinking Water and Toxic Enforcement Act of 1986, created to inform and protect California's citizens from exposures to such chemicals. Additionally the American Conference of Governmental Industrial Hygienists (ACGIH) has classified TCP as a Group A3 confirmed animal carcinogen. In exposure studies, NTP (1993) found that rats and mice ingesting low doses of TCP developed tumors in several organs, including the kidneys, preputial gland, mammary gland, liver, uterus, and oral cavity. Accordingly, all tissues that have a homologous counterpart in humans could be target organs for carcinogenicity in those exposed to TCP (Tardiff and Carson, 2010).

### **5.2.3 Non-Cancer Effects**

Exposure to high levels of TCP for short intervals of time can induce eye and throat irritation. Contact with TCP can irritate and burn the skin and eyes, while breathing TCP can irritate the nose, throat, and lungs, cause headaches, and affect concentration, memory, and muscle coordination. The earliest set of human data on the health effects of TCP comes from a study conducted in 1946 where people exposed to TCP vapors of 100 ppm for 15 minutes immediately reported eye and throat irritation (WHO, 2003).

The toxicity of TCP has been investigated in rats and mice using subchronic and chronic durations of exposure, including oral ingestion via contaminated drinking water and corn oil. Intake of contaminated drinking water resulted in histopathologic changes in the liver, kidney, and thyroid, while ingestion of TCP in corn oil yielded symptoms such as liver necrosis, increased serum cholesterol, and necrosis of the cardiac myocardium (Tardiff and Carson, 2010). As such, tests in which TCP was subchronically administered via both drinking water and corn oil both resulted in adverse health effects of vital organs such as the liver.

Furthermore, studies conducted by the National Toxicology Program (NTP) concluded that repeated and prolonged TCP exposure targeted the kidneys, liver, and pancreas (NTP, 1993). Additionally NTP noted that their findings were clouded by high premature mortality. Many of the non-cancer effects included changes in body weight, organ-to-body-weight ratios, and some hyperplasia which may have occurred in response to cell damage. In addition, animal studies have also found that there is a statistically significant decrease in litter-size after chronic exposure to TCP, which is indicative of possible reproductive harm (Chapin et al., 1997).

In summary TCP is suspected to cause kidney, liver, cardiac, and reproductive organ damage, and it is assumed that the same organs are targeted in humans (Tardiff and Carson, 2010).

#### 5.2.4 Metabolism in the Body

Based on metabolic pathways for other chloroalkanes, 1,2,3-trichloropropane can undergo dehalogenation reactions via cytochrome P-450-dependent microsomal metabolism, resulting in the formation of highly reactive intermediates that may lead to protein and DNA adducts or lipid peroxidation (Ivanetich et al., 1978). Glutathione also appears to be very important in TCP metabolism. In rats, the target organ for TCP metabolism is the liver, with the maximum corporeal concentration occurring in the liver 4 hours after intravenous TCP administration (Volp et al., 1984). Although measures are available to calculate TCP levels in blood, urine, and breath, these tests cannot determine how much TCP individuals have been exposed to or whether their health will be affected. Thus it is in individuals' best interest to reduce potential exposure to TCP.

### 5.3 Regulations and Standards

Due to the recently established health risks and the need for further studies regarding the toxicological effects of TCP, the chemical is classified by the EPA as an 'emerging contaminant.' While many regulatory standards exist (Table 5.2), there are currently no federal or state-wide maximum contamination levels (MCLs) in place for TCP.

More effective and affordable testing methods need to be developed in order to properly manage and monitor TCP levels in water so as to promote environmental and human health. As of 1992, TCP was discovered as a contaminant in 8 of the 1300 EPA National Priorities List sites; yet it remains unclear how many other NPL sites have been tested (ATSDR, 1992a). US EPA methods 8010, 8021, or

**Table 5.2** Regulatory Standards for 1,2,3-Trichloropropane

Regulatory Property	Value
California DHS* advisory action level	0.005 µg/L (0.005 ppb)
OSHA Permissible Exposure Limit (PEL)	50 ppm
NIOSH Recommended Exposure Limit (REL)	10 ppm
NIOSH Immediately Dangerous to Life and Health (IDLH)	100 ppm
EPA HEAST** Oral Cancer Slope Factor	7.0 per mg/kg/day
ACGIH Time Weighted Threshold Limit Value (TLV-TWA)	10 ppm
OEHHA recommended Public Health Goal (PHG)	0.0007 ppb

\*Department of Health Services.

\*\*Health Effects Assessment Summary Tables.

8260 are approved for TCP testing but their usefulness is limited because their quantitation limits are significantly higher than the EPA screening level for tap-water and groundwater. There are more sensitive testing methods developed by the California Department of Public Health (CDPH) that can detect TCP within the range of regulatory standards, but these are expensive and require significant laboratory expertise (SWRCB, 2009).

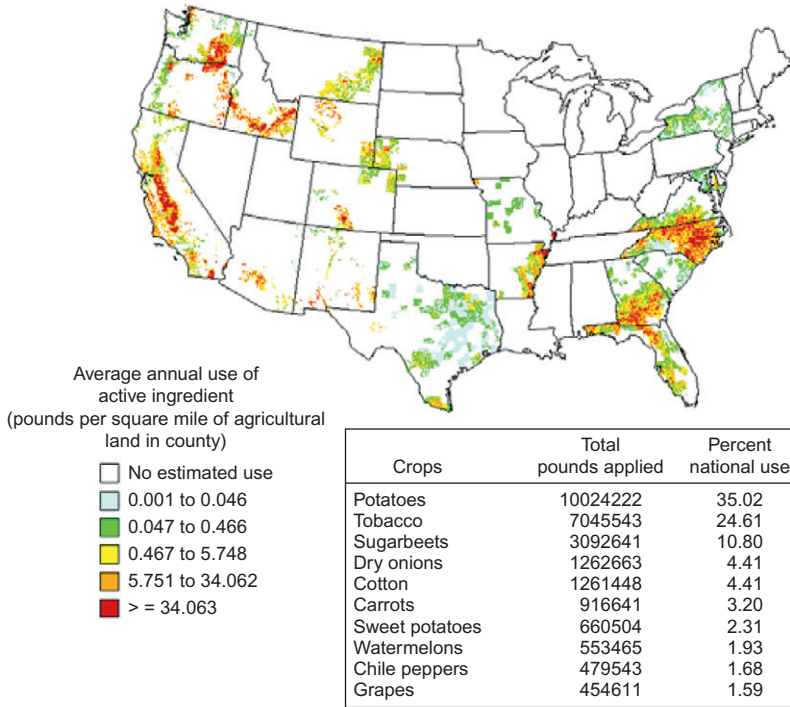
Atmospheric concentrations of TCP vary across different regions, ranging from undetectable in some urban areas, to  $0.21 \mu\text{g}/\text{m}^3$  in Montreal, Canada, and  $0.4 \mu\text{g}/\text{m}^3$  in Bochum, Germany (WHO, 2003). A sampling of groundwater in the Netherlands revealed TCP concentrations of up to  $5.6 \mu\text{g}/\text{L}$ , and similar studies of US groundwater revealed TCP concentrations ranging from  $2 \mu\text{g}/\text{L}$  in Hawaii to  $100 \mu\text{g}/\text{L}$  in New York State (WHO, 2003). Drinking water concentrations of TCP range from  $0.1 \mu\text{g}/\text{L}$  to  $0.24 \mu\text{g}/\text{L}$  (City of Shafter, 2000; WHO, 2003). It is not uncommon for TCP levels to be found above levels that are considered safe. In fact a general survey of California groundwater samples by the State Water Board found several areas – namely Kern, Fresno, Los Angeles, and Merced – with TCP concentrations of  $50\text{--}150 \mu\text{g}/\text{L}$ , which is significantly higher than the California Department of Health Services advisory action level of  $0.005 \mu\text{g}/\text{L}$  (SWRCB, 2009). The need for stricter regulatory and enforcement measures is evident.

## 5.4 The TCP–DCP Fumigant Link

Dichloropropene ('DCP') soil fumigants have been marketed for use on citrus fruits, pineapples, soybeans, cotton, tomatoes, and potatoes. They are still used today on potatoes, tobacco, carrots, peanuts, cotton, and other fruits and vegetables (Figure 5.1). Before 1978, approximately 55 million pounds of 1,3-dichloropropene were produced per year in the United States, and approximately 20 million pounds of 1,2-dichloropropene and 1,2,3-TCP were produced per year as by-products in the production of 1,3-dichloropropene. In fact, over 2 million pounds of pesticides containing 1,3-dichloropropene were used in California alone in 1978 (EPA, 2005).

The primary DCP-containing pesticides still in use in the United States today are Telone II (1,3-dichloropropene), Telone C-17 (1,3-dichloropropene and chloropicrin), and InLine (also 1,3-dichloropropene and chloropicrin), which are all manufactured by DOW AgroSciences. The European Union chose to gradually phase out the use of DCP-containing soil fumigants in 2007 (EU Directive, 91/414/EEC). Alternative soil fumigants which do not contain DCP include chloropicrin (trade name: Chloro-O-pic), metam (or metham) sodium (trade names: Vapam, Metam 426, Polefume) and methyl bromide. One serious concern of environmental policy-makers is that the phasing out of DCP fumigants might lead to increased use of even more toxic fumigants such as methyl bromide. A summary of the indicated uses of various soil fumigants is presented in Table 5.3.

A large number of sources report that TCP is present as an impurity in these DCP-containing nematicidal soil fumigants in varying concentrations, and that use of these fumigants is associated with local groundwater contamination



**Figure 5.1** Annual 1,3-dichloropropene soil fumigant for agricultural use in the US in 2002 (USGS, NAWQA).

**Table 5.3** Applications of Various Soil Fumigants (EPA, 2005)

Fumigant	Major Types of Pests Controlled		
	Nematodes	Plant Pathogens	Weeds
Methyl bromide	●	●	●
Chloropicrin		●	
1,3-Dichloropropene	●		
Dazomet	●	●	●
Metam sodium	●	●	●
Metam potassium	●	●	●

(Oki & Giambelluca, 1987; Zebarth, 1998; Tesoriero et al., 2001; WHO, 2003). It is important to note that because these fumigants are mixtures of chloropropanes, the actual concentration of TCP in these fumigants varies with each batch produced. One study found Shell D-D fumigant to contain 0.4% TCP by weight (Department of Agriculture, 1984), while another found Shell D-D to contain 6–7% TCP by weight (Carter, 1954). Telone II, a widely used DCP fumigant

manufactured by DOW AgroSciences has been found to contain up to 0.17% TCP by weight (Zebarth et al., 1998).

## 5.5 Groundwater Contamination Case Studies

### 5.5.1 Oahu, Hawaii

A number of case studies have been undertaken, primarily in Hawaii and California, to demonstrate the link between DCP-containing fumigant use and local groundwater contamination. From the 1940s to 1977, Shell D-D was used for pineapple cultivation on the Hawaiian island of Oahu. It was applied in conjunction with the fumigant 1,2-dibromo-3-chloropropane (DBCP) at 40–60 gallons per acre every 3–5 years before planting. Water well testing revealed that all TCP-contaminated wells on the island were either hydraulically downgradient, or directly within areas of pineapple cultivation (Oki and Giambelluca, 1987). Despite the fact that TCP was only a minor constituent of Shell D-D, testing of the groundwater in Oahu revealed that TCP was present in the water table at concentrations two orders of magnitude greater than either of the other two pesticides that were applied throughout the history of the island (DBCP and Ethylene dibromide).

### 5.5.2 Shafter & Merced, California

TCP groundwater contamination associated with the use of DCP fumigants was also observed in the Central Valley of California (City of Shafter, 2000). In 1999, TCP was detected in five of six active water supply wells at concentrations ranging from 0.02 to 0.11  $\mu\text{g/L}$  (EPA, 2005). TCP was found in groundwater from all wells where 1,2-dichloropropane (another co-contaminant of DCP fumigants) was detected. Although 1,3-DCP had been applied heavily (thousands of pounds per section), little to none showed up in groundwater because 1,3-DCP is more easily biodegraded than either TCP or 1,2-DCP. A study of water wells in another region of California, the heavily agricultural area of Merced, revealed that some wells contained up to 150  $\mu\text{g/L}$  of TCP (SWRCB, 2009). These studies of California water systems indicated that 1,2,2-trichloropropane (1,2,2-TCP) should also be analyzed where 1,2,3-TCP is detected in groundwater, as it is also a by-product of the manufacture of 1,3-DCP.

## 5.6 Another Toxic Soil Fumigant: Dibromochloropropane

1,2-Dibromo-3-chloropropane (hereinafter referred to as DBCP) is a soil fumigant that was often used in conjunction with TCP. Since they were applied together, TCP and DBCP are often found together in contaminated groundwater and must therefore be considered together during treatment and remediation.

### 5.6.1 Usage and Regulation

The EPA banned all uses of DBCP in 1985 (EPA, 2007). Prior to the ban, it was used as a soil fumigant to control nematodes in field crops, vegetables, fruits and nuts, greenhouse and nursery crops, and turf. DBCP was manufactured by DOW Chemical Corporation, Shell Chemical Corporation, Amvac Chemical, and many other companies prior to being banned. The various trade names of DBCP include: Fumagon, Fumazone, Nemabrom, Nema fum, Nemagon, Nemanax, Nemapaz, Nemaset, Nemazon, and Gro-Tone Nematode. In 1977, the EPA suspended all registrations for the use of products containing the compound except for use on pineapples in Hawaii. In 1985 use of DBCP on pineapples in Hawaii was also banned. In 1974, US farmers had applied 9.8 million pounds of DBCP to crops. In 1977, 831 000 pounds of DBCP was used in California alone, primarily on grapes and tomatoes (IARC, 1979). DBCP is now used only as an intermediate in organic synthesis and for research purposes (ATSDR, 1992b; NTP, 2005).

### 5.6.2 DBCP in the Environment

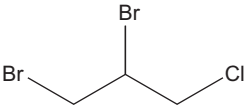
There are no known natural sources of DBCP (IARC, 1979). Data on releases of DBCP to the atmosphere, water, and soil are lacking, but current releases of the chemical to the environment that result from the production and use of the chemical are expected to be low because its current uses are limited (see above). However, contaminated soil, groundwater, and surface water remain a concern, especially at or near agricultural areas where DBCP had been extensively used in the past or where a chemical spill occurred, and from hazardous waste sites where improper disposal techniques were used.

DBCP in soil is subject both to leaching into groundwater and to volatilization to the atmosphere from near-surface soil, as has been observed in field soil studies. Small amounts of DBCP may be absorbed through the soil roots and translocated to other plant parts. Although DBCP present in water is expected to volatilize to the atmosphere, degradation of DBCP in natural waters and soil is a slow process. DBCP may be susceptible to slow biodegradation in soil and natural waters based on the observation of biologically mediated dehalogenation in certain soils. DBCP residues that do not leach or volatilize appear to be very persistent in soil based upon monitoring data. The half-life of DBCP in an aquifer with a temperature of 15°C is estimated at 141 years (ATSDR, 1992b). A summary of the chemical properties of DBCP is presented below in Table 5.4.

The fact that DBCP has similar properties to TCP makes it a significant groundwater contamination risk. Moreover the most comprehensive case studies of DBCP contamination undertaken thus far have been in California. DBCP pesticides were used heavily in California from 1955–1979 and more than 30 years since DBCP use stopped, groundwater contamination remains a serious problem. Furthermore, of the 7689 wells sampled by the California State Water Board, 364 have yielded concentrations of DBCP above the MCL of 0.2 µg/L (SWRCB, 2010). Water treatment systems are being installed on these contaminated wells and DBCP analysis continues throughout California's water supply infrastructure.



**Table 5.4** Chemical Properties of 1,2-Dibromo-3-Chloropropane (ATSDR, 1992a,b)

Property	Value
Chemical structure	
CAS registry number	96-12-8
Chemical formula	C <sub>3</sub> H <sub>5</sub> Br <sub>2</sub> Cl
Physical state	Liquid
Color	Clear to yellow to dark brown
Odor	Pungent
Molecular weight (g/mol)	236.36
Density (g/cm <sup>3</sup> )	2.093 (at 14°C)
Solubility in water (mg/L)	1230 (at 20°C)
Miscible organic solvents	Methanol, ethanol, isopropyl alcohol, hydrocarbons, halogenated hydrocarbons
Vapor pressure (mm Hg)	0.58 (at 20°C)
Henry's Law constant (atm·m <sup>3</sup> /mol)	1.47 × 10 <sup>-4</sup> (at 20°C)
Organic carbon absorption coefficient (Log K <sub>OC</sub> )	2.11–2.17
Octanol-water partition coefficient (Log K <sub>OW</sub> )	2.26 (estimated)
Melting point (°C)	6
Boiling point (°C)	196
Conversion factors	1 ppm = 9.67 mg/m <sup>3</sup> at 20°C, 1 atm 1 mg/m <sup>3</sup> = 0.103 ppm

Much like TCP contamination on the Hawaiian Island of Oahu, [Oki and Giambelluca \(1987\)](#) have linked DBCP contamination of Oahu's aquifers to the extensive application of DBCP pesticides to pineapple cultivation areas. Thus it is essential to monitor and regulate DBCP when used as a soil fumigant in order to prevent soil and groundwater contamination, thereby reducing human health impacts.

### 5.6.3 Health Effects of DBCP

While the deleterious health effects of DBCP on humans are wide ranging, the most commonly observed effect in accidental exposures has been reproductive organ damage. The reproductive effects of DBCP have resulted in a number of lawsuits against the manufacturers and users of DBCP. Most notably, the Dole Food Company refused to stop use of DBCP on its banana plantations in Latin America after the health effects of DBCP had been discovered. After years of litigation, a group of farmworkers made sterile by handling DBCP on Dole's banana plantations in the 1970s was awarded \$3.2 million dollars by a Los Angeles jury ([Spano, 2007](#)).

Similar cases were filed against DOW Chemical Corporation by factory workers at DOW who were made sterile during DBCP manufacturing. A summary of the acute, chronic, and carcinogenic health effects of DBCP on humans and animals is presented below (EPA, 2007):

- Acute exposure to DBCP produces moderate depression of the CNS and pulmonary congestion after exposure by inhalation, and gastrointestinal distress and pulmonary edema after oral exposure in humans.
- Tests involving acute exposure of rats, mice, rabbits, and guinea pigs have demonstrated DBCP to have high acute toxicity from inhalation, oral, and dermal exposure.
- Chronic exposure to DBCP by inhalation has been reported to affect the nasal cavity, spleen, adrenal gland, kidneys, stomach, and liver in rats and mice.
- Chronic exposure to DBCP causes male reproductive effects. Decreased sperm counts have been observed in men occupationally exposed to DBCP.
- Testicular effects and decreased sperm count were observed in animals chronically exposed to DBCP by inhalation.
- A study by the NTP reported tumors of the respiratory tract and tongue in male and female rats, tumors of the adrenal cortex in female rats, and tumors of the nasal cavity and lung in male and female mice when exposed to DBCP by inhalation.
- EPA has classified DBCP as a Group B2, probable human carcinogen.
- EPA has calculated an oral cancer slope factor of  $1.4 \text{ (mg/kg/d)}^{-1}$  and an inhalation unit risk factor of  $6.9 \times 10^{-7} \text{ (}\mu\text{g/m}^3\text{)}^{-1}$ .
- The Reference Concentration (RfC) for DBCP is 0.0002 milligrams per cubic meter ( $\text{mg/m}^3$ ) based on testicular effects in rabbits.
- EPA has not established a Reference Dose (RfD) for DBCP.
- ATSDR has established an intermediate oral minimal risk level (MRL) of 0.002 milligrams per kilogram body weight per day ( $\text{mg/kg/d}$ ) based on reproductive effects in rabbits.

## 5.7 Treatment and Remediation Technologies

In 2003, TCP-related issues contributed to 23% of drinking water production loss (about 1.3 trillion gallons of water) for the city of Burbank, California. As analysis for TCP becomes widespread, it is expected that many more municipalities will be forced to devote considerable resources to TCP remediation. The fact that TCP has relatively low notification level concentrations compared to many other contaminants makes remediating TCP particularly troublesome (EPA, 2005). As noted earlier, DBCP also poses a significant remediation problem for a large number of water systems. The California Department of Public Health has estimated the cost of implementing the recently established DBCP maximum contamination limit of 0.2 ppb to be \$28.6 million dollars (CDPH, 2008).

### 5.7.1 *In Situ Treatment*

A number of remediation strategies exist for groundwater and soil contaminated with TCP and DBCP. Most of these strategies are similar to those used for other chlorinated hydrocarbons. In situ, or on-site, vacuum extraction has shown moderate

success for removing TCP from contaminated soil, water, and vapor and is currently underway at a TCP-contaminated superfund site in Philadelphia, Pennsylvania (EPA, 2005). In addition, oxidants can be injected into subsurface areas prior to vacuuming to enhance the breakdown and volatilization of TCP, especially when DNAPLs are present. Another in situ remediation strategy for TCP-contaminated groundwater is the injection of hydrogen-releasing compounds into the aquifer. Hydrogen-releasing compounds function by releasing lactic acid, stimulating microbes to produce hydrogen, and thereby induce reductive dechlorination of the TCP. This remediation technique showed 99.9% reduction of TCP over 1000 days in a study performed in California and is currently being used by John Taylors Fertilizers Company and Western Farm Service, Inc. for on-site groundwater remediation (EPA, 2005). Furthermore permeable reactive barriers consisting of zero-valent granular iron have demonstrated feasibility for TCP remediation, achieving remediation levels of nearly 100% (EPA, 1997). These permeable treatment walls are installed across the flow path of groundwater plumes and take advantage of the natural movement of the contaminated water systems. Bosma (2002) demonstrated a genetically engineered bacterium that could consume, and remove, TCP as a food source, however this emerging bioengineering strategy has yet to demonstrate efficacy in large-scale natural systems.

### 5.7.2 Ex Situ Treatment

For ex situ, or off-site, treatment of TCP-contaminated groundwater, the most common method employed is granular activated carbon (GAC) adsorption. Water is pumped through a filter bed composed of granular activated carbon, and TCP contaminants adsorb to the filter (EPA, 2005). While this technique is widely used and has shown effectiveness in removing large quantities of TCP from contaminated water, there has been no documented success in reducing TCP concentrations to below the 0.005 ppb notification level. Air stripping using a packed column or low-profile sieve tray air stripper can be employed in conjunction with GAC for ex situ groundwater treatment. However air stripping alone will not reduce TCP to below

**Table 5.5** Removal Technologies for Ex Situ Treatment of TCP Contaminated Groundwater (EPA, 2005)

Treatment Technology	Application Performance Opinion
Air Stripping	Poor
Liquid-Phase Granular Activated Carbon (LGAC) Adsorption	Very Good
Advanced Oxidation	Poor
Biological Reduction	Poor
Ion Exchange	NA
Reverse Osmosis	Fair
Zero-Valent Iron Dechlorination	Fair

NA – Not applicable.

clean-up levels due to the relatively low vapor pressure and Henry's law constant for TCP. Injecting ozone and hydrogen peroxide, in a process known as advanced oxidation or HiperOxidation, has shown limited success. This treatment method is beset with high operating and maintenance costs compared to GAC and has only modest removal success (EPA, 2005).

The most common method of treatment for DBCP-contaminated drinking water is using GAC in conjunction with packed tower aeration. Most of the TCP treatment strategies mentioned above including air-stripping, advanced oxidation, permeable reactive barriers, and GAC can also be used to remove DBCP from contaminated water systems (SWRCB, 2010). A summary of the performance of various treatment technologies is presented in Table 5.5.

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