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Evaluation of Contaminant Concentrations in Wet and Dry Seasons during Pump-and-Treat Pilot Tests

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ABSTRACT

This study was performed to examine use of the pump-and-treat method for remediation of TCE, CF and CT in groundwater contaminated by DNAPL. The Woosan industrial complex is located in Wonju, about 120 km east of Seoul, Korea. Two pumping wells (KDPW7 and KDPW8) and five monitoring wells (KDMW7, KDMW8, KDMW9, KDMW10, and SKW2) were installed for the test. An asphalt laboratory is a main source of the extensive subsurface contamination at this site. To evaluate change in the concentrations of TCE, CF, and CT in groundwater in the study area, three rounds of pump-and-treat pilot tests were performed (6 July to 6 August, 22 August to 6 September, and 19 September to 2 December in 2011). The groundwater levels and the concentrations of TCE, CF, and CT exhibited negative correlations in the wet season but positive correlations in the dry season, which suggests that the TCE concentrations were mainly controlled by dilution through rainfall during the wet season and by residual TCE, CF, and CT in the unsaturated zone during the dry season. These possibilities should be considered in the full-scale remediation plan.

Key words : DNAPL, Pump-and-treat, Pilot test, TCE, Water level

1. Introduction

With industrial development and the subsequent increasing use of organic solvents in many industrial complexes, unpredicted and uncontrolled discharges of the waste solvents have caused soil and groundwater contamination, which have drawn much attention from the public (Rivett et al., 2001; Lenczewski et al., 2003; Chambers et al., 2004; Kim et al., 2005; Heo et al., 2007; Baek and Lee, 2010). The chlorinated organic solvents most frequently occurring in contaminated soil and groundwater include tetrachloroethylene (PCE), trichloroethylene (TCE), dichloroethylene (DCE), chloroform (CF), carbon tetrachloride (CT), trichloroethane (TCA), and vinyl chloride (VC). Recently, chlorinated organic solvents have been easily found in the groundwater of residential areas, as well as that of industrial areas (Hamm et al., 2006; Baek and Lee, 2010). Among the organic solvents, TCE has been the most widely used for dry cleaning, dying, glue, oil removing and detergent, and it has been produced in many manufacturing processes for airplane components, computers, electronic devices, and paints, and metals smelting (Jackson, 1998; Michael et al., 2001).

These chlorinated solvents are denser than water, and thus are called dense non-aqueous phase liquids (DNAPLs). If DNAPLs are spilled, they move into subsurface soil under gravity and some are left in the soil as residual contaminants. Light non-aqueous phase liquids (LNAPLs) are accumulating above the water table and some are spreading, while DNAPLs are penetrating the water table and steadily moving downward until impermeable layer is reached (Lee and Lee, 2003; Yu et al., 2006). If there are some fractures, faults, or cracks in the top of the bedrock, the DNAPLs can migrate into the deep bedrock and will contaminate the bedrock groundwater (Poulsen and Kueper, 1992; Oolman et al., 1995).

The pump-and-treat remedy is one of the conventional remediation methods for contaminated groundwater, and it still has been applied for containing and cleaning up contam-

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inants in spite of its some limitations (Oostrom et al., 1999). The pump-and-treat remedy is for rapidly removing contaminants, but very long-term operation is required to clean up contaminants adsorbed by soil and those in soil pores, which is called a tailing effect (Mackay and Cherry, 1989). In addition, it is difficult to remediate low levels of contamination using the pump-and-treat method, and a rebound may occur after the cessation of pumping. However, despite these shortcomings, the pump-and-treat method is still one of the most frequently used remediation methods for contaminated groundwater (Berglund, 1995; Park et al., 2011). In order to apply the pump-and-treat method efficiently, the optimum pumping rate should be determined in advance from the amount, characteristics, and distribution of the contaminants (US EPA, 1996; Young et al., 1999).

The Woosan industrial complex (the study area) was found contaminated with TCE when an environmental authority conducted a groundwater quality survey in 1995. After that, the relevant provincial governments conducted several detailed investigations of the contamination (Gangwon Province, 2005). Jo et al. (2010) conducted a study revealing TCE contamination in soils of the study area, and Yang et al. (2012) found that TCE levels in groundwater are strongly associated with groundwater levels. In addition, Chang et al. (2007) and Park et al. (2007) conducted optimization studies dealing with the cost and time for reaching remediation target levels using the pump-and-treat method. Many other studies, including those by Rivett et al. (1990), Bockelmann et al. (2001), Bauer et al. (2004), and Zeru and Schäfer (2005), have focused on analyzing contaminant distributions based on breakthrough curves while pumping.

We performed three rounds of pump-and-treat pilot tests for this TCE contaminated aquifer (from 6 July to 2 December) in 2011. We examined the relationship between water level and contaminant concentration (during wet season and dry season).

2. Methods and Materials

2.1. Study Area

The study area (specially the Road Maintenance Office of Gangwon Province; RMO) is located in a left part of the Woosan industrial complex in Wonju city, about 120 km

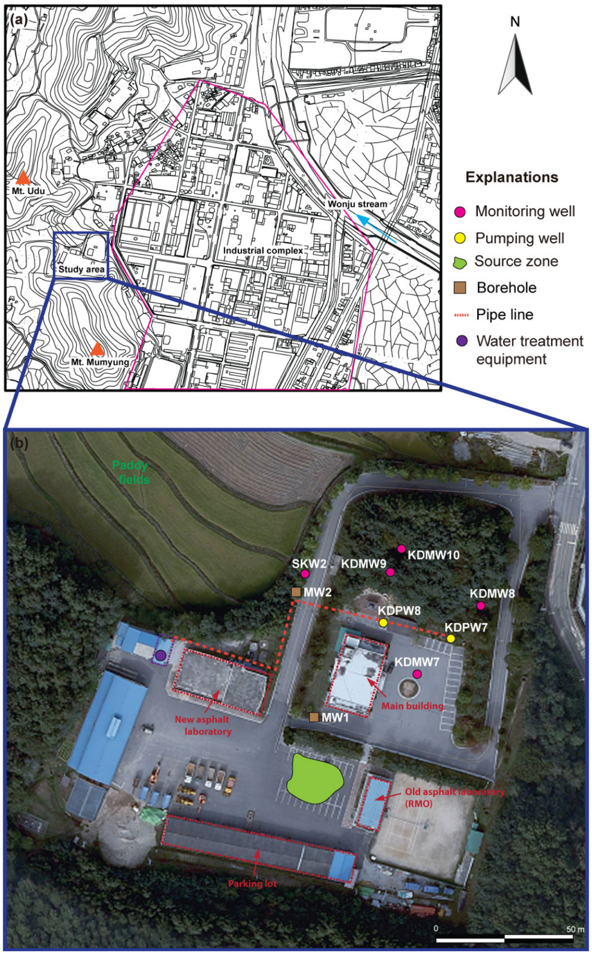

Fig. 1. Locations of (a) industrial complex in Wonju, (b) satellite photo of the study area (RMO) (source: Daum maps). The figure was modified from Cheon et al. (2013).

east of Seoul. The Woosan complex is situated in alluvial flat, extending to hills surrounded by low relief of mountains, Udusan (203.0 m) and Mumyungsan (191.7 m) (Fig. 1). The Wonju stream at the northeastern boundary of the complex runs from southeast to northeast (Gangwon Province, 2005; Baek and Lee, 2010; Jo et al., 2010). The bedrock of the study area is Jurassic biotite granite and is generally covered by the Quaternary alluvial deposit as an unconformity (Park et al., 1989; Fig. 2).

The RMO site, where the pump-and-treat pilot tests were conducted, is situated over a moderately weathered soil layer. The upper soil is thin and thus weathered biotite granite occurs near the surface. The hydrogeology of the RMO site as obtained from geologic logging data of well MW1 indicates that there are three layers consisting of (reclama-

Table 1. Summary of geologic logging for MW1 and MW2

Well	Depth (m)	Thickness (m)	Stratigraphic
MW1	2	2	Reclamation/ fill soil
	23	21	Weathered soil
	30	7	Weathered rock
MW2	7	7	Reclamation/ fill soil
	11	4	Weathered rock
	30	19	Bedrock

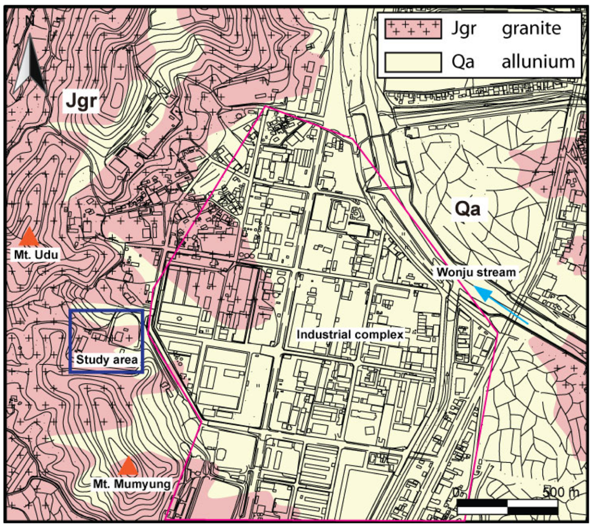

Fig. 2. General geology map of the study area (modified from KIGAM).

tion/fill) soil to 2 m depth, weathered soil to 23 m depth, and weathered rock below the weathered soil layer (Jo et al., 2010; Table 1). In addition, soil analyses revealed that the soil to a depth of 11 m is mainly comprised of brown silty sand with fine (4.8 mm) particles. The soil at 21-23 m depth is gravelly sand with less than 5% fine particles (the soil at 11-22 m depth is missing). In well MW2, the subsurface is comprised of fill soil (to 7 m depth), weathered rock (to 11 m depth), and bedrock below those two layers. Soil analyses indicate that the soil to 5 m depth is dark brown clayey sand with 12% fine particles and that to 7 m depth is dark brown silty sand. The subsurface at 11-30 m depth is a soft rock with granitic texture (the soil of 7-10 m depth is missing).

Weather data for 2002-2011 reveal that the mean annual precipitation in the city was 1,537.2 mm and the mean annual air temperature was 12.0°C. Over 60% of the total annual precipitation occurred in the wet season (June-September) due to monsoon characteristics (Chae et al., 2010). The maximum monthly air temperature was 27.1°C in the summer while the minimum monthly air temperature was −7.7°C in the winter. The four seasons were distinct and the seasonal variation in air temperature was large. For the study period (2011), the annual precipitation was 2,188 mm and the annual mean air temperature was 11.7°C. That is, the annual precipitation of 2011 was greater than the decadal mean of precipitation by 650.8 mm.

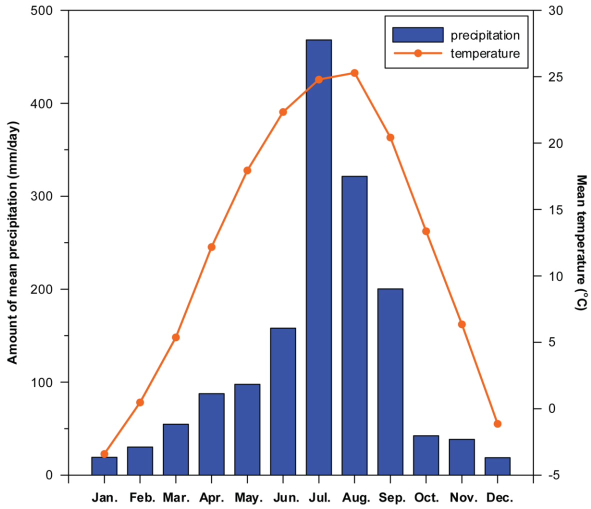

Fig. 3. Monthly precipitation and monthly mean air temperature at Wonju during 2002-2011. Data are from Korean Meteorological Administration.

The Woosan industrial complex in this study was founded in April 1970 and covers an area of 355,235 m^2. As of 2011, there were a total of 21 companies, including 10 food companies, two electrical factories, three metal companies, and two concrete manufacturers. In addition, there were 40 government buildings and commercial facilities where 4,400 people were residing (Baek and Lee, 2010; Yang et al., 2012).

An asphalt testing laboratory, considered one of the main contamination sources in the area, has been operated since 1982. At the laboratory, a variety of organic solvents were used for experiments on asphalt and concrete materials from 1982 to 1997. However, there are no records of the exact amounts of solvents used and (waste) solvents dumped, but inappropriate treatment and management of waste solvents is considered one of the main reasons for the TCE contamination in this area (Gangwon Province, 2005; Baek and Lee, 2010; Jo et al., 2010; Yang et al., 2012). Contaminated soil within the laboratory site was once remediated, but

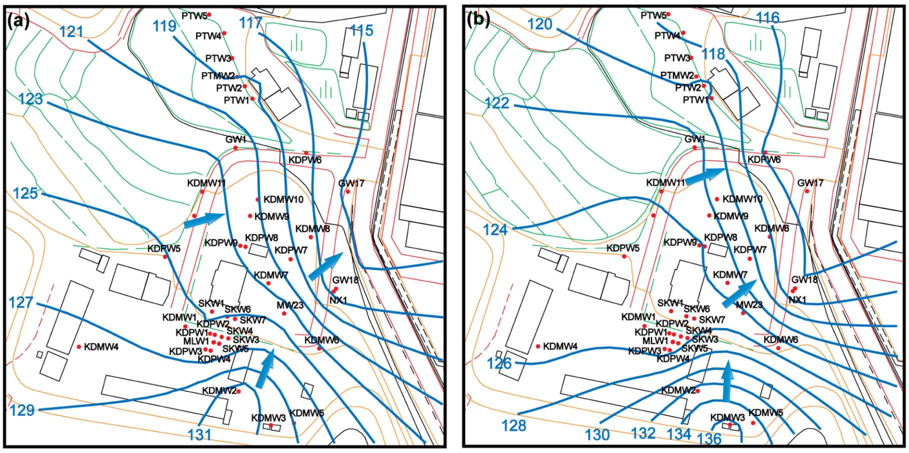

Fig. 4. Distribution of water levels (m, amsl) measured in (a) May and (b) August 2010 showing groundwater flow direction.

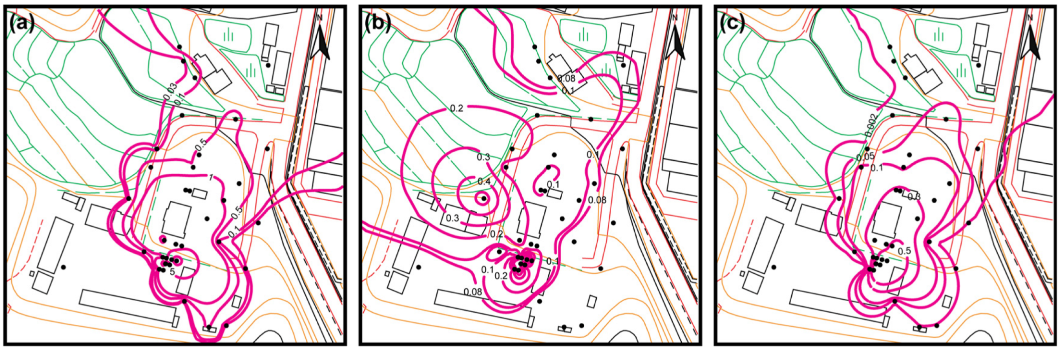

Fig. 5. Distribution of (a) TCE, (b) CF and, (c) CT in the study area (November 2010). The figure was modified from Cheon et al. (2013).

groundwater contamination exceeding Korean groundwater standards (TCE 0.03 mg/L) is ongoing, which is the cause of a public grievance (Baek and Lee, 2010).

2.2. Groundwater Flow and Contaminant Distribution

2.2.1. Groundwater flow direction

In order to examine the groundwater level distribution and its seasonal variation, we measured groundwater levels in monitoring wells at two times (May and August in 2010). In both seasons (dry and wet), the groundwater flowed mostly from the front area of the laboratory (a high elevation area) to the main gate area (well GW17) of the RMO (a low elevation area). The highest water level in May was 131 m (above mean sea level) and the lowest level was 115 m, so the seasonal difference was great (16 m). In the wet season (August), the highest water level was 136 m, which was 5 m higher than that in May, while the lowest water level was 116 m (Fig. 4).

Estimates of hydraulic conductivity using the Bouwer and Rice method (1976) range from 4.73×10^{-5} to 1.73×10^{-4} cm/sec (mean = 1.17×10^{-4} cm/sec) while those of the Cooper et al. (1967) were between 1.02×10^{-4} and 1.99×10^{-3} cm/sec (mean = 6.24×10^{-4} cm/sec) (except SKW2).

2.2.2. Distribution of contaminants

Fig. 5 shows the distribution of contaminations (TCE, CF, and CT) around the system prior to the start of the pilot pump-and-treat system in November 2010. This reveals that the contaminant plume is spreading downward from the old asphalt laboratory with the groundwater flow. The peak TCE level (14.3 mg/L) was found in front of the laboratory, and four monitoring wells also exhibited high TCE levels of 8-14 mg/L. Except for these, 40 monitoring wells exhibited an average TCE level of 0.98 mg/L (Fig. 5(a)). TCE is a volatile liquid at room temperature and is hard to dissolve in water, but its solubility of 1,100 mg/L at 25°C is very high

Table 2. Completions of wells used in this study

	Elevation (m)	Inner diameter (mm)	Well depth (m)	Well screen length (m)	Well casing length (m)	Installation (mm/dd/yy)
KDPW7	134.1	101.6	30	24	6	06/25/10
KDPW8	134.0	101.6	28	22	6	06/26/10
KDMW7	134.0	101.6	21	15	6	12/31/10
KDMW8	128.0	101.6	28	22	6	12/27/10
KDMW9	138.5	101.6	27	21	6	12/30/10
KDMW10	138.8	101.6	27	21	6	12/29/10
SKW2	131.4	101.6	30	–	–	–

compared with the Korean groundwater standard (TCE 0.03 mg/L) (Kamon et al., 2003). Therefore, most of the groundwater within the RMO site exceeds the Korean standard (used for domestic purposes). Moreover, the CF concentration (1.15 mg/L) in the backyard of the new laboratory is more than 14 times greater than the Korean standard (CF 0.08 mg/L), so most of the groundwater at the RMO site exceeded the standard. The CT level at the front of the old asphalt laboratory is the most strikingly high level (2.56 mg/L), more than 1,280 times the Korean standard (CT 0.002 mg/L). All three contaminants (TCE, CF, and CT) spread from the upgradient area to the downgradient area of the RMO site along the groundwater flow.

2.3. Pilot Pump-and-Treat System

2.3.1. Well installation

The pilot pump-and-treat system is comprised of two pumping wells, five monitoring wells, and a water treatment facility. It was placed in front of the main RMO building and its elevation is 128-139 m (amsl). For the test, six wells (except SKW2) were newly installed in the study area from June to December in 2010, and these are 27-30 m deep, tapping the weathered rock layer (Table 2). The radius of each well is 101.6 mm and, the wells (except SKW2) were screened below the casing of the top 6 m. KDMW7 was installed for monitoring any contaminant migration from the main source in the upper area. In addition, KDPW7 and KDPW8 are pumping wells (the main components of the pilot pump-and-treat system) to contain the contaminant plume that originates from the upper area. KDMW8, KDMW9, KDMW10, and SKW2 are monitoring wells and they have been sued to monitor levels of TCE, CF, and CT and thus to evaluate efficiency of the pilot pump-and-treat operation.

Table 3. Periods of the pilot tests and rebound monitoring

Test		Period (dd/mm)
Wet season	1st	32 days (06/07-06/08)
Dry season	2nd	16 days (22/08-06/09)
	3rd	75 days (19/09-02/12)
Rebound monitoring		5 days (03-07/12)

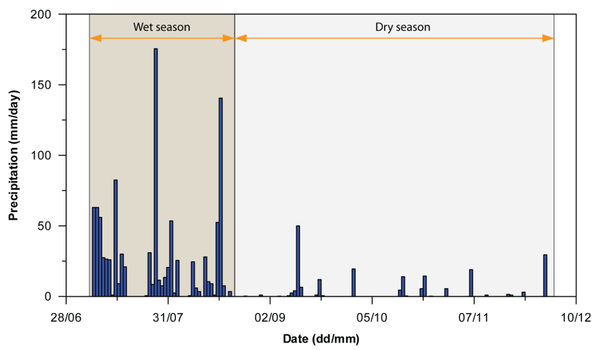

Fig. 6. Wet and dry season for daily precipitation from 06 July to 02 December 2011. Data are from Korean Meteorological Administration.

2.3.2. Operation period

The pilot pump-and-treat system was operated from 6 July to 2 December in 2011 (Table 3). The first test period (6 June to 6 August) is considered as the wet season, while the second and third tests periods (22 August to 6 September and 19 September to 2 December) are considered as the dry season. In the wet season, rainfall occurred on 22 of 32 days. The maximum daily rainfall was 175.5 mm and the total precipitation was 755.5 mm, which is equivalent to 34.5% of the total annual precipitation (2,188.0 mm). In the dry season, rainfall occurred on only 18 of 91 days. The maximum daily rainfall was 29.5 mm and the total rainfall was 124.6 mm in the dry season. In particular, there were only five days on which the daily rainfall exceeded 10 mm (Fig. 6).

Even after the cessation of pumping, we continued to monitor TCE, CF, and CT for 5 days.

2.3.3. Groundwater sampling and analysis

Groundwater and chemical analyses were conducted for two pumping wells (KDPW7, KDPW8) and five monitoring wells (KDMW7, KDMW8, KDMW9, KDMW10, SKW2). The sampling was conducted at 16:00 daily from 6 July to 7 December. The pumping rate was also measured daily. For the pumping wells, pumped water was used and for the monitoring wells, a Waterra pump (made of PVC) was used for each well to avoid cross-contamination by multiple uses. Prior to sampling, water of 3-5 well volumes was purged. The sampled groundwater was preserved at 4°C in an icebox and was transported on the sampling day to the Natural Science Research Supporting Center of Sangji University, 1 km from the study area. In the center, TCE, CF, and CT were analyzed using a gas chromatography mass spectrometry (Saturn 2100T, VARIAN). The correlation coefficients of water levels and contaminant concentrations were calculated using the commercial statistical program, SPSS.

In addition, groundwater levels, rainfall, and pumping rates were measured every hour from 6 July to 7 December in 2011. These measurements were used to reveal any relationship between the parameters and the contaminant levels. For the consecutively recorded data, auto-correlation and cross-correlation analyses were conducted. The water level data were compensated for the variation in atmospheric pressure measured at the Wonju branch of the Korea Meteorological Administration (Rasumessen and Crawford, 1997).

3. Results and Discussion

3.1. Contaminant Concentrations

3.1.1. TCE concentration

Concentrations of TCE, CF, and CT obtained in the three pilot rounds of the pilot pump-and-treat operation are summarized in Tables 4 and 5. The average TCE levels for the period ranged between 0.067 and 1.701 mg/L, and those at KDPW7 and KDPW8 were 0.521 and 1.112 mg/L, respectively. Thus, the mean TCE level of KDPW8 was twice than that of KDPW7. Among the wells in this study, KDMW7 had the highest TCE level (1.242 mg/L). This is well explained by the very high level of TCE contamination (over 14 mg/L) associated with groundwater flow in the upper area (near the old laboratory in Fig. 5). Like those of KDMW7 and KDPW8, the mean TCE level of KDMW8 was very high (0.615 mg/L). This is associated with the effects of higher TCE levels (maximum 0.738 mg/L) around KDPW7, which is 19 m upgradient from KDMW8.

The monitoring wells (KDMW9, KDMW10, and SKW2) located downgradient from the two pumping wells (KDPW7 and KDPW8) had relatively low mean concentrations that range between 0.130 and 0.206 mg/L. The TCE levels at the

Table 4. TCE, CF and CT concentrations of groundwater samples in pumping wells (KDPW7 and KDPW8) (mg/L)

		Pumping well					
		KDPW7			KDPW8		
		TCE	CF	CT	TCE	CF	CT
1st	Maximum	0.657	0.103	0.139	1.492	0.153	0.330
	Minimum	0.346	0.068	0.060	0.683	0.064	0.150
	Average	0.481	0.084	0.091	1.189	0.082	0.227
	Median	0.472	0.081	0.088	1.200	0.079	0.229
2nd	Maximum	0.556	0.067	0.111	1.553	0.077	0.342
	Minimum	0.424	0.050	0.065	1.006	0.061	0.166
	Average	0.492	0.059	0.088	1.120	0.068	0.209
	Median	0.492	0.060	0.089	1.093	0.067	0.211
3rd	Maximum	0.738	0.093	0.131	1.610	0.134	0.334
	Minimum	0.405	0.034	0.069	0.648	0.036	0.115
	Average	0.544	0.063	0.098	1.077	0.073	0.202
	Median	0.520	0.062	0.096	1.023	0.071	0.195

Table 5. TCE, CF and CT concentrations of groundwater samples in monitoring wells (KDMW7, KDMW8, KDMW9, KDMW10 and SKW2) (mg/L)

		Monitoring wells														
		KDMW7			KDMW8			KDMW9			KDMW10			SKW2		
		TCE	CF	CT	TCE	CF	CT	TCE	CF	CT	TCE	CF	CT	TCE	CF	CT
1st	Maximum	0.905	0.061	0.244	0.978	0.100	0.193	0.257	0.221	0.059	0.142	0.102	0.028	0.226	0.237	0.055
	Minimum	0.009	0.000	0.000	0.004	0.000	0.000	0.075	0.104	0.017	0.000	0.000	0.000	0.032	0.121	0.006
	Average	0.400	0.019	0.092	0.592	0.067	0.105	0.159	0.147	0.034	0.067	0.045	0.014	0.116	0.169	0.027
	Median	0.381	0.015	0.095	0.685	0.081	0.119	0.164	0.146	0.035	0.064	0.042	0.011	0.120	0.171	0.029
2nd	Maximum	1.491	0.108	0.268	0.660	0.088	0.126	0.484	0.100	0.094	0.234	0.131	0.047	0.347	0.230	0.083
	Minimum	0.265	0.012	0.059	0.523	0.069	0.085	0.232	0.077	0.045	0.144	0.069	0.032	0.156	0.078	0.037
	Average	0.770	0.047	0.140	0.595	0.077	0.111	0.313	0.088	0.062	0.186	0.096	0.038	0.207	0.130	0.049
	Median	0.716	0.038	0.137	0.597	0.077	0.110	0.295	0.088	0.059	0.188	0.092	0.035	0.200	0.119	0.046
3rd	Maximum	2.568	0.234	0.433	0.895	0.135	0.164	0.461	0.103	0.093	0.278	0.173	0.056	0.206	0.305	0.049
	Minimum	1.198	0.073	0.177	0.370	0.037	0.071	0.125	0.032	0.026	0.108	0.055	0.022	0.069	0.073	0.018
	Average	1.701	0.142	0.284	0.626	0.075	0.115	0.204	0.060	0.043	0.172	0.110	0.035	0.120	0.163	0.028
	Median	1.645	0.141	0.277	0.627	0.074	0.115	0.181	0.057	0.040	0.158	0.104	0.034	0.117	0.153	0.027

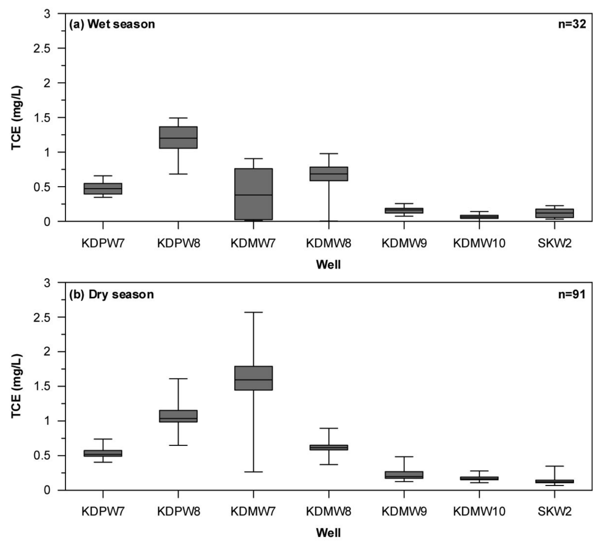

Fig. 7. TCE concentrations of groundwater samples in (a) wet season and (b) dry season.

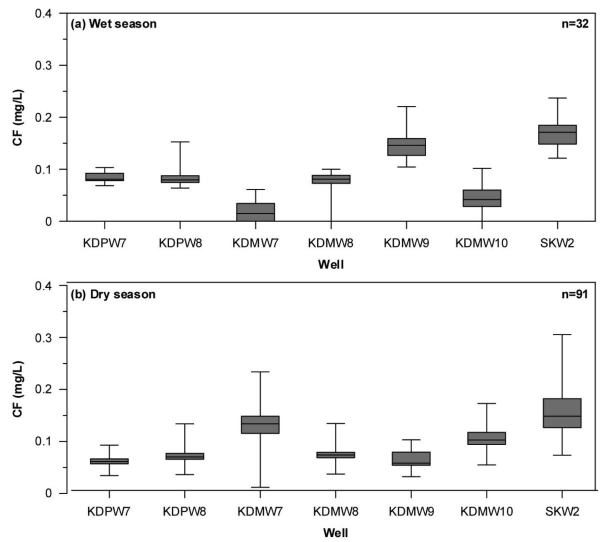

Fig. 8. CF concentrations of groundwater samples in (a) wet season and (b) dry season.

pumping and monitoring wells exhibited seasonal variations. The TCE concentrations of the other wells, except for KDPW8, were higher in the dry season than in the wet season (Figs. 7(a) and (b)). This can be attributed to the dilution effect caused by heavy rainfall (755.5 mm) in the wet season (6 July to 6 August) of 2011, equivalent to 34.5% of the total precipitation for that year.

3.1.2. CF concentration

The mean CF concentrations for the three test periods were from 0.019 to 0.169 mg/L. For the same periods, the mean CF levels at KDPW7 and KDPW8 were 0.068 and 0.075 mg/L, respectively, and so were similar. However, the downgradient monitoring wells (KDMW9, KDMW10, and SKW2) exhibited a wide variation in mean CF levels (0.045-0.169 mg/L). The main contamination source in the

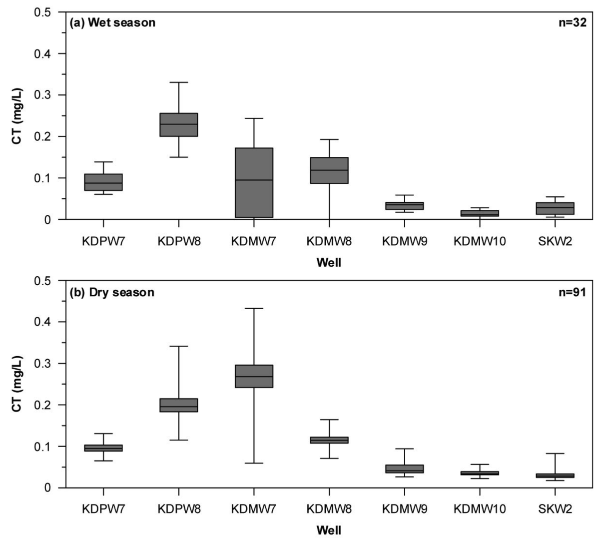

Fig. 9. CT concentrations of groundwater samples in (a) wet season and (b) dry season.

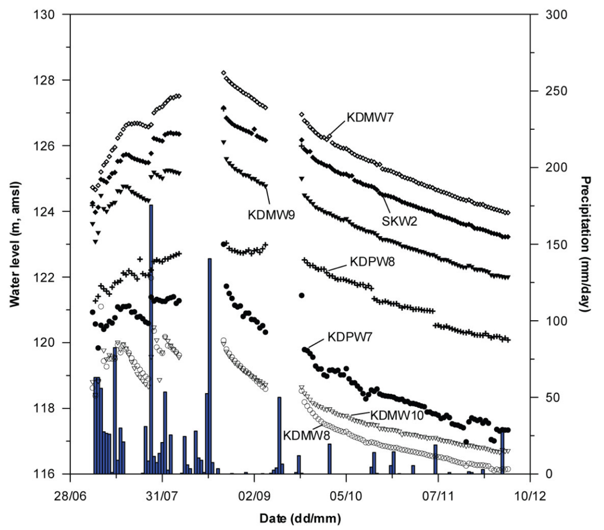

Fig. 10. Water levels in the pumping wells (KDPW7 and KDPW8) and monitoring wells (KDMW7, KDMW8, KDMW9, KDMW10, and SKW2) during the operation period of pump-and-treat.

area may be likely the new asphalt laboratory, not the old laboratory (see Fig. 5(b)). It is known that waste organic solvents (TCE and CF) had been dumped here and there within the RMO, and thus the main source area may differ with the solvent (Gangwon Province, 2005; Baek and Lee, 2010). In addition, the mean CF concentrations at the pumping wells (KDPW7 and KDPW8) were higher in the dry season (0.062 and 0.072 mg/L) than in the wet season (0.084 and 0.082 mg/L). The same phenomenon was found at the monitoring wells, except for KDMW9 and SKW2 (Figs. 8(a) and (b)). This is also closely related with the dilution effect caused by the heavy rainfall in the wet season.

3.1.3. CT concentration

The mean CT concentrations for the three tests were between 0.014 and 0.284 mg/L. Those at the pumping wells (KDPW7 and KDPW8) were 0.095 and 0.209 mg/L, respectively. Like the mean TCE level, the mean CT level of KDPW8 was twice that of KDPW7. The distribution of CT is very similar to that of TCE (see Figs 5(a) and (c)). KDMW7 exhibited the highest mean CT level (0.217 mg/L) with a maximum CT level of 0.430 mg/L. Furthermore, the mean CT level in the dry season (0.258 mg/L) was more than twice that in the wet season (0.092 mg/L) (Figs. 9(a) and (b)). This may be related with the existence of a very high CT level (maximum 1.145 mg/L) in the upgradient area of KDMW7 and with groundwater flow towards KDMW7 induced by the pilot pump-and-treat operation.

3.2. Rainfall and Groundwater Level

Fig. 10 shows rainfall and groundwater levels for the three tests. For the first test, the pumping rates of KDPW7 and KDPW8 were 5.92 and 10.24 L/min, respectively, so that of KDPW8 was twice than that of KDPW7. Over the entire operation period of 32 days, rainfall occurred on 22 days and the total rainfall was 755.5 mm. There were six days with more than 50 mm of rainfall, and the maximum daily rainfall was 175.5 mm (on 27 July). The water level of KDPW7 (amsl) was 120.93 and 121.28 m at the cessation of pumping, which constitutes an increase by 0.35 m. The water level of KDPW8 was 124.18 m initially, and in the second day after the start of pumping it decreased by 2.91 m to 121.27 m. After that, the water level continuously increased ($r^2 = 0.89$) and reached 122.71 m at the cessation of pumping. For the monitoring wells, the water levels were elevated by 0.75-2.78 m (maximum = at KDMW7) compared with the initial water levels. For the period from 6 July to 17 July, the groundwater levels of all the wells had an increasing trend ($r^2 = 0.35$-0.98) but were decreasing when rainfall was absent (Fig. 10).

However, the situation was totally different in the dry season including second and third round of the entire pilot test, when the water levels of all the groundwater wells had a

Table 6. Correlation between the water levels and the concentrations (TCE, CF and CT) for each well. The p is the probability that the parameters are un-correlated

Well	Correlation (p)								
	1st			2nd			3rd		
	TCE	CF	CT	TCE	CF	CT	TCE	CF	CT
KDPW7	−0.474 (0.006)	0.120 (0.514)	−0.491 (0.169)	0.633 (0.008)	0.324 (0.222)	0.510 (0.044)	0.310 (0.007)	−0.056 (0.636)	0.406 (3.004E-04)
KDPW8	−0.240 (0.186)	−0.073 (0.693)	−0.326 (0.069)	0.902 (1.839E-06)	0.594 (0.015)	0.900 (2.088E-06)	0.577 (5.976E-08)	0.118 (0.316)	0.518 (1.959E-06)
KDMW7	−0.731 (2.068E-06)	−0.654 (4.908E-05)	−0.611 (2.049E-04)	−0.942 (5.247E-08)	−0.918 (5.561E-07)	−0.937 (9.388E-08)	0.567 (1.173E-07)	0.039 (0.739)	0.363 (0.001)
KDMW8	−0.448 (0.010)	−0.487 (0.005)	−0.418 (0.017)	0.305 (0.250)	−0.270 (0.313)	0.282 (0.290)	0.084 (0.476)	−0.002 (0.989)	0.198 (0.089)
KDMW9	0.368 (0.038)	0.256 (0.156)	0.201 (0.269)	0.931 (1.621E-07)	0.405 (0.119)	0.906 (1.331E-06)	0.788 (5.223E-11)	0.604 (9.708E-09)	0.810 (1.314E-18)
KDMW10	−0.590 (0.001)	−0.537 (0.002)	−0.532 (0.002)	0.792 (0.001)	−0.880 (6.866E-06)	0.761 (6.095E-04)	0.771 (5.927E-16)	0.468 (2.327E-05)	0.758 (3.609E-15)
SKW2	0.519 (0.002)	0.065 (0.726)	0.521 (0.002)	0.877 (8.026E-06)	−0.661 (0.005)	0.916 (6.159E-07)	0.379 (0.001)	0.442 (7.321E-05)	0.472 (1.882E-05)

decreasing trend due to pumping. In the second test, the mean pumping rates of KDPW7 and KDPW8 were 5.69 and 10.98 L/min, respectively. The initial water level of KDPW7 was 123.00 m and pumping caused a drastic drawdown, so the water level was lowered by 1.28 m to 121.72 m in the second day. After that, the water level continuously decreased ($r^2 = 0.94$) and with a drawdown of 1.40 m reached 120.32 m at the cessation of pumping. The water level of KDPW8 was 127.12 m initially and with a drawdown of 4.09 m reached 123.03 m in the second day. After that, the water levels were between 122.71 and 123.03 m, with some fluctuations. The water levels of the surrounding wells had some drawdown (0.99-1.48 m).

In the third test, the pumping rates of KDPW7 and KDPW8 were 5.71 and 9.20 L/min, respectively. The water level of KDPW7 was 121.44 m initially but decreased greatly with pumping and reached 119.79 m in the second day of operation. After that, the groundwater level continuously decreased ($r^2 = 0.94$) and finally reached 117.34 m for a drawdown of 4.1 m. The water level of KDPW8 was 125.99 m initially and decreased greatly with pumping to reach 122.52 m in the second day. After that, the water level continuously decreased ($r^2 = 0.98$) and finally reached 120.08 m for a drawdown of 5.91 m. In addition, the water levels of the surrounding wells had drawdown of 1.94-3.00 m. The groundwater levels in the wet season were generally elevated despite pumping, but those in the dry season were normally decreased by pumping.

3.3. Groundwater Level and Contaminant Concentrations

Table 6 shows the relationships between groundwater levels and contaminant concentrations for the whole test period. The table shows that the meaningful relationships are mostly negative in the wet season but positive in the dry season. The negative correlation in the wet season means that levels of TCE, CF, and CT were decreasing as the groundwater levels were increasing. The positive correlation in the dry season indicates an elevation of contaminant concentrations with increasing water levels at the site (Cheon et al., 2013; Jeon et al., 2013).

In the first test, the numbers of wells that had negative correlations for TCE, CF, and CT were 5, 4, and 5, respectively. In the second test, the numbers of wells that had negative correlations were 1, 4, and 1, respectively. In the third test, only wells KDPW7 and KDMW8 had negative correlations and only for CF. In the wet season, the contaminant levels were lowered by the dilution effect of rainfall recharge (expressed as elevated groundwater levels). In the

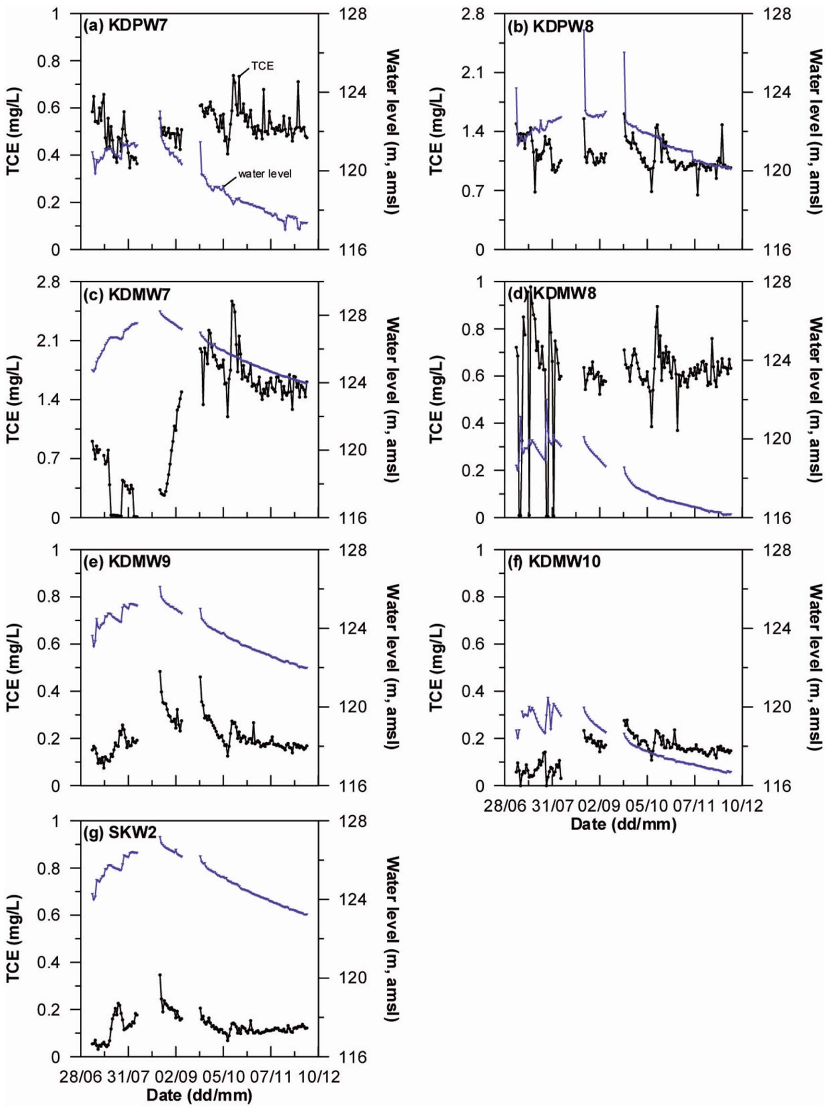

Fig. 11. Concentration of TCE and water level in the pumping wells and monitoring wells from 06 July to 02 December 2011.

dry season, the decrease in contaminant levels with depressed water levels was caused by the pilot pump-and-treat operation, but elevation of the contaminant levels with increasing water levels was caused by additional migration of contaminants from upper hot area and additional leaching of residual contaminants in the unsaturated zone (Yang et al., 2012).

The TCE, CF, and CT concentrations are highly related with the increasing and decreasing of groundwater levels. In the wet season, the pumping wells had an inverse correlation between TCE level and groundwater level, but the downgradient monitoring wells had a positive correlation (Fig. 11). In the dry season, all the wells except KDMW7 exhibited a decrease in TCE concentration with decreasing groundwater levels. However, elevation of the TCE level with decreasing water level indicates the arrival of higher contamination from hot source area. The relationship of CF and CT with groundwater level is quite similar to that of TCE (Figs. 12 and 13). That is, the pumping wells exhibited a negative correlation in the wet season but a positive correlation in the dry season. However, an upgradient well (KDMW7) exhibited an inverse relationship between contaminant levels and groundwater levels in the second test period.

3.4. Concentration after Cessation of Pumping and Contaminant Removal

We also monitored TCE, CF, and CT concentrations for

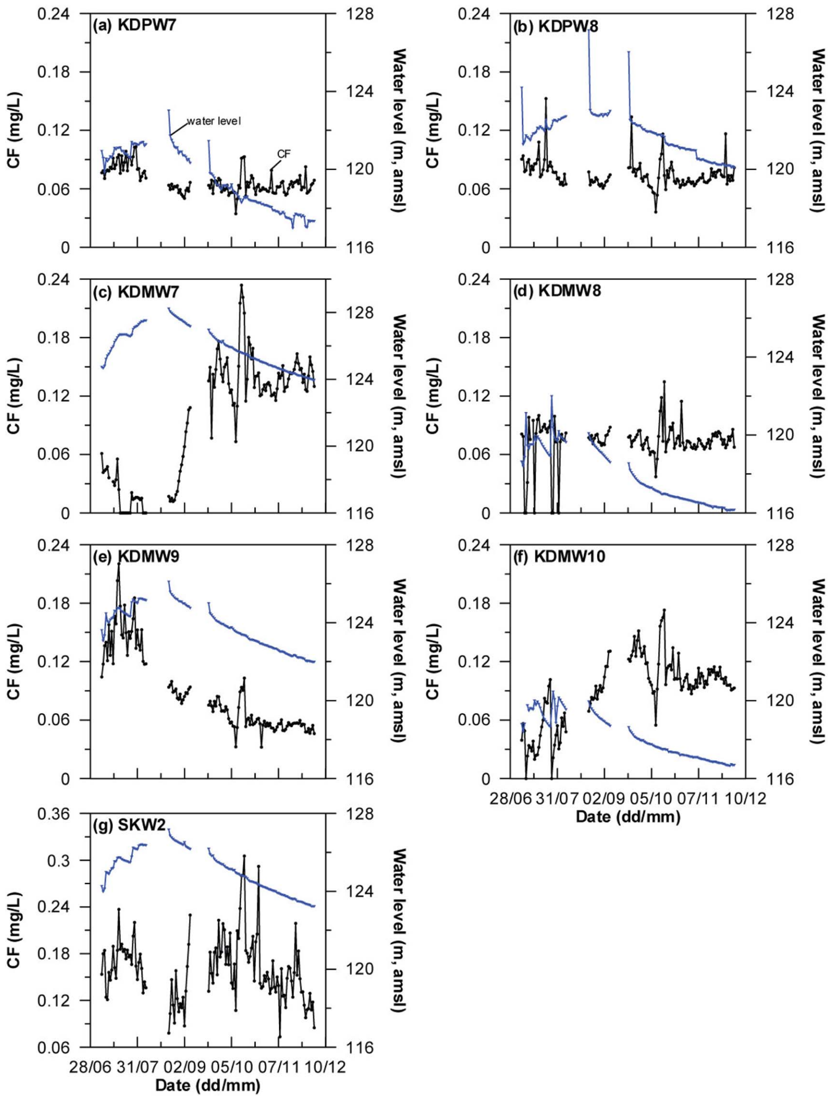

Fig. 12. Concentration of CF and water level in the pumping wells and monitoring wells from 06 July to 02 December 2011.

five days (3-7 December 2011) after the cessation of pilot operations (the third test) at the pumping and monitoring wells. The TCE concentrations at the wells on 3 December were greater than those measured just before the cessation of pumping. This means that the operation of the pilot pump-and-treat system quickly removed a fairly large amount of contaminants and lowered the contaminant concentrations. However, the TCE adsorbed to soils and in soil pores again elevated the groundwater contamination after the cessation of the remedial system, which is called rebound (US EPA, 1996). Moreover, the CT concentrations of all the wells except KDMW8 exhibited increasing trends after the cessation of pumping. However, the CF concentrations of the monitoring wells except KDMW7 and KDMW9 exhibited a continuous decrease for the monitoring period, which is perhaps because the original distribution of CF was different from those of TCE and CT (see Fig. 5).

In the pilot pump-and-treat operations, the contaminated groundwater pumped from KDPW7 and KDPW8 was transported to a nearby water treatment system through connected pipelines and was cleaned to within the Korean groundwater standards (TCE 0.3 mg/L, CF 0.08 mg/L, and CT 0.002 mg/L). Throughout the operation period, the mean pumping rates of KDPW7 and KDPW8 were 5.76 and 9.70 L/min, respectively. There were 91 days of pumping in total. The amounts of contaminants pumped or removed through

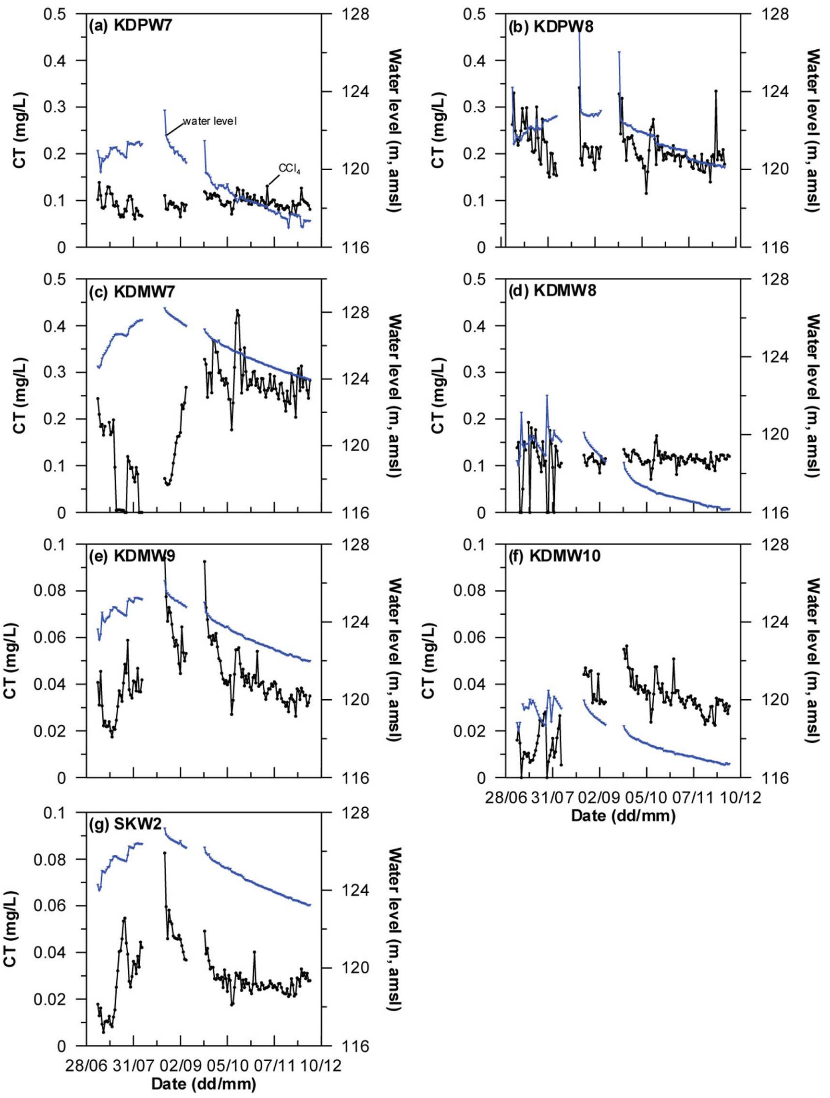

Fig. 13. Concentration of CT and water level in the pumping wells and monitoring wells from 06 July to 02 December 2011.

Table 7. Amounts of the contaminants removed during the pilot tests of the pump-and-treat system

Pilot test		KDPW7			KDPW8		
		TCE (g)	CF (g)	CT (g)	TCE (g)	CF (g)	CT (g)
Wet season	1st	130.5	22.8	24.8	557.2	38.7	106.5
Dry season	2nd	64.7	7.8	11.6	284.3	17.2	53.2
	3rd	334.8	38.8	60.2	1070.9	72.7	200.7
Total		529.9	69.4	96.5	1912.4	128.6	360.4

KDPW7 were 529.9, 69.4, and 96.5 g for TCE, CF, and CT, respectively, and those from KDPW8 were 1913.4, 128.6, and 360.4 g, respectively (Table 7). The pumping rate of KDPW8 was 1.6 times greater than KDPW7, but the amount of contaminant removal was four times greater than the latter. This is related with the higher concentrations of groundwater contamination around KDPW8 and the stronger groundwater flow due to a greater pumping rate.

4. Conclusions

In this study, we performed three rounds of pump-and-treat pilot tests for a TCE contaminated aquifer and thus examined from which the relationships between groundwater levels and contaminant concentrations. For this purpose, groundwater was pumped simultaneously from the pumping wells (KDPW7 and KDPW8) and then contaminant levels and groundwater levels were monitored at the pumping wells and five surrounding monitoring wells.

Based on the analysis of the data available from the tests, we revealed that there were two representative relationships between the groundwater levels and the concentrations of the contaminants, TCE, CF, and CT during the test period. In the wet season the contaminant levels were decreasing with increasing groundwater level (negative correlation), while in the dry season the contaminant levels were increasing with the groundwater level (positive correlation). The negative correlation in the wet season is related with the dilution effect by rainfall recharge. The positive correlation is likely the result of contaminant removal by the pumping and either the arrival of additional contaminants from the upgradient hot source area or further leaching from residual contaminants in the unsaturated zone. Therefore, in order to design a full-scale pump-and-treat remedial system and be effective in the application of the remediation system, these relationships between groundwater levels and contaminant concentrations should be carefully considered.

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