

SPRINKLER IRRIGATION: A VOC REMEDIATION ALTERNATIVE

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A sprinkler irrigation system was tested to assess its efficacy for volatilizing organic chemicals in pumped ground water. In field tests involving the analysis of more than 250 samples collected from beneath a spray irrigation system, removal rates of ethylene dibromide (EDB), 1,1,2-trichloroethylene (TCE), 1,1,1-trichloroethane (TCA), and carbon tetrachloride (CT) in samplers placed 0.5 m above the ground exceeded 95% in the vast majority of cases and approached 100% for the more volatile chemicals. As predicted by Henry's Law, CT, TCA, and TCE were significantly more volatile than EDB. The removal efficiencies of conventionally designed sprinkler irrigation systems were enhanced by using small aperture nozzles with impact pads designed to produce thin films of water. Droplet sizes produced by the various nozzle apertures and impact pad designs were measured using a phase Doppler particle analyzer and found to be one factor controlling volatilization. As predicted by the Clausius-Clapeyron equation, higher air temperatures appear to be associated with slightly increased volatilization. Using specialized stratified water droplet collectors, it was determined that longer droplet trajectories increased volatilization.

INTRODUCTION

Less costly, yet viable, treatments are needed for the remediation of contaminated ground water. Sprinkler irrigation has the potential to not only cheaply and effectively remove volatile organic compounds from contaminated ground water but also to use the water beneficially and eliminate the costly disposal of both the remediated water and the contaminants. Inherent in this alternative treatment is irrigation, a farming practice that is vital not only to the successful production of small grains in central Nebraska, but to the agricultural economy of western states where the semi-arid climate and lack of sufficient rainfall during critical growing periods necessitate the need for supplemental water. The U.S. Department of Commerce (1) reports that in the contiguous United States, ground water is the source of irrigation water for 56% of the 18.7 million irrigated hectares

(46.2 million acres). Of the cropland irrigated with ground water, 75% is in the 17 western states.

For sprinkler irrigation to gain acceptance as a primary method for remediating volatile organic compound (VOC)-contaminated ground water, three essential criteria must be met. The irrigation well(s) must be able to capture the contaminated plume(s); the risk to the public and/or environment during the water to air exchange must be *de minimis*; the VOCs must be efficiently removed from the water during irrigation.

The capability of high pumping capacity wells (>227 m³/h or >1000 gal/min) to form relatively large capture zones is well known and is the basis for delineating wellhead protection areas. There are several models that describe the zone of influence of high capacity wells. Because irrigation is seasonal, the capture zone of an

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irrigation well is present only about four months a year. In order to increase the capture potential and to reverse off-season excursions (contaminated ground water that flows past the irrigation well during the other eight months of the year when the well is not operating), pumping of the irrigation well must be heavier during the four-month period than if the well was pumped continuously. Fortunately, many irrigation wells are capable of pumping upwards of 454 m³/h (2,000 gal/min) and can compensate for the time the well is idle. Modeling by S. S. Papadopoulos and Associates (2) at the experimental site described in this paper has shown that over time, pulsed pumping will provide containment and mass removal comparable to that afforded in continuous pumping.

The atmospheric releases of the VOCs can be estimated from the mass of each individual chemical pumped annually. For example, if the concentration of 1,1,2-trichloroethylene (TCE) in the irrigation water is 750 µg/L and the pumping rate is 272 m³/h (1200 gal/min) and it is assumed that 100% of the TCE is lost to the atmosphere, 5 kg TCE/d (11 lb/d) or 590 kg TCE (1300 lb) would be volatilized to the atmosphere during the four months of operation. The Nebraska Department of Environmental Quality's Title 129 Rules and Regulations require that all new, modified, and reconstructed sources with the potential to emit 2.3 t/y (2.5 ton/y) of any toxic air pollutant or more than 34 kg/d (75 lb/d) be permitted and treated using best available control technology. At these mass removal rates, volatile emissions of TCE could approximate 3,000 µg/L before a permit would be needed. Because the irrigation well must operate continuously during the four months, sprinkler systems in other fields would be connected to the well so as not to over-water a field. Since each sprinkler system is a separate emission source, the mass of volatiles emitted from each source would be less than 0.23 t/y (0.25 ton/y). Although the emission rate at which a permit is required is dependent on the locale, the Nebraska maximum of 2.3 t/y (2.5 ton/y) appears very conservative. Pankow et al. (3) report that discharge permits generally are not necessary until the emissions exceed ≈10 t/y (≈11 ton/y). The proposed VOC emission rates are much less than those typical of urban sources. Pankow et al. (3) report that large gasoline stations with vapor recycling emission controls commonly emit two to 3 t/y (2.2 to 3.3 ton/y) of volatile compounds while clothing dry cleaners emit 5 t/y (5.5 ton/y) of 1,1,2,2-tetrachloroethylene (PCE) and large industrial degreasers emit 40 t/y (44 ton/y). Once volatilized from the sprinkler system the chemicals are rapidly dispersed in the

atmosphere and, at these emission levels, health risk models prepared by Woodward-Clyde Consultants (4), Roux Associates (5), and Geraghty and Miller (6) show that the lifetime risk of cancer would not exceed the 10⁻⁶ threshold level.

Thus, the remaining questions are how effective is conventional sprinkler irrigation in volatilizing VOCs and what adjustments are needed to optimize the volatilization efficiency? Several laboratory and field studies have demonstrated that there is significant loss of volatile compounds when water containing these compounds is applied to the land. Litton and Guymon (7) have summarized much of the research reported in the literature. Many of the soil volatilization investigations were column studies. Wilson et al. (8) investigated the fate and transport of TCE in sandy, low organic soils under unsaturated conditions. TCE concentrations of 900 and 180 µg/L were applied at a steady state rate of 14 cm/d to packed soil columns equipped with vapor traps. The air above the column was exchanged once every eight minutes. At the higher influent concentration, 58% of the total mass of the applied TCE was volatilized while 88% was volatilized at the lower concentration. There is very little information in the literature concerning the volatility of ethylene dibromide (EDB); however, a few studies have quantified the volatilization losses of dibromochloropropane (DBCP), a nematocide with a volatility similar to that of EDB, from soils. Castro and Belser (9) reported that volatilization was the dominant loss mechanism from soils, and subsequent studies by other investigators have shown that the volatilization losses may be significant. Litton and Guymon (10) confirmed that volatilization accounted for at least 85% of the DBCP loss in Hanford sandy loam soils and that trace amounts of DBCP in contaminated ground water could be removed by application to agricultural lands.

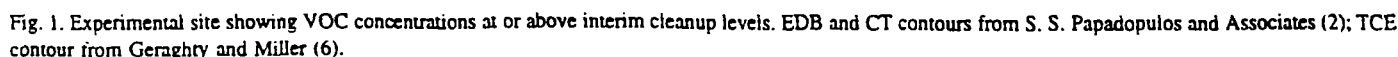
The process that occurs when VOCs vaporize from water is not well understood on a microscopic level. While it is generally conceded that increases in surface area at the air-water interface result in increased volatilization, the molecular velocities created by the sheering effects of small droplet formation may dramatically increase volatilization. Thus, VOCs dissolved in irrigation water would be much more likely to vaporize from water applied through a sprinkler irrigation system than from water applied via furrow irrigation (a ≈360-m long stream of water ≈6-cm deep open to the atmosphere) and least likely to vaporize from a drip irrigation system, which is designed to minimize evaporation. The Orange County Water District (11) investigated the extent of TCE removal through both drip and sprinkler irrigation

Wood et al. (14) evaluated a series of spray nozzles with a wide range of water flow rates and spray patterns at several sites with VOC contamination as high as 10^5 $\mu\text{g/L}$. The removal efficiency increased with decreased droplet size and increased spray trajectory. Fog nozzles which require pressures greater than 138 kPa (20 psi) and full cone nozzles operating at low pressure (<69 kPa or <10 psi) and an 8-m (24-ft) upward trajectory provided the most effective treatment, removing more

The objectives of this investigation were to demonstrate the efficacy of volatilization of VOCs by sprinkler irrigation, to enhance volatilization efficiencies by decreasing droplet size, and to accurately measure the average size droplet from the various nozzles at different pressures. Presented here are the early results of an ongoing two-year investigation.

Field site

The 20-ha (50-acre) experimental site is a furrow-irrigated corn field underlain by commingled plumes of contaminated ground water, located on the eastern edge of Hastings, NE (Fig. 1). The ground water is 36.5 m (120 ft) below the land surface and contains trace levels of the solvents TCE, 1,1,1-trichloroethane (TCA) and PCE, and the fungicides carbon tetrachloride (CT) and EDB. Also present are ultratrace quantities of solvent degradates and CT degradates such as 1,1-DCE, trans 1,2-dichloroethylene and chloroform. A grain elevator \approx 820 m (\approx 2,700 ft) upgradient is the source of the fungicides, while the solvents are allegedly from an abandoned



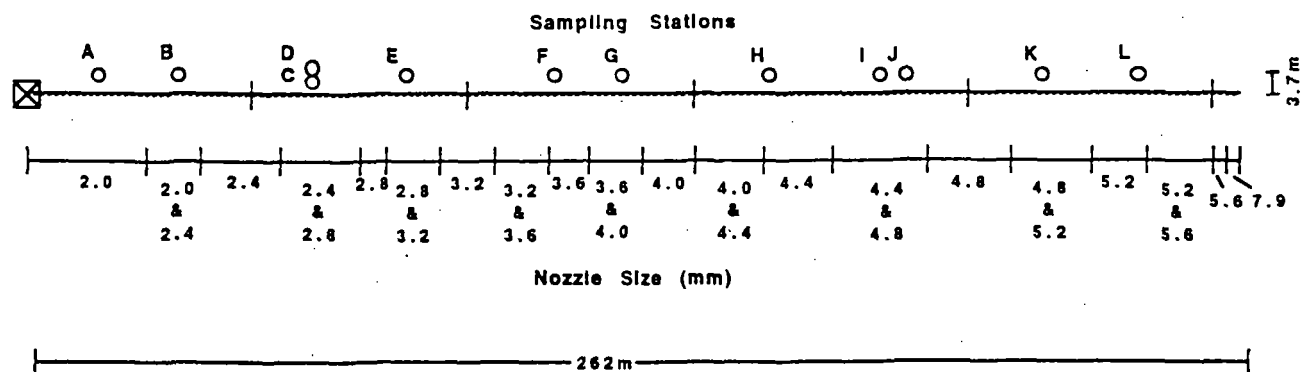


Fig. 2. Pivot arm showing distribution of nozzle sizes and locations of sampling stations.

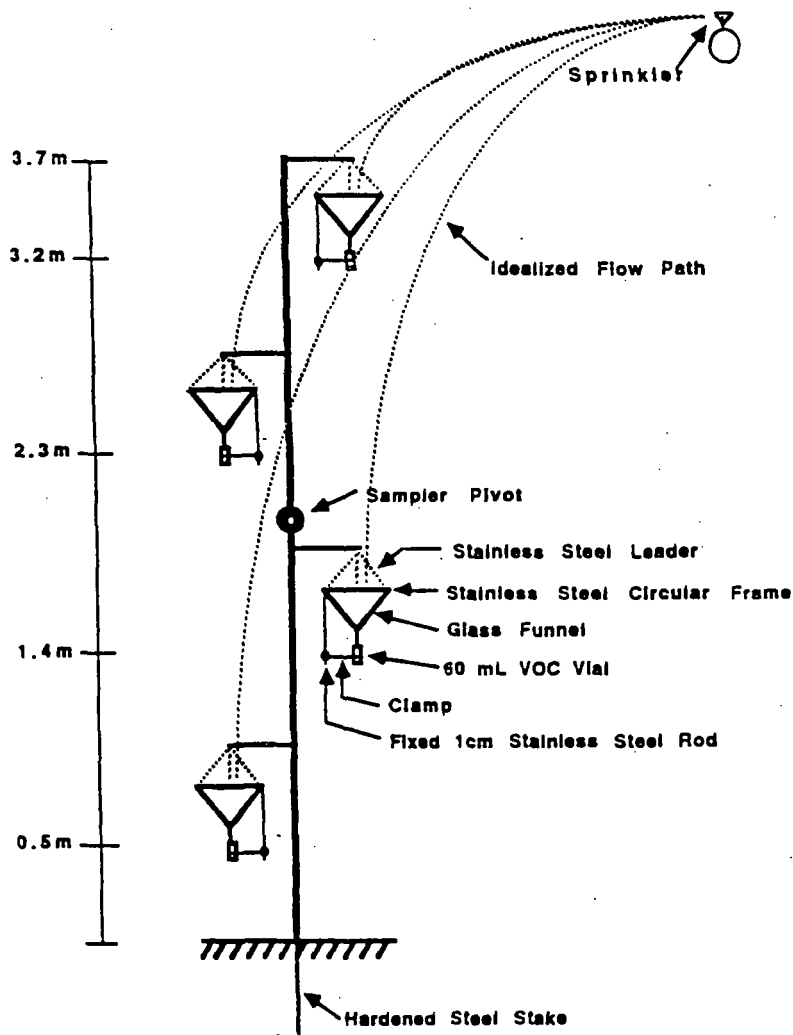


Fig. 3. Stratified water droplet collector.

landfill and industrial sites located southwest of the elevator.

The 30-m (100-ft) thick aquifer is primarily sand and gravel with an occasional silt lens. Geraghty and Miller's (15) pump test of irrigation well I-49 (Fig. 1) in January 1994 revealed that the drawdown in peripheral wells and

cluster wells screened in different horizons was radially similar. The findings imply that the aquifer is relatively homogeneous, both horizontally and vertically. The hydraulic conductivity is 70 m/d (230 ft/d).

The 40.6-cm (16-in) diameter irrigation well (I-49) was drilled in 1945 and is screened from 47.4 m (156 ft) to

its bottom at 67.2 m (221 ft). The center-pivot sprinkler irrigation unit was installed so that it can move through the corn field in a windshield wiper pattern. For this pilot investigation, however, the irrigation system remained stationary in a grassed area at the north end of the field. Equally spaced screw-in nozzles (340) nozzles were mounted on the 262-m (858-ft) pivot arm, which is 3.6 m (12 ft) above the ground (Fig. 2). The diameter of the nozzle openings ranged from 2 mm (5/64 in) at the pivot head to 7.9 mm (20/64 in) at the end of the arm. Attached to each nozzle is a plastic frame that supports an impact pad which is mounted above the nozzle opening. The design of the impact pad affects the breakup of the water as it is ejected from the nozzle. Impact pad designs are changeable and the pads conveniently snap onto the pad support. The inlet pressure at the pivot could be varied from 69 to 310 kPa (10 to 45 psi) with a tractor-driven booster pump. Both the inlet pressure and the flow rate were monitored at the pivot.

Sampling

A stratified water droplet collector, which could simultaneously collect spray at four fall heights between the pivot arm and the ground, was specially designed and constructed for this project by the Dutton-Lainson Company, Hastings, NE (Fig. 3). The sampling devices were fabricated from stainless steel. Each collector consists of four rings, each of which supports a 27.9-cm (11-in) diameter glass funnel that collects the spray. A clamp attached to a rod welded to the ring and extending below the funnel support holds a 60-mL VOC sample vial. Each funnel support is attached to a hardened steel rod welded at 0.9-m (3-ft) intervals to the main vertical support, which is mounted on a ground-anchored pivot point ≈ 2 m (≈ 6.5 ft) above the ground. The pivot on the water droplet collector enables sampling personnel to easily reach the vials. The droplets are collected at heights of ≈ 0.5 , 1.4, 2.3, and 3.2 m (1.5, 4.5, 7.5, and 10.5 ft) above the ground.

Twelve stratified water droplet collectors were installed parallel to the pivot arm. The nozzles tested in this pilot-study spray relatively fine droplets that produce fogs which can easily drift with the wind. Because the wind is southerly during the irrigation season and averages 21 km/h (13 mph) as reported by the U.S. National Oceanic and Atmospheric Agency (NOAA) (16), the 12 devices were placed on the north side of the pivot arm to collect the maximum amount of spray (Fig. 2). Samples for the measurement of input concentrations were collected frequently from a hydrant at the pivot during the experiments.

Analytical methods

All VOCs except EDB were analyzed according to U.S. Environmental Protection Agency (EPA) method 502.2, (17) using an OI Analytical VOC Analysis System equipped with a water analysis multisampler, a purge and trap sample concentrator, and a Hewlett Packard gas chromatograph with an electrolytic conductivity detector (ELCD). Because EDB's maximum contaminant level (MCL) of 50 ng/L is excessively low, EDB was concentrated by liquid-liquid extraction and analyzed by gas chromatography using an electron capture detector. The methodology followed EPA method 504 (18) except that one rather than 2 mL of hexane was used for the extraction. Every tenth sample collected in the field was a duplicate. The average relative percent difference between the field duplicates was 23.5% ($n=23$) for EDB; 16.5% ($n=22$) for TCE; 20.9% ($n=20$) for CT; and 11.9% ($n=21$) for TCA. Blanks and check samples were run after every tenth sample.

Droplet size analysis

A phase Doppler particle analyzer (PDPA) was used to measure the droplet sizes produced by the nozzles. The PDPA consists of the laser transmitter with frequency shifting, receiver, signal processor, motor controller box, and computer. The transmitter generates two coherent laser beams that are focused to an intersection point where a fringe pattern, referred to as the probe volume, results. As the droplet passes through the probe volume, the fringe pattern that is produced appears to move past the receiver at the Doppler difference frequency. Each of the three detectors in the receiver produce a Doppler burst signal with a phase shift that is linearly proportional to the droplet diameter.

The PDPA was set up in the forward scattering configuration with the receiver 30° from the forward direction of the laser transmitter (Fig. 4). Several size nozzle apertures were used in combination with different impact pad designs. The water line pressure was increased to 207 kPa (30 psi) and the nozzles were positioned 55 cm (22 in) above the probe volume so that the water droplets passing through the probe volume would have a vertical velocity perpendicular to the fringe patterns produced by the two crossed laser beams.

Field tests

On July 6, July 28, and August 12, experiments were conducted to evaluate the efficacy of sprinkler irrigation. Impact pad design and input pressure were two of the variables addressed. In chronological succession a grooved convex pad, a pad support without the pad, and

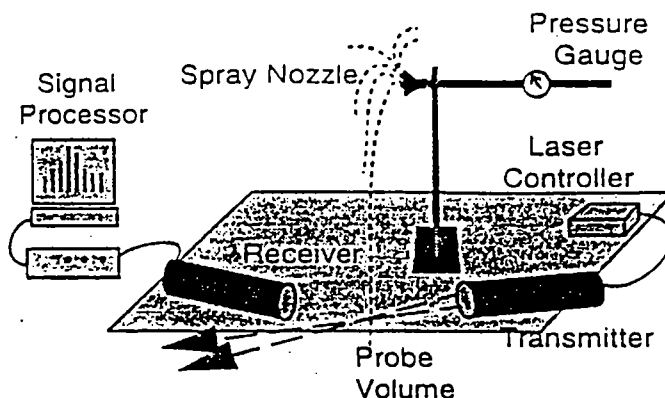


Fig. 4. Experimental setup for determining droplet diameter using the phase Doppler particle analyzer (PDPA).

a convex pad were evaluated. The grooved convex pad limits wind drift by providing channels to coalesce larger size droplets while the convex pad creates a fog composed of very small droplets. The pad support alternative was attempted to see if a flat, molded surface would be sufficient to form a thin film and small droplets conducive to volatilization.

Weather conditions during the experiments were obtained from a NOAA weather station located at the Hastings airport, which is about 3 km (2 mile) northwest of the experimental site. The lack of wind on July 25, 1994, precluded conducting a remediation experiment. Instead, concentrations of the four analytes of interest were monitored at 15 min intervals for 2 h to assess their temporal variability.

RESULTS AND DISCUSSION

Volatilization is strongly dependent upon the vapor pressure and the solubility of the chemical, although factors such as turbulence and molecular diffusion also can influence volatilization. Henry's Law relates the vapor pressure of a low solubility chemical to its aqueous concentration. It is expressed as $P_c = HC_c$ where P_c is the vapor or partial pressure of the chemical, H is Henry's Law constant ($\text{atm}\cdot\text{m}^3/\text{mol}$), and C_c is the molar concentration of the chemical in water. Henry's constant can be approximated by dividing the saturated vapor pressure by the aqueous solubility of the substance. The partitioning of the chemical between the water and air phases can be predicted by $C_a = HC_w$ where C_a is the concentration of the chemical in air (mass/volume), C_w is the concentration of the chemical in the water (mass/volume), and H is the dimensionless Henry's constant. Henry's Law constants are a function of the aqueous solubility, vapor pressure, and molecular weight of the compound. The constant is commonly expressed as a dimensionless term

and in $\text{atm}\cdot\text{m}^3/\text{mole}$. According to Wood et al. (19), the dimensionless form of Henry's Law constant can be calculated from the relationship

$$K_h = \frac{[P_{vap}] [MW] [1000]}{[P] [R] [T] [S]} \quad (1)$$

where

P_{vap} = vapor pressure of chemical (mm Hg*)
 MW = molecular weight of chemical (g/mole)
 P = atmospheric pressure (760-mm Hg*/atm)
 R = gas law constant (0.082 L-atm/mole/°K)
 T = temperature (as °K = 273° + °C)
 S = solubility (mg/L)

The equation can be further simplified to

$$K_h = \frac{16.04 [P_{vap}] [MW]}{[T] [S]} \quad (2)$$

Vapor pressure, a key variable in predicting volatilization, is much more temperature-dependent than is solubility. Average temperatures on the field test days ranged from 23°C to 34°C. The vapor pressures at different temperatures can be calculated using the Clausius-Clapeyron equation

$$\log_{10} \frac{P_{vap_2}}{P_{vap_1}} = \frac{\Delta H_{vap}}{2.303R} \cdot \frac{T_2 - T_1}{T_2 T_1} \quad (3)$$

where

P_{vap_1} = compound's vapor pressure at T_1 (mm Hg*)
 T_1 = temperature of reference vapor pressure (°K) at 25°C
 ΔH_{vap} = molar heat of vaporization (cal/mole) at 25°C

R = gas law constant (1.99 cal/mole/°K)

The values for the known variables in Eqs. 2 and 3 were obtained from the Chemical and Rubber Company Handbook of Chemistry and Physics (20) and Huling and Weaver (21). The calculated vapor pressures and Henry's Law partition coefficients for a range of temperatures encountered in the field are listed in Table 1. The order of volatility of the four analytes is $CT > TCA > TCE > EDB$. While Henry's Law coefficients can be used to describe trends in volatility in an open system, they cannot be used to quantify the amount of partitioning that will occur. In an open system there is almost infinite dilution of the released volatiles; consequently, equilibrium is never attained.

Other factors that potentially can effect the water- to-air transfer are the large changes in both temperature and pressure which occur as the ground water is pumped to the surface and released through the sprinkler irrigation system. Initially, the temperature of the irrigation water is $\approx 10^\circ\text{C}$, and the pressure of the dissolved gases at a depth more than 20 m beneath the water table is above 2 atmospheres. During sprinkler irrigation the dissolved gases rapidly exsolve from the thin film formed at the impact pad and from the small droplets formed at the film's edge. Preliminary measurements indicate a 50% reduction in concentration within 0.3 m of the nozzle. During its trajectory, the water warms very quickly to a temperature of more than 20°C .

Weather conditions at the time of the experiments are detailed in Table 2. The temperature and wind speed changed each day. The largest climatic deviation from

normal occurred on July 28, when the weather was under the influence of a Canadian high-pressure system. The temperature averaged only 23°C during the experiment and there was only a light zephyr of 8 km/h (5 mile/h). The light wind was not enough to transport the fog to the higher samplers on the collectors more than 4 m north of the pivot arm; consequently, it took an inordinately long time (20 min) to fill the upper samplers, and the samples are of drift rather than the fog. The lower two samplers, however, were engulfed in the fog and filled within a few minutes. During the July 6 and August 12 field tests when the weather conditions were closer to normal, the samplers were completely engulfed in the fog produced by the sprinklers, and the sample vials filled in about 2 min.

Samples collected from the hydrant on the center pivot indicated that the input levels of TCE were at least an order and usually two orders of magnitude greater than the maximum concentrations of the other analytes (Table 3). The data from the sampler 0.5 m above the ground (Table 2) indicate that in the five pilot tests the efficacy of TCE remediation was very good regardless of the pad design, weather conditions, or flow rate. On July 6 and August 12 the residual TCE concentrations in the lowest sampler at a majority of the collectors were very close to or below the MCL of $5\text{ }\mu\text{g/L}$ for drinking water. On July 28, the input concentrations of TCE were higher than on the other two days; however, there was still 98.5 % and 98.8% removal at 207 kPa and 310 kPa (30 psi and 45 psi), respectively, although residual concentrations were slightly higher and averaged $8.6\text{ }\mu\text{g/L}$.

While the August 12 tests indicated that the average TCE concentration was essentially at or below the MCL

Table 1. Vapor pressure, temperature, and volatility relationships of analyzed VOCs

	EDB		TCE		CT		TCA	
Temp. (°C)	P_{vap} (mm Hg°)	K_h	P_{vap} (mm Hg°)	K_h	P_{vap} (mm Hg°)	K_h	P_{vap} (mm Hg°)	K_h
10	4.8	0.015	37.6	0.28	55.9	0.61	63.9	0.51
20	8.4	0.025	59.2	0.45	89.5	0.95	102	0.78
25	13.5	0.032	73.5	0.52	112	1.25	127.5	0.96

Table 2. Field conditions and experimental results for TCE

	July 6	July 28		August 12	
Sprinkler Pad	grooved convex	pad support without pad		convex	
Temp. (°C)	31	23		34	
Wind Speed (km/hr)	22.5	8		14	
Pressure (kPa)	207	207	310	207	310
Flow (m ³ /hr)	227	261	318	261	318
Average Input Conc. (µg/L)	445	608	650	452	435
Average Conc. (µg/L) (at 0.5 m sampler)	8.2	9.0	8.2	5.5	1.9
Removed (%)	98.2	98.5	98.8	98.8	99.6

Table 3. Input concentrations of VOCs

Date	Time	TCA (µg/L)	TCE (µg/L)	CT (µg/L)	EDB (µg/L)
7/6/94	1400	5.4	495	3.8	2.5
	1600	4.2	395	3.1	2.9
7/25/94	1310	10.0	718	6.9	2.0
	1325	10.8	553	9.4	3.7
	1340	9.5	524	8.1	3.8
	1355	7.0	448	5.1	2.9
	1410	6.3	475	4.7	2.8
	1420	7.2	526	5.3	2.0
7/28/94	1318	6.5	614	5.8	3.8
	1355	4.5	551	3.8	2.3
	1445	4.6	601	3.8	1.9
	1615	4.9	680	4.0	1.8
	1700	4.5	626	3.8	2.3
	1755	4.6	646	3.8	2.0
	1810	2.8	550	3.7	1.8
	1830	4.7	626	3.7	1.8
	1855	5.1	706	4.1	1.9
8/12/94	1345	5.6	462	9.2	3.0
	1420	5.5	442	9.2	2.2
	1440	4.7	422	4.8	2.4
	1453	5.1	448	6.6	2.3

at both 207 kPa and 310 kPa, there was an obvious increase in efficacy at the higher pressure (Table 2). The increased flow rate that accompanies the increased

pressure also increases mass removal of the contaminant. As predicted by the Henry's Law coefficient, the removal of EDB was less efficient than that of TCE. Average

EDB removal efficiencies were 96.6% on July 6; 95.8% on July 28; and 97.5% on August 12. Whether the differences in remediation efficiency on the three days resulted from changes in the impact pad or the air temperature or both is as yet unknown.

Results from the stratified water droplet collectors reveal a generalized pattern of low residual VOC concentrations in the highest sampler and progressively lower concentrations as the height of the sampler above the ground surface decreases (Figs. 5, 6, and 7). The July 6 profiles for the four analytes show all the concentrations at or well below MCLs. Profiles from the July 28 and August 12 experiments (Figs. 6 and 7) show predictable decreases in concentration with increased fall height. EDB, CT, and TCA were in low ng/L concentrations in all samplers, and TCA and CT levels were generally at their detection limits of ≈ 30 ng/L upon reaching the 1.4-m sampler. During the July 28 and August 12 experiments, TCE concentrations between the 3.2-m and 0.5-m samplers were reduced by factors of ≈ 3 and 10, respectively. Increasing the inlet pressure improved volatilization (Figs. 6 and 7). Since volatilization should continue

as the droplets fall below the lowest sampler to the ground surface (≈ 0.5 m) and volatilization also will occur on plant and soil surfaces, the remediated concentrations should never threaten the quality of the ground water 36.5 m (120 ft) below.

The data indicate that most of the volatilization occurs in the ≈ 2 m space between the nozzle and the highest sampler. Subsequent remediation as the droplets fall between the 3.2-m and 0.5-m samplers is small and amounts to $<5\%$ of the total loss. Thus, the evaluation of nozzle size and impact pad design on volatilization efficiency is an exercise to fine-tune an already efficient volatilization methodology.

The July 28 experimental results indicated that volatilization efficiencies for both TCE and EDB were greater with small diameter nozzles, and consequently small size droplets (Table 4). Residual concentrations increased sharply when the diameter of the nozzles exceeded 4.5 mm, which corresponds to a droplet size of 250 μm . Increasing the inlet pressure did not increase the volatilization of TCE from the larger size nozzles but does appear to have increased the volatilization of EDB.

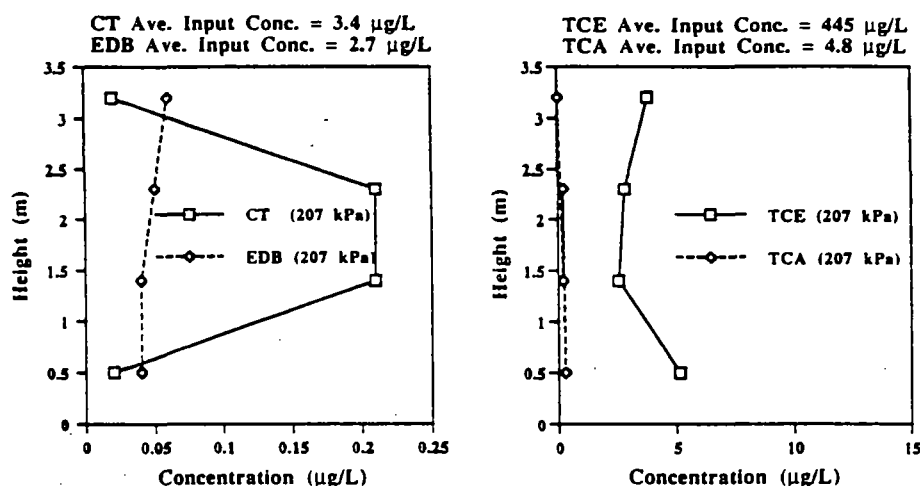


Fig. 5. July 6, 1994, experimental results for the grooved convex impact pad. Data are from collector C, which is 2.1 m north of the pivot arm.

Table 4. Effect of impact pad design on droplet size. Droplet size is arithmetic mean.

Nozzle Aperture (mm)	Pad Support without Pad (μm)	Convex Pad (μm)	Grooved Convex Pad (μm)
2.0	154.8	225.2	248.0
3.2	180.5	262.0	337.0
4.0	224.2	239.7	262.6
4.8	210.7	271.2	287.5
5.6	221.5	235.8	265.2
6.4	268.6	271.8	291.6

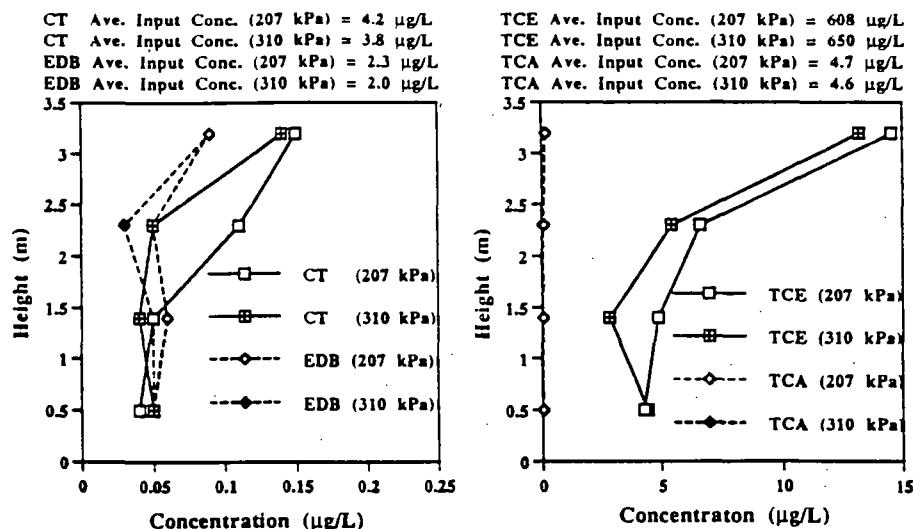


Fig. 6. July 28, 1994, experimental results for the pad support without the pad. Data are from collector C, which is 2.1 m north of the pivot arm.

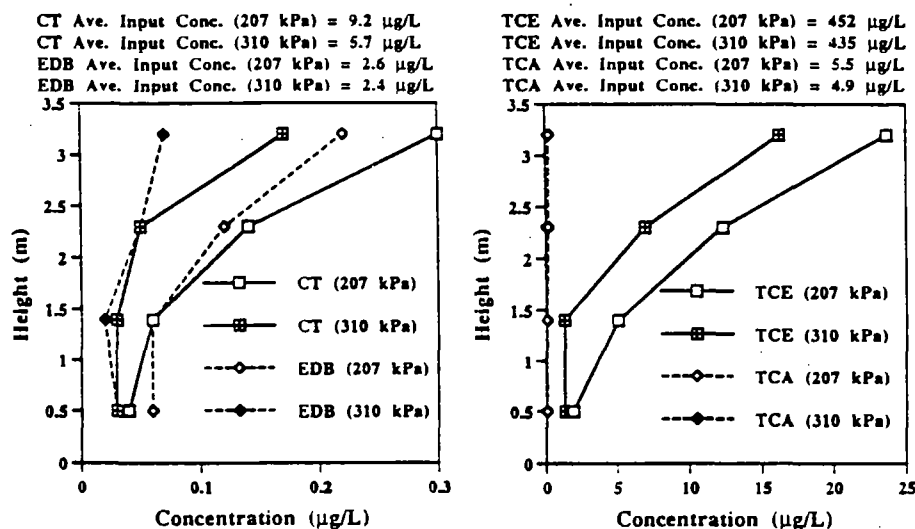


Fig. 7. August 12, 1994, experimental results for the convex impact pad. Data are from collector C, which is 2.1 m north of the pivot arm.

An increase in residual concentrations with the larger size droplets was not evident during the August 12 experiment. Increasing the input pressure, however, further lowered the average TCE concentrations. Thus, the field data are inconclusive as to the association between nozzle aperture and volatilization efficiency.

CONCLUSIONS

High capacity wells and sprinkler irrigation systems can efficiently remediate VOC-contaminated water and comply with the criteria necessary for containment and mass removal of the contaminants. The sprinkler irrigation treatment alternative provides a beneficial use for the treated water and eliminates the costly disposal of both the remediated water and the contaminants. Embracing the sprinkler irrigation alternative would save the taxpayer

and those responsible for the cleanup millions of dollars in remediation costs. Inherent in the alternative treatment is irrigation, a farming practice vital to the successful production of small grains, fruits, and vegetables in much of the high plains and western states.

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REFERENCES

1. USDOC (U.S. Department of Commerce). Census of agriculture. 1988 farm and ranch irrigation survey. Washington, DC: Bureau of the Census; 1990.
2. S. S. Papadopoulos and Associates. Draft focused feasibility study report Far-Mar-Co subsite. Hastings ground-water

- contamination site, Hastings, NE. Bethesda, MD: S. S. Papadopoulos and Associates; 1993.
3. Pankow, J. F.; Johnson, R. L.; Cherry, J. A. Air sparging in gate wells in cutoff walls and trenches for control of plumes of volatile organic compounds (VOCs). *Ground Water* 31:654; 1993.
 4. Woodward-Clyde Consultants. Final remedial investigation report. Hastings East Industrial Park remedial investigation/feasibility study Hastings, Nebraska. Overland Park, KS: Woodward-Clyde Consultants; 1990.
 5. Roux Associates. Risk evaluation of a remedial alternative for the Morrison Enterprise site, Hastings, Nebraska. Tucker, GA: Roux Associates, Inc.; 1992.
 6. Geraghty and Miller. Intermediate design report North Landfill subsite, Hastings, NE. Chicago, IL: Geraghty & Miller, Inc. Environmental Services; 1994.
 7. Litton, G. M.; Guymon, G. L. Literature review concerning the fate of DCE, TCE, and DBCP in agricultural water during irrigation and percolation through soil. Irvine, CA: Department of Civil Engineering, University of California; 1988.
 8. Wilson, J. T.; Enfield, C. G.; Dunlap, W. J.; Cosby, R. L.; Foster, D. A.; Baskin, L. B. Transport and fate of selected organic pollutants in sandy soil. *J. Environ. Qual.* 10:501; 1981.
 9. Castro, C. E.; Belser, N. O. Biodehalogenation. Reductive dehalogenation of the biocides ethylene dibromide, 1,2-dibromo-3-chloropropane, and 2,3-dibromobutane in soil. *Environ. Sci. Technol.* 2:779; 1993.
 10. Litton, G. M.; Guymon, G. L. Laboratory experiments evaluating the transport and fate of DBCP in Hanford sandy loam. *J. Environ. Qual.* 22:311; 1993.
 11. Orange County Water District. Results of an investigation of TCE removal during sprinkler and drip irrigation in the Irvine area. Irvine, CA: Orange County Water District; 1989.
 12. Med-Tox Associates. Public health risk assessment for the OCWD/IRWD proposed trichloroethylene containment program Irvine, California. Tustin, CA: Med-Tox Associates, Inc.; 1989.
 13. Firestone Tire & Rubber Company. Salinas facts. Salinas, CA: Firestone Tire & Rubber Company; 1989.
 14. Wood, P. R.; Lang, R. F.; Payan, I. L. Anaerobic transformation, transport, and removal of volatile chlorinated organics in groundwater. Ward, C. H.; Giger, W.; McCarty, P. L., eds. *Groundwater Quality*. New York, NY: John Wiley & Sons; 1985.
 15. Geraghty and Miller. Preliminary design report, North Landfill subsite, Hastings, Nebraska. Chicago, IL: Geraghty & Miller, Inc. Environmental Services; 1994.
 16. NOAA (U.S. National Oceanic and Atmospheric Administration). Annual summary with comparative data. Grand Island, Nebraska. Washington, DC: NOAA 1986.
 17. USEPA (U. S. Environmental Protection Agency). Method 502.2. Methods for the Determination of Organic Compounds in drinking water. Cincinnati, OH: USEPA, EPA-600/4-88/039; 1988.
 18. USEPA (U. S. Environmental Protection Agency). Method 504. Methods for the Determination of Organic Compounds in drinking water. Cincinnati, OH: USEPA, EPA-600/4-88/039; 1988.
 19. Wood, P. R.; DeMarco, J.; Curtis, F. W.; Harween, H. J.; Lang, R. F.; Payan, I. L. Removal of organics from water by aeration. Cincinnati, OH: USEPA; 1980.
 20. CRC (Chemical and Rubber Company). Handbook of chemistry and physics. Boca Raton, FL: CRC Press, Inc.; 1992.
 21. Huling, S. G.; Weaver, J. W. Dense nonaqueous phase liquids. *Ground Water Issue*. Ada, OK: USEPA, EPA-540/4-91-002; 1991.