

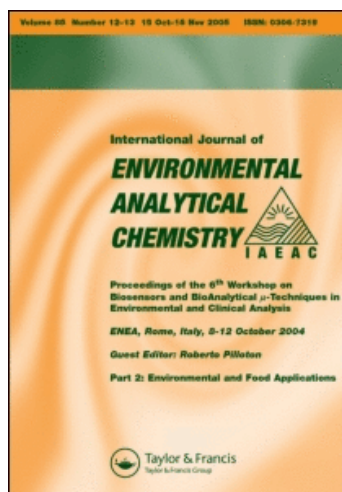
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Hydrocarbons and Aromatic Hydrocarbons in Groundwater Surrounding an Earthen Waste Disposal Pit for Produced Water in the Duncan Oil Field of New Mexico

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Hydrocarbons and Aromatic Hydrocarbons in Groundwater Surrounding an Earthen Waste Disposal Pit for Produced Water in the Duncan Oil Field of New Mexico

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Samples of groundwater and soil were collected from test pits placed 25 m intervals on five axes extending from an earthen waste disposal pit for produced water near the San Juan River of northwest New Mexico. Samples were obtained at depths of 1.2 to 1.5 m and were analyzed using GC and GC/MS techniques for purgable hydrocarbons, including benzenes, and for solvent extractable organic compounds. Water

samples from test pits down-gradient from the disposal pit contained purgable and extractable hydrocarbons that were similar to contents of the waste disposal pit. In contrast, water samples obtained from test pits up-gradient from the waste pit were free of detectable organic components. Major purgable components in the waste pit and in surrounding groundwater included saturated/unsaturated hydrocarbons and aromatic/alkylated aromatic hydrocarbons. Samples collected 25 m from the waste pit contained concentrations of all compounds greater than in samples taken at 50 m in distance on the same axis. Total concentration of purgable aromatic hydrocarbons in groundwater from test plots ranged from a high of 200 ppb at 25 m, to a low of 12 ppb at 50 m on an axis through the plume center.

INTRODUCTION

Production of natural gas and oil can be accompanied by generation of large amounts of waste liquids such as produced (or brine) water. While environmental complications from high salt and toxic metal content of produced water have been known for over two decades,^{1,2} the presence of hazardous organic compounds in these wastes has only recently been studied.³⁻⁵ Produced water can be generated both in oil and in natural gas production and is often removed at the well-head with disposal on-site in waste pits. The contents of waste pits for natural gas were characterized as complex mixtures of hydrocarbons.³ Concentrations of hydrocarbons in produced water ranged from 100 to 1,000 ppm and polycyclic aromatic hydrocarbons (PAH) were at 10 to 100 mg/kg in the non-aqueous liquid phase, which coexisted with brine water in most pits. Additionally, complex mixtures of benzenes, alkylated benzenes, PAH, and alkylated PAH were found at relatively high concentrations in each phase. These results were consistent with other reports on brine water composition^{4,5} in other basins and were supported by presence of the same compounds in natural gas from consumer distribution pipelines⁶ and discharge water from hydrostatic tests of gas pipelines.^{7,8}

Wastes from oil and natural gas wells are disposed through reinjection techniques or by storage inside waste pits, also called evaporation pits. Historically, earthen waste pits were built without clay or synthetic linings which retard migration of wastes into soil or groundwater. Unfortunately, liquid waste infiltration into ground surrounding an earthen waste pit can be as much as 93%.⁹ In other studies, extensive migration of hydrocarbon wastes from produced

water pits was projected to be insignificant,¹⁰ substantial,¹¹ and not measured.¹² Adequate treatment of brine water is complicated by small volumes generated at individual well-heads, the large number of fixed site in-field separator units, and the remote geographical location of wells.

Once organic compounds are released into a waste pit, at least four mechanisms of attenuation may occur simultaneously and include adsorption on soil,¹² biodegradation,¹³ volatilization,¹⁴ and photochemical destruction.¹⁵ Recently, hydrocarbons and PAH were found in soil below waste pits at depths of 1.8m in the San Juan Basin.¹⁶ Since pits were about 1 to 1.5 meters deep, the total depth was up to 3.3 meters from ground level. Groundwater in flood plains of New Mexico valleys may be found at 2 meters in depth and contamination of groundwater by hydrocarbons from unlined earthen waste pits was thus predicted as likely, despite mechanisms for attenuation. The objectives for this study were, (1) measurement of hydrocarbons in groundwater surrounding a waste pit site in a river flood plain, (2) determination of the extent of contamination as a function of distance from the pit, (3) comparison of waste pit contents versus groundwater composition for evaluation of magnitude of attenuation in movement, and (4) preliminary characterization of the relationship between contamination plume dimensions and estimated hydraulic gradients.

EXPERIMENTAL

Description of study area and collection of samples

The study areas as shown in Figure 1 (insert) was located in San Juan County of northwest New Mexico and was approximately 3.5km east-southeast of Shiprock, NM. The study area was located in a region referred to as the Hogback Oil Field and was located in a flood plain of the San Juan River. An oil well was identified for study based on proximity to the river and from other nearby wells. This well was defined by the following, which was displayed on a sign attached to the fence used to isolate the well and waste pit: owner, Raymond T. Duncan; lease no., 14-20-0603-10008; well I.D. no., Hogback 6 no. 11; and location, 50' FSL, 50' FWL, T29N, R16W, Sec. 6, San Juan County, NM. The oil well was equipped

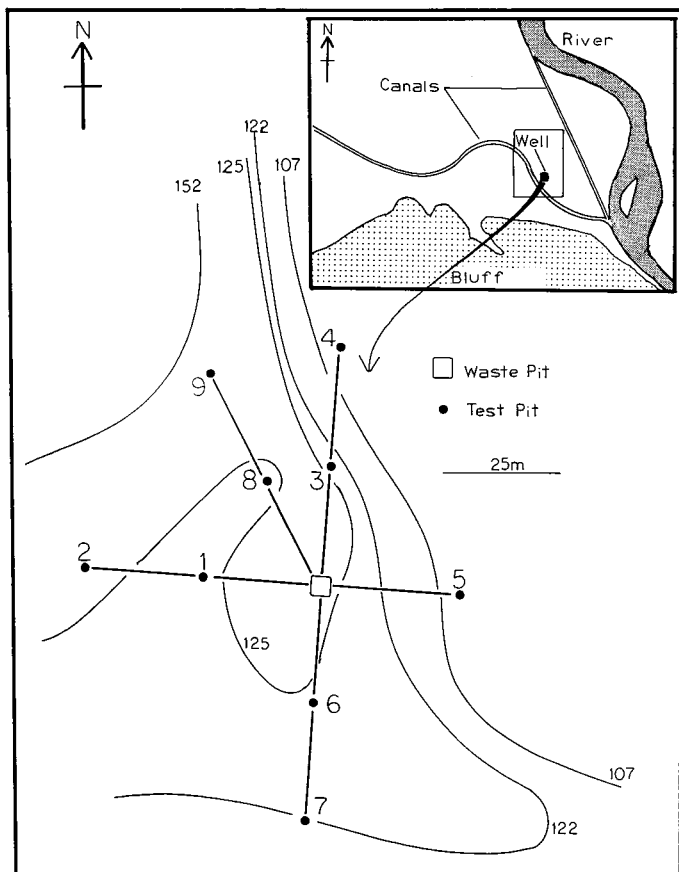


FIGURE 1 Map of study area with test pits and location (insert). The estimated hydraulic gradient is shown as contours in the groundwater level. A second pit was not placed on the axis for test pit 5, due to poor accessibility from groundcover. Depths to groundwater are shown in cm. Canals were dry.

with a standard pumpjack that was operating continuously during this study. An oil–water separator discharged wastes to an earthen waste pit. The discharge rate was approximately 16l/hr. The waste pit as shown in Figure 1 was 5.5 m long, 3.7 m wide and 1.4 m deep, and approximately 36 cm of wastes were contained in the pit.

Based on earlier survey of the study area, using a few test pits, axes were drawn over the waste pit along the lines which extended from the waste pit to bracket a plume and one axis believed to be near the center of the plume. Nine test pits were dug and labelled according to Figure 1. Test pits were dug to nearly 2 m depth using a backhoe. At each test pit, infilling of water occurred below a depth of 1.2 to 1.5 m and at test pits 1–4, 8 and 9, a dark zone of soil was evident at near 1.5 m. Moreover, the water which moved into the test pits had a hydrocarbon odor and an oil film on the surface. In contrast, in pits up-gradient from the waste pit, no dark zone was observed and no hydrocarbon odor or sheen in the water was detected during the digging process. Samples collected at each test pit were, (a) 30 ml of water for purge and trap analysis (collected in duplicate), and (b) one mason jar of the dark soil. Samples were immediately stored on ice and were returned to Las Cruces by private car. All samples were extracted and analyzed within 48 hours after collection. Samples were obtained on March 18, 1985 between 10 a.m. and 2 p.m.

Procedures for treatment of samples

Samples were prepared for analysis using three different procedures, (1) purge and trap analysis with water samples, (2) purge and trap for soil samples, and (3) extractable analysis for water samples. Samples were analyzed using gas chromatography (GC), and gas chromatography/mass spectrometry (GC/MS) both scanning and selected ion monitoring (SIM) modes of operation. In purge and trap analysis, 10 ml of water were purged for 10 min at purge gas (N_2) flow rate of 40 ml/min. A Tenax trap was used to concentrate the purgable fraction and was analyzed through thermal desorption into a GC or GC/MS. In purge and trap analysis of soil samples, 100 g of soil were placed into a 500 ml flask modified with a tube insert of fritted glass. The soil was kept at ambient temperature (25°C) during purging with a Tenax trap to concentrate purgable components. In extractable procedures, 50 ml of aqueous sample were extracted in triplicate using fresh 20 ml portions of hexane (distilled in glass grade, Burdick and Jackson, Muskegon, MI). Replicate extractions were composited and condensed to 1 ml with a rotary evaporator and stored in a 2 ml Wheaton minivial (Southland Cryogenic,

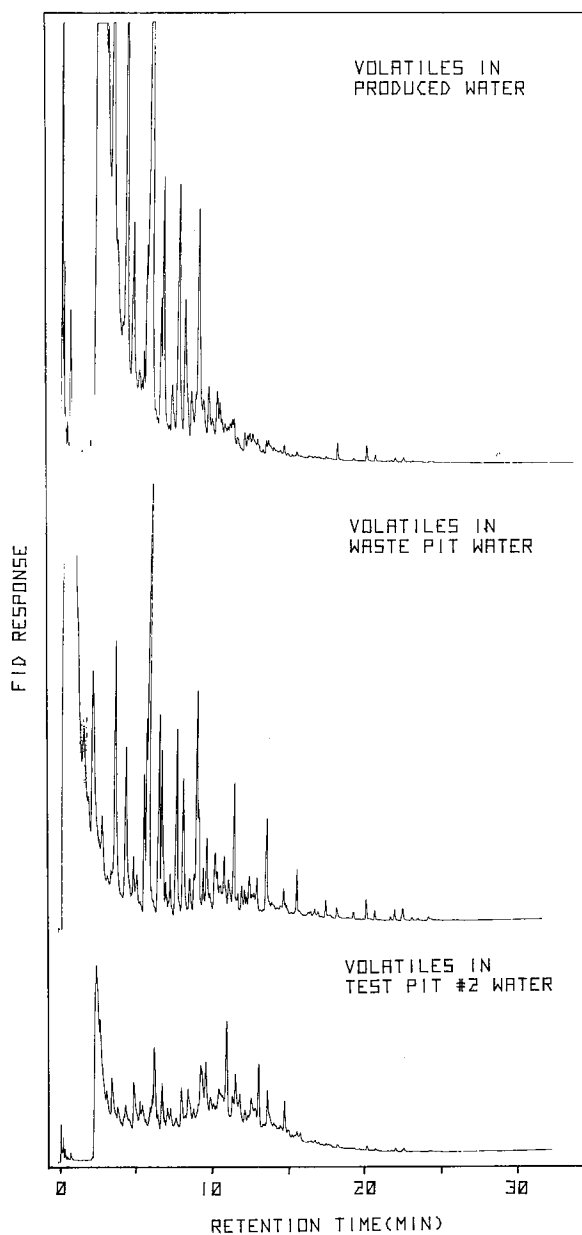


FIGURE 2 Chromatograms from GC-FID analysis of volatile components in wastewater and groundwater samples. Attenuation was same in each plot at 16×10^{-12} amps full scale.

Carrollton, TX). Volume was further reduced to 500 μ l using a stream of nitrogen gas. In thermal desorption of Tenax traps, the liner from the GC inlet was removed and replaced with the Tenax trap, which was sized originally to fit in the inlet. In analysis of solvent extracts, a 10 μ l syringe (Hamilton Co.) was used to deliver 3 to 5 μ l to the GC. In both procedures, blanks were used to measure contamination. Contamination was never detected from any procedures or materials.

Instrumentation

A Hewlett-Packard model 5880 gas chromatograph was equipped with automated splitless injector, flame ionization detector (FID), DB-5 10m capillary column, and Level 3 processor. Conditions for analysis of purge and trap samples were initial temperature, -10°C ; initial time, 1.5 min; temperature program rate, $6^{\circ}\text{C}/\text{min}$; final temperature, 160°C ; final time, 10 min; injector temperature, 120°C ; FID temperature, 270°C ; splitless time, 1.5 min; and chart speed 0.5 cm/min. Conditions for analysis of extracts were the same as before with these exceptions: initial temperature, 10°C ; final temperature, 250°C ; and injector temperature, 250°C .

A Hewlett-Packard model 5995 GC/MS was equipped with an automated splitless injector, jet separator, single disc drive, DB-5 10m capillary column, and model 7225B X-Y plotter. Chromatographic conditions in both scanning and SIM analyses were identical to those listed above for analysis of purge/trap and liquid-extraction samples. Mass spectrometer conditions for SIM analysis were window size, 0.1 amu; dwell time per ion, 100 msec; and electron multiplier voltage, 1,800 V. Ions monitored included (in amu) 57, hydrocarbons; 78, benzene; 91, toluene; 105, xylenes; 119, C_3 alkylated benzenes; and 134, C_4 alkylated benzenes. Mass spectrometer conditions in scanning analysis were scan range, 45 to 650 amu; scan speed, 690 amu/s; MS peak detection threshold, 10 linear counts; and delay between scans, 0.1 s.

RESULTS AND DISCUSSION

General observations at study site

The waste pit and area chosen for study were located in a flood

plain of the San Juan River in northwest New Mexico between Shiprock and Farmington, NM. The site was similar to at least 1,500 other nearby wells on flood plains in that the soil was largely a light-brown sand with a wide assortment of rocks and stones which seemed to comprise a substantial fraction by volume of the soil. The land surface in the flood plain was nearly flat over the region studied with less than 0.3 m difference in elevation, as estimated from visual inspection, and the vegetation was sparse. The waste pit contained nearly 36 cm of produced water with a thin film of hydrocarbon phase on the surface. Darkly stained soil along the sides of the pit suggested greater holding volume of the pit in recent past. The pit was nearly 1.5 m deep and groundwater was found at 1.8 m in test pits dug near the waste pit. As each test pit was dug, water filled in the pit to a certain level from one side of the pit, which corresponded to a high pressure condition. After about 15 minutes after a pit was dug, the inflow stopped and water samples were collected. Later, water levels were measured in each pit, a hydraulic gradient was estimated and the direction of groundwater plume was predicted. Test pits were dug at sites as shown in Figure 1. During the digging of test pits 1–4, 8 and 9 (in-plume), zones of black earth were found at about 1.7 m depth, and as the water filled in the test pit, a distinct hydrocarbon odor was discernable in the air and an oil-sheen film was observed on the groundwater. In pits 5–7 (up-gradient), odor or sheen were not observed and the soil was a light brown hue throughout at all depths. Even prior to chemical analyses, the groundwater down-gradient from the test pit was clearly different in composition than groundwater up-gradient based on smell and light reflection. This difference strongly supported groundwater contamination by hydrocarbons from the waste pit along the estimated hydraulic gradient.

Volatile hydrocarbons in waste and test pits

Volatile hydrocarbons were found in the produced water (sampled directly at the discharge pipe), the waste pit water, and in water at test pits 1–4, 8 and 9. No purgable compounds were detected in water or soil from test pits 5–7. In Figure 2, chromatograms are shown for purgable hydrocarbons in produced water, waste pit water and test pit 2 water. The chromatographic pattern for produced

water contained over 30 resolved components with carbon numbers from 4 to 12. Composition of the waste pit water, where produced water was impounded and where a certain amount of weathering should occur, is shown in the second frame of Figure 2. The concentration pattern was skewed toward larger molecular weight components seen at greater GC retention times. Such components should be expected to have lower vapor pressures and undergo less volatilization, than smaller compounds which should have greater loss due to evaporation. This process is apparent here except for the unexplained presence of a major component in waste pit water with retention time of 1 minute.

Although earthen waste pits have been called evaporation pits in the past, water in this waste pit clearly contained a large number of purgable hydrocarbons at concentrations over 10 ppm. The hydrocarbon odor discerned at test pits 1-4, 7 and 8, was confirmed in these analysis as shown in the bottom frame of Figure 2. Although this test pit was at a distance 50 m down-gradient from the waste pit, some purgable hydrocarbons were still detected in the groundwater. The pattern of regular spacing of peaks between 10 and 15 minutes retention time was characteristic of alkanes. Although concentrations were reduced in part to mechanical mixing of waste pit water and groundwater, relative peak heights were comparable between GC patterns for waste pit and for test pit waters. While some compounds may have been lost through evaporation processes, other hydrocarbons presumably migrated successfully over 50 m in the groundwater.

Although the presence of aromatic hydrocarbons in waste pit water should be unsurprising (3-5, 16), the complexity and concentrations found in waste pit water, despite possible evaporation, were remarkable. In Figure 3, SIM plots for total purgable aromatic hydrocarbons (benzene and alkylated benzenes) are shown for produced water and waste pit water. While both samples were complex, with over 70 resolved peaks in the summed SIM plot, the waste pit water was more concentrated with these compounds than the produced water, as seen in greater peak heights for nearly all components. Nevertheless, chromatographic patterns were nearly identical and supported a conclusion that photodecomposition or biodegradation of these compounds during storage in the waste pit did not drastically alter composition of produced water in the earthen waste pit.

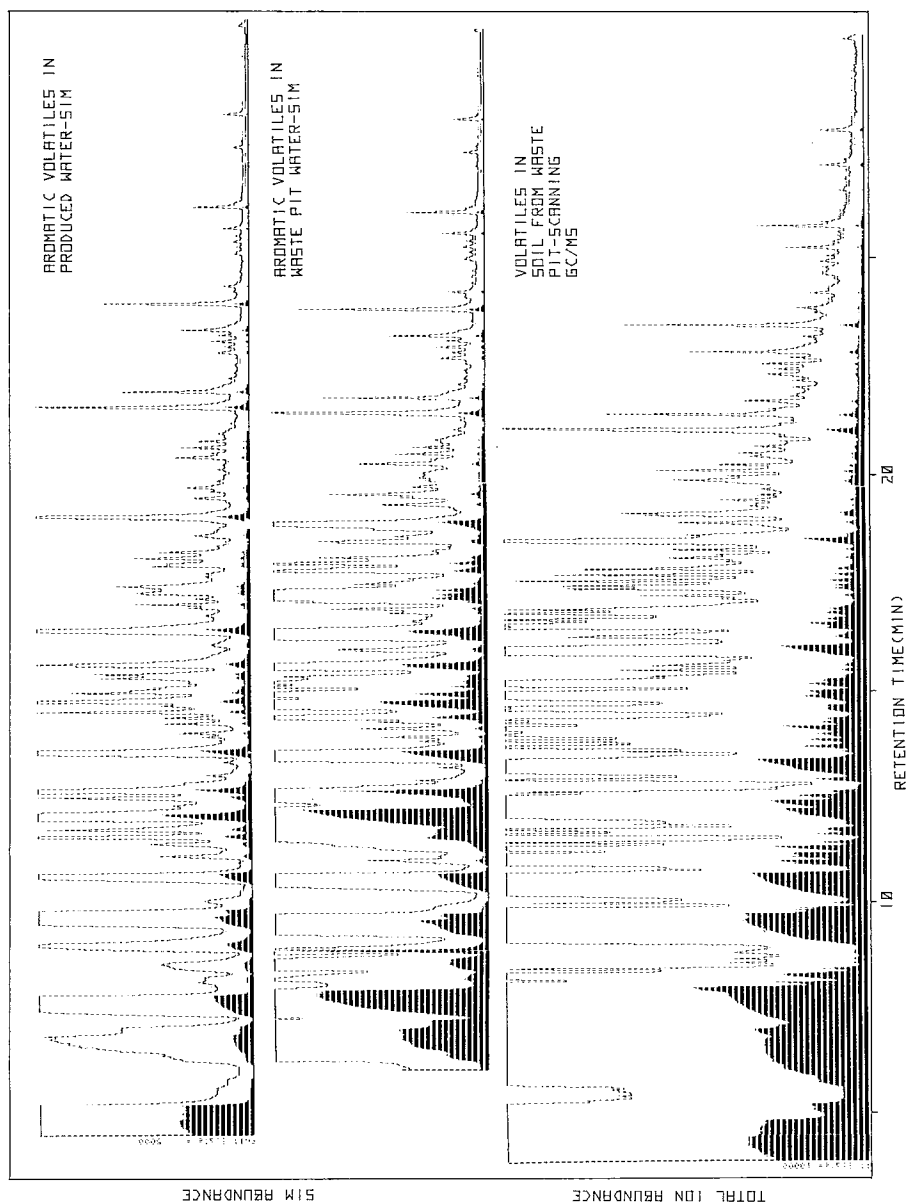


FIGURE 3 SIM plots (top two frames) and total ion chromatogram (TIC) from GC/MS analysis of volatile components in produced water, waste pit water and waste pit soil. The major components in the soil sample were aromatic hydrocarbons and alkanes, as shown in Table I. Full scale was 5,000 counts for the SIM plots and 10,000 counts for the TIC.

As expected, compounds from the produced water were also found in soil collected in the waste pit. A total ion chromatogram (TIC) for purgable compounds in this soil is shown in Figure 3. From scanning GC/MS analysis, over 50 components were resolved and identification of peaks is given in Table I. The majority of compounds in soil (and in produced water) were alkanes of carbon numbers 5 to 15, aromatic hydrocarbons, and branched/unsaturated alkenes. In Figure 4, purgable aromatic compounds in test pit 1 soil and scanning GC/MS results for test pit 1 water are shown. The compounds found in the water from test pit 1 were the same as

TABLE I
Major volatile compounds in waste pit soil and in groundwater from test pit 1

| Compound | RT ^a | Abundance waste pit soil ^b | Groundwater ^c |
|----------------------|-----------------|--|--------------------------|
| Hexane | 3.8–4.1 | 23242 | n.d. ^d |
| Hexanes ^e | 4.5–5.0 | 7872 | 1121 |
| Heptane | 5.6–7.6 | 86121 | 1985 |
| Heptanes | 7.8–7.9 | 41255 | 1942 |
| Octane | 8.1 | 16106 | n.d. |
| Toluene | 8.4 | 1860 | n.d. |
| Octanes | 8.6–10.9 | 259805 | 31740 |
| Nonane | 11.0–11.1 | 11408 | 1103 |
| Nonene | 11.3 | 8498 | n.d. |
| Xylenes | 11.5 | 12151 | n.d. |
| Nonanes | 11.6–13.2 | 105355 | 45556 |
| Decanes | 13.4–15.9 | 124909 | 95717 |
| Undecanes | 16.1–18.0 | 62915 | 169525 |
| Dodecanes | 18.8–21.5 | 24958 | 76834 |
| Tridecanes | 22.1–25.0 | 13762 | 9494 |
| Tetradecanes | 25.5 | 2481 | 2628 |

^aRT=retention time in minutes with reference to Figure 3 and 4 bottom frames.

^bAbundance values were from mass spectra collected at maxima of peaks using scanning GC/MS. Since waste pit soil values have units with grams while groundwater values have units of ml, no direct comparison was intended. Rather, values were for comparison of relative abundances of components in each sample.

^cGroundwater taken from Test Pit No. 1 as defined in Figure 1.

^dnd=Not detected. This could be due to either low concentration or failure in the computer algorithm to recognize a peak. Thus, this listing was for only the major components.

^eThe plural term is used to designate the presence of other isomers of hexane such as the branched isomers. This type of term is used similarly with other hydrocarbons in the table.

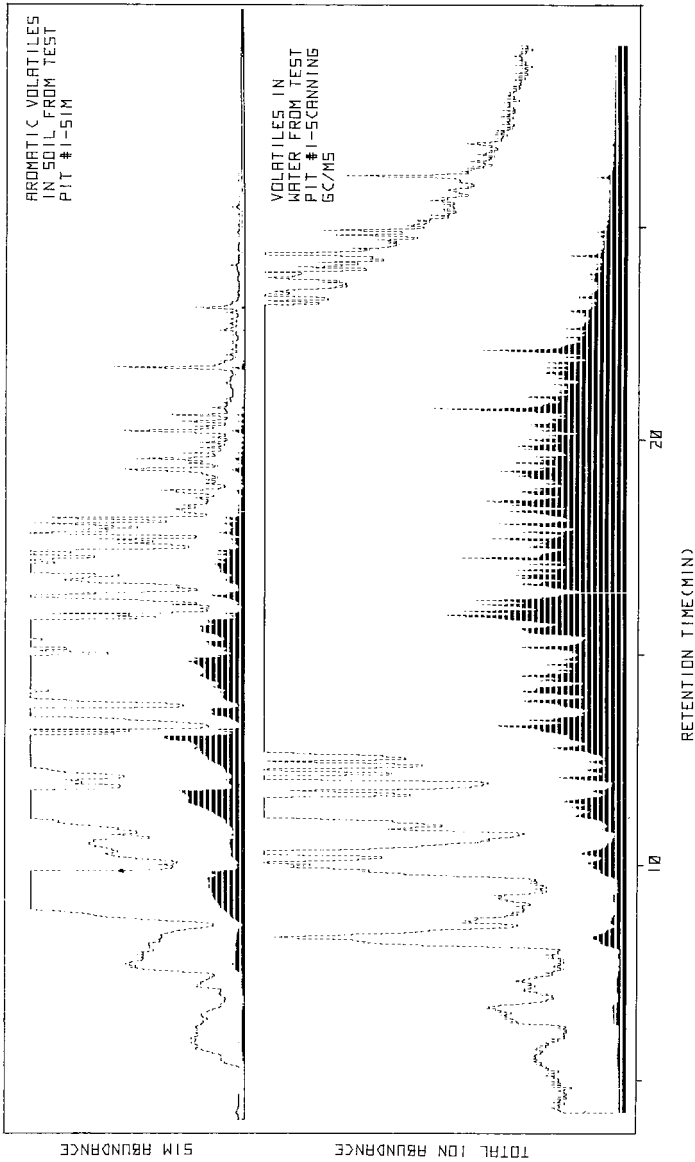


FIGURE 4 SIM plot (top) and TIC from GC/MS analysis of water and soil from test pit 1. Identifications of major components are given in Table I. Full scale was 5,000 counts for SIM plot and 10,000 counts for the TIC.

those found the waste pit soil, as given in Table I. An equilibrium between water and soil (or water entrained in soil) was suggested from these results, although these results provide no measure of soil capacity. Comparison of abundances of peaks in the pit 1 water and in the soil from the waste pit illustrate the preferential movement and fate of certain compounds. Mostly, similarity of summed SIM plots for aromatic compounds in test pit 1 soil, in waste pit water and in test pit 1 suggested an equilibrium or at least chemical exchange between soil and water. The ratio of abundance of compounds in a water/soil ratio were roughly 10 to 100 g/ml. Although a major loss of early eluting (very volatile) components occurred, compounds with retention times between 8 to 18 minutes were not attenuated and successful transport of these compounds from the waste pit into the groundwater as a plume was clear. This is further illustrated in Figure 5 where SIM plots were resolved into individual ion plots and in Table II where quantitative results for aromatic hydrocarbons are shown. Comparison of waste pit water with water from test pits 1, 2 and 5, illustrates the presence of hydrocarbons and aromatic hydrocarbons in the down-gradient pits (1 and 2) and in the waste pit, but not in the up-gradient test pit (5). Full scale values are a measure of concentration and overall volatile aromatic hydrocarbons generally showed a decrease in concentration with increased distance from the waste pit. Certain hydrocarbons decreased dramatically while others decreased very little with distance. For example, benzene and toluene decreased from 21 and 670 ppb in the waste pit to 0.1 and 0.33 ppb in the test pit 1 water, but the differences in concentration between pits 1 and 2 were less striking. The loss of these compounds, particularly the low molecular weight alkanes, supports an evaporation mechanism. Although a decrease occurred with increased distance from a waste pit for all purgable compounds, particularly the very volatile (less than carbon number 6 to 8), these results show that groundwater contamination by hydrocarbons and aromatic hydrocarbon from an earthen waste pit can lead to a decline in groundwater quality. Moreover, the benzene, toluene, and alkylated-benzenes content showed a distinct pattern (and helps to define the groundwater plume), which agreed with the expected direction of a plume from simple hydraulic arguments.

In addition to purgable components, water samples were also

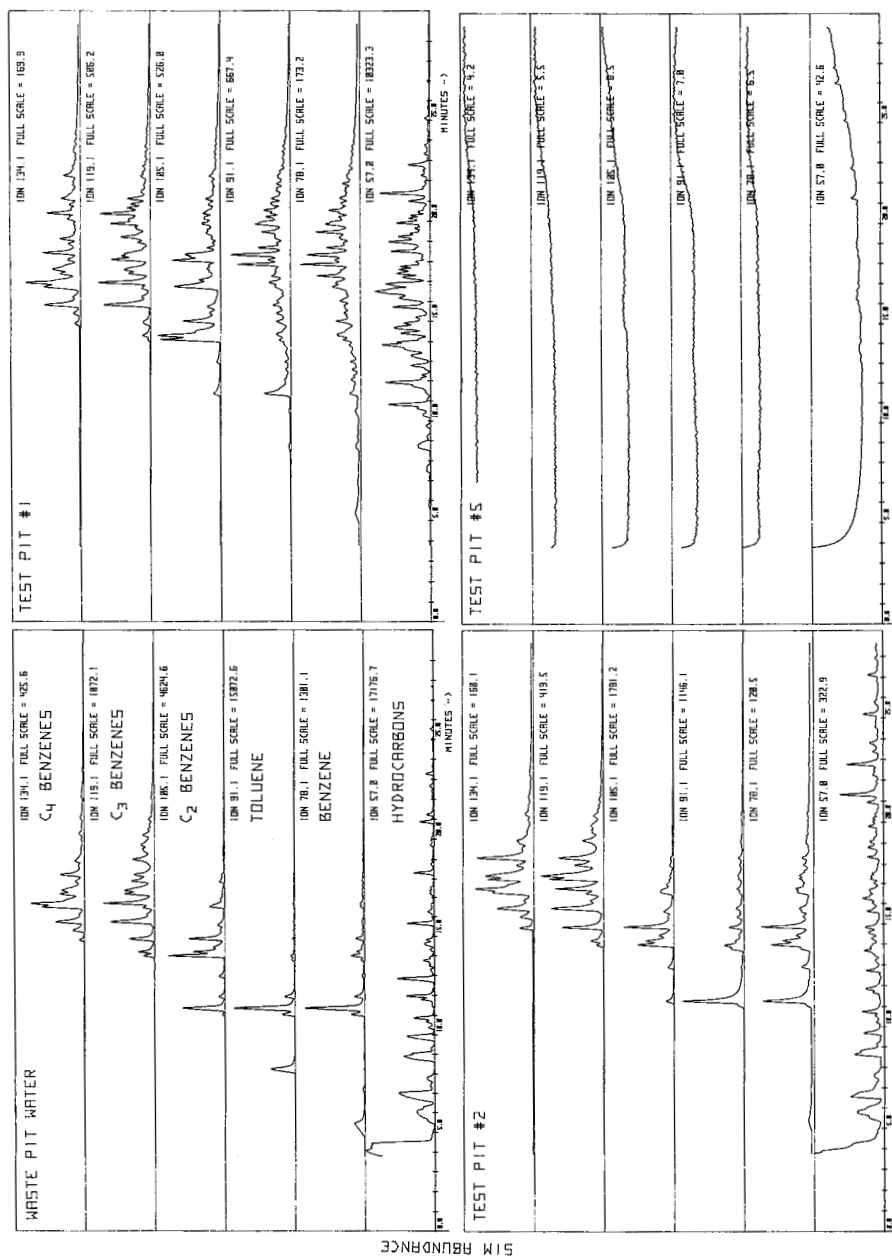


FIGURE 5 SIM plots for ions of individual aromatic compounds and alkanes in waste pit and test pit water. Locations of test pits are shown in Figure 1. Full scale values shown in each plot is related to concentration.

TABLE II

Estimated concentrations of aromatic hydrocarbons in water from waste pits and test pits

| Test pit no. | Estimated concentration (ppb) ^a | | | | |
|--------------------|--|---------|-----------------------------------|-------------------------------------|--------------------------------------|
| | Benzene | Toluene | Ethyl and dimethyl benzenes | C ₃ alkylate benzenes | C ₄ alkylated benzenes |
| 1 | 0.1 | 0.3 | 4 | 140 | 60 |
| 2 | 0.1 | 0.1 | 23 | 200 | 70 |
| 3 | n.d. ^b | n.d. | 11 | 130 | 37 |
| 4 | n.d. | n.d. | 0.3 | 0.7 | n.d. |
| 5 | n.d. | n.d. | n.d. | n.d. | n.d. |
| 6 | n.d. | n.d. | n.d. | n.d. | n.d. |
| 7 | n.d. | n.d. | n.d. | n.d. | n.d. |
| 8 | 0.4 | 0.3 | 45 | 120 | 35 |
| 9 | n.d. | n.d. | 0.7 | 8 | 3 |
| Waste pit water | 21 | 670 | 410 | 50 | 27 |
| Produced water | 160 | 3800 | 1120 | 250 | 140 |

^aEstimated concentration was used since no correction was made in the standards for a matrix effect which could be large when some samples contained a hydrocarbon film on the sample top. Moreover, calibration of the mass spectrometer was obtained using only a benzene external standard. Response factors for other alkylated aromatics was assumed as 1.

^bn.d. = Not detected above background noise.

analyzed for extractable hydrocarbons, since this fraction has been extensively characterized for produced water waste pits from gas production,³ and since volatilization should not be as pronounced with extractables as with volatiles. Results are shown in Figure 6 for GC analysis of waste pit water and of test pit water. Waste pit water was an extremely complex mixture of over 80 components at concentration of near 5 ppm. The composition of water for extractables in test pit 1 was similar to that for those in the waste pit water and was also comparable for waters in test pits 3 and 8, which were also close to the waste pit. However, at a distance of 50 m for location of pits 2, 4 and 9, concentrations of extractables was decreased dramatically, as shown in the bottom frame of Figure 6 and in Figure 7 where this pattern was consistent on each axis in the plume.

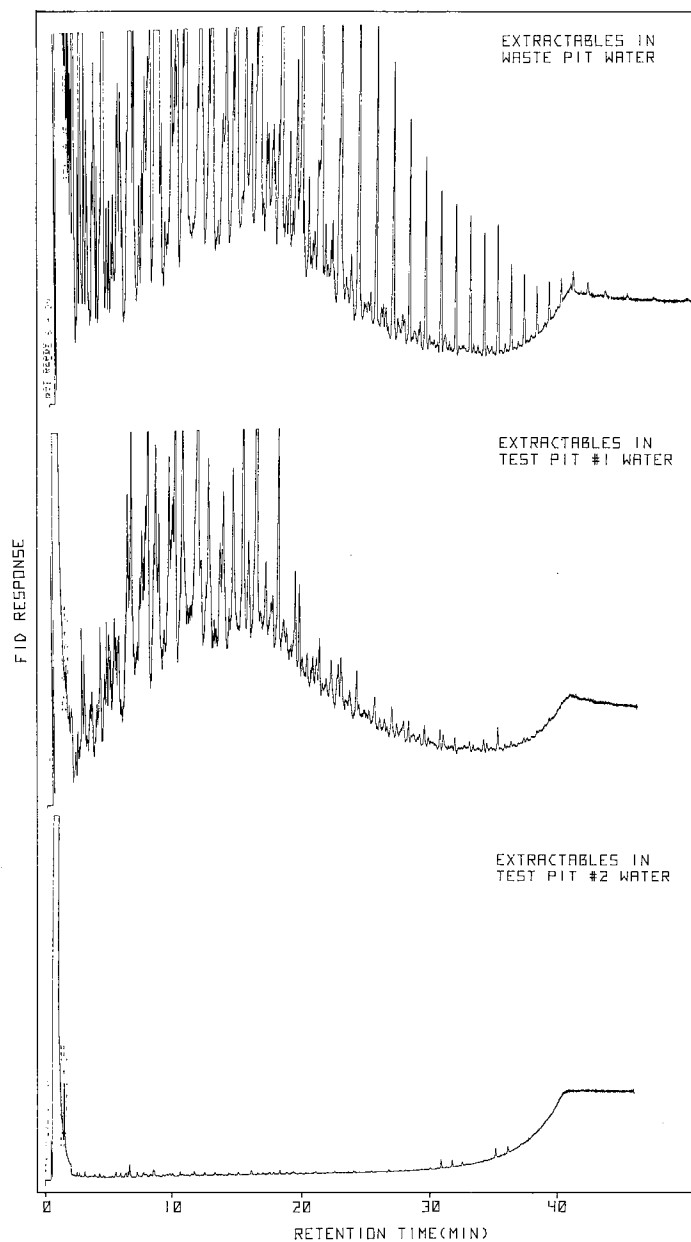


FIGURE 6 Chromatograms for GC-FID analysis of extractable hydrocarbons in samples of waste pit and test pit waters. Attenuation was 16×10^{-12} amps full scale.

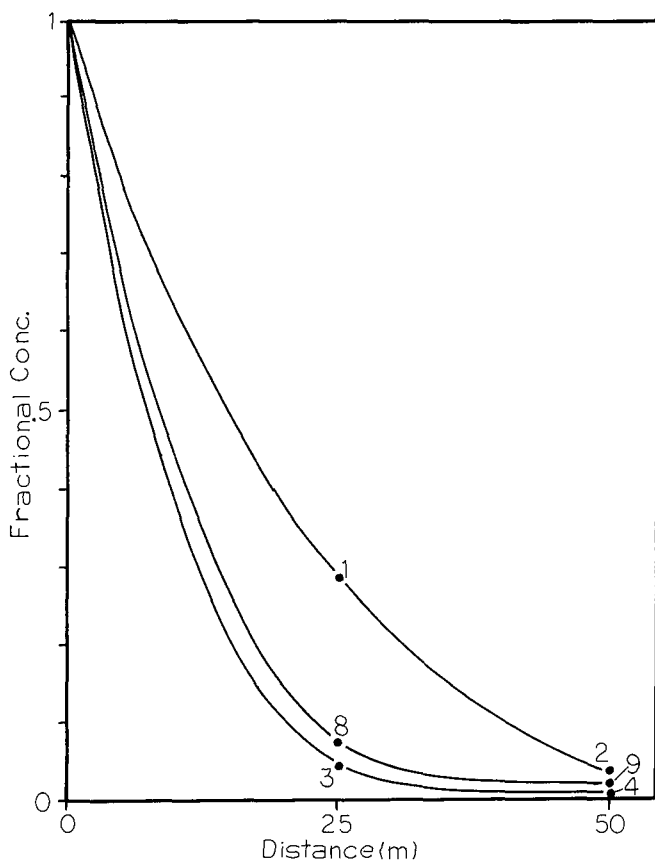


FIGURE 7 Plot of fractional concentration (versus waste pit water) for extractable hydrocarbons in test pit water. Test pits are numbered according to Figure 1.

Environmental assessment and summary

Assessments of these results may be divided into two separate but related categories. (1) The fate or reactivity of compounds in mixed soil/water/air systems, and (2) the bulk transport processes. Volatile compounds, such as benzene and toluene compounds, decreased about 99% in the first 25m and were at barely detectable levels by 50m on most of the axes in the plume. This loss can be attributed to mechanical dilution and to volatilization. In contrast, the middle

range compounds, such as C₂- and C₄-alkylated benzenes, were found in test pit water at 50 m. This behavior may have been due to vapor pressures lower than those for benzene and toluene and limited adsorption on soil. The extractable hydrocarbons, which should not be susceptible to volatilization, were found at 25 m at only 1 to 10% of the original concentration in the waste pit and concentrations at 50 m were lower still. This decrease, in contrast to the volatile compounds, was likely due to adsorption. However, biodegradation and limited volatilization cannot be dismissed. Since the groundwater and soil were in close contact and adsorption was a likely mechanism of attenuation for middle weight range and extractable compounds, then the concentration of these compounds should increase in test pits with increased loading of liquids into the waste pits. The next stage in this research should be a monitoring program to evaluate changes in test pit water over time.

Modeling bulk flow of wastes through soils is more quantitative than modeling chemical and biochemical fate of complex organic mixtures and some preliminary calculations may be used to assess the above findings. The rate at which produced water should infiltrate a porous material can be described using the Green and Ampt Equation:¹⁷

$$V_i = \left[\frac{H_w + L_f - h_{cr}}{L_f} \right] K. \quad (1)$$

Where V_i =infiltration rate; K =hydraulic conductivity of the wetted zone; H_w =depth of water above soil; L_f =depth of wetting front; and h_{cr} =critical pressure head of soil for wetting ($= > -20$ cm for coarse sands; $= > -20$ to -60 cm for medium to fine sands; and $= -50$ to < -200 cm for loams and clays). This equation can be used to estimate infiltration rates for certain physical circumstances. Using reasonable parameter values for study area of $K=30$ cm/day; $H_w=0$, $L_f=3$ m, and $h_{cr}=-20$ cm, V_i should be 32 cm/day. The rate at which a liquid infiltrates soil is highest when the soil is dry, and infiltration rates decrease with increased moisture. The infiltration rate approaches a steady-state value as the solid becomes saturated, and will be numerically equal to the vertical hydraulic conductivity of the material. This will remain essentially constant as long as the soil remains saturated and porous.

Infiltration rates are higher for coarse, open-textured materials (sandy soils) and are lower for materials having finer pores (clay soils). Final infiltration rates are typically greater than 20 mm/hr for sands and between 10 and 20 mm/hr for sandy and silty soils.¹⁸ Initial infiltration rates would be considerably higher than these values. Assuming a value of 20 mm/hr, 20 liters (0.020 m³) would infiltrate each hour for 1 m² of wetted area. Thus, virtually all liquid discharged to an unlined pit (assuming an application rate of 79.5 l per day and wetted surface area of 1 to 2 m²), potentially could infiltrate within two or three hours.

The volume of liquid required to saturate an initially dry porous material is equal to the effective porosity of the material. Sand and gravel materials typically have porosities in the range 10% to 30%, unconsolidated fine to medium sands have porosities in the range 35% to 50%, and sandstones typically have porosities in the range 5% to 30%.¹⁷ Assuming the water table is 1 m below land surface, a material having a 5% porosity could hold 50 l of liquid per 1 m² of wetted surface; a material having 30% porosity could hold 300 l of liquid per 1 m² of wetted surface; and a material having 50% porosity could hold 500 l of liquid per 1 m² of wetted surface. Using the intermediate porosity value (30%), the soil below a wetted area of 1 m² would be completely saturated within 4 days if 80 l infiltrates per day. Another consideration in bulk flow is the rate or velocity of downward movement of the produced water. Under saturated conditions, this velocity will be equal to the vertical hydraulic conductivity of the porous material divided by its porosity. Assuming a 30% porosity, vertical velocities would range from 0.028 cm per day in an unconsolidated clayey sand to 2,880 cm per day in a clean sand. Assuming an intermediate velocity of 30 cm per day, liquid introduced to an unlined pit would travel to the water table in 3.3 days if the initial water table is 1 m below land surface and soil is saturated. Actually, these calculations and experimental results were not surprising based on a prior study of core samples from a similar pit to depths of nearly 2 m.¹⁶ In that study, evidence for extensive mobility for all compounds was found. Moreover, sandy soils have been found to have limited retardation for aromatic and halogenated aromatic hydrocarbons in laboratory study²¹ and in an actual environmental aquifer.²²

Acknowledgements

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