

Final Technical Report

Evaluation of Contamination and Remediation
Manvel Saltwater Disposal Site
Brazoria County, Texas

(RRC Site No. 92-03-00003)

by

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EXECUTIVE SUMMARY

The Manvel Saltwater Disposal (SWD) site (RRC Site No. 92-03-00003), which lies within the city limits of Manvel, Texas, in Brazoria County, was investigated by the Bureau of Economic Geology during a 5-month study from July through November 1995. The study included hydrogeological investigation, waste characterization, assessment of environmental impact, and evaluation of remediation options.

Saltwater, drilling waste, and crude oil have been disposed at the site. There have been several instances of pit overflow, levee rupture, or both, resulting in contamination of the surrounding area by saltwater and crude oil. There have been several public complaints to regulatory agencies, centered on the perceived threat to ground-water quality. The site lies in the outcrop of the Beaumont Formation, where the formation is sandy enough to be a local aquifer, containing fresh water having chlorinities of less than 100 mg/L. The Beaumont lies above and is hydrologically distinct from the main water-yielding part of the Chicot aquifer.

Drilling waste and site waters were randomly sampled and chemically characterized for electrical conductivity, total metals, metals toxicity, total petroleum hydrocarbons (TPH), volatile (BTEX) and semivolatile organics, and major aqueous ionic species. An electromagnetic induction survey was conducted to measure ground conductivity for indirect determination of the magnitude of saltwater contamination at the site.

High-TPH (>2 percent), high-salinity (>500 mS/m) drilling waste has a volume of approximately 6.1 acre-ft (~10,000 yd³), is elevated in barium, iron, and zinc, and contains BTEX and polycyclic aromatic hydrocarbons below industrial risk-based concentrations for soil. Toxicity characterization of metals and organic analysis shows the drilling waste to be nonhazardous. Levee soils surrounding disposal pits are

essentially free of petroleum hydrocarbons and salt; waters in the pits (~50,000 bbl) are fresh and contain less than 0.2 mg/L TPH. Site waters have chlorinities ranging from 69 to 19,300 mg/L and elevated bromide and barium contents. Saltwater contamination on and off site is evident in the presence of high-chlorinity site waters, halophytes (salt-tolerant plants), and high ground conductivity. Conductivity increases downward, reflecting subsurface infiltration of saltwater and its lateral migration because of disposal activities at the site.

Although saltwater, organics, and metals pose a potential environmental risk, the rural setting surrounding the Manvel site has not been seriously impacted by disposal activities. There have been no reports or complaints of chloride contamination in nearby Beaumont water wells. Wells in the deeper Chicot aquifer should not be at risk because the saltwater plume lies within the shallow Beaumont, above the Chicot aquifer. Organics and metals have been largely immobilized on-site by natural processes. Moreover, any ground-water contaminants that might discharge to nearby Mustang Bayou would be diluted to negligible concentration and pose no threat to downstream bioreceptors.

Protection of public health and safety and the environment nonetheless will require management of saltwater (dissolved solids), organics, and metals. Target areas for cleanup include (1) a shallow saltwater plume that has moved off site and (2) high-TPH (2 to 4 percent), high-salinity (>500 mS/m) waste in parts of two pits. Low-TPH, low-salinity waste can be left in place with minimal risk to public health and safety and the environment. Natural restoration, following elimination of saltwater sources, is the cost-effective option for saltwater control because of the low risk for contamination of water wells and the tremendous volume of water that would need treatment (as much as 60,000,000 gal). Acceptable options for remediation of high-TPH drilling waste are offsite disposal or on-site bioremediation. Offsite disposal, at an estimated cost of \$400,000 to \$900,000, is not warranted by the apparent risk. Onsite bioremediation is the

cost-effective choice and can be achieved through land farming, in soil-slurry reactors, or by composting in soil-pile reactors. Because of the large volume of waste (~10,000 yd³) to be treated, land farming is recommended at an estimated cost of \$200,000 to \$450,000. The total cost of remediation is estimated at \$273,500 to \$528,500 and includes costs of land farming, dewatering, backfilling, and leveling the pits, and site reclamation.

INTRODUCTION

Statement of Problem

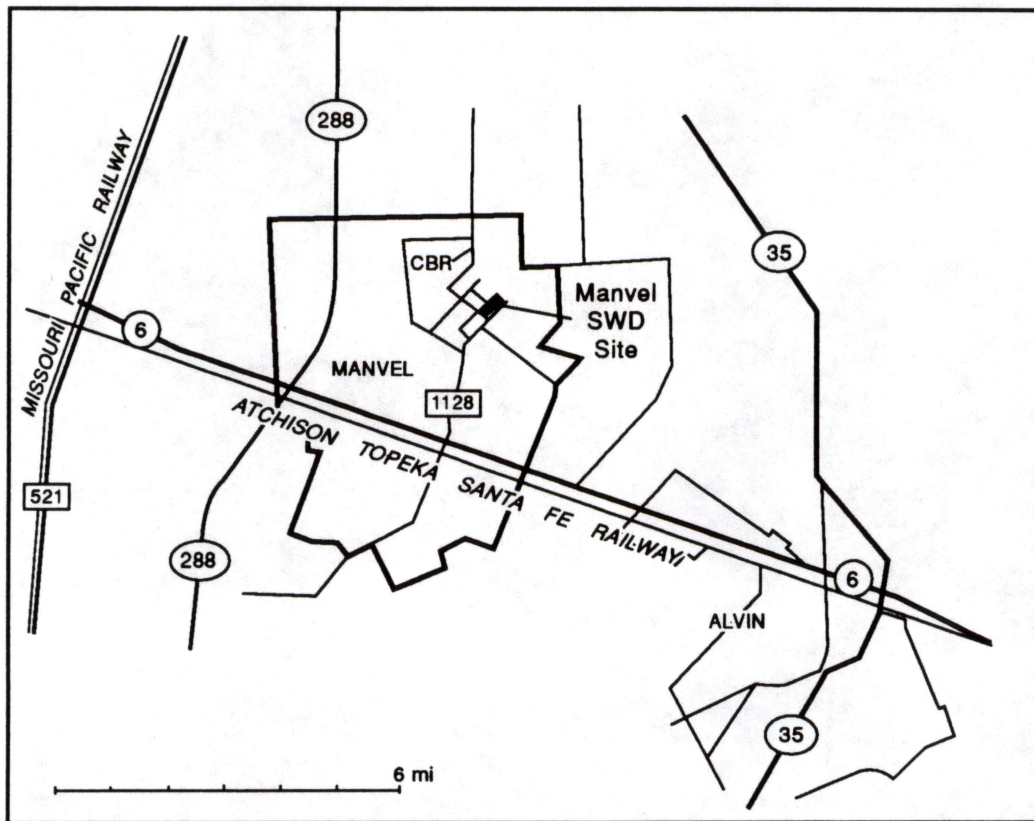
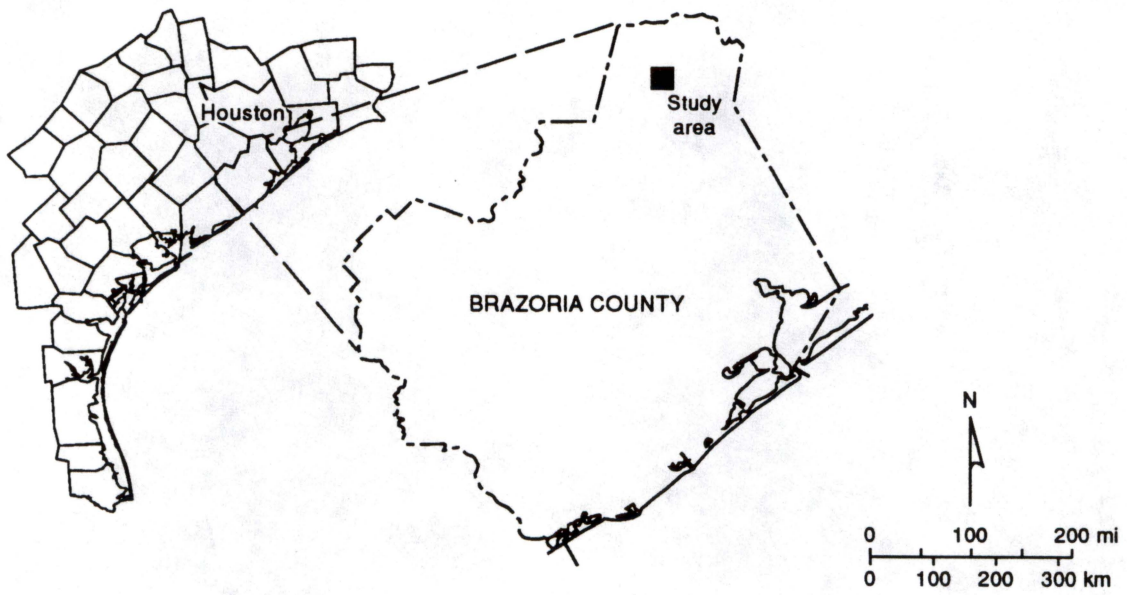
The Railroad Commission of Texas (RRC) has statutory responsibility under S.B. 1103 (72nd Legislature, 1991) for oversight of cleanup of abandoned oil field sites throughout Texas. Since 1991, RRC personnel have identified, inventoried, and ranked more than 100 sites as candidates for cleanup. The RRC ranking gives priority to contaminated sites that have had observable releases, occur in ground-water recharge zones with high soil permeability, lie near surface-water bodies or water-supply wells or both, have high public profiles and have received complaints, and are near population centers. Straightforward solutions for cleanup of surface contaminants are readily apparent for many of the sites. At other sites, however, outlining cost-effective approaches to site cleanup requires information on the less apparent subsurface extent of the contaminant and the location of contaminant sources. For these sites, the Bureau of Economic Geology (BEG) is providing more extensive site investigations for the RRC under an interagency contract. The purpose of these site investigations is to provide the required information for planning and executing an appropriate level of remediation, exclusive of surface equipment and associated minor leaks and spills.

At the request of the RRC, BEG investigated the Manvel Saltwater Disposal (SWD) site (RRC Site No. 92-03-00003) in Brazoria County, Texas, within the City of Manvel,

8 mi (12.8 km) northwest of Alvin, Texas (fig. 1). Saltwater, drilling muds, and crude oil have been disposed at the site. There have been several instances of pit overflow, levee rupture, or both, resulting in contamination of the surrounding area by saltwater and crude oil. Leakage of saltwater from unlined pits was also suspected. Saline ground water was found on-site at shallow depths. Previous analyses showed pit waste to be high in total metals (particularly arsenic, barium, lead, and zinc), petroleum hydrocarbons, and salt.

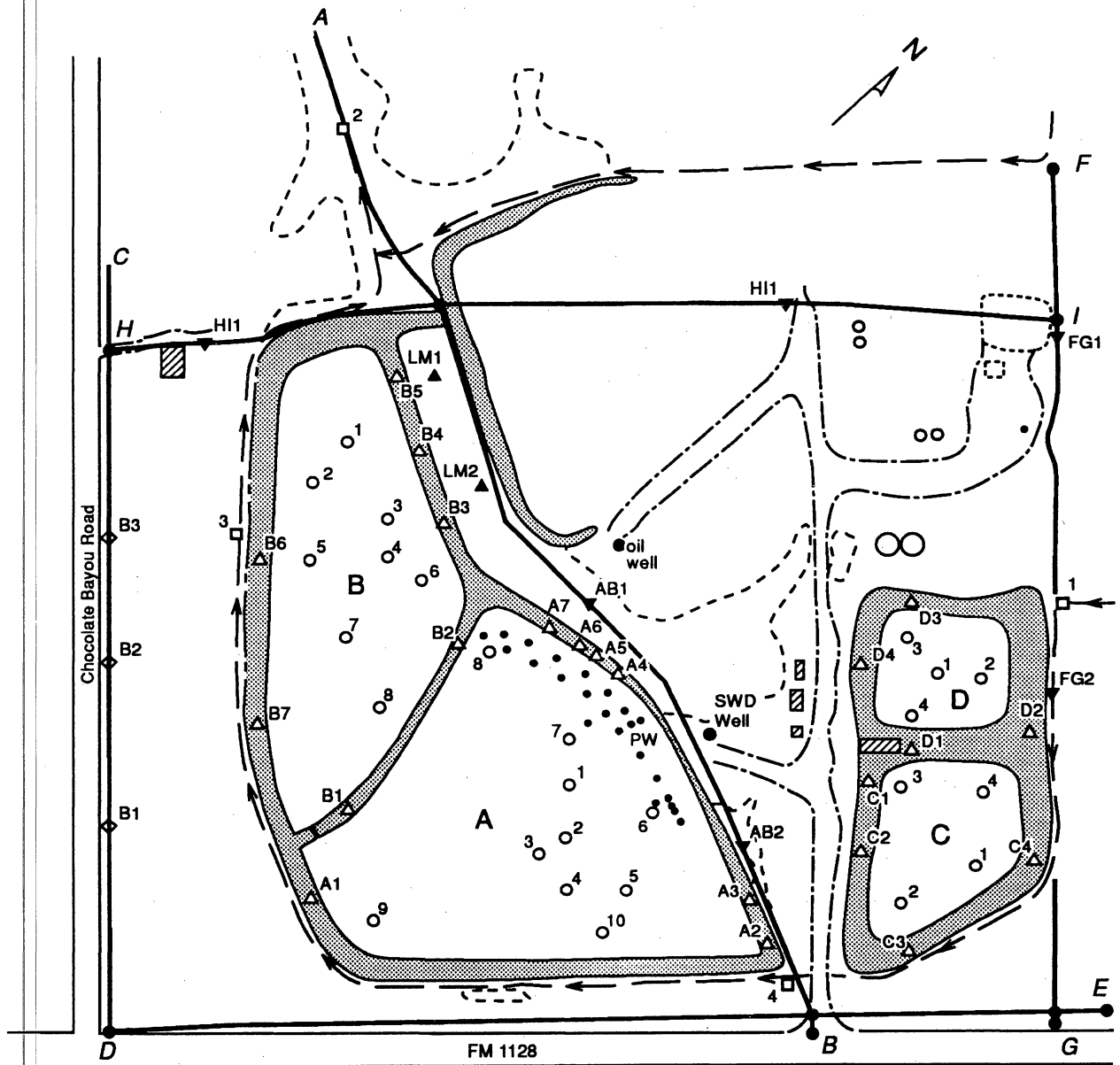
The site was first brought to the attention of regulators in 1979 through an anonymous complaint to the Texas Parks and Wildlife Department about crude oil overflow. Crude ultimately reached the southeast-flowing Mustang Bayou, approximately 0.25 mile (0.4 km) west of the site, through a tributary creek (drainage ditch) that crossed the site. Subsequent to the spill, the RRC and Texas Department of Water Resources were notified. Parks and Wildlife filed suit against Manvel Saltwater Disposal Co. and reported that there had been problems at the Manvel site prior to 1979. In 1982, an anonymous complaint reported pits covered with basic sediment and water (BS&W). At this time and in 1983, oil reportedly continued to accumulate in the skim pit. In 1984, the City of Manvel opposed granting a permit to the disposal company for a new unlined SWD pit. The permit was denied by the RRC (Docket No. 3-83,263) on the basis that leakage from the pit would endanger water quality. At the time, the City of Manvel claimed that overflow of saltwater and crude oil into the drainage ditches and ground-water contamination occurred on a regular basis at the site.

In 1988, Ms. Ruby Lavender, the current landowner, filed a complaint about the unplugged SWD well and open pits. The SWD well and an on-site oil well were subsequently plugged by the RRC on February 6, 1990, and March 3, 1993, respectively (fig. 2). During heavy rains in 1993, the pits were breached and overflowed to the surrounding area. Local headward erosion from the edge of pit A into its apron has

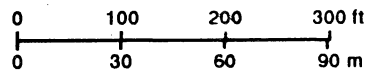


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Figure 1. Location of the Manvel SWD site, Brazoria County, Texas.



- | | | | | | |
|------|---------------------|------|-------------------------------|--|-------------------------------|
| A | Pit letter | ● | Probed sediment thickness | | Building |
| 6○ | Pit sample | ○ | Tanks | | Tanks |
| A5△ | Levee sample | | Levee | | Levee |
| LM1▲ | Levee margin sample | | Site roads | | Backfilled pits |
| 2□ | Ditch water sample | | Halophytes abundant | | Drainage ditch/flow direction |
| PW | Pore water sample | | Drainage ditch/flow direction | | |
| | | B2◇ | URM well | | |
| | | D E | EM-34 survey line | | |
| | | AB2▼ | Conductivity profile | | |



QAb1965c

Figure 2. Map of the Manvel SWD site. Shown are sample locations and EM-34 survey lines. Base map was prepared from an enlargement of a 1990 aerial photograph.

exposed crude oil seepage. In 1994, the RRC ordered Manvel Saltwater Disposal Co. to initiate cleanup operations to eliminate the pollution threat.

Objectives and Scope

The principal objectives of this investigation were to (1) identify solutions to meet RRC obligations to protect public health and safety and the environment and (2) limit potential cost to the State of Texas for cleanup by using, to the largest extent possible, nonintrusive and cost-effective techniques to define the extent of the problem. The investigation focused on determining the chemical composition and volume of pit wastes and waters, the origin and extent of saltwater contamination of local ground water, and evaluating remediation options.

The scope of work included (1) site reconnaissance, (2) preparation of a Site Investigation Plan, (3) hydrogeological investigation to determine the magnitude of contamination at the Manvel SWD site, (4) assessment of environmental impact, and (5) evaluation and recommendation of remediation options. BEG visited the site in April 1995. The Site Investigation Plan was approved by the RRC in July 1995. Field work began in late July and was completed in early September; it focused on sampling levees, pit wastes, and site waters, determining pit waste and water thickness, conducting an electromagnetic conductivity survey to determine offsite migration of saline water and its depth below land surface, and mapping the distribution of halophytes (bioindicators). A draft of this report was submitted for review and comment by the RRC in December 1995.

Site Description

The Manvel SWD site lies within the city limits of Manvel, Texas, on the Pearland USGS 7.5-minute quadrangle; it is 2.6 miles (4.18 km) north of the intersection of State

Highway 6 and FM 1128 at the intersection of FM 1128 and Chocolate Bayou Road (CBR), northeast of a Texaco tank farm (fig. 1). The site includes a plugged and abandoned saltwater disposal well and P&A oil well, four water-filled, earthen pits, consisting of two waste-disposal pits and two relatively uncontaminated ponds that are reportedly fished by the public, and assorted surface-production equipment, including four 200-bbl and two 500-bbl tanks (fig. 2).

Oil-field activities at the site date from the late 1950's and perhaps earlier, because oil production in Manvel oil field was established in the 1930's. Aerial photographs taken in 1958, 1965, 1969, 1975, and 1976 show two rectangular pits (approximately 80×100 ft [24×30 m]), one just south of the SWD well in what is now pit A and another just west of the road to the plugged oil well. At different times, two or three smaller pits existed in what is now pit A. These pits appear fluid filled, except in the 1965 photograph, and possibly served in combination as saltwater collector, oil-skim, and saltwater disposal pits for a nearby oil well, the Davis No. 1, which later became the Davis No. 1-A. They were subsequently subsumed into pit A. In late-1975, application was made to the RRC to inject saltwater into the Davis No. 1 (1-A) well in anticipation of disposal activities at the site. At this time, there were no tanks or buildings. By 1980, the site had a configuration similar to that of today; that is, (1) pits A and B are present but appeared fluid free or at the very least only partially filled, (2) pits C and D are newly dug, pit C being larger than pit D, and (3) pumping and collector pits at the northeast corner of the site are in place.

Manvel SWD Co. was incorporated in 1978 and ceased operation in July 1986. Disposal activities in the late 1970's and 1980's included disposal of saltwater, drilling waste, and associated crude oil. Saltwater was released by vacuum trucks into a concrete settling pit (fig. 2, small square at northeast corner of site, now backfilled), which was connected to the adjacent concrete-lined pumping pit. Water was pumped from there into the two 500-bbl tanks and then to the disposal well for injection. Oil

skimmed from the pits was stored in the smaller 200-bbl tanks and sold. Drilling mud and associated saltwater and crude oil were discharged primarily into pit A and secondarily into pit B on their north sides, as shown by the presence of waste aprons. An unknown number of barrels of unknown contents are present in pit B and are more numerous in pit D.

Present-day evidence of saltwater spills and leaks are salt-encrusted areas barren of vegetation (kill areas) along the north side of pits A and B, west of the SWD well. Saltwater contamination is further indicated by the presence of halophytes, or salt-tolerant plants, north of pits A and B and west of pit B (fig. 2). Luxuriant patches of sea ox-eye daisy (*Borrchia frutescens*) and seashore saltgrass (*Distichlis spicata*) are present. Both plants are common in the Texas coastal marshes; *Borrchia* tolerates salinities ranging from 8,700 to 44,300 mg/L total dissolved solids.

In the mid-1980's to early 1990's, RRC staff made several visits to the Manvel SWD site in response to complaints and to sample pit wastes and waters. Early estimates indicated the presence of several tens of thousands of barrels of water and approximately 28,000 yd³ (21,420 m³) of exploration and production drilling waste (drilling muds, fluids, and crude oil). Chemical analyses by the RRC showed the waste to have elevated arsenic, barium, lead, and zinc contents, as well as oil and grease to several percent; high electrical conductivities (EC) and sodium absorption ratios (SAR) indicated high salt loading (table 1). Analyses of the metals, using the toxicity characteristic leaching procedure (TCLP), an acetic acid leach test designed to simulate landfill conditions, show leachable metal contents that are well below TCLP limits and very much lower (<1 mg/L to a few mg/L) than total metal content. Pit waters had chlorinities of less than 1000 mg/L and very low metals content. Chlorinities of 5,000 to 6,000 mg/L were reported in 1985 (RRC files).

Table 1. Composition pit waste samples from RRC files.^a

Parameter	Units	PIT A	PIT B	PIT C	PIT D
Oil/grease	% dry wt.	7.77	5.96	0.37	0.28
pH	units	8.71	7.34	7.82	7.51
Arsenic	mg/kg	123.46	108.80	<0.74	<0.74
Barium	mg/kg	111490.00	178625.00	17077.00	9310.00
Cadmium	mg/kg	8.61	15.07	2.47	2.45
Chromium	mg/kg	142.00	158.23	48.99	73.71
Lead	mg/kg	426.02	495.09	56.32	99.75
Mercury	mg/kg	3.41	6.99	0.68	0.68
Selenium	mg/kg	<1.4	<1.4	<1.4	1.80
Silver	mg/kg	22.06	<0.12	<0.12	<0.12
Zinc	mg/kg	2940.80	3545.30	892.60	350.00
Conductivity	mmhos/cm	65.00	17.45	2.82	2.02
CEC	meq/100g	48.48	40.79	25.77	66.27
Sodium absorption ratio	units	26.98	14.09	12.39	8.74
Exchangeable Na	%	64.23	9.43	1.05	2.42
Moisture	%	37.05	39.68	37.76	35.63

^a From RRC files (New Park Environmental analyses). Total metals analyzed.

Hydrogeology

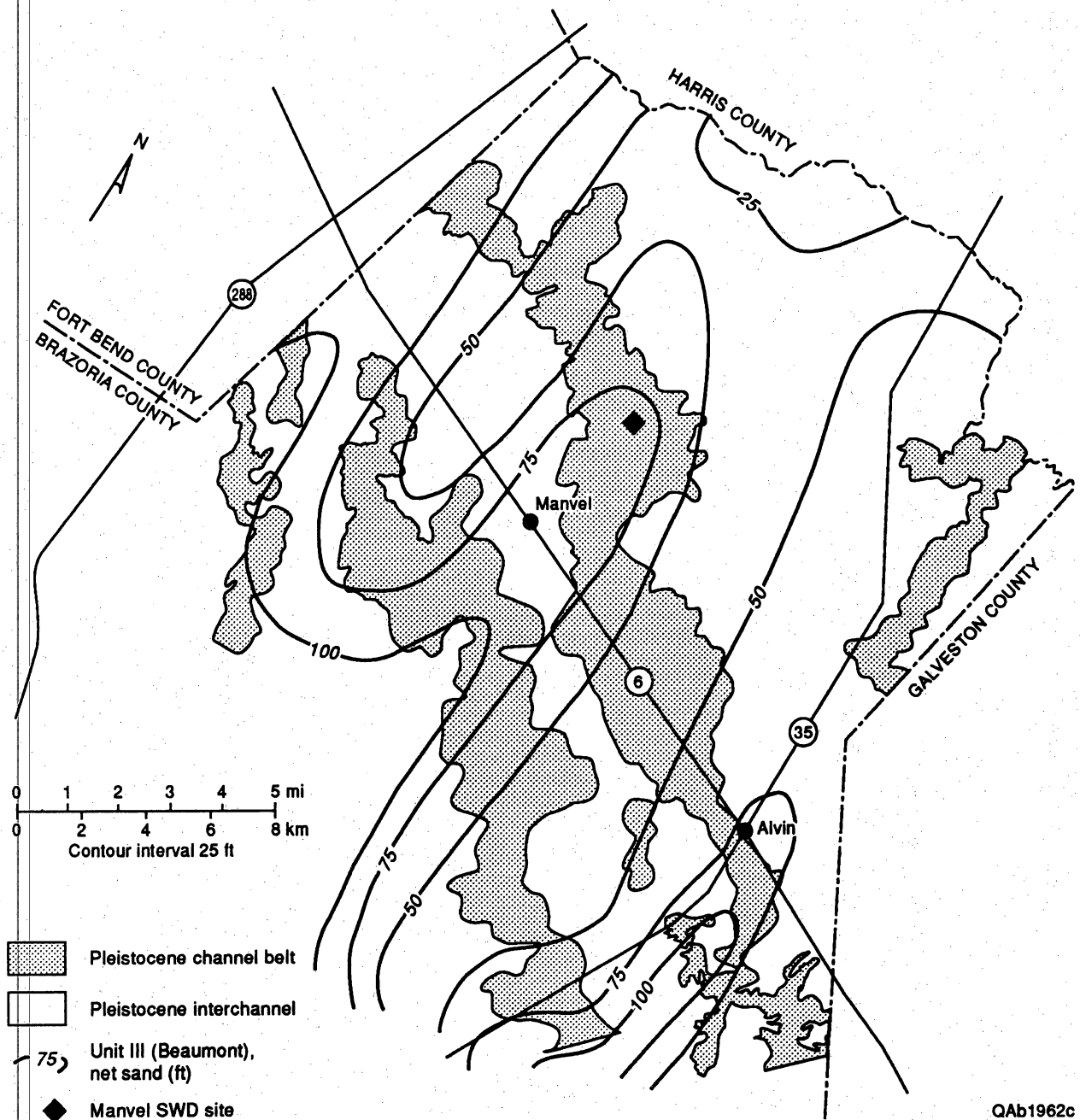
The Manvel SWD site lies in a recharge area in the outcrop of the Pleistocene Beaumont Formation (Aronow and others, 1982), which corresponds to the Beaumont Formation aquifer or the equivalent upper Chicot aquifer (fig. 3). In the vicinity of the site, the Beaumont is 200 to 225 ft thick (61 to 69 m) (Sandeen and Wesselman, 1973; Guevara-Sanchez, 1974) and corresponds to operational mapping unit III of Guevara-Sanchez (1974), representing fluvial-deltaic deposits of the ancient Brazos River system. This relict depositional grain is well preserved in the Beaumont outcrop. Surface mapping by Fisher and others (1972) shows the site to be on a southeast-trending, 2-mi-wide (3.2-km) Pleistocene channel belt composed of mainly fine-grained fluvial and distributary sands and muds (fig. 4). The net thickness of Beaumont sand beneath the Manvel site is approximately 75 ft (23 m), equivalent to a sand percentage of approximately 40 percent. A similar percentage was calculated from a 92-ft (28-m) test hole drilled essentially on-site in the southwest corner of the intersection of FM 1128 and Chocolate Bayou Road. Clearly, the Beaumont Formation is not mud dominated and contains more than enough sand to be a local aquifer.

Indeed, available data indicate high hydraulic conductivities in Beaumont (upper Chicot) sands. The arithmetic mean of 15 Brazoria County aquifer tests reported by Sandeen and Wesselman (1973) is 78 ft/d (24 m/d). Bentley (1980), on the basis of 10 bailer tests in eastern Brazoria County, calculated an average hydraulic conductivity of 13 ft/d (4 m/d), which was thought to be representative of the fluvial sand deposits. Water quality is good. In northern Brazoria County, fresh water (TDS <1,000 mg/L) is present to approximately 1,150 ft (350 m) below land surface (Sandeen and Wesselman, 1973). Within a 2-mi radius (3.2-km) of the site, chlorinity in the Beaumont (upper Chicot) aquifer ranges from 19 to 216 mg/L and averages less than 100 mg/L.

		Stratigraphic unit		Hydrologic unit	
				Sandeen and Wesselman (1973)	Dutton (1994)
QUATERNARY	HOLOCENE	Alluvium, coastal deposits		upper Chicot aquifer	Alluvium and Beaumont Formation aquifer units
	PLEISTOCENE	Beaumont Formation			
		Lissie Fm (undiff.)	Montgomery Formation	lower Chicot aquifer	upper Chicot aquifer unit
Bentley Formation					
TERTIARY	PLIOCENE	Willis Formation		Evangeline aquifer	lower Chicot and Evangeline aquifer unit
	MIOCENE	Goliad Formation			
		Fleming Formation		-----	Burkeville confining layer

QA1980c

Figure 3. Brazoria County hydrostratigraphy. In Brazoria County, the Beaumont aquifer is equivalent to the upper part of the Chicot aquifer.



QAb1962c

Figure 4. Geologic setting of the Manvel SWD site. Surface geology from Fisher and others (1972) and subsurface geology from Guevara-Sanchez (1974).

Regional ground-water flow in the unconfined Beaumont aquifer is to the southeast (fig. 5). The site is located at the eastern end of an east-west-trending topographic high that slopes south and east, and overall the potentiometric surface slopes in that direction, reflecting the topography (fig. 6). The regional hydraulic gradient is 2.16 ft/mi (0.4 m/km), or 4.1×10^{-4} (Bentley, 1980). In the vicinity of the Manvel site, however, the Beaumont potentiometric surface reflects local topography (land surface is 55 to 60 ft [17 to 18 m] above mean sea level) and drainage more than drawdown in water wells. At the site, the potentiometric surface slopes west toward Mustang Bayou at a hydraulic gradient of 56 ft/mi (11 m/km), or 1.07×10^{-2} , and northwest toward a tributary, now a drainage ditch, at a lesser gradient.

Gulfward flow in the deeper sands of the Chicot aquifer has been diverted toward the northeast because of large-scale withdrawals in the Houston area (fig. 5). Compared with the deeper aquifer system, the shallow aquifer system has undergone little development. Water levels in wells screened in the Beaumont are relatively undisturbed (Bentley, 1980). They typically range from 10 to 30 ft (3 to 9 m) below land surface in wells within a 2-mi (3.2-km) radius of the site and are at least 150 ft (46 m) above those in the underlying Chicot aquifer, indicating very strong potential for downward flow (leakage) across the Beaumont to the Chicot. Despite this, Bentley (1980) concluded that the Beaumont does not contribute significant recharge to deeper aquifers. Dutton (1994) also showed that the Beaumont is hydrologically distinct from the main water-yielding part of the Chicot aquifer. Deeper recharge may be inhibited by abundant Beaumont clay and mud layers, discharge to local drainage, and low-permeability soils.

Soils Description

The site lies primarily on soils of the Edna-Avis complex and secondarily on the Bernard clay loam in the southwest quadrant of the site (Crenwelge and others, 1981).

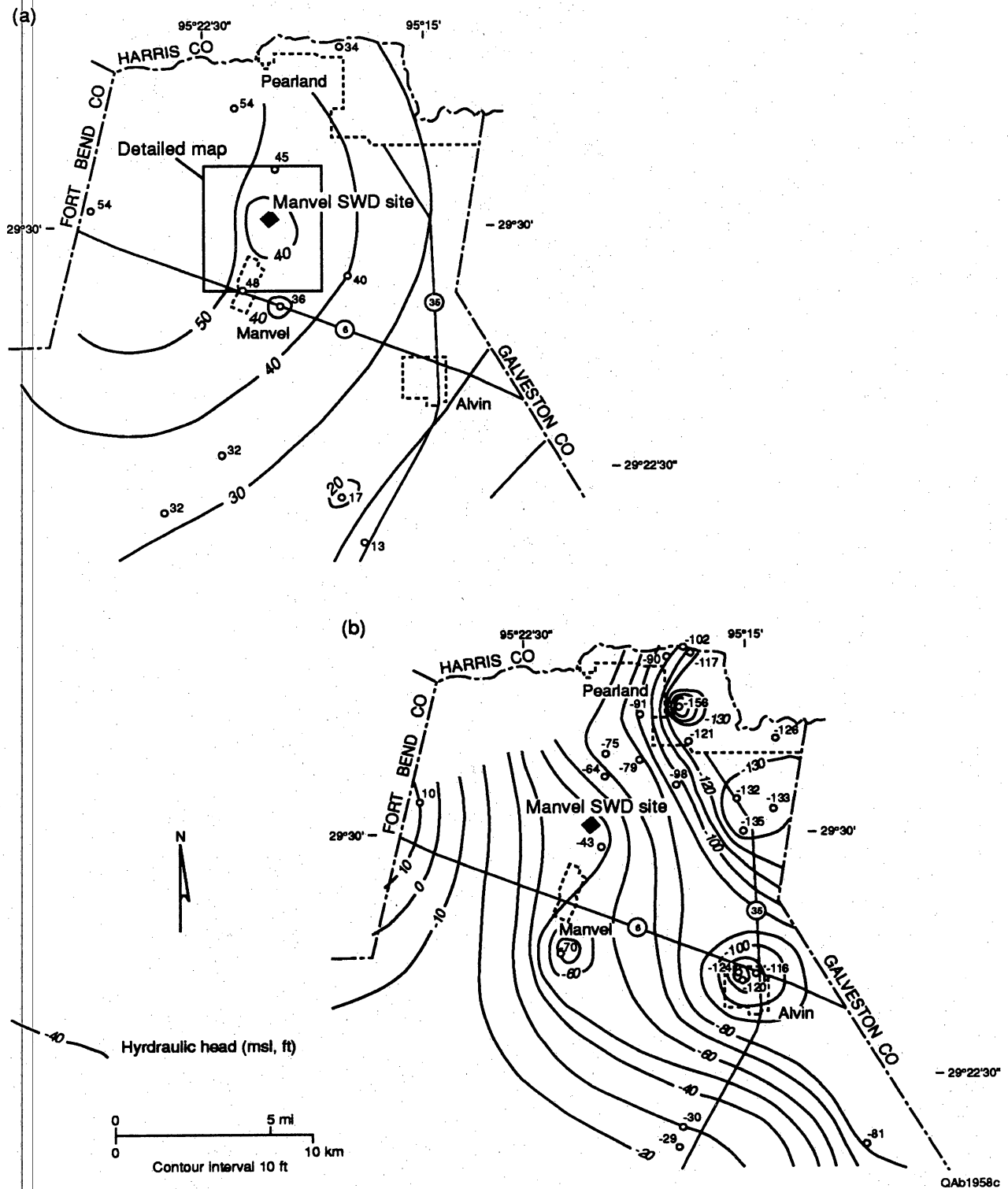
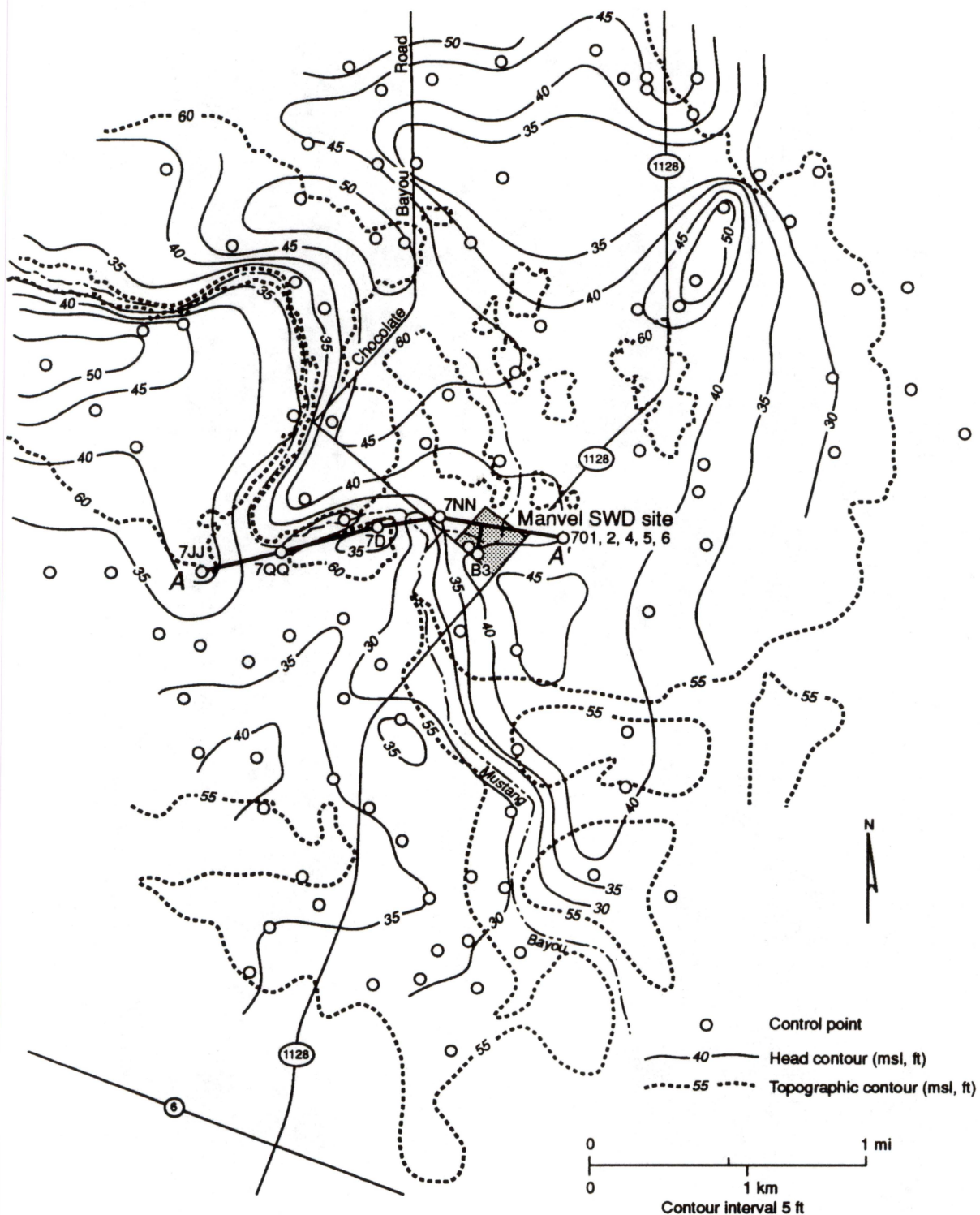


Figure 5. Beaumont (upper Chicot) (a) and lower Chicot aquifer (b) hydraulic head, 1967. Regional flow in the Beaumont aquifer is to the southeast. See figure 6 for detailed map. Heavy pumping in the Houston area has induced a cone of depression in the lower Chicot. Modified from Sandeen and Wesselman (1973).



QAb1966c

Figure 6. Beaumont hydraulic head in the vicinity of the Manvel SWD site, 1970's and 1980's. Water levels are from driller's logs of water wells to depths of less than 200 ft. Well locations are from the files of the TWDB and logs are from the files of the TNRCC.

These soils are nonsaline and to a depth of 60 inches (152 cm) are heterogeneous texturally, being composed of clay, silty clay, clay loam, silty clay loam, sandy clay loam, and fine sandy loam. A loam is soil material composed of 7 to 27 percent clay, 28 to 50 percent silt, and less than 52 percent sand. These soils are poorly to somewhat poorly drained, have very slow to slow surface runoff, very slow permeabilities (<0.06 inches/hr [<0.15 cm/hr]), a pH of 5.1 to 8.4, and a perched water table above a depth of 2 to 3 ft (0.6 to 0.9 m) during the months of December through March. They support two types of native vegetation: tall grass prairie and dense stands of hardwood or mixed pine and hardwood trees.

METHODS

Sampling

The sampling plan used at the Manvel SWD site was designed in accordance with EPA SW-846 (EPA, 1986) and employed random sampling. In random sampling, every part of a waste package has a theoretically equal chance of being sampled to achieve sampling accuracy. For waste sampling, if little or no information is available about the distribution of chemical contaminants, simple random sampling is the option of choice and was used here. For this type of sampling, all locations or points in the waste from which a sample could be collected are identified and a suitable number of samples is randomly selected from the population to obtain a representative sample. Other sampling strategies may be appropriate as more information about the contaminant distribution becomes available. For example, stratified random sampling may be appropriate if the distribution of contaminants is known well enough to allow an intelligent identification of strata (distinct divisions) and at least two or three samples can be collected from each stratum (division).

The appropriate number of samples is the fewest samples required to generate a sufficiently precise estimate of the true mean concentration of a waste contaminant. In practice, this means the minimal number of samples needed to demonstrate that the upper limit of the confidence interval (CI) for the true mean is less than the applicable regulatory threshold (RT). The equation used for estimating the appropriate number of samples to collect is:

$$N = \frac{t_{0.20}^2 S^2}{\Delta^2},$$

where

$t_{0.20}^2$ = "t" value for two-tailed CI with probability of 0.20

S^2 = sample variance

Δ = RT – sample mean

The equation shows that increased sampling effort is warranted as S^2 or the " t "_{0.20} value (probable error rate) increase and Δ decreases.

To estimate the number of samples (N) required at Manvel, existing RRC data (table 1) and land-farming regulatory thresholds were used. N was calculated for elements (cadmium, chromium, lead, and mercury) closest to the regulatory threshold and found to range from 1 to 7. On this basis, it was decided to collect 7 pit A and 7 pit B levee samples and 10 pit A and 8 pit B pit samples. Because contaminant levels in pits A and B were higher than in the smaller, less contaminated pits C and D, fewer samples were thought necessary for characterization of those pits. Four levee and four pit samples were taken for pits C and D.

Locations for levee and pit samples were randomized using a random number table. The circumference of each levee was calculated and used as the limiting number in the random number table. For example, the circumference of pit B was 1,390 ft (424 m). The first 7 numbers between 0 and 1,390 in the number table were noted and assigned sample numbers B1 through B7 in order of increasing size of the numbers selected from the table. In the field, an origin point was chosen and each sample was

located by measuring the distance counterclockwise from the origin along the levee equal to its random number. For example, B4 was 507 and would be located 507 ft from the origin.

A total of 22 levee samples were collected, 14 from pits A and B and 8 from pits C and D (fig. 2). For comparative purposes, one background sample, 600 ft (183 m) northwest of the site, and two levee-margin samples, north of pit B (fig. 2) were also collected. Soils were collected from 2-inch-diameter (5-cm) auger holes at depths of 24 to 30 inches (61 to 76 cm) and stored in zip-locked bags. In the laboratory, the samples were first split for total petroleum hydrocarbons (TPH) and then air dried, milled to pass 2-mm mesh, and composited for toxicity characteristic leaching procedure (TCLP) analysis. Four composites, one for the levee surrounding each pit, were analyzed by the RRC laboratory for TPH and TCLP metals. For each individual sample, Bureau of Economic Geology Mineral Studies Laboratory (MSL) determined pH and electrical conductivity (EC) of a 1:1 soil/deionized-water mixture. Chloride (mg/kg, dry basis) was determined for the background, levee-margin, and selected levee samples.

Pit sampling was randomized by superimposing an imaginary grid (44×44 ft [13.4×13.4 m] squares) over each pit, assigning consecutive numbers to each grid square, and selecting the squares to be sampled from a random number table equal to the number of samples to be collected in each pit. For example, for pit A there were 65 numbered squares and the first 10 numbers between 0 and 65 were chosen from the random number table for sampling. These 10 numbers were assigned the sample numbers A1 through A10.

Twenty-six pit samples were collected by piston core using clear plastic (butyrate) tubing. Ten cores were taken in pit A, eight in pit B, four in pit C, and four in pit D (fig. 2). The cores ranged in length from 2 to 4 ft (6.6 to 1.2 m) and were 1.5-inch (3.8-cm) and 2.75-inch (7.0-cm) diameter, respectively, if taken from a boat or on the exposed pit surface. Only in pit A were larger cores (8) taken. Immediately upon collection, cores

were capped with polyethylene caps and sealed with electrical tape for transport to MSL. In the laboratory, the cores were split, described, and sampled for analysis. One-half of the core was wrapped in plastic and archived in a cold room. A continuous subsample was taken from the center of each half core along its entire length, exclusive of obvious uncontaminated pit-bottom sediment. Subsamples were mechanically blended in glass jars using stainless steel apparatus, depending on sample consistency and composited for analysis of TPH, TCLP metals, volatile organics (BTEX/MTBE), and semivolatile organics (EPA method 8270, target compounds), EC, and total metals. Five pit A, four pit B, two pit C, and two pit D composites were analyzed by the RRC laboratory for TPH and TCLP metals. MSL determined EC on 1:1 mixtures. Splits of the pit A and pit B composites were analyzed by ChemSOLVE of Austin (Chemsolve) for BTEX/MTBE. Because of obviously greater organic loading in pits A and B, four composites, representing proximal and distal parts of each pit, were analyzed by Chemsolve for semivolatile organics. MSL analyzed the same composites for total metals.

Nine water samples were collected, filtered, and preserved for analysis of major cations and anions, metals, and TPH. From each pit, pit waters were bailed and collected at several locations to form one composite sample for analysis. Also, one composite of near-bottom water was collected in pit B. Two drainage-ditch samples were collected from two of three perforated plastic tubes (30 × 2.25 inches [76 × 5.7 cm]) set to facilitate the sampling of shallow ground water beneath the ditches; one surface ditch sample was collected from ponded water at the site entrance (fig. 2). One sample of waste pore water was extracted from a test core at the north edge of pit A opposite the SWD well. All analyses were done by MSL except the TPH, which was done by Chemsolve.

Electromagnetic Induction Survey

Electromagnetic induction methods use a changing primary magnetic field created around a transmitter coil to induce a current to flow in the ground, which in turn creates a secondary magnetic field that is sensed by the receiver coil. In general, the strength of the secondary field is proportional to the conductivity of the ground. An assumption inherent to the method is that the near-surface environment consists of horizontal layers of infinite lateral extent. This is not strictly true at the Manvel site, but the near-surface layers probably do have sufficient lateral extent to render this assumption valid at the scale of investigation.

Electromagnetic induction methods (Parasnis, 1973; Frischknecht and others, 1991; West and Macnae, 1991) were used to measure apparent ground conductivity at the Manvel site, which can proxy for ground-water conductivity and be used as an indirect measure of ground-water salinity beneath the site. Mapped areas of elevated ground conductivity allowed us to delineate areas of increased salinity in the shallow subsurface. Electromagnetic profiles were collected using several exploration depths to qualitatively determine the depth of saltwater migration.

A ground-conductivity survey was completed in September 1995 along five lines at the Manvel site (fig. 2). In this survey, a Geonics EM34-3 ground conductivity meter measured apparent conductivity (McNeill, 1980a). The EM34-3 supports 10-, 20-, and 40-m (33-, 66-, and 131-ft) transmitter and receiver coil separations (fig. 7) and two principal coil orientations (horizontal dipole and vertical dipole). All three coil separations were used, resulting in an effective penetration depth of 6 to 25 m (20 to 82 ft) for the horizontal-dipole orientation and 12 to 50 m (39 to 164 ft) for the vertical-dipole orientation. Conductivity values represent "bulk" conductivities, or an average conductivity of the soil volume beneath the transmitter and receiver coils, and are plotted on profiles at the midpoint between the transmitter and receiver coils.

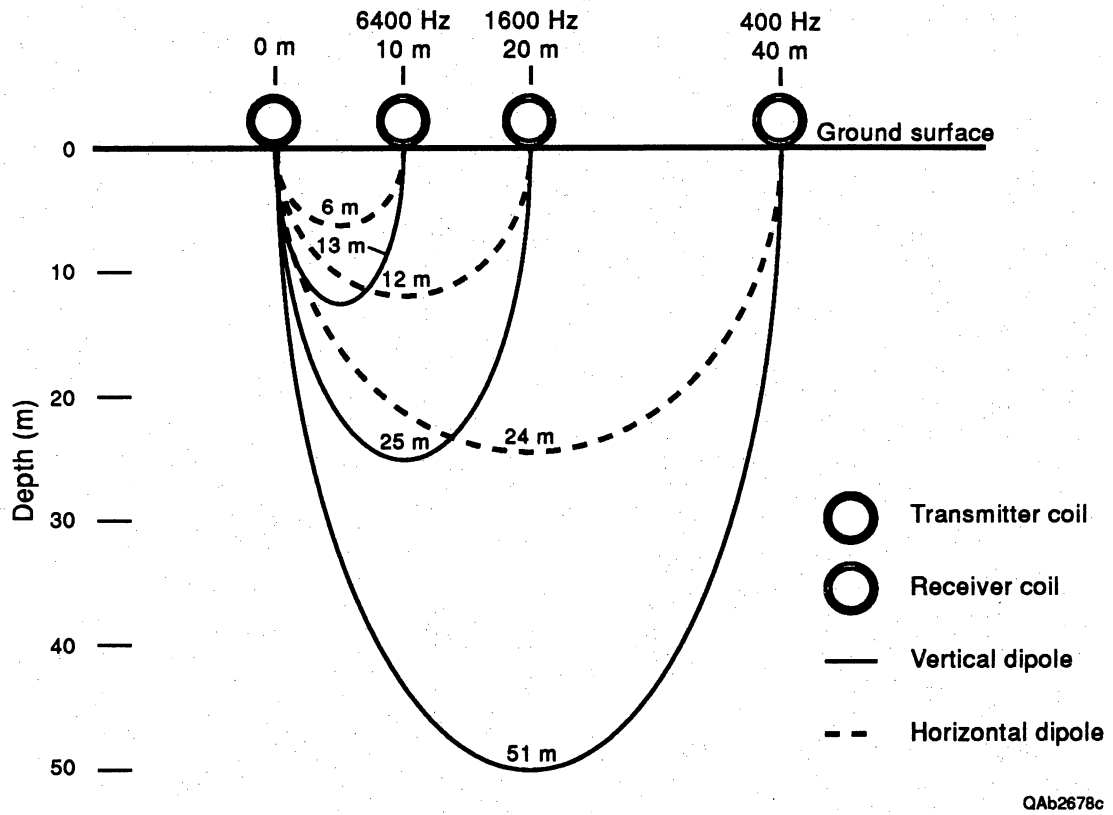


Figure 7. Effective exploration depth of various coil separations and orientations of the Geonics 34-3 ground conductivity meter.

During the electromagnetic survey, 926 ground conductivity measurements were made at the Manvel site. Conductivity measurements were made as follows: (1) the transmitter coil was placed on the ground in the horizontal-dipole orientation at a chosen station along a line, (2) the receiver coil was placed on the ground approximately 10 m (33 ft) from the transmitter coil, (3) the receiver coil position was adjusted until the separation meter on the receiver indicated the proper separation, (4) apparent conductivity was read from the meter in mS/m and logged on a digital data logger, (5) both coils were realigned in the vertical-dipole orientation at the same station locations and coil separation, (6) apparent conductivity for the vertical-dipole orientation was read from the meter and logged, and (7) the transmitter and receiver coils were moved 5 m (16 ft) along the line to the next station. The entire process was then repeated until the line was completed. After data were collected along a line for the 10-m (33-ft) coil separation, conductivity measurements were taken along each of the lines again for the 20-m (66-ft) and 40-m (131-ft) coil separations. Station spacing was 5 m for each of the three coil separations.

The effective penetration depth of the field generated by the EM34-3 increases with coil separation for a given coil orientation (fig. 7). Consequently, conductivities measured at different coil separations and orientations can be used to infer conductivity changes with depth (McNeill, 1980a,b) if lateral conductivity variations are small. The horizontal-dipole orientation has a shallower exploration depth than the vertical-dipole orientation for the same coil separation. Furthermore, conductivities obtained from the horizontal-dipole orientation are near-surface weighted; that is, for a given exploration depth, the response is largely governed by the conductivity of the uppermost third of the exploration depth. The vertical-dipole orientation has a deeper exploration depth and is more center-weighted. Conductivities obtained in the vertical-dipole mode are mostly affected by the conductivity of the middle third of the exploration depth.

Processing of EM34-3 data first required transferring the data from the digital data logger to a computer and selecting for analysis points along each profile where horizontal- and vertical-dipole data show the same conductivity trend. EMIX34 Plus, a computer program by Interpex Ltd., was used to process and interpret the data. Horizontal- and vertical-dipole conductivities for each station along a line were entered in the program, a starting conductivity model (consisting of layer thicknesses and conductivities) was entered that qualitatively fit the observed data, and then the computer displayed both the observed conductivities and conductivities calculated from the chosen model. The model was then adjusted by the user to better fit the observed data. After reasonable agreement was obtained manually, the program was directed to adjust layer thicknesses and conductivities to obtain the best statistical fit.

Analyses

Electrical Conductivity

Electrical conductivity (EC) indicates the quantity of soluble salts in an aqueous sample; it is measured on a 1:1 soil/water mixture. About 25 to 30 g of milled, air-dried soil was weighed and mixed with a calculated mass of deionized water to achieve a 1:1 mixture. The sample was mechanically shaken for 1 hr and centrifuged to obtain a particle-free liquid. EC was determined on the supernatant using a direct-readout microconductivity cell with a temperature-compensating conductivity meter. EC was read directly from the digital display and corrected to 25°C (77°F). The pH was measured on the supernatant using a combination ion-selective electrode and portable pH meter.

Water Composition

Cations were quantified by inductively coupled plasma-optical emission spectrometry (ICP-OES), a multielement technique. The anions fluoride, chloride, bromide, nitrate, phosphate, and sulfate were determined by ion chromatography. Alkalinity as bicarbonate was determined in the field by titration; pH was also measured in the field. TPH was done by EPA method 418.1, in which the sample is extracted in freon and the extractant quantified by infrared absorption.

Total Metals

Metals content in pit sediments was quantified by ICP-OES. The sample was brought into solution for analysis in two ways. A mixture of concentrated nitric, perchloric, hydrofluoric, and hydrochloric acids completely dissolves all but a few very resistant minerals (e.g., barite). Fusion with lithium borate provided the solution for determination of silica and barium.

TCLP Metals

The toxicity characterization leaching procedure (TCLP), as outlined in EPA method 1311, is intended to measure the solubility (mobility) of metals in a landfill. Eight metals are regulated by the TCLP: arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. A waste (soil) sample (20 g) is extracted with an amount of extraction fluid (400 mL) equal to 20 times the weight of the waste sample. The extraction fluid is an acetic acid solution at pH 4.93 or pH 2.88, dependent on the alkalinity of the sample. The resultant mixture is placed in a plastic bottle and rotated end over end at 30 rpm for 18 hr at room temperature (23°C [73°F]). The liquid extract is separated from the solids by filtration through a 0.6- to 0.8-micron glass-fiber filter. The

filtrate is analyzed by ICP-OES except for mercury, which is done by a mercury analyzer (cold vapor atomic absorption).

TPH

Total petroleum hydrocarbons (TPH) were determined by gravimetric techniques in a two-step process. First oil and grease is determined by method 5520E, as outlined in Standard Methods, 18th edition. On the residue so obtained, TPH is determined by method 5520F. For oil and grease, less than 3 g of sample is extracted in 230 mL of a 80:20 mixture of hexane and methyl tert-butyl ether (MTBE). The mixture is placed in a thimble filter and extracted in a Soxhlet apparatus for 4 hr. The recovered solvent is distilled in a water bath at 70°C (158°F). The weighed residue is by definition oil and grease. However, it includes any material recovered as a substance soluble in the solvent, such as other organics, sulfur compounds, and chlorophyll. No known solvent will selectively dissolve only oil and grease.

The oil-and-grease residue, 3 g of silica gel, and 100 mL of the 80:20 solvent are stirred and poured through a chromatography column to filter residue and solvent. The recovered solvent is distilled in a water bath at 70°C (158°F). The residue is weighed and by definition is TPH. The materials not eliminated by silica gel adsorption are designated hydrocarbons by this test. Silica gel has the ability to adsorb polar compounds, and consequently fatty acids are selectively removed from solution. The more polar hydrocarbons, such as complex aromatic compounds, may also be adsorbed by the silica gel.

The gravimetric technique is a useful screening step for determining the presence and level of hydrocarbon contamination and provides good results on fresh material. However, because the method reports biomass as TPH, the method demonstrates little or no decrease in hydrocarbon content as the result of bioremediation. Thus, its use is

not recommended for setting cleanup standards, monitoring decrease in soil oil content as treatment progresses, or certifying that remediation is complete (Deuel and Holliday, 1994; Troy and others, 1994). In this case, gas chromatography (GC) with flame ionization detection (FID) is the method of choice (EPA modified method 8015).

BTEX

Benzene, toluene, ethylbenzene, and xylene (BTEX) was determined by EPA method 8020, a purge and trap technique. The waste sample (5 g) is extracted in methanol (5 mL). Helium is bubbled through the methanol mixture to purge the BTEX, followed by trapping on a "charcoal" column. The trap is heated to expel the BTEX. Identification is by capillary gas chromatography with photoionization detector, followed by mass spectrometry for confirmation.

Semivolatile Organics

Semivolatile organics were determined by gas chromatography–mass spectrometry (GC-MS) according to EPA method 8270, a capillary column technique. The method quantifies most neutral, acidic, and basic organic compounds that are soluble in methylene chloride at molecular weights of less than 500 or carbon number of 40 or less. Capillary gas chromatography is used to separate compounds in the extract for their qualitative and quantitative analysis by mass spectrometry. The capillary column (30 m × 0.21 mm ID) is directly coupled to the source mass spectrometer, which is computer controlled. For soil samples, the estimated quantitation limit for determining an individual compound is about 1 mg/kg (wet weight).

RESULTS

Waste Description

The physical character of the pit wastes varies between and within pits.

Hydrocarbon-bearing drilling waste in pit A has strong hydrocarbon odor, is well bedded, wet, soft, and variegated in color, whereas that in pit B is less well bedded, dry, firm, and dark in color. In pits C and D, drilling waste when present is mainly soft, dark, and structureless muck. Hydrocarbon-stained native soil beneath the drilling waste is recognized by a distinct contact between them, weaker hydrocarbon odor, lighter color, and sandy composition.

Two kinds of waste were recovered in pit A. Drilling waste on the north, near the discharge point, is composed mainly of thin beds and lamina of buff, cream, brown, and red mud and clay, and black hydrocarbon bands. Some hydrocarbon-rich bands are up to 0.3 ft (0.1 m) thick and may seep crude oil. To the south, distal from the discharge point, cores are dominated by stiff clay, mud, and sandy mud with weak- to moderate-hydrocarbon odor and probably represent mainly oil-stained native soil composing the pit bottom. Drilling waste with strong odor is of secondary abundance.

On the north side of pit B, near the common levee with pit A, firm, dry drilling waste is underlain by firm hydrocarbon-stained sandy mud and muddy very fine-grained sand (native soil). The contact between the two intervals is marked by grass and root fragments. Both intervals exhibit strong hydrocarbon odor. To the south, drilling waste is of secondary abundance and the material cored is dominated by structureless or mottled sandy mud and muddy very fine-grained sand that becomes lighter in color and less odoriferous downward to the extent that odor disappears. Again, drilling waste is separated from the underlying material by a rooted zone.

Pit C is dominated by soft, black, gray, and brown muck in which hydrocarbon odor decreases downward or is absent. Pit D is dominated by mud and very fine-

grained sandy soil lacking hydrocarbon odor, except for core no. 4, which recovered 0.75 ft (0.23 m) of soft, dark drilling waste.

Waste Volume

Waste volume includes drilling waste and oil-stained soil and was determined by (1) probing with a metal rod at each coring point and at additional points along the north side of pit A until resistance was met to estimate thickness, (2) contouring the data, adjusted on the basis of core description and, where appropriate, thicknesses reported by New Park Environmental Services (RRC files), and (3) planimetry of the area enclosed by each contour. Total waste volume is estimated to be 11.3 acre-ft (13,940 m³), with 10.9 acre-ft (13,446 m³) in pits A and B and 0.4 acre-ft (493 m³) in pits C and D. Pit A contains 74 percent of the waste (8.4 acre-ft [10,362 m³]), which is concentrated in the north half of the pit (fig. 8, table 2).

Waste Composition

Waste composition was determined from samples collected as shown in figure 2 and composited as shown in table 3 and analyzed for EC, total metals, TCLP metals, TPH, BETX, and semivolatile organics.

EC

Electrical conductivity (EC) measured on 1:1 soil/water extracts ranges from 54 to 2,202 mS/m and are highest in pit A and lowest in pit D (table 4). The highest values, 2,202 mS/m and 1,279 mS/m, occur on the north side of pit A and correspond to total dissolved solids (TDS) contents of approximately 13,500 mg/L and 7,800 mg/L, respectively, assuming TDS equals 613 times EC in mmho/cm (Deuel and Holliday,

Table 2. Pit waste, water, and levee volume.

	Pit A	Pit B	Pit C	Pit D
Waste Volume	364,728 ft ³	110,484 ft ³	11,188 ft ³	5,174 ft ³
	13,508 yd ³	4,092 yd ³	414 yd ³	192 yd ³
	8.37 ac-ft	2.54 ac-ft	0.26 ac-ft	0.12 ac ft
Water Volume	17,643 ft ³	114,474 ft ³	90,592 ft ³	58,752 ft ³
	3,142 bbl	20,387 bbl	16,134 bbl	10,463 bbl
Levee Volume	78,372 ft ³	96,000 ft ³	63,336 ft ³	39,928 ft ³
	2,903 yd ³	3,556 yd ³	2,346 yd ³	1,479 yd ³
	1.80 ac-ft	2.20 ac-ft	1.45 ac-ft	0.92 ac-ft
	A/B^a		C/D^a	
	18,304 ft ³		17,888 ft ³	
	678 yd ³		663 yd ³	
	0.43 ac-ft		0.41 ac-ft	

^aLevee common to both pits.

Table 3. Waste sample composites and analyses performed.

Sample	Pit	Cores	Analyses					Semi-volatile organics
			EC	Total metals	TCLP metals	TPH	BTEX	
AC-1	A	7,8	X		X	X	X	
AC-2	A	1,6	X		X	X	X	
AC-3	A	2,3,4	X		X	X	X	
AC-4	A	5,10	X		X	X	X	
AC-5	A	9	X		X	X	X	
AC-6	A	1,6,7,8		X				X
AC-7	A	2,3,4,5,9		X				X
BC-1	B	1,2	X		X	X	X	
BC-2	B	3,4,6	X		X	X	X	
BC-3	B	5,7	X		X	X	X	
BC-4	B	8	X		X	X		
BC-5	B	1,2,3,4,6		X				X
BC-6	B	5,7,8		X				X
CC-1	C	2,3	X		X	X		
CC-2	C	1,4	X		X	X		
DC-1	D	1,2,3	X		X	X		
DC-2	D	4	X		X	X		

Table 4. Electrical conductivity of pit waste.

MSL ID#	SPL ID#	EC ^a	EC ^b
95-357	AC-1	22.017	2202
95-358	AC-2	12.795	1279
95-359	AC-3	1.995	200
95-360	AC-4	2.854	285
95-361	AC-5	1.411	141
95-372	BC-1	0.878	88
95-373	BC-2	5.417	542
95-374	BC-3	0.793	79
95-375	BC-4	0.544	54
95-382	CC-1	1.110	111
95-383	CC-2	1.401	140
95-388	DC-1	0.481	48
95-389	DC-2	0.899	90

^aUnits, mmho/cm
^bUnits, mS/m

1994). EC values and, presumably, salt loading in pit A decrease from the north side to the south side of the pit, away from the waste dumping point, to 141 mS/m. Similarly, in pit B the highest value is on the north (542 mS/m), which is boarded to the south by values of less than 100 mS/m. On average, EC in pit D is about 60 mS/m lower than that of pit C.

Total Metals

Total metals were analyzed on four composite samples representing proximal and distal parts of pits A and B relative to the waste dumping point. Metals content was highest in the proximal part of pit A (table 5, sample AC-6) and showed particular enrichment in calcium, iron, zinc, strontium, and barium. Total metals content in the distal part of pit A and pit B is considerably less. High iron content may reflect hematite added as a weighting agent and account for the red bands seen in the waste. Titanium is slightly elevated in all samples and perhaps reflects addition of illmenite as a weighting agent or as an adduct in lignosulfonate muds as might iron. Silica, which exceeds 70 percent in the distal part of pit A and 80 percent in pit B, reflects the dominance of sandy, oil-stained soils in those areas.

TCLP Metals

Toxicity characteristic leaching procedure (TCLP) metals are all well under EPA regulatory limits. Only barium exceeds 1 mg/L, ranging from 1.5 to 7.4 mg/L. In pit A, the range is 2.4 to 7.4 mg/L and in pit B, 0.96 to 2.4 mg/L. Two composite samples from pit C had values of 5.5 and 1.8 and from pit D values of 1.5 and 2.8 mg/L (table 6). Barium's regulatory limit is 100 mg/L.

Table 5. Total metals in pit waste.^a

MSL ID#	SPL ID#	Units	Na	K	Mg	Ca	Al	Fe
95-362	AC-6	mg/kg	6420	5060	3530	27820	24000	68740
95-363	AC-7	mg/kg	4980	6230	2510	15780	31630	13890
95-376	BC-5	mg/kg	5070	6970	2170	7100	28790	10620
95-377	BC-6	mg/kg	4200	6730	2000	4290	34420	13320
MSL ID#	SPL ID#	Units	Ti	Co	Cr	Cu	Mn	Ni
95-362	AC-6	mg/kg	1170	52	245	48	412	31
95-363	AC-7	mg/kg	1600	14	94	13 ^b	163	<14
95-376	BC-5	mg/kg	1950	12	50	13 ^b	102	<14
95-377	BC-6	mg/kg	2330	12	72	10 ^b	85	18
MSL ID#	SPL ID#	Units	Mo	Zn	As	Cd	V	Pb
95-362	AC-6	mg/kg	<10	1380	<60	4	33	262
95-363	AC-7	mg/kg	<10	355	<60	<2	32	48
95-376	BC-5	mg/kg	<10	221	<60	<2	27	47
95-377	BC-6	mg/kg	<10	156	<60	<2	33	22 ^b
MSL ID#	SPL ID#	Units	Sb	Se	Sn	Li	Be	Sr
95-362	AC-6	mg/kg	<160	<138	<18	<8	3.1	1250
95-363	AC-7	mg/kg	<160	<138	<18	24	1.5	545
95-376	BC-5	mg/kg	<160	<138	<18	19	1.4	305
95-377	BC-6	mg/kg	<160	<138	<18	23	1.5	174
MSL ID#	SPL ID#	Units	Ba	Zr	U	Th	P	
95-362	AC-6	mg/kg	173400	40.3	<500	<76	402	
95-363	AC-7	mg/kg	19200	60.4	<500	<76	209	
95-376	BC-5	mg/kg	12500	76.6	<500	<76	198	
95-377	BC-6	mg/kg	10000	84.4	<500	<76	115 ^b	
MSL ID#	SPL ID#	Units	Ce	La	SiO2	Rb		
95-362	AC-6	mg/kg	<110	45.5	300000	<1000		
95-363	AC-7	mg/kg	<110	22.0	740000	<1000		
95-376	BC-5	mg/kg	<110	23.8	818000	<1000		
95-377	BC-6	mg/kg	<110	29.9	825000	<1000		

^aAll values are on a moisture-free basis

^bReported value near detection limit

NE:< = less than indicated value

Table 6. TCLP metals and TPH in pit waste.

Parameters	Procedure	Units	AC-1	AC-2	AC-3	AC-4	AC-5
Arsenic	TCLP ^a	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Barium	TCLP	mg/L	4.4	7.4	2.6	2.9	2.4
Cadmium	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Chromium	TCLP	mg/L	<0.05	<0.05	<0.05	<0.05	<0.05
Lead	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Mercury	TCLP	mg/L	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Selenium	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Silver	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Oil + Grease	Method 5520E ^b	wt% (dry basis)	3.3	6.6	1.8	4.6	1.1
TPH	Method 5520F	wt% (dry basis)	2.4	4.1	1.3	2.8	0.64
Moisture	gravimetric	wt%	32.6	42.0	26.4	42.8	44.8
Parameters	Procedure	Units	BC-1	BC-2	BC-3	BC-4	
Arsenic	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	
Barium	TCLP	mg/L	2.2	1.6	0.96	2.4	
Cadmium	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	
Chromium	TCLP	mg/L	<0.05	<0.05	<0.05	<0.05	
Lead	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	
Mercury	TCLP	mg/L	<0.0002	<0.0002	<0.0002	<0.0002	
Selenium	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	
Silver	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	
Oil + Grease	Method 5520E	wt% (dry basis)	0.60	2.7	0.68	0.05	
TPH	Method 5520F	wt% (dry basis)	0.30	2.1	0.37	0.02	
Moisture	gravimetric	wt%	21.6	23.0	20.9	21.6	
Parameters	Procedure	Units	CC-1	CC-2	DC-1	DC-2	
Arsenic	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	
Barium	TCLP	mg/L	5.5	1.8	1.5	2.8	
Cadmium	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	
Chromium	TCLP	mg/L	<0.05	<0.05	<0.05	<0.05	
Lead	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	
Mercury	TCLP	mg/L	<0.0002	<0.0002	<0.0002	<0.0002	
Selenium	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	
Silver	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	
Oil + Grease	Method 5520E	wt% (dry basis)	0.39	0.49	0.50	1.1	
TPH	Method 5520F	wt% (dry basis)	0.31	0.48	0.05	0.63	
Moisture	gravimetric	wt%	26.1	24.7	21.4	41.1	

^aTCLP (EPA SW-846, method 1311)

^bStandard Methods (18th Ed.)

TPH

The percentage of total petroleum hydrocarbons (TPH) on a dry basis ranges from 0.02 to 4.1 and is highest (2.1 to 4.1) on the north side of pits A and B, corresponding to the waste aprons in those pits (table 6). Southward in pit A, TPH is less than 1.3 percent and in pit B, less than 0.4 percent on the flanks of its waste apron. TPH in pits C and D is less than 1 percent (0.05 to 0.63 percent).

BTEX

Benzene, toluene, ethylbenzene, and xylene (volatile aromatic hydrocarbons) concentrations were highest in pit A (table 7). Total BTEX was highest in the proximal part of pit A (55.5 and 28.5 mg/kg) and low in its distal part and in pit B (<7.5 mg/kg). Benzene content is less than xylene or toluene and probably reflects its greater solubility and volatility as well as its parent crude oils. In crude oil, benzene is commonly less abundant than toluene or xylene (Nyer, 1993). Methyl tert-butyl ether (MTBE), a gasoline additive, is present in low concentrations and indicates that refined product is not a major waste constituent.

Benzene at its highest concentration (5 mg/kg, sample AC-1) would, on the basis of the 20-times rule, be under its TCLP regulatory limit of 0.5 mg/L. If the total amount of a regulated constituent is not at least 20 times the TCLP concentration (10 mg/L for benzene), then even if all the constituent was soluble in the TCLP buffer it would still not exceed the TCLP limit (Kimbrough and others, 1995). Although there are no TCLP limits for toluene, ethyl benzene, and xylene, they are also present at no-action concentrations, being less than the Texas Natural Resource Conservation Commission's media-specific concentrations (MSC) for soil at an industrial site (GSI, 1993 per 31 TAC 335.568, Appendix II).

Table 7. BTEX in pit waste.^a

MSL ID#	SPL ID#	Source	Units	Benzene	Ethyl-Benzene	m,p-Xylenes	MTBE	o-Xylene	Toluene	Total BTEX
95-357	AC-1	pit A	mg/kg	5	11	24	<5	10.5	5	55.5
95-358	AC-2	pit A	mg/kg	3	4	10	<5	5.5	6	28.5
95-359	AC-3	pit A	mg/kg	<0.5	0.5	1	<5	<0.5	0.5	3
95-360	AC-4	pit A	mg/kg	<0.5	1.5	3.5	<5	1.5	0.5	7.5
95-361	AC-5	pit A	mg/kg	<0.5	0.5	1	<5	2	0.5	4.5
95-372	BC-1	pit B	mg/kg	<0.05	<0.05	<0.05	<0.5	<0.05	<0.05	0.25
95-373	BC-2	pit B	mg/kg	<0.5	<0.5	3	<5	1.5	<0.5	6
95-374	BC-3	pit B	mg/kg	<0.5	1	2	<5	0.5	0.5	2.5

^aAll values are on an as-received basis.
 NB: < = less than indicated value.

Although the highest BTEX totals are correlated with the highest TPH values (>2.4 percent), BTEX shows no direct correlation with TPH. For example, the highest BTEX total (55.5 mg/kg) correlates, among the high-range TPH values, with the lowest TPH of 2.4 percent. At total BTEX values of less than 8 mg/kg, TPH ranges from 0.3 to 2.8 percent.

Semivolatile Organics

The concentration of organic compounds is highest on the north side, or proximal part, of pit A (table 8, AC-6) and is dominated by polycyclic aromatic hydrocarbons (PAH's). The PAH's with the highest concentration are methyl naphthalene (70 mg/kg) and naphthalene (48 mg/kg), which are simple PAH compounds. Other PAH's of note are anthracene, chrysene, fluoranthene, phenanthrene, and pyrene. PAH's are also present in the distal part of pit A and in pit B but at very low concentrations; no PAH compound exceeds 1 mg/kg. No chlorinated compounds (pesticides and herbicides) were detected.

Naphthalene, a noncarcinogenic PAH, at its highest concentration in the pit waste is well under its soil MSC of 409 mg/kg. Anthracene and pyrene have MSC's of 3,070 mg/kg and 307 mg/kg, respectively. MSC values for other PAH's of note are unavailable. However, their risk-based concentrations, or RBC's (EPA, 1994), are well in excess of their highest reported concentrations. Benzo(a)pyrene, the most carcinogenic PAH, exceeds its RBC of 0.39 mg/kg in sample AC-6. However, its extremely low solubility (0.0013 mg/L) and volatility, as measured by its Henry's law constant of 0.1, make benzo(a)pyrene essentially immobile in soil (Ryan, 1986).

Table 8. Semivolatile organics in pit waste.^a

Organic Compound	Procedure	Units	AC-6	AC-7	BC-5	BC-6
2,4-dimethylphenol	GC-MS (8270)	mg/kg	6.5	<0.2	<0.2	<0.2
2-methylnaphthalene	GC-MS (8270)	mg/kg	70	0.62	0.36	<0.2
3&4-methylphenol	GC-MS (8270)	mg/kg	7	<0.2	0.42	<0.2
Acenaphthylene	GC-MS (8270)	mg/kg	<5	0.22	<0.2	<0.2
Anthracene	GC-MS (8270)	mg/kg	21	<0.2	0.28	<0.2
Benzo(a)anthracene	GC-MS (8270)	mg/kg	7.5	<0.2	0.24	<0.2
Benzo(a)pyrene	GC-MS (8270)	mg/kg	5.5	<0.2	<0.2	<0.2
bis(2-ethylhexyl)phthalate	GC-MS (8270)	mg/kg	13	<0.2	<0.2	<0.2
Chrysene	GC-MS (8270)	mg/kg	11	<0.2	<0.2	<0.2
Fluoranthene	GC-MS (8270)	mg/kg	19	<0.2	<0.2	<0.2
Naphthalene	GC-MS (8270)	mg/kg	48	0.7	0.92	0.3
Phenanthrene	GC-MS (8270)	mg/kg	29	0.28	0.58	<0.2
Pyrene	GC-MS (8270)	mg/kg	12	<0.2	0.3	<0.2

^aAll values are on an as-received basis.

Water Volume and Composition

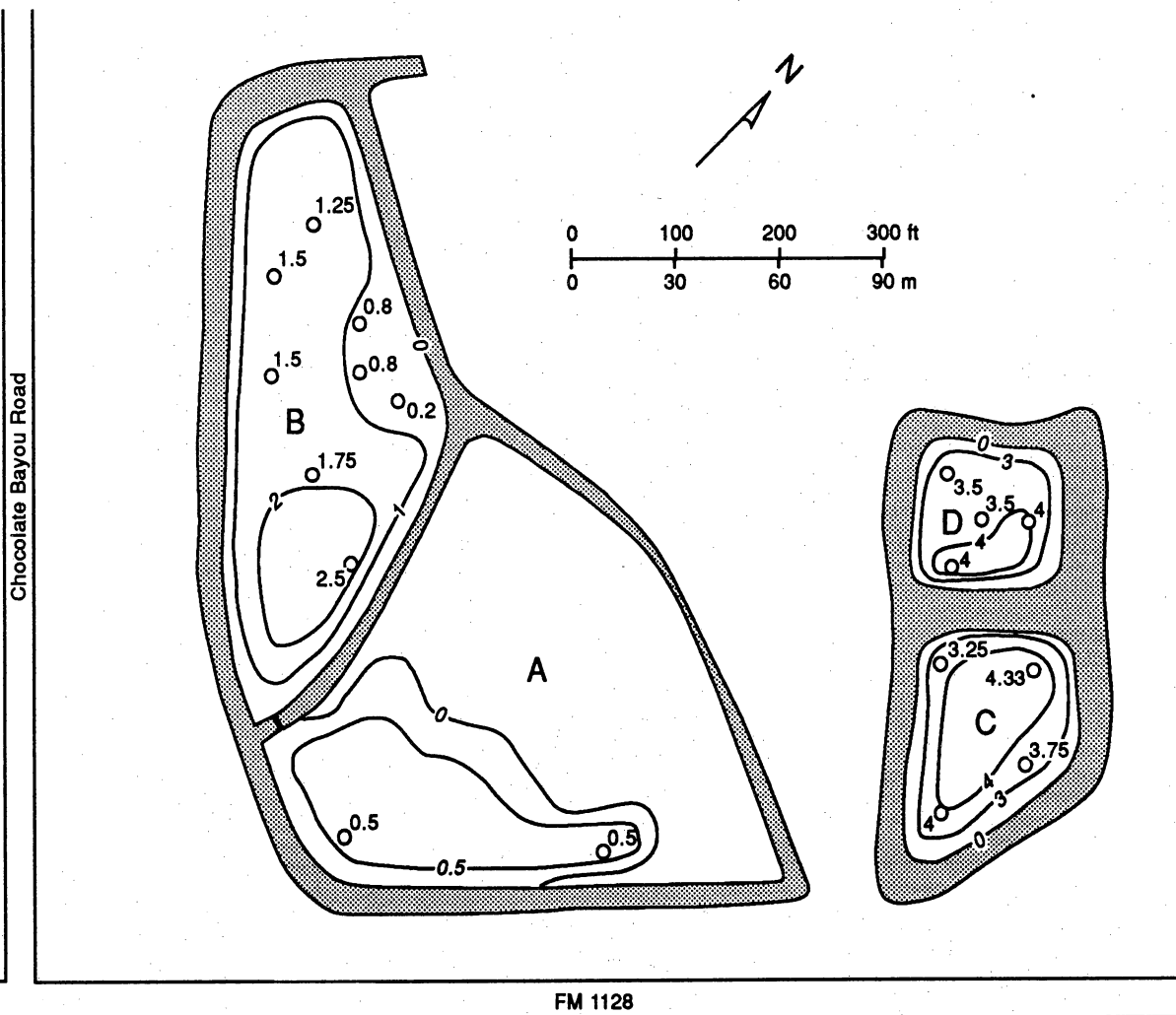
Pit water volumes were determined by estimating thickness at each coring point, contouring the data, and planimentering the area enclosed by each contour. Total water volume is approximately 50,100 bbl, with 23,500 bbl in pits A and B and 26,600 bbl in pits C and D. Pit B contains the most water, 20,4000 bbl (fig. 9, table 2). Water thicknesses were measured in early September after an extended dry spell and water was low in all pits; pit A in particular had so little water that the bottom was exposed in scattered areas.

Pit waters range in TDS content from 495 to 1,391 mg/L and have chlorinities of 69 to 679 mg/L. Bromide is elevated in all pit waters. Metals, such as chromium, arsenic, cadmium, lead, and selenium, are generally less than 1 mg/L. Strontium and barium contents (>1 mg/L) are elevated relative to most of the metals analyzed (table 9). Only barium and arsenic exceed their respective maximum contaminant levels for drinking water, 1 mg/L and 0.05 mg/L. Barium in pits A and B exceeds the Texas Surface Water Quality Standard of 2 mg/L. All pit waters contain less than 0.2 mg/L TPH.

Chemically, the most unusual waters are ditch water no. 2 (a shallow ground water collected in the drainage ditch leading to Mustang Bayou) and the pore water extracted from a pit A core. Both have high TDS content and are rich in sodium, calcium, and chloride; bromide is exceptionally high in the pore water (2,200 mg/L). Most metals are present at concentrations of less than 1 mg/L, except elevated iron (4.03 mg/L) and manganese (2.87 mg/L) in the sample from ditch no. 2, and elevated iron (2.20 mg/L), molybdenum (1.72 mg/L), and zinc (6.42 mg/L) in the pore water.

Levee Volume and Composition

Levee volume was calculated by approximating their cross-sectional shape as a rectangle. The width and length were estimated from a 1990 aerial photograph, and a



A Pit letter [shaded box] Levee 3.75 ○ Water thickness (ft) - 3 - Thickness contour (ft)
 CI variable

QAb1963c

Figure 9. Isopachous map of pit water, Manvel SWD site. Water thicknesses measured in early September 1995.

Table 9. Chemical composition of site waters.

MSL ID#	SPL ID#	Units	Sodium	Potassium	Magnesium	Calcium
95-390A	AC-1a	mg/L	315	24.0	6.5	141
95-391A	BC-1a (near bottom)	mg/L	113	11.5	6.2	38.3
95-392A	BC-2a	mg/L	112	12.1	6.3	37.7
95-393A	CC-1a	mg/L	78.6	2.2	3.7	18.5
95-394A	DC-1a	mg/L	84.5	5.6	7.5	52.2
95-395A	Ditch #2a	mg/L	8610	6.6	343	3450
95-396A	Ditch #3a	mg/L	199	0.7	5.0	56.2
95-397A	Ditch #4a	mg/L	433	6.2	5.6	65.8
95-398A	Pit A pore water(a)	mg/L	5010	185	18.5	2870

MSL ID#	SPL ID#	Units	Fluoride	Chloride	Bromide	Nitrate	Phosphate	Sulfate
95-390B	AC-1b	mg/L	4.7	679	110	ND	ND	16.0
95-391B	BC-1b(near bottom)	mg/L	1.9	168	16.1	ND	ND	3.1
95-392B	BC-2b	mg/L	1.9	169	16.3	ND	ND	3.4
95-393B	CC-1b	mg/L	0.8	69.1	9.3	ND	ND	1.4
95-394B	DC-1b	mg/L	0.9	93.1	49.4	ND	ND	34.6
95-395B	Ditch #2b	mg/L	1.1 ^a	19300	72.7	ND	ND	269
95-396B	Ditch #3b	mg/L	1.8	313	3.1	ND	ND	23.0
95-397B	Ditch #4b	mg/L	3.4	745	2.9	ND	ND	22.3
95-398B	Pit A pore water(b)	mg/L	<1.0	10000	2200	13	ND	479

ND= not detected

MSL ID#	SPL ID#	Units	CO ₃	HCO ₃	TDS	pH	EC ^b	EC ^c
95-390B	AC-1b	mg/L		95.2	1391	8.44	2.202	220.2
95-391B	BC-1b(near bottom)	mg/L		137	495	8.53	0.788	78.8
95-392B	BC-2b	mg/L		139	498	8.66	0.833	83.3
95-393B	CC-1b	mg/L		142	326	7.55	0.491	49.1
95-394B	DC-1b	mg/L		161	489	7.63	0.738	73.8
95-395B	Ditch #2b	mg/L		143	32239	6.56	47.725	4773
95-396B	Ditch #3b	mg/L		124	726	7.66	1.300	130.0
95-397B	Ditch #4b	mg/L	9.4	24.9	1309	9.26	2.222	222.2
95-398B	Pit A pore water(b)	mg/L		NR	20816	8.29	33.810	3381

Table 9 (cont.)

MSL ID#	SPL ID#	Units	V	Al	Fe	Tl	Co	Cr ^d	Hg ^d
95-390A	AC-1a	mg/L	<0.08	<0.48	<0.04	0.4	<0.06	<0.05	<0.0002
95-391A	BC-1a(near bottom)	mg/L	<0.08	<0.48	<0.04	0.5	<0.06	<0.05	<0.0002
95-392A	BC-2a	mg/L	<0.08	<0.48	<0.04	0.4	<0.06	<0.05	<0.0002
95-393A	CC-1a	mg/L	<0.08	<0.48	<0.04	0.3 ^a	<0.06	<0.05	<0.0002
95-394A	DC-1a	mg/L	<0.08	<0.48	<0.04	0.3 ^a	<0.06	<0.05	<0.0002
95-395A	Ditch #2a	mg/L	<0.16	7.84	4.03	<1.0	<0.12	<0.05	<0.0002
95-396A	Ditch #3a	mg/L	<0.08	<0.48	0.09	<0.2	<0.06	<0.05	<0.0002
95-397A	Ditch #4a	mg/L	<0.08	<0.48	<0.04	<0.2	<0.06	<0.05	<0.0002
95-398A	Pit A pore water(a)	mg/L	<0.16	<0.48	2.20	<1.0	<0.12	<0.12	NR

MSL ID#	SPL ID#	Units	Cu	Mn	Ni	Mo	Zn	As ^d	Ag ^d
95-390A	AC-1a	mg/L	<0.06	0.12	<0.14	0.24	<0.02	<0.6	<0.01
95-391A	BC-1a(near bottom)	mg/L	<0.06	<0.01	<0.14	0.1 ^a	<0.02	<0.6	<0.01
95-392A	BC-2a	mg/L	<0.06	<0.01	<0.14	0.1 ^a	<0.02	<0.6	<0.01
95-393A	CC-1a	mg/L	<0.06	<0.01	<0.14	<0.10	<0.02	<0.6	<0.01
95-394A	DC-1a	mg/L	<0.06	<0.01	<0.14	<0.10	<0.02	<0.6	<0.01
95-395A	Ditch #2a	mg/L	<0.12	2.87	<0.28	<0.20	<0.04	<1.2	<0.01
95-396A	Ditch #3a	mg/L	<0.06	0.31	<0.14	<0.10	*0.04	<0.6	<0.01
95-397A	Ditch #4a	mg/L	<0.06	<0.01	<0.14	<0.10	<0.02	<0.6	<0.01
95-398A	Pit A pore water(a)	mg/L	<0.12	0.17	0.63	1.72	6.42	<1.2	NR

MSL ID#	SPL ID#	Units	Cd ^d	Pb ^d	Sb	Se ^d	Sn	Li
95-390A	AC-1a	mg/L	<0.01	<0.01	<1.6	<0.01	<0.18	0.20
95-391A	BC-1a(near bottom)	mg/L	<0.01	<0.01	<1.6	<0.01	<0.18	0.14 ^a
95-392A	BC-2a	mg/L	<0.01	<0.01	<1.6	<0.01	<0.18	0.15 ^a
95-393A	CC-1a	mg/L	<0.01	<0.01	<1.6	<0.01	<0.18	0.12 ^a
95-394A	DC-1a	mg/L	<0.01	<0.01	<1.6	<0.01	<0.18	0.12 ^a
95-395A	Ditch #2a	mg/L	<0.01	<0.01	<3.2	<0.01	<0.36	<0.16
95-396A	Ditch #3a	mg/L	<0.01	<0.01	<1.6	<0.01	<0.18	0.08 ^a
95-397A	Ditch #4a	mg/L	<0.01	<0.01	<1.6	<0.01	<0.18	0.09 ^a
95-398A	Pit A pore water(a)	mg/L	<0.04	<0.4	<3.2	<2.8	<0.36	0.45

Table 9 (cont.)

MSL ID#	SPL ID#	Units	Be	Sr	Ba	Zr	U	Th
95-390A	AC-1a	mg/L	<0.01	4.39	11.6	<0.14	<12	<0.76
95-391A	BC-1a(near bottom)	mg/L	<0.01	1.35	3.52	<0.14	<12	<0.76
95-392A	BC-2a	mg/L	<0.01	1.33	3.51	<0.14	<12	<0.76
95-393A	CC-1a	mg/L	<0.01	0.44	1.30	<0.14	<12	<0.76
95-394A	DC-1a	mg/L	<0.01	0.81	1.88	<0.14	<12	<0.76
95-395A	Ditch #2a	mg/L	<0.02	26.1	2.98	<0.28	<24	<1.52
95-396A	Ditch #3a	mg/L	<0.01	0.38	0.23	<0.14	<12	<0.76
95-397A	Ditch #4a	mg/L	<0.01	0.78	0.40	<0.14	<12	<0.76
95-398A	Pit A pore water(a)	mg/L	<0.02	25.2	3.13	<0.28	<24	<1.52

MSL ID#	SPL ID#	Units	B	P	Ce	La	Si	Rb
95-390A	AC-1a	mg/L	0.77	<1.2	<1.1	<0.10	4.82	<14
95-391A	BC-1a(near bottom)	mg/L	0.41	<1.2	<1.1	<0.10	6.51	<14
95-392A	BC-2a	mg/L	0.42	<1.2	<1.1	<0.10	6.51	<14
95-393A	CC-1a	mg/L	0.15 ^a	<1.2	<1.1	<0.10	0.35 ^a	<14
95-394A	DC-1a	mg/L	0.09 ^a	<1.2	<1.1	<0.10	5.07	<14
95-395A	Ditch #2a	mg/L	0.51	<2.4	<2.2	<0.20	7.15	<28
95-396A	Ditch #3a	mg/L	0.15 ^a	<1.2	<1.1	<0.10	3.89	<14
95-397A	Ditch #4a	mg/L	0.28	<1.2	<1.1	<0.10	3.06	<14
95-398A	Pit A pore water(a)	mg/L	0.83	<2.4	<2.2	<0.20	3.94	<28

MSL ID#	SPL ID#	Ratio	Cl/Br	SO4/Cl
95-390	AC-1	mq/L/mg/L	6.2	0.02
95-391	BC-1(near bottom)	mq/L/mg/L	10.4	0.02
95-392	BC-2	mq/L/mg/L	10.4	0.02
95-393	CC-1	mq/L/mg/L	7.4	0.02
95-394	DC-1	mq/L/mg/L	1.9	0.4
95-395	Ditch #2	mq/L/mg/L	265	0.01
95-396	Ditch #3	mq/L/mg/L	101	0.07
95-397	Ditch #4	mq/L/mg/L	257	0.03
95-398	Pit A pore water	mq/L/mg/L	4.5	0.05

Table 9 (cont.)

CATION-ANION BALANCE

MSL ID#	SPL ID#	Units	CATIONS	ANIONS	%ERROR
95-390	AC-1	meq/L	21.877	22.668	-1.77
95-391	BC-1(near bottom)	meq/L	7.639	7.343	1.98
95-392	BC-2	meq/L	7.582	7.418	1.09
95-393	CC-1	meq/L	4.700	4.544	1.69
95-394	DC-1	meq/L	7.037	6.801	1.70
95-395	Ditch #2	meq/L	575.107	553.162	1.95
95-396	Ditch #3	meq/L	11.891	11.488	1.72
95-397	Ditch #4	meq/L	22.721	22.418	0.67
95-398	Pit A pore water	meq/L	367.311	319.673	6.93

^aReported value near detection limit.

^bUnits, mmho/cm

^cUnits, mS/m

^dData from RRC Lab TCLP metals, except Pit A pore water.

NB: < = less than indicated value, ND = not detected, NR = not reported.

4-ft (1.2-m) height was assumed from field observation and descriptions in RRC files. On that basis, total levee volume is 7.2 acre-ft (8,882 m³) (table 2), and because of the larger size of pits A and B resides mainly in the levees surrounding them (4.4 acre-ft [5,428 m³]).

Electrical conductivity of augered levee samples ranges from 35 to 204 mS/m and is highest on the north side of pits A and B and on the C and D common levee; pH is near neutral (fig. 2, table 10). Levee-margin samples north of pit B have very high conductivities (>1,200 mS/m) and correspond to high chloride content and the presence of bioindicators (kill areas and abundant halophytes). Higher chloride generally reflects higher EC.

TCLP metals are all well under EPA regulatory limits. Only barium exceeds 1 mg/L, ranging from 1.1 to 2.1 mg/L and was highest in the pit C and D samples, 2.1 and 1.6 mg/L (table 11). Levee soils are essentially free of petroleum hydrocarbons; TPH content ranges from 0 to 0.05 percent (table 11).

Electromagnetic Induction Survey

Ground conductivity data were collected along five lines at the Manvel site (fig. 2). Four lines were located around the perimeter of the site, and one was located across the site interior north of pits A and B. Perimeter lines were acquired to examine whether there was geophysical evidence of saltwater movement beyond the site boundaries. The interior line was acquired to check pits A and B and plugged wells for leakage and to determine whether there is evidence that saltwater has infiltrated the subsurface along the drainage ditch leading to Mustang Bayou.

Table 10. Electrical conductivity of levee soil.

MSL ID#	SPL ID#	EC ^a	EC ^a	pH ^a	Cl ^b
95-308	A1	0.405	40.5	7.37	
95-309	A2	0.881	88.1	7.90	
95-310	A3	0.595	59.5	7.34	
95-311	A4	2.036	203.6	6.38	507
95-312	A5	0.719	71.9	6.56	
95-313	A6	0.375	37.5	6.54	5.6
95-314	A7	0.408	40.8	6.88	
95-317	B1	0.650	65.0	6.78	
95-318	B2	0.646	64.6	6.66	
95-319	B3	0.546	54.6	6.41	
95-320	B4	1.083	108.3	6.44	202
95-321	B5	1.443	144.3	6.49	254
95-322	B6	0.414	41.4	7.26	
95-323	B7	0.467	46.7	7.25	
95-326	C1	0.409	40.9	7.42	
95-327	C2	0.512	51.2	7.44	
95-328	C3	0.376	37.6	7.53	
95-329	C4	0.351	35.1	6.60	
95-332	D1	0.684	68.4	7.04	
95-333	D2	1.202	120.2	7.40	168
95-334	D3	0.374	37.4	7.40	
95-335	D4	0.535	53.5	7.19	
95-338	BLANK	0.572	57.2	7.79	2.1
95-339	LM-1	12.3165	1232	7.60	4140
95-340	LM-2	13.9725	1397	7.33	4790

^aMeasurement performed on 1/1 aqueous extract in mmho/cm and mS/m.

^bReported on a moisture-free basis in mg/kg.

Table 11. TCLP metals and TPH in levee soil.

Parameters	Procedure	Units	PIT A	PIT B	PIT C	PIT D	BLANK
Arsenic	TCLP ^a	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Barium	TCLP	mg/L	1.1	1.1	2.1	1.6	1.4
Cadmium	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Chromium	TCLP	mg/L	<0.05	<0.05	<0.05	<0.05	<0.05
Lead	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Mercury	TCLP	mg/L	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Selenium	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Silver	TCLP	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Oil + Grease	Method 5520E ^b	wt% (dry basis)	0.13	0.06	0.24	0.17	0.06
TPH	Method 5520F	wt% (dry basis)	0.04	0.00	0.05	0.04	0.00
Moisture	gravimetric	wt%	7.6	5.5	9.0	9.2	13.0

^aTCLP (EPA SW-846, method 1311)

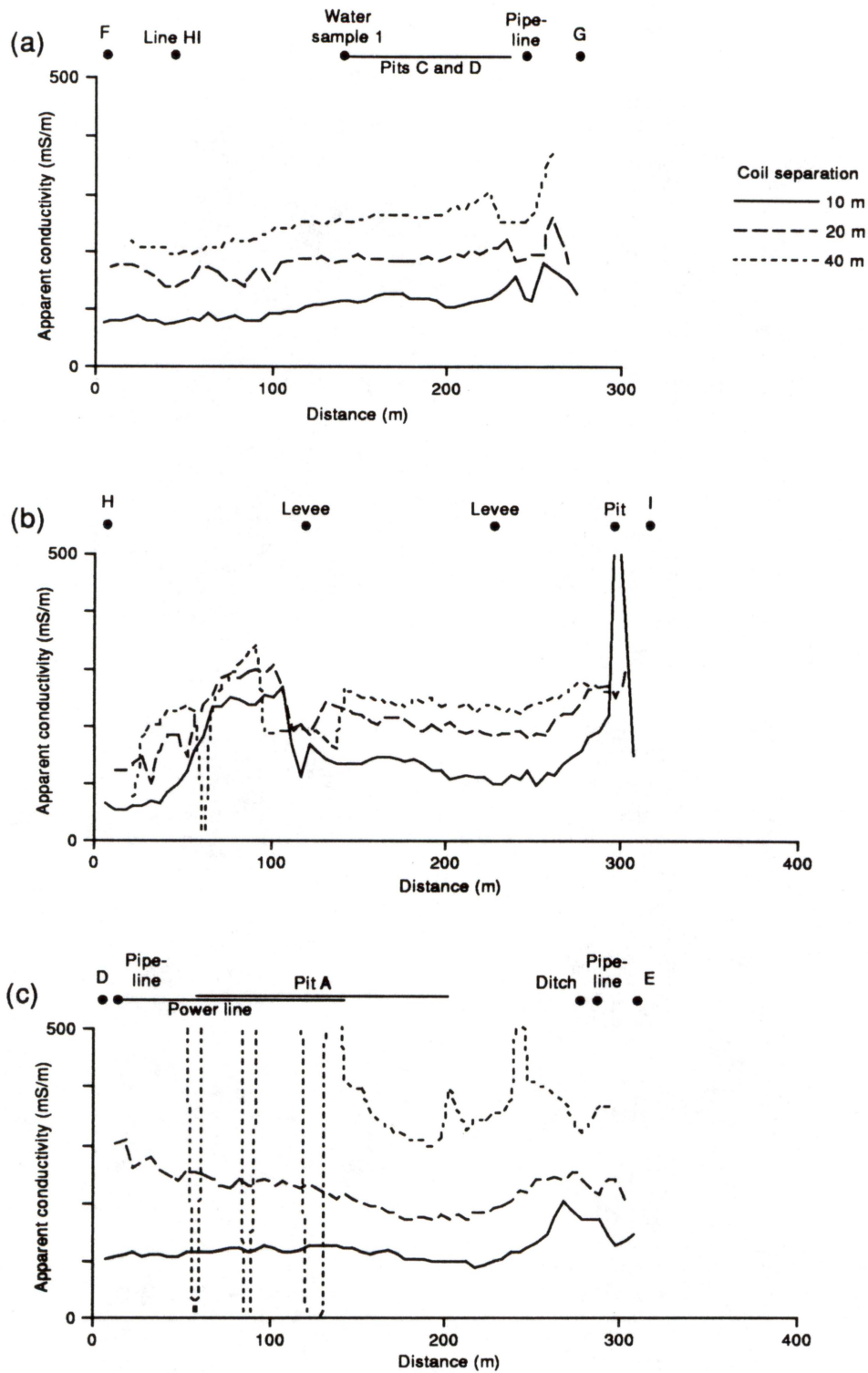
^bStandard Methods (18th Ed.)

Line FG

Line FG is located at the northeastern border of the Manvel site and is 280 m (919 ft) long (fig. 2). It is situated near the base of the levees around pits C and D and passes near a backfilled pit in the northeast part of the site. Apparent horizontal-dipole conductivities along this line are high and increase with coil separation (fig. 10a). Apparent conductivities increase from 70 to 180 mS/m at 10-m (33-ft) separation, to 135 to 260 mS/m at 20-m (66-ft) separation, to 190 to 370 mS/m at 40-m (131-ft) separation. Apparent conductivities for all horizontal-dipole coil separations decrease from the south to the north end of the line. Vertical-dipole data (fig. 11a) show the opposite trend, that of increasing apparent conductivities from south to north. South of pit C, apparent conductivities for long vertical-dipole separations become negative, suggesting that actual ground conductivity increases southward and is high enough to cause a nonlinear instrument response in the vertical-dipole orientation.

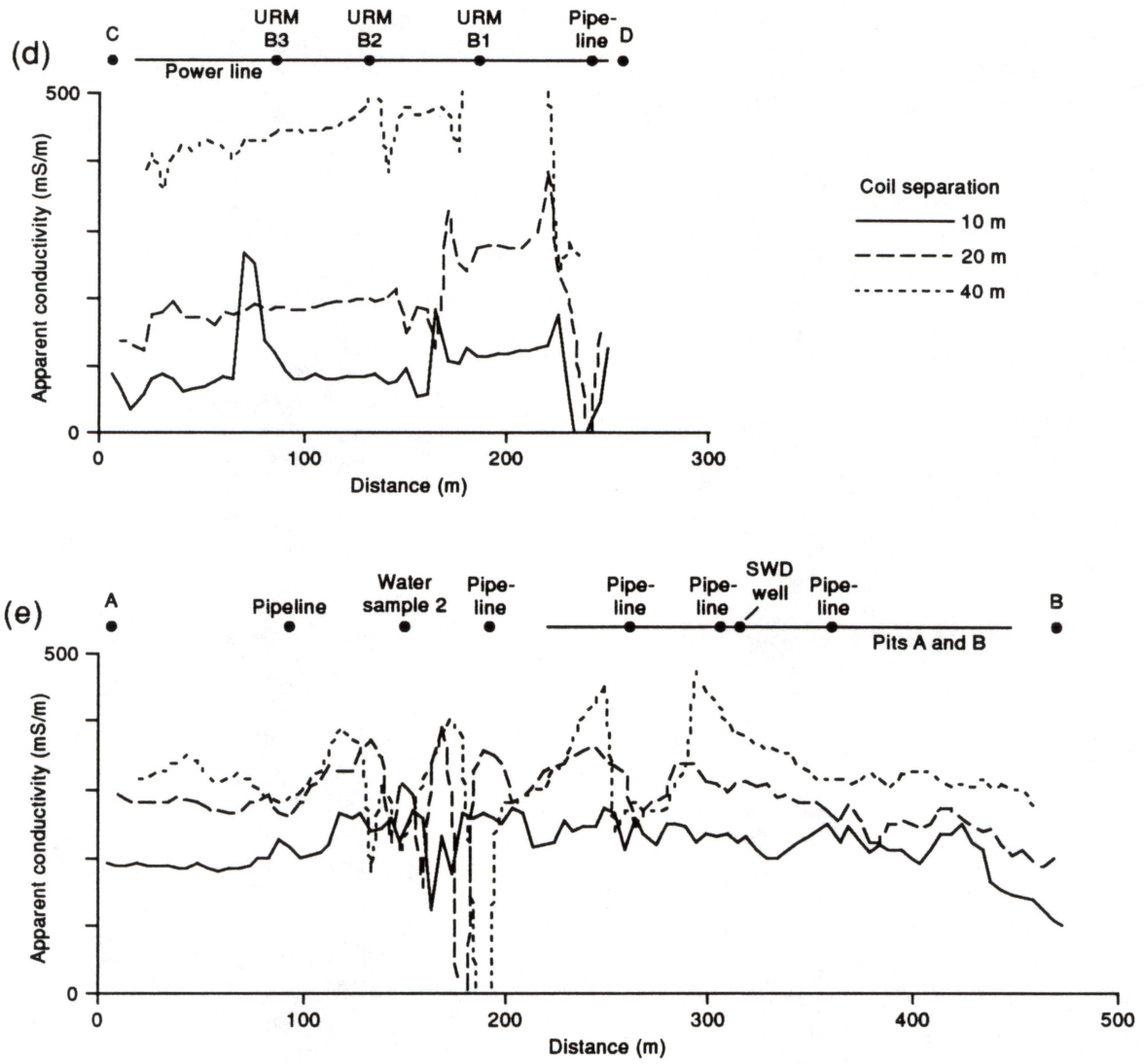
Horizontal- and vertical-dipole measurements along line FG clearly show that ground conductivities decrease northward away from pits C and D and that conductivities increase downward within the exploration range of the instrument (longer separations measure higher apparent conductivities). Erratic measurements near the south end of the line are caused by a pipeline that crosses the line. Away from the pipeline, highest conductivities are found adjacent to pits C and D. Horizontal-dipole conductivities at the north end of the line (fig. 10a), the lowest observed at the Manvel site, may represent ground conductivities that are closest to background values.

Conductivity models constructed from horizontal- and vertical-dipole measurements at two stations on line FG (figs. 2 and 12a,b) indicate that a highly conductive layer is present near the surface. At station FG1, located near a filled pit, a relatively nonconductive surface layer about 4 m (13 ft) thick is underlain by a moderately conductive layer (627 mS/m), modeled to be about 10 m (33 ft) thick



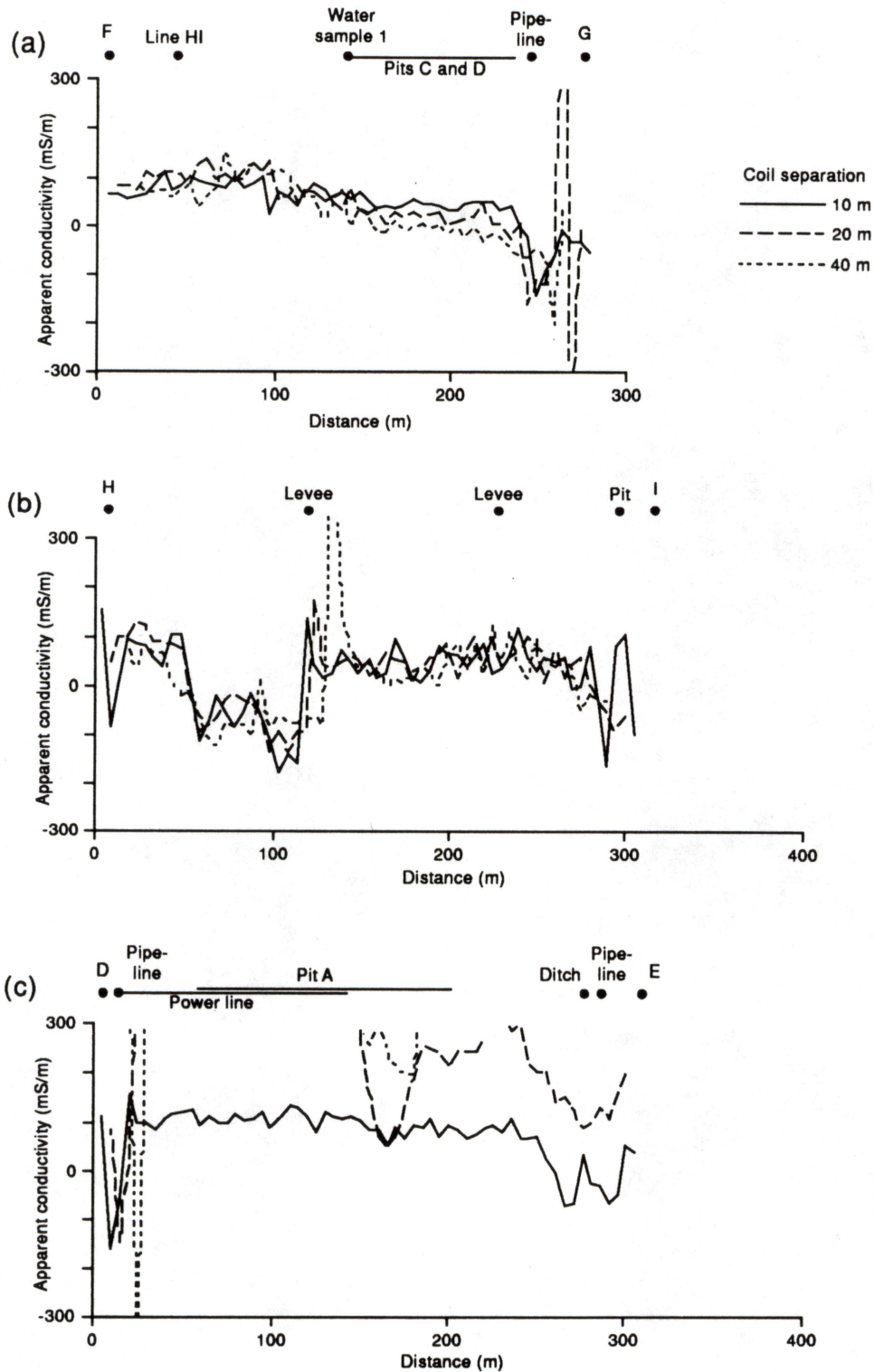
QAb2679c(a-c)

Figure 10. Apparent conductivity along geophysical lines FG, HI, DE, CD, and AB, Manvel SWD site. Conductivities measured in the horizontal-dipole mode at 10-, 20-, and 40-m coil separations. See figure 2 for location of lines.



QAb2679c(d-e)

Figure 10 (cont.)



QAb2680c(a-c)

Figure 11. Apparent conductivity along geophysical lines FG, HI, DE, CD, and AB, Manvel SWD site. Conductivities measured in the vertical-dipole mode at 10-, 20-, and 40-m coil separations. See figure 2 for location of lines.

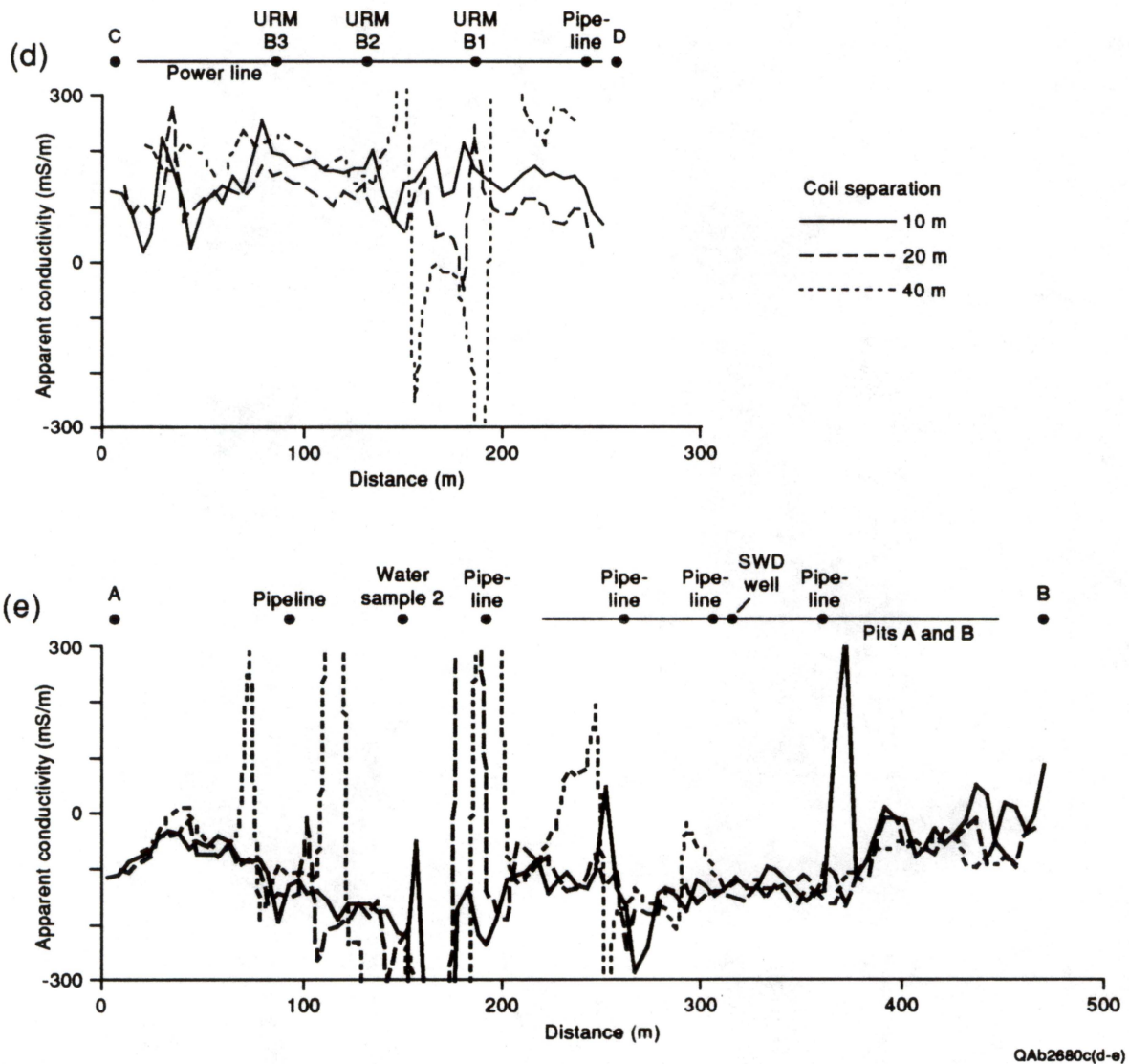


Figure 11 (cont.)

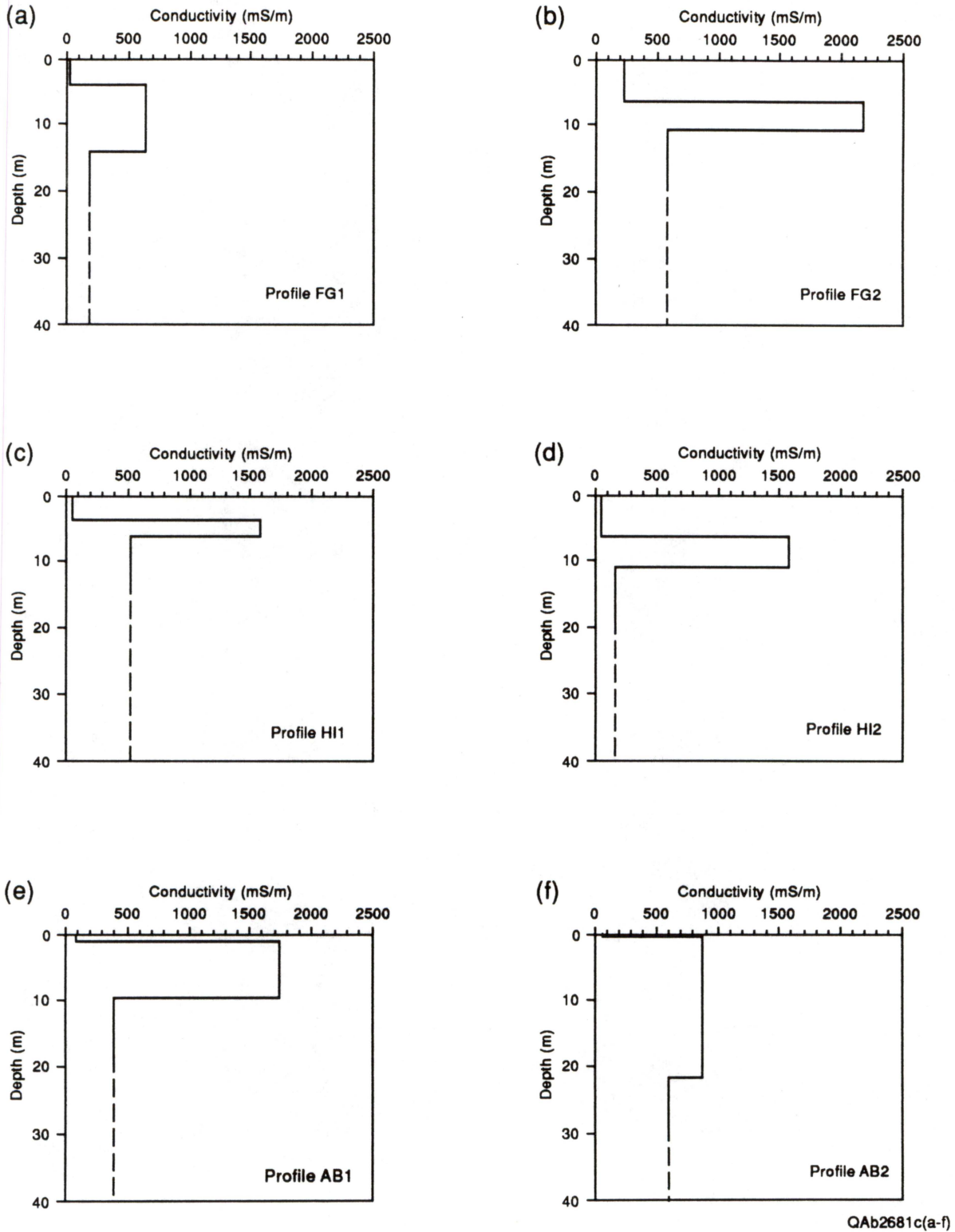


Figure 12. Models of electrical conductivity variation with depth at stations FG1 (a) and FG2 (b) along line FG, stations HI1 (c) and HI2 (d) along line HI, and stations AB1 (e) and AB2 (f) along line AB. See figure 2 for location of conductivity profiles.

(fig. 12a). Below 14-m (46-ft) depth is a less conductive layer (167 mS/m) that extends to an unknown depth. Farther south on line FG, adjacent to pit D, a profile modeled at station FG2 (fig. 12b) has a thicker zone of relatively low conductivity at the surface (6.7 m [22 ft] at 221 mS/m), underlain by an extremely conductive zone (2178 mS/m) that is modeled to be 4.3 m (14 ft) thick. Conductivities remain moderately high (about 600 mS/m) below 11 m (36 ft).

These profiles and the unprocessed horizontal- and vertical-dipole measurements both indicate elevated subsurface conductivities along the line that are caused by saltwater infiltration. The profiles can be interpreted to represent an unsaturated zone having relatively low conductivity at the surface, underlain by a highly conductive layer that probably is saturated with saltwater. Above-background conductivities in the lowest layer suggest that its upper boundary is a gradual one, actual conductivities decreasing downward from values that are higher than the modeled conductivity near the top of the layer to background values at an undetermined depth.

Line HI

This line crosses the northwestern part of the site and is 310 m (1,017 ft) long. It extends northeast from the Chocolate Bayou Road entrance to the site, passes along the levee at the west side of pit B, crosses a large, leveed area west of a north-south-trending site road, and ends at line FG near a small, backfilled pit (fig. 2). Horizontal-dipole apparent conductivities are high along the line and generally increase with coil separation (fig. 10b). Highest apparent conductivities are found for 10-m (33-ft) and 20-m (66-ft) separations at the backfilled pit. Between the filled pit and the levee at the southwest margin of the leveed area, horizontal- and vertical-dipole data show the same conductivity trend (figs. 10b and 11b). Horizontal-dipole conductivities are 100 to 150 mS/m at the 10-m (33-ft) coil separation, increase to about 200 mS/m at the 20-m

(66-ft) coil separation, and increase further to about 250 mS/m at the 40-m (131-ft) coil separation. The high conductivity at the backfilled pit reflects its former role as a saltwater pumping pit. Southwestward of the leveed area, horizontal-dipole conductivities increase and vertical-dipole conductivities are negative for all coil separations, indicating very high ground conductivities. This highly conductive area coincides with the western boundary of pit B and the presence of abundant halophytes. Horizontal-dipole apparent conductivities decrease from the edge of pit B to the end of the line at Chocolate Bayou Road.

Conductivity models along line HI were constructed from horizontal- and vertical-dipole data from stations HI1, located within the leveed area, and station HI2, located between pit B and Chocolate Bayou Road (figs. 2 and 12c,d). These modeled profiles are generally similar to those on other lines at the Manvel site: a surface zone of low conductivity underlain by a highly conductive layer, which in turn is underlain by a moderately conductive layer. Within the leveed area, the surface layer is modeled to be about 4 m (13 ft) thick and has a relatively low conductivity of 42 mS/m (fig. 12c). The underlying conductive zone is about 2.5 m (8.2 ft) thick and extends to a depth of between 6 and 7 m (20 and 23 ft). The basal layer has a moderately high conductivity of about 500 mS/m and extends to an unknown depth. Southwest of pit B, the surficial low-conductivity layer at station HI2 is modeled to be 6.4 m (21 ft) thick and is underlain by a conductive layer that is thicker than that at HI1 (fig. 12d) and extends to a depth of about 11 m (36 ft).

The high conductivities observed along line HI and the modeled, highly conductive zones in the subsurface indicate that electrically conductive fluids are present in the subsurface along this line. Similar to vertical profile sites along lines FG and AB, relatively dry near-surface sediments are shown in the model as a low-conductivity surface layer. This layer overlies a highly conductive layer that extends to a depth of 7 to 11 m (23 to 36 ft) at the two stations on line HI and is interpreted to be saltwater

saturated. Below this layer, electrical conductivity probably decreases gradually to an unknown depth.

Line DE

Line DE was acquired in the right-of-way along FM 1128 along the southeast side of the Manvel site. This line is 310 m (1,017 ft) long and passes near the levee bounding pit A (fig. 2). Horizontal-dipole apparent conductivities are high and increase with coil separation, much as they do along the other geophysical lines at the site (fig. 10c). Measurements for the 10-m (33-ft) coil separation are 100 to 200 mS/m. Conductivities increase to 180 to 300 mS/m for the 20-m (66-ft) coil separation and are higher than 300 mS/m for the 40-m (131-ft) separation. Highest apparent conductivities at the 10-m (33-ft) separation are found in a 50-m-long (164-ft) segment near the north end of the line where a culvert and drainage ditch cross FM 1128 (fig. 10c). Elevated conductivities are also observed in this area at the 20-m (66-ft) coil separation. Vertical-dipole measurements are also anomalous, showing a drop in apparent conductivity that suggests ground conductivity is sufficiently high to cause nonlinear instrument response in the vertical-dipole mode (fig. 11c). This conductive area is probably caused by relatively wet near-surface sediments in the ditch.

Elevated horizontal-dipole conductivities are also observed adjacent to the pit A levee in 20-m (66-ft) and, to a lesser extent, in 10-m (33-ft) coil-separation data (fig. 10c). More pronounced response in the 20-m (66-ft) separation data suggests that most of the conductivity increase is between the 6-m (20-ft) exploration depth of the 10-m (33-ft) coil separation and the 12-m (39-ft) exploration depth of the 20-m (66-ft) coil separation. Apparent conductivities for the 20-m (66-ft) coil separation continue to increase southward beyond the pit A levee, whereas conductivities measured at the 10-m (33-ft) separation decrease slightly. Measurements made for the 40-m (131-ft) horizontal-dipole

coil separation and for the 20- (66-) and 40-m (131-ft) vertical-dipole coil separations were clearly affected by power line noise (figs. 10c and 11c). Because of this noise, not enough valid coil configurations remain to construct vertical conductivity profiles along this line.

Line CD

Line CD was acquired in the right-of-way along Chocolate Bayou Road at the southwest boundary of the Manvel site (fig. 2). The line is 255 m (837 ft) long, is about 50 m (164 ft) southwest of the levees that surround pits A and B, and passes near the locations of shallow boreholes B1, B2, and B3 (fig. 2). Horizontal-dipole apparent conductivities are high along this line and increase with increasing coil separation (fig. 10d). A pipeline near the south end of the line causes anomalously low horizontal-dipole conductivity measurements; other anomalies in the horizontal-dipole data are found about 75 m (246 ft) from endpoint C for the 10-m (33-ft) coil separation and about 170 m (558 ft) from endpoint C for the 10- (33-) and 20-m (66-ft) coil separations. The anomaly at 75 m (246 ft) is probably caused by a pipeline crossing, whereas the one near 170 m (558 ft) coincides with the location of an overhead power line across Chocolate Bayou Road.

Horizontal-dipole conductivities generally decrease from point D to point C for each coil separation (fig. 10d). Power line noise may contribute to elevated apparent conductivities at the 40-m (131-ft) coil separation, but the trend of declining conductivity from D to C appears to be valid for this coil separation as well. Actual ground conductivities should thus generally decrease from D to C.

Water samples from boreholes B1, B2, and B3 along line CD show that chloride content and electrical conductivity increase downward from 80 mg/L chloride and 120 mS/m conductivity at 3-m (10-ft) depth to 9100 mg/L chloride and 5500 mS/m

conductivity at 10-m (33-ft) depth (URM, 1985). These data are in accord with geophysical measurements that show increasing apparent conductivity with coil separation (and thus depth) for the horizontal-dipole coil configuration. Although there are too few valid coil orientations along line CD available to calculate conductivity models, borehole sample data are also in accord with conductivity models derived from nearby sites. These models have a low-conductivity zone several meters thick at the surface; the surface layer is underlain by a conductive layer that extends to a depth of about 10 m (33 ft) (fig. 12). As is shown in the borehole data, salinities (and electrical conductivities) increase with depth in this area from 3 to 10 m (10 to 33 ft). Electrical conductivities of water samples from the boreholes are higher than actual ground conductivities because the host sediments have very low electrical conductivities.

Line AB

Line AB is an east-west interior line that extends 485 m (1,591 ft) from the bridge on Chocolate Bayou Road over the drainage ditch exiting the site to the site entrance on FM 1128 (fig. 2). The line passes near the base of levees that bound the north side of pits A and B and along the axis of the drainage ditch. The highest horizontal-dipole apparent conductivities at the Manvel site for the 10- and 20-m (33- and 66-ft) coil separations were recorded along this line (fig. 10e), as well as the most negative vertical-dipole apparent conductivities (fig. 11e). This line, along most of its extent, lies in an area of abundant halophytes and west of the SWD well. Line AB crosses several above-ground and buried pipelines, many of which cause anomalous horizontal- or vertical-dipole instrument responses.

Similar to the perimeter lines, horizontal-dipole conductivities increase with coil separation, which suggests that ground conductivities increase with depth (fig. 10e). For the 10-m (33-ft) coil separation, conductivity values range from 100 to nearly 300 mS/m,

and highest values are observed along pits A and B and down the drainage ditch west of pit B for a distance of about 100 m (328 ft). Conductivities for the 10-m (33-ft) separation are somewhat less elevated (about 200 mS/m) at the west end of the line. For the deeper sensing 20-m (66-ft) coil separation, horizontal-dipole conductivities are between 200 and 350 mS/m. These conductivities increase westward along pits A and B and reach some of their highest values adjacent to pit B (fig. 10e). The highest horizontal-dipole values, and the most negative vertical-dipole values (fig. 11e), are located along a 50-m-long (164-ft) segment just west of pit B near the site of ditch water sample no. 2 (fig. 2) and corresponds to the presence of abundant halophytes.

Two vertical-conductivity profile models constructed from horizontal- and vertical-dipole data have a sequence of conductivity layers that is similar to that in the other profiles at the site, but have thinner low-conductivity zones at the surface (fig. 12e,d). Profile AB1, located near the junction of pits A and B in an area of abundant halophytes, has a surface layer that is only 1.4 m (4.6 ft) thick and has a modeled conductivity of 86 mS/m. Below this is a highly conductive zone (1737 mS/m) that extends to a depth of about 10 m (33 ft). A moderately conductive zone (385 mS/m) is modeled below this. Similarly, profile AB2, located adjacent to pit A, has a surface layer that is modeled to be less than 1 m (<3 ft) thick and is underlain by a highly conductive zone (886 mS/m) that extends to a depth of 22 m (72 ft). Thinner, low-conductivity layers at the surface at these stations suggest that saltwater is found nearer the surface here. This interpretation is further supported by the presence of salt-tolerant vegetation along line AB. Saltwater closer to the surface along this line may also imply that near-surface salinity sources were or are located nearby, such as pits A and B or the plugged SWD and oil wells.

INTERPRETATION

The key issues at the Manvel SWD site are (1) the source and extent of saltwater contamination of shallow ground water and (2) the hazardous/nonhazardous nature of the waste in the open pits.

Saltwater Contamination

There are two known possible sources for the saltwater contamination detected at the Manvel SWD site: saltwater brought onsite and discharged into the pits and saltwater disposal well, and formation water leaking from the abandoned oil well or saltwater disposal well or both before they were plugged.

Saltwater contamination on and off site is evident in the distribution of halophytes, chemical analyses, and ground conductivity. Halophytes are abundant to the north of pits A and B, where electrical conductivity at shallow depth exceeds 1,200 mS/m in levee-margin soils (table 10), and to the west of pit B, where chloride content is 19,300 mg/L and TDS about 32,000 mg/L in ditch sample no. 2 (table 9, fig. 2). Chlorinity in well B3, along Chocolate Bayou Road, southwest of pit B, was 9,100 mg/L in 1985 at a depth of 30 ft (9 m) (URM, 1985) and is almost identical to that of the pit A pore water (table 9). Well B3 water had an electrical conductivity of 5,500 mS/m (55 mmho/cm) and a calculated TDS content of approximately 34,000 mg/L.

The electromagnetic induction survey of the Manvel site shows elevated ground conductivity within the site and along its perimeter (figs. 10 and 11). Because saltwater is a good electrical conductor and known to be present on-site, elevated conductivity is attributed to subsurface infiltration of saltwater. Ground conductivities at the site are at least 100 mS/m at shallow depths and increase to more than 300 mS/m with depth (fig. 10). Values of more than 1,500 mS/m were modeled (fig. 12). The highest ground conductivities were observed along the line crossing the site north of pits A and B

(fig. 2), where calculated vertical-conductivity profiles (fig. 12) and halophytes suggest that saltwater can be found within 1 m (3 ft) of the surface. Around the perimeter of the site, vertical-conductivity profiles show that the upper boundary of a layer containing saltwater is deeper than 2 m (6.6 m) below the surface.

From the preceding observations, it is postulated that saltwater migrated outward and downward from pits A and B into a shallow sand underlying the site (figs. 13 and 14). The modeled high-conductivity layer between depths of approximately 6.6 and 33 ft (2 and 10 m) corresponds to a shallow sand penetrated in drilling (URM, 1985).

Decrease in ground conductivities modeled at a depth of approximately 33 ft (10 m) coincides with the sand's lower boundary with an underlying red mud. Geophysical data suggest that the mud may form a leaky barrier to downward migration of saltwater and that saltwater has not reached the Chicot aquifer at approximately 200 ft (61 m) below land surface. Below the conductive layer is a less conductive zone in which conductivities decrease downward to background values at an undetermined depth below 33 ft (10 m).

High chlorinity is attributed to disposal activities at the Manvel site and not to surface water flowing onto the site. There were no halophytes observed along the drainage ditch entering the site from the northeast nor along it on the northeast side of pits C and D. Site chlorinities are well in excess of those reported for Beaumont waters prior to disposal activities. For example, in 1933, chloride content was 19 mg/L in a 60-ft (18-m) well less than 1,500 ft (457 m) east of the site (fig. 13, well no. 704). Moreover, conductivities of the Beaumont Formation, containing water of TDS content less than 1,000 mg/L, are less than 100 mS/m in the vicinity of the site (Sandeen and Wesselman, 1973). Typically, in the Gulf Coast, an aquifer fully saturated with water having a TDS content greater than 3,000 mg/L (~1,500 mg/L chloride) has a conductivity greater than 200 mS/m (Fogg and others, 1991).

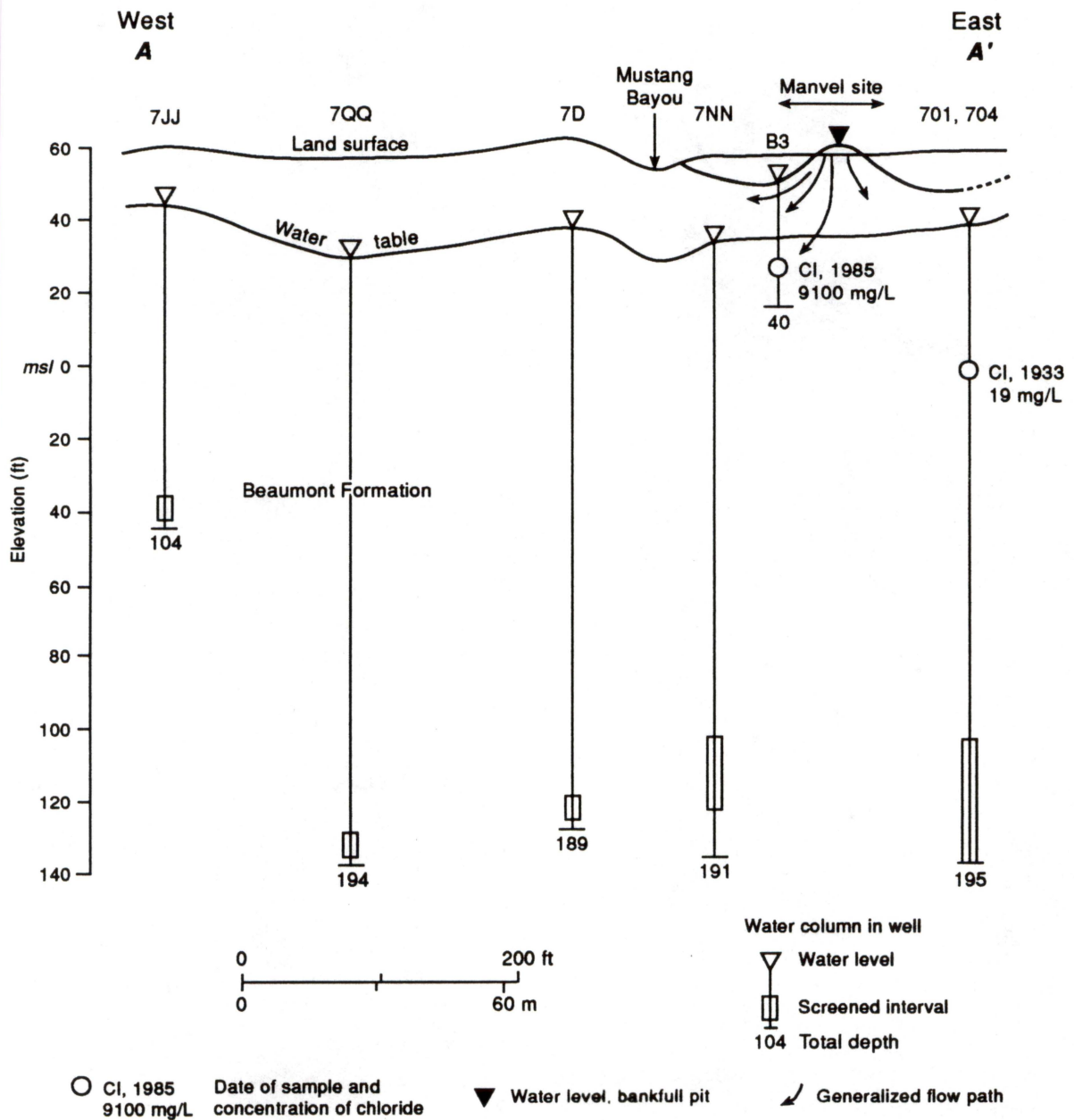


Figure 13. Hydrogeologic cross section through the Manvel SWD site. High hydraulic head at the site and density contrast causes saltwater to move downward and laterally toward Mustang Bayou. See figure 6 for location of cross section.

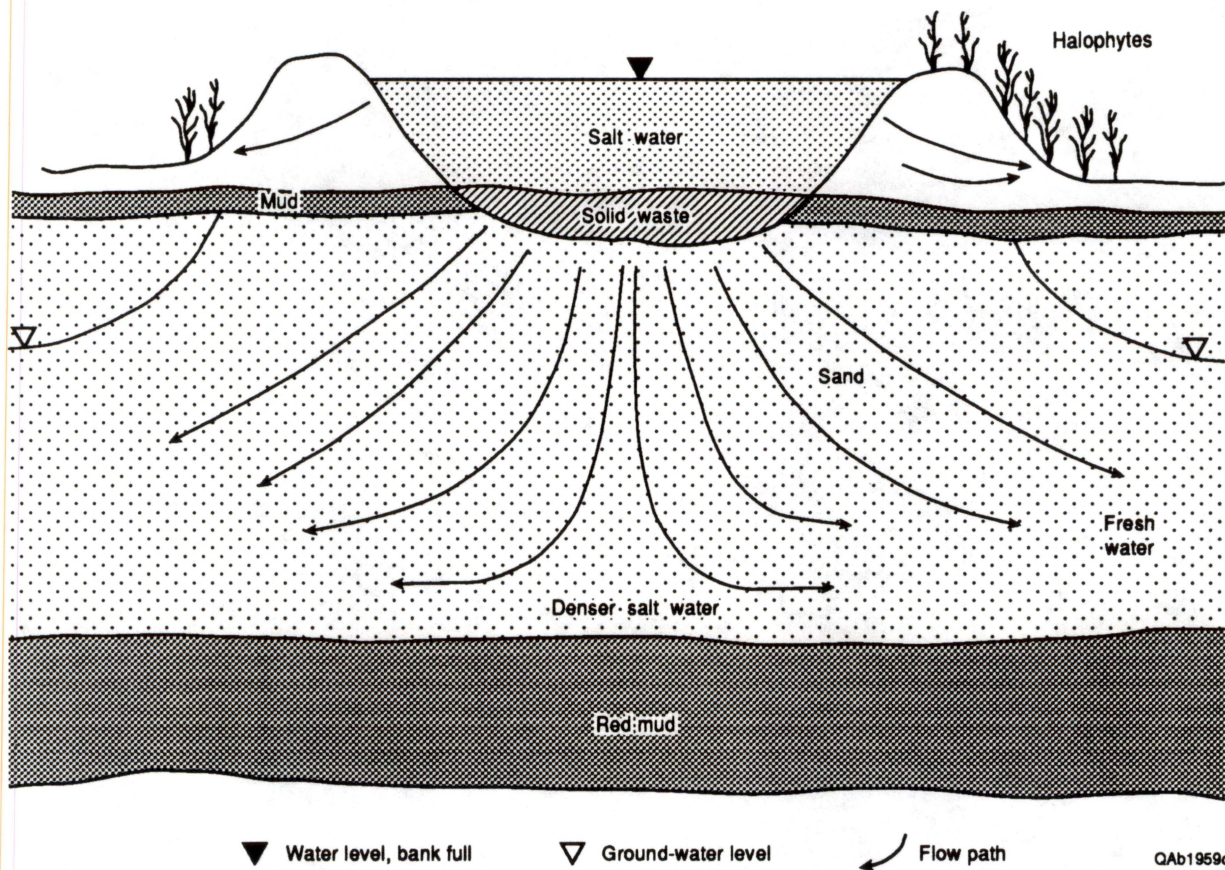


Figure 14. Schematic cross-sectional flow around a Manvel waste-disposal pit. Flow reflects conditions during disposal activities at the site. Saltwater moved laterally to levee toes and downward into the underlying sand in response to bank-full hydraulic head and its greater density and then moved laterally in response to the local hydraulic gradient. Stratigraphy based on actual drilling on the site's southwest boundary, where the sand-mud contact is approximately 37 ft (11 m) below the surface.

Saltwater associated with on-site oil production, as well as saltwater brought on-site for disposal in the SWD well, is geochemically distinct from mixtures of saltwater and drilling fluid disposed in the pits. The sulfate-to-chloride ratios of all site waters are low, typically 0.02 to 0.07 (table 9), and are characteristic of oil-field brines (Whittemore, 1995). The chloride-to-bromide ratio, however, differs among samples. Samples referred to as "ditch waters" include shallow ground waters collected beneath the ditches as well as surface water in the ditches (fig. 2). The composition of these ditch-water samples is inferred to reflect relict contamination from formation water associated with on-site oil production or saltwater brought on-site for disposal. The chloride-to-bromide ratio of ditch waters ranges from 101 to 265, which are more depleted in bromide than are pit waters and pit A pore water having chloride-to-bromide ratios of 1.9 to 10.4. A chloride-to-bromide ratio of 265 is very close to that of sea water (288) and is within the range typical of Tertiary Gulf Coast formation waters (250 to 1,000) (Land and Macpherson, 1992). It is postulated that the ditch is underlain by produced formation water sourced in the past from the SWD well or oil well or both and uncontaminated by drilling fluids discharged into the pits. These wells have leaked saltwater in the past. For example, prior to its plugging in 1993, the oil well was leaking saltwater (chloride 32,000 mg/L) at a rate of less than 1 bbl per day. Although the SWD well was sealed in 1986, perforations were not properly squeezed prior to its plugging in 1990, according to RRC files.

The low chloride-to-bromide ratio (4.5) and high total bromide content (2,200 mg/L) in pore water from pit A waste clearly identify pit waste as the source of the bromide in the pit waters. Consequently, the low ratios in pits C and D waters indicate some contamination in those pits. The source of bromide is unknown but may be the result of bromide release by organic matter undergoing diagenesis or may be anthropogenic in origin (Whittemore, 1995). The most likely source, in the absence of brominated compounds (gasoline additives, herbicides, or pesticides), are drilling fluid

additives such as calcium bromide and zinc bromide (API, 1990). The pore water is also high in calcium and zinc (table 9). However, calcium and zinc may represent any of several other drilling additives and treating agents.

If ditch waters were contaminated by drilling fluid from the pits, their chloride-to-bromide ratios would be less than 10 rather than in the hundreds. Furthermore, halophyte abundance appears controlled as much by proximity to the SWD well as to levees around the pits. Halophytes are most abundant just west of the SWD well and continuing west beyond the plugged oil well to the ditch no. 2 sample point (fig. 2). Thus, the subsurface waters sampled in the ditches apparently come from formation water produced on-site or brought on-site for injection. In other words, waters currently beneath or in the ditches do not represent those now in pits A and B nor those likely present in them since disposal activities ceased. The most likely source of this saltwater contamination, therefore, is one or both abandoned wells before they were plugged by RRC. Apparently the amount of rainfall and recharge since 1990 has not been sufficient to completely flush out this saltwater or erase its diagnostic Cl/Br fingerprint.

Electromagnetic survey (EM) lines were chosen primarily at the site margins to assess the possible extent of off-site migration of saltwater and its depth below land surface. High conductivities along the site-margin lines confirm off-site migration of saltwater (figs. 10 and 11) to depths of at least 23 to 49 ft (7 to 15 m), as predicted from the results of conductivity modeling (fig. 12a,b,c,d). The extent of saltwater migration was not directly studied but was estimated from regional hydrogeology. Hydraulic head was highest when pits were full. This drove saltwater out of the pits, both laterally through the levees—which accounts for halophytes on the levees—and downward across the pit bottom and laterally to the west and northwest in the direction of the local Beaumont hydraulic gradient (figs. 6, 13, and 14). Saltwater that leaked from the SWD well or oil well or both would also move in those directions. Saltwater flow in those directions, laterally away and downward from the source, is consistent with the

decrease in ground conductivity in those directions (figs. 10 and 11) and with increasing conductivity downward. For example, ground conductivities are highest near pit B and decrease westward along the drainage ditch (fig. 2), indicating that saltwater has migrated westward in the subsurface or as surface flow or both.

The extent of off-site subsurface movement, assuming disposal activities began 20 years ago, is estimated to be about 0.6 mi (1 km) and was calculated from the ground-water velocity equation,

$$v = \frac{KI}{\phi}$$

where K is average hydraulic conductivity of a Beaumont fluvial sand (13 ft/d [4 m/d]), I the local hydraulic gradient (0.01), and ϕ aquifer porosity (30 percent).

Waste Assessment

TCLP extracts are all below EPA regulatory limits, and thus the waste is not hazardous on the basis of its metals content (table 6). Among regulated metals, only barium exceeds 1 mg/L, which is still well below its limit of 100 mg/L. Analysis of semivolatile organics shows the absence of refined product, pesticide, and herbicide, and thus the waste is not hazardous on the basis of its organic content (table 8). The waste's physical appearance (odor and color) and absence of refined product suggest the presence of weathered, degraded crude oil. Its oxidation is indicated by the presence of oxygenated hydrocarbons (phenolics).

Only on the north sides of pits A and B does TPH exceed 2 percent. In the remainder of those pits and in pits C and D, TPH is approximately 1 percent. Although low chloride-to-bromide ratios and some dissolved barium in pits C and D waters indicate the presence of some drilling waste, the low TPH content of the waste renders it benign (table 6). On the basis of physical appearance and the lack of correlation

between BTEX and TPH content, pit B waste is thought to be an older, more weathered or degraded waste than that in pit A.

ENVIRONMENTAL IMPACT ASSESSMENT

The Manvel SWD site poses a potential threat to public health and safety and the environment through its possible impact on surface- and ground-water quality of saltwater, organics, and metals. The actual risk is governed by the likely pathways for offsite migration, rate of ground-water flow, distance to point of discharge into surface water and/or nearby wells, concentration and nature of contaminants, future land use, and state and federal regulations. The most likely pathways for offsite migration of potential contaminants in the saltwater or pit waste are via surface waters to Mustang Bayou, by ground-water discharge to the bayou, by ground-water flow to nearby wells, or all three pathways.

Migration Pathways

Surface water in Mustang Bayou has been impacted in the past via the drainage ditch leading from the site. Future impact on Mustang Bayou from surface runoff or pit overflow is not likely because there is no crude oil on the surface of the pits and their waters have TDS contents of less than 500 mg/L (table 9). However, barium and arsenic in the pit waters exceed their maximum contaminant levels for drinking water (1 mg/L and 0.05 mg/L, respectively), whereas TPH was less than 0.2 mg/L. The concentration of barium and arsenic beneath the site and off-site is unknown.

Shallow saline ground water was confirmed beneath the drainage ditch leading to Mustang Bayou and on the southwest boundary of the site. These occurrences of saltwater are 1,000 to 1,500 ft (305 to 457 m) up hydraulic gradient from Mustang Bayou (figs. 2 and 6). Assuming aquifer continuity between the site and the bayou and ground-

water flow velocity of 170 ft/yr (52 m/yr), it is likely that site saltwater has reached and been discharged to Mustang Bayou in the 20 years since disposal activities began.

Discharge is postulated to be from the shallowest Beaumont sands because hydraulic heads in deeper sands are well below the bayou (fig. 13).

The number of households possibly using shallow Beaumont ground water down hydraulic gradient between the site and Mustang Bayou is five or less, based on a count of houses visible in a 1990 aerial photograph. A well survey of private residences was not done. In the past, residences within 0.25 to 0.5 mi (0.4 to 0.8 km) of the site have used Beaumont ground water (URM, 1985) and still do today because Manvel city water is available only along Highway 6 to the south. According to RRC records, there have been no reports or complaints of chloride contamination in nearby wells. These wells are typically screened at depths of 150 to 200 ft (46 to 61 m) (fig. 13), which greatly reduces the risk of contamination by shallow saline ground water at the site. Wells in the deeper Chicot aquifer should not be at risk because the saltwater plume apparently lies within the Beaumont above the Chicot.

To track the saltwater plume between the site and Mustang Bayou, ground water and soil can be sampled and analyzed to determine the presence and concentration of such pollution indicators as chloride, bromide, barium, arsenic, electrical conductivity, and benzene or TPH. This tracking exceeds the authorized scope of this investigation. Chloride-to-bromide ratios would be used to help differentiate saline formation water from pit waters as possible sources. Benzene, because of its high solubility (1,750 mg/L), is a good indicator of organic mobility. TPH would measure total hydrocarbon contamination. Samples would be collected from both above and below the red mud layer (see fig. 14) to ensure that the saltwater plume is only in the shallow sand. Gauging flow in Mustang Bayou and sampling its waters could be done at the same time ground water and soil are sampled to confirm the prediction of no impact from discharge.

Bioreceptors

The scope of this investigation did not include sampling ground water down hydraulic gradient or in the vicinity of the site. Thus, the concentration of potential inorganic and organic contaminants in shallow ground water is unknown.

Nevertheless, potential bioreceptors are probably at very low risk. Mobility of metals in the pit waste is probably low, based on the great disparity between total and TCLP concentrations, nearly neutral pH's, and sorption on clay minerals. Metals are potentially mobile in ground water in true solution, particularly at low pH, or may be transported as colloids, or in surface water sorbed to particulate matter.

Hydrocarbon mobility is restricted by sorption on soil clays and organic matter, biological degradation, volatilization, oxidation, and relative permeability effects (Deuel and Holliday, 1994). Migration will be further limited by formation of a "natural liner" at the pit bottom. The sealing mechanism is a physical blocking of pores by particulate matter in drilling fluids. Deuel and Holliday (1994) reported that organics and heavy metals do not significantly migrate through a "natural liner." PAH's in particular are very immobile in the subsurface environment. Oil content decreases rapidly with depth; the depth at which soil oil content does not differ significantly from underlying soil is less than 2.5 ft (0.76 m) (Ryan and others, 1986). Limited downward movement is borne out in the cores taken in this investigation. Oil content decreased rapidly below the contact with drilling waste, as judged by decreasing hydrocarbon odor and lighter color.

If saltwater and associated contaminants were discharged to Mustang Bayou, dilution will serve to reduce contaminant concentrations to low levels so that the risk to potential downstream bioreceptors would be negligible. The ratio of flow in Mustang Bayou, estimated to be 75.7×10^7 ft³/yr (see below), to that delivered from the site (76.4×10^4 ft³/yr) yielded a dilution factor of approximately 1,000. For example,

chloride would be diluted from an initial concentration of 19,300 mg/L in the saltwater plume leaving the site to 19 mg/L upon discharge to Mustang Bayou. Thus, potential contaminants at much lower starting concentrations would be diluted to negligible concentrations.

Flow in Mustang Bayou was estimated from actual flow rates in two small creeks in Fort Bend County (Scott Sullivan, personal communication, 1995). Two creeks with drainage areas of 42.8 mi² (110.9 km²) and 8.65 mi² (22.4 km²), respectively, have average flow rates of 35.9 ft³/sec (1 m³/sec) and 11.8 ft³/sec (0.34 m³/sec). The average of these two rates, 24 ft³/sec (0.7 m³/sec), was used here. Flow from the site was calculated using Darcy's law, where flow rate, Q, equals KAI and A is the cross-sectional area of the source. The source area was assigned dimensions of 500 × 30 ft (152 × 9 m), where the first term is pit width (fig. 2) and the second term thickness of the sand immediately underlying the site (URM, 1985). K and I were defined previously.

Future Land Use

Although saltwater has most likely migrated off site, the environment does not appear to have been seriously impacted. However, the impact is dependent on the intended use of the Manvel site and would be different for residential or agricultural use than for industrial use or wildlife habitat. The former require higher standards than the latter. Here, the future use is defined as that prior to oil-field activities at the site or that of essentially undeveloped land in a rural setting.

Cleanup Criteria

Protection of public health and safety and the environment will require management of saltwater (TDS content), organics, and metals. Remediation for groundwater contamination is governed by state and federal primary and secondary drinking-

water standards. Maximum contaminant levels have been set for a number of organic compounds and metals under the Texas Water Code (25 TAC 337.1–337.18). Among metals in site waters, only barium and arsenic exceed their respective standards. Other regulated metals are at or less than the standard levels and present no problem. Recommended secondary standards for chloride, sulfate, and TDS are 300 mg/L, 300 mg/L, and 1,000 mg/L, respectively, and pH greater than 7.

Cleanup criteria for waste organics, as measured by TPH or oil and grease, is problematic for several reasons. TPH concentrations represent a nonunique composition of various petroleum products that changes over time upon release to the soil. Measured TPH concentrations also differ with the analytical technique (p. 26 and 27). Therefore, as a cleanup standard, TPH should be used in the context of land use, disposal method, and concentration of associated target or surrogate organic compounds.

A TPH cleanup standard of 1 percent reflects the desire of regulators to protect agricultural productivity and is favored by the RRC (Jill Hybner, personal communication, 1996). A TPH content of 1 percent is the threshold at which reduced crop yield is expected. At 1 percent or less of mixed hydrocarbons there is little or no reduction in crop yield (Deuel and Holliday, 1994). Deuel and Holliday (1994) suggested a limiting criterion of 2 percent oil and grease for agricultural and residential areas, where disposal is by land treatment. Future land use at Manvel includes neither agricultural nor residential use but that of essentially undeveloped land in a rural setting. Even at a TPH content of 2 to 4 percent, organic compounds such as benzene, naphthalene, and benzo(a)pyrene are below their respective media-specific or risk-based concentrations for soil or are virtually immobile in soil. Given expected land use and the fact that concentrations of target or surrogate organic compounds are less than action levels, a TPH limit of 2 percent is deemed protective of public health and safety and the environment at Manvel.

Waste salt content, unlike TPH, is a concern mainly because it threatens agricultural productivity. In nonagricultural settings, Deuel and Holliday (1994) suggested a limiting guideline for salt, as measured by electrical conductivity, of 400 to 800 mS/m (4 to 8 mmho/cm). A midrange value of 600 mS/m (6 mmho/cm) seems appropriate at Manvel.

Target Areas

Target areas for cleanup include (1) a shallow saltwater plume of unknown extent and (2) high-TPH, high-salinity waste in pits A and B. The saltwater plume extends west and northwest down the hydraulic gradient for an unknown distance. Chlorinities in shallow ground water on-site and just off-site range from 313 to 19,300 mg/L and exceed secondary standards for chloride. The volume of water in the contaminated 30-ft (9-m) sand directly under the 20-acre site is about 1.4 million bbl (~60,000,000 gal), assuming a fully saturated sand of 30 percent porosity.

The area of organic contamination is defined as the area having more than 2 percent TPH and is located mainly on the northern one-third of pit A and secondarily on the northern side of pit B, just west of the A/B common levee (fig. 2), where the waste package is thickest. These areas have high TPH (2 to 4 percent) and high salinity (EC > 500 mS/m) (tables 4 and 6). The volume of waste having more than 2 percent TPH is approximately 6.1 acre-ft (10,000 yd³ [7,525 m³]). The remainder of pits A and B and all of pits C and D are essentially uncontaminated; that is, these areas contain waste of mostly less than 1 percent TPH and 200 mS/m conductivity.

REMEDATION

Technology

No new technology is needed to manage saltwater, organics, and metals at the Manvel site. The goal of ground-water remediation is to control movement of the saltwater plume and reduce TDS content. Available options include no action, eliminate the source, pump and treat, and construct engineered barriers (slurry walls). The goal of waste remediation is to reduce high-TPH waste to approximately 2 percent TPH. Available options include bioremediation, dilution with uncontaminated soil, and offsite disposal at a licensed nonhazardous waste-disposal facility. No action or dilution and/or capping may be appropriate for low-TPH, low-salinity waste.

Saltwater Control

No action means doing nothing, leaving the site in its present condition, and allowing natural processes to continue. Capping reduces infiltration and the flux of potential contaminants leached from high-salinity waste into the ground water but does not eliminate the source of salt. Eliminating the source would allow natural restorative processes in the aquifer to ultimately disperse the plume concentration to acceptable levels. Alternatively, plume movement and TDS content could be controlled in less time through pump and treat, which is used to control plume movement and to reduce the concentration of contaminants. If a contaminated plume is moving off site, as it is at Manvel, the best way to control it is to pump in order to change the ground-water flow patterns and recover the water for treatment at the surface (Nyer, 1993). Slurry walls may play a role in plume containment but will not reduce TDS content. They have been shown to be effective in water-table aquifers, where the barrier can be seated in a low-permeability layer below the contaminated aquifer. Evaporation and reverse osmosis

are used for TDS removal. Evaporators use a heat source to concentrate a solution or to recover dissolved solids by boiling the water. Reverse osmosis separates a solute from a solution by applying pressure to force the solvent through a membrane. Flux rate of water through a membrane is proportional to the pressure differential across the membrane. The higher the pressure, the higher the flux rate for a given membrane (Nyer, 1993). Evaporation is a one-step process in that clean water and TDS in solid form is produced. Reverse osmosis produces clean water and brine, which requires further treatment prior to final disposal.

High-TPH Waste

No action means leaving the site in its present condition with natural processes controlling fate of waste and rate of remediation. Disposal at a licensed facility involves excavation and transport to the facility for land filling or bioremediation. Dilution to regulatory limits can be achieved by mixing waste and uncontaminated native soil. Bioremediation is the process of using microorganisms to reduce the concentration of organic compounds to safe levels and transform them to benign end products such as carbon dioxide and water. It is done under aerobic conditions because anaerobic processes are slow, result in incomplete metabolism, and produce methane. Bioremediation can be performed either ex situ or in situ. Ex situ refers to the removal of the contaminated material and placement and treatment of it directly on the land or in a constructed treatment cell. In situ refers to remediation brought about in place without excavating or removing the waste (Troy and others, 1994). Bioremediation is less disruptive than other options and is perhaps the most effective means of economically reducing the environmental risks associated with oily drilling wastes (Bandyopadhyay and others, 1994; Troy and others, 1994).

Almost all organic compounds can be degraded biologically if sufficient time and proper physical and chemical conditions are provided. Degradation of complex organic compounds such as polycyclic aromatic hydrocarbons (PAH's) is comparatively slow. Some complex compounds, termed recalcitrant or refractory compounds, are not degraded at all (Bandyopadhyay and others, 1994). Salinity and metals content generally have a minor effect on biological activities. Pore-water salinities equivalent to seawater (TDS of 35,000 mg/L [57 mmho/cm]) or higher are detrimental to bacteria, whereas among metals, only zinc at concentrations greater than 600 mg/kg is detrimental (L. E. Deuel, personal communication, 1995). In more than 90 percent of all bioremediations, natural bacteria will be the best bacteria to use for cleanup (Nyer, 1993), even in cases where PAH's are present, although there will always be cases where specialized bacteria may be needed. Rate limitations will be due to lack of nutrients and oxygen (Carberry, 1994). Thus, to overcome rate limitations, bioremediation is augmented by fertilization, aeration, and pH control. Microorganisms with specialized degradative capabilities may be obtained by selective enrichment techniques and genetic manipulation. They are acclimated to degrade different organic contaminants by repeatedly exposing them to the compounds of interest (Bandyopadhyay and others, 1994). The typical response of a microbial community to hydrocarbon pollutants is enhanced microbial activity. To an upper limit, stimulation of microbial activity is positively correlated to increasing amounts of hydrocarbons in the soil. As the biodegradable material is eliminated, the microbial community rapidly returns to its prepollution mass (Wang and Bartha, 1994). Bioremediation is achieved through land farming, in soil slurry reactors, and by composting in a soil pile reactor.

Land Farming

Land farming (land spreading and land treatment) of nonhazardous oil-field waste is under the jurisdiction of the RRC. Land spreading refers to the land farming of low-chloride (<3,000 mg/L), water-based drilling fluids and associated cuttings without a permit. Land treatment is the land farming of oily drilling wastes such as those at Manvel and generally involves the addition of nutrients and/or microbes to stimulate biodegradation. In fact, 97 percent of the oily waste disposal in Texas is by land farming (IOGCC, 1993).

Land treatment uses the assimilative capacity of the soil to decompose and contain waste in the surface soil layer. The zone of incorporation is the upper 6 to 12 inches (15 to 30 cm) of soil, and the underlying treatment zone, where additional treatment and immobilization of the waste occurs, may be as much as 5 ft (1.5 m) thick (Ryan and others, 1986). Land treatment is suitable for the treatment and disposal of most oily waste. A wide range of waste types with hydrocarbon content as high as 60 percent have been successfully treated. Saturated and aromatic hydrocarbon fractions are rapidly removed in land treatment, whereas heavy aromatics and asphaltenes degrade, but at much slower rates. The average annual oil reduction rate typically ranges from 70 to 90 percent (Ryan and others, 1986). This does not imply that 10 to 30 percent of the annual oil loading accumulates in the soil each year. The residual accumulation would continue to degrade for several years after waste applications ceased.

Soil Slurry Reactor

In this reactor, soil is combined with water to form a slurry, which is continually mixed and supplied oxygen as well as nutrients at optimum concentrations. The main problem is separation of soil and water after biochemical reaction is complete. Timely

separation of water from clay for a large volume of soil is difficult. However, if soil is sandy, liquid/solids separation will be less difficult (Nyer, 1993).

Soil Pile Reactor

In this reactor, soil is excavated and placed on a plastic liner while nutrients and bacteria, if needed, are mixed with the soil. Consequently, the pile contains all the necessary nutrients and bacteria needed to complete the biochemical reactions. Perforated pipe is placed within the pile at regular depths and intervals so that air can be sucked through the pile in order to supply oxygen. A plastic cover is placed over the entire pile to control rainwater and air-flow patterns (Nyer, 1993).

Remediation Options

Remediation is governed by the objective of the remedial action, the potential threat posed by the site, intended use of the land, available technology, and economic factors. The objective here is to protect the State's water resources against contamination by saltwater, organics, and heavy metals. Although saltwater has most likely migrated off site, the site apparently has not impaired human health or public safety nor seriously impacted the environment. Remediation commensurate with future use as undeveloped land in a rural setting is achievable using existing technology. Economics cannot be ignored under the RRC's obligation to limit potential cost to the State of Texas.

Remediation at the Manvel site can be achieved by using a mix of cleanup approaches, depending on the threat posed by the contaminant. For example, cleanup of high-TPH, high-salinity waste will require a higher level of management than low-TPH, low-salinity waste. Moreover, cleanup of high-salinity waste serves to reduce the threat of saltwater contamination by eliminating one source of saltwater. Thus, the interplay among options is a factor in choosing them.

Saltwater Cleanup

Low-cost options available for treating saltwater contamination are (1) no action, (2) eliminate the sources of saltwater, and (3) drill Beaumont replacement wells as needed. Among these options, no action is the least attractive because it does nothing to reduce the size of the saltwater plume and decrease the TDS content. At the moment, saltwater poses minimal risk to human public health and safety and the environment. Therefore, the low management option of eliminating the source of the saltwater is appropriate. This can be done by eliminating the two potential sources of saltwater. One source will be eliminated in the course of cleaning up high-salinity waste in pits A and B. According to RRC personnel, elimination of the other source, formation water, most likely was accomplished upon plugging of the on-site SWD well in 1990 and the oil well in 1993. In the unlikely event that nearby private Beaumont wells are salinized, replacement wells could be drilled as part of the overall remediation program.

A high-management, high-cost option such as pump and treat (evaporation/reverse osmosis) is probably not called for on the basis of the low risk posed by the site and the tremendous volume of water (~60,000,000 gal) that would have to be treated. However, among treatment options, evaporation/reverse osmosis is the appropriate choice because TDS reduction rather than organic contamination is the major concern. The heterogeneity of the Beaumont aquifer and the high cost of slurry walls (ECHOS, 1995) eliminate them as a feasible control option.

High-TPH Waste

Among the options available for treating high-TPH waste, the no action option is unacceptable because it does nothing to reduce TPH content to the recommended cleanup standard of 2 percent. Acceptable options include on-site bioremediation and excavation for offsite disposal. The first is less costly, whereas the second offers the

highest degree of environmental protection. In either case, the first step would be to dewater the pits and remove any abandoned barrels. To reduce suspended matter and to precipitate metals, pit water would be treated with flocculating agents and pH-adjusting chemicals, respectively. The clarified water would be either discharged to surface drainage or trucked off site for disposal.

Discharge of oil-field wastes to the State's waters is regulated by the RRC through permits issued under Rule 8(d). Discharge quality and volume, together with available data and quality standards of the receiving body of water, are used by the RRC to determine the assimilation capacity of the receiving body of water. In other words, the interaction of discharge and receiving waters is modeled to ensure that no violation of the Texas Surface Water Quality Standards occurs. No permit is issued if the discharge would cause a violation of those standards, which apply to the receiving body of water and are intended for protection of aquatic life. The surface-water standard for barium is 2 mg/L and is exceeded only by pit A and B waters, which contain less than half of the total volume of pit water (tables 2 and 9). Other metals, TDS, chlorinity, TPH, and pH of pit waters present no problems. On the basis of their chemical composition, limited volume, and allowance for dilution in the receiving body of water, it should be possible to discharge the pit waters to Mustang Bayou (Larry Hanneschlager, personal communication, 1996). The landowner and affected surface owners downstream of the discharge point must be notified. Failure to obtain a discharge permit would require more costly offsite disposal.

Abandoned barrels were not sampled in this study nor were they counted. Only when pit water levels are low do they become evident. The number of barrels in pits B and D is estimated to be between 6 and 12; no barrels were evident in pits A and C. If the barrels are empty, their contents have most likely been dispersed and they are no threat, because there is no evidence of contamination beyond that already documented. If the barrels are full of waste, their contents must be sampled and analyzed. Depending

on the results, it may be necessary to dispose of them off site at a licensed disposal facility.

Bioremediation is preceded by a biotreatability study to determine (1) organic compounds to be treated, (2) their matrix, and (3) type of microbes that will be used to degrade the target compounds (Carberry, 1994). The study is used to evaluate the biodegradation potential of the organics under site conditions, to evaluate techniques to stimulate biodegradation rates, and to obtain operating parameters for full-scale, on-site treatment. Experience shows that there are very few site limitations which cannot be overcome with appropriate design and operation.

Among the bioremediation options, land farming, which requires landowner permission, or soil-pile reduction are favored over soil slurring. The soil slurry reactor is optimum for biochemical reactions, but it is difficult to run because of liquid/solids separation problems (Nyer, 1993). The soil-pile reactor is self contained and thereby facilitates control of leachates and runoff. However, it is limited, as is the slurry reactor, by the volume of soil that can be treated in a timely manner and is more applicable to cold climates.

In land farming, selected waste is excavated, stockpiled, and then spread for bioremediation. The 20-acre site provides ample area for land treatment of approximately 6.1 acre-ft (10,000 yd³ [7,525 m³]) of high-TPH waste having 2.1 to 4.1 percent TPH. The final TPH content will depend on the percent of refractory organics in the waste, the microbial community, the nutrient balance, and the time managed. Reduction in TPH content to 2 percent or less might take more than 1 year. The degradation half-lives of the more refractory PAH's may exceed 200 days (Ryan, 1986).

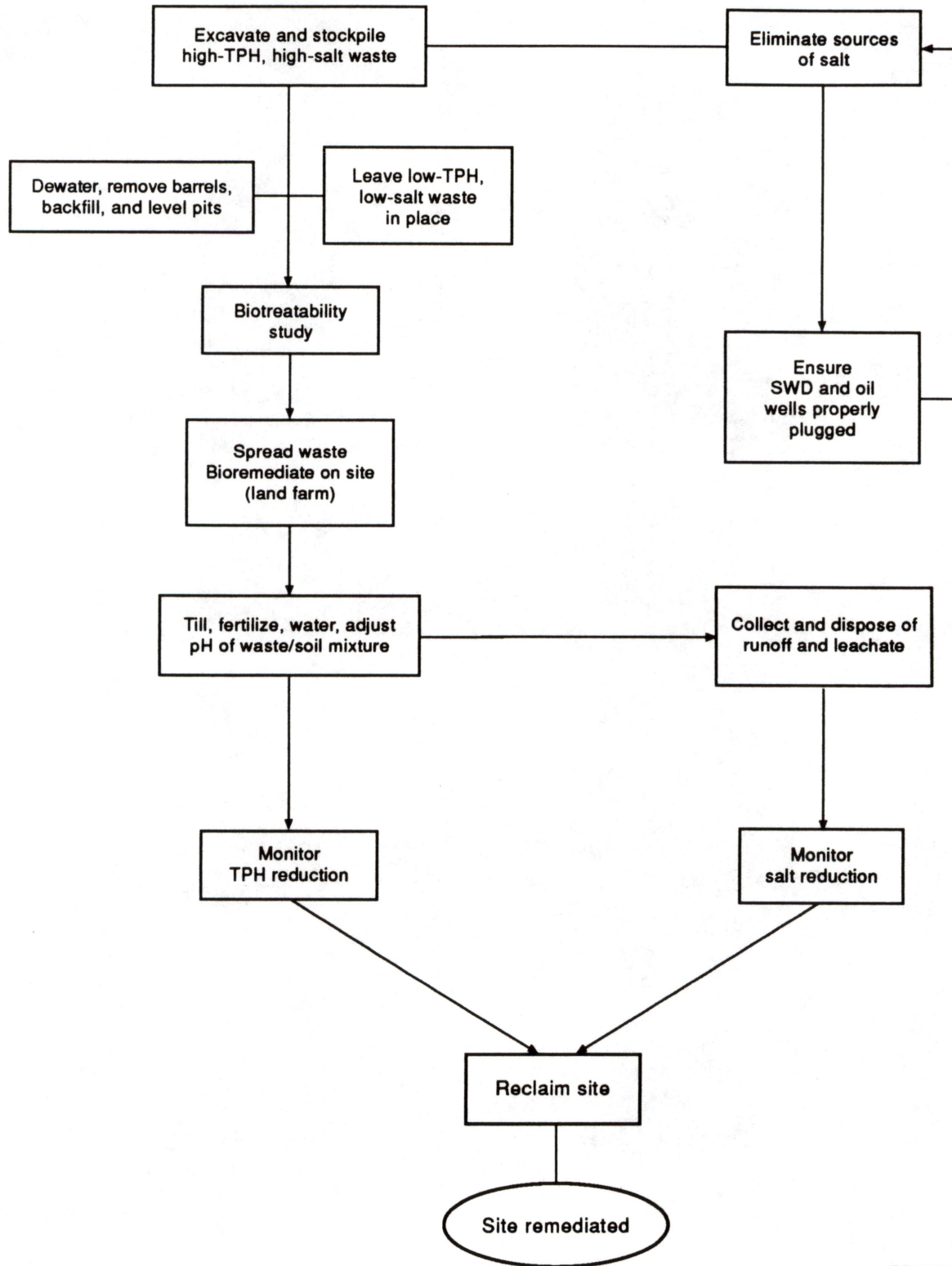
Immobilization of waste occurs in the treatment zone. Organic content decreases rapidly downward with maximum extent of migration at less than 1.5 ft (<0.46 m) below the zone of incorporation. Migration times of methyl naphthalene and

naphthalene, the most abundant organic compounds in the pit waste, through the zone of incorporation, are 60 and 25 years, respectively, and well in excess of their degradation times (Ryan, 1986; Nyer, 1993). Applied metals are also immobilized within the treatment zone (Ryan and others, 1986). Metals are of limited concern, whereas salt is of greater concern. Salt would be reduced by leaching of the waste by rainfall and would be collected by an engineered system such as drainage ditches below the elevation of the treatment pad or between wind rows of waste. Sodicity should not be a problem because the waste is calcium rich (table 5). In any event, liming to control pH to immobilize metals and maximize bacterial growth will further minimize any potential sodicity problem. The final treated waste would be left in place with minimal risk to public health and safety and the environment.

Low-TPH, low-salinity waste in the southern parts of pits A and B and in pits C and D can probably be left in place with minimal risk to the environment. Alternatively, to ensure a higher level of protection, these wastes could be mixed with native soil to further reduce TPH, salt, and metals content. At low-TPH loading (<2 percent), a mixture of 50 percent waste and 50 percent native soil would reduce TPH to less than 1 percent. Dilution alone without further treatment is all that is probably required.

RECOMMENDATIONS

At the Manvel SWD site, shallow, saltwater-contaminated ground water and high-TPH, high-salinity drilling waste require remediation (fig. 15). The options for saltwater contamination are to pump and treat the high-TDS water under the site or to eliminate the sources of saltwater and allow the aquifer to cleanse itself. The options for the high-TPH waste are off-site disposal or bioremediation on-site. Costs are option dependent and estimated here from published data (ECHOS, 1995), bids in RRC files, and vendor comments.



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Figure 15. Remediation flow chart. Schematic sequence of steps for recommended remediation of the Manvel SWD site.

Saltwater Contamination

The pump and treat option for saltwater remediation is cost prohibitive because of the tremendous volume of water that must be treated (~60,000,000 gal).

Evaporation/reverse osmosis is the appropriate treatment technology and is estimated to cost \$0.05 to \$0.10 per gallon for a total cost of \$3 to \$6 million. The cost is based on vendor comment and is a turnkey cost for combined evaporation and reverse osmosis.

Natural or passive remediation requires elimination of sources of saltwater by removing high-salinity waste from pits A and B as part of the high-TPH cleanup and ensuring that the SWD well and on-site oil well are now properly and effectively plugged. The RRC plugged the SWD well in 1990 and the oil well in 1993 and thereby most likely eliminated the formation water source of salt-water contamination.

Additional drilling and sampling of ground water and soil to track the saltwater plume downgradient from the site to Mustang Bayou would cost approximately \$5,000 to \$10,000, depending on how many monitoring wells are constructed and how many samples are taken and analyzed. A decrease in concentrations or other indicator readings would confirm that natural remediation is underway and that the sources of saltwater have been eliminated.

Drilling Waste

Offsite disposal is cost prohibitive because of the large volume of waste that must be excavated and transported. Approximately 6.1 acre-ft (10,000 yd³) of high-TPH waste will require treatment. The estimated cost to excavate, load, and transport it for offsite disposal ranges widely, from \$40 to \$90 per yd³ (ECHOS, 1995; RRC files; vendor comments), for a total cost of \$400,000 to \$900,000. The cost-effective option is to excavate and bioremediate the high-TPH waste on-site and leave the low-TPH waste in place. Bioremediation on a per-yd³ basis costs about half that for offsite disposal and is

based on direct comparison of costs for offsite disposal and bioremediation at Manvel (RRC files) and vendor comments. Thus, the total cost for bioremediation is estimated to be \$200,000 to \$450,000.

Because of the large volume of waste that must be treated, the appropriate bioremediation option is land farming. Common cost elements of a detailed cost analysis include site work, biotreatability study, waste excavation, stock piling, spreading waste, tilling (aeration), fertilization, watering, pH adjustment, runoff and leachate collection system, runoff and leachate disposal, analyses for monitoring TPH reduction, professional services, and contractor overhead and profit (ECHOS, 1995). Runoff and leachate volumes could be large, and consideration should be given to drilling a disposal well for on-site disposal.

There would be additional costs for dewatering, backfilling, and leveling the pits, a biotreatability study, site reclamation, and monitoring cleanup. The cost to pump out and discharge 50,000 bbl of water to surface drainage is \$10,000 at \$0.20 per bbl and is based on RRC bids specific to Manvel. In the event a discharge permit cannot be obtained, off-site disposal of pit water is estimated to cost \$25,000 to \$50,000, or \$0.50 to \$1.00 per bbl (vendor comments). The cost to backfill and level the pits assumes a total levee volume of approximately 12,000 yd³ that can be moved for \$2.00 per yd³ (Manvel specific bids) for a total of \$24,000. A biotreatability study was bid for Manvel in 1991 at \$2,680 and, assuming 4 percent inflation, is now estimated at \$3,100. Cost for reclamation of the 20-acre site ranges from \$1,500 to \$4,000 per acre, a total cost of \$30,000 to \$80,000, corresponding to a Manvel specific bid to return the property to natural grade and remove all roads and full reclamation based on costs to reclaim land surface mined for lignite. However, the whole site may not need to be reclaimed. Incidental costs include disposal of abandoned barrels and analyses to monitor TPH and salt reduction. Cost of barrel disposal is minimal (\$162), assuming 12 barrels require off-site disposal at a cost of \$65 per yd³. The combined cost of 24 analyses is \$1,200. Cost

of follow-up work includes installation of monitoring wells and collection and analysis of samples for approximately \$5,000 to \$10,000. In summary, the total cost for site remediation is estimated to be between \$273,500 and \$528,500 (table 12).

Conclusions

1. The recommended cleanup option for saltwater contamination is to eliminate the potential sources of saltwater (high-salt drilling waste and leaking wells) and allow the shallow Beaumont aquifer to cleanse itself.
2. Geochemical data (chloride and chloride-to-bromide ratios) indicate the presence of salty formation water uncontaminated by drilling fluids and indicate that the plugged SWD well or oil well or both have leaked saltwater in the past. Plugging the SWD well in 1990 and the oil well in 1993 by the RRC most likely eliminated this source of salt-water contamination.
3. To better define the risk to public health and safety and the environment, offsite ground water and soil, down hydraulic gradient, should be sampled and monitored to determine the presence and concentration of potential contaminants. Assuming the absence of or very low concentrations of pollution indicators or decrease with time, taking the no-action option on the saltwater plume, except to eliminate its sources, is reasonable. In the event nearby private wells are salinized, replacement wells can be drilled.
4. It is recommended that pit closure be achieved by discharging pit waters under permit to surface drainage and by backfilling and leveling the pits using levee soil.
5. To further assess environmental impact, flow rate in Mustang Bayou should be gauged to better define the dilution factor, and water in the bayou sampled and analyzed where the site drainage ditch enters the bayou to facilitate issuance of a discharge permit.

Table 12. Cost summary by remediation option.

Remediation Option	Recommended Option Cost	Alternative Option Cost
Saltwater Contamination		
Pump and treat		\$3,000,000 to \$6,000,000
High-TPH Waste		
Biotreatability study	\$3,100	
Land farm	\$200,000 to \$450,000	
Off-site disposal		\$400,000 to \$900,000
Other Costs		
Dewater pits (discharge)	\$10,000	
Dewater pits (offsite disposal)		\$25,000 to \$50,000
Backfill and level pits	\$24,000	\$24,000
Reclaim to natural grade	\$30,000	
Full reclamation		\$80,000
Incidentals	\$1,400	
Follow-up work	\$5,000 to \$10,000	
Total Cost	\$273,500 to \$528,500	\$3,529,000 to \$7,054,000

6. Land farming on site is the option of choice for decontaminating high-TPH, high-salt drilling waste in the northern parts of pits A and B. Low-TPH, low-salt waste in the southern parts of pits A and B and in pits C and D pose minimal risk to the environment and can be left in place.
7. A TPH cleanup standard of 2 percent (dry basis) is recommended on the basis of future land use and risk-based concentrations of associated target or surrogate organic compounds for soil. The suggested limiting guideline for reduction of salt is an electrical conductivity of 6 mmho/cm, measured on 1:1 salt/water mixtures.

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REFERENCES

- API, 1990, Bulletin on the generic hazardous chemical category list and inventory for the oil and gas exploration and production industry: Washington, D.C., American Petroleum Institute Bulletin E1, 86 p.
- Aronow, S., Fisher, W. L., McGowen, J. H., and Barnes, V. E., 1982, Houston Sheet: The University of Texas at Austin, Bureau of Economic Geology Atlas of Texas, scale 1:250,000.
- Bandyopadhyay, S., Bhattacharya, S. K., and Majumbar, P., 1994, Engineering aspects of bioremediation, *in* Wise, D. L., and Trantolo, D. J., eds., Remediation of hazardous waste contaminated soils: New York, Marcel Dekkar, p. 55–75.

- Bentley, M. E., 1980, Hydrogeology of the Beaumont Formation (Pleistocene), Brazoria County, Texas: The University of Texas at Austin, Master's thesis, 105 p.
- Carberry, J. B., 1994, Bioremediation of hydrocarbon-contaminated soils using indigenous microbes, *in* Wise, D. L., and Trantolo, D. J., eds., Remediation of hazardous waste contaminated soils: New York, Marcel Dekkar, p. 317-343.
- Crenwelge, G. W., Crout, J. D., Griffin, E. L., Golden, M. L., and Baker, J. K., 1981, Soil survey of Brazoria County, Texas: U.S. Department of Agriculture, Soil Conservation Service, 140 p.
- Deuel, L. E., Jr., and Holliday, G. H., 1994, Soil remediation for the petroleum extraction industry: Tulsa, Pennwell, 287 p.
- Dutton, A. R., 1994, Use of aquifer stratigraphy for building numerical models of ground-water flow: case study of the heterogeneous Gulf Coast aquifer in Matagorda and Wharton Counties, Texas: Transactions of the Gulf Coast Association of Geological Societies, v. 44, p. 185-192.
- ECHOS, 1995, Environmental restoration, assemblies cost book: Kingston, Massachusetts, R. S. Means Company, Inc., Environmental Cost Handling Options and Solutions, 320 p.
- EPA, 1986, Test methods for evaluating solid waste, physical/chemical methods, SW-846, 3rd edition: U.S. Environmental Protection Agency, variously paginated.
- EPA, 1994, Risk-based concentration table, fourth quarter 1994: Philadelphia, U.S. Environmental Protection Agency, 21 p.
- Fisher, W. L., McGowen, J. H., Brown, L. F., Jr., and Groat, C. G., 1972, Galveston-Houston area: The University of Texas at Austin, Bureau of Economic Geology Environmental Geologic Atlas of the Texas Coastal Zone, 91 p.
- Fogg, G. E., Kaiser, W. R., and Ambrose, M. L., 1991, The Wilcox Group and Carrizo Sand (Paleogene) in the Sabine Uplift area, Texas: ground-water hydraulics and hydrochemistry: The University of Texas at Austin, Bureau of Economic Geology Hydrological Folio, 70 p., 19 pls.
- Frischknecht, F. C., Labson, V. F., Spies, B. R., and Anderson, W. L., 1991, Profiling using small sources, *in* Nabighian, M. N., ed., Electromagnetic methods in applied geophysics—applications, part A and part B: Tulsa, Society of Exploration Geophysicists, p. 105-270.
- GSI, 1993, GSI user's guide, State of Texas, risk reduction rules for closure/remediation: Houston, Groundwater Services, Inc., 19 p.
- Guevara-Sanchez, E. H., 1974, Pleistocene facies in the subsurface of the southeast Texas coastal plain: The University of Texas at Austin, Ph.D. dissertation, 133 p.

- IOGCC, 1993, Texas state review, IOGCC/EPA review of oil and gas exploration and production waste management regulatory programs: Interstate Oil & Gas Compact Commission, 131 p.
- Kimbrough, D. E., Patel, J., and Wakakuwa, J., 1995, Analysis of silver and other elements by the toxicity characterization leaching procedure: American Environmental Laboratory, v. 7, no. 8, p. 1, 8-11.
- Land, L. S., and Macpherson, G. L., 1992, Origin of saline formation waters, Cenozoic section, Gulf of Mexico sedimentary basin: American Association of Petroleum Geologists Bulletin, v. 76, no. 9, p. 1344-1362.
- McNeill, J. D., 1980a, Electromagnetic terrain conductivity measurement at low induction numbers: Mississauga, Ontario, Geonics Limited Technical Note TN-6, 15 p.
- McNeill, J. D., 1980b, EM34-3 survey interpretation techniques: Mississauga, Ontario, Geonics Limited Technical Note TN-8, 16 p.
- Nyer, E. K., 1993, Practical techniques for groundwater and soil remediation: Boca Raton, Lewis Publishers, 214 p.
- Parasnis, D. S., 1973, Mining geophysics: Amsterdam, Elsevier, 395 p.
- Ryan, J., 1986, The land treatability of appendix VIII organics presented in petroleum industry wastes, *in* Loehr, R. C., and Malina, J. F., Jr., eds., Land treatment, a hazardous waste management alternative: The University of Texas at Austin, Center for Research in Water Resources, p. 347-367.
- Ryan, J. R., Hanson, M. L., and Loehr, R. C., 1986, Land treatment practices in the petroleum industry, *in* Loehr, R. C., and Malina, J. F., Jr., eds., Land treatment, a hazardous waste management alternative: The University of Texas at Austin, Center for Research in Water Resources, p. 298-318.
- Sandeen, W. M., and Wesselman, J. B., 1973, Ground-water resources of Brazoria County, Texas: Austin, Texas Water Development Board, Report 163, 202 p.
- Troy, M. A., Allen, L. B., and Jerger, D. E., 1994, Bioremediation of petroleum-contaminated soils at railroad facilities, *in* Wise, D. L., and Trantolo, D. J., eds., Remediation of hazardous waste contaminated soils: New York, Marcel Dekkar, p. 227-243.
- URM, 1985, Evaluation of potential for groundwater contamination from the Manvel Salt Water Disposal Company: prepared by Underground Resource Management, Inc., for City of Manvel, Manvel, Texas, 38 p.

- Wang, X., and Bartha, R., 1994, Effects of bioremediation on toxicity, mutagenesis, and microbiota in hydrocarbon-polluted soils, *in* Wise, D. L., and Trantolo, D. J., eds., Remediation of hazardous waste contaminated soils: New York, Marcel Dekkar, p. 175–197.
- West, G. F., and Macnae, J. C., 1991, Physics of the electromagnetic induction exploration method, *in* Nabighian, M. N., ed., Electromagnetic methods in applied geophysics—applications, part A and part B: Tulsa, Society of Exploration Geophysicists, p. 5–45.
- Whittemore, D. O., 1995, Geochemical differentiation of oil and gas brine from other saltwater sources contaminating water resources: case studies from Kansas and Oklahoma: Environmental Geosciences, v. 2, no. 1, p. 15–31.

APPENDIX

INVITATION TO BID

The RRC is soliciting TURNKEY BIDS for the purpose of conducting site cleanup and restoration activities at the Manvel Saltwater Disposal (SWD) site. This turnkey bid shall include all personnel, goods, and services necessary to access the location and remediate the site per procedures defined under services to be performed. The turnkey bid shall include any site preparation, ingress to and egress from the site, including any road building or special access problems. Bids will be awarded to the lowest turnkey bidder capable of performing services as specified.

LOCATION: The Manvel SWD site (RRC Site No. 92-03-00003) lies within the city limits of Manvel, Texas, on the Pearland USGS 7.5-minute quadrangle; it is 2.6 mi north of the intersection of State Highway 6 and FM 1128 at the intersection of FM 1128 and Chocolate Bayou Road, northeast of a Texaco tank farm. Enter the site from FM 1128, 0.15 mi (800 ft) northeast of the intersection.

NOTICE TO BIDDERS: Bidders are encouraged to inspect the site before submitting bids. This site will be available for viewing on----- . Those interested in inspecting

the site must contact the Austin RRC Office at 512/463-6765 prior to viewing date and prior to entering the site. Bids must be received at the Austin Office by 3:00 p.m. on -----
----- . Bidders may attend bid openings at -----in the Austin RRC Office, 1701 North Congress, William Travis Building, 11th floor.

KNOWN SITE DATA: The 20-acre site is an abandoned SWD site at which saltwater, drilling waste, and crude oil has been disposed. The site is crossed by abandoned and active pipelines and includes a plugged and abandoned SWD well and a P&A oil well. There are four water-filled earthen pits: two waste-disposal pits (3.02 and 1.95 acres) and two relatively uncontaminated ponds (0.63 and 0.43 acres). High-TPH (2 to 4 percent), high-salt (electrical conductivity >5 mmho/cm) drilling waste in the disposal pits has a volume of approximately 10,000 yd³, is elevated in barium, iron, and zinc, and contains BTEX and polycyclic aromatic hydrocarbons. An unknown number of barrels of unknown contents are present in at least two pits. Pit waters (~50,000 bbl) are fresh and contain less than 0.2 mg/L TPH. Soils making up the levees around pits (~12,000 yd³) are essentially free of petroleum hydrocarbons and salt. Bidders are encouraged to review the site technical report before submitting bids.

SERVICES TO BE PERFORMED: The object of the work is to dewater, backfill, and level all pits and decontaminate high-TPH, high-salt drilling waste by land farming on-site. The required scope of services includes the following.

1. Dewater pits (base bid on 50,000 bbl) and discharge to surface drainage in accord with an RRC discharge permit. Include cost of flocculating agents. Any amount over or under this volume will be billed or credited as per the amount shown on the Supplemental Bid Data on the Bid Submission Sheet.
2. Remove abandoned barrels (with unknown contents) in pits (base bid on 12 bbl) and if needed dispose of at an approved RRC permitted commercial disposal

- facility. Any number over or under 12 will be billed or credited as per the amount shown on the Supplemental Bid Data on the Bid Submission Sheet
3. Backfill all pits using existing levee soil. Level and compact area upon completion of cleanup. If the RRC representative deems clean fill dirt is necessary to complete backfilling of the pits, then cost will be determined by information provided under Supplemental Bid Data on the Bid Submission Sheet.
 4. Conduct biotreatability study in preparation for bioremediation (land farming) of drilling waste.
 5. Excavate and stockpile or otherwise store 10,000 yd³ of drilling waste. Any amount over or under this volume will be billed or credited as per the amount shown on the Supplemental Bid Data on the Bid Submission Sheet. Prior to excavation, contractor will be responsible for locating all active and abandoned lines (pipelines, utility lines, etc.) above or below ground. Site activities will be conducted to avoid rupturing or severing active lines. The contractor will submit in writing that all lines have been located and marked prior to excavation.
 6. Decontaminate the drilling waste on-site to a TPH level of 2 percent (dry basis) and soil electrical conductivity (EC) of 6 mmho/cm in accord with an RRC land farming permit. Include cost to till, fertilize, water, and adjust pH of waste/soil mixture.
 7. Monitor reduction of TPH and salt (EC) on a monthly basis. TPH to be determined by EPA modified method 8015 and EC on a 1:1 soil/water mixture using a direct-readout microconductivity cell with a temperature-compensating conductivity meter.
 8. Conduct all work during daylight hours on a daily basis, excluding weekends, until job is completed. Contractor will provide 48-hour notice to RRC prior to beginning site work. Work will be conducted continuously, weather permitting, and work will be completed within 1 year.

9. Remove all existing roadwork and return disturbed property to natural grade.

Supplemental Bid Data

Cost per barrel of pit water to flocculate, pump out, and discharge.

Cost per barrel to dispose of abandoned barrels at an approved disposal facility.

Cost per cubic yard of clean fill dirt delivered to the site.

Cost per cubic yard to excavate and store drilling waste on-site.