Comparison of the effects of geologic environment on volatile organic plume development*

William D. Adams and James E. Golden

Universal Engineering Sciences, 3532 Maggie Boulevard, Orlando, FL 32811 (USA)

Abstract

The local hydrogeologic settings of solvent waste and petroleum release sites are used to illustrate the effects of site-specific geology on contaminant plume development. Our study of waste sites focuses on U.S. coastal plain aquifers. Data were gathered to characterize these sites by means of: soil and rock borings to investigate site geology; aquifer tests to estimate hydraulic conductivity, storativity and transmissivity; and, collection and analysis of soils, sediments, surface water, and groundwater samples for laboratory analysis. The geologic environments considered for discussion include clean, sorted sands; silty sands; medium to coarse sand and shell; and stratified aquifer systems of sand, silt, clay, and limestone. Specific chemicals studied were restricted to volatile halocarbons and volatile aromatics.

1. Introduction

Volatile organic chemicals such as benzene, toluene, chloroform, methylene chloride, trichloroethylene, etc. are among the most common contaminants of groundwater in the United States. These compounds are also relatively mobile compared to other organic compounds; however, their mobility is often affected by the geologic and hydrologic environment into which they have been released. This paper compares the effects of geologic environment on the development of plumes of volatile organic compounds in three case studies. The first case is a gasoline leak in central Florida, the second is a dye products research and production facility in the Sea Island District, and the third case is an industrial waste disposal site in the Mid-Atlantic Coastal Plain.

The Atlantic Coastal Plain in the United States extends from Cape Cod to Mexico (Fig. 1). The coastal plain consists of sedimentary deposits such as sand, silt, clay, gravel, shell, limestone, dolomite, and evaporite deposits which thicken from a thin veneer of sediments at the landward edge to a great wedge
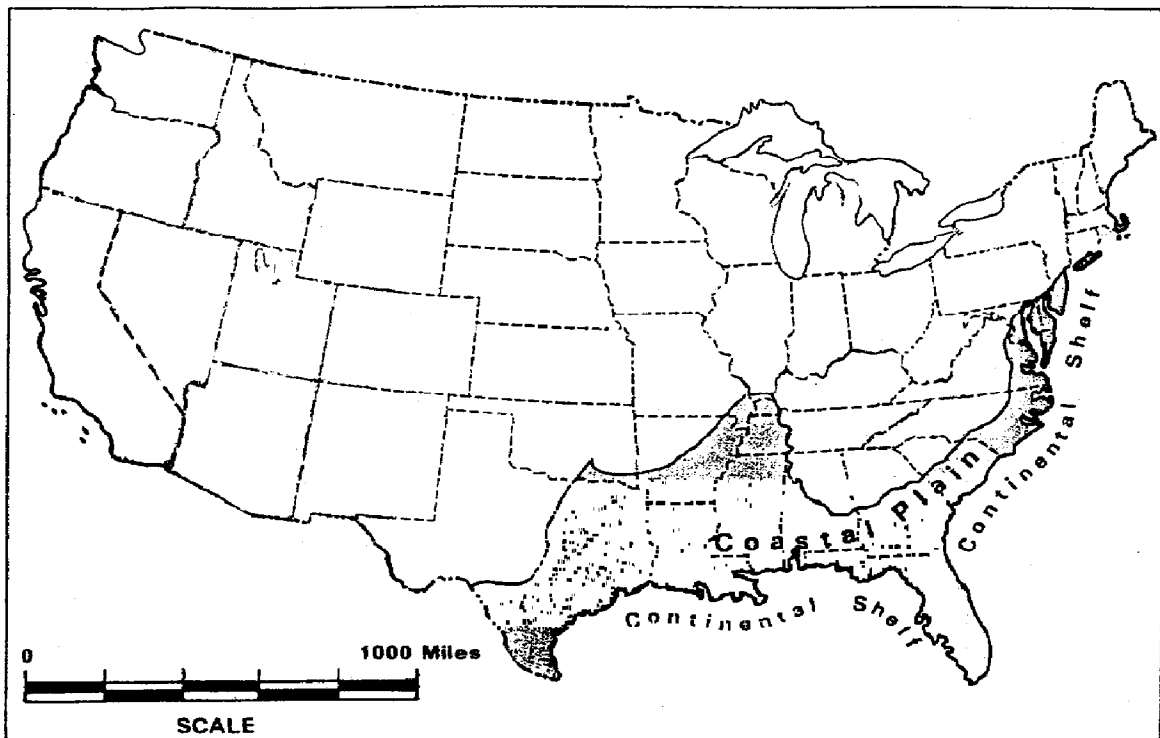
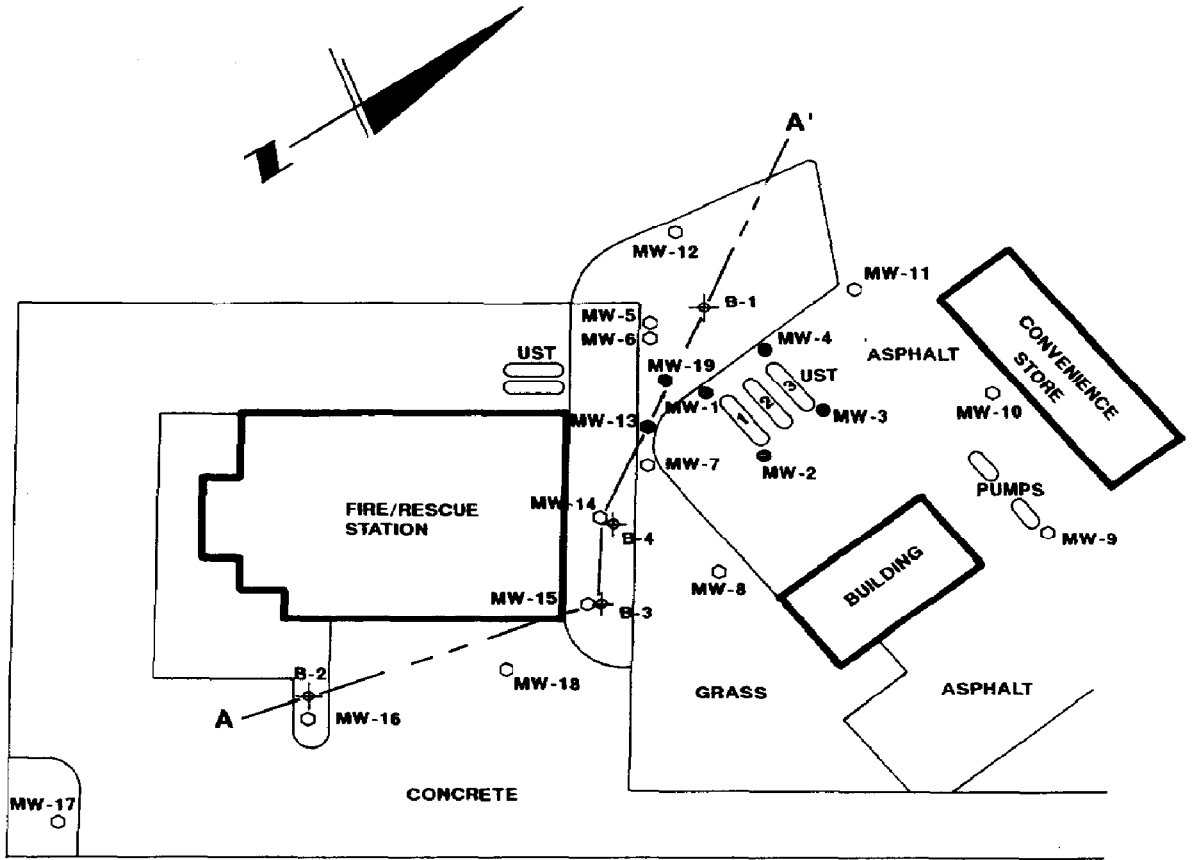Fig. 1. Atlantic coastal plain of the United States.

of sediment thousands of feet thick offshore at the continental slope. Along the Atlantic seaboard the coastal plain extends from the Fall Line, where the sediments meet more resistant igneous and metamorphic rocks of the Piedmont and New England Physiographic Provinces [1], seaward to the continental slope.

2. Case 1—Gasoline leak, Central Florida

This case involves the study of the migration of a dissolved gasoline plume in central Florida. The project site is a convenience store with gasoline storage facility that had leaked prior to June 1986. The site is on the Mt. Dora Ridge, a sandy ridge dissected by numerous relict sinkhole lakes (Fig. 2). The ridge surfaces represent a mature karst surface as evidenced by the wide range in elevations and numerous lakes formed as a result of solution activity controlled by these relict beach ridges [2]. This area has been characterized by the U.S. Geological Survey as a "high recharge" area to the underlying Floridan Aquifer, the principal potable water source for central Florida [3]. Hydrostratigraphy generally consists of a silty sand surficial aquifer on a thin or non-existent confining bed overlying the Floridan Aquifer System.

In 1984, three 8,000 gallon (30,400 L) storage tanks were installed at the

Fig. 2. Site 1 location map.

referenced facility for the initial owner (Fig. 3). During mid-July 1986 ground-water quality check of the existing compliance monitoring wells, a new owner detected high concentrations of dissolved petroleum products in the tank area

Fig. 3. Site plan.

and downgradient to some degree. Tank tightness tests were inconclusive until a small amount of the product was removed from MW-1 (Fig. 3) on July 13, 1987 and taken to a chemical laboratory for analysis by infrared spectrometry which provides a "fingerprint" of the product sample. This analysis was com-

pared against standard sample analyses of gasoline from the store supplier. A product type determination on the sample was made and the best match was regular unleaded gasoline. This tank was retested and showed a calculated loss of 0.036 gallon per hour (± 135 ml/h) on the unleaded gasoline tank. No free product has been detected in the subsurface since July 13, 1987. The unleaded tank was repaired by an interior coating of epoxy resin in August 1987. Assuming a slow (0.036 gph) release of product over the estimated 2 year life of the leak, we estimate a total leak of 630 gallons (± 2500 L) of unleaded gasoline.

2.1 Site hydrogeologic characteristics

The topography of the site displays a gradual slope to the southeast. The entire area concerned in the contamination assessment is shown within the 150 foot (450 m) contour line and lies on the southwest of an upland area with elevations as high as 175 feet (525 m) above mean sea level (msl), as shown on Fig. 2. The average water table depth from surface is 5 to 6 feet (1.5–1.8 m). An average recharge rate of 2 inches (5 cm) a month based on an annual 24 inches (0.6 m) a year will infiltrate to the shallow water table aquifer in these central Florida soils [4].

Publications of the U.S. Geological Survey and Florida Bureau of Geology indicate that central Florida is underlain by two main water bearing aquifers, the unconfined clastic aquifer and the Floridan Aquifer. A Generalized Geologic Column representative of the area is presented on Fig. 4. The surficial aquifer is characterized by Recent to Pleistocene age undifferentiated sediments ranging in thickness from 10 to 30 feet across the area. The general physical characteristics of the surficial aquifer are fine, silty, and clayey sands with isolated layers of organic rich hardpan. Beneath the surficial aquifer, late Miocene and Pliocene age undifferentiated sandy sediments are locally encountered [4].

Beneath the undifferentiated sediments, the Hawthorn Formation of Miocene Age is generally, although not always found. The Hawthorn Formation varies in thickness from 0 to 50 feet and is composed primarily of blue to green-gray phosphatic clay and cream to gray sandy dolomite and is considered the confining bed overlying the Floridan Aquifer. However, the Hawthorn Formation is thin or absent in this part of central Florida, where the Floridan Aquifer is unconfined [4].

The investigations of site hydrogeology were primarily conducted on the surficial aquifer since petroleum contamination is typically located in the thin veneer of soils near the water table. This surficial clastic aquifer was investigated by several test borings and wells to study the characteristics of the soils and identify the major aquifer flow zones. The locations of the Standard Penetration Test borings and auger borings at test wells are presented on Fig. 3. The test borings used to develop the surficial geologic cross-section are presented on Fig. 5.
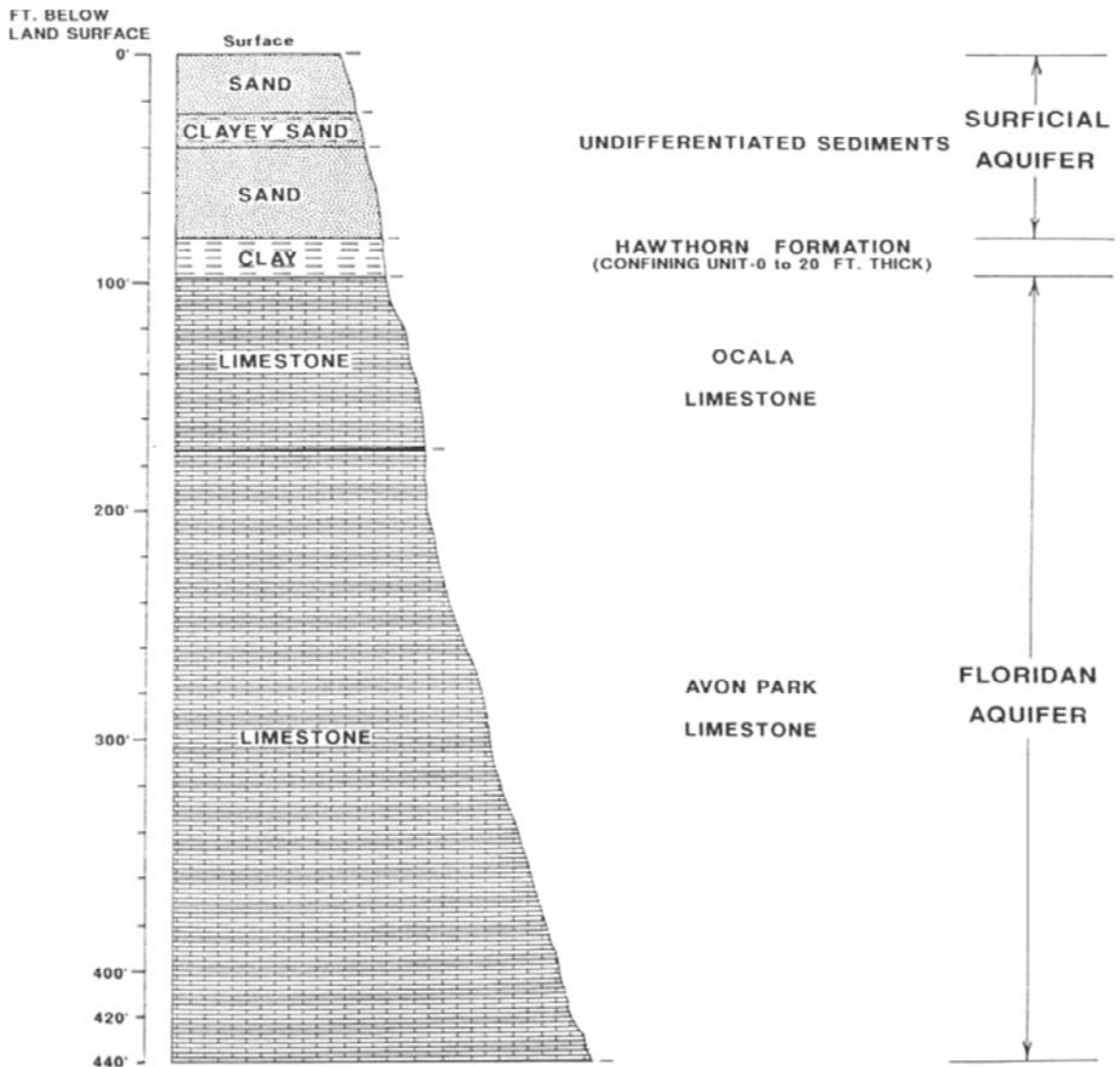
FT. BELOW
LAND SURFACE

Fig. 4. Regional geological column.

As shown, the soils encountered by the soil borings consist of two very distinct sand strata. The upper unit is composed of light-gray sand and extends from the surface to a depth of 18 feet below land surface (bls). The second unit consists of a dark-brown to black silty sand which was encountered from 18 to 35 feet below grade. The two layers are differentiated by their silt content and a notable density change. The lower unit exhibited a relative density from the ASTM Soils Classification Chart of very dense (> 100 blows/ft).

The average hydraulic conductivity (K) of the upper sands was calculated from laboratory tests using three soil samples and slug tests conducted at monitor wells 1, 2, and 7. The geometric average of these values and slug tests
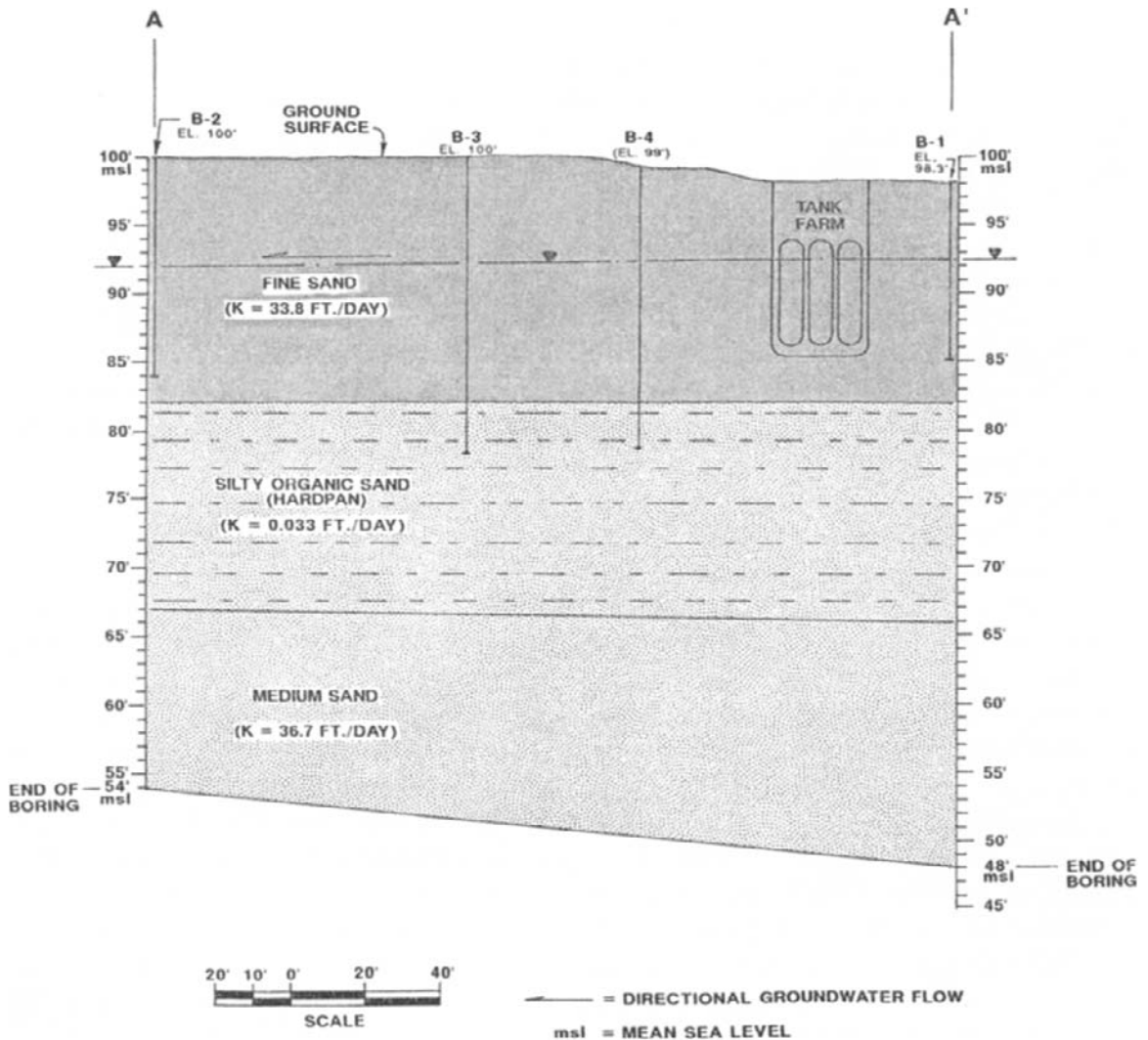
Fig. 5. Geological cross-section A-A′.

results in a hydraulic conductivity in the upper surficial aquifer in the major flow zone of 33.8 ft/d [5].

The underlying hardpan exhibited much lower hydraulic conductivity values. The interval from 20 to 45 feet of this unit was tested using two falling head laboratory tests. These analyses showed a hydraulic conductivity of 0.0514 to 0.0151 ft/d. This layer was considered the confining layer for the site due to the fact that there are four orders of magnitude between the hydraulic conductivity of the upper grey sand and this dense dark-brown hardpan layer. The hydraulic conductivity of the sand below this confining layer at 50 feet was estimated by laboratory analysis to be 36.7 ft/d.

Groundwater flow direction is to the south-southwest following topographic

slope towards a lake 3/4 mile (1.2 km) west of the site. The average water table gradient across the site, relatively low, is estimated as $i = 0.0024$ feet/foot. Seasonal water table fluctuation was as much as three feet over the study period. The horizontal seepage rate was estimated by a modified Darcian flow equation to be 0.27 ft/d or 98.6 feet per year.

An analysis of vertical head distribution in the surficial aquifer based on deep piezometers MW-13, and MW-19 indicates that there is a strong downward flow component in the aquifer just south of the tank farm area. These head measurements indicate that, although the hardpan layer from 18 to 35 feet bls shows permeabilities of a confining layer, the porosity or breaches in this unit may allow a relatively rapid vertical flow rate. Head differences between MW-13 in the hardpan layer and MW-19 in the lower sands indicate that the lower sands are semi-confined.

2.2 Hydrogeologic effects on plume migration

Groundwater quality was assessed on this site five times over the three year investigation period. Initial sampling events in June and July, 1986, at the then four existing tank farm wells, showed a very high concentration of volatile organic aromatics (VOA's) in wells MW-1 and MW-2 (17,000 and 2,400 µg/L, respectively). The partitioning of the VOA's (benzene, toluene, xylene, ethylbenzene) at this time was basically in correlation with their respective percentages in a typical unleaded gasoline and their respective solubilities in groundwater, since these wells were near the leak source [6]. However, by February 1987, the dissolved VOA plume had dispersed laterally across the tank farm to MW-4 and downgradient approximately 70 feet to just beyond the property line (Fig. 6). In July, 1987 groundwater was sampled from deep well MW-13 within the plume; this sample showed that the VOA's were confined to the upper 23 feet of the surficial aquifer. At this time the low hydraulic gradient at the center of the site and the hardpan layer had acted to retard the plume migration.

Worthy of note are the large concentrations of methyl *tert*-butyl ether (MTBE), an unleaded gasoline octane booster, detected in the March 1988 sampling, where none were detected in 1987. Since MTBE is highly soluble in groundwater (43,000 mg/L) and easily detected, we assume that this may be a result of a gasoline mixture change prior to the tank repair between the 1987 and 1988 sampling events.

Vertical plume migration of MTBE was shown to reach a depth below 30 feet in 1988, however, no other dissolved VOA's were detected (Fig. 7). MTBE has been shown to enhance the solubilities of the other more toxic gasoline derivatives, and thus, increase their mobility [7]. The State of Florida currently has a 50 µg/L clean-up criterion for this compound.

A sampling event in October 1989 showed that the benzene plume had somewhat retreated from its March 1988 size in areal extent to the property line
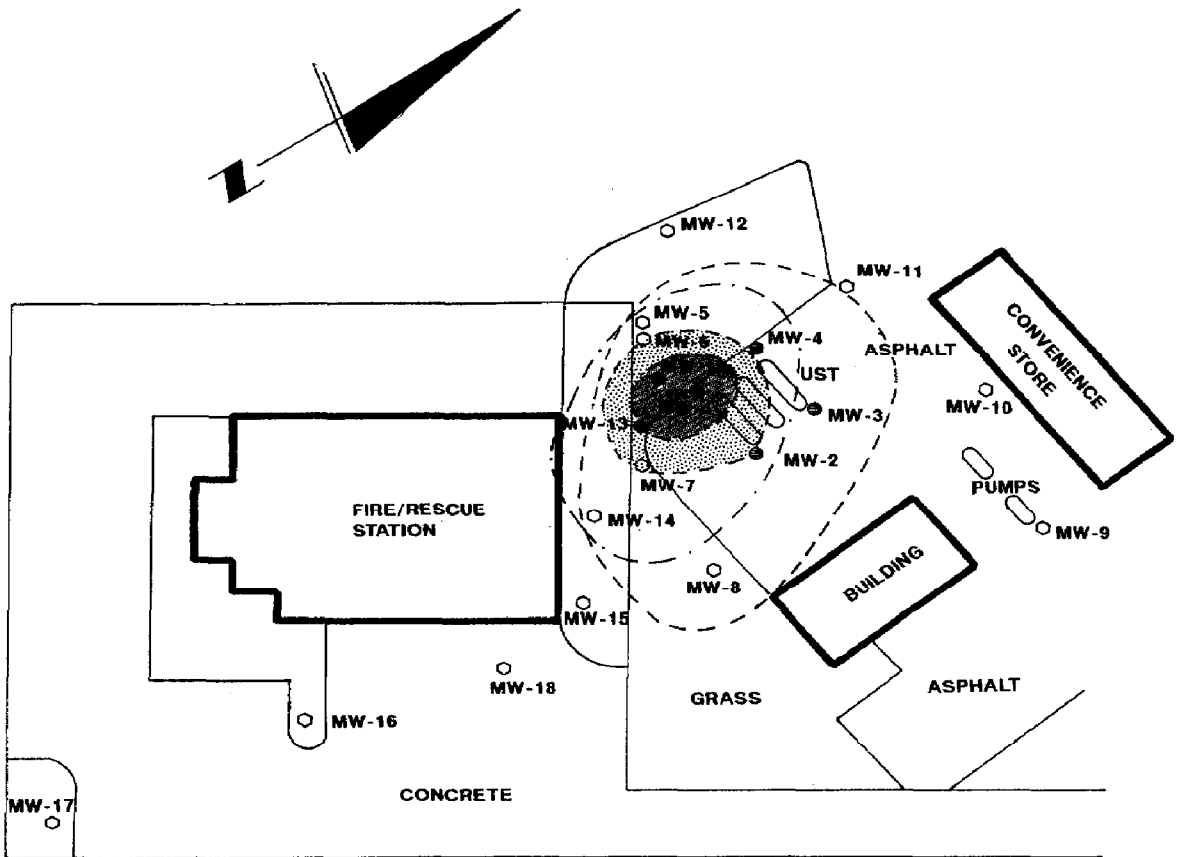
LEGEND

⊖   4" DIAMETER COMPLIANCE MONITOR WELL

●   2" DIAMETER DEEP MONITOR WELL

○   2" DIAMETER SHALLOW MONITOR WELL

UST   UNDERGROUND STORAGE TANKS

— — ⋅ — —   DISSOLVED HYDROCARBONS - 2/87

— — — —   DISSOLVED HYDROCARBONS - 10/89

GROUNDWATER FLOW DIRECTION

▓   PLUME CORE - 2/87 >5000 ppb TVOA

▒   PLUME CORE - 10/89 >5000 ppb TVOA

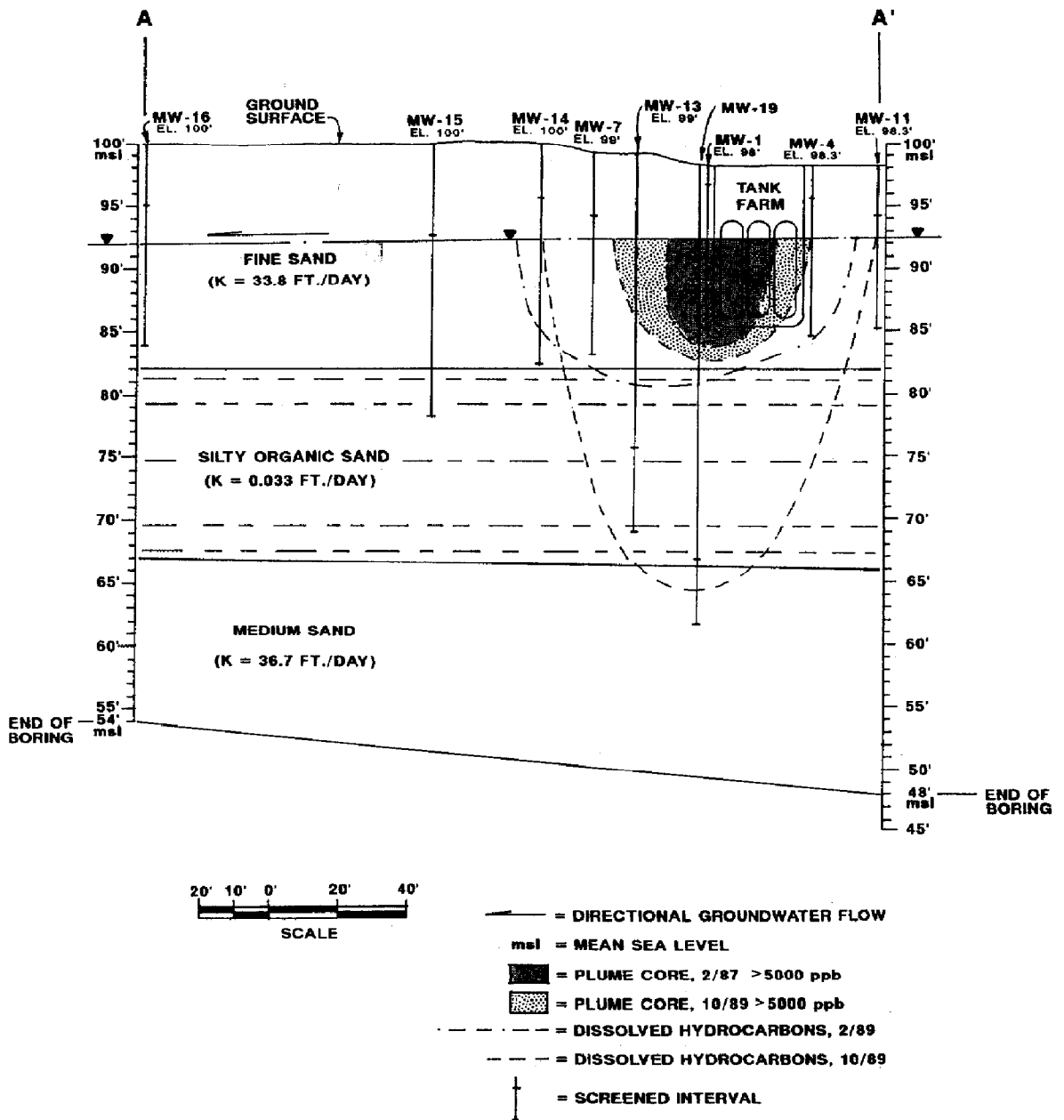Fig. 6. Historical volatile aromatic plume development.

Fig. 7. Historical vertical VOA plume development.

within 50 feet of the leak source (Fig. 6). However, this time benzene and MTBE had reached MW-19, a deep well screened at 35 feet bls (Fig. 7). This finding confirmed that the hardpan layer had only slightly retarded benzene and MTBE from migrating vertically into the lower sand bed. Our 1989 sampling shows that the other VOA's had migrated laterally through dispersion

approximately 30 feet since 1987, however, the plume had diminished on the downgradient side and retreated to the property line near MW-14 (Fig. 6).

3. Case 2–Research and production facility, Sea Island District

Our second case study addressed the development of a volatile organic plume at a dye product research and production facility, which operated from the mid-1950's until the early 1980's. This facility synthesized dye intermediates using volatile aromatics as substrate molecules for the production of dye intermediates. The principal types of syntheses conducted at the site were nitration, catalytic hydrogenation, oxidation, amination, amidation, esterification, and sulfonation.

Methods of waste disposal varied during the history of the plant. Waste handling and treatment at the plant evolved as the plant grew and as waste treatment methods changed. A review of aerial photography of the site indicates that the initial method of waste handling was to discharge liquid wastes to a drainage ditch, which led to a pair of small, unlined holding ponds southeast of the production building; this ditch later extended from the second pond to a point of discharge into the marsh. The ditch and small ponds were replaced by a single unlined holding pond and a waste lagoon by 1972; however, these were soon replaced with two spray fields and a concrete-lined holding pond in 1975. During the later years of operation, there are reports that the plant had a solvent recovery and recycling operation. However, the main point of entry for contaminants into groundwater appears to be a former unlined holding pond (Fig. 8). This former unlined holding pond received process wastes from the adjoining production area. This research and production facility is located on a small island adjacent to a tidal creek and a salt marsh (Fig. 9) within the Sea Island District of the Atlantic Coastal Plain. The Sea Islands are a complex of multigenerational barrier islands which occupy the coasts of South Carolina, Georgia, and northernmost Florida. They extend inland a considerable distance from the shore and harbor a vast salt marsh complex, which serves as a spawning ground and nursery for the sea life of this region. The site in Case 2 is approximately 18 miles inland from the Atlantic Ocean. The U.S. Environmental Protection Agency added the site to the National Priorities List in 1983.

3.1 Site hydrogeology

Sediments beneath the site that were relevant to the contaminant investigation are those containing the Floridan Aquifer and overlying units extending to the surface. The rocks described from oldest to youngest are Eocene limestones; Miocene limestones, sands and clays; and Pliocene to Holocene sands and clays [8]. Limestone in the study area consists of the middle Eocene Santee limestone and the upper Eocene Ocala limestone. The Santee limestone
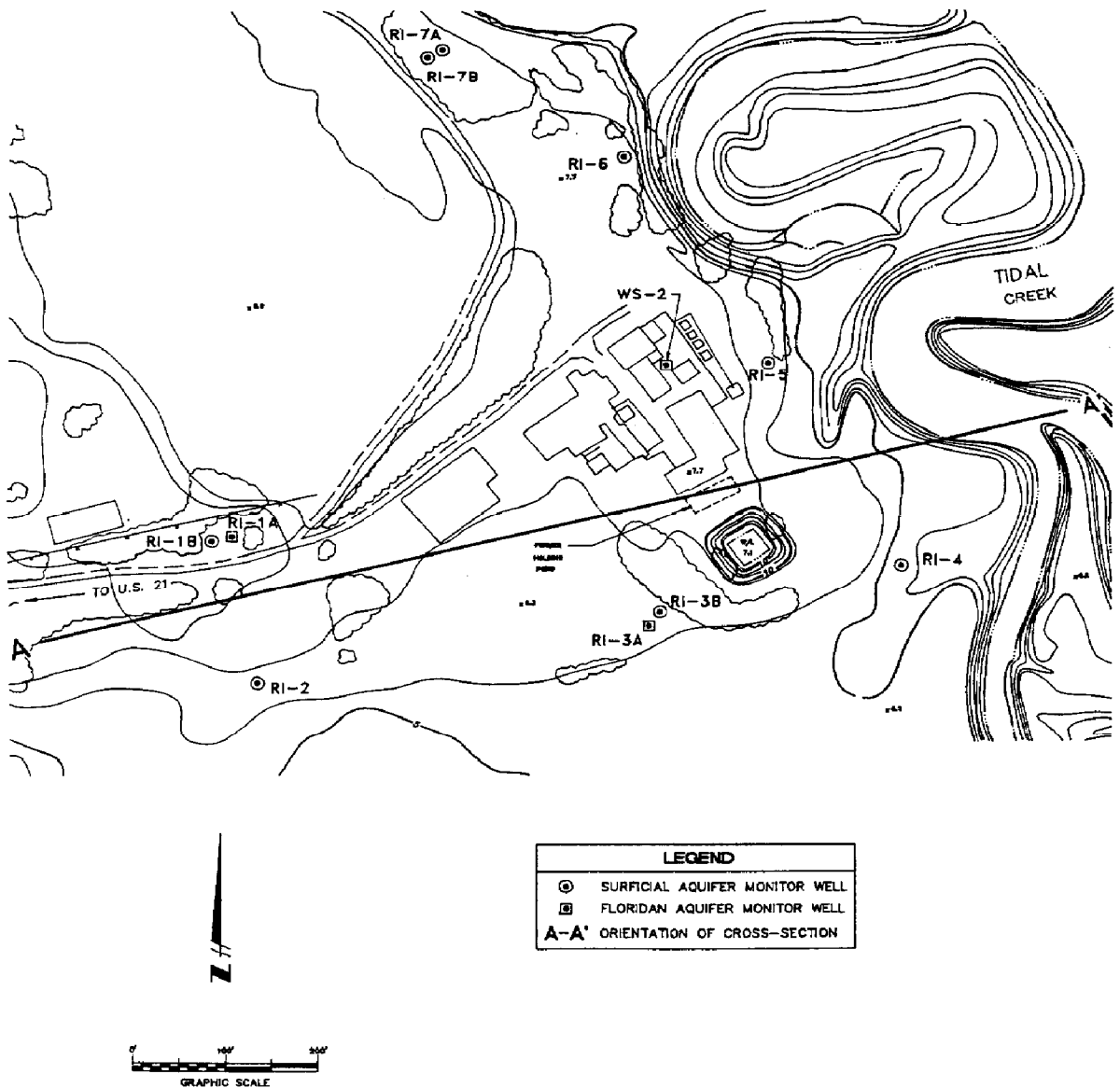
Fig. 8. Site layout, Case 2.

consists of indurated, siliceous, glauconitic, white-grey to creamy yellow lime-stone, 200–400 feet thick. The Ocala limestone in the study area is composed of a lower and an upper unit. The lower unit of the Ocala limestone is a silty, clayey, gluaconitic limestone; while the upper unit is a white-light grey highly permeable bioclastic bryozoan rich limestone 25–100 feet thick [9]. The upper unit of the Ocala limestone is the principal aquifer in the region (Floridan Aquifer), and is estimated to supply over 99% of the groundwater and more than 70% of all water used in the study area [8].

The Miocene Hawthorn Formation, where present, ranges in thickness from
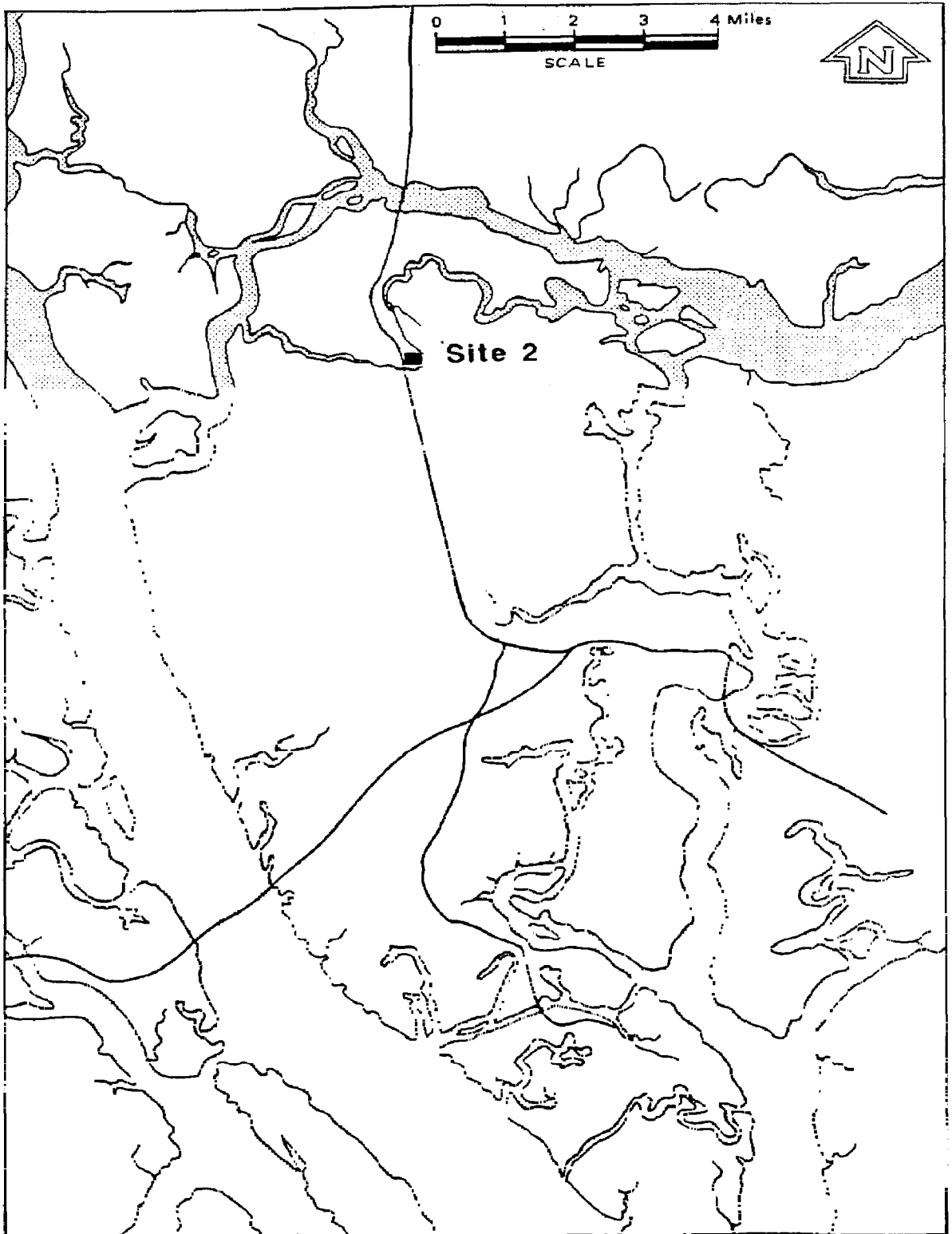
Fig. 9. Site location map, Case 2.

50 feet to less than 10 feet [9]. This formation is of variable lithology and may consist of phosphatic clayey sand to phosphatic sandy clay with associated sandy dolomitic limestone and highly phosphatic dolomitic sandy clay limestone [8]. If present, the clayey lithologies act as confining beds to the Floridan Aquifer with the dolomitic limestone yielding water to wells in hydraulic continuity with the Floridan Aquifer [8]. The Pliocene and Holocene sediments in the study area consist of unindurated clays, silts, and sands deposited by water in a marine nearshore and estuarine environment. The Floridan Aquifer corresponds with the Eocene and Miocene limestones, and the water table aquifer corresponds with the Pliocene to Holocene sands.

Subsurface investigations during the remedial investigation involved the installation of seven shallow (35 foot) monitor wells in the sands of the surficial aquifer and three wells to monitor the Floridan Aquifer (70 feet). Standard penetration tests borings were performed in conjunction with the installation of each of these wells. In addition to the wells installed specifically for the investigation, an existing water supply well, WS2, was sampled in the former production area of the plant. Well locations are indicated on Fig. 8. Hydrologic data collected during remedial investigation included daily water levels from all monitor wells, continuous water levels from wells RI1B, RI1A, RI7A, RI7B, and project tidal gage. We also collected field hydraulic conductivity data from the shallow/deep pairs of wells.

The subsurface at the site is characterized by 50 feet of fine to coarse sand, underlain by the limestones of the Floridan Aquifer (Fig. 10). The sands overlying the limestone were deposited in a marine nearshore and estuarine environment and are related to the development of the Sea Island Complex.

Water levels in the Floridan Aquifer well closest to the creek were approximately one foot higher than the water table during high tide and approximately three feet higher than the water table during low tide. In the well cluster farthest from the tidal creek the relative difference was less pronounced and the difference during high tide was approximately half a foot while the difference at low tide was approximately one foot. Tidal range in the creek was approximately 5 to 8 feet during the field investigation.

The horizontal hydraulic gradient in the surficial aquifer was consistently towards the tidal creek under both high tide and low tide conditions. However, the indicated direction of flow adjusted slightly in response to the variations in water levels in the creek. The horizontal component of flow in the Floridan Aquifer at the site was consistently towards the northwest in the direction opposite the tidal creek adjoining the site. This is more indicative of the regional flow pattern in the Floridan Aquifer and indicates a general lack of effect of the tidal creek on flow patterns in the Floridan Aquifer.

The hydrologic investigation found that there is an unconfined aquifer in the sands, which discharges to the adjoining tidal creek and salt marsh. The average hydraulic conductivity of the sands was 14.9 ft/d as measured by single
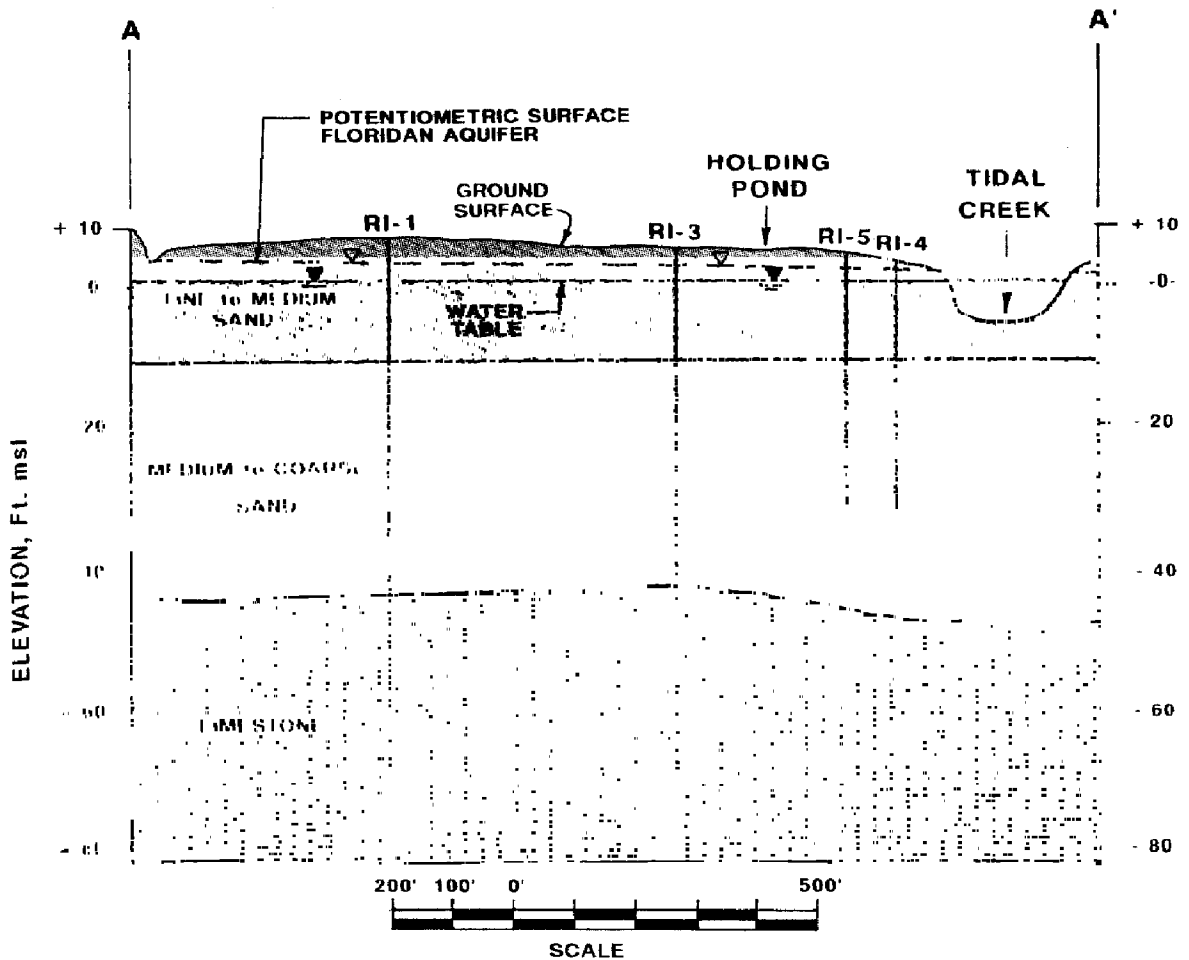
Fig. 10. Geologic cross-section A-A', Site 2.

well slug tests. Even though there was no confining unit in the conventional sense, we found that the Floridan Aquifer is partially confined by the overlying sands due to the hydraulic conductivity contrast. The Floridan Aquifer's hydraulic conductivity on average was 205 ft/d.

There was a net upward vertical hydraulic gradient from the Floridan Aquifer to the overlying unconfined sands throughout the field investigation. Average vertical gradients during the field investigation were +0.014 feet per foot (ft/ft) +0.062 ft/ft, and +0.057 ft/ft for the shallow/deep well pairs at well sites RI-1, RI-3, RI-7 respectively. The persistence of an upward hydraulic gradient indicates that the Floridan Aquifer is discharging into the water table aquifer. This is consistent with earlier reports that the site is on the northern flanks of a recharge mound for the Floridan Aquifer in this region [8,9].

3.2 Hydrogeologic effects on plume migration

Principal contaminants identified during the remedial investigation were acetone, benzene, toluene, total xylenes, 1,2-dichlorobenzene, 1,4-dichlorobenzene, 2,4-dinitrotoluene, and naphthalene. It appears that the contaminant plume in the surficial aquifer may have originated in the vicinity of the former holding pond, since the location in which high concentrations of site contaminants were detected centers around the former holding pond.

Chemical analyses of groundwater collected from the unconfined aquifer detected up to approximately 80,000 micrograms per liter total volatile organics. The plume is focused in the production area and extends northeasterly towards an area of discharge into the tidal creek and nearby salt marshes (Fig. 11). No volatile organics were detected in the Floridan Aquifer or in the creek. It is
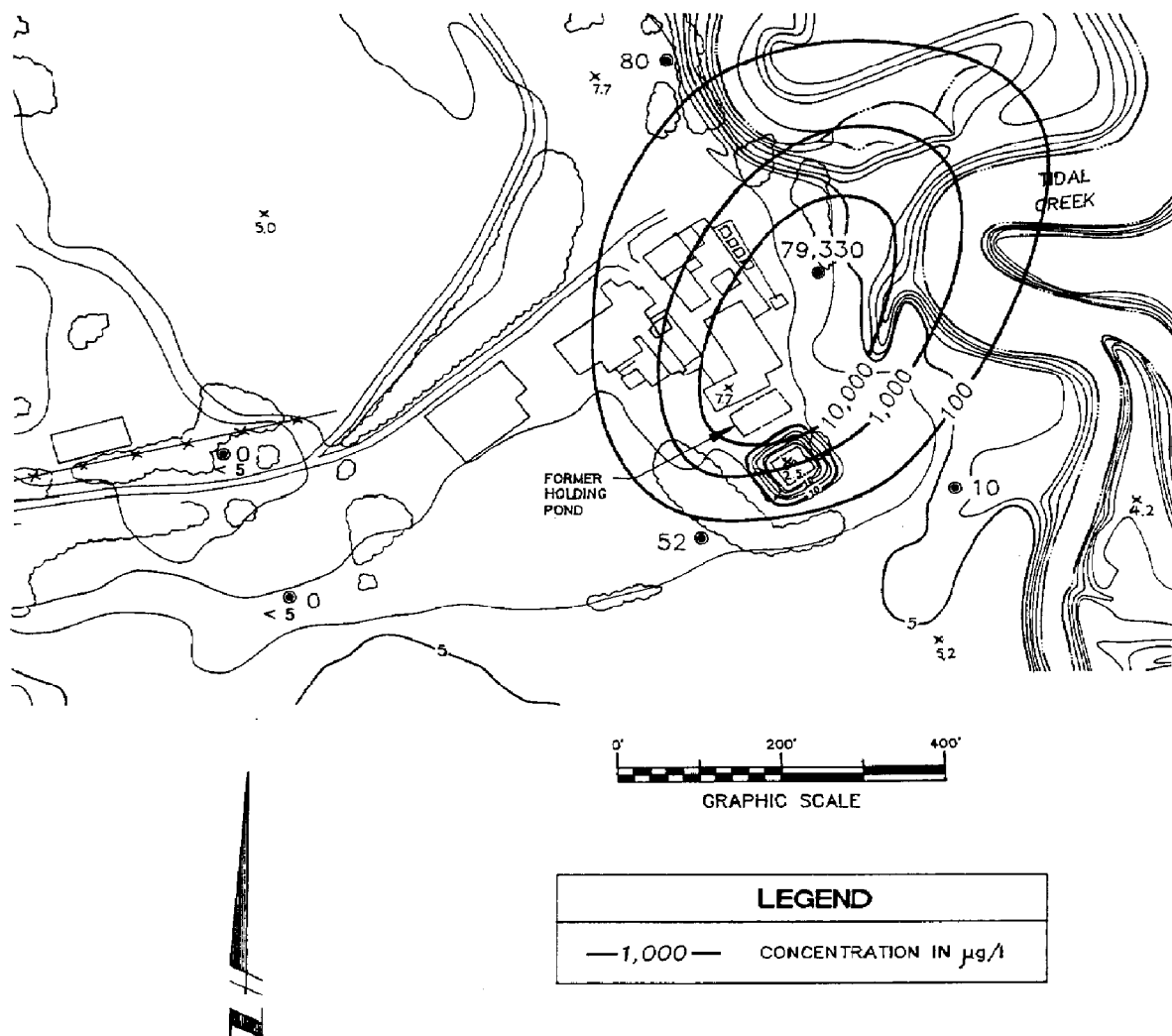

Fig. 11. Concentration of total volatile organics in shallow groundwater, Case 2.
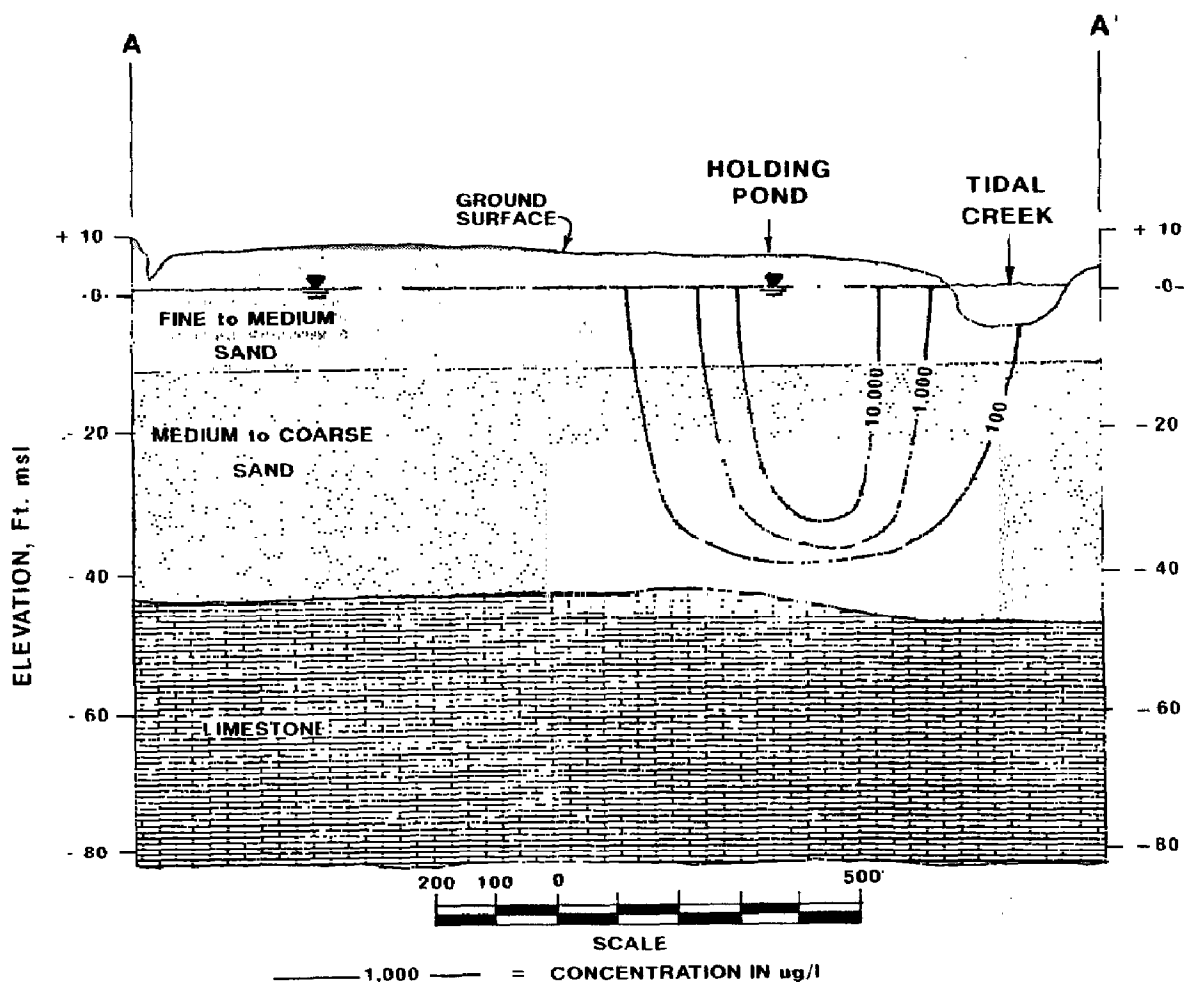
Fig. 12. Total volatile organics, cross-section A-A', Case 2.

probable that the contaminants discharged to the creek are diluted by the much greater volume of water in the creek and are therefore not detectable in the surface water. The vertical development of the plume appears to be limited by the consistent positive vertical hydraulic gradient and the proximity of a zone of discharge into the tidal creek (Figs. 10 and 12).

4. Case 3—Industrial waste disposal site, mid-Atlantic Coastal Plain

Site 3 is within the Atlantic Coastal Plain, approximately 2 miles from the Fall Line. The site was operated as a sand and gravel quarry. Earth materials were removed from two areas—the Eastern Excavated Area and the Western Excavated Area (Fig. 13). Approximately 3 acres (0.01 km²) of the site in the Eastern Excavated Area were reportedly used for the disposal of waste processing water, sludge, still bottoms, and about 90 drums of solid and semisolid
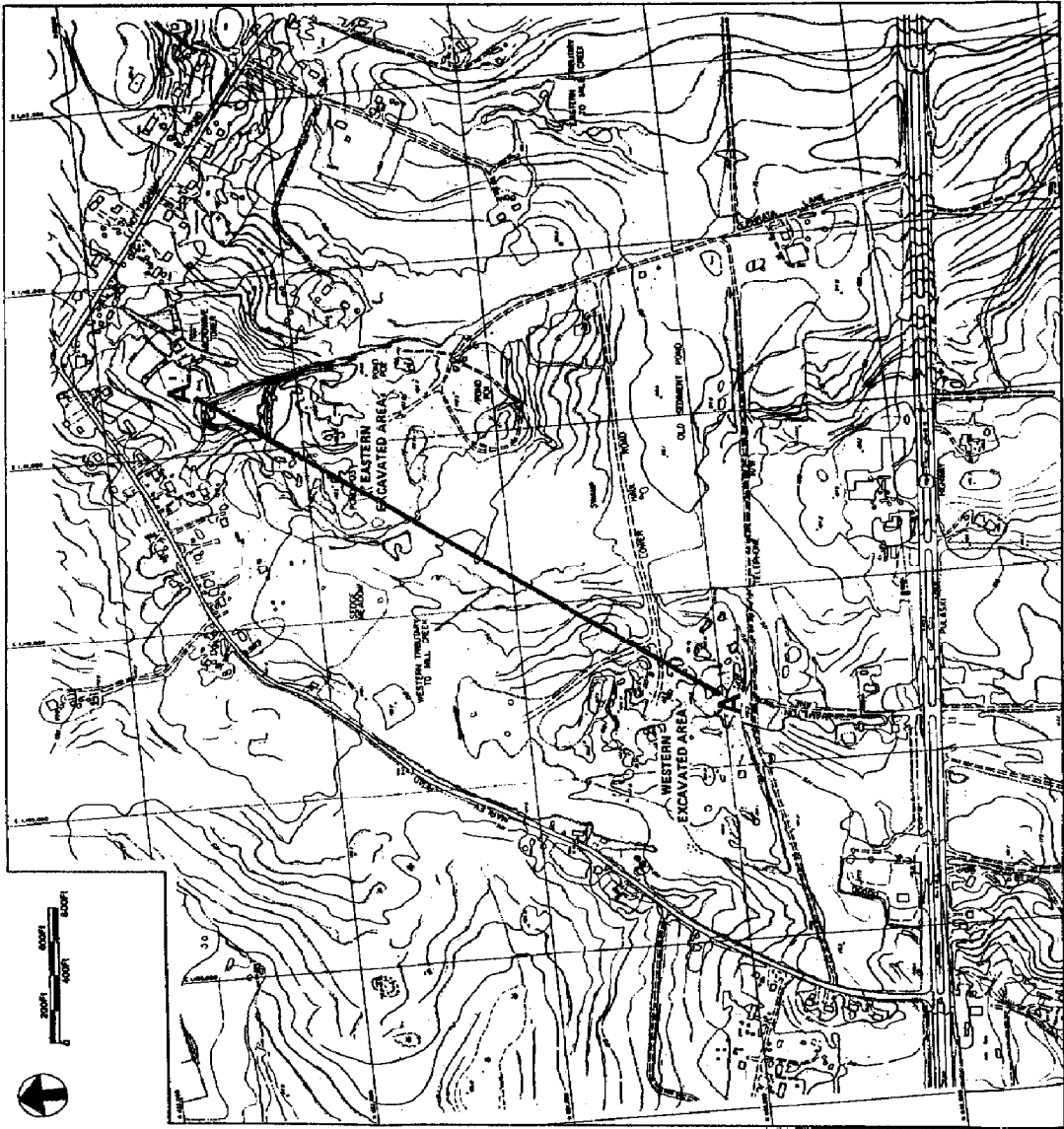
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Fig. 13. Site layout, Case 3. (Source: Base map by Air Survey Corp. of Virginia, Reston, VA, March 19, 1985.) Orientation of cross-section in A-A'.

waste between 1969 and 1974. Three pits in the Eastern Excavated Area were used as surface impoundments, where about 700,000 gallons of waste were disposed. Two hundred thousand gallons of liquid waste were removed from the site in 1974. The drums and sludges that remained were buried on-site in the excavated pits in the Eastern Excavated Area. There was no evidence of waste disposal in the Western Excavated Area.

4.1 Regional hydrogeology

Only one stratigraphic unit, the Potomac Group, is reported to outcrop in the vicinity of Site 3 [10]. The Potomac Group is of Cretaceous age and is believed to consist of fluvial, deltaic, and paludal deposits [11]. In the area of Site 3, the Potomac Group consists chiefly of quartz sand, sandy clay, and clay. Other constituents include feldspathic sands, lignite, pyrite, and quartz gravels [10].

Individual lithologic units (sand, silt, clay, gravel, etc.) are not readily traceable in the study area because the sediments have little lateral continuity, even over short distances [10]. This is typical of deposits associated with sandy fluvial systems, because the main depositional agent—a river and its tributaries is subject to dramatic variations in its flow regime and changes of course over time.

The igneous and metamorphic bedrock complex of the study area includes a variety of rock types [12]. Metamorphic rocks in the area consist of mica and chlorite schists, gneisses, and metadacites. The chief igneous rock types are granodiorite, gabbro and associated ultrabasic rocks, and metadacite. Bedrock encountered in wells beneath the site was greenish–yellow olivine, pyroxene, amphibole, biotite, quartz, and diorite gneiss.

Hydrologic properties of the Potomac Group in the study area vary over a wide range. They depend primarily on the effective thickness of sand in the saturated zone of the Potomac Group [10]. The total effective thickness of sand in the Potomac Group ranges from 5 to 755 feet in the region, and from 7 to 246 feet in the local area. Variability in effective sand thickness is caused by both variations in lithology and thickening of the Potomac group to the southeast. Transmissivity (a measure of the water transmitting properties of an aquifer) measured in the region ranges from 400 to 9,200 ft^2/d.

4.2 Site 3 hydrogeology

Subsurface investigations conducted during the remedial investigation (Phase I and Phase II) involved installation of forty monitor wells, of which nine were completed into bedrock. The geology of Site 3 consists of fluvial Potomac Group sediments that overlie fractured metamorphic bedrock. The sediments are sand, gravel, silt, and clay. Although the sediments exhibit marked lateral variations, there appear to be several laterally consistent lithologic units across much of the site (Figs. 14 and 15). These units are:
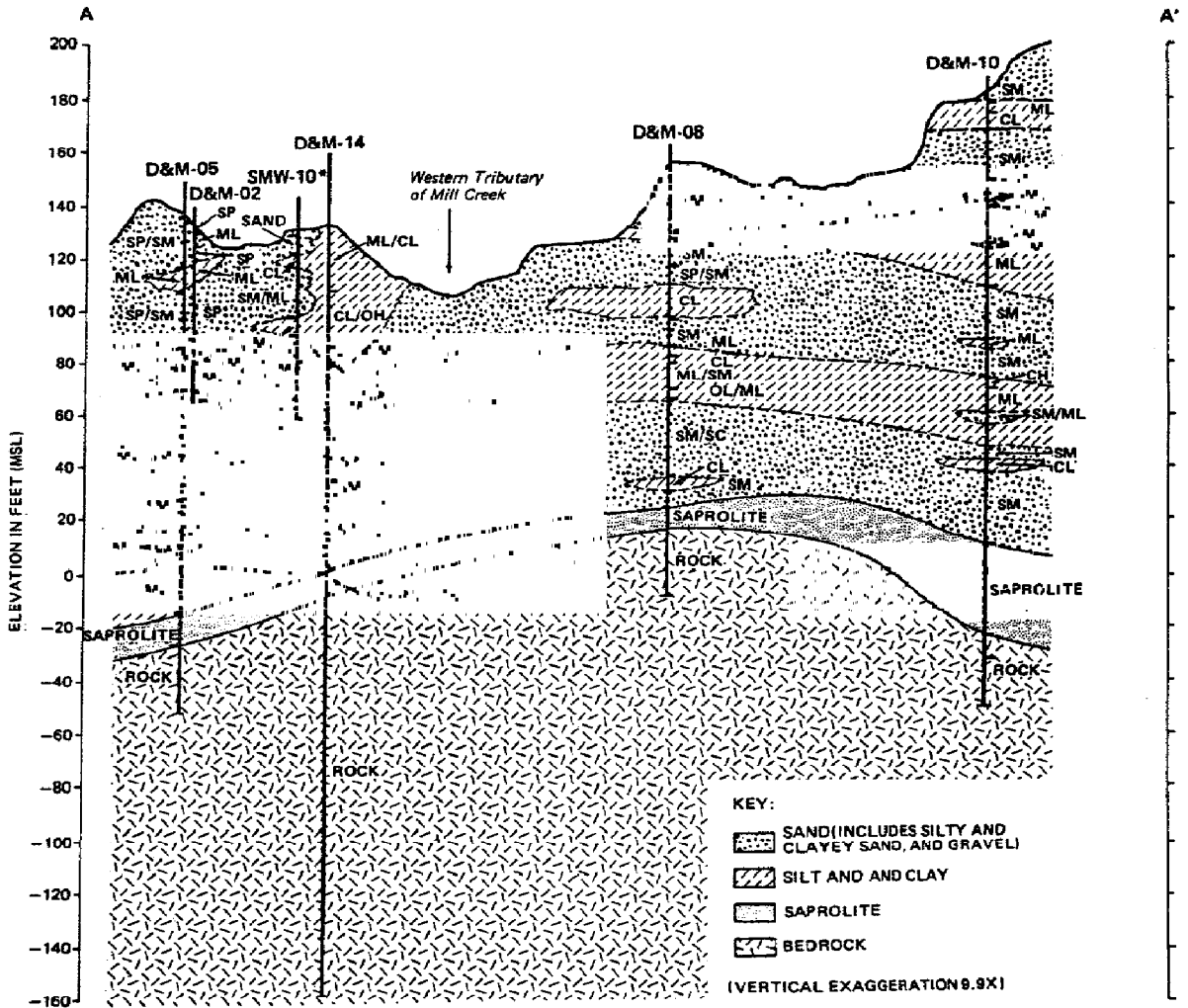
Fig. 14. Lithologic cross-section A-A', Case 3.

- An upper sand unit (apparently restricted to the Eastern Excavated Area).
- An upper silt and clay unit (also apparently restricted to the Eastern Excavated Area).
- A middle sand unit.
- A middle/lower silt and clay unit (which occurs as two units in the southwest portion of the site and appears to merge to the northeast and southeast; the middle silt and clay unit is known to be absent in one location in the Western Excavated Area).
- A lower sand unit, which is present in the northeast and southwest, but is absent in the southeast.
- A zone of weathered bedrock (saprolite), present in all locations drilled into bedrock.
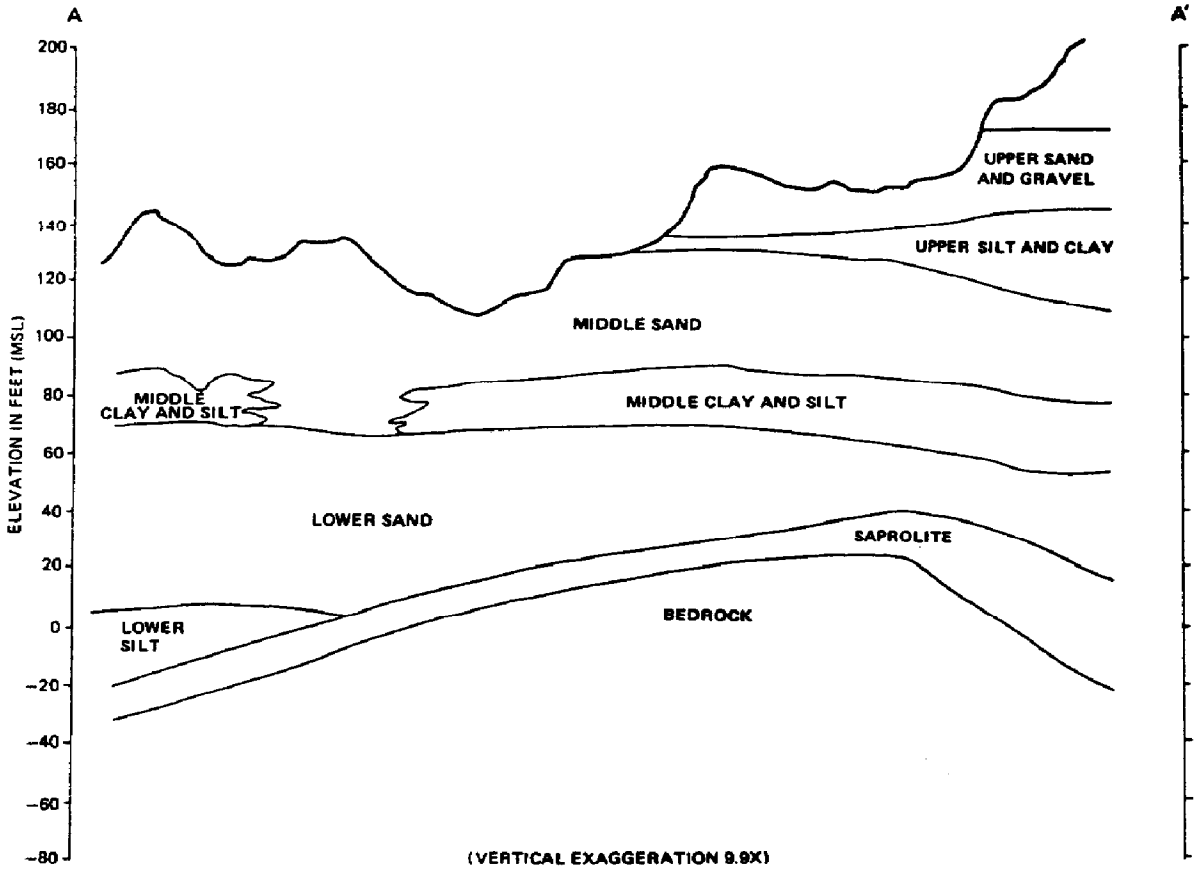
Fig. 15. Hydrogeologic units, cross-section A-A', Case 3.

· Bedrock.

Information collected in the Phase II remedial investigation indicates that there are four distinct but related groundwater flow systems at the site (Fig. 15).
· A perched water table system in the upper sand unit of the Eastern Excavated Area.
· A water table system in the middle sand unit along the valley of the western tributary of Mill Creek.
· A partially confined system in the deeper sediments (referred to as the lower sand unit).
· A bedrock system.

Groundwater in the perched water table system in the Eastern Excavated Area flows toward seeps located west, southwest, and southeast of the Eastern Excavated Area. Flow in the other water table system (middle sand unit) is generally south. The horizontal component of flow in the deeper units is toward the south or south-southwest. Vertical gradients between the deeper units
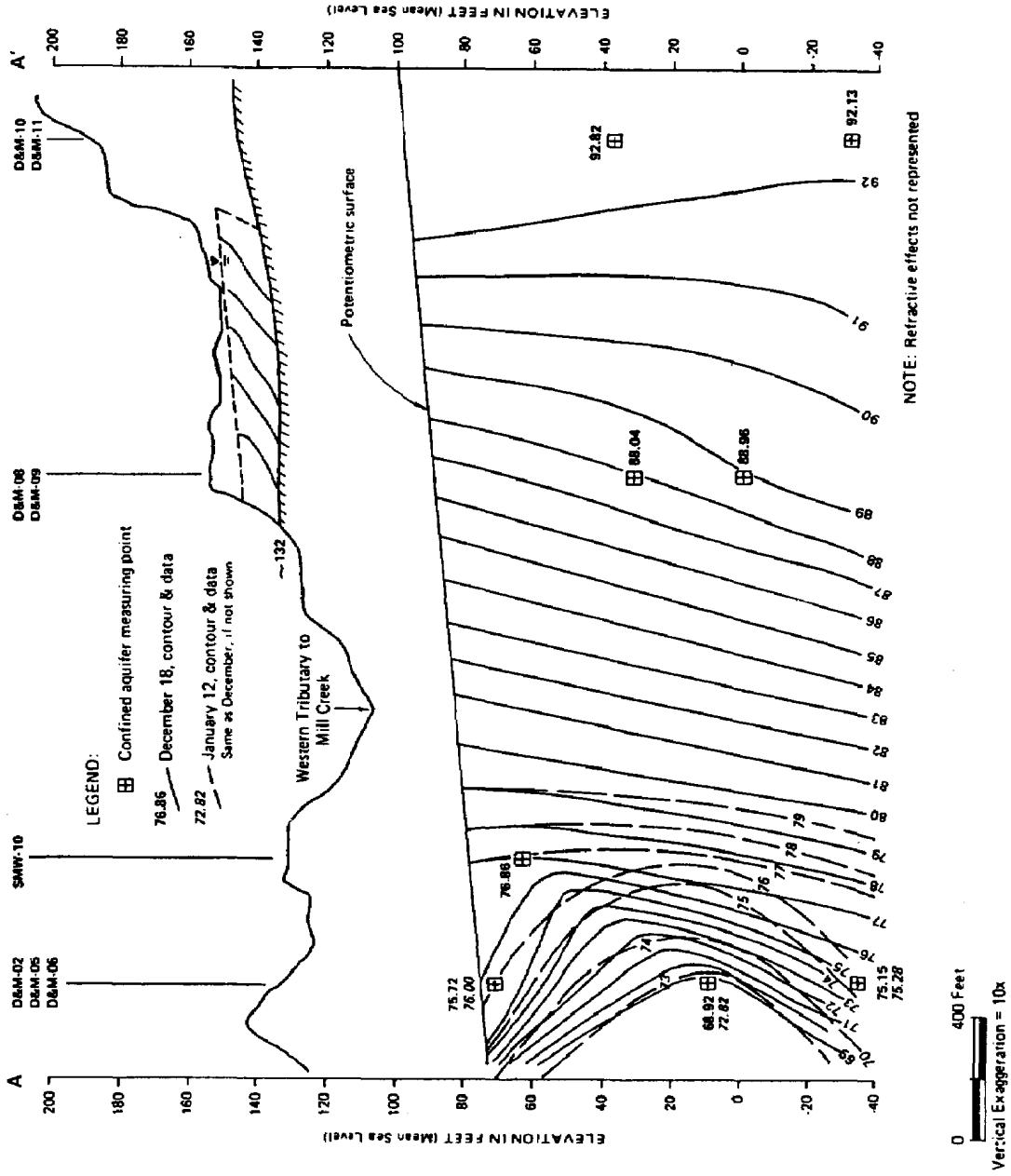
Fig. 16. Potentiometric cross-section A-A', Case 3.

are downward in the eastern portion of the site and upward in the southwestern portion. The west and southwest seeps from the upper sand unit flow into swampy and marshy areas and into the western tributary to Mill Creek. During the Phase II field investigation, it was evident that these are "losing" surface water to the water table system in the middle sand along the valley of the western tributary of Mill Creek.

4.3 Effects of hydrogeology on plume development

Groundwater in the upper sand unit (Eastern Excavated Area) contained significantly higher concentrations of organic compounds than in groundwater elsewhere on-site or deeper in the Eastern Excavated Area. The upper sand unit in the Eastern Excavated Area received the direct impact of waste disposal at MSGS, because wastes were reportedly disposed of in ponds in the Eastern Excavated Area.

Groundwater in the middle sand unit in areas downgradient (south and southeast) of the Eastern Excavated Area contained a suite of organic compounds similar to the upper sand unit but at generally much lesser concentrations. Elevated levels of organics were found in only one well. No elevated levels of metals or organic compounds were found in the middle sand unit in other areas of the site. Groundwater samples from the middle sand unit in the Western Excavated Area also were analyzed for pesticides/polychlorinated biphenyls (PCB); none were found.

Water from the lower sand unit wells contained elevated but nonhazardous concentrations of certain metals (concentrations do not exceed maximum contaminant levels (MCL) as defined by U.S. EPA). Some VOC's were present in samples from deep, unconsolidated sediments at low concentrations. Groundwater from bedrock wells on-site also contained low concentrations of metals and a few VOC's.

Potential groundwater migration pathways at Site 3 include surface seeps from the Eastern Excavated Area (which reinfiltrate into the middle sand unit), leakage through confining units, vertical migration via zones where confining units are absent, and flow via potential conduits created by unconsolidated unit-penetrating boreholes. It is possible that contaminants have migrated from the source area (upper sand unit in the Eastern Excavated Area) through the seeps to the surface, reinfiltrated into the middle sand unit, and then were distributed deeper into the system via gaps in the middle silt and clay unit (Fig. 16).

5. Conclusions

The three presented case studies illustrate the complexity of the effects of geology and surface and subsurface hydrology on the development of plumes of volatile organic compounds. Case 1 illustrates that a low permeability confining unit is not necessarily protection against the vertical migration of VOC's,

however, Case 2 seemingly illustrates the reverse principal that the absence of a low permeability confining unit does not necessarily mean that the vertical migration of volatile organic compounds is inevitable. In Case 3, the depositional environment was quite complex and this case illustrates that a complex depositional environment, coupled with topographic opportunities for migration via seeps and surface water, can create unusual patterns of volatile organic contaminant migration.

The VOA plume migration pattern of Site 1 is representative of many central Florida gasoline release sites with shallow water tables and sandy soils. VOA concentrations initially are very high, but rapidly attenuate at the margins primarily through the natural effects of dilution, dispersion, and from volatilization from the shallow vadose zone. The hydrogeologic character of this site acted to initially encourage horizontal and control the vertical migration of the VOA's, but with the synergistic effect of MTBE and local recharge, in approximately five years the vertical plume has penetrated the shallow aquitard (hardpan) and threatens the Floridan Aquifer. This site's remediation by pump and treat began in the Fall of 1991.

At Site 1, the critical factors in the vertical migration of the gasoline constituents through the low permeability confining unit appear to be the solubility of MTBE and the overall tendency of shallow ground water to recharge deeper groundwater.

In Site 2, the site operated for over twenty years as a research and production facility with disposal of wastes to unlined holding ponds adjacent to the production area. Despite that history, the volatile organic chemicals were found to be restricted to the surficial aquifer. This is apparently attributable to the consistent, positive hydraulic gradient from the deeper Florida aquifer into a zone of discharge in the water table aquifer. A probable contributing factor is the opportunity for discharge from the surficial aquifer into the tidal creek which adjoins the site. The calculated rate of seepage into the creek bed is low compared to the twice daily tidal volume; therefore, site related constituents were not detected in surface waters during the remedial investigation at Site 2. The planned remedial action for Site 2 is excavation and treatment of soils in the vicinity of the former holding pond, and treatment of water from the water table aquifer by a combination of air stripping and carbon adsorption. Site 2 is now in the remedial design phase.

At the site in Case 3, the overwhelming majority of volatile organic chemicals remain in the upper sand unit of the Eastern Excavated Area, however, compounds detected in the Eastern Excavated Area were also detected in deeper aquifer units elsewhere on this 200 acre (0.8 km^2) site. Migration from the perched water table in the upper sand unit into the middle sand unit, via seeps and subsequent recharge to the middle sand unit, seems the most likely possibility. The fluvial depositional environment has resulted in a complex hydrostratigraphy, and therefore, the precise routes of groundwater flow and contaminant migration are not resolvable by ordinary and economical means of

investigation. The remedial actions for Site 3 are planned as three operable units. The first operable unit involves treatment of water from the upper sand in the Eastern Excavated Area combined with source reduction and restrictions in the access to the site. The second operable unit involves continued monitoring of on-site and off-site groundwater in the deeper units with provisions for on-site and off-site treatment should that be necessary (the remedial investigations detected no effects of the site in off-site wells). The third operable unit planned will deal with the soils associated with the Eastern Excavated Area followed by final site closure and post closure operation and maintenance activities. As with Site 2, Site 3 is in the design phase.

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