

DESIGN, IMPLEMENTATION, AND PERFORMANCE OF THE
PRODUCT RECOVERY SYSTEM AT THE HYDRA-MATIC ATF SITE

PROGRESS REPORT

SUBMITTED TO:

MICHIGAN DEPARTMENT OF NATURAL RESOURCES

SUBMITTED BY:

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EXECUTIVE SUMMARY

Automatic transmission fluid (ATF) was discovered in a manhole adjacent to an underground storage tank system (UST) beneath the General Motors Hydra-matic Plant at Ypsilanti, Michigan. During excavation in 1985 to remove the underground storage tanks, ATF was found in the soil backfill adjacent to the tanks and free product was found floating on the perched water table. After discussions with and approval by the Michigan Department of Natural Resources (MDNR), Hydra-matic developed and implemented a work plan (Work Plan 1) for "Site Description and Problem Assessment" in 1987. The site was successfully investigated and assessed, and a final report titled "Contamination of Soil and Groundwater by Automatic Transmission Fluid: Site Description and Problem Assessment" was submitted to MDNR in January, 1989. A summary of that report is given below and the complete report is included in Appendix 2. Subsequent to the successful completion of Work Plan 1, Hydra-matic developed another work plan (Work Plan 2) to recover the free ATF (free product) from the subsurface. That work plan was presented to and discussed with MDNR. A final plan was submitted to and approved by MDNR, after which Work Plan 2 was implemented at the site in August 1988. This report describes the design, implementation, and performance of the product recovery systems at the site.

Site Description and Problem Assessment Summary (Work Plan 1)

To delineate the subsurface zones contaminated with ATF, soil-core sampling and monitoring wells were used. The number, location, and depth of cores and of monitoring wells were determined during the investigation based on: (1) inspection and analysis of soil-core samples immediately after each core was taken, (2) physical and chemical measurements of core samples at the

end of each daily sampling session, and (3) measurements in monitoring wells at several stages during the investigation.

Soil cores were taken at 54 locations and monitoring wells were installed at 53 of those locations. The soil and groundwater zones are comprised mainly of sandy materials, which have spatial heterogeneity in size distribution and hydraulic properties. Typically the groundwater zone extends from 6.5 to 13 ft below the plant floor, and it is perched above a layer of dense, gray clay. The direction of groundwater flow is influenced by local man-made structures below the plant and by isolated recharge zones in close proximity to the plant. In general, groundwater flows towards the southwest at a rate of about 17 ft/year.

About $208,000 \pm 33,000$ gal of ATF had spread under the plant over an area of $64,000 \text{ ft}^2$. The region of ATF contamination is comprised of three distinct and contiguous layers. The center layer is about 2.6-ft deep at its thickest point and extends to about 250 ft at its widest point. The soil in this zone is about 80% saturated with $133,000 \pm 21,000$ gal of ATF, which has displaced the water table into the groundwater zone. The top layer is 14 inches thick and contains about 50,640 gal of ATF held by capillary forces. The amount of ATF in this zone decreases with height above the center layer from about 80% to 20% saturation. The deepest layer is 1.0 ± 0.5 ft thick and has $24,500 \pm 12,250$ gal of ATF. Based on a residual retention of 30%, the predicted recoverable volume of ATF from the top and center layers are 35,000 and 93,000 gal, respectively. It is hoped that this combined volume of ATF (128,000 gal) could be recovered from the site by pumping.

Product Recovery Summary (Work Plan 2)

The purpose of this phase of activities at the Hydra-matic ATF site was to

develop, implement, and evaluate a pumping strategy to maximize the amount of ATF that can be recovered from the Hydra-matic site.

Conventional approaches for recovering viscous-oil contamination from soil and groundwater systems could isolate the oil from the recovery well, spread the oil deeper into the groundwater zone, and reduce the volume of recoverable oil. A new pumping strategy for improved drainage and recovery of free oil was developed, tested in a laboratory-model aquifer, and implemented and evaluated at the ATF site at the Hydra-matic plant, Ypsilanti, Michigan. This new strategy differs from conventional approaches in two important ways: (1) The oil-recovery rate is controlled to maximize the pumping rate while maintaining continuity between the oil layer in the groundwater system and the recovery well to avoid isolation of the oil in the subsurface. (2) The rate of groundwater pumping is controlled to maintain the depressed oil/water interface at its prepumped position. This approach prevents further spread of oil into the groundwater zone, prevents reduction in the volume of recoverable oil due to residual retention, and maintains a gradient for oil flow towards the recovery well.

In a model-aquifer study, about 100% of the recoverable volume of ATF was pumped from the system. The field site at Hydra-matic was instrumented with 5 recovery systems. The number and location of the recovery systems were determined based on mathematical simulations of the hydraulic response of the site to different pumping conditions. These systems have been in operation for more than 700 days (since August, 1988), during which time more than 56,000 gal. of the ATF has been recovered. This new pumping approach has been successfully evaluated, and it is being used to remove the free ATF and to decontaminate the soil and groundwater system beneath the Hydra-matic plant.

Future Plans

Two additional product recovery systems are being installed at the site to increase the overall effectiveness of draining and recovering free ATF from the contamination zone. These additional wells will increase the rate of ATF recovery and speedup remediation of the site. While Hydra-matic plans to maintain and operate the product recovery systems as long as the ATF can be drained and recovered, it is projected that product recovery would continue through 1991 by which time most of the drainable ATF would have been recovered.

At the end of pumping a large fraction of the estimated initial volume of ATF will remain trapped between the subsurface material as residual retention. GM will determine if further active remediation is necessary to protect human health and the environment. On going laboratory studies by GM have indicated that native soil bacteria from the site degrades ATF.

ABSTRACT

In a previous study, we estimated that about 208,000 gal of automatic transmission fluid (ATF) had leaked from an underground storage tank system and contaminated an area of about 64,000 ft² of the soil and groundwater system beneath the Hydra-matic plant, Ypsilanti, Michigan. The purpose of this study (Work Plan 2) was to develop, implement, and evaluate a new pumping strategy to maximize the amount of ATF that can be recovered from the Hydra-matic site. Conventional approaches for recovering viscous-oil contamination from soil and groundwater systems could isolate the oil from the recovery well, spread the oil deeper into the groundwater zone, and reduce the volume of recoverable oil. A new pumping strategy for improved drainage and recovery of free oil was developed, tested in a laboratory-model aquifer, and implemented and evaluated at a field site that is contaminated with automatic transmission fluid (ATF). This new strategy differs from conventional approaches in two important ways: (1) The oil-recovery rate is controlled to maximize the pumping rate while maintaining continuity between the oil layer in the groundwater system and the recovery well to avoid isolation of the oil in the subsurface. (2) The rate of groundwater pumping is controlled to maintain the depressed oil/water interface at its prepumped position. This approach prevents further spread of oil into the groundwater zone, prevents reduction in the volume of recoverable oil due to residual retention, and maintains a gradient for oil flow towards the recovery well.

In a model-aquifer study, about 100% of the recoverable volume of ATF was pumped from the system. A field site contaminated with about 208,000 gal of ATF was instrumented with 5 recovery systems. These systems have been in operation for more than 700 days (since August, 1988), during which time more

than 56,000 gal of the ATF has been recovered. This new pumping approach has been successfully evaluated, and it is being used to remove the free ATF from the soil and groundwater system at the Hydra-matic site.

INTRODUCTION

Automatic transmission fluid (ATF) has leaked from an underground storage tank system and spread through the subsurface in a region below a manufacturing facility (Hydra-matic plant, Ypsilanti, Michigan). Work Plan 1 was previously estimated that about 208,000 gal of ATF had spread under the plant in an area of about 64,000 ft² and to a depth of approximately 11 ft (Figure 1; Abdul et al., 1988). The region of ATF contamination is made up of three distinct and contiguous layers. The center layer (zone of free ATF) is about 2.6-ft thick at its centroid and extends to about 250 ft at its widest point. The soil in this zone is about 80% saturated with about 133,000-gal ATF, which has depressed the water table and can flow under its own hydraulic head. The top layer is about 1.2-ft thick and has about 50,640-gal ATF held by capillary forces. The ATF in the deepest layer is near the residual saturation of about 20%, is about 1-ft thick, and has about 24,500-gal ATF. The recovery of free product by pumping is being used as a first step to clean up this site. This report presents performance results of a new pumping strategy for recovery of the free ATF described above.

Commonly used product-recovery strategies include one or more of the following methods: (1) skimming the free product from a recovery well (product skimming), (2) pumping of groundwater to create a deep-drawdown cone and induce the flow of product to a recovery well (total-fluid recovery), and (3) intercepting the product in a trench or drain constructed down gradient of the zone of free product. These methods could have severe limitations for the recovery of ATF from soil and groundwater systems; a discussion of these limitations follows.

The thickness of the oil layer in a well that is open to a zone of free

oil depends on the capillary properties of the soil, the density of the oil, and the thickness of the layer of free oil in the soil (Abdul et al., 1989; Farr et al., 1990; Lenhard and Parker, 1990). The weight of the oil column in the well is supported by the surrounding water which it has displaced. Consequently, the displaced water is under stress and will simultaneously rise as oil is removed from the well, reducing the magnitude of the induced stress. As the oil is removed from the well, a fluid potential is created for both water and oil to flow from the surrounding porous medium into the well. However, the rates of flow of water and oil are inversely related to their viscosities, and since ATF is more than 60 times more viscous than water, the groundwater could replace the ATF in the well and eventually isolate it from the recovery well (Figure 2). It follows, therefore, that oil skimming alone, without pumping, could lead to the isolation of the oil from the well and that skimming alone may not be an effective method for oil recovery from a contaminated zone.

It is common practice to rapidly pump a well installed through the groundwater zone to create a deep-drawdown cone and induce the flow of free product to the well. During the development of this cone, the free product will spread downwards to ultimately establish new steady-state conditions in the region of the surface of the drawdown cone. This approach could have several disadvantages (Figure 3). First, the oil is spread to deeper and more extensive regions of the subsurface. Second, a large volume of the oil will remain as residual retention in the new regions of contamination, significantly reducing the volume of product available for recovery. Third, treatment of a large volume of contaminated water may be required.

A more recent product-recovery approach uses a product recovery pump in combination with a water-table drawdown pump. While this approach has

advantages of developing a strong gradient for product flow towards the recovery well and of separately removing oil and water, it suffers from the same disadvantages described above for the total-fluid recovery approach. The use of drains and trenches for the recovery of oils could suffer from the same limitation as a well-skimmer recovery system, in that it could lead to the isolation of the oil. In addition, one trench or drain downgradient of an oil-contaminated zone could require excessively long travel times for the oil to flow to the receptor and result in associated poor oil recovery. Further, it may not be practical to install drains or trenches in production areas of manufacturing facilities.

The aforementioned limitations and disadvantages can be minimized if a product recovery strategy using recovery wells is developed that will prevent isolation of the oil from the well and restrict the spread of the oil to previously uncontaminated zones. We have developed such a strategy, and it is based on the use of a product-recovery pump and a water-recovery pump, as illustrated in Figure 4. This approach involves the removal of free product from the well at a rate that maintains a layer of product in the well which forms a continuous layer with the free-oil zone in the adjacent porous medium. As the oil/water interface in the well starts to rise when oil is removed from the well, water is pumped from the groundwater zone at a rate only sufficient to maintain the oil/water interface in the well and medium at its original position. While this approach will create a gradient for the oil flow to the well, it will also restrict the development of a deep-drawdown cone and the further vertical spread of oil.

The performance of the proposed product-recovery strategy was evaluated in the laboratory in a two-dimensional model aquifer and in the field at the previously described ATF-contaminated site. The results of those evaluations

are presented and discussed in this report.

STUDY APPROACH

The model aquifer, the field site, and the studies conducted in these two systems are described in this section.

Laboratory Model Aquifer

The model aquifer (5.91-ft long by 4.59-ft high by 0.33-ft wide) was made of Plexiglas, which was supported from the outside by an iron frame and an aluminum base (Figure 5). The model was packed with clean sand that was air-dried and sieved through a 0.02-inch standard mesh to represent sandy material found at field sites. To construct a uniform porous medium, the sand was poured into the model in increments of 0.33-inch-thick layers, and each new layer was mixed with the previous layer by using an electric blender equipped with an extended shaft. The sand medium in the model aquifer was 5.51-ft long by 4.17-ft high by 0.33-ft wide.

One face of the model aquifer was instrumented with 26 tensiometers (T-1 through T-26 in Figure 5) for measuring the fluid pressure in the porous medium. Each tensiometer has a fluid chamber and two ports; a measuring port connected to an ATF or water manometer, and a port for flushing entrapped air from the monitoring system (Abdul et al., 1989). The fluid chamber was separated from the sand by a 0.00079-inch (20 μm) nylon membrane in the unsaturated zone and by a 0.00315-inch (80 μm) nylon membrane in the saturated zone. These membrane sizes were selected to remain saturated with either ATF or water under the range of suction head expected during the study. On each end of the medium was a 2.36-inch wide boundary reservoir. These two

reservoirs were connected at the base by a 0.49-inch-ID tube, which was used to maintain constant head conditions on the sides of the medium. A 1.97-inch-ID recovery well having eight 0.098-inch slots per inch length was installed through the center of the medium. Three 1.0-inch-ID monitoring wells (MW1, MW2, and MW3) were installed through the medium, and their locations are shown in Figure 6. These wells were first machined into longitudinal halves, and the rectangular side of the half-well was attached to the inside surface of the Plexiglas-model aquifer. By this design, it was possible to visually observe the thickness of fluids in these monitoring wells.

The water table was maintained between 29.53 and 33.46 inches (75 and 85 cm) above the base of the model aquifer, and the capillary fringe extended about 7.87 inches (20 cm) above the water table. The saturation-pressure relationship for water or ATF and the sand was determined in funnel experiments similar to those previously described by Abdul et al., 1988. From those experiments, the vertical extent of the capillary fringe under conditions of drainage was 12.99 inches for water and 7.09 inches for ATF, and for wetting conditions was 5.91 inches and 3.15 inches for water and ATF, respectively. The hydraulic conductivity (K_s) of the sand was measured in column tests using falling- and constant-head techniques (Freeze and Cherry, 1979), and it was also measured in-situ by performing a constant-rate pumping test of the model aquifer (Kruseman and de Ridder, 1970). The values for K_s from the column tests ranged from 0.047 to 0.118 inch/min while K_s from pumping tests ranged from 0.0045 to 0.0090 inch/min. The porosity of the medium was about 0.40, and the particle density was about 2.55 g/mL. Groundwater flow was maintained at 0.061 cu inch/min (1 mL/min) in the direction shown in Figure 6. This resulted in an average linear pore-water

velocity of 0.078 inch/min.

A total of 3.04 gal (11.5 L) of ATF was leaked to the surface of the sand, at the location shown in Figure 6, at an average rate of 0.392 gal/day for 7.75 days. The ATF spread laterally and vertically through the unsaturated zone and the capillary fringe, and it subsequently developed a layer of free ATF in the capillary fringe. As the thickness of the layer of free ATF increased and the pressure in the oil layer progressively exceeded the pressure in the surrounding water by the value of the capillary pressure across the ATF/water interface, the ATF/water interface was displaced progressively deeper into the groundwater zone. During this vertical displacement, the ATF was also spreading laterally through the capillary fringe. These experimental observations of oil spread through the unsaturated and saturated zones are consistent with previous observations and discussions of the spreading process (van Dam, 1967; Schwille, 1967; Schwille, 1984; Abdul, 1988). When the distribution of ATF through the system was no longer changing significantly, the ATF had spread through about 33% (2.50 cu ft) of the model aquifer and had formed a 4.27-ft long by 0.26-ft thick layer of free product. On the average, the volume of ATF in the free-ATF zone was the same as that in the ATF-fringe zone (0.98 gal). Of the remaining 1.08 gal of ATF, about 0.13 gal was stored in the wells and 0.95 gal was held in the funicular and pendular zones. This gives an average ATF saturation in the funicular and pendular zones of 24%, which compares favorably with the range of residual saturation (20 to 35%) measured in funnel experiments. Of the 1.96 gal of ATF in the zone of free product and the ATF-fringe zone, about 1.37 gal could be drained and recovered by pumping, assuming that the remaining 0.59 gal (30%) would be held in the soil pores as residual retention. The evaluation of the recovery system will be based on the extent of removal of the 1.37 gal of

drainable ATF from the zone of free ATF and the ATF-fringe zone.

Field Site

The field site is under a manufacturing plant, and it is part of a shallow, sandy groundwater system, which extends to a clay layer at a depth of about 13 ft. Except for episodes of high rainfall and snowmelt events, the position of the water table is approximately 6.5 ft below the plant floor. The saturated zone is made up of medium-fine sand with some fine pebbles. For a porosity of 0.40, an average value of hydraulic conductivity of 0.061 ^{0.002 cm/sec} inch/min (from laboratory-column tests and field-pumping tests), and a hydraulic gradient of 0.0025 obtained from flownets for the site, the rate of groundwater flow is about 17 ft/yr (Abdul et al., 1988). The saturation-pressure relationships for ATF or water and material from the site are similar to those for the sand in the model aquifer, having equivalent values for residual saturation and the thickness of the capillary fringe.

The contaminated zone occupies an area of about 64,000 ft² and contains about 208,000 gal of ATF (see Figure 1). About 133,000 gal of ATF is in the zone of free product, 50,640 gal in the fringe and funicular zones, and 24,500 gal is trapped as residual saturation in the groundwater zone beneath the zone of free ATF. Based on a residual retention of 30%, the amount of recoverable ATF from the zone of free ATF and from the fringe and funicular zones are 93,000 and 35,000 gal, respectively. It is hoped that this combined volume of ATF (128,000 gal) can be recovered from the site by pumping.

Forty one monitoring and recovery wells were installed at the site. The recovery well (combination well) was specially designed to separately pump ATF or water from the system (Figure 7). The combination well is essentially two off-centered wells; a 2.0-inch OD inner well and a shallower 4.5-inch OD outer

well. Typically, the inner and outer wells are 13- and 11-ft deep, respectively. The two wells are hydraulically isolated from each other to prevent fluid from flowing from one well to the other. Each well is opened to the surrounding medium through the screened section, which consists of parallel 0.01-inch slots (six slots/inch). Typically, the outer well is opened to the medium from 2 ft above the position of the unstressed water table to 4 ft below the water table (through the zone of free ATF), while the inner well is opened to the next 2 ft of the groundwater zone below the outer well. A pump in the outer well was used to recover the free ATF, while a pump in the inner well was used to pump groundwater from below the ATF layer and to maintain the ATF/water interface at its prepumped position.

Five recovery systems were installed at the site at the locations shown in Figure 1. The number and location of the recovery systems were determined based on mathematical simulations of the hydraulic response of the site to different pumping strategies. A 2-dimensional Galerkin finite element model, previously described by Abdul (1985), that simulates hysteretic unsaturated-saturated flow was used. The objective of the mathematical simulations was to determine the zone of influence for different pumping rates and for several boundary conditions in the wells. The plan was to use the results from these simulations to locate a minimum number of recovery stations, evaluate the performance of the recovery stations, and, if needed, install additional recovery stations to intercept and recover the ATF plume. Each cross-section through the site for modeling was 400-ft wide by 13-ft deep and was discretized into more than 2,000 nodes and more than 4,000 triangular elements. At each time step, the pressure head, the hydraulic head, and the pore saturation at each node and the boundary fluxes were calculated. Examples of a few simulations are shown in Figure 8. The results show that

when the drawdown in the recovery well is maintained at a depth of 10 ft below the plant floor, corresponding to the depth of the ATF/water interface in the region of the centroid of the ATF plume, the zone of influence of the recovery well is more than 100 ft after 10 days of pumping. By these results, the locations of the five recovery systems, shown in Figure 1, were selected from the wells previously installed at the site.

Each recovery system was equipped with two pneumatic pumps, one in the outer well to pump ATF and the other in the inner, deeper well to pump water. The on/off cycles of the pumps were automatically controlled by presetting their refill and discharge times. In addition, the on/off cycle of the water pump was controlled by a down-well bubbler sensor. A 2-inch-ID monitoring well was installed within 10 ft of each recovery well to provide information on the response of the ATF/water interface and on product thickness adjacent to the recovery well during pumping. Pumping conditions were modified to maintain the oil/water interface at its prepumping position and to maintain continuity of the ATF in the zone of free product in the medium with the ATF column in the recovery well.

RESULTS AND DISCUSSION

Results from the model aquifer and the field site will be presented in this section. These results include the response of product and water in the monitoring well located adjacent to each recovery well and the rate of recovery and accumulation of ATF. Because the results from pairs of recovery and monitoring wells at the field site are very similar, only the results from two recovery systems will be presented. Results for the other three systems

will be summarized.

Laboratory-Model Aquifer

The recovery well in the model-aquifer system was instrumented with two recovery tubes: one at the bottom of the well to pump water from the groundwater zone, and the other located within the ATF layer to separately recover the ATF (Figure 9). The ATF-recovery tube was fitted through a ping-pong ball such that the intake end of the tube floats just below the air/ATF interface in the recovery well. The rate of ATF removal was controlled to maintain a column of ATF in the well. Only the lower 1-inch section of the water-recovery tube was screened to ascertain that water was pumped from the base of the well. The water-pumping rate was gradually increased over the first 5 days of product recovery, after which the rate was kept at about 350 mL/min (0.092 gal/min) to maintain the ATF/water interface at approximately 1.80 ft above the base of the model aquifer. This level approximates the prepumped position of the ATF/water interface in the medium at monitoring well 2 (Figure 6). The water that was pumped from the recovery well was returned to one boundary well, which was directly connected to the boundary well on the opposite end of the model to maintain the same constant-head condition at both ends of the model aquifer. Make-up water was also added to the boundary well to account for evaporative losses and for any water removed with the ATF by the ATF-recovery pump. The ATF-recovery system was stopped after 31 days of pumping because at that time more than 99.9% of the fluid being pumped from the ATF-recovery tube was water.

The heights of water and ATF in the monitoring wells were visually measured at least once daily on weekdays during the recovery period. During the leak, the ATF thickness in MW1, located adjacent to the zone of the ATF

leak, increased steadily to a maximum value of 2.23 ft on the day the leak was stopped. The increase in the ATF thickness in MW2, located downgradient of the leak and adjacent to the recovery well, lagged from that observed in MW1, but the thickness continued to increase during the next 12 days after the leak was stopped to a maximum value of 1.71 ft. Subsequently, the ATF thickness in both monitoring wells decreased as the ATF spread through the capillary fringe in the direction of groundwater flow. About 45 days after the leak was stopped, and just before the start of pumping, the height to the water/ATF and ATF/air interface in MW1 was 1.91 and 2.72 ft, respectively, and in MW2 was 1.51 and 2.81 ft, respectively. The ATF thickness was 0.81 ft in MW1 and 1.30 ft in MW2.

Results from MW2 are presented in Figure 10, which shows an initial drop in the ATF/water interface as pumping started, after which the interface was maintained at an almost constant level of about 1.80 ft above the base of the model aquifer for the next 19 days. Then, the interface rose to 2.03 ft, where it remained until the end of the study. The sudden rise in the interface occurred after standing ATF in the monitoring well was pumped out. The standing ATF in the monitoring wells was removed at least once every week to ascertain that the ATF in the monitoring well was hydraulically connected to ATF in the medium. After the ATF was removed on day 22 it recovered only slightly, indicating that the free ATF was already pumped out.

The ATF/air interface and the thickness of the ATF column in the monitoring well decreased steadily with pumping. After 23 days of pumping, the product thickness in the well was very small. At this stage during the recovery process, not only was the free-ATF pumped out, but also ATF from the ATF-fringe zone was being drained and recovered. Even in the absence of a zone of free-ATF, a fully developed ATF fringe can lead to a significant

column of ATF in the monitoring well. When the thickness of the zone of free-ATF in the porous medium is zero, the ATF thickness in the monitoring well is determined only by capillary forces and fluid densities. The ratio of the ATF thickness in the well to that in the adjacent porous medium under hydrostatic conditions is described by the following equations (CONCAWE, 1979; Zilliox and Muntzer, 1975; Abdul et al., 1989):

$$H_c = p^{oa} / [(\rho_o - \rho_a)g] \quad (1)$$

$$H_w = p^{wo} / [(\rho_w - \rho_o)g] \quad (2)$$

$$H_w/H_c = (p^{wo}/p^{oa}) [(\rho_o - \rho_a) / (\rho_w - \rho_o)] \quad (3)$$

where,

H_c = thickness of the ATF capillary fringe,

H_w = thickness of the ATF column in the well,

p = capillary pressure,

ρ = fluid density,

g = gravitational constant,

a, o, w = air, oil, and water respectively

For $p^{wo} = p^{oa}$, $\rho_o = 0.869$, and $H_c = 0.26$ ft, the expected thickness of ATF in the well when the ATF fringe is fully developed and the zone of free-ATF is very thin is about 1.73 ft. This thickness is smaller than the maximum values observed in the monitoring wells during accumulation of ATF in the groundwater zone, but is larger than the values in MW1 (0.81 ft) and MW2 (1.30 ft) just prior to the start of pumping. These observations corroborate previous

discussions on the limitations of using oil thickness in monitoring wells to determine the product thickness in the porous medium (Abdul et al., 1989). The average thickness of the zone of free-ATF in the model aquifer was determined by using an ultraviolet "black light" source to locate the zone of highest saturation and by using the the ATF manometers to locate the region of that zone where the fluid pressure was higher than atmospheric pressure. By both the theoretical calculation and visual observations during the study, most of the drainable ATF was recovered by the end of the study.

The ATF-recovery rate and cumulative ATF versus pumping time are shown in Figure 11. During the first day of pumping, the ATF-recovery rate decreased rapidly from more than 1 mL/min (0.0159 gal/hr) to less than 0.1 mL/min. The rate then increased to about 0.25 mL/min during the next few days and then followed a trend of decreasing rate with continued pumping. This trend of decreasing recovery rate appears to follow a trend of decreasing height in the air/ATF interface in the monitoring well and decreasing thickness of the product layer adjacent to the recovery well (see Figure 10).

At the start of pumping, about 0.13 gal (500 mL) of ATF was in the 2-in ID recovery well, which accounts for the initial high recovery rate followed by the rapid decrease in recovery rate as that volume was being depleted. During the first few days of pumping, the effluent from the ATF-recovery tube was almost 100% ATF; however, as pumping continued, the recovered product first contained dispersed water in the ATF and then contained slugs of water separated by slugs of ATF. After 19 days of pumping, there was more water than ATF in the fluid pumped from the product tube and, by the end of the test, only trace levels of ATF were being recovered. The cumulative ATF recovered from the model aquifer increased steadily during the 31 days of pumping by which time 1.71 gal of ATF was pumped out. Intermittent skimming

from the recovery well for another 30 days recovered another 0.14 gal of ATF, giving a total volume of recovered ATF of 1.84 gal or 61% of the original spill volume.

As discussed previously, about 1.96 gal of ATF was contained in the zone of free product and the capillary zone, of which an estimated 1.37 gal could be drained and recovered by pumping. An additional 0.13 gal of ATF, initially stored in the wells, was also recovered, giving a total recoverable volume of 1.51 gal. The actual amount of ATF recovered exceeded the predicted volume by 0.33 gal, demonstrating that the recovery system performed effectively. Several factors could account for this excess volume of ATF, including underestimation of the lateral and vertical extent of the free-ATF and ATF-fringe zones, drainage of ATF from the funicular zone, overestimation of the residual volume of ATF, and uncertainties in quantifying the volume of ATF in the presence of ATF/water/air emulsions. Nonetheless, the results demonstrate that this new pumping strategy recovered most of the drainable ATF from this model aquifer.

The good performance of the product-recovery system is undoubtedly dependent on the new approach taken in this study. By maintaining the water-table drawdown at the initial position of the ATF/water interface, further spread of the ATF into the groundwater zone and reduction of the recoverable volume of ATF were minimized. In addition, by maintaining a column of ATF in the recovery well in contact with the ATF layer in the porous medium, the ATF flow to the well was maintained during pumping, and the residual volume of ATF remaining trapped in the porous medium was minimized. In the next section, the performance of this recovery method will be evaluated at the field site.

ATF Recovery at a Field Site

Five ATF-recovery systems were installed at the field site and have been in operation since August, 1988. Each system consists of a combination well (recovery well) and a monitoring well, which is located within a radius of 10 ft of the combination well. Each combination well is equipped with two pneumatic pumps: a product-recovery pump and a water-table-drawdown pump. Product or water pumping at each recovery location is independently and automatically controlled to maintain preselected pumping conditions. Because the data from the five recovery systems are quite similar in trend, only the results from locations 24 and 3 (see Figure 1) will be presented. Results from the other wells are included in Appendix 1. Recovery-well 24 is located near the prepumped centroid of the free-ATF zone, about 300-ft-down gradient of the ATF source. This location is under the plant and at least 200 ft away from the plant boundary. Recovery well 3 is located near the the tank-farm system in the region of the ATF leak, and it is only about 30 ft from the plant boundary.

Response of air/ATF and ATF/water interfaces: Results of monitoring the air/ATF and ATF/water interfaces in monitoring well 24, located 3 ft from recovery well 24, for the first 829 days of product recovery at the site, are shown in Figure 12. During the first 2 weeks of pumping, the system was frequently monitored and the pumping rates of ATF and water adjusted after each monitoring episode to establish the maximum ATF-pumping rate, to maintain a layer of ATF in the product well, and to maintain the ATF/water interface in the groundwater zone at its prepumped position. Subsequently, as understanding of the system response improved and that response became more predictable, the monitoring interval was increased to one week, then to two

weeks, then to one month, and the system is now being monitored bimonthly.

One week before each monitoring episode, the standing ATF in the 43 monitoring wells is pumped out to allow the wells to adjust to the existing conditions at the site.

The results indicate that the position of both the air/ATF and ATF/water interfaces in monitoring well 24 did not change significantly during product recovery at the site. At the start of pumping, the depth to ATF and water in the monitoring well were 6.72 ft and 10.28 ft, respectively, and there was 3.56 ft of ATF in the well. During 829 days of monitoring, the depths to ATF ranged from 6.21 to 7.81 ft, the depths to water ranged from 9.20 to 11.05 ft, and the ATF thickness in the monitoring well ranged from 1.95 to 4.31 ft. During this same period, the average depths to ATF and water were 7.04 ft and 10.36 ft, respectively, giving an average thickness of 3.32 of ATF in the monitoring well. The maximum and minimum thicknesses of the ATF column in the monitoring well were associated with the deepest and shallowest drawdown of the ATF/water interface, respectively. More discussion of this observation will follow.

Results for depth to the air/ATF and ATF/water interface from monitoring-well 3, located about 5 ft from recovery well 3, are shown in Figure 13. At the start of pumping, the depths to ATF and to water in monitoring-well 3 were 5.92 and 7.92 ft, respectively, and there was 2 ft of ATF in the well. During 772 days of pumping, the depths to ATF and water in monitoring well 3 ranged from 5.74 to 6.57 ft and from 6.64 to 8.00 ft, respectively, and the ATF thickness in the well ranged from 0.14 to 2.01 ft. During this time, the average depths to ATF and to water were 6.06 and 7.54 ft, respectively, and the average ATF thickness in the well was 1.49 ft. As was the case for monitoring well 24, the maximum and minimum ATF thicknesses observed in

monitoring well 3 were associated with the deepest and shallowest drawdown of the ATF/water interface, respectively.

Although there were unique challenges in controlling and maintaining optimum operating conditions at each of the five recovery stations, the results for the depth to ATF, the depth to water, and the ATF thickness in the five monitoring wells adjacent to each recovery well were similar over the duration of pumping. The range of fluctuation of the depth to ATF, the depth to water, and the ATF thickness for monitoring wells 3, 13, 15, 24, and 39 were: 0.83, 0.98, 0.58, 1.09, and 0.82 ft; 1.46, 1.70, 1.10, 1.85, and 2.90 ft; and 1.87, 2.15, 1.05, 2.36, and 2.30 ft, respectively. These results indicate that the ATF in the medium was always in direct hydraulic connection with the recovery well; therefore, ATF isolation from the well was avoided. Further, the almost constant position of the ATF/water interface in the well suggests that ATF was not drawn deep into the groundwater zone during pumping. These conditions were quite favorable for ATF recovery at the site, as will be demonstrated by results presented in the following section.

Rapid fluctuation of the water table during precipitation events and reduced discharge from the water pump caused by clogging of the well screen by mineral deposits and by biomass from the biodegradation of ATF made it difficult to maintain the optimum operating conditions at the recovery wells. The intake of the ATF-recovery pump was held fixed within the recovery well and had to be manually adjusted as the local water-table position changed during recharge or dry conditions. The recovery wells that were nearest to the outside of the plant building and to any recharge areas were more susceptible to rapid changes in the water-table position and needed more frequent monitoring and adjustment to maintain optimum recovery conditions. Improved product recovery systems having product intake points that float on

the product layer and automatically adjust with any fluctuation of the water table are now commercially available. Such systems could reduce the frequency of monitoring needed at product recovery sites. All the water-table drawdown wells, water pumps, and discharge lines from these pumps developed scaling and clogging soon after the start of pumping and had to be cleaned or replaced at least once every six months. Neither scaling nor biodegradation of ATF occurred in the presence of free ATF, and those water wells that intercepted high concentrations of dispersed ATF were scaled and clogged more slowly than the other water wells.

Recovery of ATF: The ATF-recovery results from recovery wells 24 and 3 are shown in Figures 14 and 15, respectively, as rate of ATF recovery and cumulative ATF recovered versus time since pumping started. The results show a very rapid decrease in the ATF-recovery rate during the first day of pumping, when the standing volume of ATF in the 4-inch-ID outer well of the combination well was being removed; thereafter, the recovery rate decreased gradually with continued pumping. At the start of pumping of recovery well 24, ATF was removed at 610 mL/min (0.161 gal/min) and water was removed at 3.3 L/min (0.872 gal/min); 829 days later, ATF was being pumped out at 42 mL/min and water at 0.7 L/min. During this time, the rate for ATF recovery ranged from 610 to 20 mL/min, the rate for water recovery ranged from 0.22 to 3.3 L/min, the average ATF-recovery rate was 95 mL/min, and the average water pumping rate was 2.04 L/min. During 829 days of pumping, the volume of ATF pumped from well 24 increased almost linearly to about 55,942 L (14,780 gal).

At the start of pumping from recovery well 3, ATF was removed at 530 mL/min (0.140 gal/min) and water at 0.21 L/min (0.055 gal/min), and during pumping for 772 days the range of ATF- and water-removal rates were from 600

to 0 mL/min and from 0.16 to 3.05 L/min, respectively. At the end of the study, the recovery rates were almost zero for ATF and 1.4 L/min for water. The average pumping rates were 236 mL/min for ATF and 0.78 L/min for water. Recovery well 3 is in the region of the previous underground storage tank system, where the area around the tanks was initially backfilled with pea gravel, and after the tanks were taken out from the subsurface the excavation was backfilled with sand. This may explain the high ATF flow rate and recovery from this location. About 55,954 L (14,688 gal) of ATF was recovered from location 3.

The average pumping rates of ATF (and water) from recovery wells 3, 13, 15, 24, and 39 during the study are 235.8 (0.78), 100.2 (0.67), 24.1 (0.107), 95.0 (2.04) and 59.6 (1.61) mL/min (L/min), respectively. By the end of the study, more than 770 days since the start of pumping, the recovery rates of ATF for the wells in the order listed above were 0, 51, 8, 42, and 17 mL/min, respectively, and for water were 1.40, 0.41, 1.96, 0.68, and 0.93 L/min, respectively. During this period a total of about 210,813 L (55,697 gal) of ATF was pumped from the five recovery wells at an average rate of 550 mL/min. The volume of ATF recovered from recovery wells 3, 13, 15, 24, and 39 was 14688, 15017, 4944, 14787, and 6259 gal, respectively.

At the start of ATF recovery, the discharge from the product pump contained almost 100% ATF. As pumping continued, however, the amount of water in the product line increased. At first, the water was dispersed or trapped in the ATF, but with time, as the fraction of water in the product increased, the water and ATF were discharged from the product line as separate slugs. These observations are consistent with those from the laboratory study. In the case of recovery well 3, it is difficult to continue to maintain a steady discharge of ATF as a separate phase by the method being used at the site.

However, with the product pump turned off for a few days, ATF accumulated in the region of the water-table drawdown cone, but this small volume of ATF was typically pumped out in a short time after the product pump was turned back on.

The maximum ATF thickness in the monitoring wells immediately next to the recovery wells occurred when the ATF/water interface was approximately at the deepest level, while the minimum ATF thickness occurred when the ATF/water interface was approximately the shallowest. It is for this reason that a common practice used in product recovery is to create a deep-drawdown cone to collect the product in the region around the well from where it could be readily pumped to the surface. However, the disadvantage of that approach is the further spread of the product deep into the groundwater system and the reduction in the volume of the product that would be available for recovery as a result of residual retention of the product by the porous medium. While the approach used in this study maintained a steady flow of ATF to the well, it also restricted the ATF to the region of the soil and groundwater system that was already contaminated.

While maintaining a shallow water-table drawdown would have the positive effects of minimizing the further vertical spread of petroleum product and of maximizing the recoverable volume of that product, it may also have an associated negative effect of limiting the zone of influence of the recovery well. This potential limitation, however, could be avoided by the use of a few more recovery wells, at only a relatively small increase in the overall cost of site assessment and remediation.

Effect of Pumping on the Free-ATF Zone: The thickness of the vertical column of ATF in the 43 monitoring wells at the site was measured in August, 1990,

more than 700 days since the start of pumping, and was used to calculate the corresponding thickness (H_m) of ATF in the contiguous porous medium. The following equations (Abdul et al., 1988) were used in the calculation, and the results are shown in Figure 16.

$$H_m = H_w - H_e \quad (4)$$

$$H_e = p^{wo} / \{(\rho_w - \rho_o)g\} \quad (5)$$

where, H_e is the thickness of ATF in the well below the base of the ATF-saturated zone, and the other parameters were as previously defined. The ATF/water capillary pressure was measured in laboratory experiments (Abdul et al., 1988) and an average value of 6.43-cm ATF (2.53 inches of ATF) was used in the calculations, while a measured value of 0.869 g/cm³ (54 lb/ft³) was used for the specific gravity of ATF.

The calculated values of ATF thickness in the porous medium were mapped out and, using linear interpolation, contours of equal thicknesses were drawn (Figure 16). The volume of ATF between two contours is the area-between-the-contours times the average thickness of the ATF layer within the two contours times the fraction of the pore volume occupied by ATF. The fraction of the pore volume occupied by ATF is the porosity (ϵ) minus the fraction of the total volume occupied by residual levels of water (θ_{rw}). This calculation for the total volume of ATF in the zone of ATF is described by the following relationship:

$$V = (\epsilon - \theta_{rw}) \sum^i (A_i \times h_{mi}) \quad (6)$$

where, A_i is the area between two adjacent contour lines and h_{mi} is the average ATF thickness for the two contour lines. For measured values of $\epsilon = 0.4$ and $\theta_{rw} = 0.07$, the volume of free ATF remaining in the subsurface is approximately 87,000 gal. Before the start of pumping, the volume of ATF in the zone of free ATF was 133,000 gal. Based on these calculations, about 46,000 gal of ATF was recovered, which compares favorably with the measured recovered volume of about 55,700 gal. As was previously reported (Abdul et al., 1988), the uncertainty in the calculated values is $\pm 21,000$ gal; therefore, the difference between the measured and calculated volume of ATF removed by pumping is within the expected range of uncertainty.

Comparison of the results in Figures 1 and 16 indicates that the ATF plume has changed significantly as a result of product recovery at the site. The maximum thickness of the free-ATF layer has been reduced from a prepumped thickness of 2.6 ft to a value of 1.5 ft. In addition, the plume is now divided into two main zones, one in the area of well 24, where the original centroid of the plume was located, and the other in the area of well 10 sandwiched between recovery wells 3 and 15. To improve the effectiveness of ATF recovery at the site, two additional pumping stations are being installed at the current locations of well 10 and well 30 and in proximity to the two centroids of the current ATF plume (see Figure 16).

An obvious question that could be asked is how much of the ATF from the field site could be recovered by pumping. While most of the drainable ATF was recovered from the laboratory model aquifer, resulting in the removal of 61% of the spill volume and an equivalent residual saturation of 16% ATF remaining in the contaminated zone, the equivalent residual saturation for the field site is difficult to predict because of the heterogeneity in the hydrogeologic properties of the site and uncertainties in the vertical and lateral

boundaries of the contaminated zone. The level of residual saturation can vary over a wide range, even in relatively simple laboratory experimental systems, because the extent of residual saturation depends on several properties of the medium and fluid, including particle size and size distribution, porosity, surface tension, fluid density, and contact angle. Kia and Abdul (1990) reported the residual retention of diesel fuel and ATF to vary from 8 to 32% in small funnels of sand, while Hoag and Marley (1986) found residual retention of 12 to 60% for gasoline in packed columns of sandy material. For field sites, which are more complex and heterogeneous than laboratory experimental systems, it would not be surprising to find even higher levels of residual retention. Nonetheless, more than 42% of the free ATF at the field site has been recovered. This represents 27% of the estimated spill volume. These results indicate that the new pumping strategy is performing as expected; therefore, application of this technology should minimize the residual ATF retention at the site.

CONCLUSIONS

A new pumping strategy has been developed to maximize the recovery of free-petroleum product contamination from soil and groundwater systems. That system uses two recovery pumps: one in the layer of oil and the other extending into the groundwater zone. Oil is pumped from the system at a rate maximizing the oil-recovery, while maintaining a layer of oil in the well and maintaining continuity between the oil in the medium with that in the well. Groundwater is pumped out at a rate to maintain the initially depressed oil/water interface at its prepumped position to prevent the further spread of oil into the groundwater zone and to prevent a reduction in the volume of

recoverable oil. This pumping strategy was tested in a laboratory model aquifer which was contaminated with ATF to create a free-ATF zone that displaced the water table into the groundwater zone. Mathematical modeling was used to locate 5 recovery systems at a 64,000 ft² site contaminated with about 208,000 gal of ATF. Most of the recoverable ATF was pumped from the laboratory system, while more than 56,000 gal of ATF was recovered from the field site during more than 700 days (since August 1988) of pumping. This new recovery system was successfully tested, it is being used to clean up the free ATF at the field site, and it could be useful at other oil-contaminated sites, particularly for the recovery of viscous oils.

Future Plans

Two additional product recovery systems are being installed at the site to increase the overall effectiveness of draining and recovering free ATF from the contamination zone. These additional wells will increase the rate of ATF recovery and speedup remediation of the site. While Hydra-matic plans to maintain and operate the product recovery systems as long as the ATF can be drained and recovered, it is projected that product recovery would continue through 1991 by which time most of the drainable ATF would have been recovered.

At the end of pumping a large fraction of the estimated initial volume of ATF will remain trapped between the subsurface material as residual retention. GM will determine if further active remediation is necessary to protect human health and the environment. On going laboratory studies by GM have indicated that native soil bacteria from the site degrades ATF.

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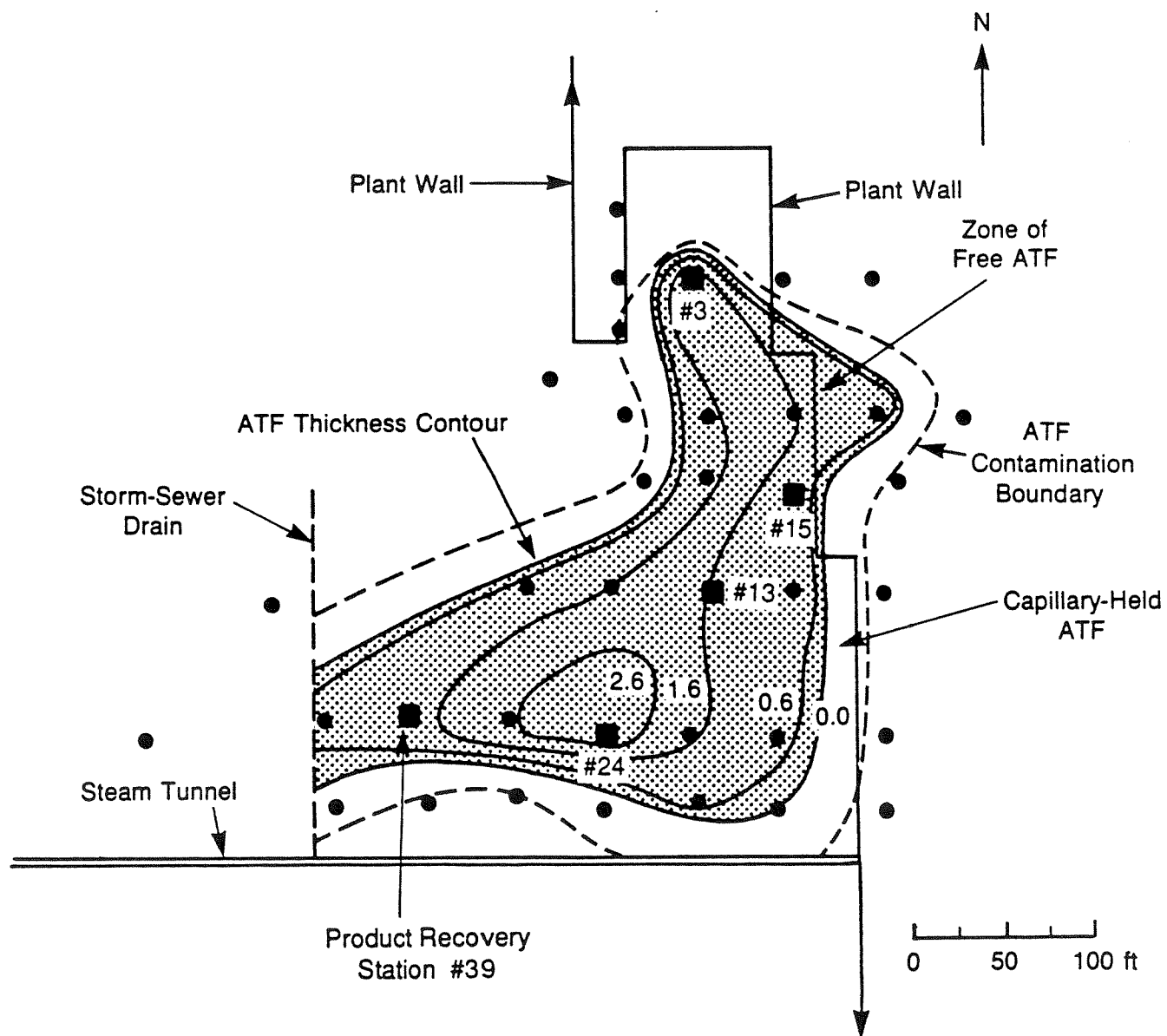


Figure 1. Lateral spread of ATF and contours of ATF thickness in feet (2.6, 1.6, 0.6, and 0.0 ft) before the start of product recovery.

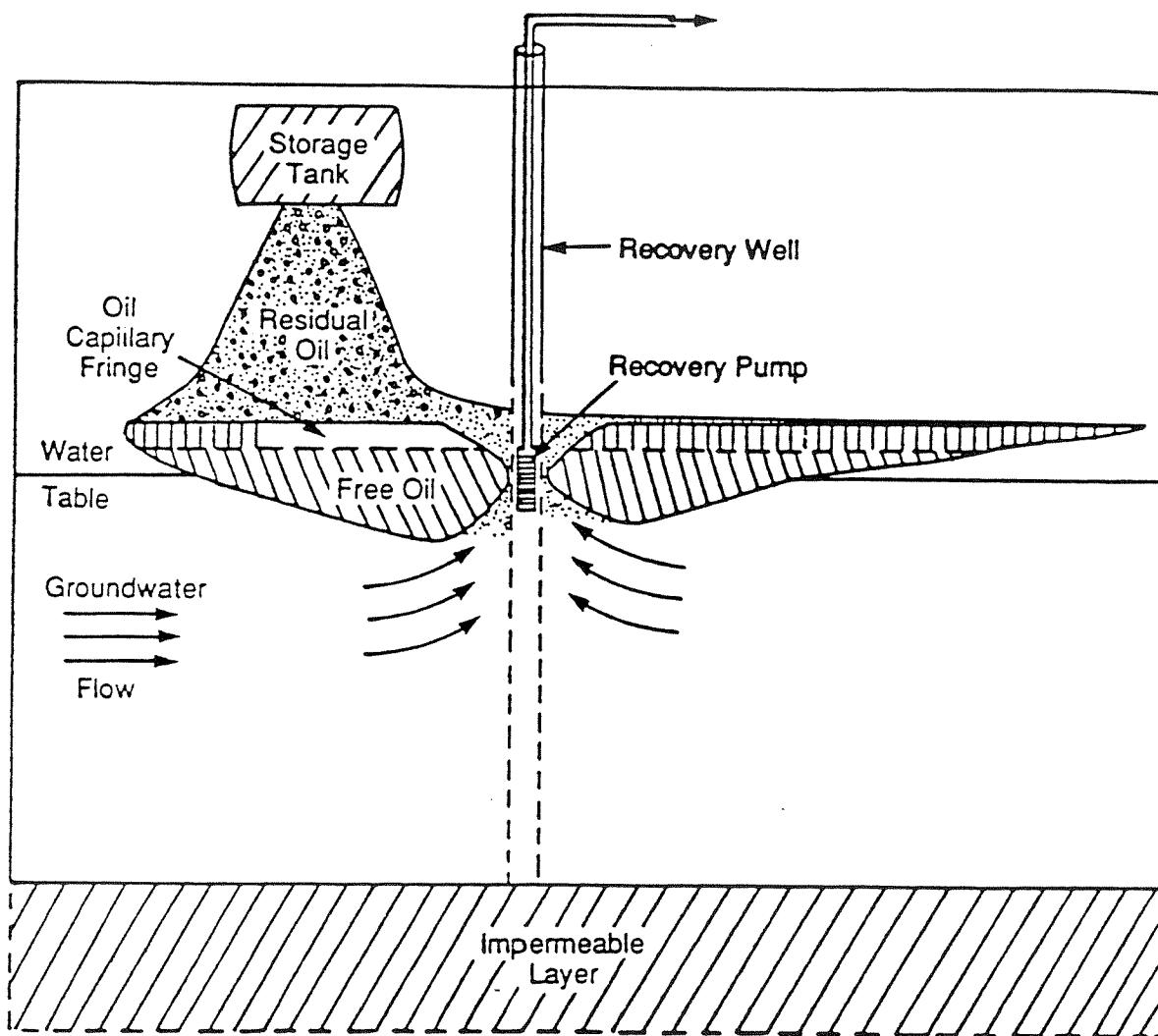


Figure 2. Oil isolation from a recovery well being skimmed to recover the free oil.

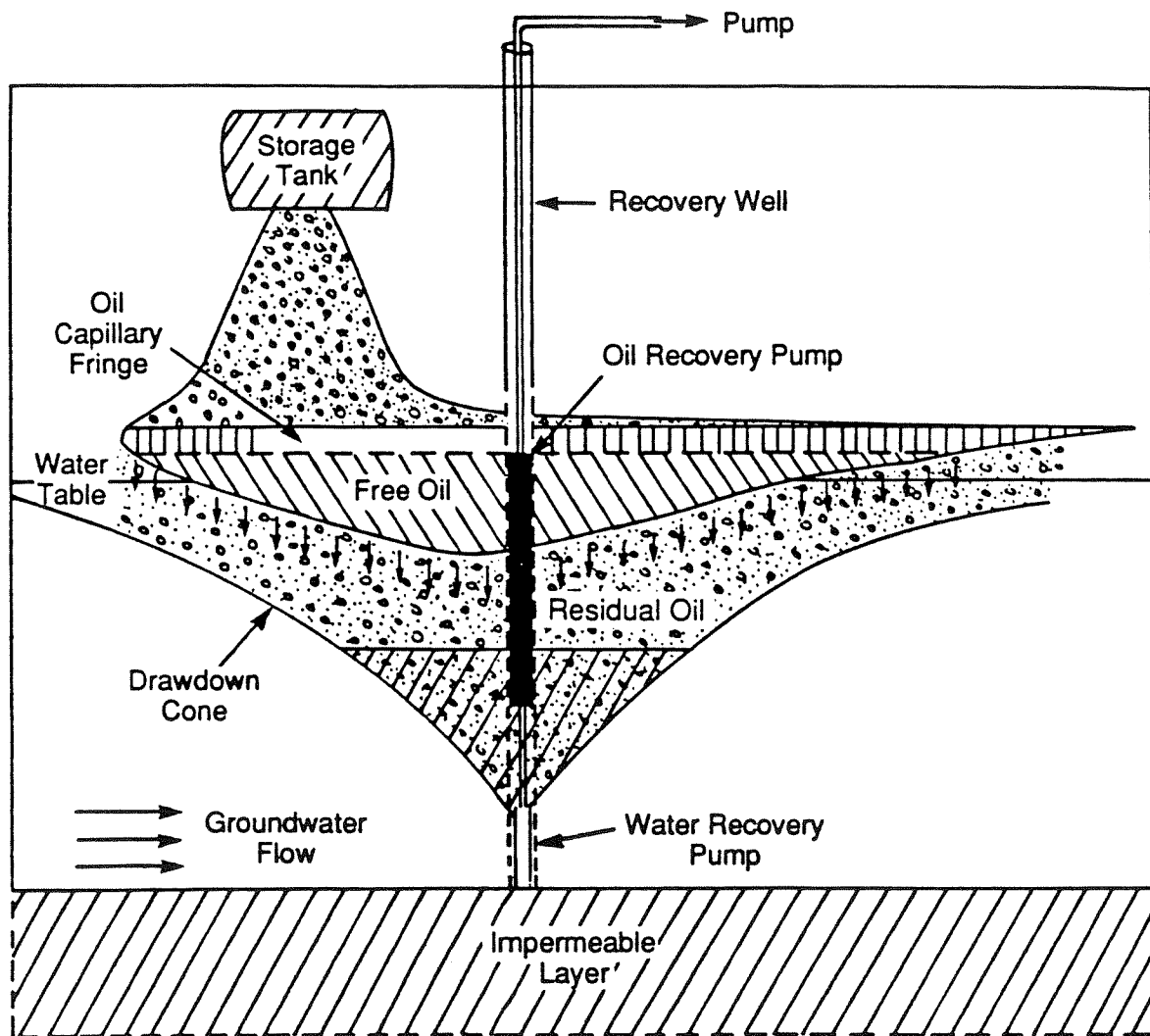


Figure 3. Effect of water-table drawdown on the spread of oil in the groundwater zone.

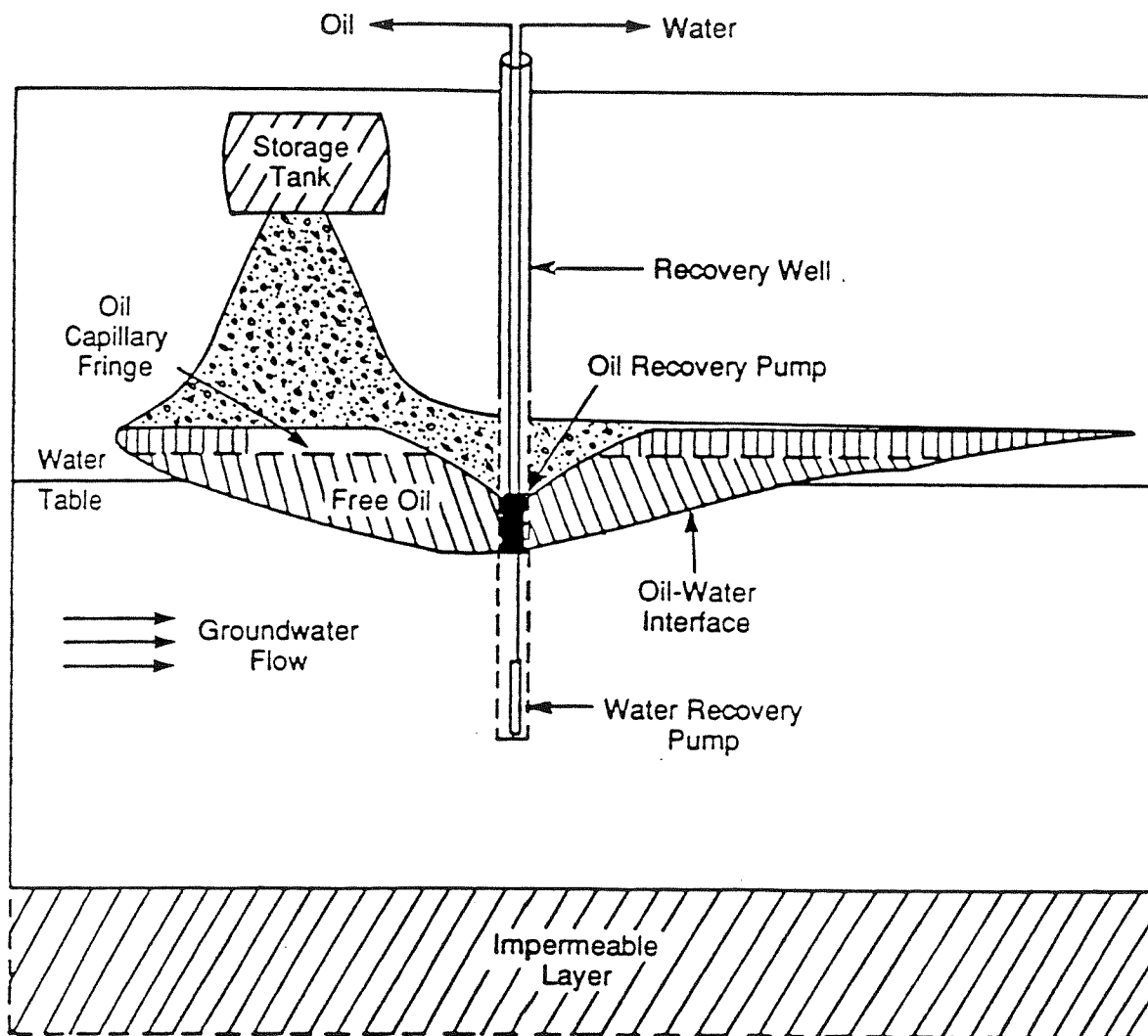


Figure 4. Controlled drawdown of the water table during oil and water recovery.

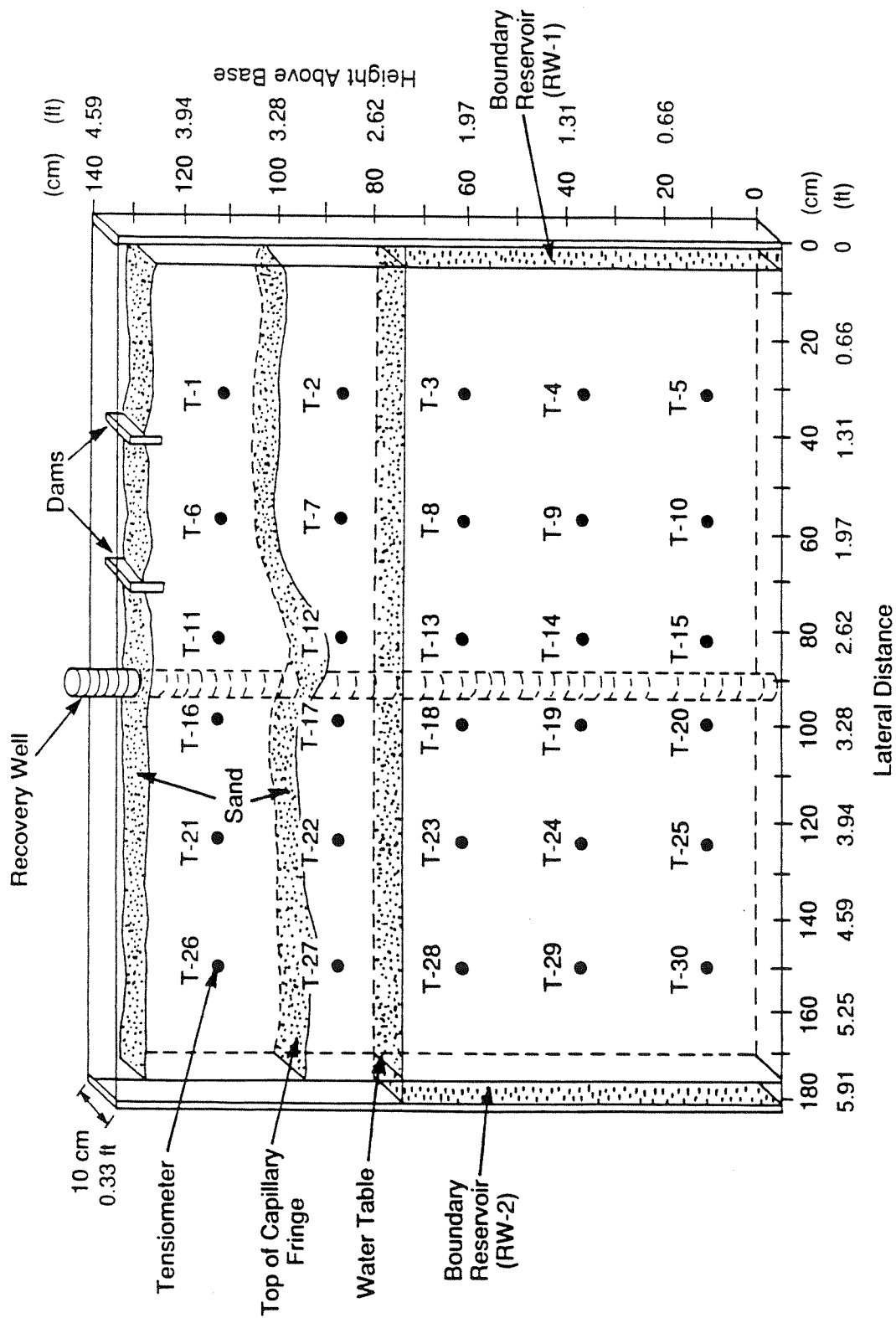


Figure 5. Schematic of model aquifer.

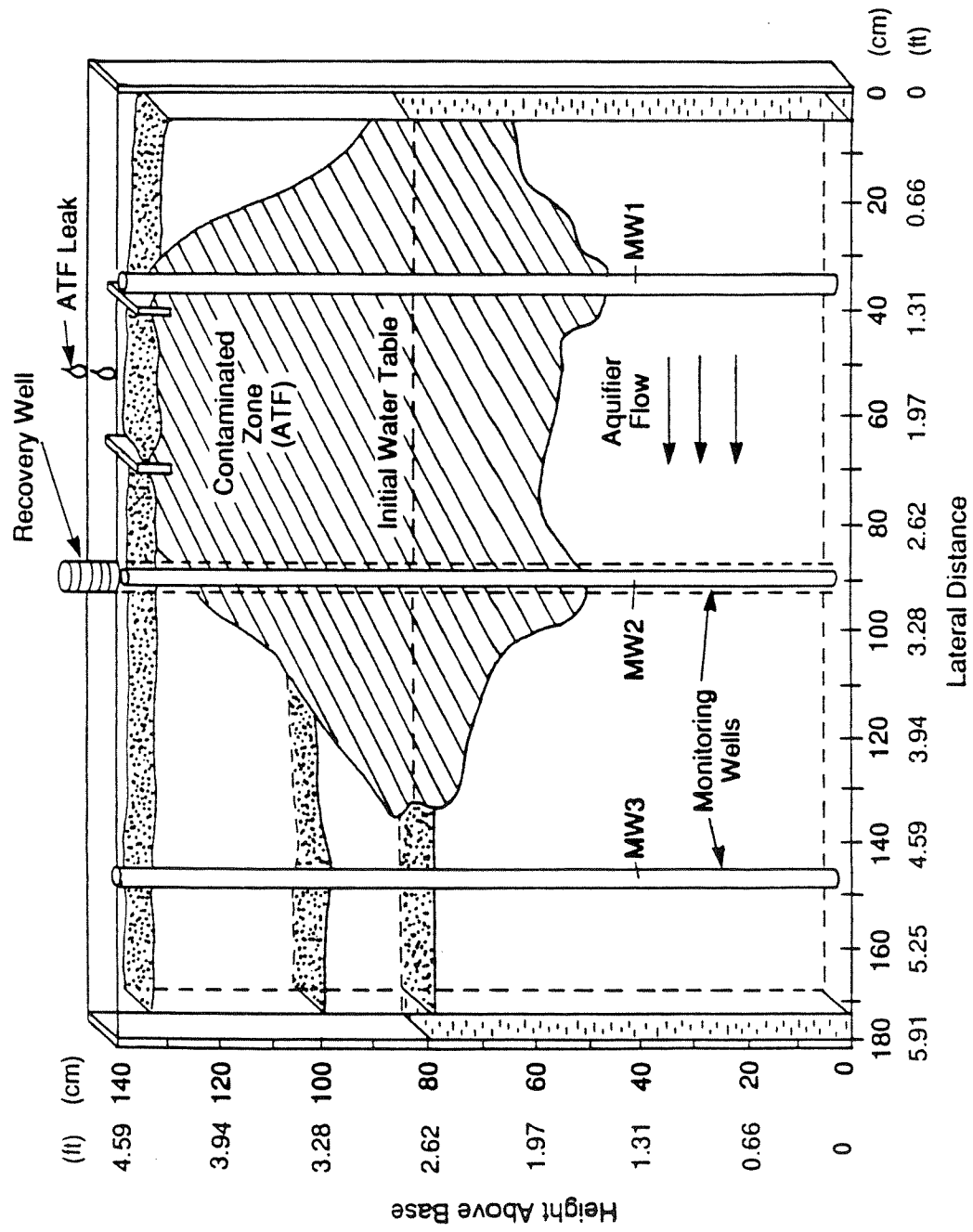


Figure 6. Lateral and vertical distribution of ATF through the model aquifer.

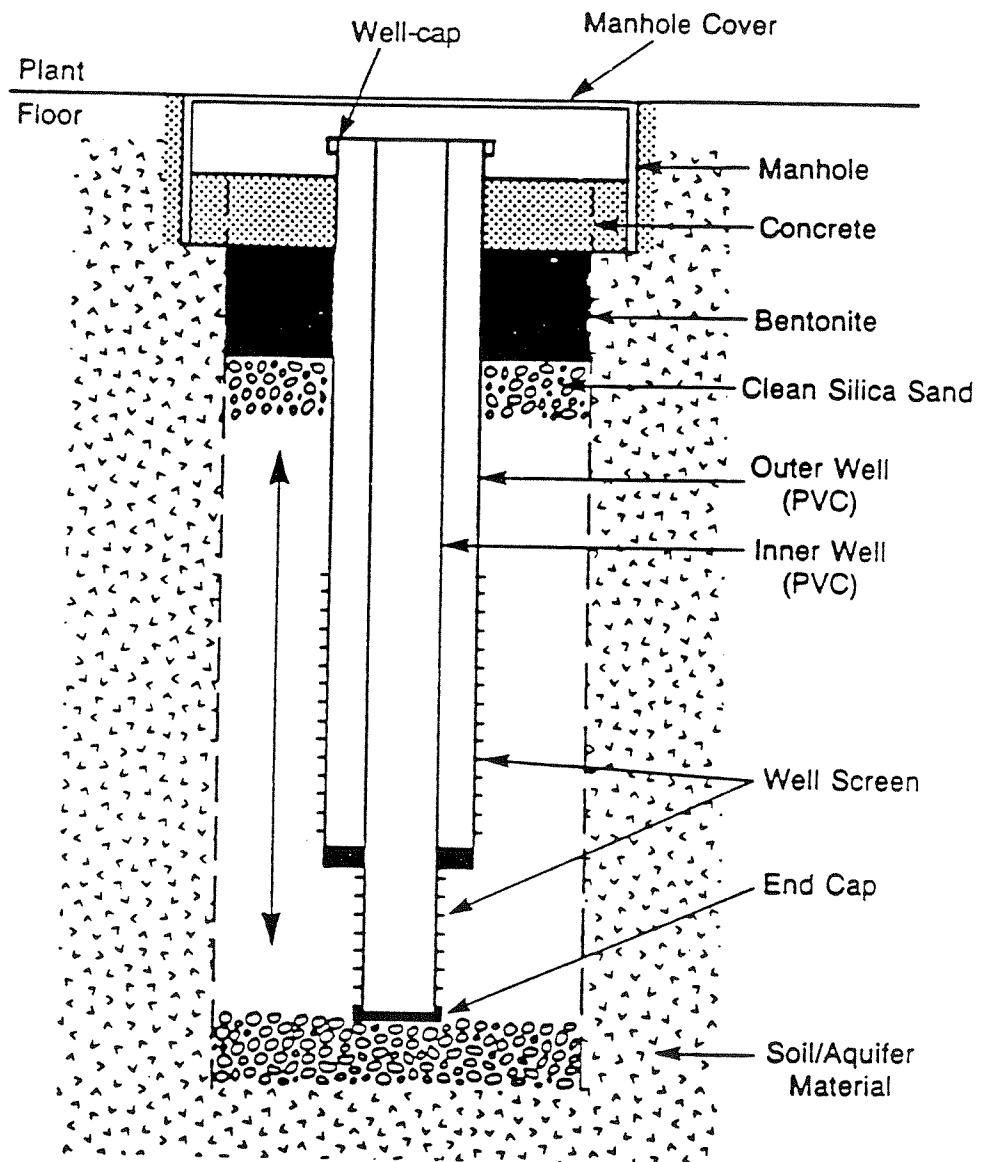


Figure 7. A schematic of well construction and installation.

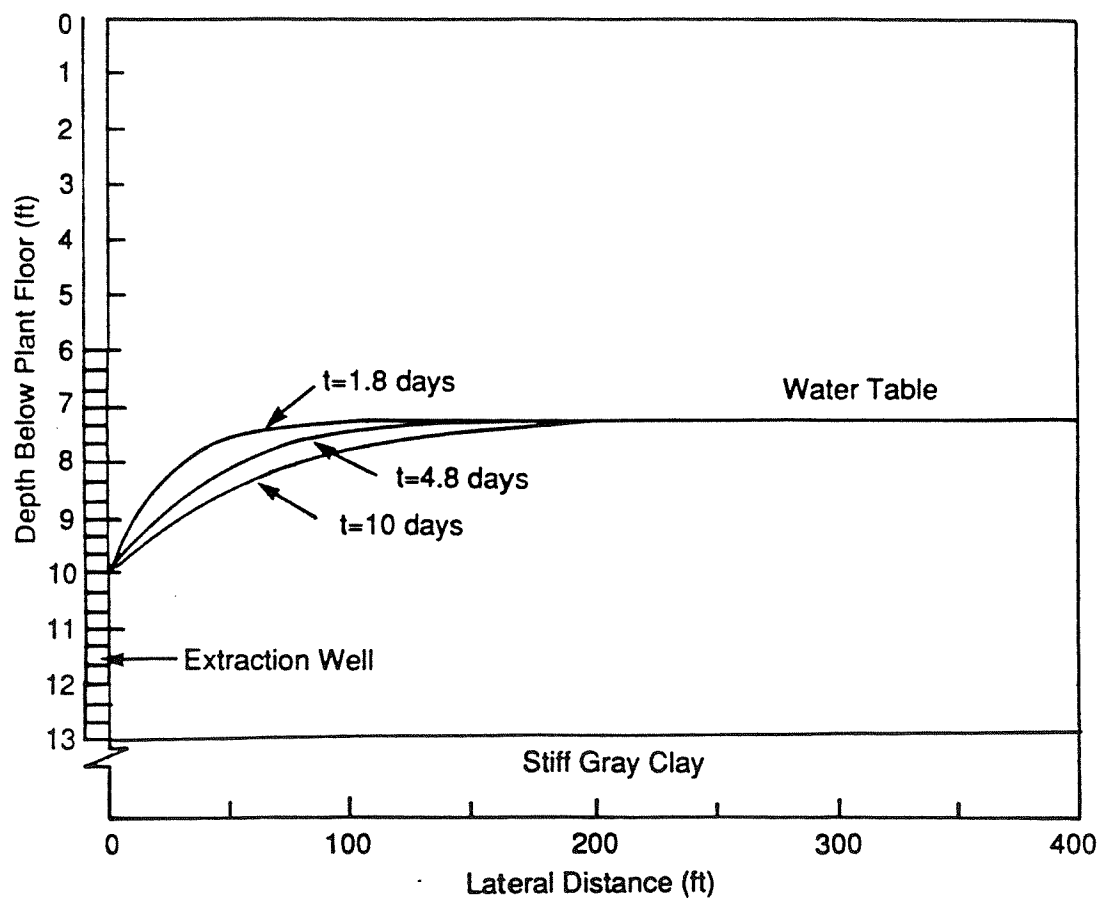


Figure 8. Mathematical modeling simulation of water-table drawdown during pumping.

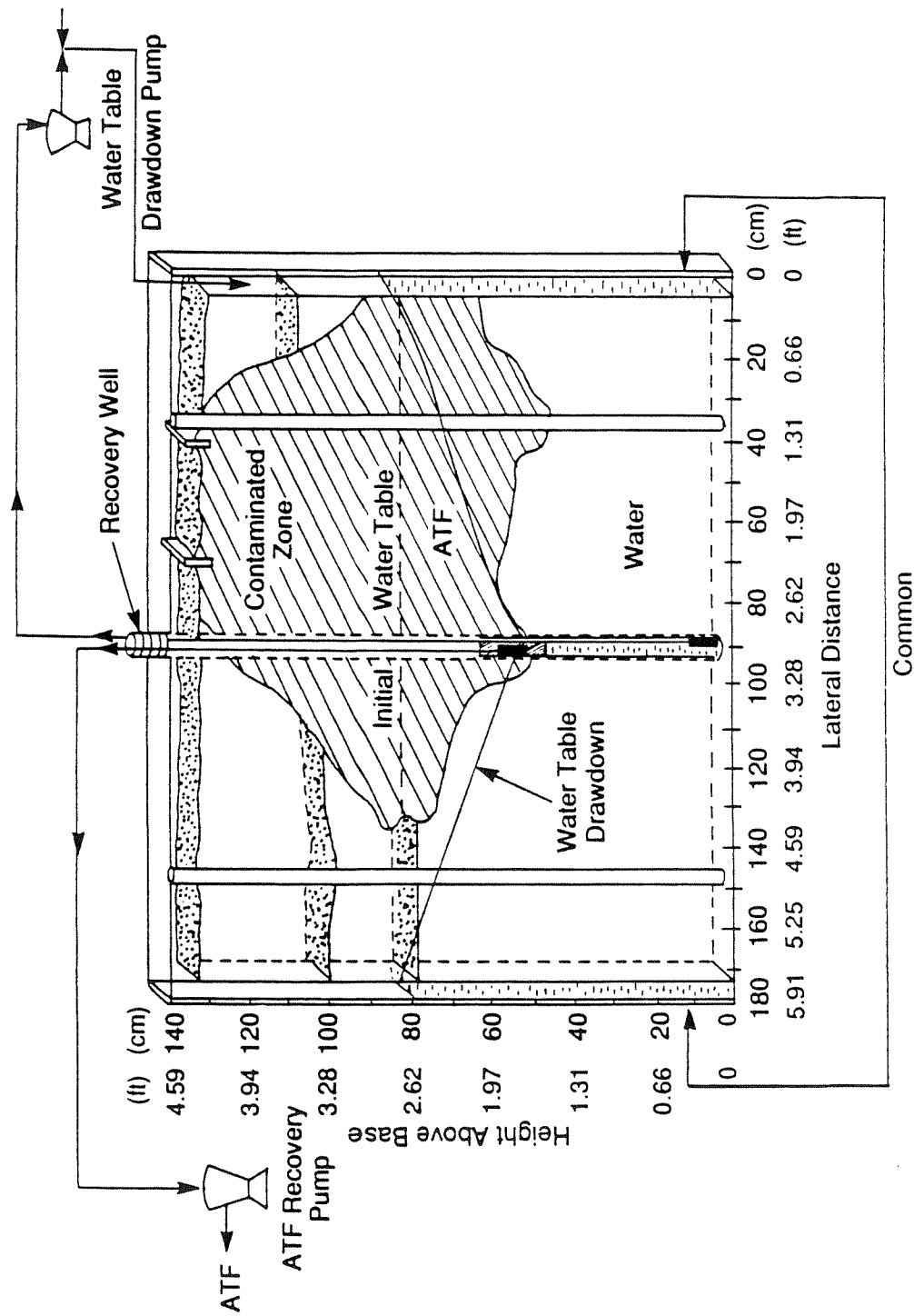


Figure 9. ATF and water recovery system used in the laboratory model aquifer.

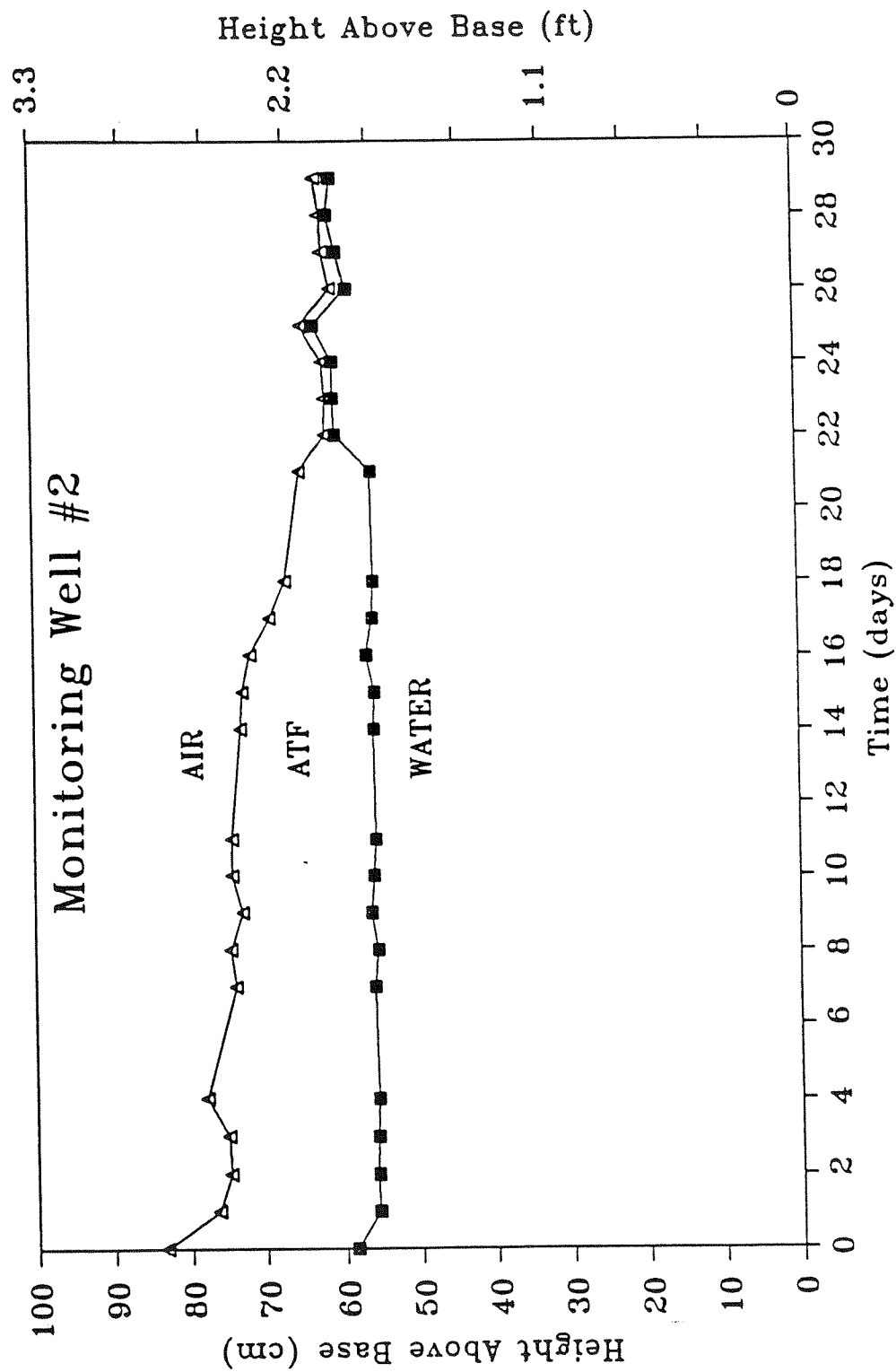


Figure 10: Response of the air/ATF and ATF/water interface in a monitoring well located adjacent to the recovery well in the model aquifer.

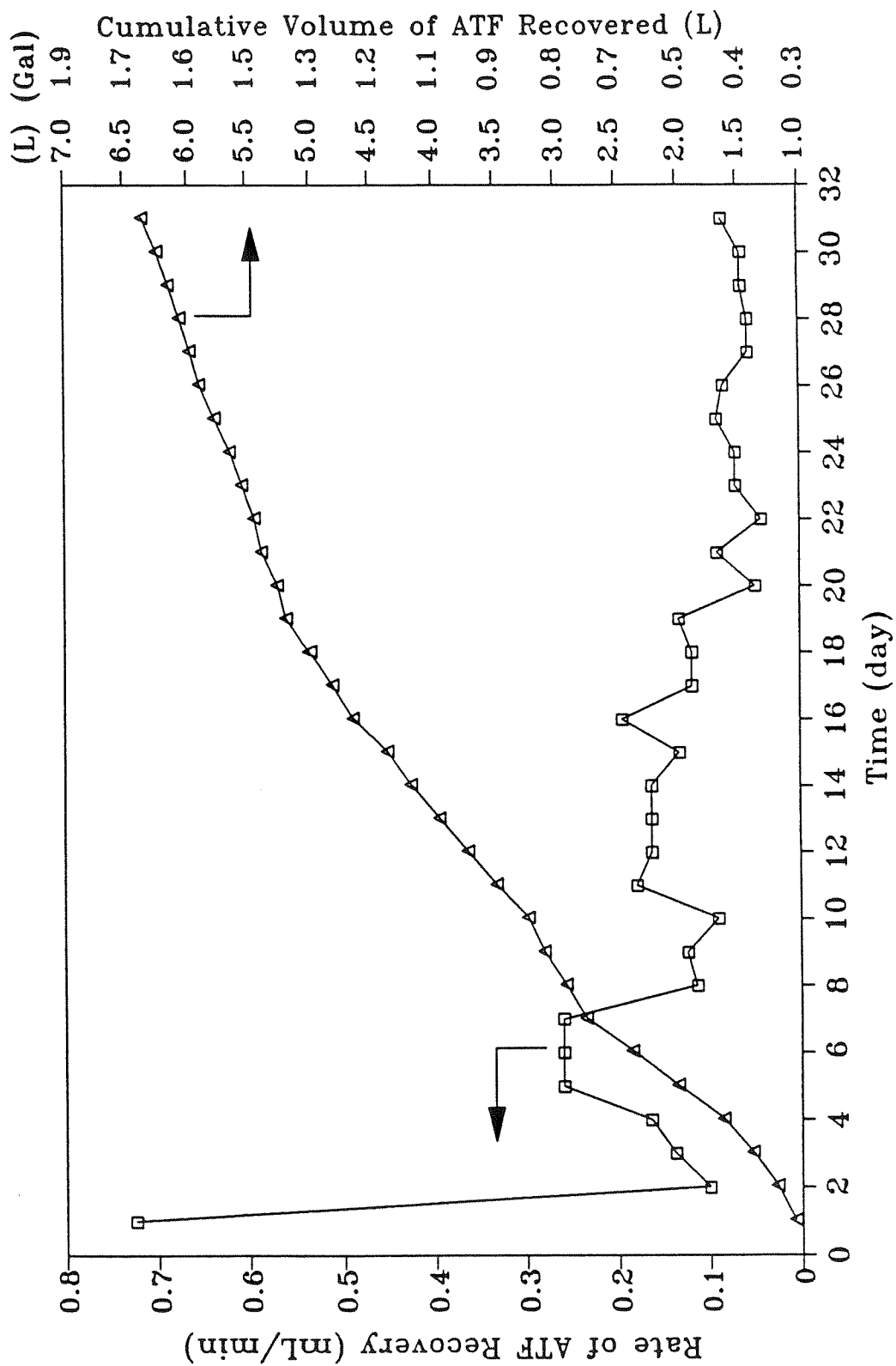


Figure 11: Recovery of ATF from the laboratory model aquifer.

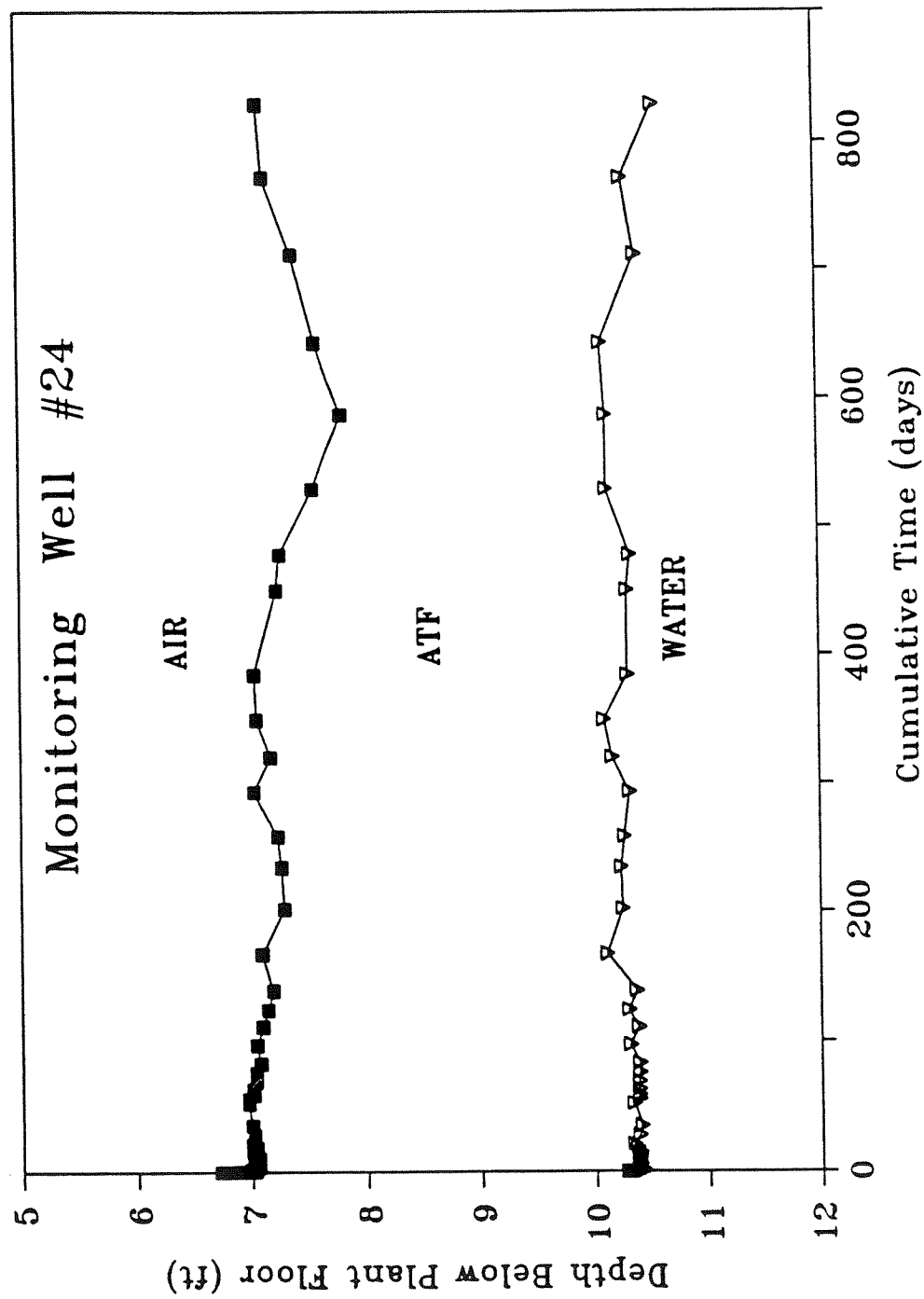


Figure 12: Response of the air/ATF and ATF/water interfaces in a monitoring well located adjacent to recovery well #24 at the field site.

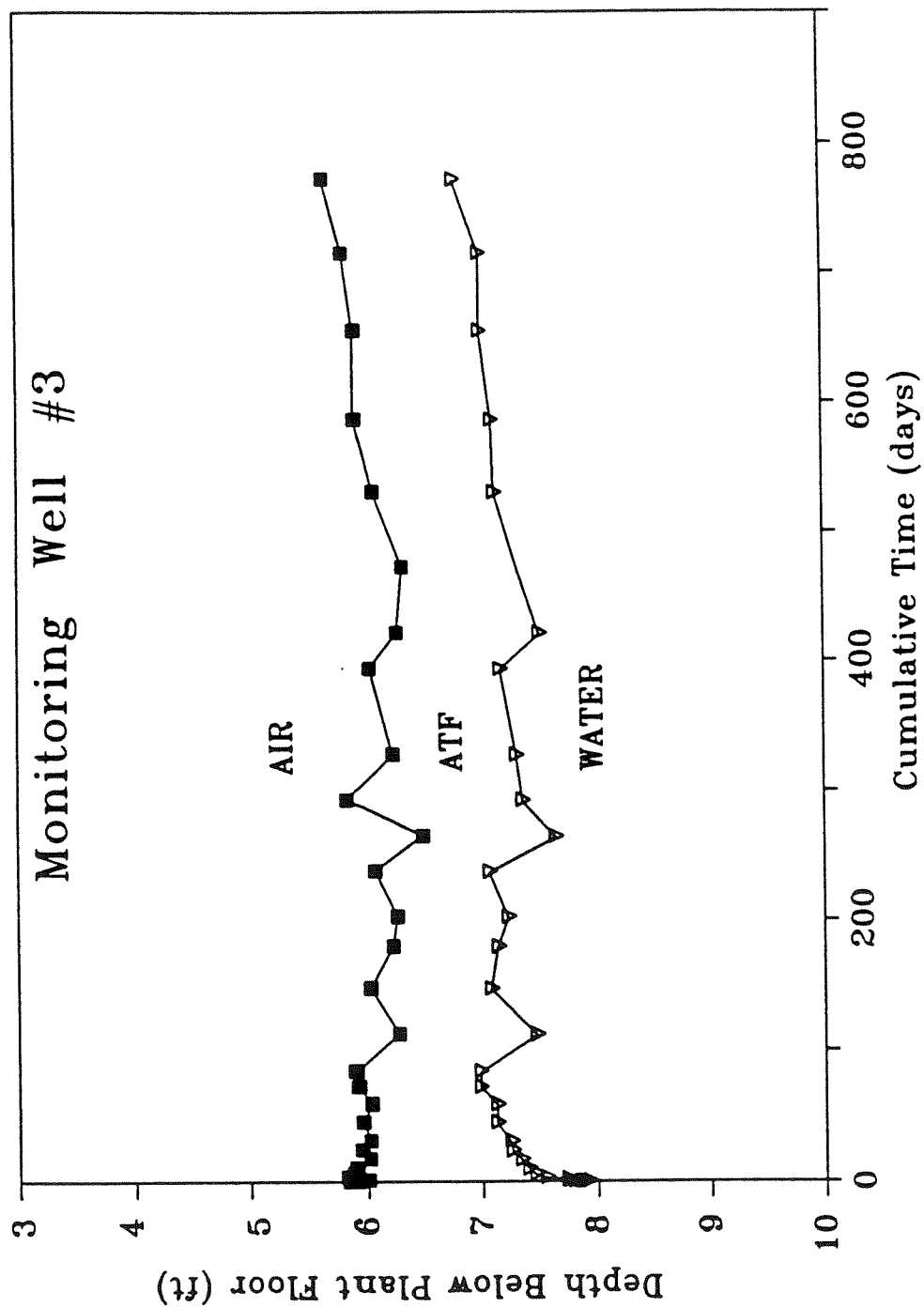


Figure 13: Response of the air/ATF and ATF/water interfaces in a monitoring well located adjacent to recovery well #3 at the field site.

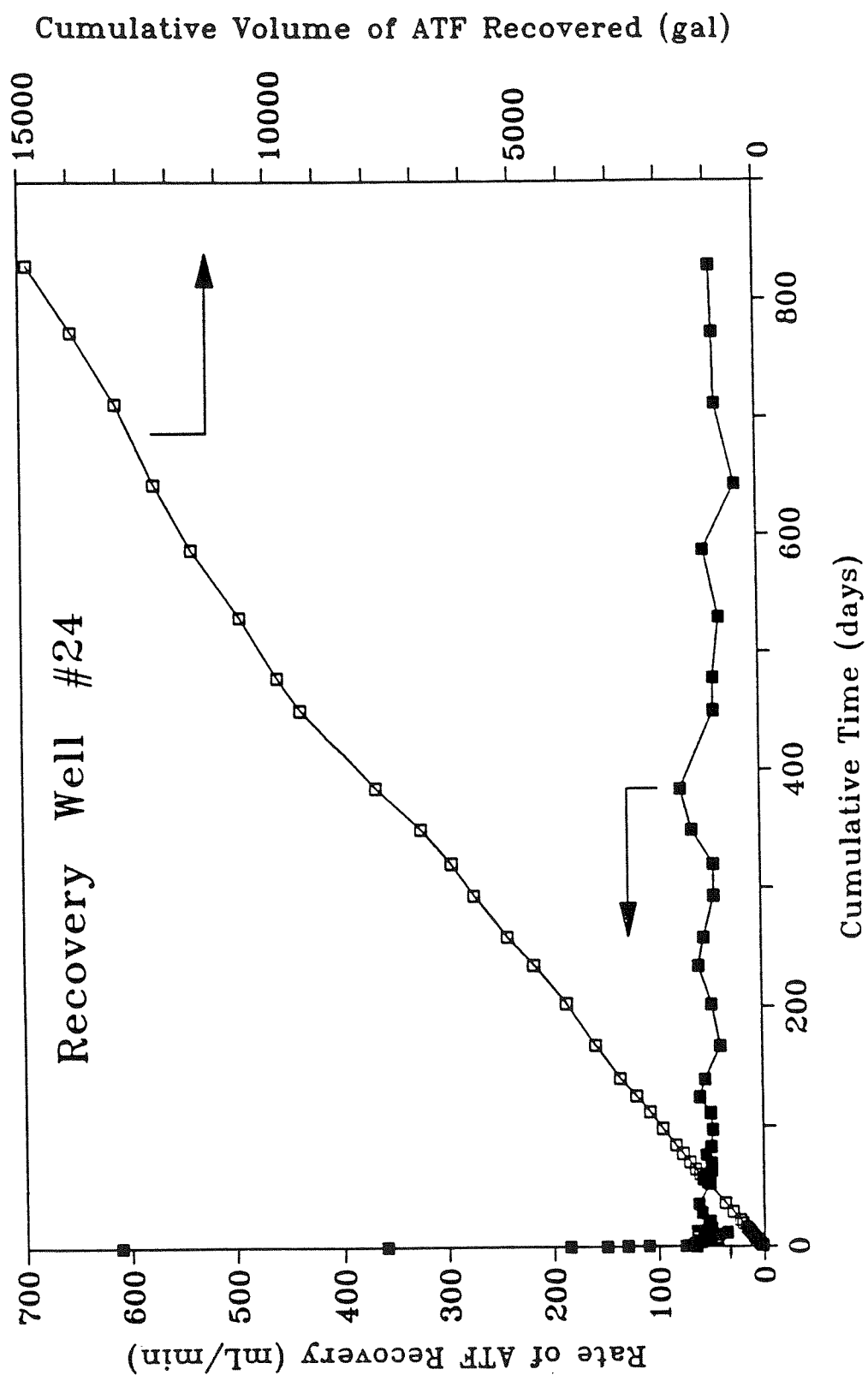


Figure 14: Recovery of ATF from Well #24 at the contaminated field site.

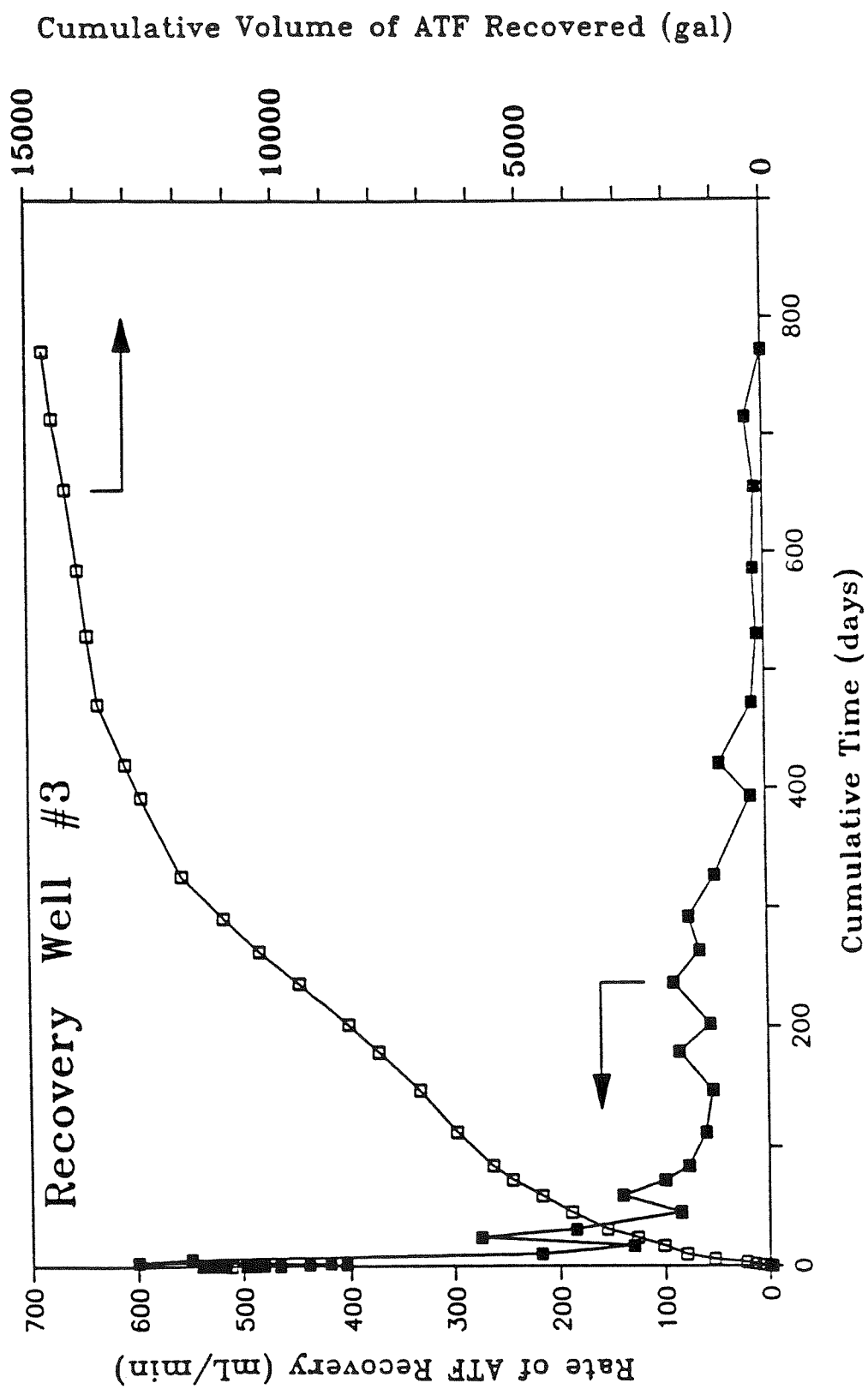


Figure 15. Recovery of ATF from Well #3 at the contaminated field site.

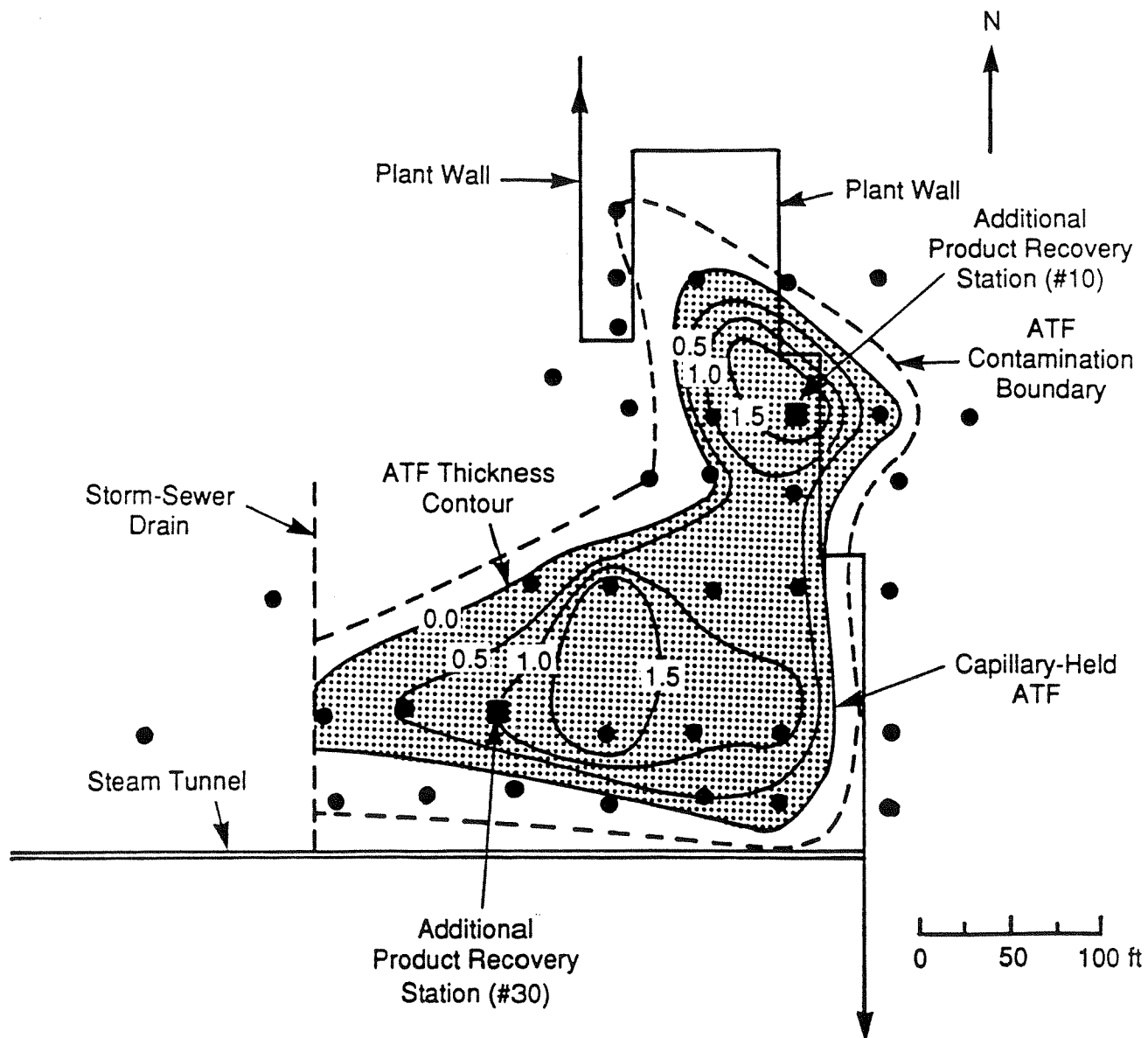
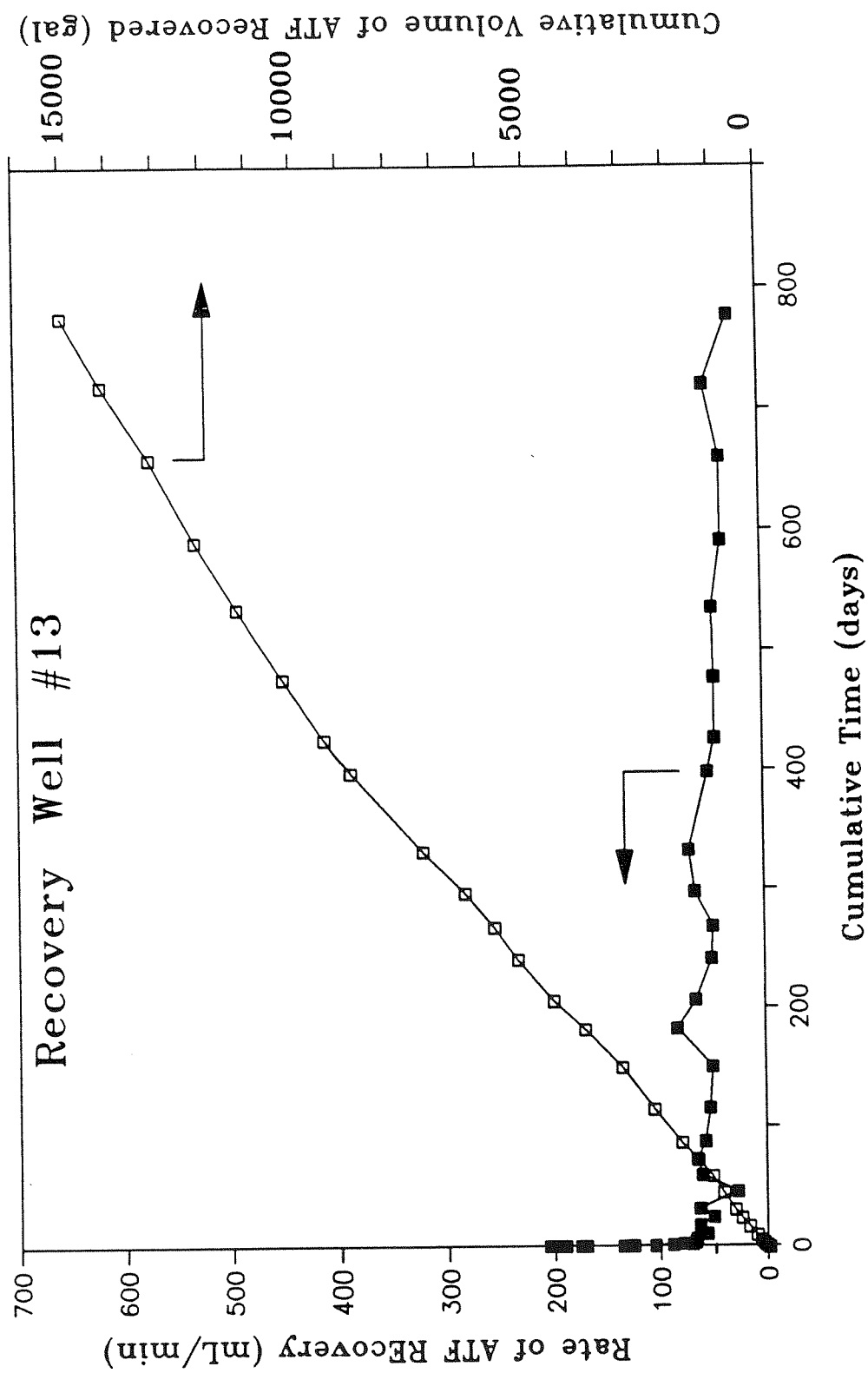


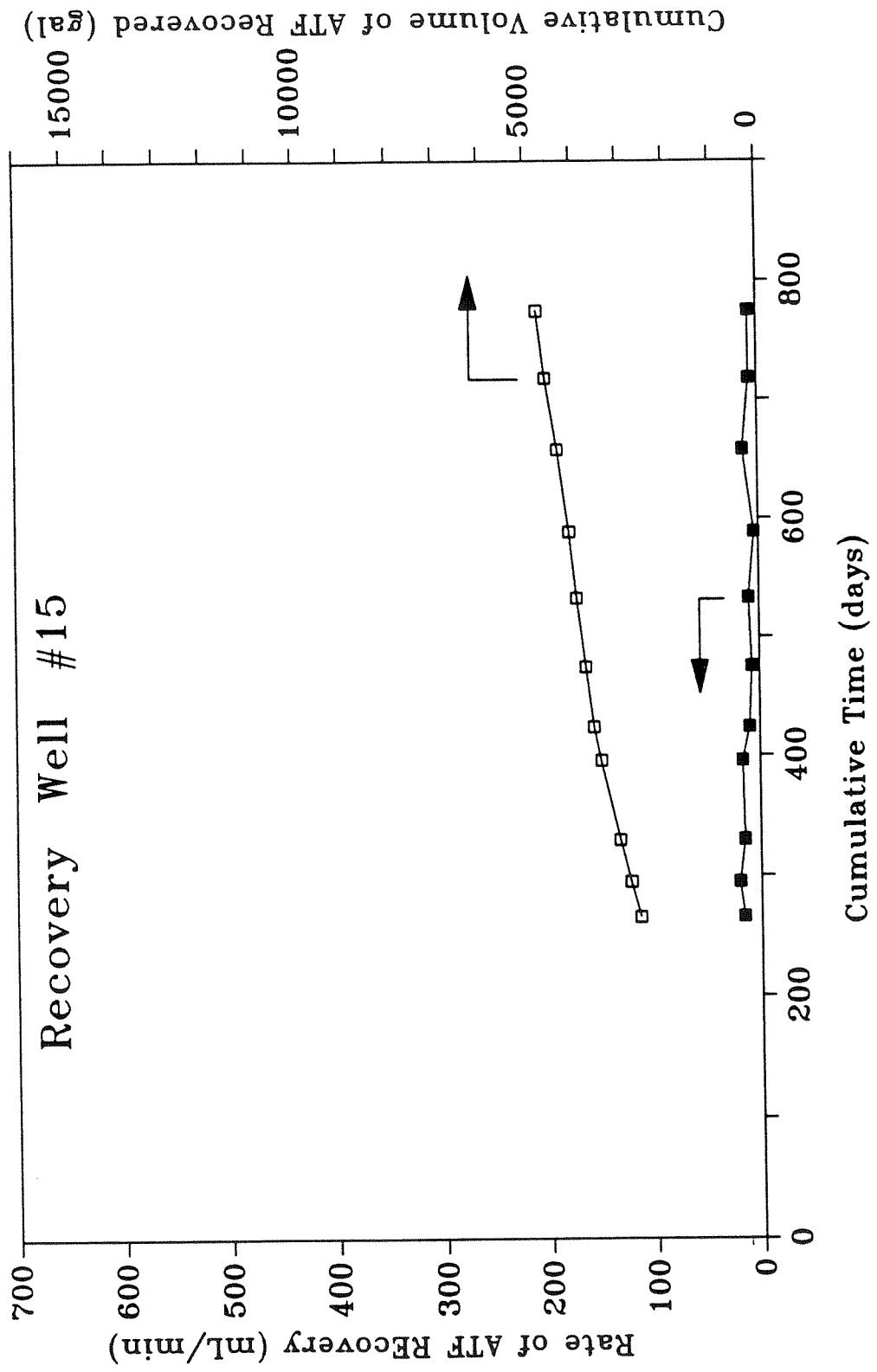
Figure 16. Lateral spread of ATF and contours of ATF thickness (ft) in the porous medium 800 days since the start of product recovery.

APPENDIX 1

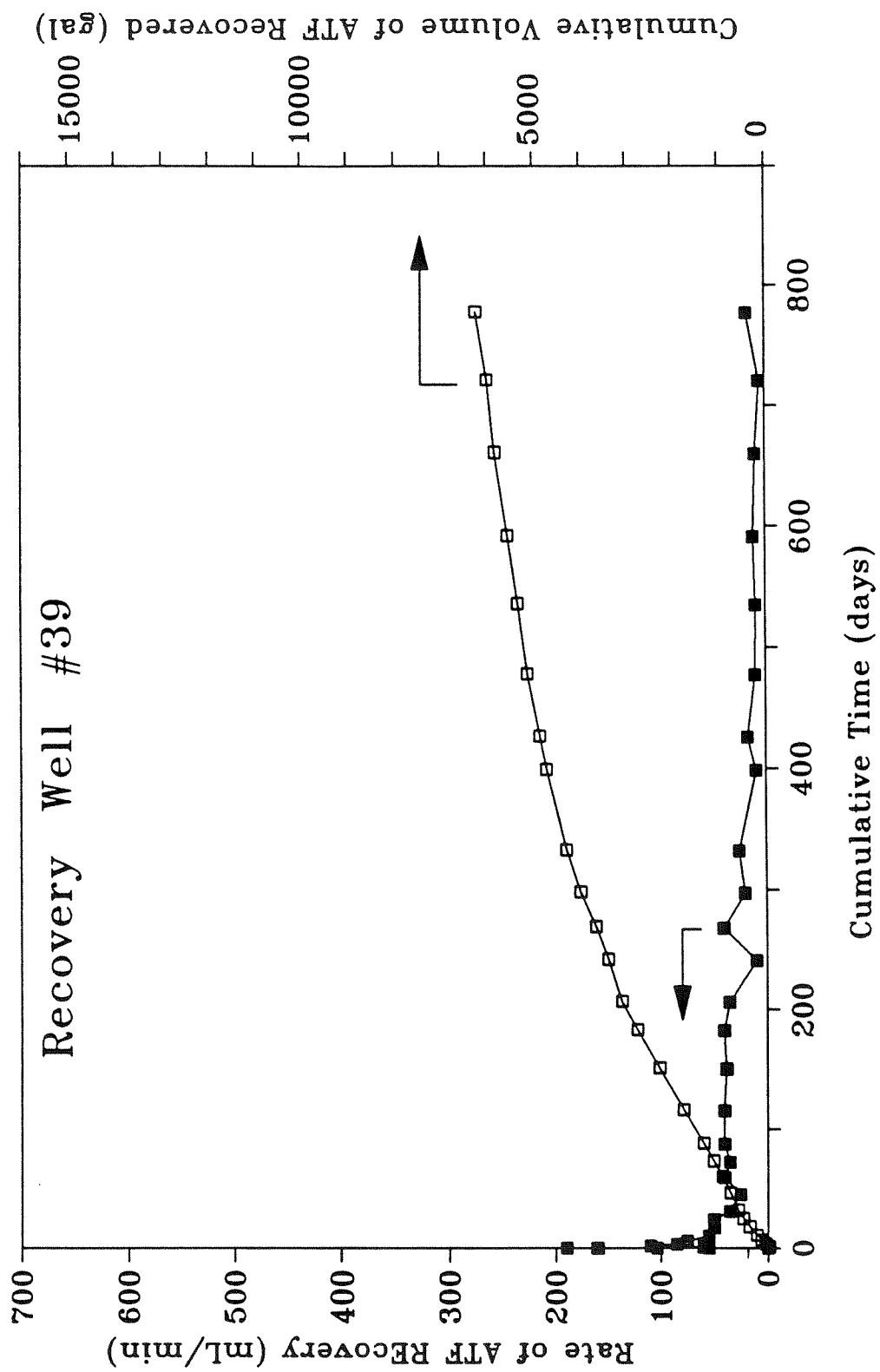
ADDITIONAL DATA FROM THE RECOVERY WELLS AT THE FIELD SITE.



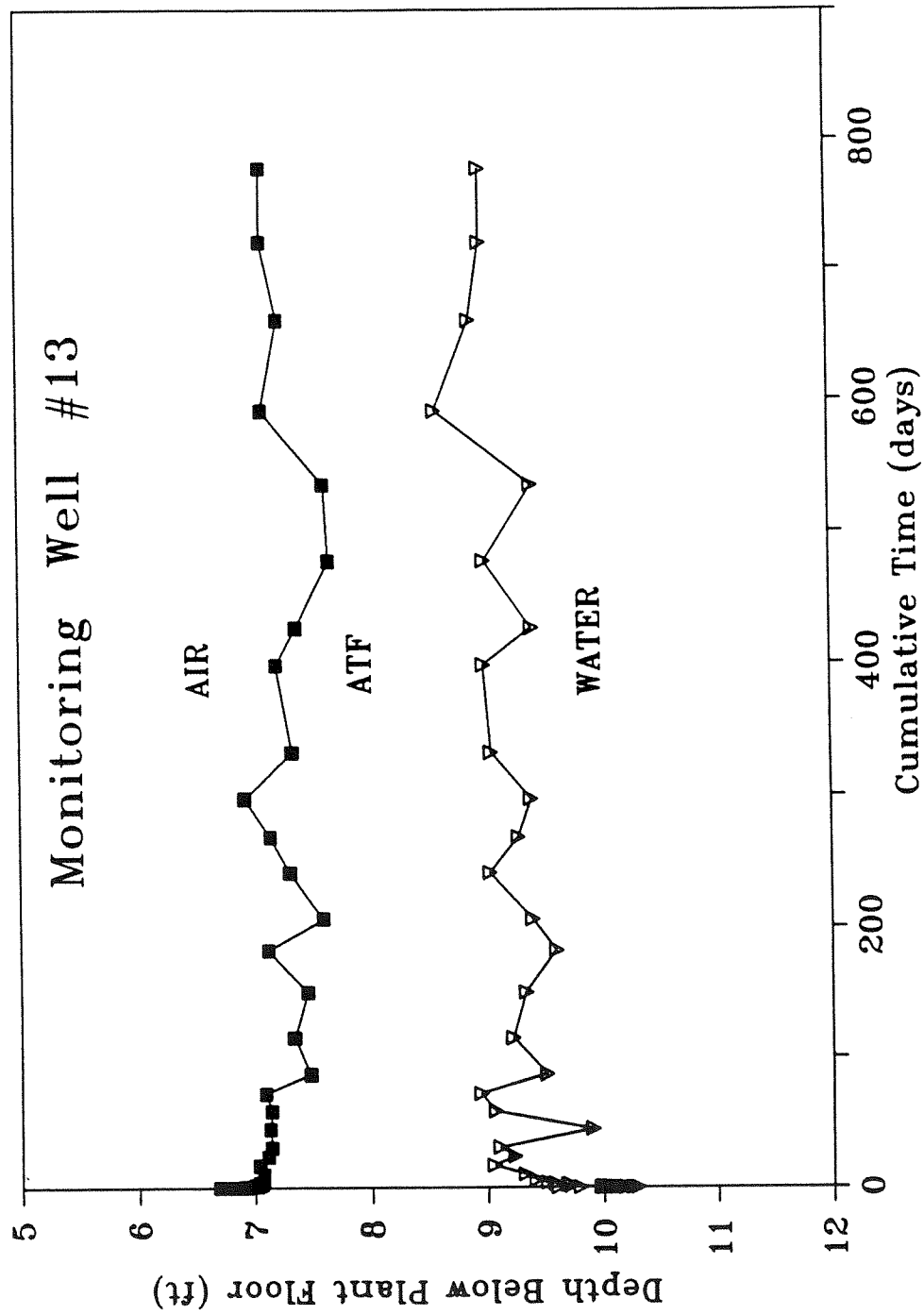
Recovery of ATF from Well #13 at the contaminated field site.



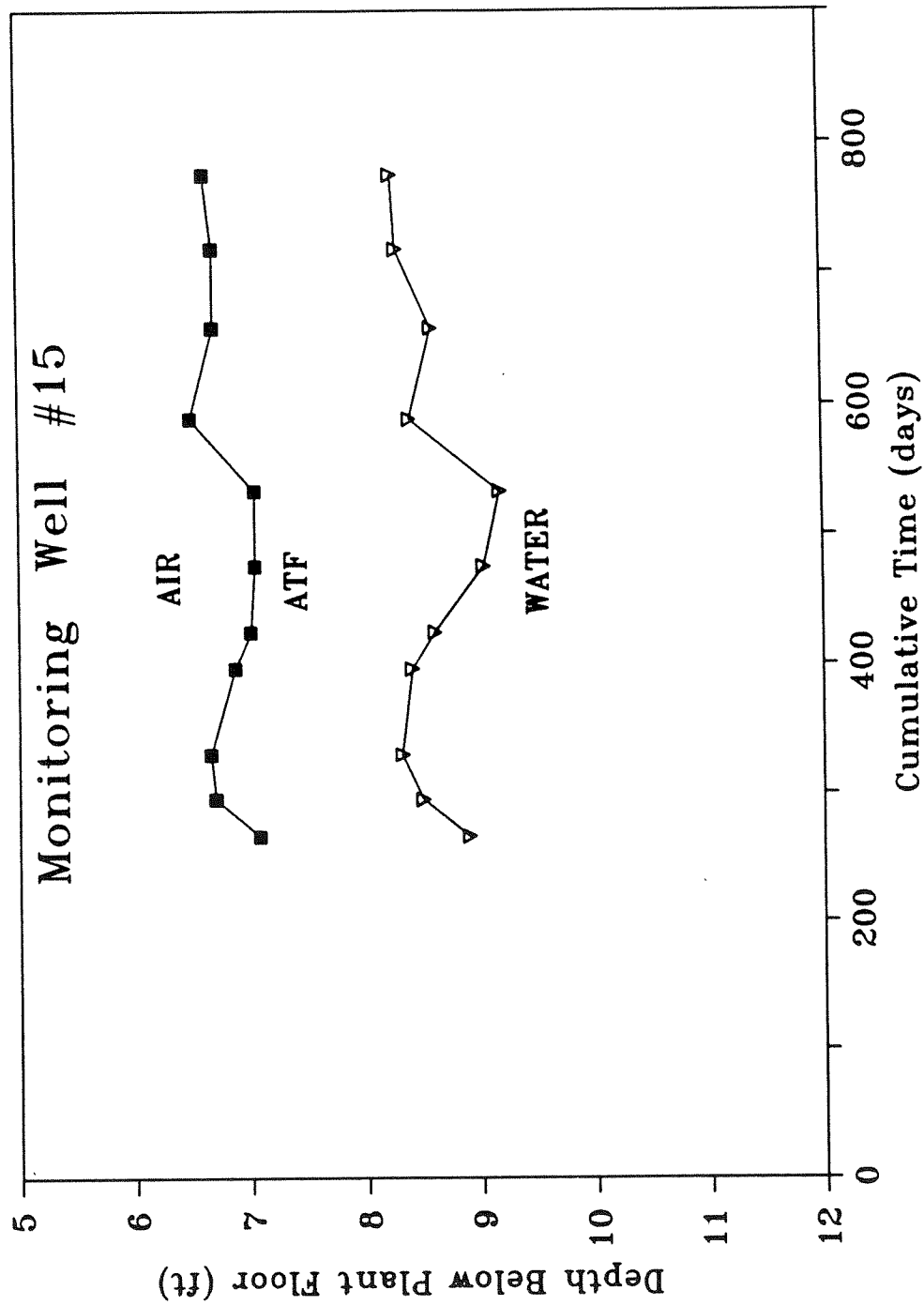
Recovery of ATF from Well #15 at the contaminated field site.



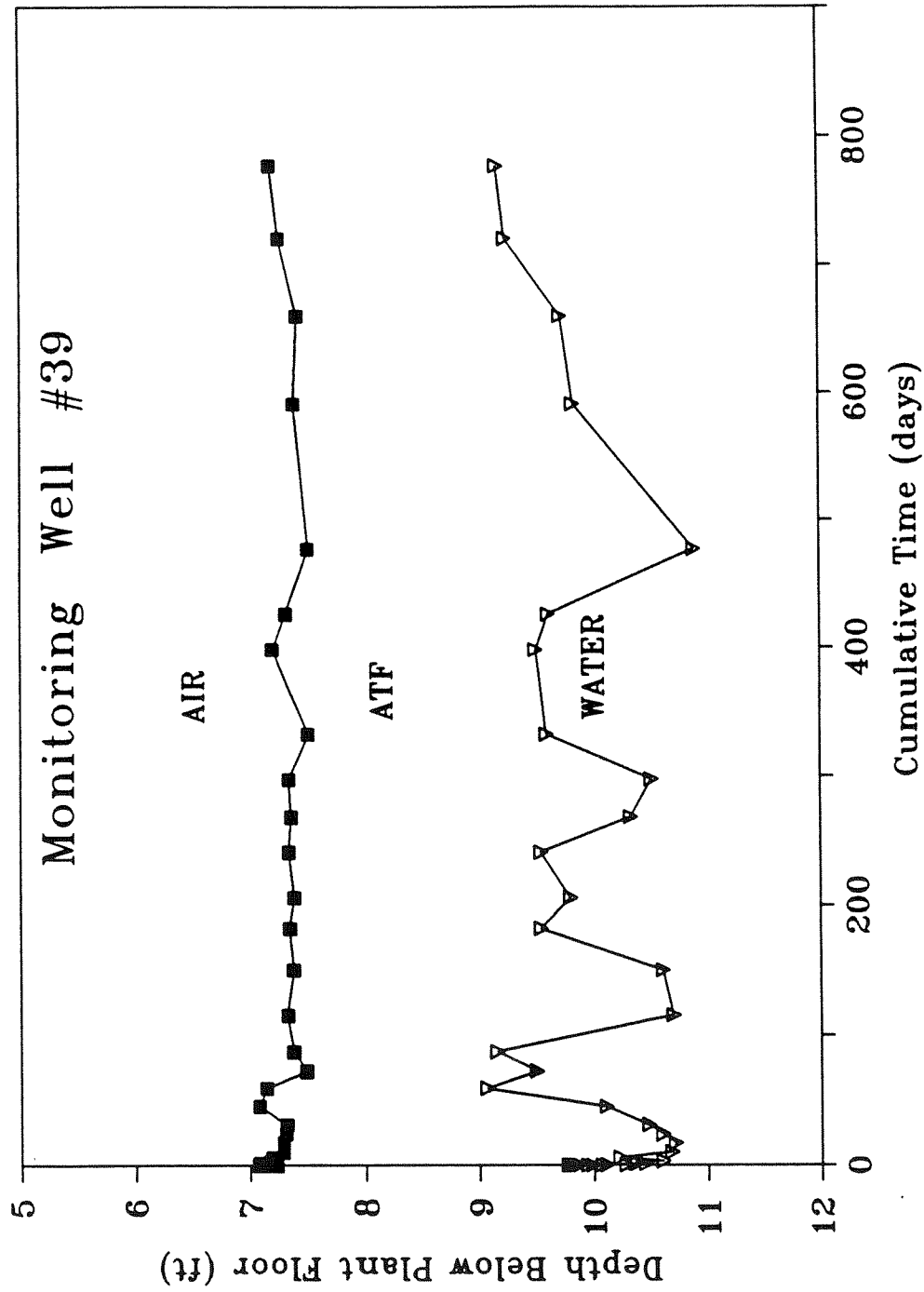
Recovery of ATF from Well #39 at the contaminated field site.



Response of the air/ATF and ATF/water interfaces in a monitoring well located adjacent to recovery well #13 at the field site.



Response of the air/ATF and ATF/water interfaces in a monitoring well located adjacent to recovery well #15 at the field site.



Response of the air/ATF and ATF/water interfaces in a monitoring well located adjacent to recovery well #39 at the field site.

APPENDIX 2

WORK PLAN 1

PURPOSE

Soil and groundwater beneath a region of the General Motors Hydra-matic Plant at Ypsilanti, Michigan, are contaminated with automatic transmission fluid (ATF). Following an agreement with Hydra-matic and the Michigan Department of Natural Resources, the GMR Environmental Science Department conducted the field investigation described in this report to define the site hydrogeology and to assess the problem. Because the ATF is viscous and slow moving, completely within GM property, and not an immediate health threat, this field study has provided a good opportunity to test the concepts and assessment methods that we have been developing in the laboratory.

SUMMARY

To delineate the subsurface zones contaminated with ATF at the Hydra-matic site, an investigative scheme relying on soil core sampling and monitoring wells was used. The investigation progressed on the basis that the number, location, and depth of cores and of monitoring wells could not be decided beforehand. Instead, these decisions were made during the investigation itself based on: (1) inspection and analysis of soil-core samples in the field immediately after each core was taken, (2) physical and chemical measurements of core samples in the laboratory at the end of each daily sampling session, and (3) measurements in monitoring wells at several stages during the development of the network of monitoring wells. This approach differs significantly from the conventional approach of randomly placing wells through the hydrogeologic system.

The field work lasted six weeks and was performed during the night (11 p.m. to 6 a.m.) to avoid disrupting operations at the plant. Soil cores were taken at 54 locations and monitoring wells were installed at 53 of these

locations.

The soil and aquifer at the Hydra-matic ATF-site are comprised mainly of sandy materials, which have spatial heterogeneity in size distribution and hydraulic properties. Typically, the aquifer extends from 6.5 to 13 ft below the plant floor, and is perched above a layer of dense gray clay. In agreement with visual observations, the flow patterns for water and ATF constructed from field measurements indicate that both water and ATF are flowing primarily towards a storm-sewer drain and are also seeping into an underground steam tunnel. The tunnel and drain extend to about 2 ft and 4 ft below the water table, respectively. The direction of groundwater flow is also influenced by other local man-made structures below the plant, and by isolated recharge zones in close proximity to the plant. However, in general, groundwater flows toward the southwest at a rate of about 17 ft/year.

The investigation showed that leakage of ATF has contaminated the soil and perched aquifer under a region of the Hydra-matic plant. It is estimated that $208,000 \pm 33,000$ gallons of ATF has spread under the plant over an area of about $64,000 \text{ ft}^2$. The region of ATF contamination is comprised of three distinct and contiguous layers. The center layer is about 2.6 ft deep at its thickest point and extends to about 250 ft at its widest point. The soil in this zone is almost completely saturated with $133,000 \pm 21,000$ gallons of ATF, which has depressed the water table into the aquifer. Further, the pressure of the ATF is higher than atmospheric and it can flow under its own hydraulic head. The top layer is about 14 inches thick and has about 50,640 gallons of ATF held by capillary forces. The amount of ATF in this zone decreases with height above the center layer from that required for almost complete saturation of the soil pore space to about 20% saturation. The amount of ATF in the deepest layer is near the residual saturation of about 20% of the pore

space between the soil and aquifer material. This layer is 1.0 * 0.5 ft thick and has 24,500 * 12,250 gallons ATF.

CONCLUSION

The contamination by ATF of a soil and aquifer system at the Hydra-matic Plant, Ypsilanti, MI has been defined. Decontamination steps will be based on this assessment.

INTRODUCTION

In 1980, automatic transmission fluid (ATF) was discovered in a manhole adjacent to underground storage tanks (UST) beneath the General Motors Hydra-matic Plant at Ypsilanti, Michigan. During excavation in the region of the UST for construction of a new tank farm in 1985, ATF was found in the soil and groundwater zones. Hydra-matic and the Michigan Department of Natural Resources (MDNR) decided to assess the problem, and Hydra-matic sought the advice of the GMR Environmental Science Department (EV). Following an agreement with Hydra-matic, members of the EV department conducted a field investigation to define the site hydrogeology and to assess the problem. Because the ATF is viscous and slow moving, completely within GM property, and not an immediate health threat, this field study provide a good opportunity to test concepts and assessment methods that members of the EV department have been developing in the laboratory. This report describes the field investigation performed during the summer of 1987 to describe the site hydrogeology and to assess the extent of contamination. Hydra-matic paid for the material and outside contractual work.

Soil and groundwater contamination by petroleum products from spills and leaks is believed to be widespread and a potentially serious environmental problem (Woodhull, 1981; Jercinovic, 1984; MDNR, 1988). When a spill or leak occurs, the following approaches are commonly used to investigate the extent of soil and groundwater contamination: (1) soil gas sampling, (2) soil core sampling, and (3) well monitoring. Soil gas sampling has been used as a reconnaissance tool to map the distribution of volatile organic compounds in the soil gas. This approach could be useful for detecting petroleum products such as gasoline, which have significant quantities of volatile components. Technologies to sample soil gas and methods for data interpretation have

advanced significantly during the last few years and are the subjects of active research and development (Diem et al., 1988; Burris and Wolf, 1988). However, soil gas sampling was not expected to help in delineating the zones of ATF contamination at the Hydra-matic site, since ATF does not contain significant quantities of volatile components.

Soil core sampling is usually accomplished by the standard split-spoon method. This method provides soil cores for visual inspection and grab samples for laboratory analysis to describe the distribution of contaminants and the geology of the site.

The third approach uses monitoring wells. In the past, monitoring wells provided the only means for site assessment and problem definition. More recently, their use has been combined with soil-gas and soil-core sampling. Typically, monitoring wells are randomly installed through the aquifer. The screened portion of the well, which allows the flow of liquid from the adjacent porous system into the well, is usually opened to the entire aquifer. Theoretical analysis and experimental results indicate that oil would flow into a well only after the oil pressure in the adjacent porous medium becomes greater than atmospheric pressure (Abdul et al., 1988). Since oil will have to accumulate and fill the soil pore spaces before its pressure becomes greater than atmospheric, the presence of oil in a well could indicate an advanced stage of oil contamination of the subsurface. Furthermore, the ratio of the oil thickness in a well to that in the adjacent porous medium depends on the properties of the oil and of the medium and on the dynamics of the flow system (Abdul et al., 1988). Estimating the oil thickness in the soil and aquifer medium continues to be a scientific challenge.

Since ATF, like many other petroleum products, is lighter than and immiscible with water, the undissolved ATF is expected to be within the zone

of water-table fluctuation. The migration of undissolved oil to and below the water table will occur only if the porous medium is highly conductive and the rate of oil leak is high (Abdul, 1987). In this regard, soil coring and installation of monitoring wells through the entire depth of the aquifer, as is the usual practice, may not always be needed, and may spread contaminants to deeper regions of the aquifer that were initially clean. Furthermore, the random placement of monitoring wells may not be a cost-effective investigative approach, as this approach proceeds without using the information and understanding of the system that is gained from observation and sampling at previous coring or drilling locations.

Automatic transmission fluid is of special interest because General Motors is one of the largest users of ATF and the migration and fate of ATF in hydrogeologic systems have not been studied previously. Unlike the more common petroleum products, gasoline and diesel fuel, ATF has high viscosity, extremely low solubility in water, and low vapor pressure. These properties could significantly influence the migration and fate of ATF in hydrogeologic systems, and the extent to which ATF leaks can be managed and cleaned up.

The overall objective of this report is to present the results of the investigation of the ATF contamination below the Hydra-matic Willow Run plant at Ypsilanti, MI. The specific objectives were to: (1) develop and implement a new approach to define the soil and aquifer zones contaminated with ATF, (2) describe the geology and hydrology of the site, (3) delineate the vertical and lateral spread of ATF, and (4) estimate the volume of ATF within the soil and aquifer system.

APPROACH

An investigative scheme relying on both soil core sampling and monitoring wells was used to delineate the extent of soil and groundwater contamination at the Hydra-matic site. The investigation progressed without predetermining the number, location, and depth of cores and of monitoring wells. Instead, these decisions were made during the investigation based on: (1) inspection and analysis of soil core samples in the field immediately after each core was taken, (2) additional analysis and physical and chemical measurements of soil samples in the laboratory at the end of each sampling session (1 and 2 provided real-time data), and (3) measurements in monitoring wells at several stages during the growth of the network of monitoring wells. This approach differs significantly from the conventional approach of randomly placing wells throughout the hydrogeologic system.

In the site investigation, the location of the first core was selected to be in an area of known soil contamination adjacent to the underground storage tanks. Soil cores were taken by the conventional split spoon (2 feet long by 1 3/8 inches I.D.) following a standard ASTM method (D1586-84). By this method, the split cylinder mounted on a drill rig was driven two feet into the soil by the impacts of a 130 lb weight dropped through 30 inches. Each split spoon, once taken out of the ground, was opened along its length and the soil core visually inspected to qualitatively describe the site geology and the presence of ATF. Based on this inspection, several two-inch sections of the soil core were immediately extracted with 1,1,2-trichloro-1,2,2-trifluoroethane (Freon-113) to determine if the soil was contaminated with ATF or any other Freon extractables. During this inspection and extraction step, the borehole for the installation of a monitoring well was drilled down to the depth of coring by using a hollow-stem auger (10 inch O.D.

by 6.5 inch I.D.). If the extracts indicated that the soil was contaminated, coring and drilling progressed in two-foot increments to a point just below the zone of contamination or to four feet below the water table, whichever was deeper, and a combination well was installed in the borehole. A schematic of a combination well is shown in Figure 1-A.

The combination well is essentially two off-centered wells with a 2.0 inch O.D. inner well and a shallower 4.5 inch O.D. outer well. Typically, the inner and outer wells are 13 and 11 feet deep, respectively. The two wells are hydraulically isolated from each other so that fluid cannot flow between them. Each well is open to the surrounding medium through a screen section consisting of parallel 0.01-inch slots (six slots per inch). Typically, the outer well is open to the medium from two feet above the water table to four feet below the water table, while the inner well is open to the next two feet of the aquifer below the outer well. This design made it possible to monitor and sample two different depths in the same location, and it could also be used to pump ATF and water from the contaminated zones separately since the outer well would capture the free oil near the water table, while the inner well would tap only into the groundwater below the ATF.

If no soil contamination was found at a location, coring and drilling continued through the aquifer and a multi-level-bundle piezometer, shown in Figure 1-B, was installed in the borehole. The multi-level-bundle piezometer is a bundle of small diameter wells, each of which is open to the porous medium for about 4 inches at a specified depth beneath the surface. The piezometer in the center of the bundle is the deepest (about 13 ft) and is made from 2.0 inch O.D. (1 1/2 inch I.D.) PVC tube to provide structural support for the other piezometers. The piezometers around the center PVC tube

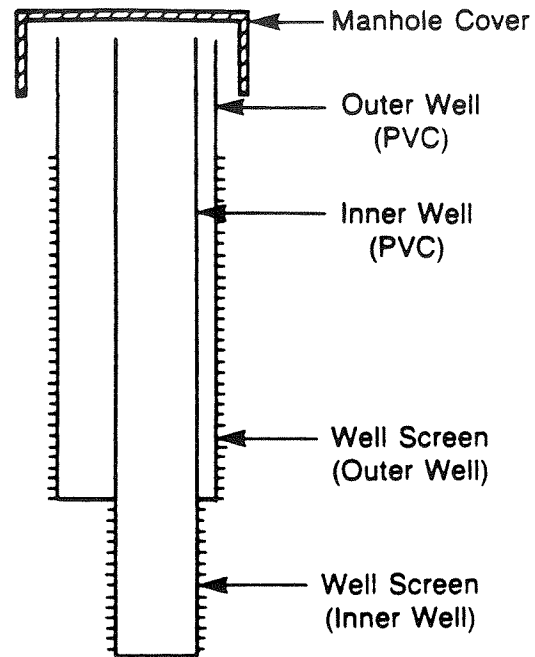


Figure 1-A. A combination well system.

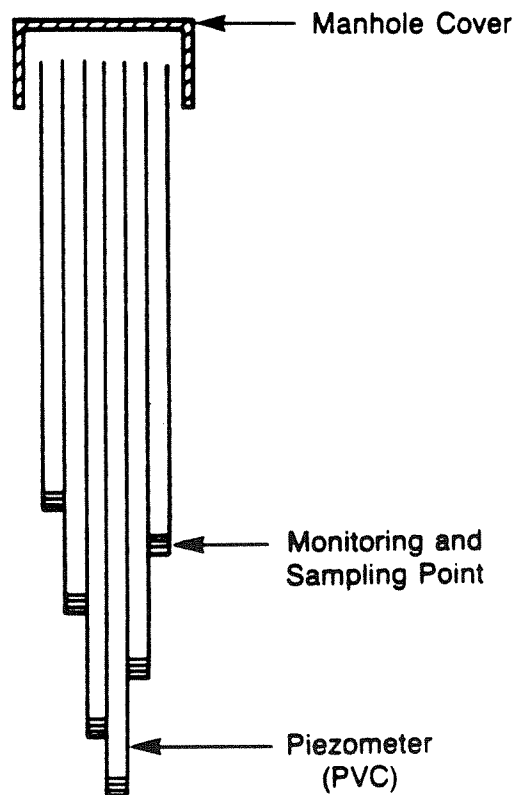


Figure 1-B. A multi-level-bundle Piezometer system.

are made of polypropylene tubes (5/8 inch I.D) and are open to the medium at intervals of about 2 ft. By sampling and monitoring each of the piezometers, vertical profiles of contaminants dissolved in the groundwater and of hydraulic conditions can be mapped. When compared to the conventional single well, which will give only one sample and one hydraulic measurement, this is a cost-effective method for collecting information on contaminant distribution and hydraulic conditions within the system.

Wells were installed through the annulus of the hollow stem auger to the depth of drilling. A schematic of an installed well is shown in Figure 2. With the well in place, coarse silica sand was poured into the annulus of the auger and around the well to fill the borehole as the auger was slowly pulled to the surface. This porous sand pack forms a conductive zone around the wells from the base of the inner well to two feet above the slotted portion of the outer well. Bentonite-clay pellets were poured on top of the sand, from about 3 ft to 1.5 ft below the floor, to seal the medium and the well from liquid penetration from the plant floor. One foot of cement was then poured on the bentonite and a manhole was placed around the well and leveled with the plant floor.

The Freon extracts and the extracted soil samples were taken to the GM Research Laboratories (GMR) at the end of each field session to perform the following tasks: identify the oil (or oils) in the extract; measure the amount of ATF in the extracts; determine the grain-size distribution of the soil; and measure the hydraulic conductivity of the soil samples to water. To facilitate these measurements and to avoid disrupting operations at the plant, field work was carried out during the night (11 p.m. to 6 a.m.), while laboratory measurements were undertaken during the daytime. At the start of each night shift, the laboratory results were incorporated into three-dimensional plots of ATF distribution and of the site geology.

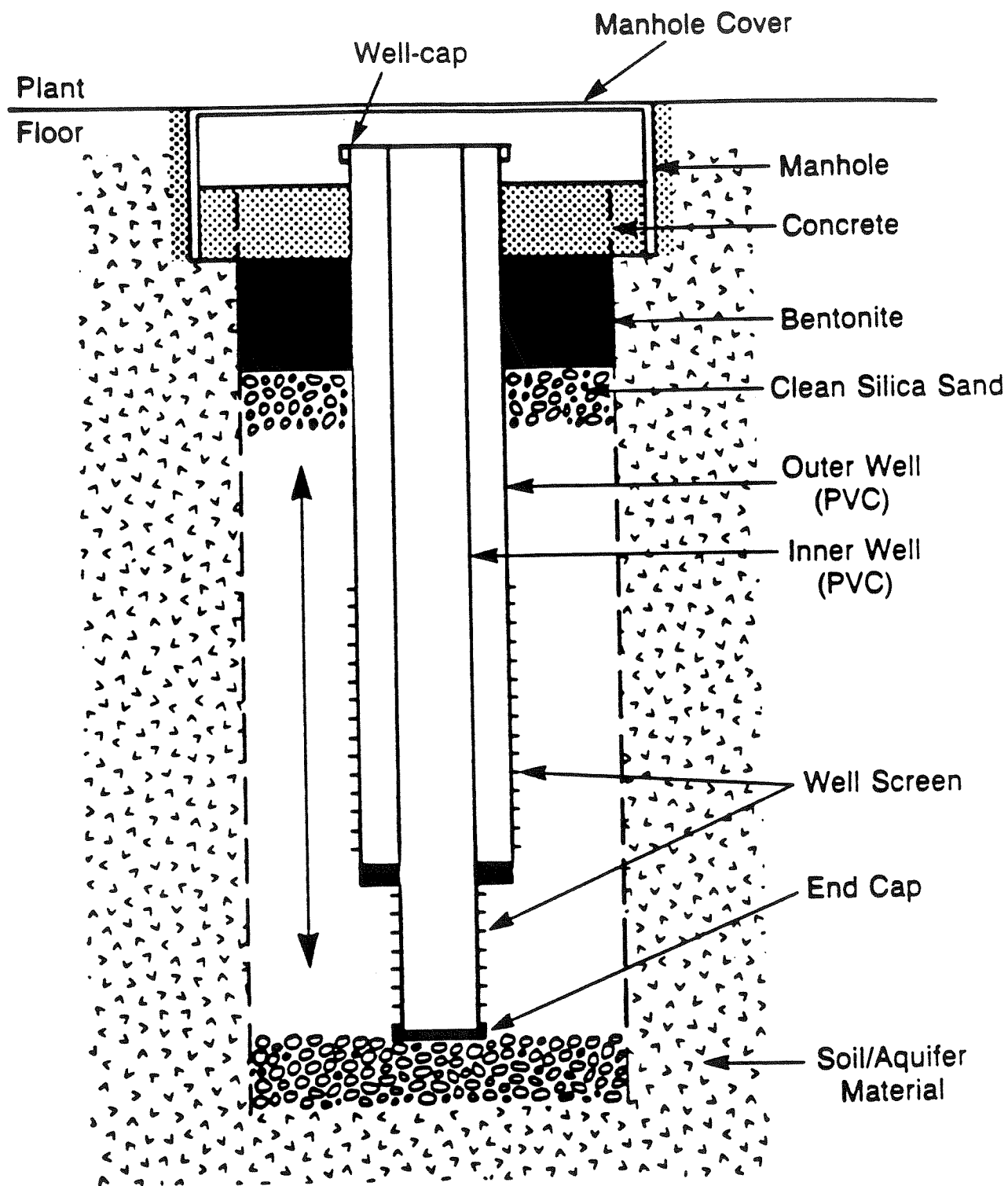


Figure 2. A schematic of well construction and installation.

Further, the following tasks were performed at the start of each field session: (1) the standing liquid in the new wells was pumped out several times to establish good hydraulic contact between the wells and the adjacent medium, (2) the depths to ATF and to water in each well were measured, and (3) the relative elevation of the wells was measured by using a surveyor's transit. These field measurements together with the laboratory results were used to update mapping of the ATF distribution and to calculate the direction and rate of flow of groundwater and of ATF.

Coring was planned for locations in the four principal directions from any location previously determined to have a layer of free ATF. The application of this plan was guided by our increasing knowledge of the geology and the hydrology of the system, and the lateral and vertical distribution of ATF. The distances between wells were guided by: 1) the need to define the site hydrology and geology, and the spread of ATF, 2) physical obstacles in the plant, and 3) the spacing that would optimize the recovery of ATF if the wells were to be used subsequently to pump out the ATF from the system.

By following this approach, coring was carried out at 54 locations and 53 wells were installed (see Figure 3). Forty-one of these wells were installed at locations inside the plant. Before soil coring could be carried out at these locations, a concrete core 9 to 13 inches thick and 12 inches in diameter had to be cut and removed from the plant floor. Of the wells, six were multibundle piezometers, forty-one were combination wells, five were single wells, and one was a double well. The double well consisted of two single wells (each two-inches O.D.) of different depths and was installed in an area where it was difficult to drill with the large diameter auger needed for the combination wells. This difficulty was caused mainly by underground structures below the plant. Thirty-nine of the wells showed an oil layer,

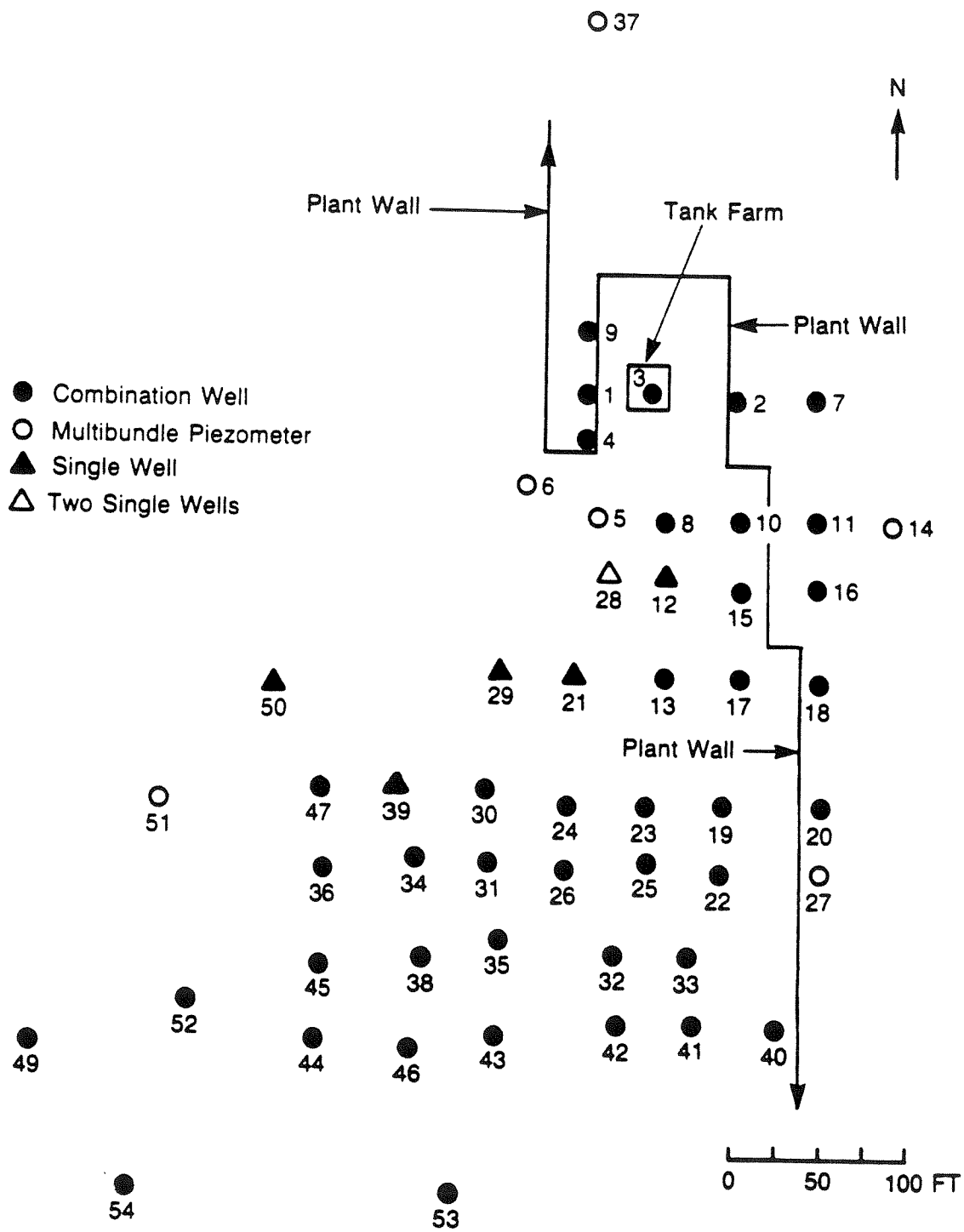


Figure 3. Locations of coring and wells.

while the remainder showed only water. The drilling was performed by Professional Services Industries, Inc., Michigan Testing Engineers Division.

MEASUREMENTS AND METHODS

ATF Extraction and Quantification

The extraction and quantification of ATF were carried out by following a procedure similar to the "Partition-Gravimetric Method" described in Standard Methods for the Examination of Water and Wastewater (1985). In the field, 30 mL of 1,1,2-trichloro-1,2,2-trifluoroethane (Freon-113) was added to about 70 g of soil in a 100 mL beaker and stirred for 5 minutes, after which the supernatant was filtered through silicone-treated filter paper to remove traces of water, and the filtrate was collected in a 250 mL boiling flask. This procedure was repeated 2 to 3 times and the supernatants were combined in the same flask. From a color comparison of the extracts with standards containing known concentrations of ATF in Freon, the presence or absence and an estimate of the amount of oil in the extracts were determined in the field. In the laboratory each extract was heated on a steam bath to evaporate the Freon, leaving behind the oil. The weight of the oil and the dry weight of the soil sample (from which the oil was extracted) were then determined and the concentration of oil was expressed as weight of oil per unit weight of soil.

The Freon extraction method was tested by treating clean sandy soil from a borehole adjacent to the contaminated zone with ATF to give a concentration of 4750 mg ATF per kg of soil, which is about 2% pore saturation. When five replicate samples of this material were extracted, the mean recovery of ATF was 92%, with a standard deviation of 8%. These results were achieved despite the relatively low initial concentration of ATF.

Identification of oil

The partition-gravimetric method does not distinguish different oil types. Therefore, this method will not indicate if there is a mixture of oils in the extracts from the soil samples. Because several oils and fluids are used at the Hydra-matic plant, and because of the potential for soil and groundwater contamination by these fluids, there was a need to identify the soil extracts to ascertain that ATF was the contaminating fluid. Chemical and physical methods of characterization were used to identify the oil extracted from the soil and the oil collected from the monitoring wells. Chemical characterization of the oil was based on infrared analyses, while physical characterization included measurements of viscosity and specific gravity. The results of these measurements will be discussed in a following section.

Geology and Grain-Size Distribution

Soil samples in the split spoon were qualitatively described to indicate macroscopic layering or stratification of the soil and aquifer material. This information was used to construct a geologic map of the soil and aquifer system. To further describe the geology, the mass fraction of the extracted soil samples in seven U.S standard sieve size ranges of greater than 500, 500-355, 355-250, 250-125, 125-75, 75-53, and less than 53 μm were determined by sieving the samples through a nest of six sieves for about 30 minutes with a standard mechanical shaker.

Hydraulic Conductivity

The hydraulic conductivity of water through the extracted soil samples from the first 20 coring locations (Figure 3), was measured in the laboratory by the falling head method (Freeze and Cherry, 1979). In these measurements,

about 50 g of soil was added to water in a glass column that was fitted at the base with a fritted-glass plate and at the top with an upright burette. The saturated hydraulic conductivity was calculated by using Equation (1) (Freeze and Cherry, 1979):

$$k_s = (aL/A\Delta t) \ln(h_i/h_t) \quad (1)$$

where, L is the thickness of the soil column, Δt is the time interval, h_i is initial head of fluid in the burette, h_t is the head of fluid in the burette after time Δt , and a and A are the cross-sectional areas of the burette and the soil column, respectively. These tests were carried out during the investigation using the soil samples that were extracted with freon. The results were used to make real-time estimates of the rate of groundwater flow.

In addition, laboratory experiments were performed after the field investigation was completed to measure the hydraulic conductivity of soil samples from the aquifer region to ATF and to water. About 350 g of soil from an uncontaminated region of the aquifer was packed into a glass column and the hydraulic conductivities of the soil to water and of the water-wet soil to ATF were measured using the constant head method (Freeze and Cherry, 1979). In these measurements, the column was held horizontal, and as the fluid was pumped through the soil column, the fluid heads at the inlet and outlet of the column were measured using manometers. To calculate the saturated hydraulic conductivity, the following equation was used (Freeze and Cherry, 1979):

$$k_s = (QL)/\{A(H_i - H_o)\} \quad (2)$$

where, Q is the flow rate through the column, and H_i and H_o are fluid heads at the inlet and outlet of the column, respectively.

Depth to ATF and Water

The depth below the plant floor to ATF or water in the wells was measured with an interface probe (Soiltest Inc., IL). This probe is a 1 inch diameter cylinder and contains two different sensor units; one for detecting the air/oil interface and the other for locating the oil/water interface. The air/oil sensor is an optical prism located at the end of the probe. This sensor detects oil by reacting to the differences in the indices of refraction of air and oil. An infrared light source is internally reflected to an infrared detector by a prism on the face of the sensor. When the prism becomes immersed in oil, the light beam is refracted away from the detector. To sense the oil-water interface a small electrical current is passed between two electrodes on the sensor to detect water and the oil/water interface. The difference in the depths to water and to ATF in each well gave the thickness of ATF in the well. A surveyor's transit was used to measure the elevation of the top of each well relative to a fixed point in the plant. From these measurements, the relative elevations of ATF and water in the wells were determined.

RESULTS AND DISCUSSION

ATF Identification

Physical and chemical methods were used to identify the type of oils present in the soil extracts and in the wells. The physical and chemical properties of oil samples from several sampling locations are shown in Table 1. This table also shows the properties of samples of the factory-fill

ATF obtained from the plant at the time of the investigation. Typical infrared (IR) spectra for factory fill ATF and oil samples from the site are shown in Figure 4.

The constituents in ATF are approximately 90% mineral oil hydrocarbons (mainly paraffinic petroleum distillates) and 10% of an additive mixture containing a methacrylate polymer for improving viscosity and other organic and metallo-organic compounds including succinimides and zinc dialkyldithiophosphates (ZDP) as detergent, antiwear, or anticorrosion additives. The infrared spectra show four prominent peaks, which were used to identify ATF in the soil extracts and oil samples from the wells. The four peaks are for esters (at a wavenumber of 1735 cm^{-1}), succinimides (1705 cm^{-1}), aromatics (1605 cm^{-1}), and ZDP (970 cm^{-1}).

Infrared spectra of oil from all the wells at the site indicated that two types of oil are present in the soil and aquifer system; ATF and a so-called "subtest oil". The subtest oil is an oil used at Hydra-matic to test transmission subassemblies; at the same temperature, its viscosity is much lower than that of ATF (see Table 1). Typical IR spectra from oil samples are shown in Figure 4. A differential comparison of the infrared spectra of factory-fill ATF and ATF recovered from coring location 8 shows relatively little difference in the intensities of the absorbance peaks, while a comparison of the ATF with subtest oil shows a much greater difference (Figure 4). Differences between the factory-fill and recovered ATF samples can result from changes made in the ATF formulation since the leak occurred as well as from the presence of various levels of subtest oil. Identification of the two oils where they existed separately was not difficult since the IR spectrum for subtest oil did not have ester and succinimide peaks (Figure 4). To identify and quantify ATF in a mixture with subtest oil, the IR spectra of standard

Table 1. Comparison of Automatic Transmission Fluid and Other Oil Samples by Infrared Spectrometry, Viscosity and Density

Sample	Infrared Absorbance (AUx10 ²) *			Viscosity (cs; 100°C)	Specific Gravity (22°C)
	Ester (1735 cm ⁻¹)	Succinimide (1705 cm ⁻¹)	ZDP (970 cm ⁻¹)		
Factory-Fill ATF	29	19	3.2	7.3	0.875
Core 8	32	18	3.2	7.1	0.865
Core 24	32	17	3.5	6.9	0.864
1:1 ATF-Subtest Oil	15	9	6.0	3.1	
Core 35	12	6	6.6	1.9	0.833
Subtest Oil	0	0	8.2	1.7	0.824
Core 32	0	0	9.0	1.7	0.825

* AU = Absorbance Unit

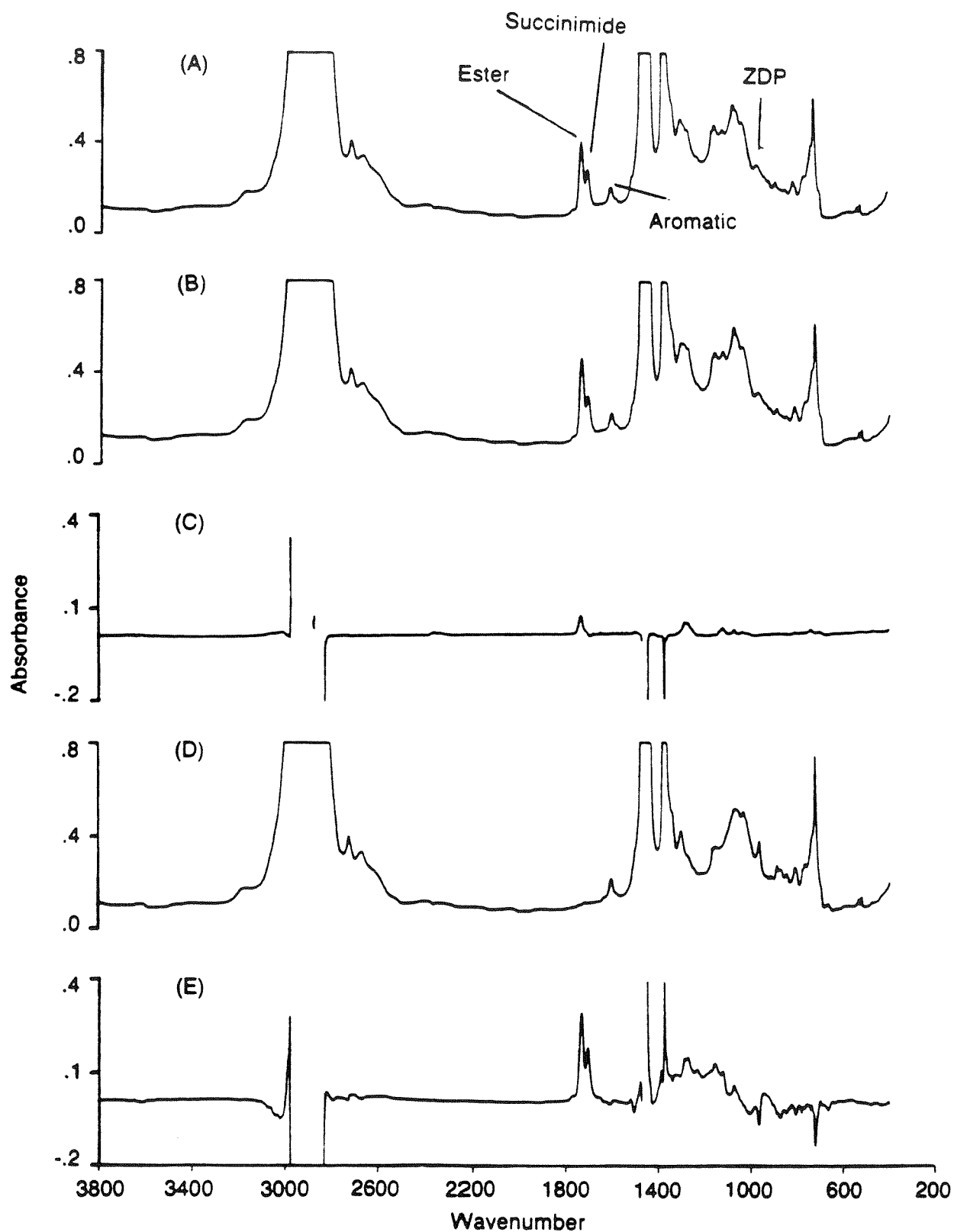


Figure 4. Infrared spectra of (A) factory fill ATF, (B) oil from core 8, (C) difference spectrum (B-A), (D) subtest oil, (E) difference spectrum (A-D). Fourier transform infrared, neat samples, 0.1 mm pathlength.

mixtures of known ratios of ATF and subtest oil were measured and the results are summarized in Figure 5. This figure shows a linear increase in IR absorbance at a wavelength of 1735 cm^{-1} (ester peak) with increasing percent of ATF in the mixture.

Typically, the viscosity at 100°C of ATF and subtest oil taken from the wells ranged from 6.51 to 7.86 and from 1.65 to 1.89 centistokes, respectively. In addition, the specific gravity (25°C) ranged from 0.864 to 0.869 for ATF and from 0.825 to 0.837 g/cm^3 for subtest oil. The differences in the values of these two physical properties of the two oils confirmed the identification of the oils when they existed separately. To help identify ATF in a mixture with subtest oil by the viscosity of the mixture, the values of viscosity of known mixtures of the two oils were measured and the results are shown in Figure 6. Identification of the oils by these physical measurements was consistent with the results already described, based on the spectroscopic measurements. However, the viscosity of the oil mixture changes nonlinearly as the composition of the mixture changes (Bondi, 1972). Although the viscosity changes of the mixtures can be described mathematically, the infrared absorbance results in Figure 5 were more easily used to estimate the amount of ATF in a mixture with subtest oil than the viscosity results in Figure 6. This is due to the lower sensitivity of viscosity at low fractions of ATF in the mixture.

Based on the infrared, viscosity and density measurements, two main zones of oil contamination were identified at the site: a zone of ATF and a zone of subtest-oil contamination. The results indicated that 22 of the wells located within the plant contained predominantly ATF, and another 17 wells contained predominantly subtest oil. A few of these wells near the boundary zone between the ATF and subtest plumes contained levels of 20 to 30% ATF mixed

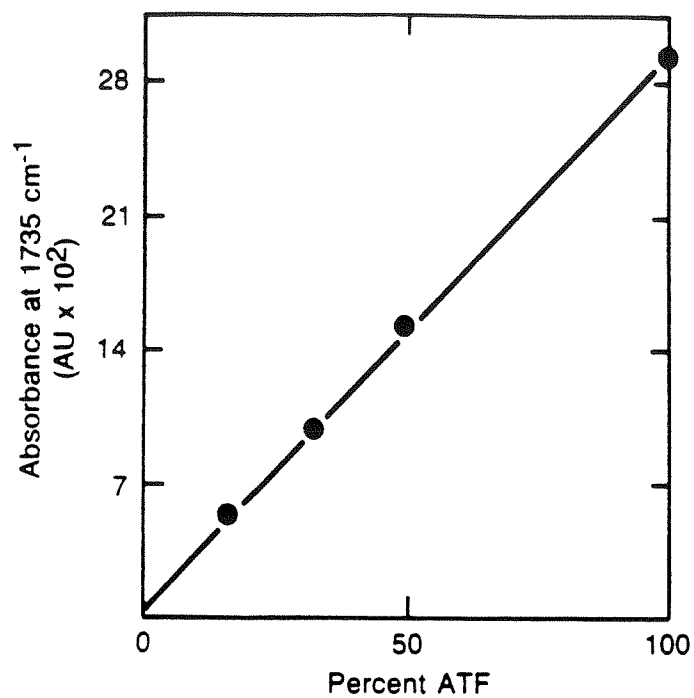


Figure 5. IR calibration curve for ATF-Subtest oil mixtures.

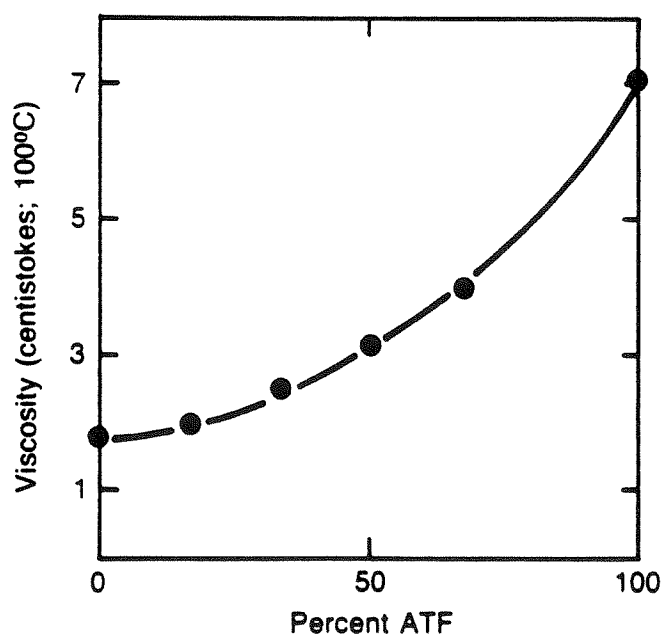


Figure 6. Calibration curve for kinematic viscosity for ATF-Subtest oil mixtures at 100°C.

with the subtest oil. The subtest oil contamination is part of a different problem arising from sources other than the ATF source and lies outside the scope of this report.

Site Geology

The soil samples were inspected during coring to describe visual changes in color and in particle size with depth. Typically, the material in the unsaturated zone, where the oxidizing potential is high, had a brownish color. In contrast, below the water table, in a chemically reducing environment, the aquifer material was typically gray. To describe the average particle size or grain size of the soil and aquifer material, the classification scheme that clay/till particles are smaller than 2 μm , silt smaller than 20 μm , medium/fine sand smaller than 200 μm , and fine gravel/coarse sand smaller than 2000 μm , was used. Following this scheme, all the material from each coring location was described and logged during coring. Some of these results are summarized in Figure 7 for an east/west cross-section including locations 47, 39, 30, 24, 23, 19, and 20 (see Figure 3) and in Figure 8 for a north/south cross-section including locations 9, 1, 4, 5, 21, 24, 26, and 42 (see Figure 3) through the contaminated site.

The results shown in Figures 7 and 8 indicate that the system is heterogeneous having several distinct layers of soil and aquifer materials. Below the concrete floor, which is about one foot thick, is a 1 to 2 foot layer of fill material consisting of a mixture of gravel, sand, and clay. Below this layer and above the water table (about 6.5 feet below the plant floor) are three layers; a fine compact black sand, a medium to fine brown sand with some gravel, and a medium to fine brown sand. Below the water table are three layers of sandy material and an underlying layer of stiff gray clay

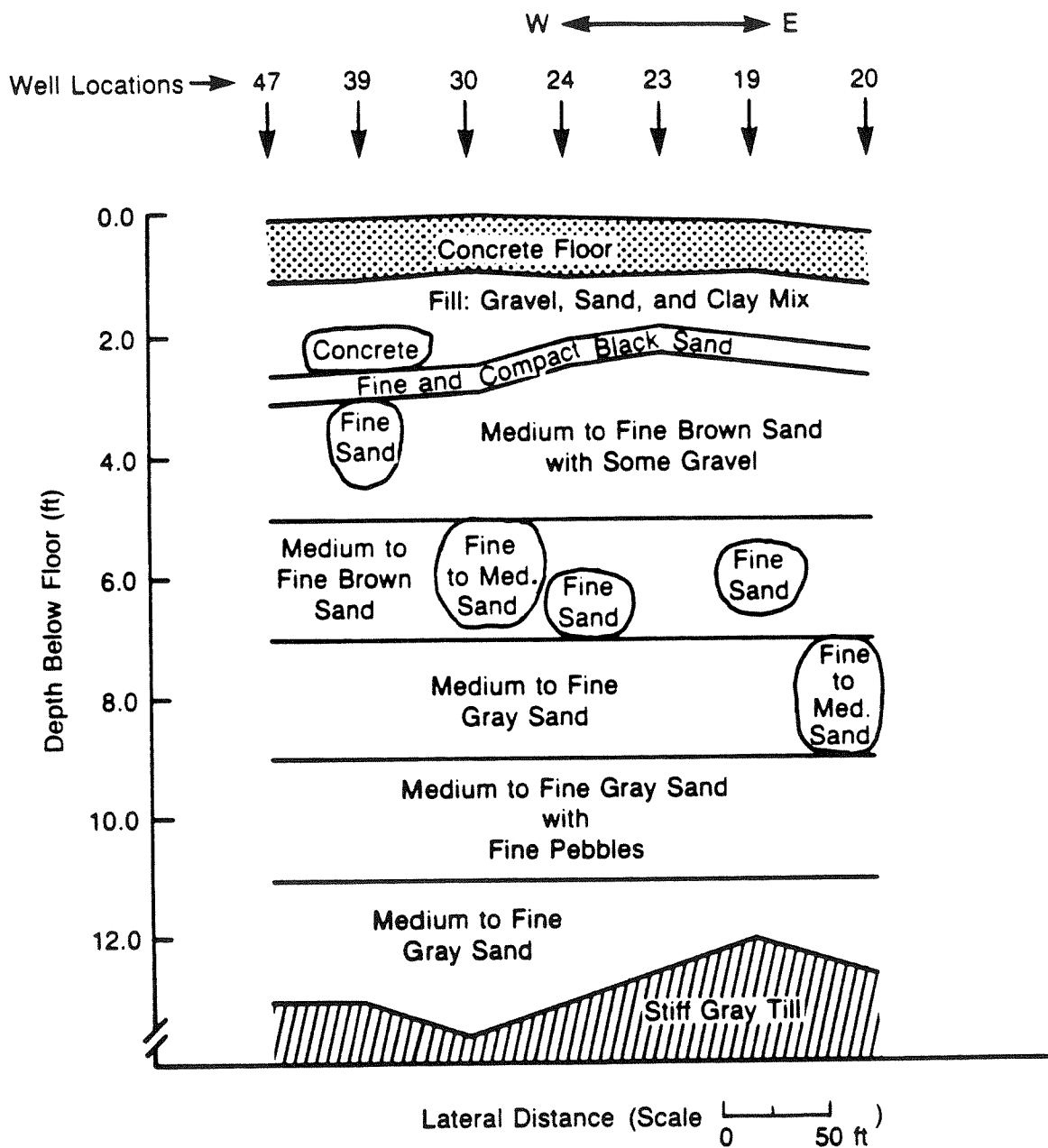


Figure 7. Geology of an east/west vertical section.

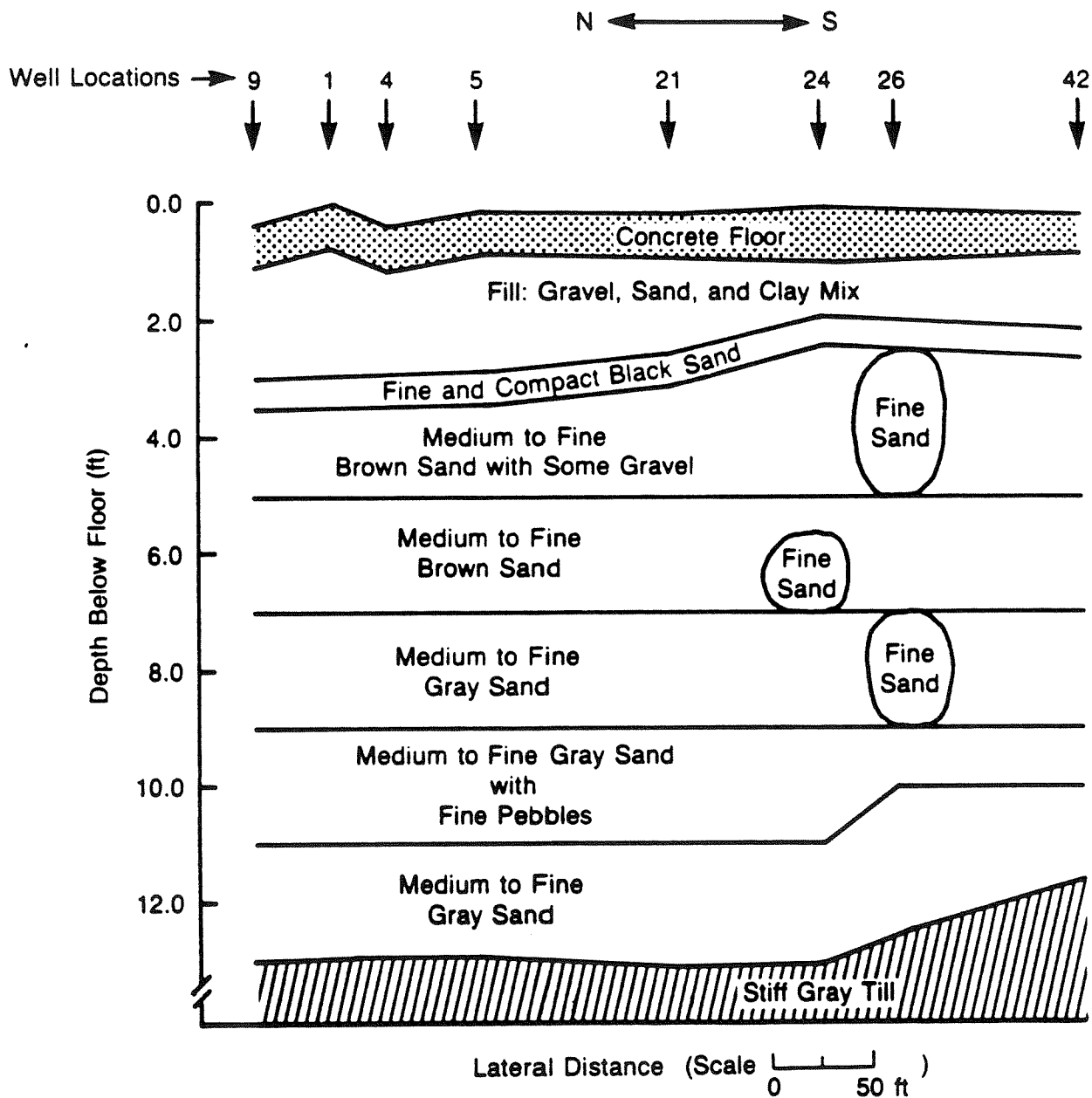


Figure 8. Geology of a north/south vertical section.

(till) that starts from 12 to 13 feet below the plant floor. The layers just below the water table and just above the clay are each about two feet thick and comprised of medium to fine gray sand. Between these layers and in the middle of the aquifer is a two-foot thick layer, from a depth of 9 ft to 11 ft, of medium to fine gray sand and fine pebbles. In addition, there are some "lenses" of fines within the medium/fine sand layers. The three sandy layers below the water table make up the unconfined aquifer (perched aquifer). The hydraulic properties of the aquifer and its flow conditions will be described in the next section.

In addition to describing the site geology during coring (Figures 7 and 8), the geology was defined by measuring the grain-size distribution of some core samples. Several core samples from each of the first 20 coring locations were sorted into seven ranges of particle size and the results for an east/west cross-section including coring locations 6, 5, 8, 10, 11, and 14 are shown in Figure 9. The solid circles in the figure indicate the depth of sampling at each coring location, while values for the average particle size are shown to the right of each circle. The average particle size is taken to be the size greater than that of 50% by weight of particles. The results shown in Figure 9 are consistent with the real-time observations made in the field during coring (Figures 7-8) that the aquifer is made up mainly of medium/fine sandy materials. It is also observed from Figure 9 that the samples from locations east (14) and west (6 and 5) in the cross-section are for the most part finer than those from the inner locations.

Flow of GroundWater

The patterns and rates of ground water flow were developed during the field investigation. This information was used with the other data to

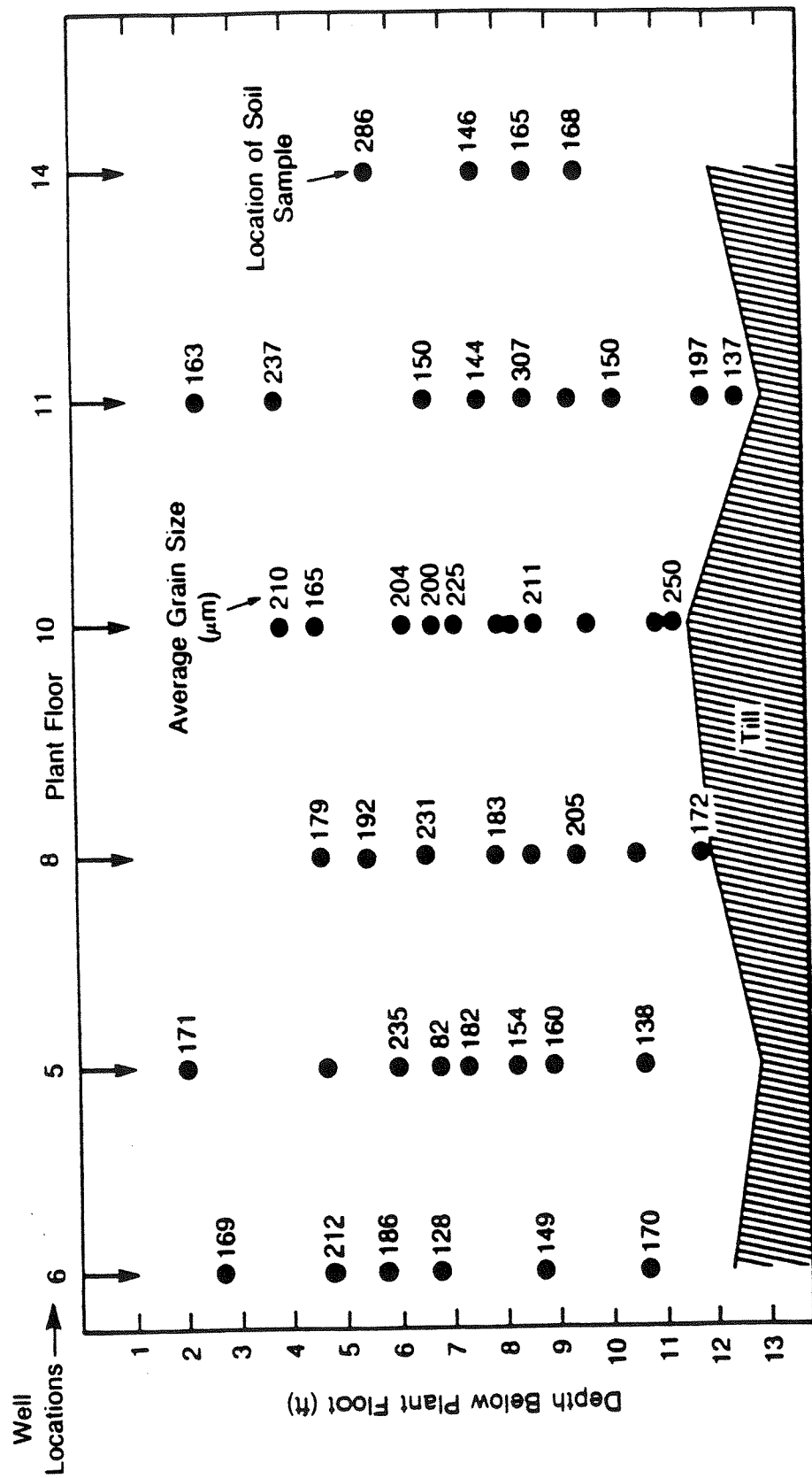


Figure 9. Average grain size for an east/west vertical section.

determine the coring locations, and particularly to determine the distance between the coring locations. To determine the direction of groundwater flow, equipotential lines or lines of equal hydraulic heads were constructed, and then flow lines were drawn perpendicular to the equipotential lines.

The hydraulic head (H) at each well location is the product of the specific gravity (ρ_i) and the thickness (h_i) of each fluid in the well above a fixed datum in the aquifer (10 ft below the ground at well location 1; $H = \sum \rho_i h_i$).

The values of hydraulic heads were plotted in plan view and linear interpolation was used to draw lines of equal potential. The equipotential lines and flow lines constructed perpendicular to them are shown in Figure 10. In the vicinity of the underground storage tanks, the flow is predominantly to the south, but it swings towards the southwest as the underground steam tunnel is approached from the north. These flow lines indicate, and field observations corroborate, that water is seeping into the steam tunnel just south of the contaminated zone.

The average linear pore water velocity (v) or average rate of groundwater flow was calculated using the following equation (Freeze and Cherry, 1979):

$$v = (k_s / \epsilon) (\Delta h / \Delta l) \quad (3)$$

where, Δh is the average change in head along the flow path, Δl is the average length of the flow path, and $\Delta h / \Delta l$ is the hydraulic gradient. For a porosity of $\epsilon = 0.40$, a measured average value of saturated hydraulic conductivity of water of 2.6×10^{-3} cm/sec (from column tests), and a hydraulic gradient of 0.0025 from Figure 10, the rate of groundwater flow is about 17 ft/yr.

The water table in the uncontaminated zone and the effective water-table position in the contaminated zone (plane of zero gauge pressure), which is the

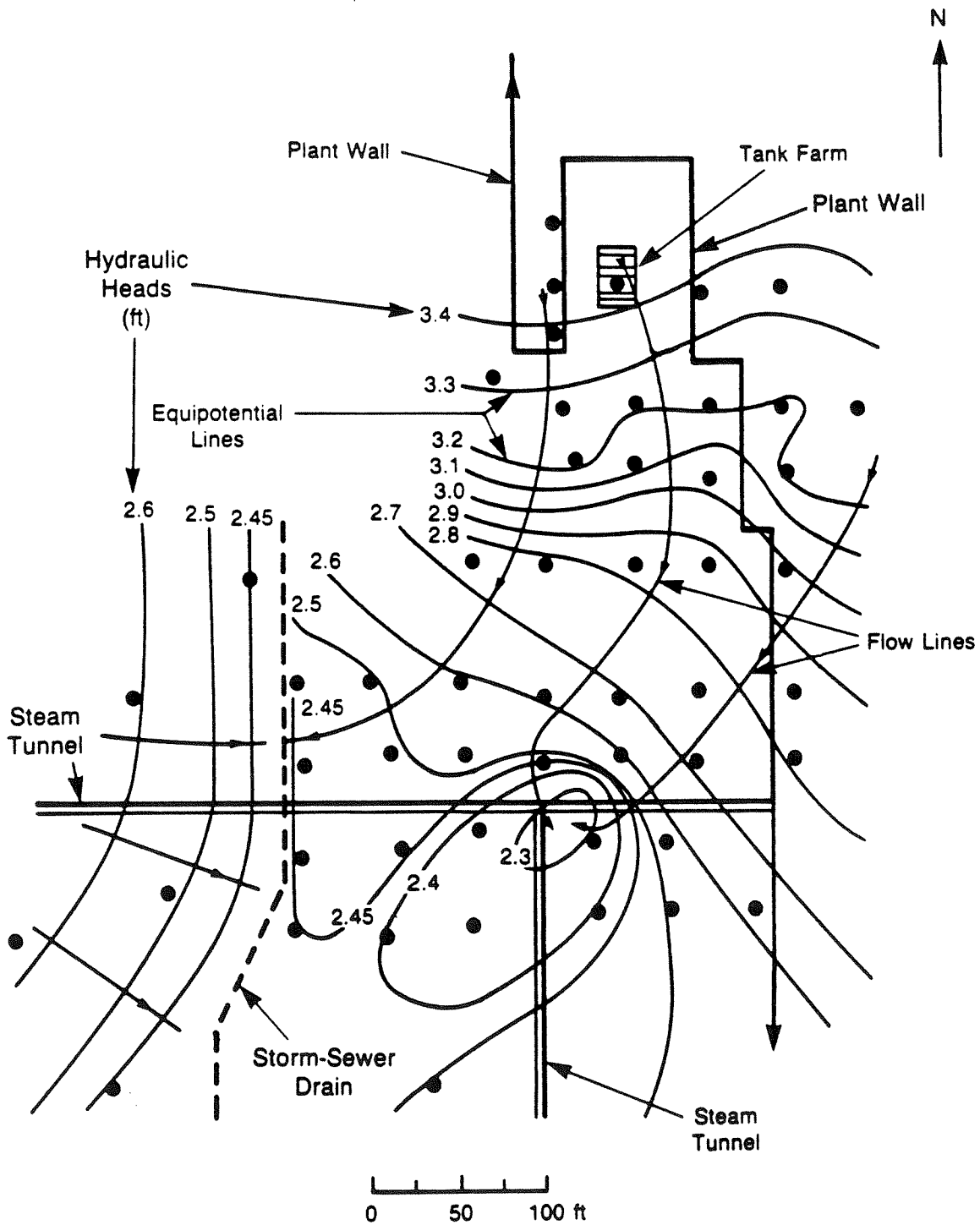


Figure 10. Flow pattern of groundwater.

level of water in the inner well of the combination well when no ATF is present in this well, was about 6.5 ft below the plant floor and slopes in the direction of groundwater flow. Several data sets collected during the summer of 1987 indicated that neither the water-table position nor the direction and rate of flow changed significantly with time. In addition, the values of the hydraulic head at several depths in the same location, as measured by the multi-bundle piezometers, indicated that there was no significant vertical gradient within the aquifer; therefore, flow is primarily horizontal. However, there could be vertical components of flow in the neighborhood of the man-made structures, such as the steam-tunnel.

Vertical and Lateral Distribution of ATF.

The ATF in samples of soil and aquifer material was extracted with Freon and quantified gravimetrically as milligrams of ATF per gram of dry material. Some of these results are shown in Figure 11 for core samples from an east/west cross-section that includes coring locations 6, 5, 8, 10, 11, and 14. The solid circles in the figure indicate the depth of sampling at each coring location, while the concentration of ATF (mg/g) is shown immediately to the right of each circle. These results indicate that there is a central region of high concentrations of ATF, which range from about 60 to 113 mg/g. Lower ATF concentrations exist above and below this central zone. Extractable ATF was not found at the extreme east and west coring locations (14 and 6, respectively); also, only low levels of ATF were found in the shallower regions of location 5, which is the next coring location west of the central zone.

While the data presented in Figure 11 can be used to define the vertical spread of ATF contamination at the site, they do not represent the entire

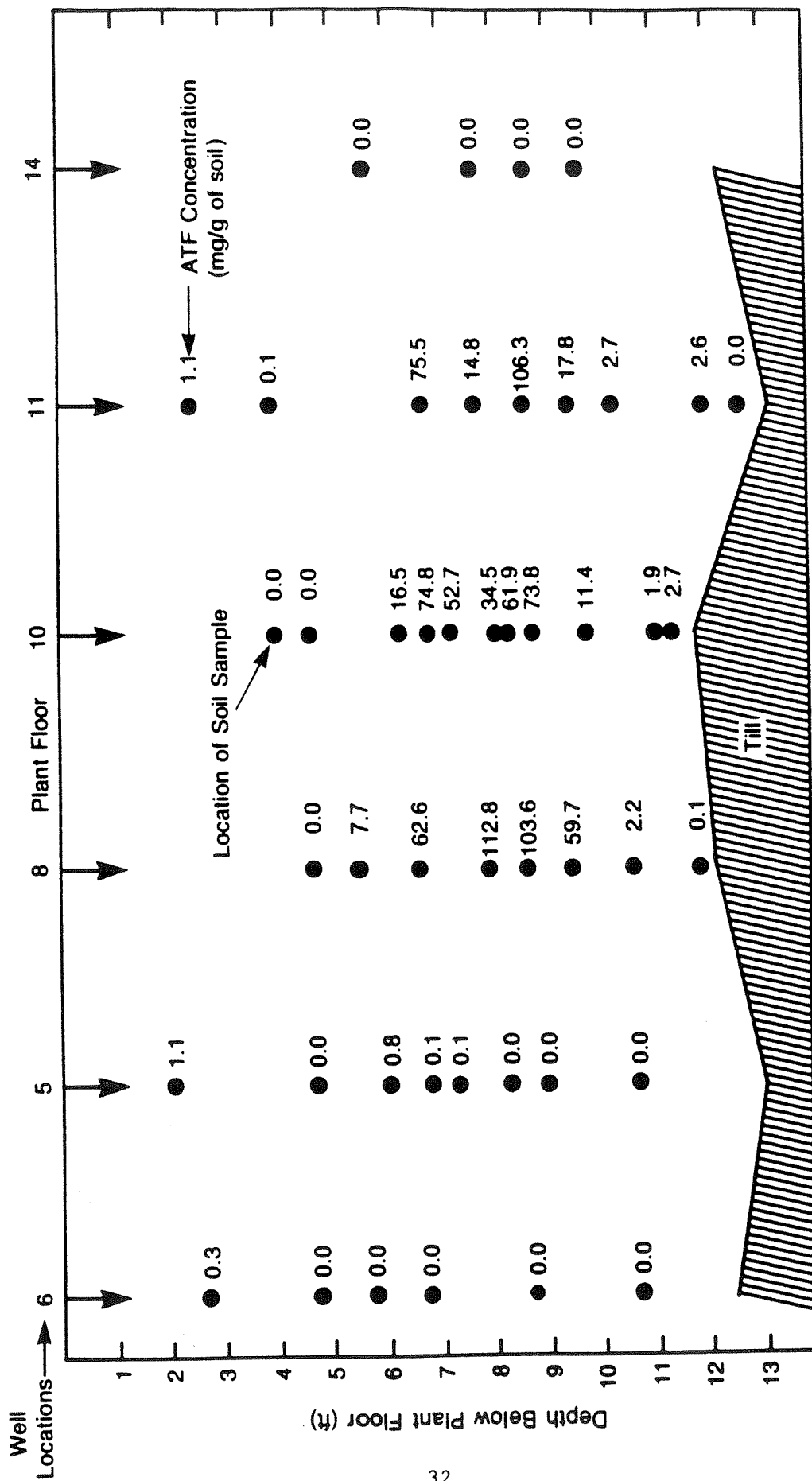


Figure 11. Distribution of ATF through an east/west vertical section.

amount of ATF in the ground. This is because some ATF (and water) drained from the cores as they were taken out of the ground in the split-spoon sampler. Therefore, the soil samples may contain more ATF (or water) than the measured values indicate. This is especially expected to occur in regions where the soil was fully saturated with ATF.

The distribution of ATF, like other petroleum products, in porous hydrogeologic systems is governed by capillary and gravitational forces. The water-table position for the cross-section in Figure 11 was about 6.5 ft below the plant floor. The ATF concentrations above the water table (see Figure 11) cannot be explained by ATF drainage from above. The cross-section shown in Figure 11, like most of the contaminated zone, is sufficiently removed from the suspected source of the leak (UST area); therefore, contamination of these regions by ATF is likely caused by the lateral spread of the ATF plume. Contamination of the area above the water table in regions removed from the leak was likely caused by the upward migration of ATF from the central zone of contamination under the influence of capillary forces. The influence of capillary forces on the distribution of ATF can be deduced from Figure 12, which shows the pressure-saturation relationship for ATF and soil samples taken from location 13. These results were obtained from laboratory experiments using a previously described experimental set-up and following a standard pressure-membrane method (Kia and Abdul, 1988). As was expected, these results indicate that capillary pressure or suction within the pores increases as saturation of the pore space decreases. Capillary pressure is zero at the ATF table, where the fluid pressure is equal to atmospheric pressure. The wetting curve in Figure 12 indicates a contamination of about one foot above the ATF table. This capillary rise together with the fluctuations in the ATF table (result of fluctuations in the water table and

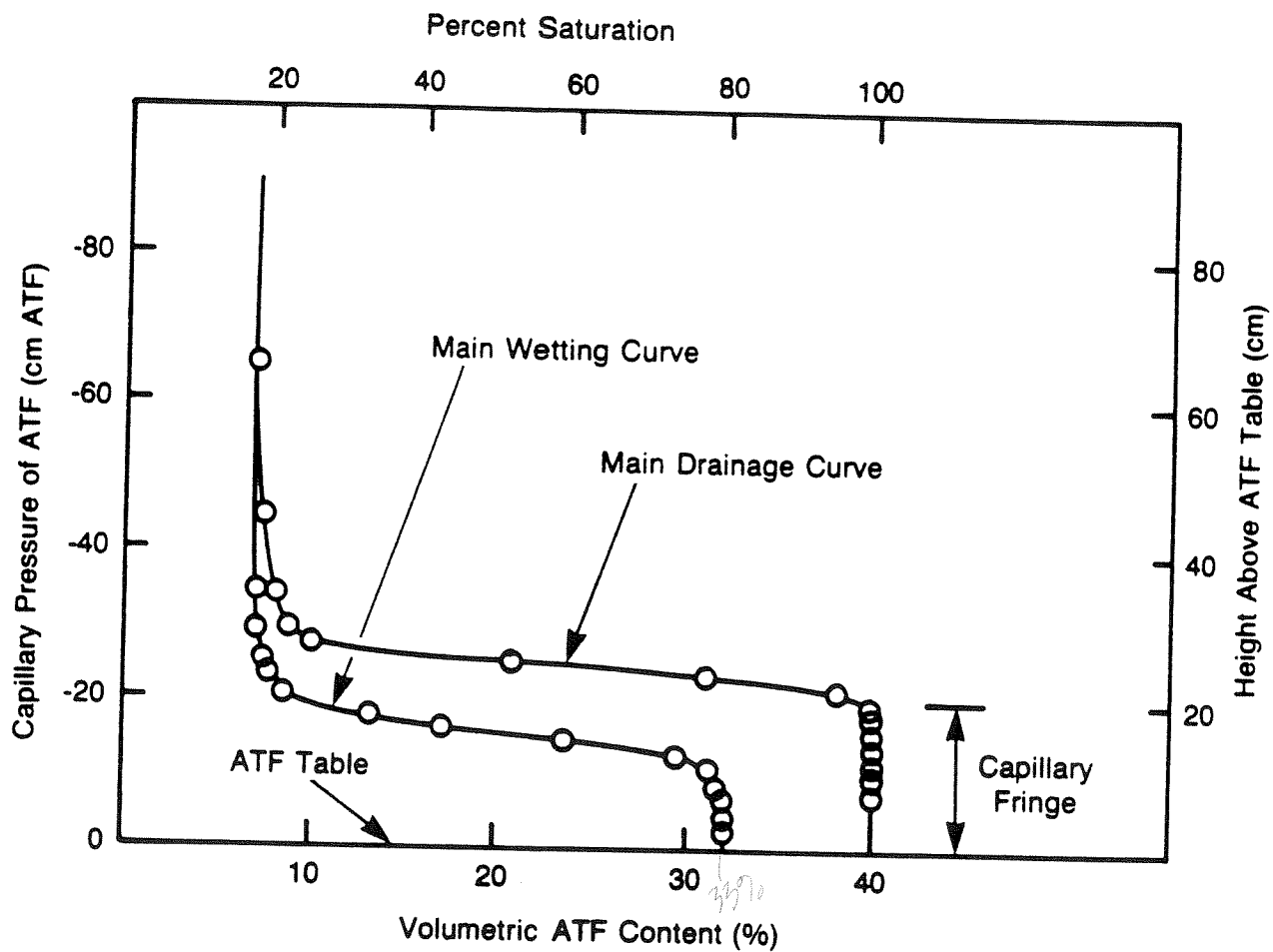


Figure 12. Saturation-pressure head curves for a system of ATF and air.

the ATF flow) could explain the contamination observed at the site in regions above the water table (above about 6.5 ft) in Figure 11. Meanwhile, the contamination at very shallow depths of 2-4 ft was likely caused by small local surface spills and not by the ATF plume underneath.

The contamination existing in the region below the central zone of contamination (9-12 ft in Figure 11) was likely caused by the greater oil thickness during the active leak of the storage system and by the seasonal fluctuation of the water table. Because of reduced recharge to the aquifer during the summer months, the water table and the central zone of ATF would fall to deeper levels. As the water table and central zone of ATF rise during the wet spring months, residual and dispersed ATF could remain in the deeper zone. Also, during the initial leak of the storage system, the large volume of the leaked oil could depress the water table and migrate deeper into the aquifer. With time, and after the leak stopped, the lateral spread of the ATF would cause reduction in the amount of free ATF floating over the water table and a corresponding rise of the water table.

Lateral east/west spread of ATF beyond the central region of ATF was not observed, perhaps because the next coring locations were more than 30 ft beyond the central zone. However, lateral spread through the water saturated zones is not expected to be significant, since such spreading would require the head in the ATF to exceed that in the surrounding water. The capillary pressure (p_c) that exists at the interface between ATF and water in the pore space is the difference between ATF pressure (p_{nw}) and water pressure (p_w) as given by the following equation (Corey, 1977; Abdul et al., 1988):

$$p_c = p_{nw} - p_w \quad (4)$$

For ATF to displace water and migrate laterally or downwards, its pressure must exceed that of water by p_c . The readiness with which ATF can displace water from the pores decreases directly as the pressure of the water increases. The fact that the water pressure is negative (below atmospheric pressure) above the water table and positive below the water table may explain why only the upper region of coring location 5 (above about 6.5 ft) is contaminated with ATF. These observations are consistent with the results of laboratory studies (Abdul, 1987)

Thickness of ATF in the Soil and Aquifer System

The thickness of the vertical column of ATF in each monitoring well was used to calculate the corresponding thickness of ATF in the contiguous porous medium. The relationship between the actual ATF thickness in the medium (h_m) and the ATF thickness in a well (h_w) is given by (Abdul et al., 1988):

$$h_m = h_w - h_e \quad (5)$$

where:

$$h_e = p_{ow} / \{(\rho_w - \rho_o)g\} \quad (6)$$

In Equation (6), h_e is the thickness of ATF in the well below the base of the ATF-saturated zone, p_{ow} is the capillary pressure between water and ATF, and ρ_o and ρ_w are the specific gravities of oil and water, respectively.

The ATF thickness in the porous medium at each well location was calculated by using Equations (5) and (6). For these calculations, a value of 6.43 cm of ATF was used for the mean capillary pressure across the ATF/water

interface. The oil-water capillary pressure was measured from laboratory experiments similar to that represented in Figure 12 using ATF and soil samples taken from location 13. The measured value of 0.869 g/cm^3 was used for the specific gravity of ATF.

The results for the ATF thickness in the medium at different well locations are presented in Figure 13. Linear interpolation was used to construct the contours of ATF thicknesses shown in Figure 13. The results show a central zone saturated with ATF (dotted area in Figure 13) extending from the region of the underground storage tanks (UST). First the ATF plume spreads for about 300 ft south of the UST and then to the west for another 200 to 300 ft. Further spread of ATF to the south was likely impeded by an underground steam tunnel that extends to about 2 ft below the water table. There is evidence of small quantities of ATF seeping into the steam tunnel through a crack in its wall.

At its centroid, which is about 300 ft south of the leak, the ATF-saturated zone is about 2.6 ft thick. This small core region is surrounded by a 1.6 ft thick ATF-saturated zone that stretches across the north to south length of the plume. Surrounding the ATF-saturated zone is a zone that is only partially saturated with ATF (undotted area in Figure 13).

To better illustrate the vertical distribution of the ATF plume, the data in Figure 13 for two vertical sections, an east/west (locations 19, 23, 24, 30, 39, and 47) and a north/south (locations 26, 24, and 21) through the ATF plume are replotted in Figure 14. These results show that the ATF plume has displaced the water table downwards from its original position or with respect to its position immediately adjacent to the zone of ATF contamination. The displacement of the water table was possible because, by Equation (4), the fluid head in the ATF was greater than that in the surrounding water. The

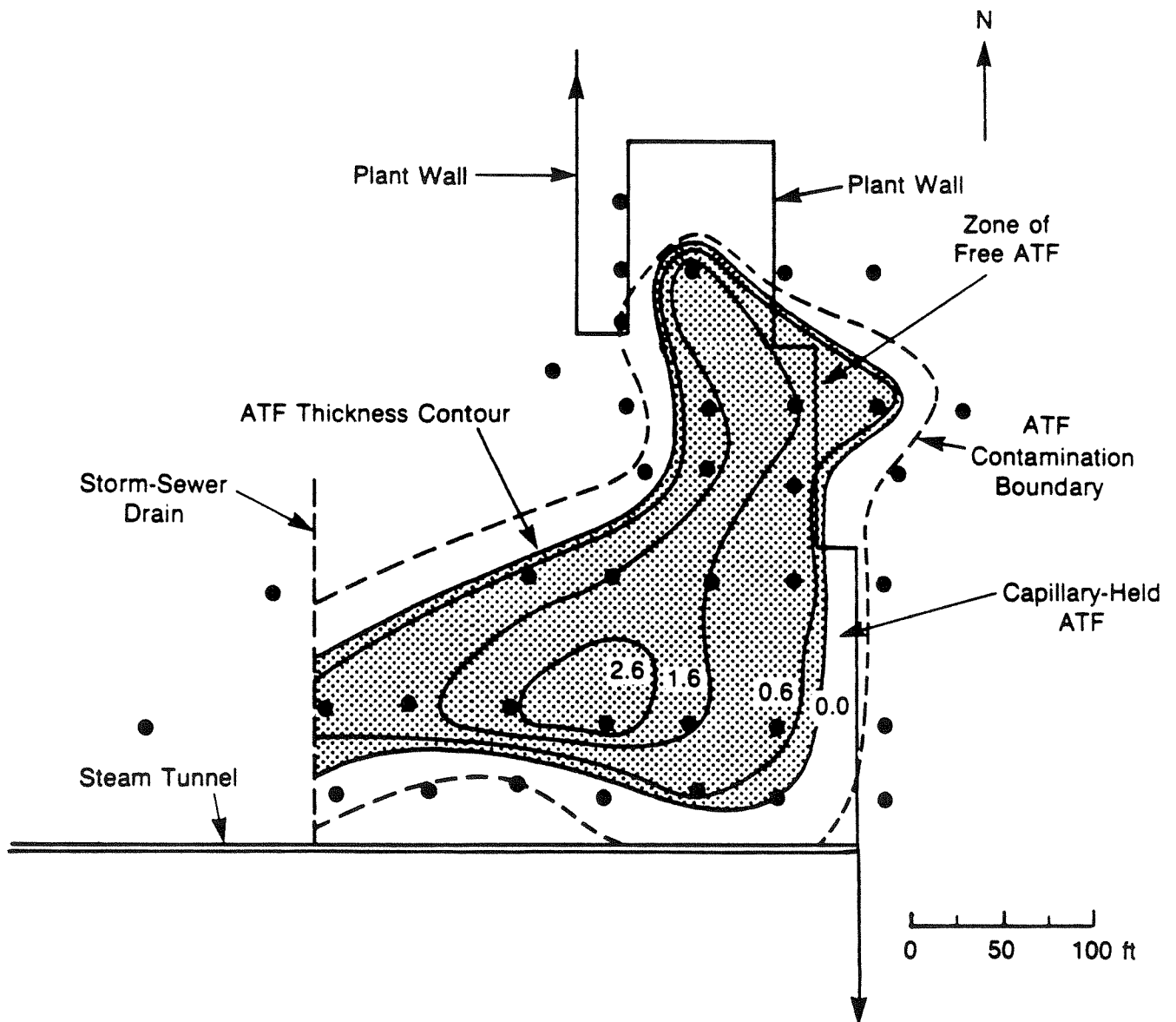


Figure 13. Lateral spread of ATF and contours of ATF thickness in feet (2.6, 1.6, 0.6, and 0.0 ft).

shape of the ATF plume is also influenced by the geology of the system. As was discussed previously, the geology at locations east (14) and west (6 and 5) of the ATF plume is for the most part finer than that at the inner locations. This may explain why the plume of ATF (Figure 13) is being channeled through locations 8, 10, and 11 and no free ATF is present in the porous medium at locations 5, 6, and 14.

The formation of an ATF-saturated zone that displaces the water table and the observed spread of ATF above and below the water table are consistent with previously published concepts and results about the spread of petroleum products in soil and aquifer systems (Abdul, 1987; Schwille, 1984; van Dam, 1967).

Quantification of ATF in the Soil/Aquifer System

As Figure 14 illustrates, there are three main zones of ATF contamination in the soil and aquifer system below the Hydra-matic plant: (1) the zone of free ATF, (2) the capillary held-ATF zone that lies above the free-ATF zone, and (3) a zone of residual levels of ATF below the zone of free ATF and within the aquifer. The amount of ATF in the soil and aquifer system is, therefore, the sum of ATF in these three zones as described below.

1. Free-ATF Zone

In the zone of free ATF, the voids of the porous medium are almost saturated with ATF, and the pressure of the ATF is greater than atmospheric. At any coring location, the thickness of the free-ATF layer in the porous medium was calculated from the ATF thickness in the well, the capillary pressure across the oil/water interface, and the specific gravity of ATF (Equations 5 and 6). The ATF thicknesses in the porous medium were mapped out

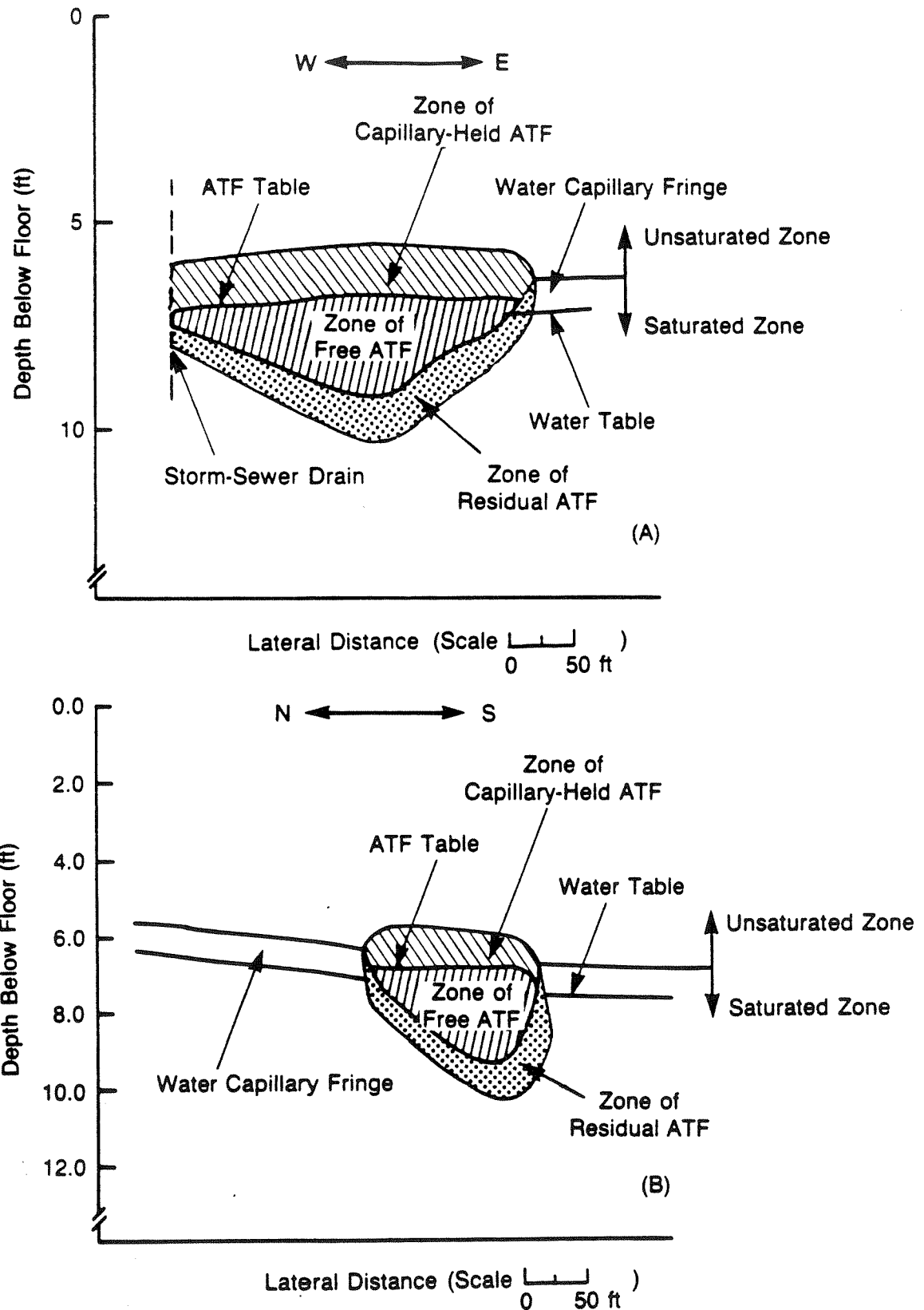


Figure 14. Two vertical sections through the ATF plume.
 A) East-west section through locations 19 to 47.
 B) North-south section through locations 21 to 26.

and, using linear interpolation, contours of equal thicknesses were drawn (Figure 13). The volume of ATF in the layer of free ATF is the sum of ATF between all the contours. The volume of ATF between two contours is "simply" the area between the contours times the average thickness of the ATF layer within the two contours times the fraction of the pore volume occupied by ATF. The fraction of the pore volume occupied by ATF is the porosity (ϵ) minus the fraction of the total volume occupied by residual levels of water (θ_{rw}). This calculation for the total volume of ATF in the zone of free ATF is described by the following relationship:

$$V_1 = (\epsilon - \theta_{rw}) \sum_{i=1}^n (A_i \cdot \bar{h}_{mi}) \quad (7)$$

where, A_i is the area between two adjacent contour lines (Figure 13) and $\bar{h}_{mi}$ is the average ATF thickness for the two contour lines. For measured values of $\epsilon = 0.4$ and $\theta_{rw} = 0.07$, the volume of free ATF is 133000 gallons.

Uncertainties in this value exist mainly from the uncertainty in the value of p_{ow} used in estimating the thickness of the ATF layer. Laboratory measured values of p_{ow} range from 5.43 to 7.43 cm ATF. This corresponds to a ± 0.21 ft uncertainty in the thicknesses of the free ATF layer and to ± 21000 gallons uncertainty in the volume of ATF.

2. Capillary ATF Above Free-ATF Zone

To estimate the amount of capillary ATF above the free-ATF zone, the saturation-pressure relationship for soil and ATF from well location 13 was measured in a laboratory experiment and is shown in Figure 12. The wetting curve in Figure 12 was taken to represent the capillary distribution of ATF above the zone of free ATF. By this data, and under static water-table conditions, ATF can rise to a height of about 35 cm above the zone of free ATF

(i.e., above the oil table). The amount of capillary ATF was calculated by multiplying the amount of ATF within a vertical column of unit cross-sectional area above the zone of free ATF (Figure 12) by the planar area of the zone of free ATF that is occupied by ATF. This calculation is described by equation (8):

$$V_2 = (\epsilon - \theta_{rw}) A \int_{h=0}^{h=h_t} S \cdot dh \quad (8)$$

where, V_2 is the volume of ATF, h_t is the maximum wetting height, S is ATF saturation at any height above the ATF table, and A is the cross-sectional area of the contaminated porous medium within the zero contour in Figure 13. Using $A = 38982 \text{ ft}^2$, $\epsilon = 0.4$, and $\theta_{rw} = 0.07$, the volume of ATF in this zone is 50640 gallons. This volume is conservative since it does not include the ATF within the zero contour and the ATF contaminated boundary in Figure 13. Further, residual levels of ATF could exist above the zone of capillary-held ATF as a result of expected fluctuations in the water table and the associated rise and fall of the zone of free ATF. Because the coring locations were typically more than 30 ft apart, the lateral boundary of the contaminated zone could not be accurately defined to adequately estimate the volume of ATF between the zero contour and the boundary of contamination. In addition, because of poor soil recovery through the unsaturated zone by the split-spoon sampler, a better delineation of the zone of residual ATF above the capillary-held-ATF zone is not possible.

3. Residual ATF Below the Free-ATF Zone

Because of seasonal fluctuations in the water table and the associated

rise and fall of the zone of free ATF, residual ATF was distributed in the aquifer below the zone of free ATF. This spread of ATF may have also resulted from a greater thickness in the free-ATF layer during the leak, which would cause the ATF to migrate deeper into the aquifer. The amount of residual ATF below the free-ATF zone was estimated by multiplying the area (38982 sq ft) under the zone of free ATF by the fraction of the porous medium occupied by the residual ATF ($\theta_{ro} = 0.084$) and the average thickness of this zone. The thickness (1.0 ± 0.5 ft) of the residual-ATF zone was based on data from soil extracts. The calculation for the volume of ATF is described by equation (9), which gives 24500 gallons ATF.

$$V_3 = \theta_{ro} A \cdot h \quad (9)$$

The main uncertainty in this calculation is that incurred in estimating an average value for the thickness of the zone of residual contamination ($h = 1.0 \pm 0.5$ ft). This variation in thickness gives an uncertainty of ± 12250 gallons ATF.

The total volume ($V_1 + V_2 + V_3$) of ATF in the soil and aquifer system at the site is about 208000 ± 33000 gallons.

Flow of ATF

Figure 15 shows the equipotential and flow lines for the free ATF. The procedure for constructing these lines is similar to that for constructing the water lines. In this case the reference datum for calculating the hydraulic heads was in the lower part of the free ATF zone. The ATF flow lines indicate a flow pattern that is consistent with that for water (Figure 10). In addition, the flow lines indicate that ATF is seeping into the steam tunnel,

as was the case for water. However, a closer inspection of Figures 10 and 15 indicates that just north of the underground steam tunnel, ATF has a stronger westerly component of flow than does water (Figure 10). This is because the flow of water towards the south is not completely impeded by the steam tunnel, since water can flow beneath the tunnel, while for the specific conditions at the site, ATF cannot. For a porosity of 0.33 (total void fraction minus fraction of voids occupied by residual levels of water) an average value of saturated hydraulic conductivity of ATF of 9.7×10^{-5} cm/sec from column tests, and an ATF hydraulic gradient of 0.0025 from Figure 15, the rate of flow of ATF calculated by using equation (3) is 0.7 ft/yr. This very slow rate of flow cannot explain the spread of ATF from the leak to the storm drain 418 ft away along the flow lines. At this rate, which is for the current hydraulic conditions at the site, it would take 597 years for the ATF to spread to its current boundaries. During the initial stage of the leak, the hydraulic gradient for ATF flow was likely higher than that currently existing at the site. This could have caused a higher rate of ATF-spread over the water table. With further spread of ATF, the hydraulic gradient decreases and the flow slows down. Also, it is suspected that layers or narrow channels of high hydraulic conductivity may be dominating the spreading process. The layer of medium/fine sand and pebbles in the middle of the aquifer (see Figures 7-9) is expected to be much more conductive to fluid flow than the other two sandy layers and may explain how the ATF has migrated more than 400 ft.

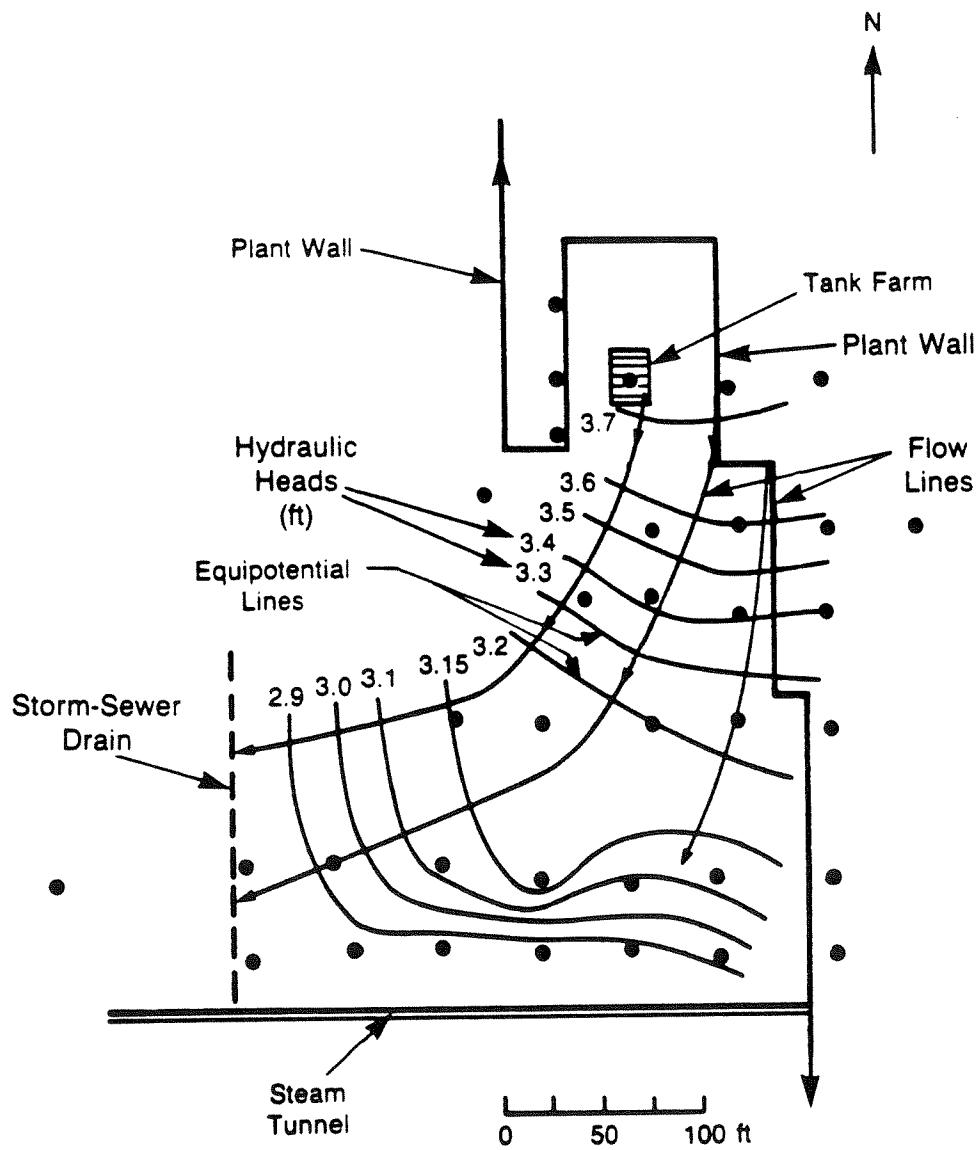


Figure 15. Flow pattern of ATF.

CONCLUDING REMARKS

With respect to this problem, the management at the General Motors Hydra-matic Assembly Plant at Ypsilanti, MI have replaced the old underground storage tank system with a new system in which the storage tanks are contained in a concrete vault. With the source of the problem removed, their main objective is to clean up the soil and the aquifer zones contaminated with ATF.

The results of this field investigation are being used in ongoing decontamination efforts involving the soil and aquifer system at the Hydra-matic plant.

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