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Interim Pump-and-Treat Remediation of a Hydrocarbon-Contaminated Aquifer

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The continuous and discontinuous release of petroleum hydrocarbons from an oil refinery in Alaska resulted in the contamination of an unconfined glacial outwash aquifer. Geologic conditions at the site allowed for the vertical migration of hydrocarbon product to the water table and subsequent formation of an areally extensive floating product layer. Since the petroleum hydrocarbon phase would provide a major source of BTX (benzene, toluene, xylene) contamination to the groundwater, interim product and groundwater recovery measures were initiated to limit aquifer degradation. Phase I remedial activities involved the operation of nine well pairs, with one well used for groundwater extraction and the other for product recovery. Phases II and III involved expansion of the recovery well network and use of a two-pump system. Petroleum product recovered was reprocessed at the refinery. Contaminated groundwater was initially treated using the refinery's wastewater treatment system, but treatment inefficiencies and continued system expansion necessitated use of a separate treatment unit. Performance evaluations indicate that the remedial phases have been successful in halting further contaminant migration and in recovering a significant volume of the released petroleum hydrocarbons.

Recently, the selection of pump-and-treat systems to restore contaminated aquifers has been questioned by environmental scientists. Travis and Doty (1990) offer several examples of sites where pumping has lowered contaminant levels, but has failed to attain the desired groundwater cleanup levels after significant periods of pumping. Even though groundwater extraction alone may not be an efficient technique for aquifer restoration, this commonly used alternative can achieve other remedial goals—such as limiting further off-site migration of contaminants, and recovering light nonaqueous phase liquids. These initial, or interim, remedial activities are typically the first in a series of measures aimed at restoring groundwater quality to acceptable health-based levels. After characterizing the contaminant distribution and transport processes, the interim pump-and-treat system can be combined with other techniques to remove and treat residual soil/groundwater contamination (Jackson and Patterson 1989).

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This article provides a case study of interim remedial measures for an unconfined glacial outwash aquifer that has been affected by the release of petroleum hydrocarbons. The purpose of this article is to describe the "phased" implementation of an interim recovery well system, and illustrate how the system was modified in light of ongoing investigations into the nature and extent of groundwater contamination.

AQUIFER CONTAMINATION BY PETROLEUM HYDROCARBONS

The uncontrolled release of hydrocarbons at or below the ground surface results in the downward migration of free-phase product through the unsaturated soil zone. The horizontal and vertical extent of the penetrating hydrocarbon body is dependent on various factors, including product viscosity, volume of product discharged, and subsurface geology (CONCAWE 1979). Vertical migration is greatest in homogeneous soils characterized by high permeabilities (sands and gravels). The downward movement of product may cease for one or more of the following reasons:

- The residual saturation of the soil is attained.
- The product encounters a relatively impermeable material (e.g., clay layer, unfractured bedrock).
- The product reaches the water table.

The soil residual saturation may be thought of as the threshold below which a nonaqueous phase liquid (NAPL) is no longer able to migrate.

The vertical migration of released hydrocarbons can be illustrated using the following formula for the maximum penetration depth resulting from a surface spill (CONCAWE 1974):

$$D = 1000V/AkR$$

where,

D = maximum penetration depth, in m
V = volume of product released, in m^3
A = spill area, in m^2
k = correction factor based on product viscosity
R = residual soil saturation, in l/m^3

Suppose 2 m^3 of no. 2 fuel oil and gasoline were spilled over 10 m^2 areas at two different locations at a large manufacturing facility. Available information indicates that the soil at the gasoline spill area is medium-grained sand, while the soil at the fuel oil spill is fine-grained sand. The depth to groundwater in the area is approximately 40 feet. Assuming typical residual saturation values of 25 l/m^3 for the medium-grained sand and 40 l/m^3 for the fine-grained sand, the estimated maximum depth of penetration would be 16 m (or 52.5 ft) in the medium-grained sand and 10 m (or 32.8 ft) in the fine-grained sand. Based on the available groundwater information, the spilled gasoline would reach the water table if no impermeable materials were present.

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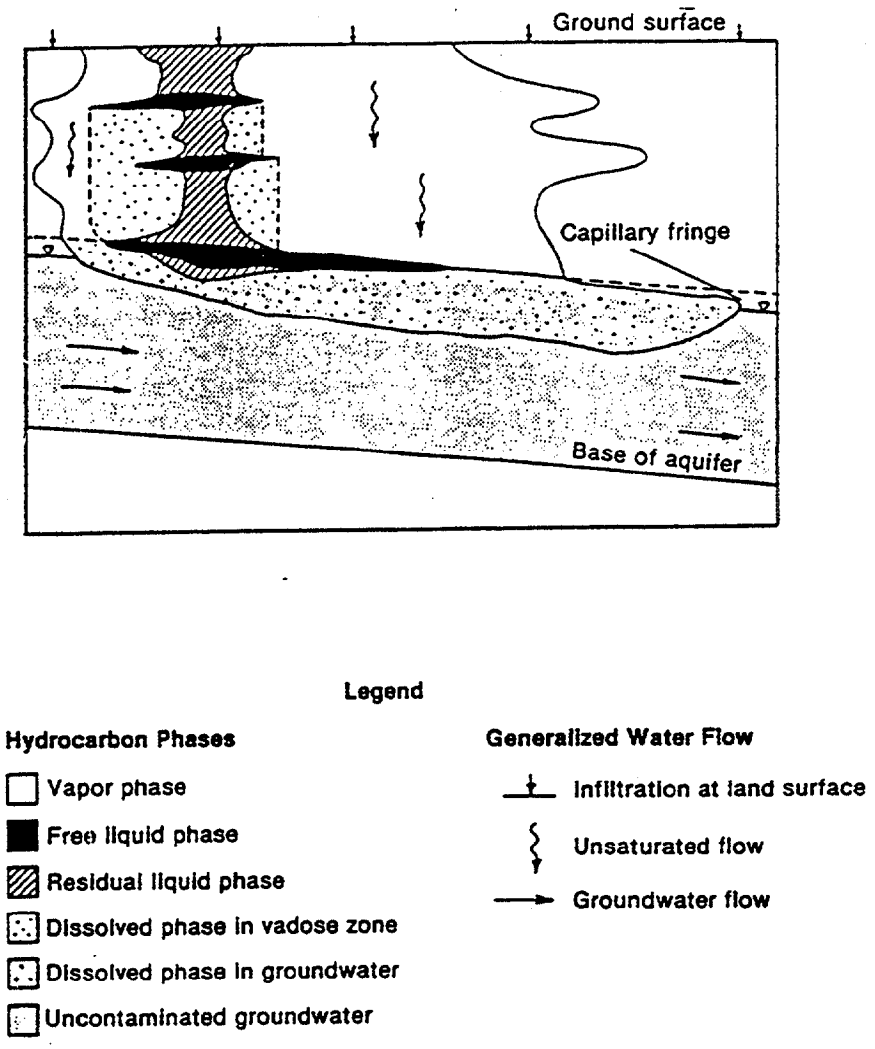
Figure 1. Distribution of Petroleum Hydrocarbon Contaminants



If a significant volume of free-phase product reaches the groundwater, it forms an immiscible layer on the water table that spreads laterally in the same direction as groundwater flow (**Figure 1**). As with migration in the unsaturated zone, the subsurface geology influences the spreading of the floating product layer. The hydrocarbon layer continues to spread across the water table until all the free-phase product is trapped by soil particles (CONCAWE 1979).

In addition, water-soluble components (e.g., benzene, toluene, xylene, or BTX) may be selectively dissolved and enter the groundwater system. Where a free product layer exists, this contamination results from direct mass transfer across the product-water interface. If product is trapped in the unsaturated zone, infiltrating water may come in contact with the product, dissolving the highly soluble components and carrying them to the groundwater.

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Hydrocarbon product and dissolved components are subject chemical oxidation and biodegradation in both the unsaturated a saturated zones. The degradation rate is generally a function of oxyg concentration, or degree of aeration (CONCAWE 1979; Barker et al. 198 The chemical and biological transformations typically form various orgar by-products, including phenols, catechols, cersols (methyl phenols) ar benzoic and hydrobenzoic acids (Gibson 1978), thus leading to further sc and groundwater contamination.

SITE CHARACTERISTICS

The refining facility described in this paper manufactures variou petroleum products (regular and unleaded gasoline, diesel fuel, jet-A fue from low- and high-sulfur crude. Process units and administrative an support buildings are located in the north-central portion of the facilit with crude and refined product storage tanks to the south and we (**Figure 2**). A wastewater treatment unit is located on the western end c the refinery.

If a significant volume of free-phase product reaches the groundwater, it forms an immiscible layer on the water table that spreads laterally in the same direction as groundwater flow.

The facility is surrounded by largely undeveloped land but othe industrial plants and refineries are located less than one mile to the wes There are two isolated marshes or fens are immediately west of the facility

In early 1987, workers noted an oily sheen on water distilled for use in the refinery laboratory. The source of laboratory water at that time was a water supply well located on the northwest portion of the refinery. This well draws groundwater from a confined artesian aquifer that is overlain by an unconfined glacial outwash aquifer. The refinery operator contracted with Environmental Strategies Corporation to determine the potential source(s) of petroleum hydrocarbon contamination to the refinery's water-supply well. The investigation concluded that contamination resulted from the release of petroleum hydrocarbons from part of an oily underground water sewer system located near the well. Additional field investigations have been conducted from mid-1987 to the present to ascertain the extent of soil and groundwater contamination beneath the facility and off-site areas.

Hydrogeologic Framework

Five regionally-extensive hydrostratigraphic units have been identified in the area. The upper unit consists of unconsolidated glacial outwash sand and gravel deposits to depths of more than 100 feet. Groundwater in this unit occurs under water table conditions. The outwash deposits are underlain by a low-permeability unit of variable thickness that consists of clay and silt with occasional thin, sand layers. This clay-silt unit serves as the upper confining layer for an artesian aquifer consisting predominantly of sand and gravelly sand with subordinate gravel, silty sand, and gravelly clay deposits.

Lithologic logs from monitoring wells indicate the presence of the shallow glacial outwash aquifer beneath the refinery. The thickness of this aquifer ranges from approximately 20 to 70 feet in the area. In the eastern portion of the facility, this aquifer is relatively thin and consists exclusively

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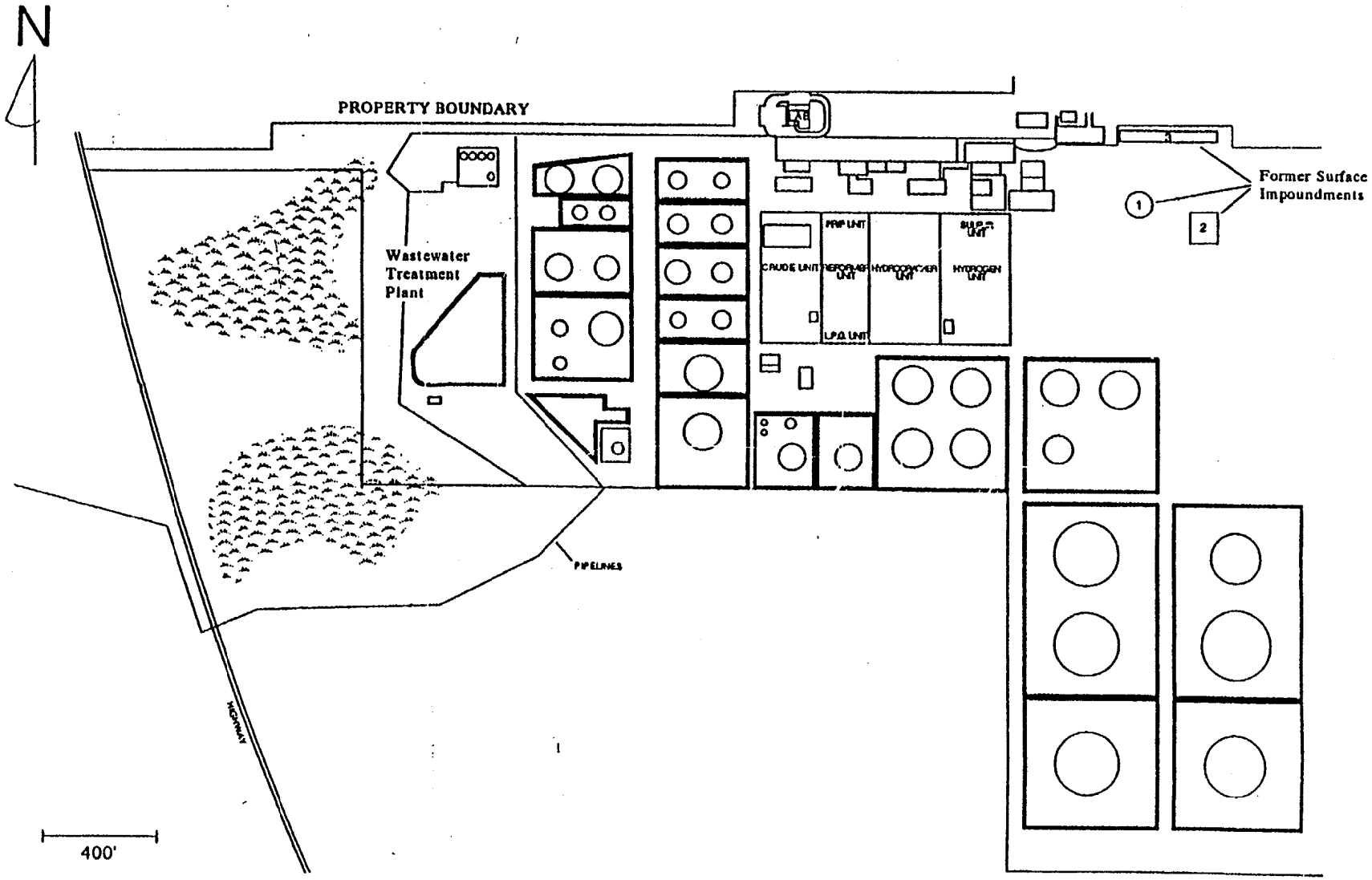
Figure 2. Facility Plan



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of stratified, well-to-poorly-sorted sand and gravel deposits with less 10% silt. The glacial outwash aquifer thickens to the west because of a in the elevation of the underlying clay-silt unit. This areal chang thickness is accompanied by increased aquifer heterogeneity as indic by the presence of thin, discontinuous layers of silt and silty clay.

Stratigraphic variation also exists in unsaturated soils above the w table. Over most of the area, permeable sands and gravels with rare clay beds are present throughout the unsaturated zone. The marsh a west of the refinery are underlain by organic-rich silt-silty clay and p deposits that reach thicknesses of 25-30 feet in some areas. These surfic low-permeability sediments support perched surface water in the mar areas, and may extend locally below the water table.

A contour map of the groundwater table in the area is provided **Figure 3.** The general west-southwest flow direction in the unconfin glacial outwash aquifer corresponds to the regional groundwater fl direction in the multiple aquifer system. Local deviations, however, su as a northwestward flow direction south of the lower marsh, indicate complex groundwater flow system in the unconfined aquifer. Water leve in paired monitoring wells screened at different depths indicate a min vertical hydraulic gradient in the aquifer, with the flow component directe upwards toward the water table. A reversal in the vertical flow compone appears to occur near industrial water supply wells completed in th confined aquifer. These local downward vertical gradients reflect leaka across the confining clay-silt layer in response to pumping from th underlying artesian aquifer.

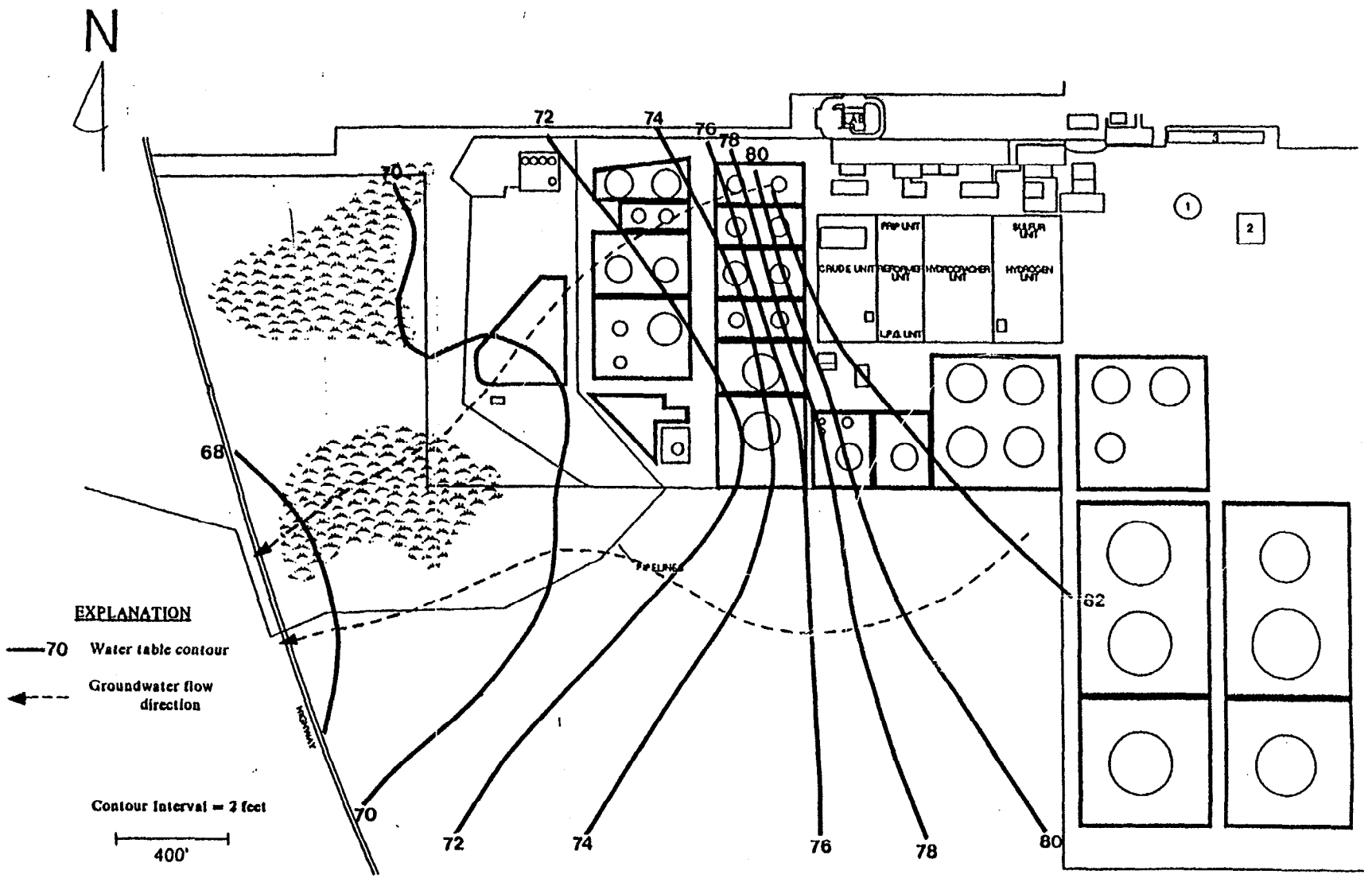
POTENTIAL SOURCES AND DISTRIBUTION OF CONTAMINATION

The operation of this oil refinery since 1969 has created a hig probability for the uncontrolled release of petroleum hydrocarbons to th soil and groundwater. Potential sources of contamination identified at th refinery include buried pipelines, the waste hydrocarbon/water sewe system, surface impoundments formally used for disposal of waste sludges and the waste material storage area. In addition to these continuo sources, noncontinuous point sources resulting from surface spills o petroleum hydrocarbons have occurred at various locations around the facility. The contaminants of concern are petroleum hydrocarbons and their associated water-soluble compounds, particularly benzene, which is a known human carcinogen, and other monoaromatics (toluene and xylene).

The groundwater investigations have defined the extent of petroleum hydrocarbon and dissolved BTX contamination in the glacial outwash aquifer over most of the area. The relatively low residual saturation associated with the sand and gravel soils beneath the refinery allowed for the rapid downward migration of released oil/product to the water table. The low specific gravity of the released product (0.82-0.86 at 45°F) caused the formation of an extensive petroleum hydrocarbon layer on top of the water table.

The distribution of floating petroleum product in wells and boreholes

Figure 3. Water Table Contour Map, and Groundwater Flow Directions - December 1989



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indicates the presence of two areally extensive contaminant plu (**Figure 4**). The floating petroleum product forms a continuous, U-sha layer on the southwestern portion of the facility and off-site ar downgradient of the facility. Product spreading has been influenced subsurface silt and clay deposits beneath the marshy area. These silt clay deposits form a low permeability barrier that caused the petrole product layer to preferentially migrate around the northern and south margins of the marsh. Chemical fingerprinting of product layer samp from beneath the refinery and the northern marsh area indicates that portion of the plume consists of naphtha (a major component of jet fu diesel fuel, and some leaded gasoline. The downgradient edge of southern product plume has not been delineated, but extends a minim of 700 feet west of the facility.

A 48-hour pumping test was conducted at the prototype product recovery well to determine the characteristics of the aquifer and to evaluate the influence of groundwater pumping on the floating product layer.

BTX contamination is extensive in the shallow glacial outwash aqui (Figure 4). The contaminant distribution indicates potential sources both the western and eastern portions of the facility. The presence of su widespread groundwater contamination reflects both the transfer of wate soluble monoaromatic constituents from the petroleum product layers, ar the hydrogeology and hydrogeochemistry of the unconfined aquif system. The high permeability of the aquifer sands and gravels wou facilitate the transport of dissolved constituents, even if migration we retarded by adsorption or other physicochemical processes. Natur degradation of contaminants is minimal because of the relatively lo oxygen concentrations in the groundwater, as indicated by the gray-t very-dark-gray color of the aquifer material. The low concentrations (< µg/liter) of phenol and other biodegradation products substantiate the lac of significant microbial breakdown of BTX contaminants in the aquife

PETROLEUM HYDROCARBON RECOVERY IN THE NORTH MARSH AREA (PHASE I)

Field investigations conducted from late 1987 through early 198 identified a large floating petroleum product plume extending from th facility southwestward under the marsh. The thickness and distribution c the plume necessitated the implementation of product-recovery measure in the area. A prototype product recovery well was installed in the are where the product was thickest. Field tests were performed to assess th effectiveness of hydraulic controls in recovering the floating product.

A 48-hour pumping test was conducted at the prototype produc recovery well to determine the characteristics of the aquifer and to evaluate the influence of groundwater pumping on the floating product layer Measurable drawdowns (corrected for the presence of the product layer) were detected in monitoring wells over 150 feet from the prototype well, indicating an extensive area of influence characteristic of highly transmissive sand and gravel aquifers. Periodic monitoring of the product layer during the test indicated that drawdown in the water table was sufficient to induce significant movement of the floating product plume. The thickness of the product layer increased in both the pumping well and adjacent observation wells (**Figure 5**). The results of the pumping tes

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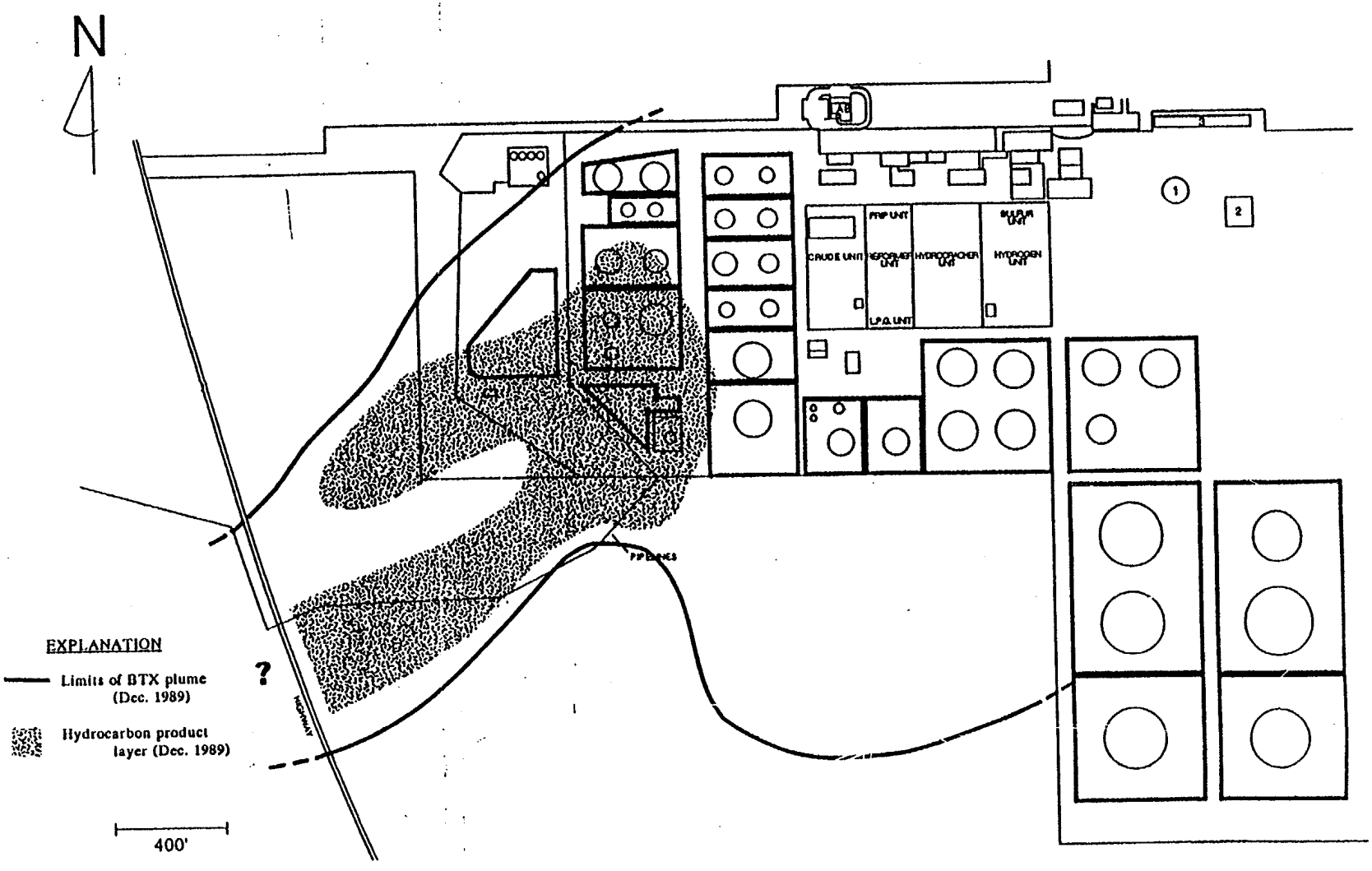
Figure 4. Areal Distribution of Floating Hydrocarbon Product and BTX Plumes



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indicated that sustained groundwater extraction would cause a redist tion of the hydrocarbon product over most of the well's drawdown

Based on these field evaluations, a petroleum product recovery system was installed in the north marsh area. The recovery sys consisted of nine well pairs in a northeast-southwest line across the floa product plume (**Figure 6**). Each well pair consisted of a shallow proc recovery well drilled to a depth of approximately 15 feet below gro surface, and a deeper well drilled to a depth of approximately 35 feet be ground surface for groundwater extraction and additional hydrocar product recovery. The selection of the well pair system was based on low product inflow rate relative to groundwater inflow encountered dur the pumping test on the prototype recovery well. This observed differe in flow rates in response to pumping is due to the higher product viscosi (1.7 - 3.0 centipoises) compared to water (1.4 centipoises). In recov wells equipped with both product and water pumps (i.e., two-pur system), the greater water inflow rate would result in a rise in the wa level inside the well casing, thus reducing the product layer thickness a limiting product recovery. For the well pair system, groundwater wi drawal from the deep wells would lower the water table and indu product layer movement toward the well location. Hydrocarbon produ that would accumulate in the cone of depression in the water table wou then be pumped to the surface at the shallow wells. The two-we technique has been widely used in other field situations because of effectiveness in recovering relatively pure product, thus facilitating pc recovery treatment (oil-water separation) in cases where the petroleu product is recycled.

. . . various factors—local hydrogeology, treatment system capacity, recovery well design—combined to hamper the system's ability to maximize product recovery and remediate the plume in this area.

In-situ remediation techniques applicable to petroleum hydrocarbo contaminants, such as biodegradation, were evaluated along with th pump-and-treat alternative. Preliminary cost analyses indicated that imple mentation of *in-situ* biodegradation could be less than one-half the tota cost for a remedial system involving product/groundwater pumping an aboveground treatment. However, this approach was deemed unsuitabl due to technical concerns based on site conditions.

Construction of the Phase I recovery well system in the marshy are extended from February to September 1988. The final recovery system design provided for the conveyance of contaminated water through a 6-inch, heat-traced PVC pipeline to the refinery where it would be eithe discharged to the wastewater treatment facility, or routed for use as process water. The product recovered from the wells would be carried by a 2-inch, heat-traced steel pipeline to an oil-water separator, and then pumped to a small, aboveground oil storage tank located within the diked area for one of the refinery's bulk storage tanks. The petroleum product would then be reprocessed at the refinery.

MODIFICATION OF THE PETROLEUM HYDROCARBON RECOVERY SYSTEM IN THE MARSH AREA (PHASE II)

Field performance tests conducted during operation of the Phase I recovery wells system showed that less than 5% of the liquid mixture

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Figure 5. Changes in Thickness of Floating Hydrocarbon Layer

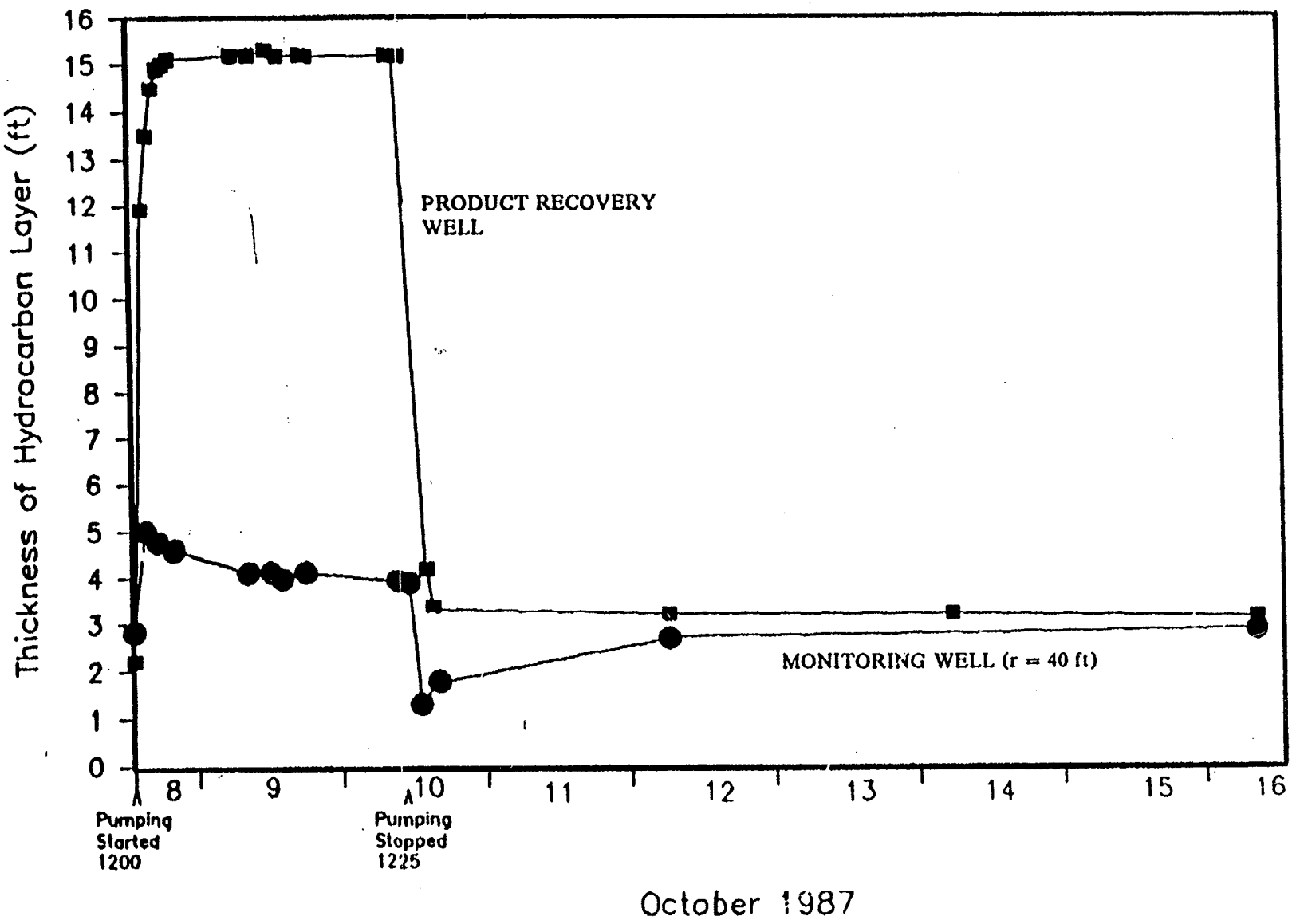

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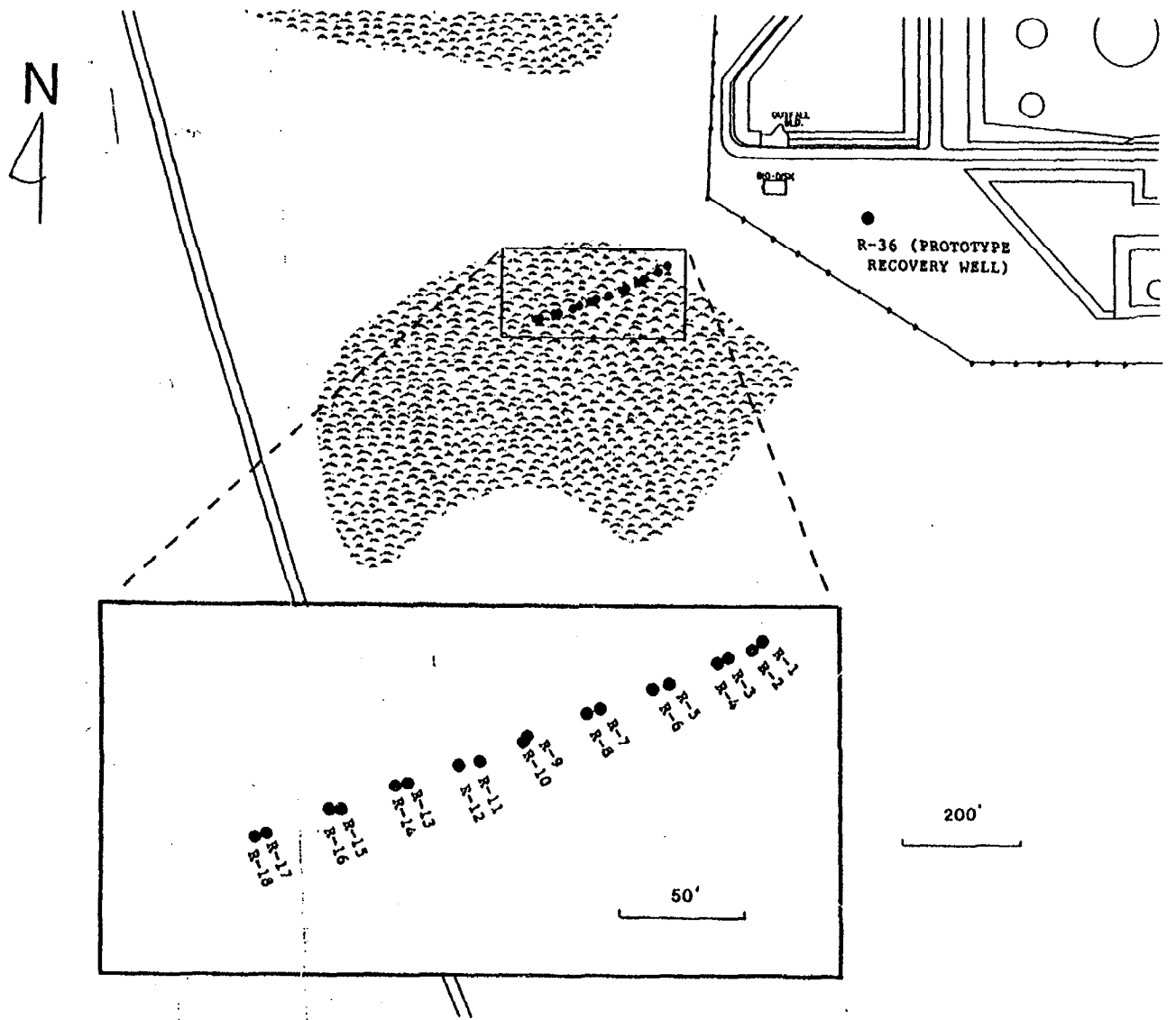
Figure 6. Location of Phase I Hydrocarbon Product Recovery Wells



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pumped from the shallow wells consisted of petroleum product. An overall evaluation of the system indicated that various factors—local hydrogeology, treatment system capacity, recovery well design—combined to hamper the system's ability to maximize product recovery and remediate the plume in this area. The expansion of the remedial system during Phase II necessitated the development of a more efficient product recovery well design. Various options were studied with respect to feasibility and cost, including:

- replacement of submersible water pumps
- replacement of product recovery pumps
- "pulsed pumping" schedule for product recovery pumps.

After an analysis of these alternatives, the existing product recovery pumps were replaced with pumps whose inlets are maintained above the product-water interface, permitting only product to enter the pump during operation. This type of product pump design would increase overall hydrocarbon recovery regardless of the thickness of the floating product layer within the well casing. In addition, both the product recovery pump and submersible water pump could be installed within a single well. The conversion to the two-pump system would significantly limit the number of recovery wells in this portion of the hydrocarbon product plume, simplifying well maintenance and permitting greater flexibility during remedial system expansion.

Expansion of the Recovery Well System

Although product recovery activities were initiated with the Phase I system, the distribution of the floating petroleum hydrocarbon plume in the immediate area necessitated modifications to the recovery well system. Monthly field measurements during the first 10 months of system operation indicated product thicknesses greater than 1 foot in monitoring wells hydraulically upgradient (northeast) and downgradient (southwest) of the Phase I recovery wells. To limit further migration of the floating hydrocarbon product plume and to accelerate product collection, the system was expanded by installing additional recovery wells in the area.

Northern Margin of the Marsh Area

Analytical and numerical groundwater flow modeling techniques were used to determine the most effective spacing for the recovery wells and groundwater pumping rates. Review of site-specific data indicated that uncertainties concerning the hydrogeology of the glacial outwash aquifer in the area could hinder the accuracy of any model results. To obtain appropriate field determinations of aquifer parameters, a pumping test was conducted in the marsh area downgradient of the Phase I recovery well pairs. Hydrogeologic information obtained from this test and previous investigations provided a sufficient data base to develop a conceptual model of the unconfined aquifer that could be used in the modeling effort.

Numerous simulations of the predicted aquifer response (i.e, water-table drawdown) were generated using different recovery well numbers,

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locations, and groundwater extraction rates. Evaluation of remedial sys performance was based on a comparison of the steady-state area influence during pumping with observed product plume distribution. analysis of model simulations indicated that effective capture of float hydrocarbon product could be achieved by using only five of the n previously installed Phase I recovery wells combined with the addition two recovery wells downgradient and one recovery well upgradi (**Figure 7**).

Modifications to the Phase I recovery well system discussed ab were conducted from September to December 1989. The new proc recovery pumps and submersible water pumps were installed in operational recovery wells. Hydrocarbon product and contamina groundwater from the additional recovery wells were added to the proc and water discharge lines for the Phase I system. Separated product fro these wells was temporarily stored and reprocessed at the refine groundwater was either treated and discharged to nearby surface wate or used as process water.

The thickness and extent of the hydrocarbon product over the area necessitated the immediate implementation of corrective measures for the product plume.

Southern Margin of the Marsh Area

Field investigations conducted during 1988 defined the distribution floating hydrocarbon product and associated groundwater contamina on the facility and the northern portion of the marsh area. However, magnitude and extent of the product and dissolved contaminant plum had not been fully defined southwest of the facility. Supplemen groundwater investigations conducted during the summer of 1989 iden fied a second elongate floating hydrocarbon product layer that covered approximately 7-acre area from the refinery west-southwest to the ro (**Figure 8**). The maximum product thickness measured in monitoring well in this area was approximately 2.3 feet.

The thickness and extent of the hydrocarbon product over the are necessitated the immediate implementation of corrective measures for the product plume. In order to limit further off-site migration of the contam nant, three recovery wells were installed within the eastern portion of the hydrocarbon product plume in areas where the layer was observed to be the thickest. The two-pump system adopted in other Phase I product recovery wells was also used for these new wells. Product recovery measures in areas further west were not initiated during the fall and winter of 1989 because of incomplete characterization of the floating product and dissolved contaminant plumes in the glacial outwash aquifer in the area.

Implementation of the above corrective action was contemporaneous with the previously discussed modifications to the Phase I recovery well system. The product and water pipeline network for the existing wells was extended to the new product-recovery wells to the south. Final disposition of extracted petroleum product and contaminated groundwater was identical to that discussed for the modified Phase I system. However, the expansion of product recovery activities during 1989 had exhausted the excess treatment capacity of the facility's wastewater treatment system. In addition to this capacity limitation, prolonged treatment times during the

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Figure 7. Hydrocarbon [illegible]

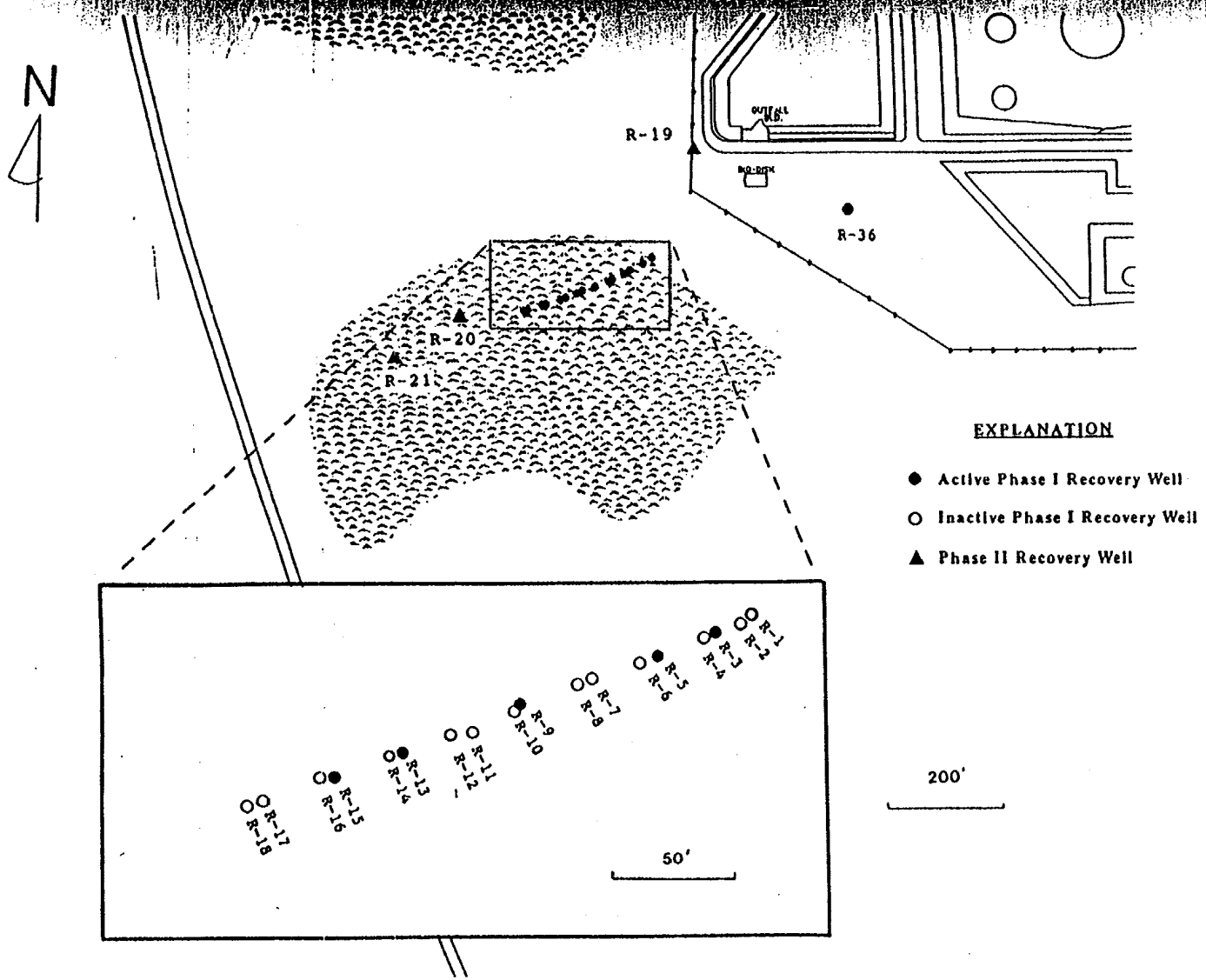
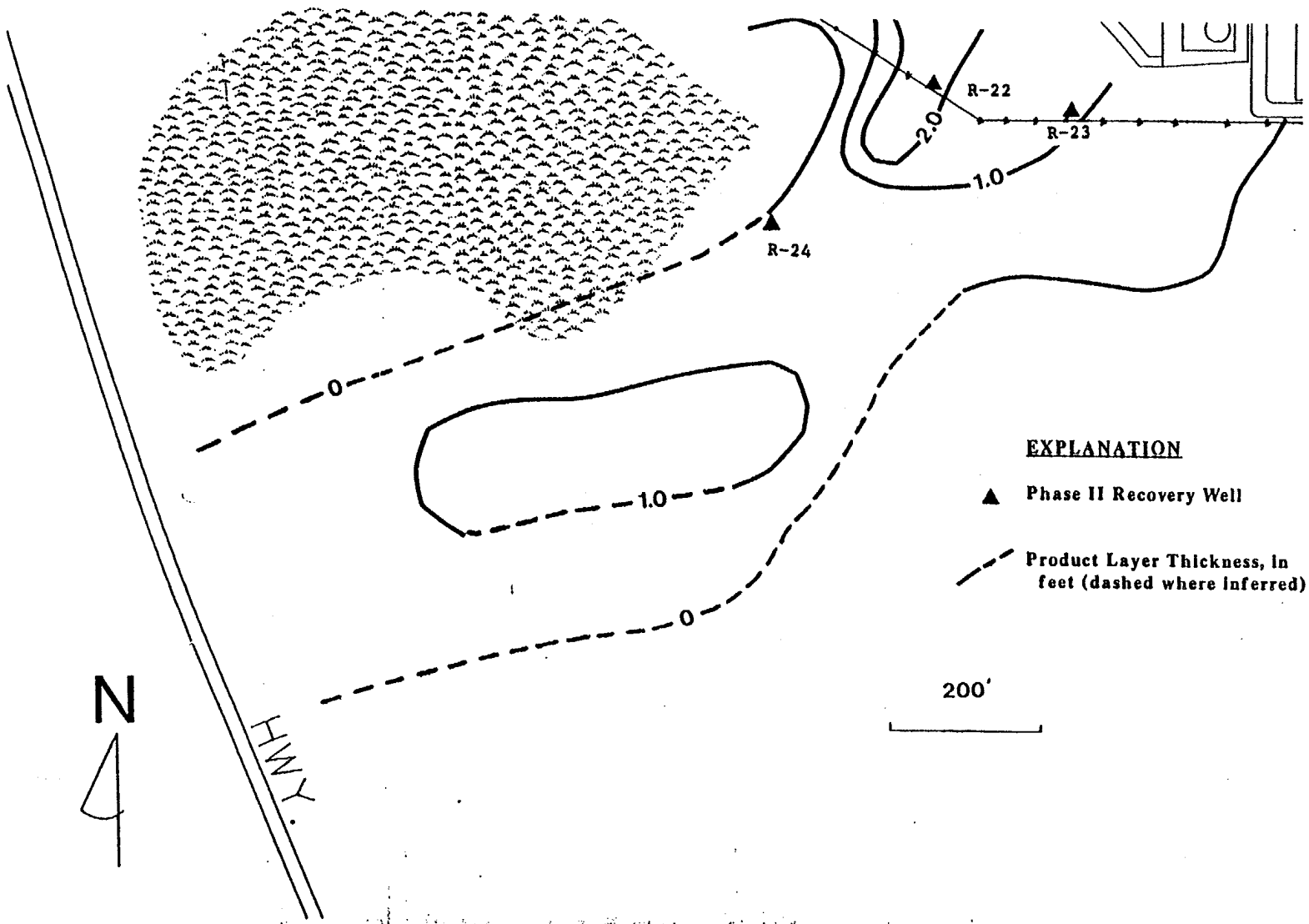


Figure 8. Phase II Recovery Wells in the Hydrocarbon Product Plume



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winter months and past maintenance problems have restricted the unit's ability to accept and treat additional sources of wastewater. Uncontrolled fluctuations in the volume of "outside" water the treatment unit could accept hindered the effectiveness of the remedial system, because design criteria assume relatively constant groundwater extraction rates. Thus, the present method of treating the contaminated groundwater must be changed to allow for more efficient operation of the recovery wells in the future.

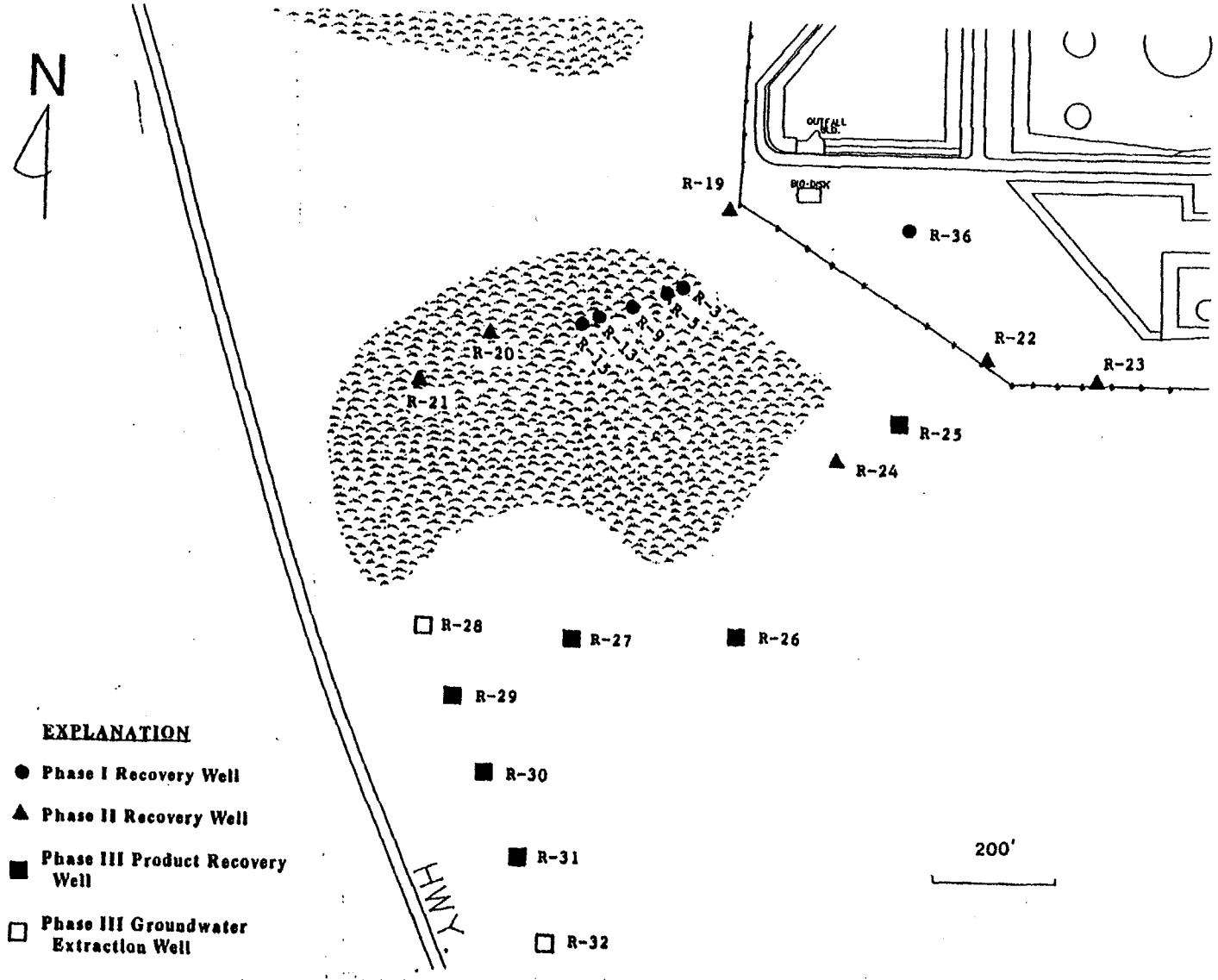
EXPANSION OF THE PRODUCT RECOVERY SYSTEM SOUTH OF THE MARSH AREA (PHASE III)

The three recovery wells installed within the southern hydrocarbon product plume during 1989 initiated remedial activities for the other area of gross contamination in the unconfined aquifer. The extension of product recovery measures westward to the road constituted the next phase in aquifer restoration. Although Phase III remedial activities primarily addressed containment of the floating hydrocarbon layer, analyses of groundwater samples for BTX contamination showed that the horizontal distribution of dissolved contaminant plume along the road was relatively limited in the glacial outwash aquifer. The narrow extent of contamination in this area would enable hydraulic containment of both floating product and dissolved plumes with a small number of recovery wells.

Groundwater flow modeling techniques similar to those used in the Phase II recovery well design were used to assess well locations and groundwater extraction rates for the Phase III system. Site-specific hydrogeologic data used to develop an accurate conceptual model of the glacial outwash aquifer were obtained from recent field investigations, and a pumping test was conducted in the eastern portion of the floating product plume. The results of the steady-steady groundwater flow simulations indicated that continuous pumping from a line of five recovery wells immediately adjacent to the road would produce a hydraulic sink capable of preventing further downgradient migration of contaminants (**Figure 9**). The northernmost and southernmost recovery wells in the line would not be equipped with product recovery pumps because of the absence of floating hydrocarbon product in these areas. Additional product recovery wells would be installed further east to expedite the removal of the floating hydrocarbon layer from the water table (Figure 9). Design for the Phase III recovery wells would be identical to existing Phase II wells presently operating in the area.

Because of problems associated with using the facility's wastewater system, the development of an alternate method of treating and disposing of the contaminated groundwater was required before the Phase III wells became operational. Previous investigations indicated that the primary contaminants of concern in the glacial outwash aquifer are benzene, toluene, and other highly soluble, volatile organic compounds typically present in refined petroleum products. An evaluation of appropriate treatment technologies and their associated costs was performed based on analytical data for BTX and other constituents, particularly iron, which

Figure 9. Recovery Wells Installed During Phase III and Previous Remedial Phases



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exhibits relatively high dissolved concentrations because of the reducing conditions in the aquifer. Two proven technologies were evaluated for treatment of the contaminated groundwater: air stripping and carbon adsorption. Because of potential problems that oxidation could pose during treatment and subsequent disposal of the effluent, both alternatives included the removal of dissolved iron as solid oxides-hydroxides precipitates early in the treatment process. Process flow schematics for both treatment alternatives are shown in **Figure 10**. Capital and annual operations and maintenance costs for each system are presented in **Table 1**. Based on the assumed groundwater flow rates and removable hydrocarbon concentrations, the cost for air stripping is considerably less than for carbon adsorption treatment.

Table 1. Estimated Costs of Treatment Systems for BTX-Contaminated Groundwater

Treatment Method	*Capital Costs*	*Operations and Maintenance Costs**
Air Stripping	$375,900	$117,400
Carbon Adsorption	$393,900	$205,700

* Cost per year

Various options were evaluated for disposal of the effluent from the treatment unit, including discharge to surface waters under a National Pollution Discharge Elimination System (NPDES) permit, indirect (surface) recharge of the glacial outwash aquifer, and direct (subsurface) recharge of the aquifer (i.e., injection). Disposal of the treated effluent to surface waters was not considered a viable alternative for the interim product recovery measures because of time constraints associated with obtaining the required discharge permits. Surface recharge was considered a potential disposal option because of the high permeability of the unsaturated sand and gravel soils in the area. This method was favored over injection wells because of its operational simplicity and lower estimated construction and maintenance costs. Supplemental geologic investigations in the proposed recharge area confirmed the technical feasibility of the surface recharge disposal option.

The completed remedial design for this area represents a three-phase groundwater recirculation system. Hydrocarbon product and BTX-contaminated groundwater would be extracted at the recovery wells interspersed throughout both plumes. After phase separation, product would be recycled in the refinery's crude unit while groundwater would be conveyed to an air-stripping treatment unit for removal of volatile organic contaminants. The treated effluent would then be conveyed to a series of recharge trenches situated south of the refinery beyond the limits of the

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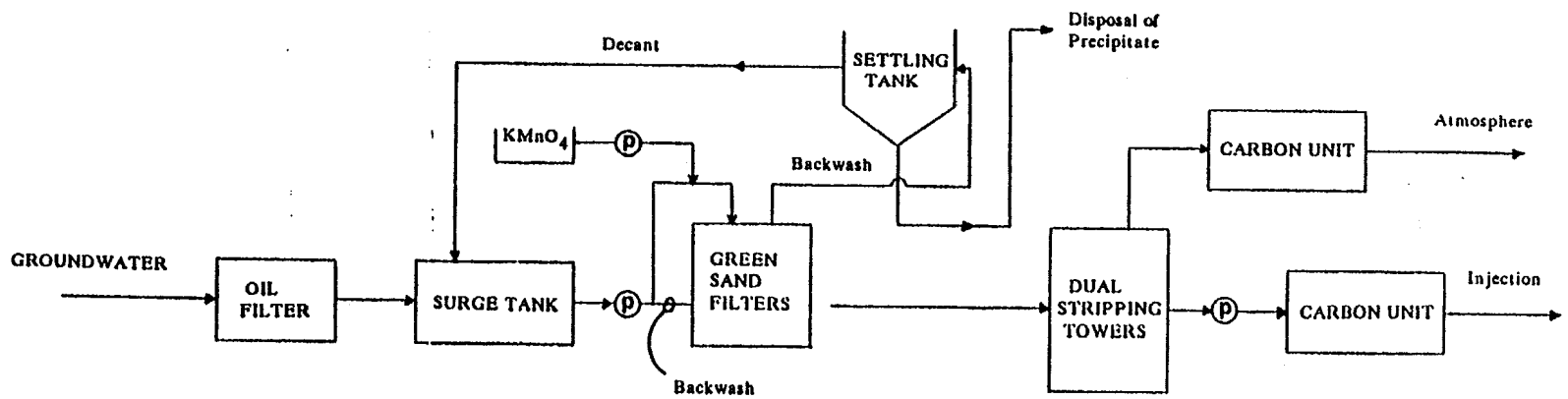
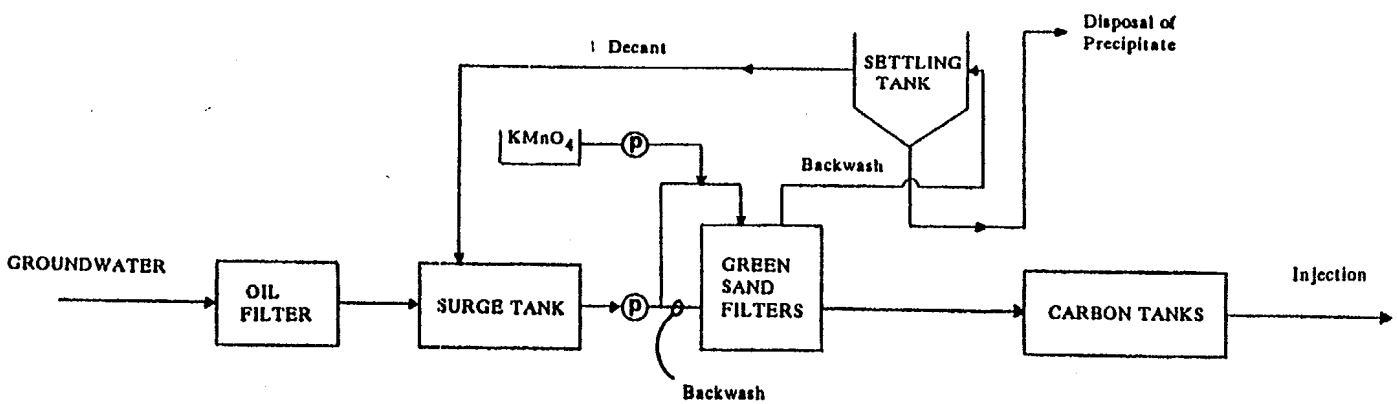
Figure 10. Treatment Schematics for Air Stripping and Carbon Adsorption Alternatives

ALTERNATIVE 1 - Air Stripping



ALTERNATIVE 2 - Carbon Adsorption



dissolved contaminant plume. This water would then recharge the unconfined glacial outwash aquifer via natural infiltration through the unsaturated zone.

Construction of all components of the Phase III remedial system is ongoing, and the projected startup date is early in 1991.

PERFORMANCE EVALUATION OF THE PHASE I AND II PRODUCT RECOVERY SYSTEMS

The overall performance of the interim remedial measures has been generally favorable, given the history of well design modifications and the pumping limitations created by using the facility's wastewater treatment unit to treat the contaminated groundwater. Field data that may be used in evaluating the pump-and-treat remediation include:

- distribution of floating product and dissolved contaminant plumes
- thickness of the hydrocarbon product layer
- volume of product recovered by the well network.

Figure 11 shows the limits of the BTX groundwater plume in the area downgradient of the recovery well system in the north marsh area. The analytical data from the monitoring well network indicate that the dissolved contaminant plume has not progressed downgradient to any significant degree. In fact, groundwater in some wells (E-55 and E-58) has exhibited decreases in BTX concentrations since initiation of remedial activities in the area.

The interpretation of thickness changes in the floating hydrocarbon layer is difficult because various processes can potentially influence the product plume on the water table.

The interpretation of thickness changes in the floating hydrocarbon layer is difficult because various processes can potentially influence the product plume on the water table. For example, substantial decreases in the thickness of the hydrocarbon product plume were noticed between July and December 1989. However, thinning of the product layer also occurred in areas outside the influence of remedial pumping. The observed reduction in product layer thickness is probably related to an increase in areal recharge to the glacial outwash aquifer in the area. During periods of high recharge, immiscible hydrocarbon product is trapped in the larger pore spaces in sandy soils, and eventually becomes disconnected from the floating product layer. This results in the creation of isolated clusters of the hydrocarbon product below the product-water interface.

Although operation of the recovery well system has varied since November 1988, a significant quantity of product has been removed from the aquifer system. As of September 1990, over 330,000 gallons of petroleum hydrocarbon product have been reclaimed by the recovery wells and recycled at the facility. A graph of the cumulative volume of extracted product is shown in **Figure 12.**

Performance evaluation of recovery wells located within the southern product plume would be premature at this time for two reasons. The entire remedial system for this area is incomplete, and recovery wells that have been brought on-line are not operating at maximum efficiency because of capacity limitations imposed by the facility's wastewater treatment system.

Figure 11. Approximate Extent of Benzene Contamination in Outwash Aquifer Downgradient of Recovery Wells

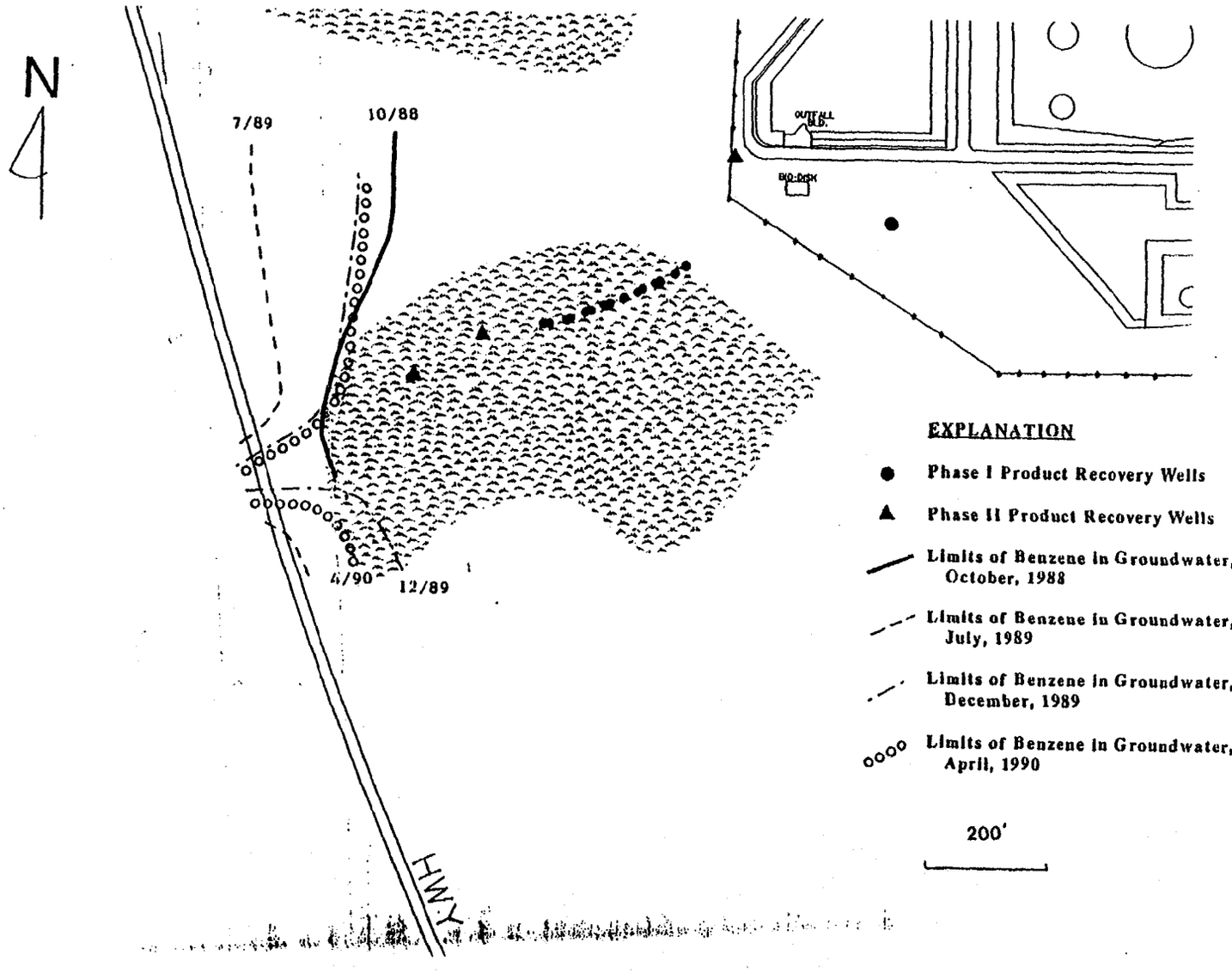


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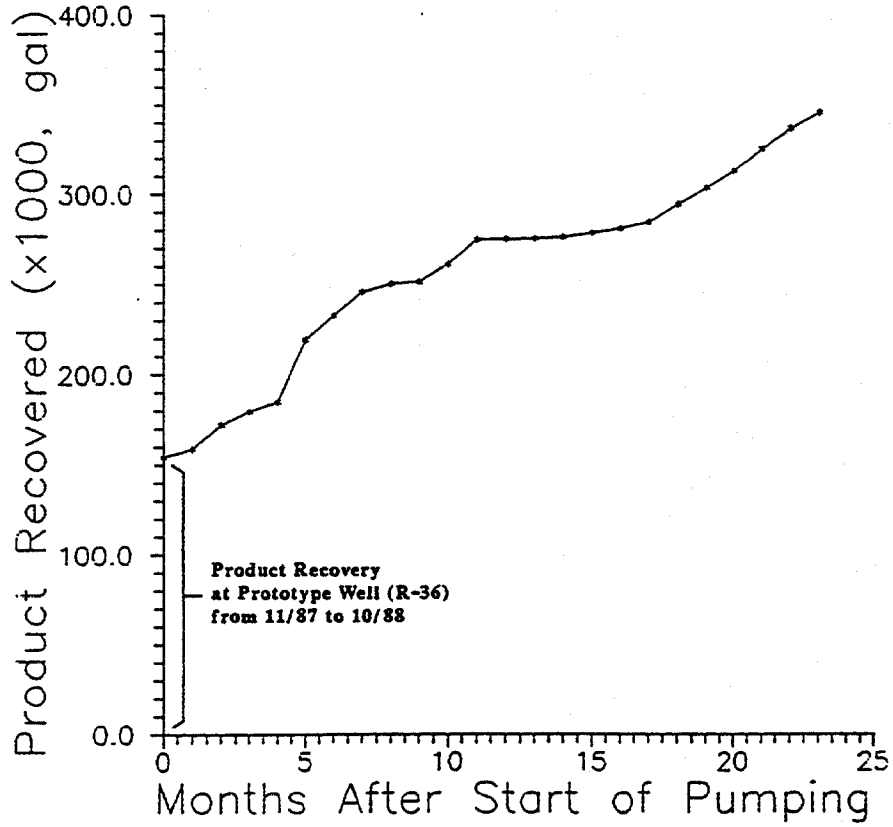
Figure 12. Cumulative Volume of Petroleum Hydrocarbon Product Recovered from Aquifer Since October 1988



CONCLUSIONS

The overall strategy followed in the cleanup of the petroleum hydrocarbon-contaminated aquifer illustrates the close interaction that often occurs between field investigation phases and implementation of appropriate remedial measures. The presence of a floating hydrocarbon product layer over a relatively large area made the design of an interim recovery system imperative, since the product would provide a continual source of BTX and other organic contaminants to the groundwater. In highly permeable sand and gravel aquifers like those in this area, pump-and-treat systems are an attractive remedial alternative because of their flexibility; additional recovery/extraction wells may be incorporated into the existing system without incurring significant additional capital costs.

The use of a phased remedial approach may also be advantageous at sites where no treatment system is required because of relatively low contaminant levels, or where excess treatment capacity exists at the facility under investigation. Although this approach would provide a significant total cost savings for aquifer restoration, problems may arise that could hamper or even stop extraction of product and/or contaminated groundwater. Before implementation of this treatment/disposal option, it should be carefully evaluated, in light of the specific contaminants present, permit

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restrictions, and engineering feasibility.

The Phase I, II, and III remedial systems were implemented to r hydrocarbon product migrating atop the water table. These recove systems will not remediate petroleum hydrocarbon contamination p in the unsaturated zone soils or residual hydrocarbons still trapped aquifer. In order to eliminate these contaminant sources, institut additional recovery systems or *in situ* treatment methods will be rec in the future. ■

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