Site Characterization, Application and Operation of Horizontal Wells for Ground Water Remediation

The Dow Chemical Company, Louisiana Division

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ABSTRACT

The Dow Chemical Company, Louisiana Division manufacturing complex is a global scale petrochemical facility which was constructed in the late 1950s. Through both past waste management practices and product spills, organic chemicals and saltwater have entered the shallow ground water underlying several areas of the manufacturing complex. Upon detection of impacts to ground water, The Dow Chemical Company implemented ground water recovery and treatment in four areas of the facility and began a voluntary site-wide subsurface assessment.

The site-wide assessment permitted characterization of subsurface conditions including the type, areal distribution and depth of compounds affecting the shallow ground water. A comprehensive database was prepared which incorporated the analytical data from soil and ground water, electric logs, cone penetrometer test data, and electromagnetic survey data. The database permitted the development of a detailed 3-D relational model showing stratigraphy, lithology, and concentrations of compounds of concern, from which future ground water remediation could be evaluated, prioritized, and implemented.

INTRODUCTION

Existing ground water recovery systems constructed at The Dow Chemical Company, Louisiana Division from 1987 through 1991, incorporated vertical wells and infiltration trenches. The logistical problems associated with these recovery systems made them costly to construct, maintain, and operate. Through an evaluation of potentially applicable remedial technologies, horizontal ground water recovery wells were determined to be the most effective remediation mechanism for the low permeability soil present in areas of impacted ground water. Horizontal wells eliminated most logistical problems associated with drilling in active chemical manufacturing areas. The hydraulic influence from a single horizontal well, average length of 800 feet, under the subsurface conditions present at the site, was equivalent to more than 30 vertical wells.

To determine the appropriate quantity and location of the horizontal recovery wells, an analytical element model was used to simulate the horizontal wells. Ground water drawdown, capture zones and steady state flow was estimated by modeling. Predicted steady state flows provided the basis for expansion of existing steam stripping facilities used to remove volatile organic compounds (VOC) from recovered process water and ground water. Also, understanding the affect of subsidence associated with dewatering of fine grained soil is critical to the application of ground water recovery systems, especially within a chemical manufacturing complex. The results of the ground water modeling were also incorporated into a site-wide subsidence model used to predict the rate and extent of subsidence. Future monitoring will be conducted to determine the actual affect of ground water withdrawal on subsidence, but the modeling results will enabled the facility engineers to make appropriate modifications to piping and structures for critical equipment.

The planned expansion of the site ground water remediation includes phased construction of horizontal ground water recovery wells completed at depths of approximately 25 and 55 feet below the surface. Phase I horizontal well construction started in February 1995 and was complete in January 1996. The Phase I work consisted of 18 horizontal wells varying in length from approximately 400 feet to 1,200 feet. Phase II consisted of seven additional wells, ranging in length from 800 to 1,100 which were installed in the Spring of 1996. Seven wells will be installed during, Phase III of which five horizontal wells will replace 224 existing vertical wells at the Block 49 landfill site.

This innovative application for directional drilling along with the use of Mixed Metal Hydroxide, a special drilling mud additive developed by The Dow Chemical Company, has permitted remediation of ground water underlying the manufacturing complex without impairing plant production.

PHYSIOGRAPHY AND GEOLOGY

The Dow Chemical Company (Dow) began operations at the Louisiana Division (LAD) manufacturing facility during the late 1950's. The facility is located on Louisiana Highway 1 between Addis and Plaquemine (Figure 1).

The shallow Holocene sediments at the site were deposited by the meandering Mississippi River. The sediments are mostly silts and clays which overlie the Pleistocene Mississippi River Alluvial aquifer, the primary potable ground water source for the area (Figure 2).

In 1990, Dow committed to conduct a voluntary, comprehensive subsurface assessment for the LAD. Existing at that time were ten known areas of impacted soil and/or ground water, six of which were already under approved remediation plans. Of the four remaining sites, one has had an approved remediation system in operation since 1993, one has been included with the site-wide assessment, and the other two have remediation plans submitted to

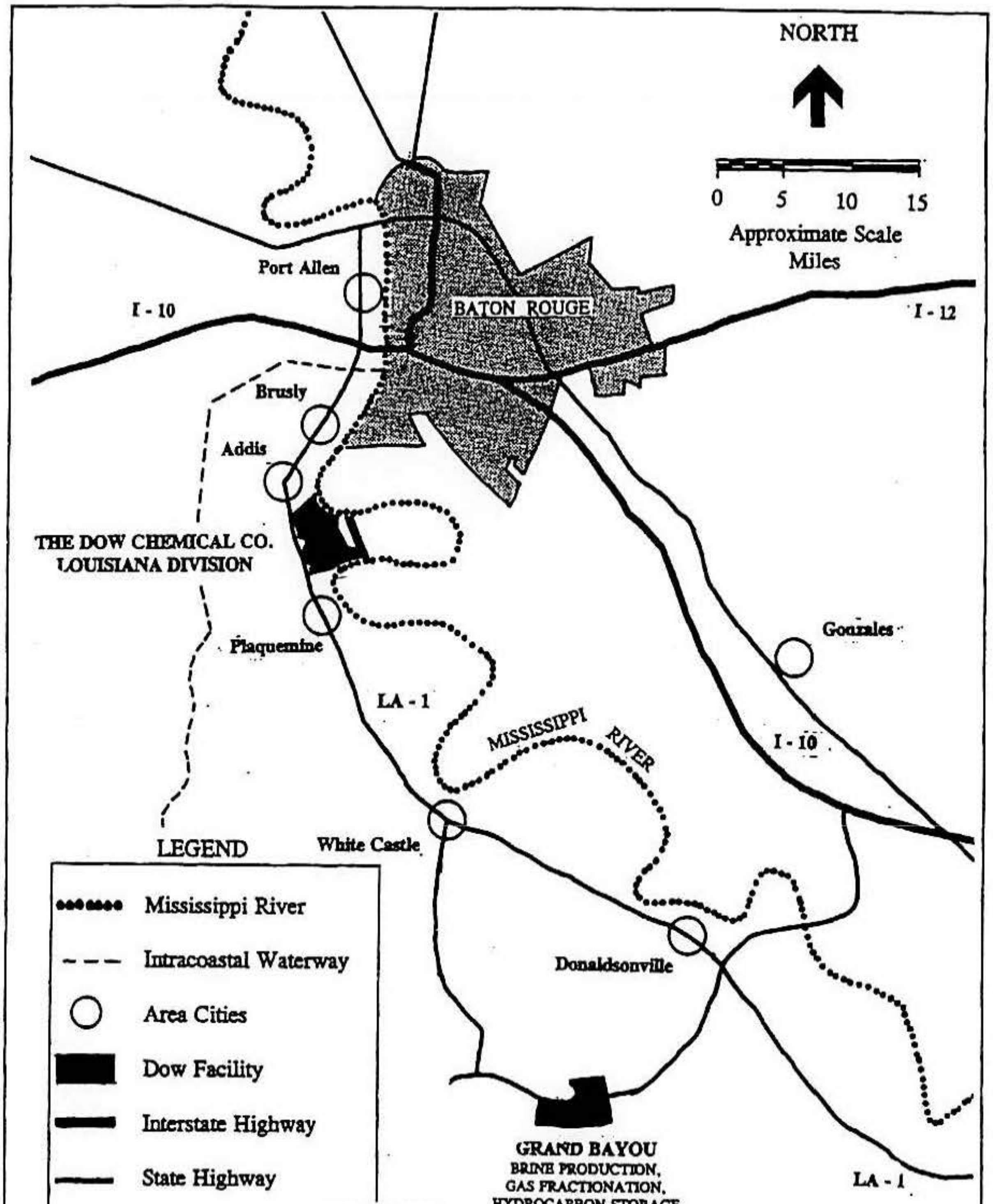

FIGURE 1
Location Map
The Dow Chemical Company, Louisiana Division

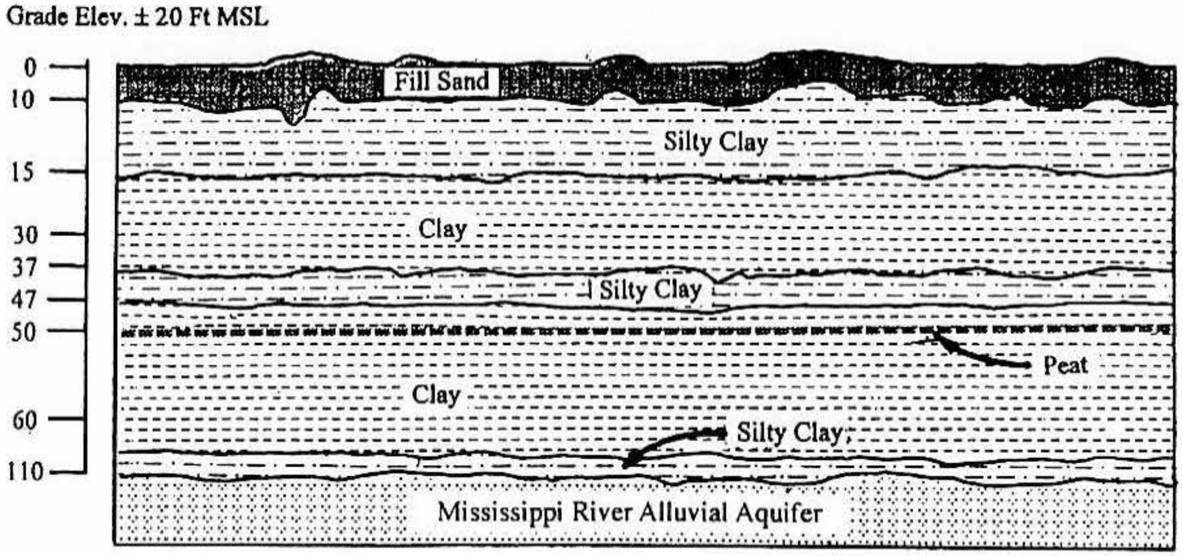

Figure 2

the appropriate agencies. The goal of the site-wide assessment was to identify and address soil and/or ground water contamination resulting from past or existing operating practices on a site-wide basis. Thus, the need arose to characterize the entire site in order to delineate contaminant plumes and develop remediation plans to address existing contamination as well as any newly discovered contamination. Figure 3 shows areas of identified contamination.

SITE CHARACTERIZATION

Prior to implementing remediation at the LAD, a realistic physical model was needed to depict the relationship between the geology, ground water hydrology, and distribution of VOCs in the subsurface. At the LAD, the lithology had to be interpreted in greater detail than was achievable with the existing data. To accomplish this, a review of all the existing data was conducted to determine the extent to which the data could be used.

Prior to beginning initial construction of the facility in the 1950s, Dow conducted a geotechnical investigation for foundation design for the plants. From the time the construction was completed to the mid 1980's, a number of other projects were undertaken within the LAD that included geotechnical investigations, water well installations, and environmental investigations. Data collected from these projects included electric logs, driller's logs, and cone penetrometer tests (CPT). These data are useful to determine the major stratigraphic units, but are not detailed enough for discreet lithologic interpretations to base the design of future remediation systems.

In order to enhance the geological data base of the facility, several additional data acquisition techniques were utilized. First, a number of locations were picked at random throughout the facility at which mud rotary borings were drilled. Drill cuttings were collected and described

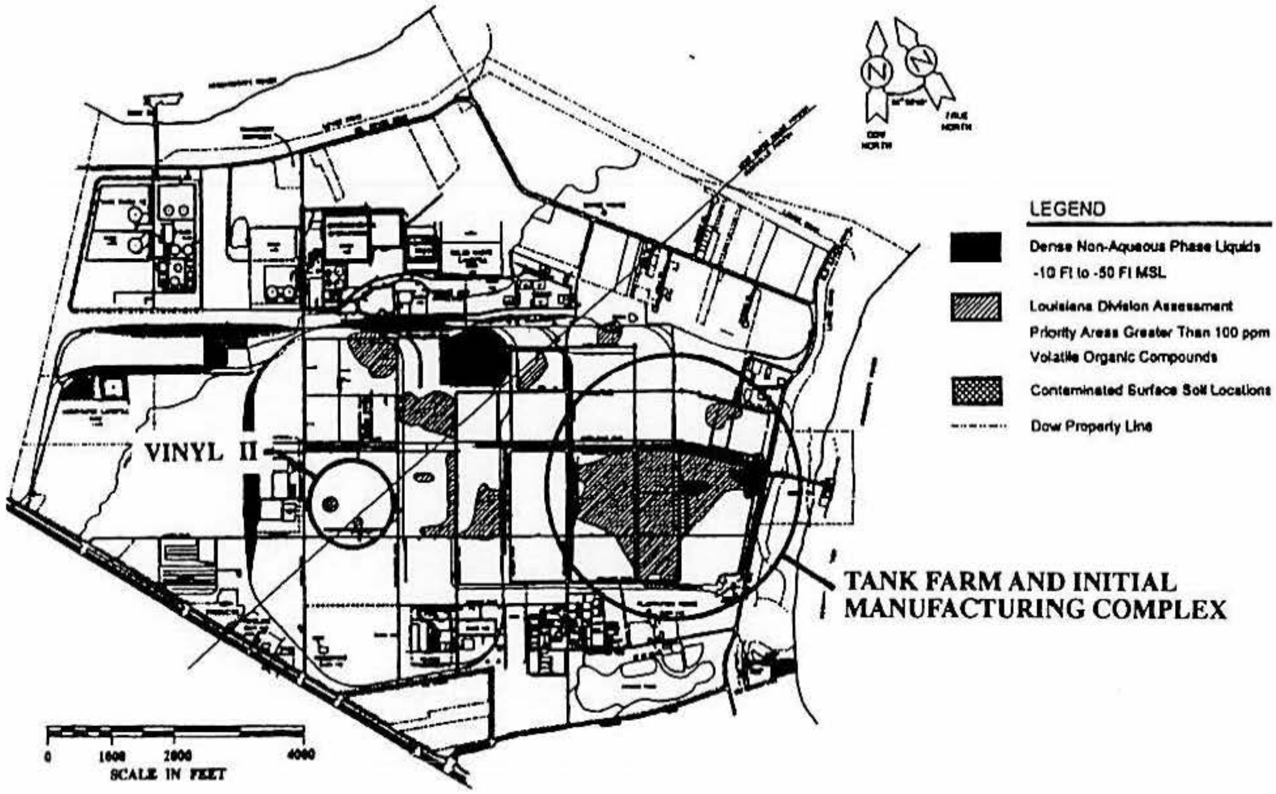

Figure 3

and, after compensating for lag time for mud circulation, a boring log was prepared. Geophysical logs including natural gamma-ray, calibrated density, electrical resistivity (single point), and caliper were run on the open borehole.

Hydraulic data was obtained initially through collection of representative soil samples from the two pervious zones and aquitards. Laboratory analysis of these samples provided values for hydraulic conductivity, porosity, and physical properties of the soils.

On average, the horizontal hydraulic conductivity (Kh) and vertical hydraulic conductivity (Kv) of the first and second pervious zones are each approximately 1x10-5 cm/sec. The Kh and Kv of the first and second aquitards are about 1x10-8. Both the first and second pervious zones are lithologically similar, being composed of clayey silt or silty clay with very thin discontinuous silt and/or sand lenses. The first and second aquitards are clay with some thin silt lenses, peat and wood. Table 1 shows the range of values from geotechnical tests conducted on several soil samples. Tests included soil classification, moisture, density, liquid limits, plastic limits, plasticity index, vertical and horizontal hydraulic conductivity, and porosity.

TABLE 1

GEOTECHNICAL TESTING SUMMARY

Geologic Unit	Boring	Depth (ft)	U.S.C.S.	wn (%)	DD (pcf)	LL (%)	PL (%)	PI	Kv (cm/sec)	Kh (cm/sec)
Holocene	Poly B-4	16-18	CL	40.60	83.40	38.20	21.05	17.20	8.1E-08	1.3E-08
Holocene	Poly B-4	23-25	CL	36.20	86.60	45.40	25.60	19.80	2.8E-07	8.9E-08
Holocene	CPE-1	10-12	CL	35.60	88.00	39.40	22.40	17.00	4.0E-07	7.8E-07
Holocene	CPE-1	20-22	CH	34.80	88.90	58.60	25.20	33.40	4.1E-08	5.2E-08
Holocene	H2O T-1	14-16	ML	31.50	95.40	33.10	24.60	8.60	4.6E-07	9.8E-08
Holocene	H2O T-1	24-26	CH	42.00	81.70	73.20	29.80	43.40	5.5E-08	--
Holocene	CAS-7	14-16	ML	38.50	87.30	43.20	26.50	16.70	1.1E-07	--
Holocene	CAS-7	27-29	CH	43.20	75.10	57.60	18.40	39.20	6.0E-09	1.5E-08
Holocene	PWR-1	12-14	ML	28.40	95.00	30.20	22.20	8.00	1.2E-06	2.4E-06
Holocene	PWR-1	21-23	CH	35.70	78.30	67.80	27.70	40.10	4.1E-08	6.2E-09
Holocene	ENIV-2	14-16	CH	--	--	56.70	18.50	38.20	3.4E-08	1.0E-08
Holocene	ENIV-2	23-25	CH	--	--	59.90	28.60	31.30	2.8E-08	1.3E-08

USCS ----- Unified Soil Classification System
wn ----- Porosity
DD ----- Density
LL ----- Liquid Limit
PL ----- Plastic Limit
PI ----- Plastic Index
Kv ----- Vertical Hydraulic Conductivity
Kh ----- Horizontal Hydraulic Conductivity

Slug tests were also performed on existing monitor wells and piezometers. On average, the hydraulic conductivity derived from the slug tests were about one order of magnitude greater than comparative tri-axial permeameter lab results. However, the slug test data were similar to steady state drawdowns produced from existing ground water recovery wells. This correlation is indicative of the development of secondary porosity, primarily through fractures, root holes, and detritus present in the soil. To enhance the data provided by the borehole geophysical surveys, a subsurface electromagnetic survey (PULSAR®) was performed. This survey was completed on a spacing of 200 feet throughout the 1,000 acre plant. The subsurface survey equipment was calibrated to borehole geophysical logs and other existing data to obtain the most accurate correlation possible.

In order to fully utilize all data available, Geo-Base®, a geologic database software was acquired. All geotechnical, geophysical, and chemical data were entered into the database. From the data included in the database, the Dynamic Graphics Earth Vision® modeling program was used to develop a 3-D model of the stratigraphy, lithology, and distribution of VOCs. Dow's Earth Sciences Department leased the program, which runs on a Silicon Graphics computer, to develop color images from which a video of the interactive program was made.

Some of the most critical data for environmental site assessments and ground water remediation is the flow direction, gradient and differences in hydraulic heads of ground water across aquitards. A number of piezometers were installed during the site-wide assessment to compliment the existing monitor wells used for measurement of the potentiometric surface in different ground water zones at the LAD. Additional water level data has been provided by the U.S. Army Corps of Engineers for ground water levels at and adjacent to, the earthen levees along the Mississippi River.

The water level data from both zones (Shallow and Deep Pervious Zones) and the Mississippi River Alluvial aquifer, have been collected since March, 1992, and have been plotted against meteorological and Mississippi River data. Figure 4 shows the plot of water elevation in several piezometers screened in the Shallow and Deep Pervious Zones and Mississippi River Alluvial aquifer along with precipitation and river elevation data.

At the LAD, the Mississippi River and Mississippi River Alluvial aquifer show a similar response in water level change and are hydraulically interconnected. The river has been dredged to depths of greater than 100 feet which intercepts the sands of the Mississippi River Alluvial Aquifer. The pervious zones, although adjacent to the river, show no evidence of hydraulic interconnection, and potentiometric highs exist at the river levee and in some areas of the canal system within the LAD.

Potentiometric surface maps for the two pervious zones have been prepared to model calibrated heads to verify the model data with locally mapped flow directions and gradients. The Shallow Pervious Zone is affected by ground water mounding along the Intake Canal; the Mississippi River levee also represents a ground water high. The Return Canal and some areas of interconnecting drainage canals have low surface water elevations causing localized ground water

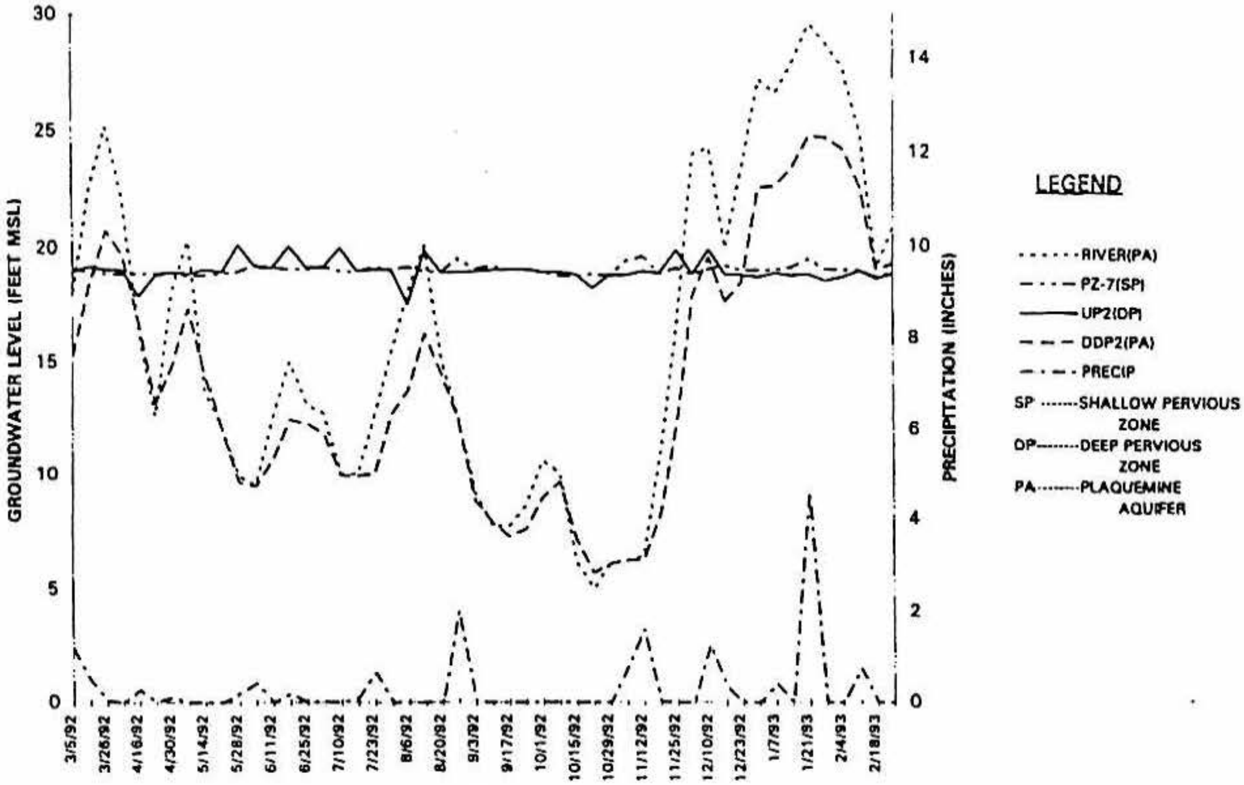

Figure 4

movement into the canal system. The Deep Pervious Zone has slight ground water mounding towards the center of the facility, but an overall inward gradient exists due to ground water mounding along the river levee.

REMEDIAL TECHNOLOGIES EVALUATION AND ENGINEERING

With the data collected during the site-wide assessment, a number of impacted areas were delineated within the facility. Potentially applicable technologies shown in Table 2 were evaluated to determine the most feasible method for ground water remediation. Through the remedial technologies evaluation, directional drilling and construction of horizontal wells was selected as the best method to provide ground water remediation beneath active process buildings and structures. The use of the horizontal wells provided significant advantages over the other technologies considered.

TABLE 2

REMEDIAL ALTERNATIVES EVALUATION

PROBABLE	NOT PROBABLE
Recovery Wells	In-situ bioremediation
-vertical	In-situ vitrification
-horizontal	
Interceptor Trenches	Soil Vapor Extraction
-shallow	Chemical Enhancement
-deep	-surfactants
Excavation	-emulsifiers
-incineration	Radio Frequency Heating
-ex-situ bioremediation	Molten Salt
-soil washing	
Barrier Walls	Plasma Torch
-physical	Air Sparging
-chemical	
-biological	
Risk Analysis	Electro-osmosis
(dissolved phase)	Electrokinetic Extraction
-no action	Hydraulic Fracturing
-monitor	
In-situ Steam	
Source Area Isolation	
(free phase)	

Important factors in the selection of the horizontal wells for this project are:

- directional drilling permitted significant set-back from the production areas minimizing interference to plant operations

- a single horizontal well eliminated numerous vertical wells and the associated pumps, piping, electrical and instrumentation equipment required for operation and system monitoring, thus lowering both the initial capital cost for system construction and long term operation and maintenance (O&M) costs

- Horizontal wells are more efficient with respect to area of influence in fine grained soils and will permit hydraulic containment of the plumes

- Less maintenance is anticipated for the horizontal wells since the well screens will remain submerged and not exposed to an atmosphere which promotes biological fouling

- Ground water treatment systems are presently in operation, and to accommodate increased flows, only minor modifications were required

- The principal disadvantage of a "pump and treat system" in general, regardless of the use of trenches, horizontal or vertical wells, is the associated long term O&M costs. However, this technology has been proven and will, over time, reduce concentration of VOCs in ground water and the potential for migration

Following the selection of horizontal wells for ground water recovery, detailed engineering was conducted to determine the quantity of horizontal wells, screen lengths and depths necessary to remediate and hydraulically contain ground water with VOC concentrations greater than 100 ppm. Analytical element models AQUAEM® and TWODAN® were used to analyze drawdown and contaminant movement to select the optimum location for the horizontal wells. The analytical element model was calibrated against the potentiometric maps and incorporated hydraulic data for recharge, leakance and boundary conditions associated with the physical features of the site.

For the Vinyl II Plant and other locations at the LAD, the models were calibrated to hydraulic heads for the Shallow and Deep Pervious Zones (Figures 5 and 6). Figures 7 and 8 show the resulting hydraulic heads, following installation and operation of the horizontal wells at steady state conditions, for the Shallow and Deep Pervious Zones, respectively. Due to a reduction in recharge, the influence from the shallow French Drain can also be seen on the shallow zone potentiometric surface map.

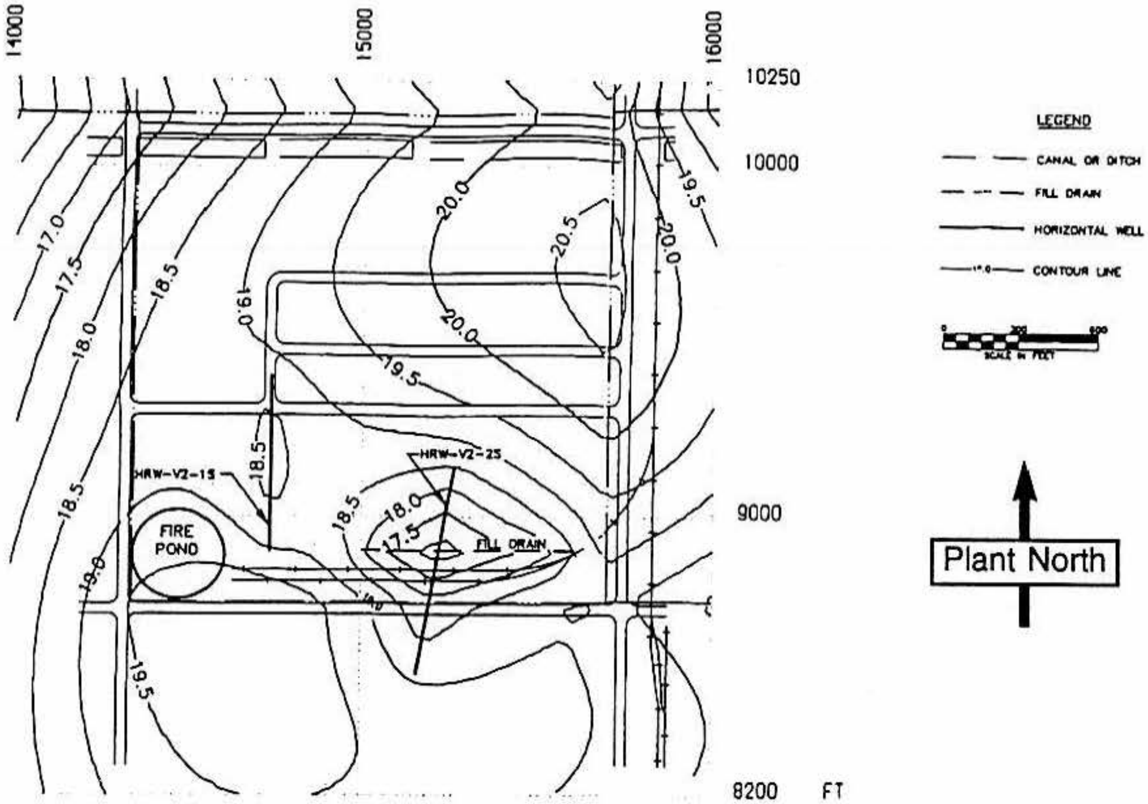

Figure 5: Vinyl II steady state shallow pervious zone potentiometric surface

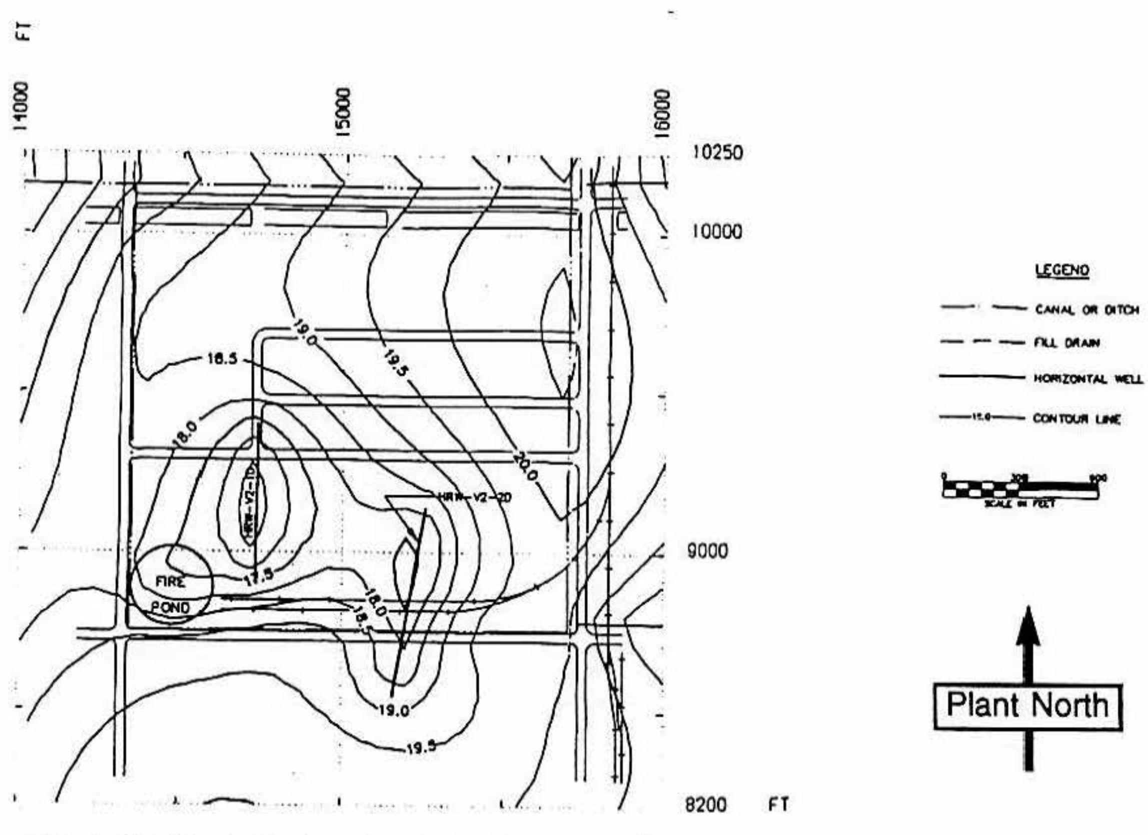

Figure 6: Vinyl II steady state deep pervious zone potentiometric surface

VINYL II SHALLOW ZONE POTENTIOMETRIC MAP SYSTEM OPERATIONAL

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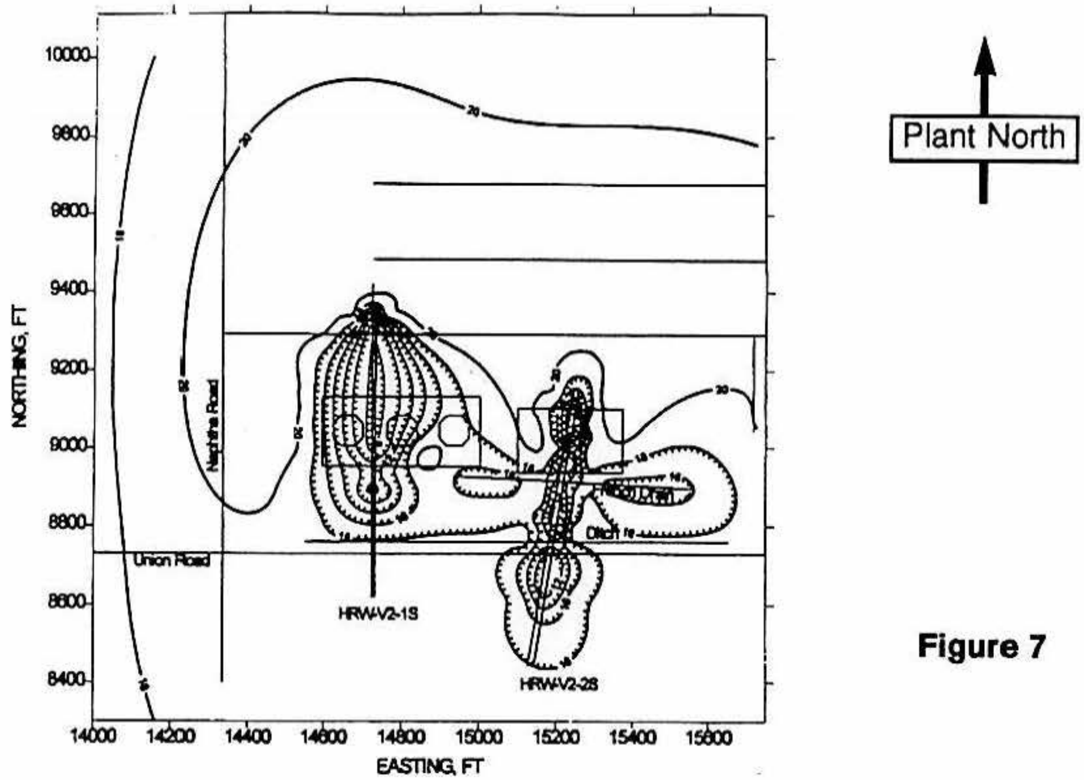

Figure 7

VINYL II DEEP ZONE POTENTIOMETRIC MAP SYSTEM OPERATIONAL

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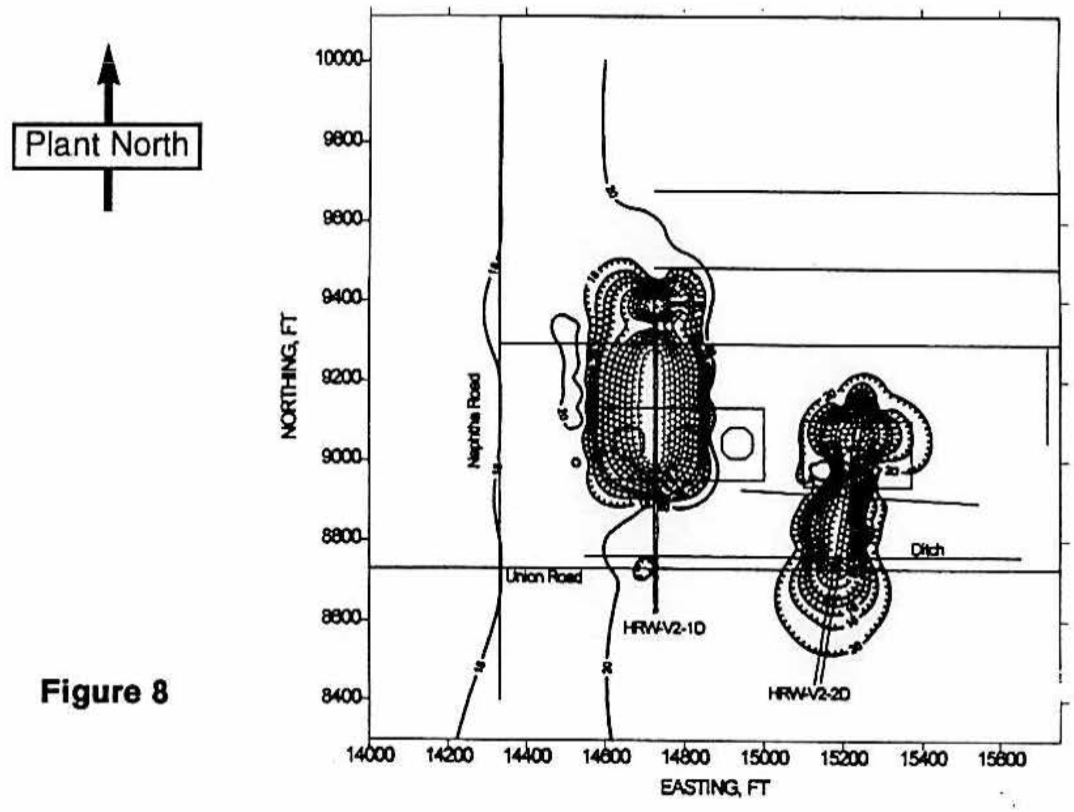


Figure 8

The results of the modeling for the Vinyl II plant provide for the installation of four horizontal ground water recovery wells, two each in both the Shallow and Deep Pervious Zones. For the remainder of the LAD, an additional 28 wells are required to meet the objectives for the site-wide hydraulic containment. Currently a total of 25 horizontal wells have been constructed during the period from February 1995 to March 1996.

Table 3 presents quarterly operating data for the horizontal wells and French Drain at the Vinyl II Plant. This data shows that hydraulic containment and VOC recovery can be achieved at very low flow rates. The deep zone wells are rated at 3 to 5 gpm and shallow zone wells are rated at 5 to 7 gpm. However due to the objective on maintaining hydraulic containment with minimal drawdown and associated subsidence, the wells typically operate at approximately .25 gpm each.

TABLE 3

VINYL 11 HORIZONTAL RECOVERY WELLS AND FRENCH DRAIN QUARTERLY RECOVERY DATA CALCULATIONS

	GW Recovered (Gal)	*VOCs Recovered (Lbs)*	*Avg. Flowrate* (Gal/min)*	*Operating Time (Days/Qtr)*
Recovery Trench				
3rd Qtr 1995	73,000	190	Inconclusive	Intermittent
4th Qtr 1995	1,776,000	1,882	19.30	64
1st Qtr 1996	1,478,910	1,538	17.12	60
2nd Qtr 1996	1,642,210	4,148	13.74	83
Trench Cumulative	**4,970,120**	**7,758**		

	GW Recovered (Gal)	*VOCs Recovered (Lbs)*	*Avg. Flowrate* (Gal/min)*	*Operating Time (Days/Qtr)*
Horizontal Wells (4)				
3rd Qtr 1995	10,930	42	Inconclusive **	Intermittent
4th Qtr 1995	73,560	587	0.80	64
1st Qtr 1996	75,760	1,517	0.88	60
2nd Qtr 1996	74,460	567	.64	81
Wells Cumulative	**234,710**	**2,713**		

* Average Flowrate is based on days of operation during each quarter

** Pumps were run intermittently during the 3rd quarter of 1995

HORIZONTAL WELL CONSTRUCTION AND DESIGN

The horizontal wells under construction at the LAD are directionally drilled using a slant drilling rig with top-headdrive. This equipment has been adapted from the pipeline drilling industry. A steerable downhole motor or jet bit assembly in conjunction with a magnetic steering tool is used to advance the borehole and keep it on course.

Well profiles were prepared which followed the lower most portion of the pervious zones. The profiles and corresponding coordinates were derived from cross-sections developed from the data contained in the Geo-Base® database. Planar coordinates were established primarily from the AQUAEM® and/or TWODAN® model output. However, adjustments to both the model and well layouts were made where potential subsurface obstructions were identified through a review of engineering drawings, and field observations. The wells generally follow a straight path in plan view, but where obstructions were identified, a deviation in well path was engineered.

The drilling rig and equipment used has the ability to drill short radius directional boreholes. However, due to the physical properties (diameter, weight, and length) of the well screen and casing, a short turning radius would be ineffective, especially on the longer wells. Therefore, the turning radius used for the curved section of the borehole was, in most cases, not less than 700 feet.

Although the average directional drilling rigs have the ability to drill and pull back 2,000 to 3,000 feet of casing, the wells constructed at the LAD are all "blind completions". In other words, there is no exit hole and all screen and casing must be pushed into the borehole. Currently, the majority of blind completions wells are limited to lengths not exceeding about 700 feet, however several wells over 1,000 feet long have been constructed during this project.

Due to the greater lengths of the wells drilled at the LAD, specialized drilling fluid systems are key to the successful installation of screen and casing. To provide a stable and gauge borehole, Mixed Metal Hydroxide (MMH) developed by The Dow Chemical Company is utilized as an additive to water based bentonite drilling mud. The addition of the MMH reduces effective viscosity as shear rate increases, thus producing a thixotropic drilling mud. This environmentally safe additive has been successfully used in numerous horizontal ground water recovery well installations and pipeline crossings. The MMH inhibits formation damage and can be easily removed from the borehole and well screen during development operations.

The selection of materials for screen and casing are critical since the recovered ground water may have high concentrations of dissolved VOCs and possibly in some areas, dense non-aqueous phase liquids (DNAPL). Also, high concentrations of chlorides increase the corrosivity of the ground water in certain areas of the LAD. Accelerated corrosion tests were performed on the materials of construction, however, based primarily on historical corrosion data from existing monitor wells and recovery wells, all production screen and casing is specified as Grade 316 L stainless steel. Well screens are pipe-based, wire wrapped, and prepacked with silica sand However, metal membrane well screens are currently being evaluated and field tested, but due to the substantially higher cost, were not selected. The curved surface casing is high density polyethylene (HDPE) pipe. Although it is susceptible to degradation from the VOC's, the HDPE is a construction convenience and protected from the formation fluids by annular cement. Figure 9 shows the generalized construction diagram for the horizontal wells.

COST ANALYSIS

Based on a comparison of the capital cost associated with the existing ground water recovery operations in Block 49 and Vinyl II, and the capital cost for the currently engineered horizontal ground water recovery wells and conveyances, construction cost can potentially be cut in half when applying horizontal wells. This comparison is based on installation of the wells and conveyances using similar materials of construction. Associated O&M costs for the horizontal wells are also anticipated to be approximate one order of magnitude lower than existing vertical wells in operation at the LAD. This is most apparent when comparing the costs related to the replacement of the 224 vertical wells at the Block 49 landfill site with only five horizontal wells.

CONCLUSION

The successful and most cost effective implementation of a ground water remediation program begins with a thorough understanding of the subsurface environment. This requires detailed data collection and evaluation to develop physical models which incorporate lithology, ground water hydrology, stratigraphy, depositional settings, and distribution and concentrations of compounds of concern. Complex databases are required to manage a variety of information used for ground water flow, contaminant transport, and data visualization models; the present day tools for remedial design.

The emphasis to remediate ground water at this facility has required nearly four years for planning, data collection, evaluation, and remediation system design. The implementation of a site-wide assessment eliminates the need for piece-meal subsurface investigations as environmental impacts are uncovered. This effort, accomplished at considerable initial cost, provides the basis for well informed decision making concerning all future environmental projects for soil and ground water remediation, waste management, and facility expansion for the LAD. For the LAD, directional drilling provides a cost effective, long term means of ground water remediation. Although directional drilling for environmental remediation is in its infancy and fewer than 300 horizontal ground water recovery wells have been completed in the United States, the technology is growing in acceptance. The technology affords industries a mechanism for accessing impacted ground water with improved efficiency without seriously impacting facility operations.

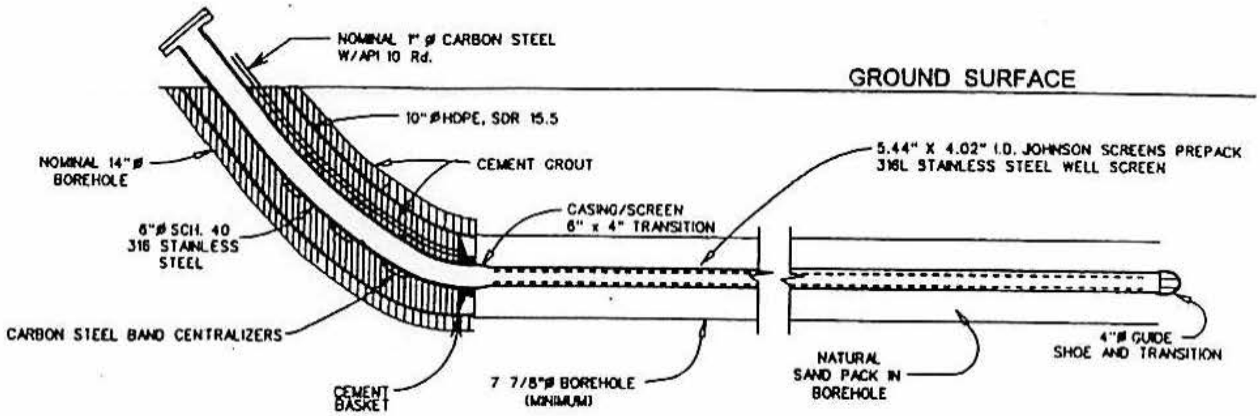


Figure 9: Horizontal well construction diagram

ACKNOWLEDGMENTS

Our thanks are extended to those individuals and companies, providing technical expertise and services for this project. The work of this team, including several years of planning, field studies, and engineering, has developed an innovative plan for ground water remediation at the Louisiana Division:

Mr. Ivy Dupree and Mr. Lucius Boudreaux, Environmental Services,
The Dow Chemical Company, Louisiana Division;
Mr. Bill Doxtater, and Mr. Chuck Oliver, Earth Sciences, The Dow Chemical Company,
Houston, Texas;
Mr. Douglas Gray, Radian International, LLC, Pittsburgh, Pennsylvania;
Ms. Melinda Chambless, Radian International, LLC.,
Plaquemine, Louisiana.

BIOGRAPHICAL INFORMATION

Eric W. Meyer, PG

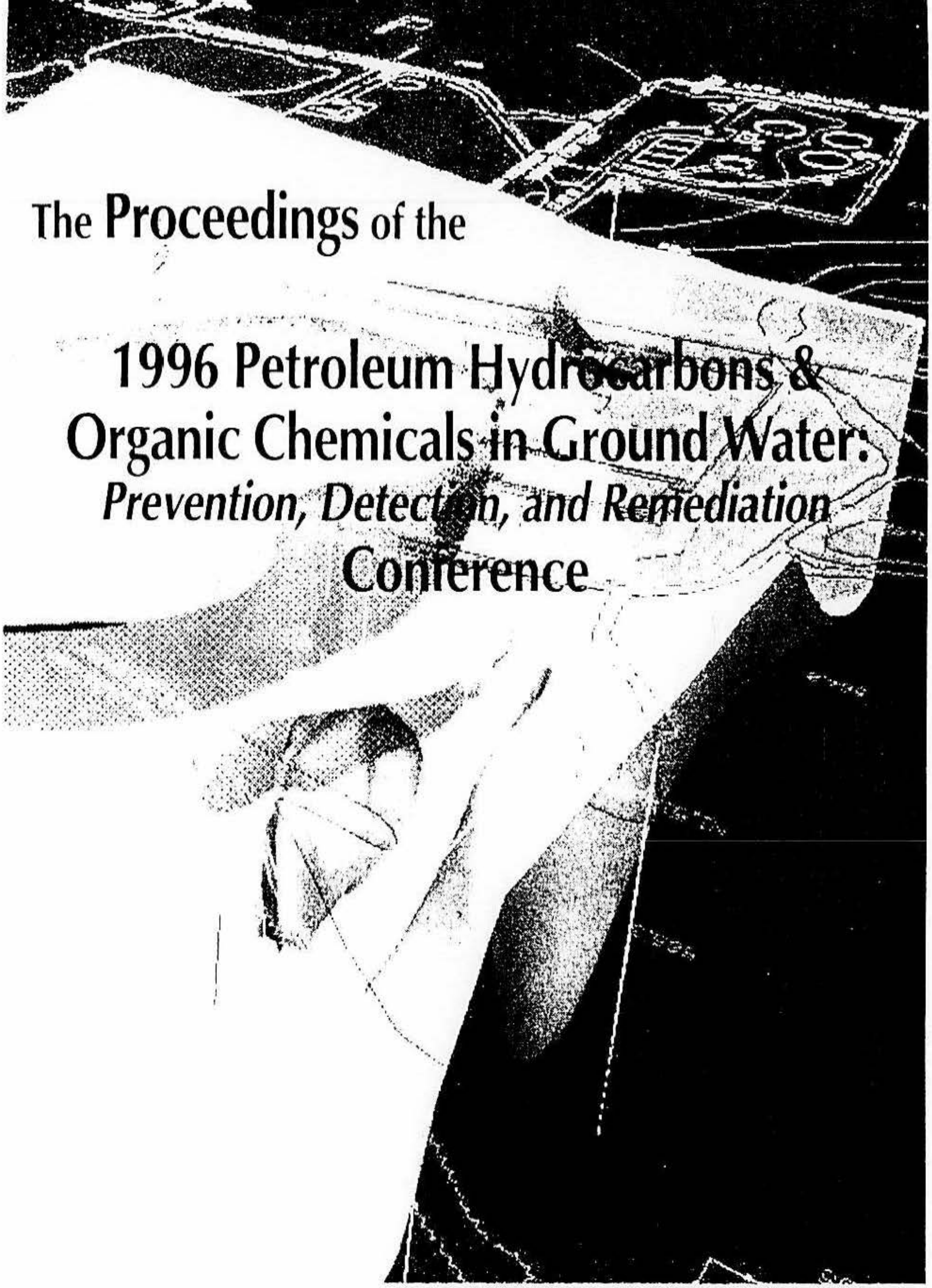
Mr. Meyer is a hydrogeologist and project manager for Radian International LLC, formally Dow Environmental, Inc.. For the past three years, he has managed the engineering and construction of a ground water recovery system for the Dow Chemical Company, Louisiana Division. The ground water recovery system incorporates more than 25 directionally drilled wells and associated pumping and treatment facilities for recovery and hydraulic containment of ground water and DNAPLs. Prior to joining Radian in 1993, he served as a consultant for 10 years, working primarily on projects involving disposal of liquid wastes by deep well injection, ground water supply development and RCRA/CERCLA assessments and corrective action. Mr. Meyer graduated from the University of Florida in 1983 with a B.S. in Geology.

David S. Bardsley, PG

Mr. Bardsley is the Manager for the Environmental Division of Drilex Systems, Inc. He is responsible for the horizontal/directional drilling and well installations provided by Drilex. Along with managing horizontal well installation projects at US Government facilities, Mr. Bardsley has managed the drilling and construction of 25 wells at the Dow Chemical Company, Louisiana Division. Prior to joining Drilex in 1993, he has worked for 9 years in the environmental drilling industry. Mr. Bardsley graduated from the University of Missouri - Rolla in 1984 with a B.S. in Geology and Geophysics.

The **Proceedings** of the

1996 Petroleum Hydrocarbons & Organic Chemicals in Ground Water:
Prevention, Detection, and Remediation
Conference



national ground water association

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