Development of an Outpost Monitoring Well Network for At-Risk Supply Wells

Using Groundwater Flow, Particle Tracking

and Solute Transport Modeling

Presented

by

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in Partial Fulfillment of the

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Abstract of the thesis

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This paper documents the use of groundwater flow, particle tracking and transport modeling to support the selection of groundwater monitoring well locations that can serve as early warning wells in identifying a future potential impact at select public supply wells. As a result of past manufacturing activities, groundwater beneath the former Grumman Aerospace facility was impacted by volatile organic compounds. Numerous public supply wells are located down-gradient of the dissolved VOC plume emanating from the Grumman site. Early detection of impending VOC impacts would enable at-risk public water supply well operators to design and construct treatment systems prior to detecting an impact at their supply wells. Through this study effort, a monitoring well network was designed to detect the VOC-impacted groundwater approximately 5 years before the dissolved plume would impact the public supply well. Monitoring well locations and screen settings were chosen to enable the monitoring of groundwater quality upgradient of the at-risk supply wells to detect the advancing VOC-impacted groundwater. This paper discusses the methods used to predict the rate of movement and anticipated flow path of VOC-impacted groundwater as it moves through the aquifer, and how that information was used to select monitoring well locations and screen settings to permit detection of impending VOC impacts to supply wells.

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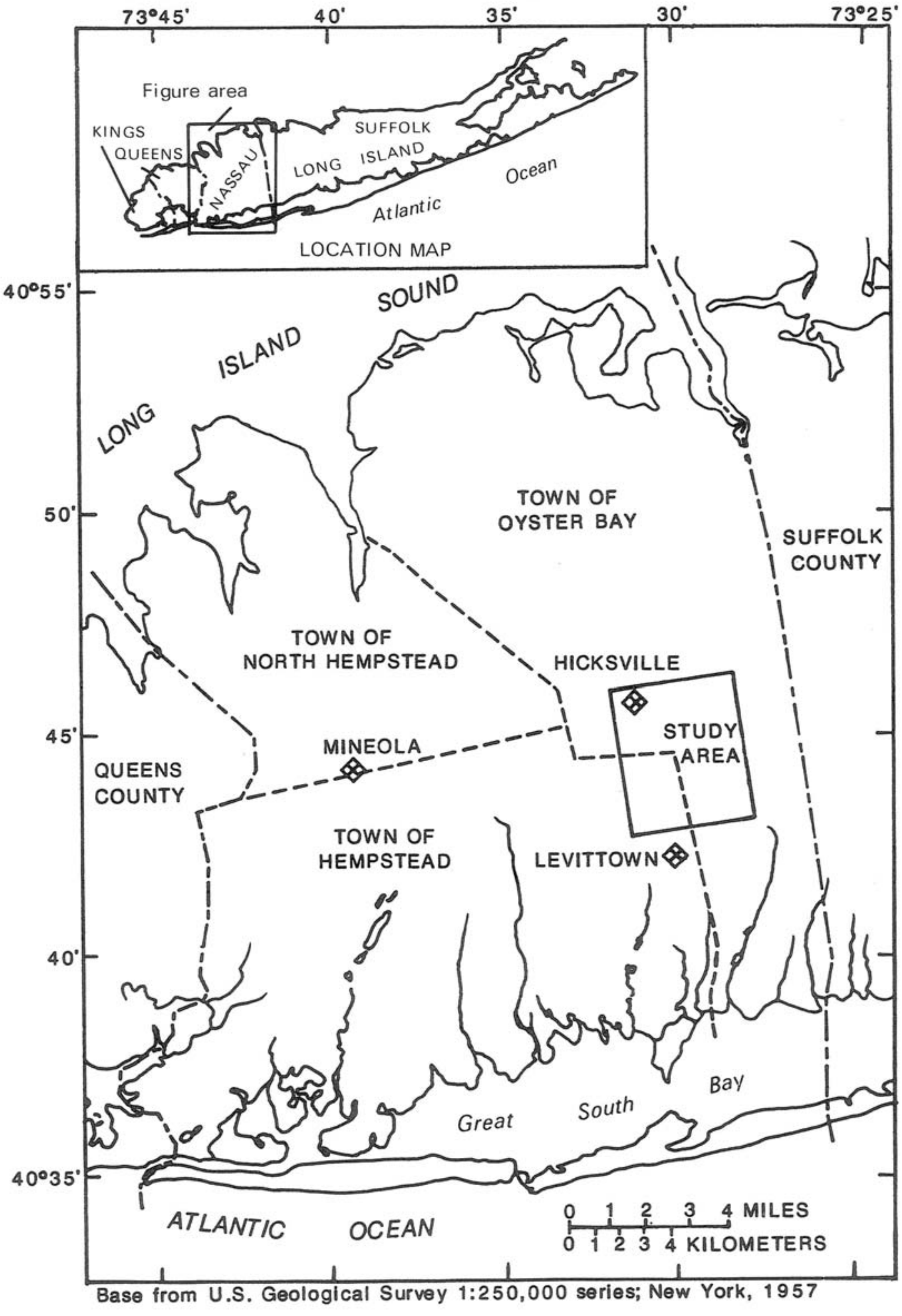
Introduction

This paper documents the use of groundwater flow, particle tracking and transport modeling to support the selection of groundwater monitoring well locations that can serve as early warning wells in identifying a future potential impact at select public supply wells.

As a result of manufacturing activities occurring between the1930's and 1980's, groundwater beneath the former Grumman Aerospace facility was impacted by volatile organic compounds. The former Grumman Aerospace facility (herein referred to as Grumman) is located in the Town of Oyster Bay on Long Island in New York State. **Figure 1** shows the location of the study area with respect to Long Island and Nassau County. East-central Nassau County, where Grumman is located, is a highly developed urban-residential and industrial-commercial area.

Numerous public supply wells are located down-gradient of the dissolved VOC plume emanating from the Grumman site. Early detection of impending VOC impacts would enable at-risk public water supply well operators to design and construct treatment systems prior to detecting an impact at their supply wells. Through this study effort, a monitoring well network was designed to detect the VOC-impacted groundwater approximately 5 years before the dissolved plume would impact the public supply well. Monitoring well locations and screen settings were chosen to enable the monitoring of groundwater quality upgradient of the at-risk supply wells to detect the advancing VOC-impacted groundwater.

This paper discusses the methods used to predict the rate of movement and anticipated flow path of VOC-impacted groundwater as it moves through the aquifer, and how that information was used to select monitoring well locations and screen settings to permit detection of impending VOC impacts to supply wells. This paper will also review similar work conducted by others to model plume movement, to predict groundwater flow directions and rates of travel, and to establish well-head protection areas. Some of those techniques will be contrasted with the procedures used in this study. Finally a comparison of the model-predicted results to observed data will be presented. For the benefit of those unfamiliar with the study area, a brief discussion of hydrogeologic setting, past manufacturing activities, and suburban development is given.



Base from U.S. Geological Survey 1:250,000 series; New York, 1957

Figure 1. Location of Study Area in eastern Nassau County, Long Island, New York.

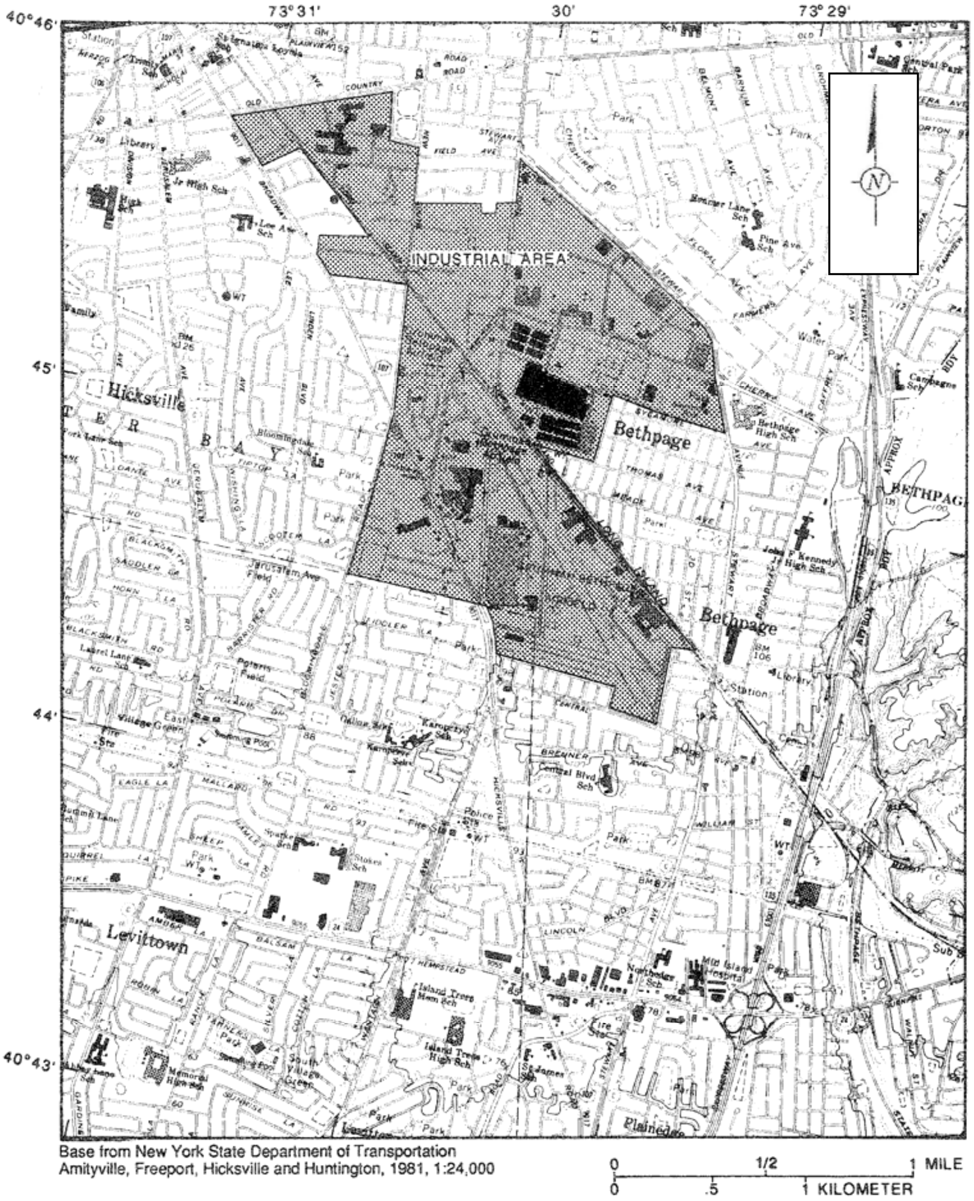
Hydrogeologic Setting

The area is underlain by approximately 1,200 ft of unconsolidated Pleistocene and Cretaceous deposits, consisting primarily of sand, gravel, silt and clay. The unconsolidated deposits have good water-transmitting properties except where clay forms continuous layers that can impede vertical groundwater flow. Overlying the Cretaceous deposits are 50 to 100 ft of Pleistocene deposits (Smolensky et al., 1990).

The four hydrogeologic units underlying the study area, in descending order are: the upper glacial aquifer (Pleistocene), Magothy aquifer, Raritan confining unit, and the Lloyd aquifer (all Cretaceous). Most public-supply water is pumped from the Magothy aquifer. The average horizontal hydraulic conductivity in the Magothy aquifer is about 50 ft per day (Smolensky et al., 1990). Pumping rates for municipal supply wells in eastern Nassau County typically range from about 500,000 to 2,000,000 gallons per day (ARCADIS, 2003).

Development of Manufacturing Facilities

Beginning in the 1930’s and continuing through the 1980’s, the Grumman Aerospace Corporation operated an aircraft manufacturing and testing facility at the Bethpage, New York site. Located in the Town of Oyster Bay, the former manufacturing facility lies in east-central Nassau County, and is now surrounded by the densely populated suburban communities of Levittown, Farmingdale, South Farmingdale, Plainview, and Bethpage **(see Figure 2)**.



Base from New York State Department of Transportation
Amityville, Freeport, Hicksville and Huntington, 1981, 1:24,000

Figure 2. Location of the Former Grumman Aerospace and Naval Weapons Industrial Reserve Plant (shaded), Nassau County, New York.

Beginning in the 1940’s, these communities began transforming from primarily farming communities to the suburban communities present today. Each of these communities relies exclusively on groundwater pumped from high-capacity supply wells as the sole source of drinking water for their residents. The manufacturing activities undertaken at the Bethpage Plant involved the machining and finishing of metals, assembly of aircraft and aircraft parts, the testing of engines, and the flight testing of aircraft (ARCADIS, Geraghty & Miller, 2000).

Groundwater Plume

The groundwater plume is believed to have developed as a result of the discharge of various solvents used in the manufacturing process to groundwater water via land surface disposal, sludge drying beds, disposal of waste liquids to onsite drywells, storm water drywells, and the onsite sewage treatment plant (Feldman et al., 1992). It is also presumed by the author that significant leakage from onsite solvent bulk storage containers contributed to the groundwater impacts.

The dissolved groundwater plume consists of a number of volatile organic compounds, but is primarily composed of trichloroethene (TCE), and tetrachloroethene (PCE). Both are solvents that were used in the course of manufacturing at the site as degreasers. Individual metal parts were cleaned following machining, and assemblies were cleaned prior to painting.

During their tenure at the site, Grumman operated as many as 16 high capacity supply wells for both potable and process water. While not all wells were in use at one time, it was not uncommon for several wells to be operating at peak capacity (~1,000 gallons per minute [gpm]) at any given time. Prior to the early 1960's when VOCs were recognized in the Grumman supply wells, the water produced from this onsite network was used for drinking. More recently (since the 1960's) the water produced has been used for air conditioning (non-contact cooling) and various manufacturing-related applications. The operation of these high capacity supply wells facilitated both the horizontal and vertical movement of dissolved solvents throughout the aquifer beneath the site.

Today, the dissolved volatile organic plume is approximately 18,000 ft long (north to south), reaches a width of 8,000 ft (east to west), and is about 600 ft thick.

Groundwater Model

A groundwater model was constructed by ARCADIS (formerly Geraghty & Miller, Inc.) for the Northrop Grumman Corporation (formerly Grumman Aerospace) to assist in the design of an Interim Remedial Measure for the containment of impacted groundwater beneath the Grumman site. In the early 1990's the groundwater flow and particle tracking computer model codes MODFLOW (McDonald and Harbaugh, 1988) and MODPATH (Pollack, 1989) were used to support the design and evaluation of various containment systems (ARCADIS, 2003). Proposed remedial and containment systems included the use of both new and existing extraction and containment wells. The proposed system has been constructed and is currently in operation.

The model has undergone a series of modifications as it was utilized to evaluate other additional impact areas south of the Grumman site. The modifications typically included adjustments to model grid cell size, the refinement of existing layers, and the addition of new model layers. The revised model was constructed using Waterloo Hydrogeologic's Visual MODFLOW PRO (Visual MODFLOW) package. Visual MODFLOW is a fully-integrated package combining MODFLOW, MODPATH, ZoneBudget, MT3D and WinPEST with a graphical user interface (Waterloo Hydrogeologic, 2005). The package allows the user to construct, calibrate, execute and evaluate the results of a model within a single software package. Currently the model grid consists of 12 model layers, each with 351 rows and 328 columns for a total of 1,381,536 model nodes. The model encompasses an area approximately 29,000 ft (east to west) by 42,800 ft (north to south) or 44.52 square miles. As expected, the model has benefited from the increased computer power of today's processors.

Model cell size varies across the model from a minimum of 50 ft by 50 ft in the areas of interest to a maximum of 780 ft by 1500 ft at the models edges. **Table 1** provides a summary of the top and bottom elevation of each model layer, its thickness, its assigned hydraulic conductivity, and the hydrogeologic unit they represent. A discussion of assigned hydraulic conductivities and the basis for their selection is provided below in the section title Flow Field Development. The extent (limits) of the model area is shown on **Figure 3**. Select roads on the figure are identified for reference.

The VOC distribution used in the model was based upon an assessment of water quality data collected from a monitoring well network consisting of monitoring wells located both on- and off-site, water quality results from a series of vertical profile borings drilled south and southeast of the site, and from water quality results reported by the water suppliers themselves. Water quality data collected from the supply and monitoring wells was averaged over a 4 year period.

Model Layer No.	Top Elevation (1) (ft msl)	Bottom Elevation (1) (ft msl)	Thickness (ft)	K(h)(2) (ft per day)	K(v)(3) (ft per day)	Hydrogeologic Unit	Unit Description (4)
1	Wt	15	variable	300	60	Upper Glacial Aquifer/ Transitional Zone	Sand, fine to coarse, gravel, glacial outwash deposits, commonly brown or tan but may be yellow or orange. Some thin local lenses of clay or silty zones.
2	15	-20	35	120	24		
3	-20	-50	30	120	24		
4	-50	-100	50	25	1	Magothy Aquifer	Sand, fine to medium, clayey in part; interbedded with lenses and layers of coarse sand and sandy and solid clay. Gravel is common in basal zone. Sand and gravel are quartzose. Lignite, pyrite, and iron oxide concretions are common. Colors are gray, white, red, brown, and yellow.
5	-100	-150	50	25	1		
6	-150	-240	90	25	1		
7	-240	-330	90	25	1		
8	-330	-420	90	25	1		
9	-420	-500	80	25	1		
10	-500	-550	50	25	1		
11	-550	-600	50	60	6		
12	-600	-700	100	60	6		

(1) Model Layer elevations were taken at the southern boundary of the former Grumman Aerospace Plant.
(2) Horizontal hydraulic conductivity.
(3) Vertical hydraulic conductivity.
(4) Taken from *Geohydrology of the Bethpage-Hicksville-Levittown Area, Long Island, New York (USGS, 1990).*
ft means feet.
msl means relative to mean sea level.
Wt means water table.

Table 1. Model Layer Thickness, Assigned Hydraulic Conductivity, and Corresponding Hydrogeologic Unit.

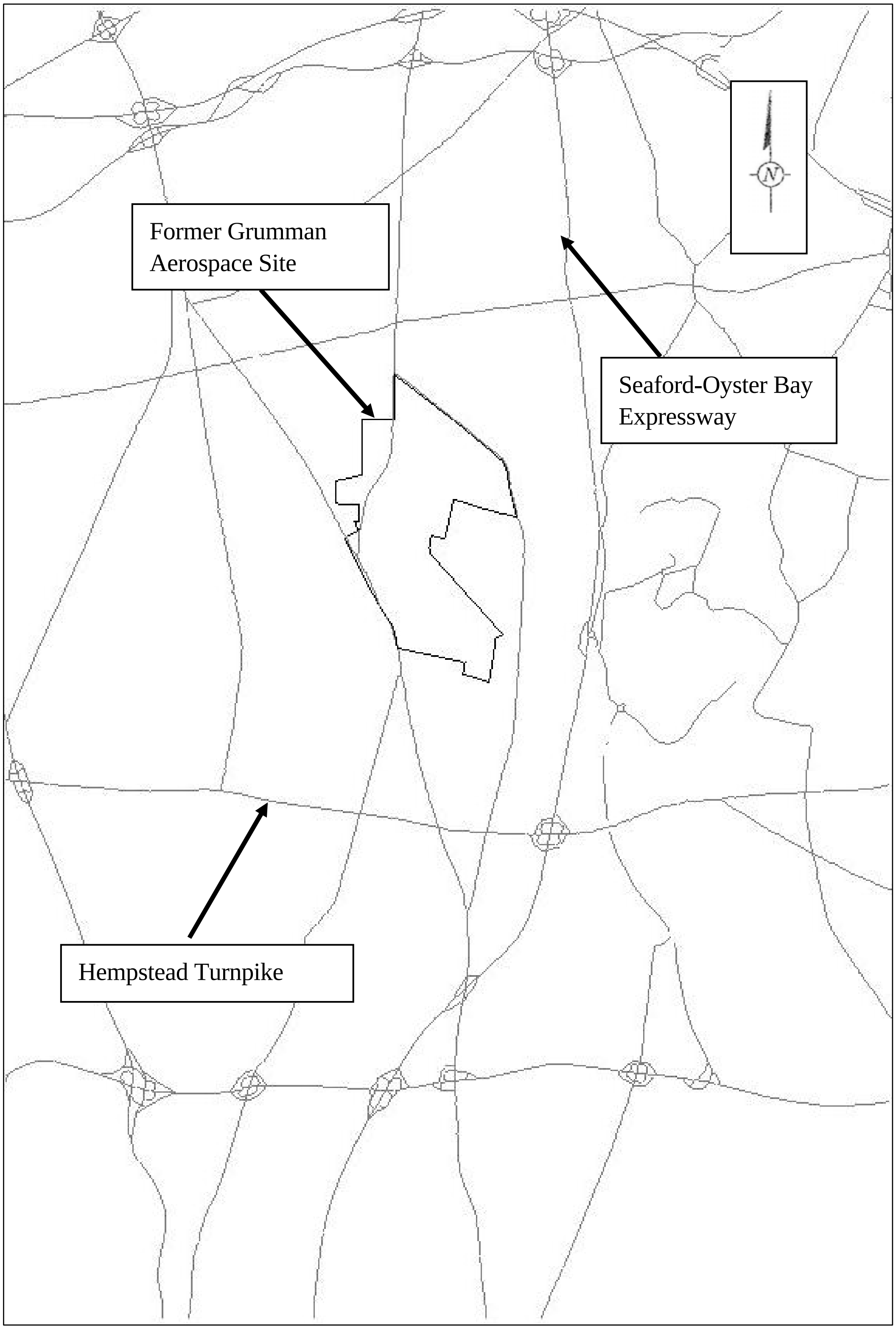


Figure 3. Plan view of the extent of the model area.

Scale: 1 inch = 5,000 feet.

Supply well screen lengths are typically on the order of multiple tens of feet in length whereas a typical monitoring well screen is 10 to 20 ft long. Longer screen lengths have the potential to provide a sample which, depending on sampling technique, may represent the average concentration in the aquifer over an area much larger the aquifer segment just outside the well's screen. For this evaluation, monitoring well data were considered to more accurately represent aquifer conditions than supply well data.

In an effort to define the leading edge of the plume, and to quantify the distribution of dissolved VOCs in portions of the aquifer with poor monitoring well coverage, a series of vertical profile borings were drilled. Vertical profile boring data were a one-time-only sample collected through a five foot long screen. A drilling rig was used to drill the vertical profile boring to the desired completion depth. A temporary well (usually 2-inch diameter steel casing with a 5 ft long screen at its bottom) was set in the completed boring and the borehole was allowed to collapse against the well. A submersible pump was set in the temporary well and the well purged and sampled. Following sampling, a pump truck was used to lift the well casing and screen approximately 10 ft to the next interval to be sampled, and the process was repeated until the well point was raised to the surface. Upon completion, a "profile" of the vertical distribution of VOCs at the borehole location is produced. Soil samples were typically collected during the drilling so that clay or silty zones could be avoided during groundwater sample collection. Upon completion of the profile boring, the borehole was abandoned and no additional samples were taken. The vertical profile boring offered the advantage of providing multiple groundwater quality samples throughout a vertical aquifer segment. When defining the initial conditions for the transport model, the vertical profile boring data helped delineate the plume between monitoring well and supply well locations both vertically and horizontally.

Figure 4 is a plan view of the extent of VOC-impacted groundwater (based on water quality data collected in 2000).

At-Risk Supply Wells

To determine which supply wells were potentially at-risk of being affected by VOC-impacted groundwater, an evaluation of the location of VOC-impacted groundwater relative to the water supply well fields was conducted. Specifically, the VOC-impacted groundwater was mapped based on analytical data derived from groundwater samples, as described above. VOC concentrations in the mapped plume ranged from 5 micrograms per liter (μg/L) to 10,000 μg/L.

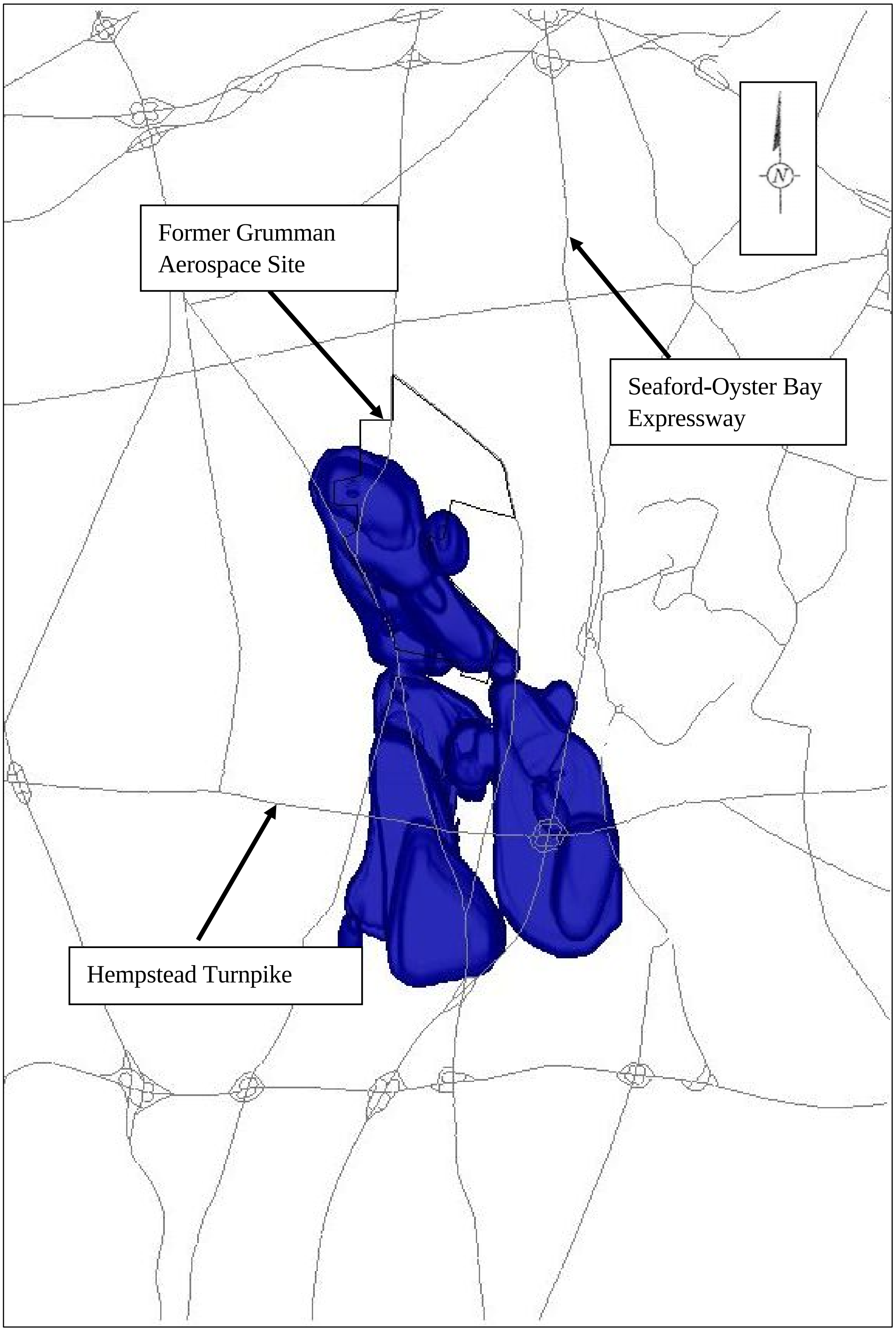


Figure 4. Plan view of extent of VOC-impacted groundwater plume. This is a top-down view of a three dimensional surface representing VOC concentrations greater than 5 µg/L in all impacted model layers.

Scale: 1 inch = 5,000 feet.

Based on the mapped distribution of VOC-impacted groundwater, and the results of preliminary solute transport simulations (conducted specifically to assess potential for impact), the following water supply well fields were identified as being at risk of being impacted by the VOC plume within 15 years:

- South Farmingdale Water District Well Field Number 1 (Well ID Nos. N4043, N5148 and N7377),
- South Farmingdale Water District Well Field Number 3 (Well ID No. N6150), and
- New York Water Service Wells 3S and 4S (Well ID Nos. N8480 and N9338).

The locations of the at-risk wells are shown on **Figure 5.** South Farmingdale Well Field No. 1 is approximately 200 ft southeast of the plumes leading edge; South Farmingdale Well Field No. 3 is at the plumes leading edge; and New York Water Service Wells 3S and 4S are about 1,200 ft downgradient of the plumes leading edge.

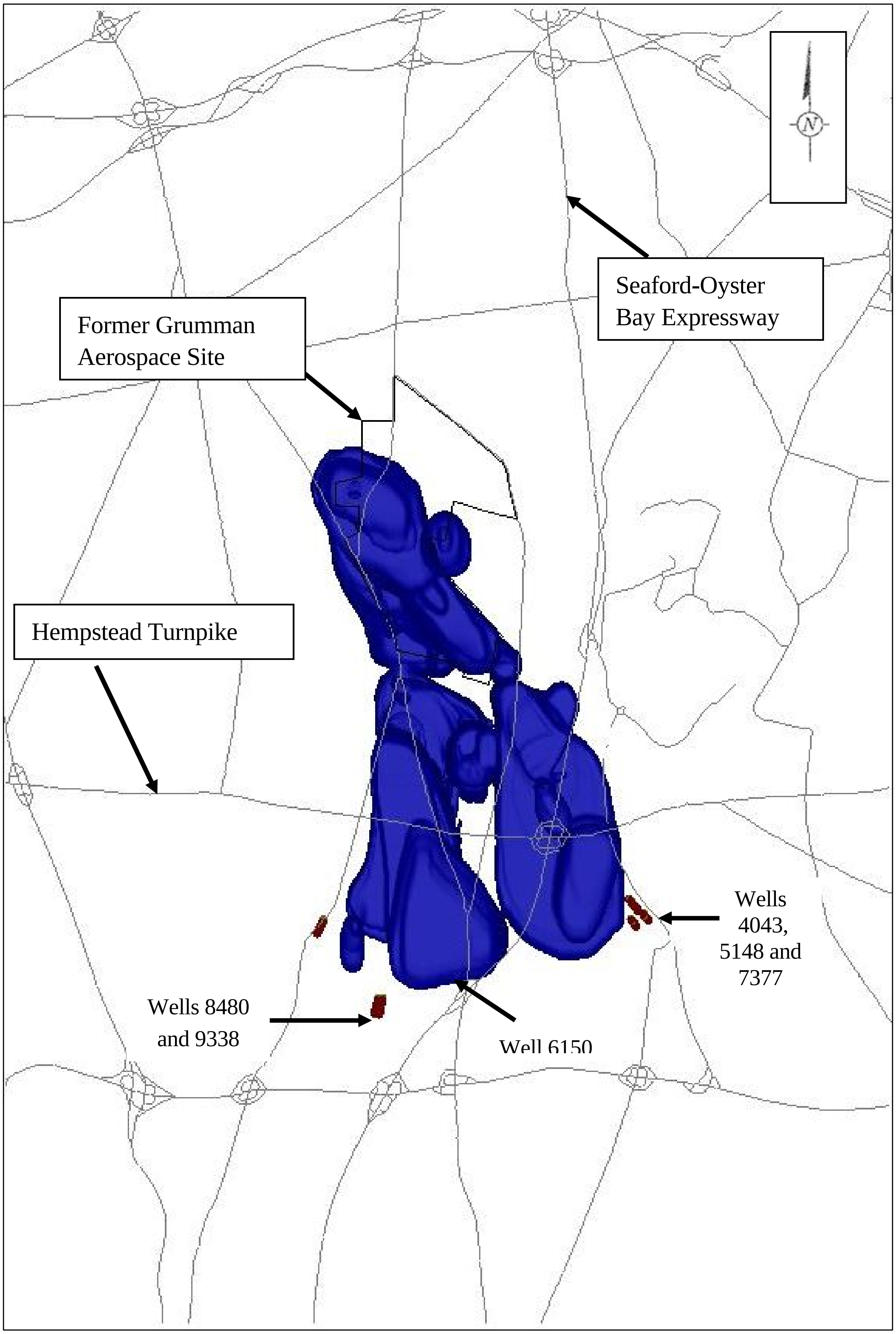


Figure 5. Locations of Public Supply Wells located downgradient of VOC-impacted groundwater plume. This is a top-down view of a three dimensional surface representing VOC concentrations greater than 5 μg/L in all impacted model layers. Scale: 1 inch = 5,000 feet.

Although numerous other water supplies exist at greater distances downgradient of the site, the well fields listed above are at-risk of an impact in the near term (within 15 years). The determination of potential for impact was based upon a model-predicted VOC concentration at the water-supply well of greater than 5 μg/L within 15 years. The threshold of 5 μg/L is based on the current maximum contaminant level for VOCs in drinking water, and the desire of the various water suppliers to distribute water with no detectable concentrations of VOCs. The intention of the threshold was to select a VOC concentration which could be reliably assessed with current analytical techniques, and would be at a sufficiently low-level such that design, construction, and operation of a treatment system could be completed before VOC concentrations in the pumped water forced the water districts to suspend production from the well.

New York State Department of Environmental Conservation (NYSDEC) Well Identification numbers, Well Screen Intervals for these supply wells, their Average Annual Pumpage, and the Number of Customers Served by the water districts are summarized in **Table 2**. It is apparent from this table that any impact to the water supply would have serious repercussions throughout the community given the number of customers serviced by these water suppliers.

The average annual pumpage reported in Table 2 was calculated from monthly production reports submitted by the water districts to the NYSDEC for the period of January 1998 through June 2001, and is the pumping rate assigned to these wells for steady-state groundwater flow simulations. Supply well screen elevations range from approximately 250 ft below sea level to nearly 700 ft below sea level.

Municipality and Well Field	Municipal Supply Well ID	Well Screen Elevation(s) (ft msl)	Average Annual Pumpage (1) (mgd)	Number of Customers Served (2)
South Farmingdale Water District Well Field No. 1	4043	-247 to -304	374,457	45,000
	5148	-284 to -299 -228 to -262	590,824	
	7377	-533 to -553 -568 to -583 -594 to -604 -657 to -683	222,150	
South Farmingdale Water District Well Field No. 3	6150	-487 to -547	558,241	
New York Water Service Wells 3S and 4S	8480	-509 to-594	1,602,533	175,000
	9338	-527 to -588	1,241,867	

ft means feet.
msl means relative to mean sea level.
mgd means millions of gallons per day.
(1) Average Annual Pumpage was calculated based on monthly production reports for the period of January 1998 through June 2001.
(2) Number of Customers taken from the 1996 Directory of the Long Island Water Conference. The number represents the population of the water district, which is typically served by multiple supply well fields.

Table 2 – Summary of Supply Well Details for supply wells downgradient of VOC-impacted groundwater.

Outpost Monitoring Well Network

The outpost monitoring well network was designed to enable the public supply well operators to detect the presence of VOC-impacted groundwater in the aquifer up-gradient of their supply wells, before the supply wells were directly affected.

To address uncertainties associated with predicting the movement of the plume over a large vertical horizon, clusters of monitoring wells rather than individual monitoring wells were installed so that various vertical horizons could be monitored. The monitoring well clusters were located such that impending supply well impacts would be detected at least 5 years before the supply well would be impacted.

However, merely detecting the presence of VOCs at the outpost monitoring well is not a sufficient indicator of the need to begin the costly process of remedial system design and construction. It is likely the plume will undergo some dispersion as it moves through the aquifer from the outpost well to the supply well. As a result, the leading edge of the plume does not move as a “front” through the aquifer; instead, as the plume advances the leading edge of the plume typically undergoes some attenuation, resulting in an apparent slowing of the plumes rate of advancement. In addition, although the regional gradient for groundwater flow in this area is generally to the southeast, portions of the aquifer are subjected to vertical as well as horizontal gradients. These vertical gradients can be the effect of local pumping centers, or differences in head developed due to stratification of the aquifer, and the presence of lower conductivity units.

To ensure that the design and construction process was not begun unnecessarily, an effort was made to determine what VOC concentration in the aquifer at the outpost monitoring well was indicative of a need to establish treatment at the supply well. More simply, what concentration, when detected at the outpost well, indicated that in 5 years or less VOC concentrations in the supply well would exceed 5 parts per billion (the maximum contaminant level [MCL] for VOCs permitted by the NYSDEC to be present in drinking water [New York State Department of Environmental Conservation, 1999]).

The model-predicted VOC concentrations at the outpost monitoring well location which are indicative of an impending exceedance of MCLs at the public supply wells within 5 years are referred to in this paper as “trigger values”. Trigger values were defined for each of the supply wells at risk of impact. Detection of a trigger value indicates the need to begin design work on a treatment system for the downgradient supply well.

Similar Work by Others

No examples of the development of this type of monitoring well network were found in the literature. However, this type of groundwater monitoring system is analogous to a well-head protection type system. Following is a summary of various papers related to the delineation of wellhead protection areas, capture zone determination, and applications of particle tracking reviewed in support of this paper.

- Bair et al. (1991) argued that the use of numerical models to develop well head protection areas was generally unnecessary and prohibitively expensive when dealing with predominantly two-dimensional flow regimes. They present a case study using analytical methods to simulate aquifer response to pumping that used the predicted heads in a particle tracking analysis to define the wells capture area.

- Wuolo et al. (1995) documented the application of the Analytic Element Method (AEM) to delineate wellhead protection areas (WHPA) for existing and proposed municipal wells in the City of Brooklyn Park, Minnesota. They also argued that for WHPA delineations, AEM models were superior to finite-element and finite-difference models because they can be more cost-effectively calibrated, modified and expanded.

- Forster et al. (1997) prepared a comparison of models for delineating wellhead protection areas in confined and semi-confined aquifers in alluvial basins which identified the significance of hydraulic conductivity in the principal aquifer in controlling the size and shape of the computed capture zones. Their study made comparisons between the semi-analytical WHPA2.0/GPTRAC, the two-dimensional numerical code FLOWPATH, and GRAPHIC GROUNDWATER, a commercial version of the three-dimensional MODFLOW and GWPATH.

- Frind et al. (2002) advocate the use of backward advective-dipsersive transport for delineating capture zone in complex multi-aquifer systems.

- Shafer (1987) presents a two-dimensional numeric code for computing time-related capture zones in around water supply wells. As in the previously described papers the focus of this effort is to protect water supply wells from impacts resulting from land development within the wells capture zone.

- Ahlfield and Sawyer (1990) describe a methodology for simulating and optimizing groundwater remediation system capture zones by allowing the computer to vary both proposed remedial wells location(s) and pumping rate(s) to develop the most cost-effective capture zone for achieving cleanup goals.

- Varijen and Shafer (1991) present a stochastic method for assessing uncertainties in time-related capture zones resulting from variability in modeled distribution of hydraulic conductivity values versus potential distributions of hydraulic conductivity.

- Springer and Bair (1992) present a comparison of analytical and numerical methods used to delineate capture zones of wells in stratified-drift buried-valley aquifers. They compared the applicability and effectiveness of the CAPZONE/GWPATH, DREAM/RESSQC, and MODFLOW/MODPATH software's.

- Schafer (1996) provided a compromise between 2D solutions for capture zones and 3D models. His method determined the capture zones around wells and drains in homogenous, anisotropic aquifers in a uniform flow field which enabled the design, placement and operation of extraction systems for contaminant plumes which partially penetrate thick aquifers.

- Buxton, Reilly, Pollack and Smolensky (1991) used particle tracking analysis to estimate deep-flow recharge areas on Long Island, New York, and to estimate the effects of development on the flow-patterns, size and shape of recharge areas.

- Zheng (1994) assessed the errors in particle tracking results caused by the limited spatial discretization of a model grid. Specifically, he assess the affects of the presence of a "weak" sink or source, and the use of a model grid with varying vertical cell dimensions within an individual layer.

The United States Geological Survey conducted a comprehensive study of the Bethpage-Hicksville-Levittown area which was described in a series of reports:

- Smolensky and Feldman (1990) described the geohydrology of the area;

- Feldman, Smolensky and Masteson (1990) described the groundwater quality of the area; and

- Smolensky and Feldman (1995) developed a three-dimensional advective transport model for volatile organics in groundwater beneath the area.

Modeling Approach

The following sections provide a detailed description of the various modeling techniques used in this study. At risk supply wells were identified through previously conducted mass transport simulations. Once identified, a multi-faceted groundwater modeling approach was used to support the selection of the locations and screen settings of the outpost monitoring well clusters. In the case of this effort, the goal was to select monitoring well locations which would be able to detect an impending impact to the supply well approximately 5 years before the impacted groundwater would be extracted at the supply well. However the rate and direction of groundwater flow near a supply well is variable. As groundwater moves through the capture zone of a well the velocity of groundwater increases; flow may not be horizontal, but may move vertically toward the well screen. Simply defining a fixed radius around the well representing a five year travel time would be inappropriate.

1. Backward particle tracking was used to establish an ellipsoid around each supply well which defined the limits of the 5 year time of travel area. Groundwater originating outside this ellipsoid would take approximately 5 years to reach the supply well.

2. Forward particle tracking from the plumes leading edge was used to isolate the flow path associated with the model-predicted fastest moving segment of the plume. This flow path was used to guide the selection of the screen zone of the monitoring wells.

3. A mass transport simulation was used to determine what concentration of VOCs at the outpost well indicated an impending exceedance of the MCL at the supply well within 5 years.

Flow Field Development

A steady-state groundwater flow model was used to develop a flow field for both the particle tracking and advective transport efforts. The model simulated the operation of public supply wells, on-site remedial wells, and on-site recharge basins. The model was calibrated to water-level measurements collected from both on- and off-site monitoring wells.

No natural lateral groundwater system boundaries exist in the vicinity of the Grumman site. To minimize the introduction of error that could potentially be introduced in the definition and specification of lateral model boundaries, the lateral boundaries assigned in the model were chosen to be at significant distances from the site. The northern model boundary generally corresponds to the regional groundwater divide that is oriented west-east and is located approximately 10,000 feet north of the site. South of the groundwater divide, under natural conditions, all recharge to the groundwater system eventually discharges to the Great South Bay/Atlantic Ocean or streams located along the south shore of Long Island (Buxton et al., 1991). Therefore, the location of representative flow lines (no flow boundaries) east and west of the site was used to select eastern and western model boundaries. These boundary conditions were chosen considering both their distance from the site and their general orientation relative to the site and the groundwater divide (perpendicular to the divide). Finally, the southern boundary location was chosen to be at sufficient distance from the site such that the assignment of constant heads to this boundary did not affect heads in the models areas of interest. The southern boundary does not correspond directly to any natural boundaries. Potentiometric surface maps for the Upper Glacial and Magothy aquifers (Busciolano, 1998) based on water-level measurements by the United States Geological Survey in April, 1997 were used as the basis for the assignment of constant heads to the models northern and southern boundaries.

Hydraulic conductivity values used in the model are presented in **Table 1**, and were initially based on published values for geologic formations on Long Island (McClymonds and Franke, 1972), on results of aquifer tests (Lindner and Reilly, 1983), on previous modeling efforts in the area (Smolensky and Feldman, 1995), and on other regional modeling efforts in Nassau County (Reilly and Buxton, 1985, Buxton and Smolensky, 1998). These values were adjusted during model calibration to produce a representative groundwater flow field. In general, the hydraulic conductivities and vertical anisotropy ratios assigned in the model are consistent with those presented by Smolensky et al. (1990).

The areal recharge rate was calculated by reviewing precipitation records from January 1984 through November 2001 for the precipitation station at MacArthur Airport located in the town of Islip, Long Island. A long-term average annual rate was established based on these data. The areal recharge rated in the model is 0.00588 feet per day (25.75 inches per year), consisting of fifty percent of the average annual precipitation, and 10% of the modeled municipal pumping representing leakage from both municipal water supply systems and sewers and general non-consumptive water use (i.e., lawn sprinkling).

The flow model was calibrated by evaluating the agreement in water levels at more than eighty-one locations. The specific calibration criteria were as follows:

- Simulated flow patterns will adequately reproduce observed flow patterns.

- The average of residuals will be within 5 percent of the range of observed hydraulic heads.

- The residual standard deviation will be within 10 percent of the range of observed hydraulic heads.

- The distribution of residuals will not show any spatial bias.

All criteria for assessing if model calibration is acceptable were satisfied. Simulated flow patterns reproduced observed flow patterns; average residuals were less than 2.4 ft; the residual standard deviation was 3.05 ft; and the distribution of residuals did not show any spatial bias. A scatterplot showing the relationship between observed and model-predicted heads for the calibration targets is shown in **Figure 6**.

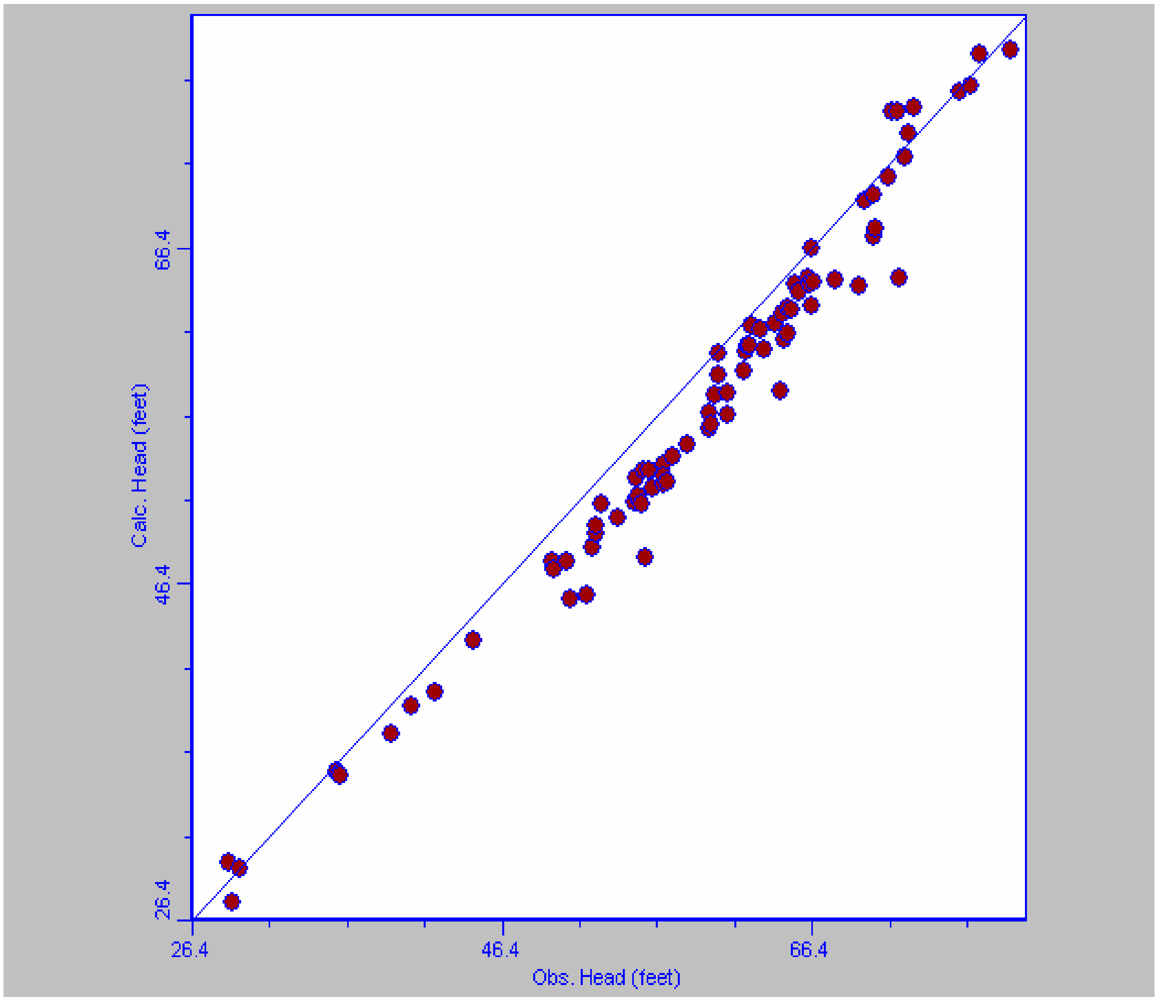


Figure 6. Observed Head vs. Calculated Head Scatterplot.

The calibration targets with the highest and lowest head values (corresponding to target locations near the northern and southern model boundaries, respectively) are evenly distributed about the 45 degree line representing observed heads equal to model-predicted heads. The remaining targets, located throughout the interior of the model, generally fall below the line representing an ideal match between observed and model predicted heads. As such, the model-predicted heads are lower than the observed heads; the model slightly under-predicts heads in the models interior.

It is the author’s opinion that the data set used to develop the calibration targets (water-levels collected in the Spring 2001) represented higher than average water-levels resulting from above average precipitation in the Spring 2001. On average 16.78 inches of precipitation fell for the months of March-July between 1984 and 2001; in the Spring of 2001, 17.65 inches of precipitation fell.

Supply Well Capture Zone Analysis

The capture zone of a supply well is the three-dimensional section of an aquifer from which the supply well extracts groundwater.

The model-predicted capture zone was determined under steady-state pumping conditions and was the area bounded (horizontally and vertically) by a distribution of particle pathlines representing the limits of flow to the supply well.

This distribution of pathlines was generated by starting particles, within, above and below the public supply well screen, and tracking the movement of these particles in an upgradient (backward) direction until their intersection with the water table. **Figure 7** provides a cross-sectional view of the particle starting locations outside the supply well screen, and in neighboring model layers. **Figure 8** provides a plan-view of the particle starting locations. The particles shown in Figure 8 represent one of the four rings of particles visible in Figure 7.

The particle pathlines defining the capture zone of each well were then truncated to represent 5-years upgradient travel from the supply well (5 years time-of-travel [TOT]); the resulting shape is that of an ellipsoid. It will take 5 years for groundwater starting at the edges of the ellipsoid to travel to the supply well. The ellipsoid was projected to land surface, resulting in an ellipse which defined potential outpost monitoring well locations.

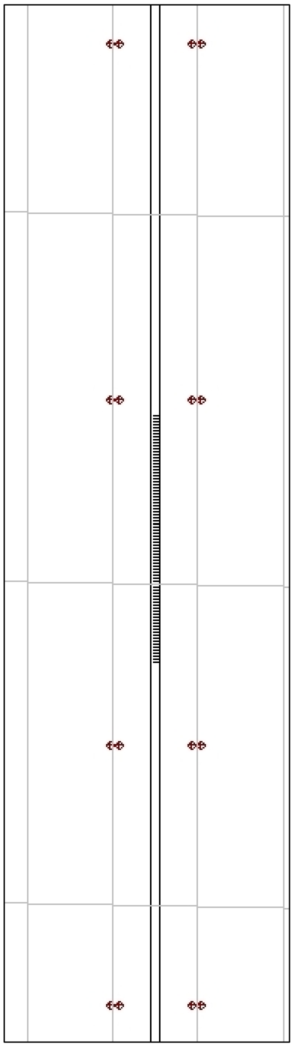


Figure 7. Cross-sectional view of particle starting locations outside supply well screen and neighboring model layers. Cells above and below well screen are 50 ft wide, and 175 ft thick.

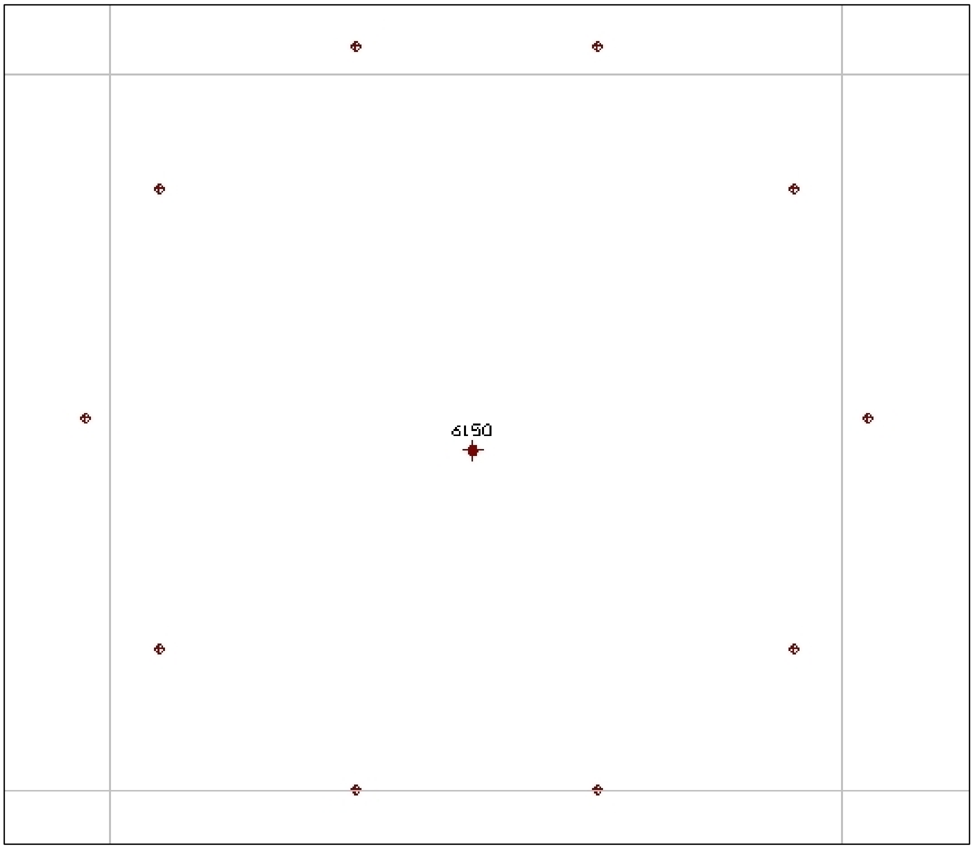


Figure 8. Plan view of particle starting locations outside supply well screen, with portions of neighboring model cells. Cell shown in center of image is 50 ft x 50 ft.

Forward Particle Tracking

Once appropriate potential locations for the outpost monitoring wells had been identified via backward particle tracking (5 year TOT ellipse), it was necessary to determine the flow path of the approaching contaminant plume. Backward particle tracking had provided an ellipse representing potential monitoring well locations, but it was necessary to know the flow path of the approaching plume to place the monitoring wells in locations which would intercept the impacted groundwater as it approached the supply well. For this effort the flowpath of interest was the flowpath representing the model-predicted fastest moving portion of the groundwater plume.

Forward particle tracking provided two key pieces of information:

- It defined an appropriate location for the outpost monitoring well relative to the supply well and plume (along the 5-year TOT ellipse), and
- It defined the screen zone of the outpost monitoring wells.

In each model layer, particle starting locations were assigned to the plumes leading edge. As previously described, definition of the VOC-plume was based on analytical data derived from groundwater samples collected in a monitoring well network (consisting of both on- and off-site wells), from water quality results from a series of vertical profile borings, and from water quality results reported by the various water suppliers located downgradient of the site. For this modeling effort, the plumes leading edge was taken to be the southernmost portion of the plume, generally represented as a concentration of 5 μg/L VOCs. **Figure 9** is a plan view showing particle starting locations in a typical layer of the model at the plumes leading edge. The bold outline in the figure represents the plume extent, and the dots running along the outline are the particle starting locations.

Based on the distribution of impacted groundwater observed during model construction, and the knowledge of differing hydraulic conductivities assigned to individual model layers, it was anticipated that the rate of movement of the plume would vary by layer. To assess the rate of layer-specific plume movement, particles were initialized along the leading edge of the plume in each model layer and permitted to travel to a receptor (supply well) or the model boundary. **Table 3** summarizes the travel time from the plumes leading edge in each of the impacted model layers to the various at risk supply wells. This assessment indicated that shallower portions of the plume tended to move faster than deeper portions (which was in agreement with the distribution of assigned transmissivity values). Despite the more rapid horizontal movement of groundwater in the shallow portion of the model, the upper portion of the plume was not predicted by the model to be the first to impact the supply well. As a result of the vertical anisotropy assigned in the

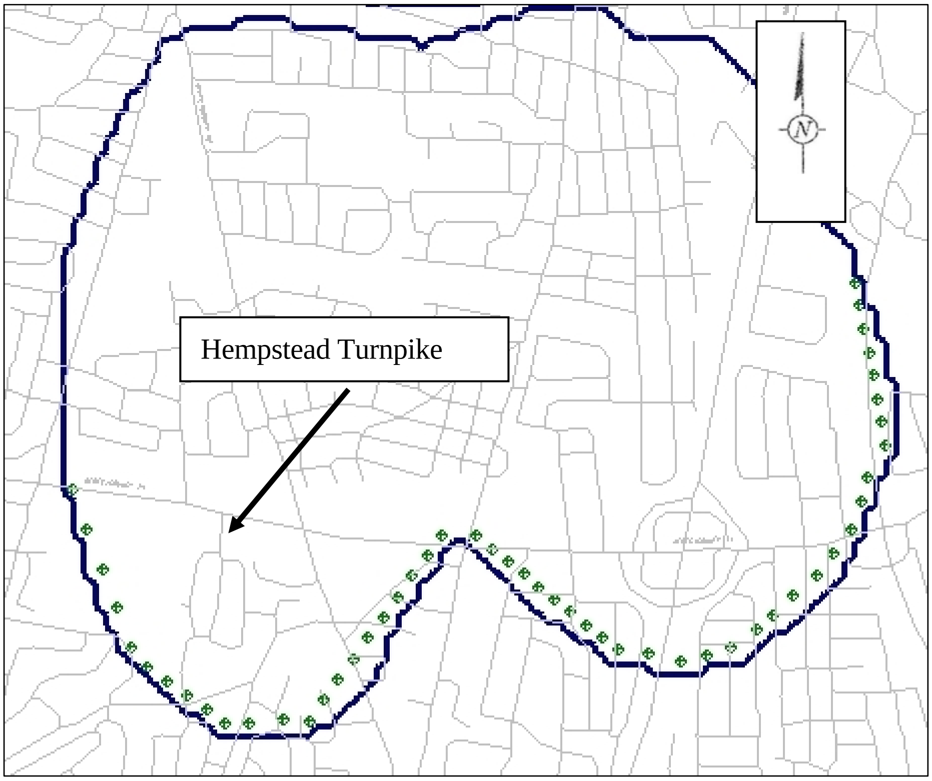


Figure 9. Plan view showing particle starting locations in typical model layer at leading edge of the off-site plume.
Scale: 1 inch = 1,800 feet.

	Model Layer									
Well ID	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
South Farmingdale Well Field 1										
4043	21	22	12	12	12	--	--	--	--	--
5148	27	--	--	--	--	--	--	--	--	--
7377	--	--	--	--	--	--	--	--	--	--
South Farmingdale Well Field 3										
6150	--	--	--	12	8	>30	>30	>30	>30	--
New York Water Service Wells 3S and 4S										
8480	23	25	17	24	24	>30	>30	>30	>30	>30
9338	--	30	23	27	24	>30	>30	>30	>30	>30

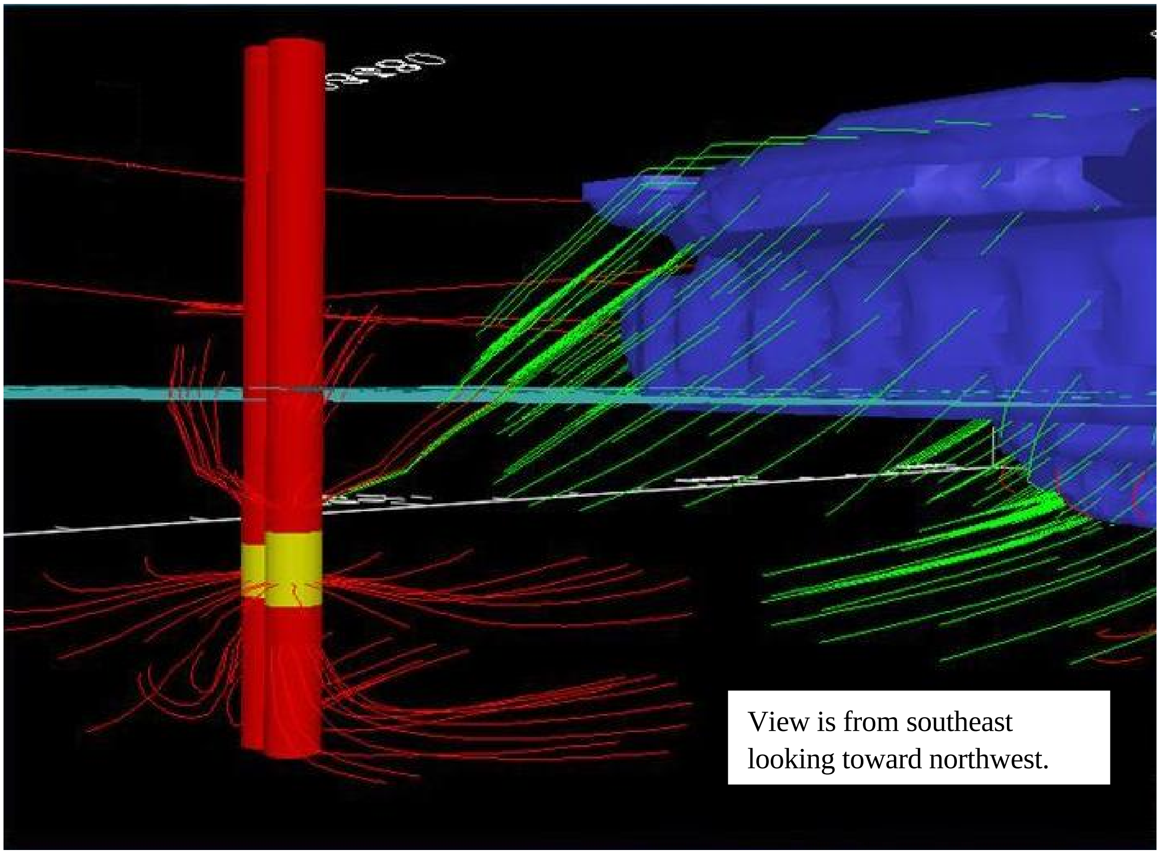
--	No model predicted detection of TVOCs.
>30	Model predicts detection of TVOCs after 30 years.

Table 3. Groundwater travel time (in years) from the plumes leading edge in each model layer to municipal supply wells.

model, vertical movement of the upper potion of the plume was impeded. In each of the cases evaluated, the segment of the plume which reached the supply well first originated from the central portion of the plume (in model layers four, five or six). However, the model-predicted aquifer horizon through which the impacts occurred was not intuitively obvious.

One would expect that having identified the fastest moving vertical segment of the plume relative to an at-risk supply well, it would be appropriate to set the outpost well screen in the same vertical horizon. Instead, the model showed that when the plume approached the supply well it was typically driven downward by the hydraulic gradients established by the pumping well (most of the supply well screens were at elevations below that of the main body of the plume). Therefore, the best location for the outpost well screen would not be the same horizon from which the impacted groundwater originated, but was usually some horizon beneath that.

Forward and backward tracked particle pathlines were graphically evaluated to determine the likely point of intersection. This was the horizon chosen for the screen zone of the outpost monitoring well. **Figure 10** is a cross-sectional view of the model showing the intersection of particle pathlines. The plume’s leading edge is visible on the right, the green pathlines are the forward tracked particles



View is from southeast looking toward northwest.

Figure 10. Cross-sectional view of model showing intersection of particle pathlines in model layer 7, the plumes leading edge and supply wells N8480 (foreground) and N9338. Supply well screens are shown in yellow; well casings are red. The figure is not to scale.

originating at the plumes leading edge, the red pathlines are the backward tracked particles originating at the supply well and truncated at 5 years TOT, and the blue line (approximately in the center of the figure) represents the top of model layer 7. The intersection of the forward and backward tracked particles occurs near the top of model layer 7 (approximately at the blue line).

Based on the image shown on Figure 10, it was determined that in the case of Supply Well N8480, it would be appropriate to screen the outpost monitoring well at a horizon equivalent to model layer 7 (240-330 ft below mean sea level). As is seen from Figure 10, the selected outpost monitoring well screen is significantly offset from the well screen of Supply Well N8480.

The predicted particle paths described above were based upon a steady-state flow field which assumed that pumping rates of the supply wells were unchanging throughout the simulation. While this assumption is not valid on a short-term basis (there is significant seasonal variability in pumping rates), it is appropriate for the multi-year simulations conducted here. However, if significant changes in production were instituted by the water suppliers, it would be necessary to have the ability to monitor those segments of the aquifer above and/or below the model-predicted flow path of the fastest moving segment of the plume. Therefore, two or more outpost monitoring well screen zones were selected for each supply well. The elevations of the selected monitoring well screen zones are given in **Table 4**.

Outpost	**Model Layer**				**Outpost Wells Screen Zones**				
Wells ID	**Number**	**Top Elevation**	**Bottom Elevation**	**Middle Elevation**	**Top Elevation**	**Bottom Elevation**	**Length Feet**	**Municipal Well Field Monitored**	**Municipal Supply Well Nos.**
OW1-1	4	-114	-170	**-142**	-122	-162	**40**	South Farmingdale Well Field 1	4043[1)], 5148, 7377
OW1-2	5	-170	-270	**-220**	-200	-240	**40**	South Farmingdale Well Field 1	4043[1)], 5148, 7377
OW1-3	6	-270	-360	**-315**	-295	-335	**40**	South Farmingdale Well Field 1	4043[1)], 5148, 7377
OW2-1	6	-265	-355	**-310**	-290	-330	**40**	South Farmingdale Well Field 3	6150
OW2-2	7	-355	-437	**-396**	-376	-416	**40**	South Farmingdale Well Field 3	6150
OW3-1	7	-354	-435	**-394.5**	-374.5	-414.5	**40**	New York Water Service 3S and 4S	8480[1)], 9338
OW3-2	9	-524	-601	**-562.5**	-542.5	-582.5	**40**	New York Water Service 3S and 4S	8480[1)], 9338

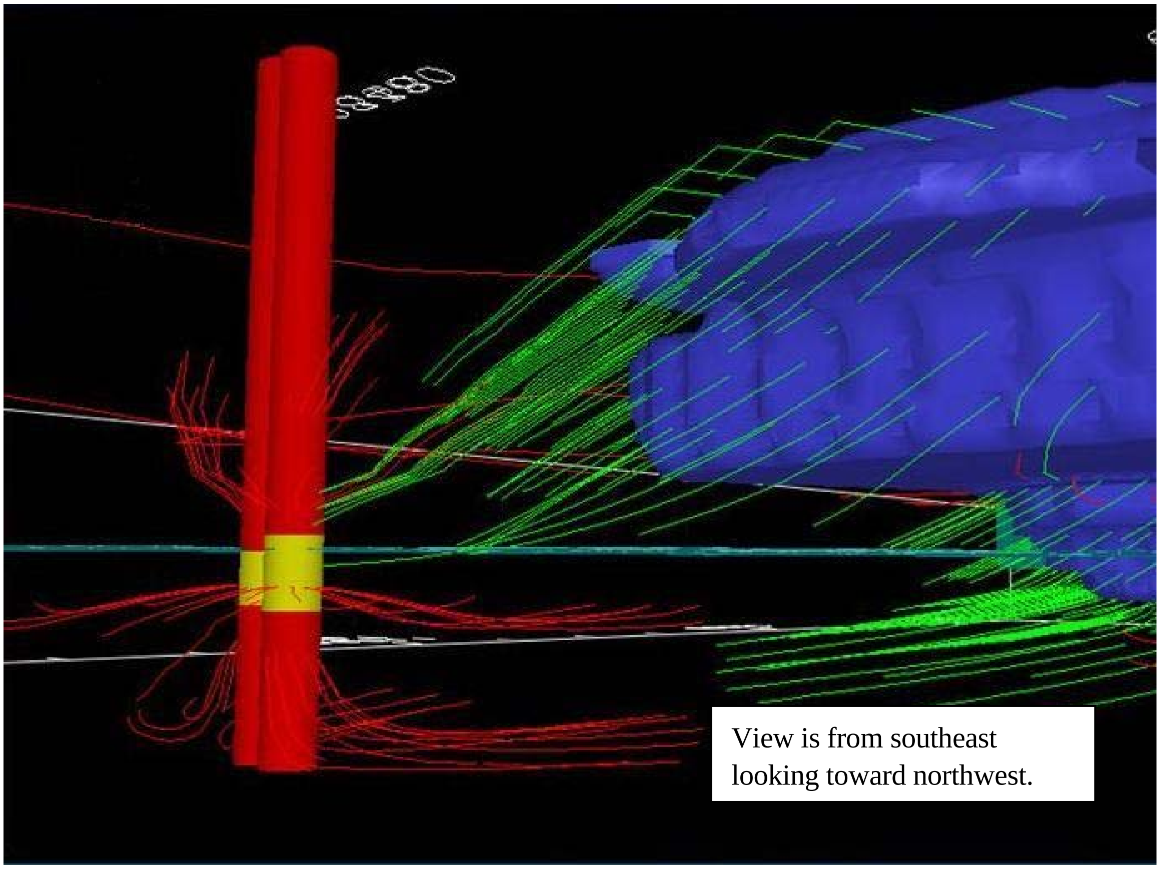
Elevations are given in feet relative to mean sea level.

(1) First well in well field predicted by modeling to be potentially impacted with VOCs; monitoring well cluster designed to monitor potential impacts at this well.

Table 4. Outpost Monitoring Well Cluster Screen Zones.

In the case of Supply Well N8480, the graphical evaluation indicated the next impact to the supply well after that passing through model layer 7 would occur when a segment of the plume passed through model layer 9. **Figure 11** is a cross-sectional view of the model showing the intersection of particle pathlines. The plume's leading edge is visible on the right, the green pathlines are the forward tracked particles originating at the plumes leading edge, the red pathlines are the backward tracked particles originating at the supply well and truncated at 5 years TOT, and the blue line (passing through the yellow segment [well screen] of supply well N8480) represents the top of model layer 9. The model predicted that the second set of particles to reach the supply well would pass through model layer 9 at 5 years TOT from the supply well.

As such, the outpost wells for supply well N8480 were recommended to be screened in the aquifer horizons equivalent to model layers 7 and 9 at a distance approximately 5 years upgradient from the supply well.



View is from southeast looking toward northwest.

Figure 11. Cross-sectional view of model output showing intersection of particle pathlines in model layer 9, the plumes leading edge and supply wells N8480 (foreground) and N9338. Supply well screens are shown in yellow; well casings are red. The figure is not to scale.

Solute Transport

The groundwater flow and transport model was used to predict the movement of the VOC plume with time. A steady-state three-dimensional groundwater flow model (described above) was used to develop the flow field which was coupled to the transport model for the simulation of groundwater plume movement. MT3D (Zheng, 1990) was used to predict the movement of the groundwater plume. The MT3D transport model is intended to be used in conjunction with any block-centered finite-difference flow model such as MODFLOW and is based on the assumption that changes in the concentration field will not affect the flow field measurably. MT3D retrieves the hydraulic heads and various flow and sink/source terms generated by MODFLOW. The MT3D transport model can simulate changes in concentration of single-species miscible contaminants in groundwater considering advection, dispersion, and some simple chemical reaction, with various types of boundary conditions and external sources or sinks.

For simplicity, the mass transport simulation was conducted assuming the occurrence of only advective transport; factors such as retardation, diffusion and dispersion, were assumed not to occur. The lack of a dispersion parameter results in a conservation of mass; areas of higher VOC concentration within the modeled plume are predicted by the model to disperse more slowly than if a dispersion parameter were used. This can be viewed as a conservative method of modeling in that without dispersion, the model will estimate higher peak concentrations at downgradient receptors.

Concentration observation points were assigned in the model to correspond to the proposed outpost monitoring well screen zones described above, and the screen zone of the at risk supply well. Use of the concentration observation point enables the model to track the concentration of VOCs at various points in the model for each transport step. With this information it is possible to predict when a particular concentration will exist at a given location in the model. **Figure 12** shows the model-predicted VOC concentrations in the at risk supply wells. Determination of the trigger value was made by determining when the model-predicted concentrations of VOCs in the supply well exceeded 0.5 μg/L, and determining the concentration the model had predicted to be in the outpost well 5 years prior to that. **Table 5** provides a summary of the model predicted trigger value, the time to reach the trigger value at the outpost well and the time to reach a detectable concentration of VOCs at the supply well.

Armed with this information it is possible for the water supplier to monitor concentrations of VOCs at a significant distance upgradient from their supply well with the knowledge that based on model predictions, the outpost well is the best indicator available of potential future impacts at the supply well. **Figures 13, 14 and 15** show the locations of outpost monitoring wells relative to supply wells N4043, N6150, and N8480, respectively. Based on the predicted time to reach a trigger value, the monitoring frequency employed at the outpost well can be optimized to minimize cost.

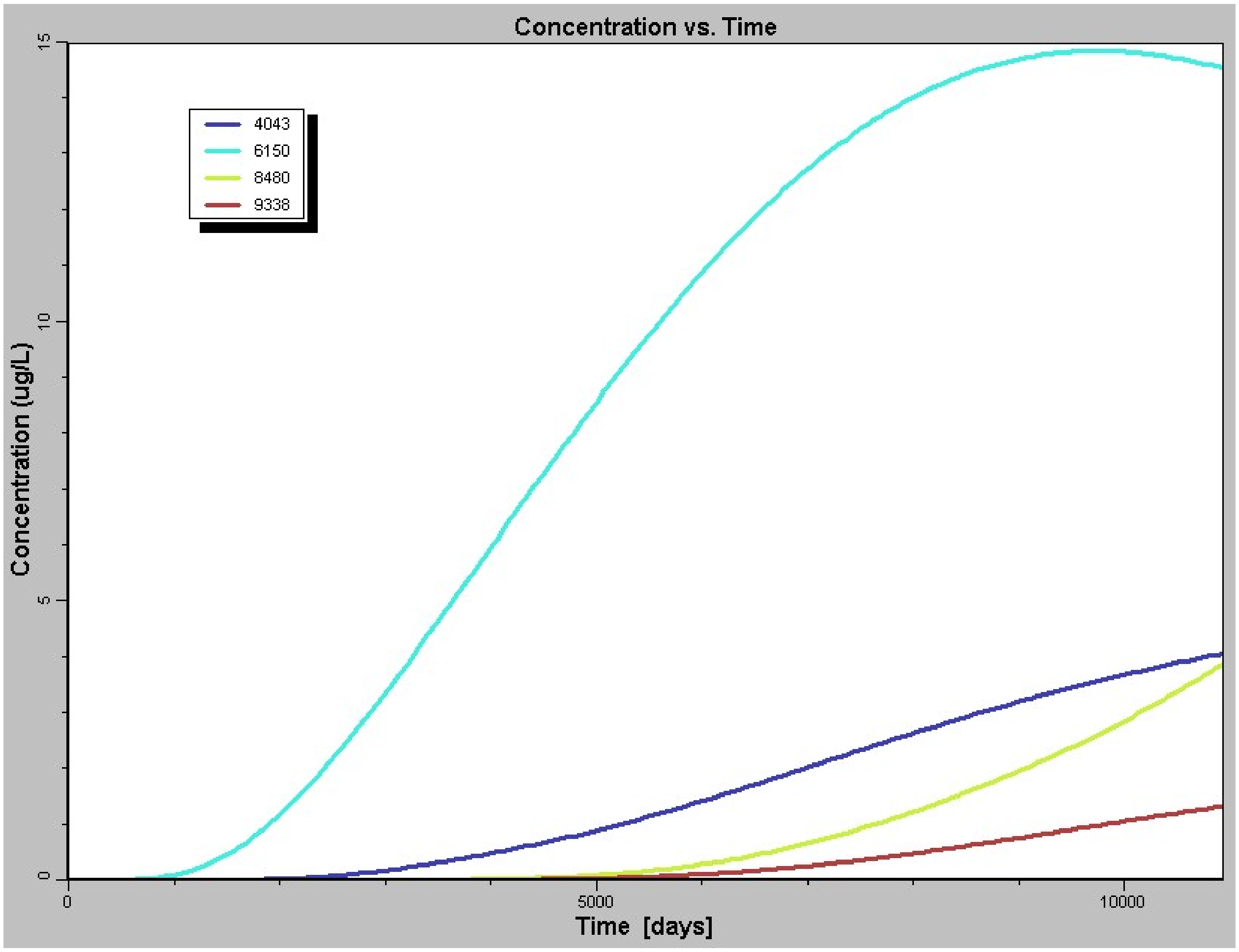


Figure 12. VOC concentration in supply wells predicted by model over next 30 years.

Outpost Well ID	Distance from Outpost Well to Municipal Supply Well (ft)	Municipal Supply Well ID	Outpost Well Trigger Value(1) (ppb)	Time to Reach Trigger Value(1) in Outpost Well (years)	Time to Detection(2) in Municipal Supply Well (years)
OW1-1, OW1-2, OW1-3	625	4043	.638	6	11
OW2-1, OW2-2	320	6150	--	--	4
OW3-1, OW3-2	975	8480	1.45	13	18

ft means feet.
ppb means parts per billion.
-- Supply well 6150 is predicted by the model to be impacted above 0.5 ppb in less than 5 years.
(1) Trigger Value is VOC concentration at outpost well 5 years before model predicted detection of 0.5 ppb at municipal supply well.
For Well 6150, travel time is too brief to determine trigger value, detection is predicted to occur in less than 5 years.
(2) Time to Detection is the number of years remaining before the model-predicted VOC concentration in the supply well reaches 0.5 ppb.
VOC means volatile organic compound.

Table 5– Summary of Model Predicted Trigger Value, Time to Trigger Value at Outpost Well and Time to Detection in Supply Well.

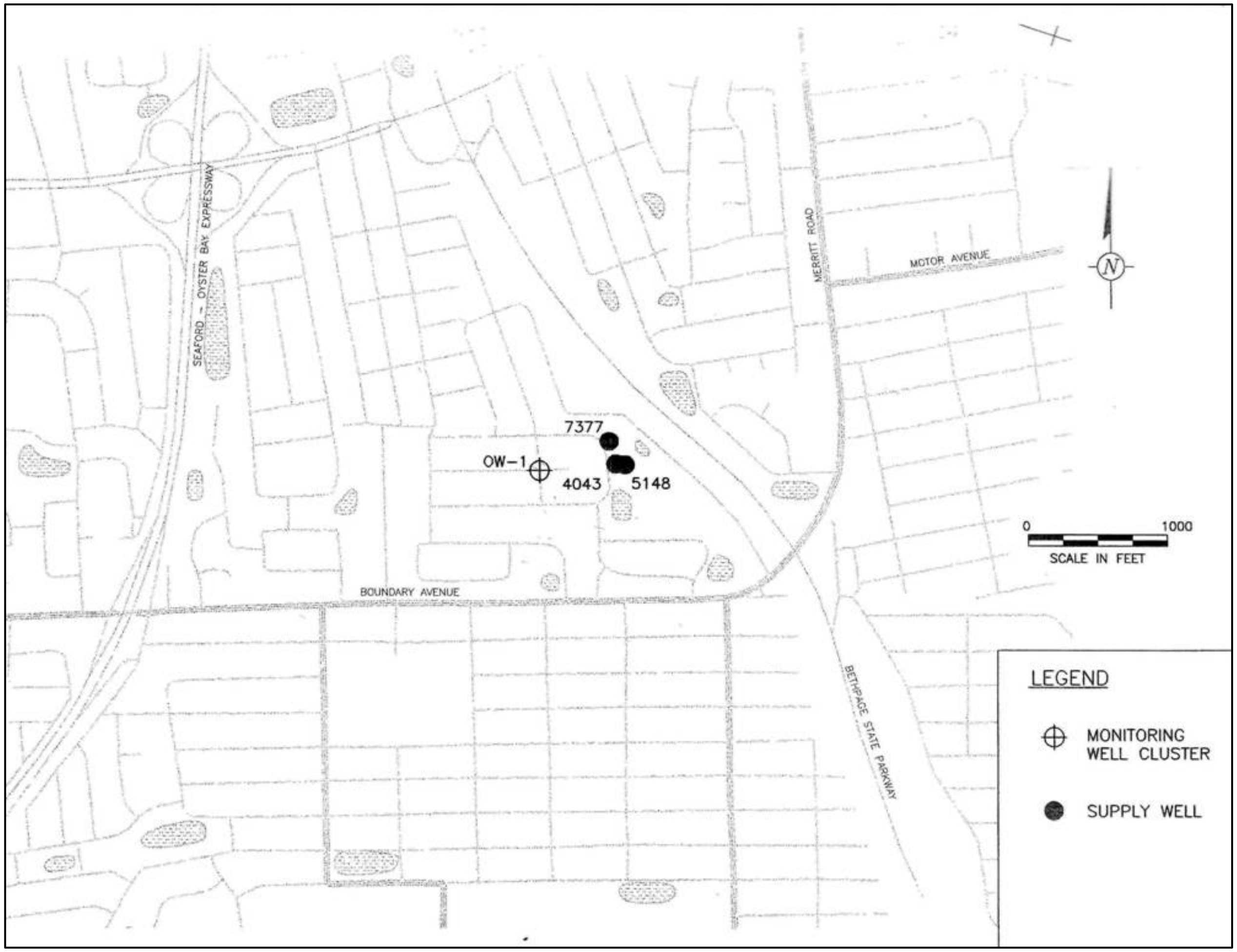


Figure 13. Outpost Monitoring Well Cluster Location for South Farmingdale's Well Field No. 1. Outpost Monitoring Well Screen Zones are given on Table 4.

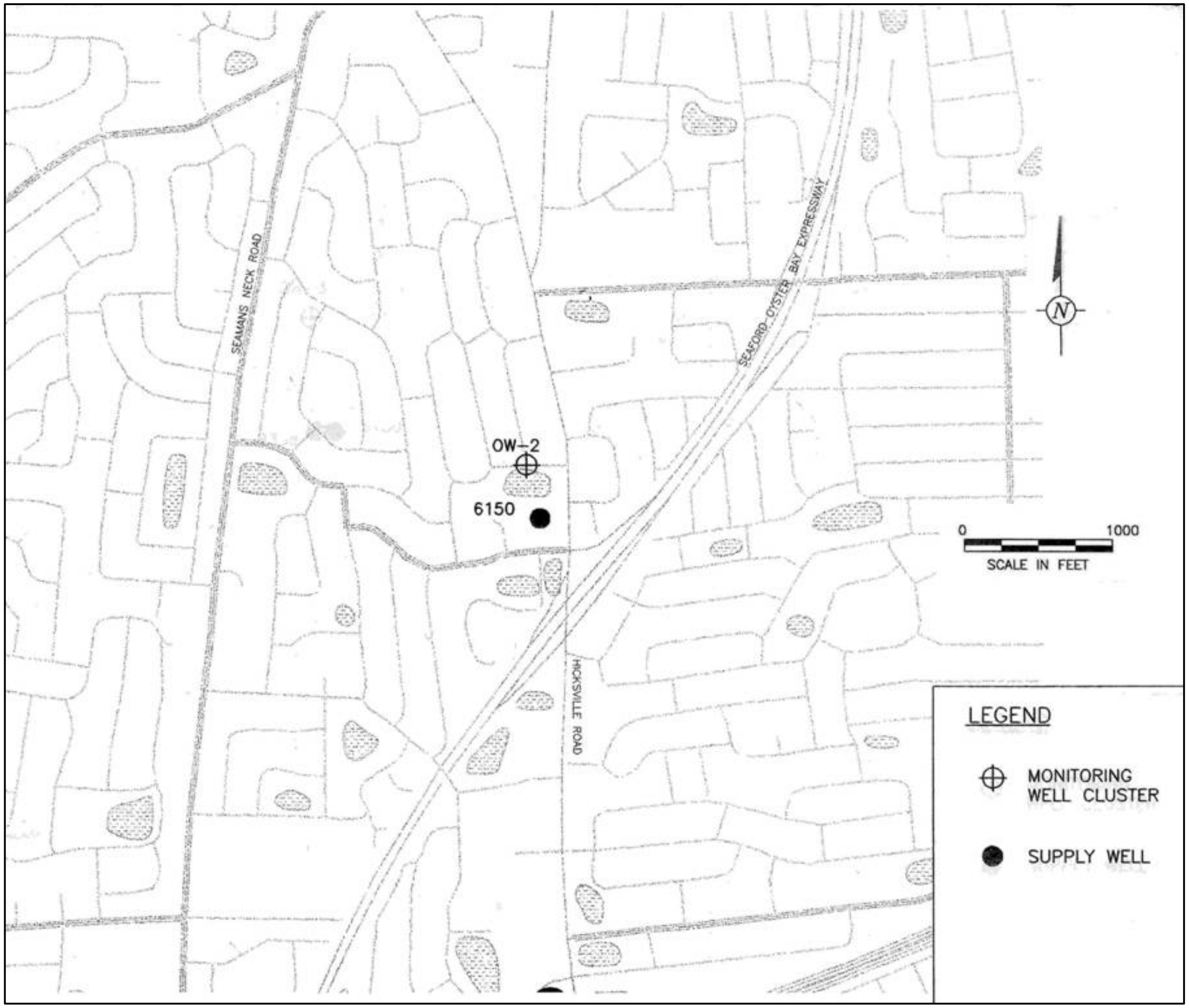


Figure 14. Outpost Monitoring Well Cluster Location for South Farmingdale's Well Field No. 2. Outpost Monitoring Well Screen Zones are given on Table 4.

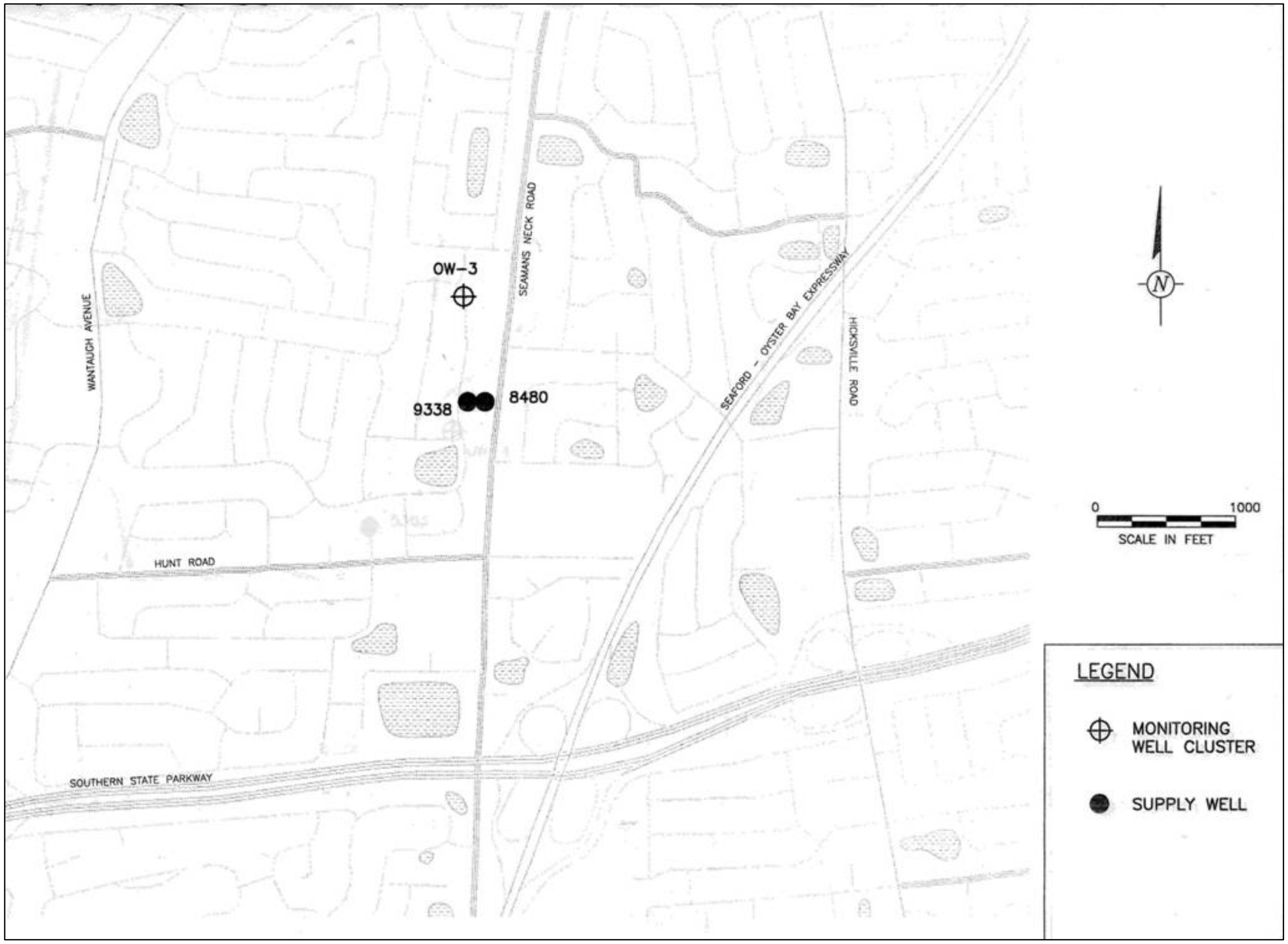


Figure 15. Outpost Monitoring Well Location for the New York Water Service Well Field (Wells N8480 and N9338). Outpost Monitoring Well Screen Zones are given on Table 4.

Comparison to Similar Work Conducted by Others

With the exception of relatively recent well head protection modeling, any work identified in the literature as being similar in nature to this modeling effort typically was conducted and documented ten or more years ago. As a result the computers used for conducting those efforts were significantly less powerful than the hardware utilized for this modeling effort. In addition to longer model run times associated with slower processors, the limitations associated with available computer memory would have constrained the models to covering smaller areas with substantially larger grid spacing. These limitations would have significantly complicated the ability of modeler to undertake such an effort. Most likely, potential impacts to individual supply wells would have had to be evaluated individually, using a set of sub-regional models.

Several of the papers reviewed during the course of this study dealt with schemes to optimize particle tracking accuracy. Simple rectangular grids with simple boundary conditions were used for these studies. The scale of these studies and the modeling presented here are not comparable. Modern computers do not impose the computational constraints which required Zheng (1994), Ahlfleld (1990), and others to evaluate optimization techniques.

In this study, the computational power of modern computers permitted the evaluation of a complex model which was able to:

1. Predict contaminant transport over a large model area.
2. Track multiple particle sets to assess the capture zones of several supply wells simultaneously.
3. Track multiple particle sets to predict the movement of the leading edge of VOC-impacted groundwater in multiple model layers, and
4. Track the movement of VOC-impacted groundwater at several proposed outpost monitoring and supply wells simultaneously.

None of the papers reviewed in support of this study discussed models with a level of complexity comparable to that of the model discussed here.

Model Limitations

The most significant factors affecting the predictive accuracy of this model are the density of available hydrogeologic and water quality data both on- and off-site, and the assumed steady-state pumping conditions.

As a result of the density of development in this area, there are a limited number of potential locations accessible to conduct the required drilling and sample collection activities. In addition, gaining access to some area typically involves lengthy and sometimes costly negotiations with property owners not only for access to conduct drilling activities, but to secure access for future monitoring of any wells installed during the investigation.

In addition to gaining access, the cost of conducting the work forces the party conducting the investigation to attempt to optimize (some might say minimize) the number of drilling and sampling locations.

Besides the data collection effort, one of the paramount assumptions used in the model is the notion of steady-state conditions. An evaluation of most water suppliers pumping records will show significant seasonal variation in pumping rates. However, for long-term predictive simulations, it is generally accepted that the use of some average pumping rate to approximate a steady-state condition is appropriate.

Of course, if the water supplier invokes a change in their typical operating methods, by either varying pumping rates, or adding or removing wells from service, the models predictions would be called into question. In this area, the density of development works in our favor, as it makes it extremely unlikely that new supply wells will be placed in as yet undeveloped well fields. More likely, if new wells were brought on line, they would be installed in existing well fields, or existing wells would be reconditioned with higher capacity screens and pumps.

Nevertheless, annual reviews of supply well pumpage throughout the model area, and a comparison of the report rates to previously modeled rates will ensure the models predictions remain as accurate as possible.

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