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Groundwater recovery and treatment for chlorinated organic compounds*

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Abstract

Groundwater, containing chlorinated solvent contaminants, is being remediated under an EPA post-closure permit at a former electronics manufacturing and assembly facility. The activities have included the installation of two recovery wells, two background monitoring wells, more than 20 downgradient monitoring wells, pump tests to estimate the area of influence of the recovery wells, and the installation and operation of an air stripping system to treat the recovered groundwater prior to discharge to a POTW. Groundwater quality is being monitored on a quarterly basis. Due to the effectiveness of the remedial measures, the long-term trend of chlorinated solvent concentrations in the groundwater is decreasing over time. The site geology is characterized by about 20 feet of overburden underlain by fractured limestone. Aerial photography and a geophysical survey were employed to locate suitable fractures for placement of the recovery and monitoring wells.

1. Introduction

This paper is based on an actual site remediation project being conducted by Dames & Moore at a former electronics manufacturing and assembly facility. However, to make the paper of wider interest and greater usefulness to readers, "poetic license" has been employed in describing some of the remediation activities and site-specific conditions. Groundwater, containing chlorinated solvent contaminants, is being remediated under an EPA post-closure permit related to the closure of a two-cell, metal hydroxide, sludge surface impoundment. In December 1986, facility management received a post-closure permit from the U.S. Environmental Protection Agency (EPA). This post-closure permit required the facility to undertake certain actions following the closure of the two-cell surface impoundment, which was completed around February 1987. These actions included the installation of recovery wells and additional onsite monitoring wells, the design and installation of an onsite

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treatment system, and an offsite investigation. Dames & Moore was retained to assist the facility in performing these tasks, most of which have been completed.

The closure procedure that was employed was designed to eliminate leachate generation. The impoundment cells were first dewatered, and the sludges were then stabilized by mixing them with cement dust. A compacted clay cap and a high-density polyethylene cover were placed over the former impoundment area to prevent any rainfall infiltration. The cap was then covered with layers of sand and topsoil prior to being seeded with grass.

2. Regional and site hydrogeology

Hydrogeologic data collected during field investigations at the site were combined with regional data to construct site cross-sections and potentiometric contour maps. The site geology is characterized by about 20 feet of overburden underlain by Tuscumbia Limestone that is fractured and weathered, resulting in the development of karst topography. The overburden consists of plastic silty clay produced by weathering of the limestone, grading downward to rock fragments, weathered rock, and bedrock. Water in the overburden occurs under both water table and confined conditions, depending on the local permeability of the clayey material, and is a source of recharge to the underlying limestone. The strata are nearly flat lying, and the regional dip is to the south at about 20 feet per mile.

While regional groundwater flow is generally to the south towards a nearby river, local groundwater flow varies from westerly in the northern part of the site to southwesterly in the southern part of the site. The average groundwater flow rate at the site is estimated to be about 0.5 foot per day.

The principal limestone aquifer is about 250 feet thick in the vicinity of the site. The majority of the water in this aquifer is stored and transmitted through openings along bedding planes, joints, faults, and other solutionally enlarged openings concentrated in the upper 100 feet of the Tuscumbia Limestone [1]. Karst features, such as those at the site, are formed by the ability of water to dissolve the limestone bedrock. Limestone is very brittle, and tectonic processes produce joint systems that provide water with access deep into the rock mass. Actual dissolving of rock is a reaction of carbonic acid with calcium carbonate of the limestone. Water forms a weak carbonic acid by reacting with carbon dioxide [2].

3. Design and installation of monitoring and recovery wells

Prior to April 1987, 24 monitoring wells had been installed in the vicinity of the former surface impoundments and adjacent offsite properties. In accordance with conditions in the post-closure permit, three new downgradient monitoring wells (9, 10, and 11), one new upgradient or background well (8), and two groundwater recovery wells (RW1 and RW2) were installed in April 1987. The three new downgradient monitoring wells were installed at the post-closure permit's points of compliance to monitor contaminant concentrations at the western property boundary. In accordance with the permit and the RCRA Groundwater Monitoring Technical Enforcement Guidance Document [3], the wells were spaced approximately 150 feet apart. Existing well 1 was used as a bench mark. Four additional new wells (12, 13, 14, and 15) were installed on an adjacent property to the south of the site in February 1990 as part of an investigation of offsite groundwater conditions. The locations of all of these wells are shown on Figs. 1 and 2 for the onsite and offsite areas, respectively.

Several of the wells have been monitored on a quarterly basis since April 1987 or earlier. These wells, which are numbered on Figs. 1 and 2, consist of monitoring wells 1 through 15. The other wells, which are shown unnumbered on Figs. 1 and 2, were also monitored prior to April 1987. Because detectable levels of contaminants were not found in the unnumbered wells, monitoring of these wells was terminated prior to April 1987.

Each of the monitoring wells installed by Dames & Moore since 1987 was constructed using 4-inch schedule 40 PVC riser and 10 feet of 0.020-inch slotted PVC screen. The screen intervals were set at approximately 35 to 45 feet below grade. A gravel filter pack was installed from the bottom of each hole to 3 to 5 feet above the top of the screen. A 2.5 to 5-foot bentonite clay seal was placed above the filter pack, and then bentonite and cement grout was used to fill in the annular space to the ground surface. Steel protective casing with locking caps were then installed.

Preliminary locations for the monitoring wells were determined by several methods, including a review of aerial photographs, a review of well recovery records for previously installed wells, and a geophysical survey. Pilot holes were initially drilled at these locations, and the rate of recharge into the holes was measured. If water recharged into a hole in less than 2 hours, a well was completed in that hole. If recharge required more than 2 hours, the pilot hole was grouted and a new location approximately 15 to 20 feet east or west of the first location was drilled.

The two recovery wells were installed on the downgradient (west) side of the former surface impoundment area. RW-2 was installed near monitoring well 5, which was known to have a high recovery rate. The general location of RW-1 was determined by the requirements that it be downgradient of the former surface impoundments and that its expected cone of depression should complement that of RW-2 to provide an effective cleanup of the groundwater contamination at the site. The two recovery wells are constructed of 6-inch stainless steel riser and stainless steel 0.010 inch screen. A 10 foot screened interval was placed opposite fracture zones that had been encountered during drilling. Since the borings had been drilled to 60 feet, stainless steel sumps

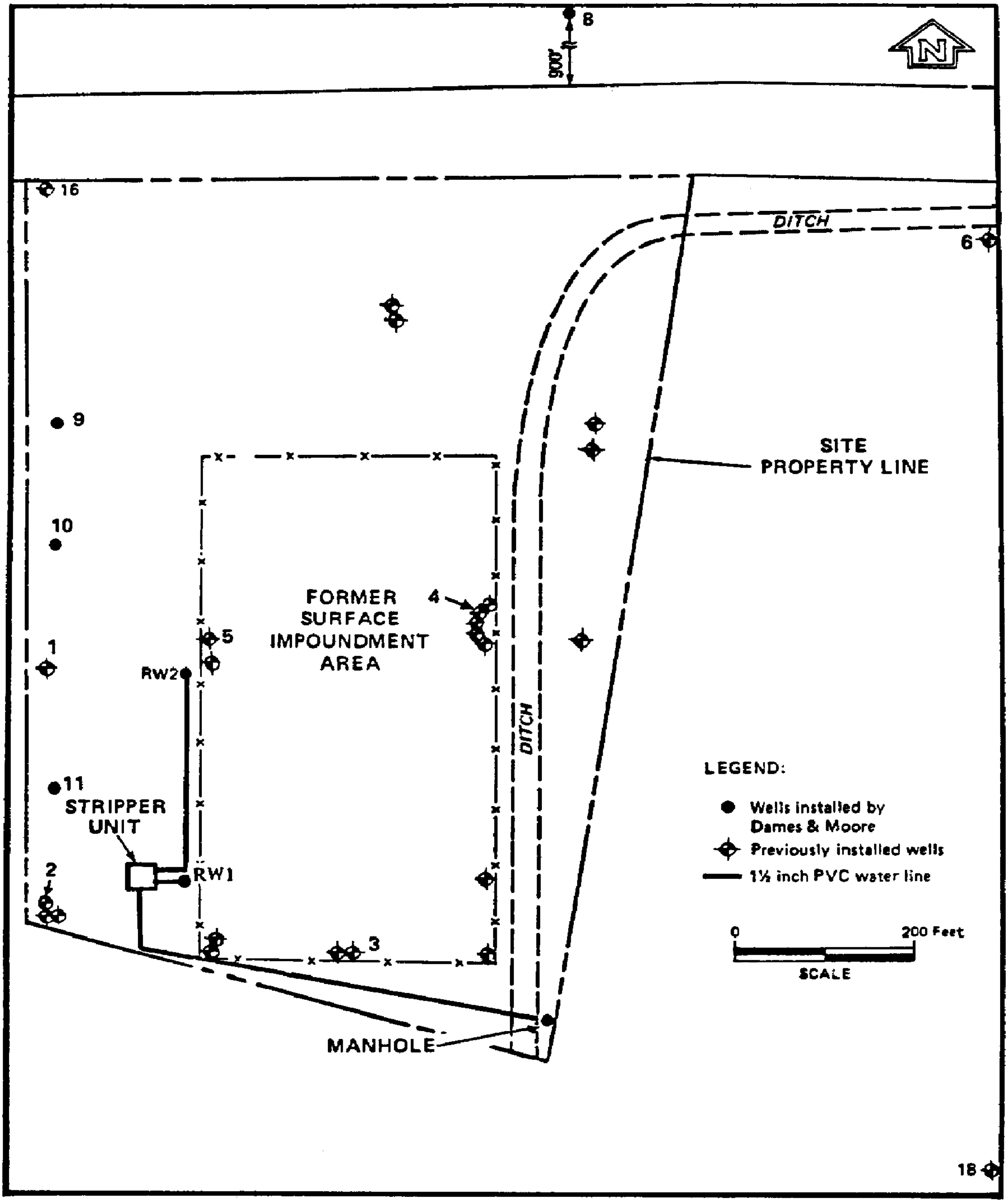

Fig. 1. Onsite monitoring and recovery well locations.

could be installed below the screened interval. Four-inch Grundfos submersible pumps were installed in the two recovery wells. The pumping rates are controlled by valves located on the pump discharge lines, while the maximum

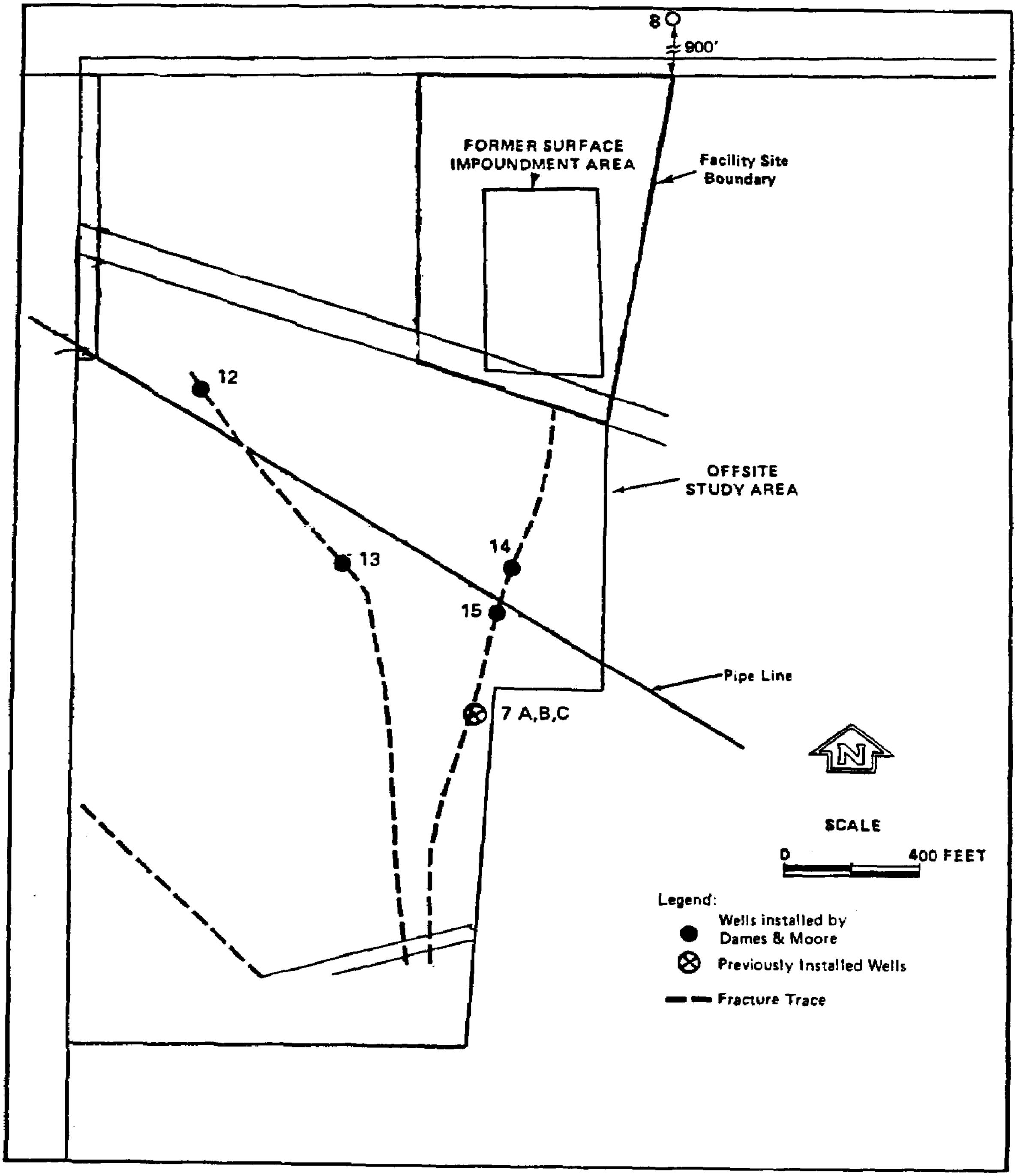

Fig. 2. Offsite monitoring well locations.

drawdown in each well is controlled by water level controllers. The controllers are electrical switching devices that turn power to the pumps either on or off, depending on the water levels in the wells. The off sensor is generally placed just above the pump, so that when water is drawn down to that level, the pump is shut off to prevent burnout. The on switch is placed somewhat below the static water level rather than adjacent to the off switch, so that on-off cycling of the pump will not be too frequent.

4. Locations of wells along fracture traces

Aerial photography and a geophysical survey were employed to locate suitable fractures for placement of the recovery and monitoring wells. A critical factor in locating monitoring and recovery wells in limestone is that they be installed in principal flow paths. Previous studies of limestone aquifers have shown that the principal flow paths are often associated with fractures in the limestone, the traces of which can sometimes be identified on aerial photographs. A fracture trace analysis using aerial photo interpretation was therefore performed. Photographs at a scale of 1:12,000 were interpreted using a mirror stereoscope with 0.7 magnification, allowing a large area of each stereo pair to be viewed at one time. The vertical exaggeration obtained in this way greatly enhanced the generally low-relief terrain in the vicinity of the site.

Primary emphasis of the aerial photo study was placed on identification of lineaments indicative of the underlying bedrock structure. Such lineaments are natural alignments visible on aerial photographs, and can include topographic depressions and prominent ridge crests, naturally straight drainage segments, and narrow, linear bands of light and dark tones that may indicate anomalous vegetation and/or soil moisture alignments. These can reflect rock boundaries, faults, or joints, which might in turn be conduits for groundwater. The aerial photo interpretation identified the approximate locations of fracture traces over an approximately six square mile area in the vicinity of the site. Based on the results of the aerial photo interpretation, it was concluded that the most frequent fracture trace trend was northwest-southeast with a secondary trend being north-south. Several fracture traces were identified at the site and adjacent properties.

To locate the wells installed on the adjacent offsite property (see Fig. 2), a geophysical survey was also conducted. An electromagnetic (EM) survey method was employed. This method was selected to detect conductivity anomalies, which are expected to occur above caverns or fracture zones in the Tuscumbia Limestone. The fractures and caverns, in turn, are expected to provide the major flow paths in the limestone aquifer, in which the monitoring wells should be installed. Equipment used for this survey consisted of a Geonics EM-31 instrument, which measures the apparent conductivity of materials by utilizing the principles of electromagnetic induction. This involves two coplanar loops, one acting as a transmitter and the other acting as a receiver. The transmitter induces circular eddy currents in the earth, which in turn produce a secondary magnetic field. The receiver intercepts the secondary magnetic field

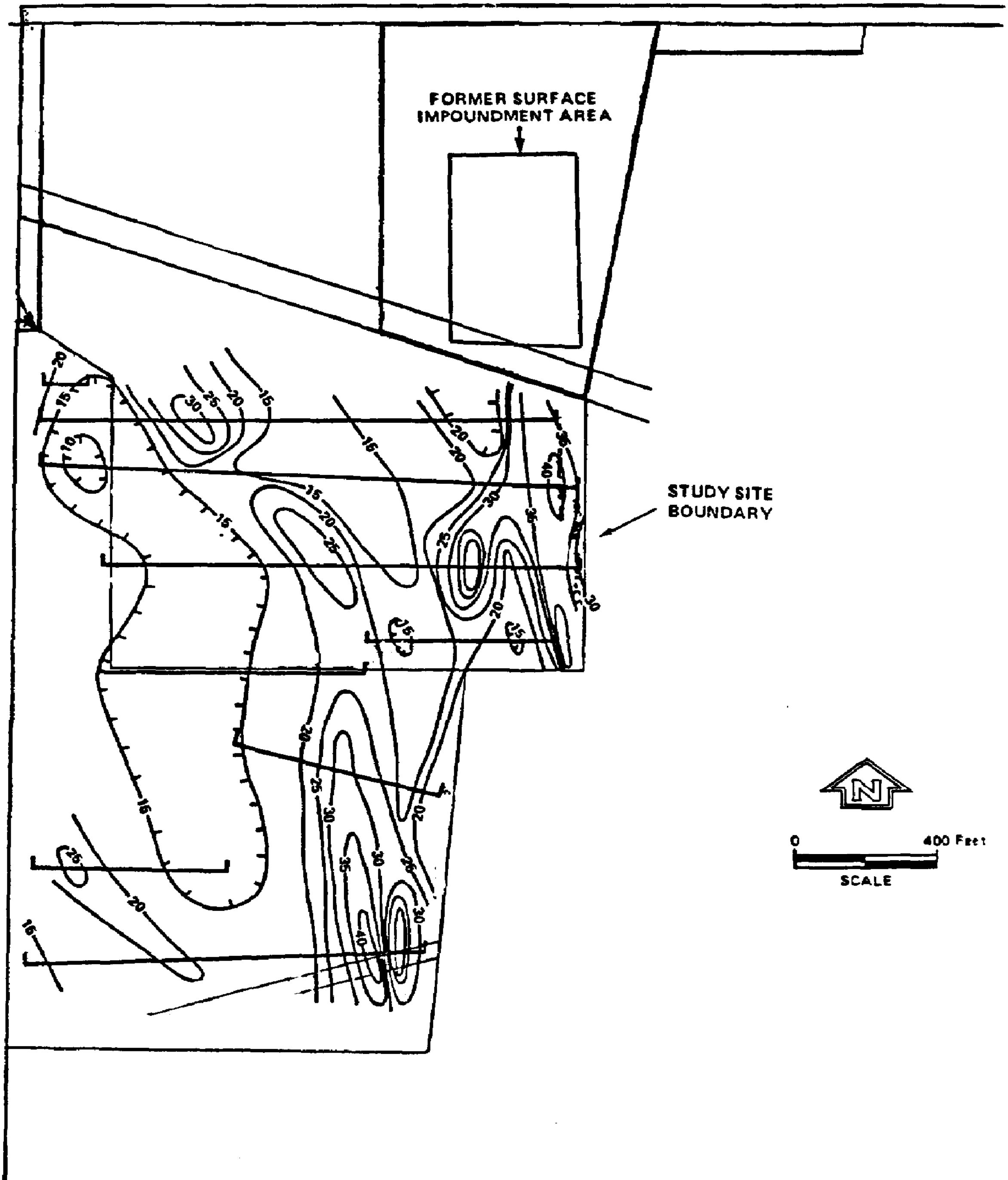

Fig. 3. Terrain conductivity contour map.

and measures the terrain conductivity by comparing the strength of the secondary field to that of the primary field. Measurements of conductivity were made at 5-foot intervals in the horizontal direction.

The terrain conductivity data collected during this survey were plotted on a site map, as shown in Fig. 3. In general, saturated fracture zones or caverns correspond to peaks on the conductivity profiles. There are several reasons for this correspondence. Massive unfractured limestone tends to have a lower electrical conductivity than either fractured saturated limestone or clay. In addition, clay thickness is expected to be greater over fracture zones than massive limestone because the former is more easily eroded and thus forms troughs in which the clay can accumulate. Finally, soil with high moisture content has a higher conductivity than soil with low moisture content. Moist soils often occur above fracture zones, which are often in topographic lows, and which provide a pathway for the soil moisture to migrate to locations of lower hydraulic potential. While it is possible that deep or moist soils could produce electrical conductivity highs not associated with fractures or caverns, the general agreement between areas with anomalously high conductivity and lineaments identified on aerial photos and caverns detected during drilling indicates that conductivity highs do indeed correspond to fracture zones.

The geophysical survey and the aerial photo interpretation generally gave similar results with only minor differences in the inferred fracture locations. The fracture locations inferred from the geophysical survey are considered to be more accurate and reliable, because they are based on actual measurements on the ground, whereas aerial photo interpretation is subject to errors when transferring data from the photos to the maps, and then to the ground. Optical distortion often occurs near the edge of the photos due to the properties of the camera lens. Also, the fracture traces identified on aerial photos would represent the intersection of the fracture with the ground surface. If the fracture is not vertical, the conductivity anomaly will be shifted away from the fracture trace in the direction of the fracture dip. The fracture traces shown on Fig. 2 are therefore based on the geophysical survey data. The nature of the fracture traces was confirmed by the discovery of solution cavities during drilling of these wells.

5. Groundwater flow direction

The depth to water in each well is measured prior to each sampling round. In order to determine the hydraulic gradients, all wells were surveyed by a Registered Surveyor. The elevation of the top of the protective casing and PVC riser was measured to an accuracy of 0.01 foot. The water level and survey data have been used to construct contour maps of the potentiometric surface in the limestone aquifer. A typical set of contours is shown in Fig. 4. The natural potentiometric surface indicates that under non-pumping conditions, ground-

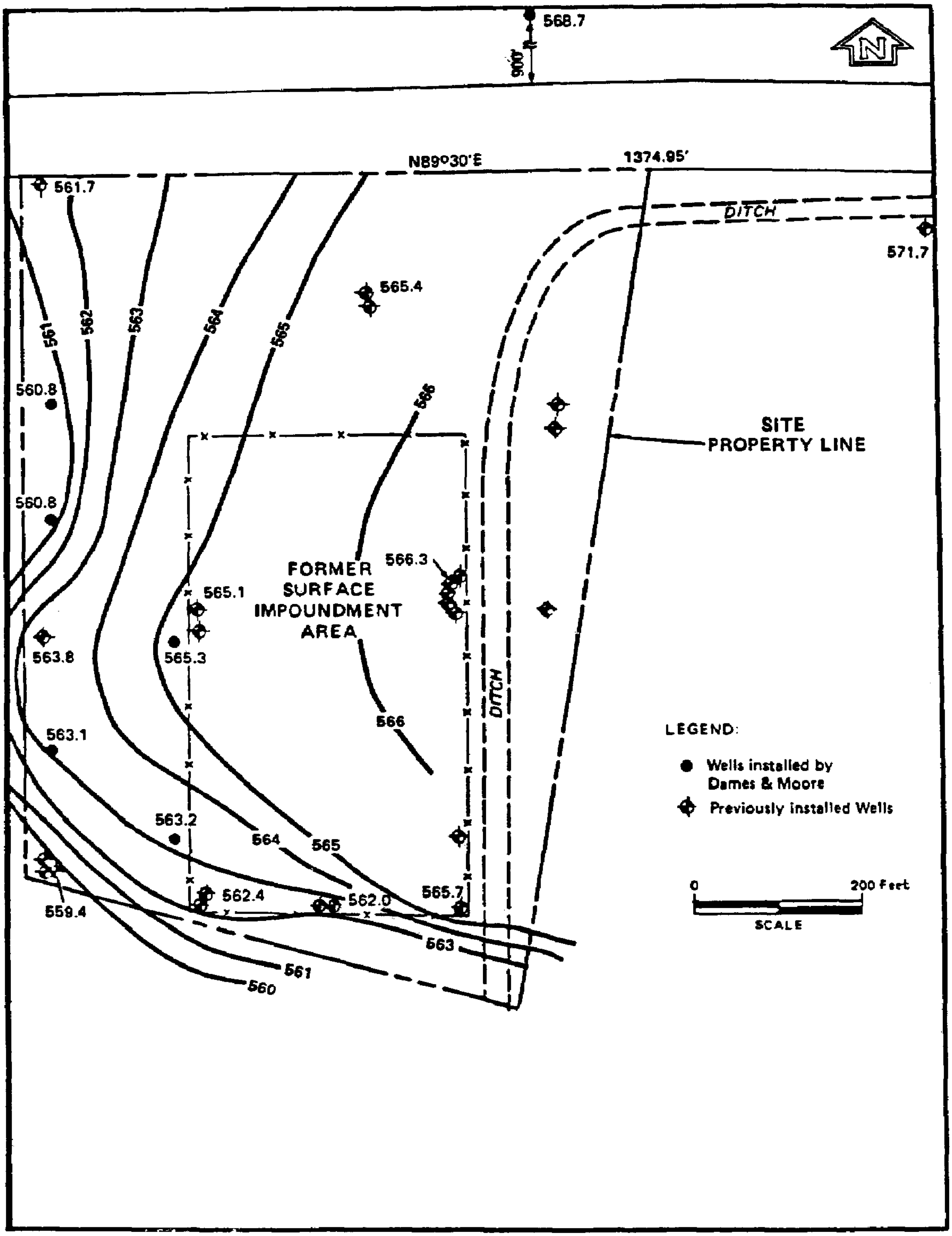

Fig. 4. Potentiometric surface in limestone aquifer before pumping.

water generally flows to the west at the northern end of the site, and to the southwest at the southern end.

6. Cone of depression of groundwater recovery wells

The effective radius of influence of the recovery wells was estimated by conducting a 46-hour pump test. The elevations for the monitoring and recovery wells, which were screened in the shallow limestone aquifer, are plotted and contoured on Fig. 5. This figure indicates that pumping of the recovery wells has formed a cone of depression centered at the downgradient end of the impoundments. The cone is oval in shape with the major axis being along the line connecting the two recovery wells. Groundwater within the cone of depression flows toward the recovery wells. The main effect of the remediation activity on offsite groundwater conditions is that it tends to prevent any further migration of contaminants form the facility to offsite locations. The pumping may also cause a hydraulic reversal which would tend to pull potential offsite contamination back to the recovery wells. The area which is affected by the pumping can be estimated by determining the radius of influence of the pumping wells. Several methods can be used to estimate the radius of influence, including projection of drawdown data, use of the Theis equations, and recharge methods.

Drawdown is defined as the lowering of the water table caused by groundwater pumping. The projection-of-drawdown method is based on the fact that if drawdown versus radial distance from a pumping well is plotted on semi-log graph paper with radial distance on the log axis, then the data points should fall on a straight line [4]. If the line is extrapolated or projected out, the distance at which zero drawdown is reached corresponds to the radius of influence of the well. For a homogeneous and isotropic aquifer, all points should fall along the same line. However, for an anisotropic aquifer such as fractured limestone, the radius of influence will depend upon the direction from the pumping well, being greater in directions intersecting the fracture zones, and smaller in directions of impermeable limestone. The radius of influence determined from the pump test data and the semi-log plot ranged from 350 feet in the direction of well 10 to 2,300 feet in the direction of well 1. These data are consistent with fracture zones determined from aerial photos.

The Theis equations were developed in 1935 by C.V. Theis to predict non-steady-state drawdown around a pumping well. The Theis equations can be expressed as follows:

$$s=\frac{Q}{4\pi T}W(U), \quad U=\frac{r^2S}{4Tt},$$

where s is the drawdown, Q the discharge, T the transmissivity, r the radius, S the storage coefficient, t the time, and $W(U)$ is the well function of U, values of which have been tabulated [4]. The following six assumptions must be made

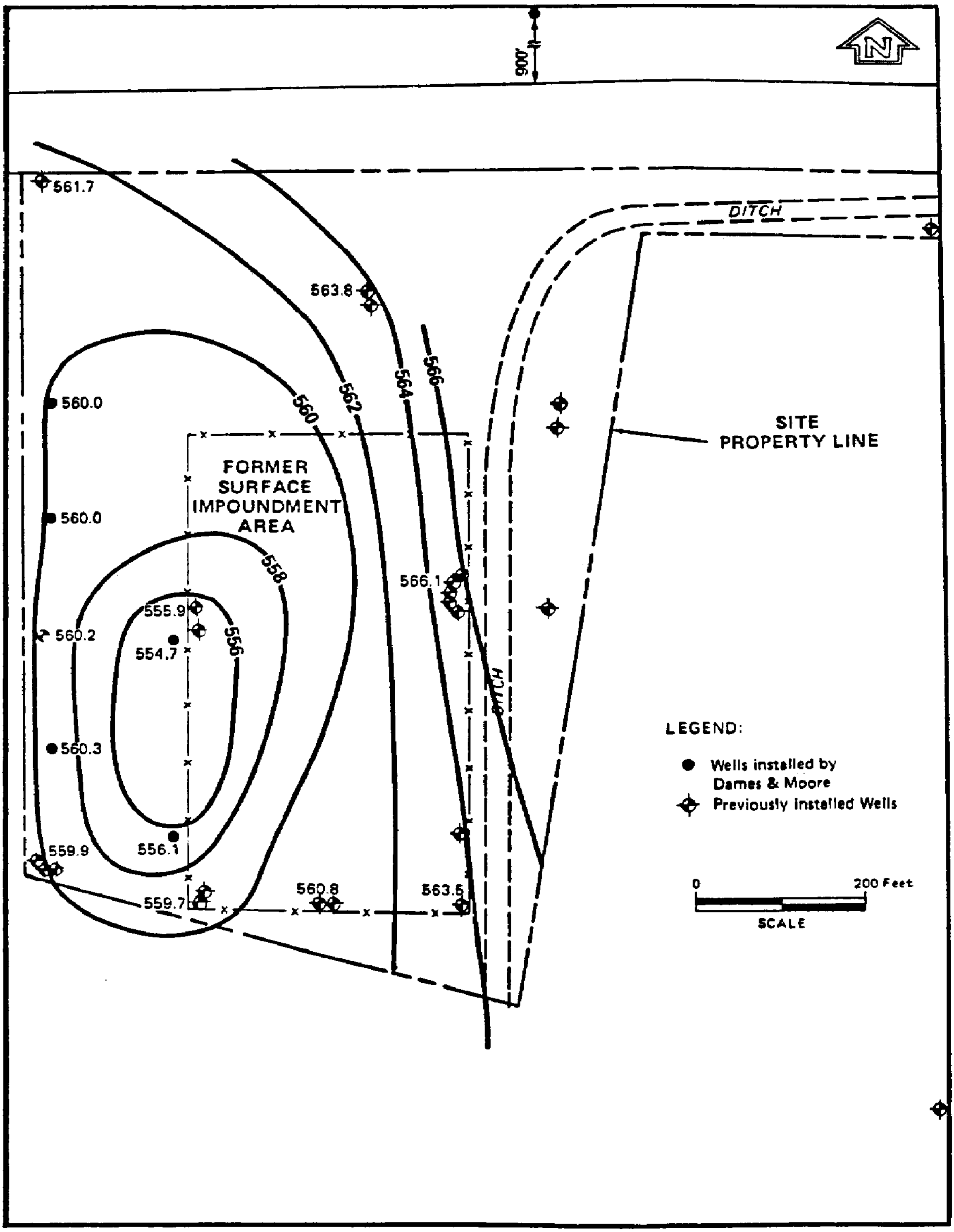

Fig. 5. Potentiometric surface in limestone aquifer after 46 hours of pumping.

in using the Theis equation: (1) the aquifer is homogeneous and isotropic, (2) the water body has infinite areal extent (i.e., its boundaries extend beyond the effects of the well in the time frame considered), (3) the discharging well penetrates the entire thickness of the aquifer, (4) the well has an infinitesimal diameter, (5) the water removed from storage is discharged instantaneously with decline in head, and (6) the aquifer is not subject to recharge. Clearly, not all these assumptions are met in the case under consideration. Assumption (1) is not met because of the fractured nature of the limestone aquifer. The radius of influence predicted by the Theis equation would be less than that which would actually occur along a fracture, but greater than that in the direction of non-fractured rock. The limitations imposed by Assumption (6) are discussed below in conjunction with the recharge method. The other assumptions are not expected to have a major impact on the prediction of the radius of influence. The variables in the Theis equation include transmissivity and storage coefficient, which were estimated from previous pumping tests on the aquifer. The pumping rate and duration of pumping were varied to determine their effect on the radius of influence. Distance versus drawdown curves predicted from the Theis equation are shown in Fig. 6. This analysis shows that under the given assumptions, the radius of influence will increase substantially with duration of pumping. The main effect of increasing the pumping rate is to increase the hydraulic gradient towards the well, and thus increase the rate of cleanup, rather than the area of cleanup.

The Theis method of determining drawdown assumes that the aquifer is not subject to recharge. This is generally not valid over a long period of time, since most aquifers are subject to recharge from precipitation. A simple method of estimating the area of influence of a pumping well receiving recharge is presented by Todd [5]. The method is based on the fact that the cone of depression of a well will expand over time until it intersects an area large enough to supply the recharge necessary to balance the discharge from the well. Thus, the only variables considered are pumping rate and recharge, and estimates of aquifer characteristics are not needed. Using the average annual recharge of 12 inches per year for the study area and a pumping rate of nine gallons per minute (gpm), a surface area of 630,500 ft^2 would be intersected by the cone of depression. If the area were assumed to be circular, the radius of influence would be 448 feet. If it is assumed that the area of the former surface impoundments does not contribute to recharge, then the radius would increase to 516 feet. This radius would increase in the summertime during the periods of low recharge, and decrease in the wintertime during periods of high recharge.

7. Air stripper for removal of volatile organic compounds

Subsequent to the installation of the recovery wells, an air stripping system was installed at the site for the removal of volatile organic compounds (VOCs)

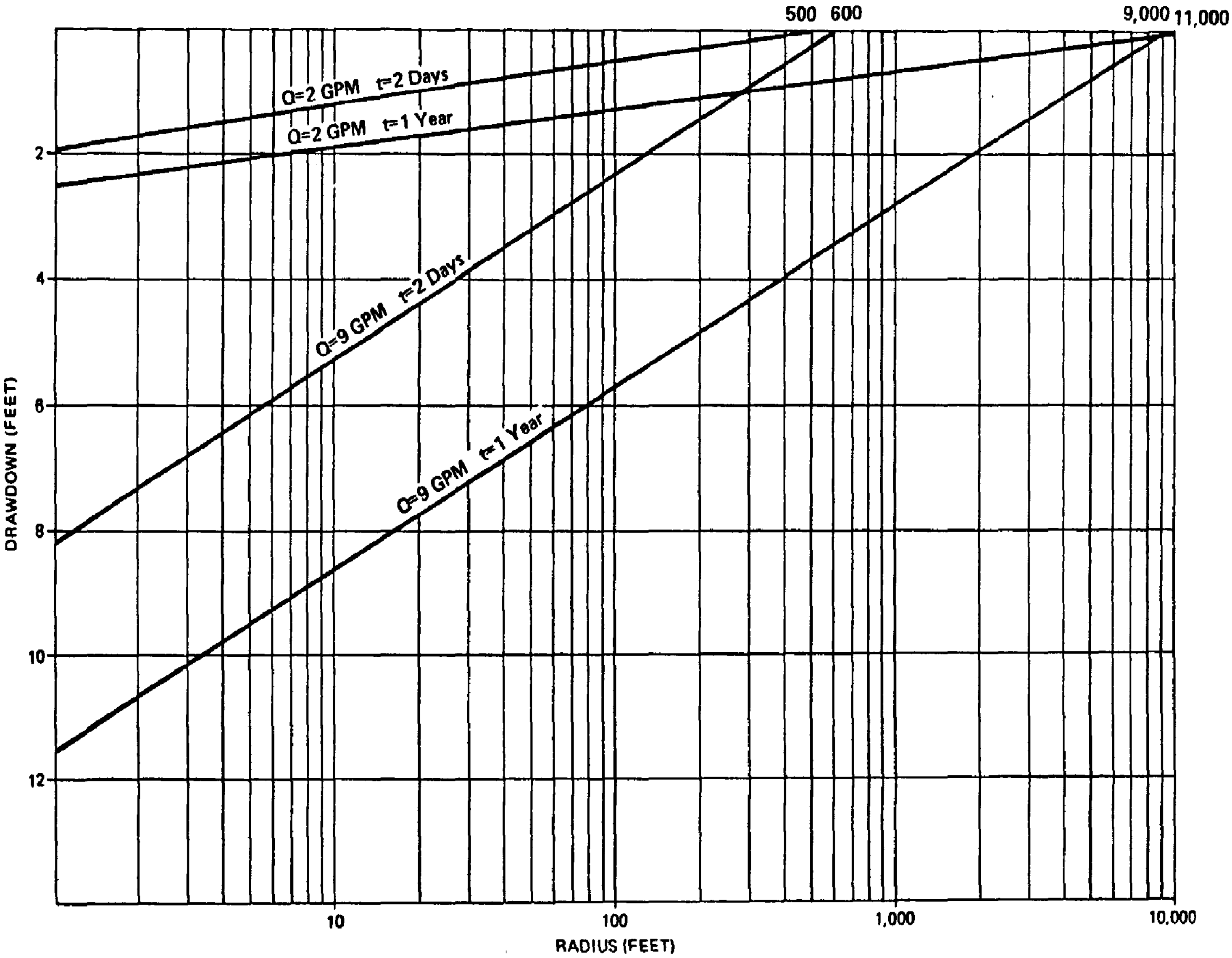

Fig. 6. Radius of influence predicted from the Theis equation.

from the groundwater. The air stripper was installed about 20 feet to the west of recovery well RW-1 (see Fig. 1). Underground piping from the two recovery wells was connected to the air stripper, which was located in a small building for protection of the treatment unit's instrumentation and control systems and other associated equipment.

Air stripping is a process in which water and air are brought into close contact with each other for the purpose of removing volatile substances from the aqueous phase. The air stripper installed at the site is constructed of FRP (fiberglass reinforced plastic), with a diameter of 1.5 feet and a height of about 27 feet. A blower is used to force air through the stripper, thereby removing the VOCs from the groundwater as it is pumped to the top of the stripping tower and flows downward through packing in the tower. The air stripper is designed to remove at least 99% of the VOCs contained in the groundwater at flow rates up to 50 gpm.

The air stripping unit was used to treat the recovered groundwater until June 1988, with the treated effluent from the stripper then being discharged to a nearby manhole connected to the municipal sewer system. Since June 1988, the recovered groundwater has been discharged directly to the municipal sewer system without first being pumped to the air stripping unit. Direct discharging of the recovered groundwater to the municipal sewer system was approved by the state regulatory agency, with the condition that contaminant concentrations in the effluent must be within the allowable limits specified in the facility's indirect discharge permit. In all cases, the measured concentrations of VOCs in the water pumped from the recovery wells have been well below the permit limits.

8. Data collection and recent trends

As discussed previously, each of the monitoring wells numbered 1 through 15 has been sampled quarterly since at least April 1987. Several of the wells were also sampled prior to April 1987. Each groundwater sample is analyzed for the following VOCs and nickel, in accordance with the facility's post-closure permit:

- 1,1-Dichloroethane
- 1,1-Dichloroethylene
- Toluene
- 1,2-*trans*-Dichloroethylene
- Trichloroethylene

Trichloroethylene is the main constituent found in the groundwater. The other VOCs listed above have also been detected during some sampling events, but at much lower concentrations and much less frequently. Nickel concentrations in the groundwater have been well below the limit established in the post-closure permit, and the concentrations of other metals have consistently been very low.

In addition to the chemical analyses performed on the groundwater samples, the concentrations of the VOCs in the water pumped from the recovery wells and the effluent being discharged to the municipal sewer system are being measured on a weekly basis, as required by the facility's indirect discharge permit. A weekly record of recovery well flow rates is also being maintained. To ensure the accuracy and reliability of the data collected in this program, several quality control measures have been implemented, including the periodic analysis of field and trip blanks and the periodic collection of duplicate samples that are sent to two different independent laboratories.

In order to summarize the chemical data and account for random fluctuations in concentration values, the average VOC concentrations for all of the sampled wells were determined. These values are plotted as a function of time in Fig. 7. The plotted VOC concentration values were determined by summing the concentrations of each individual volatile organic compound detected in each well for each sampling period. Then, the total VOC concentrations for each well were summed and divided by the number of wells sampled during the period to determine the average VOC concentrations detected during the period. The sum of the detection limits for the individual VOC parameters being measured is 26 ppb, which is therefore the baseline value that would indicate no VOCs to be present above their detection limits.

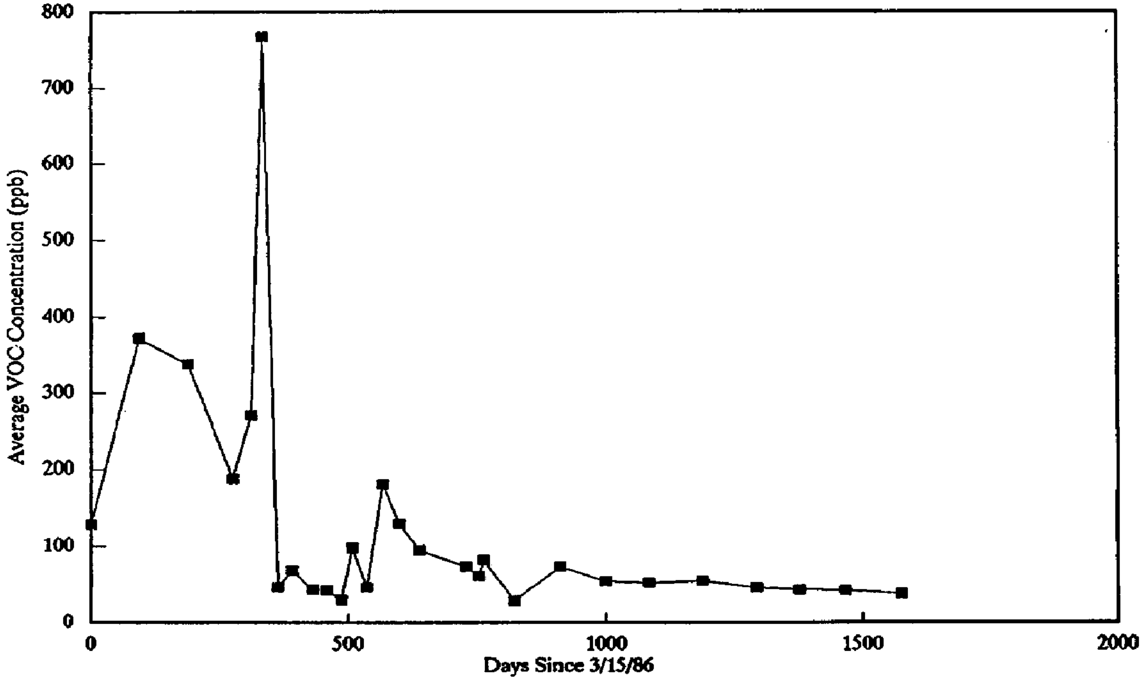

Fig. 7. Average concentration of VOCs over time (March 15, 1986–June 20, 1990).

It can be seen from Fig. 7 that the long-term trend of average VOC concentrations is decreasing over time. As the average VOC concentrations become lower, the rate of decrease also appears to be decreasing. Superimposed on the long-term decreasing trend in VOC concentrations are occasional spikes of increased concentration. A comparison of Fig. 7 with a similar graph of average water levels indicates that these spikes may be correlated with water levels. One theory that has been proposed to explain this phenomenon is that when water levels in a karst limestone aquifer fall, some contaminated water may be left behind in cavities in the unsaturated zone. When water levels rise again, this contaminated water may be brought back into the groundwater flow system and be detected as a concentration spike. As shown in Fig. 7, the last major spike occurred nearly three years ago. Thus, any cavities containing residual VOCs in the unsaturated zone may have been effectively flushed out by the earlier rises in the water level.

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