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GROUNDWATER FLOW IN A FRACTURED POROUS MEDIA AT PALOS FOREST PRESERVE, ILLINOIS

presented by

Michael L. Kohn

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GROUNDWATER FLOW IN A FRACTURED POROUS MEDIA
AT PALOS FOREST PRESERVE, ILLINOIS

By

Michael Leon Kohn

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ABSTRACT

GROUNDWATER FLOW IN A FRACTURED POROUS MEDIA
AT PALOS FOREST PRESERVE, ILLINOIS

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Low-level radioactive waste generated from the reactors was buried on-site at the Palos Forest Preserve in six foot deep trenches until late 1949, when it was excavated and removed. In 1973, tritium was detected in the dolomite aquifer at the site. The Red Gate Woods stream is suspected to have become loaded with tritium from waste burial during reactor operation and transported it to the unconsolidated materials below. Seasonal fluctuations of tritium concentrations in the dolomite aquifer at well FP5167 proximal to the picnic area were unexplained. Seasonal fluctuations were hypothesized to be the result of fluctuations in recharge through the glacial drift bringing varying amounts of tritium into the dolomite aquifer or varying fluxes of groundwater flow in the dolomite aquifer diluting a constant flux of tritium from the drift and varying the concentrations of tritium in the dolomite aquifer. A three-dimensional finite-difference groundwater flow model and a three-dimensional contaminant transport model were constructed to test the hypotheses. Modeled tritium concentration data for the two hypotheses was graphically compared and contrasted against measured tritium concentration data from well FP5167. Based on the results of graphical comparison, fluctuations in recharge are most likely the major control on the fluctuations in tritium concentrations in the dolomite aquifer proximal to well FP5167, but the variations in groundwater flux are probably also a contributing factor.

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Heartfelt thanks to my parents, Leon and Rosemary Kohn, who have provided the limitless encouragement and support throughout my entire educational process.

The deepest thanks of all I extend to my lovely and understanding wife Louise. She has supported and stood by me throughout the 1.5 years after graduate school when week-nights and week-ends were devoted to my thesis. Her love and help were freely given even when my writing was causing us not to have a life. It is solely the result of her love and support that I have achieved what I have today.

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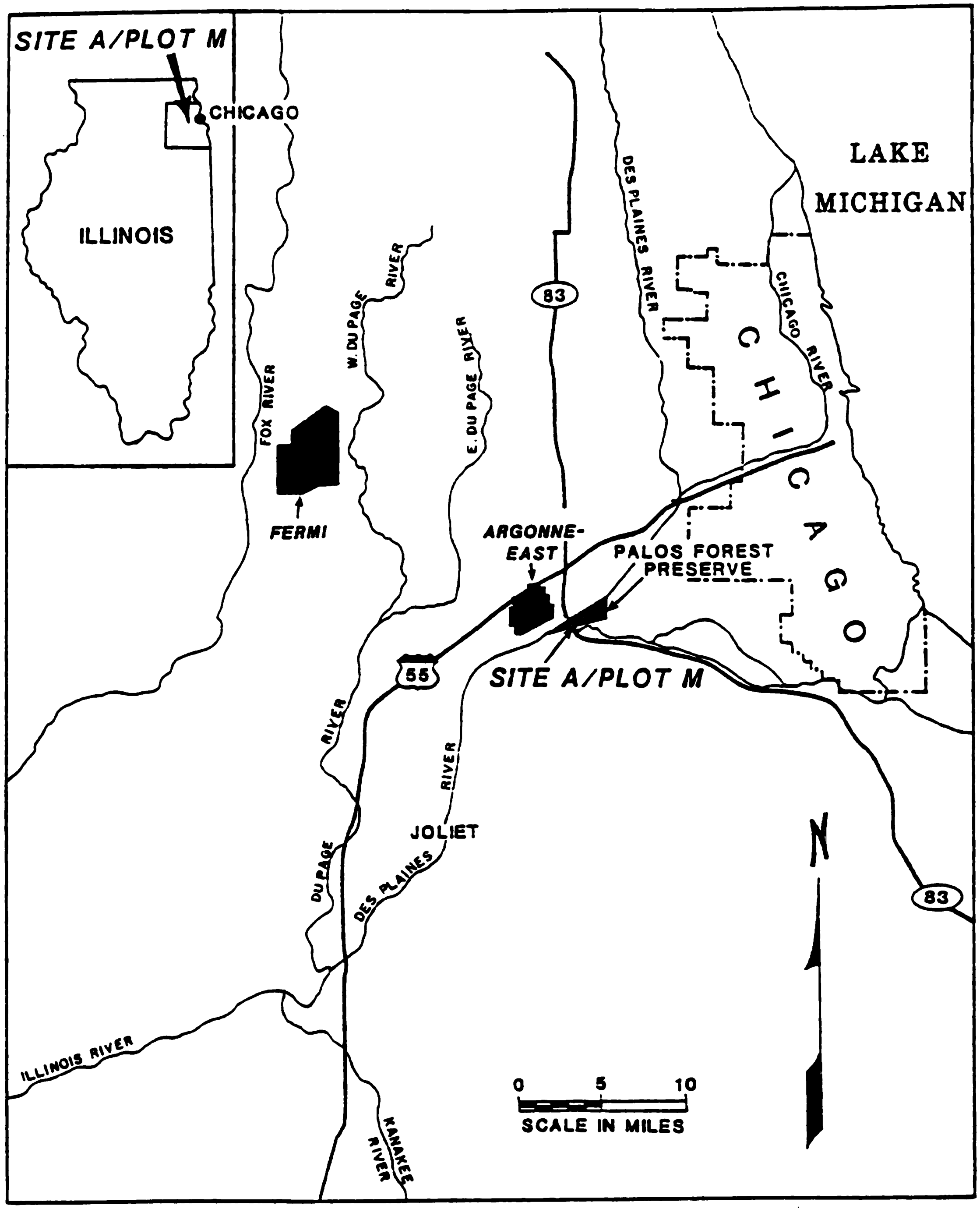
1.0 Introduction

In 1943, the U.S. Army Corps of Engineers built three of the world's first nuclear reactors in the Palos Forest Preserve, Illinois (Figure 1). Low-level radioactive waste generated from the reactors was buried on-site at Plot M in six foot deep trenches until late 1949, when it was excavated and removed (Figure 2). In 1973, tritium was detected in Forest Preserve Well 5167 (Figure 3), which is located approximately 1200 feet down gradient from the burial site, and a groundwater sampling program was implemented. Monitoring wells were installed in the glacial drift and underlying Silurian dolomite to study the migration of tritium in the groundwater. Tritium enters the dolomite aquifer at Plot M through the drift and lessens in concentration northward along the flowpath until it disappears below detectable levels after approximately 730 feet. The tritium concentrations reappear in the groundwater approximately 470 feet further along the flowpath and rise to peak concentrations that are five times greater than those in the groundwater beneath the original source at Plot M (Figure 4) before diminishing again. A proposed interpretation for this unexpected concentration gradient is that shortly after the burial of the radioactive waste, the Red Gate Woods stream became loaded with tritium and transported it into the Red Gate Woods picnic area (Figure 5). Here the stream bed materials are more permeable and the stream water entered the glacial drift below the stream and left behind high concentrations of tritium in the drift materials. Still unexplained are the seasonal fluctuations of tritium concentrations in the dolomite aquifer below the Red Gate Woods picnic area (Figure 6), which is the problem that this study will address.



Reference: "Environmental Restoration and Waste Management. Site Specific Plan: Vol. 9, Site A/Plot M", U.S. Department of Energy, Chicago Field Office. DOE/CH-9227

Figure 1: Site Location Map

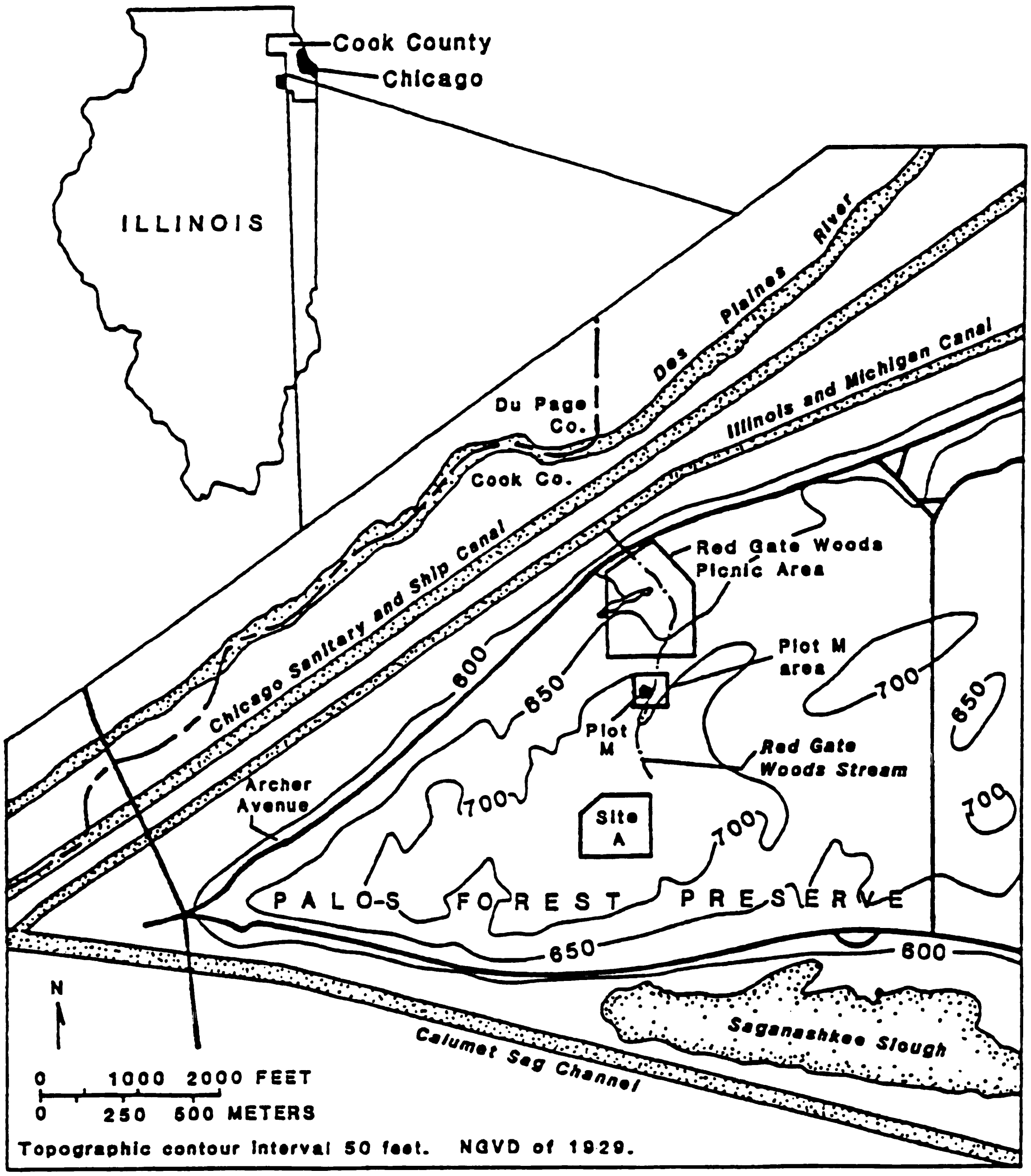
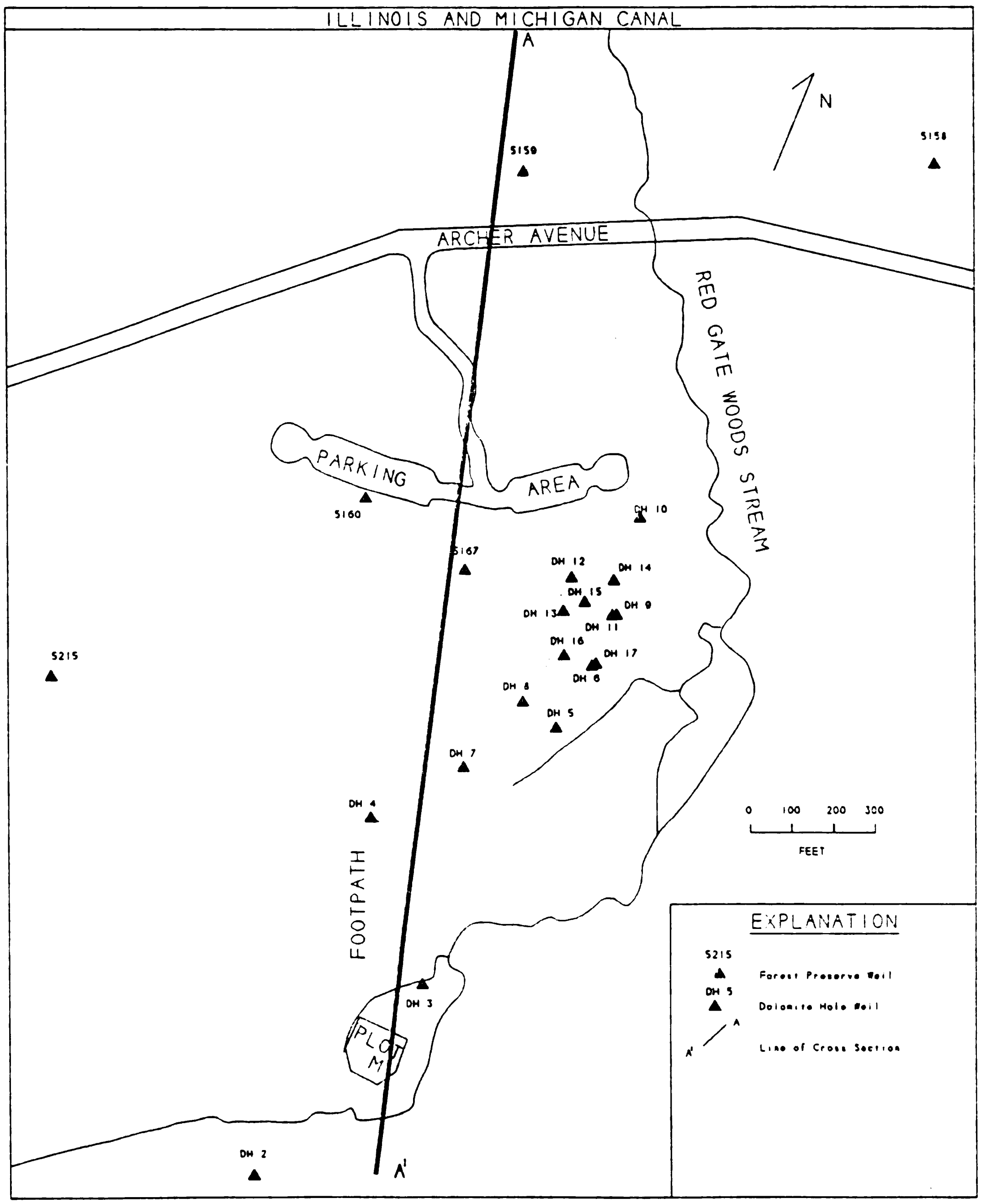


Figure 2: Site Map



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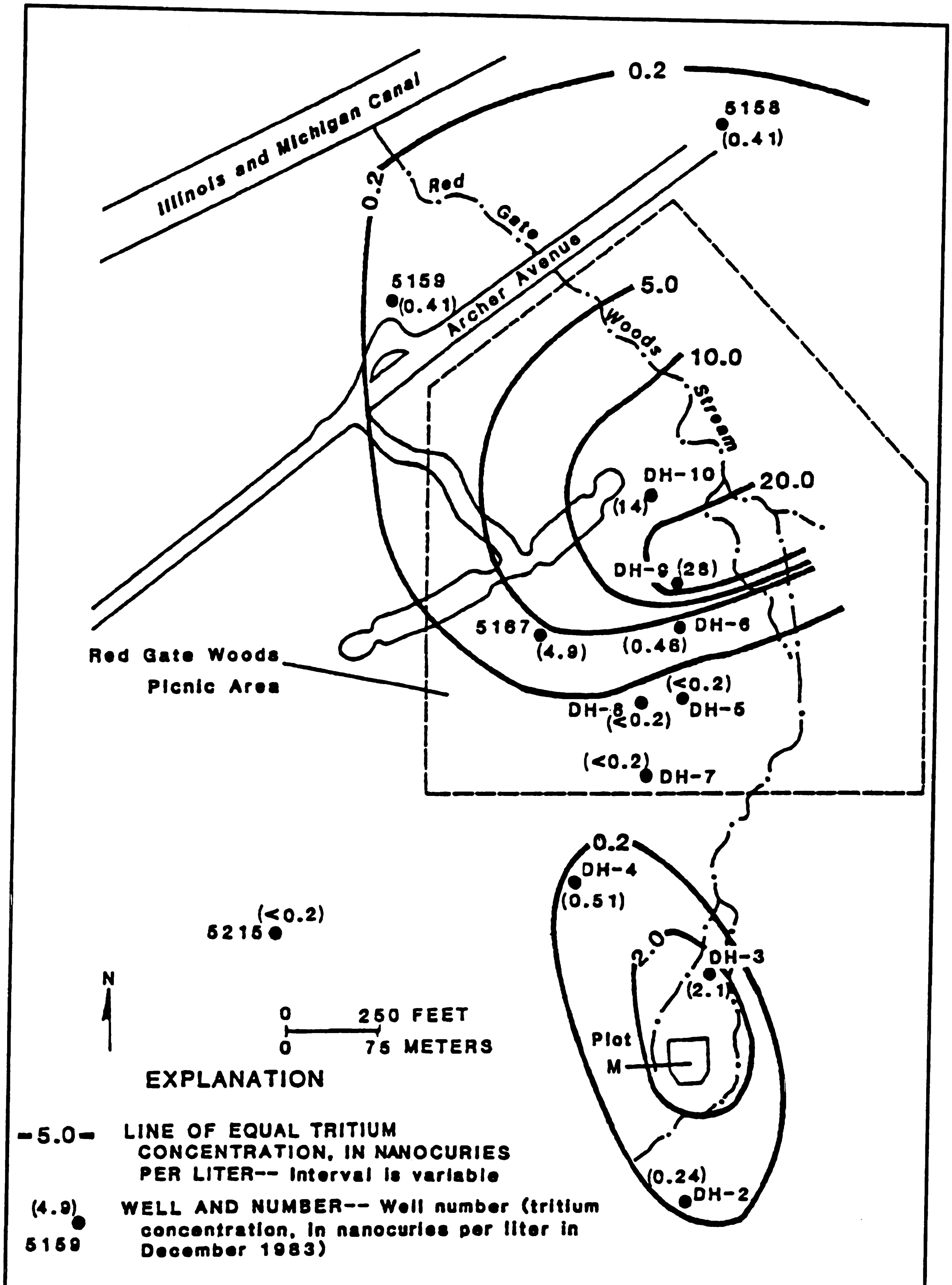
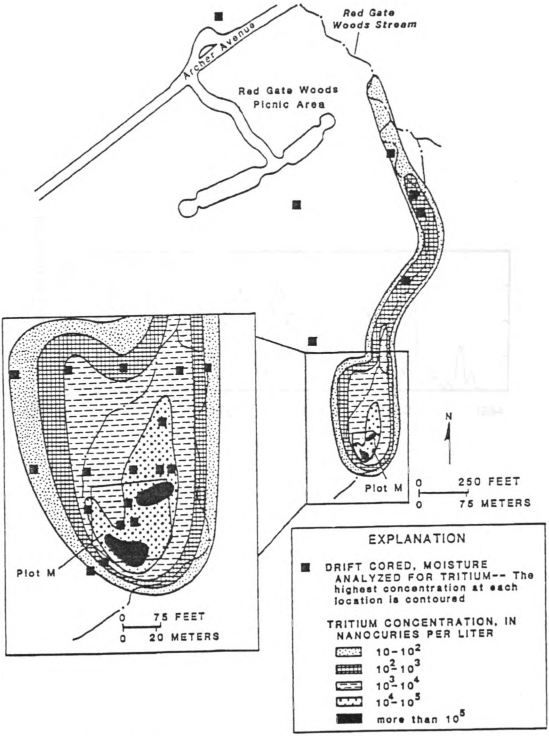


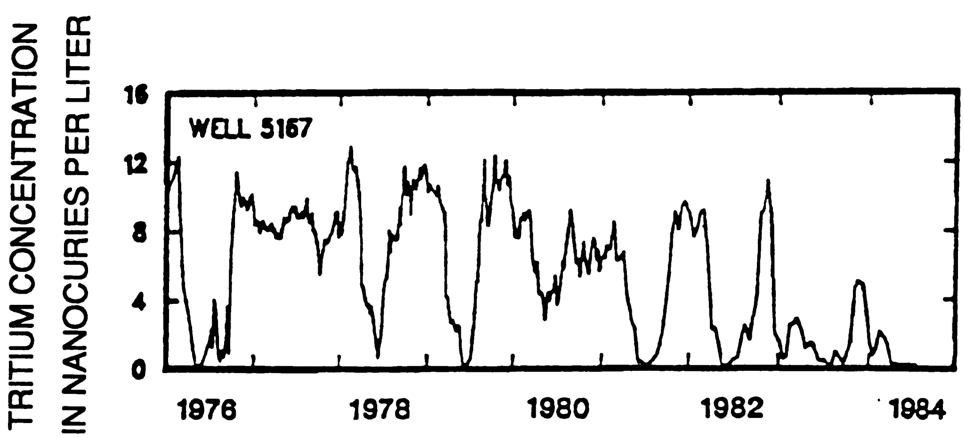
Reference: Nicholas and Healy (1988)

Figure 4: Groundwater Tritium Isocon Map for Dolomite Aquifer (December 1983)



Reference: Nicholas and Healy (1988)

Figure 5: Tritium Concentrations in Shallow Drift Materials Near the Red Gate Woods Stream



Reference: Nicholas and Healy (1988)

Figure 6: Seasonal Fluctuations in Tritium Concentrations at Well FP 5167

1.1 Statement of Purpose

The purpose of this study is to determine if the fluctuations of tritium concentrations in the dolomite aquifer at Forest Preserve Well 5167 are the result of (1) fluctuations in recharge through the glacial drift bringing varying amounts of tritium into the dolomite aquifer or (2) varying fluxes of groundwater flow in the dolomite aquifer diluting a constant flux of tritium from the drift and varying the concentrations of tritium in the dolomite aquifer. The first hypothesis represents a variation in localized recharge while the second hypothesis represents a variation in regional recharge. These two hypotheses are based on the above mentioned assumption that the major source of tritium to the dolomite aquifer in the study area is the tritium present in the glacial drift materials below the stream.

1.2 Conceptual Approach

To address the above mentioned hypotheses a through review and investigation was made of published material regarding the site. Available data was compiled to be used in the construction of a three-dimensional groundwater flow model of the site. As the available data was compiled and analyzed, the geological and hydrogeological concepts of the site were formed and enhanced. A three-dimensional groundwater flow model was constructed for the site to compute the parameters needed for the contaminant transport model (e.g.- groundwater flow rates, recharge through the drift). Assumptions were made to facilitate the characterization of hydrogeological conditions at the site with mathematical equations. The groundwater flow model was calibrated using yearly averages of hydraulic heads and precipitation. The model parameters obtained from the background review of published material were adjusted during the calibration process to create the best representation of physical parameters with mathematical equations.

The output parameters from the groundwater flow model were used as the input parameters for the contaminant transport model. Parameter values for the groundwater flow model were adjusted with regards to the contaminant transport model that was calibrated under the same conditions as the groundwater flow model. The contaminant transport model was run, one time for each hypothesis, for the months of three years that were wet, normal, and dry with regards to precipitation. The numerical results from the transport modeling of each hypothesis at Forest Preserve well 5167 were plotted and compared to the measured tritium data of the same time periods to evaluate which hypothesis produces the best match. The hypothesis that produced the best graphical match for the graph of the measured tritium data was thereby most correct. Conclusions were formed and presented as an enhanced conceptual hydrogeological model for the site.

1.3 Previous Models

Previous groundwater flow models have been constructed for the study area by Olympio (1980). The models that Olympio constructed were regional in size and consisted of a two-dimensional finite-difference areal model, a three-dimensional finite-difference areal model, and a two-dimensional finite difference cross-sectional model. The areal groundwater flow models encompassed an area of 11.7 square kilometers and had a grid spacing that varied from 100 x 100 meters to 200 x 400 meters. The three models were designed to test the conceptual hydrogeological model that Olympio had constructed for the region. The data set that Olympio used to construct the flow models was small and incomplete, necessitating the formation of numerous assumptions in order to construct the groundwater flow models. The two-dimensional model was run at steady state to test the assumption that recharge to the area was uniform, and to calculate a leakage rate from the drift to the dolomite. The one layer used in the two-dimensional model was the underlying Niagaran dolomite that represented a leaky-confined aquifer. The three-dimensional groundwater flow model was developed to simulate the steady state distribution of groundwater in both the unconfined and confined aquifers. The two layers used in the three-dimensional model were the upper unconfined glacial drift and the lower confined dolomite. The value for transmissivity of the dolomite aquifer was assumed to be homogeneous and isotropic throughout the system. Finally, a two-dimensional cross-sectional model was constructed to determine the pathways of groundwater flow through the two layer system.

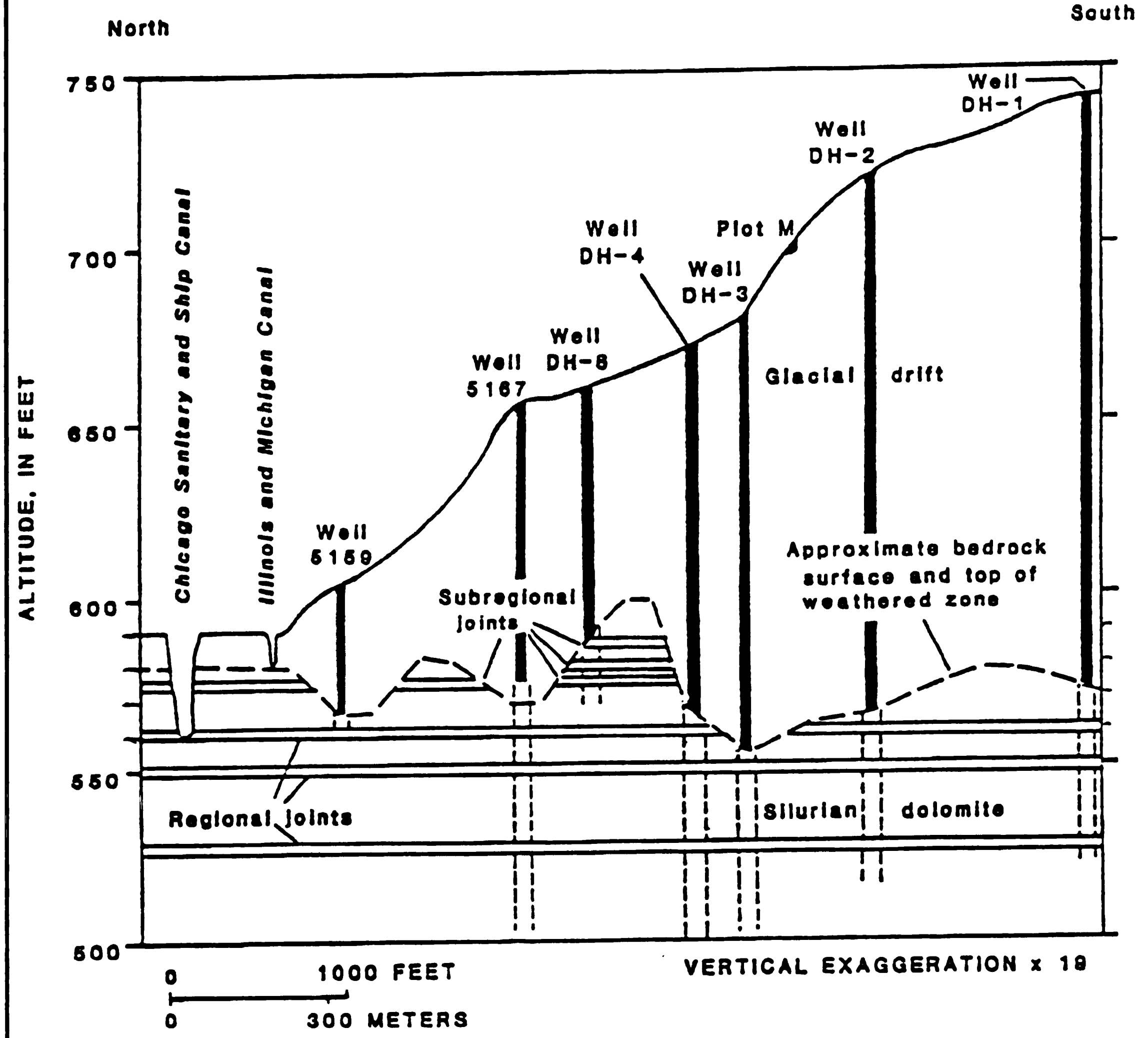
None of the flow models could be calibrated due to the lack of data and the assumptions needed to create them. A sensitivity analysis was conducted on the three-dimensional model that indicated that the most sensitive parameters were the recharge rate and the transmissivity of the dolomite. The results of the models indicated that a difference of 1 meter or less between the modeled and measured head values was sufficient, and that further investigation was needed to obtain additional data on bedrock topography and hydrogeological parameters of the aquifers beneath the study area to refine and calibrate the flow models.

2.0 Geology

The following description of the study area geology is from Nicholas and Healy (1988). The study area consists of a clayey drift overlying jointed Silurian dolomite (Figure 7).

2.1 Quaternary

The drift is made up of Quaternary materials deposited during the Wisconsinan Stage glaciation that are highly variable both laterally and vertically with respect to their lithology, structure, and degree of sorting. It is composed of the Malden and Wadsworth Members of the Wedron Formation which range in thickness over the study area from 1 to 170 feet with a thickness of approximately 140 feet beneath Plot M. The Wadsworth Till Member is a dense, clayey silt that becomes progressively better sorted with depth. Thin layers of sand and gravel are numerous in the upper 25 - 35 feet of this member. The layers range in thickness from 1 to 6 inches, dip to the northwest, and are laterally continuous for at least 300 feet beneath Plot M. Subvertical fractures that are filled with sand are also present in the upper 10 to 15 feet. The underlying Malden Till Member is composed of sandy silt and gravel which is well sorted and appears to have been reworked by glacial meltwater beneath Plot M. Between the Malden Till Member and the underlying Silurian dolomite is a thin layer (1-2 feet) of drift composed chiefly of sand and gravel, except in areas where a clayey silt layer is located on top of the drift-dolomite interface. Two valleys that have been incised by glacial meltwater into the drift of the study area are located to the north and west. To the north, the Des Plains River valley contains deposits of sand and gravel with occasional boulders. The Sag valley to the west contains thick deposits of peat and has a low gradient



Reference: Nicholas and Healy (1988)

Figure 7: Site Geological Cross Section

with no natural stream.

2.2 Silurian

The Silurian dolomite in the study area is composed of the Racine, Sugar Run, Joliet, Kankakee, and Elwood Formations (in descending order). It is the dolomite of the Racine Formation whose groundwater flow and tritium transport processes that this study will focus upon. The dolomite of the Racine Formation averages 80 feet in thickness and is a light-gray, silty and cherty, well-bedded dolomite that ranges from pure to shaley. This dolomite has been extensively weathered by solution. Outcrops of dolomite scattered along the edge of the Des Plains River and the Calumet Sag Channel indicate the dolomite is thin bedded, argillaceous, highly fractured, and contains many clay filled solution cavities that measure up to 30 x 60 feet in size. The top portion of dolomite bedrock is weathered and fractured.

The study area is located near the crest of the Kankakee arch and the strata dip slightly towards the east and southeast. Jointing in the brittle dolomite was caused by tensile stresses from subsidence of the Michigan basin and uplift of the Wisconsin and Kankakee arches. This stress caused two sets of vertical joints and a horizontal joint set that was enlarged by dissolution along bedding planes. Vertical fractures are common in the weathered zone at the top of the dolomite, but decrease in frequency and aperture below the upper few feet of dolomite (Nicholas, 1988). Horizontal joints along bedding planes have been observed in outcrops and borehole geophysical logs (Figure 7). The horizontal joints are at least hundreds of feet long and are enlarged by solution with some up to several inches wide, as seen at outcrops along the northern side of the Des Plains River valley. Acoustic and caliper logs of wells in the study area clearly show the horizontal joints. The jointing and lithology correlate between wells and appear to be continuous for at least 1600 feet. The U.S. Army Corps of Engineers collected rock cores during the construction of the Calumet Sag Channel that show horizontal joints having apertures up to 2 feet, some of which are filled with clay-to-sand sized particles of glacial origin.

For the purpose of this study, the four major horizontal joints in the upper 80 feet of the dolomite will dominate the groundwater flow system in the dolomite aquifer. They are aerially extensive with only canals or sinkholes interrupting them. The following description of the major fractures beneath the study area comes from Nicholas and others (unpublished) and Shapiro and Nicholas (1989). Interpretation of borehole geophysical logs (caliper and acoustic televiewer) indicated that there were four major horizontal fractures or fracture sets within the upper 80 feet of dolomite that range from 0.1 to 0.75 feet in aperture. The uppermost fracture set occurs in the weathered zone of the dolomite at approximately 566 feet and consists of three or more horizontal fractures that may be connected by vertical fractures. The second fracture set appears on geophysical logs as a single large aperture fracture at approximately 544 feet. Rock cores however indicate that it may consist of 5-6 small aperture fractures along bedding planes. A large aperture fracture at approximately 522 feet comprises the third fracture set, and a small aperture fracture at approximately 511 feet constitutes the fourth fracture set. Hydraulic tests using packers indicated that there are no natural hydraulic connections between horizontal fractures in the study area (Nicholas et.

al, 1988), but since many of the dolomite hole (DH) wells are uncased below the dolomite-drift interface and penetrate the depth of the above described fractures there are now anthropogenic pathways linking horizontal fractures. Beneath the dolomite, a sequence of shales and dolomites separate the upper dolomite aquifer from the lower dolomite aquifer and form a lower impervious boundary (aquitard) for the dolomite aquifer that this study will focus on.

3.0 Hydrogeology

The hydrogeology of the study area is composed of the two key components of Surface Water and Groundwater.

3.1 Surface Water

The main components of the surface water system in the study area are the Red Gate Woods stream, Chicago Sanitary and Ship Canal, Illinois and Michigan Canal, and the Calumet Sag Channel (see Figure 2). The channels and canals are recharged both by groundwater and surface water. They remain filled with water throughout the year and exhibit a relatively constant stage.

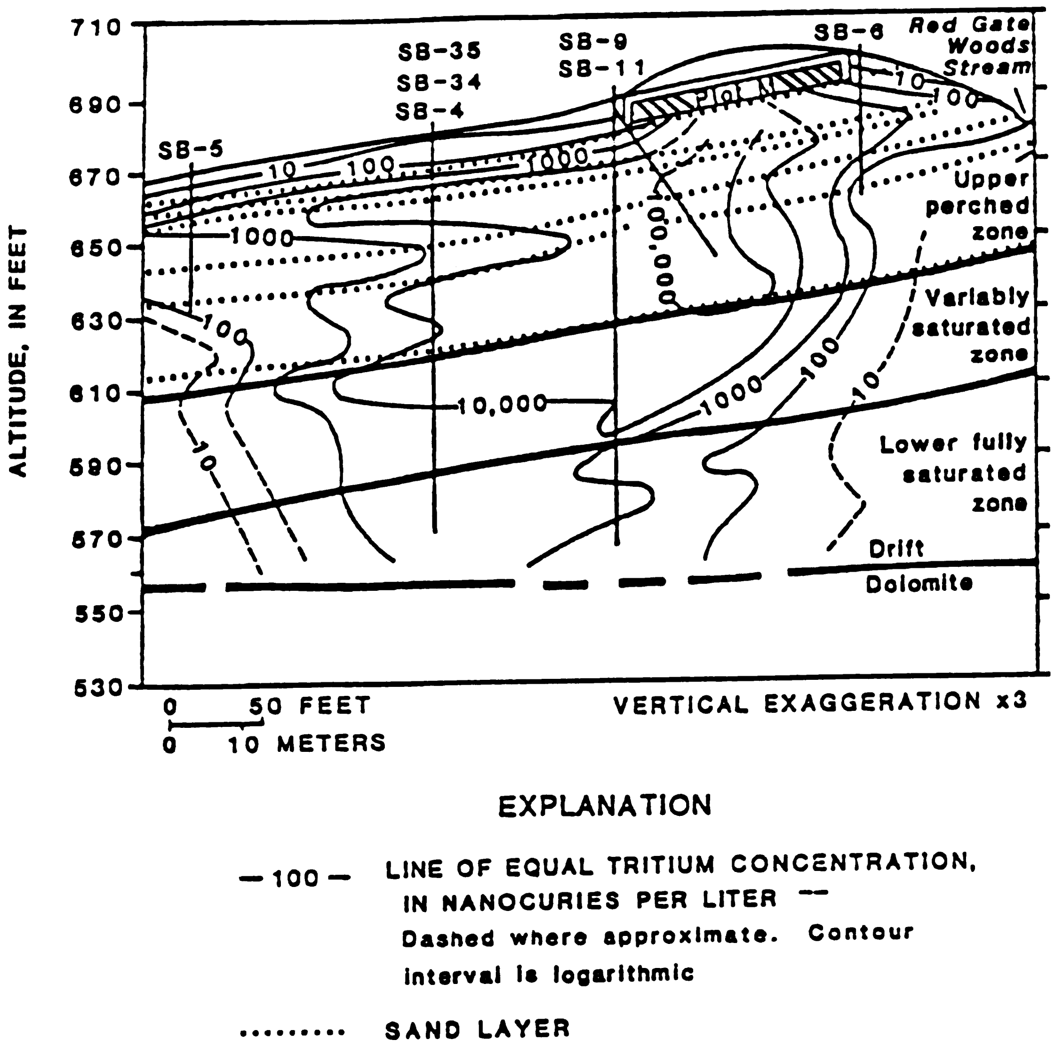
The Red Gate Woods stream is an ephemeral stream that flows, seldom other than early spring, from near Site A towards it's discharge area into the Illinois and Michigan Canal (Nicholas and Healy, 1988). The source of the streamflow comes in the forms of snowmelt, precipitation, and groundwater discharge. Proximal to Plot M, the stream is a gaining stream and then becomes a loosing stream in its lower reaches. The large degree of surface relief in the Plot M area serves to enhance the groundwater discharge into the stream. Even during periods of high flow, the stream water seldom reaches as far as Archer Avenue (Nicholas and Healy, 1988). Evidence of the gaining and loosing properties of the stream can be seen as the isocons of tritium in the streambed materials beginning proximal to Plot M and ending at the Red Gate Woods picnic area (Figure 5). During the summer months, evapotranspiration removes a sufficient amount of water from the underlying drift to lower the water table below the stream bottom. The stream occasionally flows in the fall and winter when the ground is not frozen.

3.2 Groundwater

The groundwater flow system in the study area is divided into two regions; the saturated portion of the drift, and the dolomite aquifer beneath the glacial drift. Groundwater in the drift region recharges the dolomite aquifer. The focus of this study is on the dolomite aquifer so the description of the saturated deposits of the drift will be brief.

3.2.1 Drift

The hydrogeology of the saturated unconsolidated deposits that make up the drift is complex and variable. The complex stratigraphy of the drift is composed of multiple layers with different hydraulic conductivities. Nicholas and Healy (1988) divided the hydrogeology of the drift into three zones with the following descriptions in descending order: (1) an upper perched zone (2) a variably saturated zone (3) and a lower, fully saturated zone (Figure 8).



Reference: Nicholas and Healy (1988)

Figure 8: Tritium Concentrations in Drift Core Moisture Below Plot M

The upper perched zone is composed of saturated sand layers that are surrounded by layers of clayey silt. Groundwater flow in this zone is nearly horizontal due to the lower hydraulic conductivity of the surrounding clayey silt. Water levels in this zone fluctuate due to seasonal changes in recharge, which are also reduced by the overlying concrete cap of Plot M, to the drift.

The variably saturated zone is approximately 35 feet thick and is located between the upper perched zone and the lower, fully saturated zone. The saturated materials of this zone are composed of sandy silt and gravel. This zone has a hydraulic conductivity greater than that of the bottom of the upper perched zone, thus allowing it to drain at a higher rate. This higher rate of drainage is evidenced by the piezometers installed in this zone only occasionally having water in them, hence the term "variably saturated".

The lower, fully saturated zone is composed of saturated materials that consist of silty sand and gravel. Groundwater levels in piezometers installed in this zone have a constant amount of water with levels that vary only over a very small range. The groundwater tritium isocons (Figure 8) of this zone indicates that groundwater flow is downward towards the dolomite it interfaces with.

3.2.2 Dolomite

The groundwater flow system in the dolomite aquifer is controlled by drainage areas; the Des Plains River (parallels the Illinois and Michigan canal along the study area) to the northwest, and the Calumet Sag channel to the southwest. Groundwater flows in the dolomite aquifer from the center of the Palos Forest Preserve toward the valley discharge areas (Nicholas and Healy, 1988). Leakage from the overlying glacial drift recharges the dolomite aquifer.

The dolomite has both a primary porosity which consists of the void spaces between crystalline grains, and a secondary porosity which consists of fractures and solution enlarged joints. The primary porosity of the dolomite is mostly insignificant in terms of groundwater flow, except as a storage reservoir (Nicholas and Healy, 1988). The major conduit for groundwater flow in the dolomite is the solution enlarged joints, especially those along bedding planes. There is a distinct and important relationship observed between the fractures and lithologic changes within the bedrock (Nicholas and others, unpublished). The major fractures in the bedrock occur above argillaceous layers which would have a significantly lower hydraulic conductivity and solubility. The lower hydraulic conductivity and solubility would retard the vertical component of groundwater flow across the argillaceous layers which would in turn enhance the horizontal component of groundwater flow and favor matrix dissolution above and along the top of the argillaceous layers. As the horizontal fractures are increased in aperture by this preferential process, they become preferred groundwater flow pathways and increase the effects of the dissolution process perpendicular to their axes which increases their aperture.

3.2.2.1 Dolomite Hydrogeological Parameters

The groundwater flow system within the dolomite aquifer can be divided into three different types of zones: (1) an upper weathered bedrock zone (2) dolomite rock-matrix and (3) fractures/joints within the dolomite bedrock. A large variety of borehole geophysical tests have been conducted on dolomite wells in the study area to determine the hydrogeological parameters of these zones. Horizontal joints located below an altitude of 570 feet form a regional groundwater flow system throughout the study area. A summary of the hydrogeological parameters of these three zones is presented in Table 1.

Table 1: Summary of Dolomite Hydrogeological Parameters

Zone	**Transmissivity**	**Storativity**	**Porosity**	**Hydraulic Conductivity**
Weathered Zone	120.96 ft^2/day	1.6×10^{-4}	0.200	NA
Dolomite Matrix	NA	NA	0.074	0.9504 ft/day
544 Fracture	26039.23 ft^2/day	2.2×10^{-5}	0.800	NA

The weathered zone is composed of weathered and fractured dolomite that extends from the drift-dolomite interface to an average depth of 565 feet. Within the weathered zone is a set of horizontal fractures, 3 to 4 fractures, that are connected by vertical fractures (Nicholas, 1988). Water levels in the weathered zone responded to pumping like a leaky confined aquifer, because this zone is hydraulically connected to the overlying drift (Nicholas, 1988). Inflatable packers were used to isolate the weathered zone from an altitude of 565-575 feet. Results of the test were presented by Nicholas and others (unpublished) which indicated a transmissivity of 1.4 x 10^{-3} ft^2/sec. Storativity was not included so the value of 1.6 x 10^{-4} was obtained from uncredited analysis plots of the pumping test data. A porosity of 0.20 was chosen from ranges of porosities for different geologic materials that was published by Dominico and Schwartz (1990).

The dolomite matrix that was tested for hydrogeological parameters is composed of more or less competent crystalline dolomite with possible small fractures. The altitude of the dolomite matrix extended from approximately 544-565 feet. The vertical hydraulic conductivity of the dolomite matrix was measured from laboratory analysis of rock cores which yielded values of 1.3 x 10^{-8} to 1.5 x 10^{-10} ft/s. The rock cores measured by the laboratory did not include fractures, so the dolomite matrix may yield a higher value of hydraulic conductivity than the range indicated by laboratory analysis (Nicholas, 1988). Recovery measured during a pumping test of the packed off dolomite matrix (555-565) indicated a hydraulic conductivity of 1.1 x 10^{-5} ft/sec (Nicholas and others, unpublished). During the first two seconds of pumping the matrix, water levels dropped 15 feet in the well, indicating that much of the water from this zone comes from storage. Laboratory analysis of dolomite matrix core samples collected at 123 locations yielded values of porosity that ranged from 1.7 to 18.7% (Nicholas and others, unpublished). The mean porosity was 7.4%, which falls within the range of porosity values for dolomite (0-20%) published in Physical and Chemical Hydrogeology (Dominico and Schwartz, 1990).

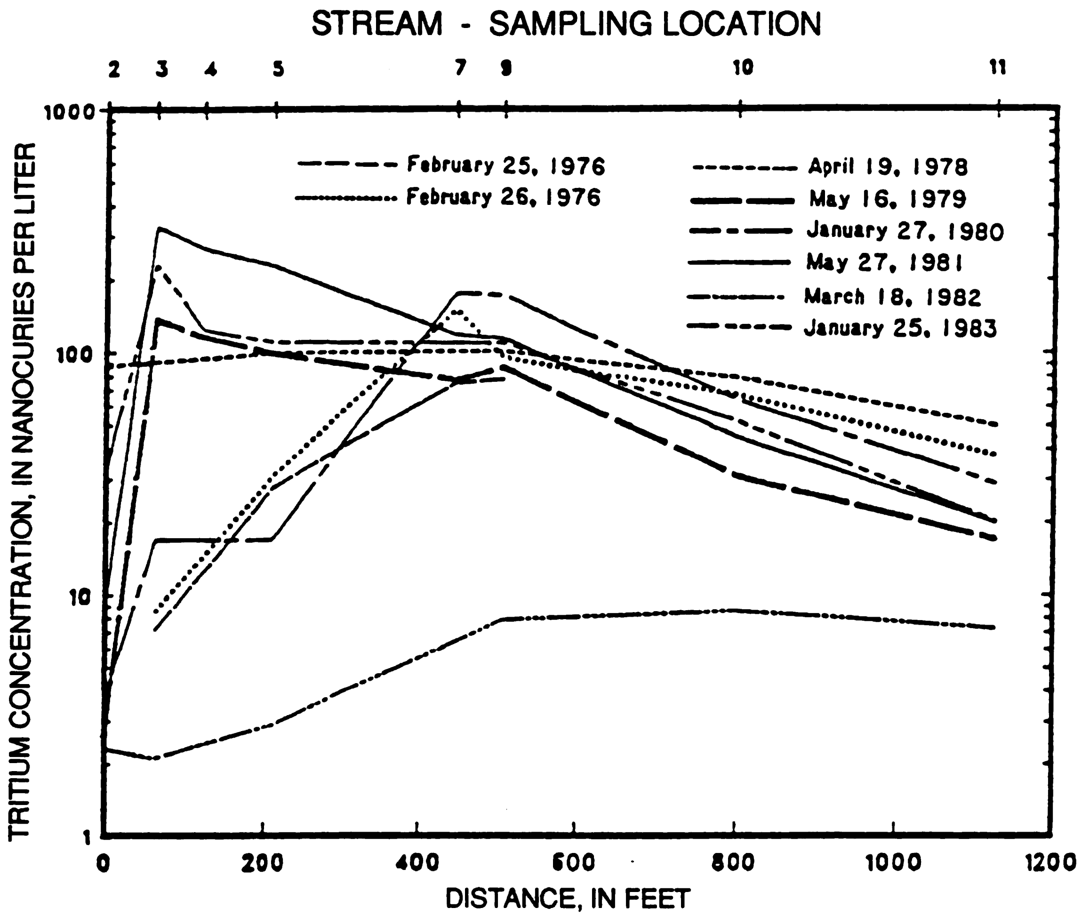
Three more major horizontal joints sets in the upper 80 feet of dolomite, that were continuous throughout the study area at altitudes of 544, 523, and 513 feet, were identified by Nicholas (1988). Nicholas and Healy (1988) estimated the hydraulic gradient of this system to be 6.25×10^{-4}. The most important and transmissive of the three above mentioned horizontal fracture is the fracture at 544 feet. The following description of the fracture at an altitude of approximately 544 feet comes from Nicholas (1988), Nicholas and others (unpublished), and Shapiro (1989). The dolomite fracture at 544 feet pumped like an infinite confined aquifer and had a transmissivity greater than any of the other fractures that were measured, which is approximately equal to the transmissivity of the entire section of dolomite measured during open-hole (packers not used) pumping tests. Analysis of the pumping tests of this fracture by Shapiro (1989), indicated a transmissivity of 0.30138 ft^2/sec and a storativity of 2.2×10^{-5}. The hydraulic connection of horizontal fracture sets by existing uncased boreholes in the dolomite was proven during open-hole tests with a flow meter that measured vertical flow. Within the first seconds of the pumping test, water flowed vertically in the observation boreholes to the altitude of the fracture being pumped. Water quality data indicates that there is minimal mixing between the water from the fracture at the altitude of 522 feet and the fracture at 544 feet. Tritium concentrations in the fracture at 544 feet are ten times less than the those of the weathered zone, which may indicate the downward flow of groundwater from the weathered zone to fractures below through open wells. Under non-pumping conditions in open wells, groundwater also flows from the weathered zone to the fracture at 544 feet. Nicholas and others (unpublished) states that the fracture at 544 feet is a flow divide, above the most argillaceous layer in the dolomite section, whose high transmissivity contributes to the low relief of the potentiometric surface measured across the site. The average width of the fracture at 544 feet is approximately 0.336 feet (Keys, 1986). Values of porosity for this fracture were not found during the literature review, so a value of 0.80 was assumed based on the likely hood that the fracture would not have a constant width nor parallel plates as an assumption of 1.0 would indicate.

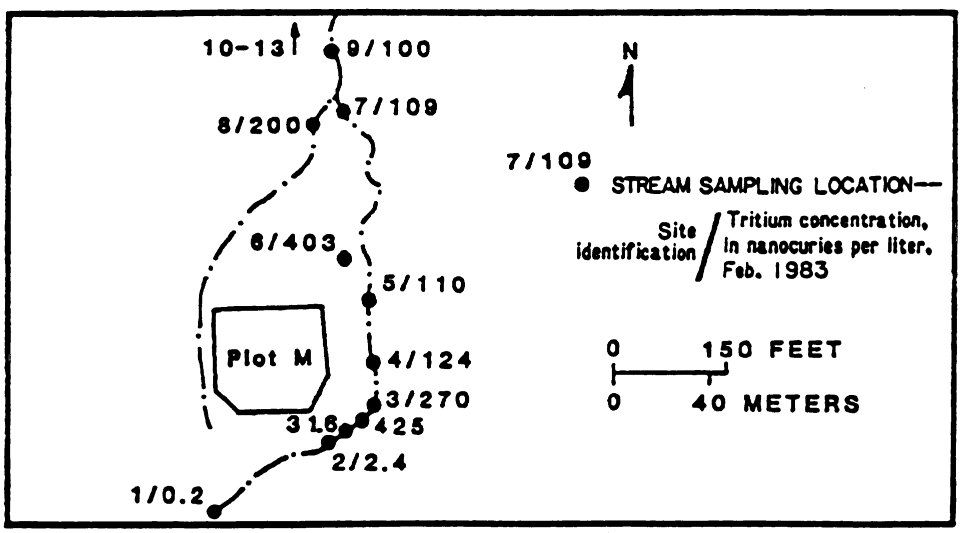
4.0 Tritium Migration

Tritium (^3H) is a radioactive isotope of hydrogen that has a half-life of 12.43 years. Tritium concentrations are traditionally reported as tritium units (TU), with 1 TU corresponding to 1 atom of ^3H in 10^{18} atoms of ^1H (Fontes, 1980). Tritium concentrations for this study are reported as nanocuries per liter (nCi/L) in groundwater at the site. One curie is the amount of material undergoing 3.7×10^{10} disintegrations per second. The measurement errors associated with the analysis of tritium at concentrations of 1.0 nCi/L or less in groundwater total $\pm$ 0.1 nCi/L (Nicholas and Healy, 1988). Tritium occurs naturally in the atmosphere and moves with the water cycle by the tritium atom substituting for the hydrogen atom in the water molecule (Reilly et. al., 1994). In this way, the tritium atom follows the path of water through the groundwater flow system. Nuclear weapons testing in 1953 increased the concentrations of tritium in the atmosphere, thereby increasing the concentrations in precipitation. During the early 1960's, tritium in precipitation reached three orders of magnitude greater concentrations than normal under natural conditions (Reilly et. al., 1994). Since the atmospheric nuclear weapons testing ban in 1963, tritium levels in the atmosphere have been steadily declining. Tritium concentrations in atmospheric precipitation are influenced by factors such as latitude, distance from the ocean, and seasons.

Elevated tritium concentrations at the study area are the result of interaction by precipitation, surface water, and groundwater with radioactive waste buried in the vicinity of Plot M during the reactor operation from 1943 to 1949. Golchert and Sedlet (1978) reported that tritiated groundwater had discharged from the glacial drift proximal to Plot M into the Red Gate Woods stream since at least 1954. The general trend of tritium concentrations in stream water (Figure 9) indicates that upgradient tritium concentrations in the stream are usually at the background level of 0.2 nCi/L, but increase proximal to Plot M and then decrease downstream as a result of dilution (Nicholas and Healy, 1988). Concentrations of tritium above background levels have been measured downstream as far as where the stream discharges into the Illinois and Michigan canal. Samples of stream water proximal to Plot M in 1983 had tritium concentrations of 31.6 to 425 nCi/L which suggest that the discharge of tritiated groundwater into the Red Gate Woods stream may occur at localized areas where the stream bottom intercepts sand lenses in the glacial drift (Nicholas and Healy, 1988).

Concentrations of tritium in groundwater in the drift below Plot M are presented in Figure 8, which indicate a downward movement of tritiated groundwater through the drift to the drift-dolomite interface. Also present is a minor lateral component of tritiated groundwater flow which may be the result of a preferred migration pathway along bedding planes and unconsolidated materials of higher hydraulic conductivity. Data from the moisture in drift cores indicates that the movement of tritiated groundwater beneath Plot M is progressing at a very slow rate (Nicholas and Healy, 1988). Data presented by Olympio (1980) indicated that the travel time for tritiated groundwater in the drift from Plot M to the drift-dolomite





Reference: Nicholas and Healy (1988)

Figure 9: Tritium Concentrations in Red Gate Woods Stream Waters

interface was 1116.66 days. Olympio (1984) concluded that the initial downward movement of tritiated groundwater occurred before the concrete cap, which cuts off the drift below Plot M from recharge (precipitation), was constructed in 1956.

Tritium concentrations in the dolomite aquifer beneath the study area are the focus of this study. Tritiated groundwater enters the dolomite at two different areas (Figure 4), forming two distinct groundwater tritium plumes (Nicholas and Healy, 1988). Concentrations of tritium and the size of the tritium plume are considerably less beneath Plot M than beneath the Red Gate Woods stream. This difference is unexpected since the concentrations of tritium and the size of the source area would seem to be much greater at Plot M rather than at the Red Gate Woods picnic area. The hydrogeological characteristics of the weathered bedrock zone make it a conduit for tritium migration from the drift into the dolomite aquifer. Wells open to the weathered bedrock zone that are along the groundwater flow path from the source beneath the stream yield the highest tritium concentrations.

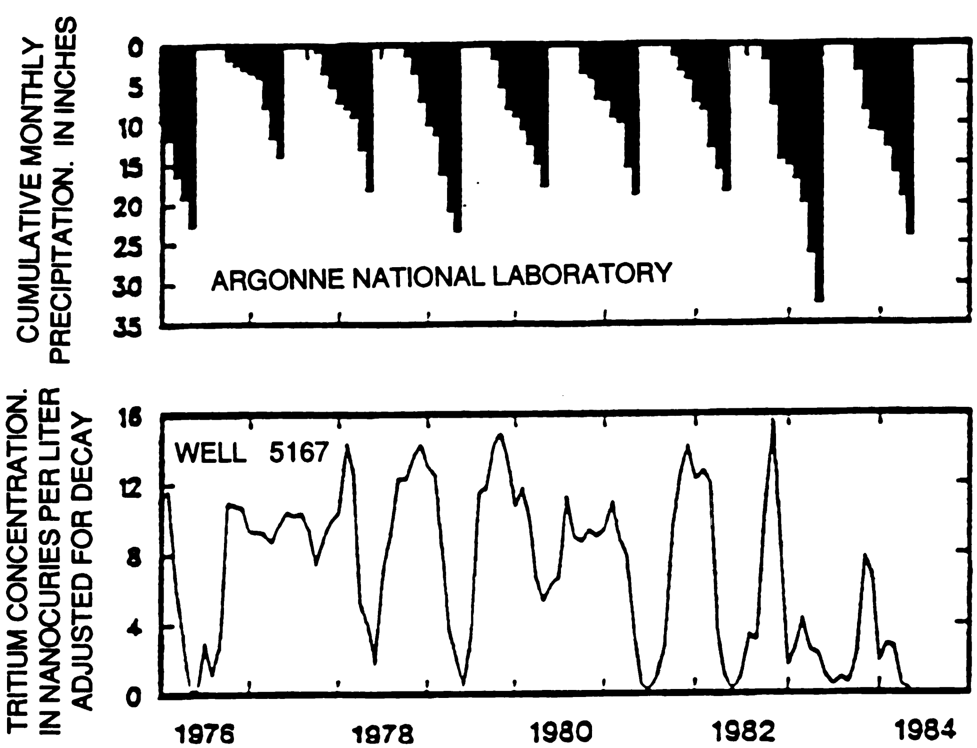
Nicholas and Healy (1988) observed that elevated concentrations of tritiated groundwater have not been detected in wells open to subregional dolomite joints (see Figure 7). The regional horizontal joints are major conduits for the migration of tritiated groundwater in the vicinity of the Red Gate Woods plume. Nicholas and Shapiro (1986) report that tritium concentrations in dolomite solution joints decrease with depth and range from 0.2 to 30 nCi/L. The tritium concentration in the adjacent dolomite matrix is less than that of the solution joints and has a maximum measured concentration of 10 nCi/L. Forest preserve well (FP) 5167 is open to the major horizontal joints. Tritium concentrations in FP 5167 have fluctuated seasonally since measurement began in 1973, ranging from background levels of 0.2 nCi/L in the summer to about 10 nCi/L in the winter (Nicholas and Healy, 1988). Nicholas and Healy (1988) noticed a lag time between major precipitation events and tritium fluctuations (decreasing concentrations) of 20 to 40 days in FP 5167. Figure 10 presents graphs of tritium concentrations and precipitation amounts over time at the same time scales. The matching of these graphs led Nicholas and Healy (1988) to conclude that, "Variations in the concentration of tritium in well FP 5167 are caused by variations in recharge to the dolomite."

5.0 Groundwater and Contaminant Transport Models

5.1 MODFLOW

MODFLOW (McDonald and Harbaugh, 1988) is a three-dimensional finite-difference computer program that was used to simulate groundwater flow conditions in the study area. The MODFLOW program simulates three-dimensional flow by using block-centered finite-difference equations that can be solved by using either the Strongly Implicit Procedure or Slice Successive Overrelaxation iterative solutions. The program uses subroutines (modules) that are grouped into packages and procedures. The packages allow the incorporation of internal and external influences on the model such as wells, rivers, recharge, drains, and evapotranspiration.

Other researchers (Huyakorn et al, 1983; and Bibby, 1981) have chosen finite element



Reference: Nicholas and Healy (1988)

Figure 10: Comparison of Fluctuations in Tritium Concentrations at Well FP 5167 With Precipitation

models to better represent an aquifer in which fractures and jointing are present. Finite element models use irregularly spaced grids, represent such tensorial concepts as transmissivities which do not coincide with coordinate axes of the model, and are more flexible in representing boundaries than finite difference models (Kinzelbach, 1986). The finite-difference model can accurately represent boundaries and capture hydrologic details in a small area by keeping the grid size small. Tensorial concepts that do not coincide with coordinate axes can be handled by aligning the model axes with the tensors of the aquifer to be modeled.

The finite-difference program MODFLOW was chosen to model the hydrogeologic conditions of the study area because of the many advantages it offered. MODFLOW uses a modular structure of subroutines to simulate specific features of the hydrologic system (sinks, rivers, drains, wells, recharge, etc.). The division of the program into modules provides the capability of examining specific hydrologic features independently, which allows for feature independent sensitivity analysis and statistical calibration modeling runs. The modular structure also allows for the incorporation of new packages without rewriting the entire model code. The advantages of a finite element model are equaled by constructing the MODFLOW finite-difference model with the above mentioned considerations. Since the testing of the hypotheses was dependent upon contaminant transport modeling, it was also important to choose a flow model that could communicate with and support a transport model. MODFLOW is the industry standard finite-difference groundwater flow model and is widely supported by a variety of post-processing models. By using the industry standard, linking with post-processing models is usually pre-established and free of de-bugging errors that may not be readily apparent and may affect model results in a negative way. The post-processing contaminant transport program MT3D (Zheng, 1992) has a pre-established link with MODFLOW.

5.2 Aquifer Characterization

The focus of the geologic and hydrogeologic investigation at the site has been on the dolomite bedrock rather than the overlying glacial drift. The quantity and quality of hydrogeological information gathered for the fractured bedrock zone is excellent, while only limited information has been gathered for the overlying glacial drift. Both of the proposed hypotheses focus on the hydrogeological properties of the bedrock zone and the transport properties within it. Due to the focus of the study and the lack of complete knowledge of the overlying drift, the conceptual hydrogeological model created focuses solely on the dolomite bedrock beneath the study area.

Figures 3 and 11 present the plan and cross-sectional views of the conceptual hydrogeological model respectively. According to Nicholas (1988), "The geology and hydraulic properties of the dolomite suggest a conceptual model of flow that is analogous to that in a layered-aquifer system. Horizontal fractures or fracture sets, such as the weathered zone are analogous to aquifers, and the dolomite matrix between the horizontal fractures is analogous to confining layers." Nicholas and Shapiro (1986) described the dolomite flow system where, "Each solution joint is hydraulically analogous to a infinite

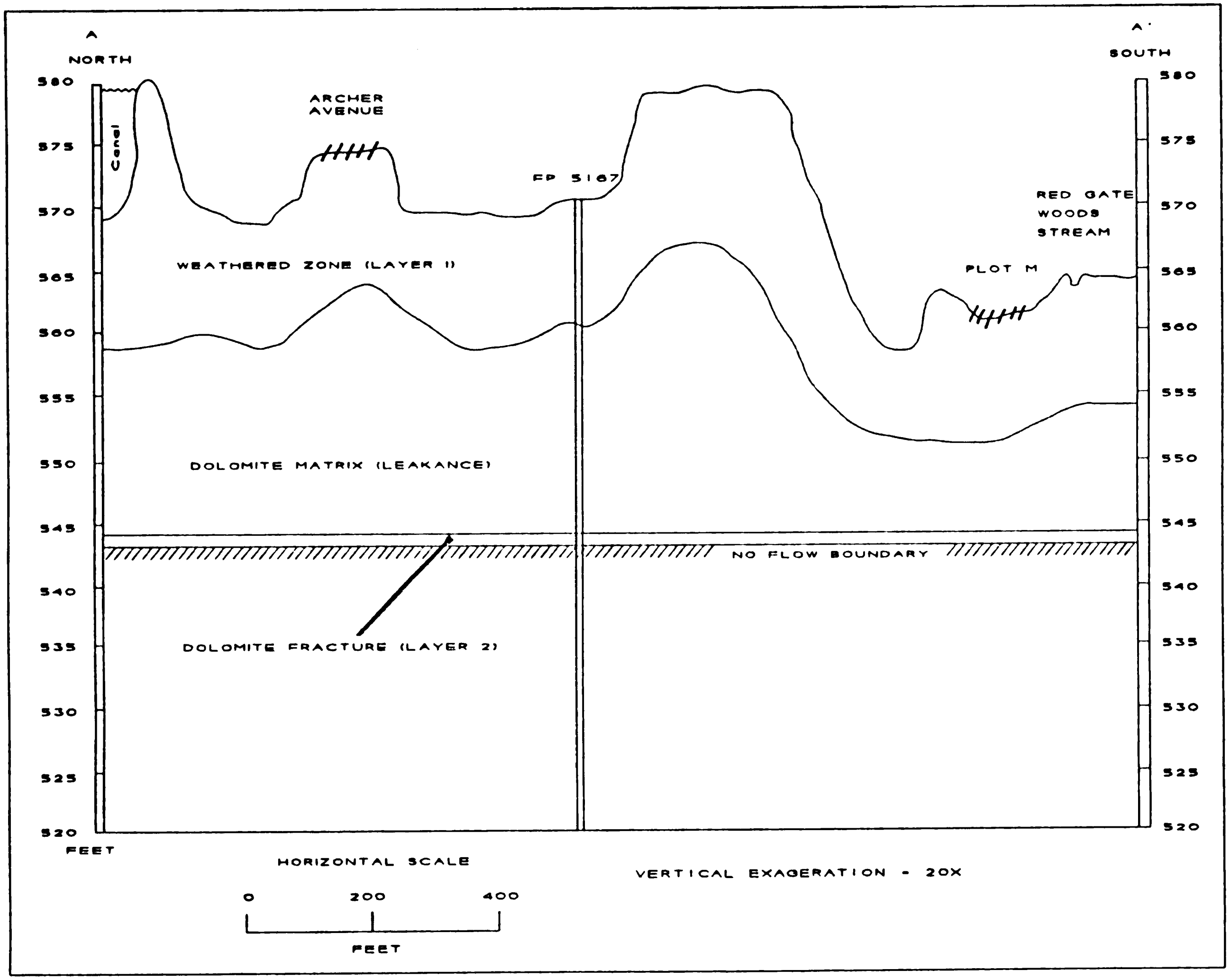


Figure 11: Model Geological Cross Section A-A'

confined aquifer that is bounded above and below by the dolomite matrix which is assumed to be impervious. However, the upper most solution joint set responds like an unconfined formation due to it's hydraulic connection with the weathered zone at the glacial drift - dolomite contact". Moffet and others (1986) stated that, "The dolomite matrix has high storage and low hydraulic conductivity relative to the fractures, which are major conduits for fluid flow." Previous descriptions of the hydrology of Silurian dolomite in northeastern Illinois haven't differentiated the properties of the matrix or unfractured rock mass, from individual fractures or zones of multiple fractures. Instead, they have assumed the aquifer to be homogeneous for the scale of the investigation (Nicholas and others, unpublished). Researchers have interpreted potentiometric, transmissivity, and water quality data as if the dolomite were a homogeneous, isotropic, porous medium. An assumption of this magnitude may be valid for studies of water supply; but at the smaller field scales, usually associated with contaminant transport where a few major fractures dominate solute transport, such an assumption is probably inappropriate. Shapiro (1989) presented mathematical solutions and interpretations for oscillatory pumping test data from dolomite wells in the study area, that were a better match for projected solutions by the dual porosity model which described the dolomite fractures and matrix separately, rather than the equivalent-porosity model which treated them as a single homogeneous unit. In constructing a groundwater flow model for this study area, the hydraulic and solute-transport properties of individual fracture will need to be described.

The model descritization focused on the dolomite bedrock where groundwater flow and tritium transport would be modeled. The weathered bedrock zone was selected as the upper model layer and the major bedrock fracture at 544 feet as the lower model layer. The dolomite matrix between the above mentioned zones was represented as a leakance value between the two zones. Communication between the major fracture at 544 feet and the lower dolomite matrix and fractures has been stated to be minimal based on groundwater quality data. The lack of communication with zones below it and the argillaceous layer underlying the fracture at 544 feet, make the bottom of the lower model layer a no-flow boundary.

Although the overlying glacial drift was not included in the model descritization, the recharge needed to achieve calibration of the flow model to measured hydraulic heads of dolomite wells will be representative of the groundwater contribution from the glacial drift, Red Gate Woods stream, and precipitation.

5.3 Initial Conditions

5.3.1 Boundary Conditions

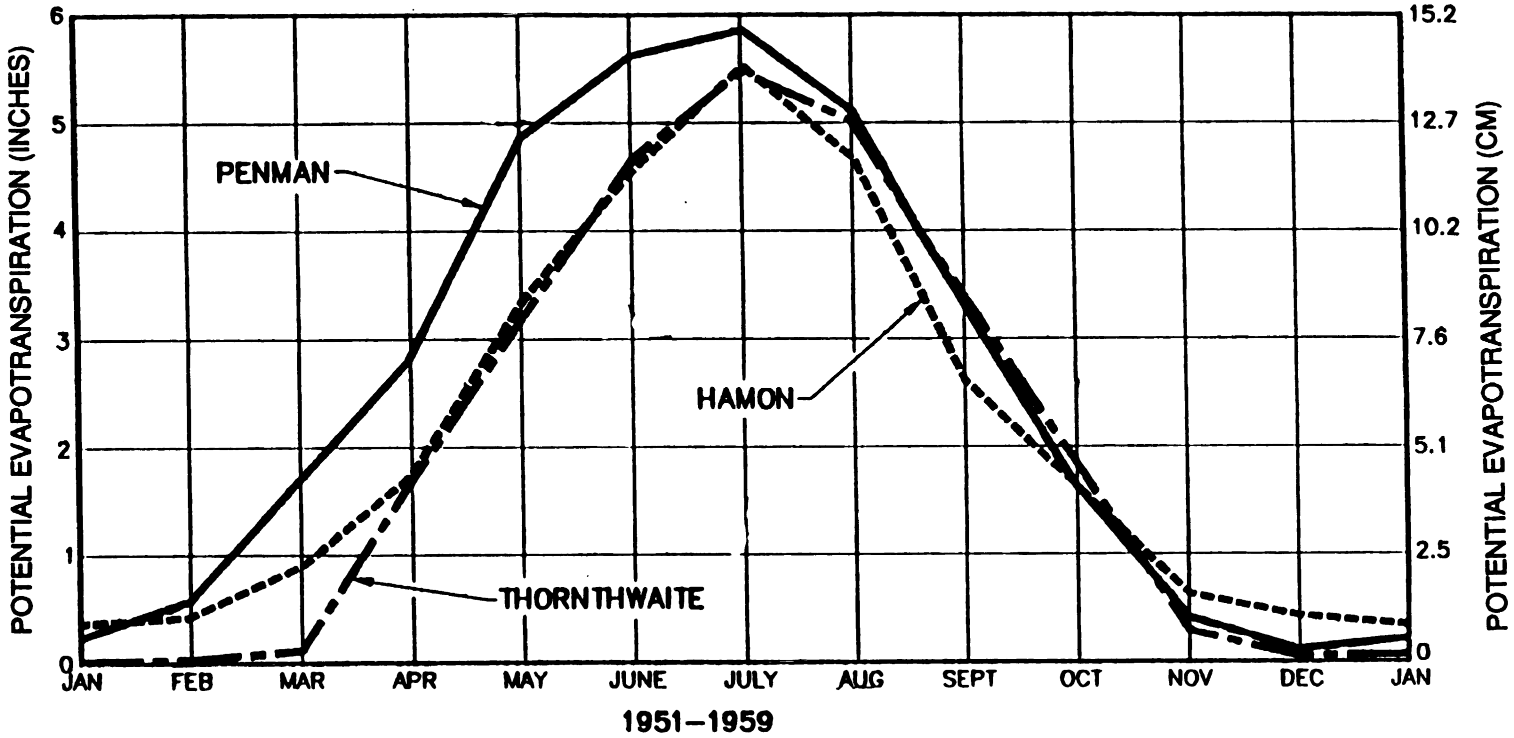
The boundary conditions for the site groundwater flow model consisted of no-flow and constant head boundaries which were set at the same value for each model layer. The north side (Illinois and Michigan canal) and the south side (DH-2) of the model area were treated as constant heads. Data for the Illinois and Michigan canal hydraulic head was unavailable so an estimate of 578 feet was used (Nicholas, communication). The constant head along the southern model boundary was chosen to equal the measured hydraulic head of DH-2 for the time period of interest. The eastern and western sides of the model area were designated as no-flow boundaries. Potentiometric surface maps of the study area indicated that groundwater flow in the model area moved approximately perpendicular to the Illinois and Michigan canal. The no-flow boundaries were located a sufficient distance away from the focus area of the model so as not to create an influence on the hydrogeological parameters that was not representative of actual groundwater flow characteristics. Golchert (1993) indicated that forest preserve well FP5215 would be a good flow boundary for the model area due to the absence of tritium in that well throughout the years of sampling, and it's side-gradient location to the groundwater migration pathway beneath Plot M and the Red Gate Woods stream.

5.3.2 Initial Parameters

The initial aquifer parameter values input into the groundwater model are presented in Table 2. The origin and explanation of many of the parameter values are discussed in previous sections. The parameters of leakance, recharge, top and bottom elevations and the topic of grid spacing will be discussed in further detail in the following sections.

5.3.2.1 Recharge

Recharge is the property used to represent the contributions from precipitation, the glacial drift, and the Red Gate Woods stream to the dolomite aquifer. Values for recharge were obtained from the cumulative monthly precipitation measured at the nearby Argonne National Laboratory from 1980-1988. Monthly precipitation values were adjusted for potential evapotranspiration occurring in Illinois (see Figure 12). The precipitation value



Reference: Jones (1966)

Figure 12: Potential Evapotranspiration Amounts in Illinois

remaining after the subtraction of the potential evapotranspiration value was then used in the groundwater flow model as recharge. Different magnitudes of the recharge value were applied to different portions of the flow model (ie. higher at the stream to represent increased contribution from the stream and the higher permeability of the streambed deposits). A summary table of yearly precipitation values and the calculation of recharge values is included in Appendix I.

Table 2: Initial Aquifer Property Values

Model Layer	Top Elevation	Bottom Elevation	Transmissivity	Storativity	Leakance
Layer 1	variable 556-600 ft	variable 546-590 ft	Tx = 120.96 ft^2/day Ty = 120.96 ft^2/day Tz = 40.32 ft^2/day	0.00016	0.09504 day^{-1}
Layer 2	544 ft	543.7 ft	Tx = 260392.32 ft^2/day Ty = 260392.32 ft^2/day Tz = 26039.232 ft^2/day	0.000022	not applicable

5.3.2.2 Leakance

Leakance is a property for which a value is assigned to represent the conductivity between model layers. In the case of the groundwater flow model constructed for the study area, the upper weathered dolomite zone (layer 1) and the lower dolomite fracture at 544 feet (layer 2) are separated by a layer of dolomite matrix that is not included as a separate layer in the flow model. Instead the hydraulic conductivity of the dolomite matrix was divided by its' thickness yielding a value with units of $days^{-1}$. To the flow model this parameter represents a communication value between model layers. The leakance value is assigned to layer 1 because the bottom of layer 2 is treated as a no-flow boundary across which communication is not made with lower layers.

5.3.2.3 Top and Bottom Elevations

Model layer top and bottom elevations were created for each model node with data compiled from Nicholas and Healy (1988), Nicholas (1988), Keys (1986), and from well construction specifications. The top of the weathered bedrock zone (layer 1) was interpreted from bedrock maps and well construction specifications. The bottom of this layer was obtained by subtracting 10 feet, the approximate thickness of the weathered zone across the site, from the top elevation at that nodal location. The top of layer 2 was the top of the major fracture (544 feet) whose bottom elevation was obtained by subtracting the fracture thickness, interpreted from acoustic televiewer logs to be 0.37 feet on average, from the top elevation.

5.3.2.4 Grid Spacing

The grid system created for the three-dimensional groundwater flow model is presented in Figure 13. Spacing between grid lines was kept small in the focus area of the model and then expanded at maximum increments of 1.5x when moving away from focus areas. Grid spacing ranged from approximately 50 to 150 feet. The purpose of keeping the grid spacing small was to capture the hydrogeological details of the focus area and to facilitate a contaminant transport process that modeled the concentration fluctuations at a single well within the study area (FP5167). The axes of the finite-difference grid were aligned parallel and perpendicular to the groundwater flow direction and the major directions of transmissivity at the site.

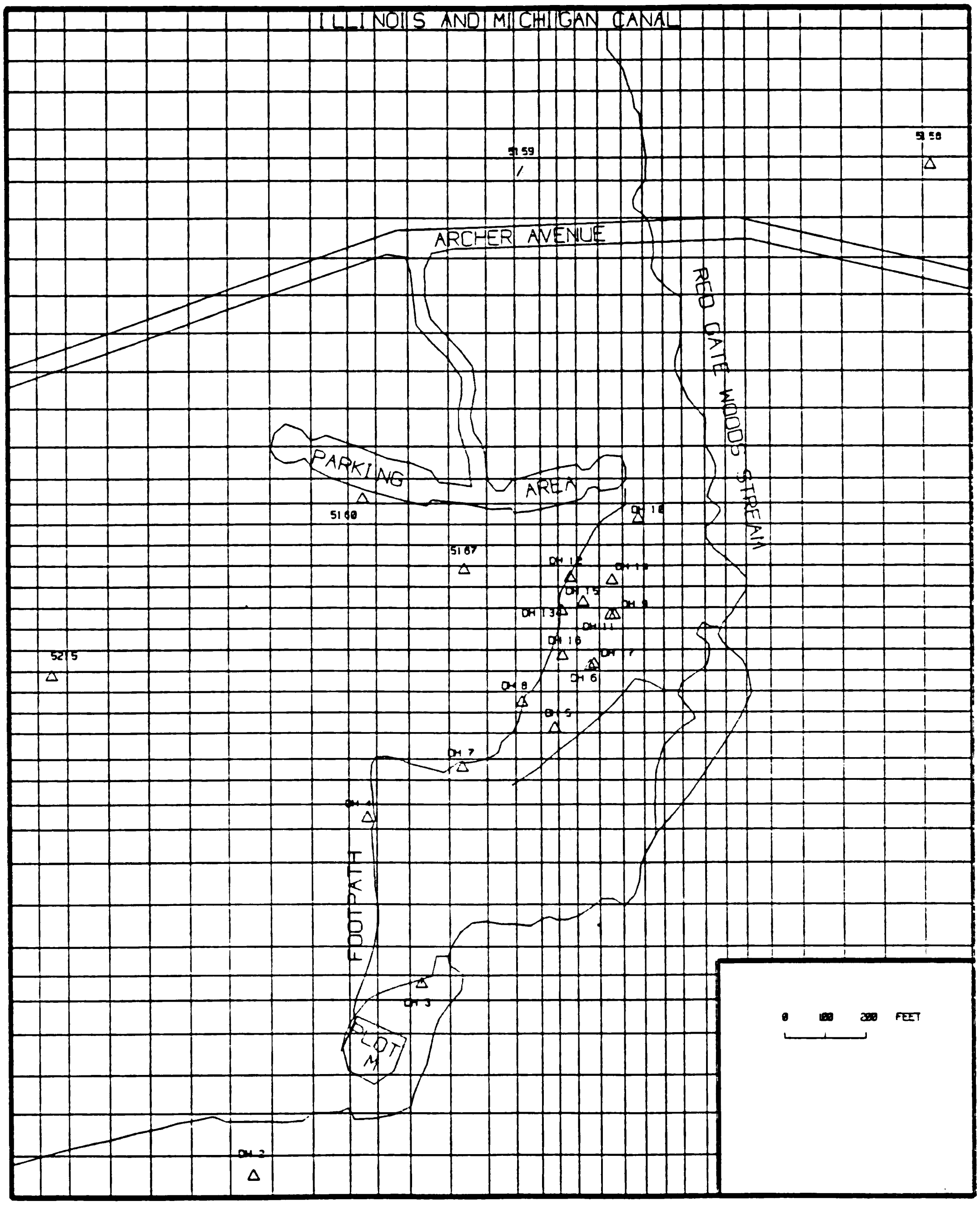


Figure 13: Model Area Map With Grid Overlay

5.3.3 Assumptions

The following assumptions were made to facilitate the characterization of hydrogeological conditions with mathematical equations:

1. Small grid spacing will facilitate the accurate representation of boundaries and hydrogeological details by the finite-difference groundwater flow model.
2. The aquifer values obtained through hydrogeological testing and laboratory analysis are representative of actual conditions at the site.
3. No-flow boundaries were placed far enough away from the model focus area to avoid creating an influence that was not representative of actual groundwater flow characteristics.
4. The hydraulic head of the Illinois and Michigan canal did not vary over the time periods being modeled, and was an accurate representation of the hydraulic head of the dolomite aquifer at that location.
5. Recharge to groundwater from precipitation and the Red Gate Woods stream can be represented by average monthly precipitation values, adjusted for potential evapotranspiration, with increased precipitation values beneath stream nodes in the flow model.
6. The major source of tritium to the dolomite aquifer in the study area is from the tritium present in the drift below the stream.

5.4 MT3D

MT3D (Zheng, 1992) is a modular three-dimensional transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems. The MT3D transport model is based on the assumption that changes in the concentration field will not affect the flow field measurably. MT3D uses the hydraulic heads and various flow and sink/source terms saved by the groundwater flow model, and automatically incorporates the specified hydrogeologic boundary conditions. The model uses a mixed Eulerian-Lagrangian approach to the solution of the advective-dispersive-reactive equation, based on a combination of the method of characteristics (MOC) and the modified method of characteristics (Zheng, 1992). This approach combines both the strength of the MOC for eliminating numerical dispersion and the computational efficiency of the modified MOC. MT3D is a contaminant transport model that was developed for use with any block-centered finite-difference flow model, but came with an pre-established link for MODFLOW.

6.0 Calibration and Sensitivity Analysis

6.1 Flow Model Calibration

Once the hydrogeological parameters had been compiled and the groundwater flow model had been constructed, the calibration process was started. To begin the calibration process, the groundwater flow model was run under steady state conditions using the average hydraulic heads from 1984 for dolomite aquifer wells as calibration targets and the canal and DH-2 as constant head boundaries. Recharge was added to the model as a series of transitional steps over three model runs, with each successive run adding to the recharge of the prior run. The first run was made without recharge to establish a baseline potentiometric surface in the absence of recharge to compare later runs against. For the second run, the average monthly recharge for 1984 was added to each model cell and termed "area recharge". Recharge nodes beneath the position of the Red Gate Woods stream were assigned an increased recharge value (10x normal) for the third run, to represent the added recharge contribution from the stream and the increased permeability of the streambed deposits (see Figure 14).

Recharge added during runs 2 and 3 did not bring the water levels at the northern end of the model area high enough to match the average hydraulic heads measured from dolomite wells. Area recharge was increased by 1 order of magnitude increments in an effort to create a hydraulic gradient that was more representative of the measured hydraulic heads. Recharge that was increased by 5 orders of magnitude greater than normal still did not bring the water levels at the northern end of the model area high enough to match the average hydraulic heads measured from dolomite wells. The corresponding increases in the greater recharge contribution from the stream nodes raised water levels of well nodes proximal to the stream higher than the measured heads and created potentiometric surfaces that were not realistic for the hydrogeological conditions at the site. Also, the increase in recharge values was far beyond what was reasonable for an average monthly recharge value for any year on record.

To address this problem, the hydraulic gradient of the site had to be reduced so recharge could have more of an effect. The current hydraulic gradient exhibited by the model was

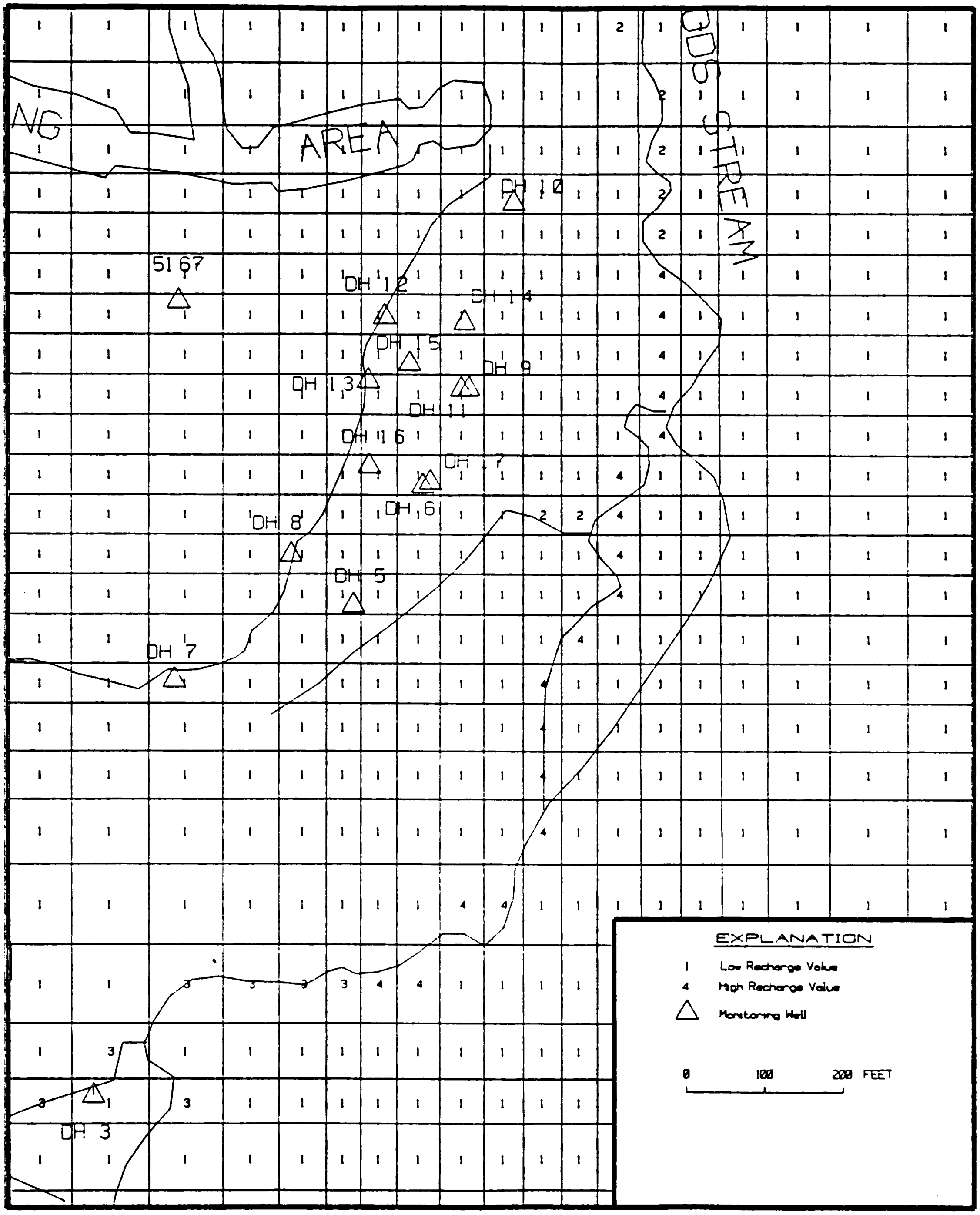


Figure 14: Recharge Node Values For Groundwater Flow Model

3×10^{-3} and the average hydraulic gradient indicated by Nicholas and Healy (1988) was 6×10^{-4}. Since the constant head value for the Illinois and Michigan canal was based on an estimate, it was raised (two feet) to 580 feet above MSL and recharge values were reduced to their original values of the third calibration run. The resulting hydraulic gradient was 1×10^{-3} whose decrease proved a much better match for the target heads measured from dolomite wells throughout the study area and closer to the value indicated by Nicholas and Healy (1988). Potentiometric surface maps from further runs indicated that an increased in recharge of 2 orders of magnitude at stream nodes from north of Plot M to the picnic area provided a better match for target heads proximal to the stream along this interval. This increased level of head matching provided a more accurate representation of the streams increased recharge contribution and the higher permeability of streambed sediments. The new potentiometric surface resulting from this modified recharge pattern also provided a groundwater migration pathway from the stream to forest preserve well FP5167, which was needed to facilitate the modeling of the hypotheses.

Once the water levels from the groundwater flow model were close to matching the average hydraulic heads measured for dolomite aquifer wells in 1984, statistical calibration runs were performed on the groundwater flow model. The initial calibration statistics from the first calibration run are presented in Table 3. The statistics from calibration runs are measures of calibration quality and are computed using residuals. Residuals were calculated by subtracting the model head from the target (measured) head. The absolute residual mean, which is an average of the absolute values of all residuals, provides a measure of the average total error of the groundwater flow model.

From the results of his three-dimensional regional groundwater flow model of the study area, Olympio (1980) indicated that a difference of 1 meter or less between measured and model hydraulic heads was satisfactory because the seasonal water level changes in the dolomite were often less than one meter. The maximum residual for the initial calibration of the groundwater flow model was 2.60 feet which is less than the 1 meter (3.28 feet) determined by Olympio, so this degree of accuracy was acceptable as a starting point.

Table 3: Summary of Model Statistics from Initial Calibration Run

Statistical Parameters	Initial Flow Model Calibration
Residual Mean	0.485612
Residual Standard Deviation	1.054892
Residual Sum of Squares	12.137548
Absolute Residual Mean	0.891335
Minimum Residual	-0.905691
Maximum Residual	2.605039
Observed Range in Head	1.848633
Residual Standard Deviation /Range in Head	0.570634

6.2 Sensitivity Analysis

With the completion of the groundwater flow model calibration process, a sensitivity analysis was performed on the groundwater flow model. The sensitivity analysis was conducted by varying each model parameter independently by a factor of 1.2x and computing calibration statistics for each variation. Separate sensitivity analysis runs were conducted for each parameter and for each model layer (ie. storativity for layer 1, storativity for layer 2, etc.). The parameters varied were transmissivity (x,y,z), leakance, recharge, and storativity. The results of the sensitivity analysis indicated that the most sensitive model parameters were recharge and transmissivity in the x and y direction for model layer 1. Leakance and transmissivity in the x and y direction for model layer 2 were sensitive to a lesser extent, and the variation of the other parameters for each model layer produced a negligible effect on the statistical results. Results of the sensitivity analysis were concurrent with Olympio's (1980) observation that the hydraulic heads in the dolomite was most affected by variation in recharge rate and transmissivity of the dolomite. Some of the parameters that were varied during the sensitivity produced groundwater flow model results that were statistically a better match for the target heads. A set of calibration heads was also added for layer 2 for a more comprehensive calibration analysis. The results of the altered parameter values on the statistical analysis are presented in Table 4.

6.3 Transport Model Calibration

The final calibration process was started, after the sensitivity analysis was completed, by initial modeling of contaminant transport for the site under steady state conditions. Contaminant transport model runs were performed using MT3D and the output parameters from the steady state groundwater flow model for average conditions during 1984. The results of each run were plotted as potentiometric surface and tritium isocon maps for each model layer of each model run. The resulting four maps for each contaminant transport run were evaluated against the groundwater flow parameters used to create the flow model and with regards to the hypotheses that assumed tritium transport from the Red Gate Woods stream to forest preserve well FP5167 with groundwater flow. For the hypotheses to be

Table 4: Comparison of Groundwater Flow Model Statistical Analysis Results

Statistical Parameters	Initial Flow Model Calibration	Final Flow Model Calibration	Layer 1 Final Calibration	Layer 2 Final Calibration
Residual Mean	0.485612	0.292118	0.074686	0.509690
Residual Standard Deviation	1.054892	0.805015	0.771954	0.778184
Residual Sum of Squares	12.137548	13.201607	5.413422	7.778184
Absolute Residual Mean	0.891335	0.706828	0.652895	0.760760
Minimum Residual	-0.905691	-1.193472	-1.193472	-0.669058
Maximum Residual	2.605039	1.710400	1.243420	1.710400
Observed Range in Head	1.848633	2.180969	1.604248	2.180969
Residual Standard Deviation /Range in Head	0.570634	0.369109	0.481194	0.356806

tested, contaminant transport of tritium from recharge proximal to the stream had to migrate beyond FP5167 and short of FP5215. Tritium was added with recharge to the model at the stream nodes earlier identified as having recharge values of 2 orders of magnitude greater than the area recharge applied over the entire model area. The MT3D units of concentration were lbs/ft^3, due to flow model parameter unit choices of days and feet, and the amount added to the recharge was 100 lbs/ft^3. The results of the first few contaminant transport model runs indicated that limited migration was progressing outwards from stream nodes in layer 1, but tritium migration with groundwater flow was occurring beneath the stream nodes in layer 2 as small isolated pockets instead of migrating towards well FP5167.

The concentration of tritium in the recharge applied to the stream nodes was the first parameter to be varied to address the migration problem. Over a series of transport runs the tritium concentration was increased to a final value of 1,000,000 lbs/ft^3. The increase in concentration increased tritium isocon values in layers 1 and 2, but failed to broaden the extent of migration in either layer. The next step was to increase the recharge associated with tritium concentration by a factor of 3x in an effort to increase the hydraulic impetus for migration, but this method also failed to increase the extent of tritium migration in either model layer.

With variations in recharge and concentration failing to increase the extent of tritium migration, variations in the aquifer parameters were implemented in a series of contaminant transport model runs. Since leakance was the key parameter linking groundwater migration pathways between the two model layers, it was the first parameter to be varied. The most important leakance nodes were beneath the stream where tritium migration would progress from the source atop layer 1 into layer 2 below. Values of leakance were increased at stream node locations over a series of transport runs. Figure 5 was used as a guide for choosing the stream nodes at which the highest amount of leakance should occur to facilitate tritium transport to well FP5167. Golchert and Sedlet (1985) indicated that a sand and gravel lense is known to underlie the stream proximal to the locations of DH-9 and DH-10 and may be connected to the dolomite in this area. This connection is evidenced by the inability to properly seat the casing of DH-9 to the drift-dolomite interface and by the highest tritium values being detected in DH-9 and DH-10 which would require a supply of water with high tritium concentrations from the source area in the drift materials beneath the stream. Stream nodes in this area were given a leakance value of higher magnitude to represent this condition. The results of increasing the leakance values beneath stream nodes did increase the extent of tritium migration in layer 2, but the maximum distance of migration only extended about half the distance from the stream to well FP5167.

Until this point in the contaminant transport model calibration process, variation of model parameters had focused on sensitive parameters whose determined values had a variability built into them due to the method of measurement and functional representation. The only sensitive parameters left to be varied were the transmissivities of layers 1 and 2. The degree of unknown fracturing and interpreted thicknesses of layer 1, compared with the detailed pumping test information obtained for layer 2, made layer 1 the first choice for variation. Through a series of separate transport runs, the transmissivity (x,y,z) of layer 1 was both increased and decreased. The results of this variation indicated that an increase in the x and y transmissivity by 2 orders of magnitude and the z transmissivity by 1 order of magnitude facilitated the migration of tritium from the stream to well FP5167. Variation of the x and y transmissivity of layer 2 showed that increasing these parameters by 3 times the original value extended the migration of tritium past well FP5167 and short of well FP5215, thus meeting the earlier stated criteria by Golchert for boundary conditions. Recharge concentrations of tritium were reduced back to the original value of 100 lbs/ft^3 with no effect on the extent of tritium migration. An observation node was placed at the location of well FP5167 in layer 2 to record values of tritium concentrations during the contaminant transport modeling process. Increased concentrations (1,000 to 100,000) are recommended for the testing of hypotheses because concentrations measured at the observation node were of smaller magnitudes that would make entry, evaluation, and manipulation difficult and visually challenging.

A final statistical analysis was performed on the groundwater flow model whose parameters had been altered during the calibration of the contaminant transport model. The results of this calibration are presented and compared to the last statistical analysis of the flow model in Table 5.

Figure 5: Final Calibration Statistics for the Groundwater Flow Model

Statistical Parameters	**Final Flow Model Calibration**	**Final Transport Model Calibration**
Residual Mean	0.292118	0.349744
Residual Standard Deviation	0.805015	0.772095
Residual Sum of Squares	13.201607	12.932129
Absolute Residual Mean	0.706828	0.704379
Minimum Residual	-1.193472	-0.894644
Maximum Residual	1.710400	1.555310
Observed Range in Head	2.180969	2.063965
Residual Standard Deviation /Range in Head	0.369109	0.374083

Comparison of the two sets of statistical analyses indicates that the parameters resulting from the final calibration of the contaminant transport model are a better match for the measured hydraulic heads of dolomite aquifer wells. The residual sum of squares, maximum residual, and the absolute residual mean were all reduced indicating that the final alteration of parameters formed a better match for measured heads and that the amount of model error was reduced.

The wells completed within the dolomite aquifer at the study area were constructed by similar methods, but to different depths (see Table 6). The wells (DH and FP) were cased off to the drift-dolomite contact and then continued on as open boreholes into the dolomite aquifer. With the different depths of open boreholes intersecting different and multiple zones within the dolomite bedrock, water level data from a few wells was difficult to match with the hydraulic gradient. Potentiometric surface maps constructed for the area by the groundwater flow model often could not match measured hydraulic heads for these few wells. Contours of measured hydraulic heads that included these wells often included bulges and sporadic variations that are not characteristic of groundwater flow within a well developed fracture system, such as the one found at the study area. Golchert (1988) reported that dolomite aquifer wells DH-6 through DH-9 and DH-10 are open to the overlying drift. These wells would not be representative for hydraulic head and tritium concentration measurements of the dolomite aquifer. Statistical analysis of calibration runs that included the hydraulic head values for these few wells produced higher residual values. The resulting sum of squares from statistical analysis of calibration runs that didn't include these few wells would be a lower number reflecting the greater degree of accuracy created by the groundwater flow model in matching the measured heads of representative wells.

Table 6: Dolomite Well Construction Elevations

Well ID	Top of Casing (ft)	Top of Bedrock (ft)	Borehole Bottom (ft)
DH-1	743.5	572	527
DH-2	721.2	568	519
DH-3	679.5	556	505
DH-4	674.6	565	394
DH-5	659.6	585	558
DH-6	656.5	583	572
DH-7	665.6	587	578
DH-8	658.2	586	570
DH-9	656.3	581	578
DH-10	645.9	565	545
DH-11	657.0	573	426
DH-12	658.2	569	427
DH-13	658.9	571	428
DH-14	653.2	571	427
DH-15	660.7	573	489
DH-16	657.0	572	485
DH-17	656.0	571	484
FP5167	651.7	567	505

Figures 15 and 16 present the final potentiometric surface maps for layers 1 and 2 resulting from the final calibration of the contaminant transport model. The final extent of tritium migration for layers 1 and 2 are presented in Figures 17 and 18. The resulting final parameter values for the groundwater flow model are presented in Table 7.

Table 7: Final Groundwater Flow Model Parameter Values

Model Layer	Top Elevation	Bottom Elevation	Transmissivity	Storativity	Leakance
Layer 1	variable 556-600 ft	variable 546-590 ft	Tx = 12096.0 ft^2/day Ty = 12096.0 ft^2/day Tz = 403.2 ft^2/day	0.00016	variable 0.04572 - 1000 day^{-1}
Layer 2	544 ft	543.7 ft	Tx = 781176.0 ft^2/day Ty = 781176.0 ft^2/day Tz = 26039.232 ft^2/day	0.000022	not applicable

7.0 Testing of Hypotheses

Two hypotheses were proposed to account for the tritium fluctuations at forest preserve well FP5167: (1) the result of fluctuations in recharge through the drift bring varying amounts of tritium into the aquifer or (2) varying fluxes of groundwater flow in the dolomite cause the dilution of a constant flux of tritium from the drift and lessen the concentrations of tritium in the aquifer. Hypothesis number 1 was modeled by using the hydraulic gradient and average precipitation for each month to represent the fluctuations in recharge through the drift. Hypothesis number 2 was modeled by using the average monthly precipitation for the year to represent a constant flux of tritium from the drift and allowing the hydraulic gradient for each month to represent the variation in fluxes of groundwater flow. Three years were chosen to model the two hypothesis; wet (1983), normal (1985), and dry (1986) conditions

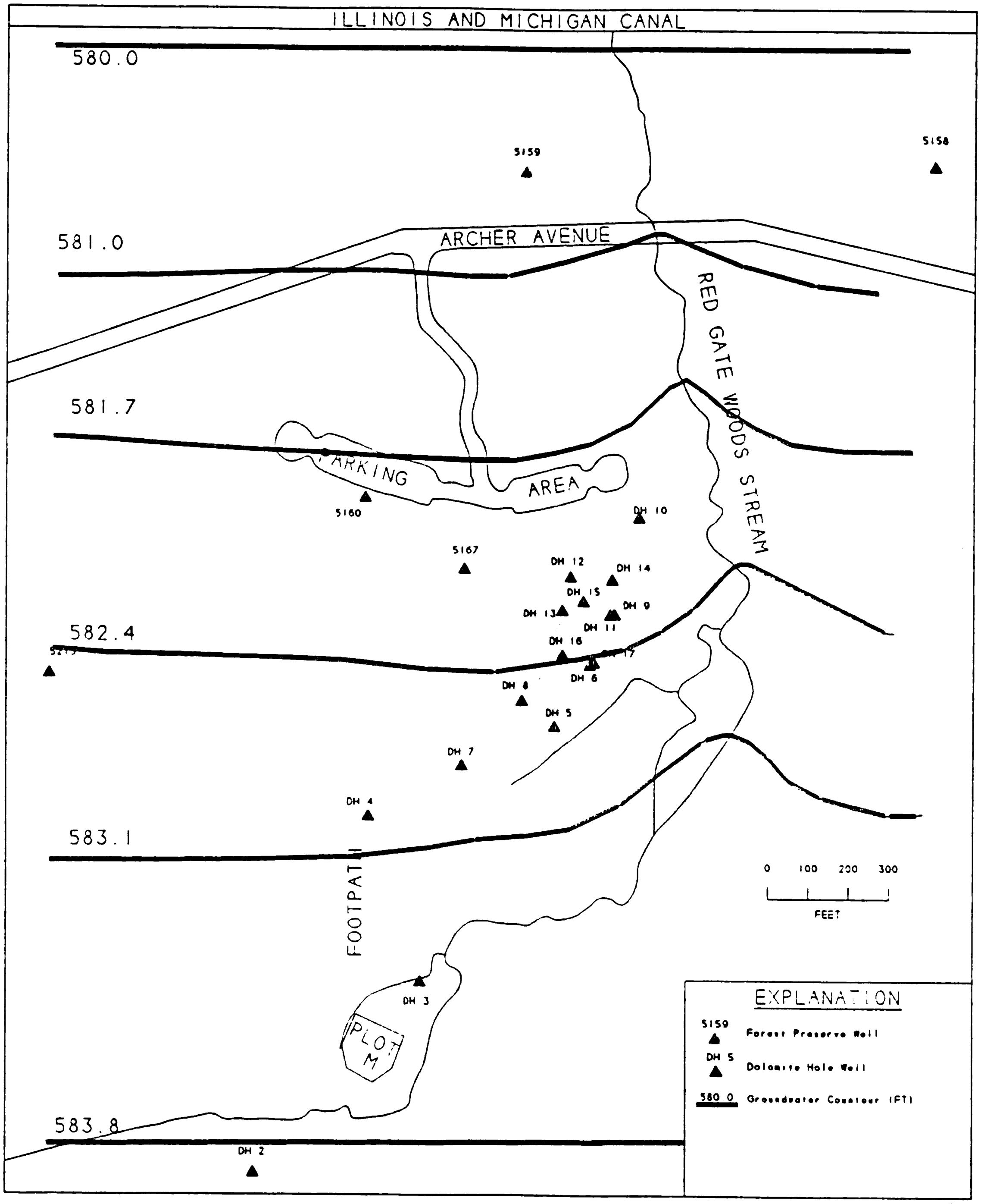


Figure 15: Potentiometric Surface Map For Layer 1

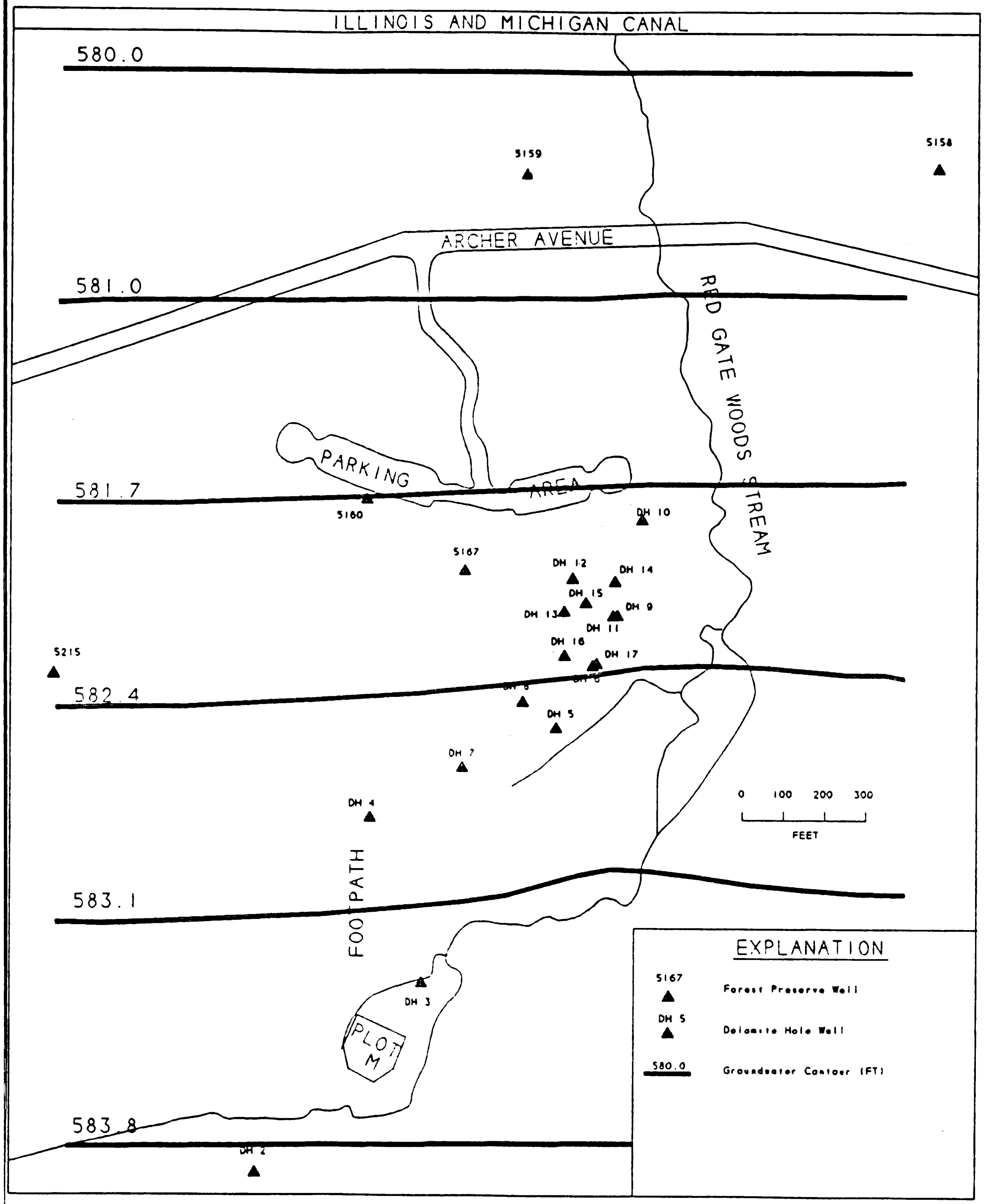


Figure 16: Potentiometric Surface Map For Layer 2

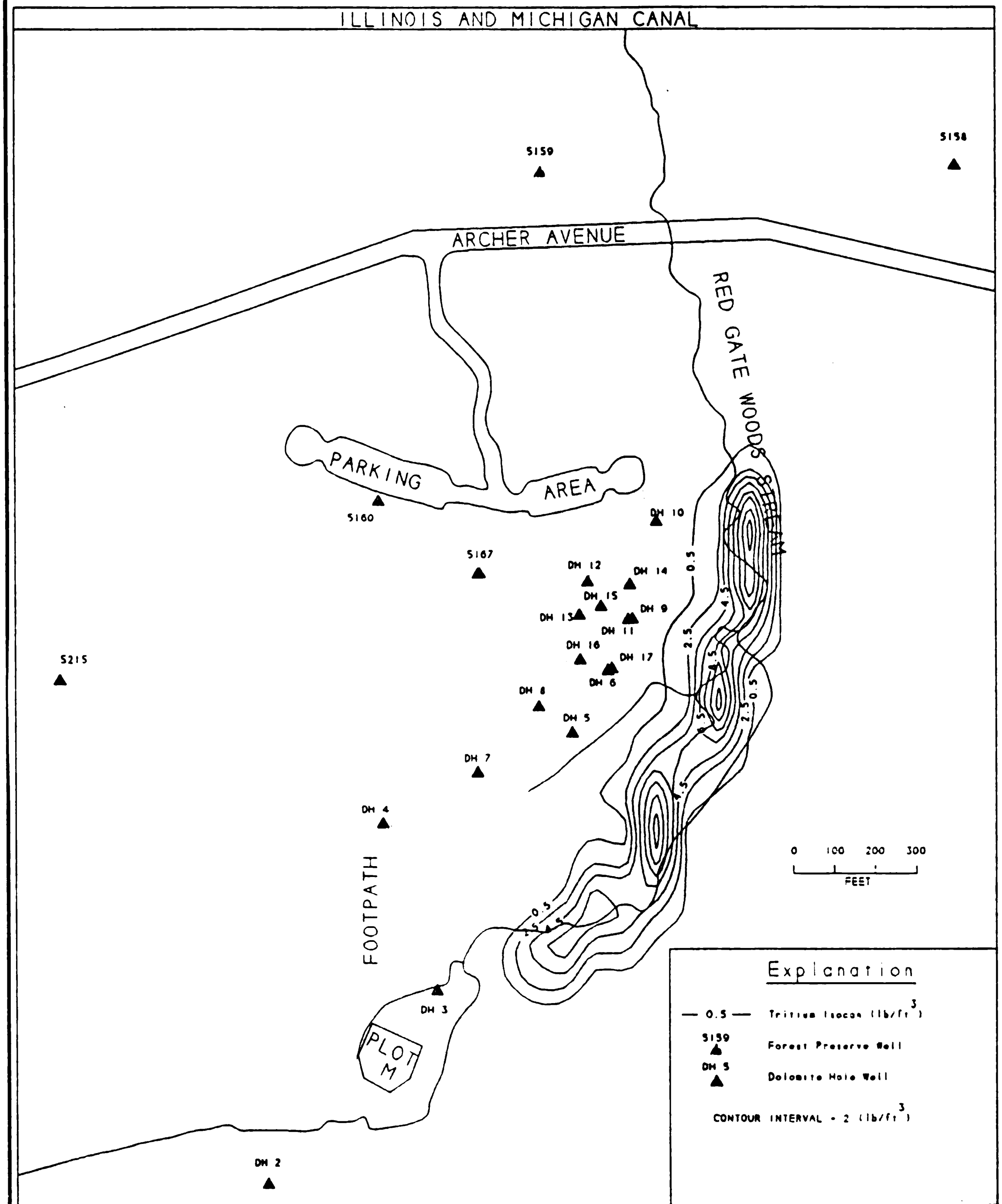


Figure 17: Groundwater Tritium Isocon Map For Layer 1

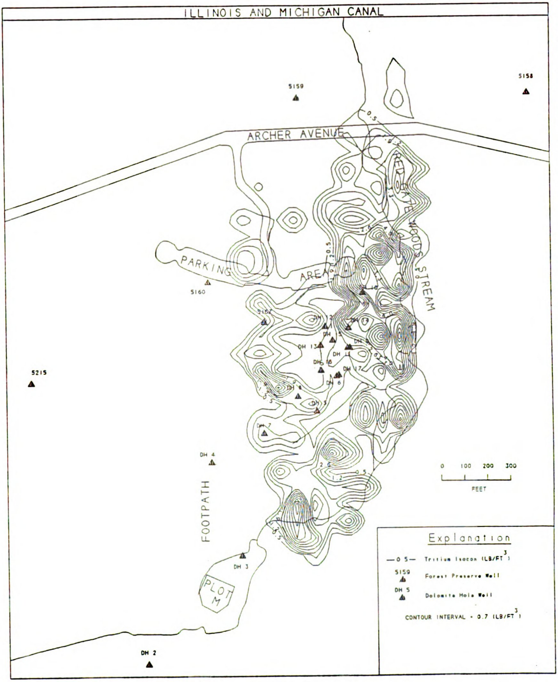


Figure 18: Groundwater Tritium Isocon Map For Layer 2

with regards to yearly precipitation amounts (see Figure 19). The resulting model concentrations of tritium at well FP5167 were recorded and graphically compared and contrasted against the measured tritium concentrations (see Appendix II, Measured Tritium Concentrations at Dolomite Aquifer Wells) at dolomite aquifer well FP5167. The concentration graph of the hypothesis that best matched the graph of measured tritium data thereby became the hypothesis that was most correct.

Two model runs were performed under transient conditions for each month that was modeled to determine the tritium concentration at well FP5167 for each hypothesis. The resulting hydraulic heads and tritium concentrations for each month and hypothesis were saved and used as initial heads and concentrations for the model runs of each hypothesis for the next month. For each month and hypothesis, the transient groundwater flow model was run to obtain groundwater flow parameter values, which were then input into the run of the transient contaminant transport model for each month and hypothesis. At the end of each transport model run hydraulic heads and tritium concentrations were saved for the next months models, and the concentration at the observation node (well FP5167) was recorded. Modeling was conducted for each month of the three years mentioned above that had the corresponding hydraulic head, precipitation, and measured tritium data.

The Illinois and Michigan canal hydraulic head was fixed at 580 feet for each model run and the southern constant head boundary was represented by the measured hydraulic head of DH-2 (see Appendix III - Water Levels in Dolomite Aquifer Wells) for the month of interest.

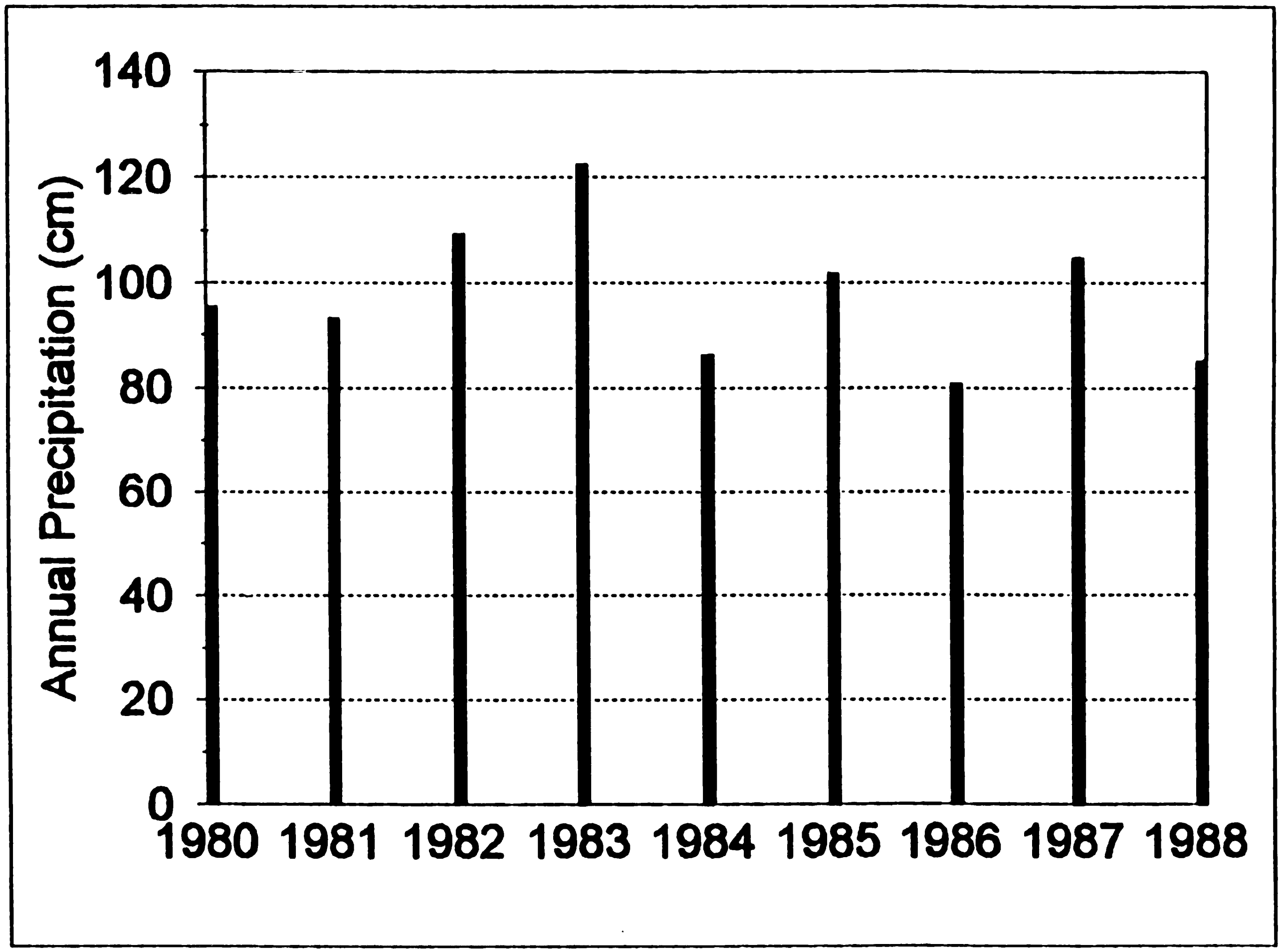


Figure 19: Annual Precipitation at Palos Forest Preserve

Constant head values were the same for each of the two model runs for the month in question. Monthly precipitation values were altered to account for evapotranspiration and monthly yearly averages were computed (see Appendix I - Precipitation Records for the Palos Forest Preserve Area). Precipitation was added to the model at varying locations and magnitudes as discussed in earlier sections of calibration and sensitivity analysis. The average precipitation value for the month was used for each model run of hypothesis number 1, and the average monthly precipitation value for the year was used for each model run of hypothesis number 2. The tritium concentration used in the recharge was set at 100,000 lbs/ft^3 to achieve concentration numbers of higher magnitudes at well FP5167 that were easier to manipulate, evaluate, and visualize.

The resulting tritium concentrations for modeling each hypothesis and the monthly average measured tritium concentration at forest preserve well FP5167 are presented in Table 8.

8.0 Summary and Conclusions

Low-level radioactive waste buried near Plot M has contaminated the soils and groundwater beneath the Palos Forest Preserve with tritium. Since 1976, seasonal fluctuations of tritium concentrations have been observed at forest preserve well FP5167. Tritium has migrated from the Red Gate Woods Stream below Plot M into the dolomite aquifer to the area proximal to well FP5167. Two hypotheses have been proposed to explain the seasonal fluctuations of tritium in dolomite aquifer well FP5167: (1) the result of fluctuations in recharge through the glacial drift bringing varying amounts of tritium into the dolomite

Table 8: Measured and Modeled Tritium Concentrations at Forest PreserveWell FP5167

Month-Year	Measured Tritium Concentration	Hypothesis # 1 Concentration	Hypothesis # 2 Concentration
Jan 83	1.00	2002.3	1950.9
Feb 83	1.65	2018.5	1950.9
Apr 83	1.65	1849.2	1950.9
May 83	1.45	1809.8	1950.9
July 83	0.28	2023.8	1950.9
Aug 83	0.55	2030.9	1950.9
Sept 83	0.39	1835.8	1950.9
Nov 83	4.85	1768.6	1950.9
Dec 83	4.10	1913.8	1950.9
Jan 85	1.7	2040.6	2000.1
Mar 85	1.2	1784.8	2000.1
Apr 85	0.1	2044.5	2000.1
May 85	0.18	2015.6	2000.1
Jun 85	0.28	2027.0	2000.1
July 85	0.16	2007.4	2000.1
Aug 85	0.37	2059.0	2000.1
Sept 85	0.65	2036.4	2000.1
Oct 85	0.55	6892.6	2000.1
Nov 85	2.40	2113.7	2000.1
Jan 86	0.22	2055.8	2070.9
Feb 86	0.21	1946.5	2070.9
Mar 86	2.3	2111.6	2070.9
Jul 86	0.36	2023.0	2070.9
Oct 86	3.15	1951.6	2070.9
Dec 86	2.85	2113.6	2070.9

aquifer or (2) varying fluxes of groundwater flow in the dolomite aquifer diluting a constant flux of tritium from the drift and varying the concentrations of tritium in the dolomite aquifer. The first hypothesis represents a variation in localized recharge while the second hypothesis represents a variation in regional recharge.

A three-dimensional finite-difference groundwater flow model was constructed to model the hydrogeological conditions at the site. The model parameters obtained from the background review of published material were adjusted during the calibration process to create the best representation of physical parameters with mathematical equations. The output parameters from the groundwater flow model were used as the input parameters for the contaminant transport model. Parameters for the groundwater flow model were adjusted with regards to the contaminant transport model that was calibrated under the same conditions as the groundwater flow model.

The results of the contaminant transport modeling of each hypothesis are graphically compared against the measured tritium concentrations at forest preserve well FP5167 in Figure 20. Measured and modeled tritium values were normalized to facilitate the graphical comparison process. Based on the assumption that each hypothesis was accurately represented by the choice of model parameters, the hypothesis that is the best graphical match for the measured tritium data would also be the most correct one. Since the graph of hypothesis number 1 represents the varying of tritium concentrations with recharge and the

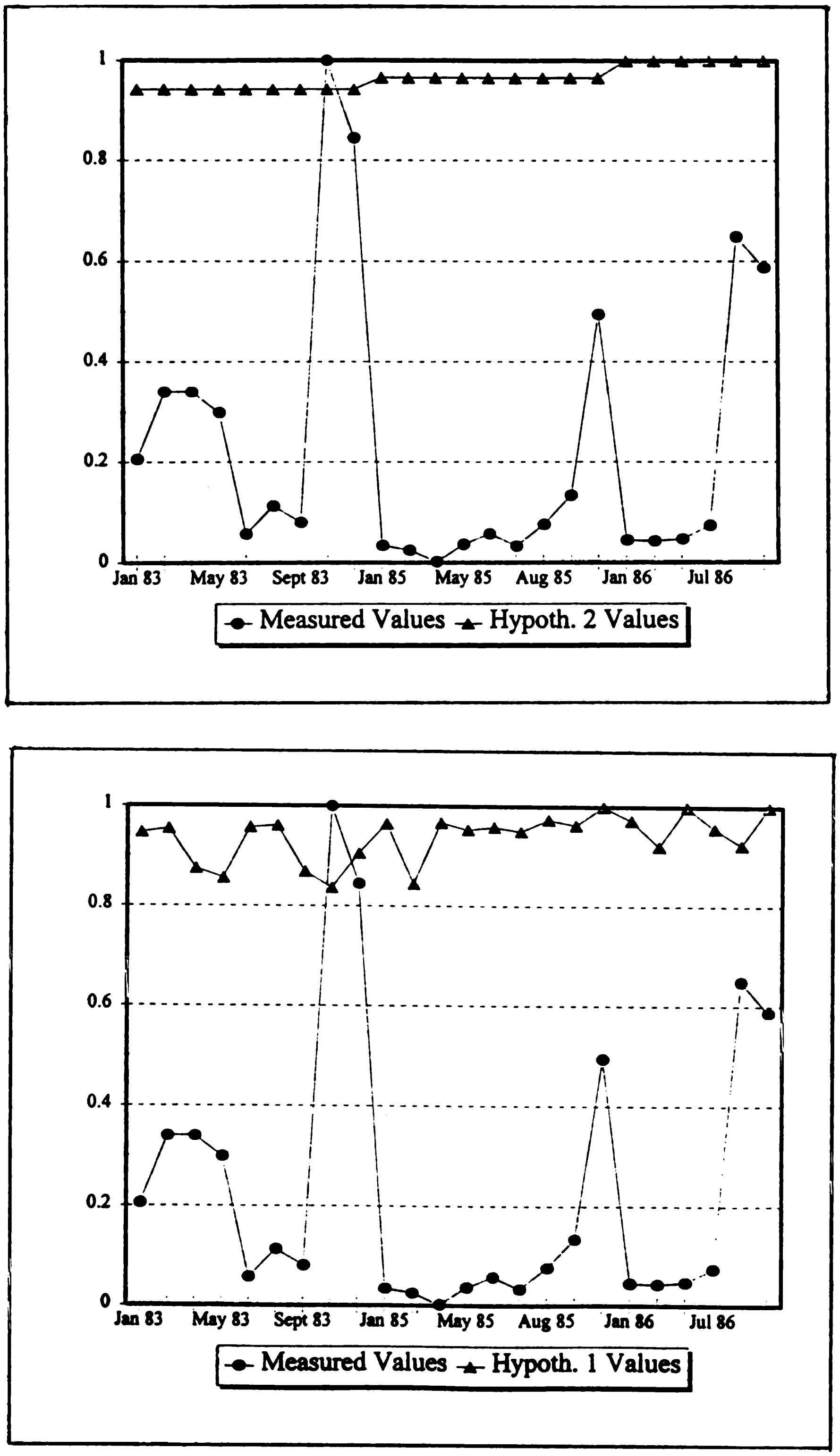


Figure 20: Comparison of Measured v.s. Hypothesis Concentration Curves

graph of hypothesis number 2 represents the varying of tritium concentrations with groundwater flow, graphical comparison suggests the variation of modeled tritium concentration fluctuations is better explained by variable recharge rates rather than variable groundwater flow rates. The trend of rising tritium concentration values for hypothesis number 2 do roughly parallel the general rising trend of measured tritium concentrations, indicating that variable groundwater flow rates may also be a contributing factor to the tritium fluctuations at well FP5167.

It is not the magnitude (numerical values) of the graph curves and peaks in Figure 20 that are important for comparison and evaluation. The shape of the curves and location (month-year) of the peaks determine which hypothesis best matches the measured tritium fluctuations at well FP5167. The concentration curve for hypothesis number 2 presents a series of three plateaus, which represent constant tritium concentrations for each year. The absence of fluctuation in model results for this hypothesis indicates that varying groundwater flow rates are not the sole cause for fluctuations in tritium concentrations in the dolomite aquifer. Since the same value for recharge was used for each month of each specific year, the constant values of tritium concentrations indicate that variations in recharge amounts are most likely the major control with regards to tritium concentrations in the dolomite aquifer. This conclusion agrees with the statement by Nicholas and Healy (1988) that "Seasonal fluctuations in tritium concentration in well 5167 are caused by variable of recharge to the dolomite."

The overall graphical shape of hypothesis number 1 is a fair match for the overall graph shape of the measured tritium data from well FP5167. The normal precipitation year (1985) provides the best match between measured tritium values and modeled tritium values for hypothesis number 1. Some of the peaks and valleys are slightly offset which may be attributed to differences in modeled and actual tritium migration times. The slight offsets may also be due to the effect of initial heads and concentrations from a month not directly preceding the modeled month (because of a lack of complete data for the prior month). The area of the graphs corresponding to May of 1985 to December of 1986 present an area of fairly constant values followed by peaks and valleys that are roughly similar between the measured tritium data and the modeled tritium data from hypothesis number 1.

The changing of measured aquifer parameter values during the groundwater flow and the contaminant transport model calibration process was performed to create a set of three-dimensional models that facilitated the modeling of tritium migration from the Red Gate Woods stream to the dolomite aquifer in the vicinity of forest preserve well FP5167. Statistical analysis of the groundwater flow models ability to match measured hydraulic heads of dolomite aquifer wells in the study area was performed to provide a control on the accuracy of the models with regards to error. Error is inherit in the methodology of parameter measurement so variation of measured parameter values is not necessarily a false representation of hydrogeological conditions at the site. Some of the parameters obtained from the literature review were varied in excess of two orders of magnitude. However, many of these variations were performed in order to represent a set of circumstances that were not accounted for during parameter measurement. Statistical analysis indicated that after the final variation (calibration) of model parameters, the groundwater flow model had greater accuracy with regards to measured hydraulic heads and less error as a result of these changes to hydrogeological parameter values.

Measured hydrogeological parameter values were also varied to achieve transport of tritium from the source area to the area proximal to well FP5167. The omission of the overlying glacial drift, due to the lack of needed measured parameters and data, could have removed a possibly significant portion of the tritium migration pathway. If the drift had been included with its lack of measured physical data, calibration would have been based on unknown values and error control would have been severely compromised. The missing contribution of tritium migration in the drift had to be accounted for by adjustment of the hydrogeological parameters of the Silurian dolomite. With a complete data set for the glacial drift and its inclusion in the groundwater flow model, the peaks and valleys of modeled tritium concentration data may have more closely matched the location (month-year) of the measured tritium concentration data. The alteration of the hydrogeological parameters of the dolomite to compensate for the missing glacial drift was an assumption that had to be made to maintain the calibration accuracy of the flow model and should not have significantly affected the ability of the flow and transport models to adequately address the above mentioned hypotheses.

An interesting observation can be found by looking at Figures 10 and 20 and comparing recharge amounts with corresponding tritium concentrations at FP5167. Comparison indicates that increased amounts of recharge result in lower concentrations of tritium in the dolomite aquifer. It would be reasonable to theorize that if recharge was the source and migration pathway for tritium into the dolomite aquifer, that increased amounts of recharge to the dolomite aquifer should bring increased concentrations of tritium. A migrational time delay does not seem to be the answer due to the fact that tritium concentrations following 1983, a very wet year, are lower than those following prior years that were had less total recharge. A more probable explanation is that the ability for the tritium source to mix with recharge is associated with a kind of reaction rate that when exceeded, the excess recharge not involved with the reaction serves to dilute the tritium that has gone into solution. Years of precipitation that meet or fall below the limitations of the reaction rate bring recharge to the dolomite aquifer that is more concentrated with respect to tritium.

It must be noted that the conclusions formed in this section are based on the assumption that the groundwater flow model created was an accurate representation of the hydrogeological parameters at the site and that the modeling method used to represent each hypothesis was also an accurate representation of the hydrogeological conditions that the hypotheses are based upon. In groundwater flow modeling no one solution is unique, there is an infinite number of parameter value combinations that could form a working solution. The statistical analysis and large number of model runs performed as part of this study were conducted to reduce potential error and provide a control on the representativeness and accuracy of the model created.

APPENDICES

APPENDIX I

Precipitation Records for the Palos Forest Preserve

Table 9: Precipitation Records for the Palos Forest Preserve

Date	Precipitation (cm)	Precipitation (feet)	Evapo. Adj. Precip.(ft)	Monthly Avg. Precip.(ft)	Year Precip. Sum(cm)
Jan-80	2.46	0.0807	0.0557	0.1060	95.43
Feb-80	4.01	0.1316	0.0899		
Mar-80	4.55	0.1493	0.0743		
Apr-80	6.35	0.2083	0.0583		
May-80	7.14	0.2343	0.0000		
Jun-80	8.08	0.2651	0.0000		
Jul-80	7.67	0.2516	0.0000		
Aug-80	21.39	0.7018	0.3184		
Sep-80	16.54	0.5427	0.3343		
Oct-80	8.76	0.2874	0.1541		
Nov-80	1.8	0.0591	0.0007		
Dec-80	6.68	0.2192	0.1858		
Jan-81	0.43	0.0141	0.0000	0.0859	93.15
Feb-81	5.56	0.1824	0.1407		
Mar-81	1.5	0.0492	0.0000		
Apr-81	14.35	0.4708	0.3208		
May-81	8.58	0.2815	0.0148		
Jun-81	15.44	0.5066	0.1316		
Jul-81	9.52	0.3123	0.0000		
Aug-81	17.68	0.5801	0.1967		
Sep-81	6.6	0.2165	0.0082		
Oct-81	4.57	0.1499	0.0166		
Nov-81	6.25	0.2051	0.1467		
Dec-81	2.67	0.0876	0.0543		
Jan-82	7.37	0.2418	0.2168	0.1577	109.32
Feb-82	1.04	0.0341	0.0000		
Mar-82	10.54	0.3458	0.2708		
Apr-82	7.06	0.2316	0.0816		
May-82	5.28	0.1732	0.0000		
Jun-82	3.96	0.1299	0.0000		
Jul-82	21.16	0.6942	0.2359		
Aug-82	9.98	0.3274	0.0000		
Sep-82	2.92	0.0958	0.0000		

Table 9 (cont'd).

Date	Precipitation (cm)	Precipitation (feet)	Evapo. Adj. Precip.(ft)	Monthly Avg. Precip.(ft)	Year Precip. Sum(cm)
Oct-82	4.78	0.1568	0.0235		
Nov-82	17.65	0.5791	0.5207		
Dec-82	17.58	0.5768	0.5434		
Jan-83	1.68	0.0551	0.0301	0.1797	122.476
Feb-83	5.236	0.1718	0.1301		
Mar-83	9.04	0.2966	0.2216		
Apr-83	19.53	0.6407	0.4907		
May-83	15.9	0.5217	0.2550		
Jun-83	10.44	0.3425	0.0000		
Jul-83	10.8	0.3543	0.0000		
Aug-83	5.28	0.1732	0.0000		
Sep-83	13.74	0.4508	0.2425		
Oct-83	11.2	0.3675	0.2341		
Nov-83	12.6	0.4134	0.3551		
Dec-83	7.03	0.2306	0.1973		
Jan-84	2.92	0.0958	0.0708	0.1027	86.35
Feb-84	3.53	0.1158	0.0741		
Mar-84	7.62	0.2500	0.1750		
Apr-84	10.44	0.3425	0.1925		
May-84	11.4	0.3740	0.1073		
Jun-84	5.13	0.1683	0.0000		
Jul-84	8.1	0.2657	0.0000		
Aug-84	5.33	0.1749	0.0000		
Sep-84	9.75	0.3199	0.1115		
Oct-84	8	0.2625	0.1291		
Nov-84	6.71	0.2201	0.1618		
Dec-84	7.42	0.2434	0.2101		
Jan-85	3.76	0.1234	0.0984	0.1386	101.77
Feb-85	8.79	0.2884	0.2467		
Mar-85	12.01	0.3940	0.3190		
Apr-85	3.76	0.1234	0.0000		
May-85	7.09	0.2326	0.0000		
Jun-85	5	0.1640	0.0000		

Table 9 (cont'd).

Date	Precipitation (cm)	Precipitation (feet)	Evapo. Adj. Precip.(ft)	Monthly Avg. Precip.(ft)	Year Precip. Sum(cm)
Jul-85	9.52	0.3123	0.0000		
Aug-85	9.91	0.3251	0.0000		
Sep-85	4.62	0.1516	0.0000		
Oct-85	12.65	0.4150	0.2817		
Nov-85	20.88	0.6850	0.6267		
Dec-85	3.78	0.1240	0.0907		
Jan-86	0.99	0.0325	0.0075	0.0762	80.58
Feb-86	6.55	0.2149	0.1732		
Mar-86	3.78	0.1240	0.0490		
Apr-86	4.7	0.1542	0.0042		
May-86	7.9	0.2592	0.0000		
Jun-86	8.86	0.2907	0.0000		
Jul-86	10.92	0.3583	0.0000		
Aug-86	2.92	0.0958	0.0000		
Sep-86	18.08	0.5932	0.3848		
Oct-86	9.53	0.3127	0.1793		
Nov-86	3.58	0.1175	0.0591		
Dec-86	2.77	0.0909	0.0575		
Jan-87	4.24	0.1391	0.1141	0.1458	104.92
Feb-87	2.51	0.0823	0.0407		
Mar-87	4.04	0.1325	0.0575		
Apr-87	5.84	0.1916	0.0416		
May-87	5.61	0.1841	0.0000		
Jun-87	5.56	0.1824	0.0000		
Jul-87	10.64	0.3491	0.0000		
Aug-87	43.43	1.4249	1.0415		
Sep-87	2.39	0.0784	0.0000		
Oct-87	4.04	0.1325	0.0000		
Nov-87	7.04	0.2310	0.1726		
Dec-87	9.58	0.3143	0.2810		
Jan-88	4.78	0.1568	0.1318	0.1139	84.99
Feb-88	3.28	0.1076	0.0659		
Mar-88	5.46	0.1791	0.1041		

Table 9 (cont'd).

Date	Precipitation (cm)	Precipitation (feet)	Evapo. Adj. Precip.(ft)	Monthly Avg. Precip.(ft)	Year Precip. Sum(cm)
Apr-88	5.28	0.1732	0.0232		
May-88	3.02	0.0991	0.0000		
Jun-88	2.67	0.0876	0.0000		
Jul-88	6.95	0.2280	0.0000		
Aug-88	8.61	0.2825	0.0000		
Sep-88	9.63	0.3159	0.1076		
Oct-88	12.83	0.4209	0.2876		
Nov-88	16.38	0.5374	0.4791		
Dec-88	6.1	0.2001	0.1668		

APPENDIX II

Measured Tritium Concentrations at Dolomite Aquifer Wells

Table 10: Measured Tritium Concentrations at Dolomite Aquifer Wells

Date	5167	5159	5158	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
Jan-80	8.1	1.6	0.2									
Feb-80	8.8	1.3	0.2	0.24	1.12	0.2						
Mar-80	7.7	1.2		0.23	1.01	0.2						
Apr-80	5	1.6	0.2	0.2	1.08	0.2						
May-80	3.9	1.2		0.2	1.08	0.2						
Jun-80	4.7	1.4		0.42	1.19	0.2						
Jul-80	4.9	1		0.42	1.07	0.2						
Aug-80	8.3	0.7										
Sep-80	6.5	0.6		0.24	1.13	0.2						
Oct-80	6.3	0.9		0.31	1.1	0.22						
Nov-80	6.7	1		0.55	1.27	0.2						
Dec-80	6.5	0.8		0.31	1.09	0.33						
Jan-81	6.7	1.3	0.2									
Feb-81	7.8	1.2	0.2	0.2	1.18	0.35						
Mar-81	6.3	0.9	0.2	0.22	1.2	0.2						
Apr-81	5.5	1.1	0.2									
May-81	2.5	2.1	0.2	0.23	1.2	0.2						
Jun-81	0.4	1.7	0.2	0.2	1.4	0.2						
Jul-81	0.2	1.2	0.2	0.2	1.24	0.2						
Aug-81	0.6	0.7	0.2	0.2	1.18	0.2						
Sep-81	1.9	0.6	0.2	0.2	1.2	0.2						
Oct-81	6.5	0.5	0.2	0.2	1.33	0.2						
Nov-81	8.6	0.4	0.2									
Dec-81	9.6	2.8	0.2	0.22	1.36	0.2						
Jan-82	8.3	0.4	0.2									
Feb-82	8.6	0.4	0.2	0.2	1.3	0.2						
Mar-82	8.1	0.4	0.2	0.2	1.61	0.2						
Apr-82	2.3	2.6	0.2	0.2	1.39	0.2						
May-82	0.7	2	0.2									
Jun-82	0.2	1.2	0.2	0.2	1.58	1.58						
Jul-82	0.6	0.7	0.2	0.33	1.41	0.22			0.22			
Aug-82	2.2	0.7	0.27	0.22	1.54	0.29	0.18					
Sep-82	2.1	0.6	0.2	0.2	1.5	0.2						

Table 10: Measured Tritium Concentratic

Date	5167	5159	5158	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
Oct-82	6.6	0.6	0.2	0.2	1.48	0.2	0.2	0.2	0.2	0.2	10.2	
Nov-82	10.2	0.6	0.2									
Dec-82	5.5	0.4	0.2	0.23	0.2	1.59	0.2	0.3	0.2	0.2		
Jan-83	1	1.5	0.22	0.2	1.49	0.2						
Feb-83	1.7	1.5	0.2	0.2	1.68	0.2	0.2	0.5	0.2	0.2	17.9	
Mar-83	2.8	1.3	0.2									
Apr-83	1.6	1.7	0.2				0.2	0.3	0.2	0.3	19.7	
May-83	1.5	1.6	0.2				0.2	0.3	0.2	0.2	24.8	
Jun-83	0.7	1.3										
Jul-83	0.4	0.7	0.52				0.2	0.5	0.2	0.2	24.5	
Aug-83	0.6	0.8	0.52				0.2	0.5	0.2	0.2	26.5	
Sep-83	0.4	0.5	0.88				0.32	0.3	0.2	0.3	24.1	4
Oct-83	1.4	0.4	0.51									
Nov-83	4.9	0.5	0.49	0.64	2.03	0.2	0.92	3.4	0.2	1.3	24.3	14.3
Dec-83	4.1	0.4	0.41	0.24	2.1	0.51	0.2	0.4	0.2	0.2	27.6	13.6
Jan-84	1.1	0.5	0.26									
Feb-84	1.8	0.7	0.2	0.59	1.81	0.2	0.2	0.3	0.2	0.2	24.8	11
Mar-84	1.6	0.6	0.27									
Apr-84	0.3	1.6	0.23	0.35	1.79	0.2	0.21	0.5	0.2	0.3	29.4	7.9
May-84	0.2	1.55	0.2	0.21	1.62	0.2	0.2	0.57	0.24	0.2	27.2	6.76
Jun-84	0.2	1.2		0.2	1.67	0.2	0.2	0.33	0.2	0.22	28.3	5.98
Jul-84	0.2	0.7		0.21	1.51	0.2	0.2	0.37	0.2	0.2	28.8	6.89
Aug-84	0.2	0.48	0.43	0.2	1.57	0.2	0.2	0.35	0.2	0.2	27.4	6.61
Sep-84	0.2	0.32	0.31									
Oct-84	0.885	0.305	0.25	0.2	1.54	0.2	0.44	0.27	0.2	0.2	26.8	7.18
Nov-84	0.25	0.265	0.3									
Dec-84	2.5	0.245	0.21	0.2	1.52	0.2	0.2	0.29	0.2	0.2	26.5	6.94
Jan-85	1.55	0.26	0.2	0.2	1.58	0.2	0.2	0.2	0.2	0.2	26.3	6.91
Feb-85	1.55	0.435	0.2		1.62							
Mar-85	1.25	0.81	0.23	0.2		0.2	0.2	0.47	0.2	0.2	25.7	7.04
Apr-85	0.2	1.45	0.2	0.2	1.53	0.2	0.2	0.34	0.2	0.2	27	6.41
May-85	0.23	1.55	0.24	0.27	2.04	0.2		0.6	0.32	0.2	28.5	6.5
Jun-85	0.275	0.84	0.37	0.36	1.85	0.21	0.2	0.75	0.2	0.2	31.1	6.73

Table 10 (cont'd).

Date	5167	5159	5158	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
Jul-85	0.21	0.61	0.41	0.2	1.47	0.2	0.22	0.36	0.2	0.2	2	9.54
Aug-85	0.375	0.41	0.2	0.2	1.54	0.2	0.2	0.31	0.2	0.2	21.6	10.33
Sep-85	0.65	0.4	0.23	0.38	1.65	0.2	0.2	0.29	0.2	0.2	22.1	10.7
Oct-85	1			0.29	1.71	0.2	0.2	0.37	0.2	0.2		10.57
Nov-85	2.4	0.405	0.47	0.2	1.54	0.2	0.2	0.43	0.2	0.2	26.4	11.89
Dec-85	1.43	0.35	0.2									
Jan-86	0.225	0.78	0.2	0.2	1.64	0.2	0.2	0.38	0.2	0.2		7.02
Feb-86	2.1	0.67	0.2	0.2	1.45	0.2	0.2	0.36	0.2	0.2	26.96	6.85
Mar-86	2.3	0.655	0.2	0.2	1.61	0.2	0.2	0.69	0.2	0.2	26.74	7.41
Apr-86	0.485	0.68										
May-86	0.205	0.805	0.2					0.67			28.46	7.11
Jun-86	0.2	0.64	0.2									
Jul-86	0.365	0.665	0.25	0.2	1.63	0.2	0.2	0.77	0.2	0.2	26.22	6.78
Aug-86	0.46	0.57	0.2					0.81				7.06
Sep-86	1.21	0.505	0.2									
Oct-86	3.15	0.51	0.2	0.2	1.57	0.2	0.2	0.52	0.2	0.2		7.6
Nov-86	1.8	0.725	0.2									
Dec-86	2.85	0.79	0.28	0.2	1.96	0.2	0.31	1.18	0.2	0.2		7.29
Jan-87	2.9	0.63	0.2									
Feb-87	2.85	0.41	0.2					0.6			21.8	7.7
Mar-87	3.1	0.38	0.29	0.2	1.8	0.2	0.4	1	0.2	0.2	23.4	7.9
Apr-87	1.9	0.21	0.2		1.7						22	7.3
May-87	0.485	0.475	0.2									
Jun-87	0.98	0.475	0.2	0.2	1.9	0.2	0.2	1.4	0.2	0.2	20.7	7.5
Jul-87		0.615	0.2					1.4			21.7	7
Aug-87	3	0.7	0.2									
Sep-87	1.755	0.635	0.3	0.2	1.4	0.3	0.3	3	0.5	0.2	22.3	7.5
Oct-87	0.2	0.585	0.2					2.5			22.3	7
Nov-87	0.43	0.705	0.2					3.1			25	9
Dec-87	0.995	0.61	0.2									
Jan-88	0.27	1.41	0.2					2.8			21.3	7.3
Feb-88	0.2	1.695	0.2	0.2	1.8	0.2	0.2		0.2	0.2		
Mar-88	0.2	1.81	0.2									

Table 10 (cont'd).

Date	5167	5159	5158	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
Apr-88	0.2	1.72	0.2									
May-88	0.2	1.82	0.2									
Jun-88	0.2	1.815	0.2	0.2	1.6	0.2	1	7	0.2	0.2	19.7	6.8
Jul-88		1.735	0.2									
Aug-88	0.2	1.36	0.2	0.2	1.8	0.2	0.2	1.6	0.2	0.2		6.6
Sep-88	0.2	1.1	0.2									
Oct-88	0.34	0.62	0.2					1.7			11.8	6.8
Nov-88	0.455	0.47	0.2	0.2	1.8	0.2	0.2	2	0.2	0.2	11.3	6.6
Dec-88	0.405	0.28	0.2									

Data from ANL Site Surviellence Reports (Golchert, 1980-1988)

APPENDIX III

Water Levels in Dolomite Aquifer Wells

Table 11: Water Levels in Dolomite Aquifer Wells

DATE	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10	DH-11	DH-15	DH-16	DH-17
Jan-83	581.61		581.61										
Feb-83	581.95		581.75										
Apr-83	583.9		583.7										
May-83	584.02		583.82										
Jul-83	582.95		582.75										
Aug-83	582		581.8										
Sep-83	581.05		580.85										
Nov-83	580.89		580.69										
Dec-83	582.35		582.15										
Feb-84	583.4	584.19	584.07	582.09	582.11	583.59	583.82	584.17	582.19				
Apr-84	585.04	584.82	584.78	582.75	582.79	584.31	584.81	584.76	582.86				
May-84	584.74	584.47	584.53	582.54	582.57	584.18	584.46	585.52	582.62				
Jun-84	584.42	584.11	584.09	582.11	582.08	584.1	584.5	585.85	582.21				
Jul-84	583.73	583.44	583.44	581.45	581.42	583.61	584.05	585.67	581.54				
Aug-84	583.34	583.04	583.06	581.1	581.05	583.26	583.78	585.21	581.17				
Oct-84	583	582.75	582.74	580.75	580.86	582.85	583.27	584.35	580.84				
Dec-84	583.44	583.15	583.15	581.12	581.05	583.15	583.7	584.02	581.24				
Jan-85	583.72	583.45	583.44	581.46	581.42	583.32	583.81	584.12	581.52				
Mar-85	585.82	585.57	585.56	583.55	583.7	584.48	585.98	574.25	583.7				
Apr-85	585.29	585.07	585.05	582.96	583.11	584.46	584.75	583.88	583.22				
May-85	584.6	584.29	584.32	582.31	582.05	584.3	584.9	585.19	582.38				
Jun-85	583.89	583.6	583.64	581.7	581.63	583.77	584.34	583.83	581.72				
Jul-85	583.45	583.16	583.19	581.19	581.14	583.41	583.6	585.1	581.26				
Aug-85	582.9	582.5	582.53	580.55	580.71	582.89	582.79	584.84	580.61				
Sep-85	582.89	582.6	582.62	580.61	580.05	582.99	582.95	585.31	580.67				
Oct-85	583.19	582.97	582.97	580.96	580.99	582.95	582.86	581.46	581.07				
Nov-85	584.17	583.97	583.99	582.02	581.97	583.53	583.38	582.57	582.09				
Jan-86	583.57	583.44	583.37	581.4	581.32	583.31	583.36	582.18	581.41				
Feb-86	583.94	583.68	582.75	581.73	581.7	583.5	583.54	582.53	581.87				
Mar-86	584.55	584.34	584.34	582.39	582.31	583.9	583.72	583.2	582.43				
May-86					581.4			582.67	581.58	581.33			
Jul-86	583.34	583.07	583.1	581.14	581.14	583.25	583.36	581.66	581.32	581.6			
Aug-86					580.7			581.33	580.69	580.41			

Table 11 (cont'd).

DATE	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10	DH-11	DH-15	DH-16	DH-17
Oct-86	583.48	583.24	583.25	581.26	581.16	583.17	583.2	582.43	581.12	580.86			
Dec-86	583.64	583.4	583.52	581.54	581.53	583.36	583.17	582.29	581.67	581.39			
Feb-87					581.5			582.32	581.4	581.15	581.04	581.13	581.13
Mar-87	584.16	583.9	583.9	581.88	581.7	583.39	580.02	583.34	581.99	581.82	581.62	581.71	581.78
Apr-87					582.18			583.22	582.24	581.95		581.95	581.96
Jun-87	583.78	583.65	583.59	581.65	581.49	583.63	584	583.35	581.62	581.37	581.25	581.38	581.42
Jul-87					580.98			583.03	581.13	580.87	580.77	580.85	580.87
Sep-87	584.23	583.92	584	582.06	581.98	583.77	583.99	583.28	582.11	581.86	581.76	581.83	581.87
Oct-87					581.17			582.44	581.24	580.97	580.89	580.98	581.01
Nov-87					581.23			582.62	581.37	581.12	581.05	581.13	581.2
Jan-88					582.34			583.63	582.61	582.36	582.26	582.38	582.39
Feb-88	584.78	584.56	584.58	581.85		584.42	584.44						
Jun-88	584.04	583.75	583.5	581.8	581.76	584.05	584.43	583.74	581.57	581.29	581.22	581.53	581.36
Aug-88	583.01	582.67	582.76	580.86	580.56	583.29	583.88	582.86	580.76	580.47	580.37	580.45	580.47
Oct-88					580.34			582.11	580.39	580.2	580.1	580.22	580.24
Nov-88	582.85	582.55	582.6	580.7	580.55	583.09	583.62	582.53	580.31	580.43	580.32	580.41	580.45

Data from ANL Site Survielence Reports (Golchert, 1983-1988)

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