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WATER SUPPLY NEEDS AND SOURCES ASSESSMENT: ALTERNATIVE WATER SUPPLY STRATEGIES INVESTIGATION: BRACKISH GROUND WATER: SOURCE IDENTIFICATION AND ASSESSMENT

by

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EXECUTIVE SUMMARY

St. Johns River Water Management District (SJRWMD) is investigating the technical, environmental, and economic feasibility of selected alternative water supply strategies. These investigations are being conducted in support of regional water supply planning intended to identify feasible water supply alternatives that will meet future public supply needs without undesirable environmental impacts. The SJRWMD-sponsored program includes investigations conducted by several consultants, including CH2M HILL, and by District staff.

The primary water supply options under consideration include increased supply, demand reduction, and increased system storage to better manage existing supplies. Several alternative water supply options, including the development of lower-quality or brackish ground water resources, are under consideration.

This technical memorandum (TM) addresses the availability of lower-quality or brackish ground water as an alternative water supply source. The TM characterizes the brackish ground water resources within the SJRWMD Priority Water Resource Caution Area, including the following parameters of interest:

- Thickness of the Upper Floridan aquifer
- Depth to the 250-milligram per liter (mg/L) isochlor
- Depth to the 1,000-mg/L isochlor
- Thickness of the brackish water within the Upper Floridan aquifer
- Percentage of brackish water within the Upper Floridan aquifer
- Recharge rate to the Upper Floridan aquifer

Mapping each of these parameters was accomplished by applying Geographic Information System (GIS) techniques.

Criteria were then developed to rank each of the above parameters. In general, areas where the Upper Floridan aquifer is relatively thick and contains mostly brackish ground water with chloride concentrations ranging from 250 to 1,000 mg/L are most attractive for water supply development. In addition, ground water discharge areas are preferred to ground water recharge areas because the potential for undesirable impacts to nearby wetlands is less in discharge areas. Using relative rankings for each of the parameters, areas with low, medium, and high potential for development of brackish ground water supplies were identified.

Six candidate brackish ground water withdrawal sites were then identified, based on relative water supply development potential and proximity to demand centers. The six candidate withdrawal sites are located in St. Johns, Volusia, Seminole, Orange, and Brevard counties. Each candidate withdrawal site was analyzed to identify long-term changes in water quality due to pumping. A saltwater and freshwater upconing analysis was used to predict expected water quality changes as a function of both time and pumping rate. The upconing analysis is based on local hydrogeology and water quality and considers several different production well configurations, well pumping rates, and pumping durations.

Results of the upcoming analysis, conducted for all six candidate withdrawal sites, indicate that water quality will change with both duration of pumping and pumping rate. However, in all cases, the rate of change can be minimized by careful wellfield design and operation.

Adequate well spacing is very important. In this analysis, wells were spaced at 2,500-feet intervals and rather large well spacing will be required to minimize future changes in brackish ground water quality. Pumping rate is also important. Lower pumping rates will help minimize future water quality changes. Proper wellfield design and operation will ensure the long-term viability of each candidate brackish ground water withdrawal site evaluated in this investigation.

The results of the upconing analysis provide the information necessary to develop preliminary brackish ground water supply options for comparison to other water supply development alternatives. The results also provide the information necessary to develop planning-level brackish ground water development cost estimates as a function of total water supply quantities developed for each candidate withdrawal site. Each of the candidate sites selected and analyzed may be used to characterize a typical hydrogeologic framework in the Floridan aquifer and serve as a basis for cost estimates for locations with similar characteristics.

This TM is the first in a series addressing the feasibility of developing brackish ground water supplies to augment existing and future public water supply needs. Other brackish ground water TMs, prepared as part of the SJRWMD Alternative Water Supply Strategies Assessment, include TM D.2.c *Brackish Ground Water: Treatment Technology Assessment* (CH2M HILL, 1997) and TM D.3.b *Brackish Ground Water:*

Planning-Level Cost Estimates (CH2M HILL, 1998). The treatment technology TM assesses available brackish ground water treatment technologies and provides a basis for estimating the costs associated with developing brackish ground water supplies.

The costs TM considers the source characteristics presented in this TM and the treatment technologies identified in the treatment technology TM and develops planning level costing procedures applicable to the candidate brackish ground water source areas identified and evaluated here.

The brackish ground water investigation is a joint effort between CH2M HILL and SJRWMD staff. The source identification and assessment, presented here, was conducted by SJRWMD staff. The brackish ground water technologies and cost TMs were prepared by CH2M HILL.

CONTENTS

FIGURES

FIGURES

FIGURES

TABLES

INTRODUCTION

Public water supply within the St. Johns River Water Management District (SJRWMD) is generally provided by high-quality ground water. Several characteristics of SJRWMD's ground water resources make potable ground water the water supply source of choice. First, ground water is inherently reliable — an important attribute for public water supply. Second, treatment requirements and costs are often minimal because of the general good quality raw ground water. Third, if the resource is developed and managed properly, the quality of raw ground water remains stable.

To date, high quality reliable and inexpensive ground water has been developed as the major source of public water supply within SJRWMD. However, it is unlikely that all additional future water supply needs can be met by increased use of high quality ground water resources without incurring unacceptable environmental impacts. Therefore, SJRWMD has initiated an investigation of the feasibility of alternative water supply strategies.

PROJECT BACKGROUND

SJRWMD previously evaluated the potential impact of increased high-quality ground water withdrawal through the year 2010 (Vergara, 1994). Based on this evaluation, SJRWMD identified areas in which supply problems are now critical or are likely to become critical. An increase in high-quality ground water withdrawal could adversely impact area water resources, including impacts on natural systems, ground water quality, and existing legal users.

SJRWMD is investigating the technical, environmental, and economic feasibility of alternative water supply strategies as a means of preventing existing and projected adverse impacts. The SJRWMD-sponsored program includes investigations conducted by several consultants, including CH2M HILL, and by District staff.

The primary water supply options under consideration include increased supply, demand reduction, and increased system storage to better manage existing supplies. Increased supply options under consideration include:

- Potable ground water with mitigation of adverse impacts
- Surface water
- Lower-quality (brackish) ground water

- Artificial recharge
- Reuse of reclaimed water
- Water supply systems interconnections
- Optimization of ground water withdrawal locations

Increased system storage could include the use of reservoirs, aquifer storage recovery (ASR) facilities, or ground storage tanks. Demand reduction may be achieved by various water conservation initiatives. In many cases, a combination of increased supply, increased system storage, and demand reduction could provide the most environmentally acceptable and cost-effective future water supply systems.

PURPOSE AND SCOPE

This technical memorandum (TM) addresses the availability of lower-quality or brackish ground water as an alternative water supply source. Lower-quality or brackish ground water is defined as ground water that exceeds regulatory standards for potable water with respect to one or more inorganic constituents such as chloride, sodium, sulfate, and total dissolved solids (TDS). In this TM, suitable locations for the withdrawal of brackish water are identified and ranked, tested with numerical models, and results are developed for incorporation into the SJRWMD Alternative Water Supply Strategies Assessment.

This TM is the first in a series addressing the feasibility of developing brackish ground water supplies to augment existing and future public water supply needs. Other brackish ground water TMs, prepared as part of the SJRWMD Alternative Water Supply Strategies Assessment, include TM D.2.c *Brackish Ground Water: Treatment Technology Assessment* (CH2M HILL, 1997) and TM D.3.b *Brackish Ground Water: Planning-Level Cost Estimates* (CH2M HILL, 1998). The treatment technology TM assesses available brackish ground water treatment technologies and provides a basis for estimating the costs associated with developing brackish ground water supplies.

The costs TM considers the source characteristics presented in this TM and the treatment technologies identified in the treatment technology TM and develops planning level costing procedures applicable to the candidate brackish ground water source areas identified and evaluated here.

The investigation of brackish ground water as a potential water supply source is a joint effort between CH2M HILL and SJRWMD staff. The source identification and assessment, presented here, was conducted by SJRWMD staff. CH2M HILL provided editorial and report preparation support. The brackish ground water technologies and cost TMs were prepared by CH2M HILL.

GIS METHODOLOGY AND ITS APPLICATION

OBJECTIVE OF GIS ANALYSIS

The objective of the Geographic Information System (GIS) analysis was to identify candidate brackish ground water withdrawal locations that could be developed to help meet future water supply needs. SJRWMD used a two-step approach to identify desirable sites and to evaluate the potential of using brackish ground water from these selected sites. First, the SJRWMD GIS database was used to identify sites and to process the hydrogeolgic data for evaluation. The information obtained from that data evaluation was then applied to the analytical and numerical upconing model to determine the amount of lower-quality ground water quantities and qualities at the study sites under various pumping scenarios. CH2M HILL will use the upconing model results to develop planning-level cost estimates for each candidate brackish ground water withdrawal location. The development and application of the GIS method, and a numerical upconing ground water model, are presented in the following text.

BACKGROUND

In the 1994 *Needs and Sources Assessment,* SJRWMD investigated the impacts of projected 2010 ground water withdrawals to delineate areas that have, or are projected to have, inadequate ground water available to meet the projected 2010 demand (Vergara, 1994). The identified Priority Water Resource Caution Area for the 1994 Needs and Sources Assessment (Figure 1) was chosen as the study area for this investigation. As part of the new 1999 *Needs and Source Assessment,* SJRWMD is investigating use of lower-quality ground water to help meet the projected demands for these areas. As part of this investigation, a GIS methodology was developed to identify areas within the Upper Floridan aquifer that could be suitable for developing lower-quality ground water sources to meet the growing needs of these areas.

The GIS methodology for this investigation consisted of an overlay procedure, using the GRID module of ARC/INFO. The ARC/INFO GIS platform used for this study was a SUN ULTRA Sparc Workstation using the SUN SOLARIS UNIX operating system running ARC/INFO Version 7.1.1. The GIS overlay procedure incorporated data layers that characterize the hydrogeology of the Upper Floridan

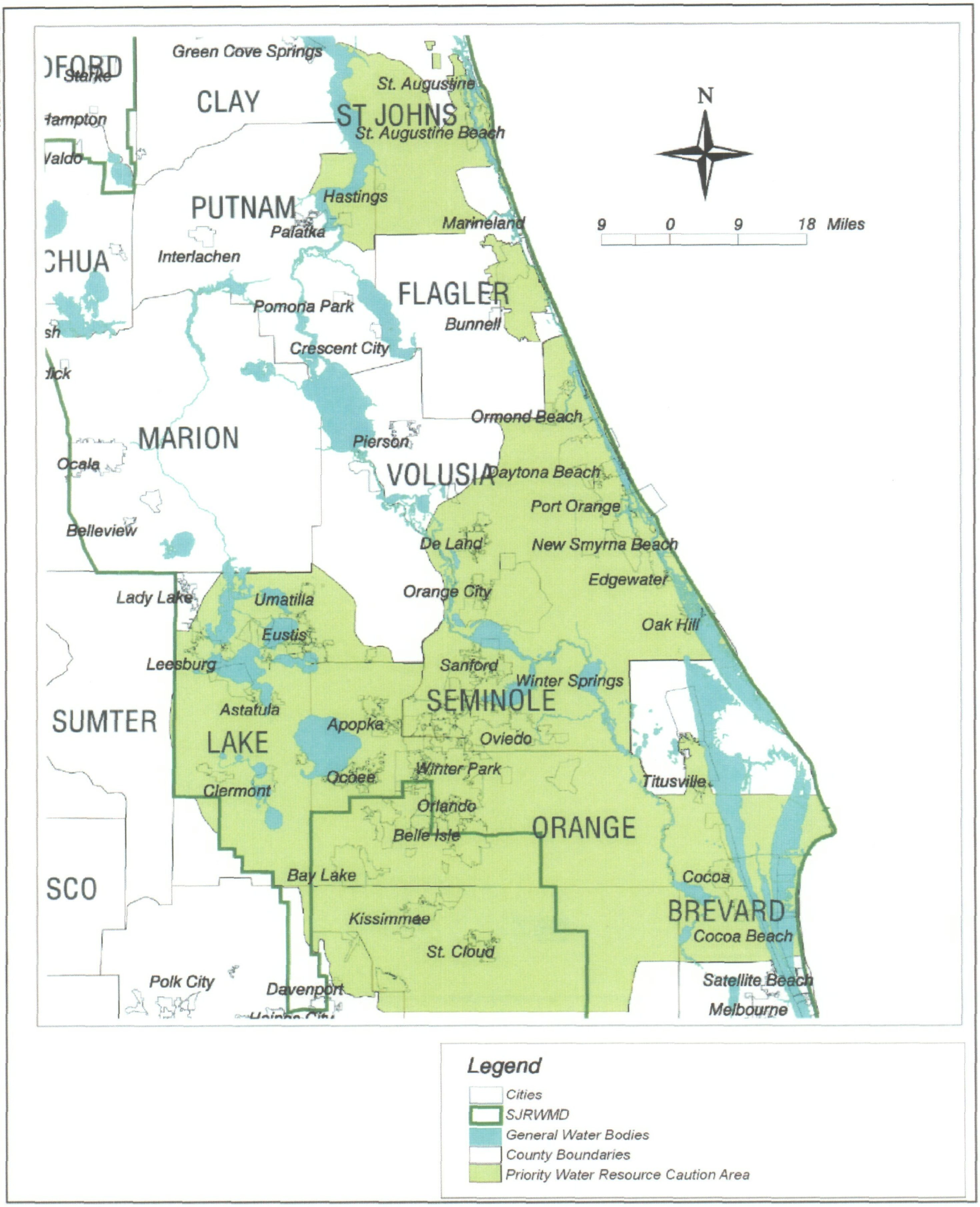

Figure 1. 1994 Needs and Sources Assessment Priority Water Resource Caution Area

aquifer. These data layers were collected, converted to GIS format, ranked, and then combined to identify areas in the aquifer that would be suitable for lower-quality ground water development.

GIS DATA

The two main sources for input data in this investigation were the U.S. Geological Survey (USGS) and SJRWMD. USGS and SJRWMD have performed several investigations to describe the hydrogeology and geology of the Floridan aquifer system in SJRWMD. The USGS and SJRWMD also collect data on water quality in the Floridan aquifer system. The following is a list of data and sources used for this study:

- Digitized contours of the elevations of the significant hydrogeologic units identified by Miller (1986). Contour data were digitized by Nick Supulvida, USGS, Altamonte Springs, Florida. Important data layers for use in this study included the following:

  –Top of the upper semiconfining unit
  –Top of the rock of the Upper Floridan aquifer
  –Top of the middle semiconfining unit
  –Bottom of the middle semiconfining unit
  –Bottom of the Lower Floridan aquifer system

- Digital ARC/INFO contours of the elevation of chlorides in the Floridan aquifer were developed by McGurk, Burger, and Toth (1998) from water quality well observations and time domain electromagnetic readings (publication pending), as follows:

  –Elevation of the 250-milligram per liter (mg/L) isochlor chloride concentration layer

  –Elevation of the 1,000-mg/L isochlor chloride concentration layer

  –Elevation of the 5,000-mg/L isochlor chloride concentration layer

- Digital ARC/INFO data of several hydrogeologic units of the Floridan aquifer from work done by Boniol et al. (1993) for Technical Publication SJ93-5, *Mapping Recharge to the Floridan Aquifer Using a Geographic Information System.*

  –Calculated recharge to the Upper Floridan aquifer
  –Thickness of the upper semiconfining unit

- General elevation data from the digital elevation models developed from the USGS 1-foot topographic quads (available though SJRWMD's GIS library).

GIS ANALYSIS

The first step in the GIS analysis was to convert all the data into ARC/INFO GRIDs, the raster-based data format for cell modeling in ARC/INFO. All layers were converted to the Triangular Irregular Network format and then to the raster format from the original elevation contours. All GRIDs were created with a common cell size of 100 meters for the entire water resource caution area.

Four main layers were used to identify potentially suitable sites for development of lower-quality ground water. Histograms of the four layers were developed to identify significant breaks in the range of the data values (see the text sections that follow). Each data layer was then divided into three levels with *high, medium,* and *low* denoting areas with the most desirable to least desirable characteristics. Table 1 shows the specific divisions chosen for the ranks for all layers in this part of the analysis. The final step in the GIS analysis involved combining the four layers to develop an output layer with the same high, medium, and low ranking. This output layer identifies the most desirable areas for lower-quality ground water development (Figure 2).

First Layer: Thickness of the Upper Floridan Aquifer

A histogram of the thickness of the Upper Floridan aquifer was developed, based on work done by Miller (1986) (Figure 3) and on the number of grid cells with different ranges of thickness (Figure 4). The range of the data was divided into three equal intervals to develop a ranking from high to low. This layer was necessary to determine the thickness of brackish water in the aquifer. Thicker areas of brackish water in the aquifer were assumed to be more desirable for the development of ground water. This assumption is based on the relative magnitude of the impacts of upconing of brackish water and pressure reductions in the potentiometric surface of the Upper Floridan aquifer.

Table 1. Ranges for Low-, Medium-, and High-Suitability Ranking

Layers	Units	Low	Medium	High
Thickness of the Upper Floridan Aquifer	ft	0 - 100	100 - 300	300 - 750
Thickness of Brackish Water in the Upper Floridan Aquifer	ft	0 - 235	235 - 470	470 - 710
Percentage of Brackish Water in the Upper Floridan Aquifer	percent	0 - 33.3	33.3 - 66.7	66.7 - 100
Recharge to the Upper Floridan Aquifer	in./yr	23 - 11	11 - 3	3 - (-20)

Note: ft = feet
in./yr = inches per year

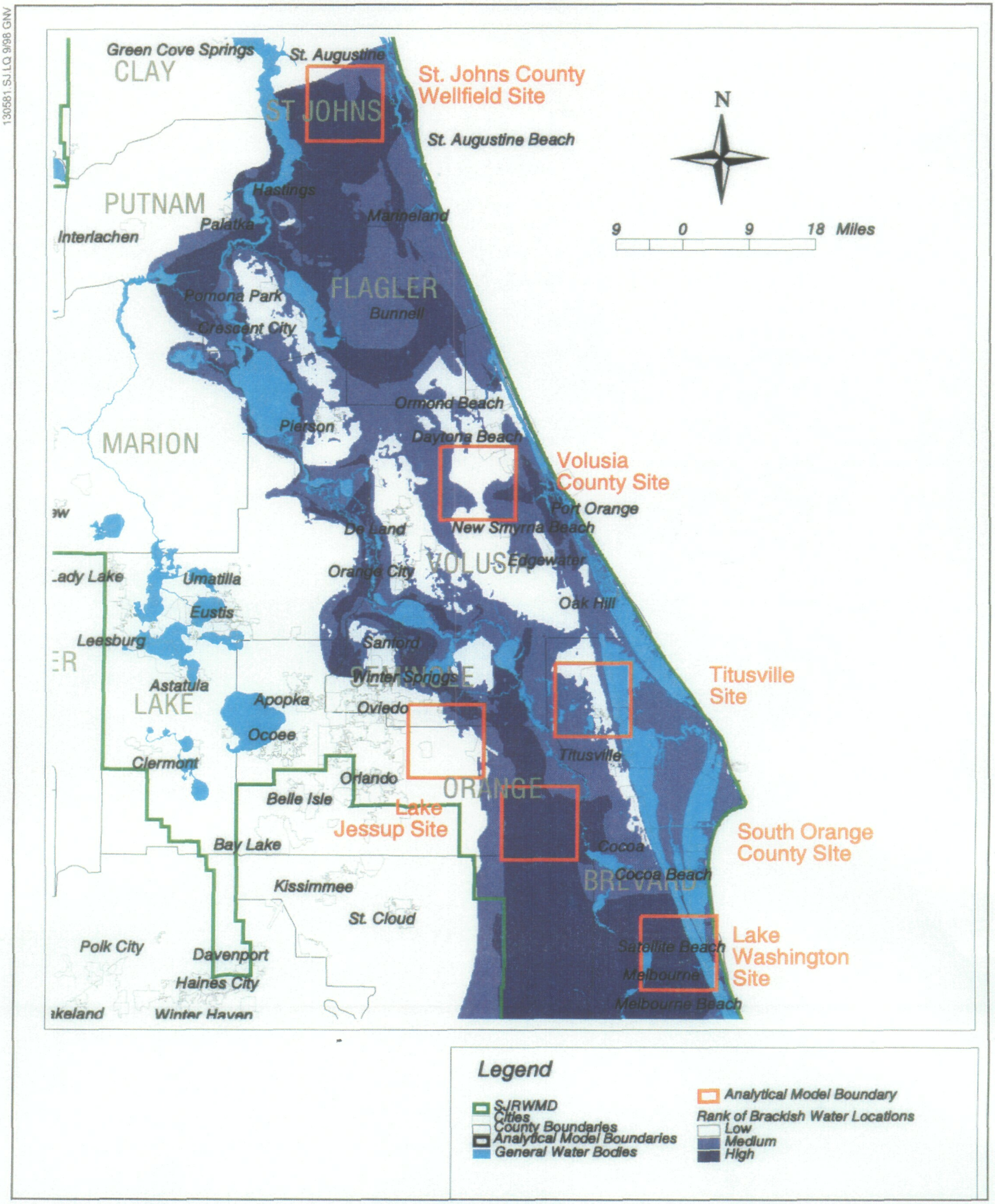

Figure 2. Rank of Lower-Quality Ground Water Withdrawal Locations in the Upper Floridan Aquifer

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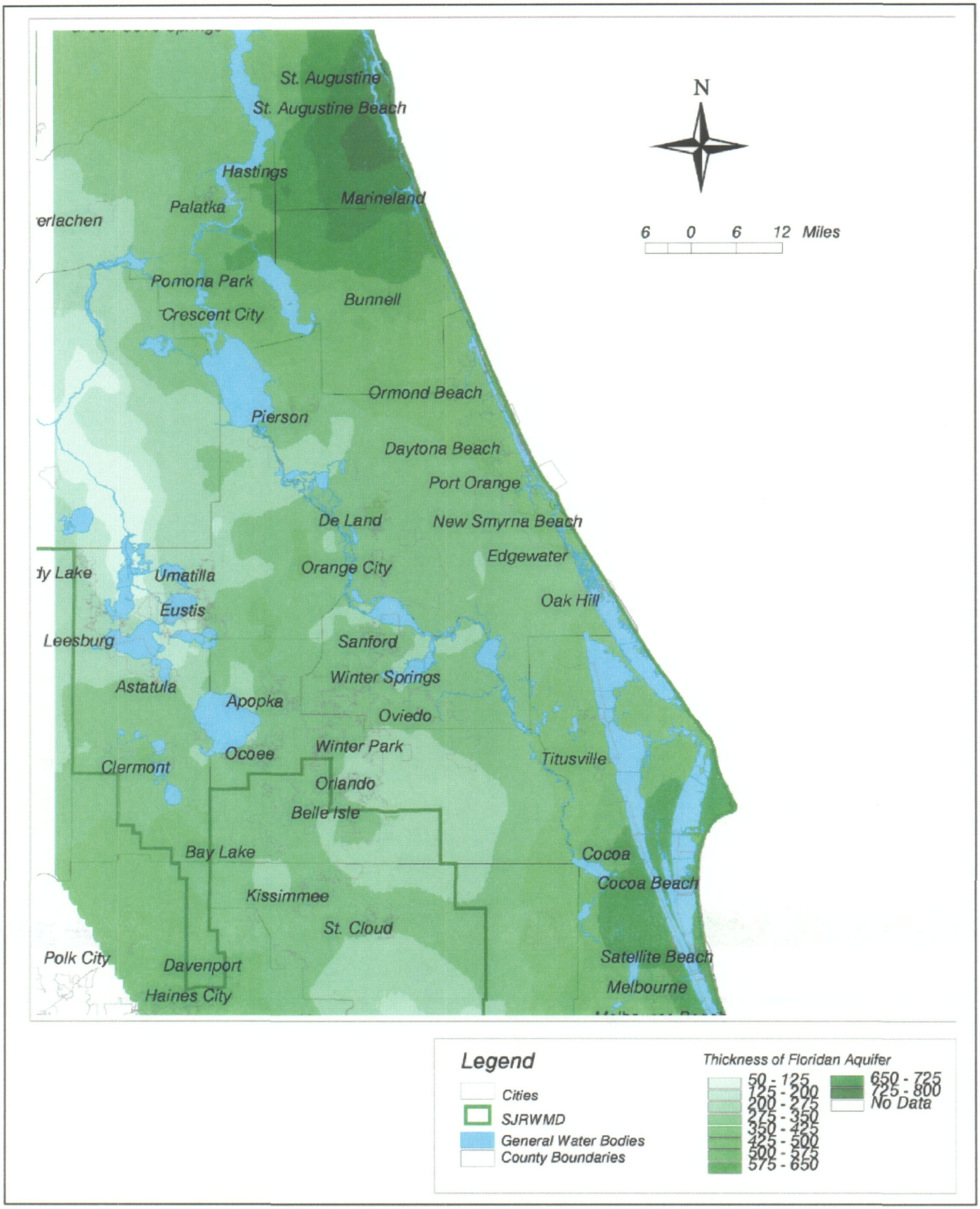

Figure 3. Thickness of the Upper Floridan Aquifer

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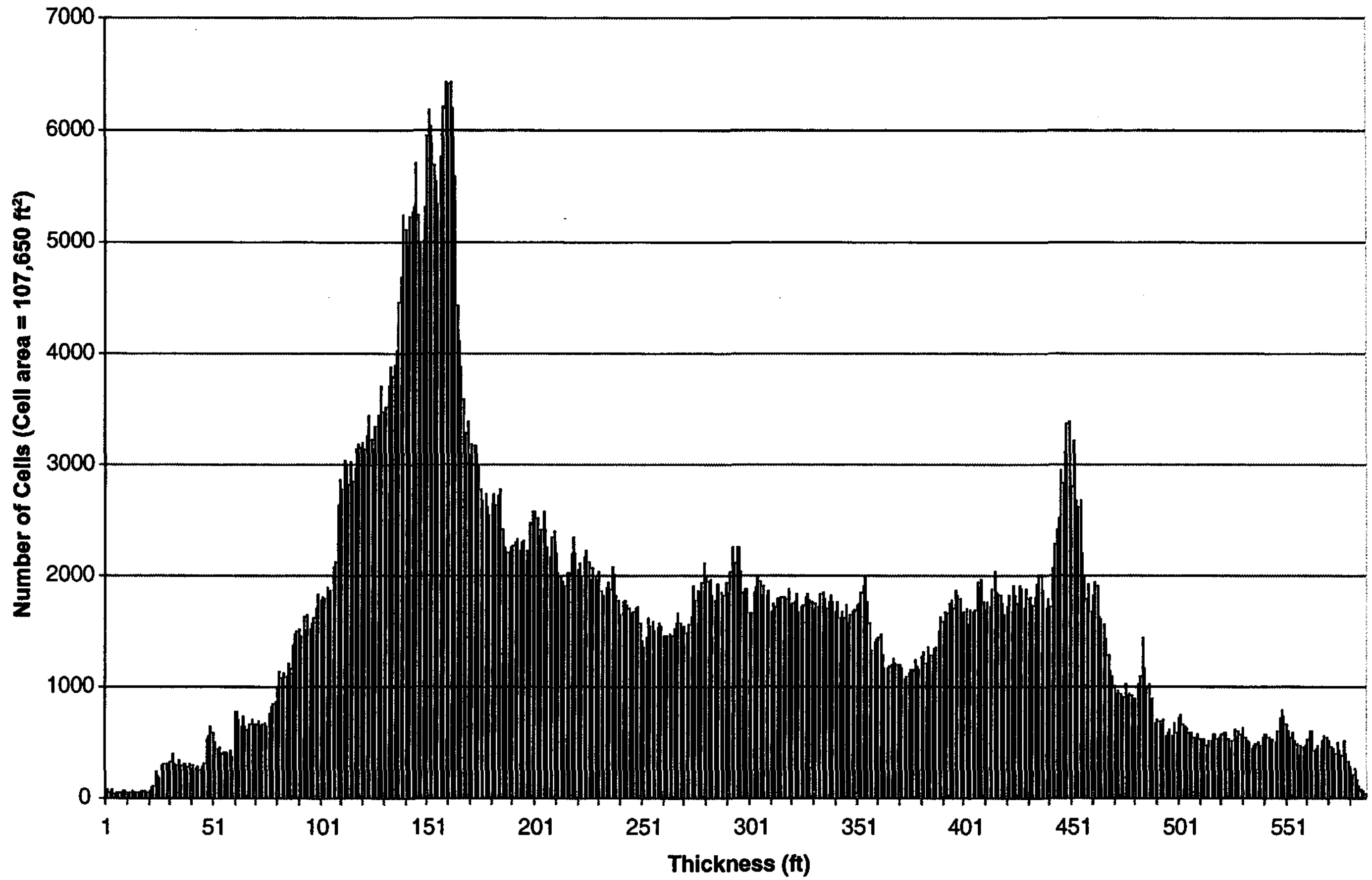

Figure 4. Histogram of Thickness of the Upper Floridan Aquifer in the Study Area

Second Layer: Thickness of Brackish Water

The second layer developed was the thickness of brackish water between chloride elevation surfaces of 250 and 1,000 mg/L. Figures 5 and 6 show the elevations of 250-mg/L and 1,000-mg/L isochlors, respectively, in the Floridan aquifer. Figure 7 is a plot of the thickness of the brackish water, generated by taking the difference in the elevations of these isochlor surfaces for the Upper Floridan aquifer and the thickness of the Floridan aquifer (Layer 1). A histogram was developed to divide and rank the thickness of brackish water in this layer from high to low (Figure 8). Areas with a greater thickness of brackish water were assumed to be more desirable for developing lower-quality water based on withdrawal effects. Withdrawals from the brackish water zone cause movement of the brackish water. Sections of the aquifer with greater thickness of brackish water have potentially less movement from withdrawals.

Third Layer: Percentage of Brackish Water

A third layer was developed from the first two layers to define the percentage of brackish water in the aquifer (Figure 9). The thickness of brackish water was divided by the thickness of the Upper Floridan aquifer and then multiplied by 100 to define this percentage. A histogram was developed to divide and rank the percentage of brackish water in this layer from high to low (Figure 10). Areas with a higher percentage of brackish water were considered more desirable because less high-quality water was available.

Fourth Layer: Recharge to the Upper Floridan Aquifer

The fourth layer was directly taken from the work done by Boniol et al. (1993), defining recharge to the Upper Floridan aquifer (Figure 11). A histogram was developed for this layer to divide and rank the discharge and recharge from or to the aquifer (Figure 12). Areas displaying discharge characteristics were considered more favorable for ground water withdrawals because of the possibility of less impact of drawdown from ground water withdrawals in the Floridan aquifer on the surficial aquifer and wetlands.

GIS RESULTS

Six sites were selected for further study in the analytical portion of this analysis (Figure 2). The selected sites are located in a variety of

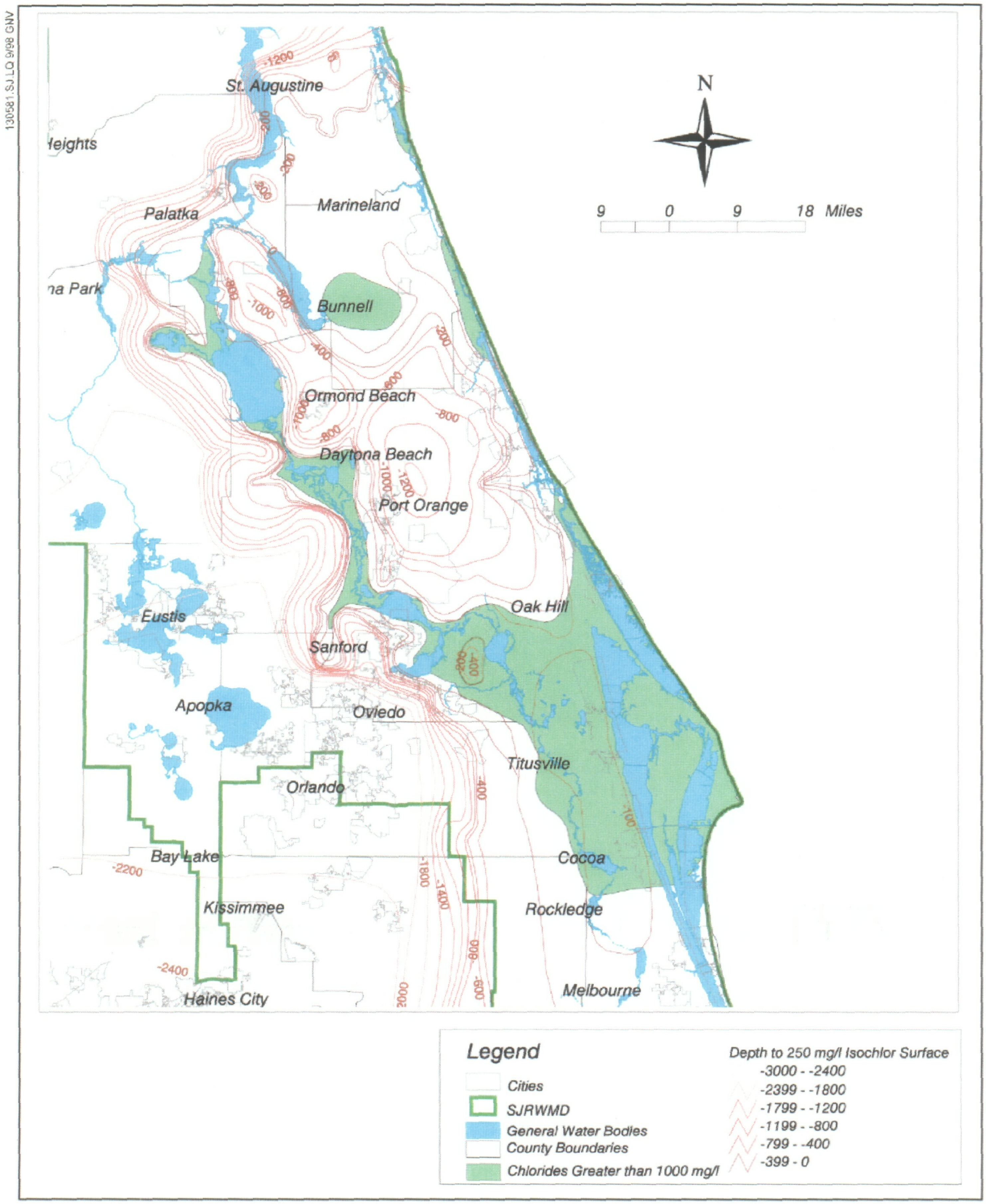

Figure 5. Elevation of the 250-mg/L Isochlor Surface in the Floridan Aquifer

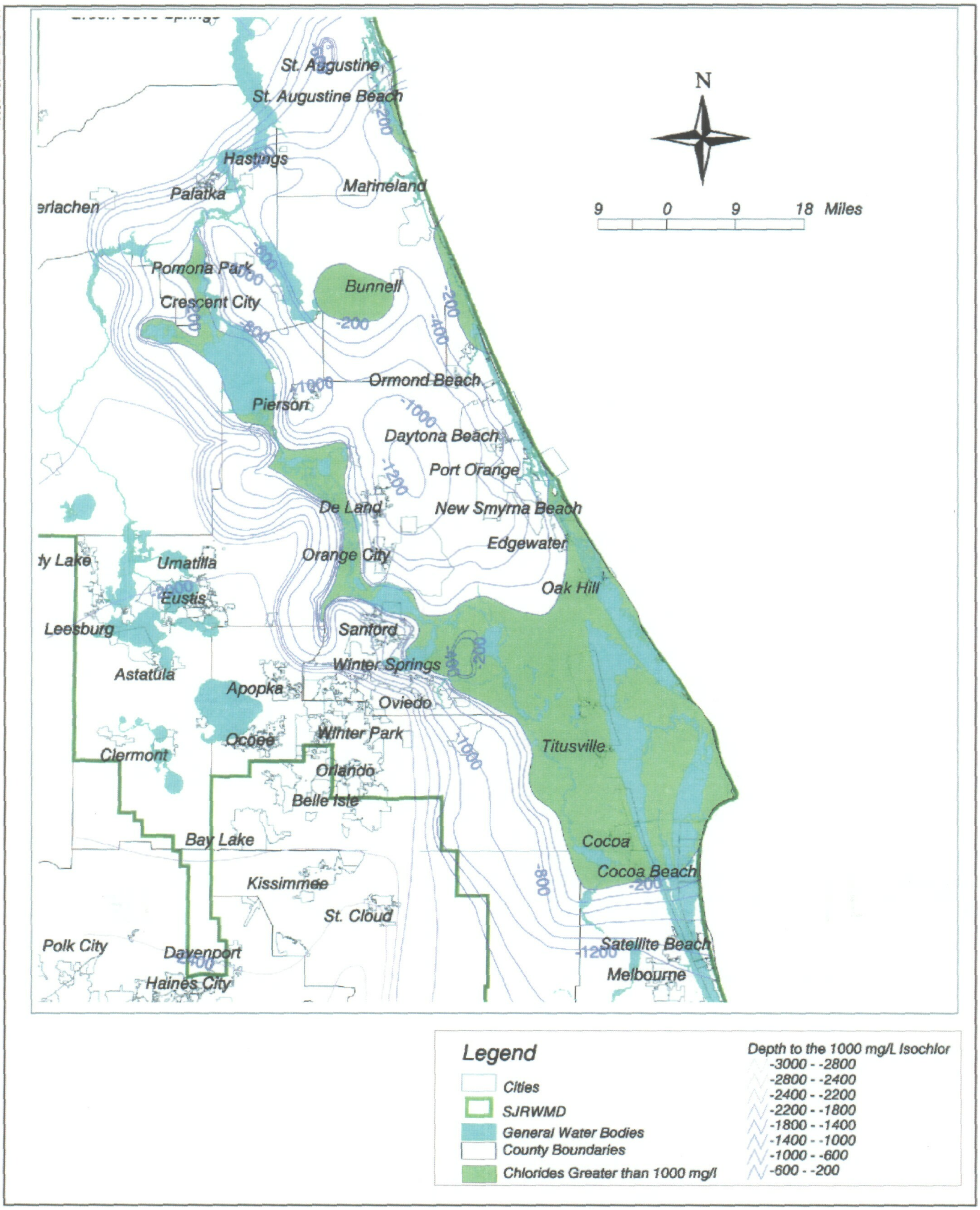

Figure 6. Elevation of the 1,000-mg/L Isochlor Surface in the Floridan Aquifer

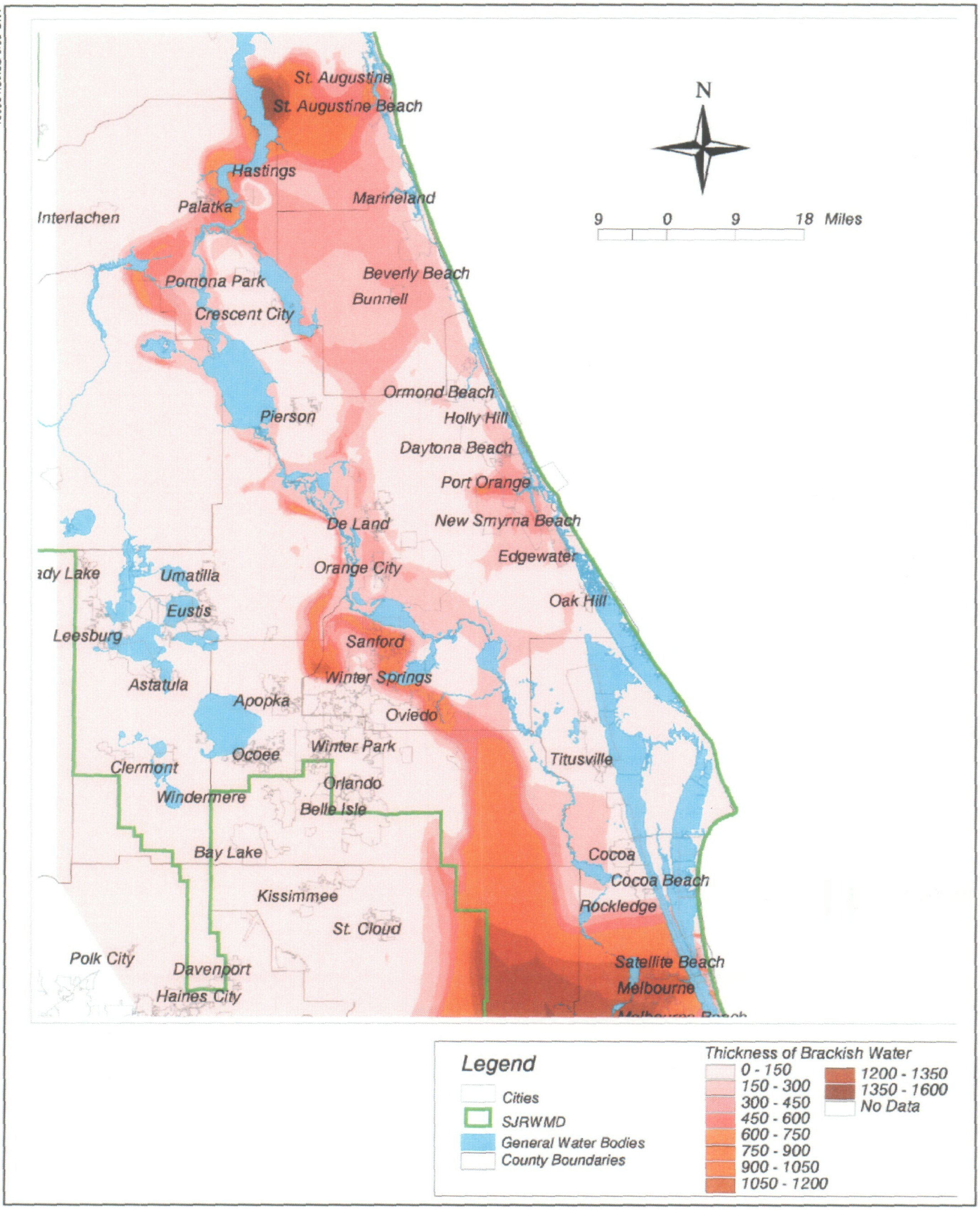

Figure 7. Thickness of Brackish Ground Water in the Upper Floridan Aquifer between 250 and 1,000 mg/L

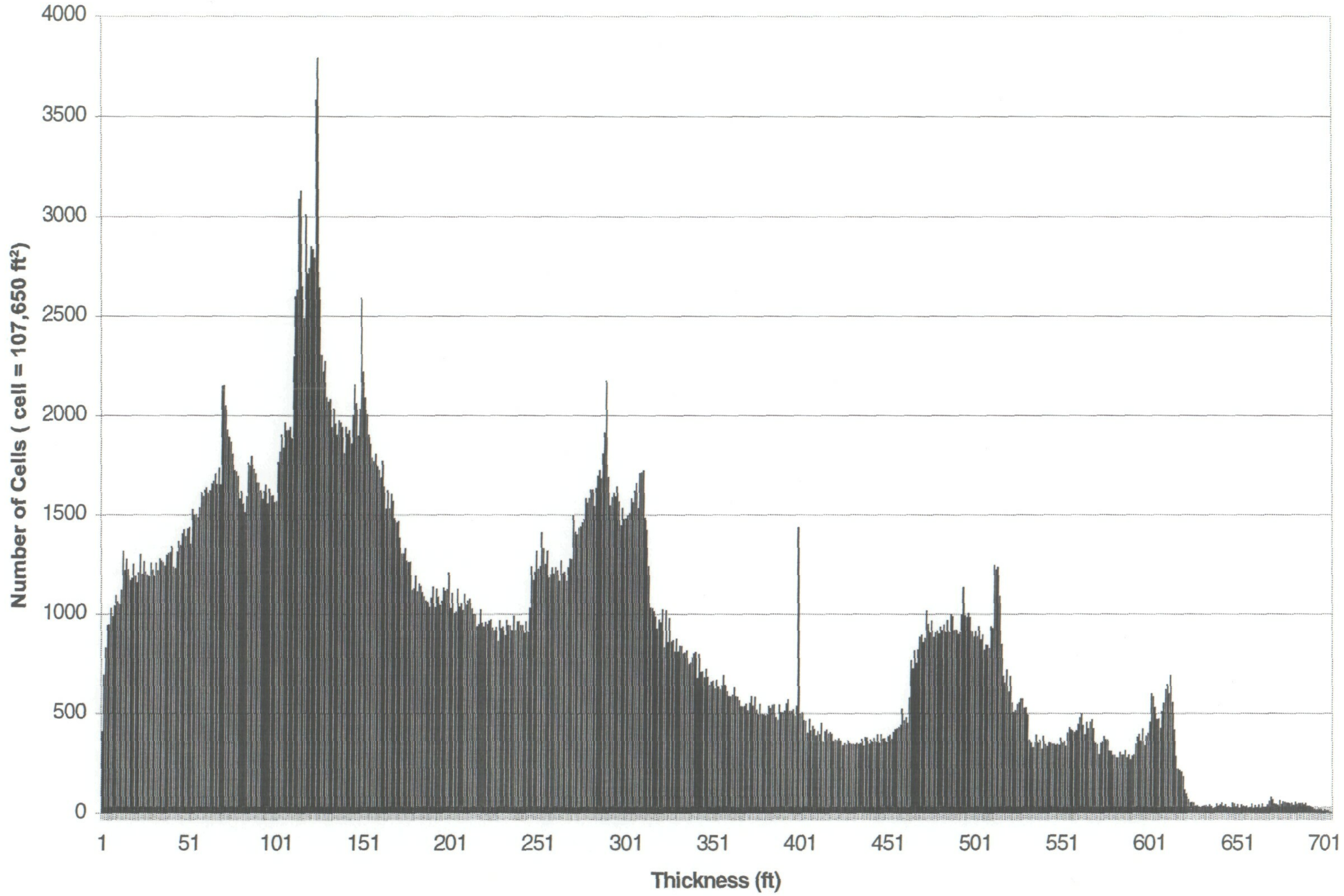

Figure 8. Thickness of Brackish Water Histogram

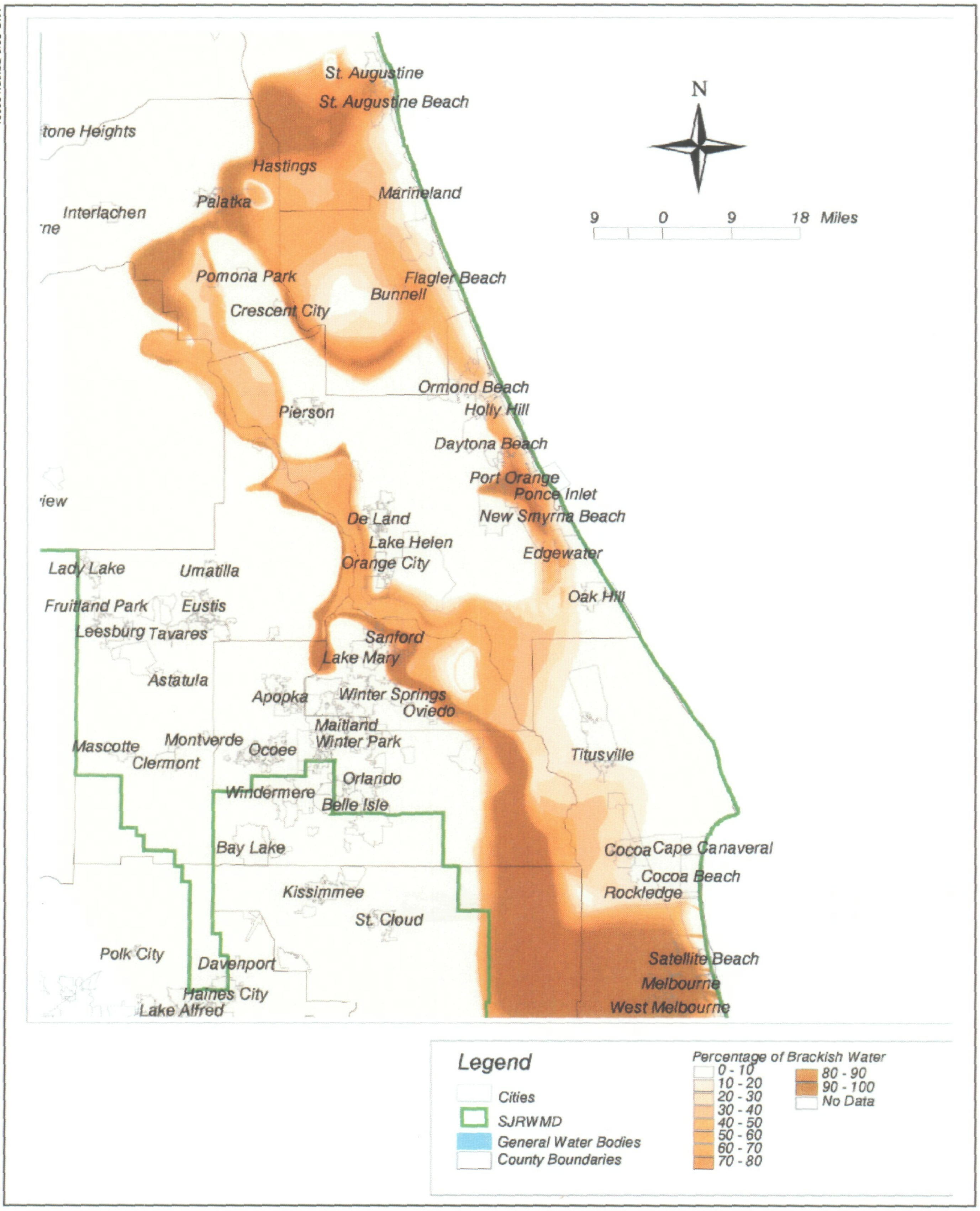

Figure 9. Percentage of Brackish Ground Water in the Upper Floridan Aquifer

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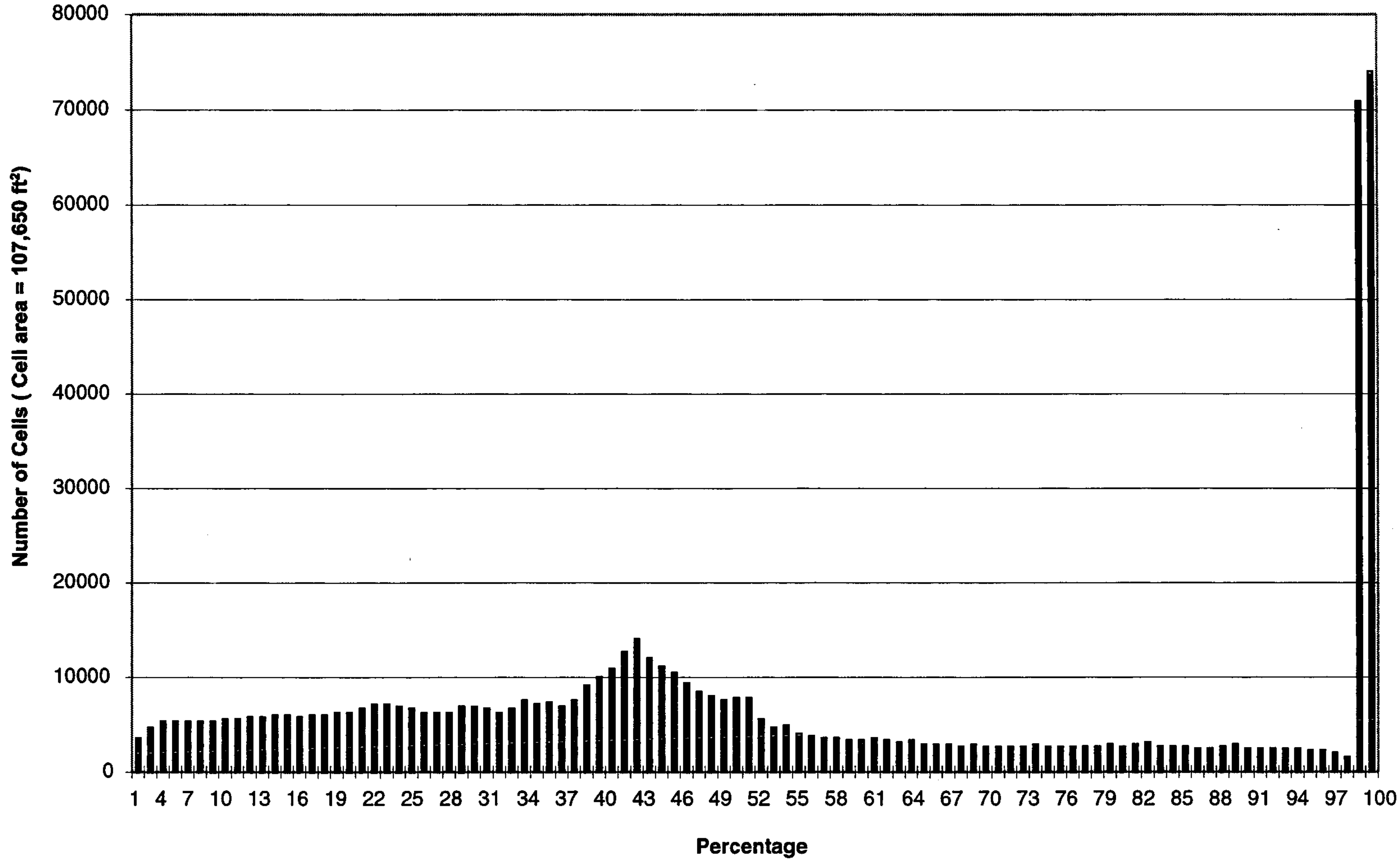

Figure 10. Histogram of Percentage of Brackish Water in the Upper Floridan Aquifer in the Study Area

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Figure 11. Recharge to the Upper Floridan Aquifer (in./yr)

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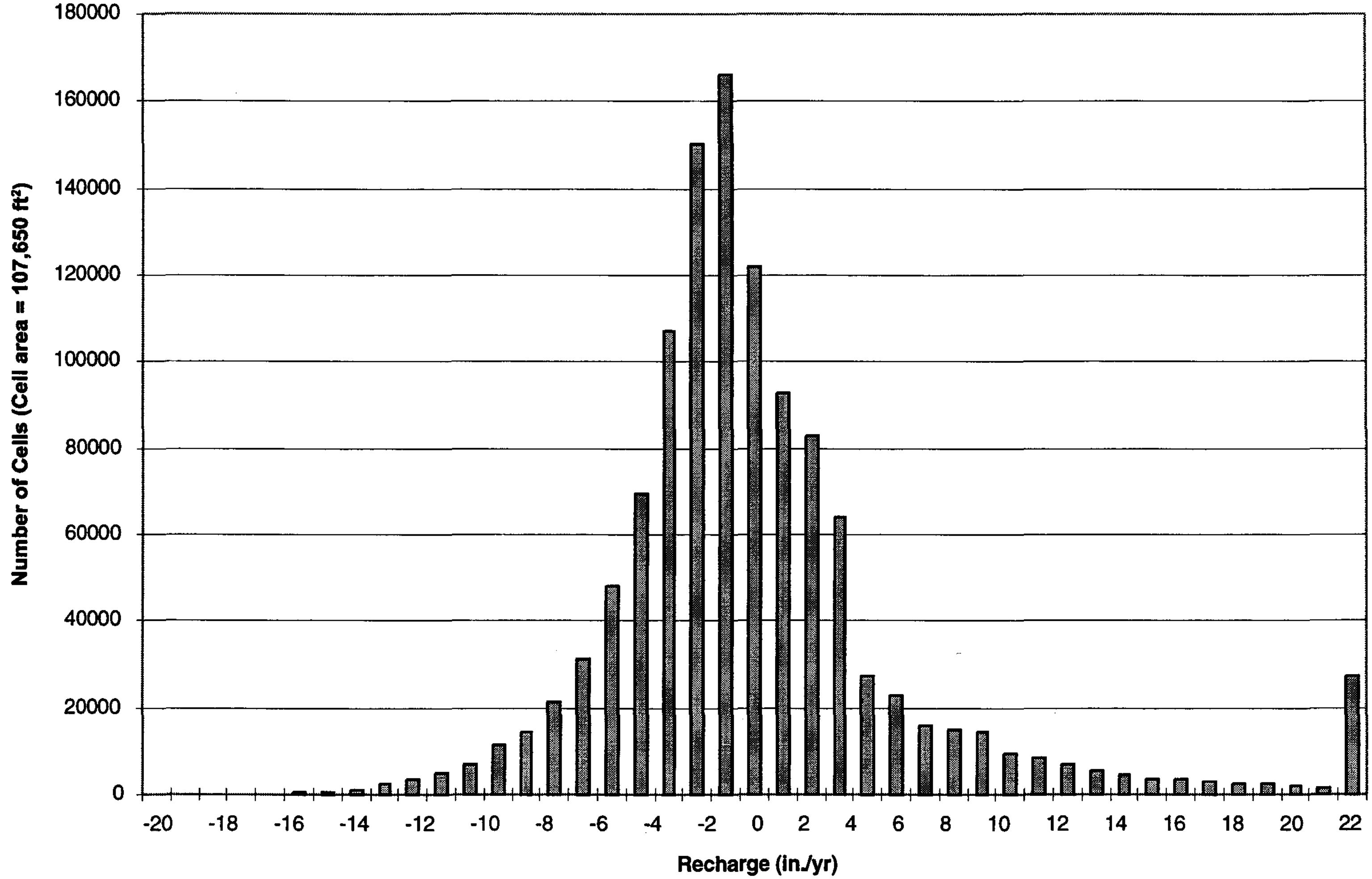

Figure 12. Histogram of Recharge to the Floridan Aquifer in the Study Area

hydrogeologic settings to provide several scenarios for withdrawing lower-quality water. The GIS analysis identified areas with characteristics suitable for lower-quality ground water withdrawals and ranked them as high, medium, and low based on the combination of the four layers for the analysis.

The areas most suitable for brackish ground water withdrawals were located in St. Johns, Seminole, Brevard, and Osceola counties. The first three sites were located in areas with *high sutability* levels for most or all of the four layers. These areas are located in regions with a thick section of aquifer, a thick section of brackish water resulting in a large percentage of brackish water in the aquifer section, and within discharge areas. Based on the GIS analysis, analytical and numerical model grids were located at the following sites for further analysis: the St. Johns County wellfield site, the Lake Washington site, and the Volusia County site.

Three additional sites were chosen in areas that were not identified by the GIS analysis as the most suitable areas for lower-quality ground water development. These sites are located in Titusville, South Orange County, and the Lake Jessup area. These sites were chosen to explore the development of lower-quality ground water in areas that may not be most suited for its development. These candidate sites could, however, meet certain projected public water supply needs if found to be cost-effective.

Once the six sites were located from this analysis, the GIS was used to develop the input data for the analytical portion of the modeling. A GIS procedure was used to capture the data from all four layers for use in the analytical and numerical models.

SALTWATER AND FRESHWATER UPCONING ANALYSIS

In the Floridan aquifer, fresh water generally overlies the denser, salty water. The location, vertically and horizontally, of the freshwater/saltwater interface boundary is dependent on the hydrogeologic conditions in the aquifer system. In response to pumping from a well in the freshwater zone, the saltwater/freshwater interface moves vertically upward toward the pumping well (Figure 13). Under some conditions, a stable upcone of freshwater/saltwater interface develops, and the well continues to discharge fresh water. Under other conditions, the well induces a greater upconing of saline water, and the well discharge becomes saline to a degree that depends on the discharge rates, pumping duration, and the local hydrogeologic conditions.

An analytical saltwater upconing model that assumes the existence of a sharp interface between the freshwater and saltwater was applied in this analysis (Motz, 1992). The model also assumes the occurrence of a critical rise in the interface, above which only an unstable saltwater cone can exit; thereby resulting in water quality deterioration.

A modified analytical model, based on Motz's upconing model, was applied to the selected study sites to evaluate the drawdown at the pumping well, and the rise of interface for three chloride concentrations: 5,000; 7,500; and 9,500 mg/L individually. In addition, a numerical density-dependent transport model (Koulekey, 1986) that assumes a transition zone between the fresh water and the salt water was used to evaluate the saltwater upconing problem for various well configuration scenarios, at the selected study sites, under 750-; 1,000-; and 1,250-gallon per minute (gpm) pumping conditions. The sharp-interface method assumes that the salt water and fresh water are immisicible fluids, and the mixing of salt water and fresh water by the hydrodynamic dispersion process is not considered. The density-dependent, solute-transport numerical method assumes that the salt water and fresh water are miscible fluids, and a transition zone caused by the hydrodynamic dispersion is considered. The results of drawdowns and rise of interface based on the analytical model were used to verify the soundness of the numerical model procedure. Numerical model results are presented in this report to demonstrate the change of chloride concentration versus pumping period for various wellfield configurations.

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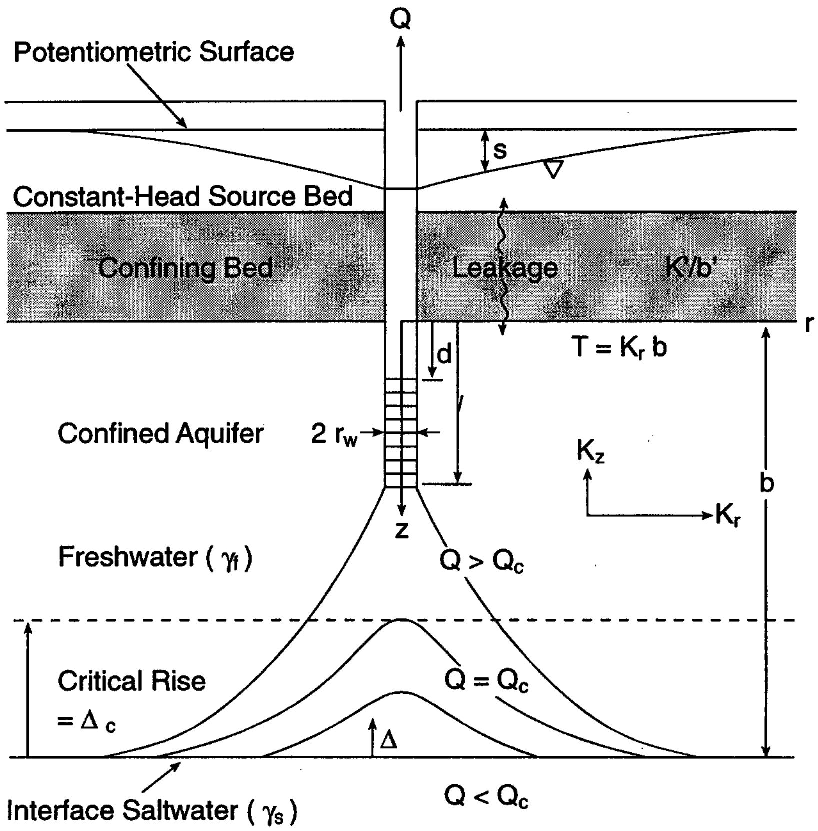

Figure 13. Saltwater Upconing Due to Pumping from a Well in a Leaky Confined Aquifer

ANALYTICAL METHODOLOGY OF SALTWATER UPCONING

An analytical model constructed by Motz (1992) was modified and used to evaluate the upconing of salt water beneath a well pumping fresh water from an aquifer overlain by a leaky confining bed. The drawdown was calculated along the saltwater/freshwater interface due to a well partially penetrating the freshwater zone. The Ghyben-Herzberg relation was used to calculate the rise of the freshwater/saltwater interface. The rise of the saltwater interface in response to the pumping rate under a steady-state pumping condition was determined in terms of aquifer and confining bed properties and the degree of penetration of the pumping well.

DRAWDOWN SOLUTION

In an aquifer overlain by a leaky confining bed, the steady-state drawdown along the saltwater/freshwater interface line at a depth of b and a distance of r from a single steadily discharging well that is screened between the penetration depths d and l is (Motz, 1992) (Figure 13):

$$S_i = \frac{Q}{2\pi T}\left[K_o\left(\frac{r}{B}\right) + \frac{f}{2}\right] \tag{1}$$

where:

$$\frac{1}{B} = \left[\frac{K'}{b'K_r b}\right]^{1/2} \tag{2}$$

and:

$$f = \frac{4b}{\pi(l-d)} \sum_{n=1}^{\infty} \frac{(-1)^n}{n}\left[\sin\left(\frac{n\pi l}{b}\right) - \sin\left(\frac{n\pi d}{b}\right)\right] - \tag{3}$$

$$K_o\left[\left(\frac{K_z}{K_r}\right)^{1/2}\left(\frac{n\pi r}{b}\right)\right]$$

where:

b	=	thickness of aquifer
b′	=	thickness of confining bed
d	=	distance from top of aquifer to top of well screen
Ko	=	modified Bessel function of the second kind, zero order
Kr	=	horizontal hydraulic conductivity of aquifer
Kz	=	vertical hydraulic conductivity of aquifer
K′	=	vertical hydraulic conductivity of confining bed
K′/b′	=	leakance of the confining bed
L	=	distance from top of aquifer to bottom of well screen
N	=	summation index
Q	=	pumping rate of well
R	=	radial distance from well
S	=	drawdown at r and z due to pumping
Z	=	vertical coordinate measured downward from top of aquifer

For multiple wells pumpage, the drawdown along the interface is:

$$S_i = \sum_{m=1}^{m=M} \frac{Q_m}{2\pi T}\left[K_o\left(\frac{r_m}{B}\right)+\frac{f_m}{2}\right] \tag{4}$$

UPCONING OF SALTWATER/FRESHWATER INTERFACE

Based on the Ghyben-Herzberg relation, the rise in the saltwater/ freshwater interface due to the drawdown along the interface is (Bear, 1979):

$$\Delta = \delta \sum_{m=1}^{m=M} \frac{Q_m}{2\pi T}\left[K_o\left(\frac{r_m}{B}\right)+\frac{f_m}{2}\right] \tag{5}$$

where:

$$\delta = \frac{\gamma_f}{\gamma_s - \gamma_f} \tag{6}$$

The largest drawdowns and resulting interface rises generally will occur beneath each of the pumping wells. Equation (5) was incorporated in the modified analytical model to evaluate the impact of multiple pumping wells on drawdown and the response of the upward rise of the sharp freshwater/saltwater interface.

NUMERICAL METHODOLOGY OF SALTWATER UPCONING

Traditional approaches to solving the upconing problem assumed a sharp interface between the fresh and saline water. These approaches fail to include the physical process of the transient zone between fresh water and salt water, and neglects the existence of the vertical flow below the well. A three-dimensional numerical saltwater upconing model developed by Koulekey (1986) considers the transition zone between the fresh water and the salt water, and the effect of vertical flow occurring above and below the partially penetrating pumping wells. The numerical model utilized simultaneously the ground water flow governing equations of continuity, motion, and solute transport, subject to specific boundary conditions. The model was designed to evaluate the drawdown distributions, the growth of the saltwater mound, the development of the transition zone, and the chloride distribution in the affected pumping zone and at the pumping wells. Details of the governing equations of continuity, flow motion, and solute transport in the freshwater, the transition, and the saltwater zones are presented in Koulekey (1986). General discussions of model design and model assumptions are presented as follows.

CONCEPTUALIZATION OF THE SALTWATER UPCONING PROBLEM

The conceptualization of the freshwater and saltwater aquifer system for the numerical model is shown in Figure 14. The ground water flow region consists of a freshwater zone R_f and a saltwater zone R_s. This two-zone region is separated by a transition zone Ω_T. The freshwater zone R_f is overlain by a semiconfining layer; the saltwater zone is bounded below by a confining layer. The boundary between the fresh water and the salt water, the transition zone itself, is bounded by two surfaces, Z_t above and Z_b below. The lower boundary of the transition zone Z_b is called the *saltwater front*. The initial position of the saltwater front is located horizontally at Z_o. The pumping rate is Q and the infiltration and/or evapotranspiration is expressed as R. The vertical subdivisions of the ground water flow system for the model are depicted in Figure 15. The vertical discretization for the numerical model is described as follows.

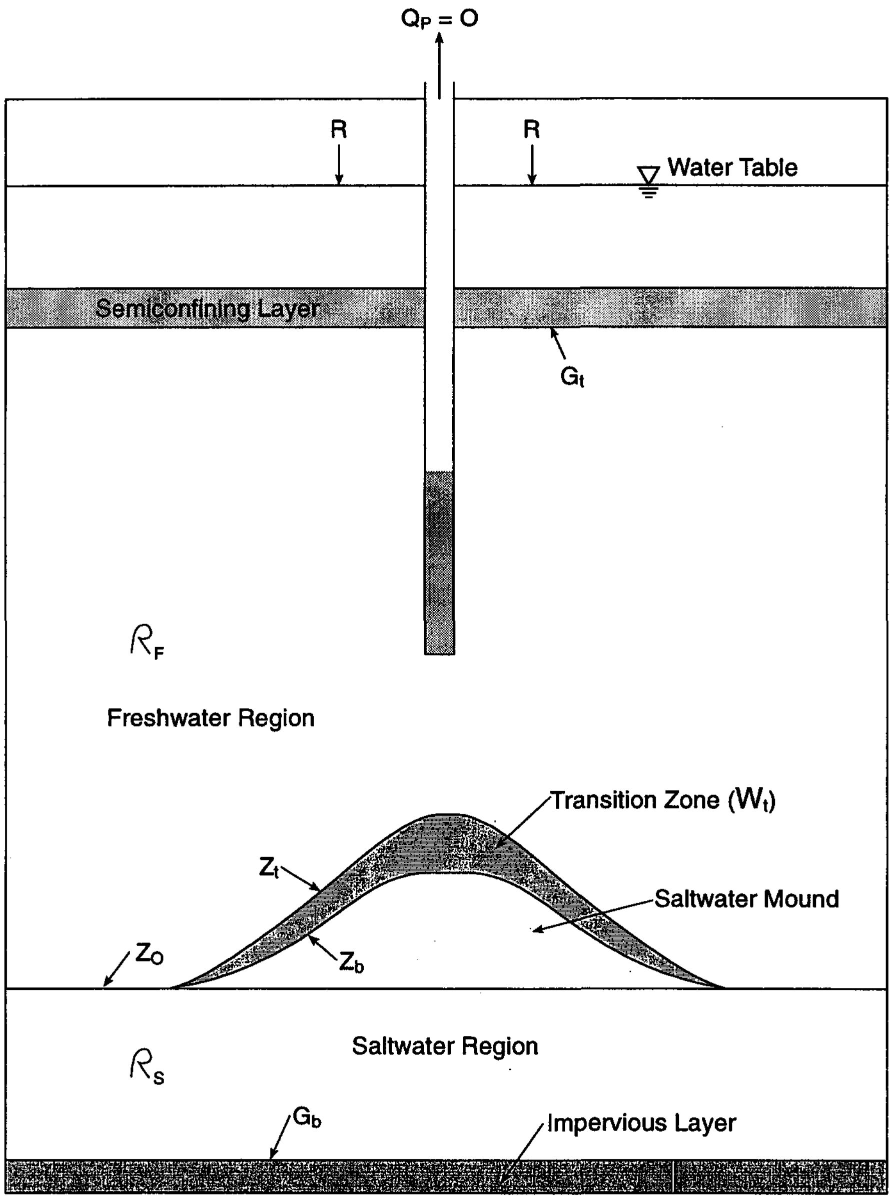

Figure 14. Geometry of the Saltwater Upconing Problem

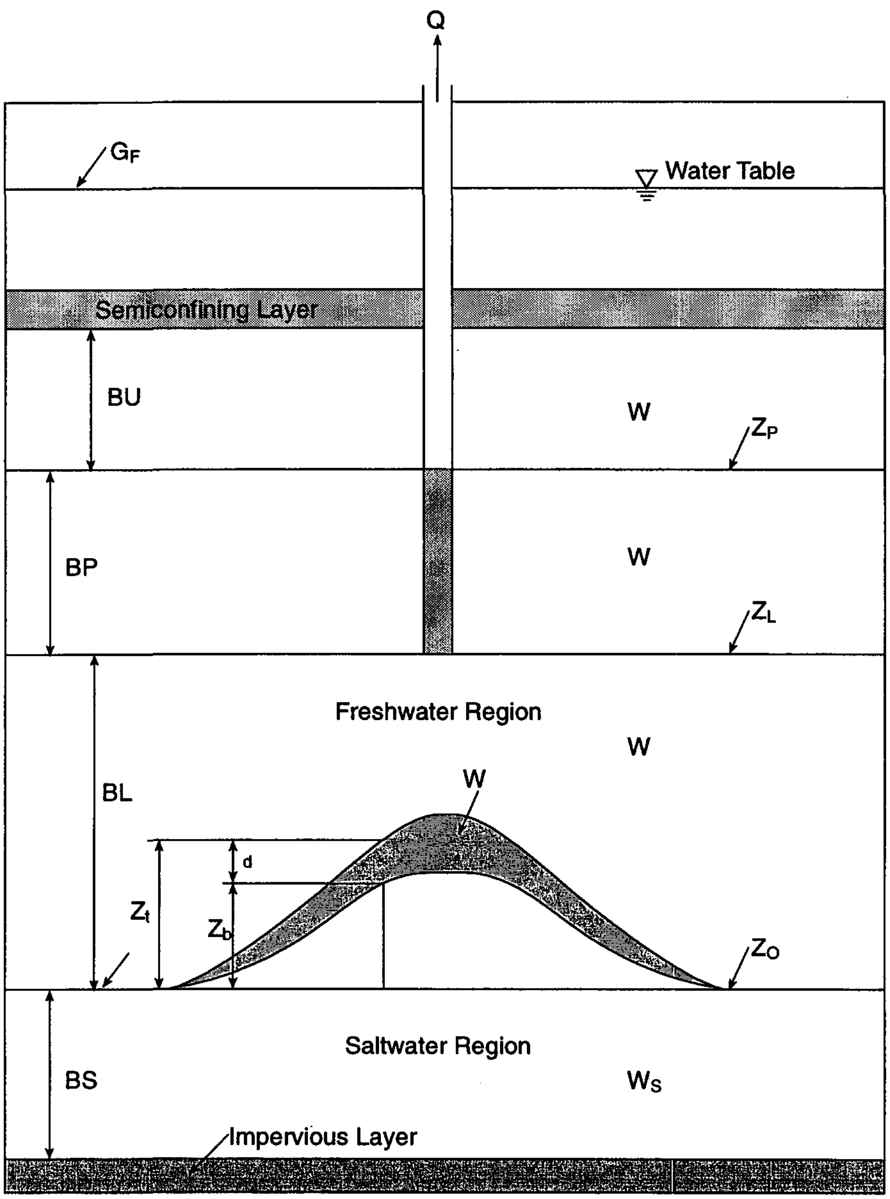

Figure 15. Vertical Subdivisions of the Aquifer System

Water Table Layer

The water table layer is a free surface, allowing recharge of water to the freshwater zone and/or loss of water through evapotranspiration. It is bounded below by a semiconfining bed through which leakage can occur. The water table in the model is treated as a source or sink layer.

Upper Zone Ω_U

The upper freshwater zone Ω_U is bounded above by the semiconfining layer and below by an imaginary surface of elevation Z_p, which is defined by the elevation of the top of the screened portion of the well with respect to the initial position of the front Z_o. Ground water flow in the upper zone consists of the vertical and horizontal flow components.

Pumpage Zone Ω_P

The pumpage zone Ω_P represents a layer with a thickness corresponding to the screened portion of the well. It is bounded above by the surface Z_p and below by the surface Z_l, which is defined by the elevation of the bottom of the screened portion of the well. The ground water pumped from this zone and the ground water flow in the zone is basically flowing in a horizontal direction.

Lower Zone Ω_L

The lower water zone Ω_L, or the *transport zone,* is the layer between the pumpage zone and the saltwater zone. It is bounded above by the surface Z_l and below by the surface Z_o. When water is withdrawn from the pumpage zone, the water in the lower zone is divided into three distinct subregions. The saltwater mound subregion exists between Z_o and Z_b. The freshwater subregion exists between Z_t and Z_l.

The transition zone is defined as the zone in which the chloride content varies from the salt water at the front of the saltwater zone at Z_b to the fresh water at the elevation of Z_t. The thickness of the transition zone is defined as the difference between Z_t and Z_b.

Ground water flow in the lower zone consists of both vertical and horizontal components. In addition to the potential flow in the lower zone, a mass transfer (dispersion) due to the density difference between salt water and fresh water also exists in the lower water zone.

Saltwater Zone Ω_S

The saltwater zone Ω_S is bounded above by the surface Z_o, the original position of the saltwater front, and below by a confining layer Γ_S. The chloride concentration in the saltwater zone is assumed to be constant everywhere, including the front Z_o. The flow in the saltwater zone also has horizontal and vertical components.

ASSUMPTIONS IN ANALYSIS OF SALTWATER UPCONING

The following assumptions were considered in the analysis of saltwater upconing:

1. The flow is three-dimensional.
2. The coordinate coincides with the principal directions of the porous medium.
3. Fresh water and salt water are miscible.
4. The porous medium is nonisotropic and nonhomogeneous.
5. The density of the fluid is a function of chloride concentration.
6. Flows in the saltwater mound zone and the transition zone result from flows in the lower water zone.
7. Dispersion is used to determine the solute transport in the transition zone.
8. The solute transport in the pumpage zone Ω_P is a total mixing process caused by advective flow in the pumpage zone.

The basic ground water and solute transport equations used in the analysis of the saltwater upconing problem are the equations of continuity, motion, solute transport, and the density relationship state equation. The formulation of the finite difference formula and the three-dimensional numerical solute transport model are documented by Koulekey (1986). The applications of the numerical saltwater upconing model at six selected sites are discussed in the text that follows.

SALTWATER UPCONING SITE STUDIES

The objectives of the upconing analysis were to use available aquifer characteristics and chloride distribution data at the six selected sites to evaluate the change of chloride concentrations in the pumping zone and at the wells for three different pumping rates during four pumping periods. Three well configuration scenarios, consisting of one well, three wells, and five wells, were used for the numerical evaluation. The results of the analysis will be used to evaluate the cost of developing the six individual candidate withdrawal sites to meet public supply needs. The analytical and numerical upconing model results for the study sites are discussed in the text that follows.

LAKE WASHINGTON SITE

Analytical Modeling

Based on SJRWMD's GIS database, the geologic units at the Lake Washington site form a hydrologic system consisting of a surficial aquifer system, an intermediate confining bed, and the Floridan aquifer system. The Floridan aquifer system in the study area is divided into three zones— the Upper Floridan aquifer, a middle semiconfining layer, and the Lower Floridan aquifer. Table 2 presents the average elevations of the hydrologic units based on GIS database, and the associated hydraulic parameter values (Hydro Designs, Inc., 1990). The average elevations of the chloride isochlor with concentrations of 250 mg/L; 1,000 mg/L; and 5,000 mg/L at the study site are located about –52; -1,042; and -1,393 feet National Geodetic Vertical Datum of 1929 (NGVD) (Figure 16).

The site-specific parameters required for the analytical model were determined as follows. Based on the GIS database and available reports, the required input data for the analytical upconing model (Figure 13) are b = 600 feet, d = 150 feet, l = 300 feet, d/b = 0.25, and l/b = 0.50. The Kz/Kr ratio is assumed to be 0.10, the transmissivity for the Upper Floridan aquifer is 92,800 square feet per day (ft^2/day), and the leakance of the intermediate confining bed is assumed to be 9.26E-05/day.

The modified analytical upconing model (Motz, 1992) was applied using three chloride concentrations (5,000; 7,500; and 9,500 mg/L) as the sources of chloride in the aquifer system. The purpose of the analytical model was to investigate drawdowns and changes in

Table 2. Hydrologic Units and Characteristics at Lake Washington Site

Characteristics of Hawthorn Layer:	
1. Top of Hawthorn layer	-75 (ft-msl)
2. Bottom of Hawthorn layer	-210 (ft-msl)
3. Thickness of Hawthorn layer	135 (ft)
4. Average leakance of confined Hawthorn layer	9.26E-05 (1/day)
5. Vertical hydraulic conductivity of Hawthorn unit	0.0125 (ft/day)
6. Horizontal hydraulic conductivity of Hawthorn unit	0.25 (ft/day)
Characteristics of Upper Floridan Aquifer:	
7. Top of Upper Floridan aquifer	-210 (ft-msl)
8. Bottom of Upper Floridan aquifer	-790 (ft-msl)
9. Total depth of Upper Floridan aquifer	580 (ft)
10. Transmissivity based on data (Hydro Designs, Inc., 1990)	92,800 (ft2/day)
11. Average horizontal hydraulic conductivity	160.00 (ft/day)
12. Vertical hydraulic conductivity (assuming 1 to 20 ratio)	8.00 (ft/day)
Characteristics of Middle Semiconfining Unit:	
13. Top of middle confining unit	-790 (ft-msl)
14. Bottom of middle confining unit	-1,220 (ft-msl)
15. Total depth of Upper Floridan aquifer	430 (ft)
16. Transmissivity (Hydro Designs, Inc., 1990)	2.49E+02 (ft2/day)
17. Average horizontal hydraulic conductivity	0.58 (ft/day)
18. Vertical hydraulic conductivity (assuming 1 to 20 ratio)	0.029 (ft/day)
Characteristics of Lower Floridan Aquifer:	
19. Top of Lower Floridan aquifer	-1,220 (ft-msl)
20. Bottom of Lower Floridan aquifer	-2,960 (ft-msl)
21. Total depth of Lower Floridan aquifer	1,740 (ft)
22. Transmissivity (Hydro Designs, Inc., 1990)	N/A
23. Average horizontal hydraulic conductivity	N/A
24. Vertical hydraulic conductivity (assuming 1 to 20 ratio)	N/A

Based on GIS data provided by SJRWMD and Hydro Designs, Inc., 1990.

Note: ft-msl = feet mean sea level
ft/day = feet per day
N/A = not available

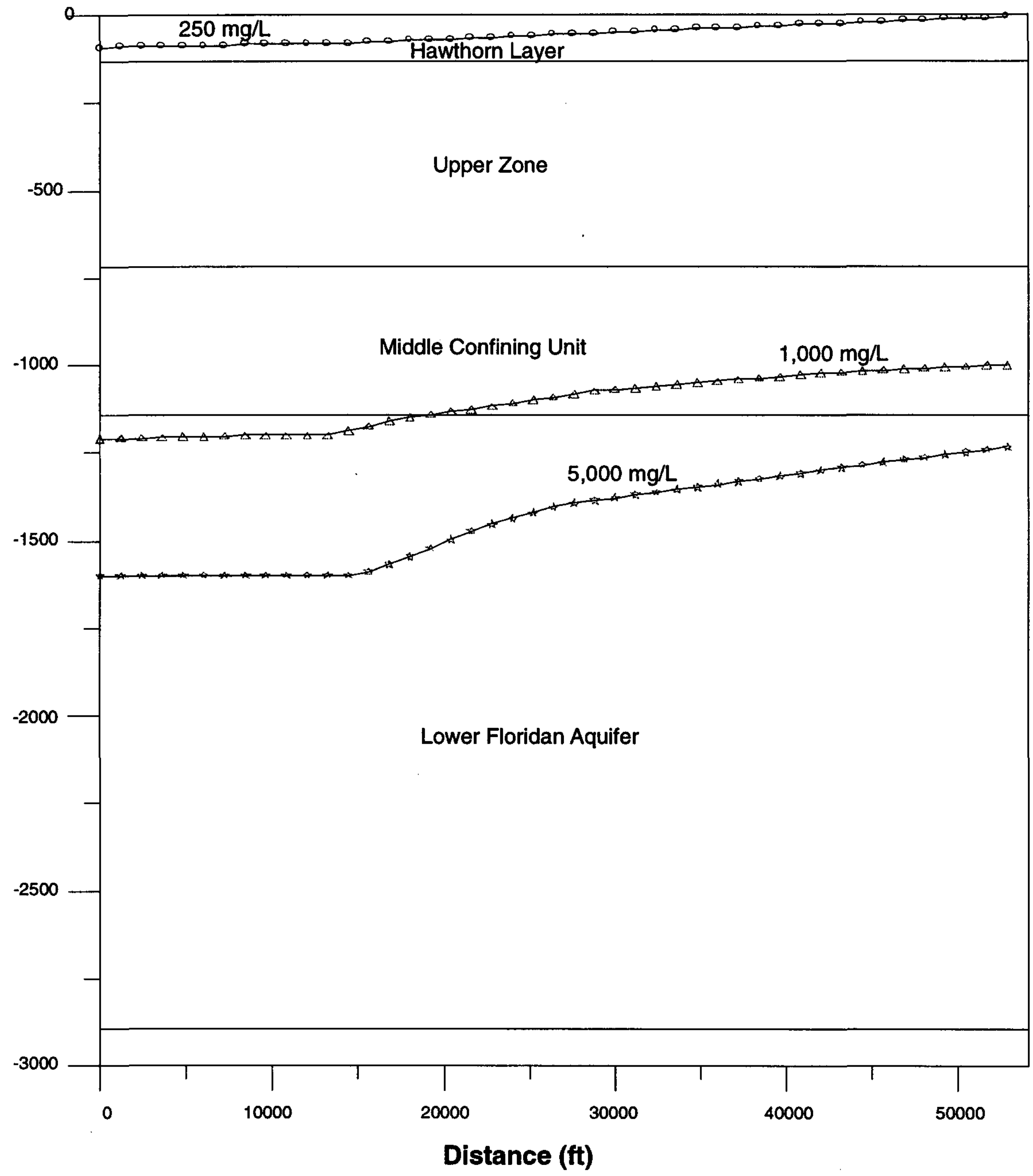

Figure 16. Geological Cross Section at the Lake Washington Site

chloride concentrations at the pumping well due to three pumping rates applied to a single partially penetrating production well. Three chloride concentrations (5,000; 7,500; and 9,500 mg/L) at the bottom of the Upper Floridan aquifer were assumed to represent the freshwater/ saltwater interface for the analytical model. The potential rise of the interface line as a result of the three pumping rates of 750; 1,000; and 1,250 gpm were evaluated, with the results presented in Table 3. The relationship between the upconing height and pumping scenarios for the three assumed chloride concentrations at the interface line are shown in Figure 17. Table 3 and Figure 17 indicate that the rise of the interface for the 5,000-mg/L chloride concentration is higher than the rise for the 9,500-mg/L chloride concentration.

Numerical Modeling

The numerical upconing model was used to evaluate the chloride concentration distribution in the pumping zone and at the wells in response to three pumping rates under a transient pumping condition. The pumping duration for this numerical modeling was divided into 5, 10, 15, and 20 years. Available information at the Lake Washington site, summarized in Table 2, was used in this numerical upconing modeling study.

The average thickness of the upper confining bed is about 125 feet, and the average leakance is about 9.26E-05/day. It was determined that the vertical hydraulic conductivity for the upper confining bed is about 0.0125 ft/day. The transmissivity is reported to range from 6,685 to 133,689 ft^2/day (Hydro Designs, Inc., 1990). An average transmissivity value of 92,800 ft^2/day was used to represent the Upper Floridan aquifer in the model. The total thickness of about 600 feet in the Upper Floridan aquifer was divided into three layers — the upper layer (BU), the pumpage layer (BP), and the lower layer (BL) in the upconing model. The partially penetrating production well consists of the upper fresh water zone, BU, of 150 feet; the opening screened layer, BP, of 150 feet; and the lower water zone, BL, of 300 feet from the bottom of the production to the top of the middle confining layer. This is a conceptual well design used in the upconing model for this study site.

Figure 16 shows the vertical profile representing the aquifer hydrologic units used in the numerical model. Three well configuration scenarios — one well, three wells, and five wells — were evaluated to determine the responses of the aquifer system and chloride distribution in the pumping layer, and at the production wells, for these three scenarios.

Table 3. Interface Upconing Height vs. Pumping Rate, Lake Washington Site

Q (gpm)	Drawdown (ft)	Upconing Height (ft)		
		9,500 mg/L	7,500 mg/L	5,000 mg/L
750	0.83	68.3	86.5	129.8
1,000	1.10	90.7	114.9	172.3
1,250	1.38	113.4	143.6	215.4

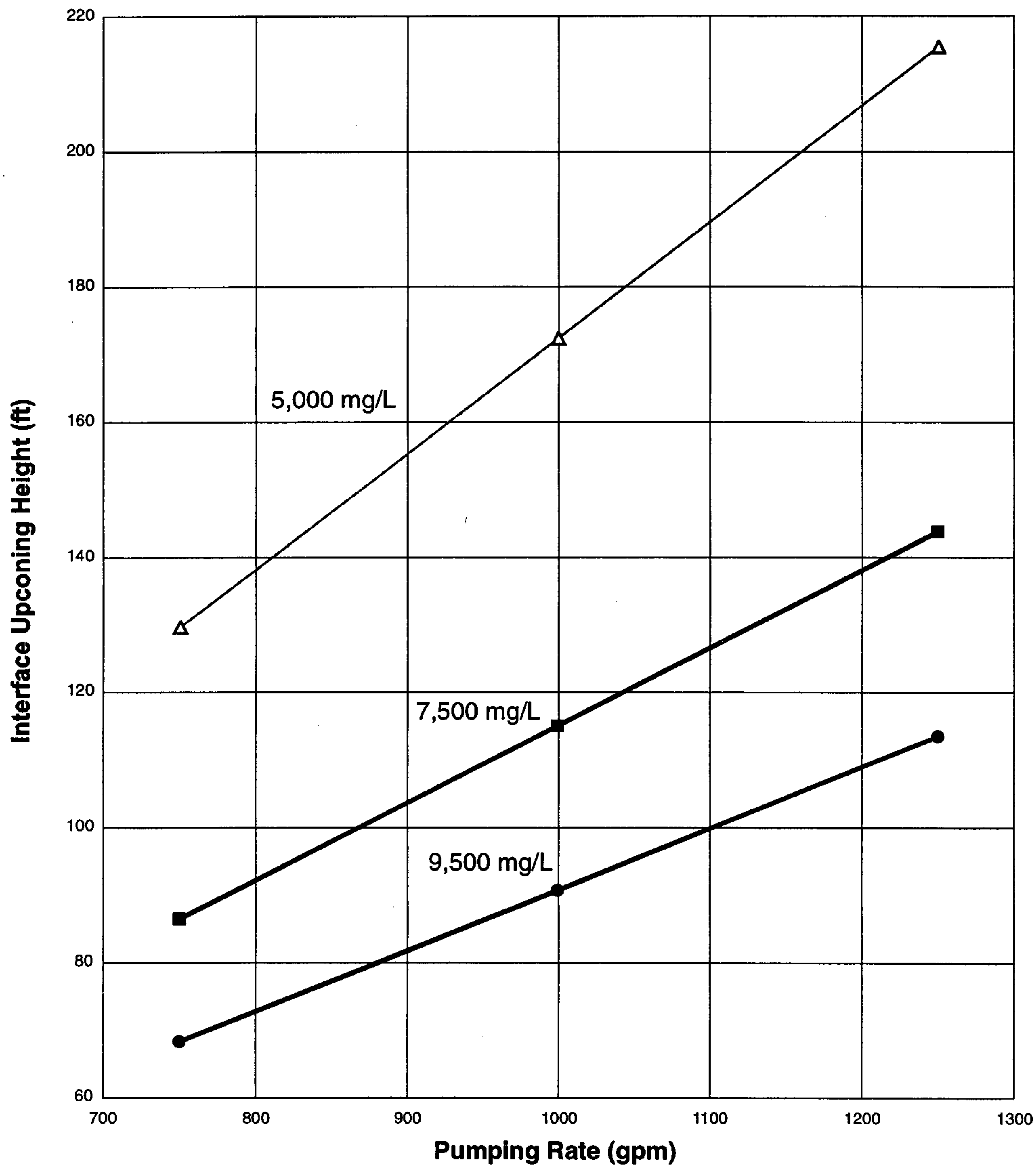

Figure 17. Interface Upconing Height vs. Pumping Rate for the Lake Washington Site

The space between two wells in the well configuration is 2,500 feet. The diameter of the well is 12 inches. Three pumping rates (750; 1,000; and 1,250 gpm) were used to evaluate the pumpage effects on chloride distribution. The results of upconing for various pumpages and pumping durations are as described below.

Table 4 presents the results of the upconing model for the three pumping rates at 5, 10, 15, and 20 years of pumping duration for three well configuration scenarios. The largest drawdowns at the production wells for one-, three-, and five-well configurations during continuous pumping at 1,250 gpm are 1.8 feet, 3.5 feet, and 4.7 feet, respectively. The potential maximum rise of the lower-quality ground water beneath the production wells for these three scenarios for the 20 years pumping duration range from 48.0 feet to 129.1 feet. The simulated chloride concentrations at the production wells for these three scenarios for the 20-year pumping duration range from 262.8 mg/L to 434.4 mg/L.

Figure 18 shows the change in chloride concentration at the production well versus 5, 10, 15, and 20 years of pumping duration for the one-well configuration under the 750-; 1,000-; and 1,250-gpm pumpages. The average chloride concentration at the production well is 262.8 mg/L for this one-well configuration at the end of 20 years.

Figure 19 shows the change in chloride concentration at the production well versus 5, 10, 15, and 20 years pumping duration for the three-well configurations under the 750-; 1,000-; and 1,250-gpm pumpages. The average chloride concentration at the production well is 369.7 mg/L for this three-well configuration at the end of 20 years.

Figure 20 shows the change in chloride concentration at the production well versus 5, 10, 15, and 20 years pumping duration for the five-well configurations under the 750-; 1,000-; and 1,250-gpm pumpages. The average chloride concentration at the production well is 434.4 mg/L for this five-well configuration at the end of 20 years.

TITUSVILLE SITE

Analytical Modeling

Based on SJRWMD's GIS database, the geologic units at the Titusville site form a hydrologic system consisting of a surficial aquifer system, an intermediate confining bed, and the Floridan aquifer system. The Floridan aquifer system in the study area has been divided into three zones — the Upper Floridan aquifer, a middle confining layer, and the Lower Floridan aquifer. Table 5 presents the average elevations of the

Table 4. Lake Washington Chloride Concentration vs. Pumping Rate and Duration

Time (yrs)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)
	One-well configuration											
5	1,073,580	1.1	0	250	1,440,000	1.5	0	250	1,800,000	1.8	0	250
10	1,073,580	1.1	0.4	250	1,440,000	1.5	3.8	250	1,800,000	1.8	9.1	250
15	1,073,580	1.1	6.2	250	1,440,000	1.5	15.4	250	1,800,000	1.8	26.5	250
20	1,073,580	1.1	15.2	250	1,440,000	1.5	30.6	250	1,800,000	1.8	48	262.8
	Three-well configuration											
5	1,073,580	2.1	1	250	1,440,000	2.8	4	250	1,800,000	3.5	8.2	250
10	1,073,580	2.1	12.9	250	1,440,000	2.8	24.3	250	1,800,000	3.5	36.8	250
15	1,073,580	2.1	30.1	250	1,440,000	2.8	50.4	251.5	1,800,000	3.5	72.2	271
20	1,073,580	2.1	49.9	251.3	1,440,000	2.8	79.9	283.3	1,800,000	3.5	111.9	369.7
	Five-well configuration											
5	1,073,580	2.8	1.8	250	1,440,000	3.8	5.8	250	1,800,000	4.7	10.8	250
10	1,073,580	2.8	16.4	250	1,440,000	3.8	29.5	250	1,800,000	4.7	43.9	250
15	1,073,580	2.8	36.2	250	1,440,000	3.8	59.4	253.4	1,800,000	4.7	84.2	290.7
20	1,073,580	2.8	58.9	253.1	1,440,000	3.8	92.9	312.2	1,800,000	4.7	129.1	434.4

Note: Well space = 2,500 ft

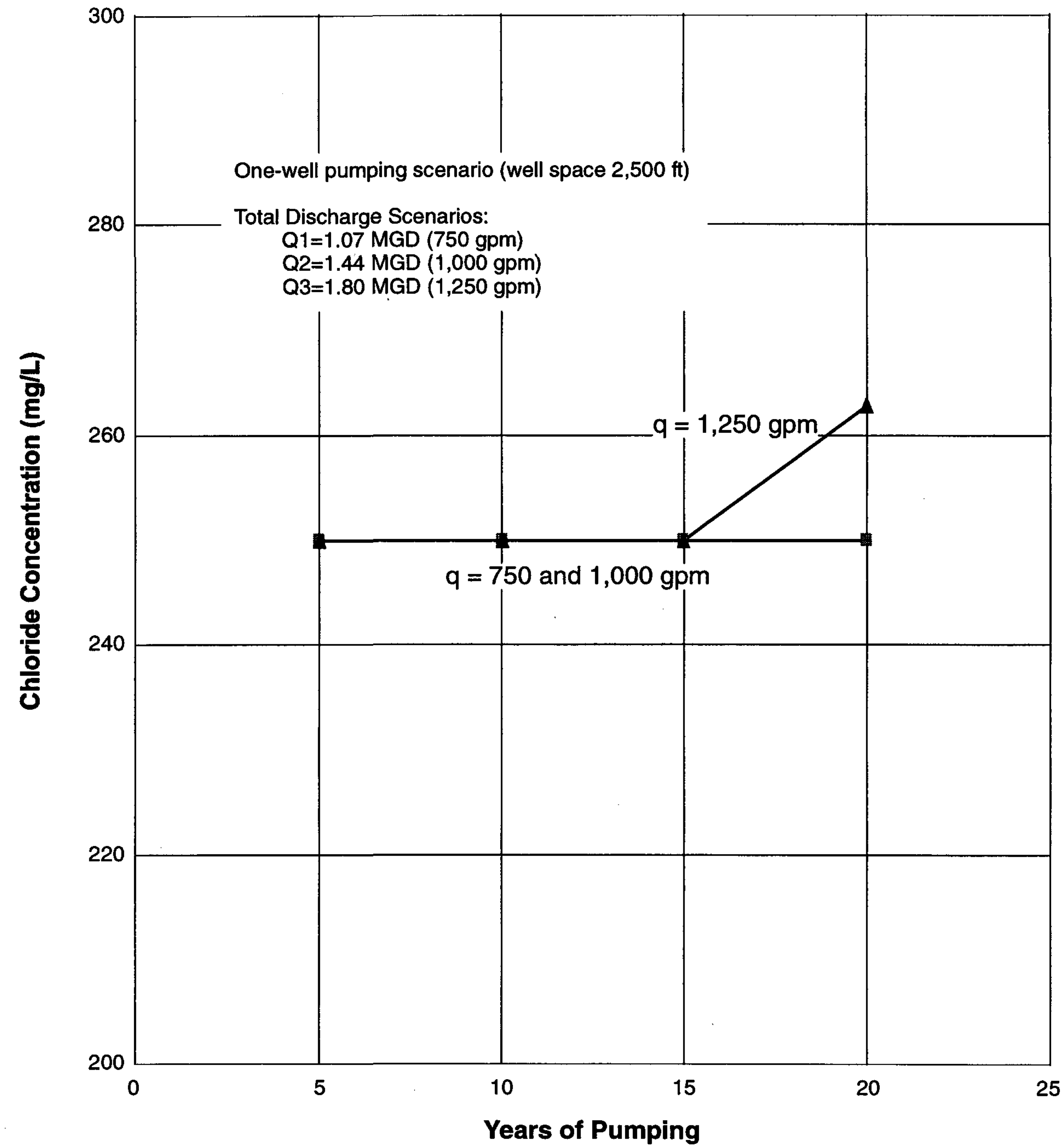

Figure 18. Chloride Concentration as a Function of Pumping Duration for the Lake Washington Site–One-Well Configuration

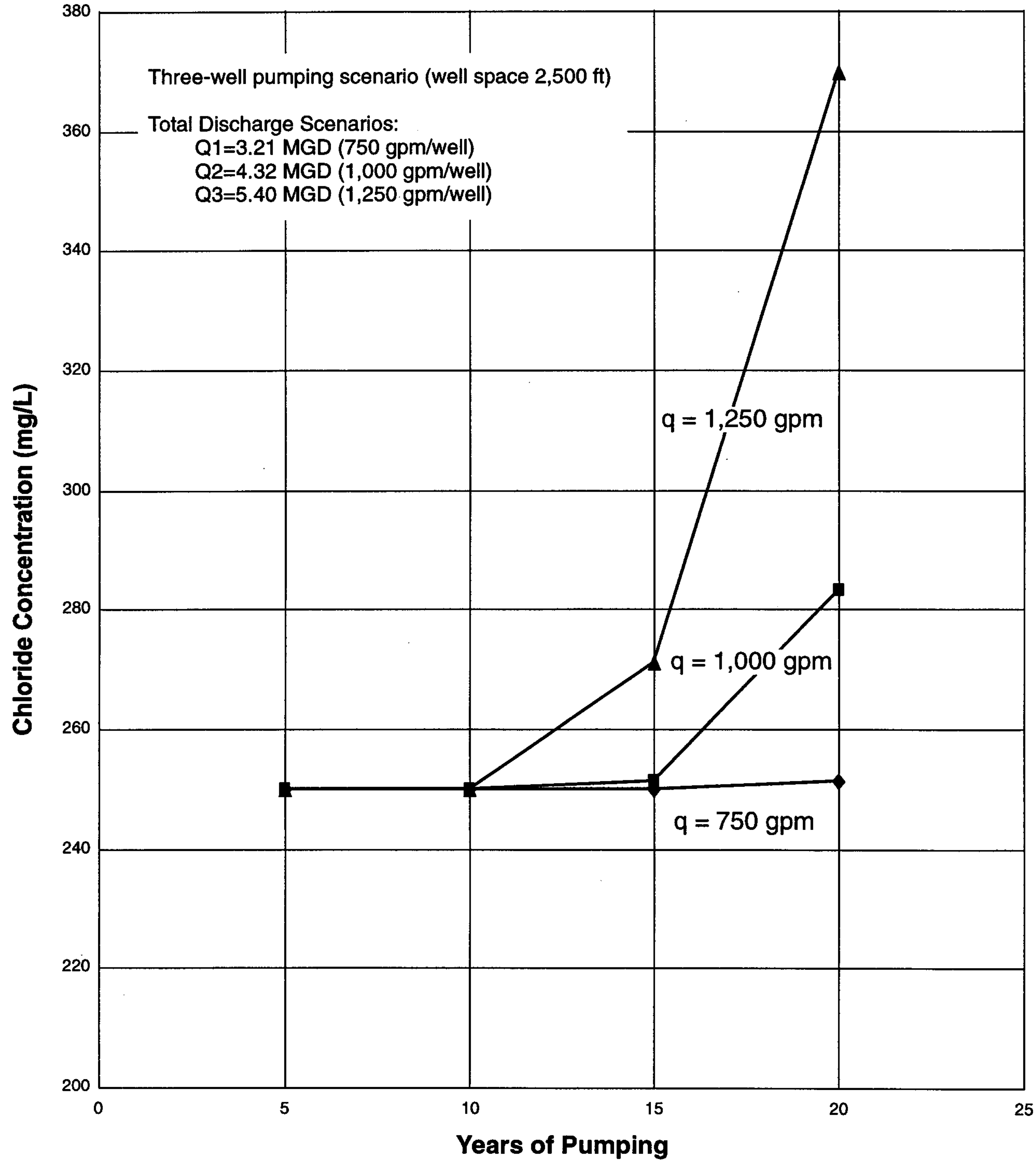

Figure 19. Chloride Concentration as a Function of Pumping Duration for the Lake Washington Site–Three-Well Configuration

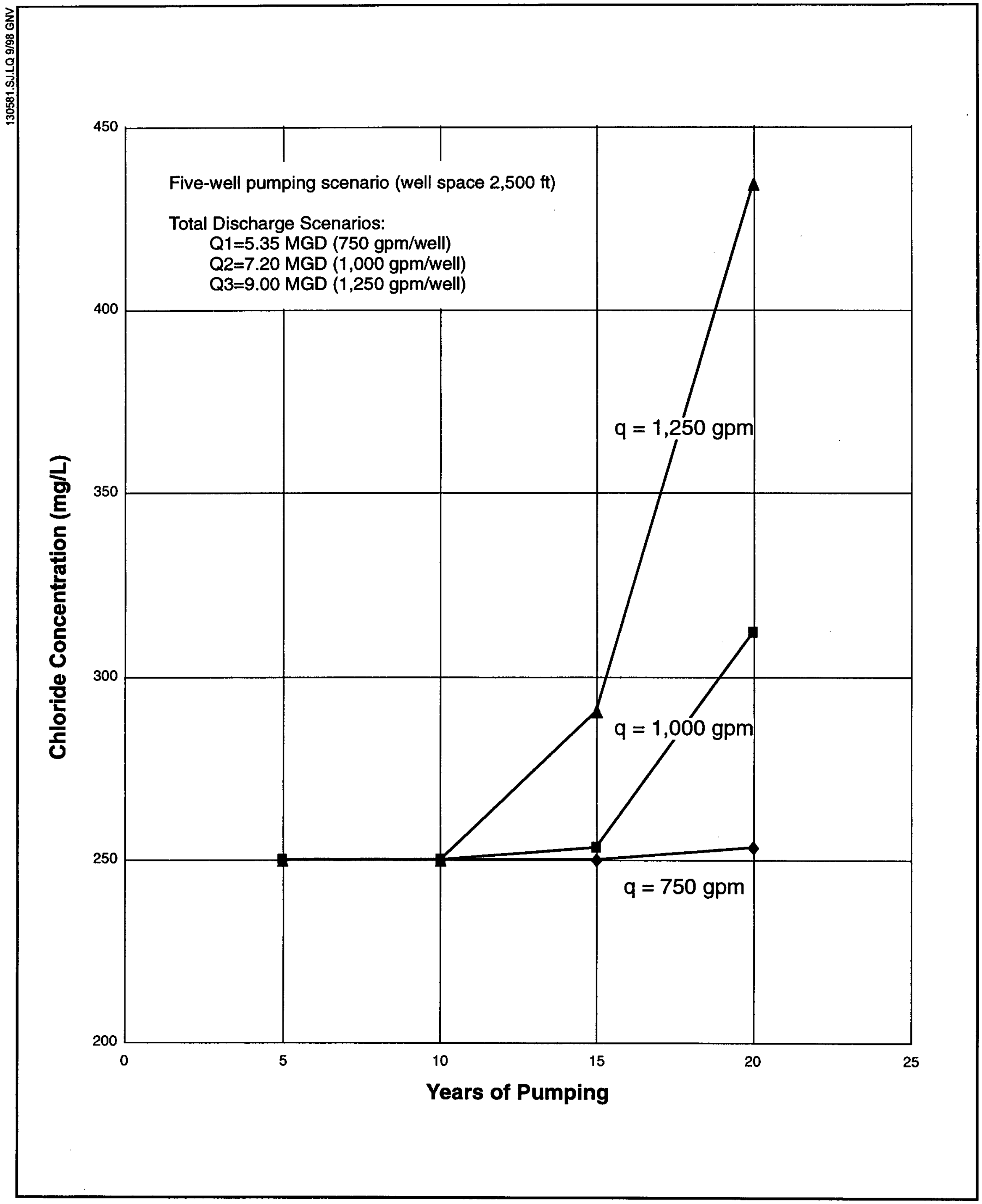

Figure 20. Chloride Concentration as a Function of Pumping Duration for the Lake Washington Site–Five-Well Configuration

Table 5. Hydrologic Units and Characteristics at the Titusville Site

Characteristics of Upper Confining Unit:	
1. Top of Hawthorn layer	-50 (ft-msl)
2. Bottom of Hawthorn layer	-100 (ft-msl)
3. Thickness of Hawthorn layer	50 (ft)
4. Average leakance of confined Hawthorn layer	0.000065 (1/day)
5. Vertical hydraulic conductivity of Hawthorn unit	0.00325 (ft/day)
6. Horizontal hydraulic conductivity of Hawthorn unit	0.065 (ft/day)
Characteristics of Upper Floridan Aquifer:	
7. Top of Upper Floridan aquifer	-100 (ft-msl)
8. Bottom of Upper Floridan aquifer	-500 (ft-msl)
9. Total depth of Upper Floridan aquifer	400 (ft)
10. Transmissivity based on data (Williams, 1995)	60,000 (ft2/day)
11. Average horizontal hydraulic conductivity	150.00 (ft/day)
12. Vertical hydraulic conductivity (assuming 1 to 20 ratio)	7.50 (ft/day)
Characteristics of Middle Semiconfining Unit:	
13. Top of middle confining unit	-500 (ft-msl)
14. Bottom of middle confining unit	-1,000 (ft-msl)
15. Total depth of Upper Floridan aquifer	500 (ft)
16. Transmissivity (Williams, 1995)	2.50E+02 (ft2/day)
17. Average horizontal hydraulic conductivity	0.5 (ft/day)
18. Vertical hydraulic conductivity= leakance depth	0.025 (ft/day)
Characteristics of Lower Floridan Aquifer:	
19. Top of Lower Floridan aquifer	-1,000 (ft-msl)
20. Bottom of Lower Floridan aquifer	-2,480 (ft-msl)
21. Total depth of Lower Floridan aquifer	1480 (ft)
22. Transmissivity (Tibbals,1990)	60,000 (ft2/day)
23. Average horizontal hydraulic conductivity	40.54 (ft/day)
24. Vertical hydraulic conductivity (assuming 1 to 20 ratio)	2.03 (ft/day)

Note: Based on GIS data provided by SJRWMD and Williams, 1995.

hydrologic units based on the GIS database, and the associated hydraulic parameter values (Williams, 1995). The average elevations of the 250; 1,000; and 5,000 mg/L isochlors at the study site are located about -95, -200, and -200 feet NGVD (Figure 21). The following text discusses the results of the sharp interface upconing model and a three-dimensional numerical model.

The site-specific parameters required for the analytical model were determined as follows. Based on the GIS database, the thickness of the aquifer above the assumed interface at the bottom of the Upper Floridan aquifer is b = 500 feet. In addition, d = 100 feet, l = 200 feet, d/b = 0.20, and l/b = 0.40. The Kz/Kr ratio is assumed to be 0.10, the transmissivity for the Upper Floridan aquifer is 60,000 ft^2/day, and the leakance of the upper confining bed is assumed to be 6.5E-05/day.

The modified analytical upconing model (Motz, 1992) was applied by using three chloride concentrations (5,000; 7,500; and 9,500 mg/L) as the sources of brackish water in the aquifer system. The purpose of the analytical model was to investigate drawdowns and changes in chloride concentrations at the pumping well due to three pumping rates applied to a single partially penetrating production well. Three chloride concentrations (5,000; 7,500; and 9,500 mg/L) were assumed at the bottom of the Upper Floridan aquifer to represent the freshwater/saltwater interface for the analytical model. The simulated responses of the interface as a result of the 750-; 1,000-; and 1,250-gpm pumping scenarios were evaluated (Table 6). Figure 22 shows the relationship between upconing height and pumping scenarios for the three assumed chloride concentrations at the interface. Table 6 and Figure 22 indicate that the rise of the interface for the 5,000-mg/L chloride concentration is higher than the rise for the 9,500-mg/L chloride concentration.

Numerical Modeling

The numerical upconing model was used to evaluate the chloride concentration distribution in the pumping zone and at the wells in response to three pumping rates under a transient pumping condition. The pumping duration for this numerical modeling is divided into 5, 10, 15, and 20 years. The available information at the Titusville site (Table 5) was used in this numerical upconing modeling study.

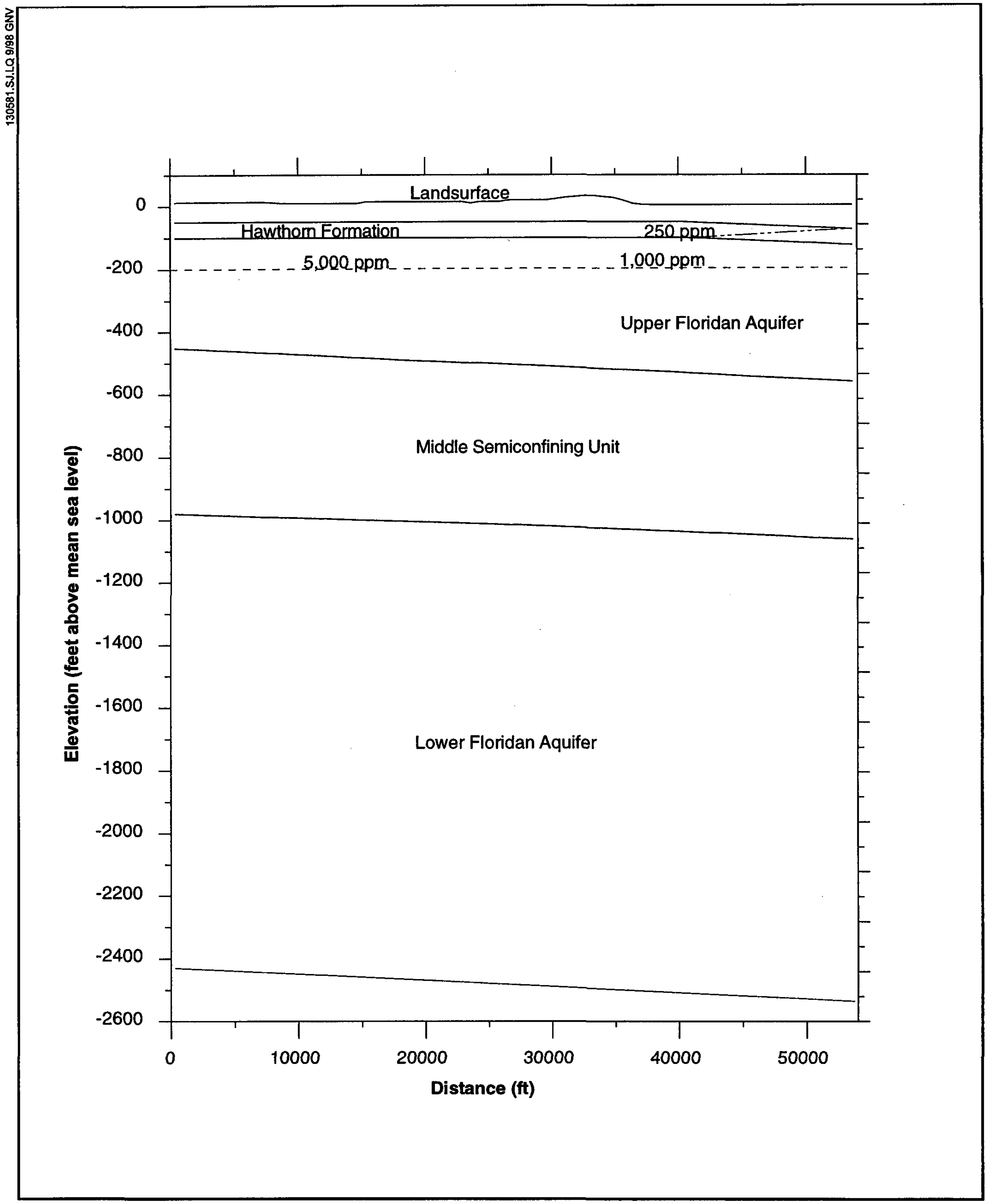

Figure 21. Typical Cross Section at the Titusville Site

Table 6. Interface Upconing Height vs. Pumping Rate, Titusville Site

Q (gpm)	Drawdown (ft)	Upconing Height (ft)		
		9,500 mg/L	7,500 mg/L	5,000 mg/L
750	1.57	129	163.4	245.2
1,000	2.10	172	217.9	326.8
1,250	2.62	215	272.4	408.6

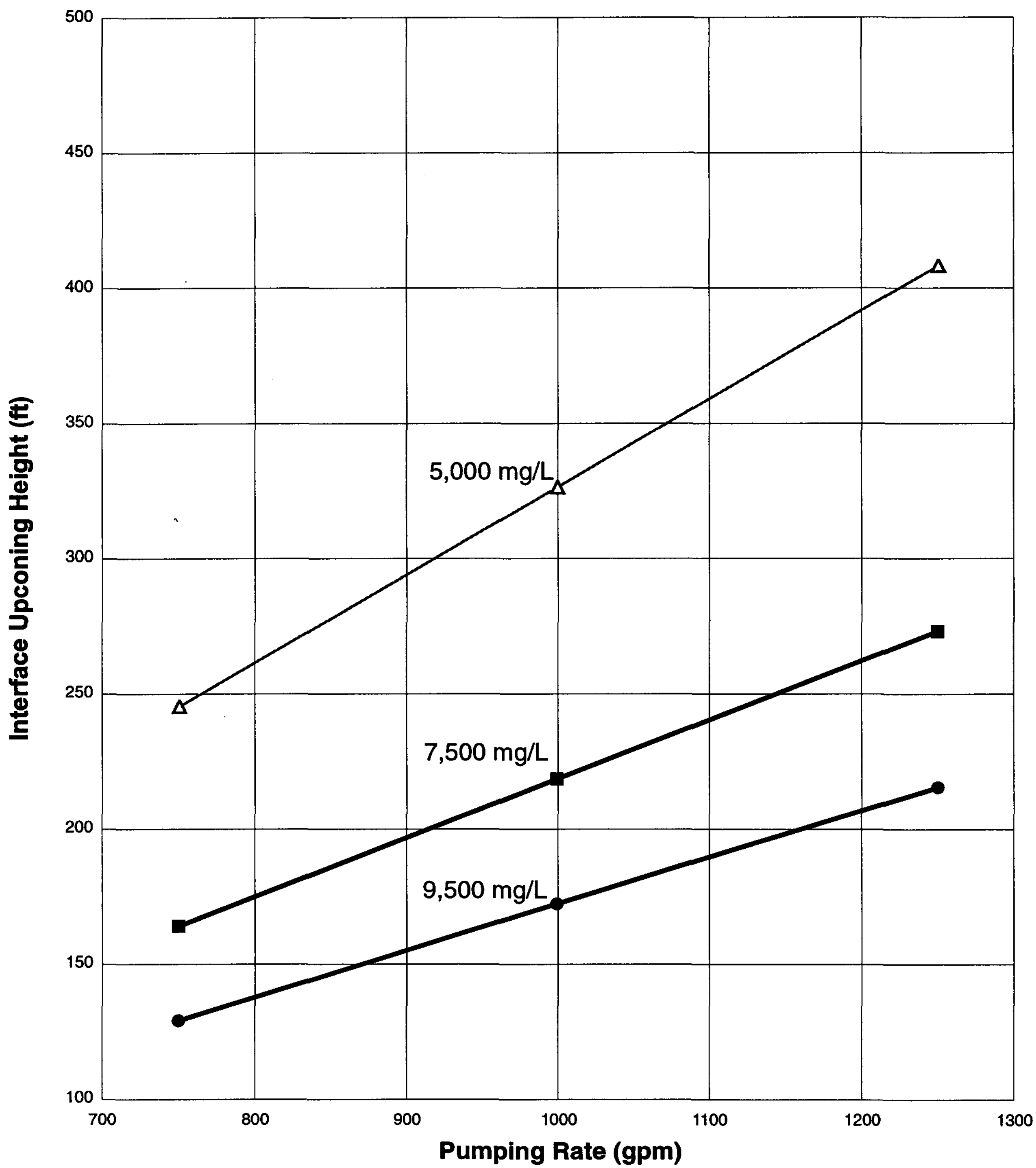

Figure 22. Interface Upconing Height vs. Pumping Rate for the Titusville Site

The average thickness of the upper confining bed is about 50 feet, and the average leakance is about 6.50E-05/day. It was determined that the vertical hydraulic conductivity for the upper confining bed is about 0.065 ft/day. The transmissivity is reported to range from 35,000 to 100,000 ft^2/day (Tibbals, 1990). An average transmissivity value of 60,000 ft^2/day was used to represent the Upper Floridan aquifer in the model. The total thickness of about 400 feet in the Upper Floridan aquifer was divided into three layers — the upper layer (BU), the pumpage layer (BP), and the lower layer (BL) in the upconing model. The partially penetrating production well consists of the upper freshwater zone, BU, of 100 feet; the screened layer, BP, of 100 feet; and the lower water zone, BL, of 200 feet from the bottom of the production to the top of the middle confining bed. This is a conceptual well design used in the upconing model for this study site.

Figure 21 shows the vertical profile representing the aquifer hydrologic units used in the numerical model. Three well configuration scenarios — one well, three wells, and five wells — were evaluated to determine the responses of the aquifer system and chloride concentration distribution in the pumping layer, and at the production wells, for these three scenarios. The space between two wells in the well configuration is 2,500 feet. The diameter of the well is 12 inches. Three pumping rates of 750; 1,000; and 1,250 gpm were used to evaluate the pumpage effects on chloride concentration distributions. The results of the upconing analysis for various pumpages and pumping durations are discussed in the following text.

Table 7 presents the results of the upconing model for the three pumping rates at 5, 10, 15, and 20 years pumping duration for three well configuration scenarios. The largest drawdowns at the production wells for the one-, three-, and five-well configurations during 20 years of continuous pumping at 1,250 gpm are 2.7, 4.9, and 6.5 feet respectively. The potential maximum rise of the lower-quality ground water beneath the production wells for these three scenarios for 20 years pumping duration range from 31.1 feet to 105.4 feet. The simulated average chloride concentrations at the production well range from 100.0 mg/L to 247.3 mg/L.

Figure 23 shows the change in chloride concentration at the production wells versus 5, 10, 15, and 20 years pumping duration for the one-well configuration under the 750-; 1,000-; and 1,250-gpm pumpages. The average chloride concentration at the production well at the end of 20 years of pumpage at 1,250 gpm is 100.0 mg/L.

Table 7. Titusville Chloride Concentration vs. Pumpage and Pumping Period

Time (yrs)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)
	One-well configuration											
5	1,073,580	1.6	0	250	1,440,000	2.2	0	250	1,800,000	2.7	0	250
10	1,073,580	1.6	0.1	250	1,440,000	2.2	2.1	250	1,800,000	2.7	5.3	250
15	1,073,580	1.6	3.5	250	1,440,000	2.2	9.4	250	1,800,000	2.7	16.7	250
20	1,073,580	1.6	9.3	250	1,440,000	2.2	19.4	250	1,800,000	2.7	31.1	250.2
	Three-well configuration											
5	1,073,580	2.9	1.1	250	1,440,000	3.9	3.7	250	1,800,000	4.9	6.9	250
10	1,073,580	2.9	10.6	250	1,440,000	3.9	19.3	250	1,800,000	4.9	28.8	250
15	1,073,580	2.9	23.7	250	1,440,000	3.9	39.2	250	1,800,000	4.9	56	289.9
20	1,073,580	2.9	38.9	250	1,440,000	3.9	61.9	330.2	1,800,000	4.9	86.8	649.9
	Five-well configuration											
5	1,073,580	3.9	2.3	250	1,440,000	5.2	5.8	250	1,800,000	6.5	9.9	250
10	1,073,580	3.9	14.5	250	1,440,000	5.2	25	250	1,800,000	6.5	36.5	250
15	1,073,580	3.9	30.4	250	1,440,000	5.2	48.9	251.6	1,800,000	6.5	68.9	351
20	1,073,580	3.9	48.5	251.2	1,440,000	5.2	75.9	439.2	1,800,000	6.5	105.4	1027.3

Note: Well space = 2,500 ft

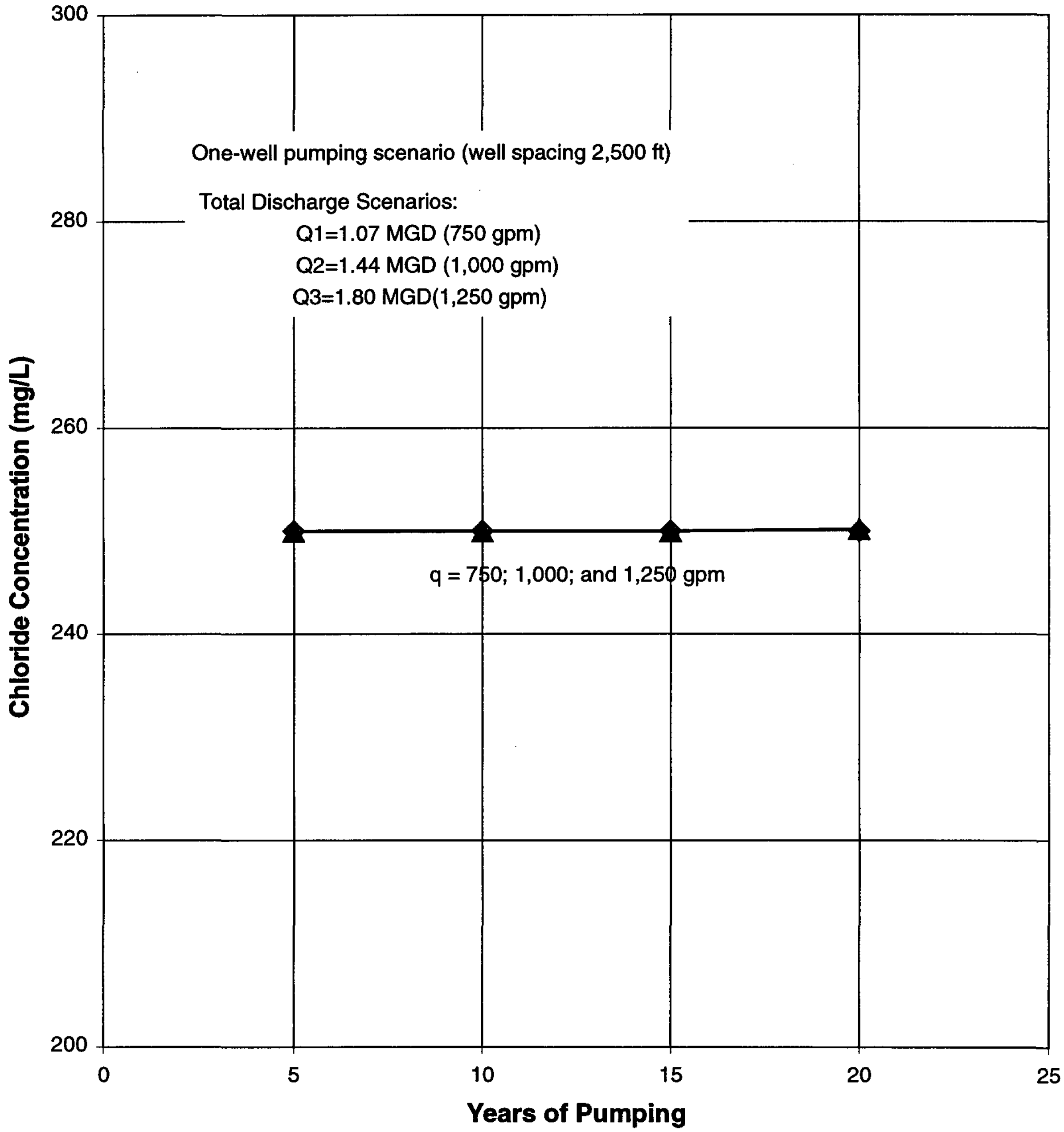

Figure 23. Chloride Concentration as a Function of Pumping Duration for the Titusville Site–One-Well Configuration

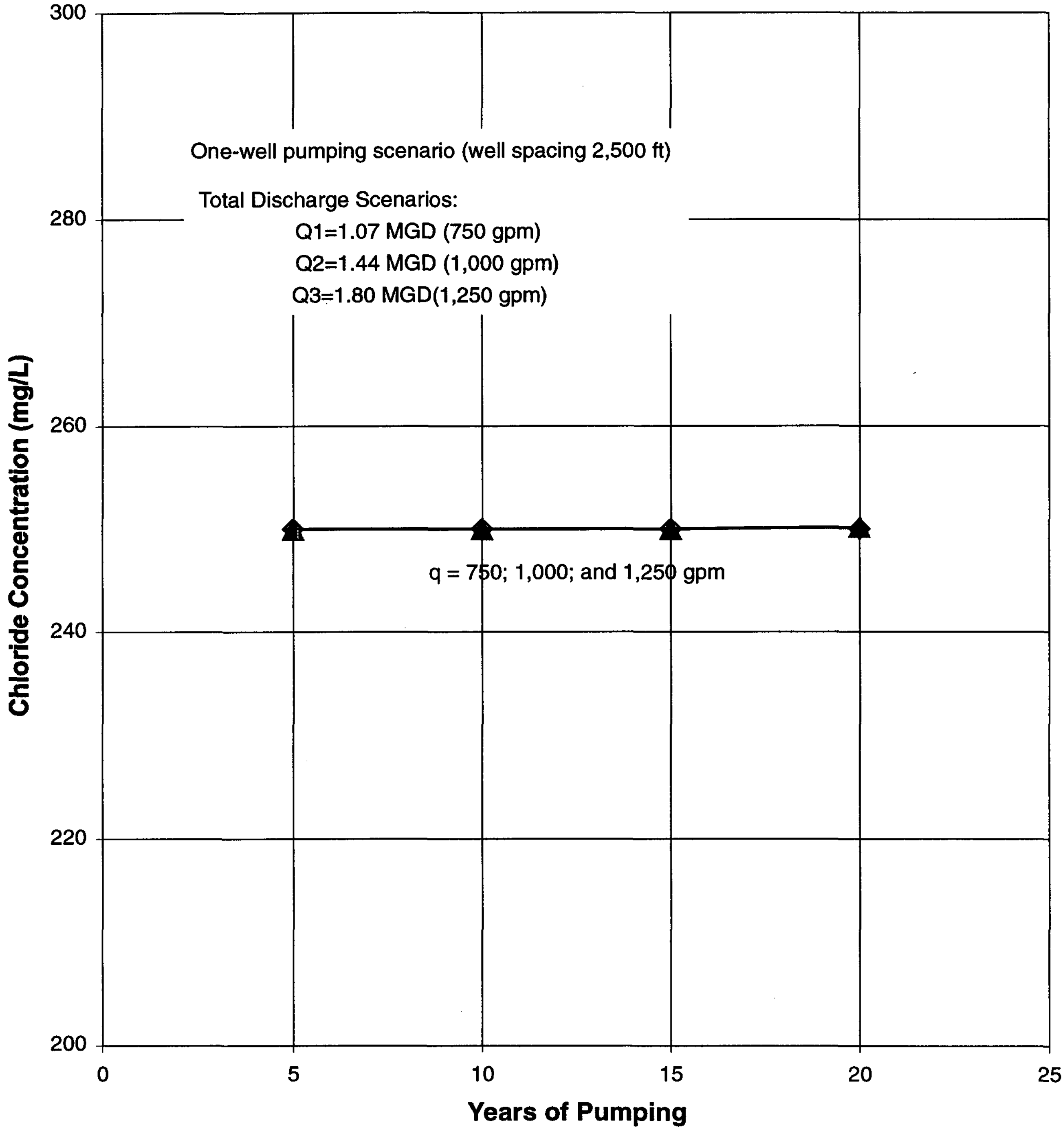

Figure 23. Chloride Concentration as a Function of Pumping Duration for the Titusville Site–One-Well Configuration

Figure 24 shows the changes in chloride concentration at the production well versus 5, 10, 15, and 20 years pumping duration for the three-well configurations under the 750-; 1,000-; and 1,250-gpm pumpages. The average chloride concentration at the discharge point at the end of the 20 years pumpage of 1,250 gpm is 175.8 mg/L.

Figure 25 shows the changes in chloride concentration at the production well versus 5, 10, 15, and 20 years pumping duration for the five-well configurations under the 750-; 1,000-; and 1,250-gpm pumpages. The average chloride concentration at the discharge point at the end of the 20 years pumpage of 1,250 gpm is 247.3 mg/L.

EAST ORANGE COUNTY SITE

Analytical Modeling

Based on SJRWMD's GIS database, the geologic units at the East Orange County site form a hydrologic system consisting of a surficial aquifer system, an intermediate confining unit, and the Floridan aquifer system. The Floridan aquifer system in the study area has been divided into three zones — the Upper Floridan aquifer, a middle confining layer, and the Lower Floridan aquifer. Table 8 presents the average elevations of the hydrologic units, based on the GIS database, and the associated hydraulic parameter values (Tibbals, 1990). The average elevations of the chloride isochlors with concentrations of 250; 1,000; and 5,000 mg/L at the study site are located about -88.3, -686.6, and -1051.0 feet NGVD. The following text discusses the results using the sharp interface upconing model and a three-dimensional numerical model.

The site-specific parameters required for the analytical model were determined as follows. Based on the GIS database, the thickness of the aquifer above the assumed interface line at the bottom of the Upper Floridan aquifer is b = 450 feet. In addition, d = 100 feet, l = 200 feet, d/b = 0.25, and l/b = 0.45. The Kz/Kr ratio is assumed to be 0.10, the transmissivity for the Upper Floridan aquifer is 60,000 ft^2/day, and the leakance of the upper confining bed is assumed to be 1.0E-04/day.

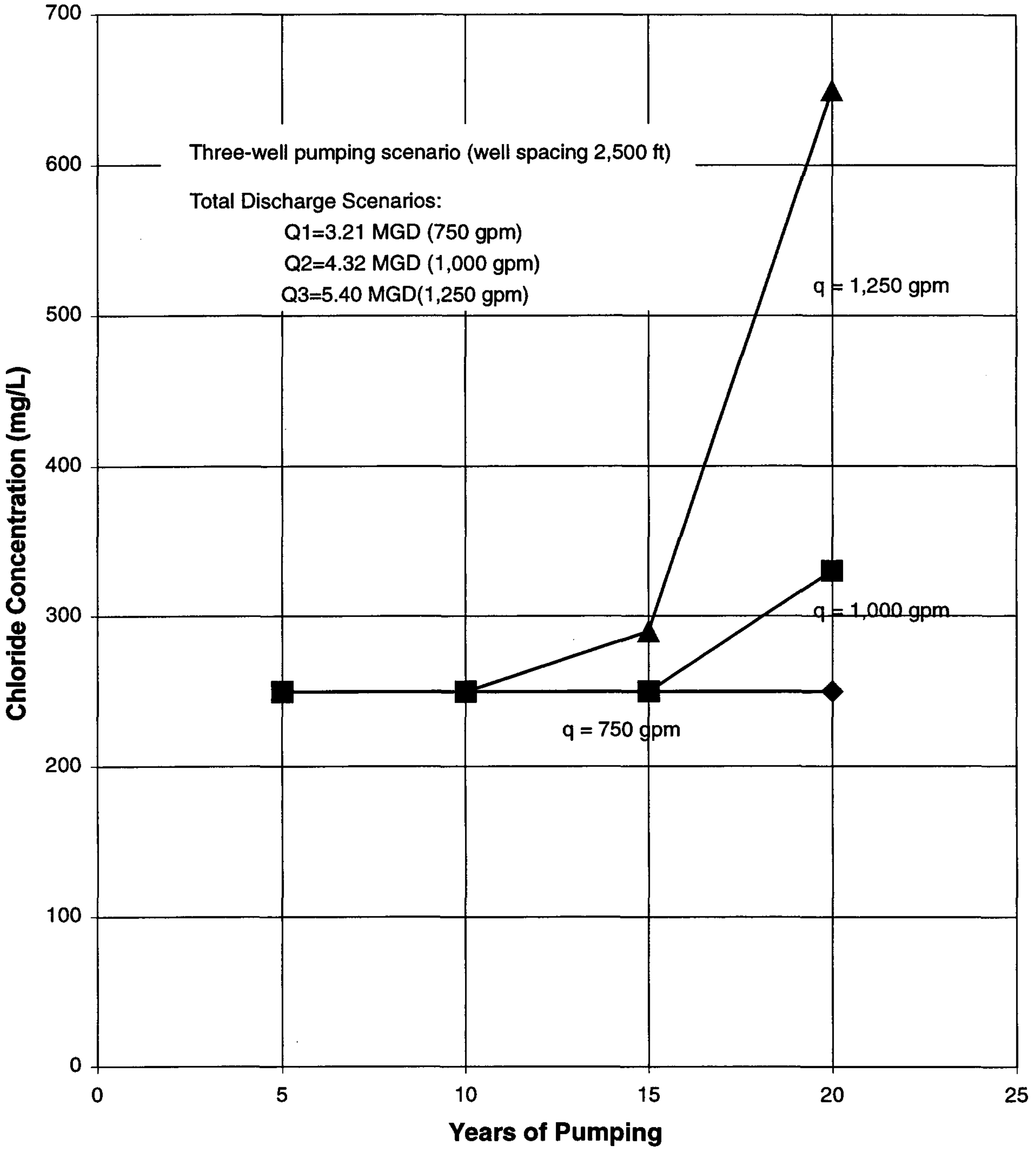

Figure 24. Chloride Concentration as a Function of Pumping Duration for the Titusville Site–Three-Well Configuration

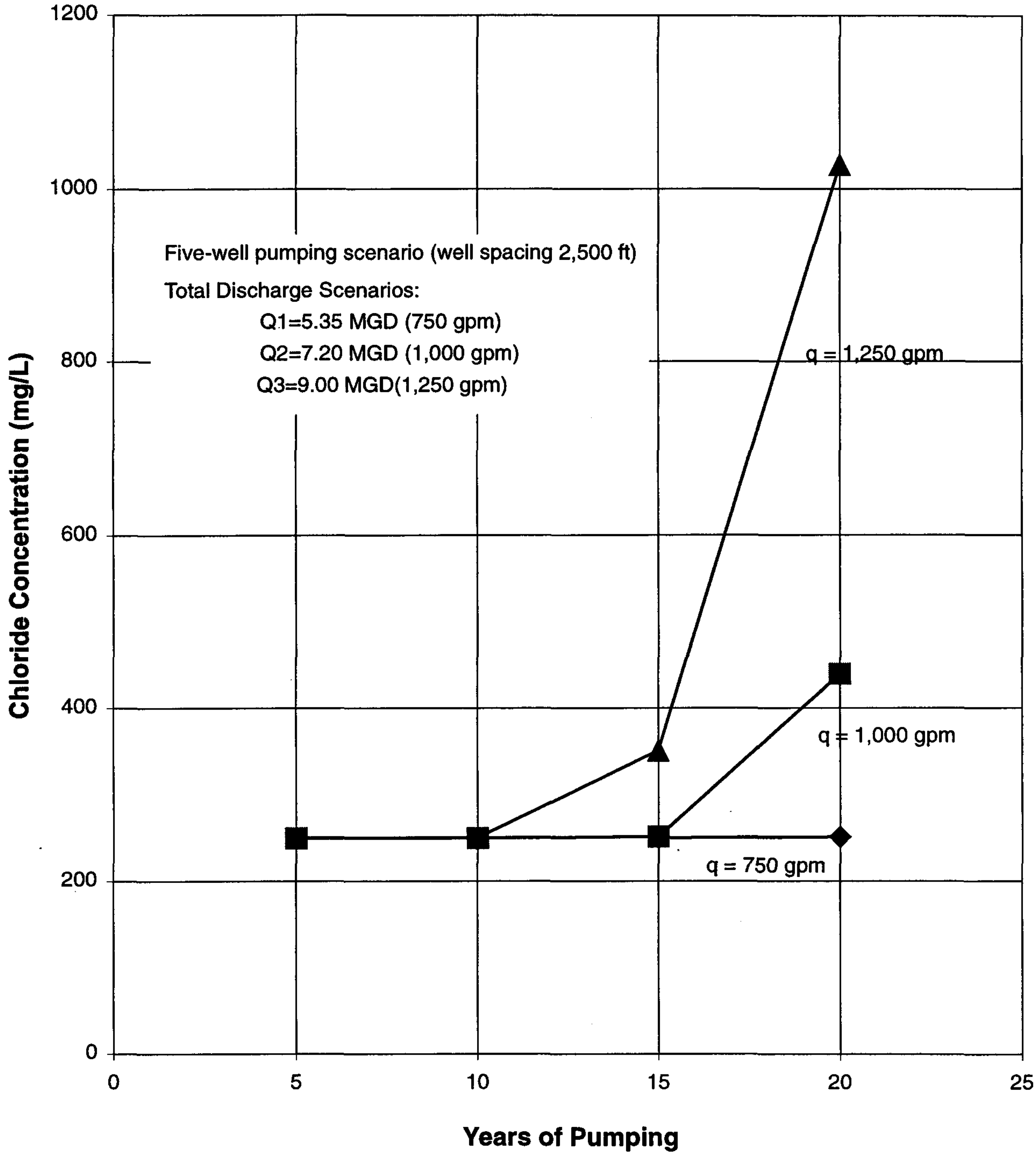

Figure 25. Chloride Concentration as a Function of Pumping Duration for the Titusville Site–Five-Well Configuration

Table 8. Hydrologic Units and Aquifer Characteristics at the East Orange County Site

Characteristics of Intermediate Confining Unit:	
1. Top of Hawthorn layer	-10 (ft-msl)
2. Bottom of Hawthorn layer	-135 (ft-msl)
3. Thickness of Hawthorn layer	125 (ft)
4. The average leakance of confined Hawthorn layer	0.0001 (1/day)
5. Vertical hydraulic conductivity of Hawthorn unit	0.0125 (ft/day)
6. Horizontal hydraulic conductivity of Hawthorn unit	1.25 (ft/day)
Characteristics of Upper Floridan Aquifer:	
7. Top of Upper Floridan aquifer	-135 (ft-msl)
8. Bottom of Upper Floridan aquifer	-635 (ft-msl)
9. Total depth of Upper Floridan aquifer	500 (ft)
10. Transmissivity based on data (Phelps and Schiffer, 1996)	100,000 (ft2/day)
11. Average horizontal hydraulic conductivity (Phelps and Schiffer, 1996)	200.00 (ft/day)
12. Vertical hydraulic conductivity (assuming 1 to 100 ratio)	2.00 (ft/day)
Characteristics of Middle Semiconfining Unit:	
13. Top of middle confining unit	-635 (ft-msl)
14. Bottom of middle confining unit	-1,180 (ft-msl)
15. Total depth of Upper Floridan aquifer	545 (ft)
16. Transmissivity	2.97E+02 (ft2/day)
17. Average horizontal hydraulic conductivity	0.545 (ft/day)
18. Vertical hydraulic conductivity (assuming 1 to 20 ratio)	0.02725 (ft/day)
Characteristics of Lower Floridan Aquifer:	
19. Top of Lower Floridan aquifer	-1,180 (ft-msl)
20. Bottom of Lower Floridan aquifer	-2,680 (ft-msl)
21. Total depth of Lower Floridan aquifer	1,500 (ft)
22. Transmissivity	N/A
23. Average horizontal hydraulic conductivity	N/A
24. Vertical hydraulic conductivity (assuming 1 to 20 ratio)	N/A

Note: Based on GIS data provided by SJRWMD and Phelps and Schiffer, 1996.

The modified analytical upconing model (Motz, 1992) was applied using three chloride concentrations (5,000; 7,500; and 9,500 mg/L) as the sources of chloride in the aquifer system. The purpose of the analytical model was to investigate drawdowns and the changes of chloride concentrations at the pumping well due to three pumping rates applied to a single partially penetrating production well. Three chloride concentrations (5,000; 7,500; and 9,500 mg/L) were assumed at the bottom of the Upper Floridan aquifer to represent the freshwater/saltwater interface for the analytical model. The simulated responses of the interface as a result of the 750-; 1,000-; and 1,250-gpm pumping scenarios were evaluated (Table 9). Figure 26 shows the relationship between the upconing height and the pumping scenarios for the three assumed chloride concentrations at the interface. Table 9 and Figure 26 indicate that the rise of the interface for the 5,000-mg/L chloride concentration is higher than the rise for the 9,500-mg/L chloride concentration.

Numerical Modeling

The numerical upconing model was used to evaluate the chloride concentration distribution in the pumping zone and at the wells in response to various pumping rates under transient pumping conditions. The pumping duration for this numerical modeling is divided into 5, 10, 15, and 20 years. The available information at the East Orange County site (Table 8) was used in this numerical upconing modeling study.

The average thickness of the intermediate confining bed is about 125 feet, and the average leakance is about 1.00E-04/day. It was determined that the vertical hydraulic conductivity for the intermediate confining bed is about 0.0125 ft/day. The transmissivity is reported to range from 74,000 to 210,000 ft^2/day (Tibbals and Frazee, 1976). An average transmissivity with a value of 100,000 ft^2/day was used to represent the Upper Floridan aquifer in the model. The total thickness of about 450 feet in the Upper Floridan aquifer was divided into three layers — the upper layer (BU), the pumpage layer (BP), and the lower layer (BL) in the upconing model. The partially penetrating production well consists of the upper freshwater zone, BU, of 100 feet; the screened layer, BP, of 100 feet; and the lower water zone, BL, of 250 feet, from the bottom of the production to the top of the middle confining. This is a conceptual well design used in the upconing model for this study site.

Table 9. Interface Upconing Height vs. Pumping Rate, East Orange County Site

Q (gpm)	Drawdown (ft)	Upconing Height (ft)		
		9,500 mg/L	7,500 mg/L	5,000 mg/L
750	1.03	84.7	107.1	160.9
1,000	1.38	112.9	143	214.5
1,250	1.72	141.2	178.8	268.2

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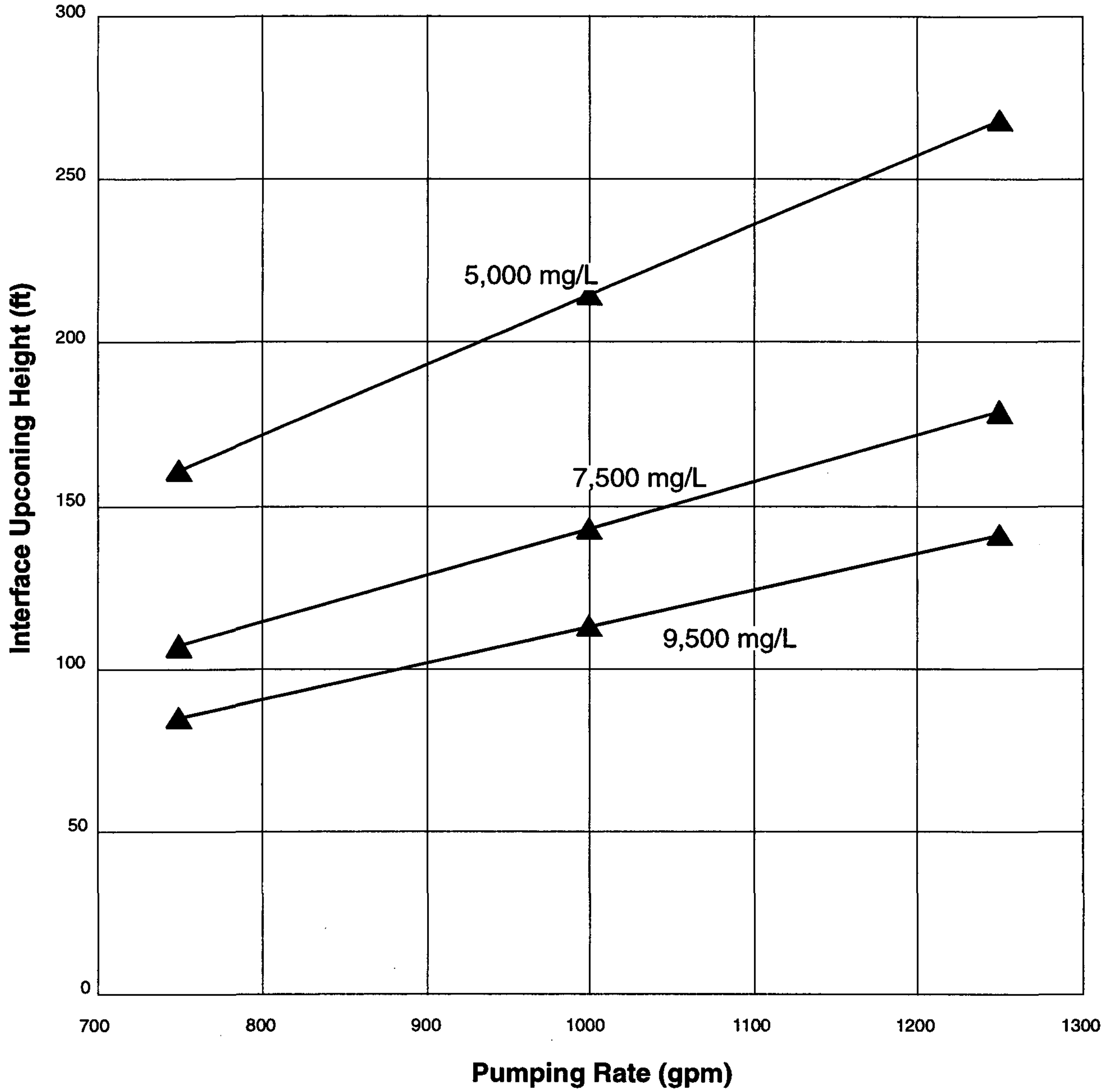

Figure 26. Interface Upconing Height vs. Pumping Rate for the East Orange County Site

Figure 27 shows the vertical profile representing the aquifer hydrologic units used in the numerical model. Three well configuration scenarios — one well, three wells, and five wells — were evaluated to determine the responses of the aquifer system and the chloride distribution in the pumping layer, and at the production wells, for these three scenarios. The space between two wells in the well configuration is 2,500 feet. The diameter of the well is 12 inches. Three pumping rates (750; 1,000; and 1,250 gpm) were used to evaluate the pumpage effects on chloride concentration. The results of upconing for various pumpages and pumping duration are described in the following text.

Table 10 presents the results of the upconing model for the three pumping rates at 5, 10, 15, and 20 years pumping duration for three well configuration scenarios. The largest drawdowns at the production well for these three well configurations during continuous pumping at 1,250 gpm are 2.0, 3.6, and 4.8 feet respectively. The upconing of lower quality ground water beneath the production wells for these three scenarios during the 20-year pumping duration range from 32.3 feet to 120.6 feet. The simulated average chloride concentrations at the production wells for these three scenarios for the 20-year pumping duration range from 190.8 mg/L to 443.3 mg/L.

Figure 28 shows the changes in chloride concentration at the production wells versus 5, 10, 15, and 20 years pumping duration for the one-well configuration under the 750-; 1,000-; and 1,250-gpm pumpages. The average chloride concentration at the production well at the end of 20 years of pumpage of 1,250 gpm is 190.8 mg/L.

Figure 29 shows the changes in average chloride concentration at the production wells versus 5, 10, 15, and 20 years pumping for the three-well configurations under the 750-; 1,000-; and 1,250-gpm pumpages. The average chloride concentration at the discharge well at the end of 20 years of pumpage at 1,250 gpm is 353.8 mg/L.

Figure 30 presents the changes in average chloride concentrations at the production wells versus 5, 10, 15, and 20 years of pumping for the five-well configurations under the 750-; 1,000-; and 1,250-gpm pumpages. The average chloride concentration at the production well at the end of 20 years of pumpage at 1,250 gpm is 443.3 mg/L.

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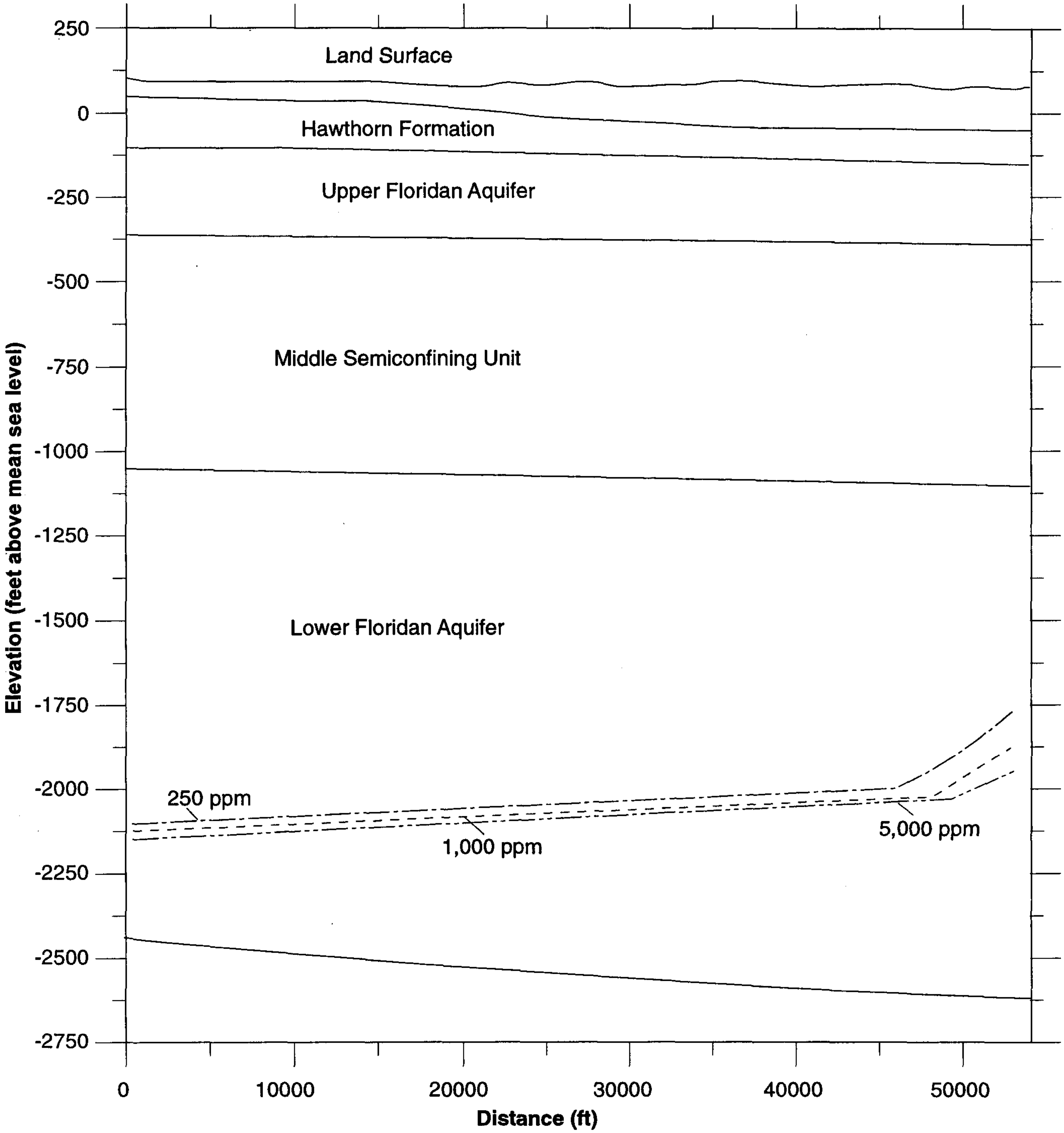

Figure 27. Typical Cross Section for the East Orange County Site

Table 10. East Orange County Chloride Concentration vs. Pumping Rate and Duration

Time (yrs)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)
	One-well configuration											
5	1,073,580	1.2	0	150	1,440,000	1.6	0	150	1,800,000	2	0	150
10	1,073,580	1.2	0	150	1,440,000	1.6	0.7	150	1,800,000	2	3.6	150
15	1,073,580	1.2	1.9	150	1,440,000	1.6	7.8	150	1,800,000	2	15.8	150.7
20	1,073,580	1.2	7.7	150	1,440,000	1.6	18.8	153.8	1,800,000	2	32.3	190.8
	Three-well configuration											
5	1,073,580	2.1	0.4	150	1,440,000	2.9	2.4	150	1,800,000	3.6	5.6	150
10	1,073,580	2.1	9.6	150	1,440,000	2.9	19.3	150	1,800,000	3.6	30.4	151.9
15	1,073,580	2.1	24.5	150.1	1,440,000	2.9	42.5	165.5	1,800,000	3.6	62.4	214
20	1,073,580	2.1	42.1	164.8	1,440,000	2.9	69.4	238.4	1,800,000	3.6	99.1	353.8
	Five-well configuration											
5	1,073,580	2.9	1.1	150	1,440,000	3.8	4.3	150	1,800,000	4.8	8.7	150
10	1,073,580	2.9	13.7	150	1,440,000	3.8	25.7	150	1,800,000	4.8	39	155.2
15	1,073,580	2.9	31.8	150.7	1,440,000	3.8	53.5	182.7	1,800,000	4.8	77.1	263
20	1,073,580	2.9	53	181.4	1,440,000	3.8	85.5	296.9	1,800,000	4.8	120.6	443.3

Note: Well space = 2,500 ft

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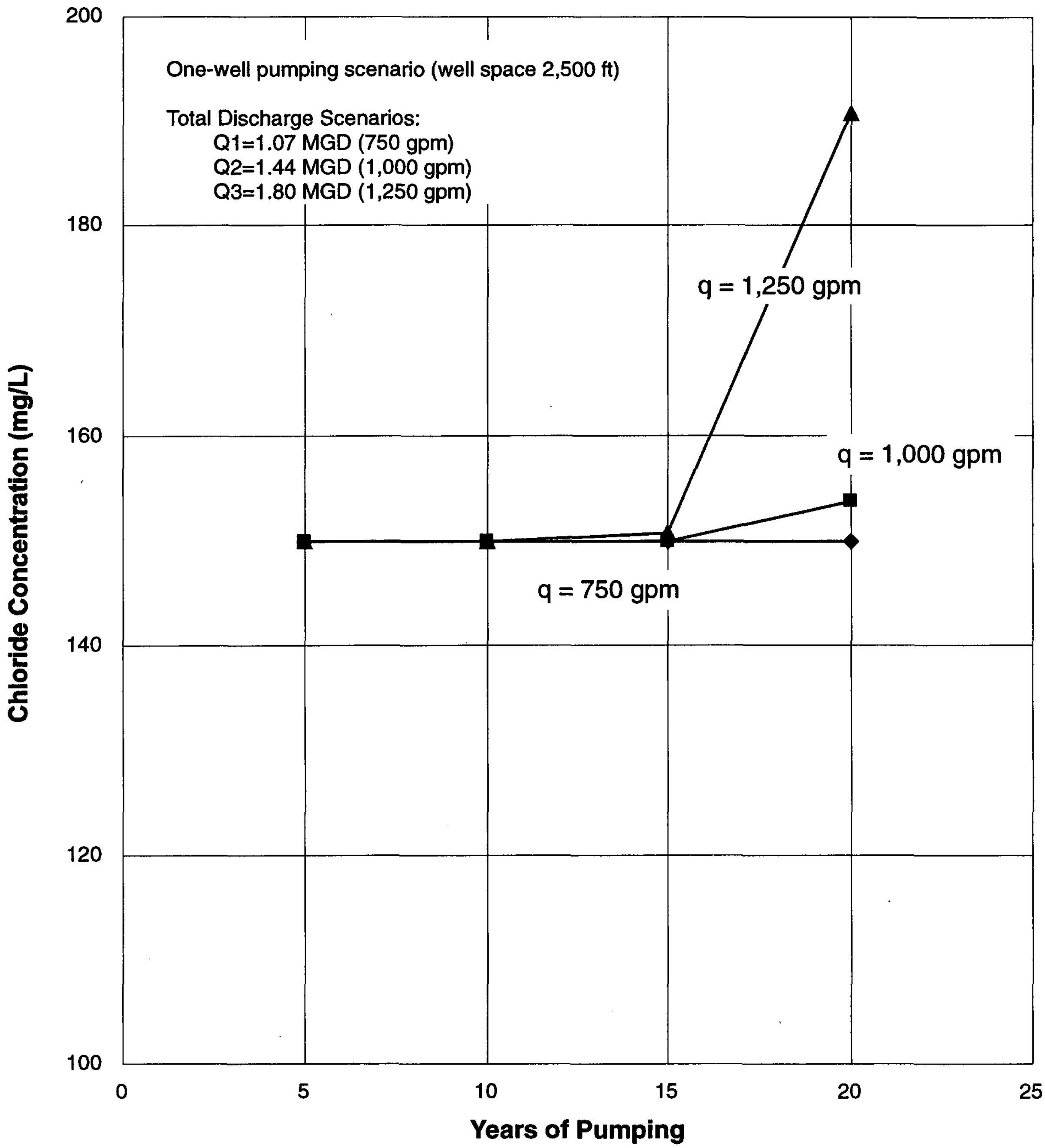

Figure 28. Chloride Concentration as a Function of Pumping Duration for the East Orange County Site–One-Well Configuration

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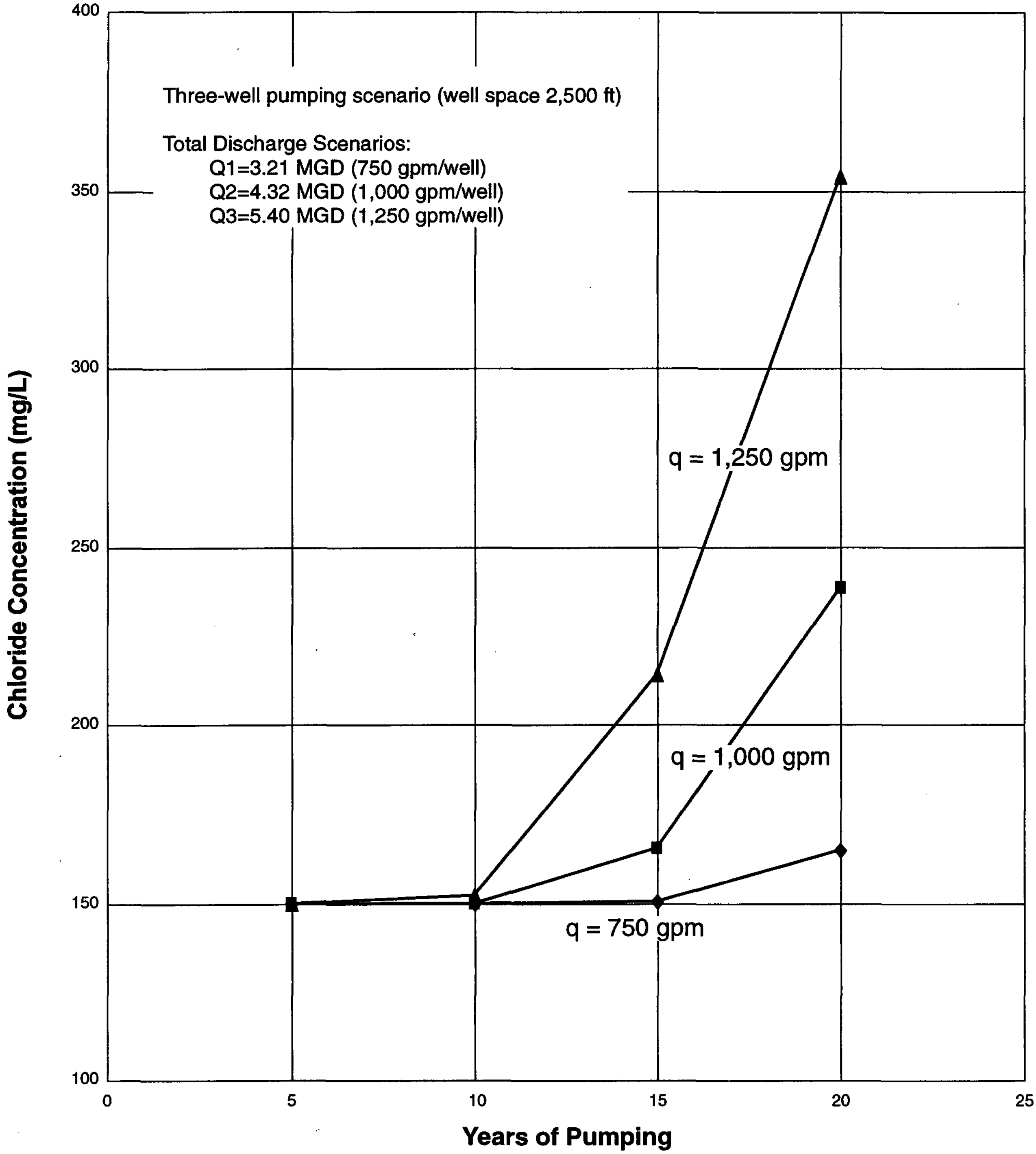

Figure 29. Chloride Concentration as a Function of Pumping Duration for the East Orange County Site–Three-Well Configuration

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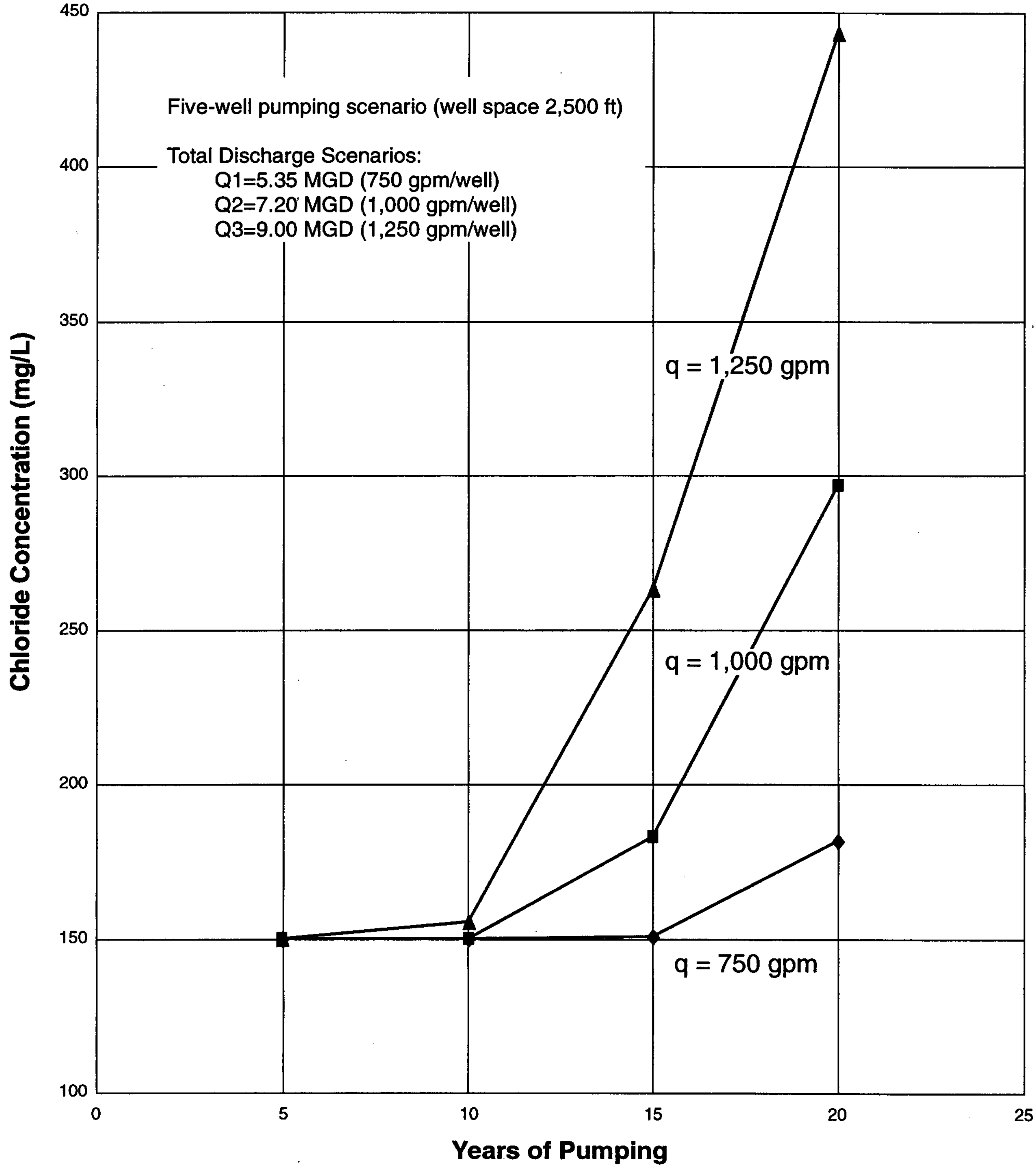

Figure 30. Chloride Concentration as a Function of Pumping Duration for the East Orange County Site–Five-Well Configuration

VOLUSIA SITE

Analytical Modeling

Based on SJRWMD's GIS database, the geologic units at the Volusia site form a hydrologic system consisting of a surficial aquifer system, an intermediate confining unit, and the Floridan aquifer system. The Floridan aquifer system in the study area has been divided into three zones — the Upper Floridan aquifer, a middle confining layer, and the Lower Floridan aquifer. Table 11 presents the average elevations of the hydrologic units based on GIS database, and the associated hydraulic parameter values (Williams, 1995). The average elevations of the chloride isochlors with concentrations of 250; 1,000; and 5,000 mg/L at the study site are located about -798, -920.1, and -937.1 feet NGVD. The following text discusses the results using the sharp interface upconing model.

The site-specific parameters required for the analytical model were determined as follows. Based on GIS database and published reports, the required input data for the analytical upconing model (Figure 10) are b = 350 feet, d = 100 feet, l = 200 feet, d/b = 0.35, and l/b = 0.60. The Kz/Kr ratio is assumed to be 0.10, the transmissivity for the Upper Floridan aquifer is 58,000 ft^2/day, and the leakance of the upper confining bed is assumed to be 1.5E-05/day.

The modified analytical upconing model (Motz, 1992) was applied using three chloride concentrations (5,000; 7,500; and 9,500 mg/L) as the sources of chloride in the aquifer system. The purpose of the analytical model was to investigate drawdowns and the changes of chloride concentrations at the pumping well due to three pumping rates applied to a single partially penetrating production well. Three chloride concentrations (5,000; 7,500; and 9,500 mg/L) were assumed at the bottom of the Upper Floridan aquifer to represent the freshwater/saltwater interface for the analytical model. The simulated movement of the interface as a result of the 750-; 1,000-; and 1,250-gpm pumping scenarios were evaluated (Table 12).

Figure 31 shows the relationship between the upconing height and pumping scenarios for the three assumed chloride concentrations at the interface. Table 12 and Figure 31 indicate that the rise of interface for the 5,000-mg/L chloride concentration is higher than the rise for the 9,500-mg/L concentration.

Table 11. Hydrologic Units and Aquifer Characteristics at the Volusia Site

Characteristics of Intermediate Confining Unit:	
1. Top of Hawthorn layer	15 (ft-msl)
2. Bottom of Hawthorn layer	-30 (ft-msl)
3. Thickness of Hawthorn layer	45 (ft)
4. Average leakance of the confined Hawthorn layer	1.50E-05 (1/day)
5. Vertical hydraulic conductivity of Hawthorn unit	0.000675 (ft/day)
6. Horizontal hydraulic conductivity of Hawthorn unit	0.0675 (ft/day)
Characteristics of Upper Floridan Aquifer:	
7. Top of the Upper Floridan aquifer	-30 (ft-msl)
8. Bottom of the Upper Floridan aquifer	-380 (ft-msl)
9. Total depth of the Upper Floridan aquifer	350 (ft)
10. Transmissivity based on data (Williams, 1997)	58,000 (ft2/day)
11. Average horizontal hydraulic conductivity (Williams, 1997)	165.71 (ft/day)
12. Vertical hydraulic conductivity (assuming 1 to 100 ratio)	1.66 (ft/day)
Characteristics of Middle Semiconfining Unit:	
13. Top of middle confining unit	-380 (ft-msl)
14. Bottom of middle confining unit	-730 (ft-msl)
15. Total depth of Upper Floridan aquifer	350 (ft)
16. Transmissivity	1.23E+02 (ft2/day)
17. Average horizontal hydraulic conductivity	0.35 (ft/day)
18. Vertical hydraulic conductivity (assuming 1 to 20 ratio)	0.0175 (ft/day)
Characteristics of Lower Floridan Aquifer:	
19. Top of Lower Floridan aquifer	-730 (ft-msl)
20. Bottom of Lower Floridan aquifer	-2,170 (ft-msl)
21. Total depth of Lower Floridan aquifer	1,440 (ft)
22. Transmissivity	N/A
23. Average horizontal hydraulic conductivity	N/A
24. Vertical hydraulic conductivity (assuming 1 to 20 ratio)	N/A

Note: Based on GIS data provided by SJRWMD and Williams, 1997

Table 12. Interface Upconing Height vs. Pumping Rate, Volusia Site

Q (gpm)	Drawdown (ft)	Upconing Height (ft)		
		9,500 mg/L	7,500 mg/L	5,000 mg/L
750	1.46	120	152	228
1,000	1.95	160	202.6	303.9
1,250	2.44	200	253.3	379.9

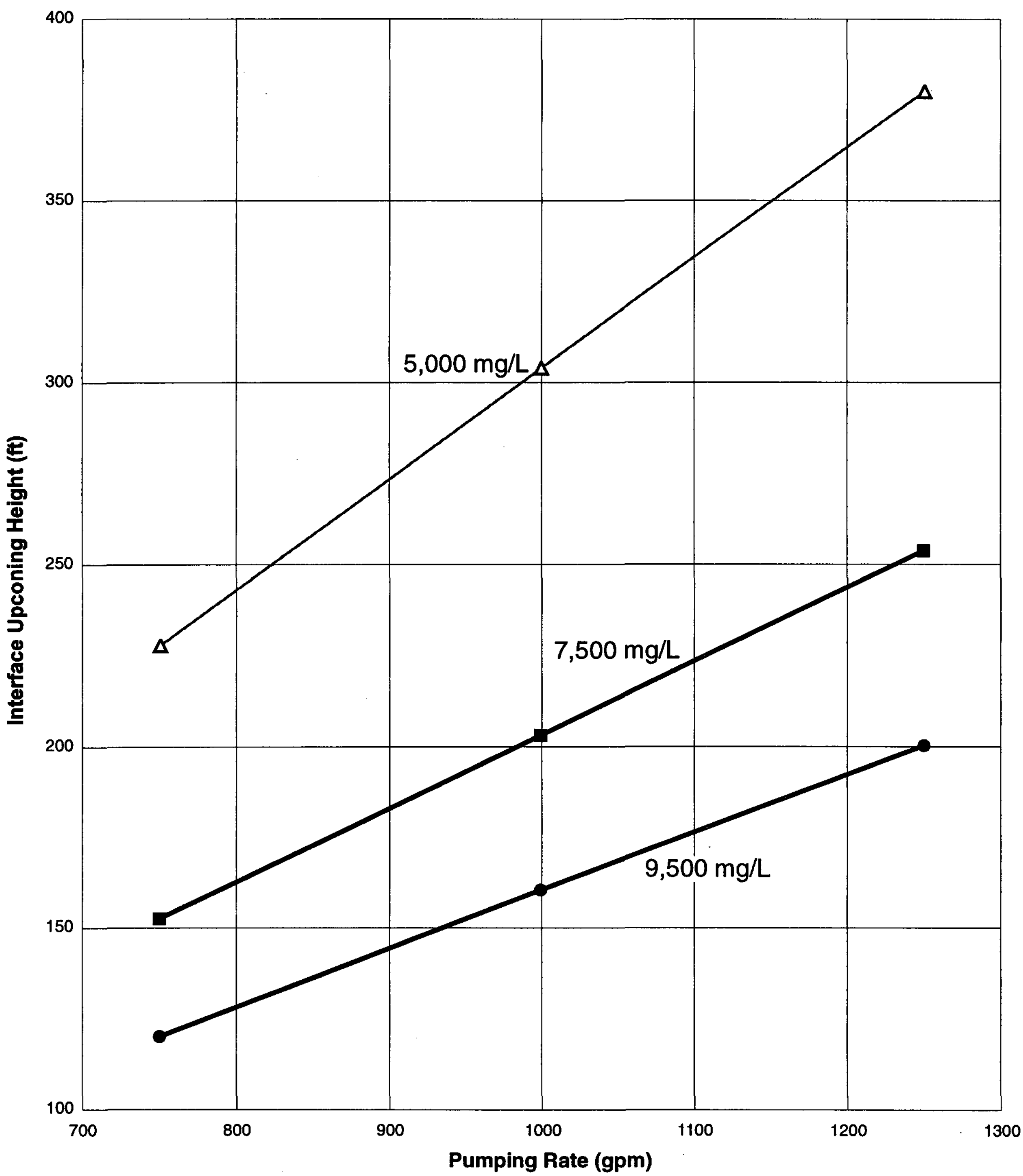

Figure 31. Interface Upconing Height vs. Pumping Rate for the Volusia Site

Numerical Modeling

The numerical upconing model was used to evaluate the chloride concentration distribution in the pumping zone and at the wells in response to various pumping rates under transient pumping conditions. The pumping duration for this numerical modeling is divided into 5, 10, 15, and 20 years. The available information at the Volusia site, summarized in Table 11, was used in this numerical upconing modeling study.

The average thickness of the intermediate confining bed is about 45 feet, and the average leakance is about 1.50E-05/day. It was determined that the vertical hydraulic conductivity for the intermediate confining bed is about 0.0675 ft/day. The transmissivity is reported to range from 10,000 to 100,000 ft^2/day (Phelps and Schiffer, 1996). An average transmissivity value of 58,000 ft^2/day was used to represent the Upper Floridan aquifer in the model. The total thickness of about 350 feet in the Upper Floridan aquifer was divided into three layers — the upper layer (BU), the pumpage layer (BP), and the lower layer (BL) in the upconing model. The partially penetrating production well consists of the upper freshwater zone, BU, of 100 feet; the screened layer, BP, of 100 feet; and the lower water zone BL of 150 feet from the bottom of the production zone to the top of the middle confining layer. This is a conceptual well design used in the upconing model for this study site.

Figure 32 shows the vertical profile representing the aquifer hydrologic units used in the numerical model. Three well configuration scenarios — one well, three wells, and five wells — were evaluated to determine the responses of the aquifer system and chloride distribution in the pumping layer and at the production wells. The space between two wells in the well configuration is 2,500 feet. The diameter of the well is 12 inches. Three pumping rates (750; 1,000; and 1,250 gpm) were used to evaluate the pumpage effects on chloride concentration. The following text discusses the results of upconing for various pumpages and pumping durations.

Table 13 presents the results of the upconing model for the three pumping rates at 5, 10, 15, and 20 years pumping duration for three well configuration scenarios. The largest drawdowns at the production wells for the three well configurations during continuous pumping at 1,250 gpm are 3.4, 5.3, and 7.3 feet. The upconing of the lower quality ground water beneath the production wells for these three scenarios during the 20-year pumping duration range from 94.4 feet to 147.0 feet.

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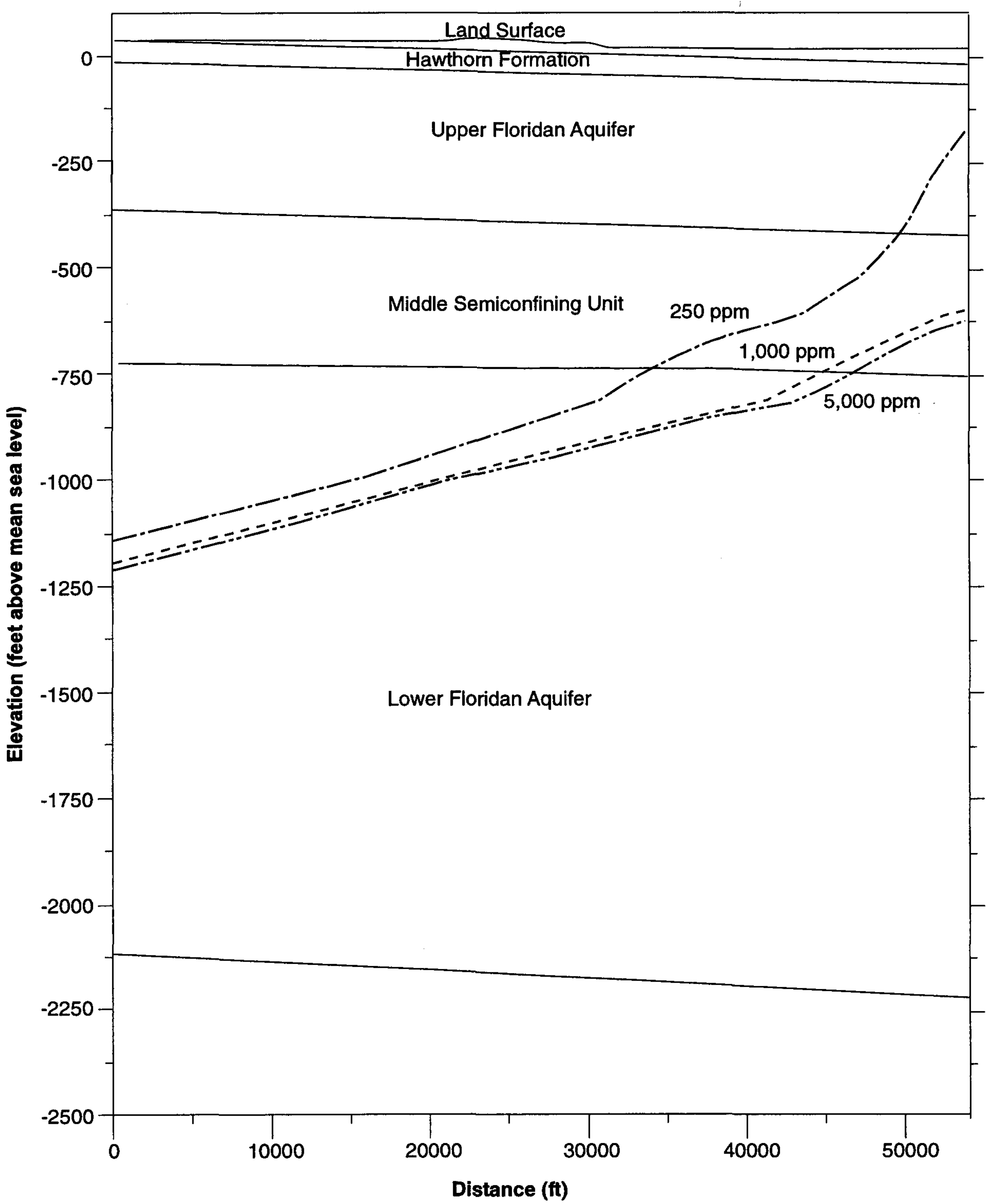

Figure 32. Typical Cross Section at the Volusia Site

Table 13. Volusia Chloride Concentration vs. Pumping Rate and Duration

Time (yrs)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)
	One-well configuration											
5	1,073,580	2	1.1	20	1,440,000	2.7	3.9	20	1,800,000	3.4	7.6	20
10	1,073,580	2	11.8	20	1,440,000	2.7	21.6	20.3	1,800,000	3.4	32.3	27.4
15	1,073,580	2	26.6	22.4	1,440,000	2.7	43.7	43.2	1,800,000	3.4	61.8	74.2
20	1,073,580	2	43.3	42.6	1,440,000	2.7	68.1	85	1,800,000	3.4	94.4	125.8
	Three-well configuration											
5	1,073,580	3.2	5.3	20	1,440,000	4.2	10.5	20	1,800,000	5.3	16.2	20
10	1,073,580	3.2	22.2	20	1,440,000	4.2	35.8	24	1,800,000	5.3	50	38.5
15	1,073,580	3.2	42.5	29.3	1,440,000	4.2	65	63.8	1,800,000	5.3	88.7	110
20	1,073,580	3.2	64.5	62.8	1,440,000	4.2	96.9	125.6	1,800,000	5.3	130.8	183
	Five-well configuration											
5	1,073,580	4.3	6.9	20	1,440,000	5.8	12.8	20	1,800,000	7.3	19.3	20
10	1,073,580	4.3	26.1	20.1	1,440,000	5.8	41.2	26.8	1,800,000	7.3	57.1	48.5
15	1,073,580	4.3	48.7	35.2	1,440,000	5.8	73.9	81.2	1,800,000	7.3	100.2	136.1
20	1,073,580	4.3	73.3	79.9	1,440,000	5.8	109.3	154.1	1,800,000	7.3	147	213.8

Note: Well space = 2,500 ft

The simulated average chloride concentrations at the production well for these three scenarios for the 20-year pumping duration range from 125.8 mg/L to 213.8 mg/L.

Figure 33 shows the changes in average chloride concentration at the production wells versus 5-, 10-, 15-, and 20-year pumping durations for the one-well configuration under the 750-; 1,000-; and 1,250-gpm pumpages. The average chloride concentration at the production well at the end of 20 years of pumpage at 1,250 gpm is 125.8 mg/L.

Figure 34 shows the change in average chloride concentration at the production wells versus 5-, 10-, 15-, and 20-year pumping durations for the three-well configurations under the 750-; 1,000-; and 1,250-gpm pumpages. The average chloride concentration at the production well at the end of 20 years of pumpage at 1,250 gpm is 183.0 mg/L.

Figure 35 shows changes in average chloride concentration at the production well versus 5, 10, 15, and 20 years pumping duration for the five-well configurations under the 750-; 1,000-; and 1,250-gpm pumpages. The average chloride concentration at the production well at the end of 20 years of pumpage at 1,250 gpm is 213.8 mg/L.

ST. JOHNS COUNTY SITE

Analytical Modeling

Based on SJRWMD's GIS database, the geologic units at the St. Johns County site form a hydrologic system consisting of a surficial aquifer system, an intermediate confining unit, and the Floridan aquifer system. The Floridan aquifer system in the study area has been divided into three zones — the Upper Floridan aquifer, a middle confining layer, and the Lower Floridan aquifer. Table 14 presents the average elevations of the hydrologic units based on the GIS database, and the associated hydraulic parameter values (Spechler and Hampson, 1984). The average elevations of the chloride isochlors with concentrations of 250; 1,000; and 5,000 mg/L at the study site are located about -396.6, -986.9, and -1123.1 feet NGVD. The following text discusses the results using the sharp interface upconing model.

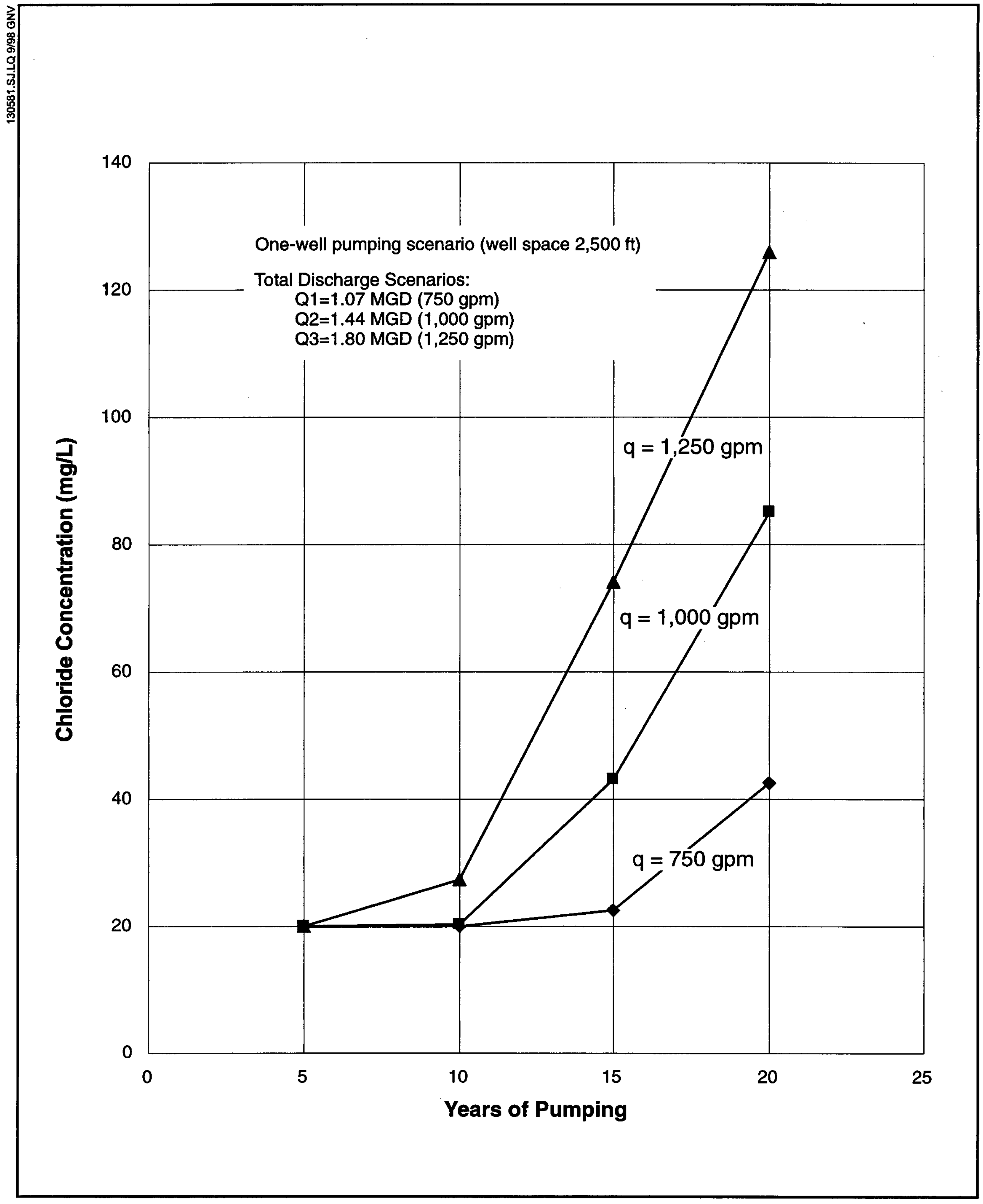

Figure 33. Chloride Concentration as a Function of Pumping Duration for the Volusia Site–One-Well Configuration

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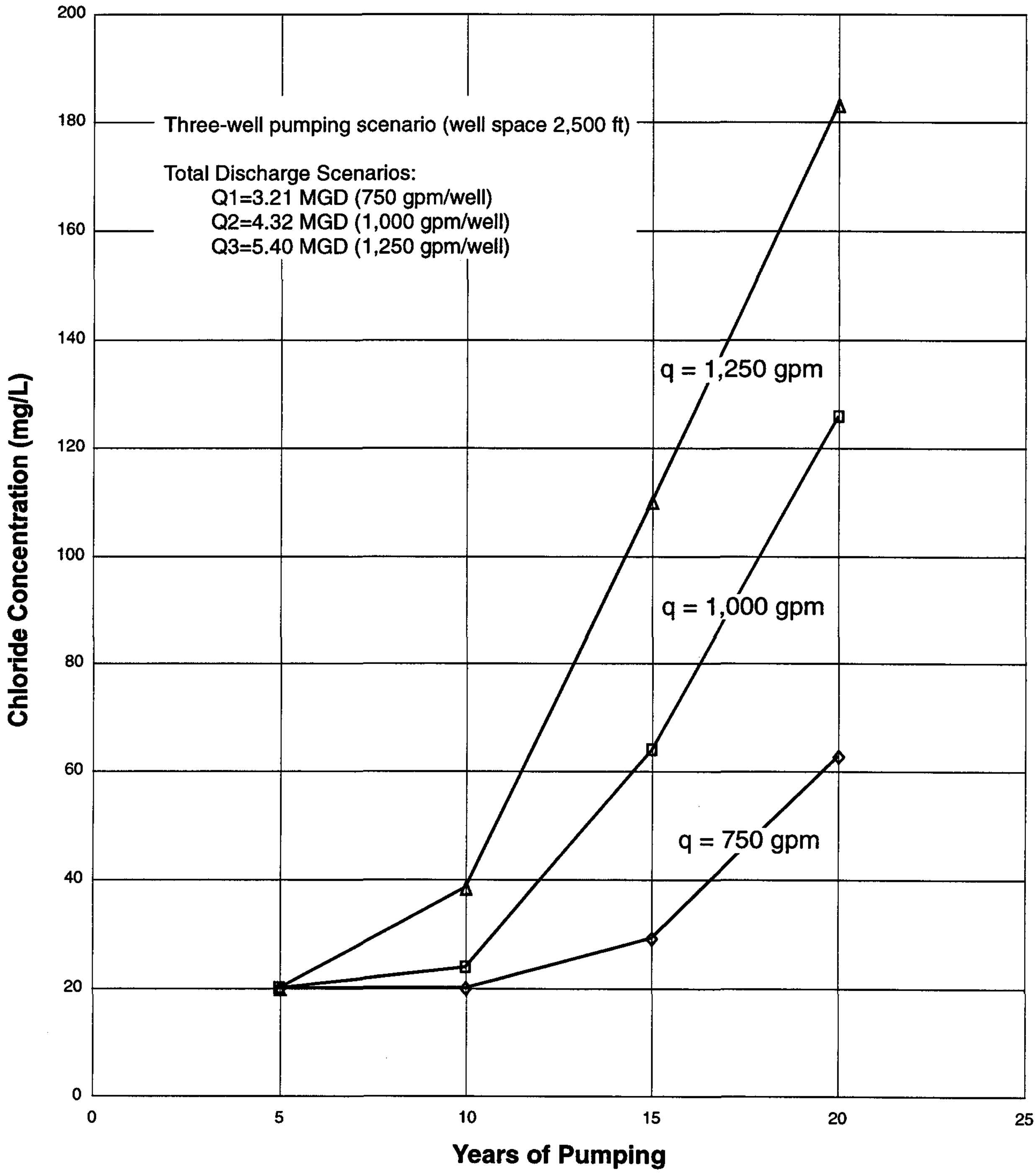

Figure 34. Chloride Concentration as a Function of Pumping Duration for the Volusia Site–Three-Well Configuration

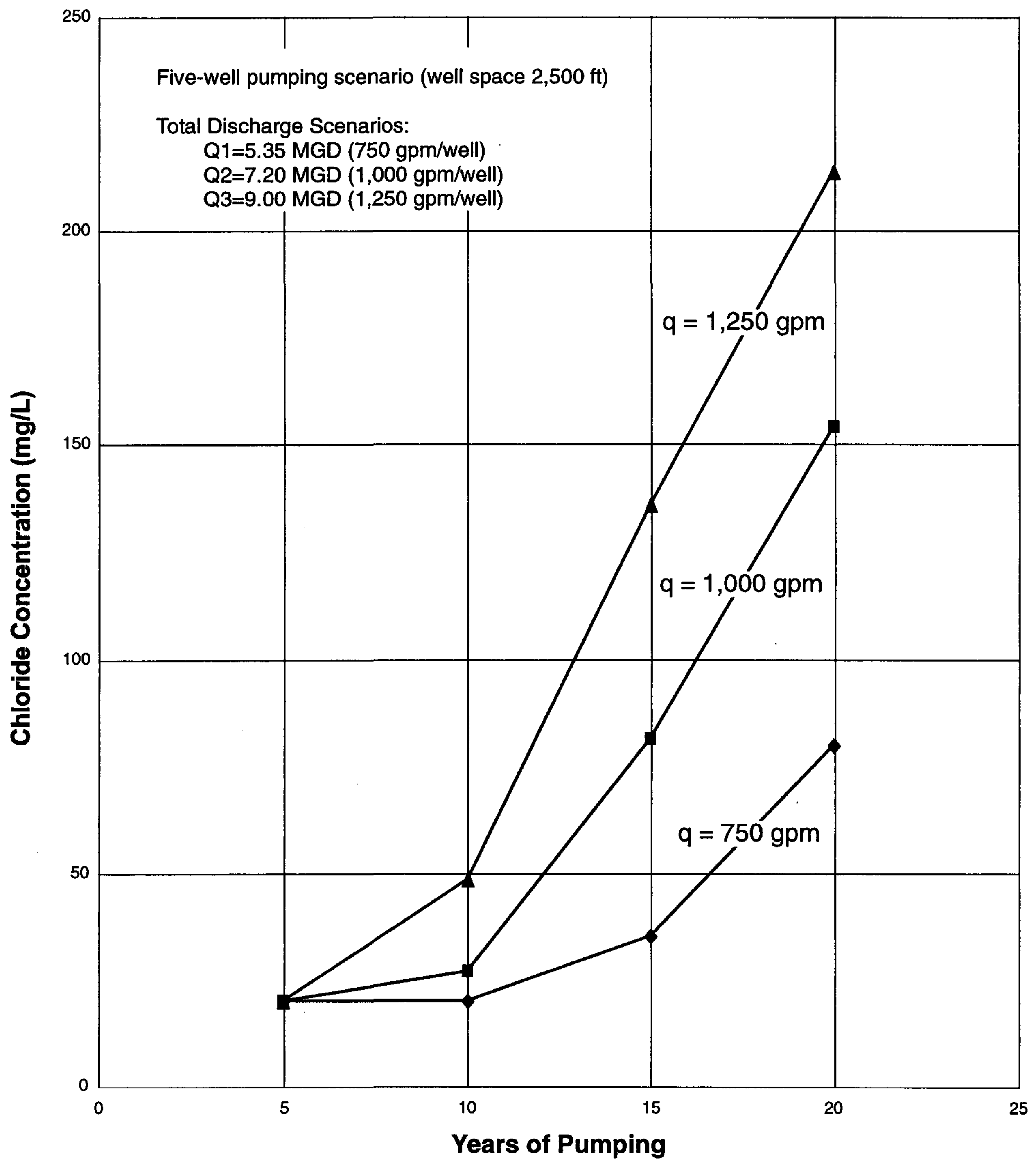

Figure 35. Chloride Concentration as a Function of Pumping Duration for the Volusia Site–Five-Well Configuration

Table 14. Hydrologic Units and Aquifer Characteristics at the St. Johns County Site

Characteristics of Intermediate Confining Unit:	
1. Top of Hawthorn layer	-50 (ft-msl)
2. Bottom of Hawthorn layer	-200 (ft-msl)
3. Thickness of Hawthorn layer	150 (ft)
4. Average leakance of confined Hawthorn layer	1.00E-05 (1/day)
5. Vertical hydraulic conductivity of Hawthorn unit	0.0015 (ft/day)
6. Horizontal hydraulic conductivity of Hawthorn unit	0.15 (ft/day)
Characteristics of Upper Floridan Aquifer:	
7. Top of Upper Floridan aquifer	-200 (ft-msl)
8. Bottom of Upper Floridan aquifer	-800 (ft-msl)
9. Total depth of Upper Floridan aquifer	600 (ft)
10. Transmissivity based on data (Williams, 1997)	30,000 (ft2/day)
11. Average horizontal hydraulic conductivity (Williams, 1997)	50.00 (ft/day)
12. Vertical hydraulic conductivity (assuming 1 to 100 ratio)	0.50 (ft/day)
Characteristics of Middle Semiconfining Unit:	
13. Top of middle confining unit	-800 (ft-msl)
14. Bottom of middle confining unit	-855 (ft-msl)
15. Total depth of Upper Floridan aquifer	55 (ft)
16. Transmissivity	3.03E+00 (ft2/day)
17. Average horizontal hydraulic conductivity	0.055 (ft/day)
18. Vertical hydraulic conductivity (assuming 1 to 20 ratio)	0.00275 (ft/day)
Characteristics of Lower Floridan Aquifer:	
19. Top of Lower Floridan aquifer	-855 (ft-msl)
20. Bottom of Lower Floridan aquifer	-2,085 (ft-msl)
21. Total depth of Lower Floridan aquifer	1,230 (ft)
22. Transmissivity	N/A
23. Average horizontal hydraulic conductivity	N/A
24. Vertical hydraulic conductivity (assuming 1 to 20 ratio)	N/A

Note: Based on GIS data provided by SJRWMD and Williams, 1997.

The site-specific parameters required for the analytical model were determined as follows. Based on GIS database and published reports, the required input data for the analytical upconing model (Figure 10) are b = 600 feet, d = 100 feet, l = 150 feet, d/b = 0.20, and l/b = 0.45. The Kz/Kr ratio is assumed to be 0.10, the transmissivity for the Upper Floridan aquifer is 58,000 ft^2/day, and the leakance of the upper confining bed is assumed to be 1.5E-05/day.

The modified analytical upconing model (Motz, 1992) was applied by using three chloride concentrations (5,000; 7,500; and 9,500 mg/L) as the sources of chloride in the aquifer system. The purpose of the analytical model was to investigate drawdowns and the changes of chloride concentrations at the pumping well due to three pumping rates applied to a single partially penetrating production well. Three chloride concentrations (5,000; 7,500; and 9,500 mg/L) at the bottom of the Upper Floridan aquifer were assumed to represent the freshwater/ saltwater interface for the analytical model. The simulated responses of the interface as a result of the 750-; 1,000-; and 1,250-gpm pumping scenarios under steady-state condition were evaluated (Table 15). Figure 36 shows the relationship between the upconing height and the pumping scenarios for the three assumed chloride concentrations at the interface. Table 15 and Figure 36 indicate that the rise of the interface for the 5,000-mg/L chloride concentration was higher than the rise for the 9,500-mg/L concentration.

Numerical Modeling

The numerical upconing model was used to evaluate the chloride concentration distribution in the pumping zone and at the wells in response to various pumping rates under transient pumping conditions. The pumping duration for this numerical modeling is divided into 5, 10, 15, and 20 years. The available information at the St. Johns County site was used in this numerical upconing modeling study (Table 14).

The average thickness of the intermediate confining bed is about 45 feet, and the average leakance is about 1.50E-05/day. It was determined that the vertical hydraulic conductivity for the intermediate confining bed is about 0.0015 ft/day. The transmissivity (Bermes, Leve, and Tarver, 1963) ranges from 23,000 to 39,000 ft^2/day. An average transmissivity with a value of 30,000 ft^2/day was used to represent the Upper Floridan aquifer in the model. The total thickness of about 600 feet in the Upper Floridan aquifer was divided into three

Table 15. Interface Upconing Height vs. Pumping Rate, St. Johns County Site

Q (gpm)	Drawdown (ft)	Upconing Height (ft)		
		9,500 mg/L	7,500 mg/L	5,000 mg/L
750	3.42	280.8	355.7	533.5
1,000	4.56	374.3	474.1	711.2
1,250	5.70	467.9	592.7	889

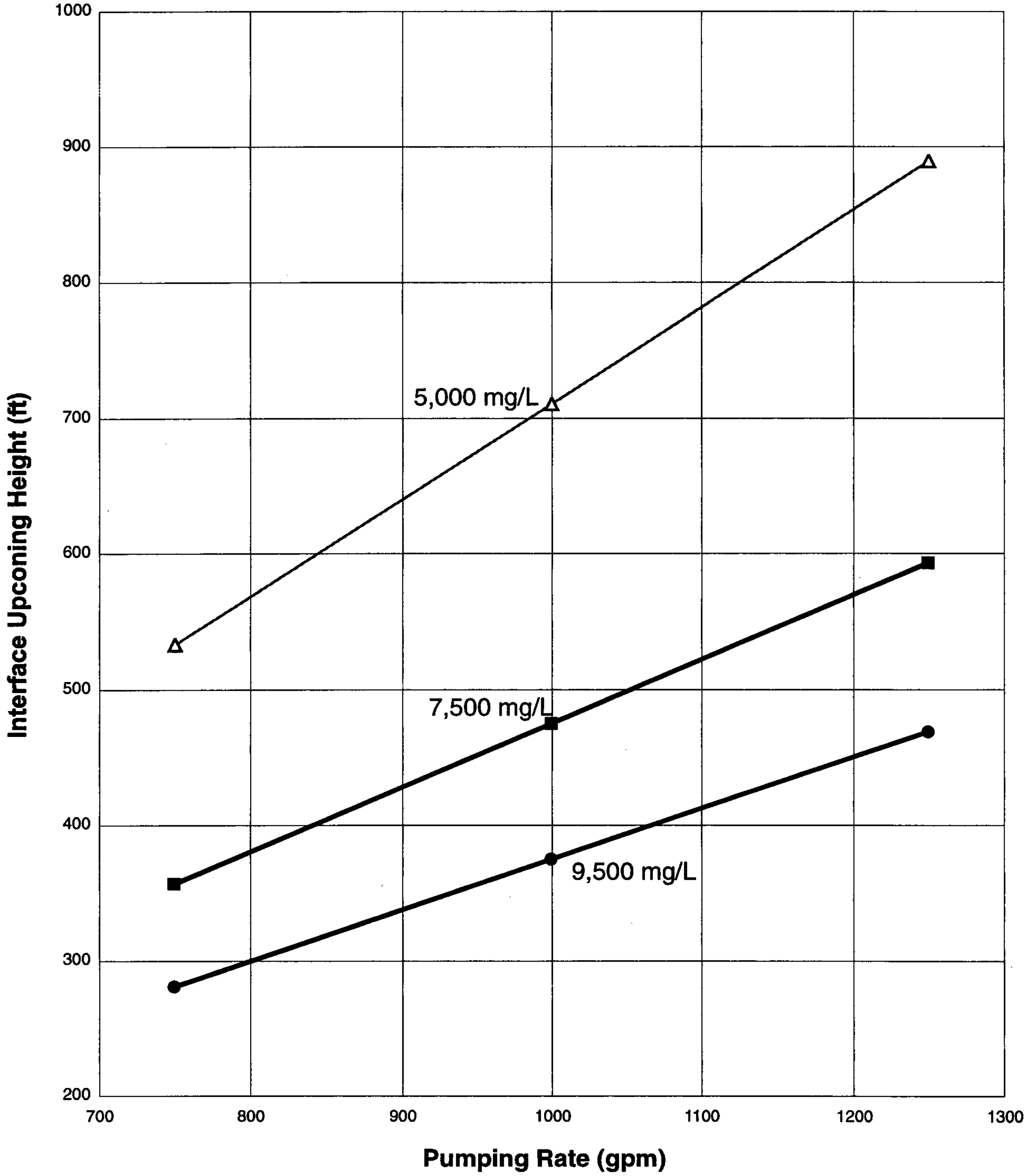

Figure 36. Interface Upconing Height vs. Pumping Rate for the St. Johns County Site

layers — the upper layer (BU), the pumpage layer (BP), and the lower layer (BL) in the upconing model. The partially penetrated production well consists of the casing layer, BU, of 100 feet; the screened layer, BP, of 150 feet; and the lower layer, BL, of 350 feet from the bottom of the production wells to the top of the middle confining layer. This is a conceptual well design used in the upconing model for this study site.

Figure 37 shows the vertical profile representing the aquifer hydrologic units used in the numerical model. Three well configuration scenarios — one well, three wells, and five wells — were evaluated to determine the responses of the aquifer system and chloride distribution in the pumping layer, and at the production wells. The space between two wells in the well configuration is 2,500 feet. The diameter of the well is 12 inches. Three pumping rates (750; 1,000; and 1,250 gpm) were used to evaluate the pumpage effects on chloride distribution. The following text discusses the results of upconing for various pumpages and pumping duration.

The results of the upconing model for the three pumping rates at 5, 10, 15, and 20 years pumping duration for three well configuration scenarios are presented in Table 16. The largest drawdowns at the production wells for the three well configurations during a continuous pumping at 1,250 gpm are 5.5, 10.4, and 14.1 feet. The potential raise of the lower-quality ground water beneath the production wells for these three scenarios during the 20 years pumping duration range from 52.6 feet to 129.0 feet. The average chloride concentrations at the production well range from 153.9 mg/L to 314.7 mg/L.

Figure 38 shows the average chloride concentration change at the production well versus 5, 10, 15, and 20 years pumping duration for the one-well configuration under the 750-; 1,000-; and 1,250-gpm pumpages. The chloride concentration at the pumping well at the end of 20 years of pumpage at 1,250 gpm is 153.9 mg/L.

Figure 39 shows the average change in chloride concentration at the production well versus 5, 10, 15, and 20 years pumping duration for the three-well configurations under the 750-; 1,000-; and 1,250-gpm pumpages. The chloride concentration at the pumping well at the end of 20 years of pumpage at 1,250 gpm is 247.2 mg/L.

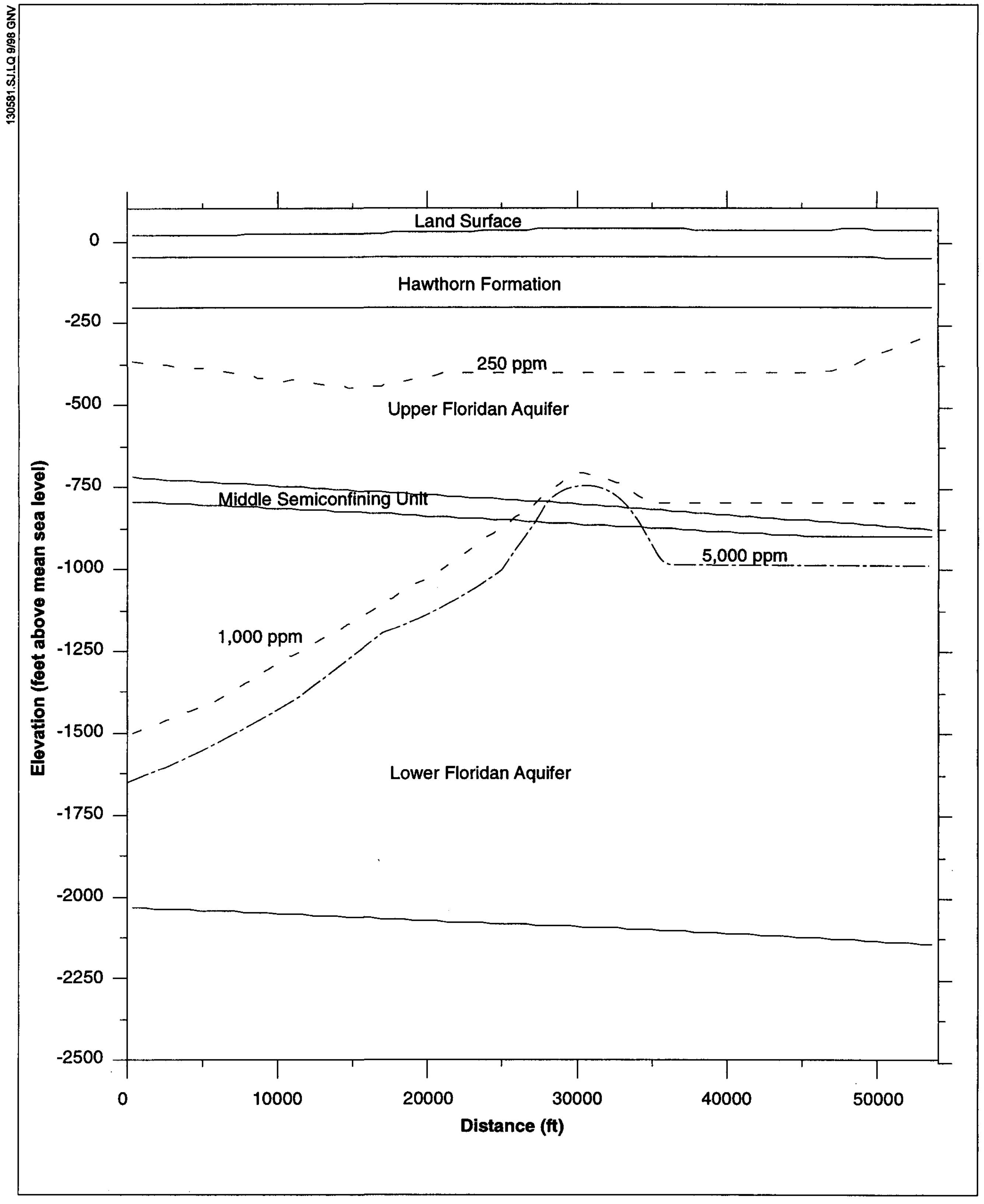

Figure 37. Typical Cross Section at the St. Johns County Site

Table 16. St. Johns Chloride Concentration vs. Pumping Rate and Duration

Time (yrs)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)
	One-well configuration											
5	1,073,580	3.3	0	150	1,440,000	4.4	0.1	150	1,800,000	5.5	1.2	150
10	1,073,580	3.3	2.9	150	1,440,000	4.4	7.8	150	1,800,000	5.5	13.8	150
15	1,073,580	3.3	10.6	150	1,440,000	4.4	20.5	150	1,800,000	5.5	31.6	150
20	1,073,580	3.3	20.2	150	1,440,000	4.4	35.6	150	1,800,000	5.5	52.6	153.9
	Three-well configuration											
5	1,073,580	6.2	3.3	150	1,440,000	8.3	7.3	150	1,800,000	10.4	12	150
10	1,073,580	6.2	17	150	1,440,000	8.3	28.4	150	1,800,000	10.4	40.7	150
15	1,073,580	6.2	34.1	150	1,440,000	8.3	53.8	150.2	1,800,000	10.4	74.5	162.8
20	1,073,580	6.2	53.3	150.2	1,440,000	8.3	81.8	172	1,800,000	10.4	112	247.2
	Five-well configuration											
5	1,073,580	8.4	4.6	150	1,440,000	11.3	9.5	150	1,800,000	14.1	15	150
10	1,073,580	8.4	20.7	150	1,440,000	11.3	33.9	150	1,800,000	14.1	47.9	150
15	1,073,580	8.4	40.5	150	1,440,000	11.3	62.8	151	1,800,000	14.1	86.5	177
20	1,073,580	8.4	62.3	150.9	1,440,000	11.3	94.7	195.5	1,800,000	14.1	129	314.7

Note: Well spacing = 2,500 ft

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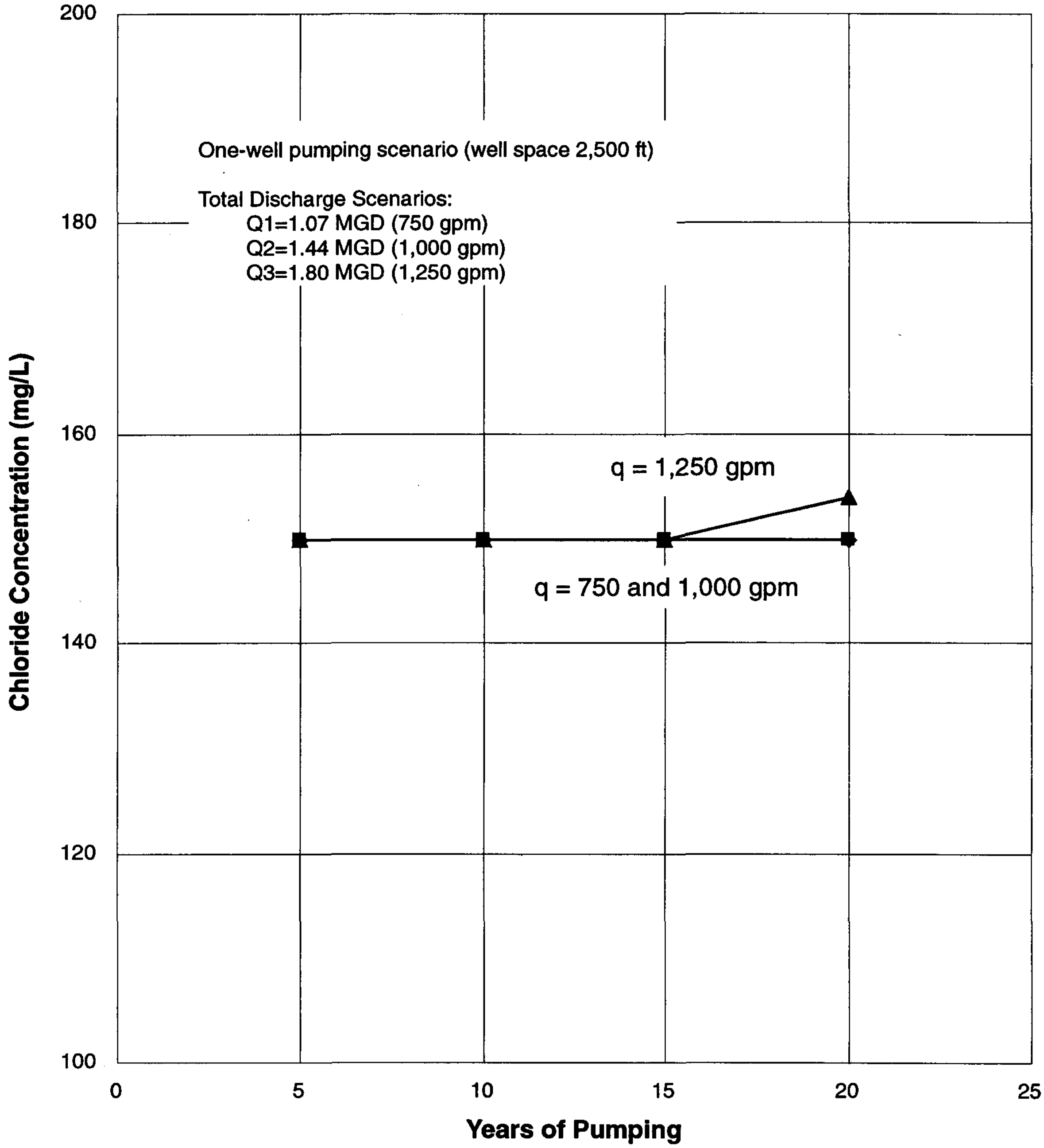

Figure 38. Chloride Concentration as a Function of Pumping Duration for the St. Johns County Site–One-Well Configuration

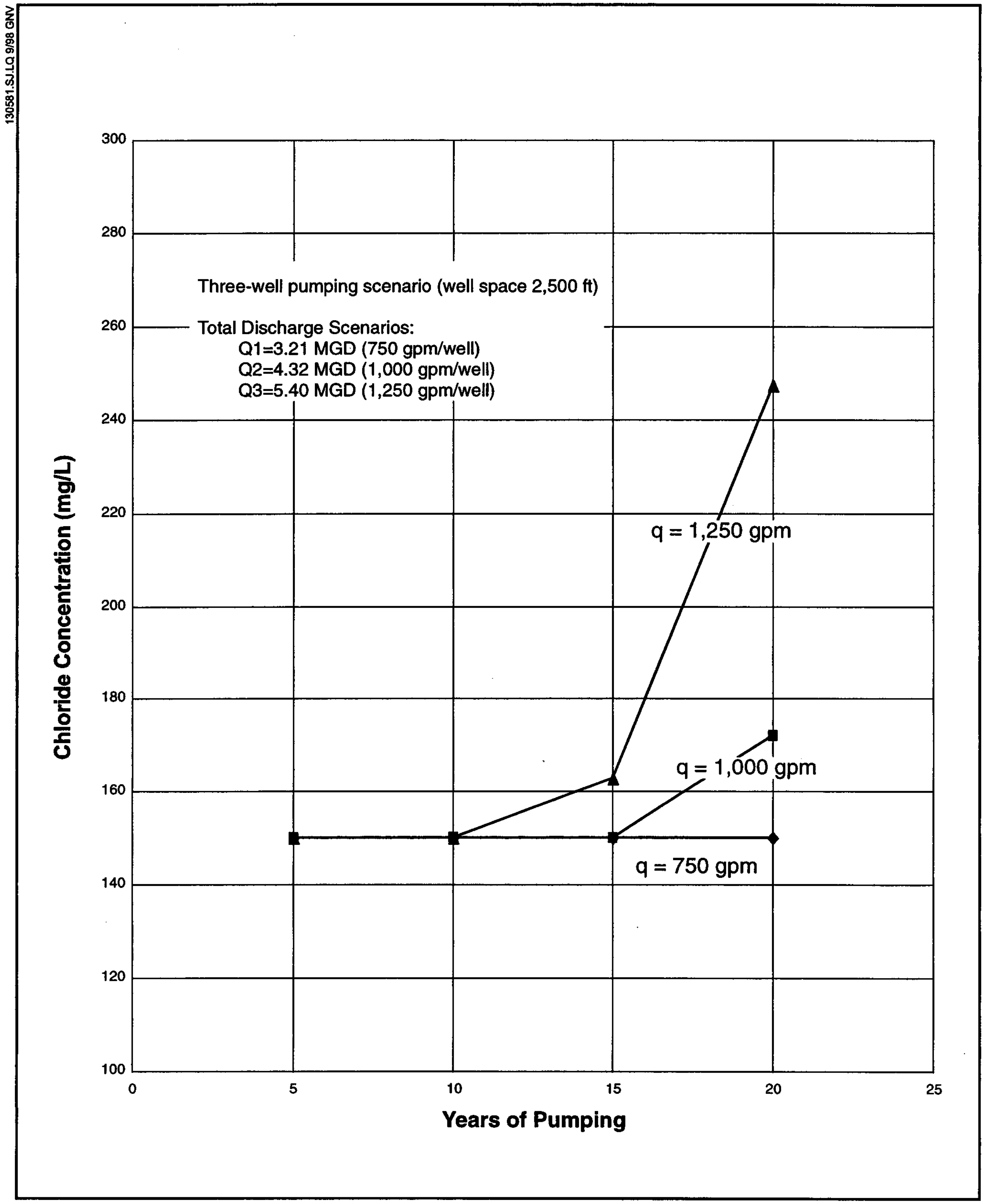

Figure 39. Chloride Concentration as a Function of Pumping Duration for the St. Johns County Site–Three-Well Configuration

Figure 40 shows the average change in chloride concentration at the production well versus 5, 10, 15, and 20 years pumping duration for the five-well configurations under the 750-; 1,000-; and 1,250-gpm pumpages. The chloride concentration at the pumping well at the end of 20 years of pumpage at 1,250 gpm is 314.7 mg/L.

LAKE JESSUP SITE

Analytical Modeling

Based on SJRWMD's GIS database, the geologic units at the Lake Jessup site form a hydrologic system consisting of a surficial aquifer system, an intermediate confining unit, and the Floridan aquifer system. The Floridan aquifer system in the study area has been divided into three zones — the Upper Floridan aquifer, a middle confining layer, and the Lower Floridan aquifer. Table 17 presents the average elevations of the hydrologic units based on the GIS database, and the associated hydraulic parameter values (Phelps and Rohrer, 1987). The average elevations of the isochlors with concentrations of 250 mg/L; 1,000 mg/L; and 5,000 mg/L at the study site are located about -1413.3 feet, -1543.8 feet, and -1595.2 feet NGVD. The following text discusses the sharp interface upconing model results and a three-dimensional numerical model.

The site-specific parameters required for the analytical model were determined as follows. Based on the GIS database and published reports, the required input data for the analytical upconing model (Figure 10) are b = 300 feet, d = 100 feet, l = 100 feet, d/b = 0.30, and l/b = 0.60. The Kz/Kr ratio is assumed to be 0.10, the transmissivity for the Upper Floridan aquifer is 43,000 ft^2/day, and the leakance of the upper confining bed is assumed to be 1.5E-05/day.

The modified analytical upconing model (Motz, 1992) was applied by using three chloride concentrations (5,000; 7,500; and 9,500 mg/L) as the sources of chloride in the aquifer system. The purpose of the analytical model was to investigate drawdowns and the changes of chloride concentrations at the production well due to three pumping rates applied to a single partially penetrating production well. Three chloride concentrations (5,000; 7,500; and 9,500 mg/L) at the bottom of the Upper Floridan aquifer were assumed to represent the freshwater/ saltwater interface for the analytical model. The responses of the potential rise of the interface as a result of the 750-; 1,000-; and 1,250-gpm pumping scenarios under steady-state conditions were evaluated

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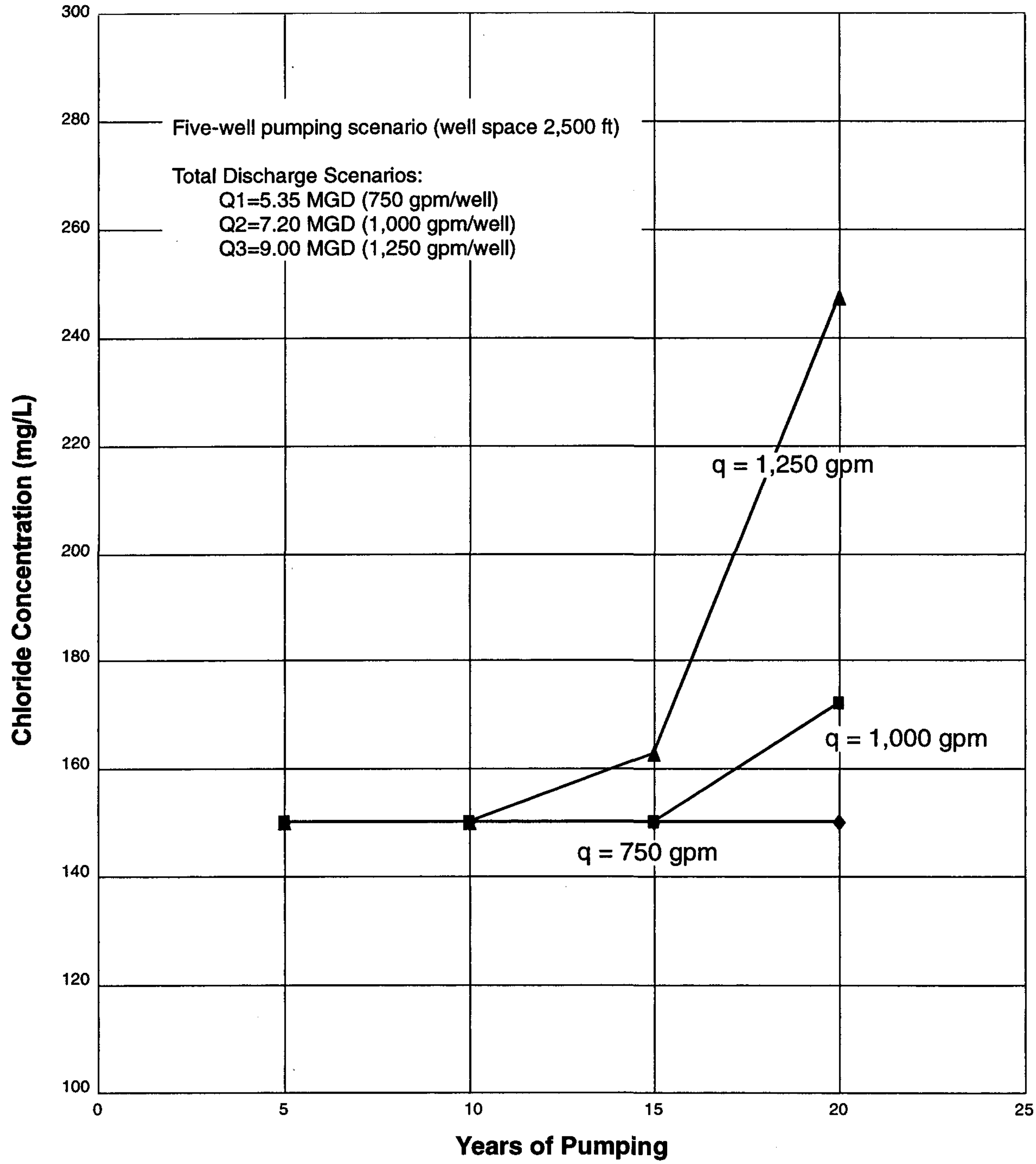

Figure 40. Chloride Concentration as a Function of Pumping Duration for the St. Johns County Site–Five-Well Configuration

Table 17. Hydrologic Units and Aquifer Characteristics at the Lake Jessup Site

Characteristics of Intermediate Confining Unit:	
1. Top of Hawthorn layer	-25 (ft-msl)
2. Bottom of Hawthorn layer	-90 (ft-msl)
3. Thickness of Hawthorn layer	65 (ft)
4. The average leakance of confined Hawthorn layer	1.00E-05 (1/day)
5. Vertical hydraulic conductivity of Hawthorn unit	0.00065 (ft/day)
6. Horizontal hydraulic conductivity of Hawthorn unit	0.065 (ft/day)
Characteristics of Upper Floridan Aquifer:	
7. Top of Upper Floridan aquifer	-90 (ft-msl)
8. Bottom of Upper Floridan aquifer	-360 (ft-msl)
9. Total depth of Upper Floridan aquifer	270 (ft)
10. Transmissivity based on data (Phelps and Rohrer, 1987)	43,000 (ft2/day)
11. Average horizontal hydraulic conductivity	159.26 (ft/day)
12. Vertical hydraulic conductivity (assuming 1 to 100 ratio)	7.96 (ft/day)
Characteristics of Middle Semiconfining Unit:	
13. Top of middle confining unit	-360 (ft-msl)
14. Bottom of middle confining unit	-980 (ft-msl)
15. Total depth of Upper Floridan aquifer	620 (ft)
16. Transmissivity	3.84E+02 (ft2/day)
17. Average horizontal hydraulic conductivity	0.62 (ft/day)
18. Vertical hydraulic conductivity (assuming 1 to 20 ratio)	0.031 (ft/day)
Characteristics of Lower Floridan Aquifer:	
19. Top of Lower Floridan aquifer	-980 (ft-msl)
20. Bottom of Lower Floridan aquifer	-2,415 (ft-msl)
21. Total depth of Lower Floridan aquifer	1,435 (ft)
22. Transmissivity	N/A
23. Average horizontal hydraulic conductivity	N/A
24. Vertical hydraulic conductivity (assuming 1 to 20 ratio)	N/A

Note: Based on GIS data provided by SJRWMD and Phelps and Rohrer, 1987.

(Table 18). Figure 41 shows the relationship between upconing height and pumping scenarios for the three assumed chloride concentrations at the interface. Table 18 and Figure 41 indicate that the rise of the interface for the 5,000-mg/L chloride concentration is higher than the one for the 9,500-mg/L chloride concentration.

Numerical Modeling

The numerical upconing model was used to evaluate the chloride concentration distribution in the pumping zone and at the wells in response to various pumping rates under transient pumping conditions. The pumping duration for this numerical modeling is divided into 5, 10, 15, and 20 years. The available information at the Lake Jessup site (Table 17) was used in this numerical upconing modeling study.

The average thickness of the intermediate confining bed is about 65 feet, and the average leakance is about 1.50E-05/day. It was determined that the vertical hydraulic conductivity for the intermediate confining bed is about 0.00065 ft/day. The transmissivity ranges from 35,000 to 100,000 ft^2/day (Tibbals, 1981). An average transmissivity value of 43,000 ft^2/day was used to represent the Upper Floridan aquifer in the model. The total thickness of about 350 feet in the Upper Floridan aquifer was divided into three layers — the upper layer (BU), the pumpage layer (BP), and the lower layer (BL) in the upconing model. The partially penetrating production well consists of the casing layer, BU, of 100 feet; the screened layer, BP, of 100 feet; and the lower layer, BL, of 150 feet from the bottom of the production to the top of the middle confining layer. This is a conceptual well design used in the upconing model for this study site.

Figure 42 shows the vertical profile representing the aquifer hydrologic units used in the numerical model. Three well configuration scenarios—one well, three wells, and five wells—were evaluated to determine the responses of the aquifer system and chloride distribution in the production zone and at the production wells for these three scenarios. The space between two wells in the well configuration is 2,500 feet. The diameter of the well is 12 inches. Three pumping rates (750; 1,000; and 1,250 gpm) were used to evaluate the pumpage effects on chloride distribution. The results of upconing for various pumping rates and durations are discussed as follows.

Table 18. Interface Upconing Height vs. Pumping Rate, Lake Jessup Site

Q (gpm)	Drawdown (ft)	Upconing Height (ft)		
		9,500 mg/L	7,500 mg/L	5,000 mg/L
750	3.67	301.4	381.8	572.7
1,000	4.89	401.8	509	763.4
1,250	6.12	502.3	636.2	954.3

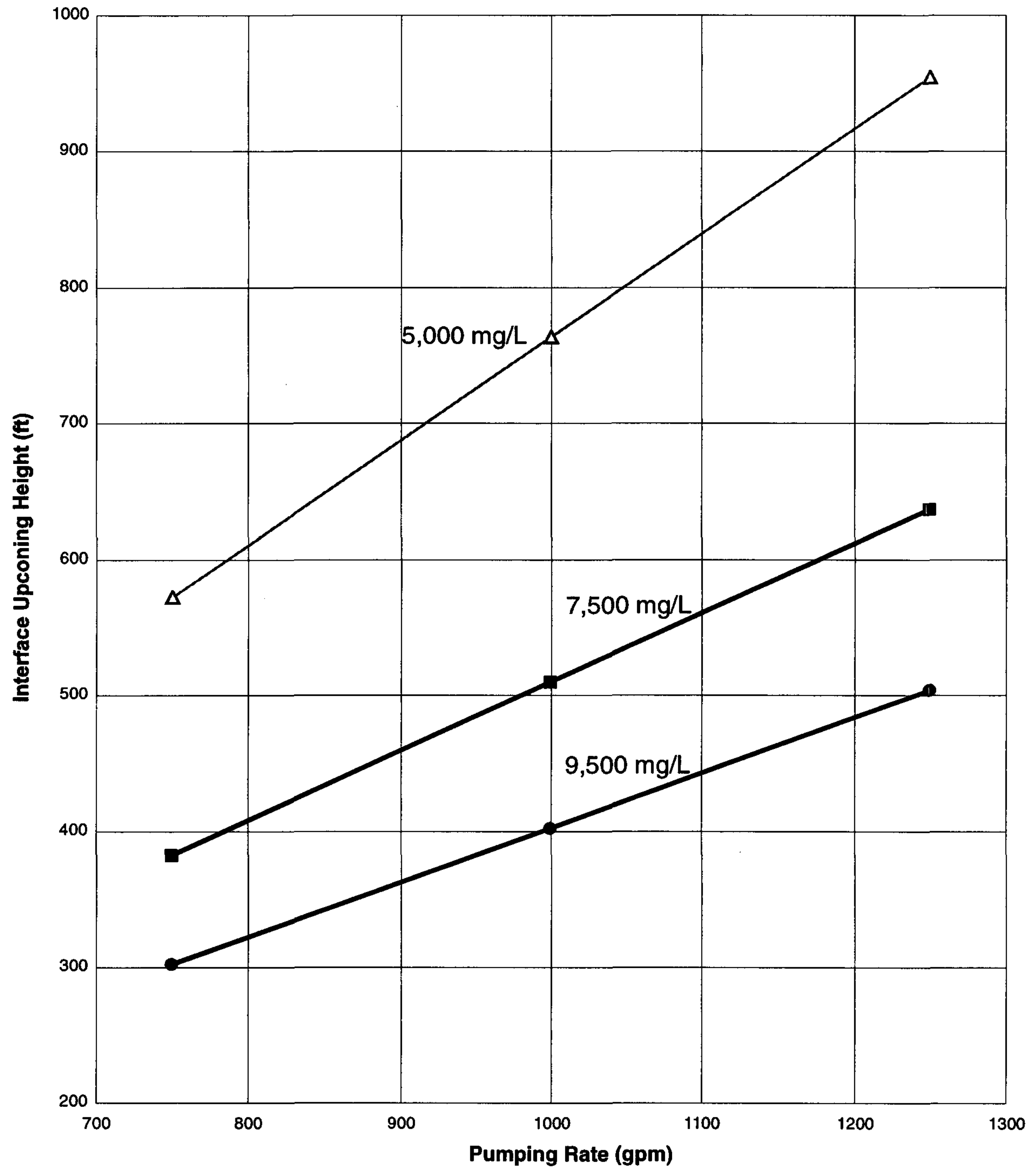

Figure 41. Interface Upconing Height vs. Pumping Rate for the Lake Jessup Site

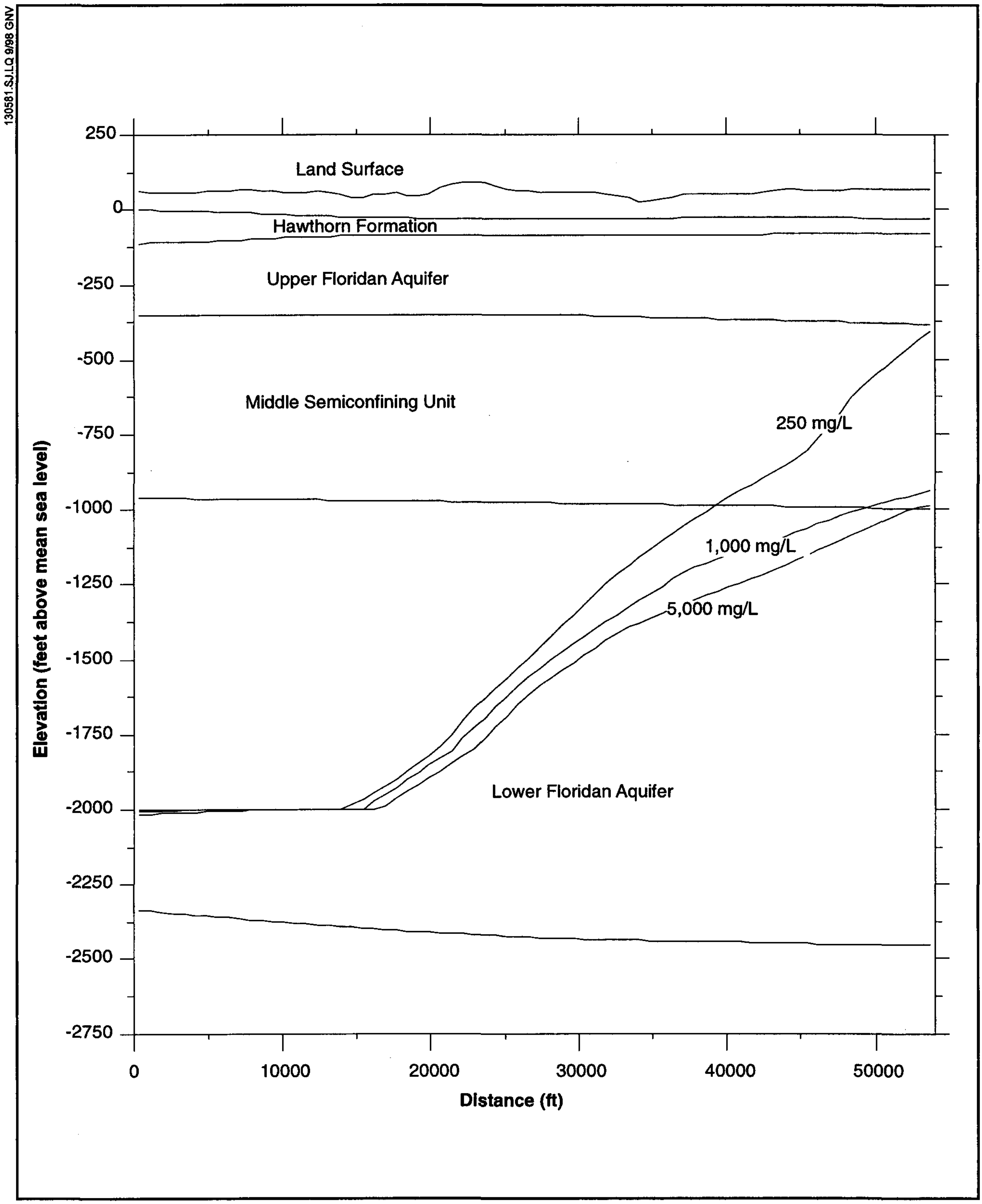

Figure 42. Typical Cross Section at the Lake Jessup Site

Table 19 presents the results of the upconing model for the three pumping rates at 5, 10, 15, and 20 years pumping duration for three well configuration scenarios. The largest drawdowns at the production wells for the three well configurations during continuous pumping at 1,250 gpm are 2.5, 4.7, and 6.4 feet. The potential rise of the lower-quality ground water beneath the production wells for these three scenarios during the 20 years pumping duration ranges from 226.8 feet to 5,498.1 feet. The chloride concentrations at the production wells range from 89.4 mg/L to 154.4 mg/L.

Figure 43 shows the average chloride concentration change at the discharge well versus 5, 10, 15, and 20 years pumping duration for the one-well configuration under the 750-; 1,000-; and 1,250-gpm pumpages. The chloride concentration at the pumping well at the end of the 20 years pumpage at 1,250 gpm is 89.4 mg/L.

Figure 44 shows the average chloride concentration change at the production wells versus 5, 10, 15, and 20 years pumping duration for the three-well configurations under the 750-; 1,000-; and 1,250-gpm pumpages. The chloride concentration at the pumping well at the end of 20 years of pumpage at 1,250 gpm is 192.4 mg/L.

Figure 45 shows the average chloride concentration change at the production well versus 5, 10, 15, and 20 years pumping duration for the five-well configurations under the 750-; 1,000-; and 1,250-gpm pumpages. The chloride concentration at the pumping well at the end of 20 years of pumpage at 1,250 gpm is 230.4 mg/L.

WELL CONFIGURATION

Table 20 presents the total depth, casing depth, and screen interval of the Upper Floridan wells used in this upconing study.

Table 19. Lake Jessup Chloride Concentration vs. Pumping Rate and Duration

Time (yrs)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)
	One-well configuration											
5	1,073,580	1.5	0	20	1,440,000	2	0.8	20	1,800,000	2.5	2.7	20
10	1,073,580	1.5	5.2	20	1,440,000	2	11.6	20	1,800,000	2.5	18.9	21
15	1,073,580	1.5	15	20	1,440,000	2	27	28.3	1,800,000	2.5	40.3	48.9
20	1,073,580	1.5	26.7	28	1,440,000	2	45	57	1,800,000	2.5	64.9	89.4
	Three-well configuration											
5	1,073,580	2.8	5.1	20	1,440,000	3.8	10.1	20	1,800,000	4.7	15.8	20
10	1,073,580	2.8	21.7	20	1,440,000	3.8	35.2	24.3	1,800,000	4.7	49.5	39.9
15	1,073,580	2.8	41.9	30	1,440,000	3.8	64.7	66.8	1,800,000	4.7	89	115.3
20	1,073,580	2.8	64.2	65.7	1,440,000	3.8	97.5	131.7	1,800,000	4.7	133	192.4
	Five-well configuration											
5	1,073,580	3.8	7	20	1,440,000	5.1	13	20	1,800,000	6.4	19.6	20
10	1,073,580	3.8	26.5	20.2	1,440,000	5.1	42.1	28.6	1,800,000	6.4	58.6	53.2
15	1,073,580	3.8	49.8	38.3	1,440,000	5.1	76.1	89.1	1,800,000	6.4	104	148.7
20	1,073,580	3.8	75.5	87.8	1,440,000	5.1	113.8	168.3	1,800,000	6.4	154.4	230.4

Note: Well spacing = 2,500 ft

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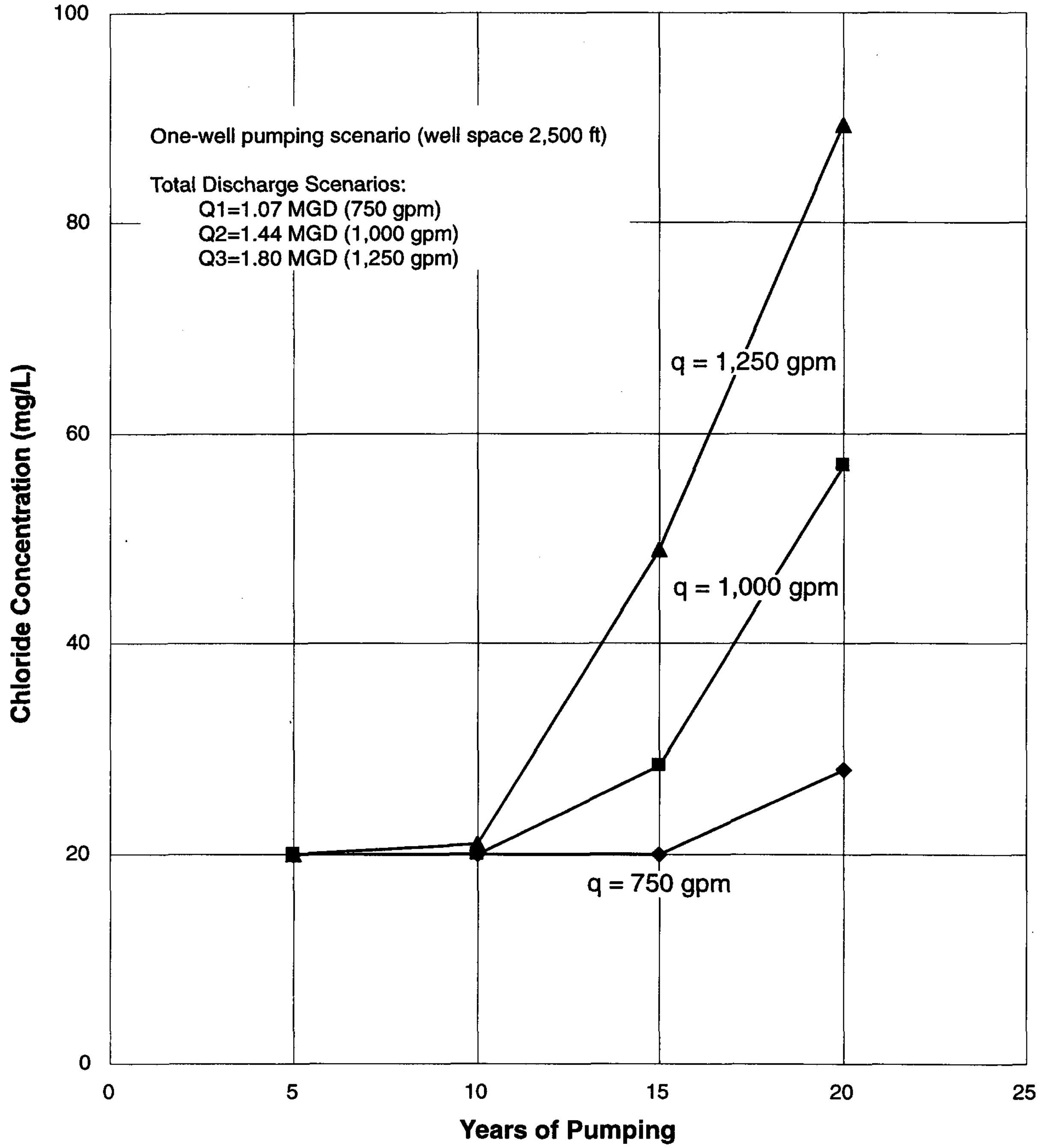

Figure 43. Chloride Concentration as a Function of Pumping Duration for the Lake Jessup Site–One-Well Configuration

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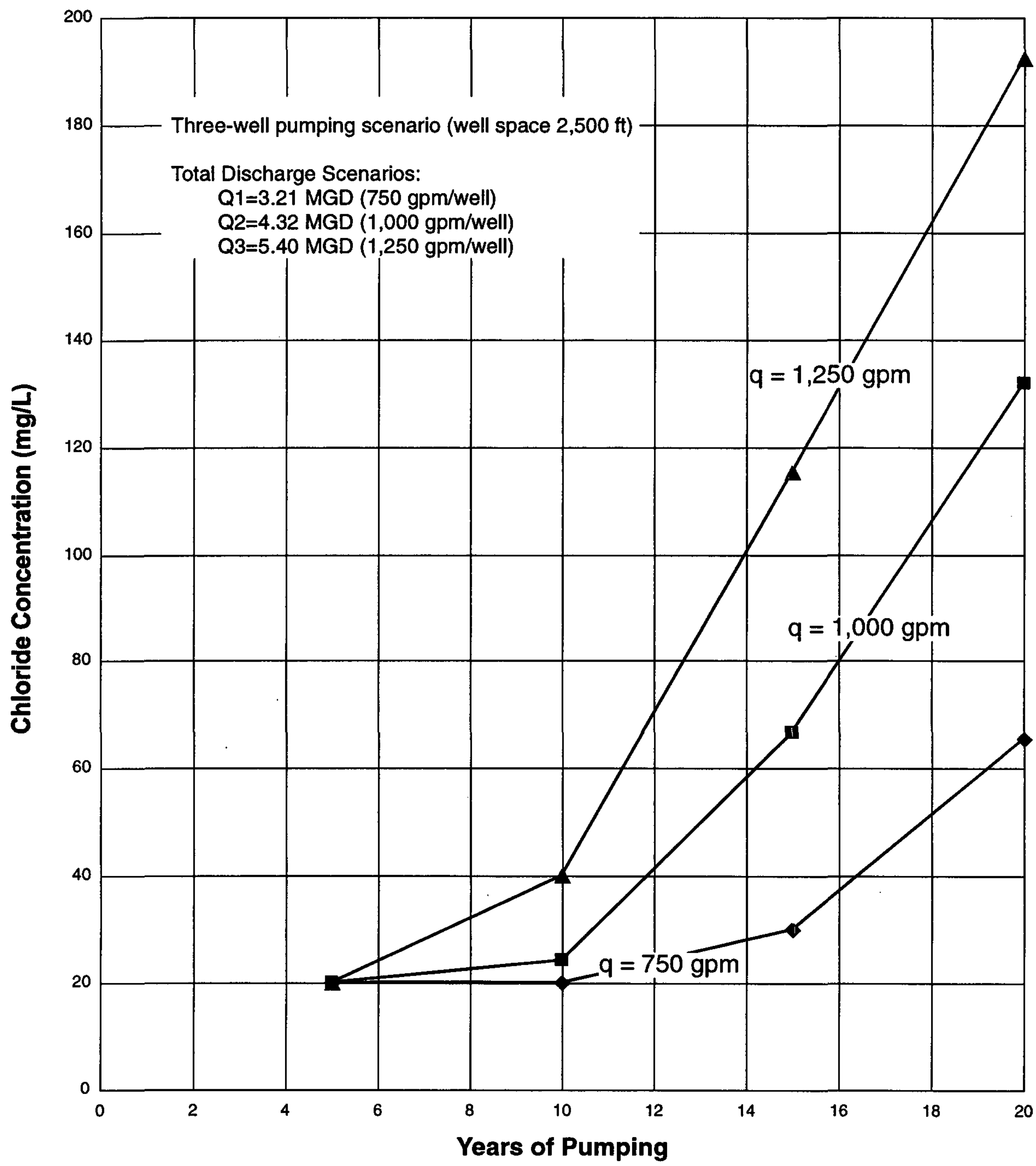

Figure 44. Chloride Concentration as a Function of Pumping Duration for the Lake Jessup Site–Three-Well Configuration

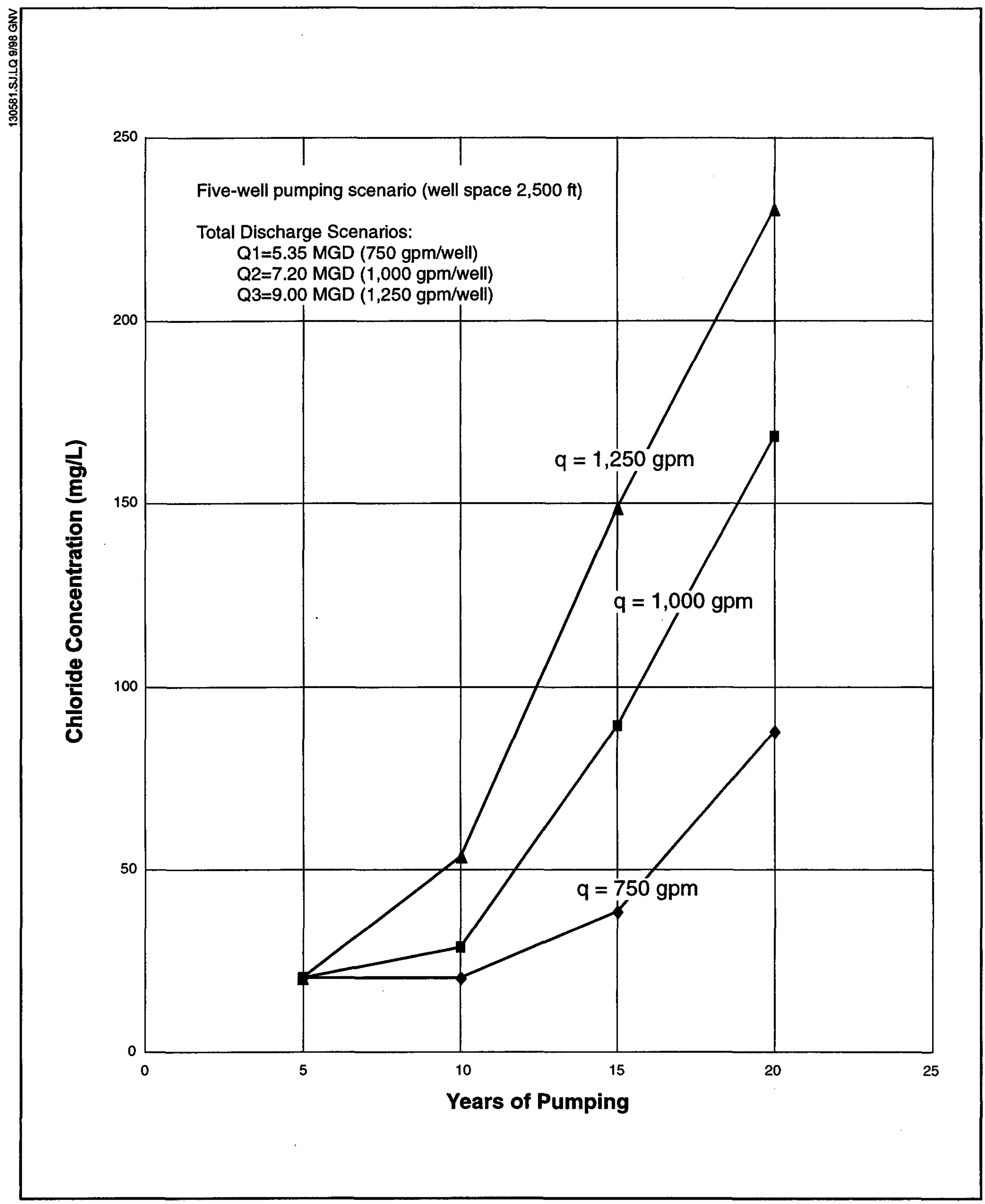

Figure 45. Chloride Concentration as a Function of Pumping Duration for the Lake Jessup Site–Five-Well Configuration

Table 20. Total Partially Penetrated Well Depth, Casing Depth, and Opening Screen Interval

Model Site	Total Depth (ft/bls)	Casing Depth (ft/bls)	Opening Screen Interval (ft)	Mixing Zone (ft)	Diameter (inches)
Lake Washington	525	375	150	300	12
Titusville	325	225	100	250	12
East Orange County	350	250	100	250	12
Volusia	300	200	100	150	12
St. Johns	475	275	150	250	12
Lake Jessup	375	275	100	150	12

Note: ft bls = feet below land surface

VERIFICATION OF THE UPCONING NUMERICAL MODEL

The six sites for this study were selected to investigate the potential for upward movement of lower-quality water into the conceptual wellfield configurations. Some brackish ground water supply facilities currently in operation within SJRWMD have only been in operation for a short time, and long-term transient changes, like those simulated at the six candidate brackish ground water withdrawal sites, have not had time to develop.

Based on available ground water quality data, four wells within the City of Cocoa's wellfield (wells 14, 15, 16, and 17 located in eastern Orange County) were chosen for this model verification analysis. The spacing between the selected wells is about 2,500 feet. The wellfield has been in operation for many years. More than 30 years of data concerning the magnitude of ground water withdrawals and chloride concentration are available for those wells.

Site-specific USGS data (Phelps and Schiffer, 1996) are summarized and applied to the numerical upconing model. A five-well configuration with a pumping rate ranging from 5.5 mgd to 9.0 mgd for 5, 10, 15, and 20 years of pumpage was used in the simulation. The well spacing for this model simulation was 2,500 feet. The average chloride concentration for this scenario was calculated and compared with the chloride concentration at City of Cocoa wells 14, 15, 16, and 17. The average minimum chloride concentration for these four wells during a 20-year data measurement period was 32.5 mg/L. The average maximum chloride concentration for these four wells during a 20-year data measurement period was 133.75 mg/L (Table 21). The simulated average chloride concentrations for a 20-year pumpage period, using pumping rates of 5.4 mgd to 9.0 mgd, ranged from 56.4 mg/L to 145.9 mg/L. These results are compatible with the measured chloride concentration at the Cocoa wellfield. Table 22 presents the model results of the average chloride concentration for the simulated wellfield as a function of pumping rate and duration of pumping.

Figure 46 shows the average chloride concentration change at the production well versus pumping duration for the one-well configuration under the 750-; 1,000-; and 1,250-gpm pumpages. The chloride concentration at the pumping well at the end of 20 years of pumpage at 1,250 gpm is 68.2 mg/L.

Table 21. Cocoa Wellfield—Ground Water Monitoring Network, 1994 Cocoa Wellfield Well Data

Well Name	Depth (ft/bls)	Casing (ft/bls)	Diameter (inches)	Pump Capacity (gpm)	Chloride		
					Minimum (mg/L)	Maximum (mg/L)	Mean (mg/L)
Cocoa 14	761	252	12	2,100	38	160	76.23
Cocoa 15	702	262	12	2,100	38	230	62.8
Cocoa 16	600	255	12	2,100	27	90	48.18
Cocoa 17	600	252	12	2,100	27	55	39.89
Average	665.75	255.25			32.5	133.75	56.775

Note: Phelps and Schiffer, 1996.

Table 22. Chloride Concentrations at Cocoa Wellfield Wells 14, 15, 16, and 17 vs. Pumping Rate and Duration

Time (yrs)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)	Pumping Rate (gpd)	Drawdown (ft)	Upconing Height (ft)	Chloride (mg/L)
	One-well configuration											
5	1,073,580	1	0	35	1,440,000	1.4	0	35	1,800,000	1.8	0.8	35
10	1,073,580	1	2.7	35	1,440,000	1.4	9	35	1,800,000	1.8	17	35
15	1,073,580	1	12.6	35	1,440,000	1.4	26.2	35.5	1,800,000	1.8	41.5	43.5
20	1,073,580	1	25.8	35.4	1,440,000	1.4	47	47.9	1,800,000	1.8	70.6	68.2
	Three-well configuration											
5	1,073,580	2	3	35	1,440,000	2.6	8	35	1,800,000	3.3	13.9	35
10	1,073,580	2	20.5	35	1,440,000	2.6	35.7	35.2	1,800,000	3.3	52.1	39
15	1,073,580	2	43.3	36.4	1,440,000	2.6	69.7	48.4	1,800,000	3.3	97.7	73.3
20	1,073,580	2	69	48	1,440,000	2.6	107.5	83	1,800,000	3.3	148.5	122.5
	Five-well configuration											
5	1,073,580	2.7	4.4	35	1,440,000	3.6	10.3	35		4.5	17.3	35
10	1,073,580	2.7	24.8	35	1,440,000	3.6	42	35.5	1,800,000	4.5	60.6	42.3
15	1,073,580	2.7	50.7	37.6	1,440,000	3.6	80.4	57.1	1,800,000	4.5	112	88.8
20	1,073,580	2.7	79.7	56.4	1,440,000	3.6	123	100.5	1,800,000	4.5	169.1	145.9

Note: Well spacing = 2,500 ft

Figure 47 shows the average chloride concentration change at the production well versus pumping duration for the three-well configurations under the 750-; 1,000-; and 1,250-gpm pumpages. The chloride concentration at the pumping well at the end of 20 years of pumpage at 1,250 gpm is 122.5 mg/L.

Figure 48 shows the average chloride concentration change at the production well versus pumping duration for the five-well configurations under the 750-; 1,000-; and 1,250-gpm pumpages. The chloride concentration at the pumping well at the end of 20 years of pumpage at 1,250 gpm is 145.9 mg/L.

Two comparisons between the observed values and the simulated values are most meaningful. The first is a comparison of the average maximum observed concentrations to the corresponding end-of-period simulation values for the three- and five-well simulations. The mean of the maximum observed chloride concentrations is 134 mg/L, and the mean of the end-of-period simulated values for the three- and five-well configurations are 123 mg/L and 146 mg/L, respectively.

The second comparison is the average observed chloride concentration versus the average simulated chloride concentration. The average observed value over the 20-year monitoring period is 57 mg/L. The average simulated values are 49 mg/L for the three-well configuration and 56 mg/L for the five-well configuration. In both cases, the simulated and observed results are in substantial agreement.

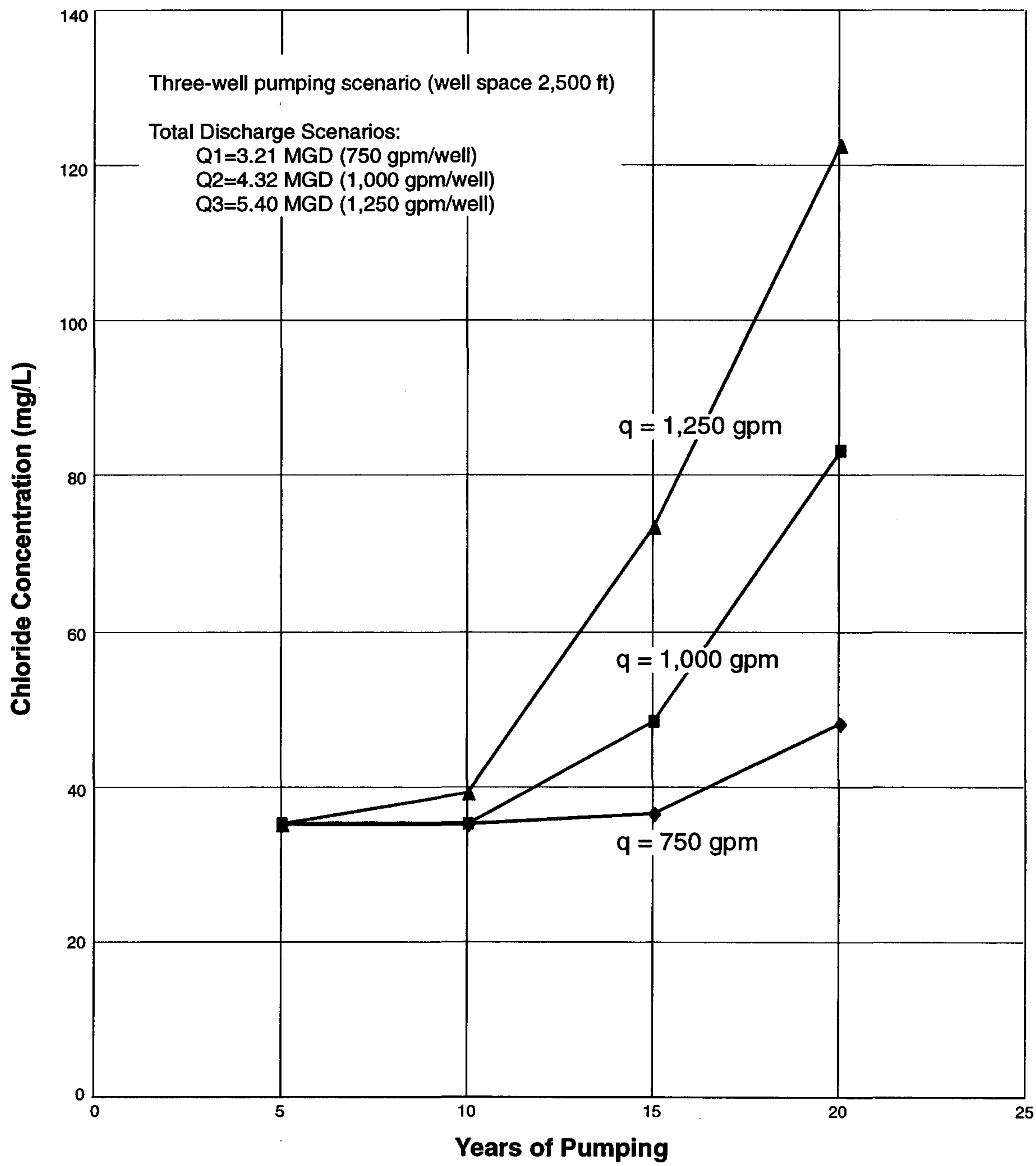

Figure 47. Chloride Concentration as a Function of Pumping Duration for the Cocoa Wellfield–Three-Well Configuration

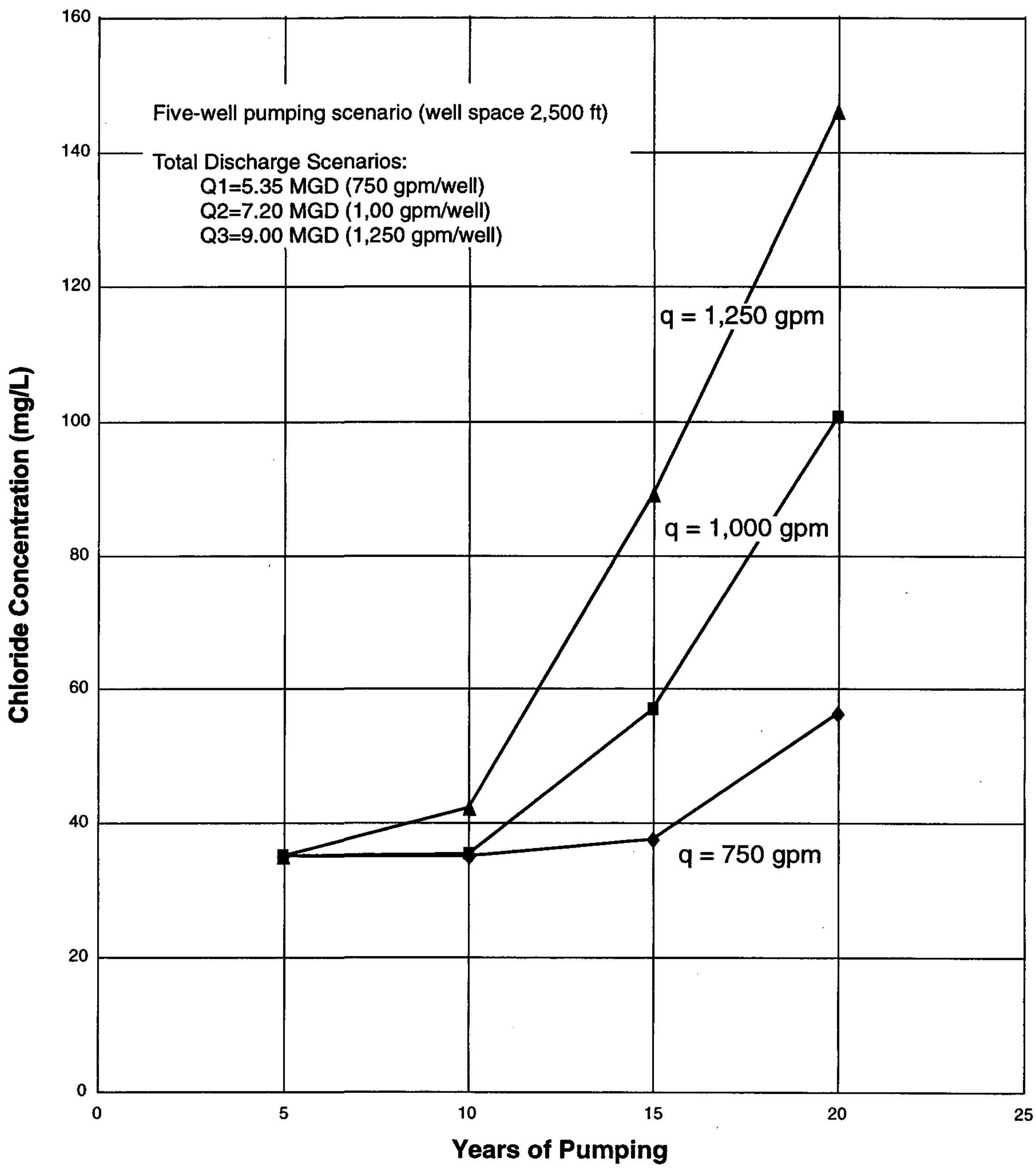

Figure 48. Chloride Concentration as a Function of Pumping Duration for the Cocoa Wellfield–Five-Well Configuration

SUMMARY AND RECOMMENDATIONS

SUMMARY

This TM characterizes the brackish ground water resources within the SJRWMD Priority Water Resource Caution Area. Brackish ground water parameters of interest include:

- Thickness of the Upper Floridan aquifer
- Depth to the 250-mg/L isochlor
- Depth to the 1,000-mg/L isochlor
- Thickness of the brackish water within the Upper Floridan aquifer
- Percentage of brackish water within the Upper Floridan aquifer
- Recharge rate to the Upper Floridan aquifer

Mapping each of these parameters was accomplished by applying GIS techniques to the SJRWMD GIS database.

Criteria were then developed to rank each of the above parameters. In general, areas in which the Upper Floridan aquifer is relatively thick and contains mostly brackish ground water with chloride concentrations ranging from 250 to 1,000 mg/L are most attractive for brackish water supply development. In addition, ground water discharge areas are preferred to ground water recharge areas because the potential for undesirable impacts to nearby wetlands is less in discharge areas. Using relative rankings for each of the parameters, areas with low, medium, and high potential for developing brackish ground water supplies were identified.

Six candidate brackish ground water withdrawal sites were then identified, based on relative water supply development potential and proximity to demand centers. The six candidate withdrawal sites are located in St. Johns, Volusia, Seminole, Orange, and Brevard counties. Each candidate withdrawal site was analyzed to identify long-term changes in water quality due to pumping. A salt water upconing analysis was used to determine expected water quality changes as a function of both time and pumping rate. The upconing analysis is based on local hydrogeology and water quality and considers several different production well configurations, well pumping rates, and pumping durations.

The results of chloride concentration simulations at the withdrawal points based on the five-well configuration for 20 years continuous pumpage at 1,250 gpm for the study sites are summarized here. The average chloride concentration at Lake Washington site is 434 mg/L. The average chloride concentration at the Titusville site is 247 mg/L. The average chloride concentration at the East Orange County site is 443 mg/L. The average chloride concentration at the Volusia site is 214 mg/L. The average chloride concentration at the St. Johns County site is 315 mg/L, and the average chloride concentration at the Lake Jessup site is 230 mg/L. These values indicate slightly brackish conditions after 20 years of continuous withdrawal at 9 mgd.

Results of the upconing analysis, conducted for all six candidate withdrawal sites, indicate that water quality will change with both duration of pumping and pumping rate. However, in all cases, the rate of change can be minimized by careful wellfield design and operation.

Adequate well spacing is very important. In this analysis, wells were spaced at 2,500-feet intervals and rather large well spacing will be required to minimize future changes in brackish ground water quality. Pumping rate is also important. Lower pumping rates will help minimize future water quality changes. Proper wellfield design and operation will ensure the long-term viability of each candidate brackish ground water withdrawal site evaluated in this investigation.

The results of the upconing analysis also provide the information necessary to develop preliminary brackish ground water supply options for comparison to other water supply development alternatives. The results provide the information necessary to develop planning- level brackish ground water development cost estimates as a function of total water supply quantities developed for each candidate withdrawal site.

RECOMMENDATIONS

The six candidate brackish ground water withdrawal sites identified and evaluated in this TM should be carried forward into the costing phase of this investigation. Brackish ground water supply cost estimates should be developed and reported in the final TM of this series, D.3.b, *Brackish Ground Water: Planning Level Cost Estimates.*

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