DRAFT TECHNICAL MEMORANDUM

Development of a Variable-Density Groundwater Flow Model to Simulate the Florida Keys Aqueduct Authority's (FKAA's) Proposed Floridan Aquifer Wellfield at the J. Robert Dean Water Treatment Plant in Florida City, Miami-Dade County, Florida

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PROJECT NUMBER:	328239.FF.LB

1.0 Introduction

This technical memorandum documents groundwater modeling that was conducted under Task F of Florida Keys Aqueduct Authority (FKAA) Task Order CH4-05: "Engineering Services for the Design and Permitting of a Floridan Aquifer Wellfield for the Reverse Osmosis Expansion of the J. Robert Dean Water Treatment Plant."

Currently, the FKAA withdraws approximately 20 million gallons per day (mgd) of groundwater from the Biscayne aquifer at the J. Robert Dean Water Treatment Plant (WTP), in Florida City, Florida. After lime-softening treatment at the plant, potable water is pumped at up to 250 pounds per square inch (psi) through a 36-inch transmission pipeline for a distance of 130 miles, to Key West.

Projected population growth in the Keys will require the FKAA to produce up to nearly 8 mgd of additional treated water over the next 20 years. Due to limits on increased withdrawals from the Biscayne aquifer, the FKAA has elected to develop the deeper, brackish, Floridan aquifer as an alternative water supply source. The water from the Floridan aquifer will be treated with a reverse-osmosis (RO) WTP at the FKAA's J. Robert Dean facility.

This technical memorandum (TM) documents groundwater modeling that was conducted to evaluate future drawdown and water quality for the Floridan aquifer wellfield. A site-specific variable-density groundwater flow model was developed based on a regional variable-density flow model of the Floridan aquifer system in southeast Florida developed by HydroGeoLogic (2006) for the South Florida Water Management District (SFWMD). The model input files and documentation for this model were obtained under a public records request from the SFWMD.

1.1 Model Objectives

The objective was to develop a three-dimensional variable density transient groundwater model for the area around and including the proposed wellfield. The model will be used to estimate long-term water quality and water levels for Floridan aquifer production wells at the site. Additionally, the modeling task will identify data gaps and uncertainty to help guide data-collection efforts on subsequent phases of the project. Because the Floridan aquifer is a brackish-water aquifer in South Florida, the variable-density code SEAWAT-2000 (Langevin et al., 2003) was selected to simulate movement of water in the aquifer.

1.2 General Setting

The FKAA's J. Robert Dean WTP is located in Florida City, as shown in **Exhibit 1**. **Exhibit 2** depicts the locations of the Floridan aquifer supply wells simulated in the model described in this TM.

EXHIBIT 1
FKAA WTP Location

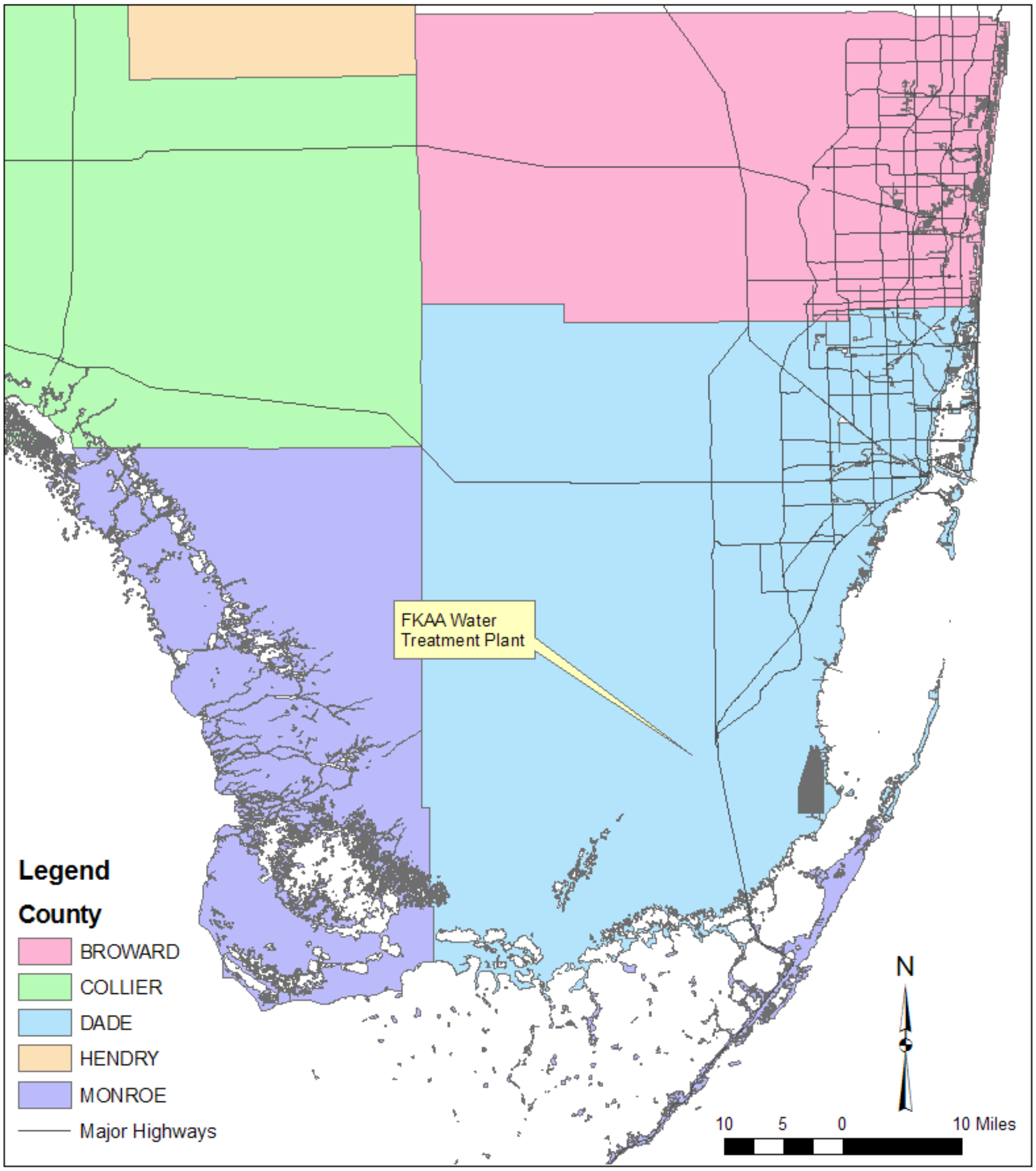
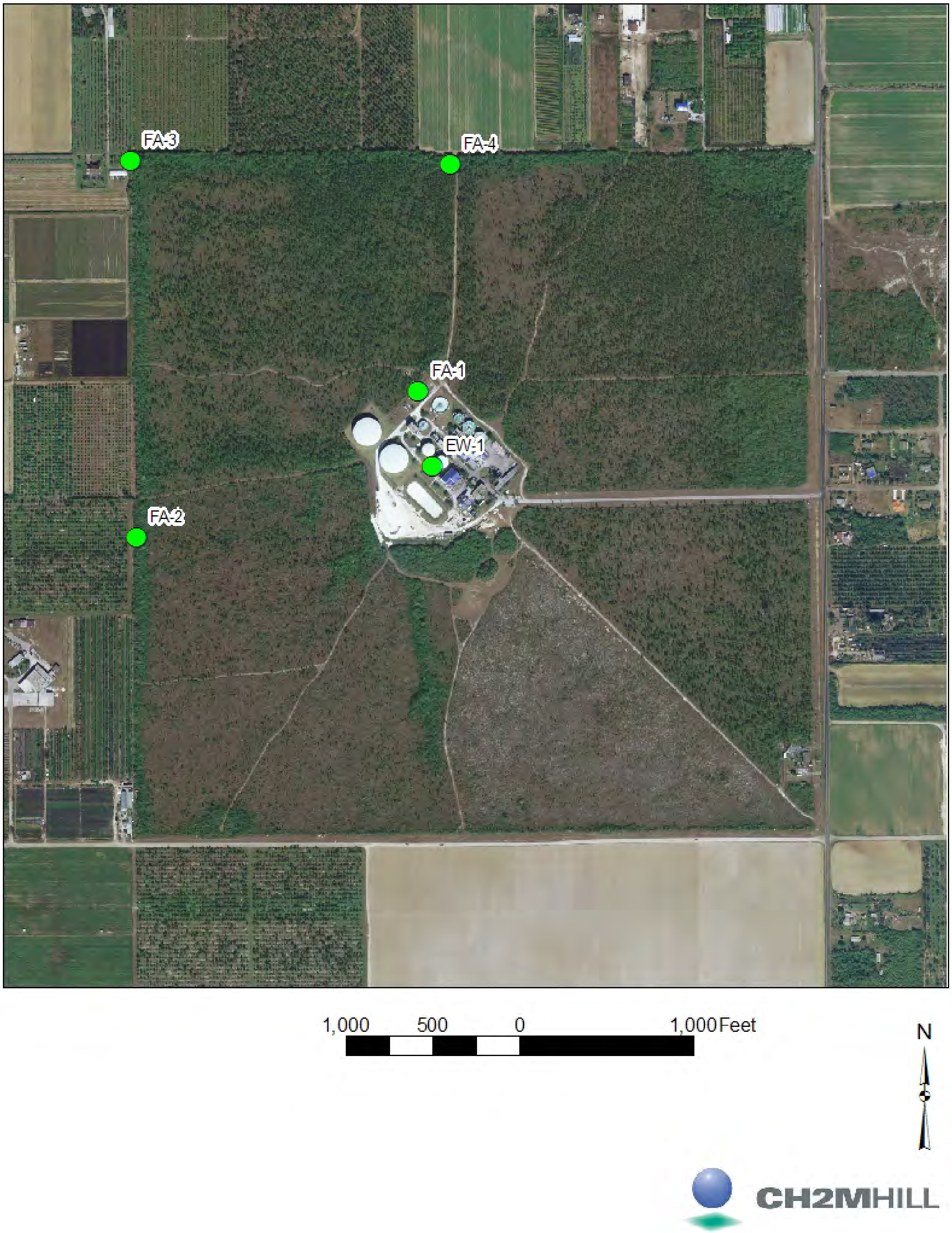


EXHIBIT 2
Floridan Aquifer Well Locations



2.0 Conceptual Model

The study area is located in Miami-Dade County, in southeastern Florida. Detailed descriptions of the hydrogeology are found elsewhere (Reese, 1994; Reese and Alvarez-Zarkikan, 2007). A brief summary of relevant geology and hydrogeology is presented in this section.

Aquifers present in the area include the Surficial Aquifer System, locally referred to as the Biscayne aquifer, and the Floridan Aquifer System. The two aquifer systems are separated by the Intermediate Confining Unit. The Floridan Aquifer System is generally described as being composed of the Upper Floridan aquifer, the Middle Confining Unit, and the Lower Floridan aquifer. Recently, the Upper Floridan aquifer has been subdivided in the area of interest based on the presence of two major flow zones, called the Upper and Middle aquifers (HydroGeoLogic, 2004; Reese and Alvarez-Zarkikan, 2007). This naming convention is used in this TM and associated modeling to assist in comparing results and properties from the regional model, the Lower East Coast Density Dependent Floridan Aquifer System model (referred to as ECFASI [HydroGeoLogic, 2006]), to the local model.

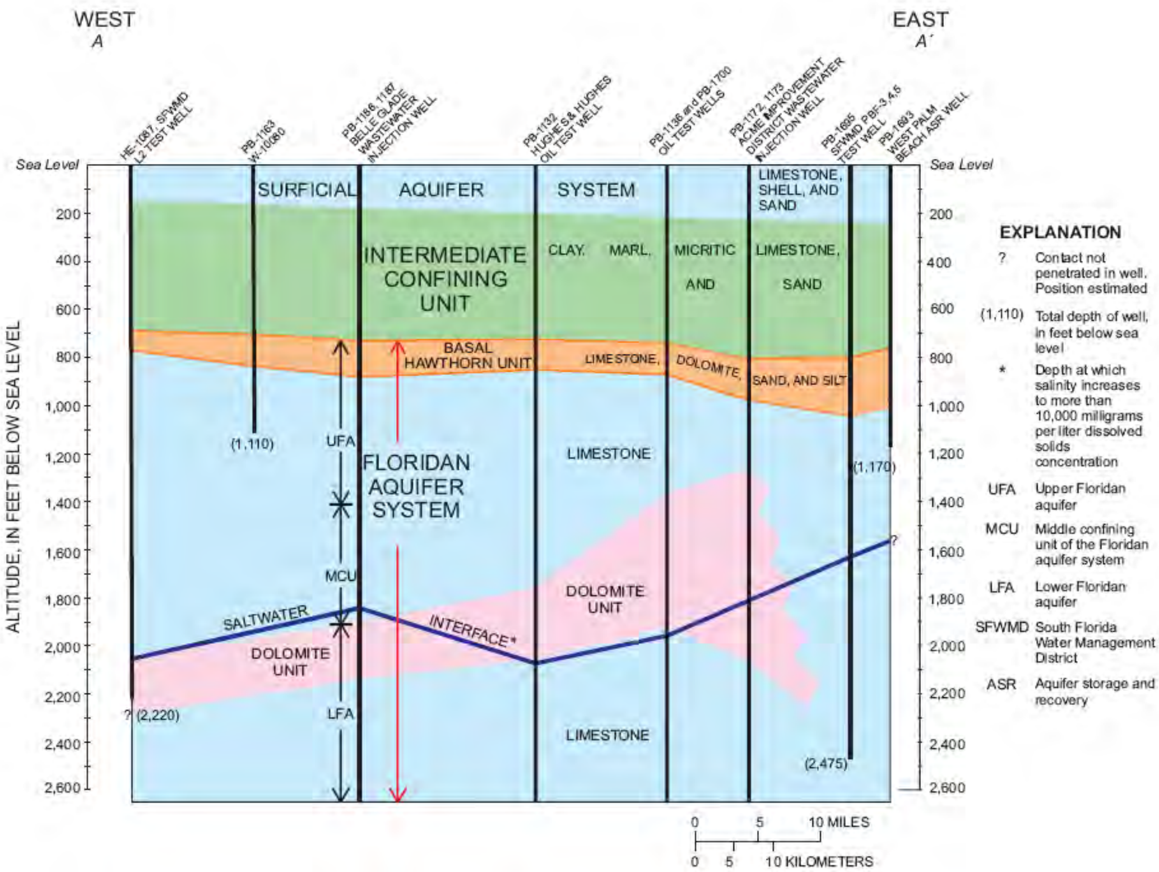
The Upper Floridan aquifer is capable of yielding significant quantities of groundwater. Its complex hydrogeology is composed of multiple aquifer units with variable water quality, generally deteriorating with increasing depth. There is variable confinement between the aquifer units, which results in a leaky system, allowing for potential up-coning of the poor quality water if well withdrawals are locally too high and wells are constructed to depths near the saline water. Water quality in the Floridan Aquifer System is divided into brackish, transition zone, and saline. Based on regional water quality data and samples collected from interval tests and packer tests at the site (CH2M HILL, 2003), water quality in the Upper Floridan ranges from approximately 2,500 milligrams per liter (mg/L) total dissolved solids (TDS) at 1,000 feet below ground surface (bgs) to approximately 10,000 mg/L TDS near 1,500 feet bgs.

Two major flow zones are present at the site. The upper flow zone extends from approximately 880 feet to 1,090 feet bgs. This zone consists of relatively higher quality water, but the transmissivity is low. The lower zone extends from 1,190 feet to the total depth of Exploratory Well EW-1. This zone has much higher transmissivity, but water quality deteriorates with depth, as described above.

Exhibit 3 depicts the conceptual model of the hydrogeology of the Floridan Aquifer System in south Florida.

The groundwater model of the site was developed using an existing regional groundwater model, ECFASI (HydroGeoLogic, 2006), and data collected from two Floridan aquifer wells drilled on the wellfield site. Aquifer properties, regional water level, and water quality trends were based on the ECFASI model.

EXHIBIT 3
HydroGeoLogic Cross-Section of the Floridan Aquifer System, South Florida
From Reese (2002)



3.0 Computer Code Description

The computer code SEAWAT-2000 (Langevin et al., 2003) was selected for the modeling effort since it is capable of simulating the flow of variable-density fluids. SEAWAT-2000 simulates the movement of groundwater, accounting for the effects of density differences caused by variable concentrations of chlorides and TDS. The model was developed by combining MODFLOW (McDonald and Harbaugh, 1988) and MT3DMS (Zheng and Wang, 1988) into a single program that solves the coupled flow and solute-transport equations.

3.1 Assumptions and Limitations

The correlation between TDS and chloride concentrations is approximately linear in south Florida (Reese 1994). It is assumed that geochemical reactions affecting TDS concentration are not significant. TDS concentration is used as the primary component affecting fluid densities. Fluid density is assumed to be solely a function of the concentration of dissolved constituents and is calculated by Equation 1:

$$\rho = \rho_f + EC \qquad (1)$$

where:

ρ = density of saline groundwater

ρ_f = density of fresh groundwater (TDS concentration = 0 mg/L) = 1,000 kilograms per cubic meter (kg/m^3)

E = a dimensionless constant having an approximate value of 0.7143 for salt concentrations between zero and seawater

C = salt concentration

For example, for a groundwater with a TDS concentration of 10,000 mg/L, the equation would result in 1,000 kg/m^3 + 0.7143 * 10 kg/m^3 = 1,007.143 kg/m^3. The density of pure seawater with a TDS concentration of 35,000 mg/L is estimated to be approximately 1,000 kg/m^3 + (0.7143 * 35 kg/m^3) = 1025 kg/m^3, approximately 2.5 percent denser than fresh water.

Like MODFLOW, SEAWAT-2000 assumes an equivalent porous medium with uniform parameters within a given model cell. The level of detail in representing individual fractures and solution features is limited to the vertical and horizontal discretization of the model domain. The Floridan aquifer is a fracture-dominated system exhibiting karstification with flow zones at regional unconformities (Reese and Alvarez-Zarikian, 2007). Therefore, groundwater flow through individual flow paths within a model cell is averaged across the entire cell. This affects the solute transport aspects of the modeling because simulated velocities of groundwater may be considerably lower than actual which may result in the simulated movement of the dissolved constituents to be under-predicted. These limitations become more important with the smaller scale model because local effects have more significant effect on observed results. Because of the scale of the wellfield model, the magnitude of pumping in the model, and the availability of data, it is not possible to model individual fractures and solution features and it is appropriate to assume an equivalent porous medium.

SEAWAT-2000 assumes isothermal flow, which may not be applicable for the Floridan aquifer. Kohout (1965, 1967) and Kohout et al. (1977) proposed that circulation patterns in the Floridan aquifer are due to geothermal heating of inland-flowing seawater in the Boulder Zone. While others (Vernon, 1970; Sproul, 1977) have offered different theories; the Floridan aquifer is not isothermal. For the local scale model focusing primarily on the Upper

Floridan aquifer, the total range of temperature and its effect on flow is expected to be negligible.

3.3 Solution Techniques

MODFLOW assumes a constant fluid density, so SEAWAT-2000 expresses the density of the water in terms of freshwater equivalent head. This concept relates the height of a column of fresh water (equivalent fresh water head) to a column of brackish water (observed head) which applies the same pressure at a specified elevation. This allows MODFLOW to correctly apply its flow equations for waters with different densities without explicitly simulating density. The relationship between freshwater equivalent head and density is shown in Equation 2:

$$h_f = \frac{P_N}{\rho_f g} + Z_N \qquad (2)$$

where:

h_f = freshwater equivalent head

P_N = pressure at point N

ρ_f = density of fresh water

g = acceleration due to gravity

Z_N = elevation of point N

According to Equation 2, the equivalent freshwater head can vary with pressure, elevation, and the water density.

The conversion between head as measured in the native aquifer water and equivalent freshwater head is made using the following relations (Equations 3 and 4):

$$h_f = \frac{\rho_s}{\rho_f} h - \frac{\rho_s - \rho_f}{\rho_f} Z \qquad (3)$$

$$h = \frac{\rho_f}{\rho} h_f + \frac{\rho - \rho_f}{\rho} Z \qquad (4)$$

where:

ρ_s = density of saline (brackish) groundwater

With freshwater equivalent heads established, SEAWAT-2000's governing equation for variable-density flow in terms of freshwater equivalent heads is:

$$\frac{\partial}{\partial\alpha}\left(\rho K_{f\alpha}\left[\frac{\partial h_f}{\partial\alpha}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial\alpha}\right]\right)+\frac{\partial}{\partial\beta}\left(\rho K_{f\beta}\left[\frac{\partial h_f}{\partial\beta}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial\beta}\right]\right)+$$
$$\frac{\partial}{\partial\gamma}\left(\rho K_{f\gamma}\left[\frac{\partial h_f}{\partial\gamma}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial\gamma}\right]\right)=\rho S_f\frac{\partial h_f}{\partial t}+\Theta\frac{\partial\rho\partial C}{\partial C\partial t}-\overline{\rho}q_s \qquad (5)$$

where:

$K_{f(\alpha,\beta,\gamma)}$ = freshwater hydraulic conductivity along the α,β, and γ axes; calculated as:

$$K_f=\frac{k\rho_f g}{\mu_f} \qquad (6)$$

where:

k = intrinsic permeability

μ_f = viscosity of fresh water under standard conditions

S_f = fresh water head specific storage

t = time

θ = porosity

C = solute concentration

$\overline{\rho}$ = density of water entering from a source or leaving from a sink

4.0 Model Development

The ECFASI model covers an area 55 miles in the east-west direction by 200 miles in the north-south direction. It consists of 14 layers representing aquifers from the Surficial Aquifer System to the Boulder Zone below the Lower Floridan aquifer. The grid spacing was uniform at 2,400 feet.

A new local scale model was created to investigate effects of pumping at the FKAA's Floridan aquifer wellfield. In order to maintain as much of the information and structure developed for the ECFASI model, an effort was made to use as much of this model as possible. Maintaining the structure of this model will also assist with future updates to the local model. **Exhibit 4** depicts the extent of the ECFASI model and the FKAA model.

The ECFASI model structure was extracted for the Upper Floridan aquifer and the top of the Upper Middle Confining Unit. The range of extracted cells from the ECFASI model is from Row 311 to Row 400, and from Column 21 to Column 105. The bottom elevations of each of these three model layers and all aquifer parameters were exported to a local model. Two model layers were added to the extracted model structure to represent the Upper Flow Zone identified in EW-1 and Well 1. Two constant thickness layers were added to the model to represent the upper flow zone and confining unit identified during drilling of the on-site wells. Layer 5 elevations were used in the model but aquifer hydraulic conductivity values were increased based on calculated total transmissivity at the site. A no-flow boundary is present below layer 5, representing the Middle Confining Unit present in the ECFASI model.

Model elevations in the area of the new wellfield are presented in **Exhibit 5**.

EXHIBIT 4
Model Grid Extent

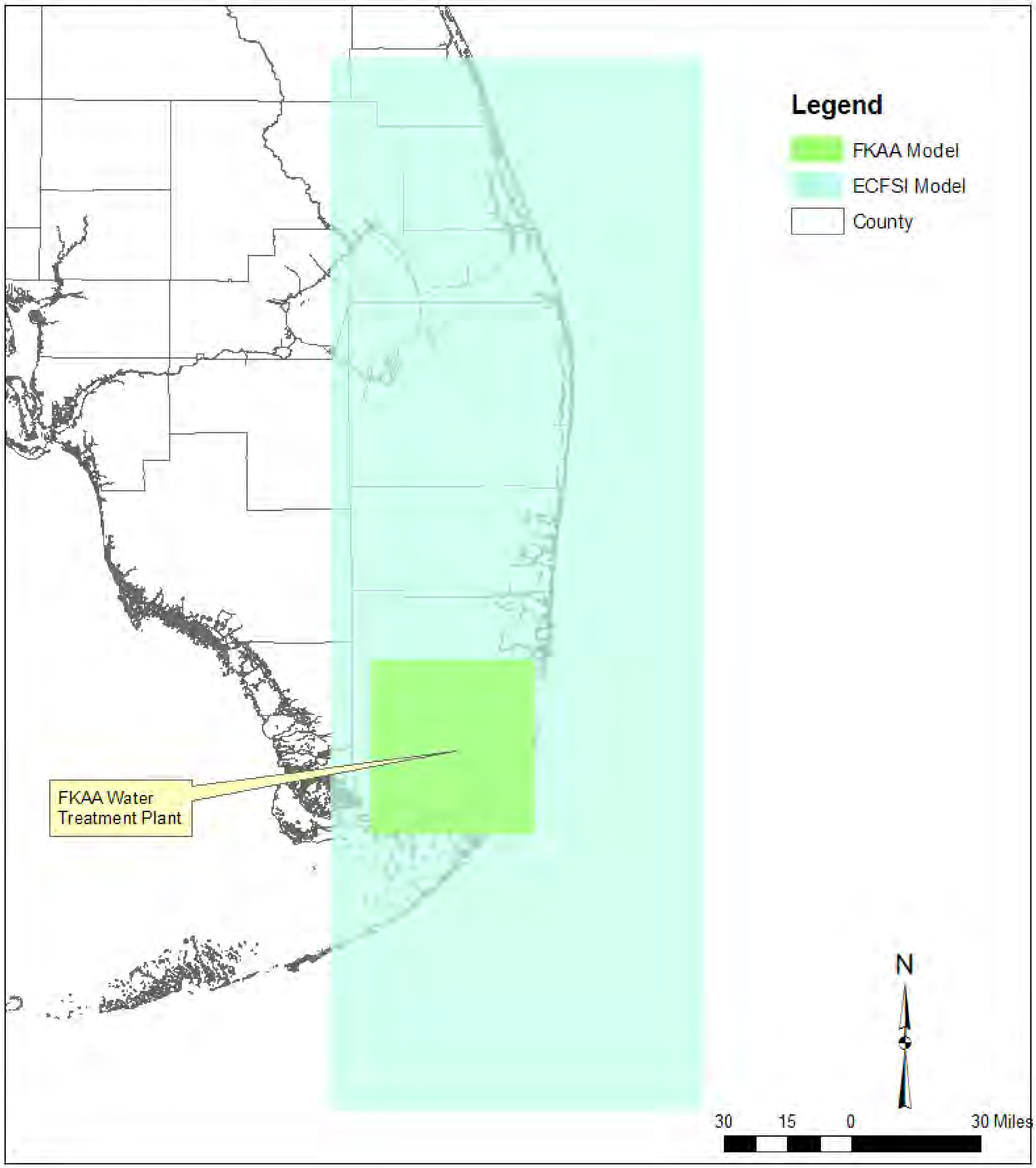


EXHIBIT 5
Model Structure near the FKAA Wellfield

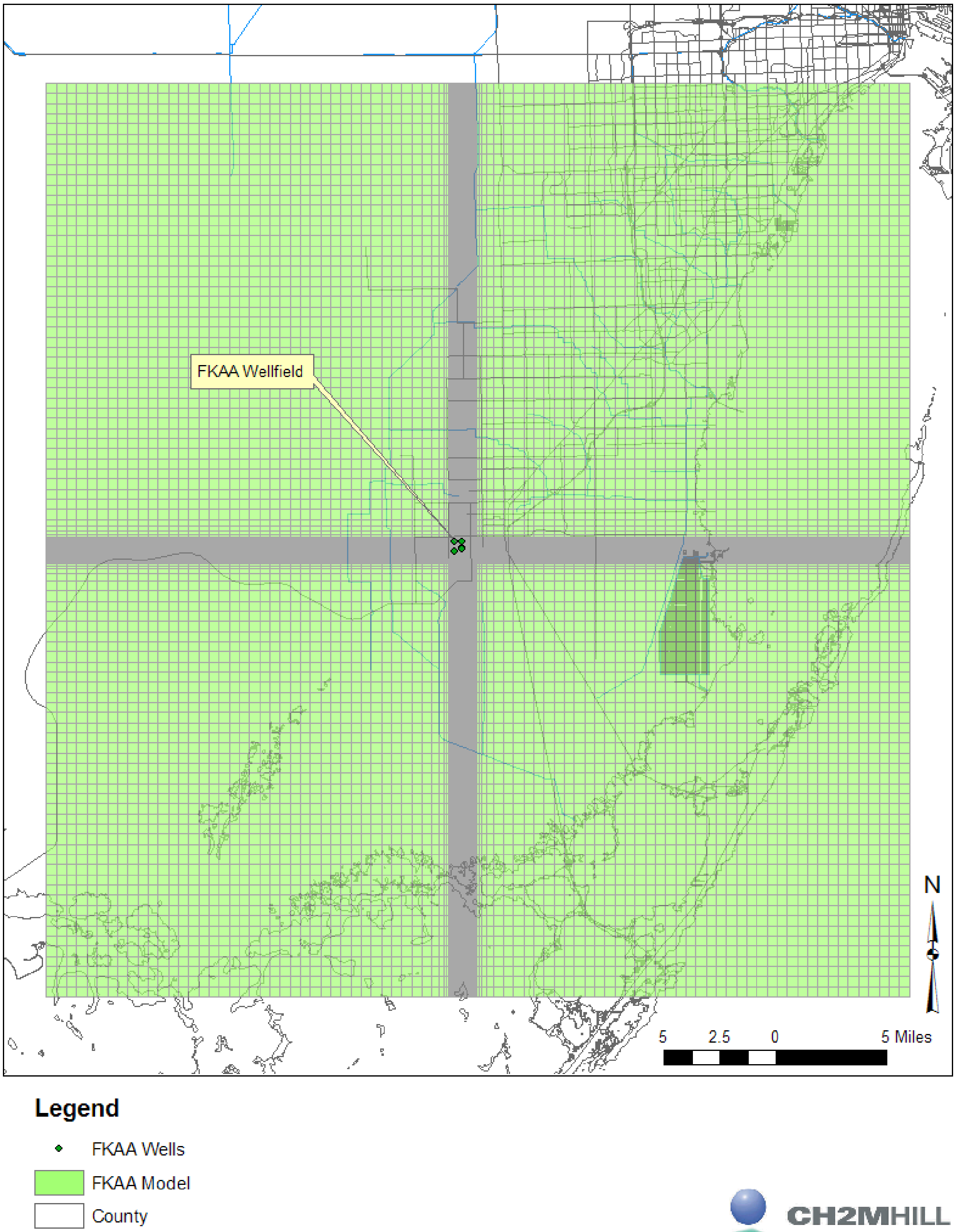
ECFASI Layer	FKAA Layer	Hydrogeologic Unit	Top Elevation (feet)	Bottom Elevation (feet)
21	1	Lower Hawthorn	-880	-1020
21	2	Confining Unit	-1020	-1100
3	3	Upper Floridan	-1100	-1180
4	4	Upper Floridan	-1180	-1265
5	5	Upper Floridan2	-1265	-1415

Notes:
1. FKAA Model Layer 1 elevations fall within ECFASI Layer 2; however, ECFASI Layer 2 elevations and properties were not used in the FKAA Model.
2. Elevations for ECFASI Layer 5 were used but properties were modified.

Model Grid

The model origin is located at 296,352 feet north, 720,200 feet east Florida State Plane NAD 83 HARN. The model grid is set up with a minimum grid size of 100 feet near the wellfield, expanding to a maximum grid spacing of 2,400 feet away from the wellfield. The locations of the 2,400-foot cells correspond to the cell locations in the original ECFASI model. The model extents are shown on **Exhibit 4.** The model consists of 142 rows, 137 columns, and five layers for a total of 97,270 cells. The model is approximately 41 miles in the north-south direction, by 39 miles in the east-west direction. **Exhibit 6** depicts the model grid geometry.

EXHIBIT 6
FKAA MODEL GRID



Production Wells

Wells in the FKAA Wellfield penetrate two main flow zones separated by a confining layer. Each well was represented in the model producing water from layers 1 through 3. This corresponds to open-hole intervals between approximately 880-feet bgs and 1,175-feet bgs. The total pumping rate was distributed across each of the layers proportional to the layer transmissivity.

Boundary Conditions

No flow boundaries are used at the top and bottom of the model domain, representing the Intermediate Confining Unit above the Upper Floridan, and the Middle Confining Unit below. Based on parameters chosen in the ECFASI model and response during pump tests, the approximation of no-flow boundaries is reasonable.

The lateral extents of the model are represented with Specified Head/Specified Concentration Boundaries. The specified head and concentration values were taken from the ECFASI model run representing conditions in December 2004. Boundary condition heads for the long-term simulation were varied over time to represent the large withdrawal from the wellfield. A Theis drawdown analysis was performed as a starting point to estimate drawdown at the model boundary over the course of 10 years. The drawdown at the boundary was reduced based on vertical leakance from the lower layers. This was accomplished by comparing results inside the model domain to specified results at the boundary through a trial-and-error process until a reasonable match was obtained. For the 10-year simulation, drawdown at the boundary was approximately 4 feet.

Aquifer Parameters and Initial Conditions

Aquifer parameters were chosen based primarily on the regional ECFASI model. The values of horizontal conductivity were retained for layers 3 and 4, representing the lower flow zone at the site. The hydraulic conductivity of layer 5 in the FKAA model was estimated to be 50 percent of the value in the main flow zone, a significant increase from the ECFASI model where this layer represented the top of the Intermediate Confining Unit. Applying the factor to the known hydraulic conductivity in layers 3 and 4 allowed the model to retain the general hydraulic conductivity trends included in the ECFASI model while matching the total aquifer system transmissivity calculated during pumping tests at the site. **Exhibits 7** through **11** show the distributions of horizontal and vertical hydraulic conductivity.

EXHIBIT 7
Layer 1 Horizontal (Kx) and Vertical (Kz) Hydraulic Conductivity Distribution

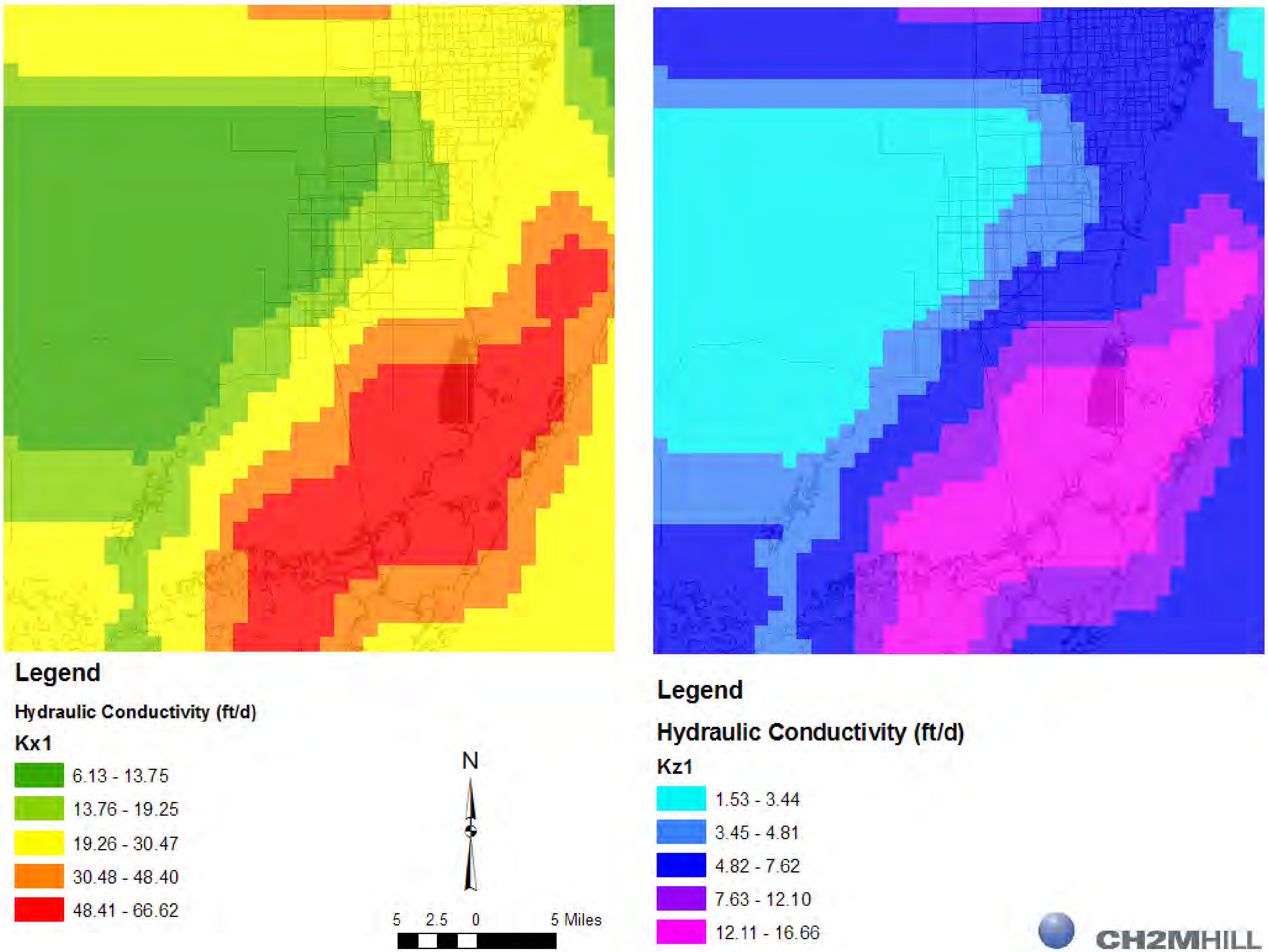


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EXHIBIT 8
Layer 2 Horizontal (Kx) and Vertical (Kz) Hydraulic Conductivity Distribution

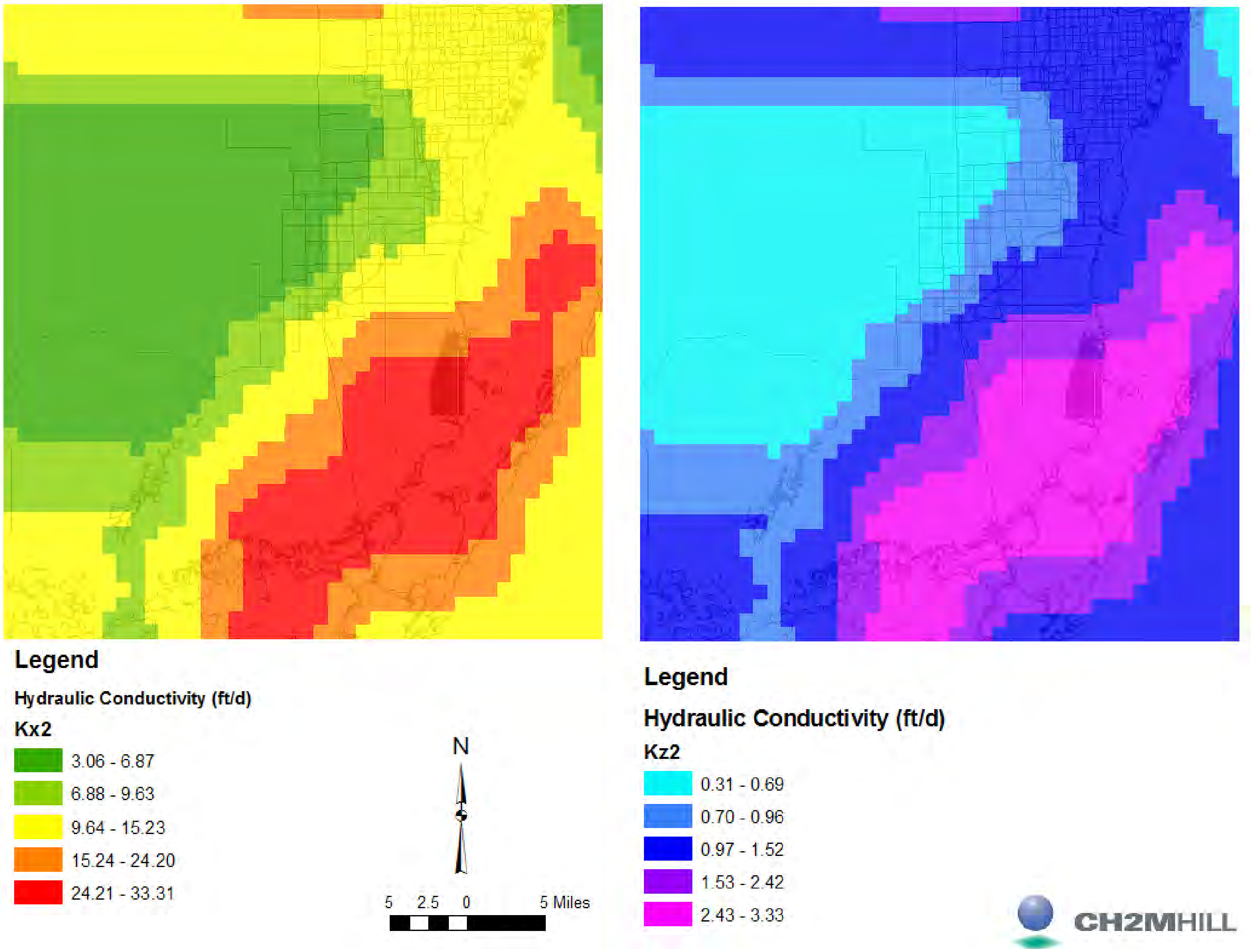


EXHIBIT 9
Layer 3 Horizontal (Kx) and Vertical (Kz) Hydraulic Conductivity Distribution

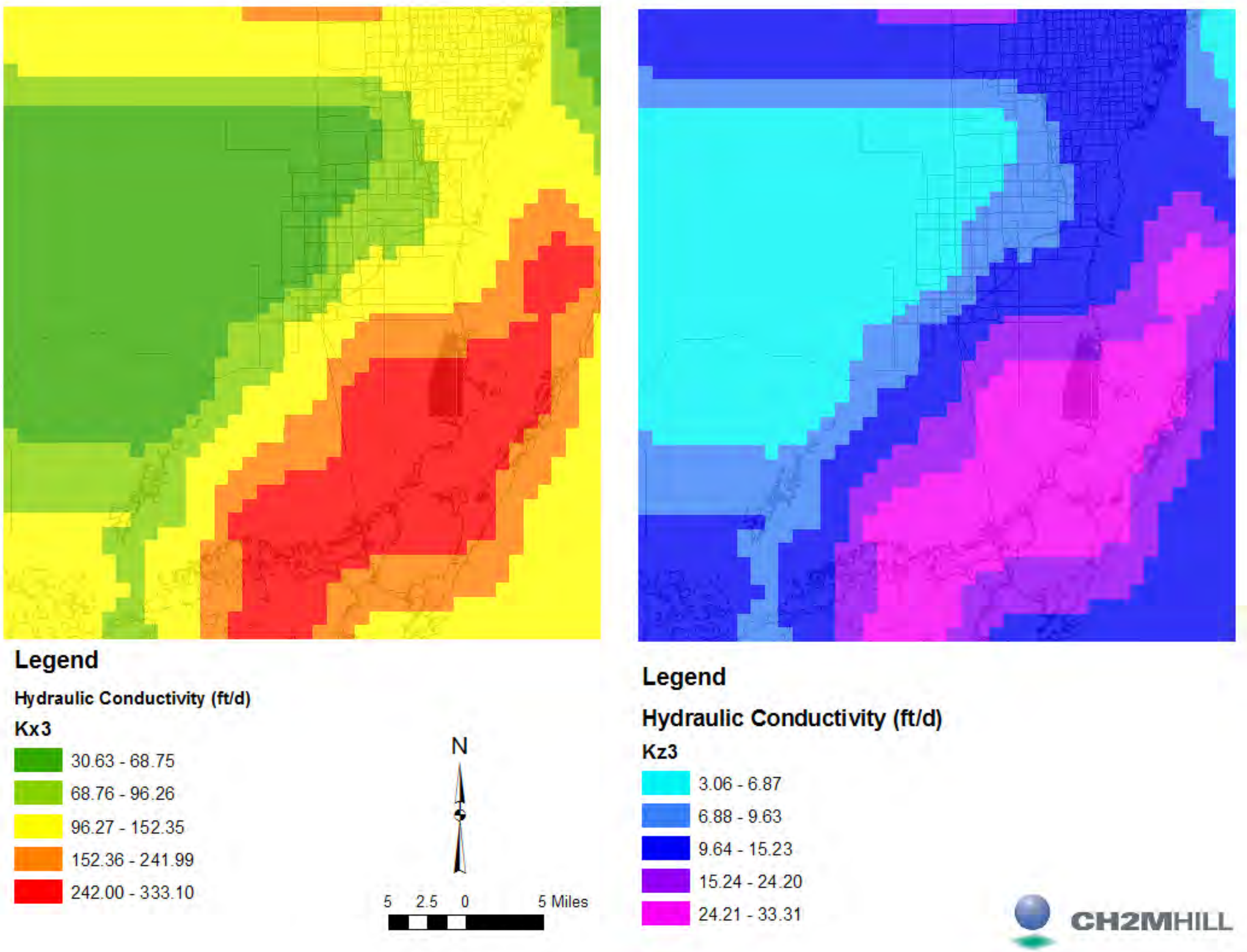


EXHIBIT 10
Layer 4 Horizontal (Kx) and Vertical (Kz) Hydraulic Conductivity Distribution

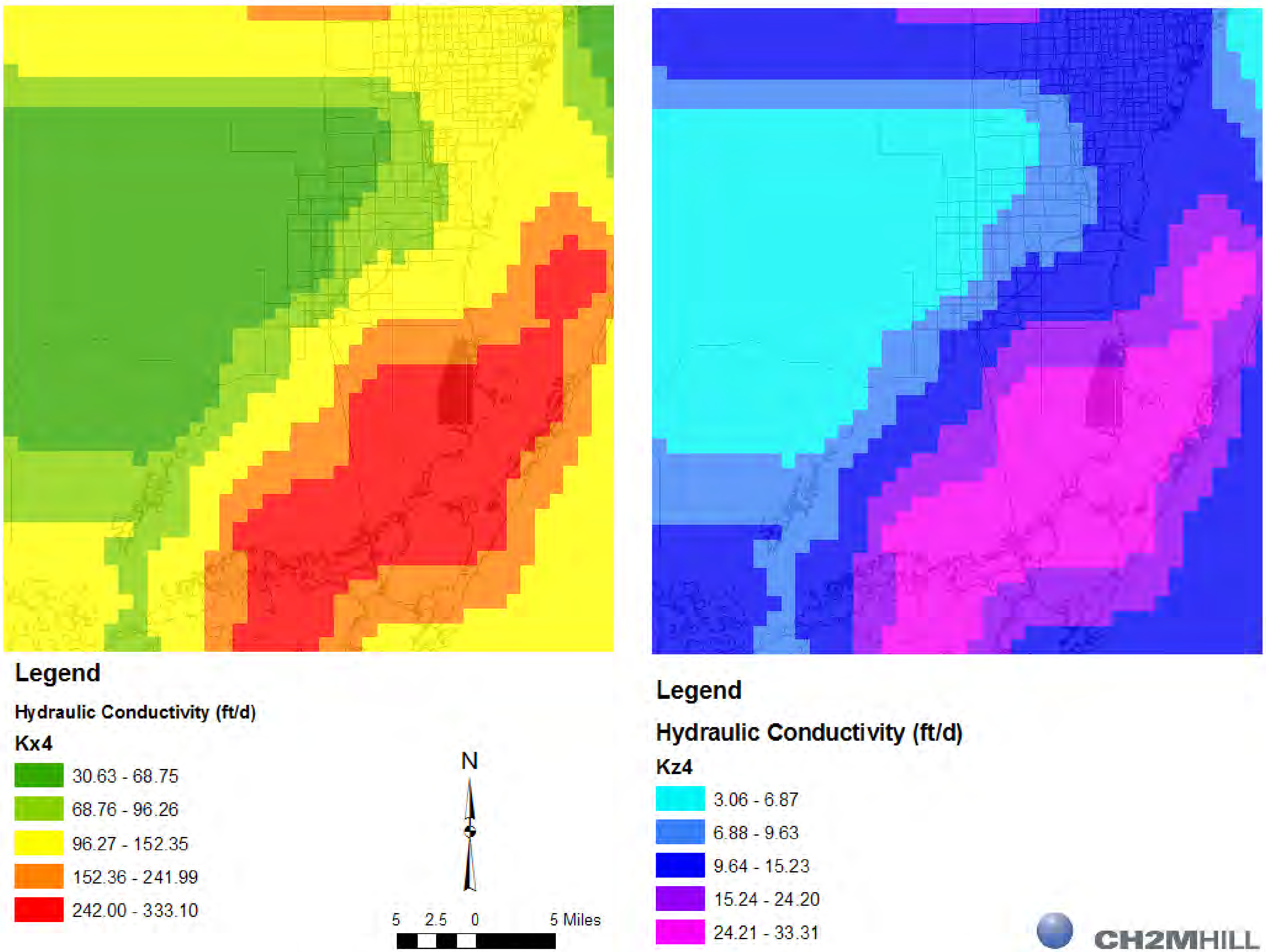
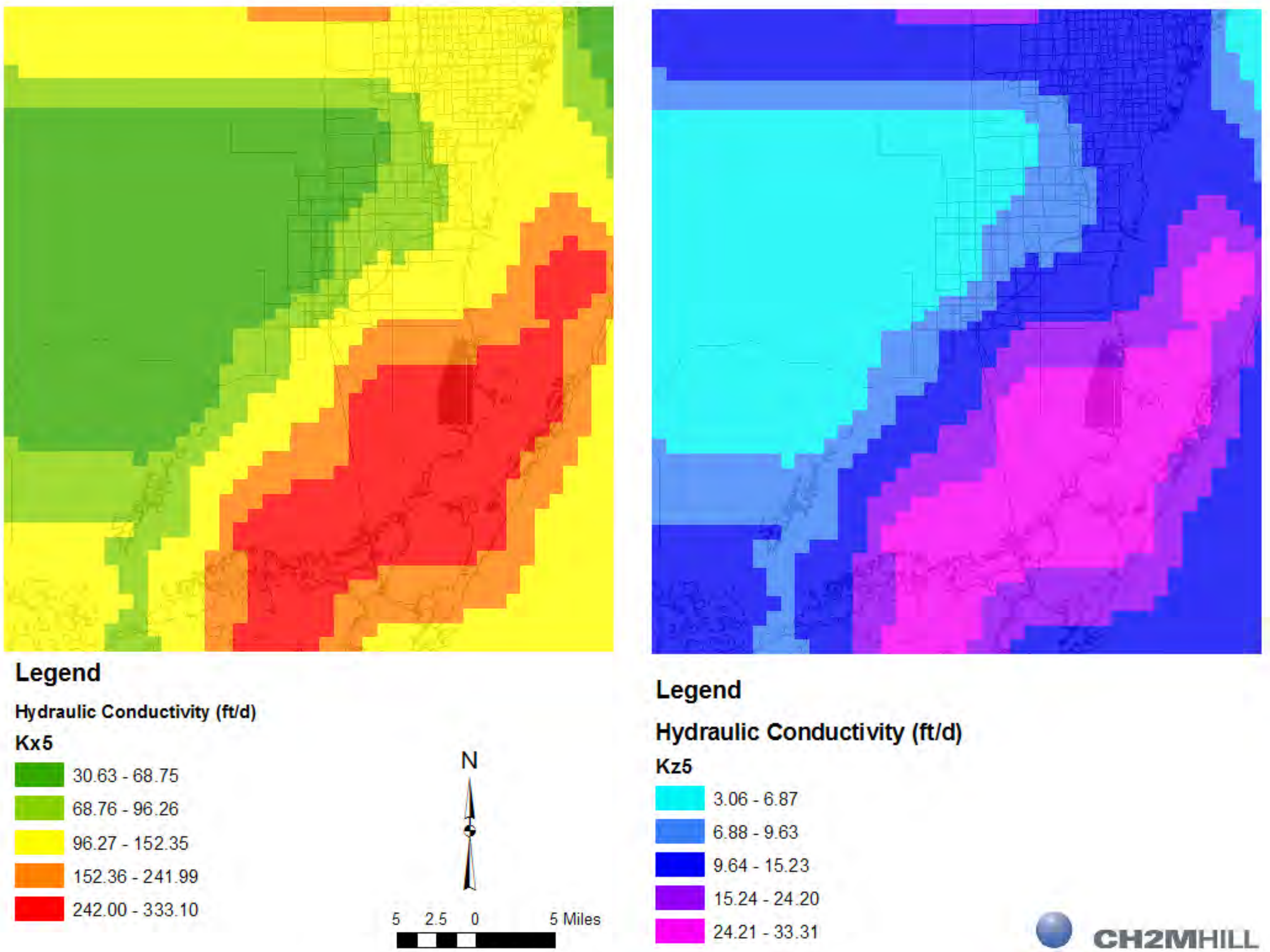


EXHIBIT 11
Layer 5 Horizontal (Kx) and Vertical (Kz) Hydraulic Conductivity Distribution



Initial heads and concentrations for layers 3 through 5 of the FKAA model were taken from the ECFASI model. Concentrations in layer 5 were retained from the regional model. These concentrations are significantly higher than the concentrations in layers 3 and 4, providing a significant source of saline water to the upper layers during pumping. For the new layers 1 and 2, initial concentrations were set at 50 percent of the initial concentration of layer 3. Again, applying a factor to the property value allowed the model to retain the general trend in water quality while approximately matching observed site-specific conditions. **Exhibits 12** though **16** show the distributions of initial concentrations in the model.

EXHIBIT 12
Initial Concentrations (Seawater Fraction), Layer 1

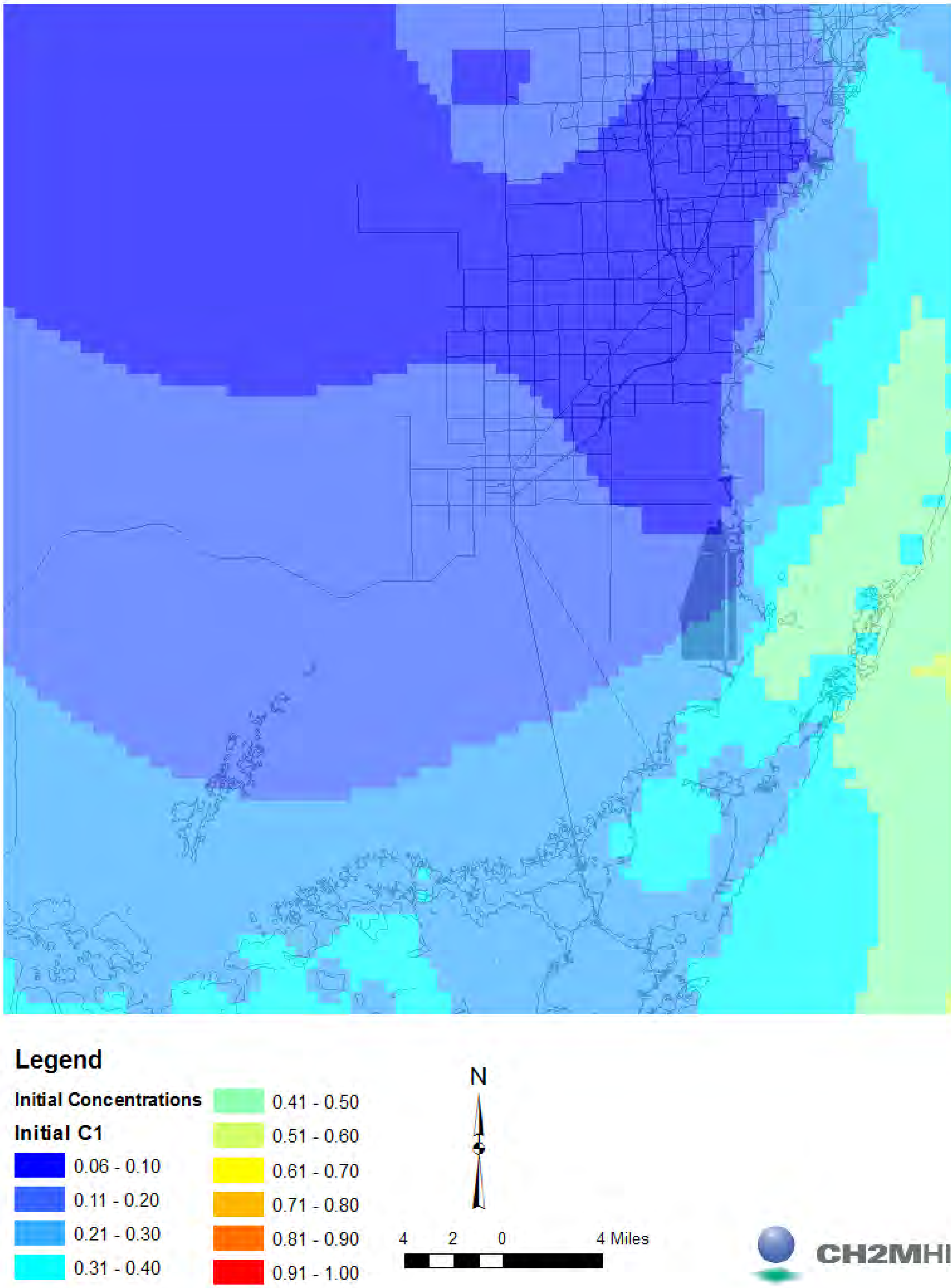


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EXHIBIT 13
Initial Concentrations (Seawater Fraction), Layer 2

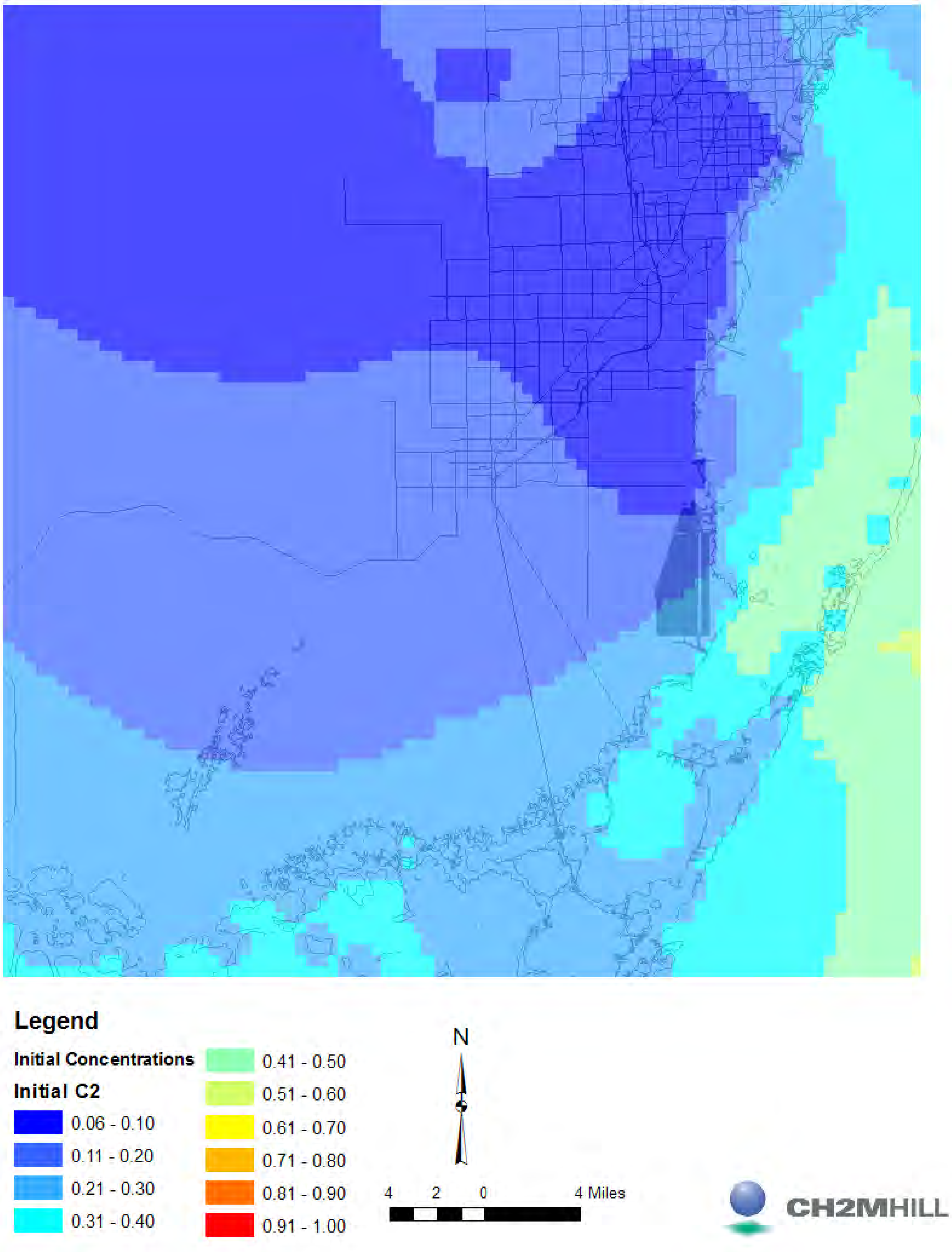


EXHIBIT 14
Initial Concentrations (Seawater Fraction), Layer 3

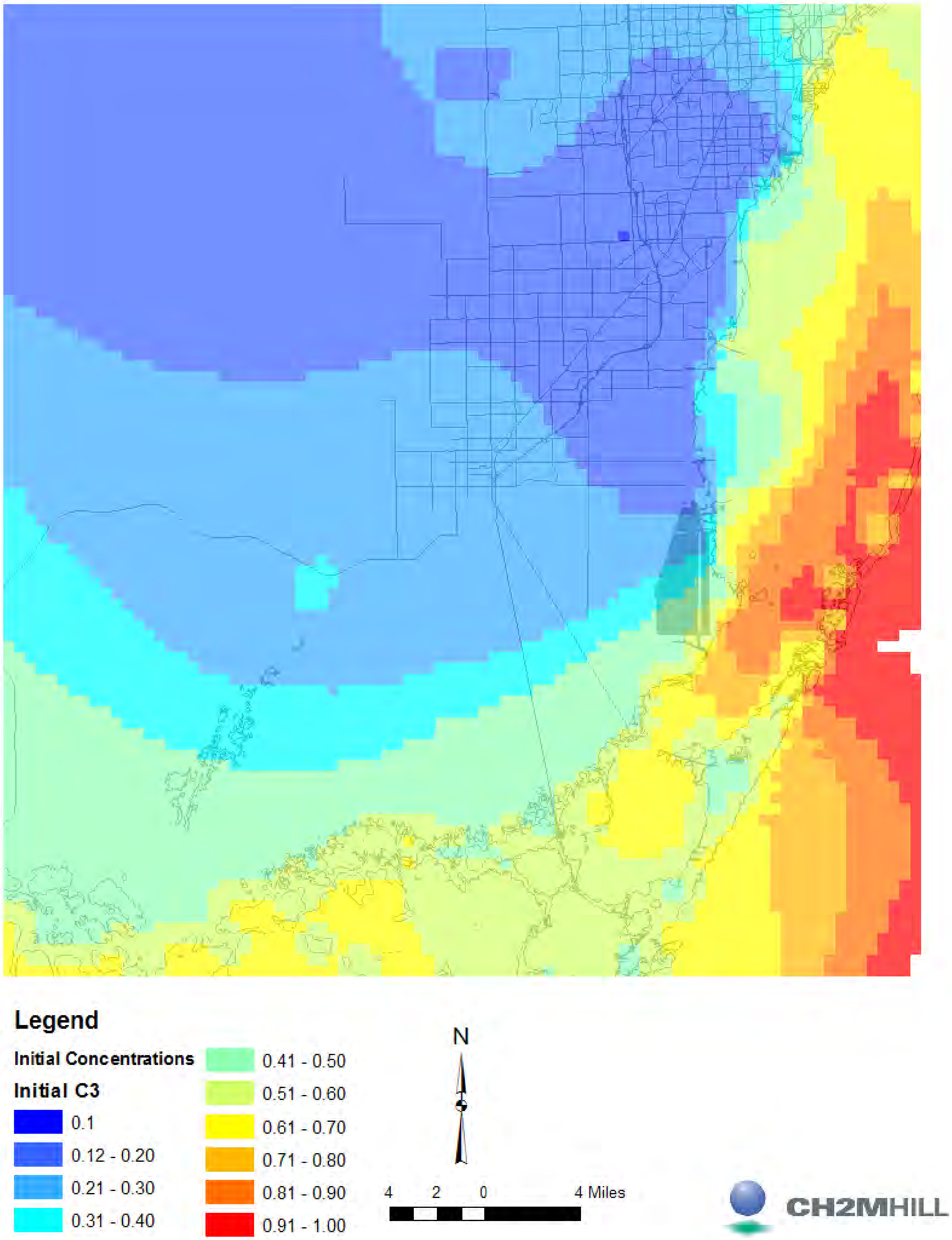


EXHIBIT 15
Initial Concentrations (Seawater Fraction), Layer 4

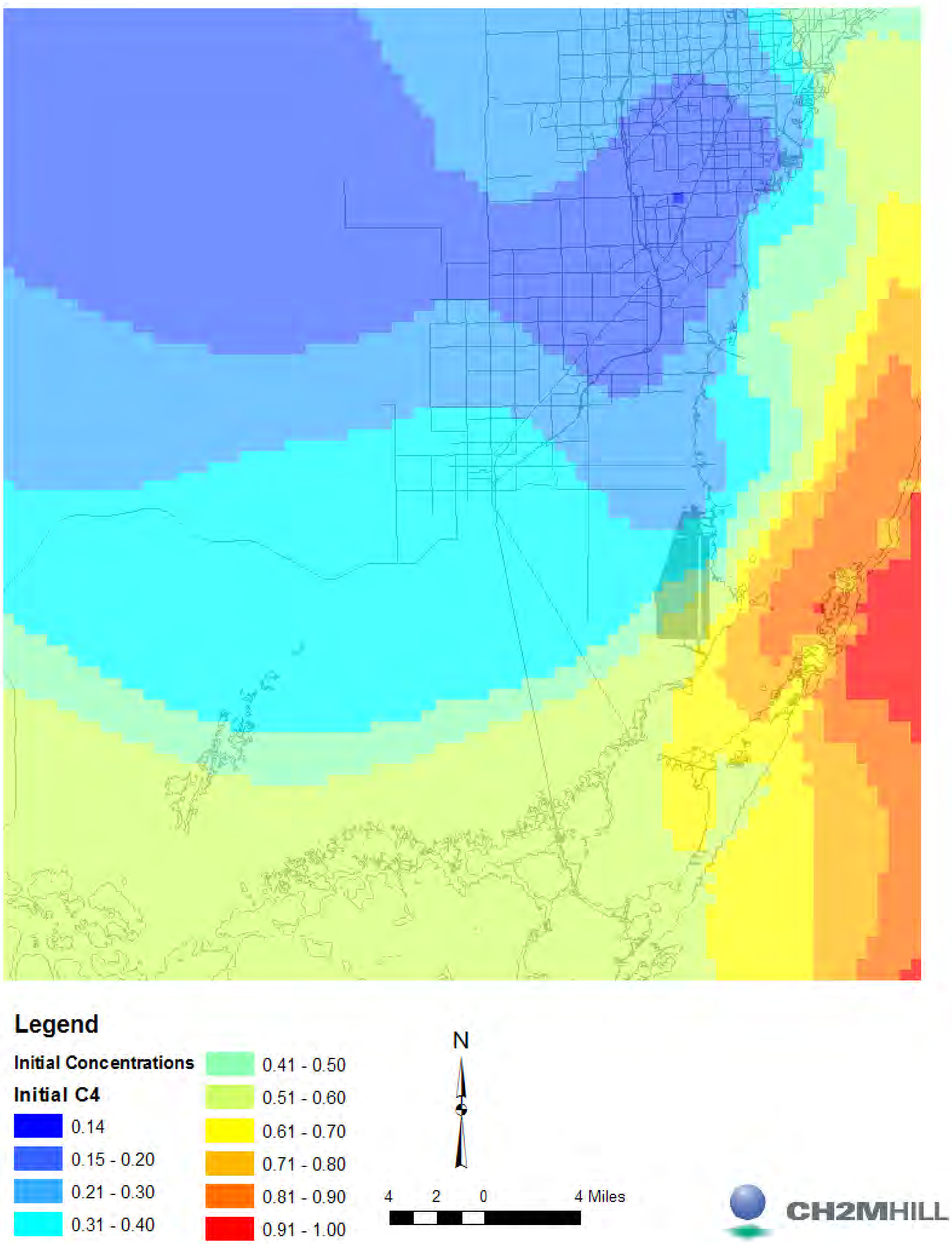
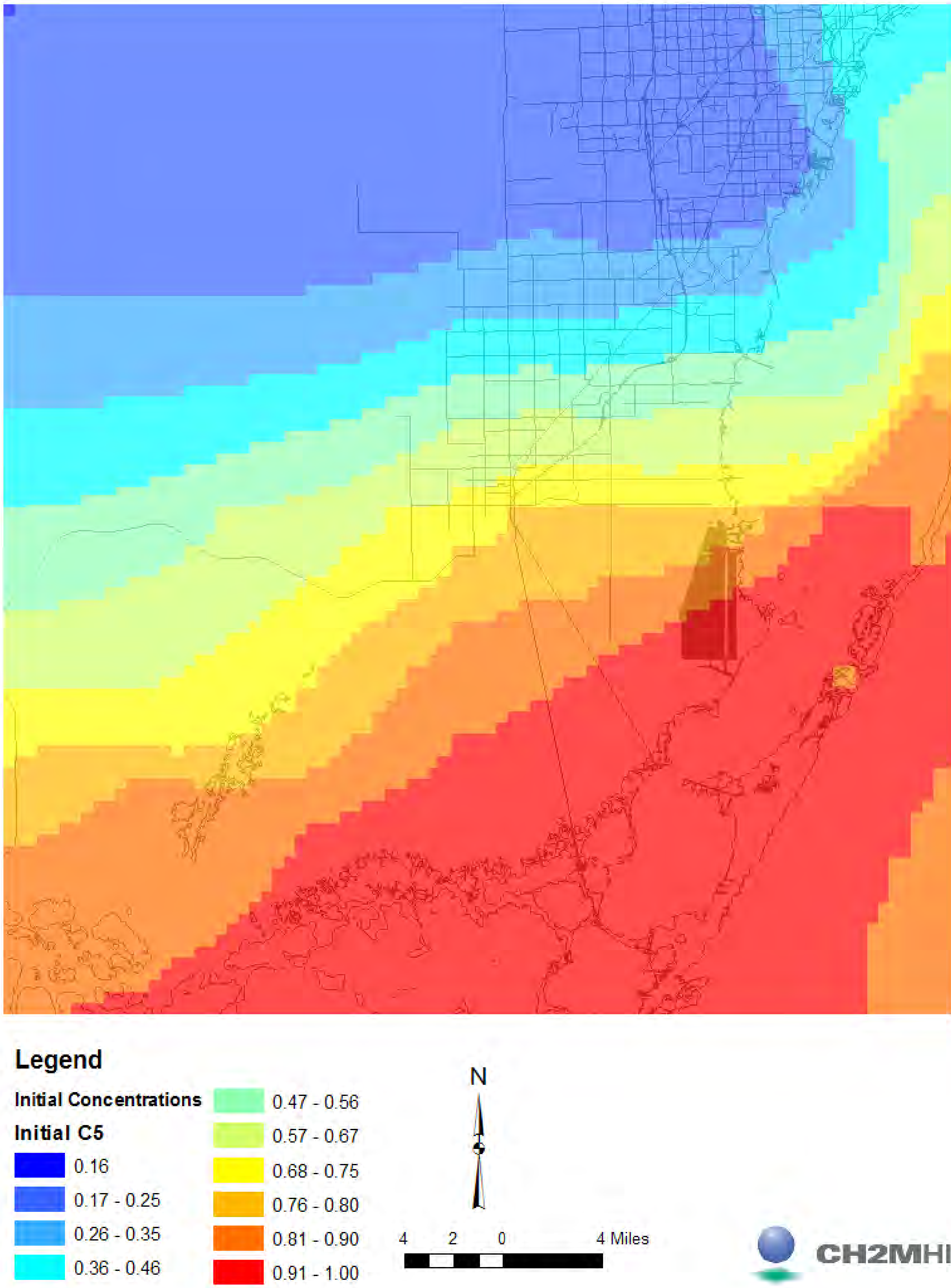


EXHIBIT 16
Initial Concentrations (Seawater Fraction), Layer 5



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5.0 Model Calibration

The model was calibrated to the 72-hour aquifer performance test (APT) conducted on the aquifer storage and recovery (ASR) well from July 23 to July 26, 2007. **Exhibit 17** depicts the observed and simulated water levels (drawdown) in wells EW-1 (blending well) and FA-1 (ASR well).

EXHIBIT 17
APT Test Data

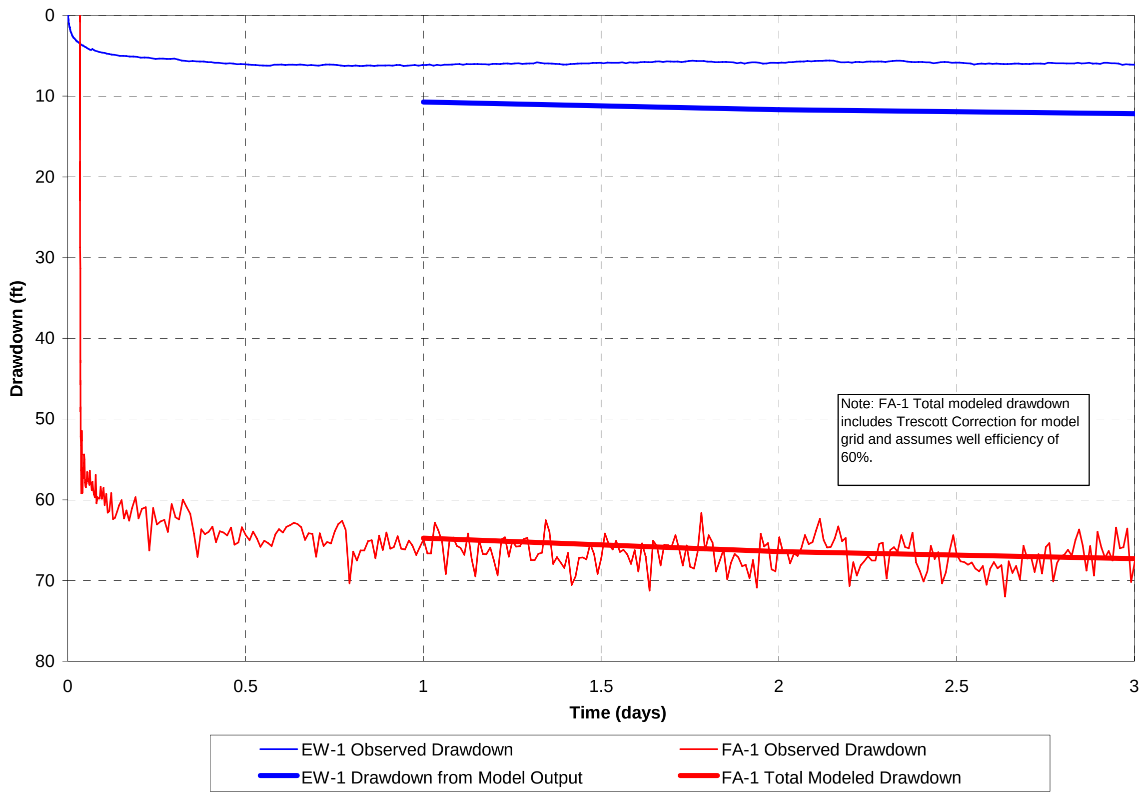
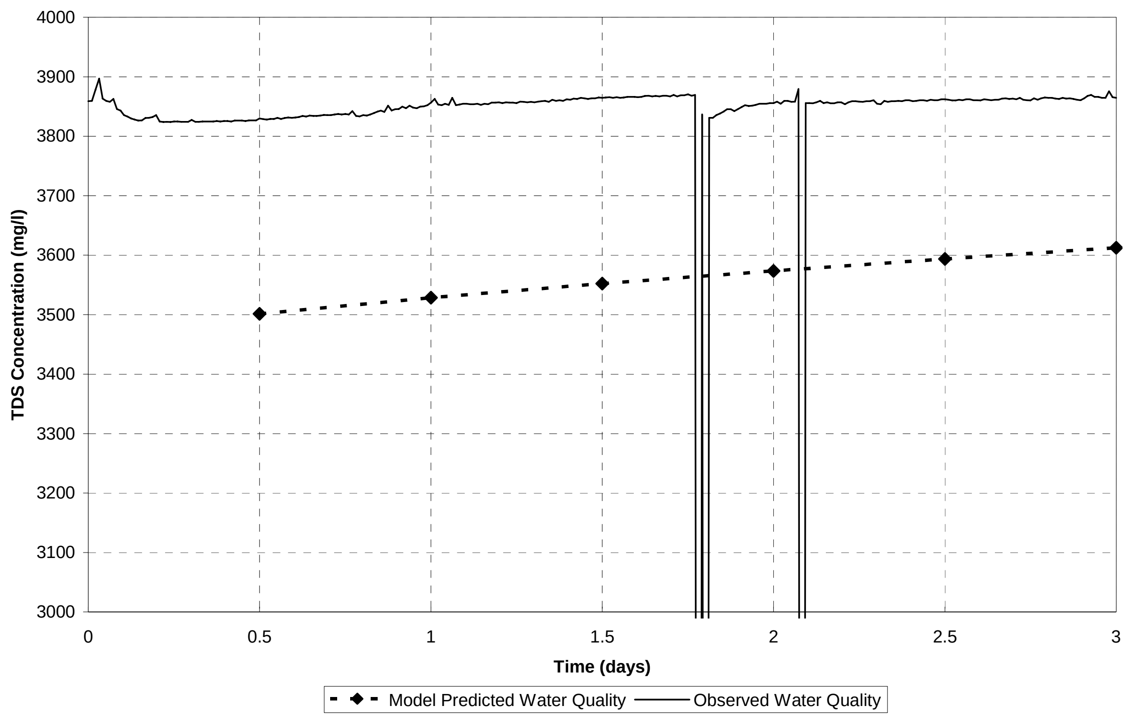


Exhibit 18 depicts the observed and simulated water quality for Well FA-1 during the 72-hour APT.

EXHIBIT 18
APT Test Data



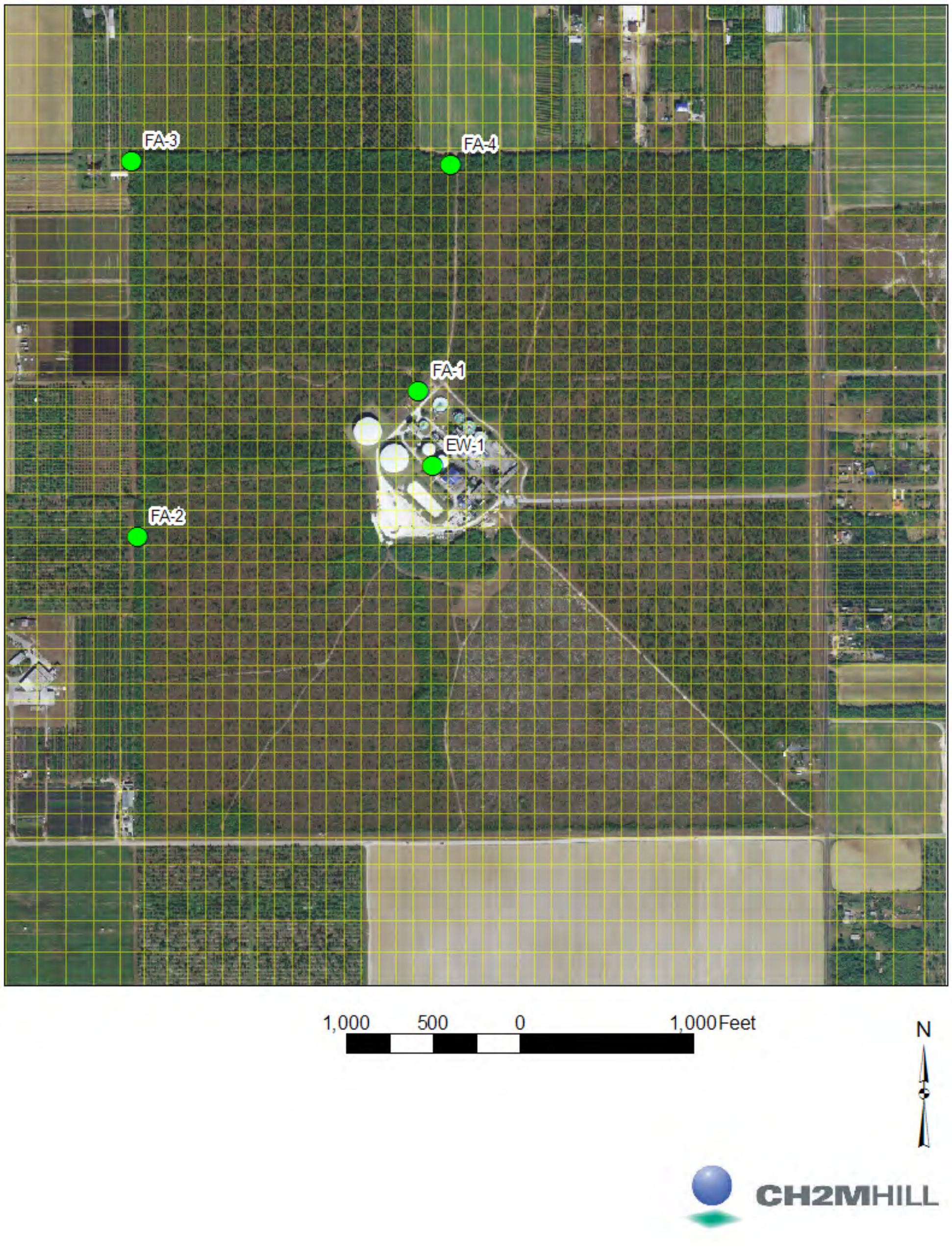
Drawdown values for the wells are average values calculated from the total drawdown in each of the 3 layers penetrated by the wells. Drawdown in the pumping well was adjusted using the Trescott correction to calculate the drawdown in the small-diameter well from model output of average drawdown in a 100-foot by 100-foot cell. In addition, a well-efficiency factor of 60 percent was applied representing the well's incomplete connection to the full transmissivity of the aquifer. No correction factors were applied to the drawdown values from the monitor well. The model over-predicts the drawdown at the monitor well by approximately 5 feet over 3 days. Applying a higher well-efficiency factor results in the model under-predicting drawdown at the pumped well. The hydraulic calibration appears to be a good compromise. Predicted water quality (TDS concentration) is within approximately 10 percent of the observed value. The water quality calibration appears to be adequate for the preliminary predictive simulations.

The mass balance for flow and solute were both evaluated for the simulation and both were well within acceptable limits. The model flow budget discrepancy was less than 1 percent. The relative MT3D mass-balance error was essentially zero.

6.0 Predictive Simulations

When completed, the FKAA's RO WTP will be supplied by five wells. Wells FA-1, FA-2, FA-3, and FA-4 are the main production wells. Well EW-1 will be used as a blending well. **Exhibit 19** depicts the locations of the simulated wells the modeled locations of the wells and the model grid spacing.

EXHIBIT 19
Floridan Aquifer Wells and Model Grid



The model was run with all 4 production wells operating at 2.39 mgd and Well EW-1 (blending well) operating at 0.7 mgd. **Exhibit 20** depicts the expected drawdown during 10 years of operation. The drawdown in the figure has again been corrected using an assumed 60 percent well efficiency and a Trescott correction to convert model cell drawdown to expected drawdown at the well. Drawdown in wells FA-1, FA-2, FA-3, and FA-4 is on the order of 90 to 100 feet. Due to its lower pumping rate, the simulated drawdown in Well EW-1 (blending well) is approximately 70 feet after 10 years.

EXHIBIT 20
Simulated Drawdown, 10 Years

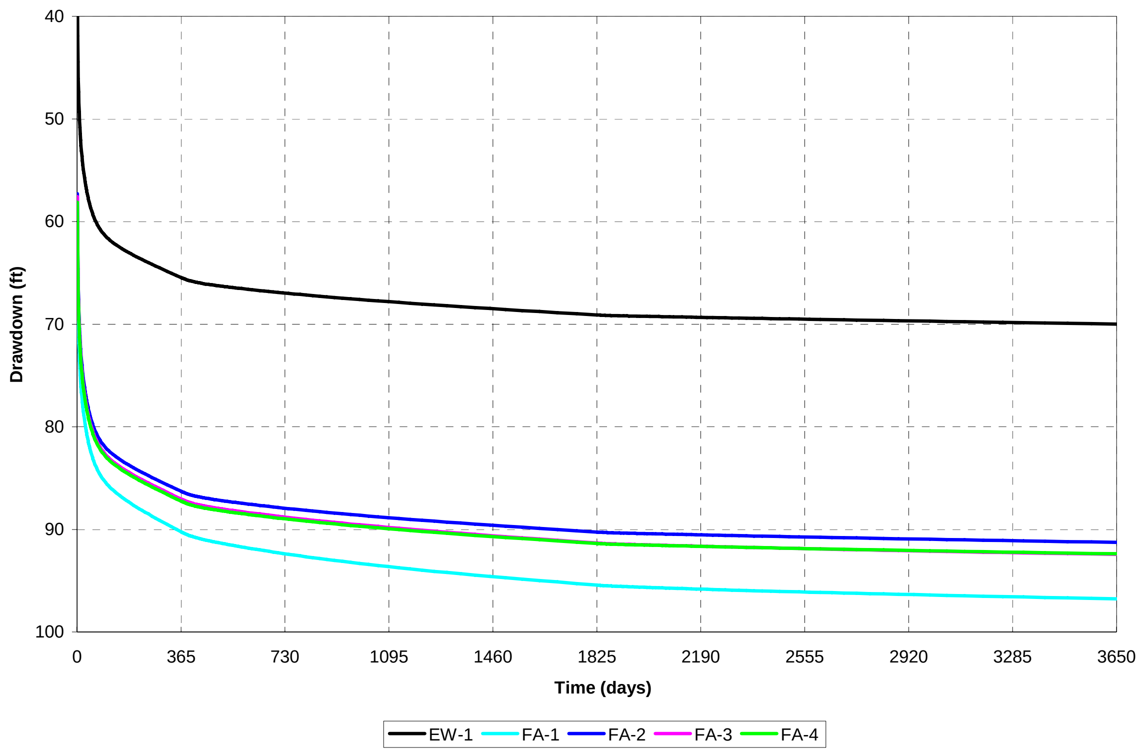
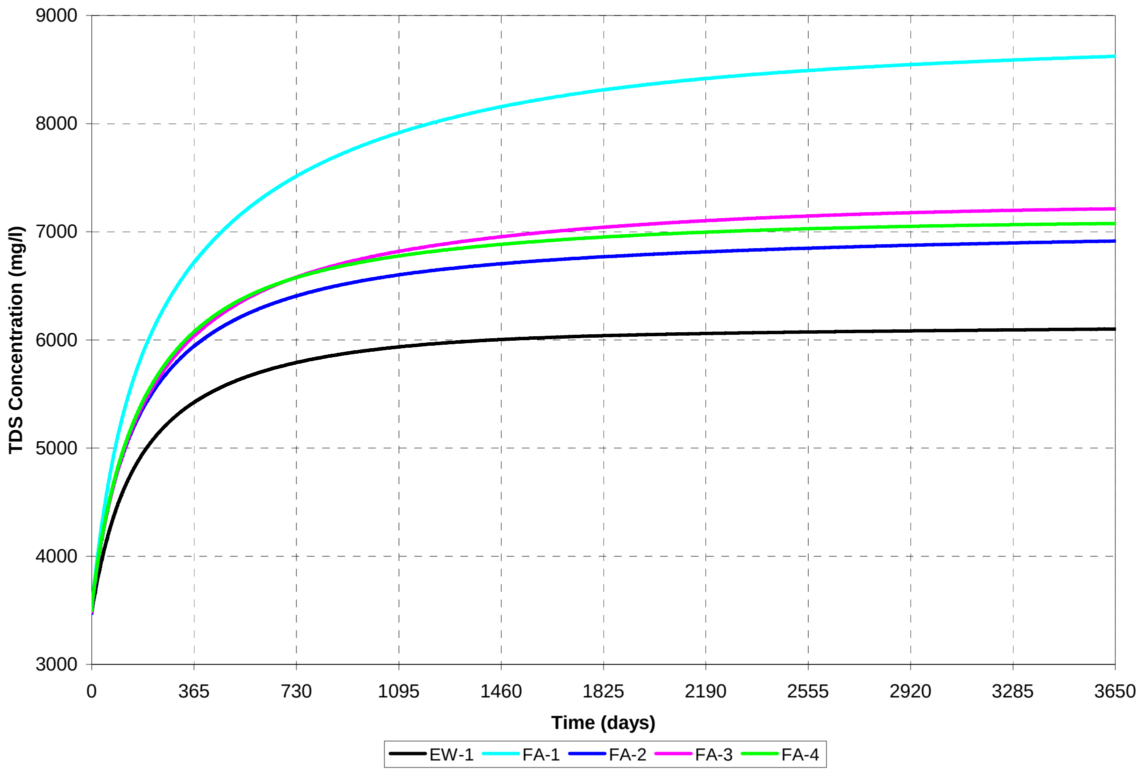


Exhibit 21 depicts the simulated TDS concentration in each well during the 10-year simulation period. As described above, the production wells are completed across model layers 1 through 3 with production from each zone proportional to the local transmissivity of the layer. The composite TDS concentration in the well was calculated based on the flow and concentration entering the well from each of the layers.

EXHIBIT 21
Simulated TDS Concentrations, 10 Years



The mass balance for flow and solute were both evaluated for the simulation and both were well within acceptable limits. The model flow budget discrepancy is approximately 1.4 percent. The MT3D mass balance error was less than 1 percent. The flow budget discrepancy is a little higher than during the calibration run, most likely due to the longer time steps required for the long term simulation.

7.0 Model-Specific Limitations

The variable-density SEAWAT-2000 model developed for the FKAA wellfield can be used to develop an understanding of the potential movement of saline groundwater under the influence of pumping from the proposed wellfield.

Data collected from the site provide a good indication of water quality and transmissivity at the site. Actual values of vertical hydraulic conductivity are not as well defined and were based on ratios of horizontal to vertical hydraulic conductivity. The long-term model run predicts water quality and drawdown at 10 years. Extrapolating data collected over 3 days during the aquifer performance test to 10 years provides an indication of potential changes in head and water quality and drawdown but there is significant uncertainty because the water quality changes observed over 3 days were small compared to those expected over 10 years.

The large withdrawals over 10 years result in drawdown at the boundaries as described in Section 4 of this memorandum. The high variability in aquifer parameters makes predictions of aquifer response away from the wellfield more uncertain. However, the changes in head at the boundaries are very small compared to drawdown observed in the area of the wellfield.

Pumping at the wells was distributed across three layers proportional to the transmissivity of the layers. The resultant heads did not match exactly and were averaged to estimate predicted values of head in the well.

Currently, the model does not include additional users of the Upper Floridan aquifer within the model domain. The construction and operation of additional wells in the area may affect the water levels and water quality.

Despite these model-specific limitations, it is expected that the model provides a good estimate of future conditions in the wellfield. These limitations may be evaluated further during future phases of the project as additional data is collected and analyzed.

8.0 Summary and Recommendations

Results of the predictive modeling indicate that high-TDS water from the lower part of the Upper Floridan aquifer is likely to move up to the production zone over time. The maximum simulated concentration was on the order of 8,600 mg/L.

The hydraulic capacity of the aquifer appears to be adequate to support long term production based on aquifer parameters from the ECFASI model and data collected at the site.

Larger stresses on the aquifer and additional individual pump tests on the remaining planned three wells will be helpful in quantifying the variability at the site and provide additional data for future model refinement. Also, the model should be updated after long-term operation of the facility is underway and data collected should be compared to model estimates. The model can then be refined and operating plans can be adjusted if necessary. Finally, planned updates to the ECFASI should be reviewed and evaluated to determine the effect on the FKAA wellfield model estimates.

9.0 References

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