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An Iterative Modeling Procedure To Evaluate Drawdowns In a Coupled-Aquifer System: SURFDOWN and MODFLOW Models

by

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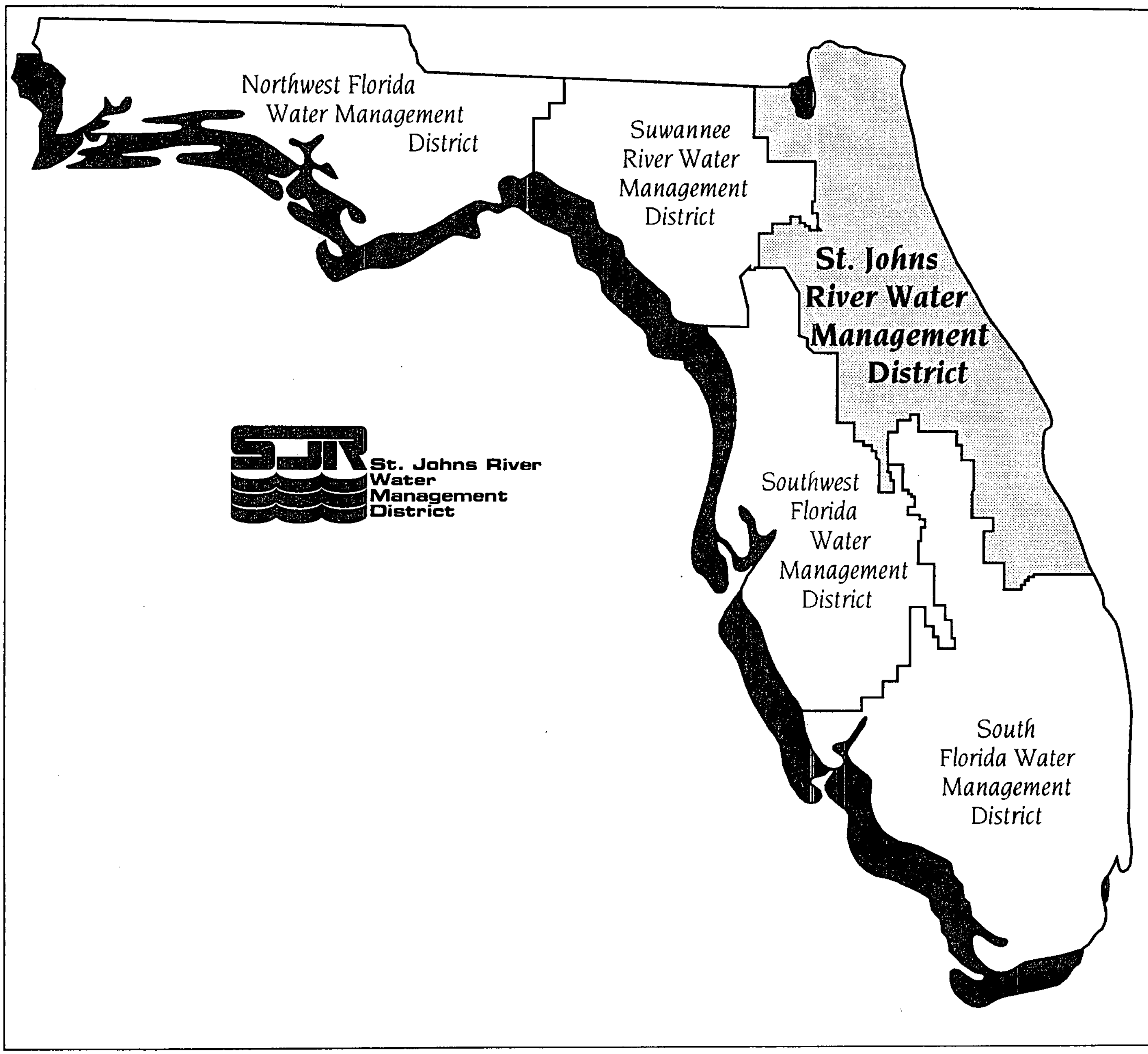

The **St. Johns River Water Management District** (SJRWMD) was created by the Florida Legislature in 1972 to be one of five water management districts in Florida. It includes all or part of 19 counties in northeast Florida. The mission of SJRWMD is to manage water resources to ensure their continued availability while maximizing environmental and economic benefits. It accomplishes its mission through regulation; applied research; assistance to federal, state, and local governments; operation and maintenance of water control works; and land acquisition and management.

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EXECUTIVE SUMMARY

The St. Johns River Water Management District and its consultants have constructed several regional and subregional ground water flow models to evaluate the effects of ground water withdrawals on the elevation of the potentiometric surface of the Floridan aquifer system. In these models, the MODFLOW ground water flow modeling code of the U.S. Geological Survey was used to simulate the Floridan aquifer system. These models focused mainly on simulating the changes in the elevation of the potentiometric surface of the Floridan aquifer system. In most of these models, the surficial aquifer system was treated as an inactive layer. The regional and subregional models, therefore, did not include the simulation of drawdowns in the surficial aquifer system as a result of pumping water from the Floridan aquifer system.

This report presents an analytical drawdown model, SURFDOWN, which was developed to calculate these induced drawdowns in the surficial aquifer system. The SURFDOWN model is an analytical, coupled-aquifer, steady-state model. It reads input files for and output files from the MODFLOW model. The SURFDOWN and MODFLOW models are used iteratively to determine the drawdowns in the water table of an unconfined aquifer and to adjust the drawdowns in the elevation of the potentiometric surface of a confined aquifer. The SURFDOWN model is written in FORTRAN computer language. It consists of 12 subroutines. A main program serves as a central control point to direct program flow through the SURFDOWN model and the iterative procedure.

The iterative procedure using the SURFDOWN and MODFLOW models was verified by comparing the drawdown data with other model-generated data on drawdowns. Drawdowns were calculated for a conceptual coupled-aquifer ground water flow system using three computational schemes. The results of all three schemes were in agreement; the iterative procedure was verified.

Then, the iterative procedure was applied to a modified version of a regional ground water flow model that used the MODFLOW code. This model was modified such that the water table was treated as an inactive layer in the model rather than an active layer. The drawdowns in the surficial aquifer system using the iterative procedure compared very well with those projected by the original model. Similarly, the predicted drawdowns for the Upper Floridan aquifer using the iterative procedure are almost identical to the drawdowns determined by the original model. This application of the iterative procedure provides an additional verification of the SURFDOWN and MODFLOW iterative procedure. This application also proved that the iterative technique is a cost-effective approach to correcting the problem of a constant-head assumption for the surficial aquifer used in regional models of flow in the Floridan aquifer.

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INTRODUCTION

The St. Johns River Water Management District (SJRWMD) and its consultants have constructed several regional and subregional ground water flow models to evaluate the effects of ground water withdrawals on the elevation of the potentiometric surface of the Floridan aquifer system. In these models, the MODFLOW code of the U.S. Geological Survey (USGS) (McDonald and Harbaugh 1988) was used to simulate flow in the Floridan aquifer system. These models focused mainly on simulating the changes in the elevation of the potentiometric surface of the Floridan aquifer system. In most of these models, the surficial aquifer system was treated as an inactive layer (constant hydraulic head). In other words, the models treated the surficial aquifer system as an infinite source of water supply or a "sink" related to other aquifer systems. The regional and subregional models, therefore, did not simulate drawdowns in the surficial aquifer system caused by pumping water from the Floridan aquifer system.

The drawdown impact on the surficial aquifer system is an important element in evaluating impacts to environmentally sensitive areas in SJRWMD. In order to evaluate the pumping impacts on the surficial aquifer system, SJRWMD could either rerun the ground water flow models to incorporate an active surficial aquifer system or use a mathematical approach to update the predicted drawdowns in the Floridan aquifer system and to determine the induced drawdowns in the surficial aquifer system. Considering the complexity of the Floridan aquifer system, tremendous cost and time would be required to revise the data and to recalibrate all the models; therefore, rerunning the regional and the subregional MODFLOW models was not a cost-effective approach. Instead, an iterative procedure was developed and used to update the predicted elevations of the potentiometric surface of the Floridan aquifer system and to determine the induced drawdowns in the surficial aquifer system. This procedure uses an analytical model (SURFDOWN), which is based on Motz's (1978) linear algorithm, and a USGS numerical model (MODFLOW).

The relationship between the drawdown in an unconfined aquifer and pumping water from a confined aquifer is a complicated ground water flow process involving many hydrologic and hydraulic parameters. When ground water is pumped from a confined aquifer (e.g., the Floridan aquifer system) of a two-layered aquifer system, pumping lowers the elevation of the potentiometric surface of that aquifer. Consequently, water in an overlying unconfined aquifer (e.g., the surficial aquifer system) can move downward into the confined aquifer by means of vertical leakage through a confining layer. In general, pumping water from a confined aquifer causes a drawdown in the water table of the unconfined aquifer and reduces the loss of water through evapotranspiration and surface runoff in the unconfined aquifer. The magnitude of this drawdown depends on the pumping rate and the degree of hydraulic connection between the unconfined and confined aquifers. To simplify the calculation of ground water response in a confined aquifer, many researchers (e.g., Hantush 1967; Neuman and Witherspoon 1969) assumed the source of water in the unconfined aquifer to be infinite and not affected by pumping water from the confined aquifer. In other words, no induced drawdowns occur in the unconfined aquifer. The consequence of using this simplified assumption of an infinite source of water in the unconfined aquifer results in an underestimate of drawdown in the confined aquifer.

Leakage of water from an unconfined aquifer through a confining layer into a confined aquifer is an important component in the ground water flow process. Motz (1978) published a linear analytical algorithm to evaluate the impact of pumping water from a confined aquifer on the drawdown in the unconfined aquifer. Motz assumed that leakage of water to the confined aquifer is from the unconfined aquifer (Figure 1). The hydrologic response of the ground water system to this leakage is a reduction in evapotranspiration loss from the unconfined aquifer and a lowering of the water table in the unconfined aquifer. If pumping continues long enough for a new equilibrium to be established, the water pumped from the underlying confined aquifer will be balanced by the surplus of water in the unconfined aquifer due to a reduction in evapotranspiration loss, the decreased surface runoff by lowering the water table in the unconfined aquifer, and the lateral flow in the unconfined aquifer. In the iterative procedure, the SURFDOWN model only considers the reduction of evaporation loss in the unconfined aquifer. It assumes that the net results due to lateral inflow and outflow and surface runoff are balanced and are not considered by the SURFDOWN model. In other words, the unconfined aquifer is not

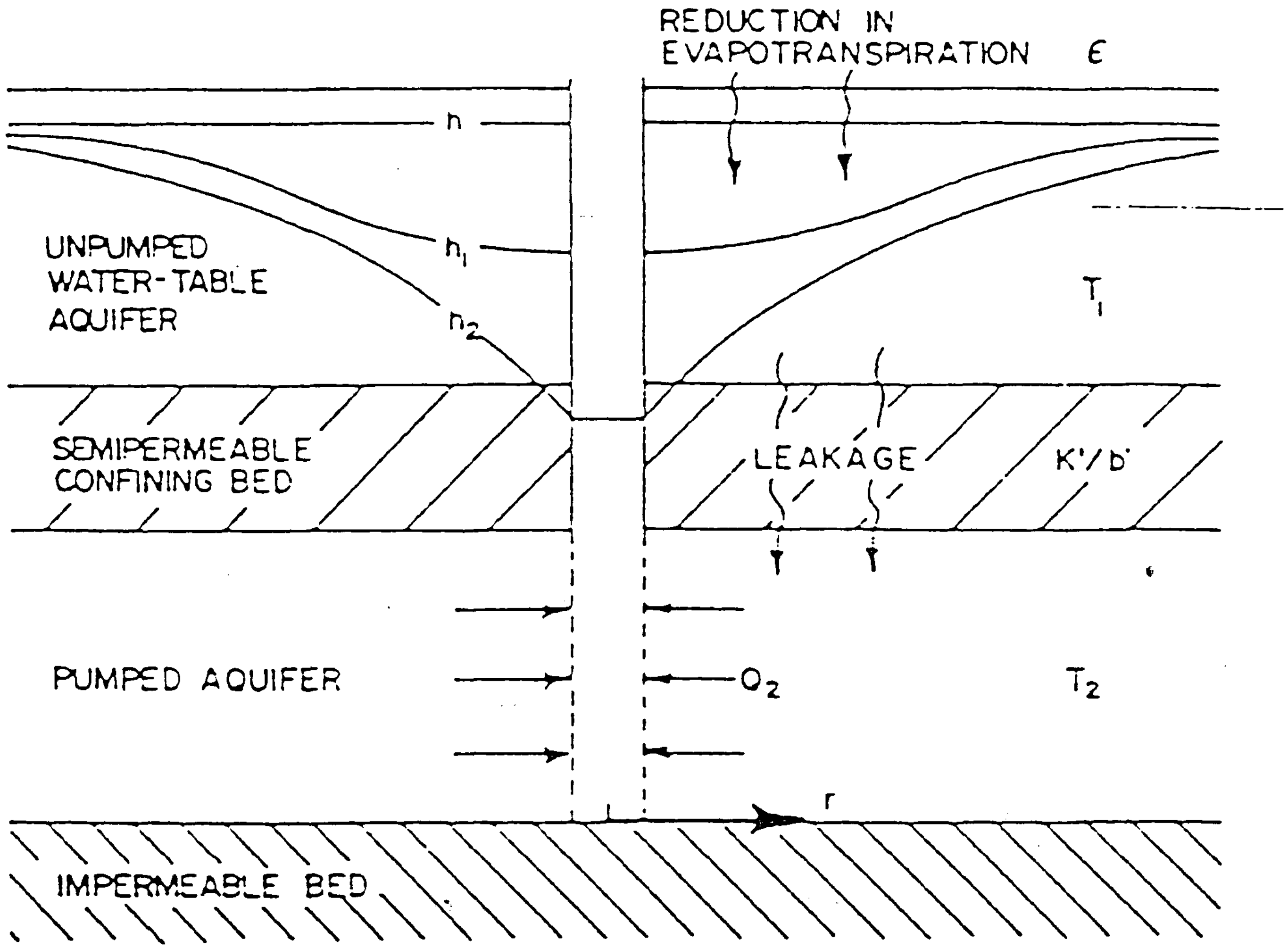


Figure 1. Sketch of a coupled water table aquifer and a confined aquifer (pumped aquifer) (Motz 1978)

assumed to be an infinite source of water to the underlying confined aquifer. An equilibrium position is established between the surface of the water table in the unconfined aquifer and the potentiometric surface in the confined aquifer.

The discussion of the linear algorithm, the iterative procedure of using a linear analytical model (SURFDOWN) and a numerical model (MODFLOW), and the verification and application of the iterative procedure are presented in the following chapters.

LINEAR ALGORITHM

An analytical linear algorithm that calculates the steady-state drawdowns of a coupled, two-aquifer ground water system is discussed in the following sections.

LINEAR EQUATIONS

The linear differential equations (Motz 1978) and boundary conditions that represent a coupled, two-aquifer ground water system in which pumpage from the confined aquifer is balanced by a reduction in evapotranspiration from the unconfined aquifer can be written as follows:

$$\frac{d^2 s_1}{d r^2} + \frac{1}{r}\frac{ds_1}{dr} - \frac{s_1}{B_0^{\,2}} + \frac{s_2 - s_1}{B_1^{\,2}} = 0 \quad (1)$$

$$\frac{d^2 s_2}{dr^2} + \frac{1}{r}\frac{ds_2}{dr} - \frac{s_2 - s_1}{B_2^{\,2}} = 0 \quad (2)$$

$$s_1 = 0 \text{ at } r \to \infty \quad (3)$$

$$s_2 = 0 \text{ at } r \to \infty \quad (4)$$

$$\lim_{r \to 0}\left(r\frac{ds_1}{dr}\right) = -\left(\frac{Q_1}{2\pi T_1}\right) = 0 \quad (5)$$

$$\lim_{r \to 0}\left(r\frac{ds_2}{dr}\right) = -\left(\frac{Q_2}{2\pi T_2}\right) \neq 0 \quad (6)$$

$$s_1 = h - h_1 \quad (7)$$

$$s_2 = h - h_2 \quad (8)$$

where:

$$\frac{1}{B_0^{\,2}} = \frac{\varepsilon}{T_1} \tag{9}$$

$$\frac{1}{B_1^{\,2}} = \frac{K'}{b'T_1} \tag{10}$$

$$\frac{1}{B_2^{\,2}} = \frac{K'}{b'T_2} \tag{11}$$

and where:

s_1 = drawdown (L) of unconfined aquifer
s_2 = drawdown (L) of confined aquifer
r = radial distance (L) from pumping well
Q_1 = pumpage (L^3T^{-1}) from unconfined aquifer
T_1 = transmissivity (L^2T^{-1}) of unconfined aquifer
Q_2 = pumpage (L^3T^{-1}) from confined aquifer
T_2 = transmissivity (L^2T^{-1}) of confined aquifer
h = hydraulic head (L) unaffected by pumping
h_1 = water table elevation (L) in unconfined aquifer affected by pumping
h_2 = potentiometric surface elevation (L) in confined aquifer affected by pumping
ε = reduction in evapotranspiration rate per unit of water table drawdown (T^{-1})
K'/b' = leakance (T^{-1}) of confining unit
L = unit of length
T = unit of time

Equations 1 and 2 are based on the following assumptions. Horizontal flow prevails in both the unconfined and confined aquifers. Vertical flow between the unconfined and confined aquifers is represented by leakage through a confining unit that separates the unconfined aquifer from the underlying confined aquifer. Transmissivity is equal to the product of the hydraulic conductivity and the thickness of the saturated aquifer. No water is pumped from the unconfined aquifer. The reduction rate in evapotranspiration loss is formulated as a linear function of the drawdown in the unconfined aquifer. The bottom of the coupled, two-aquifer ground water system is assumed to be an impervious boundary.

LINEAR SOLUTION

The analytical linear solution is presented in this section for a coupled, two-aquifer ground water system that calculates the drawdowns in the unconfined and confined aquifers under steady-state conditions. The solution of drawdown is a function of the pumping rate from the confined aquifer, the transmissivities of each aquifer system, the leakance of the confining unit, and the evapotranspiration reduction rate per unit of water table drawdown in the unconfined aquifer. The solution to a coupled, two-aquifer, steady-state flow equation represented by Equations 1 and 2 is written as follows (Motz 1978):

$$s_1 = \left(\frac{Q_2}{2\pi T_2}\right) \frac{-K_0(r\omega_1) + K_0(r\omega_2)}{C_1 + C_2} \qquad \textbf{(12)}$$

$$s_2 = \left(\frac{Q_2}{2\pi T_2}\right) \frac{C_1 K_0(r\omega_1) + C_2 K_0(r\omega_2)}{C_1 + C_2} \qquad \textbf{(13)}$$

where:

$$C_1 = \frac{1}{\omega_1^{\,2} B_2^{\,2} - 1} \qquad \textbf{(14)}$$

$$C_2 = \frac{1}{1 - \omega_2^{\,2} B_2^{\,2}} \qquad \textbf{(15)}$$

$$\omega_1^{\,2} B_2^{\,2} = \frac{\left(\frac{\varepsilon}{L}\frac{T_2}{T_1} + \frac{T_2}{T_1} + 1\right) + \sqrt{\left(\frac{\varepsilon}{L}\frac{T_2}{T_1} + \frac{T_2}{T_1} + 1\right)^2 - \frac{4\varepsilon T_2}{L T_1}}}{2} \qquad \textbf{(16)}$$

$$\omega_2{}^2 B_2{}^2 = \frac{\left(\frac{\varepsilon}{L}\frac{T_2}{T_1} + \frac{T_2}{T_1} + 1\right) - \sqrt{\left(\frac{\varepsilon}{L}\frac{T_2}{T_1} + \frac{T_2}{T_1} + 1\right)^2 - \frac{4\varepsilon T_2}{L T_1}}}{2} \quad \textbf{(17)}$$

and where:

$K_0(\,)$ = modified Bessel function of second kind, zero order
L = leakance (T^{-1}) of the confining unit

Variables ω_1 and ω_2 are defined as functions of the ratio of the evapotranspiration reduction rate to leakance and the ratio of the transmissivity of the unconfined aquifer to the transmissivity of the confined aquifer, respectively.

In developing this algorithm, the change in the elevation of the water table in the unconfined aquifer is assumed to be insignificant compared to the total saturated thickness of the unconfined aquifer. In other words, the transmissivity of the unconfined aquifer is assumed to be a constant. The principle of superposition, therefore, is used to determine the drawdowns in both the unconfined and confined aquifers caused by multiple wells pumping from the confined aquifer at various locations. The drawdowns in the unconfined aquifer as a function of the pumpage from the confined aquifer and the hydrologic parameters of the two-aquifer ground water system are determined using Equation 18; the drawdowns in the confined aquifer caused by multiple pumping wells are determined using Equation 19.

$$s_1 = \sum_{i=1}^{N_p} \frac{Q_i}{2\pi T_i} \frac{-K_0(r_i\omega_1) + K_0(r_i\omega_2)}{C_1 + C_2} \quad \textbf{(18)}$$

$$s_2 = \sum_{i=1}^{N_p} \frac{Q_i}{2\pi T_i} \frac{C_1 K_0(r_i\omega_1) + C_2 K_0(r_i\omega_2)}{C_1 + C_2} \quad \textbf{(19)}$$

where:

N_p = the total number of pumping wells
Q_i = the pumping rate at well i in the confined aquifer

r_i = the distance between the pumping well and a node in the model
T_i = the transmissivity parameter at well location i

If the pumped well is located at the model nodal point, then the calculated radius, r_i, will be zero. A zero radius will cause an unstable model simulation. If a zero radius occurs, a 1.0-foot (ft) radius is used to prevent numerical instability.

Because the hydraulic parameters and coefficients used in Equations 18 and 19 are known, a closed-form relationship between the drawdown in the unconfined aquifer and the drawdown in the confined aquifer under a multiple pumping wells scenario can be determined by using Equation 20.

$$s_1 = s_2 \frac{\sum_{i=1}^{N_p} \frac{Q_i}{T_i} \frac{-K_0(r_i\omega_1) + K_0(r_i\omega_2)}{C_1 + C_2}}{\sum_{i=1}^{N_p} \frac{Q_i}{T_i} \frac{C_1 K_0(r_i\omega_1) + C_2 K_0(r_i\omega_2)}{C_1 + C_2}} \qquad \textbf{(20)}$$

The Analytical SURFDOWN Model

Using the linear analytical solution of Equation 20 and the coefficients presented in Equations 9–11 and 14–17, an analytical drawdown model, SURFDOWN, was developed. The SURFDOWN model is an analytical, coupled-aquifer, steady-state model designed to determine drawdowns in the unconfined aquifer as a function of drawdowns in the confined aquifer. The model can be run using either a constant or variable grid-space model domain, and it reads input files for and output files from the MODFLOW model. The drawdowns of the confined aquifer, the evapotranspiration reduction rate in the unconfined aquifer, and the vertical leakance of the confining unit between the unconfined aquifer and the confined aquifer are required for the SURFDOWN model. The drawdowns in the confined aquifer are estimated first using the MODFLOW model, assuming a constant water table condition. The SURFDOWN and MODFLOW models are used iteratively to determine the drawdowns in the water table of the unconfined aquifer and to adjust the drawdowns in the potentiometric surface of the confined aquifer.

The SURFDOWN model is written in FORTRAN computer language. It consists of 12 subroutines (appendix). A main program serves as a central control point to direct program flow through the SURFDOWN model and the iterative procedure.

ITERATIVE PROCEDURE

The regional and subregional models developed at SJRWMD focus mainly on simulating the changes in the elevation of the potentiometric surface in the Floridan aquifer system; the elevation in the water table of the surficial aquifer system was treated as a constant-head boundary in the models. In other words, the models were run assuming that the surficial aquifer system was an infinite source of water supply. No drawdowns in the surficial aquifer system were simulated using the MODFLOW model. The results of model simulation using a constant water table assumption, in general, would underestimate the drawdowns in the Florida aquifer system. Instead of revising the models to include an active water table in the surficial aquifer system, an iterative procedure using the SURFDOWN and MODFLOW models was used to calculate the drawdowns in the surficial aquifer system and to revise the predicted drawdowns in the Floridan aquifer system.

The iterative procedure starts with a simulation of the MODFLOW model. A constant hydraulic-head boundary condition is assigned to the unconfined aquifer layer in the model (e.g., the surficial aquifer system) and the model simulates drawdowns in the confined aquifer (e.g., the Floridan aquifer system) under a steady-state condition. The simulated drawdowns in the confined aquifer then are used as input to the SURFDOWN model to calculate the induced drawdowns in the unconfined aquifer. The induced drawdowns in the unconfined aquifer are subtracted from the initial constant-head boundary in the unconfined aquifer to arrive at a revised constant-head boundary for a subsequent MODFLOW run. This represents the end of the first iteration.

In subsequent iterations, the MODFLOW simulation is repeated using the revised constant-head boundary conditions for the unconfined aquifer. Each simulation results in an improved estimate of drawdowns in the confined aquifer. Again, the results of the drawdowns in the confined aquifer are used as input to the SURFDOWN model for the determination of the corresponding drawdowns in the unconfined aquifer. The differences in the amount of drawdown in the unconfined aquifer between the current iteration and the previous iteration then are subtracted from the constant-head boundary to update the constant-head boundary in the unconfined aquifer used in a subsequent iteration.

If the differences between the drawdowns in the unconfined aquifer system from the "current" iteration and the drawdowns from the previous iteration do not satisfy a preset closure criterion, another iteration will be repeated starting with the MODFLOW model. In general, the drawdowns in the unconfined aquifer increase from one iteration to the next, but the magnitude of the drawdown change generally decreases from one iteration to the next. This iterative procedure will be terminated if the maximum drawdown difference between one iteration to the next is less then a preset closure criterion. The final drawdowns for both the confined and unconfined aquifers are then calculated and used to determine the predicted elevation of the water table in the unconfined aquifer and the predicted elevation of the potentiometric surface in the confined aquifer.

VERIFICATION OF THE ITERATIVE PROCEDURE

A conceptual coupled-aquifer system was designed to verify the iterative procedure. This ground water system consisted of an unconfined aquifer system (the surficial) and a confined aquifer system (the Floridan) separated by a leaky confining layer. Ground water was pumped from the confined aquifer.

Three different computational schemes were used to compute the drawdowns in the coupled-aquifer system. The first computational scheme used the analytical, coupled-aquifer linear solutions as represented by Equations 12 and 13—the DRAWDOWN model. The second computational scheme used the numerical MODFLOW flow model. The third computational scheme used the SURFDOWN and MODFLOW iterative procedure. The drawdowns obtained by using these three computational schemes were compared to verify the credibility of the iterative procedure.

The input data and the results of these three computational schemes are discussed in the next sections. The assigned hydraulic and hydrologic parameter values for these three computational schemes are presented in Table 1.

Table 1. Conceptual model input parameters

Input Parameter	Surficial Aquifer System	Confining Unit	Floridan Aquifer System
Transmissivity (ft^2/day)	330	NA	33,000
Leakance (day^{-1})	NA	2.7×10^{-3}	NA
Evapotranspiration reduction rate ([ft/day]/ft)	1.35×10^{-3}	NA	NA
Saturated thickness (ft)	50	NA	NA
Hydraulic conductivity (ft/day)	6.6	NA	NA
Pumping rate (ft^3/day)	NA	NA	385,000

Note:
NA = not applicable
ft^2/day = square feet per day
(ft/day)/ft = feet per day per foot
ft/day = feet per day
ft^3/day = cubic feet per day

DRAWDOWN SOLUTION

The DRAWDOWN model used a linear analytical solution to calculate the amount of drawdown in a coupled, two-layered (unconfined and confined), leaky aquifer (Huang 1996, draft). The DRAWDOWN model calculated the decline in the potentiometric surface of the Floridan aquifer system and the induced drawdowns in the surficial aquifer system caused by pumping water from the Floridan aquifer system.

The input data used in the DRAWDOWN model (Table 1) were

- Transmissivity of 330 square feet per day (ft^2/day) for the surficial aquifer system
- Transmissivity of 33,000 ft^2/day for the Floridan aquifer system
- Reduction rate for evapotranspiration of 1.35 x 10^{-3} feet per day per foot ([ft/day]/ft)
- Leakance of 2.7 x 10^{-3} day^{-1}
- Pumping rate of 385,000 cubic feet per day (ft^3/day)

The calculated drawdowns in the surficial aquifer system ranged from about 0.1 ft to 3.9 ft at a radial distance of about 15,000 ft from the pumping well. The value of drawdown (s_1) versus the radial distance from the pumping well (r) represents drawdown in the unpumped surficial aquifer system (Figure 2). The calculated drawdowns in the Floridan aquifer system ranged from about 18 ft near the pumping well to 0.1 ft at a radial distance of 16,500 ft from the pumping well. The value of drawdown (s_2) versus r represents drawdown in the pumped Floridan aquifer system (Figure 3).

MODFLOW SOLUTION

The MODFLOW model used two active layers to represent a two-layer, leaky aquifer system. Layer 1 represented the surficial aquifer system; layer 2 represented the Floridan aquifer system. Ground water was pumped from the Floridan aquifer system. The model domain was

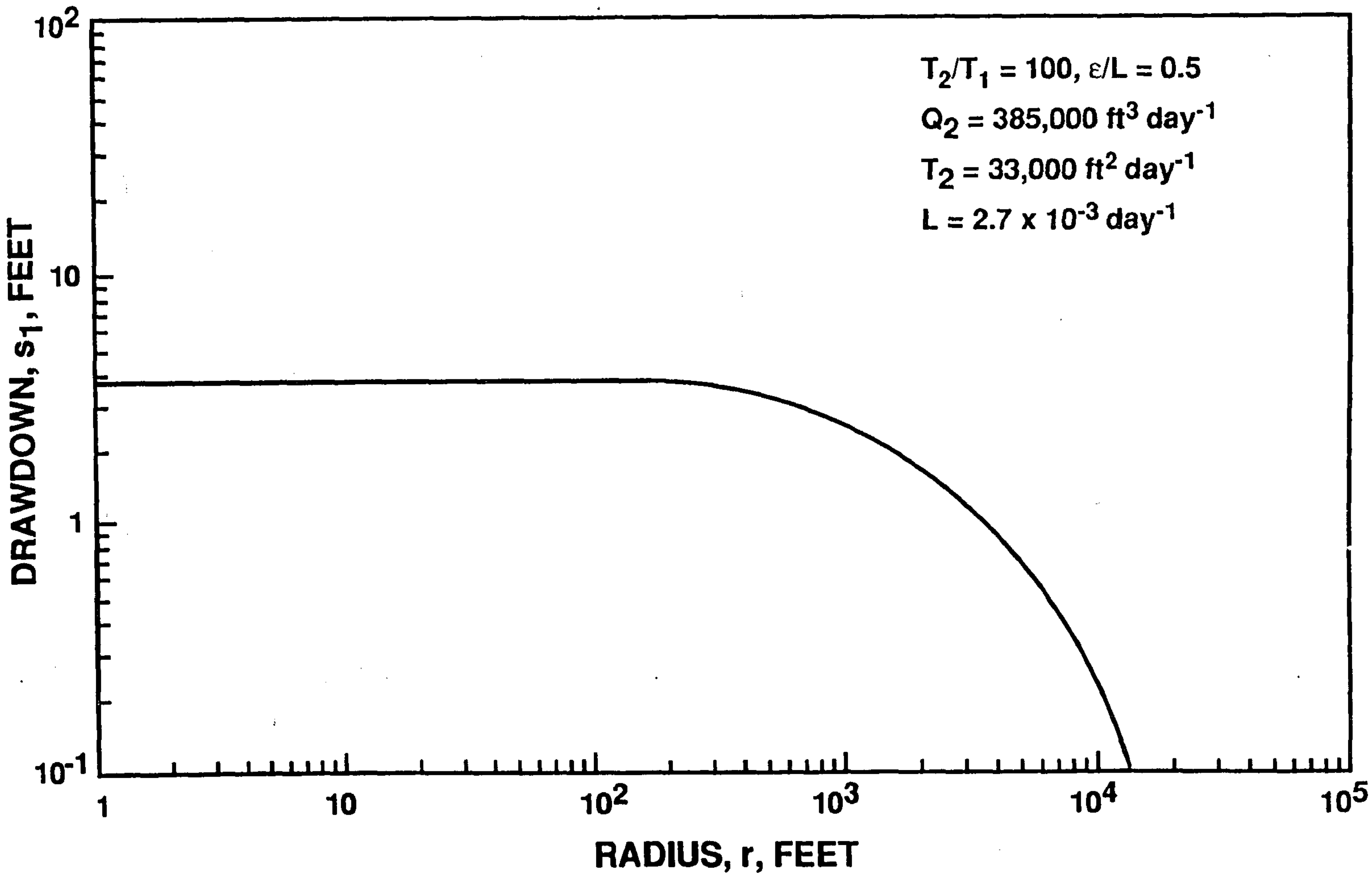


Figure 2. Drawdown in the surficial aquifer system using the DRAWDOWN model

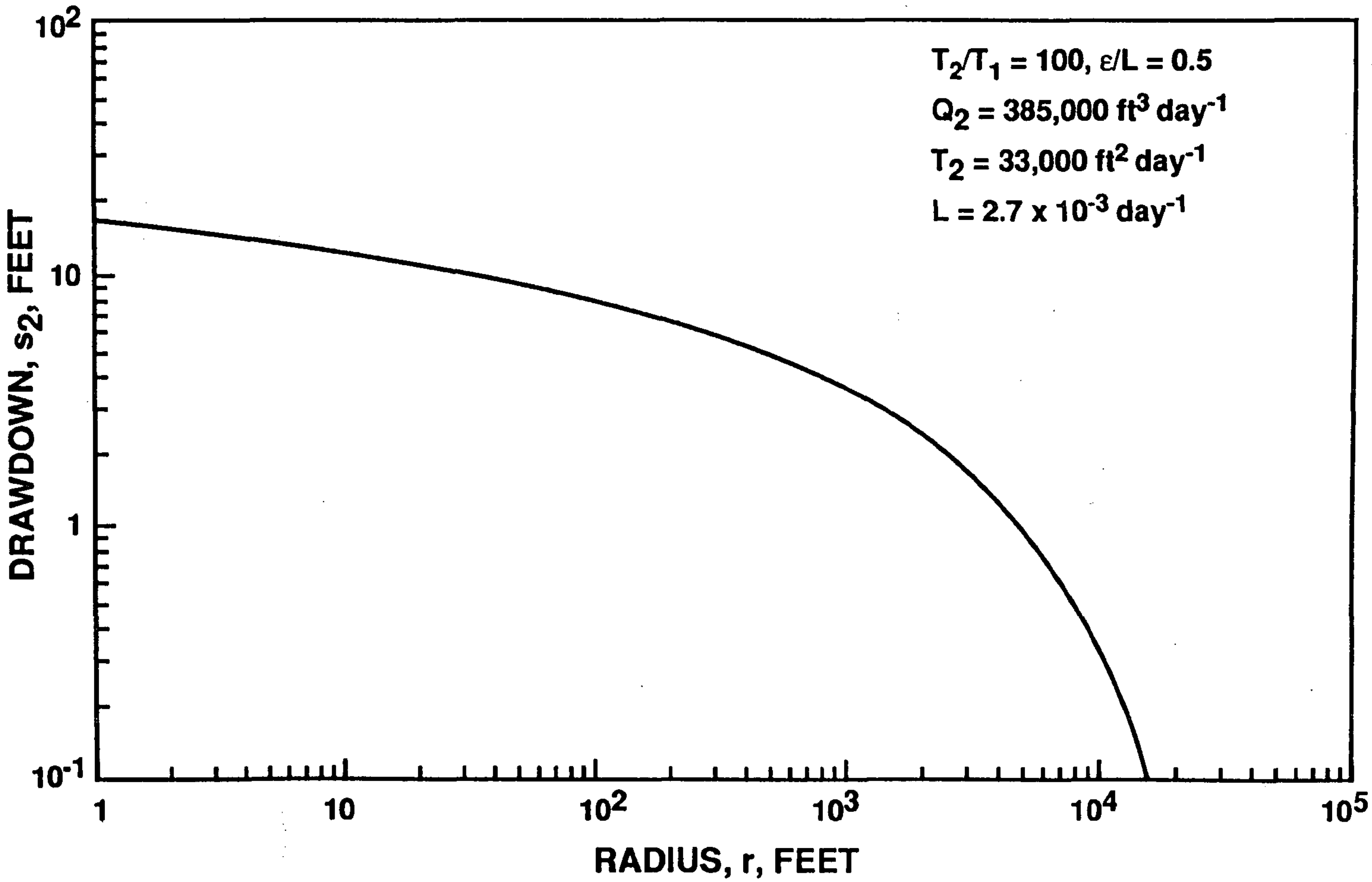


Figure 3. Drawdown in the Floridan aquifer system using the DRAWDOWN model

constructed using 45 rows and 45 columns and a constant grid spacing of 1,000 ft in both the *x* and *y* directions. Constant heads were assigned along the outer rows and columns in both layers. The hydraulic conductivity was 6.6 feet per day (ft/day), and the initial saturated thickness was 50 ft (Table 1). The transmissivity of layer 2 was 33,000 ft^2/day, and the leakance value used between layers 1 and 2 was 2.7×10^{-3} day^{-1}. The pumped well was located in layer 2 at the intersection of row 23 and column 23; the discharge rate was equal to 385,000 ft^3/day. Net recharge to layer 1 was represented by a constant areal recharge rate of 2.5 feet per year, or 6.85×10^{-3} ft/day. A maximum evapotranspiration rate of 6.85×10^{-3} ft/day was assumed to occur at a specified water table elevation of 0.0 ft (land surface) to represent the equilibrium condition that existed between evapotranspiration and recharge before pumping began. The extinction depth, or the cutoff depth at which evapotranspiration would cease, was assumed to be 5 ft. In the MODFLOW model, the evapotranspiration rate decreases linearly from the maximum rate at the specified elevation to zero at the extinction depth as the water table declines. The slope of this relationship is equivalent to the evapotranspiration reduction rate of 1.35×10^{-3} (ft/day)/ft. A closure criterion of 0.001 ft was set to terminate the simulation of the MODFLOW ground water flow model.

The MODFLOW model was run to steady state. The results of the predicted drawdowns in the surficial aquifer system at incremental distances of 1,000 ft from the node where the pumped well was located compared quite well with the calculated drawdowns from the DRAWDOWN model (Figure 4). Similarly, the results of the predicted drawdowns in the Floridan aquifer system at incremental distances of 1,000 ft from the node where the pumped well was located compared very well with the calculated drawdowns from the DRAWDOWN model (Figure 5).

ITERATIVE SOLUTION

The iterative procedure (SURFDOWN and MODFLOW models) was used to compute drawdowns for comparison with the drawdowns from the analytical DRAWDOWN model. The surficial aquifer system was treated as an unconfined layer. In the MODFLOW model of this iterative procedure, layer 1 represented a constant-head (inactive layer) aquifer system (the surficial). Layer 2 represented an active, confined aquifer

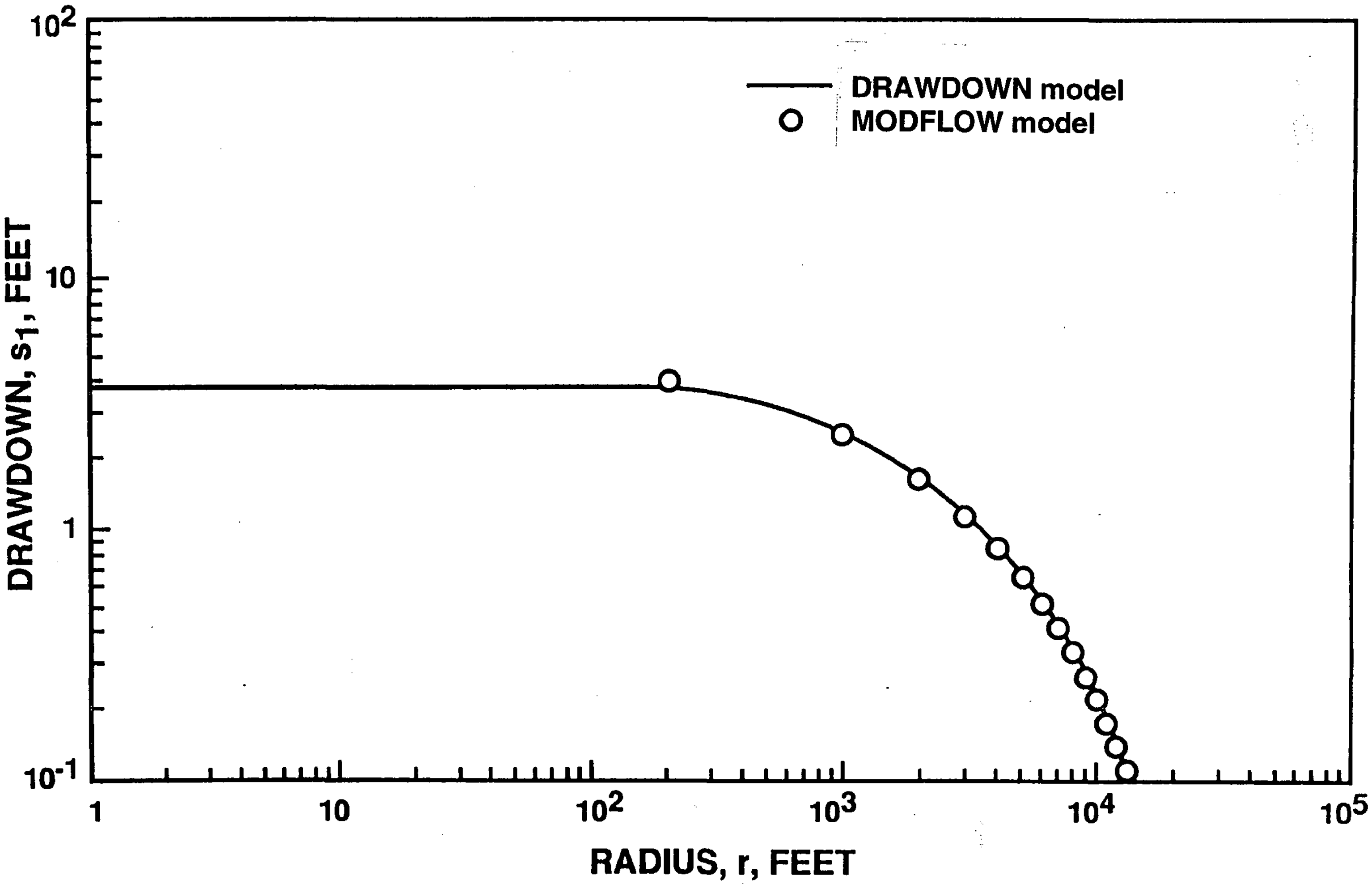


Figure 4. Comparison of drawdowns in the surficial aquifer system using the MODFLOW and DRAWDOWN models

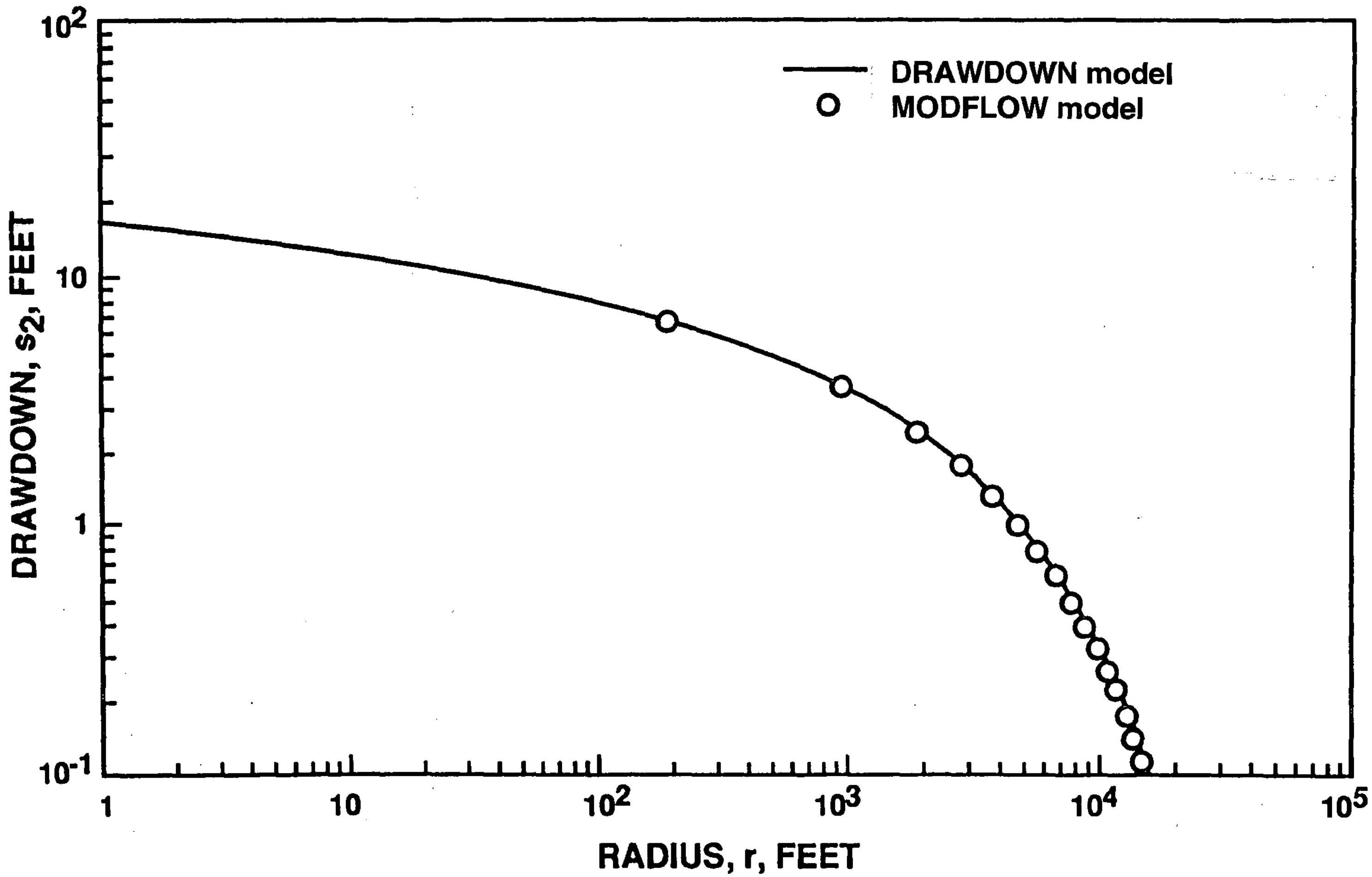


Figure 5. Comparison of drawdowns in the Floridan aquifer system (with an active surficial aquifer system) using the MODFLOW and DRAWDOWN models

system (the Floridan), underlying a confining layer. Input files used in the MODFLOW model to represent a coupled-aquifer system with a constant-head aquifer system and an active, confined aquifer also were used as input files for the SURFDOWN model, which was run to determine drawdowns in both aquifers.

The MODFLOW model for this iterative procedure consisted of 45 rows and 45 columns with a constant grid space of 1,000 ft. Constant heads were assigned at all the nodes in layer 1 of the unconfined aquifer system (the surficial) and along the outer rows and columns in layer 2 of the confined aquifer system (the Floridan). The hydraulic conductivity used for layer 1 was 6.6 ft/day, and the initial saturated thickness used was 50 ft (Table 1). The transmissivity used for layer 2 was 33,000 ft^2/day. The leakance value used between layers 1 and 2 was 2.7×10^{-3} day^{-1}. The pumped well was located in layer 2 at the intersection of row 23 and column 23; the discharge rate was equal to 385,000 ft^3/day. A closure criterion of 0.001 ft in hydraulic-head difference was set, and the MODFLOW model was run to steady state.

The SURFDOWN model then was run using the input files for and the output files from the MODFLOW model as input files. In this procedure to verify the iterative solution, the convergence criterion for the MODFLOW model was set at 0.001 ft, and 13 iterations were required to achieve closure. The calculated drawdowns in the surficial aquifer system at incremental distances of 1,000 ft from the node, where the pumped well was located, compared quite well with the drawdown results from the analytical DRAWDOWN model (Figure 6). Similarly, the calculated drawdowns in the Floridan aquifer system also compared quite well with the results from the analytical DRAWDOWN model (Figure 7).

SUMMARY

Based on the test results, the analytical, coupled-aquifer solution of the DRAWDOWN model can be reproduced using the MODFLOW model with an active surficial aquifer system. Similarly, the results obtained from the iterative procedure (SURFDOWN and MODFLOW models) also are in excellent agreement with the DRAWDOWN model.

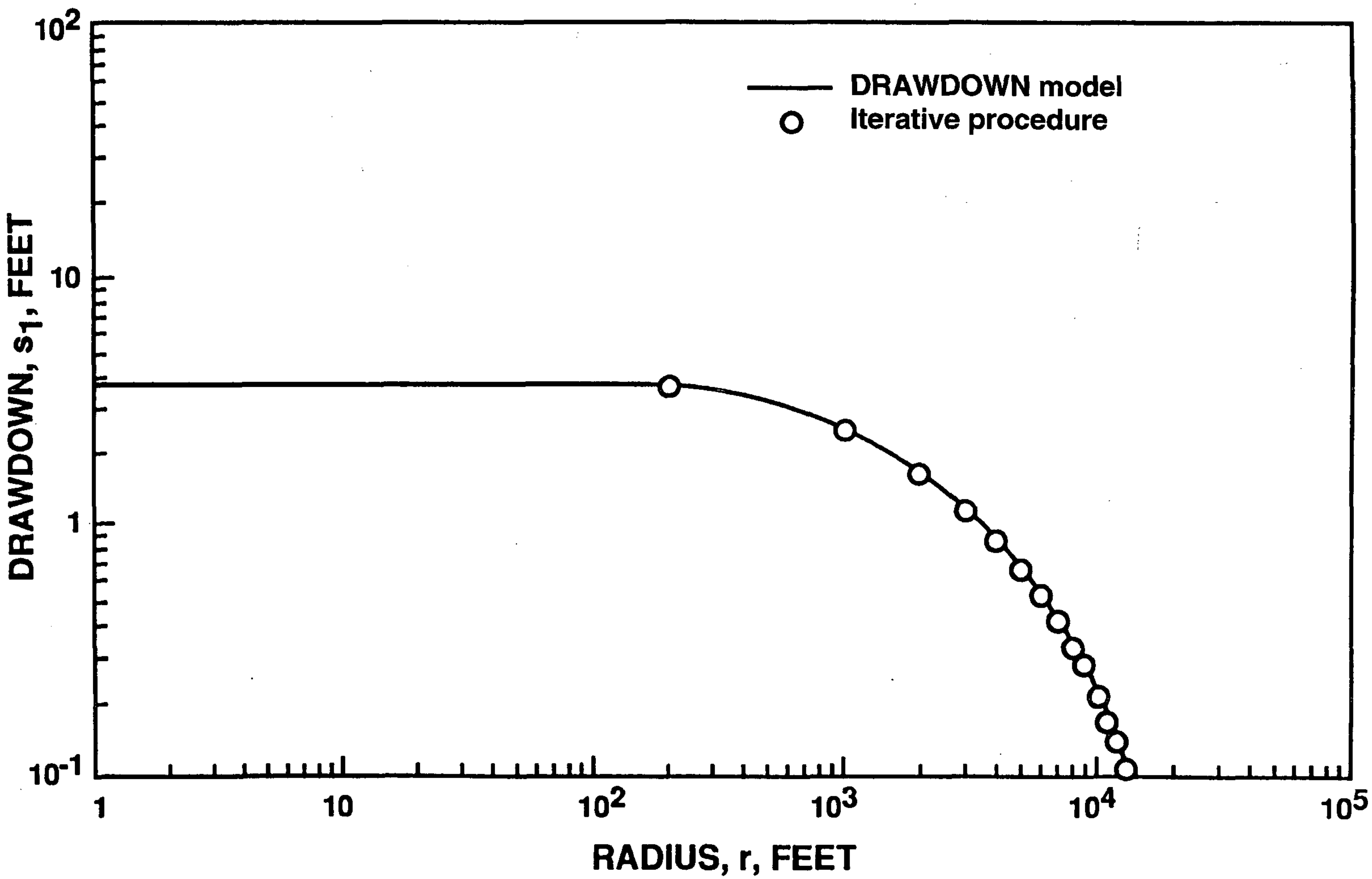


Figure 6. Comparison of drawdowns in the surficial aquifer system (inactive) using the iterative procedure and the DRAWDOWN model

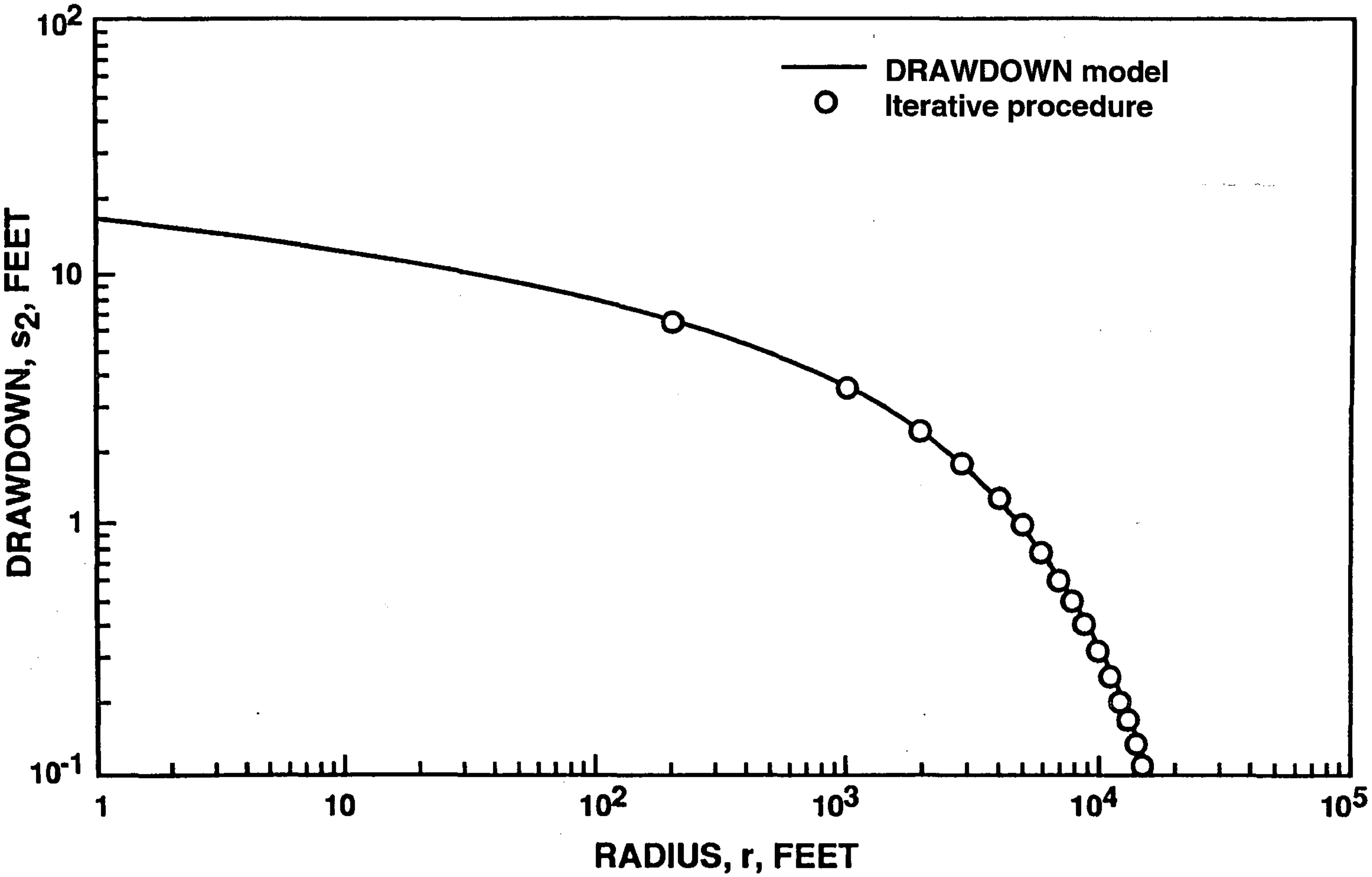


Figure 7. Comparison of drawdowns in the Floridan aquifer system (with an inactive surficial aquifer system) using the iterative procedure and the DRAWDOWN model

This test case demonstrated that the iterative procedure was designed well and verified. The application of the SURFDOWN and MODFLOW iterative procedure to an SJRWMD regional ground water flow model is demonstrated in the next chapter.

APPLICATION OF THE ITERATIVE PROCEDURE

Seven numerical ground water flow models based on regional scales and calibrated to steady-state conditions were developed by the staff of SJRWMD and its consultants. The purpose of developing these regional ground water flow models was to simulate the effects of the 1988 and the projected 2010 ground water withdrawals on the elevation of the potentiometric surfaces of the Upper and Lower Floridan aquifers. The pumping impact on these aquifers was demonstrated by the elevation difference of the potentiometric surfaces between the years 1988 and 2010. Only two of these regional ground water flow models were designed using an active surficial aquifer layer in the models. Five models treated the surficial aquifer system as an inactive layer. A constant-head boundary condition was assigned to the inactive surficial aquifer system, which would result in an underestimate of impact on the Floridan aquifer system. The iterative procedure (SURFDOWN and MODFLOW models) was developed to remedy this problem of underestimation.

The 1988 and 2010 projected changes in the elevation of the water table in the surficial and Floridan aquifer systems for these five MODFLOW models were revised using the iterative procedure. These revised elevations are more representative of the ground water system than those produced by the regional ground water flow models that assumed a constant elevation of the water table. For these five models, the difference between the revised elevations of the potentiometric surface in 2010 and the simulated potentiometric surface in 1988 was calculated in order to evaluate the impact of projected ground water withdrawals on the Floridan aquifer system. The application of the iterative procedure to a regional ground water flow model (the Volusia model), which treated the surficial aquifer system as an active layer, is discussed as follows.

THE VOLUSIA MODEL—ACTIVE SURFICIAL AQUIFER SYSTEM

The regional MODFLOW model selected for this comparison is a ground water flow model for the Volusia ground water basin (Williams 1996, draft). This model is a three-dimensional, finite-difference representation of the surficial and Floridan aquifer systems in the geographical area generally encompassing Volusia County and coastal east-central Florida. The model has three hydrogeologic layers representing the surficial aquifer system and the Upper and Lower Floridan aquifers. The confining unit between the surficial and Floridan aquifer systems and the semiconfining unit between the Upper and Lower Floridan aquifers are represented by distributions of leakance that vary over the region. There are 7,826 cells in each model layer with the smallest grid cell, 0.25 by 0.25 mile, in the vicinities of the major water supply wellfields. The model simulates the water table in the surficial aquifer system as an active layer, incorporating the processes of evapotranspiration, recharge to the surficial aquifer system, streamflow, and surface runoff.

The simulated drawdowns in the surficial aquifer system, based on the projected 2010 water use, ranged from 0.0 ft to 6.7 ft (Figure 8). The simulated drawdowns in the Upper Floridan aquifer, based on the projected 2010 water use, ranged from 0.0 ft to 27.6 ft (Figure 9) (Williams 1996, draft).

THE VOLUSIA MODEL—INACTIVE SURFICIAL AQUIFER SYSTEM

In order to perform the comparison, a version of the Volusia model with a constant head (inactive) in the surficial aquifer system, a source/sink layer, was developed. This MODFLOW version of the model then was run iteratively with the SURFDOWN model to determine the drawdowns in the surficial and Floridan aquifer systems. The simulated drawdowns in the surficial aquifer system ranged from 0.0 ft to 6.2 ft, based on the projected 2010 water use (Figure 10). The simulated drawdowns in the Upper Floridan aquifer ranged from 0.0 ft to 28.0 ft, based on the projected 2010 water use (Figure 11) (Williams 1996, draft).

THE VOLUSIA MODEL—COMPARISON

The drawdown configurations using the iterative procedure compared very well with those projected by the original MODFLOW version of the model, which used an active water table in the surficial aquifer system. In both cases, the maximum drawdown in the surficial aquifer system is approximately 6 ft and occurs in the vicinity of the Daytona Beach

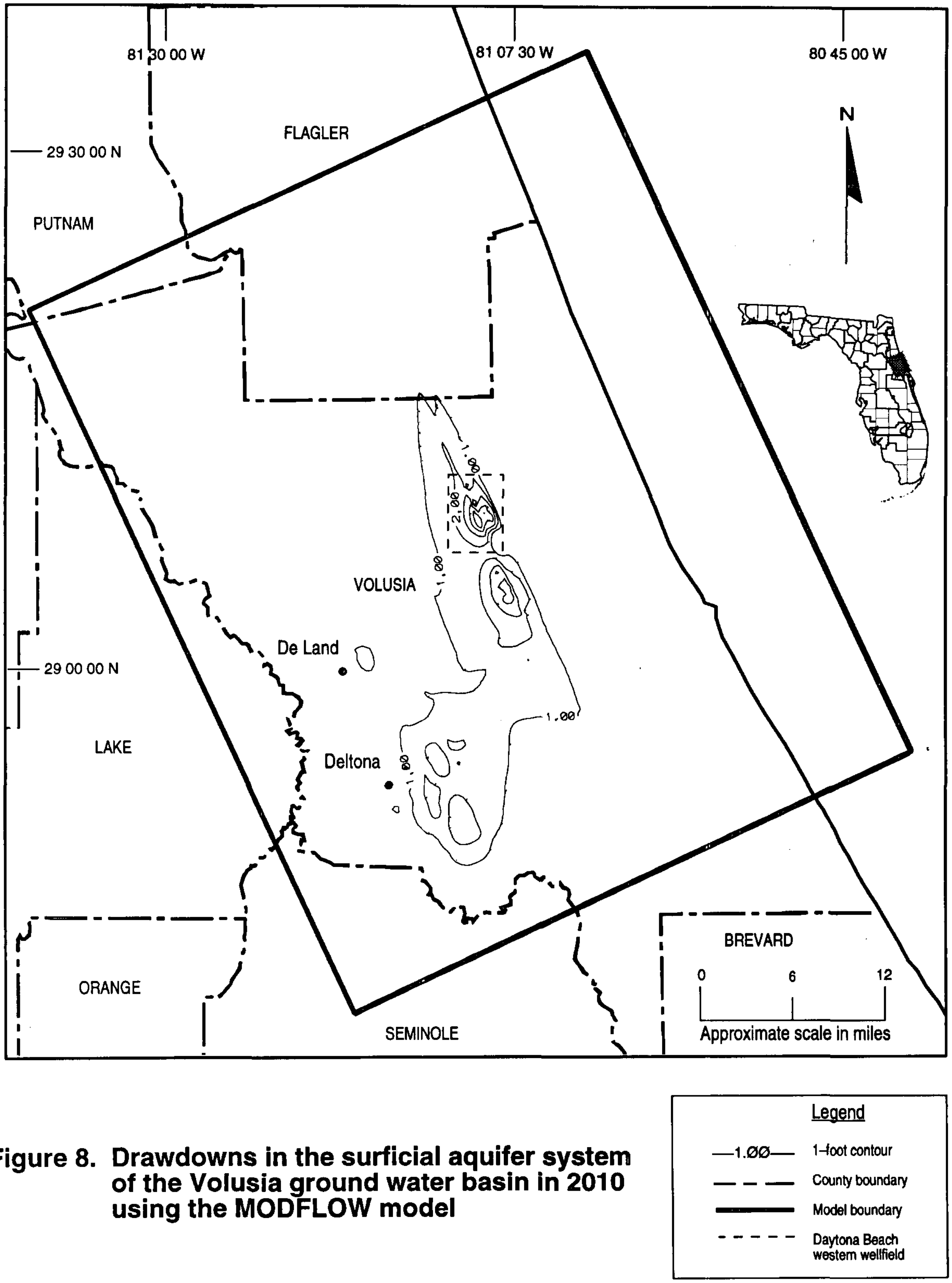


Figure 8. Drawdowns in the surficial aquifer system of the Volusia ground water basin in 2010 using the MODFLOW model

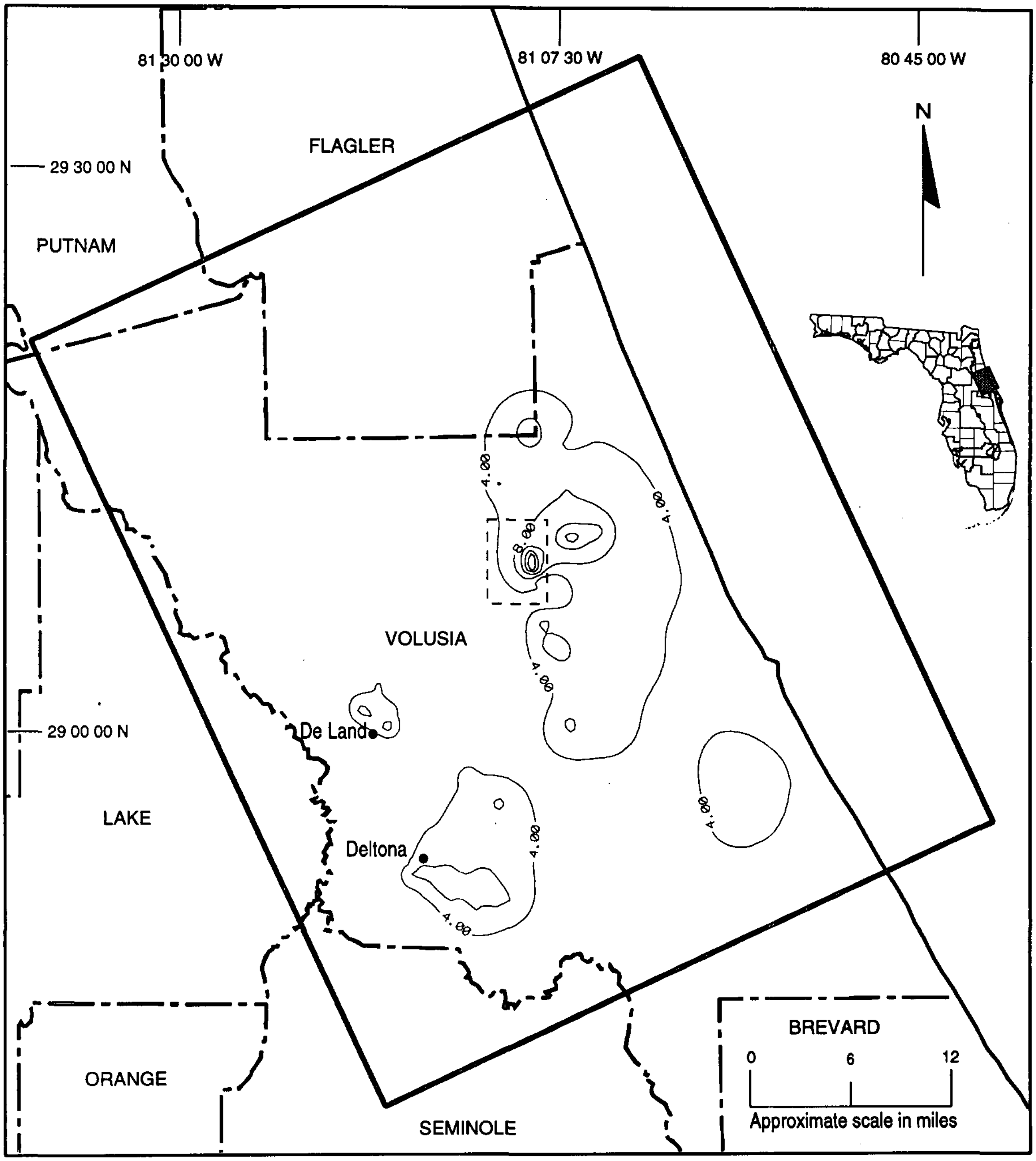


Figure 9. Drawdowns in the Upper Floridan aquifer of the Volusia ground water basin in 2010 using the MODFLOW model

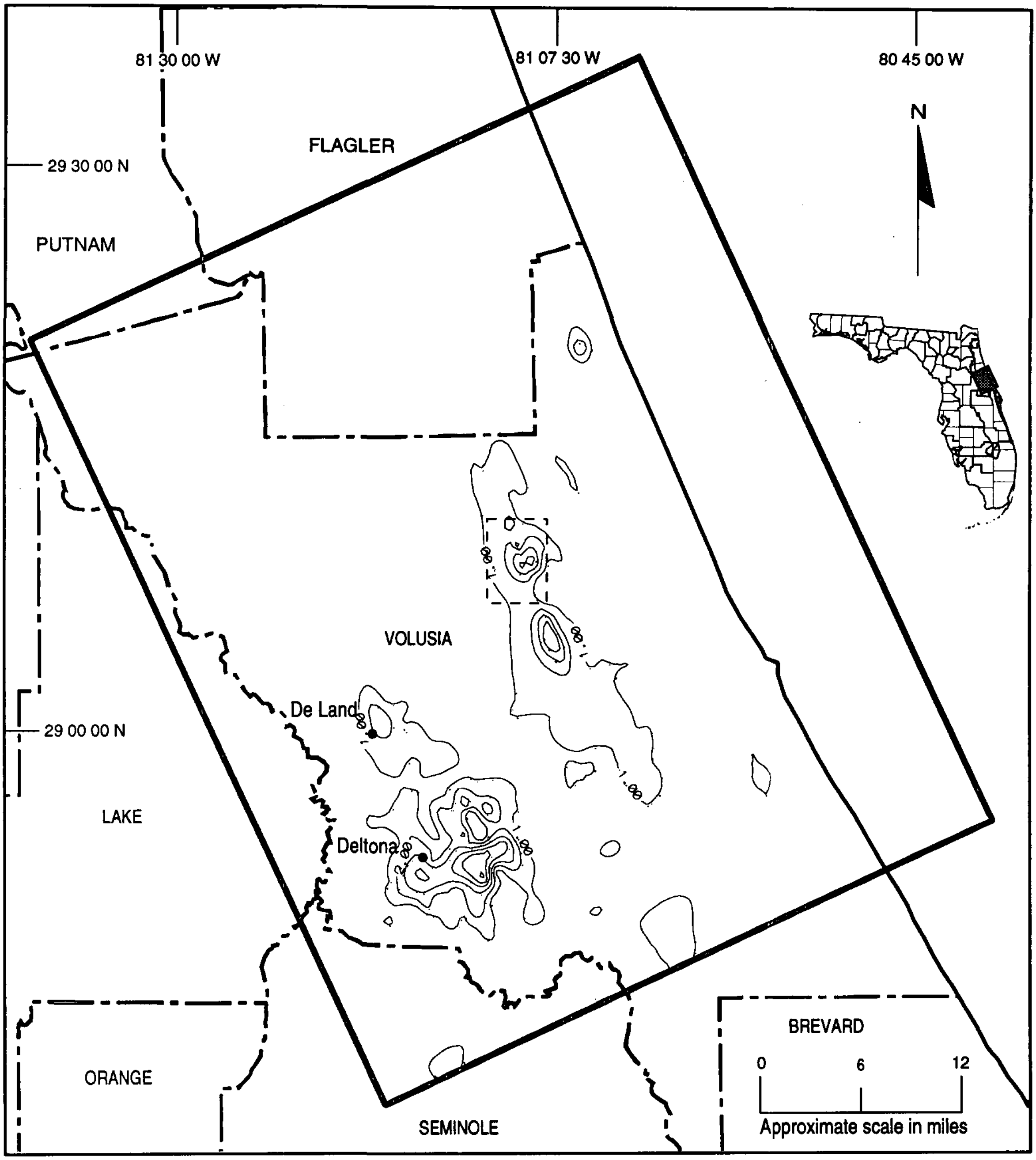
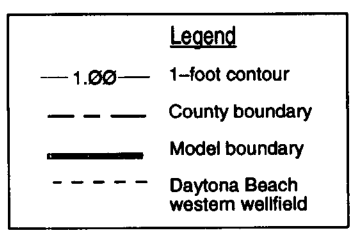


Figure 10. Drawdowns in the surficial aquifer system of the Volusia ground water basin in 2010 using the iterative procedure



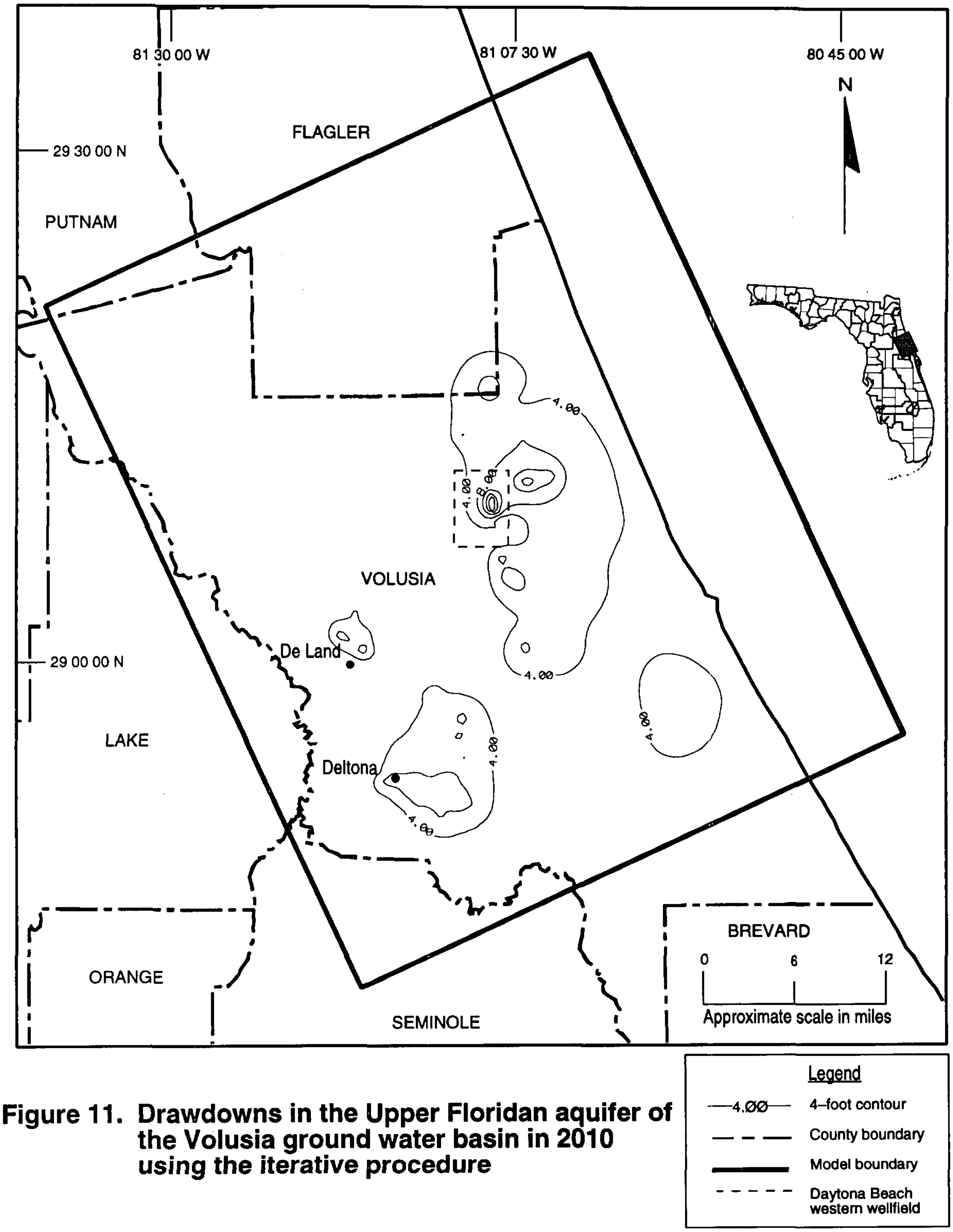


Figure 11. Drawdowns in the Upper Floridan aquifer of the Volusia ground water basin in 2010 using the iterative procedure

western public supply wellfield. The predicted drawdowns in the surficial aquifer system based on the iterative technique differ slightly from the original MODFLOW model results. These difference areas are mostly located in the vicinity of the Deltona area and some isolated areas (e.g., De Land) (Figures 8 and 10).

The predicted drawdowns for the Upper Floridan aquifer, using the iterative technique (Figure 11), are similar to the drawdowns determined by the original version of the MODFLOW model using an active surficial aquifer system (Figure 9). The maximum drawdown of approximately 28 ft in the Upper Floridan aquifer occurs at the Daytona Beach western public supply wellfield.

These comparisons provide an additional verification of the SURFDOWN and MODFLOW iterative technique. The close comparison of the drawdown configurations in both the surficial aquifer system and the Upper Floridan aquifer for the Volusia ground water basin has provided credibility for the iterative procedure as a cost-effective approach. The iterative procedure can be used to correct the problem of a constant-head assumption in the surficial aquifer system that is incorporated into several of the regional ground water flow models created by SJRWMD using the MODFLOW code.

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APPENDIX: ITERATIVE PROCEDURE

SURFDOWN MODEL STRUCTURE

The SURFDOWN model is written in FORTRAN computer language. it consists of 12 subroutines. A main program serves as a central control point to direct program flow through the SURFDOWN model and the iterative procedure.

Subroutine BASRD

This subroutine reads the BAS package input file used in the MODFLOW model. From this file, the subroutine reads the grid description data and the IBOUND boundary array values for the unconfined aquifer. A value of 1 in the IBOUND array of the unconfined aquifer represents a variable-head cell during the simulation period. Water table drawdowns in the unconfined aquifer will be calculated at these locations. If, however, the IBOUND array of the BAS package contains a value of –1, indicating a constant-head cell, no water table drawdowns are calculated for the unconfined aquifer.

Subroutine BCFRD

This subroutine reads the BCF package input file used in the MODFLOW model. The subroutine reads two arrays, DELR and DELC, to determine the distance between each grid cell in the row and column direction within the model domain. Based on the LAYCON variables, which represent the type of aquifer layer designed in the BCF input file, the subroutine reads the aquifer parameter values for hydraulic conductivity, transmissivity, leakance, and bottom and top elevations of either the unconfined aquifer or the confined aquifer.

Subroutine DDNRD

This subroutine reads an unformatted output file created by the MODFLOW model. The output file contains the simulated drawdown values for the confined aquifer.

Subroutine TCALC

This subroutine calculates the transmissivity in the unconfined aquifer based upon hydraulic conductivity, bottom elevation, and head values of the unconfined aquifer, when LAYCON has a value of 1 or 3. Otherwise, the transmissivity of the unconfined aquifer is a direct input to the model.

Subroutine COORD

This subroutine determines the row and column coordinate (x,y) for the center of each grid cell, based upon a (0,0) reference point located in the upper left corner of the MODFLOW model coordinate system.

Subroutine WELRD

This subroutine reads the WELL package input file used for the MODFLOW model and organizes well fluxes into a two-dimensional array that represents the total well flux out of each cell in the confined aquifer (e.g., the Floridan aquifer system) of the model. WELRD also includes an option to read flux values between the Lower and Upper Floridan aquifers and to add these values to the two-dimensional well flux array. This subroutine also reverses the sign of the well flux array to be consistent with the drawdown computation operation of the analytical process.

Subroutine DRAWDN

This subroutine calculates hydrologic coefficients for the ground water flow using Equations 14–17. The hydrologic coefficients and the aquifer parameter values (e.g., transmissivities, leakance, and well fluxes) then were used to calculate the drawdown in the unconfined aquifer based on drawdowns in the confined aquifer. The DRAWDN subroutine skips the calculation procedures if the hydraulic head in the unconfined aquifer is constant (i.e., IBOUND = –1). The subroutine will terminate the calculation if the drawdown in the confined aquifer is less than the preset convergence criterion of 0.001 foot.

Subroutine CLS

This subroutine clears the screen.

Subroutine OUTPT

This subroutine determines what to do with the drawdown values calculated in the DRAWDN subroutine. The OUTPT subroutine queries the user to determine if this is the first cycle in the iterative procedure. If the answer is yes, then the constant layer in the unconfined aquifer will be updated and the MODFLOW model will be rerun. The results of drawdowns in the elevation of the potentiometric surface of the confined aquifer then will be used and the iterative procedure will proceed with the SURFDOWN model. If the answer is no, then a file is automatically read that contains drawdown values that were calculated during the previous iteration. Differences between the current and the previous iteration are calculated and sorted by maximum and minimum values. At this point, the user can either update the water table head values in the unconfined aquifer for the next MODFLOW run or create the output files containing the hydraulic heads and drawdowns at each nodal cell in the unconfined and confined aquifers, if the maximum drawdown difference has met the closure criterion.

Subroutine XYZ

This subroutine creates "xyz" files that contain x and y coordinates for the center of each cell, determines hydraulic head values, and calculates drawdowns in the unconfined and confined aquifers. The reference coordinate point (0,0) is located in the lower left corner. An xyz file is used for contour plot purposes. A computer graphics package, such as the SURFER program, can directly read the xyz files in ASCII format and generate grid files for hydraulic or drawdown contour plots.

Subroutine BESK

This subroutine computes the modified Bessel function of the second kind, zero order (K_0) for a given argument, which is used in the linear solution of drawdowns for the unconfined and confined aquifers.

Subroutine WURB2

This subroutine computes the nonsteady, leaky-aquifer well function, *W(u)*. The well function is an exponential integral formula that represents the aquifer drawdown response to an argument variable, *u*. The argument variable is expressed as a function of aquifer transmissivity, storage coefficient, radial distance from the pumping well, and the period of pumping operation. The WURB2 subroutine is written in FORTRAN language based on a BASIC program (Walton 1984).

MODEL INPUT FILES

The following input files for and output files from the MODFLOW model are used as input files for the SURFDOWN model.

- A BAS package file containing an IBOUND array with –1 values assigned to all the model cells in the unconfined aquifer layer
- An unformatted output file containing the initial head values in the unconfined aquifer
- An unformatted output file containing the simulated hydraulic head results for both the unconfined and confined aquifers
- An unformatted file containing drawdown results for the confined aquifer
- The WELL package file
- An unformatted file containing cell-by-cell flux values from the Lower Floridan aquifer, if required

ITERATIVE PROCEDURE

The iterative procedure using the analytical SURFDOWN model and the numerical MODFLOW model is mainly designed to optimize the use of the existing MODFLOW package files and to calculate and to adjust the drawdown results in the unconfined and confined aquifers in a cost-effective way. The iterative procedure (SURFDOWN and MODFLOW models) was designed to be relatively straightforward. At the beginning of the iterative procedure, the program sequentially prompts the user for either filenames or answers to questions as follows.

<prompt for BAS pkg filename>

If the file in the response contains a variable IBOUND array for the unconfined aquifer, then model cells with –1 values will be set at a constant level. The drawdowns will be set to zero in the unconfined aquifer. If the file in the response contains a uniform IBOUND array, then drawdown values for the unconfined aquifer will be calculated for all model cells (subroutine BASRD).

<prompt for BCF pkg filename>

Enter the name of the BCF package file used for the MODFLOW simulation. The program writes messages to the screen describing which arrays are being read (subroutine BCFRD).

<prompt for file containing confined aquifer
(e.g., Upper Floridan aquifer) drawdown values>

Enter the unformatted file name containing the confined aquifer drawdowns created during the previous MODFLOW simulation (subroutine DDNRD).

<prompt for file with layers 1 and 2 heads>

Enter the unformatted file name containing ending head values for the confined and unconfined aquifers from the previous MODFLOW simulation (subroutine DDNRD).

<prompt for WELL pkg filename>

Enter the name of the WELL package input file that contains a different pumpage from the WELL package of the previous MODFLOW simulation (subroutine WELRD). At this point, a screen message appears with the following question.

<Do you want to consider the Lower Floridan fluxes?>

If no, then the program switches to the next step, reading the evapotranspiration rate (ET) (see below).

If yes, then

<prompt for unformatted BCF flux file>

Enter unformatted file name containing the cell-by-cell flux values created using the previous MODFLOW simulation.

<message to screen: ET rate used>

<message to screen: calculating drawdowns>

Because the procedure must calculate the influences of each well on each cell in the model, this step may take a long time.

At the end of the computation, a screen message appears with the following question.

<Is this the first iteration?>

If yes, then the SURFDOWN model run will continue.

If no, the program automatically reads a premade file that contains the calculated drawdowns from the previous iteration of this program in order to calculate the differences between the current and previous iterations (subroutine OUTPT).

<message about the range of drawdowns, differences from the previous drawdowns, and a question: Do you wish to update the constant heads in the unconfined aquifer (e.g., surficial) in order to run MODFLOW again?>

If yes, then

<Type filename to write updated heads in the unconfined aquifer>

Enter the name of file to serve as an unformatted file containing constant heads in the unconfined aquifer for a subsequent run of the MODFLOW model. Note that this file then will be used as the starting constant-head file for the unconfined aquifer in the next MODFLOW simulation.

If no, the iterative procedure has reached the preset closure criterion and the following message appears.

<message: iteration procedure complete, program will automatically create xyz files containing unconfined and confined aquifer heads and drawdowns>

As with other programs that run interactively based on a series of prompts and replies, this program may be run in a batch mode. The batch file is created by making a file that has the answers to the prompts and then typing "SURFDOWN<files" at the command line, where *files* is the name of a file that contains the inserts to all prompts. Because the MODFLOW model also can be run in this manner, one can set up a procedure to run the MODFLOW model and the SURFDOWN model repeatedly for several iterations from an additional batch file.