Post Audit of a Numerical Prediction of Wellfield Drawdown in a Semiconfined Aquifer System

by Mark Stewart[a] and Christian Langevin[a,b]

Abstract

A numerical ground water flow model was created in 1978 and revised in 1981 to predict the drawdown effects of a proposed municipal wellfield permitted to withdraw 30 million gallons per day (mgd; 1.1×10^5 m^3/day) of water from the semiconfined Floridan Aquifer system. The predictions are based on the assumption that water levels in the semiconfined Floridan Aquifer reach a long-term, steady-state condition within a few days of initiation of pumping. Using this assumption, a 75 day simulation without water table recharge, pumping at the maximum permitted rates, was considered to represent a worst-case condition and the greatest drawdowns that could be experienced during wellfield operation. This method of predicting wellfield effects was accepted by the permitting agency.

For this post audit, observed drawdowns were derived by taking the difference between pre-pumping and post-pumping potentiometric surface levels. Comparison of predicted and observed drawdowns suggests that actual drawdown over a 12 year period exceeds predicted drawdown by a factor of two or more. Analysis of the source of error in the 1981 predictions suggests that the values used for transmissivity, storativity, specific yield, and leakance are reasonable at the wellfield scale. Simulation using actual 1980–1992 pumping rates improves the agreement between predicted and observed drawdowns. The principal source of error is the assumption that water levels in a semiconfined aquifer achieve a steady-state condition after a few days or weeks of pumping. Simulations using a version of the 1981 model modified to include recharge and evapotranspiration suggest that it can take hundreds of days or several years for water levels in the linked Surficial and Floridan Aquifers to reach an apparent steady-state condition, and that slow declines in levels continue for years after the initiation of pumping. While the 1981 "impact" model can be used for reasonably predicting short-term, wellfield-scale effects of pumping, using a 75 day long simulation without recharge to predict the long-term behavior of the wellfield was an inappropriate application, resulting in significant underprediction of wellfield effects.

Introduction

Statement of Problem

A post audit of a numerical model compares the model's predictions with field observations at least several years after the predictions have been made (Konikow 1986). Post audits can provide valuable perspectives on the use of numerical models to predict the effects of stresses on a ground water system (Alley and Emery 1986; Goode and Konikow 1990; Konikow 1986; Lewis and Goldstein 1982; Person and Konikow 1986).The predictive ability of numerical models is often, incorrectly, associated with a model's ability to reproduce a calibration data set (Freyberg 1988). Without assessing model performance over the prediction period through a post audit, it is not possible to make a general assessment of the predictive ability of numerical models, or to discover common reasons for poor predictions. While post audits can obviously improve the predictive ability of a specific model, they can also provide guidance for improving the predictive ability of numerical models in general. This paper describes a post audit of a numerical flow model used to predict wellfield drawdowns in the Floridan Aquifer.

A numerical model was used in 1979, and revised in 1981, to support the consumptive use permit application for the Cross Bar Ranch wellfield (Leggette, Brashears, and Graham Inc. [LBG] 1981), in west-central Florida (Figure 1). The application was for the withdrawal of an annual average of 30 mgd (1.1×10^5 m^3/d) of ground water from the semiconfined Floridan Aquifer system. The application process requires that a prediction be made of the hydrologic effects of the proposed withdrawals. As stated in the model report, the model was used for calculating the projected effects of ground water withdrawals (LBG 1978).

An important conceptualization used by the permit applicant is that a semiconfined aquifer achieves a steady-state condition soon after the initiation of pumping, and that a "worst-case" impact model based on this assumption would conservatively predict drawdown effects of long-term pumping at the wellfield. The model predictions "simulated a worst-case situation by running the model for 75 days without any water table recharge" (LBG 1978). The predicted drawdowns are those produced by the 75 day long transient simulations. The Southwest Florida Water Management District (SWFWMD) used and accepted this type of analysis until 1992 or later (SWFWMD 1992). The goal of the permitting agency, SWFWMD, was that the proposed withdrawals would meet the "5-3-1" rule, under worst-case conditions. That is, drawdowns at the wellfield boundary from permitted withdrawals would not exceed 5 feet (1.5 m) in the Floridan Aquifer, 3 feet (0.9 m) in the Surficial Aquifer, and 1 foot (0.3 m) in a surface water body. The objective of the "5-3-1" rule was to avoid excessive drawdowns in the water table, the Floridan Aquifer, or lakes adjacent to the wellfield. In 1978, the wellfield contained extensive lakes and wetlands and was surrounded by lakes and wetlands on three sides.

Wellfield withdrawals began in 1980. After an increase in wellfield withdrawals in the late 1980s from less than 21 mgd (8×10^4 m^3/day) to greater than 21 mgd, field observations began to suggest underprediction of drawdown by the 1981 model. After a five-year period of below-average rainfall from 1989-1993, it was clear from

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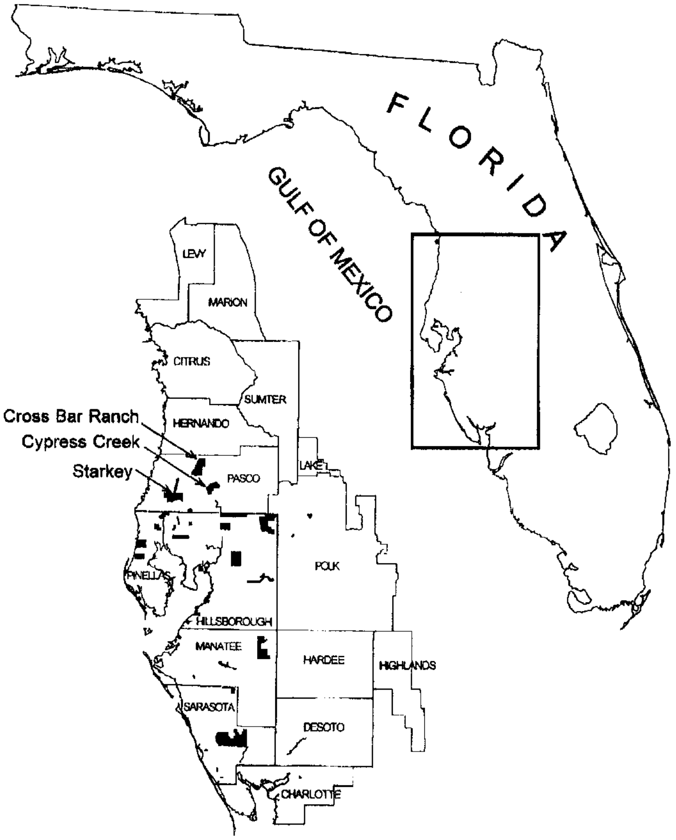

Figure 1. Cross Bar Ranch wellfield, Pasco County, Florida. Major municipal wellfields are shown in black.

field observations that the original 1981 model had significantly underpredicted the drawdowns that would result from withdrawals near the permitted average daily withdrawal rate of 30 mgd (1.1×10^5 m^3/day). In 1992, SWFWMD notified the wellfield operator that the model was no longer considered valid (SWFWMD 1992).

The objective of this post audit is to compare model-predicted drawdowns against observed heads over the 12 year period of wellfield operation (1980 through 1992), and to determine the probable source of errors in predicting the effects of pumping. The evaluation period, 1980 through 1992, corresponds to the 12 year period that the model was used by the wellfield operator to predict the effects of pumping. This post audit is of particular interest as the effects of the wellfield on surrounding wetlands became the subject of a legal and technical controversy starting in 1992 (Stewart 1998).

Hydrologic Setting

The Cross Bar Ranch wellfield is located in west-central Florida (Figure 1). The wellfield is about 2.5 miles wide and 5 miles long (4×8 km) and covers about 8000 acres (32 km^2). The principal aquifer in central Florida is the Tertiary Floridan Aquifer System (Miller 1986). At the Cross Bar Ranch wellfield, the hydrologic system consists of four principal hydrostratigraphic units (Hutchinson 1985) (Table 1). The uppermost unit is the Surficial Aquifer. It consists of fine sand, with some silt and clay. It has a hydraulic conductivity of 1 to 10 feet/day (0.3 to 3 m/day), and is 20 to 30 feet thick (6 to 9 m). Separating the Surficial Aquifer from the Upper Floridan Aquifer (called the "Floridan Aquifer" here) is the Upper Confining Unit, a discontinuous clayey sand to sandy clay averaging 10 to 20 feet (3 to 6 m) in thickness. This unit is frequently breeched by sinkholes, which connect the Surficial and Floridan Aquifers. The leakance of the semiconfining unit is 5×10^{-4} to 3×10^{-3} day^{-1}, increasing from south to north within the wellfield (Hutchinson 1985). The Floridan Aquifer lies below the Upper Confining Unit and consists of Tertiary age limestones and dolostones, and is about 900 feet (300 m) thick. The transmissivity of the Upper Floridan is about 5×10^4 feet^2/day (4600 m^2/day) in the central and southern parts of the wellfield, and about 1.2×10^5 feet^2/day (11,000 m^2/day) in the northern part. The base of the Upper Floridan Aquifer is the Middle Confining Unit, a low porosity dolostone with intergranular anhydrite (Miller 1986; Hutchinson 1985). The Middle Confining Unit separates the Upper Floridan Aquifer from the Lower Floridan Aquifer. The Lower Floridan Aquifer contains highly mineralized water in west-central Florida, and is not a source of potable water (Miller 1986).

Table 1
Geology, Hydrostratigraphy, and 1978/1981 Model Conceptualization at Cross Bar Ranch

Geology (from Hutchinson 1985)	**Hydrostratigraphy** (from Miller 1986)	**Model** (LBG 1979)
Fine to very fine sand; increasing silt and clay with depth; 20–30 ft (6–9 m) thick	Surficial Aquifer	Layer 1 Unconfined
Clayey, silty sand to sandy clay; breached in places by sinkholes; 10–20 ft (3–6 m) thick	Upper Confining Unit	Leakance term between layers 1 and 2
Limestone and dolostone; 900 ft (274 m) thick	Upper Floridan Aquifer	Layer 2 confined
Dolostone, limestone with intergranular anhydrite	Middle Confining Unit	Lower model boundary

Hydrologic Testing

In 1978, three aquifer stress tests were completed as part of the evaluation of the wellfield and to develop hydrologic data for the predictive model (LBG 1978). Three large capacity pumping wells were constructed in the south, central, and northern parts of the wellfield. Near each pumping well, three Floridan and four Surficial Aquifer monitoring wells were also installed. Pumping tests were conducted for each well cluster, at rates of 2200 to 3500 gallons per minute (1.2×10^4 to 1.9×10^4 m^3/day) for 18 days. A total of 22 Floridan and 30 Surficial Aquifer wells were monitored during the 1978 testing period.

A larger wellfield-scale pumping test was conducted in 1981. In December 1980, pumping at the wellfield ceased. After water levels in the Floridan Aquifer recovered, in January 1981, pumping at five wells in the central and northern parts of the wellfield recommenced at a combined rate of 18 mgd (6.8×10^4 m^3/day) for 21 days, then a combined rate of 14 mgd (5.3×10^4 m^3/day) for nine more days, for a total of 30 days. Data from this wellfield-scale pumping test were used to revise the 1978 predictive model constructed on the basis of the 1978 aquifer testing (LBG 1981).

Hydrologic Anomaly

In an early investigation of the wellfield (LBG 1976), it was noted that there is a marked steepening of the gradient of the potentiometric surface of the Floridan Aquifer across the central part of the wellfield. South of this boundary, the water table was at or near the land surface under pre-pumping conditions. North of the boundary, the water table was 10 feet (3 m) or more below the land surface. Extensive wetlands and ponds existed south of the boundary, but not north of it. This boundary was termed the hydrologic anomaly.

The 1978 pumping tests and additional testing in 1979 (LBG 1979) showed that observation wells on the opposite side of the anomaly had reduced drawdowns as compared to observation wells on the same side of the anomaly as the pumping well. Geophysical and drilling investigations in the 1979 investigation did not reveal any apparent change in the Surficial Aquifer or the Upper Confining Unit associated with the anomaly. At this point, the anomaly was attributed to a narrow, linear zone of lower transmissivity (LBG 1978, 1979).

Model Description

1978 Model

The data obtained during the 1978 hydrologic testing were used to construct a numerical model to predict the drawdown effects of pumping within the wellfield (LBG 1978). The Cross Bar model used the Prickett and Lonnquist Aquifer Simulation Model (PLASM; Prickett and Lonnquist 1971). It was a two-layer, quasi-three-dimensional model, with the Surficial and Floridan Aquifers as active layers, and the Upper Confining Unit being simulated by a leakance term between model layers 1 and 2 (Table 1). The model used a 30 row by 30 column grid, with a constant spacing of 2000 feet (608 m). A uniform hydraulic conductivity was used for the Surficial Aquifer. Modeled Floridan transmissivities increase from about 5×10^4 feet^2/day (4600 m^2/day) in the south part of the model, to about 1×10^5 feet^2/day (9300 m^2/day) in the north, with the hydrologic anomaly represented as a zone of lower transmissivity of 9.3×10^3 feet^2/day (864 m^2/day) (Figure 2). The gap in the low transmissivity zone shown in Figure 2 is part of the 1981 data set.

The 1978 model was developed as an "impact" model. That is, the model is designed to simulate the drawdown caused by pumping at the Cross Bar Ranch wellfield, but it does not simulate the regional ground water flow system. The model does not attempt to replicate actual regional or local heads, but calculates drawdowns from initially horizontal water table and Floridan potentiometric surface levels. The initial water levels in layers 1 (Surficial) and 2 (Floridan) were equal, with an initial saturated thickness of 25 feet (7.6 m) in layer 1, throughout the model. Layer 1 was modeled as an unconfined aquifer, in that transmissivity is function of head in the layer. The model used barrier boundaries at the edge of the model grid.

1981 Revision

In 1981, the 1978 model was revised and recalibrated on the basis of the results of the 1981 wellfield-scale pumping test. The recalibration involved modification of some values for transmissivity, storage, and leakance, and the model boundaries were extended outward by increasing the grid to 50 rows by 50 columns. The recalibration improved the model's predictive abilities, as shown by the calibration measures in Table 2 (LBG 1981). The observed drawdowns in Table 2 were obtained by subtracting observed heads from the regional, pre-pumping potentiometric surface of the Floridan Aquifer. The observed heads are from the 1981 wellfield-scale pumping test. Calculated heads were obtained with the 1978 and 1981 models, using withdrawals during the 1981 30 day pumping test.

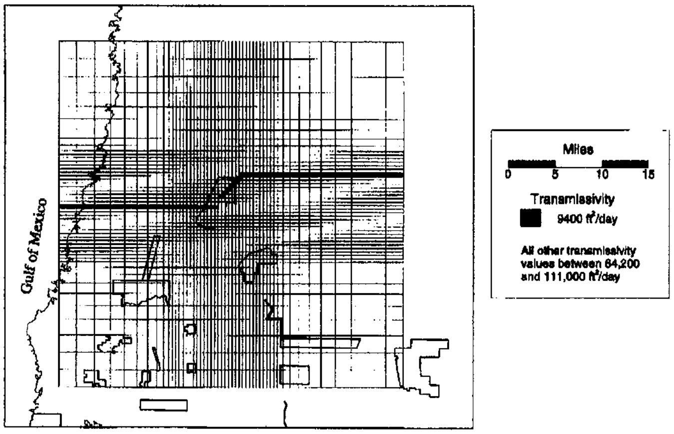

Figure 2. Position of the "hydrologic anomaly" in the 1979 and 1981 PLASM models.

Table 2
Comparison of Calibration Errors Between Observed and Calculated Heads in the Floridan Aquifer for the 1978 and 1981 Models. (Simulation is for the 1981 30 day wellfield-scale pumping test [LBG 1981])

Model	Mean Error	Mean Absolute Error
1978	–0.46 ft (0.14 m)	0.57 ft (0.17 m)
1981	–0.12 ft (0.04 m)	0.38 ft (0.12 m)

1985 MODFLOW Model

The 1978 and 1981 models used the PLASM code. The conceptualization of both models, including the distribution of hydrologic variables, the geometry of the model grid, and the results of the model simulations are described in two reports (LBG 1978, 1981). The PLASM model uses a system whereby modules can be added to the basic code to accommodate problem-specific needs for model capabilities. The data input formats for the 1978 and 1981 PLASM models were modified specifically for the Cross Bar simulations, and do not use standard PLASM input. Several data sets from the 1978 and 1981 PLASM models were obtained, but they are unannotated, and as a result neither the original 1978 nor 1981 PLASM model codes can be exactly duplicated. In 1985, the 1981 PLASM model and its original input files were converted to a MODFLOW (McDonald and Harbaugh 1983) model to support the 1986 repermitting of the wellfield (CH2M Hill 1986). The MODFLOW model duplicates the results of the 1981 PLASM model. The 1985 MODFLOW model was used to conduct this post audit of the predictions of the 1981 PLASM model. The predicted drawdowns discussed in this study were generated using the 1985 MODFLOW model and the simulation data presented in the 1978 and 1981 reports. The results closely duplicate the figures of predicted drawdowns presented in the 1978 and 1981 reports (LBG 1978, 1981).

Model Predictions

The 1978 and 1981 PLASM models were designed to predict the drawdown effects of pumping the Cross Bar Ranch wellfield at permitted rates of 30 mgd (1.1×10^5 m^3/day) average daily withdrawals and 45 mgd (1.7×10^5 m^3/day) maximum daily withdrawal. The models were set up as impact models, with all pre-pumping heads set to zero. As it was assumed, on the basis of field observations, that potentiometric surface elevations of the Floridan Aquifer stop declining and reach an apparent steady-state condition within a few days of the initiation of pumping, a series of 75 day long simulations was used to predict the long-term response of the wellfield (LBG 1978). Pumping rates were at the permitted maximums. No

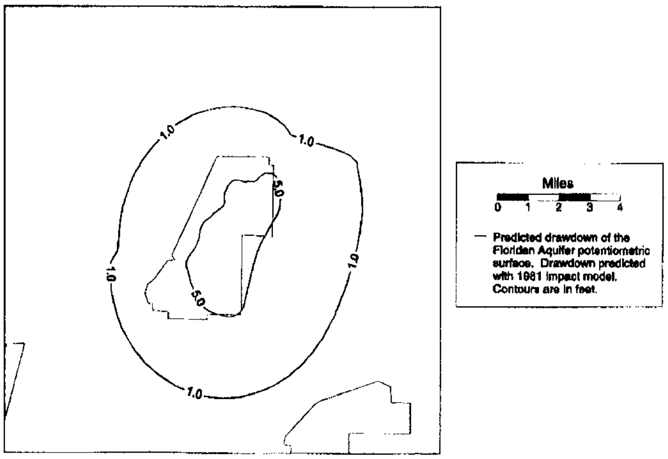

Figure 3. Predicted drawdowns in the Floridan Aquifer for the 1981 model for a 75 day simulation. Pumping scenario is 30 days at 30 mgd (1.1×10^5 m³/day), 15 days at 45 mgd (1.7×10^5 m³/day), and 30 days at 30 mgd. Drawdowns are in feet (1 foot = 0.3 m).

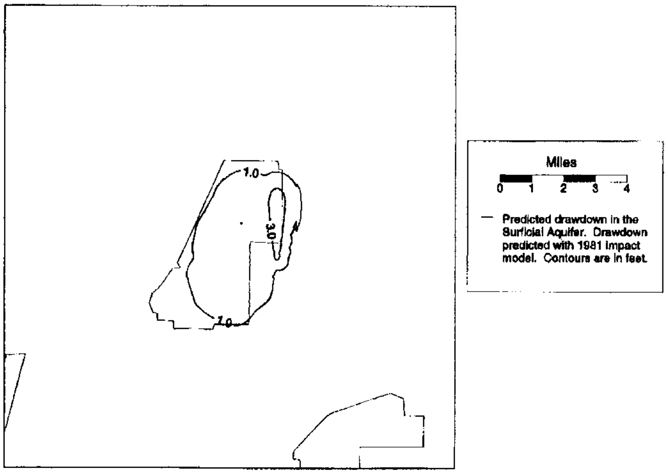

Figure 4. Predicted drawdowns in the Surficial Aquifer for the 1981 model for a 75 day simulation. Pumping scenario is 30 days at 30 mgd (1.1×10^5 m³/day), 15 days at 45 mgd (1.7×10^5 m³/day), and 30 days at 30 mgd. Drawdowns are in feet (1 foot = 0.3 m).

recharge was used in the models to simulate a long period without rainfall (LBG 1978). It was estimated that a 75 day long period without rainfall has a recurrence interval greater than 100 years (LBG 1978). The model documentation does not make a distinction between rainfall and recharge to the water table. Pumping at the Cypress Creek Wellfield was considered in some of the early predictions, as withdrawals began at Cypress Creek in 1978.

As an example, Figure 3 shows the 1981 model results for the Floridan Aquifer obtained using a pumping schedule of 30 days at 30 mgd (1.1×10^5 m³/day), 15 days at 45 mgd (1.7×10^5 m³/day), and 30 days at 30 mgd (LBG 1981). The 5 foot (1.5 m) drawdown contour lies mostly within the wellfield boundaries, extending about one mile beyond the wellfield to the east. The results for layer 1, the Surficial Aquifer (Figure 4), predict that drawdowns of the water table greater than 3 feet (0.9 m) are restricted to the wellfield. Drawdowns of 1 foot (0.3 m) or greater extend about one mile (1.6 km) east of the wellfield. In general, the predictions suggest that the assumed worst-case drawdowns will come close to meeting the 5-3-1 rule of the permitting agency. As stated in the modeling report, "after 75 days of no water table recharge, drawdown in the Artesian [Floridan] Aquifer is 5 feet at the property boundary. The decline in the water table is 1 to 2 feet." As the predictions were assumed to be for recharge conditions with a long recurrence interval (LBG 1978), the predictions of the 1981 model were used to infer that the 5-3-1 rule would not be violated during normal wellfield operation.

It is clear from statements in the modeling reports (LBG 1981) that the model predictions were considered to be realistic and long term. To quote from the 1981 report, "The revised [1981] model accurately simulates the present observed effects and then should provide projected impacts for future pumping that will be very similar to effects observed in the field" (LBG 1981). The 1978 report (LBG 1978) states, however, that "the water table continues to decline throughout the simulation period."

Observed Water Level Changes, 1980 to 1992

Difference Maps

Because the 1981 simulation is an impact model, the results are given in drawdowns from a uniform water level, not in actual head values. Output from the model cannot be directly compared with observed heads in the Surficial and Floridan Aquifers. In order to derive the apparent drawdown created by pumping at the Cross Bar Ranch wellfield, post-1980 water levels in observation wells are subtracted from 1980 water levels. The resulting apparent drawdown is positive when post-1980 levels are lower than 1981 levels, and negative when post-1980 levels are higher. Water level difference maps were prepared by contouring the differences in observed heads.

May 1980 water levels were chosen as the "pre-pumping" levels. The two previous years, 1978 and 1979, were relatively wet, and potentiometric surface levels in those years were higher than those in 1980. The use of either the 1978 or 1979 water levels as the pre-pumping level might overestimate the observed drawdown. We chose to be conservative in our estimates of apparent drawdowns. Prior to 1978, little information was available on the potentiometric surface at Cross Bar Ranch. Pumping commenced at Cross Bar Ranch in April 1980, so the May 1980 potentiometric surface levels contain some drawdown effects of pumping. Using the May 1980 levels means that the estimates of observed drawdown are conservative; that is, actual drawdowns are probably greater.

Observed Drawdowns

The difference maps which show apparent drawdown for the years 1981 through 1992 can be divided into two groups (Figure 5). The first group includes the years 1981 through 1987. The potentiometric surface difference map for 1985 is an example (Figure 6). During this period, average daily withdrawals from the wellfield were less than 21 mgd (2.8×10^4 m³/day), and the observed drawdowns (Figure 6) are similar to those predicted by the 1981 model (Figure 3), which used withdrawal rates of 30 to 45 mgd (1.1×10^5 to 1.7×10^5 m³/day).

Starting in 1988, the average daily withdrawals increased, reaching 25 mgd (9.5×10^4 m³/day) by 1992. Observed drawdowns increase with increasing withdrawals (Figure 5). The potentiometric surface difference map for 1992 shows an extensive cone of depression centered on the wellfield (Figure 7). Maximum apparent drawdowns exceed 15 feet (4.6 m), and the 5 foot (1.5 m) drawdown contour extends many miles beyond the wellfield. The shape of the contours on the southeast side of the wellfield suggests that by 1992 significant overlap had occurred between the cones of depres-

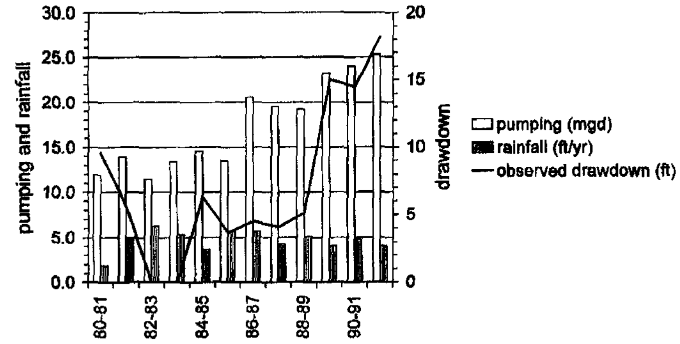

Figure 5. Comparison of rainfall at St. Leo with average daily pumping rate and observed drawdown at Cross Bar Ranch wellfield, for the period May 1980 through May 1992. Rainfall is in inches (1 inch = 2.54 cm), pumping is in mgd (1 mgd = 3.8 × 10^3 m^3/day), and drawdown is in feet (1 foot = 0.304 m).

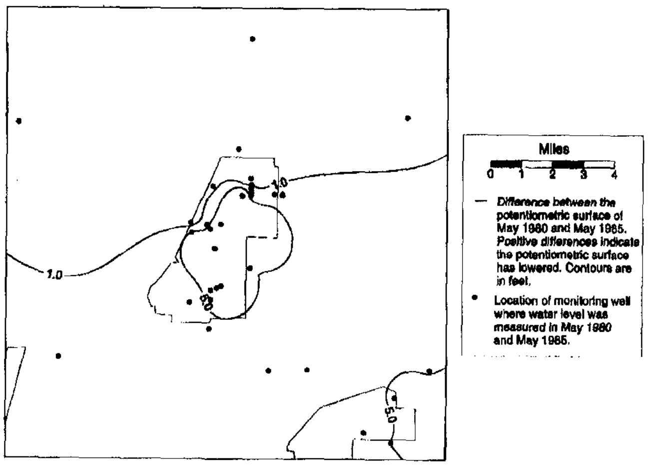

Figure 6. Difference between the May 1980 Floridan Aquifer potentiometric surface and the May 1985 Floridan Aquifer potentiometric surface. Contours are in feet (1 foot = 0.3 m).

sion of the Cross Bar Ranch and Cypress Creek wellfields. In general, apparent drawdowns on the 1992 difference map (Figure 7) are at least twice as large as the drawdowns predicted by the 1981 model. (Figure 3).

Discussion

The 1981 model significantly underpredicts the effects of pumping after 1987, when average daily withdrawal rates exceed 21 mgd (2.8 × 10^4 m^3/day). The 1981 model was based on a "worst-case" assumption of no rainfall for 75 days, a meteorologic condition with a recurrence interval estimated to be greater than 100 years (LBG 1978). Again, the model documentation does not distinguish between rainfall and recharge. The lower rainfall period of 1989 through 1992 was a period of reduction of average rainfall, but was not equivalent to 75 days without rain. As the model simulations made in 1978 and 1981 significantly underpredict the observed drawdowns in 1992 (Figure 7), the simulations must contain errors in one or more of the areas of conceptualization, values of hydraulic variables, or stresses.

Hydrologic Variables

The 1981 model was calibrated to an extensive, multi-well, wellfield-scale pumping test, with aggregate pumping rates of 14 to 18 mgd (5.3 × 10^4 to 6.8 × 10^4 m^3/day). The reported calibration

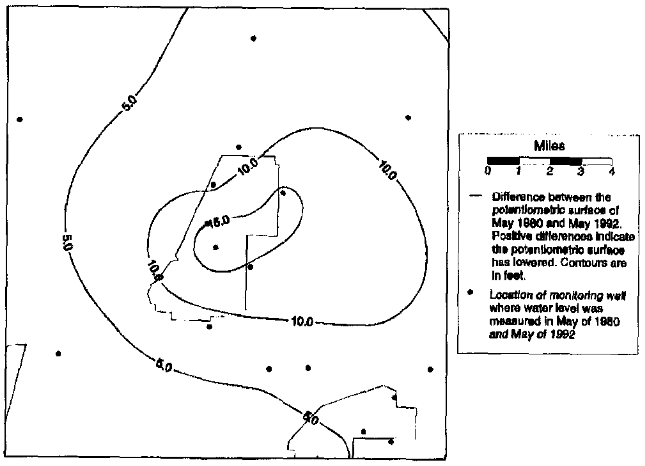

Figure 7. Difference between the May 1980 Floridan Aquifer potentiometric surface and the May 1992 Floridan Aquifer potentiometric surface. Contours are in feet (1 foot = 0.3 m).

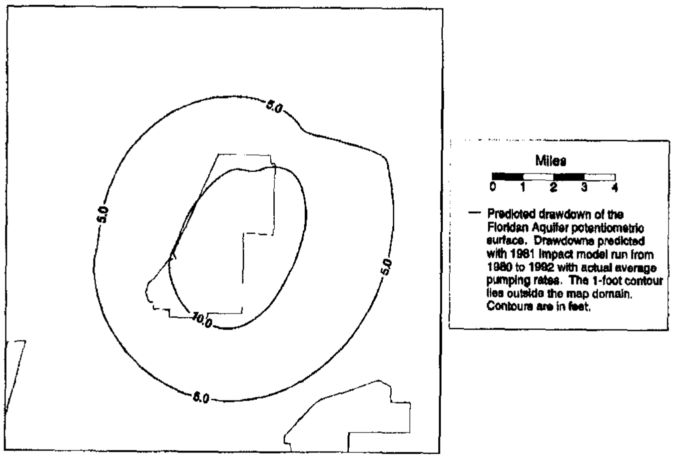

Figure 8. Drawdowns in the Floridan Aquifer produced by running the 1981 model from 1980 to 1992 using actual average annual pumping rates. Drawdowns are in feet (1 foot = 0.3 m).

measures (Table 2) suggest that the 1981 model can duplicate the 1981 30 day pumping test well. The calibration was matched to apparent drawdowns within the 8000-acre (32 km^2) wellfield. Little or no information was available for areas beyond the wellfield, but observed drawdowns extend several miles beyond the wellfield boundaries. The values of transmissivity, storage, and leakance used in the 1981 model are probably reasonable within the wellfield, where they were calibrated to observed drawdowns, but may not be appropriate when pumping effects extend beyond the wellfield.

The calibration process required estimating the value of transmissivity, leakance, and storativity at every finite-difference cell by comparing the model results to observed drawdowns at a limited number of observation wells within the wellfield. The calibration solution is always severely underconstrained, so that many different combinations of the hydraulic variables can be matched to the observed data, leading to nonunique solutions. A model may be able to reproduce the calibration data set reasonably well, but its predictive ability may be poor if the predictive simulation is extended beyond the calibration data, either spatially or temporally. The 30 day pumping test may not have been a sufficient spatial and temporal stress to allow the calibrated model to predict long-term regional effects of pumping. The model is an impact model, simulating drawdowns, so only areas of the model affected by the 30

Table 3
Comparison of the Elevations of the Water Table in August 1979, with Elevations of the Bottom of the Surficial Sand, in the Northern Part of the Cross Bar Ranch Wellfield

Well	Elevations in Feet [m]		Saturated Thickness of Sand in Feet [m]
	Water Table	Bottom of Sand	
NRW	<45 (dry) [<13.7]	55 [16.7]	0 [0]
NWO-1	<38 (dry) [<1.2]	38 [11.6]	0 [0]
N-12	40.8 [12.4]	27 [8.2]	14 [4.3]
NOW1	46.4 [1.41]	37 [11.2]	9 [2.7]
C-1	<48 (dry) [<14.6]	60 [18.2]	0 [0]
NOW1	48 [14.6]	40 [12.1]	8 [2.4]
CB-13	49 [14.9]	40 [12.1]	9 [2.7]
C-2	49 [14.9]	60 [18.2]	0 [0]
C-3	49 [14.9]	48 [14.6]	1 [0.3]
NWO-2	<33 (dry) [<10]	52 [15.8]	0 [0]

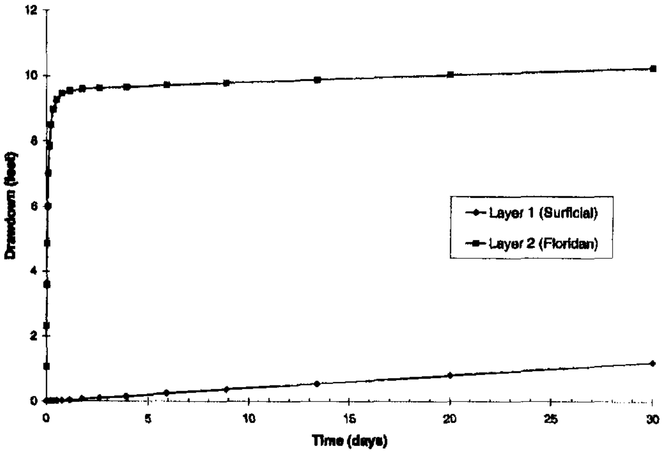

Figure 9. Response of simulated water levels for the Floridan and Surficial Aquifers, using the 1981 model, 30 mgd (1.1×10^5 m³/day) total pumping, and a 30 day simulation. Data are from a model cell near the center of the wellfield.

day test could be calibrated. It would be expected that years of pumping would influence an area larger than that affected by the 30 day test. Most of the monitoring wells used for calibration are within the wellfield, but observed drawdowns extend several miles beyond the wellfield.

In the 1981 model simulations, the initial saturated thickness of the Surficial Aquifer was set at 25 feet (7.6 m) throughout the modeled area. This may have seemed reasonable, as the average thickness of the Surficial Aquifer within the wellfield is 25 feet (7.6 m) (LBG 1978). The water table, however, in the northern part of the wellfield was 25 to 30 feet (6 to 9 m) below land surface under predevelopment conditions (LBG 1976). Comparison of well logs and water table elevations suggests that there were less than 5 to 10 feet (1.5 to 3 m) of saturated thickness of the Surficial Aquifer in the northern part of the wellfield under pre-development conditions, or no saturated zone within the fine sand of the water table aquifer (Table 3). This means that in the northern part of the wellfield, the Surficial Aquifer contained significantly less stored water than assumed in the 1981 model. This additional stored water in the model would buffer the predicted effects of pumping. For example, each foot of drawdown in the Surficial Aquifer yields enough water over the area of the wellfield to sustain a 30 mgd (1.1×10^5 m^3/day) withdrawal rate for 86 days. The model documentation states "The water table continues to decline throughout the simulation period" (LBG 1978). If actual pumping progressively dewaters the Surficial Aquifer, then the overestimation of Surficial Aquifer storage would significantly buffer the effects of pumping predicted by the model, particularly as the transient, predictive runs only simulated 75 days of pumping. In 1992, SWFWMD ran a simulation of the 1985 MODFLOW model with a "severely depressed" water table, and found that the results "indicate a much greater drawdown effect" (SWFWMD 1992).

Stresses

The 1981 model has no recharge, and the model predictions were made for a 75-day period, pumping at maximum permitted rates. To assess the effects of not simulating the actual stresses from 1980 to 1992, the boundary conditions of the 1981 model were changed to constant heads and the model was run for 12 years, using the actual average daily pumping rates for each year, including pumping at the Cypress Creek wellfield. Adding the actual stresses and running the model for 12 years, not 75 days, improves the prediction of Floridan water levels significantly (Figure 8). In this scenario, however, withdrawals are derived from lateral flow from the boundaries, not recharge, which is not physically realistic as most water pumped from the wellfield is derived from the water table (Hutchinson 1985).

Conceptualization and Application

The 1978 and 1981 models use a quasi-three-dimensional discretization. The Upper Confining Unit is represented as a leakance term between model layers 1 and 2. This could be a source of error for transient simulations, as the release of water from storage in the semiconfining unit is not simulated. The leakance values calculated from the aquifer stress tests range from 5×10^{-4} to 3×10^{-3} day^{-1} (LBG 1978, 1981), indicating that the semiconfining unit is thin and relatively permeable. Time-drawdown curves from aquifer stress tests within the wellfield match well to analytical solutions which do not consider release from storage in the semiconfining unit. Ignoring release from storage in the semiconfining unit would cause model predictions to overestimate drawdowns, but the model underestimates long-term drawdowns. For these reasons, the quasi-three-dimensional conceptualization does not appear to be a significant source of predictive error.

The 1978 and 1981 models used barrier boundaries. Running the model for the 75 day simulations with constant head boundaries does not change the model results. For the 75 day simulations used for predictions, the choice of boundary conditions does not influence the results.

The 1978/1981 models assume that the 75 day, no-recharge simulations represent "worst-case" scenarios (LBG 1978). This assumption is apparently based on field observations that show drawdowns in the Floridan Aquifer reaching an apparent steady-state condition within a few days of the start of pumping, and that under pre-pumping conditions, both the Surficial and Floridan water levels responded quickly to rainfall (LBG 1976, 1978). In the 1978/1981 simulations, Floridan water levels reach a near steady-state condition within about a day, then slowly decline in response to increasing declines in Surficial Aquifer levels (Figure 9). Because pre-pumping hydrographs show Surficial and Floridan levels following each other closely (LBG 1976, 1978), it was apparently assumed that the resumption of recharge after 75 days would raise

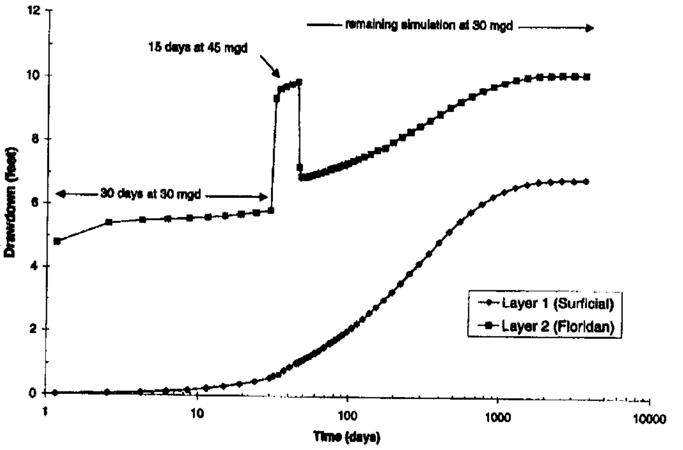

Figure 10. Drawdowns from a 10 year simulation using the 1981 model modified to include recharge and evapotranspiration. Data are from a model cell in the north-central part of the wellfield.

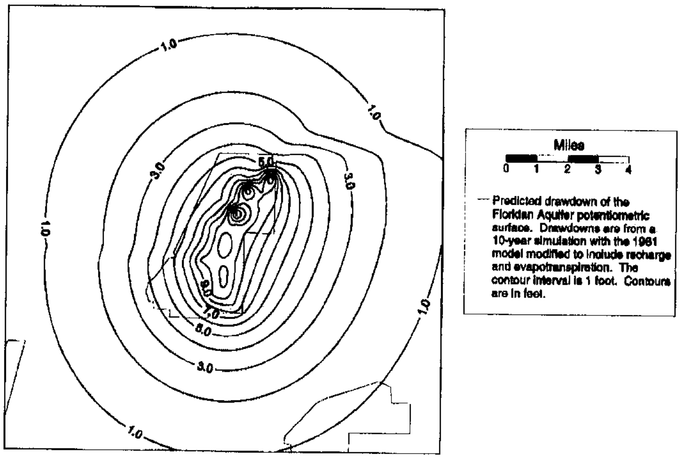

Figure 11. Simulated drawdown in the Floridan Aquifer after 10 years of pumping using the 1981 model modified to include recharge and evapotranspiration. Drawdowns are in feet. The contour interval is 1 foot (0.3 m).

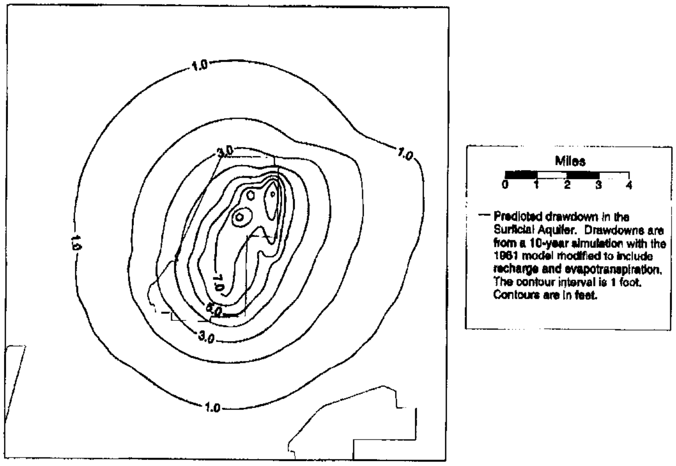

Figure 12. Simulated drawdown in the Surficial Aquifer after 10 years of pumping using the 1981 model modified to include recharge and evapotranspiration. Drawdowns are in feet. The contour interval is 1 foot (0.3 m).

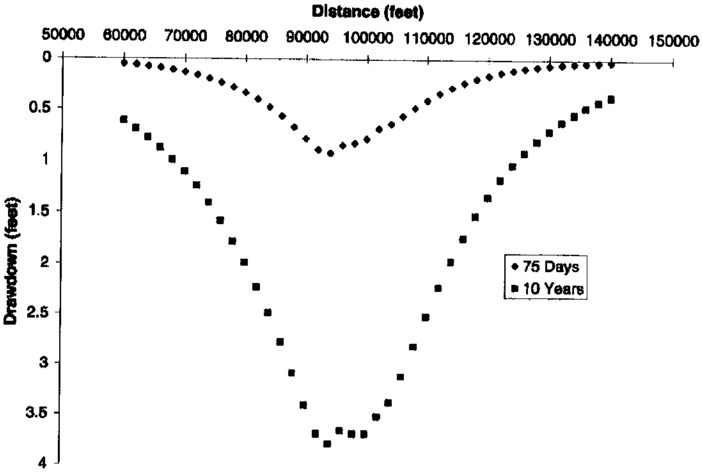

Figure 13. East-west profile of water levels in the Surficial Aquifer across the northern boundary of the wellfield after 75 days of pumping without recharge, and 10 years with recharge available from salvaged ET.

Floridan levels above the minimum levels reached after 75 days of pumping without recharge. This assumption was not tested in the 1978/1981 simulations. As the simulated drawdowns after 75 days of pumping without recharge significantly underpredict observed wellfield effects, the no-recharge, "worst-case" assumption may be in error.

To test this assumption, the 1981 model was run for 75 days without recharge, then beyond 75 days with a source of recharge. A source of recharge was added by including both recharge and evapotranspiration (ET) in the 1981 model, with recharge set equal to maximum potential ground water ET. As described by Motz (1996) and Liu and Polmann (1996), this creates a coupled aquifer system where water levels will not change in the absence of pumping. Lowering Surficial Aquifer levels reduces ET, until the recharge from salvaged ET and leakage equals the water being pumped from the Floridan. At this point the coupled system achieves steady state. Salvaged ET in the field is derived from lakes, wetlands, baseflow, and the root zone of plants.

A value of 15 inches/year (0.38 m/year) was used for recharge and maximum ground water ET, with an ET extinction depth of 10 feet (3.04 m). Hutchinson (1985) used a water budget calculation to estimate that the Surficial Aquifer lost 15 inches/year (38 cm/yr) to ET and baseflow under predevelopment conditions. A 10 foot (3.04 m) ET extinction depth was used by Hutchinson (1985) in a numerical model of the Cross Bar area, and was used for the ET extinction depth in this simulation. Simulated pumping rates were 30 mgd (1.1×10^5 m^3/day) for 30 days, 45 mgd (1.7×10^5 m^3/day) for 15 days, then 30 mgd to 10 years. Recharge and ET rates were set to zero for the first 75 days, as in the 1981 simulations.

During the 10 year simulation, the Surficial Aquifer does not reach steady-state until about 2500 days after the start of pumping, or about seven years. This time to reach steady state will vary with the recharge rate, ET rate, and extinction depth used in the simulation, but for any reasonable set of values, the time required for Surficial Aquifer levels to reach steady-state is at least several years. The plot of drawdown versus time (Figure 10) clearly shows that in this coupled system, Floridan Aquifer levels continue to decline until Surficial Aquifer levels reach steady state after seven years. The assumption of a 75 day, no recharge, "worst-case" pumping scenario is not a valid application of the calibrated 1978/1981 model. Steady-state drawdowns in the Floridan and Surficial Aquifers predicted by the modified 1981 model (Figures 11 and 12) greatly exceed the drawdowns predicted in 1981 (Figures 3 and 4). The greatest difference is in the Surficial Aquifer (Figure 4 versus Figure 12), as the 75 day simulation is much too short to create significant drawdowns in the Surficial Aquifer. An east-west profile of heads in the Surficial Aquifer after 75 days and 10 years of simulation along the northern boundary of the wellfield illustrates this point (Figure 13). Maximum drawdown after 75 days is about 0.7 feet (0.21 m), and is about 3.8 feet (1.2 m) after 10 years, a difference greater than a factor of 5.

Drawdowns in the Floridan Aquifer predicted by the 1981 model modified to include recharge and ET (Figure 11) are similar to observed drawdowns in 1992 (Figure 7) within the wellfield, but underpredict drawdowns outside the wellfield, particularly to the east. While the 75 day, "worst-case" conceptualization is a major source of predictive error, the use of an impact model, which does not simulate the regional flow system, may be another significant source of error, particularly outside the wellfield. The 1978/1981 model appears to underestimate the long-term effects of well interference between the Cross Bar Ranch wellfield and the Cypress Creek wellfield.

Conclusions

The 1978/1981 models were calibrated to extensive hydrologic tests, including a 30 day wellfield-scale pumping test. The hydrologic values in the 1981 model are appropriate for short-term wellfield-scale predictions of drawdown. Using the 1981 hydrologic values and actual stresses from 1980 to 1992 significantly improves the prediction, suggesting that errors in the values used for hydrologic variables are not the principal cause of the poor prediction.

The principal error in the 1979 and 1981 predictions is the assumption that simulated drawdowns after 75 days of pumping a semiconfined aquifer without recharge represents a true steady-state, "worst-case" condition. This conceptual error is made more serious by using a uniform 25 foot (7.6 m) saturated thickness for the Surficial Aquifer, while field data suggest that the Surficial Aquifer may be partially saturated or dry in the northern part of the wellfield (LBG 1978), reducing the available storage for long-term withdrawals.

A simulation using a modification of the 1981 model that adds a source of recharge, salvaged ET, using the coupled aquifer conceptualization of Motz (1996), shows that it may take as long as seven years after pumping starts for the coupled Floridan/Surficial Aquifer system to reach steady state at the Cross Bar Ranch wellfield. This implies that, in coupled aquifer systems with significant storage in a surficial aquifer and a significant ground water ET rate, effects of pumping at a large wellfield may not become apparent for several years after the initiation of pumping. This was the case for the Cross Bar Ranch wellfield, where drawdowns in excess of the 1981 predictions were observed seven to eight years after the initiation of pumping. In particular, drawdowns greater than 1 foot (0.3 m) in the Surficial Aquifer were predicted in 1981 to be restricted to the wellfield. Field observations in the early 1990s suggest that drawdowns in excess of 1 foot (0.3 m) in the Surficial Aquifer extend several miles beyond the wellfield boundaries. SWFWMD concluded that the excessive drawdowns had adversely affected several thousand acres of wetlands and shallow lakes near the wellfield (SWFWMD 1996). In September 1997, the governing board of SWFWMD approved new management levels for the Cross Bar Ranch wellfield which would reduce withdrawal rates to approximately 12 to 15 mgd (4.4×10^4 to 5.5×10^4 m^3/day) (SWFWMD 1997).

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