Refinement of the
District Wide Regulation Model for
Southwest Florida Water Management District

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Prepared for

Southwest Florida
Water Management District
Brooksville, Florida

Prepared by

esi Environmental
Simulations
Inc.

Reinholds, Pennsylvania

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1.0 INTRODUCTION

1.1 Study Objectives

Environmental Simulations, Inc. (ESI) was retained by the Southwest Florida Water Management District (District) under contract 05CON000056 to make improvements to the District Wide Regulatory Model (DWRM) and to the Focus Telescopic Mesh Refinement (Focus TMR) technique in ESI's Groundwater Vistas software. The original DWRM Model (referred to as DWRM Version 1 in this report) was constructed and calibrated by ESI under Contract 02CON000177 and documented by ESI in 2004.

The goal of the current project was two-fold. First, ESI recalibrated the District Wide Regulation Model (DWRM) to steady-state conditions in 1995, followed by transient calibration to the period from 1996 through 2002. Other tasks were also undertaken as part of this recalibration effort and these are described in the next section. The revised DWRM is now called DWRM Version 2.

The second goal was to update and refine the Focus Telescopic Mesh Refinement (Focus TMR) technique that streamlines the District's review of Water Use Permits. These revisions are described in the next section.

1.2 Scope of Work

The scope of work for this project consisted of two parts, improvements to the DWRM (ESI 2004) and improvements to the Focus TMR technique, as implemented in Groundwater Vistas. There were eight tasks associated with the improvements to the DWRM, as follows:

1. The original scope called for a comparison between stream baseflow measurements for major rivers and those computed by the DWRM as a further calibration test. In the final analysis, however, the comparison was made on six drainage basins studied by Geurink et al. (2000) at the University of South Florida (USF). This change was made because recharge data from the USF study formed the basis for recharge and base flows in the DWRM.

2. Spring flows were compared to those computed by the model. In DWRM Version 1, spring flow targets were not used. Spring flows used in the original USGS Mega Model

(Sepulveda 2002) were added to the steady-state calibration of DWRM Version 2**.**

3. Another model layer was added to represent PZ2 in the Intermediate Aquifer System (IAS). DWRM Version 1 was based on the USGS Mega Model (Sepulveda 2002) which only had one layer for the Intermediate Aquifer System (IAS). The conceptual model for DWRM Version 1 was that this IAS layer represented PZ3. In the DWRM Version 2, the IAS was split into PZ2 and PZ3 layers, similar in concept to the Southern District Model (Beach 2003).

4. Layer top and bottom elevations for all layers were revised based on the new Florida Geological Survey (FGS) stratigraphic maps. The latest draft of the FGS stratigraphic elevation maps were obtained by the District and these maps were used to update the DWRM layer elevations.

5. Model parameters were revised in areas of the DWRM where District staff identified discrepancies between the DWRM and field data. This task included meeting with the staff of each District office to determine their opinions on the accuracy of the DWRM in their region. The DWRM was then modified based on those discussions, as well as new APT data. This task also included recalibration of the steady-state DWRM based on the new data and the results of other relevant tasks (Task 1, 2, 4, 7). One change to the calibration approach was that the time period for steady-state conditions was changed to be the calendar year 1995.

6. The DWRM was calibrated transiently to the period from 1996 (just after the period of the steady-state DWRM calibration) to 2002. The transient model used 1 month stress periods. The District supplied the pumping well history and water level history for key wells. Water levels were obtained for wells that have good water level measurement history. The original scope of work called for calibration to between 20 and 30 key monitoring wells in different aquifers and different regions. The final calibration used a total of 125 wells.

7. A post-audit of the DWRM and Focus TMR performance was performed. The post-audit involved a comparison between results of the Focus TMR on the DWRM Version 1 and DWRM Version 2 for those sites analyzed in the previous contract and for those sites where problems had been identified since the DWRM Version 1 was released.

8. An analysis was conducted into the possibility of changing the recharge methodology in the DWRM to include total infiltration and evapotranspiration. This task involved a literature search on the topic and focused on models constructed in the District that used ET, as well as methods and data related to ET in the District.

Three tasks were conducted in the improvement of the Focus TMR technique, as outlined below:

1. A standardized report has been implemented for the Focus TMR software. Additional features were added to this report to make the standardized reports more useful to Staff.

New improvements included the ability to incorporate graphics (contour maps, etc.) into the report, the ability to identify where model parameters have changed, and the automation of the export of GIS shapefiles for use by District staff in preparing GIS maps of the model results.

2. The Southern District Model is undergoing recalibration efforts by District staff. This second task involved modifying the Focus TMR procedure to work with the new Southern District Model. This task was not completed because a new version of the Southern District Model was not created during this contract.

3. Miscellaneous modifications were made to the Focus TMR functionality based on District staff comments and suggestions. These improvements are documented later in this report.

2.0 Revisions to DWRM

2.1 Introduction

Numerous revisions were made to the parameterization of the DWRM Version 1 as part of the recalibration and those changes will be described in Chapter 3. The modifications documented in this chapter relate to major structural changes to DWRM Version 1. These include revising all layer elevations based on the FGS structural contour maps on aquifer units, the addition of another layer in the Intermediate Aquifer System (IAS) to represent PZ2, changes to river conductance, and changes to recharge distribution.

2.2 Revise Layer Elevations

The Florida Department of Environmental Protection (Florida Geological Survey) issued new contour maps for the tops of geologic units within the District. These maps were provided to the District by Jonathan Arthur in two formats. One was a shapefile of contour lines for each unit and the other was an ESRI ArcGIS grid file that was used to create the contours. Both formats were used in defining new elevations for the DWRM.

The layer bottom elevations were assigned in the DWRM using a 3-step procedure. In the first step, shapefiles of contours were interpolated in Groundwater Vistas for the bottom of each layer. This was done because the grid files obtained from FGS did not cover the entire DWRM area. By interpolating values from the contours, all cells in each layer were assigned bottom elevations using an inverse distance approximation. Figures 2.1 through 2.4 show the FGS structural contours for the base of the SAS, PZ2, PZ3, and UFA, respectively.

In the second step, the ArcInfo grid files obtained from FGS were converted to SURFER grid files using the USGS dlgv32 Pro software (upgraded to the commercial version – Global Mapper Version 6). The surfer grid files were then imported into Groundwater Vistas.

Importing grid files is more accurate than using interpolation from the contours. However, the grid files do not cover the entire area of the DWRM. At the edge of the grid coverage, there are discontinuities in layer elevations due to the two different interpolation methods. This is not a serious problem, though, because the purpose of assigning layer elevations was for assigning wells in the model and those wells are located predominantly where there is grid coverage. The new layer elevations do not otherwise affect model calculations because transmissivity is assigned to most model layers directly and is not being computed from layer thickness.

The third step in assigning layer bottom elevations was for areas where the Intermediate Aquifer System (IAS) does not exist, mainly in the northern part of the District. In these areas, the same method employed in the District Wide Regulation Model (DWRM) Version 1 were used in the DWRM Version 2. This method simply made the PZ2 and PZ3 layers (layer 2 and 3 in the DWRM) 10 feet thick. It was further assumed that the top of the IAS, as interpreted by the FGS, was correct. Any overlaps between the top of IAS (bottom of layer 1) and the top of the model (e.g. land surfact) were adjusted by moving the top of layer 1 upwards, maintaining a minimum 5 ft thickness in layer 1.

2.3 Add New IAS Layer

After the layer elevations were revised, as described above, the original layer 2 of DWRM Version 1 was split into two layers. The base of the new PZ2 layer was defined from the FGS's map of the top of the Tampa Formation (see Figure 2.2).

As a start for the revised calibration, PZ2 and PZ3 were initially assumed to have the same transmissivity and leakance distributions. The transmissivity and leakance for the two units were subsequently modified independently during calibration. Boundary conditions for PZ2 and PZ3 were also the same and these were not modified during calibration. Pumping wells were reassigned to the DWRM after the layer elevations were revised and the IAS split into two units.

After the new PZ2 layer was added the following layer designations exist for the DWRM Version 2:

Layer 1	Surficial Aquifer System (SAS)
Layer 2	Intermediate Aquifer System PZ2
Layer 3	Intermediate Aquifer System PZ3
Layer 4	Upper Floridan Aquifer (UFA)

- Layer 5 Lower Floridan Aquifer (LFA)

2.4 Revise River Conductance

During the early stages of model calibration, it was noticed that there were many areas where vertical flow of water between the SAS and deeper layers was very high (over 40 inches per year). Further analysis showed that the cause of these high vertical flows was high leakage of water from river cells assigned to layer 1 (SAS). River conductance values were initially the same as the DWRM Version 1, ranging from 10,000 ft^2/d to 1,000,000 ft^2/d, with major rivers and lakes, and the Gulf of Mexico at the highest values.

Conductance values are computed from the following equation:

$C = K \times L \times W / D$

Where K is the hydraulic conductivity of the river bottom material (ft/d), L is the length of the river in the model cell (ft), W is the width of the river (ft), and D is the thickness of river bed material (ft). To put these values in prespective, the value of 1,000,000 ft^2/d for a major river assumes that the length of the river is 5,000 ft., the width of the river is 100 feet, the K is 2.0 ft/d and the thickness of river material is 1 ft. The K value of 2.0 ft/d is equivalent to a fine sand.

To reduce the high vertical flows between the SAS and the underlying aquifers, the conductance values of all river cells were reduced by one order of magnitude. Thus, major rivers and lakes now have a conductance of 100,000 ft^2/d and very small features have a conductance of 1,000 ft^2/d. The Gulf of Mexico was kept at the original 1,000,000 ft^2/d. Figure 2.5 illustrates the conductance values assigned to river cells in the model. Dark green cells have the highest conductance values (100,000 ft^2/d for rivers and lakes and 1,000,000 ft^2/d for the Gulf of Mexico), while the lightest green represents minor features that have a conductance of 1,000 ft^2/d. The intermediate green color represents a conductance of 10,000 ft^2/d.

Another change was also made to the distribution of river cells in the DWRM. In Version 1 of the DWRM, all lakes were simulated as river cells. After significant discussion with District staff, it was decided that large lakes should have a net flux of zero. This means that recharge and inflows to the lake are balanced by evaporative losses in the lake over the long term. For this reason, lakes covering more than half of one grid cell were identified and river boundary conditions in those cells were removed.

Another consequence of this large-scale reduction in conductance within river cells was that some parts of the SAS exhibited simulated heads above land surface after the draft calibration. In the final calibration drain cells were added to these areas to reduce heads, effectively acting like an evapotranspiration loss. The goal was to ultimately remove these drains during calibration by a comparable drop in recharge and/or an increase in river base flows. However, although most of the drains removed little or no water, removal of these drains caused an instability in the model. Therefore, these drains remain in the final model. The mass balance of these land surface drains is described in Chapter 4.

2.5 Recharge Distribution

In DWRM Version 1, recharge was based in part on the USGS Mega Model and also on rainfall distribution. Only a portion of the northern part of the District had recharge estimates from the Mega Model (Sepulveda 2002). The remaining DWRM area was estimated from rainfall and the understanding that the net recharge should be in the range of 2 to 4 inches per year.

During development of DWRM Version 2, recharge was reevaluated. Recharge estimates from Geurink et al (2000) replaced the original DWRM Version 1 estimates for a large part of the District, as shown in Figure 2.6. These recharge estimates represented the amount of precipitation that infiltrates into the aquifer, including base flow to streams, but excluding the amount of water lost to evapotranspiration.

Recharge rates from the Geurink study range from 0.29 inches per year to 23.4 inches per year in the area shown in Figure 2.6 and are considerably larger than those rates used in the DWRM Version 1. A check on river base flow was also performed, as described in Chapter 4.

In the draft calibration, it was found that recharge rates in the northeastern portion of the District were too low. This area was outside the Geurink (2000) study and also outside the original Sepulveda (2002) study and therefore retained the low estimate from the DWRM Version 1. In the final calibration, the recharge in this area was increased to 15 inches per year.

3.0 Steady-State Calibration

3.1 Introduction

The steady-state calibration of the DWRM Version 2 was originally designed to be a revision to the previous calibration of DWRM Version 1, which represented the time frame from August 1993 through July 1994. However, District staff questioned the accuracy of pumping data available for that time frame. In addition, ESI and the District could not verify the origin of pumping records and monitoring well data used by the USGS for the calibration of the Mega Model (Sepulveda 2002). Thus, a search was made for another suitable steady-state time frame for the calibration.

A review of the available water level data was conducted by District staff to determine the best time frame for a steady-state calibration after 1994. This analysis included an evaluation of the variability in water levels over time. It was determined that calendar year 1995 was as stable as any year since 1994, pumping data for that time period was thought to be accurate and available, and a sufficiently long transient calibration period could be performed after the steady-state calibration period. For these reasons, a new time frame of calendar year 1995 was chosen for the stead-state calibration.

3.2 Calibration Targets

During calibration, model results are compared to field measurements in order to quantify the degree of error in the calibration. The locations where these comparisons are made are called calibration targets. In the DWRM Version 2, calibration targets consist of water levels from monitoring wells and flow rates at springs. A total of 1,039 water level targets and 54 spring flow targets were utilized in the steady-state calibration.

Water level targets were obtained from four sources, including the District's WMDB database, the District's WUPS database, Tampa Bay Water's database, and the USGS May and September potentiometric surface reports for the Upper Floridan Aquifer. The water level targets are shown in Table 3.1, including the target name, coordinates, model grid cell location, average water level for 1995, and the source of the data. Most of the targets (496) came from the District's WMDB database and 213 from the District's WUPS database. The Tampa Bay Water database provided 153 of the targets and the USGS semi-annual reports provided the remaining 177 targets.

Water level targets were selected from the various data sources in the following order of priority:

1. District WMDB database
2. Tampa Bay Water database
3. District WUPS database
4. USGS reports

The order was primarily based on the quantity of data available at any given location. The District WMDB and Tampa Bay Water databases tended to have more data through time than the other two data sources. The USGS had the fewest data points with only May and September measurements. The USGS data were used, however, because these wells were located in areas that had no other calibration targets available.

Initially these data sources provided a total of 1,528 wells after eliminating wells that were within 500 feet of each other. Additional wells were deleted, however, where there was extreme clustering of wells around one or two grid cells. Most of this clustering was in the Surficial Aquifer System.

The flux targets used in the recalibration of the DWRM were taken from the calibration of the USGS Mega Model (Sepulveda 2002) because comparable spring flow data for 1995 were not available from the District or USGS. Pumping and rainfall were not significantly different between the 1993 through 1995 time frames. Therefore, the spring flux data should be a reasonable approximation of 1995 calibration conditions. These flux targets are shown in Table 3.2.

3.3 Calibration Approach

Calibration of the DWRM Version 1 used the PEST-ASP (Doherty 2001) software and the relatively new pilot point and regularization methods (Doherty 2003). Since that time, several new techniques have been added to the pilot point method and these new techniques were utilized in the calibration of the DWRM Version 2, as described below.

In traditional calibration techniques, a relatively small number of zones are used to calibrate the model. Each zone covers many cells in the model and within each zone, properties such as hydraulic conductivity are constant. The result is a piece-wise homogeneous aquifer configuration in which large areas of the each aquifer have homogeneous properties. The problem with the zone approach is that the location of the boundary of each zone is largely unknown. In practice, the locations of zone boundaries are based on the modelers intuition and trial-and-error calibration techniques.

By contrast, the pilot point method of calibration produces a continuous hydraulic conductivity (and leakance) field that has a unique value in each cell of the model. The calibration process estimates a value of hydraulic conductivity (or transmissivity) and/or leakance at each pilot point and the group of pilot points within each model layer are interpolated to obtain a property value for each cell. The interpolation technique that is typically used is kriging.

The pilot point method is not without its own problems. One problem is determining where the pilot points should be placed in the model. Another is the fact that each pilot point is a parameter, requiring one model simulation for each iteration of the nonlinear least-squares estimation. In order to obtain a smooth interpolation across the model, many pilot points (often hundreds) are required. A third problem is that often it is not possible to estimate both horizontal hydraulic conductivity (or transmissivity) and vertical hydraulic conductivity (or leakance).

Doherty, the author of the pilot point technique, has published guidelines for the location of pilot points. Pilot points are best placed in a pattern similar to the pattern of calibration targets; that is, near the location of observation wells where water level measurements are compared to model-computed heads. Pilot points should be more numerous where calibration targets are more numerous and they should be placed between the target wells. Pilot points should also be placed between the target wells and exterior model boundaries (Doherty 2003).

Fortunately, the DWRM runs very quickly because it uses a regular grid, is not too large by today's standards, and is running in steady-state. Thus, the number of pilot points is not really an issue in terms of model run-time. The number of pilot points does become an issue, though, when it comes to parameter estimation. One rule of nonlinear least-squares estimation is that the number of parameters cannot exceed the number of observations (targets). Even when the number of parameters is a small percentage of the number of observations, there can be problems in estimating all parameters. Doherty (2003) has implemented a new technique called regularization to allow PEST-ASP to estimate large numbers of parameters in pilot point runs. In regularization, additional observations are added. The additional observations are called prior information and require that the estimated values at adjacent pilot points be no more heterogeneous than necessary to match observed water levels (called smoothness regularization) or that the pilot point values differ as little as possible from their initial value (called preferred value regularization). With regularization, then, it is possible to have a larger number of pilot points than calibration targets.

In the DWRM Version 1, smoothness regularization was used. However, preferred value regularization was used in the calibration of the DWRM Version 2. This was done primarily because of a change in philosophy related to the desired transmissivity of the Upper Floridan Aquifer (UFA). In the DWRM Version 1, non-APT pilot points were not allowed to go higher than 2 to 10 million square feet per day, but could go as low as 1,000 ft^2/d and there was no preferred pattern to the distribution of transmissivity.

This philosophy was changed in DWRM Version 2 calibration after discussions with District staff. In this new approach, the minimum transmissivity of the UFA was increased to 40,000 ft^2/d, except in Pinellas County, where it could go as low as 10,000 ft^2/d. In addition, the transmissivity map published by Andrews (1990) for the UFA formed the basis for the preferred pattern of transmissivity in the UFA during calibration. Pilot points were assigned initial transmissivity values from the Andrews map and the upper and lower limits on transmissivity were also estimated from the same map. Thus, each pilot point had a preferred value. The same was true of APT locations, where the preferred value was the interpreted result of the aquifer test.

Aquifer Performance Test (APT) locations were reviewed by District staff and incorporated into the calibration as special pilot points where the initial pilot point value was the interpreted transmissivity from the APT. The upper and lower bound was based on the quality of the APT. Good APT values were only allowed to fluctuate up to 10% from the interpreted value. Fair APT results were allowed to vary by 25% and poor results could vary by up to 50%. The APT locations used in the pilot point calibration are summarized in Table 3.3.

A total of 1,916 pilot points were used in the calibration of the DWRM Version 2. Most (1,375) were transmissivity pilot points. Table 3.4 shows the distribution of pilot points among the aquifer units. Pilot point locations for hydraulic conductivity/transmissivity in the SAS, PZ2, PZ3, and UFA are shown in Figures 3.1, 3.2, 3.3, and 3.4, respectively. Leakance pilot points for the interface between the SAS and PZ2 are shown in Figure 3.5. Leakance pilot points for the interface between the PZ2 and PZ3 are shown in Figure 3.6. Finally leakance pilot points for the interface between PZ3 and the UFA are shown in Figure 3.7.

The leakance values between the UFA and LFA were kept at the DWRM Version 1 values, except in Sumter County where new values were provided by District staff after review of an APT at The Villages. Transmissivity of the LFA was also maintained at the original DWRM Version 1 values, but also with the exception of Sumter County. The LFA was not recalibrated because it occupies a relatively small portion of the District and because there are no calibration targets for the LFA.

In the DWRM Version 1, pilot points were initially placed on a uniform grid within each layer and then modified such that more pilot points were located in areas of higher calibration target density. In the DWRM Version 2, transmissivity pilot points were first placed using a triangulation of the calibration targets. In this method, triangles are drawn such that calibration targets formed the vertices of the triangles. Pilot points where then placed at the center of each triangle. This created a network of pilot points that was proportional to the density of calibration targets. After the triangulated network of pilot points was placed in the model, another set of pilot points was added such that no grid cell was more than 75,000 ft from a pilot point. The latter technique makes sure that there are pilot points between the calibration targets and outer model boundaries. For leakance pilot points, the first step placed pilot points at each calibration target and then used the technique to fill in around the edges.

3.4 Calibration Results

There are many ways to judge the quality of a calibration. The DWRM calibration was judged by comparing the calibration statistics to the goals used in the DWRM Version 1 calibration and through an analysis of spatial bias in the model.

What constitutes an acceptable calibration is very subjective and no standards have ever been put forth by ASTM or in the scientific literature. ESI has always proposed, however, that key calibration statistics be used as a first step in setting calibration goals. These goals include the following:

- Residual standard deviation divided by range in head for all targets should be less than 0.10 (10%)
- Absolute residual mean divided by range in head for all targets should be less than 0.10 (10%)
- Residual mean divided by range in head for all targets should be less than 0.05 (5 %)

A residual is the difference between a measured water level and the model-computed water level. The residual is calculated as the observed head minus the model-computed head. Thus, a negative residual occurs where the model-computed head is too high and a positive residual is where the model-computed head is too low. Calibration statistics and evaluation of goals should be applied on a model-wide basis and for each layer in the model that has calibration targets.

The statistical analysis of the DWRM calibration is provided in Table 3.5. The table shows the residual mean, residual standard deviation, absolute residual mean, and range in residuals. The residual mean uses both positive and negative residuals and thus should be close to zero if the positive and negative residuals balance each other. The absolute residual mean is computed after all residuals are made positive and is thus an average error in the model. Statistics are also provided for each model layer in Table 3.5.

The statistics for the DWRM calibration meet and greatly exceed the calibration goals described above. In general, the new calibration is better in the Surficial Aquifer System but a bit worse in the IAS and UFA in terms of the absolute residual mean and residual standard deviation. The slightly higher errors in the IAS and UFA were a result of more tightly constraining how far the transmissivity could vary during calibration. In the DWRM Version 1, PEST was given a much larger range over which transmissivity could vary. This larger range allowed a tighter fit to observed water levels. However, the resulting transmissivity distribution was found to be too low in many areas. The new calibration approach, on the other hand, was much more constraining in terms of how PEST could vary transmissivity, at the expense of slightly higher errors. These errors, however, are still well within the goals described above.

In the DWRM Version 1, there was a big difference in calibration quality between the aquifer units, with the match in the SAS being much worse than the IAS and UFA. In the new calibration, the residual statistics are much more consistent between units. The absolute residual mean varies between 2.3 and 3.3 ft. The residual standard deviation varies between 3.1 and 4.5 ft. With a total range in water levels across the model on the order of 165 ft, these values are quite low. The calibration goals described above are based on dividing the residual statistics by the range in head, with a goal of 10% for the residual standard deviation and absolute residual mean. The percentages for the new calibration range from 1.8 to 4.6%, as shown in Table 3.5.

Detailed data for all calibration targets used in the DWRM are provided in Table 3.6, including the name, location, observed water level, computed water level, and residual. Note that the weight of each target is not given. Unlike the original calibration where some targets were assigned a low weight to remove them from adversely impacting the calibration, the new calibration used a uniform weight of 1.0 for water level targets.

Another aspect of the new calibration was the use of flux targets representing springs. Springs are represented in the model as drains. The amount of water pumped from each drain (flux) was then compared to observations of spring flow as determined by Sepulveda (2002). Sepulveda’s spring flux targets were used because comprehensive spring flow data for 1995 could not be found. The flux targets and their residuals are shown in Table 3.7. Note that, like water level targets, weights are not shown. While Sepulveda did use weights for flux targets, they were not used in the new DWRM calibration. Data in Table 3.7 are in units of cubic feet per day.

The results of the calibration to spring flows also meet the calibration goals described above. The absolute residual mean divided by the total range in flows is only 1 percent. The standard deviation divided by the range in flows is 3.1 percent. Both are much lower than the established goal.

Evaluating flux targets is not as simple as water levels because the numbers are so large. In order to put the residuals into perspective, Table 3.7 also shows the percent error at each spring flow target. These errors range from almost zero to a high of 30 percent. Over 80% of the targets, however, are in error by less than 10 percent and 60 percent are less than 5 percent. Only four of the 52 targets are in error by more than 20 percent.

The other main calibration goal was to limit spatial bias, which means that large areas of the model will not have all negative or all positive residuals. The goal is to have positive and negative residuals mixed together so that there is no significant over- or under-prediction of water levels in large areas. Most model calibrations have spatial bias. The goal is to keep it to a minimum, which is very subjective.

Spatial bias is not a statistic but rather a more qualitative analysis. In order to evaluate the degree of spatial bias in the DWRM, plots were made for each aquifer unit showing residual circles at each target well location. The circles are plotted in two colors; red for negative residuals and blue for positive residuals. In addition, the size of the circle is proportional to the error. Larger circles represent larger residuals. Figures 3.8, 3.9, 3.10, and 3.11 show residual circles for the SAS, PZ2, PZ3, and UFA layers, respectively.

On the District scale, there is no significant bias in residuals for any of the aquifer units. There is some local-scale bias, though. In the SAS (Figure 3.8), there is a bias towards high residuals in Sarasota County. Central Polk and Central Manatee Counties exhibit generally low residuals.

In PZ2 (Figure 3.9), there is a bias towards high residuals in southwestern Manatee County and central Polk County. However, the errors in these locations are quite small. In PZ3 (figure 3.10), the most obvious bias is a low bias (blue circles) in Sarasota County and western DeSoto County.

Bias in the UFA is most obvious in Highlands County where water levels are too low and east-central Hillsborough County where water levels are too high. In addition, most of the residuals in Citrus County are too high. The bias in Hillsborough County is not quite as dramatic as pictured in Figure 3.11 because there are too many targets to plot. Figure 3.20 shows a closer look at this area with the actual residuals plotted. While the bias is definitely there, there are also targets of opposite sign within these areas.

Other ways of evaluating spatial bias is to plot observed water levels versus computed water levels on a graph, as shown in Figure 3.12. In an ideal calibration, the plot would be a straight line at a 45-degree angle, indicating that observed values equal model-computed values of head. The degree of scatter about that ideal line shows the degree of bias in the calibration. The graph in Figure 3.12 illustrates that the calibration of the DWRM is very good, although there are a few outliers. There are a lot fewer outliers, however, than the DWRM Version 1 calibration. Of the 1,039 water level targets, only 4 are in error by more than 15 ft and only 25 are in error by more than 10 ft.

Figure 3.13 is an alternative graph that can be plotted to evaluate calibration quality. This plot shows the observed water levels plotted versus the residual. Unlike the graph in Figure 3.12, the graph in Figure 3.13 should show no trend. There should be equal scatter above and below the zero residual line. In the case of the DWRM, there is little trend to the data.

Water table contour maps for the SAS in the calibrated model are provided in Figures 3.14 (northern portion of the District), 3.15 (central portion of the District), and 3.16 (southern portion of the District). The water table in the SAS is very complex as one would expect. Heads are generally higher on the eastern or inland side of the model and are lower near the coast. The most noticable feature in the northern half of the District (Figure 3.14) is the large area of dry cells in Hernando, Levy, and Marion Counties. These are areas where the land surface elevations are high and where surface water features are generally lacking. In addition, there is relatively little confinement separating the UFA from the SAS.

Some of the dry cells in the northern half of the District are real and others may be related to lack of precision in defining the basal elevation of the SAS. In any case, however, there is a lack of SAS data in this area so no conclusions can be reached with regard to the percentage of dry cells that are not realistic.

The potentiometric surface in the PZ2 is shown in Figure 3.17 for the portion of the IAS that is permeable. The potentiometric surface in the PZ3 is shown in Figure 3.18 for the portion of the IAS that is permeable.

The potentiometric surface of the UFA was plotted for the northern (Figure 3.19), central (Figure 3.20), and southern (Figure 3.21) portions of the District like the SAS water table. Also shown in these figures are the residuals at target locations. As with the residual circle analyses, red numbers are negative residuals and blue numbers are positive residuals. In general, all residuals are quite low, with the exception of western Hillsborough County and southern Pasco County where there is a cluster of three residuals with errors of about 10 feet. Significant attention was paid to this area during calibration. The bias in this area is much less significant than in the draft calibration. During the final calibration, the recharge in this area was reduced slightly and the leakance between layers was manually adjusted after the pilot point calibration.

The other area of high residuals is in central Citrus County (Figure 3.21). Since residuals along the coast and along the eastern boundary of Citrus County are low, it must be a local problem. Transmissivity in that area was capped at 10,000,000 ft^2/d. It is possible that transmissivity is locally higher than that. It could also be that recharge is too high. Recharge in the area of the high residuals is about 22 inches per year and was taken from Sepulveda (2002) without modification.

3.5 Parameter Distributions

Calibration using the pilot point technique results in a complex pattern of hydraulic properties, as described above. Figure 3.22 depicts the calibrated pattern of hydraulic conductivity (ft/d) in the SAS. Figures 3.23, 3.24 and 3.25 show the transmissivity distribution in PZ2, PZ3, and UFA, respectively.

Hydraulic conductivity in the SAS ranges from about 0.1 to 265 ft/d, with most areas varying between 10 and 50 ft/d. The District's Aquifer Characteristics Report shows a range of hydraulic conductivity in the SAS from 0.1 to over 300 ft/d, with most in the range of 10 to 50 ft/d. The results of the DWRM calibration, then, are within reasonable limits based on these field data. The arithmetic average hydraulic conductivity of the SAS pilot points is 38 ft/d and the log mean value is 21 ft/d.

The transmissivity of the PZ2 ranges from about 135 ft^2/d to 25,000 ft^2/d, with most values between 1,000 and 10,000 ft^2/d. The APT data shown in Table 3.3 indicate a range in PZ2 transmissivity from 160 to 13,300 ft^2/d. The model computed values are generally within these ranges. The arithmetic average transmissivity of PZ2 is 3,400 ft^2/d and the log mean transmissivity is 1,800 ft^2/d.

The transmissivity of the PZ3 ranges from about 31 ft^2/d to 25,000 ft^2/d, with most values between 1,000 and 10,000 ft^2/d. Beach (2002) describes the transmissivity of PZ3 in the IAS as being between 30 and 15,400 ft^2/d. The APT data shown in Table 3.3 indicate a range in PZ3 transmissivity from 1 to 17,900 ft^2/d. The model computed values are generally within these ranges. The arithmetic average transmissivity of PZ3 is 3,000 ft^2/d and the log mean transmissivity is 2,100 ft^2/d.

The transmissivity of the UFA ranges from about 13,000 ft^2/d to 10,000,000 ft^2/d in the calibrated DWRM. In the southern part of the District, the maximum transmissivity in the model was set to 2,000,000 ft^2/d based on the results of APTs in the area. UFA transmissivities in the northern portion of the District were allowed to be as high as 10,000,000 ft^2/d, which was about the maximum transmissivity in the original Mega Model. Most of the transmissivities in the

UFA were on the order of 100,000 ft^2/d. APT data used in the calibration for the UFA range from 13,000 to 9,300,000 ft^2/d with an average of about 190,000 ft^2/d. The arithmetic average transmissivity of the UFA in the model is 646,000 ft^2/d and the log mean transmissivity is 146,000 ft^2/d.

Hydraulic conductivity and transmissivity values in the model fit within the general ranges reported by other modelers and by the District in APT results. Also, as described above, pilot points were added to the calibration for good quality APT data which forced the model to be close to these data at the APT sites. The result is a transmissivity field within each model layer that conforms to field measured transmissivity values and elsewhere within the ranges reported in the literature and by the District's APT database.

Leakance values for the interface between the SAS and PZ2 (layers 1 and 2) are shown in Figure 3.26 and range from about 1.0×10^{-7} d^{-1} to 0.01 d^{-1}. Most of the higher leakance values are for the northern part of the Distrct where the SAS is in contact with the UFA. Figure 3.27 shows the leakance values for the interface between the PZ2 and PZ3. These values range from about 1.0×10^{-7} d^{-1} to 0.01 d^{-1} with most values being around 0.001 d^{-1}. Figure 3.28 shows the leakance values between PZ3 and the UFA. Figure 3.29 shows the effective leakance between the SAS and UFA across the District. The effective leakance is higher in the northern part of the District, as expected, due to the lack of a confining unit between the SAS and UFA. The average leakance north of Hillsborough County is 0.033 d^{-1} and the log-mean effective leakance is 0.0073 d^{-1}. The effective leakance from Hillsborough County southward is much lower with an average of 0.0015 d^{-1} and a log-mean value of 0.000014 d^{-1}. It is difficult to compare leakance values to other models and field data because the values depend a lot on the conceptual model and layer thicknesses.

3.6 Sensitivity Analysis

A sensitivity analysis is typically part of the documentation of model calibration (ASTM 1993). Two types of sensitivity are presented in this section. In the first type of analysis, the scaled sensitivity of each pilot point is discussed. In the second, the bulk sensitivity of model parameters is presented.

The sensitivity of each pilot point is presented in Table 3.4 and shown graphically in Figures 3.1 through 3.7. The sensitivity coefficient of each point has been scaled between 0 and 1, with higher values representing more sensitive parameters. Pilot point locations in Figures 3.1 through 3.7 have been grouped into 5 categories to illustrate the change in pilot point sensitivity spatially. Separate figures are provided for hydraulic conductivity/transmissivity and leakance pilot points.

The most sensitive pilot point is a leakance pilot point in layer 2 (Kz136) located where Hillsborough, Polk, Hardee, and Manatee Counties meet. In fact, 7 of the most sensitive pilot points are leakance pilot points. The most sensitive transmissivity pilot point is in northwest Pasco County in the UFA (Kp613). All of the top 10 most sensitive transmissivity pilot points are in the UFA. The most sensitive transmissivity pilot point outside the UFA is in PZ2, but is 137th on the list of most sensitive pilot points with a sensitivity of 0.09.

Another trend is that pilot points for both transmissivity and leakance are least sensitive in the northern part of the District. This trend is not as obvious in the UFA, however, it makes sense since most of the water level targets are in the southern portion of the District.

Another way to look at sensitivity is to evaluate the impact of bulk parameters on calibration statistics. In order to test the bulk sensitivity of model parameters, the hydraulic parameters of each aquifer were tested together. The following parameters were tested in the sensitivity analysis:

- Hydraulic conductivity of the SAS (layer 1) – called Kx1 in Figure 3.30
- Transmissivity of the PZ2 (layer 2) - called Kx2 in Figure 3.30
- Transmissivity of the PZ3 (layer 3) - called Kx3 in Figure 3.30
- Transmissivity of the UFA (layer 4) - called Kx4 in Figure 3.30
- Leakance between SAS and PZ2 - called Leakance1 in Figure 3.30
- Leakance between PZ2 and PZ3 - called Leakance2 in Figure 3.30
- Leakance between PZ3 and UFA - called Leakance3 in Figure 3.30
- Recharge - called Recharge1 in Figure 3.30

- Boundary conductance for minor streams called River Cond0 in Figure 3.30
- Boundary conductance of major rivers called River Cond1 in Figure 3.30
- Boundary conductance of intermediate rivers called River Cond2 in Figure 3.30

Eleven model simulations were run for each parameter. During each simulation, a single parameter was multiplied by a factor between 0.5 and 1.5. The calibration statistics were compiled for each of the 143 simulations and a series of curves were plotted as shown in Figure 3.30. Each curve represents the response of the model to varying one parameter. Curves that show significant change represent sensitive parameters. Those curves that are flat are indicative of insensitive parameters.

The most sensitive parameters in the model are the transmissivity of the UFA (Kx4 in Figure 3.30) and recharge. Both of these parameters show by far the largest change in the sum of squared residuals in the range of 0.5 to 1.5. The leakance values are also sensitive, primarily for runs with values less than the calibrated value. This is consistent with the results of pilot point sensitivity where leakance pilot points were, in general, more sensitive than transmissivity pilot points. River conductances are also more sensitive in the lower end of the range of values tested.

Another important conclusion to draw from Figure 3.30 is that all parameter curves reach a minimum value of the sum of squared residuals at or near a multiplier of 1.0. The latter represents the parameter values in the calibrated model. Thus, given all the assumptions in the model, this set of parameters is optimum in terms of overall calibration quality.

4.0 Model Mass Balance

4.1 Introduction

A mass balance analysis was conducted on the steady-state calibration of the DWRM Version 2. One purpose of this analysis is just to illustrate the water budget within the model so that District staff can evaluate whether it makes sense. The other is to document the comparison between base flow in streams, as described in the first chapter on the scope of work for this contract. The mass balance of springs was discussed in the previous chapter on calibration and will not be discussed in any detail in this chapter.

4.2 District-Wide Water Balance

The steady-state calibration for calendar year 1995 shows a total inflow of water to the District of about 7,282 million gallons per day (MGD) or 973,611,000 cubic feet per day. The water budget for the model is broken down into basic components in Table 4.1 with flows shown in cubic feet per day, million gallons per day, and as a percentage of the total budget. The water budget was computed by digitizing a polygon along the Gulf of Mexico on the west and then incorporating the entire model to the east of the coast. This was done because there are large fluxes between constant heads and rivers in different layers representing the Gulf of Mexico. These fluxes are an artifact of the way the model was constructed and so are not included in the water budget for the active portion of the model grid.

The components of the water budget include recharge from precipitation, river gains and losses, constant head inflows and outflows, drain outflows (springs and swamps from the Sepulveda model), General Head Boundary (GHB) inflows and outflows, and well discharges. Recharge, as previously described comes from estimates of Sepulveda (2002) in the north and Geurink et al (2000) in the south. Constant heads are primarily the eastern boundary in the SAS and southern portion of the Gulf Coast including Tampa Bay. General Head Boundaries represent the eastern boundary of the model in layers 2 through 5, where the original DWRM was carved out of the larger Sepulveda model. Wells represent estimated water use for 1995 as determined by the District.

Most of the inflow to the model (73%) comes from precipitation recharge. The remaining inflows are evenly split between lateral inflows from constant heads in the SAS and river (and lake) losses. Some of these river losses also represent inflow along the coast in the north where river cells were used to represent the Gulf of Mexico in the SAS. About one quarter of the total discharge in the model is baseflow to rivers. That is, a portion of the water that infiltrated from precipitation flows horizontally in the SAS to the rivers and is discharged as baseflow. Another 31% discharges to drains (primarily springs and swamps along the coast) and 20% discharges to adjacent water management districts (St. Johns River, South Florida, and Suwannee River). About 16 percent of the total water budget (1,150 MGD) is pumping from wells.

Approximately 24% of the total drain flux represents a reduction in recharge in areas where water levels approach land surface. This amounts to about a nine percent reduction in total recharge in the model. Considering that the recharge estimated from the Geurink (2000) study was derived from a model, it is not unreasonable to have a discrepancy of 10% or more in the calculations.

One component of interest to the District is the amount of water that recharges the Upper Floridan Aquifer. Figure 4.1 presents a color-shaded map of recharge through the top of layer 4 (UFA) of the DWRM. The units are in inches per year. Red cells indicate recharge rates of 40 inches per year or higher. Most of these cells are in the northern part of the District where the UFA is in direct contact with rivers and lakes. Only a few cells in the southern portion of the District have a UFA recharge over 40 inches per year and those are all on the Highlands Ridge area. Most of the southern portion of the District receives a few inches per year to the UFA, except in the ridge area to the east. Dark blue cells in Figure 4.1 are areas where the UFA discharges upwards to layer 3. These are primarily along the coast and along major rivers.

The water budget was also summarized by County, as shown in Table 4.2. The information includes the same components of the water budget as described above and shown in Table 4.1, as well as inflows and outflows to adjacent counties and other districts. Figure 4.2 shows a graph of recharge and pumping by county. Polk County receives the largest volume of recharge and also has the largest total pumping (240 MGD). Manatee County has the largest ratio of pumping to recharge of any county with pumping representing over half of the available recharge.

4.3 Stream Base Flows

The recharge applied to layer 1 of the DWRM represents the amount of water that infiltrates into the subsurface minus evapotranspiration. Thus, included in the recharge rate is the amount of water that discharges to rivers and streams as baseflow. Geurink et al (2000) also computed the baseflow component for each of 144 basins and these values were compared to the DWRM river flux in six larger basins. These basins included the Peace River, Myakka River, Manatee River, Little Manatee River, Alafia River, and the Hillsborough River. Table 4.3 shows the model-computed baseflow for each basin, Geurink's estimate (called USF estimate in Table 4.3), and the difference. Figure 4.3 shows the location of each basin and the basin number from Geurink's study and Figure 4.4 shows the six larger basins used in the base flow calculations of this section.

On a regional scale, the DWRM baseflow is within 20% of the Geurink estimate. The model rivers are overestimating baseflow, which means that there is less recharge to the underlying formations than Geurink had estimated. However, considering the large scale of the model and the difficulty of simulating groundwater flow in the SAS using 5,000 ft grid cells, this discrepancy should be acceptable.

On the scale of any individual basin, the matches cover a large range, with some basins being overestimated and some underestimated. Five of the six basins are within 25 percent of the estimated baseflow. The Hillsborough River is the worst match, with the model computing about 2.7 times too much flow. The other five basins are much closer to the estimated flow.

Sepulveda (2002) also had difficulty with the Hillsborough River, underestimating flow by a factor of 2. Table 4.4 presents all of Sepulveda's baseflow estimates for the Mega Model. The total discrepancy for all basins was 58 percent with seven of ten basins in error by more than 50%. This shows the difficulty of matching baseflow in a regional scale model.

5.0 Transient Calibration of the DWRM

5.1 Transient Model Construction

The DWRM was calibrated transiently to the period from 1996 (just after the period of the steady-state DWRM calibration) to 2002. The purpose of the transient calibration was to determine the storage properties of the aquifers. Therefore, no attempt was made to adjust transmissivity and leakance during the calibration.

The transient model used 1 month stress periods. The first stress period represented 1995 steady-state conditions, followed by 84 monthly stress periods. The latter were transient stress periods. MODFLOW2000 (Harbaugh et al 2000) allows each stress period to be defined as steady-state or transient.

The District supplied the pumping well history for all wells in the District, as well as from South Florida Water Management District, St. Johns River Water Management District, and Suwannee River Water Management District. Average monthly pumping rates were assigned to each well in the database from 1996 to 2002.

Recharge was applied to each stress period based on the 1995 steady-state rate and modified using District rain gage data. Recharge data from the USF study (Geurink et al 2000) could not be used since it was only estimated through 1998. Rather than mix the USF data with another method, it was decided to use one consistent method for estimating recharge. Rain gages with continuous rainfall records from 1995 through 2002 were obtained from the District. A Surfer grid file was then created for each month of the transient period (84 total). Each grid file contained interpolated recharge change factors. The factors were computed by dividing the monthly rainfall amount by the average annual 1995 rainfall amount at each gage. These Surfer grid files were then multiplied by the 1995 recharge rates to obtain a monthly estimate of recharge.

River and drain cells were not modified from their steadystate values. Therefore, all rivers and drains in the DWRM used one constant value for stage and conductance. River and drain conductances were not further calibrated in the transient calibration.

Constant head values in the Surficial Aquifer System were also not changed during the transient calibration. However, these heads are at least 10 miles outside the District on the east and should not affect model calculations significantly.

General Head Boundary (GHB) cells in the Upper Floridan Aquifer were adjusted transiently based on the May and September potentiometric surface maps from the USGS. Water level changes at wells were not used because such data did not exist. Water levels were estimated at 6 locations along the eastern boundary of the model from the USGS potentiometric surface maps. These water level changes with time were then used to adjust GHB heads in the UFA. The largest change for any given 6-month season was 8 feet and the average water level change was about 3 feet.

5.2 Calibration Targets

Water levels were obtained for wells that have good water level measurement history. The original scope of work called for calibration to between 20 and 30 key monitoring wells in different aquifers and different regions. The water level data for each well consisted of monthly average water levels computed by the District.

The final calibration used a total of 125 wells, all of which came from the WMDB database. Wells in PZ2 are shown in Figure 5.1. Wells in PZ3 are shown in Figure 5.2. Wells in the UFA are shown in Figures 5.3, 5.4, and 5.5 for the northern, central, and southern portions of the District, respectively. Transient calibration was not attempted in the SAS. Appendix A lists the transient water level data used in the calibration.

The usual method for calibrating a transient model, at least from a statistical view point, is to match changes in water levels rather than actual water levels. This is done because the model starts out with a calibration bias at each target, either too high or too low. That bias will usually carry through the transient calibration. Any methodology used to calibrate the model will be attempting to not only match changes in water levels but also to overcome that early bias. By matching changes in water levels, the initial bias is removed and the calibration procedure can focus on water level changes.

Matching water level changes is usually implemented in Groundwater Vistas by using drawdown targets instead of head targets. The only problem with this approach is that hydrographs are not intuitive. That is, when the hydrograph goes up, it actually means that water levels drop, and vice-versa. Therefore, another strategy was used in the transient calibration of the DWRM. Rather than match changes in water levels using drawdown targets, each observed hydrograph was offset either up or down a fixed amount so that it starts out without any bias (Doherty, 2005, personal communication). In this manner, the calibration is still based on water level changes but the hydrographs are also intuitive.

5.3 Calibration Approach

The original approach for the transient calibration was to make adjustments only to storage coefficients using automated methods such as PEST (Doherty 2001) with and without pilot points. After numerous attempts to calibrate the model using these automated procedures, it was found that some adjustments to recharge were also required in the northern part of the District where there is no confinement between the SAS and UFA. Most of the hydrographs underestimated the degree of water level rise associates with the El Nino event in late 1997 through 1998 and the drop in water levels after that period. Manual adjustments to recharge were made during calibration, primarily in the 1997/1998 time period. Recharge during late 1997 was increased and then decreased in late 1998.

After recharge adjustments were made in some areas in the north, the calibration proceeded by making additional adjustments to storage coefficients. A zone-based approach as chosen, where the initial model used data from District Aquifer Performance Tests (APT). The log value of storage was contoured in SURFER and then imported into Groundwater Vistas using two zones per log cycle. These zones were then adjusted slightly during calibration. The end result, however, is a pattern of storage that calibrates the model and is consistent with District APT data.

5.4 Calibration Results

Results of the transient calibration are presented using some of the same techniques as described in Chapter 3 for the steady-state calibration. A statistical analysis of residuals is presented in Table 5.1 and an overall plot of all water levels versus simulated values is shown in Figure 5.6. In a statistical sense, the transient calibration exhibits the same degree of error as the steady-state calibration. The residual standard deviation and absolute residual mean are both in the 2 to 4 feet range, which is 1.4 to 3.4 percent of the range in head. While these statistics are good, they can be misleading for a transient calibration. Therefore, additional graphical displays are presented to help document and evaluate the degree of calibration.

One way of illustrating how well hydrographs match spatially is to plot the amplitude ratio on a map. In computing the amplitude ratio, the amplitude or maximum difference in head over the transient period is determined for both the observed and simulated hydrographs. The amplitude of the simulated hydrograph is then divided by the observed hydrograph. A ratio of 1.0 indicates a very good match. A very small value indicates that the simulated hydrograph is flat relative to the observed hydrograph. A very large value means that the simulated hydrograph shows much larger fluctuations than observed. The amplitude ratio at each target is shown in Figures 5.7, 5,8, and 5.9 for PZ2, PZ3 and the UFA, respectively. In these figures, blue symbols mean that the simulated and observed hydrograph amplitudes are close to each other, green are intermediate, and red are poor matches. Triangles indicate amplitude ratios less than 1 and circles are amplitude ratios greater than 1.

The amplitudes in PZ2 and PZ3 seem to be more underpredicted in southern Polk and Hardee Counties. However, there were really not enough targets to determine a significant trend. In the UFA, there are more close matches in the north than in the south, although the hydrographs in Desoto County are all very good.

Hydrographs for all wells are shown in Appendix B, where they are presented in alphabetical order by county. These hydrographs are the real test as to how well the model matches reality. The majority of hydrographs match the basic cycle in water levels. That is, when the observed hydrograph increases, so does the simulated hydrograph. Figures 5.13, 5.14, and 5.15 are selected hydrographs showing a good match, an intermediate match, and a poor match, respectively. The good match in Figure 5.13 was taken from a well in Desoto County, which has the best matches in general of any county in the model. Each cycle in the observed hydrograph is matched by the simulated graph and the magnitude of the fluctuations also matches very well.

The intermediate match in Figure 5.14 was taken from a well in Pasco County and exhibits a common problem in the hydrographs. That is, the fluctuation trends are matched very well but one or more parts of the graph do not fluctuate enough. For example, in Figure 5.14, the first two and a half years of the simulation match quite well. In the remaining years, the peaks are over-predicted. This indicates that further refinement of transient recharge in the north could improve the calibration.

The example of a poor match (Figure 5.15) is similar to the intermediate match but much worse. In this case, the simulated hydrograph fluctuates a small amount at the right times but the magnitude of fluctuation is not nearly large enough. A lot of work went into trying to correct the worst hydrographs. However, simply changing the storage coefficient could not correct these graphs.

Since additional changes to the storage coefficient were not able to create better matches than those shown in Appendix B, some other variable must be adjusted. As mentioned above, recharge was adjusted in the northern part of the District in some time periods. We now believe that achieving better correspondence between the observed and simulated hydrographs would require simultaneous calibration of the steady-state and transient models to fine-tune the transmissivity field in the model.

The final distribution in specific yield and storage coefficient for SAS, PZ2, PZ3, and the UFA are shown in Figures 5.10 through 5.13, respectively. Specific yield values for the SAS (Figure 5.10) range from 0.01 to 0.3 and are within the range of values reported by the District for APTs. Storage coefficients in the other layers were divided into several zones with values ranging from 0.00001 to 0.001. The position of each zone was established based upon an interpolation of APT data within each aquifer unit. The philosophy during calibration was to maintain the storage coefficients at their APT values in PZ2, PZ3 and the UFA and to modify the SAS specific yield where necessary to match the hydrographs. In this manner, the use of the model for impact assessment would best match field data in the aquifers where most of the production takes place.

6.0 Potential Use of ET in the DWRM

6.1 Introduction

The DWRM, like most groundwater models in the District, assumes a net recharge rate where effects of evapotranspiration (ET) have been removed. This approach simplifies the use of MODFLOW but neglects a potentially important part of the subsurface conceptual model. The purpose of this section is to describe how ET is used in MODFLOW, how ET has been simulated in the past within the District and in central to south Florida, how ET can be estimated and measured, and potential future directions of modeling with respect to ET.

6.2 ET in MODFLOW

MODFLOW has had the capability to simulate ET in a simple way since it was first developed by the USGS (McDonald and Harbaugh 1988). The original ET package takes as input an ET surface (usually land surface), a maximum ET rate at land surface, and an extinction depth. The theory is that ET will decrease linearly to zero at some depth below land surface, the extinction depth. The inherent assumption in this original ET package is that ET only occurs at the water table. It neglects evaporation and transporation within the root zone. Thus, recharge values entered in MODFLOW when using the ET Package must be a net infiltration where runoff and shallow ET rates have been subtracted.

A revised ET Package was released with MODFLOW2000 (Harbaugh et al 2000), called the Segmented ET Package or ETS1 (Banta 2000). In the ETS Package, a user-defined function can be used to make ET nonlinear with depth. There is still the underlying assumption, though, that ET is only related to the position of the water table with respect to land surface.

Two new approaches to ET have recently been proposed for MODFLOW. The first, called the Surface/Vadose-Zone Package (SV), was developed by GeoTrans (2004) for the St. Johns River Water Management District (SJRWMD). The second will be released soon by the USGS for the newest version of MODFLOW called MODFLOW2005. The new package is called the Unsaturated Zone (UZF1) Package (Prudic et al 2006). Both of these new packages include the movement of water within the unsaturated zone in a simplistic way so that ET losses from the root zone can be simulated.

The SJRWMD's SV Package is based on MODFLOW2000 and takes as input the following information:

- Precipitation rate
- Minimum ET rate
- Potential ET (PET)
- ET extinction depth
- Antecedent Moisture Content
- Vadose Zone Porosity
- Vadose Zone Leakance (1/T)
- SCS Curve Number

The SV Package looks at a moisture balance within the unsaturated zone when computing the ET rate for each time step. In addition, not all precipitation is allowed to infiltrate and rejected precipitation is allowed to run-off into lakes. This formulation is more realistic than the ET or ETS Packages of MODFLOW and MODFLOW2000 because it takes into account the fact that some ET will be removed before the water reaches the water table. In addition, the user does not need to estimate run-off and shallow ET in computing a net recharge to the water table. Total precipitation is entered directly.

There are some disadvantages, however, to the SV approach. The first is that it requires the use of the GeoTrans Lake Package rather than the more standard USGS LAK3 Package. Also, since it was not developed by the USGS, it will not gain a lot of use or acceptance outside the SJRWMD.

The UZF1 Package by the USGS is very similar in concept to the SV Package. It has not been officially released, however, it will be available soon for the new version of MODFLOW called MODFLOW2005. Data input for UZF1 include the following information:

- Infiltration rate
- Maximum ET rate
- ET Extinction Depth
- Initial Moisture Content
- Maximum Unsatured Zone Moisture Content
- Vertical Hydraulic Conductivity of the unsatured zone

Like SV, if the amount of infiltration specified cannot be accommodated by the unsatured zone, the excess water is allowed to run off into streams (using the new SFR Package) or lakes (using the LAK3 Package). The input is also simpler than the SV Package. There are likely subtle differences between the two packages that would only become apparent after a more careful review. However, both packages are a step forward in the use and calculation of ET in MODFLOW.

6.3 District Models with ET

Few models within the District have incorporated ET directly. The only model published by the District that incorporates ET is the Northern Tampa Bay (NTB) model (Hancock and Basso 1993). The NTB model used a constant value of the maximum ET rate equal to 19.3 inches per year with an extinction depth of 10 feet. The maximum ET rate was computed from a pan evaporation rate measured at Lake Padgett in Pasco County. The pan evaporation was converted to potential ET by multiplying by a coefficient of 0.7. The potential ET was then multiplied by another coefficient (0.89) to get the maximum groundwater ET rate. The authors referenced a thesis by Gibney (1983) as the source of these coefficients.

The Hernando County model (HydroGeoLogic 1997) did not use ET in the MODFLOW model. However, they did reference the calculation of ET in coming up with a net recharge rate in the model. The authors used the same assumptions as Hancock and Basso (1993), referencing the same coefficients and the same thesis by Gibney.

Two models by the SJRWMD overlap the SWFWMD and utilized ET in their model formulation. These models include the East-Central Florida model (McGurk and Presley 2002) and the North-Central Florida model (Motz and Dogan 2004). Both models computed the groundwater ET rate by first assuming a minimum ET rate that was used to compute net recharge. This was a way of dealing with the fact that some ET occurs in the shallow root zone before the water reaches the water table and is apparently based on work by Sumner (1996).

The East-Central Florida model used three ET zones with maximum rates of 19, 20, and 21 inches per year. The higher rate of 21 inches per year occurred in the overlap with SWFWMD. The extinction depth was a constant value of 6 feet. The ET rate was computed by first estimating the maximum evaporation rate from a free-water surface, ranging from 46 to 49 inches per year. A minimum ET rate of 27 inches per year was then subtracted from the maximum rate to come up with the final groundwater ET rate of 19 to 21 inches per year. These values were comparable to the value used in the NTB model.

The North-Central Florida model used a similar approach by first estimating a maximum ET rate and subtracting a minimum ET rate. The minimum ET rate in this model, however, was 30 inches per year. The final maximum ET rate for most of the model area was 15.7 inches per year, with locally higher rates up to 32.8 inches per year. The extinction depth was reported by Motz and Dogan to be 5 ft. However, a review of the data input files for this model showed an extinction depth of 10 ft. It is not clear why the value was changed.

The only other model that covers SWFWMD and incorporates ET is the USGS model by Knowles et al (2002). The Knowles model covers parts of Lake, Sumter, Polk, Marion, and Pasco Counties in the District. Knowles et al (2002) made similar assumptions to the East-Central Florida model of SJRWMD. A maximum ET rate, based on pan evaporation, was estimated to be 51 inches per year. A minimum rate of 27 inches per year was then subtracted from the maximum rate yielding a maximum groundwater ET rate of 24 inches per year. The extinction depth was assumed to be 13 feet.

Another study related to modeling was the USF recharge study (Geurink et al 2000). Pan evaporation rates were first multiplied by a factor of 0.7 as in the NTB model. Pan rates were distributed using Thiessen polygons. Each catchment then received an ET rate based on its position relative to these Thiessen polygons, the percentage cover of wetland and upland, and estimated depth to the water table. ET rates ranged from 31 in/yr to 46 in/yr with a area-weighted average of 38 in/yr. Figure 6.1 shows the ET rates for each catchment.

6.4 ET Measurements

Most ET measurements reported by the USGS use the eddy correlation method (Bidlake et al 1993, Knowles 1996, Sumner 1996), which is a micrometeorological method. ET can also be estimated using simple mathematical models such as Penman-Monteith, Penman, and Priestley-Taylor. Sumner (1996) provides a good discussion of the various methods for measuring and estimating ET. Also, as described above, many groundwater models base ET on pan evaporation rates which are more widely available.

Within the District, Bidlake and other (1996) measured ET in Sarasota County in several different vegetation types from 1988 to 1990. They used the Bowen ratio variant of the eddy correlation method. ET rates ranged from a low in a cypress swamp of 38.2 inches per year (in/yr) to a high in a pine flatland of 41.7 in/yr.

Yager and Metz (2003) conducted a study in northwest Hillsborough County in which an unsaturated zone model (LEACHM) was used to estimate ET rates from 1996 through 1999 for three vegetation types and soil conditions. They estimated an average ET rate of 35.7 in/yr for shallow-rooted vegetation in coarse soil, 42.9 in/yr for deep-rooted vegetation in coarse soil, and 38.5 in/yr for shallow-rooted vegetation in fine-grained soil. They found that ET rates were lower during El Nino (November 1997 through September 1998) and lower still for La Nina (October 98 through March 1999).

Several other studies have been conducted in adjoining water districts. Knowles (1996) used a water budget approach and the Priestly-Taylor method calibrated to eddy correlation data to estimate ET rates in northern Marion County. He estimated that the average ET rate from 1965 to 1994 was 37.9 in/yr. He also concluded that ET rates are double during the 4-month wet season than they are during the rest of the year.

Knowles and others (2005) studied ET in Volusia and Lake Counties and estimated an upland ET rate of 42 in/yr and a wetland ET rate of 58 in/yr. They also reported a large seasonal variation in ET from 23 to 67 in/yr. German (2000) also found a large seasonal variation in ET for the everglades. He studies nine sites and estimated an annual average ET rate of 47.2 in/yr. ET rates were highest during summer (81.6 in/yr) and lowest in winter (21.6 in/yr).

Sumner (1996) studied ET for one year on the Lake Wales Ridge in Orange County in successional vegetation in a deforested area. He estimated the annual average ET in this area to be 26.8 in/yr and concluded that this represents the minimum ET rate for central Florida because the plants in the study area were shallow-rooted and the soils were well drained with a deep water table. Apparently this minimum ET rate computed by Sumner forms the basis for the SJRWMD approach of subtracting 27 in/yr from infiltration rates to come up with a net recharge.

Sumner (2001) conducted another study in Volusia County for cypress and pine forests subjected to fire. He used an energy-budget variant of the eddy correlation method. He measured an annual rate for 1998 of 36.1 in/yr and 42.1 in/yr for 1999. He also found that these rates were both about 75% of precipitation.

6.5 Recommendations for DWRM

Coming up with an ET strategy for the DWRM is difficult because of the large variability in ET estimates derived from field studies. However, some recommendations can be offered in terms of where to start. Sumner (2006) offers a good discussion of the relative merits of the various methods of estimating ET. Two of his conclusions are particularly interesting. The first conclusion was that in the humid subtropical environment, the high temporal variability of precipitation determines the amount of water available for recharge. This in turn supports the use of a relatively coarse approximation of ET. Another conclusion from Sumner is that annually invariant, mean monthly vegetation coefficients performed best at his site in estimating ET. This means that if good precipitation data are available, ET can be estimated by simply determining the vegetation type and time of the year.

Perhaps a good place to start in using ET within the DWRM would be to estimate these monthly vegetation coefficients and establish a GIS coverage of vegetation type (if it does not already exist). The District is close to having a very detailed measurement of precipitation through One-Rain. The combination of these three sources of information would then provide a good estimate for the overall water budget within the District at any point in time.

The only other piece that is missing is the choice of MODFLOW package for simulating ET.

7.0 Focus Telescopic Mesh Refinement Improvements

7.1 Introduction

The purpose of the DWRM was to provide a convenient platform from which to evaluate the impacts of proposed withdrawals on adjacent users and on surface water and wetlands using a new technique called Focus Telescopic Mesh Refinement of Focus TMR. The current contract included tasks related to improving the calibration of the DWRM and also to improving the Focus TMR procedure in Groundwater Vistas. This chapter documents the changes made to the Focus TMR software.

Improvements to Focus TMR included the addition of new options to the procedure and also updating the GIS shapefiles used to define wells and boundary conditions in the local-scale models. These improvements are summarized as follows:

- Create new shapefiles for well pumping that include rates from 1992 to 2002.
- Create new shapefiles for well pumping for St. Johns River Water Management District, South Florida Water Management District, and Suwannee River Water Management District.
- Revise the Aquifer Availability Map.
- Revise all shapefiles of rivers, wetlands, and lakes to be more consistent.
- Add the option of simulating lakes using the new USGS LAK3 Package in MODFLOW2000.
- Add the option of choosing any year between 1992 and 2002 as the base year for impact assessment.

The first three items above were accomplished by Mike Kelley of the SWFMWD and provided to ESI for use with Focus TMR.

7.2 Aquifer Availability

The Aquifer Availability map is used to determine which aquifers can supply water at any point in the District and in the buffer area surrounding the District. This map has evolved over time as the Intermediate Aquifer System (PZ2 and PZ3 in the DWRM Version 2) has been investigated.

Figure 7.1 shows the current Aquifer Availability map that will be used in DWRM Version 2. The legend shows nine different areas with a five-letter descriptor. The five letters can either be an underscore character (_), indicating that that particular aquifer is not available, or a letter representing the aquifer that is available. The first letter is an "S", indicating that the Surficial Aquifer System can be pumped. The second character is a "2" for PZ2 and the third character is a "3" for PZ3. The fourth and fifth letters are U or L for Upper Floridan or Lower Floridan Aquifers, respectively.

In general, only the Upper and Lower Floridan Aquifers are available in the northern part of the District. The IAS (PZ2 and PZ3) are only available in the south. The SAS is only available for pumping in the Highlands Ridge area. When a Focus TMR model is created in Groundwater Vistas, this map is used to modify which model layers are available for each well in the model.

7.3 Revised Shapefiles

A key feature of Focus TMR is that regional boundary conditions in the SAS are removed and new boundary conditions are imported from shapefiles at the more refined scale. All shapefiles in the new Focus TMR procedure have been replaced with a more consistent set of shapefiles provided by the District. These shapefiles are referred to as "NHD" shapefiles (National Hydrologic Data) that have been digitized at the 1:24,000 scale. As in the previous contract, ESI then intersected the NHD shapefiles with USGS Digitial Elevation Models (DEMs) to assign elevations to the streams, lakes, and wetlands.

The new shapefiles include the following ones:

- SWFWMD_NHD_coastline.shp (Figure 7.2)
- Majorrivers.shp (Figure 7.2)
- Majorrivers2.shp (Figure 7.2)
- Lakes.shp (Figure 7.2)
- Riverupdate_reservoirs.shp (Figure 7.3)
- Riverupdate_stream.shp (Figure 7.3)
- Riverupdate_waterbodies.shp (Figure 7.3)
- Riverupdate_wetlands.shp (Figure 7.5)
- SWFMETA_aq.shp (Figure 7.6)
- SRMETA_aq.shp (Figure 7.6)
- SFMETA_aq.shp (Figure 7.6)
- SJRMETA_aq.shp (Figure 7.6)

These shapefiles are imported into the Focus TMR model in the general order listed above. Shapefiles shown in Figure 7.2 are first, followed by Figure 7.3, then Figure 7.4, and finally wetlands in Figure 7.5. The Lakes shapefile contains all lakes with areas greater than 20 acres. The riverupdate_waterbodies shapefile contains all lakes less than 20 acres.

The last four shapefiles in the list above are wells for the SWFWMD, Suwannee River Water Management District, South Florida Water Management District, and St. Johns River Water Management District, respectively. The well locations are shown in Figure 7.6. This is a significant improvement over the previous version because wells outside the District are now much more accurately located. In addition, these shapefiles contain average pumping data for each year between 1992 and 2002.

7.4 New Focus TMR Options

The Focus TMR technique in Groundwater Vistas functions the same as in the previous version, but with two new options. First, there is a check-box that allows the USGS LAK3 Package to be used to simulate lake stage fluctuation. This option in shown on Figure 7.7 and is labeled “Use Lake Package” on the dialog in Groundwater Vistas. When this option is checked, which is the default now, any stressed lake that lies at least partially within the buffer zone (fine grid area) will be simulated as a lake instead of a river. All other lakes will be simulated as a rivers.

There are two other lake options selected using the drop-down list to the right of the lake checkbox. The default option is to simulate stressed lakes using the LAK3 package. The second option is to simulate all lakes using the LAK3 Package. This option often presents problems, however, as the simulation may not converge or may yield unrealistic lake stage and drawdown. The final option is to simulate lakes using high hydraulic conductivity (K). If the latter is chosen, lakes are not simulated with a boundary condition. A high hydraulic conductivity is instead placed within the lake in the SAS (layer 1). In all lake options, recharge is zero within the lake.

The second option is the year for well pumping. This option is labeled “Year for Estimated Use Pumping Rates” on the Groundwater Vistas dialog (Figure 7.7). The year 2001 is the default, which is consistent with the previous version.

In addition to these two new options, the “Model Type” drop-down list has been expanded to include the DWRM Version 2 and the Southern District Model Version 2 (see Figure 7.7). All other options work in the same manner as in previous versions.

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TABLES

FIGURES

Note on Scale of Figures: The scale bar displayed on each figure has the length of the bar written beneath the bar. For example, many of the figures have a scale bar that is 200,000 feet wide. The number written beneath the bar is the total length of the bar.