South Palm Beach County Ground Water Flow Model

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Preface

The objective of this report is to document the ongoing development of the South Palm Beach County Ground Water Flow Model. The present report only documents the development process. Applications of the model will be discussed in separate reports.

This document is divided into six sections: purpose, physical features, initial model construction, model calibration, and conclusions. Additional information on the supporting Hydrologic and Geographic Information Systems (GIS) databases, sensitivity analyses, and calibration results can be found in the appendices. As the model is improved to address its limitations and to support future applications, the documentation will be updated to reflect these changes. It is hoped that this model will continue to serve as a useful tool in water resources planning, water use permitting, the conceptual engineering design of regional water supply projects, and other efforts related to Everglades restoration and water resource management in South Florida. Any comments or questions related to either this report or the model itself are welcome and may be forwarded to the following address:

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1. Introduction and Purpose

1.1 Background

The South Palm Beach County Ground Water Flow Model is the third in a series of models developed for the SAS in Palm Beach County. The first model was developed by Shine et al. (1989) to assess the ground water resources of eastern Palm Beach County. In particular, this effort involved the development and application of two models; one for the northern portion of the county (north of the C-51 Canal) and a second for the southern portion (south of the C-51 Canal). A second version of the model was developed by Yan et al. (1993) in which the models for the northern and southern portions of the county were combined into a single model. The current model was developed specifically to support the Central and Southern Florida (C&SF) Project Comprehensive Review Study (Restudy) and the Lower East Coast regional water supply plan efforts including many significant refinements. These refinements include better spatial and temporal resolutions, the incorporation of major wetland systems (e.g., Water Conservation Area 1 (WCA-1) and WCA-2A), and a detailed representation of the Lake Worth Drainage District canal system.

The Water Preserve Areas (WPA) Feasibility Study was initiated along with the Restudy in August 1995. In May 1997 it was split out into a separate study that scheduled for completion in September 2001. The WPA Feasibility Study evaluates the size, location, and operational aspects of the recommended by the Restudy components. The high-resolution ground water models developed as a part of this effort will be used to evaluate these proposed structural improvements.

The *Lower East Coast Regional Water Supply Plan* (LEC plan, SFWMD, 2000) is mandated by the Florida Water Resources Act, Chapter 373 Florida Statutes (F.S), to assure that adequate water is available to meet future urban and agricultural, and natural system demands within the planning area through 2020. A combination of water resource and water supply development projects is proposed to determine how well the proposed facilities and operational changes meet water demands during a 1-in-10 year drought condition, while protecting the natural system.

1.2 Model Objectives

Hydrologic models are the main tools being used to evaluate the benefits and impacts of the water supply improvements proposed by the Restudy and the LEC Plan. The benefits and impacts will be evaluated through the systematic use of selected hydrologic performance measures which are quantitative indicators of how well an alternative meets a specific objective. The hydrologic performance measures were constructed to analyze relative differences in model output from various scenarios including the current base case, the future base case and variations on the future base case. Examples of performance measures include stage duration curves for wetlands and reservoirs, ground water level hydrographs, and ground water flow across selected boundaries.

2. Description of Physical Features

2.1 Hydrogeology and Hydrostratigraphy

As part of this effort, an updated conceptual model of the Surficial Aquifer System (SAS), which underlies southern Palm Beach and northern Broward counties was developed. To accomplish this objective, all the available hydrogeologic and geophysical data related to the SAS within the model boundaries shown in Figure 2.1.1 was compiled, reviewed, and analyzed. A database was developed containing the hydraulic aquifer properties required for ground water model construction. The hydrogeologic data collected and analyzed includes lithologic descriptions of 351 boreholes, estimated hydraulic conductivity ranges from 351 borehole sediments, and geophysical traces from 30 boreholes. The 30 boreholes of geophysical traces included gamma, neutron, and resistivities. This data was used to describe the geologic framework of the SAS by constructing hydrogeologic cross-sections. The cross-sections were then used to assist in the design and development of the conceptual ground water flow model.

2.1.1 Data Sources and Literature Search

Most of the hydrogeologic data pertaining to the SAS within southern Palm Beach and northern Broward Counties was previously compiled, analyzed, and reported by either Miller (1987), Fish (1988), or Shine et al. (1989). This data includes lithologic logs prepared by Causaras (1984) and the results of a variety of hydraulic conductivity tests. Additional lithologic, hydrologic, and geophysical information was extracted from Parker et al. (1955), United States Army Corps of Engineers (USACE) design memorandums, South Florida Water Management District (SFWMD) regulation database, and various public water supply utilities throughout the area. These data sources coupled with geophysical logs provided most of the information required to delineate the hydrogeologic layers used in the South Palm Beach Ground Water Flow Model. Enhanced borehole geophysics from additional literature sources were used to refine some of the cross-sections. Appendix E.1 lists all the sources of the geologic/hydrogeologic information compiled for this model.

Figure 2.1.2 depicts all the boreholes with lithologic, geophysical, and aquifer pump test data that were compiled for the study area. Figure 2.1.2 also displays the transects used to create hydrogeologic cross-sections for the study area. Appendix F, describes the approximate ranges of hydraulic conductivity values assigned to the sediments at specific depth intervals within the SAS.

2.1.2 Geophysical Methods

The District obtained 30 geophysical logs to verify the lithology of the SAS in southern Palm Beach and northern Broward counties. The traces obtained were gamma, neutron, and resisitivity logs. These logs were superimposed on a hydrostratigraphic cross-section and are shown in Appendix E.1 and Appendix E.2. This methodology aided in validating model layer boundary selections. A brief description of the different geophysical methods employed is given in Appendix E-2.

2.1.3 Data Analysis and Review

Lithologic descriptions, Aquifer Performance Tests (APTs), and geophysical logs were reviewed and analyzed to assess the hydraulic characteristics of the SAS within the study area. Table 2.1.1, modified from Fish and Stewart (1991), gives approximate ranges of hydraulic conductivity based on lithology. At each well for which lithologic data was available, this method was used to assign an approximate hydraulic conductivity range to each interval. When available, hydraulic conductivity data obtained from aquifer pump tests were assigned over the tested depth intervals in place of the estimated hydraulic conductivity ranges. In such cases, aquifer test data containing hydraulic conductivity values replaced hydraulic conductivity values obtained by lithology. For example, in Appendix F, a borehole identified as PB-1558 in which an aquifer test (tst1) was conducted within the interval of -73 to –133 feet, NGVD 29. The resultant hydraulic conductivity value was 40 feet per day. This value replaced hydraulic conductivity values based solely on lithologic characteristics inferred from Fish (1988). At that point, these hydraulic conductivity profiles coupled with the lithologic and geophysical descriptions were used to create hydrogeologic cross-sections throughout the SAS underlying the study area. Such cross-sections were refinements, where possible, of those provided by Fish and Stewart (1991).

2.1.3.1 Geohydrologic Delineation of the Surficial Aquifer System

The cross-sections in **Appendix F** contain hydraulic conductivity ranges as they pertain to the selected layers of the subsurface features. Cross-sections A-A through I-I depicted in **Appendix F** are examples of the hydrogeologic boundaries used to delineate the model layers. This was accomplished for each borehole within the cross-sections and a range of hydraulic conductivity values was assigned as they relate to depth and lithologic descriptions. The values were then averaged over the entire thickness and extrapolated to similar hydraulic conductivity value ranges to the next borehole. Some boreholes were overlain by geophysical traces. These traces were used to correlate hydrogeologic units between boreholes.

Southeastern/Southwestern Study Area: The SAS is reported to be more than 175 feet thick at the Southeastern/Southwestern boundary of the study area (borehole PB-1104, cross-section G-G). The SAS within the southeastern portion ranges in depth from approximately 25 feet NGVD to more than 200 feet below land surface. The most productive zone, the zone of secondary permeability (ZOSP), occurs between 30 to just over 200 feet below land surface. The SAS within the southwestern area of Palm Beach County diminishes to an estimated thickness of 50 feet. Its range of depth can vary from 25 feet to approximately 75 feet below land surface and does not comprise of the ZOSP, as shown in cross-section G-G.

TABLE 2.1.1 Geologic Formation and Hydraulic Conductivity

Horizontal Hydraulic Conductivity (feet/day)		Sediments-Lithology and Porosity	Geologic Formation
Qualitative Description	Range		
Very high	>1000	Solution-riddled limestone, commonly shelly or sandy	Qf, Qa
		Calcareous sandstone, may be shelly or have shell fragments, solution holes; or riblike channels	Qa, Tt
		Coralline limestone, reefal, very porous	Qk
High	100-1,000	Gray, shelly limestone, locally sandy, relatively soft	Tt
		Limestone or calcareous sandstone interbedded with sand or with sand partially filling cavities	Qa, Tt, Qf
		Coarse shell sand and quartz sand	Tt
		Dense, charcoal gray to tan limestone with some solution channels, usually shelly or sandy	Ttu
Moderate	10-100	Very fine to medium, relatively clean, quartz sand	Qp,Qa,Qt
		Fine to medium quartz and carbonate sand	Tt
		Cream-colored limestone with minor channels	Qf,Qa
		Tan, cream, or greenish limestone, locally containing shelly sand	Tt
		Calcareous sandstone and sand	Tt,Qa
		Slightly clayey or sandy, gray limestone Oolitic limestone	Tt
Low	0.1-10	Very fine to medium sand with some clay, silt, or lime mud; locally shelly	Tt,Qf,Qa
		Soft gray or buff limestone with silt and fine sand	Tt
		Dense, calcareous sandstone	Tt
		Light-green, fine-grained foraminiferal limestone with very fine quartz sand	Tt
		Dense, hard limestone with very small cavities or channels approximately equal mixtures of sand, shell fragments, and lime mud	Qf
Very low to practically Impermeable	<0.1	Green clay or silt; locally with very fine sand; siltstone, claystone, often sandy	Tth,Ttl,Ttu
		Sandy, shelly lime mud	Tt
		Very dense, hard limestone with no apparent solution cavities or fractures	Qf

Qa,	Anastasia Formation	Th,	Hawthorn Formation
Qf,	Fort Thompson Formation	Tt,	Tamiami Formation
Qk,	Key Largo Limestone	Tth,	undifferentiated Tamiami Formation and Hawthorn Formation
Qm,	Miami Oolite		
Qp,	Pamlico Sand		
		Ttl,	Tamiami Formation, lower part
		Ttu,	Tamiami Formation, upper part

Reference: Fish (1988)

Northeastern/Northwestern Study Area: The SAS is reported to be approximately 150 feet thick at the Northeastern/Northwestern boundary of the study area. The cross-section A-A, shows the zone of secondary permeability ranges in thickness from 105 feet thick in the west at borehole PB-1562, to approximately 100 feet thick in the east at borehole PB-655. According to cross-section A-A, borehole PB-655 is the eastern most extent of the productive zone, ZOSP.

Based on the literature review, the following layering scheme was developed for the model. The layers are described below in descending order with respect to modeling layer objectives and geologic units. The general lithology and stratigraphy of the SAS underlying the site can be subdivided into six major units or layers:

Layer 1: The uppermost unit, Layer 1, is comprised of organic peats, sands, soils, and caprock which covers the entire western sector of Palm Beach County. The organic peat, sands, and soils are usually separated by calcareous mud, which in places is dense limestone (cap rock). The thickness of this cap rock varies from a foot near cross-section located on the western perimeter, L-7 Levee to up to 10 feet along the L-40 Levee. The hydraulic conductivity of the layer varies from 30 to 200 feet per day. This unit of peats and sands thickens westward in southern Palm Beach, is found from land surface to approximately five feet below land surface.

Layer 2: Layer 2 is comprised of a fine to medium-grained silicate sands, shells, and limestones to depths of approximately 25 feet below land surface. This layer represents undifferentiated deposits (Pamlico Formation) and it overlies the ZOSP.

Layer 3: The third layer consist of coquina rock deposits (Anastasia Formation) near the eastern coastline of Palm Beach County and is contemporaneous with the alternating fresh and brackish water marine marls, limestones, and calcitic limestones of the Fort Thompson Formation and extends westward towards the WCAs. It ranges in depth from approximately 25 to 85 feet as depicted in cross-section A-A, for borehole PB-11558. This unit is notorious for containing vuggy cores and well-solutioned cavities. It makes up the upper part of the ZOSP.

Layer 4: Layer 4, considered also to be part of the Fort Thompson Formation, consists predominantly of porous limestone, sandstones, shells, and calcified beds. This unit varies in depth and thickness from approximately 85 to 125 feet as depicted in cross-section A-A, for borehole PB-1558. This unit also has a wide range of solution cavities.

Layer 5: Layer 5, part of the upper Tamiami Formation, is comprised of moderate to fair permeabilities. This formation is dominated by reefal, micritic sands, shells, and dirty grey sandstones and limestones. It is also considered to lie beneath the ZOSP. Its depth ranges from approximately 100 to 140 feet.

Layer 6: Layer 6 is comprised of very low permeability sediments and essentially makes up the boundary of the lower Tamiami Formation. These sediments are sandy and silty, and grade into thin beds of green phosphatic clays. The lower Tamiami Formation constitutes the base of the SAS.

The age of the above mention formations range from the upper Miocene to the Pleistocene (Land, Rodis, and Schneider, 1972). However, Miller (1987) suggests that the SAS is composed of multiple units which range in age from Pliocene (Tamiami Formation) to Pleistocene (Pamlico Sands). Whichever the case, the subsequent descriptions of hydrostratigraphic units are a result of more than one depositional environment and more than one episode of sea level rise and retreat.

Pamlico Sands, Anastasia, and Fort Thompson Formations: The Pamlico sands and Anastasia limestones and the Fort Thompson Formations comprise the bulk of the SAS sediments that underlie the South Palm Beach County Ground Water Flow Model area. The sediments pertaining to these units are primarily composed of sand, sandstone, shell, silt, calcareous clay (marl), and limestone deposited during the Pleistocene and Pliocene epochs. In western two-thirds of Palm Beach County (cross-sections A-A and C-C.), the sediments within the SAS are poorly consolidated sands, shells, and sandy limestones. The calcareous clays, silts, and very poorly sorted materials typically result in relatively low permeabililities (Miller, 1987). Sediments that comprise the eastern portions of southern Palm Beach County are categorized as having high permeable, better sorted, and having less silty clay content. As depicted in Figure 2.1.2, the majority of public water supply wells (ACME 14, South Shore, Boca Raton, PBC-SYS1, PBC-SYS3, and Parkland), aquifer test wells (USGS-Site 12, USGS-Site 11, USGS-Site 9, USGS-Site 8, USGS-Site 5, USGS-Site 2, and USGS-Site1) penetrate this highly permeable zone, all of which are located near the eastern coast of Palm Beach County. This zone also known as the ZOSP is the result of limestone that was dissolutioned during the changes in sea levels and the changes in water chemistry that occurred during the Pleistocene. The resulting process continues only now the driving force of solvent is rainwater. The rain percolates through the organic material and becomes a slight acidic solution which dissolves the carbonate material (limestone). According to various geologist's drill logs from the western agricultural areas it is becoming more apparent from vuggy cores that solutioning of the limestone is an on going process.

The SAS is underlain by a silty, sandy, clayey substrate of the Tamiami Formation. The compilation, mapping and extrapolation of hydraulic properties were used to quantify the regional transmissivity values. The result of this study indicates a need to conduct APTs in areas lacking hydraulic property measurements, especially below WCAs, and the ZOSP.

2.2 Surface Water Management

The SAS is an unconfined aquifer system recharged by rain, along with leakage from canals and other surface water bodies. Within the model domain is an extensive network of surface water management systems that have a significant effect on the ground water. The District canals incorporated into the model include the C-51, C-15, C-16, Hillsboro, and the C-14 canals. In addition, the model incorporates the numerous surface water management systems operated by independent drainage and water control districts as shown in Figure 2.2.1. These include the Lake Worth Drainage District, the Acme Improvement District, the Loxahatchee Groves Water Control District, the Indian Trail Improvement District, and the West Palm Beach Water Catchment Area south of the M canal within Palm Beach County. The water control districts within Broward County include the North Springs Improvement District, the Pine Tree Water Control District, the Cocomar Water Control District, Water Control District 2, Sunshine Drainage District, Coral Springs Improvement District, Turtle Run Drainage and Improvement District, Coral Bay Control and Drainage District, and Water Control District 3. Data regarding the operations of the independent drainage districts were compiled from a variety of sources including the system operators, SFWMD permit files, aerial photographs, field inspections, and real estate (REDI) maps.

2.2.1 Water Control Districts within Palm Beach County

Lake Worth Drainage District

The Lake Worth Drainage District (LWDD) is the largest and the oldest water control district within the modeled area. The boundaries of the LWDD are approximately Okeechobee Boulevard in the north, WCA-1 in the west, the Hillsboro Canal in the south and the E-4 Canal in the east. The canal system of the LWDD is comprised generally of seven equalizing canals (E-1W, E-1, E-2W, E-3, E-2E, E3, and E4) running from north to south, extending the length of the District. Along with the equalizers, are approximately 50 lateral canals (L-1 through L-50), spaced at approximately one-half mile intervals, and running from east to west. The canals provide water to agriculture, industrial, public water supply, and landscaping water uses. The canal network also provides recharge to the Surficial and Biscayne aquifers, and drainage for central and southeastern Palm Beach County during storm events.

The canals generally range in size from six to 10 feet deep and 50 feet wide for the equalizing canals and three to six feet deep and 30 feet wide for the laterals canals. The LWDD maintenance water levels for the canals range from 16 feet in the central and western portions of the District to 4.5 feet in southeastern Boca Raton. Maintained canals levels generally decrease from 16 feet in the west E-1 Canal to 8.5 feet at the E-4 Canal located on the east side of the drainage district. The LWDD operates 17 major control structures and numerous minor control structures to control discharge into the SFWMD canals (C-51, C-16, C-15, and Hillsboro canals) and to maintain optimum water levels throughout the LWDD. The releases by LWDD to the SFWMD canals are made in conjunction with the operations of the SFWMD to ensure the District canals have the capacity to receive the flows (Mock, Roos & Associates, Inc., 1992, Mock; Roos & Associates, Inc., 1996). Four basins exist within the LWDD and they are the C-51, C-15, C-16, and Hillsboro canal basins. A brief description of these basins is given below:

The C-51 (West Palm Beach Canal) Basin is located in the northern quarter of the LWDD. The majority of the basin south of the C-51 Canal is maintained at 13 feet NGVD. The eastern portions of the basin are controlled at 8.5 feet; while the western portion is maintained at 16 feet. The project canals and the control structures in the C-51 Basin provide flood protection and drainage for the basin, discharge flood flow from the L-8 Basin to tide, supply water to the basin during periods of low natural flow, and maintain a ground water table elevation west of S-155 adequate to prevent intrusion of salt water into the aquifer.

The C-16 (Boynton Canal) Basin is located in the north central portion of the LWDD. The maintained water levels range from 16 feet in the E-1 Canal, to around 13 feet in the E-2 and E-3 canals to around 8.5 feet at the E-4 Canal. The project canals and the control structures in the C-16 Basin provide flood protection and drainage for the basin, and maintain ground water elevations west of S-41 adequate to prevent intrusion of salt water into local ground water. The basin also has the L-23-W tieback Canal where two gravity feed culverts located at S-2 on the L-40 Levee take water from WCA-1 when it is available.

The C-15 Basin is located in the south central portion of the LWDD. The maintained water levels range from 16 feet in the west to approximately 8.5 feet in the east. The project canals and the control structures in the C-15 Basin provide flood protection and drainage for the basin, and maintain a ground water table elevation west of S-40 adequate to prevent intrusion of salt water into local ground water.

The Hillsboro Canal Basin is located in the southern portion of the LWDD. The canals within the basin are maintained at various stages ranging from 16.0 feet in the northwest to tidal in the southeast. The project canals and the control structures in the Hillsboro Canal Basin have five major functions: (1) provide flood protection and drainage for the basin; (2) supply water to the basin during periods of low natural flow; (3) convey excess water from WCA-1 to tide; (4) intercept and control seepage from WCA-2A; and (5) maintain a ground water table elevation west of Deerfield Lock adequate to prevent intrusion of salt water into local ground water.

Acme Improvement District

The Acme Improvement District is located west of State Road 7 and south of State Road 80. The Acme District is divided into two primary basins divided by Pierson Road. The basin north of Pierson Road is known as Basin A, and the area south of Pierson Road is Basin B. Basin A is substantially developed with single-family residential units and comprises approximately 72 percent of the basin area. Basin B, however, has a much lower density of development with the primary land uses being rural residential lots, groves, and nurseries, with a substantial presence of stables and horse ranches.

During the wet season, the pump stations and other outfall structures are operated to maintain a canal stage of 11 feet NGVD within Basin A. The system is operated at a stage of 12 feet NGVD during the dry season. The canal stages within Basin B are maintained at 13 feet NGVD in both the wet and dry seasons (SFWMD, 1996). The Acme Improvement District also operates two pumping stations, PS #1 and PS #2, on the northeastern perimeter of WCA-1, on the L-40 Canal. The stations pump excess water from the basin for drainage into WCA-1. PS #1 discharges water into WCA-1 through a gated culvert in the L-40 Canal, and PS #2 makes its connection to WCA-1 through the G-94D structure.

Loxahatchee Groves Water Control District

The Loxahatchee Groves Water Control District is located north of the C-51 Canal. The discharge structures, A, D, and G, are operated to control discharges into the C-51 Canal and to maintain a stage of 17.5 feet NGVD during the dry season and a stage of 14.5 feet NGVD during the wet season. (SFWMD Surface Water Management Permit No. 50-01682-S. July, 1988).

Indian Trail Water Control District

The Indian Trail Water Control District (ITWCD) located north of the C-51 Canal is divided into two basins: the lower M-1 Basin and the M-2 Basin. The structural control elevations for the dry, transitional, and wet months in the Lower M-1 Basin are 17.0, 16.5, and 15.0 NGVD, respectively. The surface water management system for the Lower M-1 Basin consists of swails, ditches, and canals that convey runoff to Pump Station No. 2, which is located at the northern end of the Lower M-1 Basin (ITWCD, 91084.78 permits Feb 1996).

The M2 Basin is comprised of 11 subbasins. Each has a separate outfall point into the M-2 Canal. The M-2 Canal is owned and operated by the Seminole Water Control District. The total drainage area for all 11 basins is about 42,000 acres. The currently permitted control elevation is 17.5 feet NGVD for the dry season and 14.5 feet NGVD for the wet season (ITWCD, 91084.88 permits March 1993)

Seminole Water Control District

The Seminole Water Control District (SWCD) operates a water control system for agricultural purposes that serve approximately 4,000 acres north of the C-51 Canal. The SWCD consists of five north-south canals, a series of lateral canals, and a main outfall canal at its connection to the C-51 Canal. Water is withdrawn from the M Canal by three irrigation culverts, A, B and C, as part of the SWCD operations. The system is gravity controlled, with all discharge directed to the main outfall canal. The control elevation of the system is set at 14.5 feet NGVD during the wet season and 17.5 feet NGVD during the dry season (Ref. Permit No. 50-00021-S, 92, Application No.960528-15, 96).

City of West Palm Beach Water Catchment Area and Water Supply System

The City of West Palm Beach Catchment Area is located near the M Canal and is at the northern boundary of the model. The water catchment area is part of the City's surface water supply system. Water is withdrawn from the L-8 Canal, and conveyed through the M Canal into the city's 1,000 acres of water supply lakes. Runoff is captured and stored in a 12,400 acre wetland/upland preserve. The hydraulic facilities within the city's surface water supply system consist of inflow and outfall structures and facilities, internal control structures, and a conveyance system with structures along the M-Canal, Clear Lake, WCA-1, and Lake Mangonia (Mock, Roos & Associates, Inc., 1996).

2.2.2 Water control districts within Broward County

The water control districts within northern Broward County that are within the model boundary include the North Springs Improvement District, Pine Tree Water Control District, Cocomar Water Control District, Water Control District 2, Sunshine Drainage District, Coral Springs Improvement District, Turtle Run Drainage and Improvement District, Coral Bay Control and Drainage District, and Water Control District 3. Most of the water control districts in northern Broward county were modeled as drains with maintenance elevations obtained from SFWMD permits.

2.3 Regional Wetlands

The largest wetlands in the model domain are WCA-1 and WCA-2A. Also included in the model as wetlands are the Strazzulla Tract and the Loxahatchee mitigation bank areas that form a buffer between WCA-1 and the developed areas to the east. The wetland areas modeled are shown in Figure 2.3.1.

WCA-1 also knows as the Arthur R. Marshall Loxahatchee National Wildlife Refuge, has an area of 227 square miles. The vegetation in WCA-1 consists predominantly of wet prairies, sawgrass prairies, and aquatic slough communities along with tree islands which are interspersed throughout the area. WCA-1 is enclosed on all sides by levees and provides storage for excess rainfall, excess runoff from agricultural drainage areas of the C-51 and Hillsboro canals, and excess water from Lake Okeechobee. The inflows to WCA-1 are through the S-5A, and G-251 structures, S-6 pump station, and two pump stations in the ACME Water Control District. Water outflows from WCA-1 through the S-10 structures into WCA-2A when the stage in WCA-1 exceeds the regulation stage. Water also outflow from WCA-1 through the S-39 and G-94 structures to maintain water levels in the LWDD.

WCA-2A has an area of 173 square miles with vegetation cover types consisting of open water sloughs, large expanses of sawgrass intermixed with cattail, and drowned tree islands dominated by willow. WCA-2A is also enclosed on all sides by levees and provides water supply to the east coast urban areas of Broward County. Water inflows into WCA-2A through the S-10 structures and the S-7 pump station, which discharges drainage water from the Everglades Agricultural Area (EAA) via the North New River Canal. The outflows from WCA-2A are primarily through the structures S-11A, S-11B, and S-11C into WCA-3 based on regulation schedules. Relatively minor outflows also occur through the S-38, S-144, S-145, and S-146 structures.

The Strazzulla Tract contain the only remaining cypress habitat in the eastern Everglades and one of the few remaining sawgrass marshes adjacent to the coastal ridge. The Loxahatchee Mitigation bank wetlands are located south of the Strazzulla Tract.

2.4 Water Use

The largest consumptive use of ground water in Southern Palm Beach County is public water supply. In addition to public water supply, agricultural and nonagricultural uses like golf course and landscape irrigation also account for water use. The primary source of public water supplies in this region is the SAS, although there are some surface water users like the city of West Palm Beach in the northern area of the model. Within the SAS, most of the withdrawals are from the ZOSP, though some of the public wells extend below the ZOSP in the northern and eastern areas of the model. The locations of the primary wellfields in the modeled area are given in Figure 2.4.1.

3. Initial Model Construction

The current version of the model was constructed with the hydrogeologic, wetland,and surface water management systems described earlier to address the modeling objectives. The major components of the model are discussed below:

3.1 Model Code and Grid Design

3.1.1 USGS Modeling Code MODFLOW

The United States Geological Service (USGS) modeling code MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) is the most widely used program in the world for simulating ground water flow. MODFLOW was selected for model development and the application objectives for the following reasons:

- It has been widely accepted in the ground water modeling profession for over ten years.
- The code is well documented, within the public domain, and works on many different computer systems.
- The code is readily adaptable to a variety of ground water flow systems.
- The modular structure of the code facilitates any modifications required to enable its application to the types of unique ground water flow problems encountered in southern Florida, and allows for new simulation features to be added with relative ease.
- Each simulation feature of MODFLOW has been extensively tested.

3.1.2 Model Grid

The spatial limits of the finite-difference grid for this model are shown in Figure 2.1.1. The spatial coordinates shown were selected so as to align the cells of this grid with those of an adjacent, overlapping model located immediately to the south. Horizontally, all of the cells are square with a dimension of 500 feet. While the resolution of this grid may seem somewhat excessive in relation to its spatial extent, the benefits derived from selecting such a fine resolution include, but are not necessarily limited to the following:

- Better accuracy of computed water table drawdowns near wellfields.
- Increased accuracy of base flows to canals.
- A reduced likelihood that two features of interest will occupy the same cell (useful for regulatory applications).
- An improved capability for incorporating complex structural improvements into the model.

3.2 Ground Water Flow System

3.2.1 Vertical Discretization

The conceptual model based on hydrostratigraphy was aggregated further for modeling purposes into five model layers as shown in Figure 3.2.1. The top wetland layer is restricted to the extensive wetland systems within the model domain and includes WCA-1, WCA-2A, the Strazzulla Tract, and the Loxahatchee Mitigation bank areas. It consists of ponded surface water, as well as the peat, sand, and caprock layers underlying the wetlands. The bottom elevation of the wetland layer varies from –10 to five feet NGVD. Layer 2 represents the sand and shell layers overlying the Biscayne aquifer, where the bottom elevation varies from –25 to –100 feet NGVD. Layers 3 and 4 represent the Biscayne aquifer, the most productive interval within the SAS. The Biscayne aquifer in southern Palm Beach County is also referred as the ZOSP. The bottom elevation of the Biscayne aquifer within the model domain varies from –90 to –210 feet NGVD. The relatively large thickness of the Biscayne aquifer and the fact that most of the production wells are present in this zone made it desirable to subdivide this zone into two layers. The model layer below the Biscayne aquifer is comprised of the relatively less permeable sequences of clays, silts, and limestones of the Hawthorn Group. It is also considered to be within the intermediate confining unit that lies between the SAS and the Floridan aquifer. The bottom of this layer was set at a constant elevation of –300 feet NGVD since not enough data was available to clearly demarcate the transition from the SAS to the intermediate confining unit.

3.2.2 Aquifer Parameters

The hydraulic properties of the SAS were estimated in part through APTs performed by the USGS, SFWMD, USACE, and independent consultants. In addition, specific capacity tests, lithologic correlations and geophysical logs were used, where applicable, to estimate the hydraulic properties.

3.2.2.1 Hydraulic Conductivity

The geologic control wells used to derive point estimates of hydraulic conductivity within each model layer are shown in Figure 2.1.1. The spatially-varying layer elevations were also one of the attributes for the control wells. The actual value assigned for the hydraulic conductivity was the logarithmic mean of the minimum and maximum values for each range. The hydraulic conductivities assigned to the various lithologic units were used to compute a mean horizontal hydraulic conductivity within each layer at each control well.

The computed point values for each control well was used to estimate the hydraulic conductivity within each layer. For the wetland layer of the model, which incorporates peat, sand and caprock layers underlying the WCAs, a composite horizontal hydraulic conductivity K_x and vertical hydraulic conductivity K_z was calculated based on the individual layer thickness and conductivity using the equations given below:

$$K_x = \frac{\sum_{i=1}^{3} K_i b_i}{\sum_{i=1}^{3} b_i} \tag{3.1}$$

$$K_z = \frac{\sum_{i=1}^{3} b_i}{\sum_{i=1}^{3} b_i / K_i} \tag{3.2}$$

where b_i is the thickness and K_i the horizontal hydraulic conductivity of the individual layers. The horizontal hydraulic conductivity for peat was assumed to be 100 feet per day (Danish Hydraulic Institute, 1999), and for sand it was assumed to be 57 feet per day based on slug tests performed by the USACE (1960). The horizontal hydraulic conductivity of caprock varied spatially within the wetland layer and the values were between 30.0 and 200.0 feet per day based on the shallow slug tests performed by the USACE (1960).

The vertical conductance term VCONT used by MODFLOW incorporates both vertical hydraulic conductivity and thickness values between the midpoints of each model layer. It was calculated assuming a anisotropy of 1:10 between vertical and horizontal hydraulic conductivities. This value represents more or less a textbook value and was used given the uncertainty associated with assigning hydraulic conductivity values for the lithologic units that were not detailed intervals.

3.2.2.2 Specific Yield and Storage

A constant value of 0.2 was used for the specific yield of the top layer when it is unconfined. At times when the water table rises above the land surface as in the wet season, an option in MODFLOW (laycon=3) is used to switch the layer to a confined layer, and in this case, a value of 1.0 is used as the storage value for open water. A value of 10^{-6} ft^{-1} was used for all other layers for the specific storage. It represents a typical value for limestone.

3.3 Wetland Flow System

The Wetland package (Restrepo et al., 1998) was the customized MODFLOW package used to simulate overland flow within the wetland areas of the model. The spatially varying vegetative cover was accounted for in the wetland package by the use of vegetative resistance coefficients. The wetland model conceptualizes these areas as isolated wetlands with user-specified inflows or outflows. The city of West Palm Beach's Water Catchment Area located south of the M Canal was not modeled as a wetland, since it is not only located outside the evaluation area for this model, but also located adjacent to the model boundary.

Both WCA-1 and WCA-2A were modeled using the diversion option of the wetland package. For purposes of computational stability the net inflow was applied uniformly over all the cells of each WCA for each time step. The net inflow is the difference between the inflows and outflows through the structures of each WCA. The Strazzulla Tract and Loxahatchee mitigation bank areas were modeled as wetlands having no structural inflows or outflows.

The methodology employed by the Wetland package for simulating overland flow is based on the following relationship between discharge per unit width, flow depth, hydraulic gradient, and hydraulic conductance of the wetland:

$$q = K_w h^{\beta} S_f^{\alpha} \tag{3.3.1}$$

where q is the discharge per unit width (L^2/T), h is the flow depth (L), S_f is the hydraulic gradient, K_w is the hydraulic conductance coefficient for overland flow ($L^2/T/L^{\beta}$), β is an exponent related to the vegetation micro topography and the stem density-depth distribution, and α is an exponent that reflects the degree of laminar or turbulent flow conditions.

Equation 3.3.1 represents a formulation used in earlier investigations of overland flow in wetlands. Examples of this can be found in Kadlec (1990), Hammer and Kadlec (1986), and Chescheir et al. (1987). Table 3.3.1 provides values of $K_{w,}$ β, and α cited by Kadlec (1990) for various wetland environments found in Michigan and eastern North Carolina.

TABLE 3.3.1 Experimental Values of $K_{w,}$ β, and α Cited by Kadlec (1990)[*]

Source	Location	K_w ($ft^2/day/ft^{\beta}$)	β	α
Kadlec (1990)	Houghton Lake, Michigan	87×10^8	2.5	0.7
Kadlec, et.al. (1981)	Houghton Lake, Michigan	1.2×10^8	3.0	1.0
Hammer and Kadlec (1986)	Houghton Lake, Michigan	2×10^8	3.0	1.0
Chescheir et al. (1987)	Eastern N.C.	7.9×10^8	3.0	1.0
Chen (1976) Kentucky Blue Grass Bermuda Grass	 Laboratory Laboratory	 228×10^8 65.6×10^8	 3.75 3.75	 0.50 0.39

Published values of K_w were converted from International Systems units to the English units shown

It is worth observing that the values of β and α appear to be consistently equal (or close) to 3.0 and 1.0, respectively. A second important observation is that K_w tends to be on the order of 10^8 $ft^2/day/ft^\beta$ regardless of the experimental site location. All of this suggests that setting $K_w = 10^8$ $ft^2/day/ft^\beta$, $\beta = 3.0$, and $\alpha = 1.0$ would provide a good starting point for model development. However, as will be explained in a later section, numerical difficulties can result when a value of K_w this large is used. Consequently a maximum value of $K_{max,w} = 10^6$ $ft^2/day/ft^\beta$ was applied to those wetland areas with the sparsest vegetation. A minimum value $K_{min,w}$ equal to 30 percente of the maximum was applied to wetland areas covered with the most dense vegetation. All other types of wetland classes were assigned a value of hydraulic conductance K_w which is between the two extremes. An exponential function was used to compute K_w to interpolate values from the range $K_{max,w}$ and $K_{min,w}$. All wetland classes were assigned an ordinal value, K_n, between 1 and 7, based on flow resistance criteria, before fitting the exponential function. The resulting relationship between K_w, K_n, and Flucs_Level 3 landuse code (used to map the different types of wetland vegetation) is shown in Table 3.3.2.

TABLE 3.3.2 Relationship between Vegetation Type and Hydraulic Conductance Coefficient

Flucs_ lev1 Code	Flucs_ lev3 Code	K_n	K_w ($ft^2/day/ft^\beta$)	Flucs_ lev1 Name	Flucs_ lev3 Name	Located within wetland areas mainly at this location:
H	510	7	1,000,000	Water	Waterwa ys	Canals surrounding WCA-1 and WCA-2A
WFCY	621	5	812,059	Wetland	Cypress	Strazzulla Tract
WFCM	6218					
WN	641	4	707,338	Wetland	Freshwat er marshes	Predominant vegetation in WCA-1 and WCA-2A
WFMX	630	4	707,338	Wetland	Forest mixed	Loxahatchee National Wildlife Refuge
WNSG	6411	3	592,005	Wetland	Sawgrass	Northwest of WCA-2A
WNCT	6412	2	460,653	Wetland	Cattail	Canal boundaries and Northeast of WCA-2A
WXH	6172,	1	300,000	Wetland	Mixed hardwoo d	Tree islands interspersed throughout WCA-1 and WCA-2A
M	617					

3.3.1 Boundary Conditions for the Wetland Flow System

In the wetlands package the WCAs are bound by the following physical boundaries:

- Permeable aquifer at the bottom
- Levees along side boundaries which include the following:
  - WCA-1 impounded by three levees: L-7, L-39, and L-40 Canals
  - WCA-2 impounded by six levees: L-6, L-35B, L-36, L-38E, L-38W, and L-39 Canals

Hydrologic boundaries were represented in WCAs by the following conditions:

- Specified flow boundaries which simulate the following:
  - Inflows and outflows using diversion option for the wetlands package,
  - Recharge across the water table using the MODFLOW Evapotranspiration/Recharge package
- Head-dependent flow boundaries which simulate the following:
  - Leakage through L-7, L-6, L-35B, and L-38E Canals applied to the layer beneath wetlands (simulated by the MODFLOW GHB package)
  - Leakage through L-36 Canal applied to the layer beneath wetlands (simulated by the MODFLOW River package)
  - Leakage through the soils and shallow geologic layers specified using the VCONT term computed internally by the wetland package
  - Evapotranspiration across the water surface

The levee L-39 Borrow Canal between WCA-1 and WCA-2A was accounted for in the wetland package by the use of a multiplication factor for the horizontal interblock conductance between wetland cells. A relatively small value of the interblock conductance was used to model the levee a barrier with no seepage through the wetland layer.

3.3.2 Diversions of the Wetlands Package

Inflows and outflows across water control structures at WCA-1 and WCA-2A were modeled using the diversion option of the Wetland package. The diversion option models the water artificially diverted by pumping or gravity from or to the wetland areas. The diversion option in the wetland module was used in the model to take water out from a group of cells in WCA-1, and to spread it over the receiving cells in WCA-2A. For purposes of computational stability the net inflow (difference between the inflows and outflows through the structures of each WCA) was applied uniformly over all the cells of each WCA for each time step.

3.3.3 Wetland-Aquifer Interactions

The model layer representing the wetland flow system is comprised of the overland flow regime, the peat and organic soil layer, and the underlying shallow geology formations of sand and caprock. The bottom elevation of the wetland layer varies from –10 to five feet NGVD and the land surface elevation varies from eight to 16 feet NGVD. The shallow geologic layers and the overland flow regime were incorporated into the wetland layer to effectively address the numerical problems associated with the drying and rewetting of model cells within this layer. Incorporation of this larger aggregated layer prevented the frequent wetting and drying of cells which would have ocurred if the wetland layer was comprised of only the overland flow regime.

The horizontal hydraulic conductivity (HYMUC), vertical to horizontal anisotropic ratio (VHYMUCR), and specific yield are the hydrogeologic parameters needed for the wetland module to model the flow in the wetland layer. The HYMUC value for the wetland layer was computed as the hydrologically equivalent horizontal hydraulic conductivity given the horizontal hydraulic conductivity values for peat, sand, and caprock. The VHYMUCR value was computed after calculating the hydrologically equivalent vertical hydraulic conductivity of the wetland layer. In calculating the equivalent vertical hydraulic conductivity it was assumed that the peat layer was more conductive vertically than horizontally, while sand and caprock were assumed to be isotropic. The specific yield was set to a constant value of 0.2 for the shallow geologic zone and 0.9 for the overland flow zone. The anisotropic ratio, VHYLY2R, was set to a constant value of 0.1 for the top aquifer layer.

3.4 Land Surface Elevation

The Land Surface Digital Elevation Model (DEM) for the South Palm Beach County Ground Water Flow Model was created from the data sources which are shown in Table 3.4.1. The spatial locations of the data points are shown in Figure 3.4.1. The geographic region corresponding to the location of the data sources is also provided.

The University of Florida (1992) survey of WCA-1 was conducted by Dr. Richardson, who measured points throughout WCA-1. According to Sosnowski (1994), while conducting the survey, Dr. Richardson treated subareas of WCA-1 as a level pool and the depths of water at points within the region were measured. The water depths were subtracted from the level pool elevation to obtain the point land surface elevations. The elevations were referenced to the NGVD 27 vertical datum.

The WCA-2A data was obtained from a 1993 report submitted by Keith and Schnars Survey, Inc. to the District. In their survey, 15 benchmarks were established throughout WCA-2A and these were the basis for the survey of more points around the benchmarks. The elevations were referenced to the NGVD 88 vertical datum, and were converted to the NGVD 27 datum using the NGS VERTCON 2.0 program.

TABLE 3.4.1 Data Sources for Land Surface Elevation

Source	Area
University of Florida (1992)	WCA-1
Keith and Schnars Survey, Inc. (1993)	WCA-2A
National Geodetic Survey (NGS) Benchmark elevations	Urban areas of southern Palm Beach and Northern Broward Counties
USGS quad sheets (1960)	Urban areas of southern Palm Beach and northern Broward counties
Surveyed land surface elevations at USGS observation wells	WCA-2A, urban areas of southern Palm Beach and northern Broward counties

The National Geodetic Survey (NGS) benchmark surveys were referenced in both the NGVD 29 and NAVD 88 datums. Elevations referenced to the NAVD 88 datum were converted to the NGVD 29 datum using the VERTCON (NGS Version 2.0) program. Sosnowski (1994) reports that the elevations can be recessed below, projected above, or flush with ground level. Data points selected were flush with ground surface and generally away from man-made features.

The USGS quad sheets with spot elevation data were used for the urban areas of the modeled area. The elevations were surveyed by the USGS in the late 1960's and were referenced to the NGVD 29 vertical datum.

The USGS observational wells are a part of the water level monitoring network maintained by the USGS. The surveyed land surface elevations which are referenced in the NGVD 29 vertical datum and published in the Water Resources Data Volumes for 1994 and 1995 were used (USGS, 1994 and USGS, 1995).

DEMs were created separately for WCA-1, WCA-2, and the urban areas east of the protection levees. The DEM for WCA-1 was obtained as an Arc Info grid coverage from the University of Florida (1992, University of Florida)

3.5 Canals

3.5.1 Canal Classification

The interaction of the canal network with the aquifer was modeled using the River and Drain packages. The canals were classified as "rivers" or "drains" depending on whether they were maintained or only used to drain the aquifer. For both cases, model input included canal stages and values for a conductance term defining the degree of interaction between the canal and the aquifer. Measured water levels at stage monitoring stations were used to define the hydraulic grade line elevations.

The MODLFOW River and Drain packages were used to simulate the interactions between ground water and canals. It should be emphasized here that most, if not all, of the canals within the model domain do not adhere strictly to the definition of a "river" that is inherent to MODFLOW. This is essentially due to the fact that, as discussed previously, canal stages and ground water levels within this region are often highly interdependent while the MODFLOW based conceptualization of a river assumes that canal stages are independent of ground water levels and remain constant over a given stress period. However, if a relatively short stress period length is used, the use of the River package in this type of environment will generally yield acceptable results.

The canal classifications, either river or drain, used in the model are shown in Figure 3.5.1. Canal reaches were classified as a "drain" when they were either bound between an upstream terminus and a downstream control structure or it was felt that they did not carry enough flow to provide significant amounts of recharge to the aquifer. Otherwise, canal reaches were classified as rivers.

3.5.2 Conceptual Cross-Section

The use of either the River or Drain package requires as input a conductance parameter that reflects the head losses incurred by flow between the canal and the aquifer. For a given canal reach, this conductance parameter should reflect the wetted perimeter of the channel as well as the properties of the sediment bed located along the canal aquifer interface (McDonald and Harbaugh, 1988). In particular, the conductance terms input to the model were formulated using a conceptual canal cross-section with trapezoidal geometry, side walls that are nearly in direct connection with the surrounding aquifer, and a sediment bed covering the bottom. Here, some head loss through the canal side walls is assumed to occur through a thin sediment layer. The basis for this conceptualization and the methodology used to compute the resulting values for conductance are discussed by Wilsnack and Nair (1998).

3.5.3 Canal Sediment Properties

Table 3.5.1 contains the available hydraulic conductivity data for the canal sediments. These data suggest that variations of several orders of magnitude are possible. Initially, all canal reaches were assigned a sediment hydraulic conductivity value of 1.0 feet per day, but were varied between 0.01 and 10 feet per day during the calibration process

TABLE 3.5.1 Hydraulic Conductivity Data for Canal Sediments

K_s (ft/day)	Test Method	Source
0.03	Core/permeameter	Chin (1990)
0.12	Computed from canal stage and flow measurements	Miller (1978)
0.98	Core/laboratory	Miller (1978)
9.80	Core/laboratory	Miller (1978)

3.5.4 Geometric Cross-Sectional Properties

Estimates of the bottom elevation, bottom width, and side slopes of the various canal reaches were used to determine canal wetted perimeters for each stress period. Sources of data for these canal properties included as-built drawings, surveys, and design specifications.

3.5.5 Canal Stages

Mean daily stages for each canal reach were needed not only for direct input to the River and Drain packages but also to compute the required conductance values. Canal stages were based on the available stage monitoring stations shown in Figure 3.5.2. Where monitoring station location coincides with a structure, both headwater and tailwater elevation data were usually available.

The manner in which stages were assigned to canal reaches was varied and somewhat subjective. For each canal reach bounded between two stations (Figure 3.5.2), the hydraulic grade line profile was typically estimated in a stair-step fashion where an upstream portion of the canal reach is assigned data from the station located at the upstream end, a downstream portion of the canal reach is assigned stage data from the station located at the downstream end, and the remaining portion of the canal reach in between is assigned the average of the two data values. In contrast, the hydraulic grade line profile in some canal reaches was assumed flat and based on the nearest stage station. For example, certain canals classified as drains were assigned constant hydraulic grade line elevations equal to their downstream control elevations.

3.6 Rainfall Recharge and Evapotranspiration

MODFLOW's Evapotranspiration (ET) and Recharge packages were used to simulate the processes of ET and rainfall recharge. These packages required the following input:

- Recharge rate
- Potential Evapotranspiration (PET)
- Evapotranspiration surface
- Extinction depth
- IEVT and IRCH arrays

The recharge rate and PET rates were calculated using the same Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) based approach employed by the South Florida Water Management Model (Brion et.al., 1999). This methodology is based on a daily mass balance of the unsaturated zone that quantifies infiltration to and ET from the water table. The rainfall stations used for this analysis are shown in Figure 3.6.1. For more information on this approach, the reader is referred to Brion et.al (1999), and Restrepo and Giddings (1994).

The ET surface elevations and extinction depths were constructed using the shallow and deep root zone depths associated with the different land use types. The ET surface was set at land surface elevation minus the shallow root zone depth while the extinction depth was assumed to be equal to the difference between the shallow and deep root zone depths. The IEVT and IRCH arrays represent the layers to which ET and recharge are to be applied. These arrays were set equal to one in areas where the wetland layer is active and two elsewhere.

3.7 Water Supply Pumpage

The locations and attributes of water supply wells were obtained from the District's Water Use and Permits Division. Monthly public water use was extracted from utility reports submitted to the District as a part of the permit limiting conditions. Also included in the reports were the well depths and the casing intervals. Based on this information, along with the percentage allocation among the different wells within each permit, average daily pumpages were assigned to each well in the model data sets. The pumpage was distributed between the model layers based on the layer transmissivities as outlined by McDonald and Harbaugh (1988).

3.8 Boundary Conditions

The boundaries of the active model domain were represented through the General Head Boundary (GHB) package. The GHB package simulates head dependent flows and requires the specification of a conductance term and an external head. Figure 3.7.1 depicts the locations of the boundaries. The northern boundary is located along the M canal, Clear Lake, and Lake Mangonia. The western boundaries of the active model area include the L-8 Canal, the L-7 Levee and Borrow Canal (WCA-1), the L-6 Levee and Borrow Canal (WCA-2A) and the L-38E Levee and Borrow Canal (WCA-2A). The southern boundary of the model traverses the L-35B Levee and borrow canal along with the C-14 Canal in Broward County. The eastern boundary of the model is located along the Intercoastal Waterway.

The northern, western and southern boundaries were all modeled in essentially the same manner. The conductances of the aquifer layers were calculated using a flow length equal to one half of the length of a cell and the conductivity of the aquifer. The Conductance (C) for a boundary cell is given by:

$$C = \frac{k \cdot t}{250}$$

where k is the horizontal conductivity of the aquifer and t is the thickness of the cell in the vertical direction. The stages along the northern and southern boundaries were based on the water levels in the canals, while any boundaries located west of the levee system were based on the nearest available measured stages.

The eastern boundary condition is based on monthly averaged historical tidal data from the Riviera and Hillsboro monitoring station. Monthly average tidal stages at this station were calculated from October 1, 1973 through February 29, 1980, the operational period of record for this station (Krishnan and Gove, 1993). In addition, unlike the stages along the other boundaries, the presence of the freshwater-saltwater interface along the eastern boundary necessitated certain corrections to the tidal stages and conductances. First, the concept of equivalent freshwater heads was used to express the vertical pressure distribution along the boundary in terms of freshwater heads. Equivalent freshwater heads were calculated using the following formula:

$$H_{eq} = (H_s - L_e)(\gamma_s/\gamma_f - 1) + H_s$$

where

H_{eq}	=	the equivalent freshwater head at the boundary
H_s	=	the tidal stage
L_e	=	the elevation within the aquifer where the equivalent freshwater head is to be applied
γ_s	=	the specific weight of salt water
γ_f	=	the specific weight of fresh water

In order to avoid large vertical flows at the boundary while mimicking the natural processes at this location, the following scaling factor was applied to the conductance values along the coastal boundary:

$$Sc = \left(\frac{d}{d_b} - 1 \right)^2 \cdot 0.1$$

where Sc is the scaling factor, d is the depth to the center of the boundary cell in question and d_b is the depth to the bottom of the SAS (Restrepo, 1998, personal communication). This scaling factor has the effect of greatly reducing conductances in the deeper layers of the model. Conceptually, this reflects the assumption that the freshwater-saltwater interface is a sharp interface that does not move. Given this, fresh water in the deeper layers of the model must flow up and over this interface and leave the model through the upper layers.

3.9 Initial Conditions

For both the dry and wet periods of record of calibration, the initial conditions were established from the USGS monitoring sites where water level data existed for the first day of the period of record. The Arc Info based Inverse Distance Weighting Interpolation scheme was used to estimate water levels at each cell location. The interpolation procedure was applied separately for WCA-1 and WCA-2, which are enclosed by levees, and the rest of the modeled domain located east of the levee system.

4. Model Calibration

4.1 Objectives

The primary objective of the history matching effort was to improve the model capabilities in replicating historical water levels and canal base flows within an acceptable margin of error. In order to replicate the capabilities of the model for a wide range of historical conditions two different hydrologic periods were chosen: a relatively dry period from June 1, 1988, through June 30, 1989, and a relatively wet period from June 1, 1994, through June 30, 1995. Both the history matching periods were preceded by a three-month warm up, period in order to help minimize the effects of initial conditions on computed water levels.

The model was calibrated under both steady state and transient conditions. In this first phase of calibration the comparisons only involved history matching of heads. Model calibrations are not unique since numerous input parameters can be adjusted in various combinations to get the same match between observed and simulated head values. It is anticipated that for the second phase of calibration in addition to water levels, base flows accumulated over selected reaches of canals should also be compared to increase the likelihood of a more unique calibration.

4.2 Sensitivity Analysis

4.2.1 Preliminary Sensitivity Analysis

A preliminary sensitivity analysis was conducted on the effects of varying model input parameters on the computed steady state water table elevations in an effort to improve the overall understanding of the modeled system. For this sensitivity analysis the parameter values were changed one at a time and the changes in the water levels were studied by creating sensitivity maps in Arc View. The results of this preliminary analysis are presented qualitatively in Table 4.2.1 and Table 4.2.2 for the dry and wet periods of record. The results are confined to overall qualitative changes in the wetland and the top aquifer layer. A more rigorous analysis of the sensitivity of the model results to parameter variations will be pursued after the initial calibration phase.

TABLE 4.2.1 Results of Sensitivity Analysis for the 1988-1989 Period of Record.

Parameter	Corresponding Change	Range of Head difference: Minimum	Range of Head difference: Maximum	Areas Most Affected
Conductivity	times 10	0	0.56	WCA-2 south boundary
	divided by 5	-6.01	2.99	Pws wellfieldls, LWE1 south
ET	times 2	0.03	7.95	WCA's
Recharge	times 2	0.01	7.95	WCA's
Et Surface	plus 1.0 ft	0	1.01	WCA's
	minus 1.0 ft.	-1.01	0	WCA's
Extinction Depth	times 2	-0.71	0	small area in WCA-2
	divided by 2	0	0.31	Minimal effect
General Head Conductance	times 10	-0.9	1.05	Eastern boundary
	divided by 10	-1.42	2.41	Along the north-eastern general head boundary
General Head Stage	plus 0.5 ft	-1.18	0.02	Along the general head boundary
	minus 0.5 ft.	-1.11	0.02	Along the general head boundary
Pumpage	plus 30%	-1.91	0	Pws wellfields
	minus 30%	0	2.14	Pws wellfieds
River & Drain Conductance	times 10	-0.76	0.55	Along Hillsboro canal and LWDD canals
	divided by 10	-1.15	1.46	Along Hillsboro canal, LWDD canals, and C-51 basin
River & Drain Stage	plus 0.5 ft.	0	0.51	All areas
	minus 0.5 ft.	0.51	0	All areas
Vcont	times 10	-1.31	1.97	Along C-51, small areas in LWDD, and south-east boundary
	divided by 10	-1.71	2.57	Along C-51, small areas in LWDD, and south-east boundary
Wetland Beta Coefficient	plus 1.000	0	0.05	Minimal effect
	minus 1.000	0	0.05	Minimal effect
Wetland Hymuc	times 10	-0.05	0.55	Minimal effect
	divided by 10	-0.49	0	Minimal effect
Wetland Kadlec K (base K = 100,000)	times 2	0	0.65	Minimal effect
	divided by 2	0	1.41	Small area south-east of WCA-2
Wetland Vhmucr & Vhyly2r	times 10	0	0.07	Minimal effect
	divided by 10	-0.11	0.08	Minimal effect

TABLE 4.2.1 Results of Sensitivity Analysis for the 1994-1995 Period of Record.

Parameter	Corresponding Change	Range of Head difference		Areas Most Affected
		Minimum	Maximum	
Conductivity	times 10	0	0.56	WCA-2 south boundary
	divided by 5	-6.01	2.99	Pws wellfiells, LWE1 south
ET	times 2	0.03	7.95	WCA's
Recharge	times 2	0.01	7.95	WCA's
Et Surface	plus 1.0 ft	0	1.01	WCA's
	minus 1.0 ft.	-1.01	0	WCA's
Extinction Depth	times 2	-0.71	0	small area in WCA-2
	divided by 2	0	0.31	Minimal effect
General Head Conductance	times 10	-0.9	1.05	Eastern boundary
	divided by 10	-1.42	2.41	Along the north-eastern general head boundary
General Head Stage	plus 0.5 ft	-1.18	0.02	Along the general head boundary
	minus 0.5 ft.	-1.11	0.02	Along the general head boundary
Pumpage	plus 30%	-1.91	0	Pws wellfields
	minus 30%	0	2.14	Pws wellfieds
River & Drain Conductance	times 10	-0.76	0.55	Along hillsboro canal and LWDD canals
	divided by 10	-1.15	1.46	Along hillsboro canal, LWDD canals, and C-51 basin
River & Drain Stage	plus 0.5 ft.	0	0.51	All areas
	minus 0.5 ft.	0.51	0	All areas
Vcont	times 10	-1.31	1.97	Along C-51, small areas in LWDD, and south-east boundary
	divided by 10	-1.71	2.57	Along C-51, small areas in LWDD, and south-east boundary
Wetland Beta Coefficient	plus 1.000	0	0.05	Minimal effect
	minus 1.000	0	0.05	Minimal effect
Wetland Hymuc	times 10	-0.05	0.55	Minimal effect
	divided by 10	-0.49	0	Minimal effect
Wetland Kadlec K (base K = 100,000)	times 2	0	0.65	Minimal effect
	divided by 2	0	1.41	Small area south-east of WCA-2
Wetland Vhmucr & Vhyly2r	times 10	0	0.07	Minimal effect
	divided by 10	-0.11	0.08	Minimal effect

4.2.2 Sensitivity to Initial Conditions

A sensitivity analysis was performed to evaluate the effects of initial water levels on the model-computed transient results. In particular, the analysis was undertaken to assess the length of time beyond the start of the simulation when the computed transient results become insensitive to the initial conditions. Sensitivity analysis were performed for both the dry and wet periods of record and, in each case, the simulations were identical to the base case simulation, except that initial water levels were a foot higher and a foot lower, respectively. The results of this analysis are presented in Appendix C for both, the wet and dry period, of record. The results suggests that outside of the wetland areas of the model, significant errors in initial conditions could significantly influence the model results for almost one to two months. As one would expect, it is also seen that the influence dramatically reduces if the monitoring point is in close proximity to a canal or a feature where boundary conditions are specified. It is also observed that the error reduces drastically in the urban areas after a period of approximately a month.

In contrast within the wetland areas of the model, the effect of errors are very significant and persist for the entire period of the simulation. The wetland areas of the model apparently have a very large "memory" and the results are very much dependent on the initial conditions for all periods of the simulation. The reasons for this effect are primarily due to the large storage associated with the WCAs and the fact that monitoring points are located further away from any boundary conditions. An increase or decrease of the initial water level by approximately a foot adds or removes a large volume from the overall water budget. The WCAs are modeled as isolated wetlands, from which water can leave only through the bottom layers, whose hydraulic conductivities are not as high as the Biscayne aquifer. It is suggested that a more detailed analysis be performed on the effects of initial conditions in the wetland areas. This analysis should also address errors in initial conditions resulting from the techniques and data used to construct initial water level arrays.

4.3 Steady State Calibration

4.3.1 Objectives

The main purpose of the steady state calibration was to come up with an initial set of model parameters before proceeding with the more intensive transient calibration. Since the steady state calibration does not involve any storage term, the effort was also used to study the effects of other hydrogeologic parameters on model results**.** The selected approach was to apply average stresses of each period of record to the model as steady state stresses. Given these conditions, the selected calibration criterion was based on the notion that computed water levels should at least fall within the range of observed water levels and, preferably, closer to the mean than either the maximum or minimum value.

4.3.2 Results

The results of the steady state calibration are provided in Figure 4.3.1 and Figure 4.3.2 for the dry and wet periods of record respectively. The figures indicate the locations where the calculated water level was within one standard deviation from the mean of the observed range. Also shown are the locations where the model calculated values were outside the observed mean plus or minus 1 standard deviation range.

4.4 Transient Calibration

4.4.1 Objective

The transient calibrations completed so far were restricted to history matching of heads. The criterion used for the transient calibration was as follows: the absolute value of the difference between the observed and the computed water levels at a given well location was less than 1.0 feet for at least 75 percent of that portion of the calibration period of record, where data was available. The parameters adjusted for the transient calibration included horizontal hydraulic conductivity and canal conductance.

4.4.2 Location of Monitoring Wells

A total of 37 USGS and SFWMD water level gages were used in the wet calibration period while a total of 24 gages were available for the dry calibration period. The wet period has more observation wells available since some of the District gages in WCA-2 became operational only in late 1994. The locations of all wells and staff gages used for the calibration of the model are given in Figures 4.4.1 and 4.4.2 for the two periods of record. Although the USGS observation wells have recorders that record the hourly water levels for each day, only the daily maximums are processed and stored in the USGS Automated Data Processing System (ADAPS) database. Hence, these ground water levels (as opposed to end-of-day water levels) were the only ground water levels data available for history matching.

4.4.3 Results

The transient calibration results are shown in Table 4.4.1 for the wet period of record and in Table 4.4.2 for the dry period. The tables show the percentage of time that the calibration criterion cited above was met. Also shown in the table are the mean error (bias) and the standard deviation of the residuals.

TABLE 4.4.1 Calibration Statistics for the Wet Period (June 1, 1994 – June 30, 1995).

No.	Gagename	Percent within 1 foot	Mean Error	Std. Dev. Error	Within Eval Area	Comments
1	PB-809	92.9	-0.329	0.462	N	
2	PB-99	99.7	-0.085	0.508	N	
3	PB-1639	53.7	-1.181	0.819	Y	
4	PB-1491	2.8	2.918	1.009	Y	Boca Raton Wellfield
5	PB-732	96.5	-0.425	0.324	Y	
6	PB-1684	94.7	-0.338	0.269	Y	
7	PB-1661	92.2	-0.343	0.420	Y	
8	PB-900	79.6	0.571	0.542	Y	
9	PB-561	73.8	-0.796	0.642	N	
10	PB-683	79.8	-0.595	0.490	Y	
11	PB-1680	89.2	0.551	0.365	Y	
12	PB-685	83.8	-0.034	0.690	N	
13	PB-445	97.0	-0.148	0.506	Y	
14	G-1260	43.0	-0.965	1.209	N	Southeast Broward County
15	G-2739	85.8	0.457	0.567	N	
16	G-1213	85.9	-0.302	0.783	N	
17	G-1315	61.5	-0.318	1.049	N	Southeast Broward County
18	G-1215	27.3	-1.197	2.100	N	Southeast Broward County
19	G-2031	98.1	-0.092	0.314	N	
20	G-2147	25.7	-1.717	1.106	N	Southeast Broward County
21	G-1316	98.9	0.306	0.357	N	
22	G-853	55.0	-0.756	1.330	N	Southeast Broward County
23	G-616	94.1	0.019	0.623	N	
24	1-9*	100.0	0.083	0.301	N	
25	1-8T*	100.0	0.098	0.314	N	
26	1-7*	100.0	0.199	0.238	N	
27	2-17*	100.0	0.072	0.189	N	
28	2-19*	76.6	-0.723	0.848	N	Southeast Boundary of WCA-2
29	2A-300_B*	100.0	-0.234	0.227	N	
30	2A-17_B*	100.0	0.065	0.194	N	
31	2-15*	100.0	0.118	0.334	N	
32	WCA2RT*	100.0	-0.105	0.169	N	
33	WCA2F4*	100.0	0.064	0.197	N	
34	WCA2E4*	100.0	-0.066	0.219	N	
35	WCA2E1*	95.6	-0.123	0.408	N	
36	WCA2F1*	95.6	-0.206	0.385	N	
37	WCA2U1*	100.0	0.120	0.195	N	

*USGS and District Gages in Water Conservation Areas

TABLE 4.4.2 Calibration Statistics for the Dry Period (June 1, 1988 – June 30, 1989).

No.	Gagename	Percent within 1 foot	Mean Error	Std. Dev. Error	Within Eval Area	Comments
1	PB-561	69.4	0.062	1.051	N	
2	PB-809	93.4	-0.453	0.366	N	
3	PB-99	92.9	-0.620	0.296	N	
4	PB-683	82.3	-0.500	0.591	Y	
5	PB-445	97.5	-0.403	0.332	Y	
6	PB-900	72.7	0.794	0.767	Y	
7	PB-1491	0.0	7.348	1.502	Y	Boca Raton Wellfield
8	PB-732	98.0	-0.044	0.433	Y	
9	PB-88	89.4	0.149	0.675	Y	
10	PB-1495	15.7	1.322	0.351	Y	May have survey problems
11	G-1260	76.2	0.374	0.700	N	
12	G-1213	50.9	0.405	1.061	N	Southeast Broward County
13	G-1315	46.3	-0.906	1.029	N	Southeast Broward County
14	G-1215	51.4	0.425	1.126	N	Southeast Broward County
15	G-2031	95.7	0.444	0.482	N	
16	G-2147	74.7	-0.508	0.675	N	
17	G-1316	98.0	-0.362	0.299	N	
18	G-853	19.8	1.942	0.950	N	Southeast Broward County
19	G-616	46.0	-1.512	1.061	N	Southeast Broward County
20	1-9*	95.7	-0.616	0.298	N	
21	1-8C*	71.1	0.574	1.035	N	
22	1-7*	65.3	0.364	0.849	N	
23	2A-300_B*	6.1	-1.885	0.462	N	South boundary of WCA-2
24	2A-17_B*	87.1	-0.047	0.698	N	

*Gages in Conservation Areas where water levels were below land surface part of the time.

A comparison of the two calibration periods of record show that, in general, the model performs better during the wet season than in the dry season. This is especially true in the wetland areas. The results also show that while all of the gages in the WCAs met the calibration criteria for the wet period of record, only two of the five gages met the criterion during the dry period of record when the water levels were below land surface. Apparently simulations of wetland stages are fairly accurate when the water levels are above land surface and there is overland flow. It is possible that when no overland flow exists the uncertainties inherent to characterization of the shallow wetland geology result in an under prediction of heads in the wetland layer. Errors in ET-based parameters could be another factor.

Shortcomings in both the model itself and the water level data prevented calibration targets from being met within certain areas. For example, in the urban areas, it is apparent that the model does not meet the calibration criteria in southeastern Broward County. This is at least partially due to the fact that the operational criteria of the secondary canals within this area cannot be adequately represented by the River and Drain packages. Also, the proximity of observation wells to local stresses sometimes precludes the use of their data for history matching with a finite-difference model. For example, the model was consistently overpredicting water levels at the well PB-1491 since it is within the city of Boca Raton's wellfield. In addition, several of the observation wells had suspected errors in their measuring point elevations and these discrepancies are summarized in Table B.3.1. Some of these were corrected or verified, while others could not be addressed since the observational wells are no longer in service. For example at well PB-445 in Boynton Beach, the model was consistently underpredicting, and this was corrected after the well was resurveyed by the USGS. The USGS observational well PB-900 in the city of Boca Raton, on the other hand, is no longer in service since it was destroyed by road construction in November 1996.

Perhaps one of the most significant obstacles to achieving calibration goals was posed by the somewhat inappropriate nature of much of the available water level data. As mentioned earlier, the historical ground water levels currently available from the USGS database are daily maximum values. In contrast, the model computes the heads for the end of each day. Significant differences can exist between daily maximum and end-of-day ground water levels. Also, most of the canal stage data available for the LWDD, which comprises a large portion of the model domain, are only spot measurements and not the mean daily stages that should be used for model input.

5. Conclusions and Recommendations

5.1 Model Capabilities and Limitations

The ground water model developed simulates the hydrogeology of the SAS within southern Palm Beach County as well as the overland flow in the wetland systems. However, the current version of the model has been calibrated only with respect to water levels. The model has not been calibrated for base flows due to resource limitations. This limitation of the model should be kept in mind while evaluating canal base flow or ground water flow across selected boundaries. Consequently, stage duration curves for wetlands and ground water level hydrographs needed for comparative type analysis are the primary type of hydrologic performance measures that the model is capable of supporting.

5.2 Future Improvements

Recommended future improvements to the model include the following:

- Conduct sensitivity and uncertainty analysis of all model parameters to improve the overall model calibration
- Acquire the necessary data and resources to calibrate the model for base flows
- Perform a sensitivity analysis of the wetland model parameters to understand the dynamics of the wetland aquifer interactions when the water level goes below the land surface
- Addition of new packages that will incorporate the Recharge/ET computations into the simulation model and avoid the use of preprocessed values
- Resolve the discrepancies associated with monitored daily maximum values and the model computed end-of-day values with the USGS
- Formulate cooperative agreements with the secondary water control districts to improve the data collection efforts for stage monitoring
- Incorporation of improved solver packages that are better suited to handle the nonlinear features and the large ill-conditioned matrices inherent to the model
- A better representation of the freshwater-saltwater- interface located along the eastern boundary
- Simulate canal flows
- Simulate operational criteria for the 298 Districts within Broward County

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Appendix A: GIS Database

The specific components of the GIS database used to support model construction can be viewed by accessing the associated ARCVIEW project. Discussions of the primary components are provided below.

A.1 General Features

Using the GIS software ARC INFO, a GIS database was constructed for the purpose of storing, editing, querying, and displaying all of the spatial data required to construct the model. Table A.1.1 provides an overview of the predominant features of the current GIS database.

TABLE A.1.1 Major GIS Database Features

Model Feature	ARC INFO Feature Class	Attribute Storage
Wetland diversion cells IBOUND	Region subclass	Region attribute table
Land use model grid quarries	Polygon	Polygon attribute tables Look-up (INFO) tables
Canals Outer boundary	Route subclass	Continuous events
Stage and flow gages Wells (all types) Land surface elevation	Point	Point attribute tables
Land surface elevation All matrix-type input	GRID	Floating point or integer GRIDS

A.2 Coverages of Aquifer Properties

A.2.1 Geologic Control Wells

A point coverage of the geologic control wells shown in Figure 2.1.1 was constructed and used to store the estimated hydraulic conductivity ranges as well as the bottom elevations of the various lithologic units. The resulting coverage was used to construct point coverages of horizontal hydraulic conductivity and vertical conductance for each relevant model layer.

A.2.2 Hydraulic Conductivity

Both a point coverage and a raster coverage (GRID) of mean horizontal hydraulic conductivity were constructed for each model layer. Each point coverage was derived from the geologic control well coverage where the Inverse Distance Weighted function of the ARC/INFO GRID module was used to construct the raster coverages from the respective point coverages. Considering the heterogeneous nature of the SAS, it was felt that this spatial interpolation technique was a suitable choice since it results in interpolated values that are somewhat biased towards the closest measured values. Raster coverages of VCONT values was created from the horizontal hydraulic conductivity coverages using map algebra techniques and assuming an anisotropy of 1:10 between the vertical and horizontal hydraulic conductivities.

A.2.3 Storage and Specific Yield

Specific yield for model Layers 1 and 2 assumed the constant values indicated previously.
A constant value was also used for the specific storage of all layers which were confined. Since the thickness of these layers varied, GRIDS were created for each confined layer depicting the storage coefficient values. For layer 2, map algebra techniques were used to increase the value of storage coefficient to 1.0 in the nonwetland areas to account for the conversion to confined conditions when the water table was higher than land surface.

A.3 Coverages of Wetland Properties

A.3.1 Wetland Layer Elevations

The bottom elevation of the wetland layer was set at the bottom elevation of the caprock layer where extensive wetlands exist and at land surface elsewhere (Figure 2.3.1). A raster coverage depicting these layer bottom elevations was constructed from the land surface elevation GRID (see Section A.10) and the Layer 1 IBOUND GRID using Boolean-based map algebra techniques afforded by the ARC INFO GRID module.

A raster coverage of ZBOTT, a parameter of the Wetlands package that depicts land surface elevation within the wetlands, was initially set equal to land surface elevation.

The elevation values along the L-39 Levee were increased by five feet to prevent overland flow from WCA-1 to WCA-2 along the levee.

A.3.2 Other Properties

Table A.1.1 lists those wetland properties that are included in the GIS database as Region subclasses of the model grid coverage.

A.3.3 Conversion of Coverages to the Wetland Package Input Data Set

The primary input data set to the Wetland package contains records depicting the address and hydraulic conductance of each wetland cell. These records were constructed by first converting the IBOUND region subclass for the wetland layer to a polygon coverage. This coverage, the model grid coverage, and the land use coverage were then combined through an overlay process. The resulting coverage attribute table was joined to the look up INFO table relating land use to hydraulic conductance. This final attribute table was used to generate a text file containing the required information for each wetland cell.

The diversion option for the Wetland package contains records depicting the address and the net flow (inflow-outflow) distributed for each diversion cell. If the net flow was positive it is assumed that the wetland cells in question receive this amount from external sources, and if the net flow was negative water was taken out of those cells to external sinks. These records were constructed by first converting, the IDIV region subclass for the wetland layer to a polygon coverage. This coverage, and the model grid coverage, were then combined through an overlay process. The resulting array was linked to a spreadsheet relating structure name to net flow. A FORTRAN program counted the number of cells for each diversion region (WCA-1 and WCA-2) and spread the net flow for each time step evenly over each subregion to create the diversion records for the Wetlands package.

A.4 Canals

The locations of the canal centerlines were stored in the GIS database as a line coverage with a route subclass. Figure 2.2.1 shows the canals that were included in the model. The route system along with the events shown in table A.4.1 were used to assign the necessary attributes to each canal. Techniques similar to those described by Wilsnack and Nair (1998) were used to construct the River and Drain package input data sets from these canal attribute events along with the stage data.

A.5 Land Use

A separate vector coverage of land use was used to support each of the calibration periods of record. One reflects conditions around 1988 while the second coverage depicts land uses that existed around 1994. The level 3 land use classification descriptors were LU3 (text) for the 1998 coverage and FLUCCS_CODE (numerical code) for the 1994 coverage. A crossover table that linked the LU3 categories to the FLUCCS_CODE numerical values was created. The land use coverages were used to construct the ET surface arrays, the extinction depth arrays and the input data sets for the Wetlands package. To accomplish this, two look up INFO tables were used: one depicting the relationship between land use and root zone depths and another relating land use to the wetland hydraulic conductance coefficient. ET surface and extinction depth grids were constructed in the manner described by Wilsnack and Nair (1998). The development of the input data sets to the Wetland package was discussed in section A.3.3.

TABLE A.4.1 Events Used to Associate Canal Attributes with the Canal Route System

Attribute	Event Type	Comments
Model cell address	Linear	Constructed through overlay of the route system onto the model grid coverage
Bottom elevation	Continuous	Used for layer assignments
Bottom width	Continuous	
Side slope	Continuous	
Bottom sediment bed thickness	Continuous	Subject to adjustment during the calibration process
Side wall sediment layer thickness	Continuous	Subject to adjustment during the calibration process
Sediment hydraulic conductivity	Continuous	Subject to adjustment during the calibration process
Canal classification	Continuous	River, Drain or GHB
Stage station assignment	Continuous	

A.6 Public Water Supply Wells

A point coverage of the public water supply wells discussed previously was constructed to represent the well locations in the GIS database. The available well construction data were stored in the attribute table for this coverage. The techniques used to construct the Well package input data set from this coverage are discussed in Wilsnack and Nair (1998).

A.7 Outer Boundary

The boundaries of the active model area are stored in a line coverage with a route system (Figure 3.7.1). Similar to the canal route system, this boundary route system is associated with continuous events that designate the stage monitoring stations whose data are used to define the stage along each section of the boundary. Other events associated with this route system include linear events representing cell addresses and the hydraulic conductivity of each model layer. These events were constructed through overlays of the route system onto relevant polygon coverages and were used to compute the boundary conductances as discussed previously. The input data set to the General Head Boundary package was constructed from these events using a procedure that is similar to the one used to construct input data sets to the River and Drain packages.

A.8 Model Grid Coverage

A polygon coverage with the geographic limits shown in Figure 2.1.1 was constructed in order to represent the model grid in the GIS database. Cell attributes stored in the attribute table were limited to row and column numbers along with a multiplier term for hydraulic conductivity. All other model parameters stored within the grid coverage were included as Region subclasses (Table A.1.1).

A.9 Land Surface Digital Elevation Model

Digital Elevation Models (DEM) were created separately for WCA-1, WCA-2, and the urban areas east of the protection levees. The DEM for WCA-1 was obtained as an Arc Info GRID coverage from the University of Florida. It was converted to a polygon coverage and then to a grid with a cell size of 500 feet using the POLYGRID command in Arc Info. For WCA-2A and the urban areas of the modeled area, the DEMs were created using the TOPOGRID command in Arc Info. The method uses an iterative finite difference interpolation technique and is optimized to have the computational efficiency of local interpolation techniques like the inverse distance weighted interpolation, without losing the surface continuity of global interpolation methods like kriging and splines. Although the method using the drainage enforcement option, is ideal for creating a hydrologically correct DEM in a natural watershed, for purposes of creating elevation models in urbanized areas this option was not exercised. The DEM's created for the three distinct areas were combined into a single DEM for the entire model area using map algebra techniques. (Figure A.9.1.)

Appendix B: Hydrologic Database

B.1 Rainfall and Potential Evapotranspiration

Daily rainfall and PET data for the calibration periods of record were extracted from the hydrologic database used to support the South Florida Water Management Model (Brion et al., 1999). The supporting documentation for this model provides information on available rainfall and PET stations within the model domain.

B.2 Canal Stages

Mean daily canal stages were compiled, where available, over the calibration periods of record for each of the monitoring stations shown in Figure 3.4.2. Most of these data were obtained from DBHYDRO while some were extracted directly from the USGS ADAPS database and LWDD canal stage readings. As expected, numerous data gaps existed within each period of record at a number of these stations. Since continuous time series were needed to generate model input data sets, steps were taken to fill in these gaps using the most appropriate of the following techniques:

- Correlation with other nearby stations
- Compute mean daily stages from available break point data
- Estimate mean daily stages from daily staff gage readings
- Substitute representative historical time series or average values for the missing values
- Estimate missing stages over the data gap using linear interpolation

B.3 Ground Water Levels and Wetland Stages

Historical water level data were compiled for each of the monitoring stations shown in Figures 4.4.1 and 4.4.2. The ground water levels represent maximum daily values while the surface water data (i.e., water levels in wetlands) consist of mean daily stages. Both types of data were used for history matching purposes. Also, data were not continuously available at each site. For a number of stations, data were only available over several months.

The measuring point elevations of a selected set of observation wells were resurveyed by District staff and compared to the elevations published by the USGS. These comparisons are provided in Table B.3.1. According to USGS staff (Scott Prinos, 1999, personal communication) possible causes of these discrepancies would include, but not necessarily be limited to, the following:

- Undocumented structural changes to the monitoring apparatus that would change the measuring point elevation
- Common survey errors such as erroneous measurement readings
- A faulty datum plan where different benchmarks using in the surveys were never tied together

TABLE B.3.1 Discrepancies in Surveyed Measuring Point Elevations for Selected Observation Wells.

Site Name	SFWMD Measuring Point Elevation (1999) (feet NGVD)	USGS Measuring Point Elevation (1998) (feet NGVD)
PB-900	21.52	22.86
PB-685	19.86	19.33
PB-1661	24.26	23.10
PB-1639	19.54	19.73
PB-561	20.89	20.81

Appendix C: Sensitivity of the Model to Initial Conditions.

C.1 Wet Period.

This appendix contains the individual hydrographs that depict the sensitivity of the model to initial conditions over the 1993-94 period of record. These hydrographs can be viewed for any of the gages listed below by clicking on the associated hypertext link.

WCA-1-7	**G-2739**	**WCA2E4**
WCA-1-9	**PB-1639**	**WCA2F4**
WCA-2-17	**PB-1680**	**WCA2U1**
WCA-2A-17_B	**PB-445**	**WCA2E1**
WCA-1-8T	**PB-683**	**WCA2F1**
WCA-2A-15	**PB-732**	**WCA2RT**
WCA-2A-19	**PB-900**	
WCA-2A-300_B	**PB-1491**	
G-1213	**PB-1661**	
G-1260	**PB-1684**	
G-1316	**PB-561**	
G-2147	**PB-685**	
G-1215	**PB-809**	
G-1315	**PB-99**	
G-2031		

C.2 Dry Period

This appendix contains the individual hydrographs that depict the sensitivity of the model to initial conditions over the 1988-1989 period of record. These hydrographs can be viewed for any of the gages listed below by clicking on the associated hypertext link.

WCA-1-7

WCA-1-8C

WCA-1-9

WCA-2A-17_B

WCA-2A-300_B

G-1213

G-1215

G-1260

G-1315

G-1316

G-2031

G-2147

G-616

G-853

PB-1491

PB-1495

PB-445

PB-561

PB-683

PB-732

PB-809

PB-88

PB-900

PB-99

Appendix D: Calibration Results

D.1 Wet Period

These figures portray the computed, measured, and residual hydrographs for each well, for the 1993-1994 period of record. These hydrographs can be viewed for any of the gages listed below by clicking on the associated hypertext link.

WCA-1-7	G-2739	WCA2E4
WCA-1-9	PB-1639	WCA2F4
WCA-2A-17	PB-1680	WCA2U1
WCA-2A-17_B	PB-445	WCA2E1
WCA-1-8T	PB-683	WCA2F1
WCA-2A-15	PB-732	WCA2RT
WCA-2A-19	PB-900	
WCA-2A-300_B	PB-1491	
G-1213	PB-1661	
G-1260	PB-1684	
G-1316	PB-561	
G-2147	PB-685	
G-1215	PB-809	
G-1315	PB-99	
G-2031		

D.2 Dry Period

These figures portray the computed, measured, and residual hydrographs for each well, for the 1988-1989 period of record. These hydrographs can be viewed for any of the gages listed below by clicking on the associated hypertext link.

WCA-1-7	**PB-1491**
WCA-1-8T	**PB-1495**
WCA-1-9	**PB-445**
WCA-2A-17_B	**PB-561**
WCA-2A-300_B	**PB-683**
G-1213	**PB-732**
G-1215	**PB-809**
G-1260	**PB-88**
G-1315	**PB-900**
G-1316	**PB-99**
G-2031	
G-2147	
G-616	
G-853	

Appendix E: Hydrogeologic Information Sources and Geophysical Methods

Appendix E.1 Hydrogeologic Information Sources

Causaras,(1985), *Geology of the Surficial Aquifer System, Broward County, Florida.* United States Geological Survey Water Resources Investigations Report 84-4068, 167p. and 2 sheets.
This investigative report describes the geologic framework of the SAS through the use of lithologic descriptions and cross-sections of Broward County and Southern Palm Beach County.

USACE (1951), *Agricultural and Conservation Areas Supplement 7 Design Memorandum Permeability Investigations by Well Pumping Test.*
This report summarizes the prediction of the probable quantity of underseepage along the proposed levee alinements on behalf of the WCAs.

Fish.(1988), *Hydrogeology Aquifer Characteristics and Ground Water Flow of the Surficial Aquifer System, Broward County, Florida*
The purpose of this addendum was to modify the authorized plan for improvement of the conveyance canals system as presented in the main report (Part 5, Supplement 52). It also summarizes the design considerations for enlarging the existing C-304 reach of Miami Canal and S-151 to provide for concurrent deliveries to the coastal tributary reach of Miami Canal (C-6) including the Miami Wellfield area, the park, and southern Miami-Dade County.

Keys. (1989), *Borehole Geophysics Applied to Ground-Water Investigations*
This report describes the application of various borehole geophysical tools.

Miller. (1987), *Lithology and Base of the Surficial Aquifer System, Palm Beach County, Florida*
This report evaluates the SAS and the geologic framework of Palm Beach County.

Parker et al. (1955), *Water Resources of Southeastern Florida*
This report describes the quantity, quality, sources of water, thickness and extent of water bearing formations (aquifers) and their hydraulic characteristics.

Russell and Wexler, (1993), *Hydrogeology and Simulation of Ground Water Flow near the Lantana Landfill, Palm Beach County, Florida*
This report contains summary of data describing regional and local hydrogeology at the Lantana Landfill.

Shine et al. (1989), *Ground Water Resource Assessment of Eastern Palm Beach County, Florida, Part I and II*
This report presents the results of a ground water resource assessment of eastern Palm Beach County by the compilation and evaluation of hydrogeologic data.

Swayze, L.J. (1984), *Hydrogeology of a Zone of Secondary Permeability in the Surficial Aquifer of Eastern Palm Beach County*
This report presents the regional extent of the highly permeable zone.

E.2 Geophysical Methods

E.2.1 Gamma Log

The basic principle of the gamma log is to help identify lithologic and stratigraphic boundaries. The gamma log detects radiation that is originating from Potassium 40 isotope and isotopes of Uranium and Thorium as they decay. These isotopes are common to clays and shales. The radiation is measured with a scintillation counter, where gamma particles produce light flashes in the scintillation crystal. The light flashes are photomultiplied, converted to electron pulses, and measured as a count rate per second(cps). Thus, the higher the count rate, the greater the radioactivity that exists within a rock.

E.2.2 Neutron Log

Neutron logs are made with a source of neutrons in the probe and detectors that provide a record of the neutron interactions that occur in the vicinity of the borehole. Most of these neutron interactions are related to the quantity of hydrogen present, which, in ground water environments, is largely a function of the water content of the rocks penetrated by the borehole. These logs are typically used to measure porosity and percent saturation. The measurements are in counts per second. (Keys, 1989).

E.2.3 Resistivity

Resistivity logs are used to measure the apparent resistivity of subsurface materials. By definition, resistivity includes the dimensions of the material being measured and, therefore, is an intrinsic property of that material (Keys, 1989). Basically, a current is passed between electrodes, the most common spacing of electrodes being 16 and 64 inches, and the voltage drop of one volt unit is measured between the potential electrodes. The current is maintained constant, so that the higher the resistivity between the two electrodes the greater the voltage drop will be. Applications for this method include determination of rock bulk resistivity, aquifer-water resistivity, and other water quality parameters. It is also useful in spatial correlations of geologic and hydrogeologic units (layer boundaries and thickness).

Appendix F. Hydrogeologic Cross-Sections

These Cross-sections can be viewed for the ones listed below by clicking on the associated hypertext link

Section A-A’

Section B-B’

Section C-C’

Section D-D’

Section E-E’

Section F-F’

Section G-G’

Section H-H’

Section I-I’