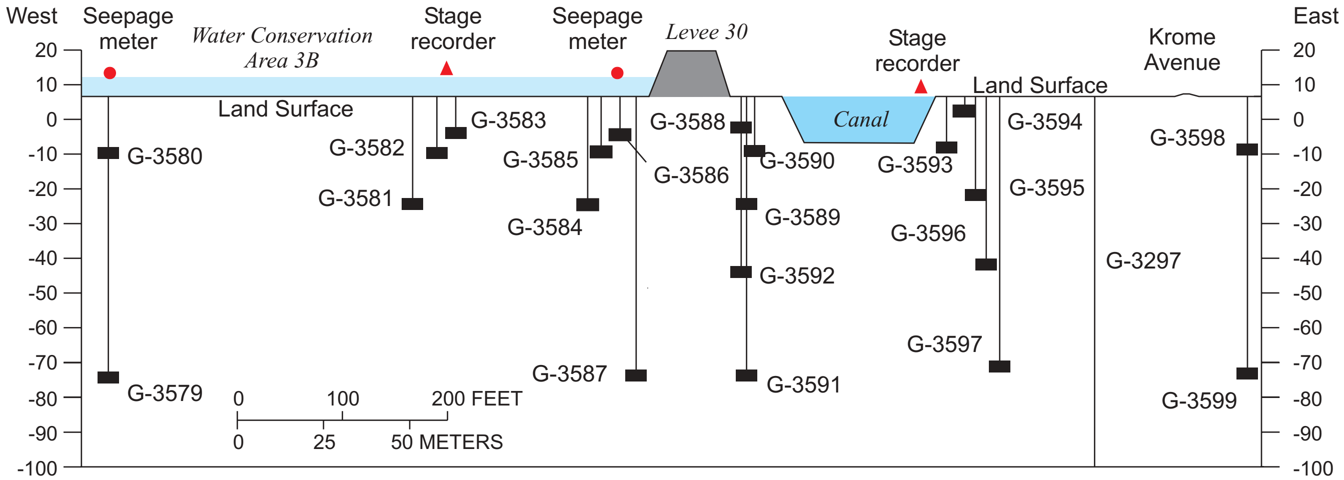
Methods to Quantify Seepage Beneath Levee 30, Miami-Dade County, Florida



U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 01-4074

Prepared as part of the
U.S. GEOLOGICAL SURVEY SOUTH FLORIDA
PLACE-BASED STUDIES PROGRAM

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By Roy S. Sonenshein

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Tallahassee, Florida
2001

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Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929–a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Methods to Quantify Seepage Beneath Levee 30, Miami-Dade County, Florida

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Abstract

A two-dimensional, cross-sectional, finite-difference, ground-water flow model and a simple application of Darcy's law were used to quantify ground-water flow (from a wetlands) beneath Levee 30 in Miami-Dade County, Florida. Geologic and geophysical data, vertical seepage data from the wetlands, canal discharge data, ground-water-level data, and surface-water-stage data collected during 1995 and 1996 were used as boundary conditions and calibration data for the ground-water flow model and as input for the analytical model.

Vertical seepage data indicated that water from the wetlands infiltrated the subsurface, near Levee 30, at rates ranging from 0.033 to 0.266 foot per day when the gates at the control structures along Levee 30 canal were closed. During the same period, stage differences between the wetlands (Water Conservation Area 3B) and Levee 30 canal ranged from 0.11 to 1.27 feet. A layer of low-permeability limestone, located 7 to 10 feet below land surface, restricts vertical flow between the surface water in the wetlands and the ground water. Based on measured water-level data, ground-water flow appears to be generally horizontal, except in the direct vicinity of the canal. The increase in discharge rate along a 2-mile reach of the Levee 30 canal ranged from 9 to 30 cubic feet per second per mile and can be attributed primarily to ground-water inflow. Flow rates in Levee 30 canal were greatest when the gates at the control structures were open.

The ground-water flow model data were compared with the measured ground-water heads and vertical seepage from the wetlands. Estimating the horizontal ground-water flow rate beneath Levee 30 was difficult owing to the uncertainty in the horizontal hydraulic conductivity of the main flow zone of the Biscayne aquifer. Measurements of ground-water flows into Levee 30 canal, a substantial component of the water budget, were also uncertain, which lessened the ability to validate the model results. Because of vertical flows near Levee 30 canal and a very low hydraulic gradient east of the canal, a simplified Darcian approach simulated with the ground-water flow model does not accurately estimate the horizontal ground-water flow rate. Horizontal ground-water flow rates simulated with the ground-water flow model (for a 60-foot-deep by 1-foot-wide section of the Biscayne aquifer) ranged from 150 to 450 cubic feet per day west of Levee 30 and from 15 to 170 cubic feet per day east of Levee 30 canal. Vertical seepage from the wetlands, within 500 feet of Levee 30, generally accounted for 10 to 15 percent of the total horizontal flow beneath the levee. Simulated horizontal ground-water flow was highest during the wet season and when the gates at the control structures were open.

INTRODUCTION

In an effort to restore predevelopment flow conditions to the Everglades in southern Florida, water managers must balance ecosystem restoration efforts with the needs to maintain adequate water supplies for public and agricultural use and to prevent flooding.

Drainage projects that began in the 1880's have altered the ecosystem in southern Florida. By the early 1990's, only 50 percent of the historical Everglades remained; the rest had been drained for agriculture and urban development. In response to hurricane-induced flooding of these developed areas of the historic Everglades in 1947, the United States Congress authorized the Central and Southern Florida Flood Control Project in 1948. This enormous undertaking required using levees, canals, pumping stations, and vast water-conservation areas to control ground-water levels. The initial phase of this effort was the construction of an interconnected network of levees and adjacent canals from central Palm Beach County to southern Miami-Dade County (Ogden and Davis, 1994). This network of levees and canals (fig. 1) prevents Everglades sheetflow from flooding developed areas to the east.

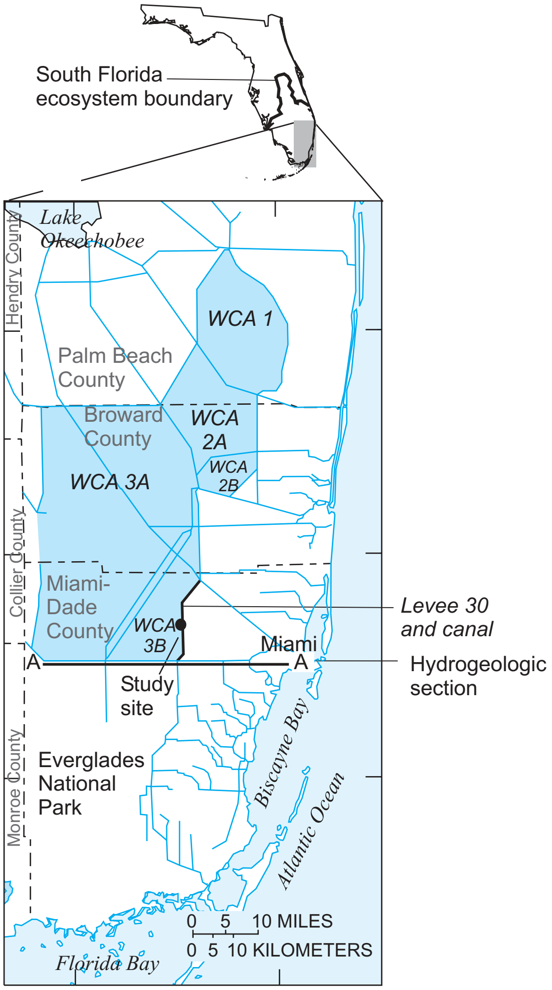

Figure 1. Southeastern Florida showing location of study site, water-conservation areas (WCA), primary canals, and hydrogeologic section.

Accounting for the most substantial sources of hydrologic inflows and outflows to and from the Everglades ecosystem is critical to the South Florida Place-Based Studies Program (McPherson and others, 1995). This program is a collaborative effort by the U.S. Geological Survey (USGS) working with other Federal, State, and local agencies and Indian Tribes to provide earth-science information needed to resolve land-use demands and water issues in southern Florida. As part of this effort, the USGS, in collaboration with the U.S. Army Corps of Engineers, conducted a study in 1995 and 1996 to evaluate methods for quantifying seepage beneath Levee 30 and resultant losses from Water Conservation Area (WCA) 3B (fig. 1) to the underlying Biscayne aquifer. WCA 3B is a major source of surface water for Everglades National Park. Water impounded in WCA 3B also provides recharge for municipal well fields (Sonenshein and Koszalka, 1996) east and south of Levee 30, and Levee 30 canal delivers water to agricultural areas to the south.

Purpose and Scope

The purposes of this report are to: (1) quantify the rates of ground-water seepage beneath Levee 30 in the west-central part of Miami-Dade County, and (2) evaluate the two methods used to quantify seepage rates. A two-dimensional, cross-sectional, finite-difference ground-water flow model and an analytical model based on Darcy's law were used to estimate seepage rates. Geologic and geophysical data, vertical seepage data, canal discharge data, and water-level data were collected during 1995 and 1996 to aid in the quantification of ground-water seepage beneath Levee 30. Comparisons between the methods, field data, and previous studies were made to determine the relative accuracy of the different methods. The methods evaluated in this report could serve as a valuable tool for water managers in their endeavors to restore historical flow patterns in the Everglades ecosystem.

Description of Study Site

The study site is located along Levee 30 in Miami-Dade County, Fla., and is about 6.5 mi (miles) north of Tamiami Canal (fig. 2). Levee 30, completed in 1954, is about 14 mi long and runs north-south along the eastern boundary of WCA 3B. Levee 30 canal, about 15- to 20-ft (feet) deep and 150-ft wide, parallels

Levee 30 about 50 ft to the east. Krome Avenue, a two-lane road (not shown in fig. 2), is located about 200 ft east of the canal. Water in Levee 30 canal may flow either northward or southward, depending on the status of control structures S-32A and S-337 to the north and S-335 to the south. The site is bordered by the Pennsuco wetlands to the east (fig. 2), a remnant of the Everglades located outside of the levee system that confines the water-conservation areas and Everglades National Park.

General Hydrogeology and Aquifer Characteristics

The geology and some aquifer characteristics of the study site are well defined based on previous geologic analyses (Causaras, 1987) and aquifer tests (Fish and Stewart, 1991) from wells located at the site. The surficial aquifer system underlies the study site to a depth of about 170 ft below land surface (Causaras, 1987, section A-A′, sheet 1). A section showing the hydrogeologic framework of the surficial aquifer system in central Miami-Dade County is shown in figure 3.

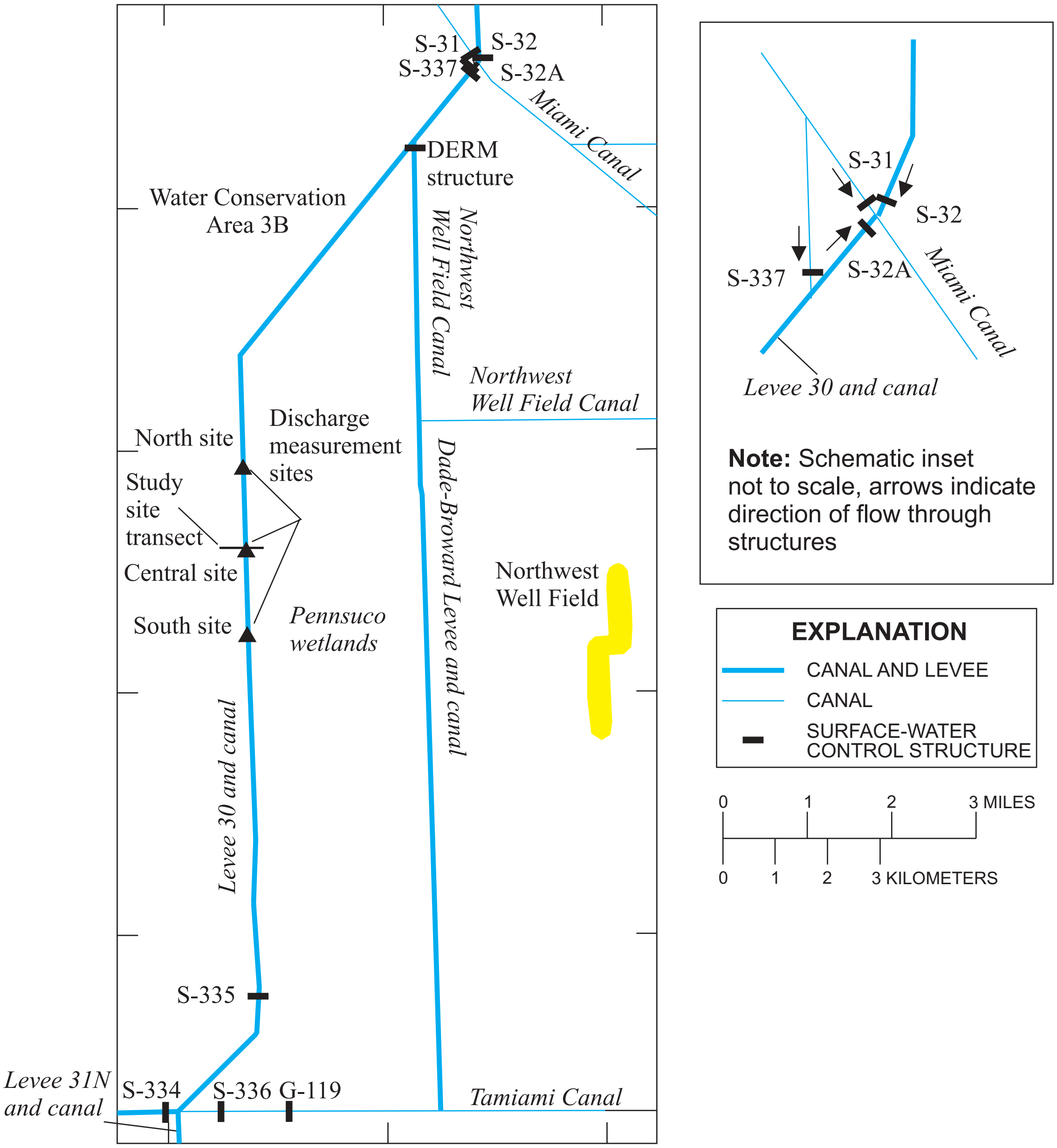

Figure 2. Study area showing study sites, primary canals, levees, control structures, and discharge measurement sites.

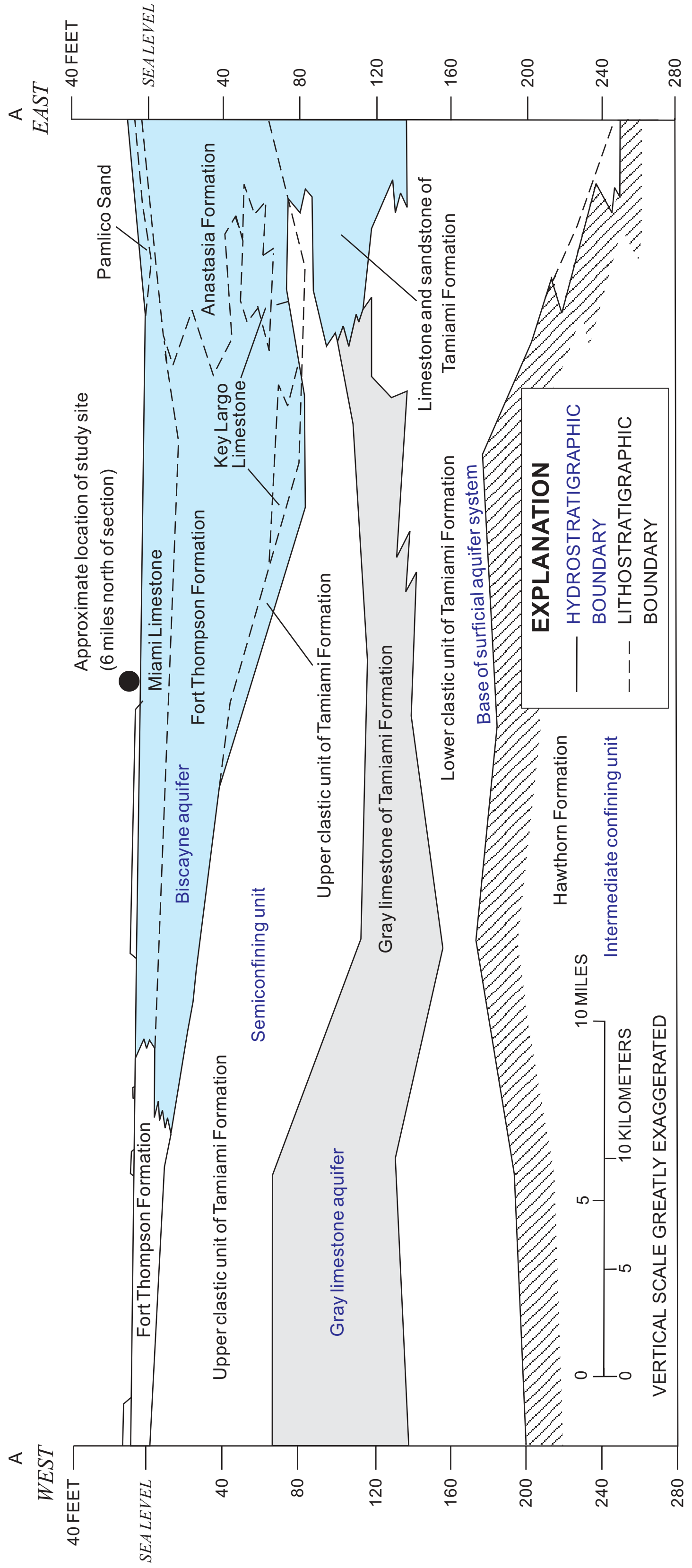

Figure 3. Geologic formations, aquifers, and confining units of the surficial aquifer system in central Miami-Dade County (from Fish and Stewart, 1991).

The unconfined Biscayne aquifer, which is the upper part of the surficial aquifer system, underlies the study site to a depth of about 60 ft below land surface. The Biscayne aquifer is composed primarily of highly permeable limestone, including (from land surface downward) the: Miami Limestone, Fort Thompson Formation, and Key Largo Limestone all of Pleistocene age and part of the Tamiami Formation of Pliocene age. In the wetland areas, a thin layer of peat overlies the Biscayne aquifer. Below the Biscayne aquifer, the surficial aquifer system consists of less permeable limestone, sand, and sandstone of the Tamiami Formation. Hydraulic conductivity was estimated to be 29,000 ft/d (feet per day) in the Biscayne aquifer and 470 ft/d in the Tamiami Formation below the Biscayne aquifer (Fish and Stewart 1991, p. 28). Regional water-table maps indicate that ground water flows from west to east, perpendicular to and beneath Levee 30 (Sonenshein and Koszalka, 1996, figs. 3 and 4). In an earlier study, the Northwest Well Field, which is located about 4 mi east of Levee 30 (fig. 2), had no influence on water levels near Levee 30 (Sonenshein and Hofstetter, 1990).

Rainfall and Control-Structure Operation

Within the study area, the Biscayne aquifer is recharged by rainfall on upland areas that infiltrates to the aquifer directly and by surface water that seeps downward through wetland sediments to the aquifer. Annual rainfall in southeastern Florida ranges from 30 to 100 in. (inches) and averages more than 60 in. (Jordan, 1984, p. 19-20). Rainfall follows a seasonal pattern; usually, about 70 percent of the annual rainfall occurs from June to October (Jordan, 1984, p. 22). Water stored in the wetlands seeps into the ground during the year, recharging the Biscayne aquifer.

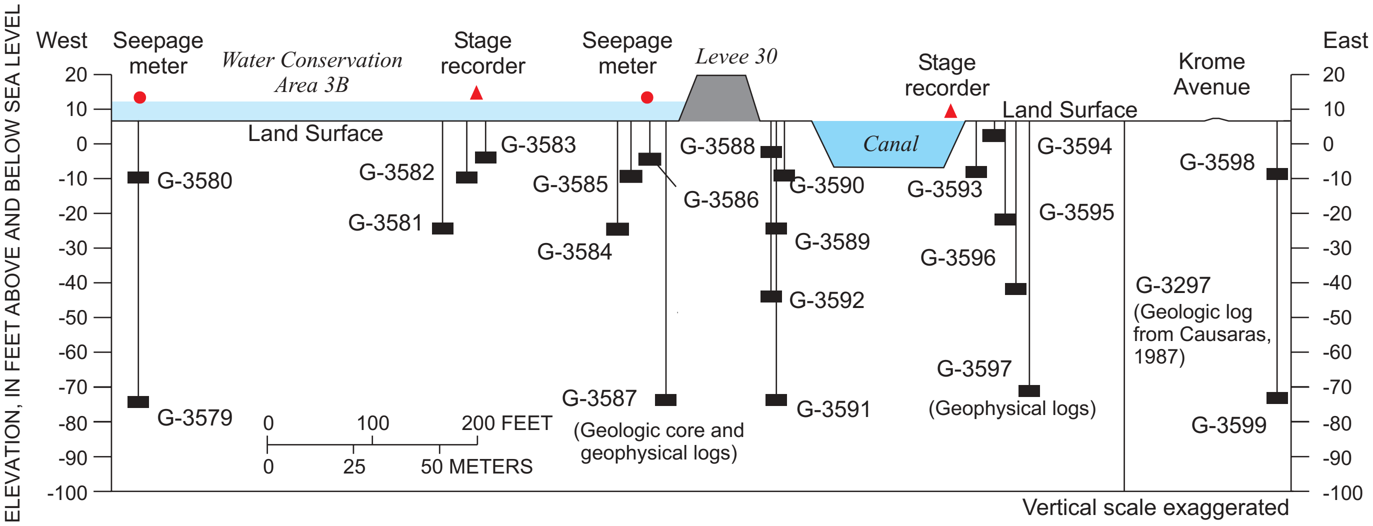

Figure 4. Transect through the central study site showing location of wells, stage recorders, and seepage meters.

Levee 30 canal was constructed to receive water that seeps beneath Levee 30. The canal is well connected to the Biscayne aquifer; however, because sediments on the bottom of the canal are less permeable (Miller, 1978), most of the water enters or leaves the canal through its nearly vertical sides. Flow in Levee 30 canal can be both northward and southward depending on the operational status of the four control structures in or adjacent to the canal (fig. 2), ground-water levels adjacent to the canal, and the location along the canal. Structure S-335, a gated spillway located about 6 mi south of the study site at the southern end of Levee 30 canal, is used to control flows into Tamiami Canal and Levee 31N canal. The Miami-Dade County Department of Environmental Resources Management (DERM) structure, a gated spillway located about 5.25 mi north of the study site, is used to control flows into the Northwest Well Field Canal to the east, but does not restrict flows in Levee 30 canal. Structure S-32A, a gated culvert located about 6.75 mi north of the study site at the northern end of Levee 30 canal, is used to control flows into Miami Canal downstream of structure S-31. Structure S-337, a gated spillway located near structure S-32A, is used to control flows into Levee 30 canal from Miami Canal upstream of structure S-31.

All structures usually are closed to prevent flooding of downstream areas and are only opened (under certain conditions) to provide water to downstream areas or to lower water levels in WCA 3B. During these periods, flow is toward the open structure (S-32A or S-335). When the gates were closed during the study period, the head difference ranged from 0.30 to 1.35 ft across structure S-335, 1.75 to 2.50 ft across the DERM structure, 2 to 4 ft across structure S-32A, and 0.8 to 2.0 ft across structure S-337. Flows in the Northwest Well Field Canal generally were between 120 and 150 ft^3/s (cubic feet per second) when the DERM structure was closed. The downstream gradient in the Northwest Well Field Canal resulted in seepage from Levee 30 canal around the DERM structure. The high head differences across structure S-32A and the DERM structure resulted in northward flow in Levee 30 canal at the study site when all four structures were closed.

Previous Studies

Several publications are available that describe the evaluation of seepage beneath levees and between canals and the Biscayne aquifer in southeastern Florida. Seepage beneath a test levee prior to construction of Levee 30 was evaluated by the U.S. Army Corps of Engineers (1952). Seepage beneath Levee 30 at its northern end was evaluated by Klein and Sherwood (1961). Seepage from Lake Okeechobee was evaluated by Meyer and Hull (1969) and McKenzie (1973). The effect of canal bottom sediments on infiltration into the Biscayne aquifer from Miami Canal was evaluated by Miller (1978). Ground-water flow beneath Levee 35A in Broward County was evaluated by Swayze (1988). Chin (1990) used data in the vicinity of Levee 31N canal and Snapper Creek Canal Extension to develop a method for estimating canal leakage to the Biscayne aquifer.

Acknowledgments

The author wishes to express appreciation to the many USGS colleagues who assisted in the project. John Goebel serviced the continuous recorders and processed the data. Robert Mooney installed the seepage meters and assisted with data collection. Steven Memberg assisted with data collection. Judson Harvey analyzed the seepage meter data. Eduardo Patino and Keith Overton obtained discharge measurements. Ronald Reese analyzed the geologic core. Gina Tillis, Sally Garson, and Lillian Ruiz-Feltman worked on the ground-water flow model and assisted with the data analysis.

DATA COLLECTION AND EVALUATION

Data collected for use in the models to estimate the seepage rate beneath Levee 30 included a geologic core, geophysical logs, vertical seepage measurements, canal discharge measurements, and continuous groundwater and surface-water-level readings. Aquifer properties were obtained from core permeability and porosity tests. The data were collected and evaluated for use in defining model boundary conditions and model input parameters and to calibrate the flow model. The data also were used as the input values for the simple application of Darcy's law.

Data Collection

A geologic core from 5 to 74 ft below land surface was obtained during the drilling of monitoring well G-3587 (fig. 4 and table 1). A lithologic log of the core was prepared (app. I), and tests were performed by Core Laboratories (1995) on 10 plugs from the core to determine permeability and porosity (app. II). Natural gamma and resistivity logs were obtained from monitoring wells G-3587 and G-3597 (app. III) using borehole geophysical tools.

Table 1. Inventory data of ground-water wells drilled for the study

[Location of wells shown in figure 4]

Well No.	Site identification number	Latitude	Longitude	Well depth (feet below land surface)	Remarks
G-3579	255130080291601	255130	802916	82	
G-3580	255130080291602	255130	802916	17	
G-3581	255130080291301	255130	802913	32	
G-3582	255130080291302	255130	802913	17	
G-3583	255130080291303	255130	802913	11	
G-3584	255130080291101	255130	802911	32	
G-3585	255130080291102	255130	802911	17	
G-3586	255130080291103	255130	802911	12	
G-3587	255130080291104	255130	802911	82	Geologic core and geophysical logs
G-3588	255130080290601	255130	802906	10	
G-3589	255130080290602	255130	802906	32	
G-3590	255130080290603	255130	802906	17	
G-3591	255130080290605	255130	802906	82	
G-3592	255130080290604	255130	802906	52	
G-3593	255130080290401	255130	802904	17	
G-3594	255130080290402	255130	802904	7	
G-3595	255130080290403	255130	802904	32	
G-3596	255130080290404	255130	802904	52	
G-3597	255130080290405	255130	802904	82	Geophysical logs
G-3598	255130080290101	255130	802901	17	
G-3599	255130080290102	255130	802901	82	

Two vertical seepage meters were installed in WCA 3B, one about 30 ft west of Levee 30 and the other about 500 ft west of the levee (fig. 4). The meters were built and operated using the cylinder method described by Lee (1977). Similar meters are being used in other areas of the Everglades (Harvey, 1996) as part of the USGS South Florida Place-Based Studies Program. Seepage measurements were made for 6 days between September and December 1996, with a collection period ranging from 1 to 4 hours.

Surface-water discharge measurements were made at three sites in Levee 30 canal (fig. 2) under various hydrologic conditions for 6 days from November 1995 to December 1996: at the transect (central study site), about 1 mi south of the transect (south study site), and about 1 mi north of the transect (north study site). Flow velocities in Levee 30 canal are very low, generally less than 0.2 ft/s (foot per second) when the gates are closed. An Acoustic Doppler Current Profiler (ADCP), which is capable of measuring very low water velocities in three dimensions (Simpson and Oltmann, 1992), was used to determine the total discharge rate at each site. The discharge rate generally was determined from the average of a minimum of three measurements made at an individual site. The ADCP has been used to measure discharges near coastal control structures in Miami-Dade County (Swain and others, 1997) and at other locations in southern Florida.

Two continuous recording surface-water-level (stage) stations and 21 continuous recording ground-water monitoring wells were installed along a transect, approximately 1,000 ft long that is perpendicular to and bisected by Levee 30 (fig. 4 and table 1). Stage recorders were installed 200 ft west of Levee 30 and in Levee 30 canal. The wells are located in six different clusters; each cluster contains two to five wells with depths ranging from 7 to 82 ft below land surface. The five 82-ft-deep wells were completed in the Tamiami Formation below the Biscayne aquifer; the remaining wells were completed in the Biscayne aquifer beneath a hard rock layer located from about 7 to10 ft below land surface. All of the wells were completed with 4-in-diameter polyvinyl chloride (PVC) casing with about 2 ft of open hole below the casing.

The wells in each cluster ideally should be aligned parallel to the levee, and in turn, be parallel to the lines of equal hydraulic head. Water-level differences between wells in a cluster then would be solely the result of vertical differences, and the Dupuit assumption could be validated. Because of the logistics of drilling, especially in the wetland areas, this well arrangement was not always feasible, with distances up to 44 ft between wells in a cluster. Thus, differences in water levels between wells within a cluster could be the result of horizontal differences, vertical differences, or both.

Float wheels and shaft encoders were installed at each surface-water station and on each well. Stage and ground-water-level data were collected hourly to the nearest 0.01 ft using electronic satellite data-collection platforms. Tapedown measurements were made every 1 to 2 months to check the recorded data. Because of the low hydraulic gradients, the data were carefully verified, and periods of questionable or unreliable data were eliminated from the final record. Data were collected over an 11-month period from February to December 1996.

An engineer’s level and leveling rod were used with standard USGS surveying procedures (Kennedy, 1988) to establish measuring point elevations at each stage recorder and well. The reference datum is the National Geodetic Vertical Datum of 1929. Accurate, relative water levels were needed for the study because of the low hydraulic gradients at the study site. Conditions at the site were not ideal for surveying to the accuracy required for the study, which was due, in part, to high water in WCA 3B and relatively large elevation changes over a short distance due to the levee. Therefore, differential levels to determine relative measuring point elevations were obtained several times during the study to verify the differences in measuring point elevations.

Data Evaluation

Data were evaluated for reliability and for their potential use in defining and delineating the ground-water flow model and the simplified Darcian approach. The subsequent sections present an evaluation of geologic and geophysical data, vertical seepage measurements, surface-water discharge measurements, and water-level data.

Geologic and Geophysical Data

Lithologic and geologic core data for well G-3587 from this study (app. I and II), lithologic data for well G-3297 from a previous study (Causaras, 1987), and geophysical borehole logs for wells G-3587 and G-3597 were used to make a comparative analysis between wells and to aid in determining the aquifer layering and properties for use in the models. The natural gamma and electromagnetic induction geophysical borehole logs for wells G-3587 and G-3597 are given in appendix III. Locations of all wells are shown in figure 4.

A comparative analysis of the lithologic and geophysical logs between wells indicated little horizontal variability in the geologic properties of the surficial aquifer system. A layer of low-permeability limestone less than 2 ft thick (fig. 5A) was present, beginning at 7 ft below land surface in well G-3587 and at 10 ft below land surface in well G-3297. The low permeability of the limestone is evident from the plug data presented in appendix II. The top surface of this low-permeability zone is a geologic disconformity, which is a result of surface exposure caused by minor sea-level regression that followed deposition (Scott, 1997, p. 67). This surface is believed to be the top of the Q3 layer of the Fort Thompson Formation (Perkins, 1977, p. 137-139). Intervals of highly permeable limestone (fig. 5B) characteristic of the Biscayne aquifer were present in well G-3587 between 10 and 74 ft below land surface, as indicated by the lithologic logs (app. I) and the permeability tests (app. II).

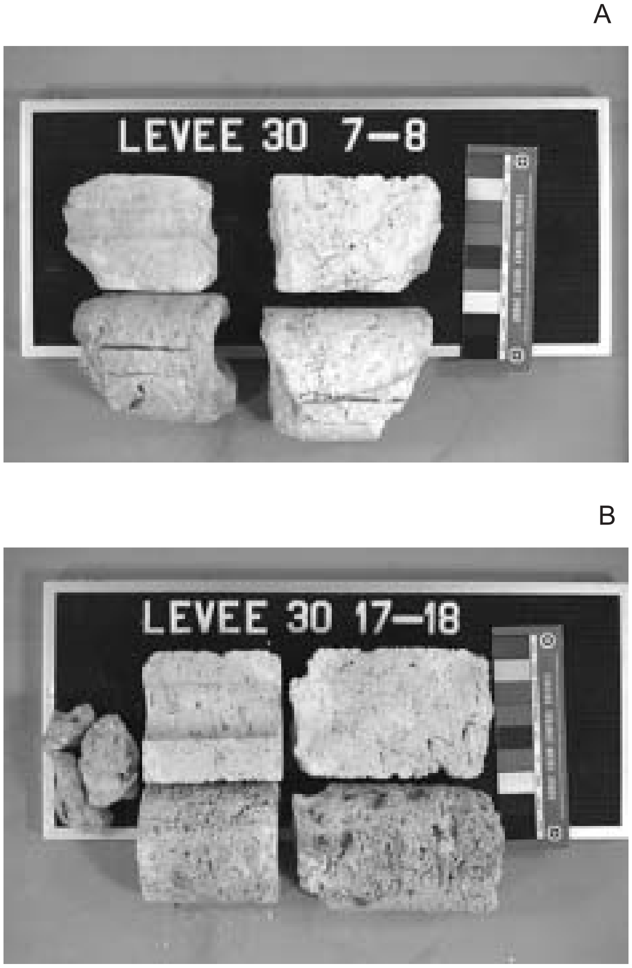

Figure 5. Rocks of Pleistocene age in well G-3587, including (A) low-permeability complex of the Fort Thompson Formation from 7 to 8 feet below land surface, and (B) highly permeable limestone of the Fort Thompson Formation from 17 to 18 feet below land surface.

Vertical Seepage Measurements

Vertical seepage data indicated that a considerable amount of water was seeping from WCA 3B into the ground water above the low-permeability limestone near the levee. The seepage rate at the east meter site (30 ft west of Levee 30) averaged five times the seepage rate of the west meter site (500 ft west of Levee 30). The seepage rate varied in time at the east and west meter sites (fig. 6 and table 2). In December 1996 when the canal control structures were open, the seepage rate increased at each site with an increase in head difference. However, the seepage rate at the west meter site on December 4, 1996, was more than double the average rate of the earlier measurements; whereas the rate increase was only 25 percent at the east meter site. Thus, the seepage rate is related to the distance from the levee and to the head difference between surface and ground water.

Surface-Water Discharge Measurements

Surface-water discharge measurements (table 2) were used to determine the rate of ground-water exchange with Levee 30 canal under various hydrologic conditions. Two factors to be considered when evaluating and using the discharge data are: (1) the number of measurements (only six sets of measurements were made), and (2) the precision of the measurements. Each discharge rate (table 2) is the average of three to five sequential measurements at a site. For the higher discharge rates, the range of values at a site can be small compared to the differences between sites. For the lower discharge rates, the range of values at a site can be large compared to the differences between sites. Although there was some consistency between the measurements, additional measurements are needed to verify some of the initial results presented in this report.

Discharge rates at the north, central, and south study sites (fig. 2) were greatest when the control structures were open, and generally increased in the direction of flow, indicating net inflow of ground water. The

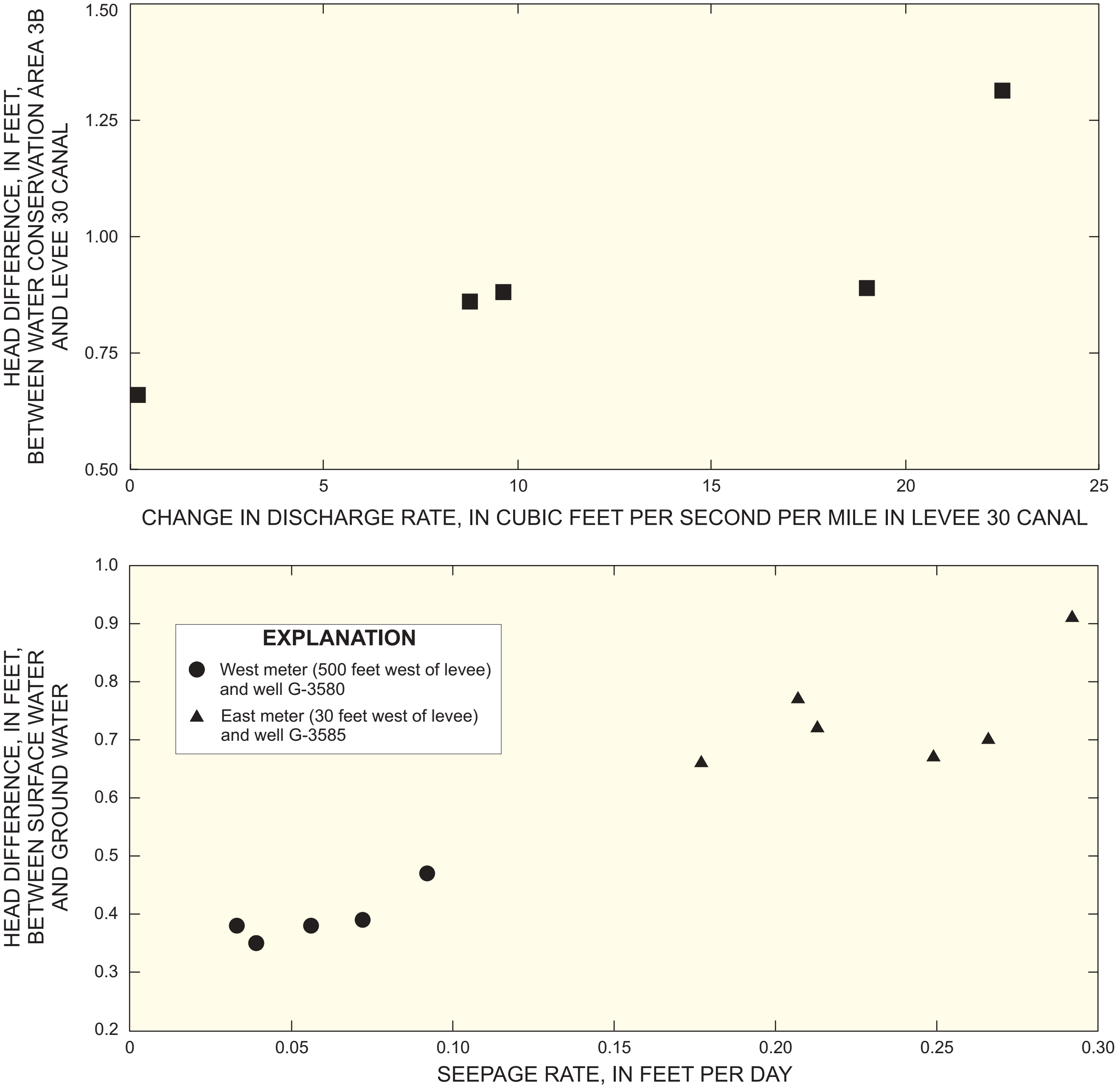

Figure 6. Relations between head difference and change in discharge rate and between head difference and seepage rate.

gate at structure S-32A was open during the first set of discharge measurements (November 7, 1995), and the gates at structures S-335 and S-337 were open during the last set of discharge measurements (December 3, 1996). Flow was to the north when the gate at structure S-32A was open and to the south when the gates at structures S-335 and S-337 were open. Flow was to the north at all three study sites during the first four sets of measurements made when the gates at the structures were closed (table 2).

The discharge rate increased in the direction of flow for all sets of measurements, except on June 6, 1996, when there was little difference in discharge rate in the canal between the three discharge measurement sites. For the other three sets of discharge measurements (February 23, 1996, September 27, 1996, and November 27, 1996) made when the gates at the structures were closed, the increase ranged from 9 to 19 ft^3/s/mi (cubic feet per second per mile). The discharge rate increased between 20 and 30 ft^3/s/mi when

Table 2. Seepage and surface-water discharge measurement data

[-- Data not collected]

Date of measurement	Discharge[1] (cubic feet per second)			Seepage rate (feet per day)		Stage (feet above sea level)		Water level (feet above sea level)			Remarks[2]
	North site	Central site	South site	West meter	East meter	Water Conservation Area 3B	Levee 30 canal	Well G-3580	Well G-3585	Well G-3588	
11-07-95	109	81	50	--	--	--	--	--	--	--	Flow to north, gates at structure S-32A open
02-23-96	38	--	19	--	--	7.87	6.99	7.55	7.24	7.18	Flow to north
06-06-96	41	40	40	--	--	7.52	6.86	7.27	7.02	6.98	Flow to north
09-23-96	--	--	--	0.056	0.266	8.49	7.58	8.11	7.79	7.73	
09-27-96	54	--	16	.039	.249	8.41	7.52	8.06	7.74	7.67	Flow to north
10-30-96	--	--	--	.033	.213	8.69	7.77	8.31	7.97	7.92	
11-27-96	27	--	9	.039	.177	8.28	7.41	7.93	7.62	7.58	Flow to north
12-03-96	-265	-282	-310	--	--	8.20	6.92	7.71	7.27	7.21	Flow to south, gates at structures S-335 and S-337 open
12-04-96	--	--	--	.092	.292	8.18	6.92	7.71	7.27	7.19	Gates at structures S-335 and S-337 open
12-16-96	--	--	--	.072	.207	8.07 8.07	7.03 7.22	7.68 7.69	7.30 7.35	7.26 7.31	Gates open at start of seepage data collection but closed during measurement. Other data collected when gates open (top data set) and closed (bottom data set)

[1] Positive discharge values indicate northward flow, and negative discharge values indicate southward flow.

[2] Gates at all structures along Levee 30 canal were closed except where noted.

the gates at the structures were open. The increase in discharge rate has a generally linear relation to the head difference between WCA 3B and Levee 30 canal (fig. 6).

The increase in discharge rate along the 2-mi canal reach that encompasses the north, central, and south study sites can be attributed primarily to ground-water inflow. The head difference between ground water at well G-3588 (near the canal) and Levee 30 canal stage during the discharge measurements ranged from 0.12 to 0.29 ft; the head difference between WCA 3B and the Levee 30 canal stage ranged from 0.66 to 1.28 ft (table 2). No rainfall events had an impact on the discharge rate before or during the six sets of discharge measurements. By comparison, Swayze (1988, p. 14) reported an average seepage rate of about 10 ft^3/s/mi in Levee 35A canal bordering WCA 2B to the north. At that site, the head difference between WCA 2B and the canal ranged from 4.8 to 6.4 ft. The higher head difference at that site is the result of lower permeabilities in the Biscayne aquifer than at the Levee 30 site.

Water-Level Data

Cross sections showing lines of equal hydraulic head (fig. 7) and based on ground- and surface-water-level measurements depict the overall ground-water flow pattern in the study area. Ground-water flow appears to be generally horizontal, except in the direct vicinity of Levee 30 canal. Ground water from the west flows into the canal near the surface, but seems to flow beneath the canal with increasing depth. Near the surface, a ground-water divide is almost always present between the canal and the easternmost monitoring wells. Ground water near the surface immediately east of the canal flows toward the canal; the remaining ground water flows to the east. The ground-water divide is east of the easternmost monitoring wells when the gate at structure S-335 is open. Because of the very low water-level gradients, interpretation of flow based on the cross sections alone is difficult.

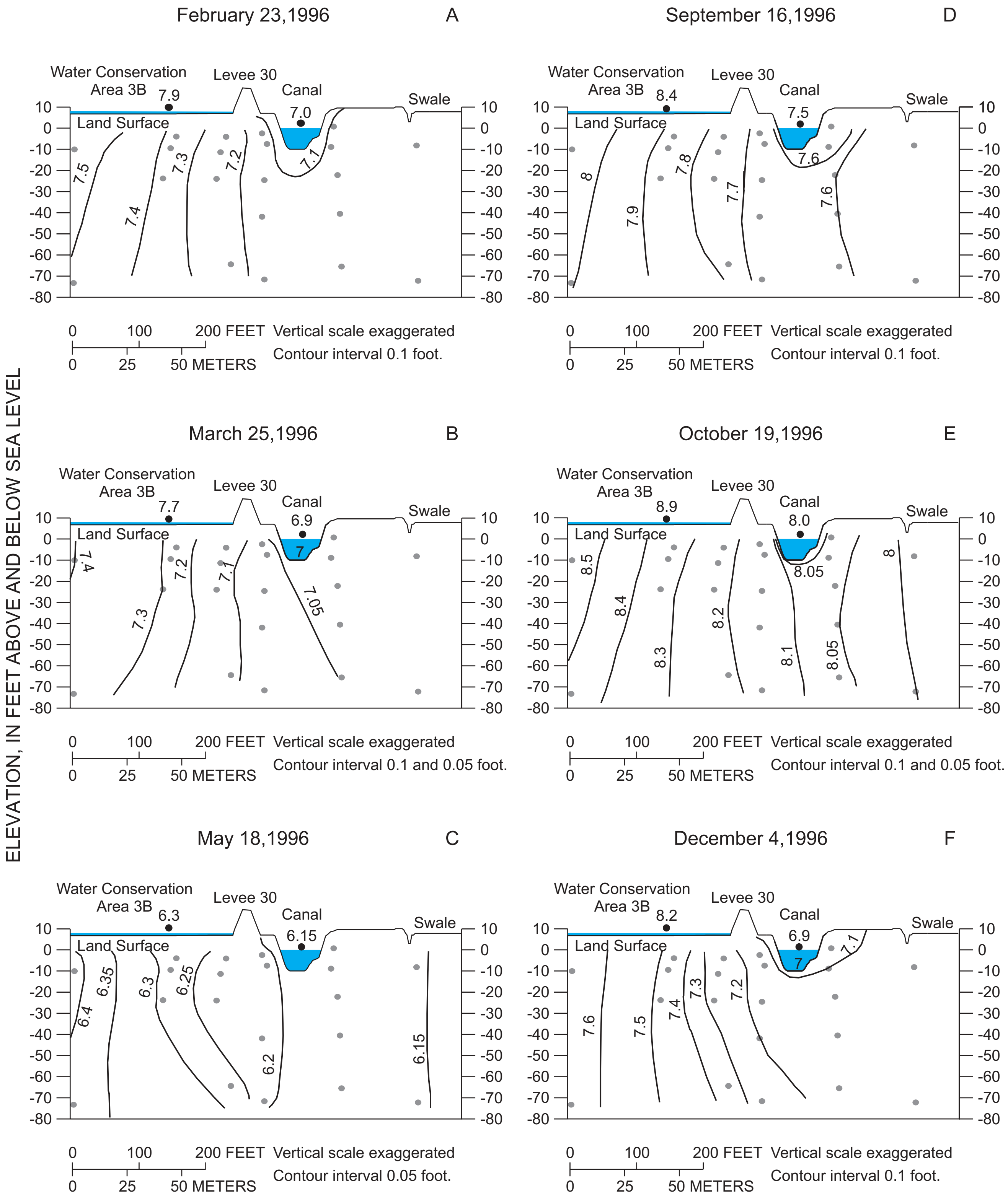

Figure 7. Lines of equal hydraulic head in the study area, February to December 1996.

A comparison of hydrographs for the surface-water stations and selected ground-water wells (fig. 8) indicates a good hydraulic connection between ground water below the low-permeability limestone and surface water. Ground-water levels rise rapidly in response to increases in the stage in WCA 3B resulting from rainfall (fig. 8). Ground-water levels also respond rapidly to changes in canal stage. When the gate at structure S-335 was open in March, April, and December 1996, the canal stage dropped rapidly (fig. 9), and seepage into Levee 30 canal increased. Consequently, ground-water levels decreased in all wells. The magnitude of the ground-water-level response decreased with distance from the canal. For example, lowering the canal stage by 0.4 ft on December 2 resulted in a 0.3-ft decline in ground-water levels at wells near the canal and a 0.15-ft drop at well G-3580, located more than 600 ft west of the canal. From March 29 to April 4, 1996, a mechanism problem caused the gate to close slowly. Thus, the canal stage gradually rose, resulting in increased ground-water levels.

Stage in WCA 3B also responds to changes in canal stage, although the response is much slower than the response of ground-water levels. When the gate at structure S-335 was open, the rate of stage decline generally was higher than when the gate was closed. This is evident in the hydrographs for March and April (fig. 9). For example, the rate of stage decline in WCA 3B increased from 0.013 ft/d to between 0.03 and 0.04 ft/d, following the opening of the gate at structure S-335 in March. When the gate was closing slowly from March 29 to April 4, 1996, the stage in WCA 3B continued to drop (even though ground-water levels were increasing), but at a lower rate of 0.01 ft/d.

Vertical head differences in the ground water below the low-permeability limestone were very small (fig. 7). The presence or absence of large differences may be attributed to the accuracy limits of the measurements and the design of the well clusters. The only

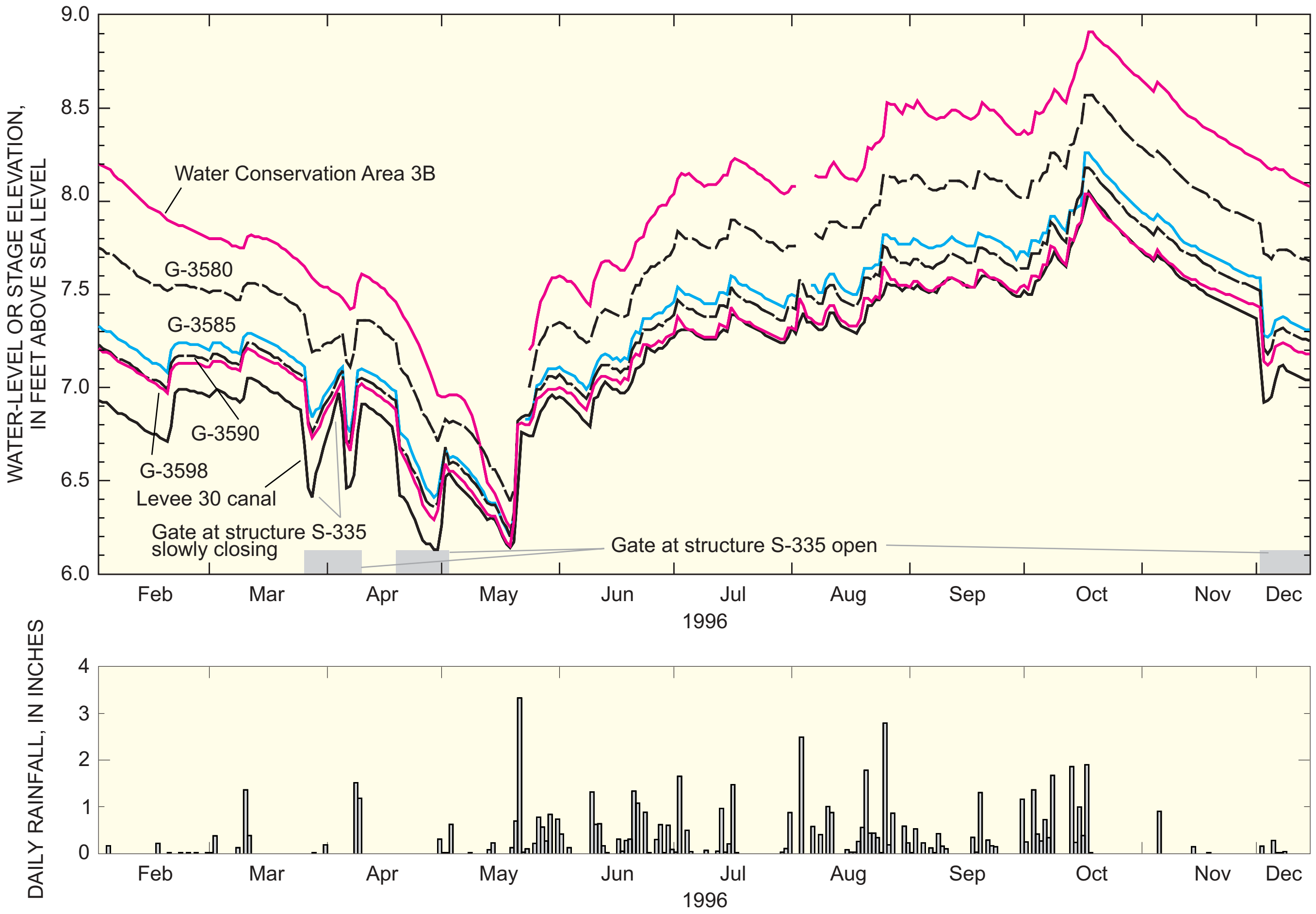

Figure 8. Water-level or stage elevation, gate openings, and rainfall for selected stations from February to December 1996.

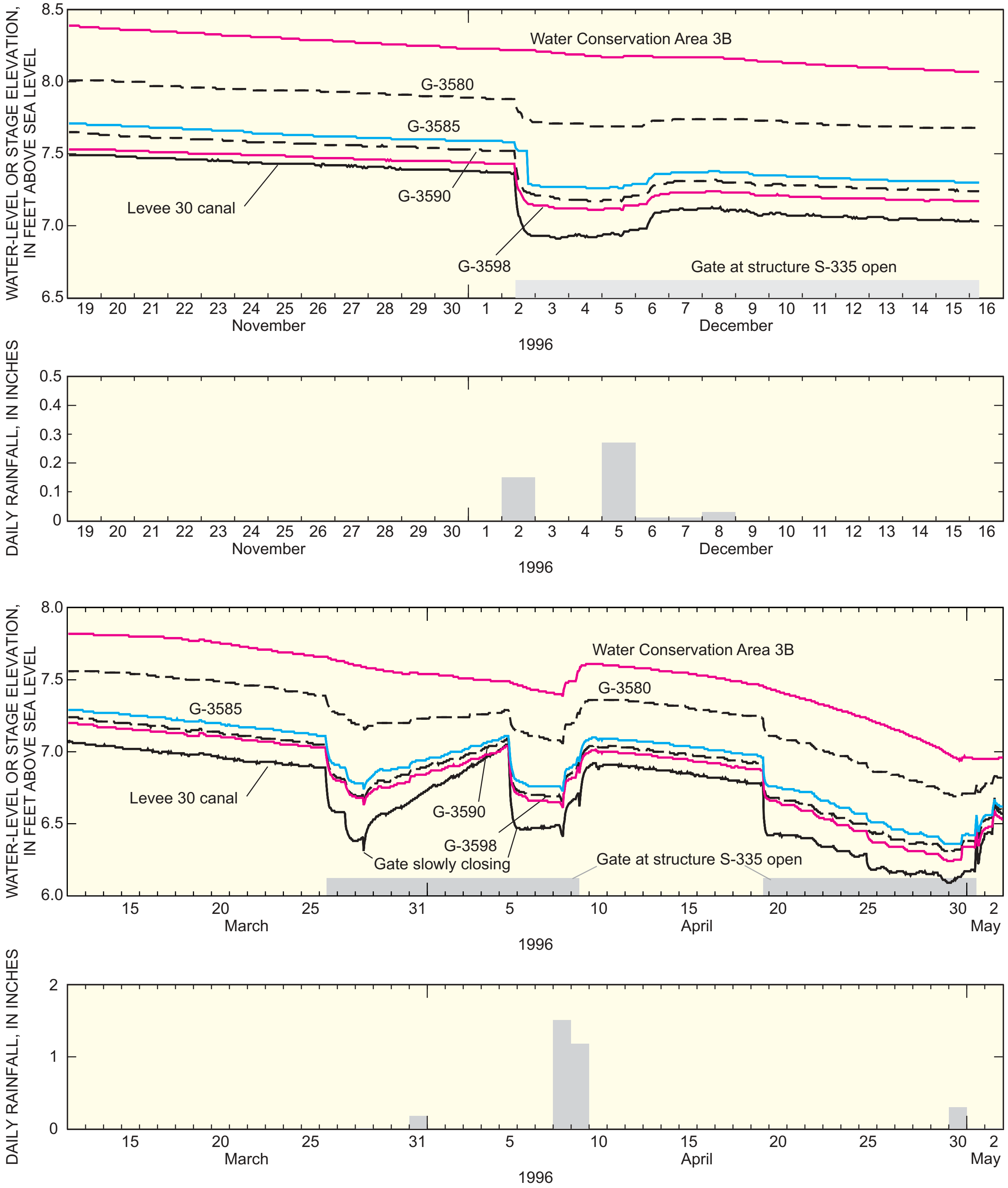

Figure 9. Water-level or stage elevation, gate openings, and rainfall for selected stations during March, April, and May 1996 and November and December 1996.

significant vertical difference greater than 0.05 ft was found within clusters west of the levee, between wells completed below the base of the Biscayne aquifer and wells completed within the Biscayne aquifer. At the westernmost well cluster, the vertical component of the gradient was always downward, and the head difference ranged from 0.02 to 0.13 ft. At the well cluster on the western side of the levee, the vertical component of the gradient was usually upward, and the head difference was greater than 0.05 ft for 22 percent of the time. This head difference may be a result of the upward gradient created by drainage into Levee 30 canal.

Vertical head differences are the controlling factor in seepage between wetland surface water and ground water. The gradient between the stage in WCA 3B and ground-water levels is a result of the low-permeability limestone at 7 to 10 ft below land surface. Differences between the stage in WCA 3B and ground-water levels (table 3) varied with time and location (fig. 10). Much of the variability at a site occurred when the stage was near land surface (May 1996) and when gates at the control structures were open. From June to November 1996, the variability was considerably less, with head differences ranging from 0.19 to 0.41 ft (between WCA 3B and well G-3580) and 0.45 to 0.75 ft (between WCA 3B and well G-3584). These head differences are substantially less than those for the entire period when differences ranged from -0.17 to 0.48 ft (fig. 10C) and -0.03 to 0.90 ft (fig. 10B). A similar relation can be found between the stage in Levee 30 canal and ground-water levels in well G-3588 (fig. 10A); head differences ranged from -0.27 to -0.10 ft (June-November) and from -0.39 to -0.04 ft (February-December).

The vertical head differences are affected by the difference in stage between Levee 30 canal and WCA 3B. Under current conditions, these differences in stage are considerably less than those measured during an earlier period in 1959-60 (Klein and Sherwood, 1961, p. 11). During 1959-60, the difference in stage ranged from 2.2 to 4.7 ft. From February to December 1996, the difference in stage ranged from 0.11 to 1.27 ft, suggesting that the vertical seepage rate is considerably less now than during the 1959-60 study.

Horizontal ground-water head differences between well clusters also varied with time (fig. 11 and table 3). Generally, the smallest mean head differences occurred in May 1996 when the stage in WCA 3B was near land surface. In some instances, the head difference was negative, indicating that the ground-water flow direction may have reversed. The values, however, were very low (less than 0.05 ft), and measurement error may have accounted for some of the negative head differences that were measured; in particular, the head differences between wells G-3584 and G-3590 located west and east of the levee, respectively.

Table 3. Vertical and horizontal head differences, February 1 to December 15, 1996

Surface-water site	Well No. or surface-water site	Vertical head difference (feet)[1]		
		Mean	Minimum	Maximum
Water Conservation Area 3B	G-3580	0.30	-0.17	0.48
Water Conservation Area 3B	G-3584	.61	-.03	.90
Levee 30 canal	G-3588	-.18	-.39	-.04
Water Conservation Area 3B	Levee 30 canal	.84	.11	1.28

Western well No.	Eastern well No.	Horizontal head difference (feet)[2]			Distance between wells (feet)	Mean horizontal water-level gradient (feet per foot)
		Mean	Minimum	Maximum		
G-3580	G-3583	0.19	0.10	0.27	313	6×10^{-4}
G-3583	G-3584	.11	.01	.19	124	9×10^{-4}
G-3584	G-3590	.07	-.02	.12	155	4×10^{-4}
G-3593	G-3598	.01	-.05	.07	262	4×10^{-5}

[1] Negative values indicate surface-water head is less than ground-water head; negative values also are given for comparison between two surface-water sites where noted. Positive values indicate the opposite.

[2] Negative values indicate east-west gradient, positive values indicate west-east gradient.

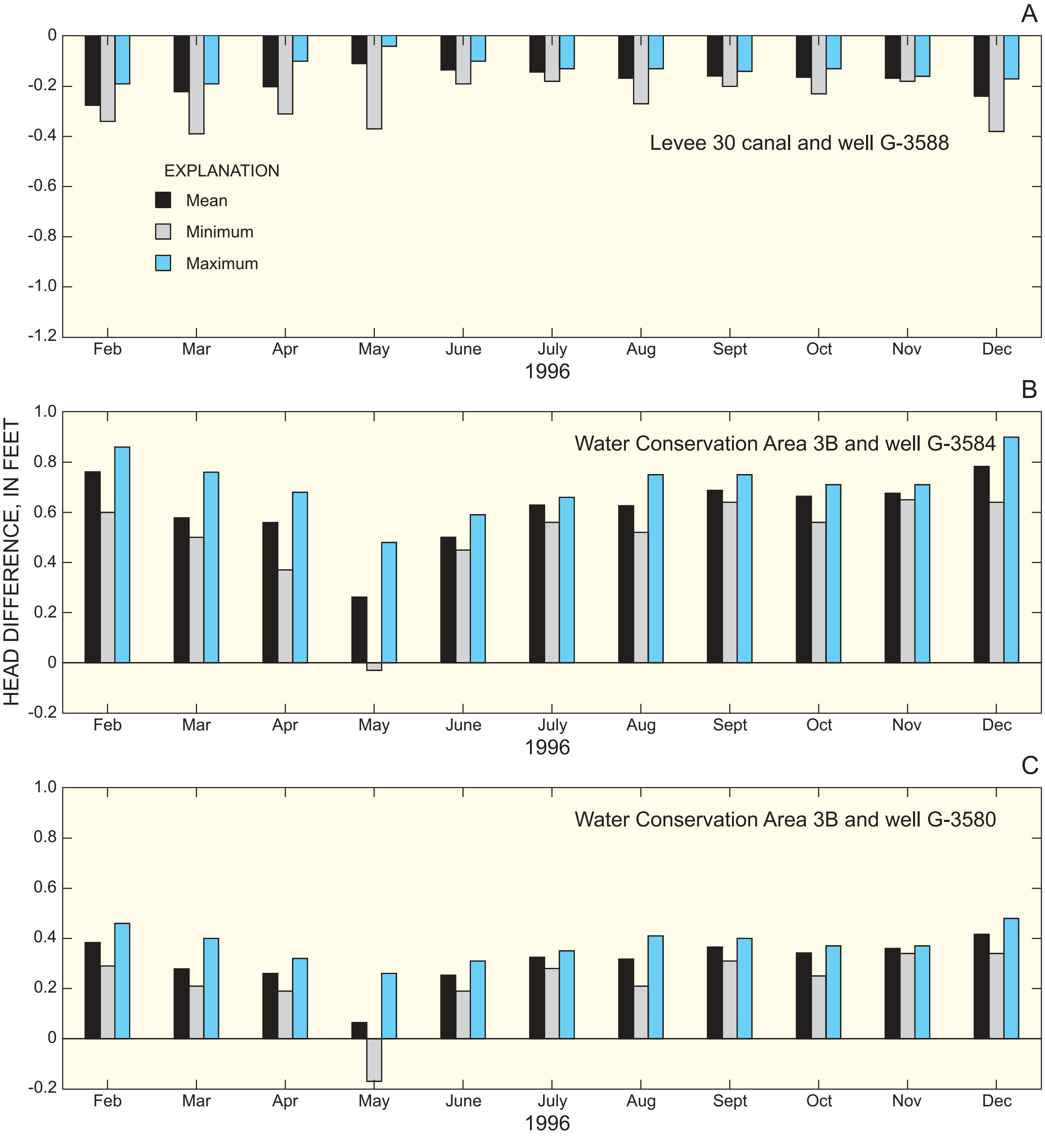

Figure 10. Average monthly vertical head differences between selected surface-water sites and ground-water wells, February to December 1996.

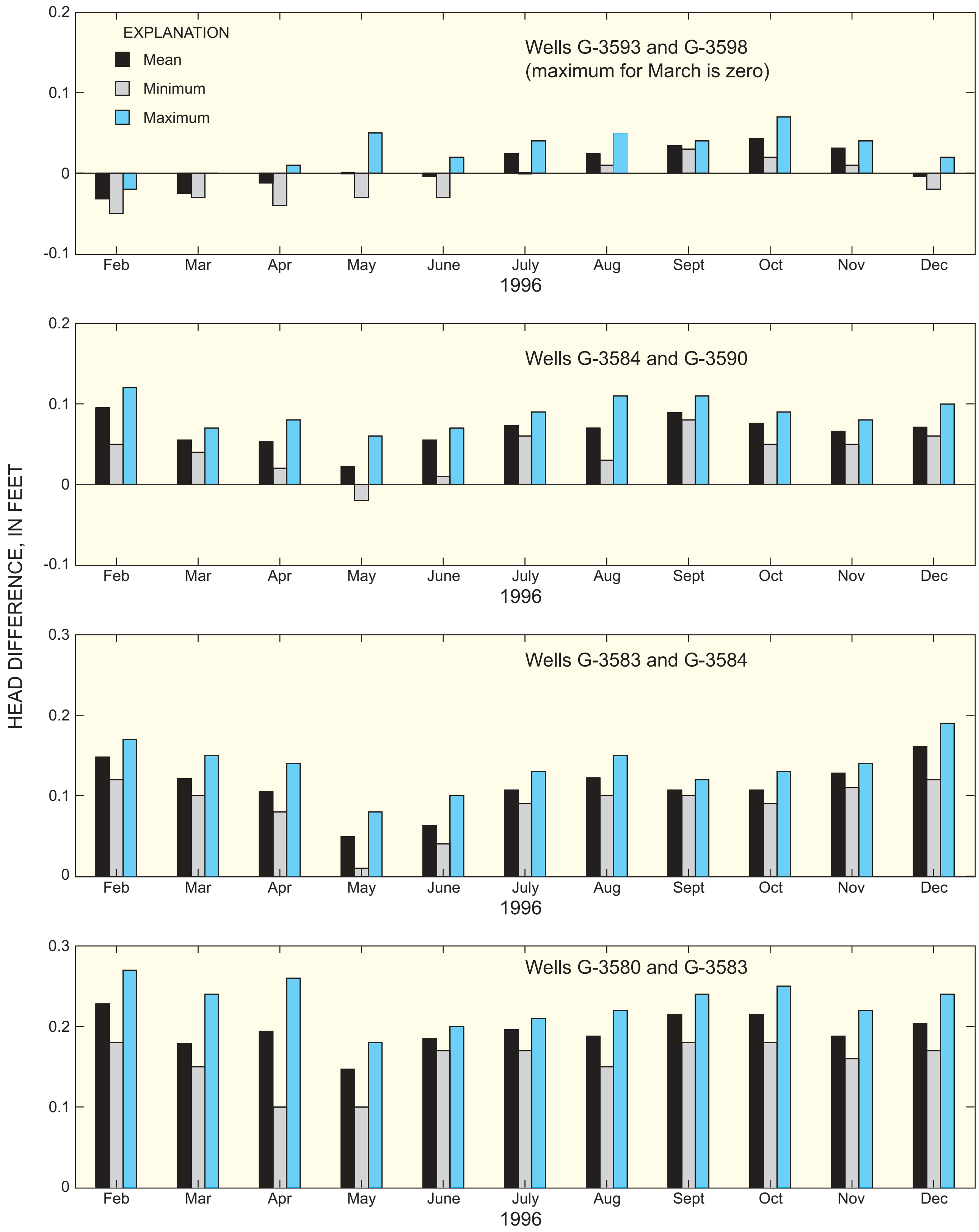

Figure 11. Average monthly horizontal head differences between selected ground-water wells, February to December 1996.

Horizontal ground-water head gradients (table 3) are a major factor in the variability in the rate of ground-water flow. The highest mean horizontal gradient was on the west side of the levee between wells G-3584 and G-3583 (table 3); the mean gradient was more than double the mean gradient beneath Levee 30 (wells G-3584 and G-3590) and about 50 percent greater than the mean gradient between the western pair of wells (wells G-3580 and G-3583). The lowest mean gradient was between wells located east of the canal (G-3593 and G-3598), with an average gradient equal to 10 percent of the average gradient beneath the levee (table 3). The variability in the mean horizontal gradient by location may be caused, in part, by the variability in the vertical gradient and seepage across the low-permeability limestone. Additional research, beyond the scope of this study, is needed to further evaluate this variability. Mean gradients west of the levee, between 6×10^{-4} and 9×10^{-4} ft/ft (feet per foot), are about equal to 10 percent of the gradient reported for 1960 (Klein and Sherwood, 1961, p. 17). This difference is consistent with the higher difference in stage between the canal and WCA 3B in 1960 compared to 1996.

QUANTIFICATION OF SEEPAGE BENEATH LEVEE 30

A numerical ground-water flow model and a simple application of Darcy's law of ground-water flow were used to quantify seepage rates beneath Levee 30 in Miami-Dade County. A description of the two approaches and a discussion of the results are described herein.

Ground-Water Flow Model

A two-dimensional, cross-sectional, finite-difference, ground-water flow model based on the USGS modular, three-dimensional, ground-water flow model code MODFLOW (McDonald and Harbaugh, 1988) was used to simulate flow in the surficial aquifer system in the vicinity of Levee 30 and seepage into Levee 30 canal. Although the surficial aquifer system in southern Florida contains layers of highly porous and dense limestone, it can be modeled as an equivalent porous medium, as previously documented through the use of aquifer tests (Fish and Stewart, 1991, p. 13-24) and through successful calibration of porous-media models of the surficial aquifer system (Merritt, 1996; Swain and others, 1996). The MODFLOW code is capable of simulating ground-water flow in anisotropic, heterogeneous, and layered aquifer systems. A block-centered, finite-difference approach is employed in the code to simulate ground-water levels and flow, using parameter specifications that quantify aquifer characteristics (transmissivity, specific yield and storage, and vertical conductance) and aquifer stresses (recharge, evapotranspiration, well withdrawals, and surface-water interactions). A cross-sectional model was used because of the relative horizontal homogeneity of the aquifer characteristics within the surficial aquifer system near Levee 30. Because of the constant-head surfaces in the wetlands and the canal and the lack of stresses on the ground-water flow system, subsurface flows are generally perpendicular to Levee 30 canal at the study site.

Steady-state simulations for 6 different days in 1996 in which flow was believed to be at steady state were made to determine the rate of ground-water flow beneath Levee 30. The six steady-state periods represented a variety of hydrologic conditions that included high and low stages in WCA 3B and high flow in Levee 30 canal resulting from the gate opening at structure S-335. Steady-state simulations were considered adequate because of relatively constant head gradients in the flow system over time. Transient conditions, such as rainfall or gate openings, may have resulted in the invalidation of the assumption of steady-state conditions. There was no rainfall within 2 days of any of the days selected for modeling. The control structures were open for 2 days prior to and during the December simulation.

The Basic package and the Block-Centered Flow package were used for the simulation model, and the General-Head Boundary and Evapotranspiration packages were used to model boundary conditions. The model was evaluated using water-level, discharge, and vertical seepage data collected during the study.

Model Grid

The cross-sectional model grid, 1,074 ft in length from west to east, consisted of 1 row, 392 columns, and 29 layers (fig. 12). The model grid contained 11,368 cells, of which 533 were inactive and 278 were constant-head cells. Locations of the easternmost and westernmost wells (fig. 4) were used to define the extent of the model. The western boundary is 500 ft west of the levee, and the eastern boundary is 286 ft east of the

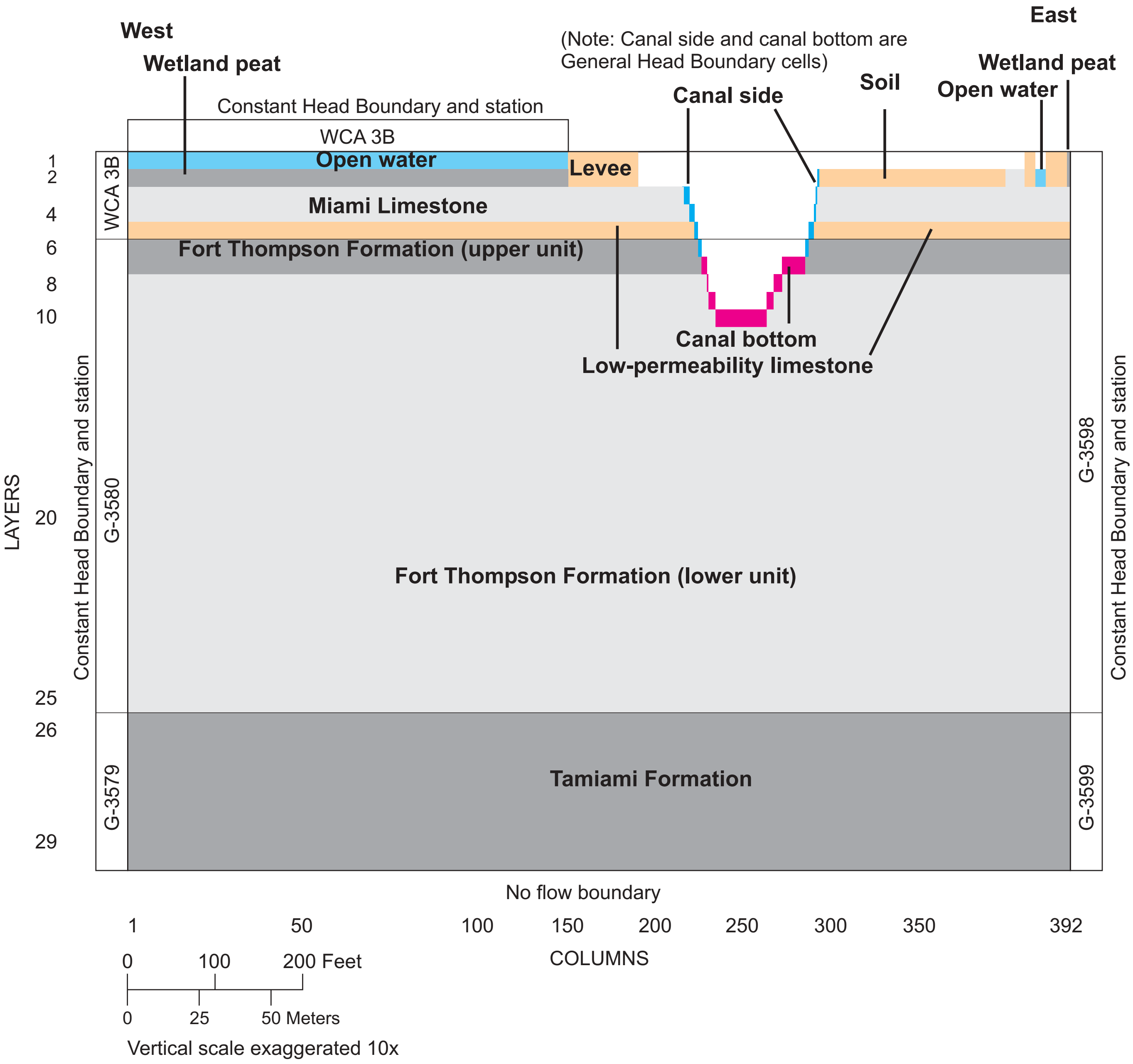

Figure 12. Model grid showing materials having characteristic hydraulic conductivities used for the model and location of model boundary cells.

canal. The water-level data from these wells were used to specify accurate boundary conditions, with the expectation that these boundaries were at a sufficient distance to avoid boundary effects in the area of interest (canal and levee). Moving the boundaries farther from the canal would have required estimating these boundary conditions. The row was 1 ft wide, the columns were 2 ft wide near the canal and levee, and 4 or 6 ft wide near the edges of the model. The thickness of the model (82 ft) was selected to encompass the Biscayne aquifer and part of the surficial aquifer system (part of the Tamiami Formation) below the Biscayne aquifer. The lower part of the model was included to determine if flow occurred between the Biscayne aquifer and the upper Tamiami Formation. The top 18 layers were 2-ft thick, the next 10 layers were 4-ft thick, and the bottom layer was 6-ft thick. Relatively smaller dimensions were used near the canal and levee in an attempt to model the relatively fine-scaled flow patterns anticipated in that part of the flow system.

Boundary Conditions

Constant-head boundaries were specified in layer 1 in WCA 3B and at both the eastern and western ends of the grid (table 4). The water surface in WCA 3B was considered spatially uniform in the study area, and stage data from the single site was used for the entire boundary. No data were available to indicate any difference between stage in WCA 3B and ground-water levels above the low-permeability limestone at the western boundary. Therefore, the stage value in WCA 3B at the western boundary was used as the constant head in the cells (wetland peat and Miami Limestone) above the thin low-permeability limestone. The water levels in the shallow wells (well G-3580 at the western boundary and well G-3598 at the eastern boundary) were used to define the constant head for the cells of the low-permeability limestone and Fort Thompson Formation. The water levels in the deep wells (G-3579 at the western boundary and G-3599 at the eastern boundary) were used to define the constant head for the cells of the Tamiami Formation at the bottom of the model. The water level in shallow well G-3598 at the eastern boundary also was used to define the constant head in the cells of wetland peat in layers 1 and 2 of the model. The bottom of the model is a no-flow boundary.

The General-Head Boundary package was used to simulate the hydraulic interaction between the canal and the aquifer. Seventy-nine grid cells, each 2 by 2 ft, were used to represent the canal (fig. 12, canal side and canal bottom cells). The General-Head Boundary package requires the use of a conductance term, which is *equal* to the hydraulic conductivity of the river bed confining material *multiplied* by the cross-sectional area of flow and *divided* by the thickness of the confining bed. The conductance value for general-head cells at the bottom of the canal was set to a relatively low value of 1 ft^2/d (square foot per day) because of the very fine grained sediment along the bottom. The conductance term for the general-head cells on the side of the canal was difficult to determine because there is little if any confining material. The hydraulic conductivity of the bed material for the cells on the side of the canal should be similar to the adjacent cell, but the thickness of the bed material is difficult to define. Therefore, the conductance value for the general-head cells on the side of the canal was used as a calibration parameter to match the model results to the measured fluxes into the canal. The final conductance value used in the model for these general-head cells was 1,000 ft^2/d, which is generally consistent with the hydraulic conductivity values of the adjacent cells. The stage value in the Levee 30 canal was used as the constant head in the cells specified in the General-Head Boundary package.

Hydraulic Properties

Lateral hydraulic conductivity values were initially assigned based on previous aquifer test data from well G-3297 (Fish and Stewart, 1991, p. 28), previous model results (Chin, 1990; Merritt, 1996; and Swain and others, 1996), and the results of the lithologic log (app. I) and the geologic core data (app. II) obtained from well G-3297. Each grid cell was associated with a particular geologic material (table 5); each grid layer generally was assigned to the same material (fig. 12).

Table 4. Constant-head boundary conditions used in ground-water flow model

Date of measurement	Surface-water stage (feet above sea level)		Water level (feet above sea level)				Remarks
	Water Conservation Area 3B[1]	Levee 30 Canal	Well G-3580 (column 1, layers 5-25)	Well G-3579 (column 1, layers 26-29)	Well G-3598 (column 392, layers 1-25)	Well G-3599 (column 392, layers 26-29)	
02-23-96	7.87	6.99	7.55	7.48	7.13	7.16	Dry season
03-25-96	7.67	6.91	7.40	7.36	7.04	7.06	Dry season
05-18-96	6.29	6.16	6.41	6.36	6.16	6.16	Dry season
09-16-96	8.45	7.54	8.07	8.01	7.54	7.54	Wet season
10-19-96	8.91	8.02	8.56	8.45	7.99	8.00	Wet season
12-04-96	8.18	6.92	7.70	7.66	7.12	7.14	Gate open

[1] Also used for column 1, layers 1-4.

Table 5. Material properties used in calibrated flow models

Material	Lateral hydraulic conductivity (feet per day)	Thickness[1] (feet)	Layer No.[2]	Remarks
Open water	1,000,000	2	1	Water Conservation Area 3B wetland layer
Open Water	1,000,000	2	2	Drainage ditch, eastern edge of model
Levee	10	4	1-2	Thickness of levee required for model
Soil	100	2	1	
Wetland peat	50	2	2	Below Water Conservation Area 3B open water
Wetland peat	50	4	1-2	Pennsuco wetlands, eastern edge of model
Miami Limestone	1,000	4	3-4	
Low permeability limestone	1	2	5	
Fort Thompson Formation (upper unit)	3,000	4	6-7	
Fort Thompson Formation (lower unit)	10,000	50	8-25	
Tamiami Formation	500	18	26-29	

[1] Thickness range given for materials with variable thickness.

[2] Some layers consisted of varying materials.

Lateral hydraulic conductivity values were assigned to each material type and then modified during the trial-and-error calibration process. Materials associated with the aquifer were assigned based on the lithologic logs obtained from wells G-3297 (Causaras, 1987) and G-3587 (app. I). Because of the fine scale grid of the model compared with the previous models, there was not always a corresponding material in the earlier models to the materials used for this study. Additionally, the previous models generally covered a much larger area, and average values for a material were used for large areas of the model. Thus, the final calibration-derived lateral hydraulic conductivities were often different than the values for similar material in the previous models.

The open water within WCA 3B and a drainage ditch on the eastern side of the model were treated as highly permeable material and assigned a calibration-derived lateral hydraulic conductivity of 1,000,000 ft/d; Merritt (1996) and Swain and others (1996) used a value of 3,000,000 ft/d. Levee, wetland peat, and soil material were all treated as relatively impermeable material and assigned calibration-derived lateral hydraulic conductivities of 10, 50, and 100 ft/d (table 5), respectively. Previous models used a value of 10 ft/d for similar material. The low permeability limestone was not modeled in earlier studies, but based on the geologic core data, the limestone was treated as nearly impermeable, with a lateral hydraulic conductivity of 1 ft/d. The Miami Limestone was assigned a calibration-derived lateral hydraulic conductivity of 1,000 ft/d, less than the 4,500 to 5,000 ft/d used by Chin (1990) and Merritt (1996) and the 5,000 to 20,000 ft/d used by Swain and others (1996). Based on the lithologic log and the geologic core data, the Fort Thompson Formation was split into an upper unit and a lower unit. The upper unit was assigned a calibration-derived lateral hydraulic conductivity of 3,000 ft/d, similar to the 500 to 5,000 ft/d used by Merritt (1996). The lower unit was assigned a calibration-derived lateral hydraulic conductivity of 10,000 ft/d, less than the 20,000 to 30,000 ft/d used in the previous models and the 29,000 ft/d estimated for well G-3297 (Fish and Stewart, 1991). The lateral hydraulic conductivity of 29,000 ft/d estimated by Fish and Stewart (1991) represents the hydraulic conductivity of the most permeable zones. The average value of lateral hydraulic conductivity used for the lower Fort Thompson

Formation is substantially lower, and thus, the calibrated value of 10,000 ft/d can be considered reasonable. The Tamiami Formation was assigned a lateral hydraulic conductivity value of 500 ft/d based on the hydraulic conductivity value of 470 ft/d estimated for well G-3297 (Fish and Stewart, 1991). Probes of the canal bottom indicated a minimum of 2 to 3 ft of very fine grained sediment along the bottom. Therefore, canal bottom sediments were treated as a nearly impermeable material. Vertical hydraulic conductivity was set equal to 10 percent of the lateral hydraulic conductivity for each cell with one exception. The horizontal conductivity and vertical conductivity were set to the same value for the canal bottom material.

Evapotranspiration

Maximum evapotranspiration rates used in the model were obtained from previous work by Merritt (1996, p. 90). The maximum evapotranspiration rates varied by month, ranging from 0.08 to 0.18 in/d (inches per day). A single evapotranspiration rate was used for each simulation, but the rate varied between simulations. The evapotranspiration was calculated in the topmost cell not specified as inactive. The elevation of the evapotranspiration surface was set to 8 ft, the top of layer one. The extinction depth was set to 8 ft, below the bottom of the lowest layer (layer three) where evapotranspiration was calculated. However, because almost half of the surface cells, including the wetland cells, were modeled as constant-head cells, it was not necessary to specify evapotranspiration rates for these cells. Evapotranspiration was between 0.5 and 2 percent of the water budget, and thus, was considered to have little effect on the model results and was not considered a critical parameter in the calibration process.

Calibration

The model was calibrated for steady-state conditions for 6 days in 1996 (table 4). All parameters were manipulated within expected values during the calibration period. The model showed appreciable sensitivity for two parameters: (1) the lateral hydraulic conductivity in the Fort Thompson Formation, and (2) the general-head boundary conductance value for the general-head cells along the sides of the canal. As previously discussed, the conductance value for the general-head cells along the sides of the canal is consistent with the hydraulic conductivity values of the adjacent cells. Therefore, only the lateral hydraulic conductivity in the Fort Thompson Formation was estimated using the model-calibration process. Because the boundary conditions constrained the ground-water levels, model output was compared with field measurements of vertical seepage from WCA 3B, ground-water inflows to Levee 30 canal, and ground-water levels.

Simulated ground-water levels were compared with measured ground-water levels at the 17 wells not used for determination of boundary conditions (table 6). The difference between the simulated and measured values was generally less than 0.05 ft. In most instances, the calibrated value was higher than the measured value.

Simulated vertical flow rates from WCA 3B to ground water were compared with the flow rates measured using the vertical seepage meters. The simulated vertical flows were calculated by dividing the model cell-by-cell flow term for a representative cell by the area of the cell. For the west seepage meter, the model-simulated value for column 17, about 60 ft east of the meter location, was used because of model boundary effects. The measured seepage rate at the west meter ranged from 0.033 to 0.056 ft/d when the gates at structures S-32A, S-335, and S-337 were closed between September and November (table 2). The simulated rates in September and October were 0.038 and 0.035 ft/d, respectively. When the gates at structure S-335 were open in December 1996, the measured seepage rate at the west meter (table 2) increased to 0.092 ft/d (table 2), and the simulated rate increased to 0.048 ft/d.

The simulated rate varied greatly from cell to cell near the east meter, with the rate increasing toward Levee 30. For example, the simulated seepage rate in September was 0.335 ft/d at the east meter (about 30 ft west of the levee), 0.195 ft/d at 20 ft west of the meter, and 0.615 ft/d at 20 ft east of the meter. The measured seepage rate at the east meter ranged from 0.177 to 0.266 ft/d when the gates at structures S-32A, S-355, and S-337 were closed between September and November (table 2). When the gates were open at structure S-335 in December, the measured seepage rate at the east meter was 0.292 ft/d (table 2), and the simulated rate was 0.445 ft/d.

Simulated inflows to Levee 30 canal obtained from the volumetric budget for the model are compared herein with the average inflows computed from the results of discharge measurements (table 7). The simulated inflows were all within the total inflow range of measured discharge. On May 18, 1996, results indicated considerably lower simulated inflow to the canal because very little water was ponded in WCA 3B. Discharge measurements were not made in Levee 30 canal to provide verification of the results.

Table 6. Measured and calibrated water-level data for the ground-water flow model

[Measured and calibrated water levels in feet above sea level, -- missing data]

Well number	Dates of measurement											
	February 23, 1996		March 25, 1996		May 18, 1996		Sepember 16, 1996		October 19, 1996		December 4, 1996	
	Measured	Calibrated	Measured	Calibrated	Measured	Calibrated	Measured	Calibrated	Measured	Calibrated	Measured	Calibrated
G-3581	7.39	7.39	7.31	7.26	6.29	6.33	7.87	7.90	8.34	8.38	7.49	7.48
G-3582	7.37	7.38	7.28	7.25	6.28	6.32	7.87	7.89	8.34	8.37	7.48	7.46
G-3583	7.36	7.37	7.23	7.24	6.26	6.32	7.86	7.88	8.32	8.36	7.46	7.45
G-3584	7.23	7.30	7.13	7.18	6.23	6.28	7.76	7.80	8.22	8.28	7.28	7.35
G-3585	7.24	7.29	7.12	7.17	6.22	6.28	7.76	7.79	8.22	8.27	7.27	7.34
G-3586	7.23	7.28	7.12	7.17	6.24	6.27	7.76	7.78	8.15	8.26	7.21	7.33
G-3587	7.27	7.27	7.12	7.16	6.29	6.27	7.79	7.77	8.23	8.25	7.38	7.31
G-3588	7.18	7.21	7.08	7.11	6.23	6.24	7.69	7.71	8.16	8.19	7.19	7.23
G-3589	7.17	7.21	7.06	7.11	--	6.24	7.69	7.71	8.16	8.18	7.18	7.23
G-3590	7.17	7.20	7.06	7.10	6.24	6.23	7.67	7.70	8.15	8.18	7.18	7.22
G-3591	7.15	7.21	7.06	7.11	6.21	6.24	7.66	7.72	8.12	8.18	7.23	7.23
G-3592	7.19	7.22	7.08	7.11	6.20	6.24	7.67	7.71	8.13	8.19	--	7.24
G-3593	7.11	7.14	7.02	7.04	6.17	6.19	7.58	7.61	8.06	8.08	7.10	7.12
G-3594	7.13	7.14	7.03	7.04	6.17	6.19	7.57	7.61	8.07	8.07	7.09	7.12
G-3595	7.13	7.14	7.03	7.05	6.18	6.19	7.59	7.61	8.06	8.07	7.14	7.13
G-3596	7.10	7.14	7.03	7.05	6.20	6.19	7.60	7.61	8.05	8.07	7.14	7.13
G-3597	7.15	7.14	7.05	7.05	6.18	6.19	7.62	7.61	8.08	8.07	7.17	7.13

Table 7. Simulated and measured ground-water inflows to Levee 30 canal

Ground-water flow model			
Date	**Total inflow (cubic feet per day per foot of canal reach)**	**Stage difference between wetlands and canal (feet)**	**Remarks**
02-23-96	307	0.88	Gates at structures closed
03-25-96	273	.76	Gates at structures closed
05-18-96	107	.13	Low water in Water Conservation Area 3B
09-16-96	203	.91	Gates at structures closed
10-19-96	185	.89	Gates at structures closed
12-04-96	432	1.26	Gates at structures open

Measured discharge	
Total inflow range (cubic feet per day, per foot of canal reach)	**Measurement condition**
139 - 311	Gates at structures closed
327 - 491	Gates at structures open

Sensitivity Analysis

The sensitivity of the ground-water flow model to changes in selected input parameters was determined using data for October 19, 1996. Because of the similarities between simulations, a sensitivity analysis was not performed for the other simulations. Based on results from the calibration process, the lateral hydraulic conductivity in the Fort Thompson Formation was determined to have a substantial impact on the estimated seepage beneath Levee 30. The lateral hydraulic conductivity in the Fort Thompson Formation was doubled and halved for the sensitivity analysis. The variables used for analysis were ground-water levels, ground-water inflows to the canal, and total flow entering and leaving the model domain. There was no effect on the vertical flow from WCA 3B.

Ground-water levels were insensitive to parameter changes and showed a maximum variation of 0.03 ft for each sensitivity simulation. (Ground-water levels are insensitive to parameter changes because the model is constrained by constant-head boundary conditions on three sides.) Ground-water inflows to Levee 30 canal increased and decreased by 24 percent when the lateral hydraulic conductivity in the Fort Thompson Formation was doubled or halved, respectively. The total volumetric flow budget increased by 60 percent when the lateral hydraulic conductivity value in the Fort Thompson Formation was doubled and decreased by 34 percent when the value was halved.

Model Results

The simulations were analyzed based on the variation in total horizontal ground-water flow in the model layers above the Tamiami Formation (table 8, layers 3-25), in vertical seepage from WCA 3B (table 8, columns 17-150), and in ground-water flow to the canal. During the dry-season simulations in February and March 1996, the horizontal ground-water flow on the western side of Levee 30 was 320 and 280 ft^3/d (cubic feet per day), respectively, compared to 25 and 15 ft^3/d, respectively, on the eastern side of the model.

Table 8. Horizontal flow rates in the ground-water flow model and the Darcian approach at selected locations and vertical flow from Water Conservation Area 3B calculated by the ground-water flow model

[-- Incomplete water-level data, flow not calculated]

Date	Total horizontal flow (cubic feet per day)[1]							Ground-water flow model	
	Ground-water flow model (layers 3 to 25)			Darcian approach[2]				Total ground-water flow to Levee 30 canal (cubic feet per day)	Total vertical flow from Water Conservation Area 3B[6] (cubic feet per day)
	440 feet west of levee (column 16)	Western side of levee (column 150)	200 feet east of canal (column 370)	West to central sites[3]	Central to east sites[3]	Beneath levee[4]	East of canal[5]		
02-23-96	280	320	25	310	470	260	-20	305	45
03-25-96	245	280	15	190	560	240	-30	270	35
05-18-96	150	150	65	160	320	--	30	85	5
09-16-96	295	340	140	380	340	330	70	200	45
10-19-96	310	355	170	410	360	270	140	185	45
12-04-96	390	450	30	410	680	350	20	430	60

[1] Positive flow is from west to east, and negative flow is from east to west.

[2] Analytical flow calculated using a 60-foot section equivalent to ground-water flow model layers 3 to 25. Selected analytical model properties are given below. No flow is assumed for layers 3 to 5, except for beneath the levee.

[3] West site is represented by well G-3580; central site is represented by wells G-3581, G-3582, and G-3583; and east site is represented by wells G-3584,G-3585, and G-3586.

[4] Beneath levee is represented by Water Conservation Area 3B and Levee 30 canal and wells G-3584, G-3585, and G-3586 (east site) and by wells G-3588, G-3589, and G-3590 (eastern side of levee).

[5] East of canal is represented by wells G-3593, G-3594, G-3595, and G-3598.

[6] Row 1, columns 17 to 150.

[7] No flow assumed for layer 5.

Model layers	Thickness (feet)	Lateral hydraulic conductivity (feet per day)	Site used for water level				
			Western side of levee			Eastern side of levee	East of canal
			West site	Central site	East site		
3-4	4	1,000	See footnote 4		Water Conservation Area 3B	Levee 30 canal	See footnote 4
5	2	1	See footnote 7		See footnote 7	See footnote 7	See footnote 7
6 - 7	4	3,000	G-3580	G-3583	G-3586	G-3588	G-3594, G-3598
8 - 18	22	10,000	G-3580	G-3582	G-3585	G-3590	G-3593, G-3598
19 - 25	28	10,000	G-3580	G-3581	G-3584	G-3589	G-3595, G-3598

Vertical seepage from WCA 3B east of the model boundary accounted for about 13 percent of the total horizontal flow (table 8). Ground-water inflow to Levee 30 canal was equal to about 95 percent of the total ground-water flow in model layers 3 to 25 on the western side of Levee 30. The simulated flow paths (fig. 13) show the movement of ground water. All ground water above the low-permeability limestone and some ground water in the Fort Thompson Formation are discharged to Levee 30 canal. Some ground water above the low-permeability limestone east of Levee 30 canal also is discharged to the canal.

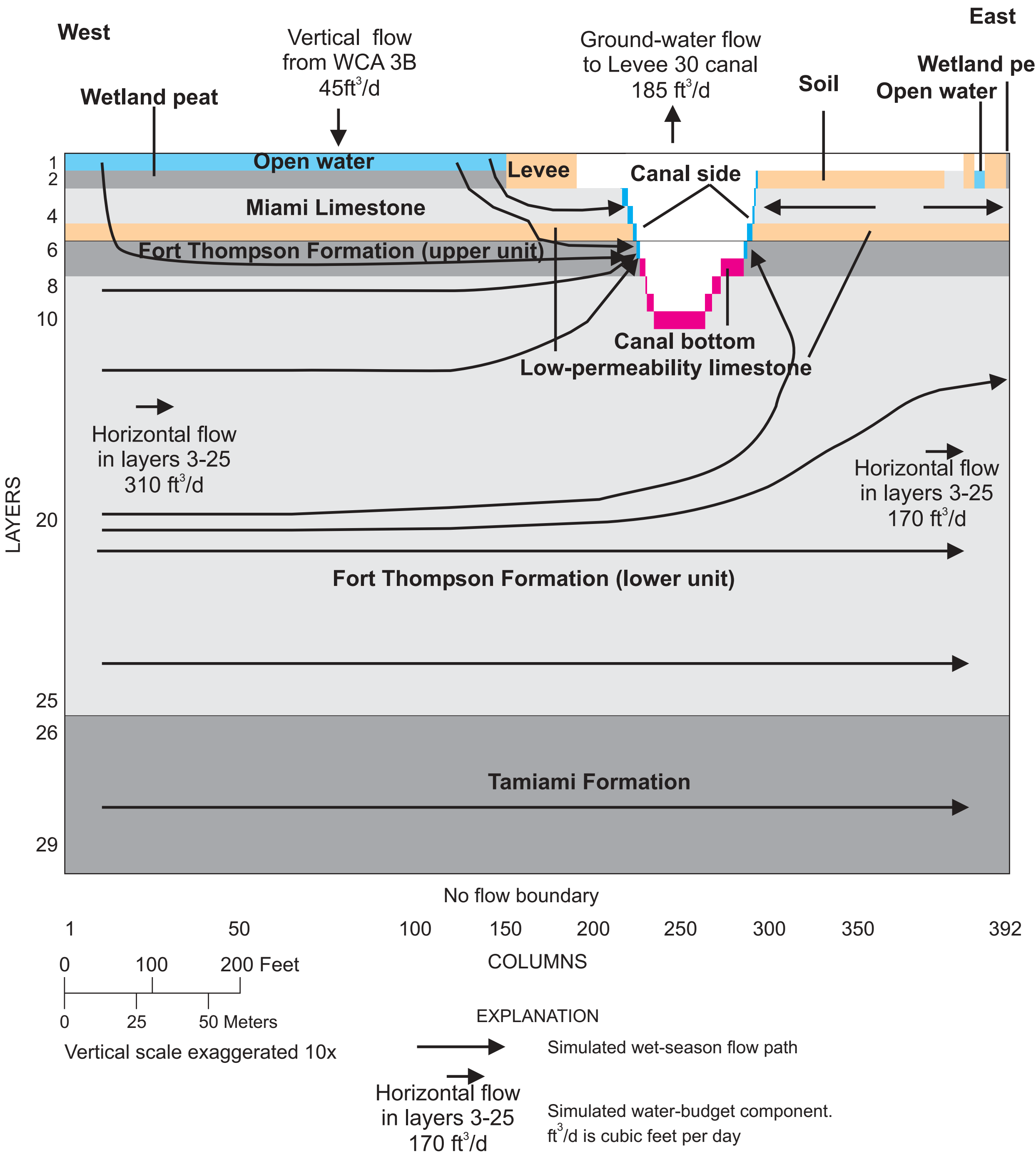

Figure 13. Model grid showing simulated wet-season flow paths and the water budget for the October 19, 1996 simulation.

During the dry-season simulation in May 1996, the horizontal ground-water flow was about half the flow as the earlier simulations. Lower flow in May occurred because there was almost no ponded water in WCA 3B, resulting in vertical seepage of only 5 ft^3/d. Ground-water inflow to Levee 30 canal was equal to about 57 percent of the total ground-water flow in model layers 3 to 25 on the western side of Levee 30.

The horizontal ground-water flow on the western side of Levee 30 was higher during the wet-season simulations in September and October 1996 (340 and 355 ft^3/d) than during the dry-season simulations in February and March 1996 (320 and 280 ft^3/d). The ground-water flow on the eastern side of the model in September and October 1996 was about 45 percent of the flow on the western side of the levee (table 8). Vertical seepage from WCA 3B east of the model boundary accounted for about 14 percent of the total horizontal flow in February, March, September, and October. Ground-water inflow to Levee 30 canal was equal to about 95 percent of the total ground-water flow in model layers 3 to 25 on the western side of Levee 30 during the dry-season simulation, but only 55 percent during the wet-season simulations.

Horizontal ground-water flow was highest (450 ft^3/d) on the western side of Levee 30 in December 1996 when the gates at the control structures were open (table 8). Ground-water flow was about 95 percent lower on the eastern side of the model, which is similar to the February and March 1996 simulations. Vertical seepage from WCA 3B east of the model boundary was also highest in December 1996 (table 8), but still accounted for less than 15 percent of the total horizontal flow. Differences in flow between December and the other periods were a result of the higher gradients between ground-water levels and the canal stage caused by the gate openings of the control structures. Ground-water inflow to Levee 30 canal was equal to almost 95 percent of the total ground-water flow in model layers 3 to 25 on the western side of Levee 30.

Simplified Darcian Approach

An analytical approach based on a simple application of Darcy's law (Heath, 1987, p. 12) was used to determine the approximate flow rate in the Biscayne aquifer between pairs of monitoring wells from February to December 1996 (fig. 14). Darcy's law is expressed by $Q = K\left(\frac{\partial}{\partial x}\right)hA$, where Q is the flow rate in the aquifer, K is the hydraulic conductivity, $\left(\frac{\partial}{\partial x}\right)h$ is the hydraulic gradient, and A is the cross-sectional area at a right angle to the flow direction through which flow occurs. The primary assumption of this approach is that flow is horizontal and vertical flow is negligible (Dupuit-Forcheimer assumption). In fact, the ground-water head may vary with depth at the study site, particularly in the vicinity of the levee and canal, indicating vertical flow. The analytical model, however, can still provide approximate values for the flow rate at points in the aquifer where the effects of Levee 30 and its canal are believed to be minimal.

The approximate flow rate was determined using the gradients for four cross sections – two sections on the western side of Levee 30, one section beneath the levee, and one section east of Levee 30 canal (table 8). A 60-ft-thick section, equivalent to ground-water flow model layers 3 to 25, was used in the calculation. Hydraulic conductivity values from the calibrated flow model were used. Flow was calculated in each layer using water-level data from representative wells (table 8). Lateral flow in layers 1 to 3 was considered negligible because of the low horizontal hydraulic conductivity and because flow was generally vertical in these layers, especially beneath WCA 3B.

The highest flows simulated with the analytical model generally were found between the central and eastern sites on the western side of the levee (fig. 14). The difference between flows at this section and the section to the west was greatest during the dry-season period from February to April 1996. Total flows decreased in sections to the east. The lowest simulated flows were east of the canal, as would be expected if the canal were acting as a drain. During the dry-season period from February to April 1996, these flows remained relatively close to zero or were negative, indicating water flowing from east to west.

Because there are no sinks in the flow system beneath the levee, the decrease in flows beneath the levee can only be explained if vertical flows toward the canal are substantial; vertical flows are not accounted for in the analytical model. As described earlier, vertical differences in measured ground-water levels were minimal. Because of the high hydraulic conductivity, however, ground-water gradients coming from differences in ground-water levels below the detection limits of the monitoring equipment can result in substantial ground-water flows.

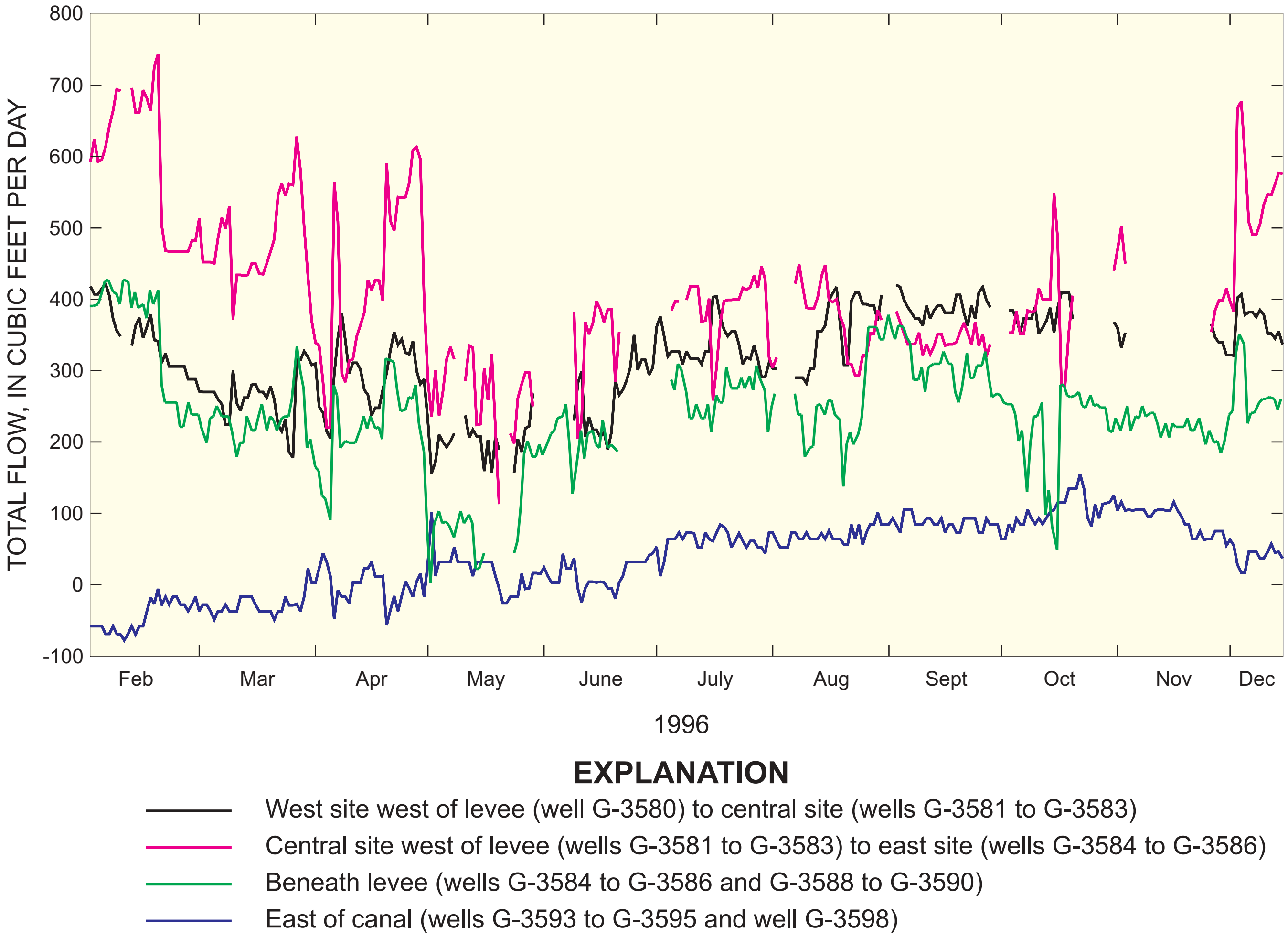

Figure 14. Horizontal flows computed with the analytical approach, February to December 1996.

EVALUATION OF METHODS TO QUANTIFY SEEPAGE

Results from the ground-water flow model illustrate the non-uniqueness problem encountered when attempting to solve the ground-water flow equation $\left(Q = K\left(\frac{\partial}{\partial x}\right)hA\right)$. In the analysis presented in this report, there are two unknown variables in the equation: the flow rate in the aquifer, Q, and the hydraulic conductivity K. By placing constant-head boundaries on three sides of the model, the horizontal gradient, $\left(\frac{\partial}{\partial x}\right)h$, is constrained. Q is proportional to K, and thus, any combination of Q and K could match a measured head gradient in the flow model. Thus, it is possible to match a measured head gradient by adjusting Q or K. Because K cannot be measured exactly and no horizontal aquifer flow data, Q, are available for calibration, it is difficult to accurately determine the horizontal flow rates using this ground-water flow model. The range of values used for the lateral hydraulic conductivity in the Fort Thompson Formation in the sensitivity analysis, however, is representative of the range of values obtained from the aquifer test data from well G-3297 and generally used in modeling the Biscayne aquifer.

The use of constant-head boundaries on three sides of the model also constrains the model solution for ground-water levels. For example, the parameter with the largest effect on the horizontal flow rate based on the sensitivity analysis, lateral hydraulic conductivity in the Fort Thompson Formation, had little effect on the ground-water levels used to calibrate the model. If heads had not been specified for the wetland layer in WCA 3B, then an additional unknown would have been added to the equation, the net vertical recharge at this boundary, a combination of recharge and evapotranspiration. Vertical recharge rates were measured at several locations and compared favorably with model-calculated rates. Constraining the model using specified head boundaries eliminated the need to include estimates of recharge and evapotranspiration rates in the model data sets.

Another limitation of the ground-water flow model is the methodology and assumptions made in determining the flow rate from the aquifer into the canal. Because flows to the canal are a major part of the total water budget in the model, it is important to estimate these values as accurately as possible during model calibration. Flow measurements were made at 1-mi intervals in the canal; therefore, estimates of seepage values based on measured data were uniform in each reach. Additionally, the velocities generally were very low (less than 0.2 ft/s) and difficult to measure accurately, even with the ADCP equipment that was used for the study. Ideally, measurements would have been made at intervals less than 1 mi, but the variation in flow rate generally was not great enough to measure accurately at a smaller interval.

Results based on the numerical model and the Darcian approach (table 8) generally were in agreement for flows on the western side of the levee. The flows east of the canal, however, differed considerably between the two methods. The flows calculated with the ground-water flow model ranged from 1.2 to 2 times the flows calculated with the Darcian approach. During periods of lower flow in February and March 1996, the flows calculated using the Darcian approach were toward the canal, in the opposite direction of the flows calculated with the ground-water flow model. Because of the flat water-level gradient east of the canal, the water-level differences cannot be measured accurately enough to use in the analytical model over the short distance between the well sites used for the analytical model.

Results of this study were compared with those from previous studies. Stallman (1956, p. 20), estimated seepage at 1,600 ft^3/d/ft (cubic feet per day per foot), equivalent to 97 ft^3/s/mi for a 1-ft head difference from WCA 3B to Levee 30 canal using an electric analog model. Stallman's results were determined to be much higher than those measured for this study, with most of the seepage occurring within 200 ft of the levee. Analytical models (Stallman, 1956, p. 21) using lower vertical permeability resulted in values as low as 390 ft^3/d/ft (24 ft^3/s/mi), which were within the range of results obtained for this study. Klein and Sherwood (1961, p. 22) used field data collected at a site near the northern end of Levee 30 and calculated a flow of 8,800 ft^3/d/ft (540 ft^3/s/mi) into the canal for a 10-ft head difference. Thus, assuming a linear relation for a 1-ft head difference, seepage into the canal would be 880 ft^3/d/ft, which again was determined to be much higher than the results for this study. In an earlier study conducted at Levee 35A in WCA 2B, Swayze (1988) used water-budget and analytical approaches to calculate an underflow of 36 x10^6 ft^3/d for the entire 15.6-mi levee or about 440 ft^3/d/ft of levee for a 5.6-ft head difference. This included a loss to Levee 35A canal of 15.7 x 10^6 ft^3/d for the entire levee or 190 ft^3/d/ft of levee.

A small-scale test levee (400-ft long) investigation by the U.S. Army Corps of Engineers (1952) near Levee 30 resulted in a calculated loss of about 110 ft^3/d/ft (7 ft^3/s/mi) for each foot of head difference between the ponded surface water and the canal. Although the small scale of the test makes it difficult to relate to the study area, the results are similar to those of the present study.

Based on the results of this study as well as previous studies, additional data are needed to more accurately determine both the total ground-water seepage rate beneath Levee 30 and the source of the ground-water flow. Borehole flow-meter measurements can be used in uncased boreholes to determine the rate and direction of vertical flow in the ground water. Horizontal flow rates may be measured using a tracer test and estimates of aquifer porosity. A tracer study was successfully used in Cape Cod, Mass. (LeBlanc, and others, 1991), using an array of closely spaced multilevel samplers to map the movement of an induced tracer. Finally, data are needed farther than 500 ft west of Levee 30 to determine an accurate water budget for WCA 3B. The vertical seepage rate throughout WCA 3B, the lateral extent of influence of Levee 30 canal on the vertical seepage rate, and the direction of ground-water flow throughout WCA 3B were not determined from the data collected nor the modeling results. Also unknown is the extent of the low-permeability limestone and the resulting vertical gradient between the ponded water in WCA 3B and the ground water beneath the low-permeability limestone.

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APPENDIXES

Appendix I. Lithologic log of well G-3587

[L30-80, site 9, site identification number 255130080291104, prepared by Ronald S. Reese, well completed March 1995, land-surface elevation (approximate) - 6 feet above sea level]

Geologic unit and Quaternary subaerial exposure surface (Perkins, 1977)	Depth (feet below land surface)	Lithology	Grain size	Permeability estimate	Porosity type	Description
Q4		No recovery	NO DATA			Muck
Miami Limestone	5.0 - 6.0	Calcarenite or grainstone	Fine	Moderate	Moldic fine to very fine	Limestone, gray with whitish patches, oolitic with fossil fragments, ooids dissolved out, some large vugs filled with muck toward the top
Q4	6.0 - 7.0	No recovery	NO DATA			
Q3	7.0 - 7.5 (fig. 5A)	Limestone	Fine	Very low	None to vuggy	Limestone, grayish pink, very dense, well cemented, some fine quartz grains, some dissolution cavities
	7.5 - 9.0	Sandy limestone	Fine	Low	Intergranular with pinpoint vugs common	Limestone to sandstone, grayish white; well sorted, rounded quartz grains common to predominant, root zone structure
	9.0 - 10.0	Limestone	Fine	Moderate to high	Abundant small vugs	Limestone, gray, mottled, becomes broken at base (may be bioturbated), calcarenitic
	10.0 - 10.5	Limestone, freshwater shells	Clay	High to very high	Large irregular vugs	Limestone, gray to grayish brown, fossils common in dense matrix, including small gastropods, micritic
	10.5 - 12.0	No recovery	NO DATA			
	12.0 - 13.5	Limestone, freshwater shells	Clay	Low to moderate	Moldic with some vugs	Limestone, gray to grayish brown, fossiliferous, clayey, abundant gastropod molds
	13.5 - 14.0	Limestone	Clay	Very low to low	Some pinpoint to small vugs	Limestone, grayish white, dense, micritic, crystal lined vugs, root zone structures, grades down into
Fort Thompson Formation	14.0 - 16.0	Calcarenite and sandy limestone	Fine	Low to high	Intergranular	Limestone, gray, calcarenite, quartz sand common in places, churned appearance in places, becomes more broken toward base, oolitic(?), lost circulation at 14 to 15 feet
	16.0 - 17.0	No recovery	NO DATA			
	17.0 - 18.0 (fig. 5B)	Limestone, marine shells	Coarse	High	Abundant moldic and intergranular	Limestone, gray to brownish gray, fossil coquina, abundant moldic porosity, gastropods and scallops
	18.0 - 20.0	Limestone, freshwater shells	Clay	Moderate	Vugs, some large	Limestone, dark-gray to gray, massive to mottled, fossiliferous (large gastropods), large vertical burrows(?), vugs may not be well connected, clayey, micritic, some silt and fine sand
	20.0 - 20.5	Calcarenite	Fine	Moderate	Intergranular	Limestone, brownish gray, calcarenitic, fine grained, micritic, abundant gastropods and clams
	20.5 - 22.0	No recovery	NO DATA			
Q3	22.0 - 22.5	Calcarenite	Clay	High	Vertical vugs common	Limestone, mottled light-gray with dark-gray patches, vertical or near vertical dissolution features common with infilling of dark-gray material as above (18-20 feet), matrix is light-gray with fine calcarenite, may be some root zone structure

Appendix I. Lithologic log of well G-3587--(Continued)

[L30-80, site 9, site identification number 255130080291104, prepared by Ronald S. Reese, well completed March 1995, land-surface elevation (approximate) - 6 feet above sea level]

Geologic unit and Quaternary subaerial exposure surface (Perkins, 1977)	Depth (feet below land surface)	Lithology	Grain size	Perme-ability estimate	Porosity type	Description
Q2 Fort Thompson Formation	22.5 - 23.0	Limestone	Clay	High	Same as above	Same as above
	23.0 - 23.5	Limestone, marine shells	Clay	High	Same as above	Same as above
	23.5 - 24.5	Limestone	Very fine	High	Same as above	Same as above
	24.5 - 25.5	Calcarenite	Very fine to fine	Very high	Highly vuggy	Limestone, light-gray, very fine calcarenite, broken into large, irregular, knotty chunks, grades into very fine sparite
	25.5 - 25.75	Same as above	Fine to medium	Very high	Same as above	Limestone, as above, one piece, large irregular solution holes, abundant small shells and fragments of shells, mostly clams
	25.75 - 32.0	No recovery	NO DATA			
	32.0 - 33.0	Limestone, marine shells to calcarenite	Coarse	Low	Common moldic, some large vugs	Limestone, gray to light-gray, calcarenite (fine to medium-grained) to shell fragment grainstone, micritic, top foot is relatively dense with whole marine shells
	33.0 - 34.0	Same as above	Fine to medium	Moderate	Same as above	Same as above
	34.0 - 34.5	Same as above	Coarse	High	Same as above	Same as above
	34.5 - 36.5	Limestone, freshwater shells	Clay	Low	Common moldic, pinpoint vugs common in places	Limestone, gray to brownish gray, mostly micrite but some fine-grained calcarenite, freshwater gastropods common, large vertical dissolution feature feeds into vertical, curved dissolution surface
	36.5 - 37.0	No recovery	NO DATA			
Q2	37.0 - 37.25	Limestone, freshwater shells	Clay	Very low to low	Large vertical dissolution features	Same as in 34.5 to 36.5 foot depth interval.
Q1 Fort Thompson Formation	37.25 - 38.0	Limestone	Clay to very fine	Very low to low	Same as above	Limestone, light-gray, micritic to very fine grained, dense, may be some sparite, root zone structure
	38.0 - 40.0	Limestone, marine shells to calcarenite	Fine to coarse	Moderate to very high	Common moldic	Limestone, gray, shell coquina to shell fragment grainstone to calcarenite, fine grained with quartz sand has 0.25 foot of micrite 0.5 foot from top, which is relatively dense, becomes very broken toward base
	40.0 - 42.0	No recovery	NO DATA			
	42.0 - 42.5	Limestone, marine shells to calcarenite	Coarse	High	Numerous vugs, some large	Limestone, light-gray, similar to 38.0 to 40.0 foot depth interval, coarse grained, micritic, abundant large shell fragments
	42.5 - 43.5	Limestone, freshwater shells to calcarenite	Clay to very fine	Low	Moldic	Limestone, brown, micritic, with abundant gastropod molds grading to limestone, light-grayish brown with some calcarenite toward base; 3 inches from bottom is 0.5 inch thick siltstone bed with wavy top and bottom, may be some quartz sand above and below it
	43.5 - 47.0	No recovery	NO DATA			
	47.0 - 47.25	Limestone, freshwater shells	Fine	Low	Moldic	Limestone as in 42.5 to 43.5 foot depth interval, grading into calcarenite with fine-grained quartz sand

Appendix I. Lithologic log of well G-3587--(Continued)

[L30-80, site 9, site identification number 255130080291104, prepared by Ronald S. Reese, well completed March 1995, land-surface elevation (approximate) - 6 feet above sea level]

Geologic unit and Quaternary subaerial exposure surface (Perkins, 1977)	Depth (feet below land surface)	Lithology	Grain size	Permeability estimate	Porosity type	Description
Fort Thompson Formation	47.25 - 48.25	Limestone, marine shells to calcarenite	Fine to coarse	High to very high	Large vugs common	Limestone, light-gray, fine to very coarse calcarenite with abundant large shells (marine), some well preserved; broken in bottom 5 inches
	48.25 - 49.5	Limestone	Clay	Low to moderate	Some large vugs	Limestone, light-chocolate brown, micrite, clayey, dense, root zone structure(?) at top, some large near vertical vugs, calcarenitic from above filling holes
	49.5 - 52.0	No recovery	NO DATA			
	52.0 - 53.5	Limestone, marine shells to calcarenite	Fine to coarse	Very high	Large vugs	Limestone, gray to gray-brown, shelly calcarenite, less shells and more fine grained toward base with quartz sand common
	53.5 - 54.0	Limestone, freshwater shells	Clay to silt	Low	Moldic	Limestone, light-chocolate brown, silty, micritic, abundant gastropods in top half and more silty and sandy in bottom half
	54.0 - 54.5	Sandy limestone	Silt to fine	Low	Intergranular	Same as above
Q1	54.5 - 57.0	No recovery	NO DATA			
Tamiami Formation	57.5 - 58.5	Limestone, marine shells to sandy limestone	Fine	Low to moderate	Intergranular	Limestone, dark-gray, sandy to micritic, dense, fossiliferous, has solution features filled with fine-grained shelly calcarenite
	58.5 - 59.5	Calcarenite	Coarse	Moderate	Interparticle	Limestone, dark-gray to brown, conglomerate, abundant large marine shells (broken and transported), sandy matrix, has irregular fragments of dark-gray to black micritic limestone (?), top surface is irregular and sloping (scour surface?) with small coral heads on surface in growth position
	59.5 - 62.0	No recovery	NO DATA			
	62.0 - 62.5	Limestone, marine shells to calcarenite	Coarse	Moderate to high	Interparticle	Limestone, gray to light-brown, calcarenite, dense, micritic to sparry matrix, bryozoans(?) in places
	62.5 - 64.0	Same as above	Fine to coarse	Low	Small vugs common	Limestone light- to dark-gray, calcarenite, dense, coarsening downward, rock fragment pebbles at bottom
	64.0 - 65.5	Same as above	Coarse	High	Vugs common, especially toward base	Limestone, dark-gray, conglomerate, rock fragment pebbles (black sandy micrite), large shells and shell fragments
	65.5 - 66.0	Sandy limestone	Fine	High	Large interconnected vugs	Limestone to sandstone to sand, gray to light-brown, mostly fine grained, becomes soft and crumbly toward base, black pebbles common in places
	66.0 - 66.5	Sandstone or sand	Medium	Very high	Same as above	Same as above
	66.5 - 72.0	No recovery	NO DATA			
	72.0 - 74.0	Limestone, marine shells	Coarse	High	Very high interparticle	Limestone, gray, coquina, very coarse grained, relatively well sorted broken shell fragments, fine- to medium-grained quartz sand common in places between fragments, top 1 inch is very fine grained quartz sandstone
	74.0 - 77.0	No recovery	NO DATA			

Appendix II. Geologic core data for selected intervals, well G-3587

[Data from Core Laboratories Inc. (1995). L30-80, site 9, site identification number 255130080291104, from Core Laboratories file DAL-95158, well completed March 1995, land-surface elevation about 6 feet above sea level. <, less than the value]

Sample No.	**Depth interval (feet below land surface)**	**Plug data**		**Whole core porosity (percent)**
		Permeability to air[1] (feet per day)	**Porosity[2] (percent)**	
IV	7.0 - 7.4	<2.44 x 10^{-7}	3.5	Not measured
2V	8.5 - 8.8	0.356	18.2	Not measured
3V	13.3 - 13.9	14.5	18.6	Not measured
4V	17.0 - 17.5	23.2	45.0	47.5
5V	34.0 - 34.4	.478	39.6	36.3
6V	37.3 - 37.8	.888	15.6	Not measured
7V	48.3 - 49.4	1.34 x 10^{-4}	11.2	Not measured
8V	54.2 - 54.4	4.54	30.4	Not measured
9V	58.3 - 58.7	1.68	22.6	Not measured
10V	63.5 - 64.0	6.59 x 10^{-5}	7.2	Not measured

[1] Values originally reported in millidarcies.

[2] Porosity measured on a plug taken from the core.

Appendix III. Geophysical logs of wells G-3587 and G-3597