Numerical Simulation of a Plume of Brackish Water in the Biscayne Aquifer Originating from a Flowing Artesian Well, Dade County, Florida

United States Geological Survey Water-Supply Paper 2464

Prepared in cooperation with the Metro-Dade Department of Environmental Resources Management

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By MICHAEL L. MERRITT

Prepared in cooperation with the
Metro-Dade Department of Environmental
Resources Management

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2464

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
GORDON P. EATON, Director

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1996

For sale by the
U.S. Geological Survey
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Denver, CO 80225

Library of Congress Cataloging in Publication Data

Numerical simulation of a plume of brackish water in the Biscayne aquifer originating from a flowing artesian well, Dade County, Florida / Michael L. Merritt.
p. cm. — (U.S. Geological Survey water-supply paper ; 2464)
"Prepared in cooperation with the Metro-Dade Department of Environmental Resources Management."
Includes bibliographical references.
Supt. of Docs. no.: I 19.13:2464
1. Groundwater flow—Florida—Simulation methods. 2. Saltwater encroachment—Florida—Simulation methods. 3. Biscayne Aquifer (Fla.) I. Metropolitan Dade County (Fla.). Dept. of Environmental Resources Management. II. Title. III. Series.
GB1197.7.M465 1996
551.49'09759—dc20 96–27893
CIP

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CONVERSION FACTORS

Multiply	By	To obtain
acre	0.4047	hectare
cubic foot per second (ft^3/s)	0.028317	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per second (ft/s)	0.3048	meter per second
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06308	kiter per second
inch (in.)	25.4	millimeter
inch per day (in/d)	25.4	millimeter per day
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meters per second
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

°C = 5/9 (°F - 32)

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 both the United States and Canada, formerly called Sea Level Datum of 1929.

Numerical Simulation of a Plume of Brackish Water in the Biscayne Aquifer Originating from a Flowing Artesian Well, Dade County, Florida

By Michael L. Merritt

Abstract

In 1979, a reconnaissance of the quality of ground water in the surficial Biscayne aquifer underlying a marginal wetlands area in central Dade County, southeastern Florida, revealed a plume of water containing anomalously high concentrations of chloride and other inorganic constituents extending downgradient through an agricultural area. The source, a flowing artesian well drilled in 1944, was plugged in 1985, and a study into the potential effects of the contamination on proposed regional well-field development was undertaken by the U.S. Geological Survey, in cooperation with the Metro-Dade Department of Environmental Resources Management.

The simulation of the variation in the extent of the plume of brackish water and the orientation of its longitudinal axis from 1944 to 1985 was partly based on flow velocities computed by a numerical model of regional ground-water flow. Heads computed by the regional model were used as boundary conditions for a subregional model with finer discretization in which solute-transport calculations were performed using finite-difference solution techniques. Preliminary sensitivity analyses indicated that plumes similar to the measured one could be simulated by using a relatively large longitudinal dispersivity (250 feet) and a small transverse dispersivity (0.1 foot). This transverse dispersivity value was sufficiently large that concentrations were vertically uniform except when dilution by canal recharge was a significant factor. However, the simulated dispersion normal to the average flow direction seemed to be caused primarily by variations in the direction of flow and not by transverse dispersion in the plane of flow.

During the latter part of the 40-year simulation period, canals and levees were constructed that penetrated and, especially during periods of intense rainfall, recharged or drained the Biscayne aquifer in the region contaminated by the brackish water. Two model designs were used to simulate the plume during this period of time. In one, the canals were explicitly represented as strings of narrow grid cells having a high value of hydraulic conductivity. Drainage during periods of high water table was represented by algorithms simulating the operation of control structures in the canals. In the other version, canals were not represented. Both model designs used the same boundary condition specifications and omitted the surface layer of overland flow from transport computations.

Neither simulation of the plume was entirely successful in replicating observed data. The model design incorporating the canals more accurately simulated changes in the directional orientation of the plume caused by recharge or drainage of the aquifer by the canals after periods of above-average rainfall and the reversal of such directional changes during periods of below-average rainfall. The simulated changes in the directional orientation of the thin, narrow plume were accompanied by large salinity fluctuations at the location of observation wells. At these locations, computed concentrations are consistent with measured data. The model design omitting the canal representation more accurately

simulated the downgradient extent of the plume, although upgradient concentrations were substantially overestimated. The model design incorporating the canals apparently overestimated the effect of the canals in leaching the plume or in diluting it with freshwater.

The region in which simulated chloride concentrations were highest was shown to diminish in extent during periods of high rainfall. However, simulated dilution and flushing of the brackish water was shown to cause the region containing water of marginal salinity to enlarge in extent during these same periods. The simulation based on the canal representation indicated that the plume would be entirely dispersed by 1994, but the simulation without canals showed a remnant plume to persist beyond 2003. Simulation (without canals) of a large regional well field in one of the proposed locations indicated that the effect of pumping on the gradual southward movement of the dissipating plume would be negligible.

INTRODUCTION

In past decades, communities, farmers, and individual homeowners in Dade County (fig. 1), southeastern Florida, found potable water to be easily available from the surficial Biscayne aquifer, which locally extends virtually to land surface and is characterized by high transmissivity. Well fields near the coast supplied ample quantities of freshwater to residential communities; inland, farmers found plentiful water of good quality at shallow depths for irrigation of crops.

In recent years, the rapidly increasing population of the region has begun to tax the limits of this ground-water resource. An early sign was saltwater intrusion into some coastal well fields, probably caused by overpumping and by the lowering of water levels in the interior by overdrainage. As the saltwater intrusion problem worsened during the 1970's, the problem of contamination also emerged as a serious constraint on water supply. In 1983, the former Medley Well Field (fig. 1) was permanently closed because industrial contaminants in the aquifer had migrated to its wells (Technical Advisory Committee for the Proposed West Well Field, written commun., January 1987). The aquifer that was so productive because it was close to land surface and easily recharged by an average annual rainfall of 59 in/yr (inches per year) was, for this same reason, easily subject to pollution by contaminant spills. Because no other source in Dade County is used for public supply, its need for protection from contamination was recognized in 1979 by the U.S. Environmental Protection Agency with its designation as a sole-source aquifer.

When a minor contamination episode occurred in the Alexander Orr Well Field, which, with the Southwest and Snapper Creek Well Fields, supplies water to the southern part of Dade County, water managers realized that the location of these well fields in areas of urban and industrial development made them also susceptible to contamination. In addition, the well fields were reaching their maximum permitted capacity as a result of the increasing demand for water. Dade County began a process of technical consultation and review of plans for a West Well Field to be located inland in the central part of the county, west and hydraulically upgradient of developed lands, and bordering on wetlands that are being acquired by Everglades National Park. The proposed location required Dade County planners to deal with concerns about dewatering wetlands and demands from other interests, such as agriculture, competing for the finite water resource. Currently (1995), Dade County is preparing an environmental impact statement.

In addition to these concerns, there emerged an additional potential contamination threat that could jeopardize the quality of water supplied by the proposed new well field. A U.S. Geological Survey (USGS) field study (Waller, 1982) delineated a plume of brackish water in the Biscayne aquifer of central Dade County. The brackish water flowed from an artesian well drilled by oil prospectors in 1944 in what was, until recently, Chekika State Recreation Area. The chloride concentration of the well discharge was about 1,200 mg/L, about 6 percent of that (19,000 mg/L) which characterizes seawater.

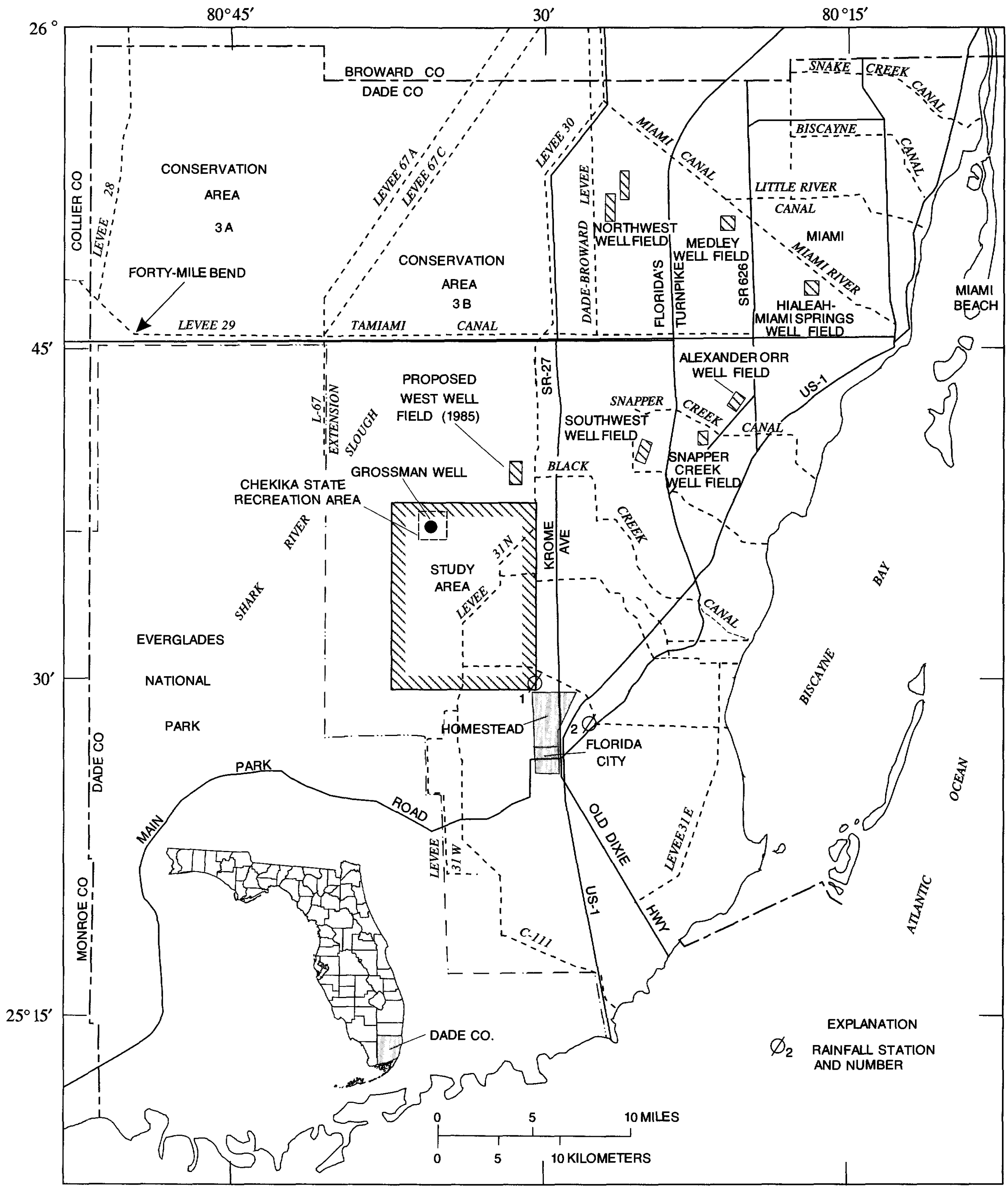

Figure 1. Location of the study area and major well fields in Dade County.

The well was plugged in 1985. Although the degree of mineralization in the plume was only moderate, it was still sufficiently high that treatment costs for water from the proposed well field would increase if the brackish water were to reach public-supply wells. According to the U.S. Environmental Protection Agency (1977), water used for public supply should have a chloride concentration that does not exceed 250 mg/L.

To determine the future extent and rate of dissipation of the plume of brackish water, and its possible interaction with the proposed well field, the USGS, in cooperation with the Metro-Dade Department of Environmental Resources Management (DERM), began a study using numerical modeling techniques. The study of a contaminant plume clearly marked by a conservative constituent in a generally pristine setting was considered to have significant research interest. In addition, the application of solute-transport calculations to a problem of large spatial and temporal scales and the effect of surface-water flows on the plume of brackish water posed unusual difficulties. The use of solute-transport calculations in the analysis of field problems of the type described herein is not common, and obtaining a solution that permitted the objectives of the analysis to be realized was also recognized as a problem having research interest. The demonstration of the use of computer simulation methods for replicating the transport of a substance from a point source in the Biscayne aquifer was also expected to be of interest to local water managers and others concerned with the protection of the sole-source aquifer.

Purpose and Scope

This report describes the application of a numerical simulator of ground water flow and solute transport that was used to study the development of a plume of brackish water from 1944 to 1985 and to estimate the future rate of movement and dispersal of the plume and possible interaction with a proposed new well field. Various hydrologic data were collected, compiled, and analyzed and are presented in this report to describe the flowing artesian well and quality of discharging water, describe the hydrology of the Biscayne aquifer in Dade County, and delineate the extent of the plume of brackish water. Theoretical problems concerning the representation of solute-transport processes are summarized. The results of analyses of the sensitivity of the simulator to dispersivity parameter values are compared with the measured body of brackish water for the purpose of calibrating the model. The interaction of the plume of brackish water with a local system of controlled drainage canals is assessed by using the simulator.

Previous Studies

A study conducted in 1972-73 by the Department of Biology of the University of Miami (Adler, 1973) revealed subtle effects on aquatic plant communities in areas inundated during the wet season by discharge from the artesian well in Chekika State Recreation Area, but detected no effect on the surrounding wetlands or farmlands. However, a ground-water quality reconnaissance conducted in 1978-79 by the USGS (Waller, 1982), in which analyses of water samples from wells were supplemented by surface-resistivity measurements, clearly established the presence of an extensive plume of brackish water in the Biscayne aquifer.

Using the wells constructed as part of the study by Waller (1982), personnel of DERM continued a program of periodic water-quality sampling from 1982 until early 1987, nearly 2 years after plugging of the well. Additional surface-resistivity surveys were also conducted. Results of the DERM monitoring and investigatory program were documented by Labowski (1988). Data from the USGS and DERM programs were used in a study conducted by the Department of Civil and Architectural Engineering of the University of Miami (Chin, 1988) to obtain a field test of a stochastic dispersion model.

The present study was based largely on data describing the hydrogeology of the surficial aquifer system in Dade County provided by a USGS study that included the drilling of numerous test holes and a program of aquifer testing from 1983 to 1985. A product of the study was a comprehensive hydraulic analysis of the Biscayne aquifer in Dade County (Fish and Stewart, 1991). Detailed analyses of lithology at various wells, including one drilled near the site of the flowing well, were documented by Causaras (1987). Correlative cross sections were also prepared by Causaras. Water-quality aspects were documented by Sonntag (1987). Earlier, a general description of hydrologic conditions in the study area was provided by a USGS areal study of hydrologic conditions in a region known as the East Everglades, which is bounded by L-29 on the north, Levee 31N on the east, and Everglades National Park on the west (fig. 1). Results of this study (Schneider and Waller, 1980; Waller, 1983) helped to better define hydrologic conditions in the vicinity of the plume.

The use of numerical simulation techniques in the present study required a realistic representation of seasonally varying flow patterns in the Biscayne aquifer. This was a difficult simulation problem in that the ground-water flow system in Dade County is substantially affected by the seasonal occurrence of flowing surface water in Everglades National Park and in the adjacent wetlands to the south and east, and by an extensive system of levees and canals that utilize control structures to regulate flow. An approximation for allowing grid cells that become dry to rewet and become active parts of the simulated ground-water flow system again was developed for a generic simulation code to make possible the simulation of wetlands. This method has been documented separately (Merritt, 1994a). The canal system implements a complex management strategy of surface-water routing that directly influences the ground-water flow system. The resolution of these representational problems in developing a regional flow model became a principal focus of the study, and results of the work have also been documented separately (Merritt, 1995a). When completed, the regional flow model provided the hydraulic boundary conditions to drive the subregional solute-transport model used to simulate the plume of brackish water.

Because widely varying measurements of the flow rate of the artesian well have been reported, a simulation analysis was performed to establish the most probable flow rate and its variation over time. These results have been documented separately in a supporting paper (Merritt, 1995b). The artesian zone that was the source of the brackish water discharge was described in detail in a report presenting results of tests of injection, storage, and recovery of freshwater near Hialeah, Fla. (Merritt, 1994b).

Acknowledgments

The author is grateful to James L. Labowski, formerly with DERM, whose support and interest helped to initiate the study and contributed substantially to its progress. The author is also grateful for assistance provided by his former USGS colleague, Bradley G. Waller, who helped the author to better understand the water-management system and general hydrology of Dade County.

The author expresses thanks to all individuals and institutions that provided assistance and background information. These include James Brenenstuhl, Ranger, Chekika State Recreation Area; personnel of the Metro-Dade Historical Museum of South Florida; and Nevin D. Hoy (USGS, retired), whose retentive memory provided background details not previously recorded.

DRILLING OF ARTESIAN WELL AND HYDROLOGIC CONSEQUENCES

In 1917, an individual named Samuel Grossman purchased 23,000 acres of rocky glades land in central Dade County that included the 1-square mile section 25, until recently Chekika State Recreation Area. A natural hardwood hammock, located in the section and rising 1 to 2 ft (feet) above the surrounding grassy rocky glades land, was labeled Grossman Hammock on the USGS topographic map of 1956. West of the hammock is a physiographically anomalous feature, an elongated ridge rising about 0.5 ft above surrounding land surface and marked by clumps of hardwood vegetation. It extends generally westward about 3 mi (miles) and is now referred to as Grossman Ridge. Grossman Hammock and Ridge lie on the eastern edge of a vast, seasonally inundated wetlands region known as the Everglades. The southern part of the Everglades, south of Tamiami Canal (fig. 1), is Everglades National Park, administered by the National Park Service.

Native Americans were said to have stopped living in Grossman Hammock in 1916 (tour notes of Mineral Springs, undated). When the Grossmans visited the area in the early 1920's, they found surviving examples of typical local Native American crops in the vicinity (Mark L. Grossman, quoted in the Miami Herald, June 21, 1970). Attempts by the Grossmans to raise tomatoes by rock-plow farming were successful (Mark L. Grossman, quoted in Miami News, November 15, 1965) but were uneconomical because the remoteness of the area thwarted efforts for timely harvesting and delivery to markets. An official Dade County map of 1941 shows a rock road (an unimproved road characteristic of southern Dade County's thin and rocky topsoil) leading to the remote farm.

Figure 2 shows the study area and the location of Grossman Farm Road in relation to other roads and highways existing in the late 1940's. The zigzag route of Grossman Farm Road west of Krome Avenue (U.S. Highway 27) still exists as paved roads of the network shown in figure 3, a 1991 map of the study area.

In April 1944, use of the farm for oil exploration began with the drilling of a well near Grossman Hammock by the Miami Shipbuilding Company. The drilling activity reached the attention of Mr. Herman Gunter, Chief Geologist of the Florida Geological Survey (FGS), when the driller visited a FGS office to report that freshwater (later determined to be brackish) with an odor of sulfur flowed from about 1,200 ft in his oil test well. Mr. Gunter wrote a letter to Mr. Garald G. Parker, Chief Geologist of the Miami office of the USGS, requesting that he investigate the matter; whereupon Mr. Parker requested of Mr. Nevin D. Hoy that he visit the site.

When Nevin D. Hoy arrived at the well site on December 23, 1944, all drilling equipment had been removed, and water flowed from a piece of 12-inch diameter casing jutting about 1 to 2 ft above land surface. The flow was estimated to be about 2,350 gal/min (gallons per minute), based on the height of the jet above the lip of the casing, and a water sample was collected (N.D. Hoy, U.S. Geological Survey, written commun., December 23, 1944). The chloride concentration was determined to be 1,150 mg/L in a rough field titration (G.G. Parker, U.S. Geological Survey, written commun., December 26, 1944). A later laboratory analysis by the USGS indicated a chloride concentration of 970 mg/L, a dissolved-solids concentration of 1,810 mg/L, and a specific conductance of 4,490 µS/cm. In the well schedule prepared by Mr. Hoy on December 23, 1944, the casing was described as being of black iron and to extend to about 500 ft below land surface. The depth of the well was stated to be 1,200 ft, but was later reported by Mr. McCord, owner of a local oil company, to be 1,248 ft deep. The well was assigned the USGS local number S-524 (the prefix indicating that it was a supply well) as shown in figures 2 and 3 and came to be known locally as the "Grossman well."

According to Hoy's recollection, the Grossman well was located in an otherwise undistinguished section of rocky glades land with no trees in the immediate vicinity. (Rocky Glades is a term applied to the occasionally inundated transitional region lying between the Everglades and urbanized lands of higher elevation. In this region, limestone of the Biscayne aquifer extends to land surface and is not covered with peat deposits because the average annual period of inundation is not sufficiently long for a permanent layer to form.) The topography at the site was described as flat on the well schedule. This would indicate that the present high land surface and lush vegetation in the vicinity of the well are artificial, and that the natural hardwood hammock lies some distance to the northwest of the well. On his subsequent visits, Nevin Hoy recollects that the well was crudely capped by an inverted drill bit, and pieces of wood were jammed around this irregular plug to reduce the amount of water escaping through openings. Not all openings were effectively plugged, and jets of water 6 to 10 ft high rose from the wellhead.

According to Adler (1973), a small (1.5-acre), shallow (4 ft deep) pond at the site "was formed in the mid-1940's by the construction of soil dikes to contain the well discharge." A second, smaller pond 15 to 20 ft deep was excavated in 1947 to obtain fill for building the soil embankments to the south and east of the two ponds. When the water table is high, water from the second pond spills southward over the rocky glades land contained in the soil embankments. The embankments prevent further southward surface flow of the artesian water into adjacent grassy rocky glades land.

The drilling of a 11,520-foot oil well (USGS local number G-3234) by the Coastal Petroleum Company took place from October to December 1949. The deep oil well site is likely within several hundred feet of the previously drilled artesian well (S-524), possibly in a presently heavily vegetated area directly east of the northern end of the present lake (fig. 4). The vegetation conceals any existing evidence that would identify its precise location. According to James Brenenstuhl (Florida Department of Parks and Recreation, oral commun., 1990), the well produced only a small amount of oil (legally, a "dry hole") and was shut down in the early 1950's.

In the early 1950's, Mark L. Grossman landscaped the area around the flowing Grossman well with the intention of building a recreational area and spa centered about the shallow 1.5-acre pond formed by the soil dikes in the mid-1940's, which he named Lake Chekika in recognition of a chief of the Seminoles who led his people against the U.S. Army in the Seminole Wars. This name was used on the USGS topographic map of 1956.

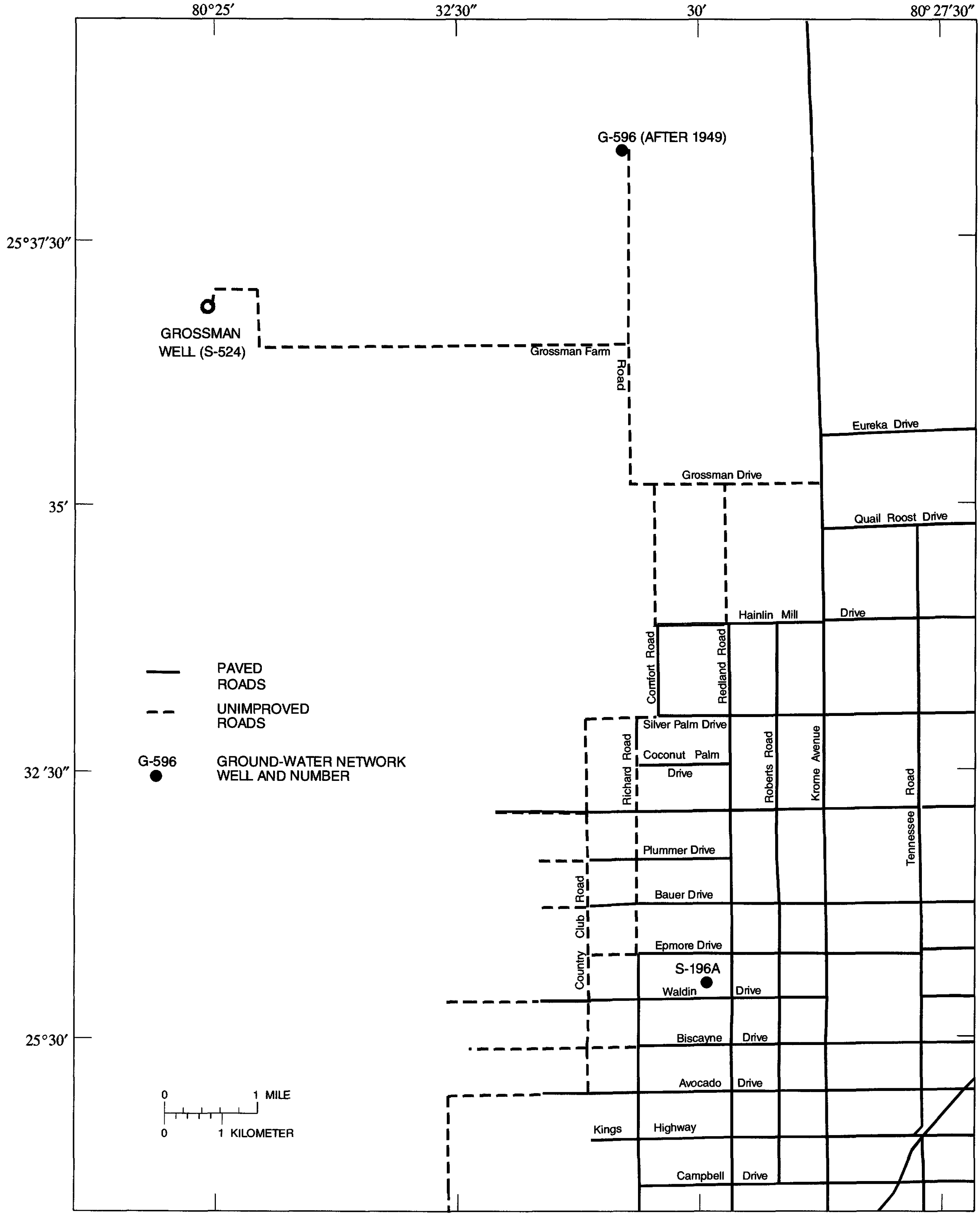

Figure 2. Local roads in the study area as they existed in the late 1940's and locations of two wells providing ground-water level data at that time.

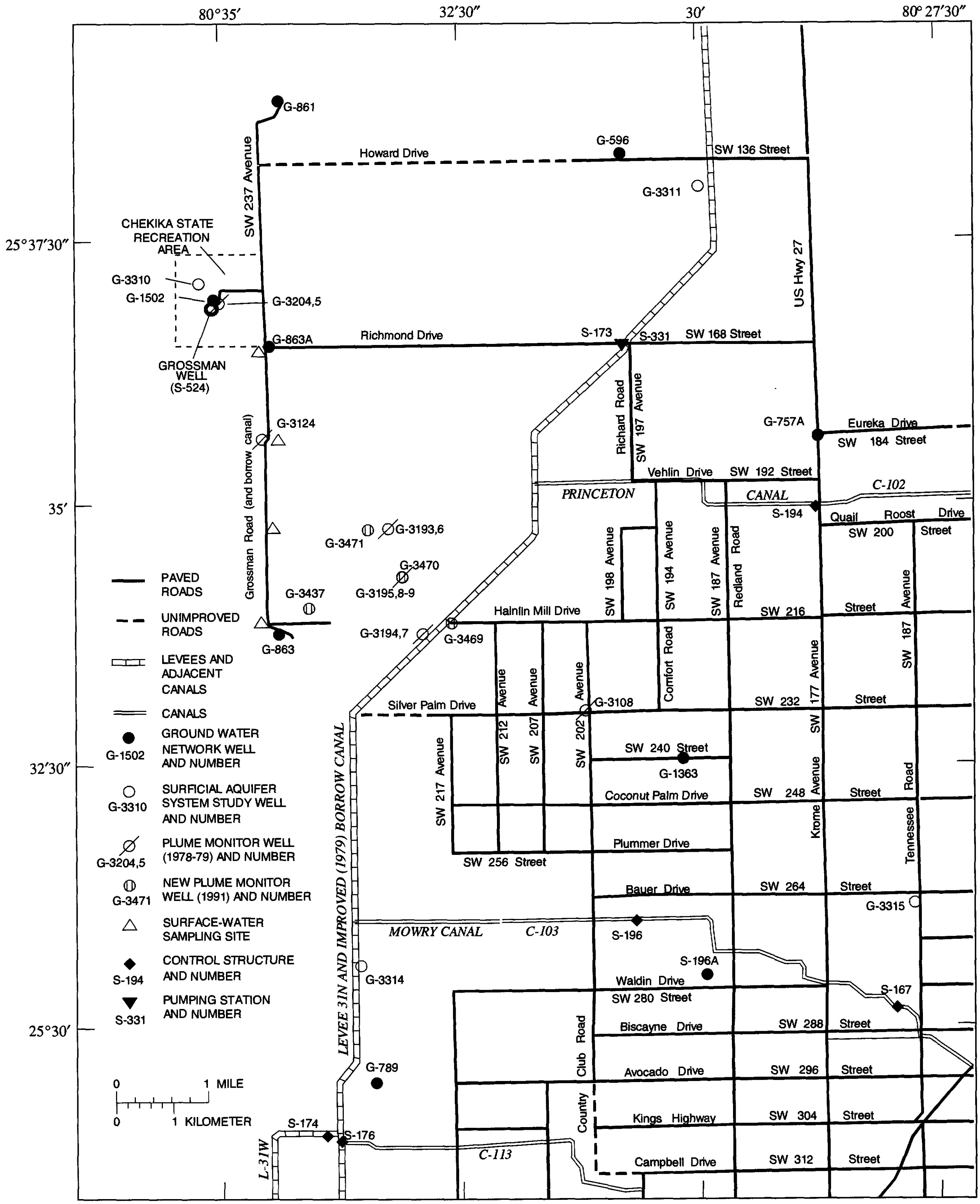

Figure 3. Local roads, levees, canal reaches, and control structures in the study area as they existed in 1991 and locations of wells providing various data for the study.

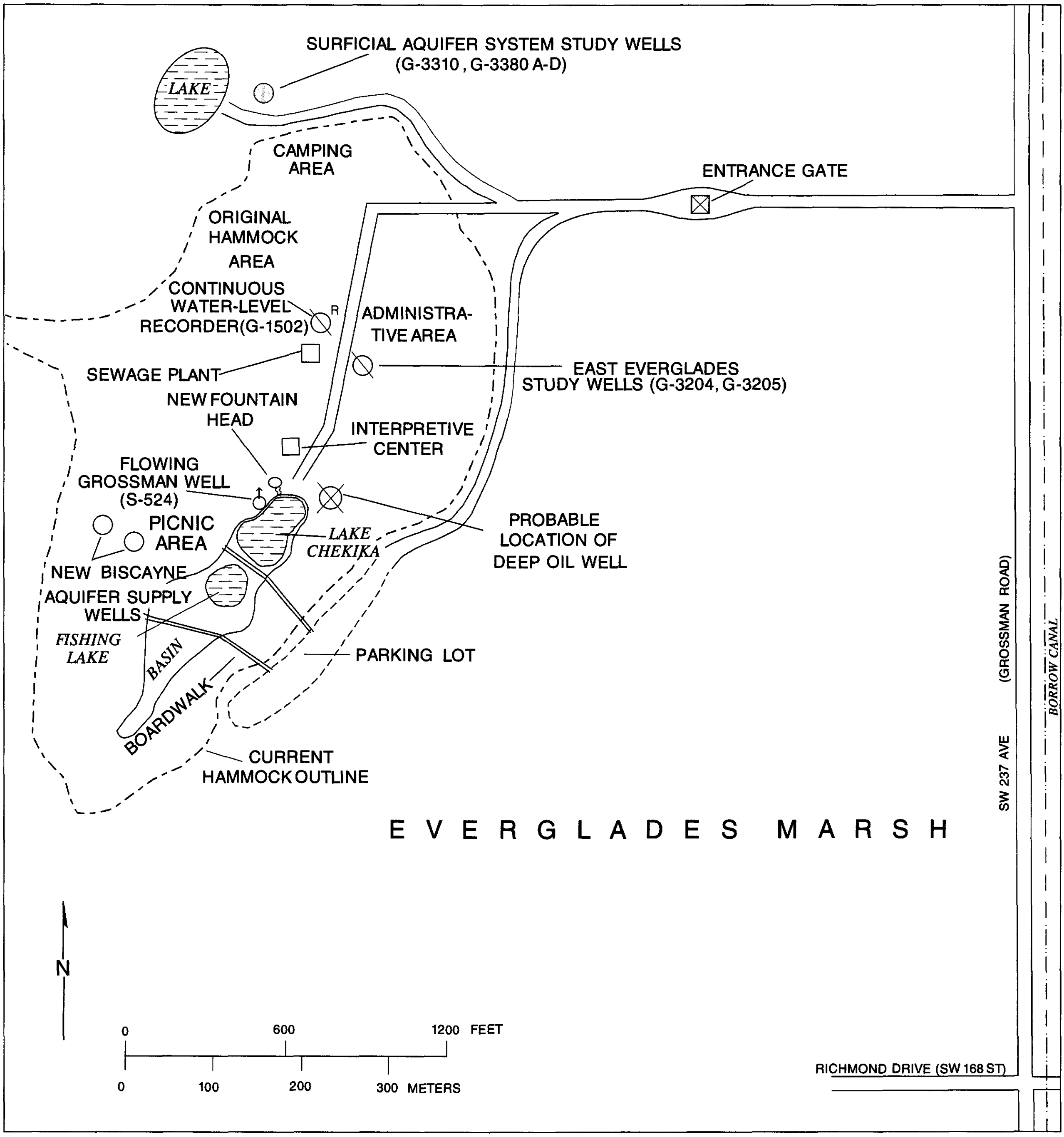

Figure 4. Locations of wells and various cultural and geographical features in Chekika State Recreation Area.

The flowing well, located on the spoil bank, was then surrounded by an ornamental cairn of rocks, around which was a small pool from which water cascaded over an artificial waterfall into the lake (fig. 5). Water overflowed from the lake by way of a spillway into the deeper borrow pit, which penetrated permeable rocks of the Biscayne aquifer and was stocked with fish. During the wet season, overflow from the borrow pit (the "fishing lake" in fig. 4) spilled into the slough to the southwest enclosed by the spoil banks. Called "Mineral Springs and Lake Chekika," the park was opened to the public in 1954. A campground was added to the natural hardwood hammock area north of the lake.

The shallow lake was lined with clayey or marly material. According to James Brenenstuhl (Florida Department of Parks and Recreation, oral commun., 1990), sections of the clay layer under the lake periodically collapsed into cavities of the underlying aquifer, allowing direct infiltration, and were then patched with sand and concrete. Fill material was used to raise low spots to the west of the lake to form a picnic area, and the area was landscaped with exotic ornamental plants that thrived on the brackish water flowing from the well.

Landscaping the area immediately surrounding the Grossman well must have raised the spill level of water to about 7 to 10 ft above average land surface in the surrounding area, which was about 7 to 8 ft above sea level. No records exist for verification, but the casing must have been extended vertically. Both Mark L. Grossman and M. Brooks (a brother-in-law) related to Frederick W. Meyer (USGS, retired) that the flow from the well either diminished substantially or ceased altogether in the mid-1950's. Apparently, the flow was escaping through rust holes in the upper part of the casing and directly entering the Biscayne aquifer. In November 1958, a contract was awarded "to install packer and an 80-ft section of 8-in. plastic casing with cement in the top of the well" (F.W. Meyer, U.S. Geological Survey, file notes, March 1969). No record is available describing the actual remedial procedure, and it is not known whether the liner was sealed at the bottom, which would have required use of a packer and that the well be "killed" (flow stopped with a plug of brine). Meyer (1971) believed that some flow continued to be lost to the aquifer through the annular space between the 8-inch plastic liner and the 12-inch iron casing.

A shallow USGS well (G-863A) was drilled in 1959 near the park entrance (fig. 3) and equipped with a continuous recorder to measure the local water-table altitude. Part of what is now called Richmond Drive, the western part of the access road, was paved (probably in 1961) to provide access to Federal Aviation Agency transmitting towers. The north-south section of the road outside the park was also paved and was extended to the towers, 2 mi to the north and 3 mi to the south, and the road was paralleled by a borrow ditch that supplied material for its construction. In late 1961, G-863A was replaced with shallow wells equipped with continuous recorders at the northern (G-861) and southern (G-863) ends of this new road.

Following the Alaskan earthquake of 1964, the Grossman well was reported in statements by the owners to the newspapers to have doubled its flow and to have maintained the increase. A USGS team (Howard Klein, F.A. Kohout, and F.W. Meyer) visited the site and measured the flow to be 1,170 gal/min. Subsequent visits in 1965 and 1969 by F.W. Meyer resulted in identical flow measurements. Howard Klein (written commun., 1964) observed that short-term head fluctuations of as much as 2 ft had occurred in some wells after the earthquake, but heads quickly returned to normal levels. Any flow increase from the Grossman well would have been equally short lived.

In 1966-67, Levee 31N was extended southward below structure S-173, and Princeton and Mowry Canals (fig. 3) leading to outlets at the coast of Biscayne Bay (fig. 1) were constructed as part of an ongoing U.S. Army Corps of Engineers water-control project in southern Florida. Levee 31N was bordered by a borrow canal, which was deepened later in 1979. Manually operated structure S-194 in Princeton Canal and S-196 in Mowry Canal, constructed in 1960-67, controlled inflows to these canals from the Levee 31N borrow canal.

In June and August 1969, the FGS logged the Grossman well for the first time. The well was found to be 1,248-foot deep, and casing bottoms were found to be at depths of 82 ft (8-in. plastic liner) and 485 ft (12-inch black iron casing) below land surface. The well was logged again by the USGS in 1974 and by the South Florida Water Management District (SFWMD) in 1983.

In 1970, the private park was purchased by the State of Florida for $950,000 and opened to the public as Grossman Hammock State Park. Between July 1972 and February 1973, the Department of Biology of the University of Miami conducted the previously cited study of aquatic vegetation in the area

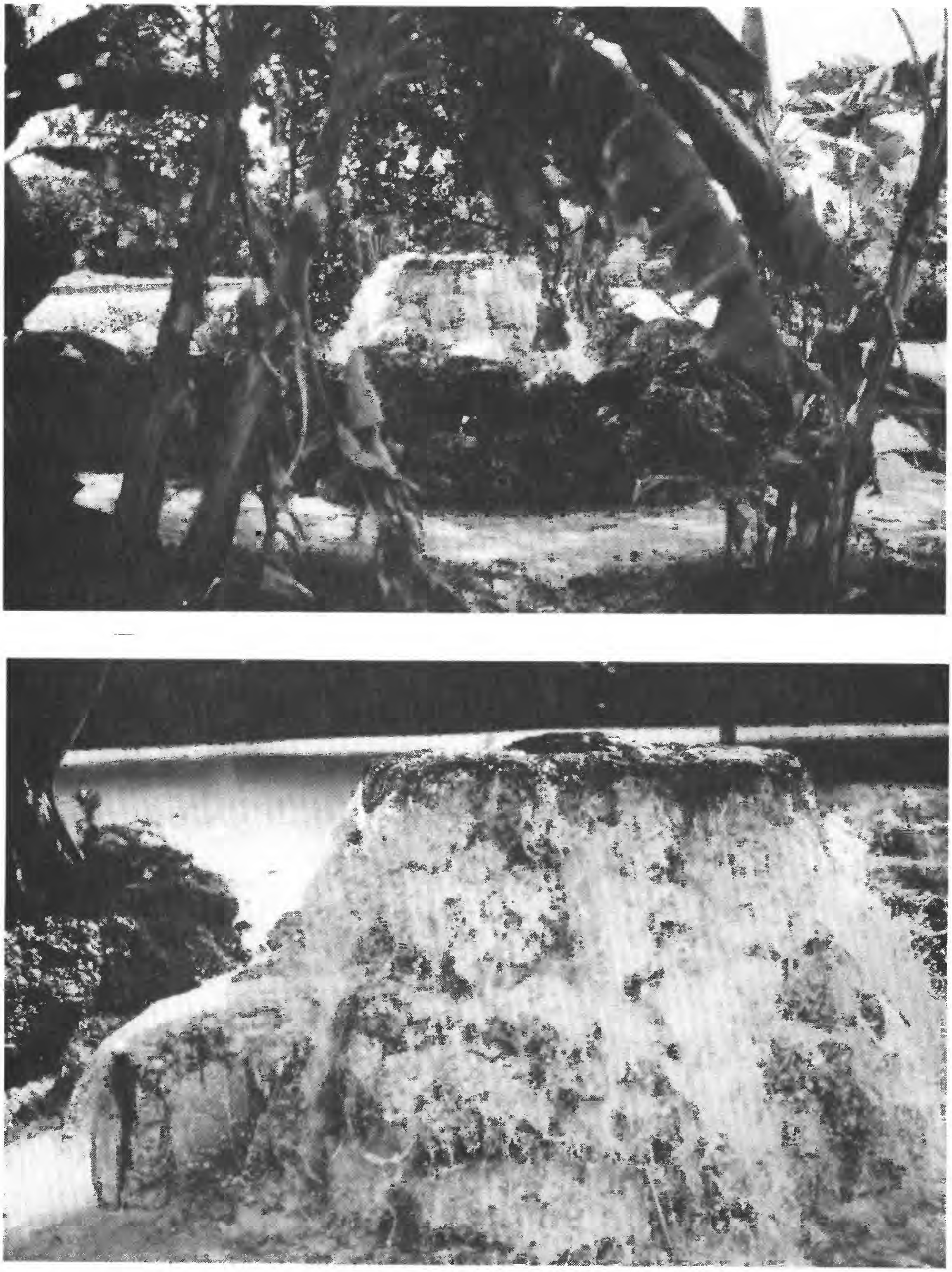

Figure 5. Two views of a flowing artesian Grossman well at Chekika State Recreation Area and surrounding landscape in June 1970.

surrounding the flowing well (Adler, 1973). In December 1974, the park was renamed Chekika State Recreation Area. Richmond Drive (SW 168 Street) was paved in 1978, permitting direct straight-line access from Krome Avenue (U.S. Highway 27). In this and the following year, the USGS water-quality reconnaissance revealed the presence of a plume of brackish water in the Biscayne aquifer southeast of the park (Waller, 1982). In 1983, as part of the USGS Surficial Aquifer System Study (Fish and Stewart, 1991), a test hole was drilled to 250 ft in the park (fig. 4, G-3310).

As a result of the USGS study, DERM concluded that the flowing well was contaminating the Biscayne aquifer and should be plugged. However, the Florida State Department of Natural Resources was given time to develop an alternative source of water to maintain Lake Chekika, the principal attraction of the park. After two wells were drilled into the Biscayne aquifer that were open between 30 and 45 ft below land surface, the flowing well was plugged on March 7, 1985. Water from the Biscayne aquifer wells was pumped to a new ornamental fountain structure located at the north end of the lake.

As related orally to the author in 1988 by the contractor performing the plugging, cement with an accelerator was pumped into an interval from 530 to 370 ft below land surface. The cement hardened very quickly, forming a plug. During a second cement lift, pressure was lost at 30 ft, and no increase in the cement level was accomplished with further pumping. After allowing time for hardening, a third stage of cement filled the liner to land surface. The pressure loss at 30 ft probably indicated that the liner had collapsed and that the cement was filling the annulus between the liner and the 12-inch casing.

Following the plugging, DERM continued the water-quality reconnaissance at a network of observation wells in the vicinity. When the program was discontinued in January 1987, little change had been observed at any but the two closest wells (fig. 4), hydraulically upgradient of the flowing well (Labowski, 1988). The USGS sampled wells of the network that remained available in 1989, and three new wells were drilled by the USGS in 1991.

In October 1991, large areas of State-owned land in the "East Everglades," the non-park area bounded by Everglades National Park on the west, Tamiami Canal and Levee 29 on the north, and Levee 31N on the east (fig. 1), were donated to Everglades National Park to facilitate plans for an enlargement of the park to encompass areas of historic overland sheetflow. The donated land included Chekika State Recreation Area, which became the Chekika entrance to Everglades National Park, and which continued to serve as a public recreational area. On August 24, 1992, vegetation in the area surrounding the park and some park structures were severely damaged by Hurricane Andrew. For nearly 2 years afterward, the park and camping area were closed for reconstruction, but are now open once again as part of Everglades National Park.

HYDROGEOLOGIC CONDITIONS IN THE STUDY AREA

A description of hydrogeologic conditions in the study area is presented in the subsequent sections of this report. Included are a generalized delineation of stratigraphy from the surface to the Upper Floridan aquifer and a description of geologic, hydraulic, and chemical properties of the Biscayne aquifer. The Upper Floridan aquifer is the source of water that flowed from the Grossman well and has contaminated the surficial Biscayne aquifer. A description of geologic, hydraulic, and chemical properties of the Upper Floridan aquifer in the study area is presented in a supporting report (Merritt, 1995b) that describes analyses of variations in the flow rate from the artesian well. Results of the flow-rate analyses are summarized herein to describe the rate of the point-source loading of the Biscayne aquifer by the brackish flow. Specifically, the next sections (in ascending order) describe: (1) the lithology and stratigraphy of the study area, (2) the flow rate of the Grossman well, (3) the chemical quality of artesian discharge, and (4) various properties of the Biscayne aquifer.

Lithology and Stratigraphy

A description of the lithology of the surficial aquifer system near Chekika State Recreation Area (Causaras, 1987) was based on rock samples acquired during drilling of a 250-foot test hole (USGS local number G-3310) located about 1,500 ft north of the flowing Grossman well. At this location, the surficial aquifer system is comprised of the surficial Biscayne aquifer of Pleistocene age, underlain by materials of lower permeability of the Tamiami Formation. In the Biscayne aquifer, the Miami Limestone is underlain by the Fort Thompson Formation. Causaras identified the bottom of the surficial aquifer system, the boundary between the Tamiami Formation of Pliocene age and the Hawthorn Formation of Miocene age, as occurring at 215 ft. The latter formation is principally a sandy, silty, clayey marl. According to Meyer (1989), the Tampa Limestone of Miocene age might underlie the Hawthorn Formation. Rocks of Miocene age are underlain by the Suwannee Formation of Oligocene age. The Tampa Limestone and the upper part of the Suwannee Formation are marly, and the occurrence of consolidated limestone near the base of the Suwannee Formation marks the surface of the Floridan aquifer system. The Suwannee Formation is underlain successively by the Ocala Limestone and the Avon Park Formation of Eocene age. However, the Ocala Limestone pinches out in the center of the peninsula (Meyer, 1989) and is probably not present at Grossman Hammock.

Lithologic descriptions from the well site extending to the depth of the Grossman well (1,250 ft) are available only from the drilling of the well itself. The drilling log from the nearby 11,500-foot oil well lacks detail, merely referring to "lime," with "sand and shells" found in the line above 762 ft. The descriptions of samples from the Grossman well by Louise Jordan (Sun Oil Company, written commun., November 1944) begin at 290 ft and are included in a supporting report (Merritt, 1995b, app. 1). The emphasis in these descriptions is on the identification of fossil species. Clayey sand is found to 475 ft. Miocene and Oligocene fossils were found to 1,150 ft, which is identified (with some reservations as to the exact depth) as the top of the Claiborne Formation (equivalent in stage to the Avon Park Formation in southern Florida).

Caliper logs run by the SFWMD and FGS indicated a highly rugose borehole between 1,170 and 1,210 ft that suggested the presence of solution features. The SFWMD gamma log showed an interval of high counts between 1,125 and 1,175 ft that correlates with phosphatic beds near the base of the Oligocene throughout southern Florida (Meyer, 1989, p. 13). Thin, discrete flow zones considered part of the Upper Floridan aquifer often occur near the Eocene-Oligocene contact below this marker bed, as discussed in the report of injection, storage, and recovery tests at Hialeah (Merritt, 1994b). This was confirmed at the Grossman well site by the three FGS fluid velocity logs that indicated a single flow zone between 1,180 and 1,205 ft. The FGS fluid resistivity log and the SFWMD temperature log indicated that this zone was the only source of flow from the well.

Flow Rate of Grossman Well

The discrepancy between the flow rate of 2,350 gal/min from the artesian zone (part of the Upper Floridan aquifer) measured in 1944 and the rate of 1,170 gal/min measured in 1964, 1965, and 1969 suggested the need for a detailed analysis to determine the correct rate and its likely variation with time. In addition, previously cited changes in the design of the Grossman well, its deteriorating condition, and the escape of some flow through rust holes in the casing are factors that complicate the determination of flow-rate variations. (The flowmeter logging equipment used in 1969 only provided estimates of relative flow velocity in counts per minute and required an independent flow measurement for calibration.)

The flow rate from the Grossman well was estimated by numerical simulation analysis using the Subsurface Waste Injection Program (SWIP) code (INTERCOMP Resource Development and Engineering, Inc., 1976; INTERA Environmental Consultants, Inc., 1979). The numerical simulation required the development of a new technique for representing the artesian well (Merritt, 1995b). It also required the construction of a reasonably accurate hydraulic model of the source aquifer. The advantages that were provided by the numerical simulation approach were the ability to account for: (1) friction losses in the casing and wellbore and their variation with time, and (2) recharge through overlying and underlying leaky confining layers and from aquifer boundaries representing the undersea outcrops at the edge of the continental shelf.

The numerical analysis considered two scenarios corresponding to conditions existing in 1944 and 1964-69. When the 1944 measurement of 2,350 gal/min was made, the well casing extended 2 ft above land surface. When the 1964, 1965, and 1969 measurements of 1,170 gal/min were made, the well casing extended about 7 ft higher, had an 80-foot section of 8-inch liner hung in the top of the well, and was probably allowing water to escape into the Biscayne aquifer through rust holes in the original casing. Because flowmeter logging indicated an approximate 20 percent reduction of flow at the base of the plastic liner, the true loading of the Biscayne aquifer with brackish water from the Upper Floridan aquifer could have occurred at a rate of about 1,400 gal/min. In addition, 20 years of artesian flow could have drawn down the aquifer by 1964. The objective of the simulation analysis was to establish that the flow measurement made just after the well was drilled was consistent with the one made 20 years later.

All computations with SWIP began with a set of equilibrium conditions that were a calibrated steady-state representation of flows in the Upper Floridan aquifer in southern Florida. Only scattered data from the aquifer in this region were available for the calibration, and the simulation was considered to be highly generalized. Results of the simulation analyses indicated that the effects of upward leakage through the confining unit underlying the Upper Floridan aquifer and recharge from the outcrop boundaries tended to decrease the drawdown resulting from the artesian flow. In fact, the computed flow rate was nearly constant after 1 week of simulated flow. When 1944 well conditions (diameter and height of exit point) were represented, the measured 1944 flow rate was simulated with an aquifer transmissivity of slightly less than 17,500 ft^2/d (feet squared per day). When this transmissivity value was used under 1964 conditions, the simulated flow rate was about 1,930 gal/min, or about 65 percent greater than the rate measured in 1964. When 1964 well conditions were represented, the measured 1964 flow rate was simulated with an aquifer transmissivity of 8,875 ft^2/d. A hypothetical 1964 flow rate of 1,400 gal/min was simulated with a transmissivity value of about 11,125 ft^2/d. When these transmissivity values were used under 1944 conditions, the simulated flow rates increased by 19 percent, but were still substantially less than the discharge of 2,350 gal/min measured in 1944.

An analysis in which 1964 well conditions were represented, and in which the increased roughness of the casing from 20 years of deterioration caused by exposure to brackish Upper Floridan aquifer water was represented, also resolved only part of the discrepancy between measured 1944 and 1964 flow rates. Most likely, factors not amenable to model analysis, such as a slight error in one of the flow measurements or an incorrect estimate of the loss of flow through the corroded well casing, might have contributed to the discrepancy. The flow measurements of 1964, 1965, and 1969 (1,170 gal/min) are accepted as valid and representative for most of the period of flow from the well. Because the flowmeter data indicated a 20 percent loss of flow at the base of the plastic liner, a higher rate of about 1,400 gal/min was used in simulations of the plume of brackish water.

Chemical Quality of Artesian Discharge

Samples of water discharged from the Upper Floridan aquifer through the Grossman well have been obtained at various times between 1944 and 1978. Measurements of temperature and results of analyses for concentrations of chloride, sulfate, and dissolved solids are listed in table 1. The 1944 sulfate concentration is given as listed in the typed laboratory report, but is evidently in error, as are the chloride and sulfate concentrations reported in August 1974. The 1944 laboratory chloride and dissolved solids values seem too low and are also probably in error, unless some process causing change in the quality of the flowing water occurred in the 18.5 years before the next sample was obtained. With these erroneous and questionable values excluded, the mean value of measured specific conductance and mean concentrations of chloride, sulfate, dissolved solids (residue at 180 degrees Celsius), and dissolved solids (sum of constituents) are about 4,760 µS/cm, 1,230 mg/L, 470 mg/L, 3,070 mg/L, and 2,900 mg/L, respectively. These values are about 6.5 to 8.5 percent of those characteristic of seawater and are comparable to those found at other wells completed in the Upper Floridan aquifer in Dade County (Reese, 1994).

Biscayne Aquifer

The Biscayne aquifer, comprising the upper part of the surficial aquifer system, is emergent at land surface in most of the study area. The estimated thickness of the Biscayne aquifer, based on data from three locations in the study area (fig. 3) where test holes were drilled as part of a comprehensive drilling program in 1985 (Causaras, 1987), varies from 45 to 70 ft (fig. 6). Separate thicknesses for the Miami Limestone and the Fort Thompson Formation comprising the Biscayne aquifer are shown in figure 6. The Fort Thompson Formation increases in thickness to the south and southeast, whereas the Miami Limestone seems to thicken slightly in an easterly direction. The thickness of the Biscayne aquifer at well G-3311 (not shown in fig. 6) was 50 ft.

Table 1. Analyses for selected constituents in the Grossman well discharge

Date	Temperature (degrees Fahrenheit)	Specific conductance (microsiemens per centimeter)	Chloride (milligrams per liter)	Sulfate (milligrams per liter)	Dissolved solids (milligrams per liter)	
					Residue at 180 degrees Celsius	Sum of constituents
[1]12-23-44	--	--	1,150	--	--	--
[2]12-23-44	76.0	4,490	[3]970	[3,4]48	[3]1,180	--
6-14-63	--	4,330	1,300	490	3,360	3,110
4-29-64	76.0	4,780	1,200	480	3,000	2,850
[5]7-06-65	76.0	--	1,225	--	--	--
[5]10-26-68	76.0	4,800	1,210	--	--	--
10-18-73	--	4,450	1,200	430	--	2,860
11-15-73	78.0	5,070	1,300	470	--	2,950
1-29-74	--	5,170	1,300	530	--	--
4-20-74	--	5,000	1,300	490	--	--
8-22-74	77.0	4,500	[3]13	[3]8.9	--	--
1-27-75	--	5,100	1,200	460	--	--
9-17-75	75.0	4,770	1,200	420	2,950	2,790
10-27-78	--	4,700	1,200	480	2,980	2,860
Mean....		4,760	1,230	470	3,070	2,900

[1]Rough Field titration (G.G. Parker, U.S. Geological Survey, written commun., December 26, 1944).
[2]U.S. Geological Survey laboratory analysis.
[3]Anomalous values identified in the text have been omitted from the computation of the means.
[4]As listed in the laboratory report.
[5]Field titration by U.S. Geological Survey Miami Subdistrict office personnel.

Lithology and Hydraulic Properties

In the study area, the Miami Limestone (as characterized by Hoffmeister and others, 1967) is described by Causaras (1987) as oolitic and the Fort Thompson Formation as sandy biomicritic or biosparitic limestone. Both formations are described as vugular to cavernous throughout much of their thicknesses, and significant confining beds seem to be absent. Cavities up to 1 ft in vertical thickness were encountered when drilling through these formations. The Fort Thompson Formation is underlain at the three test hole locations by quartz sand or sandstone of the Tamiami Formation.

The transmissivity of the Biscayne aquifer is so great that Fish and Stewart (1991) merely describe it as "greater than 1,000,000 ft^2/d" throughout most of central and southern Dade County. The estimated average hydraulic conductivity of the Fort Thompson Formation in western Dade County is cited as "tens of thousands of feet per day, possibly exceeding an average of 40,000 ft/d (feet per day)." Step-drawdown tests were performed at the three sites shown in figure 6. At these sites, Fish and Stewart (1991) derived hydraulic conductivity estimates ranging from 27,000 to 37,000 ft/d. Slight errors in estimating well losses assumed great significance in the pump-test analyses so that the hydraulic conductivity estimates were not considered highly precise. A value of 30,000 ft/d was used for much of the Biscayne aquifer in southern Dade County in calibrating the regional flow model (Merritt, 1995a) Sensitivity analyses demonstrated that 50 percent variations of this value had only a moderate effect on computed heads.

An analysis presented in the report describing the regional flow model correlated intense rainfall events with rises in the ground-water table measured in well S-196A (fig. 3) and indicated a value of 23 percent for the specific yield of the upper part of the Miami Limestone. It was assumed that this was indicative of the effective porosity of the entire thickness of the Biscayne aquifer. The range of variation of individual estimates indicated that the analysis could support effective porosity estimates ranging from 20 to 25 percent. Parker and others (1955, p. 219) judged that a value of 15 to 20 percent would best represent the relation between recharge amounts and water-table rises. The value used in calibrating the regional flow model was 20 percent. This was also the value used by Appel (1973) in simulating the Biscayne aquifer with an electrical analog model.

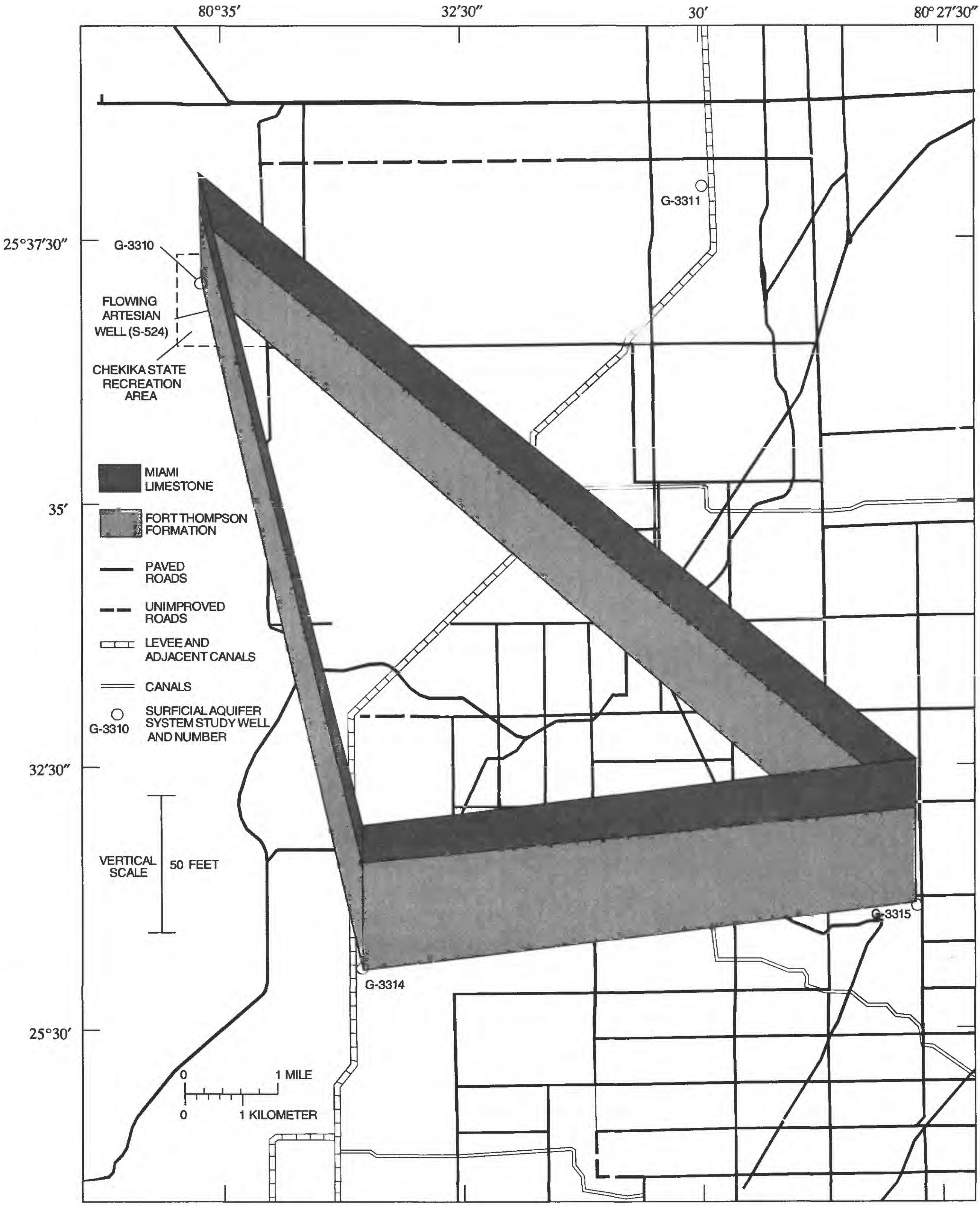

Figure 6. Estimated thickness of formations comprising the Biscayne aquifer in the study area.

Dispersive Properties

Although water-level gradients and the hydraulic conductivity and effective porosity of the aquifer material determine an average velocity for water in the Biscayne aquifer and, in particular, a velocity for the discharging brackish water after its percolation into the aquifer, the speed of movement of individual fluid parcels varies about this average as a result of a complex set of hydraulic processes referred to as mechanical dispersion. Individual fluid particles move through carbonate solution channels that vary in tortuosity, and fluid movement varies across the cross-sectional area of each channel. After a period of downgradient movement of the brackish water, the displacement of the native water is not uniform because of the variability of the net speed of fluid parcels in the direction of general fluid motion. Therefore, in a spatially averaged sense, there is a gradual variation in water composition in the direction of fluid movement in which the composition ranges from that of the intruding brackish water to that of the native freshwater. The region in which the spatially averaged water composition is a mixture of the two waters is referred to as the transition zone. The spatial variation of the ratio of the two waters in the mixture was stated mathematically by Reeder and others (1976) as:

$$C/C_o = 1/2 \ erfc\left[\frac{r-R}{(4/3 \ \alpha_l \ R)^{1/2}}\right] \qquad (1)$$

where:

C/C_o is a unitless fraction having values ranging from 0 to 1 and representing the relative concentration at radius r of one of the two fluids in the mixture,

erfc is the complimentary error function,

R is defined by $V = \pi\theta h R^2$ (θ is aquifer porosity and h is the thickness of the injection zone)—R is the radius (L) of the injected water mass if no dispersion were to occur, V is the volume (L^3) of fluid in a cylinder of aquifer material of height h, radius R, and porosity θ, and

α_l is the longitudinal dispersivity (L).

Mathematical descriptions of the Fickian diffusion algorithms often used for a theoretical description of the transition zone are provided by Scheidegger (1961) and Bear (1972), and the concepts have been summarized by Merritt (1985) and in a discussion of numerical methods for solute-transport simulation (Merritt, 1993). Generally, characteristic lengths (longitudinal and transverse dispersivities) describe the degree of dispersion that occurs in the direction of flow and perpendicular to the direction of flow.

The breadth (width or degree of attenuation) of the transition zone is implicit in the choice of a value for longitudinal dispersivity in equation 1. A small longitudinal dispersivity would imply a relatively sharp interface (a narrow transition zone in which the spatial variation of the water composition occurs rapidly over a small longitudinal interval). A large longitudinal dispersivity would imply a broad or diffuse interface (a wide transition zone in which the spatial variation of the water composition occurs gradually over a large longitudinal interval). The value of transverse dispersivity (α_t) determines the degree to which the plume of brackish water tends to spread perpendicularly to the direction of flow in each horizontal slice in the plane of flow. The value also determines the degree to which the brackish water will spread vertically into zones of fresher water. This is important in cases where a significant vertical stratification of water quality is caused by different rates of nonnative water movement in layers of contrasting lateral permeability.

The dispersive properties of flow in the Biscayne aquifer are not known to have been measured in any independent study. The author has used values of 65 ft for dispersivities in radial flow from a well during tests of injection, storage, and recovery in the Upper Floridan aquifer near Hialeah (Merritt, 1994b). However, dispersion coefficients exhibit various forms of scale dependence, and the assignment of the appropriate dispersivity values is problem dependent. Evidence for characteristic dispersivities will, therefore, be sought from the calibration process of this study, in which values of dispersivity will be arbitrarily varied until the dimensions and degree of dispersal of the computed plume match a description of the plume based on the available data in at least a qualitative sense.

Solute also diffuses on a molecular scale in ground water. The degree of molecular diffusion of ions from saline water into freshwater is specified parametrically in most mathematical models by a coefficient of molecular diffusivity that has the same units as aquifer transmissivity (L^2/T). In simulating the injection, storage, and recovery of freshwater at

Hialeah (Merritt, 1994b), a calibration of solute transport away from and back toward the well in a thin flow zone overlain and underlain by brackish water was obtained by using a molecular diffusivity value of 0.0002 ft^2/d.

However, when vertical ionic diffusion is not an important process, the effect of molecular diffusion is probably negligible compared to that of mechanical dispersion in large-scale solute movement in carbonate rocks. When the effects of molecular diffusion and mechanical dispersion are grouped conceptually or in mathematical formulations for computing purposes, the group of processes is referred to by the term hydrodynamic dispersion.

Surface- and Ground-Water Interaction

Historically, the wetlands north, west, and south of Chekika State Recreation Area have been regularly inundated during the annual wet season. Except for a peat-covered northwestern triangle, all of the study area west of Levee 31N (fig. 3) and some areas east of the levee are considered part of the rocky glades region (Merritt, 1995a, fig. 3). The area is subject to occasional inundation, but has a pock-marked rocky surface generally not covered with peat. There is no effective confining layer to impede the downward percolation of flowing surface water into the aquifer or to generate a significant vertical head gradient, so the presence of flowing surface water implies that heads in the aquifer are also above land surface. In severe storm events, much of the study area can be flooded. During Tropical Storm Dennis in August 1981, only isolated sections of the eastern part of the study area escaped flooding, and Chekika State Recreation Area was inundated for several days.

Construction of the levee and canal system (fig. 3) in the 1960's did not substantially affect the hydrologic regime of Chekika State Recreation Area and the surrounding wetlands, although significant changes in ground-water flow directions occurred. A slight lowering of the water table throughout the region resulted from construction in 1962 of Levee 29 along the Tamiami Canal to the north (fig. 1). The canal system has been used to drain floodwaters and lower the water table in a region north of the study area. The success of its use for lowering the water table is a result of the direct hydraulic interconnection between canals and the Biscayne aquifer into which the canals are excavated. Although the canal bottoms become covered with relatively impermeable sediments, the vertical canal walls are generally unlined with sediments, allowing easy interchange of water with solution channels in the aquifer (Chin, 1990). Since 1983, control structures in the study area (S-167, S-174, S-176, S-194, and S-196) have usually been open to permit waters flowing through pumping station S-331 to be discharged toward the ocean through the canal system. Because of the direct connection between the canals and the aquifer, this water-management policy has resulted in a general raising of the water table in the part of the study area east of Levee 31N (Merritt, 1995a). Some of the greatest increases have been in the vicinity of well S-196A (figs. 2 and 3).

Rainfall Recharge and Evapotranspiration

Average annual rainfall in southern Dade County from 1940 to 1992 was 62.25 in. based on rainfall data from two stations near Homestead in the southeastern part of the study area. Individual yearly rainfall totals in southern Dade County (fig. 7) have varied from 94.1 in. in 1947 to 37.0 in. in 1971. To support construction of the regional flow model, Merritt (1995a) prepared statistical summaries of available rainfall data showing that an average of about 61 in/yr of rain fell between 1945 and 1989 at the rain gage at Homestead Agricultural Experiment Station (no. 1 in fig. 1), where well S-196A is located (figs. 2 and 3). Summer (May-October) rainfall totals averaged about 75 to 80 percent of the annual totals. Long-term trends were generally not evident, except for a pronounced monotonic decrease in average October rainfall.

Since 1986, the rainfall record from the Homestead Agricultural Experiment Station, slightly northwest of Homestead, has been incomplete, and a more dependable data source has been the Homestead Field Station of the SFWMD located slightly east of Homestead (no. 2 in fig. 1). Rainfall records from this site have been compiled since 1968. Rainfall data have also been obtained since 1980 from the S-331 pumping station and since 1984 from near the source of the brackish water in Chekika State Recreation Area. The analysis of summer (May-October) rainfall data at these sites between 1985 and 1989 showed that annual average summer rainfall totals were 45.6 in. in Chekika State Recreation Area, 40.0 in. at S-331, and 39.5 in. in Homestead. The higher summer average

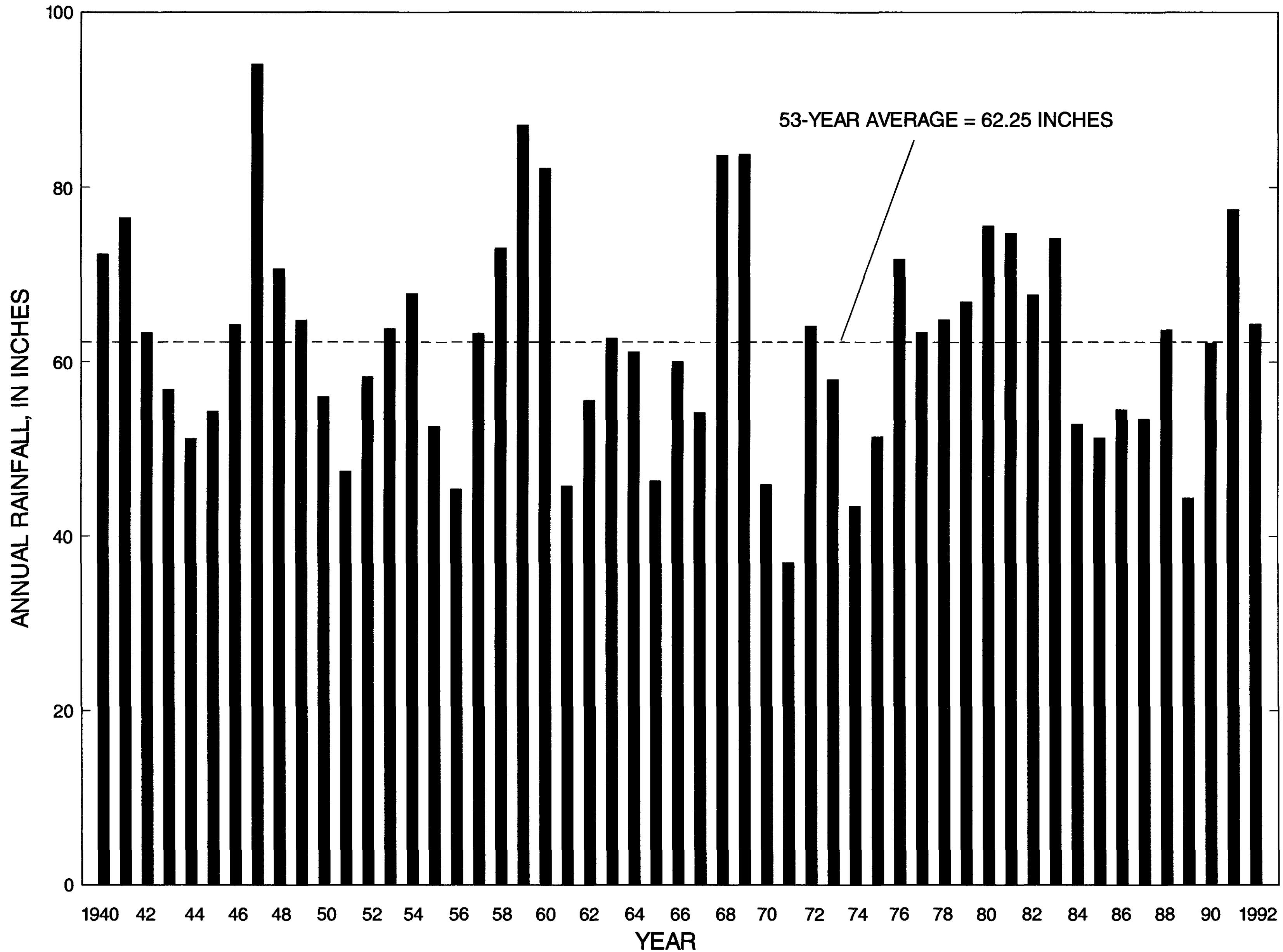

Figure 7. Annual rainfall in southern Dade County, 1940-92 calendar years. Rainfall totals for years before 1982 are from the Homestead Agricultural Experiment Station; later totals are from the South Florida Water Management District Homestead Field Station.

measured in the recreation area is consistent with a comparison of values in every individual year and is higher than the 5-year summer average at any other rainfall station in southern Dade County. The S-331 summer average is the second highest, and the Homestead summer average is the third highest. The explanation for this geographic variation is said to be related to a pattern of circular advection of air masses between the warm land mass and the cooler Atlantic Ocean that occurs in summer. The circulation pattern is modified by the prevailing pattern of onshore easterly winds so that thunderheads form over various inland regions as determined by the easterly wind velocity (Eric Schwartz, South Florida Water Management District, oral commun., 1993).

The term evapotranspiration refers to the combined processes of evaporation and transpiration. Evaporation can occur from surface-water bodies and from the unsaturated and saturated soil zones. Transpiration is the process by which plants take in water through their roots below land surface and release it through leaves, stems, and woody material. In many numerical models of ground-water flow, the rate of evapotranspiration is assumed to decrease monotonically as a linear function of the water-table depth below land surface until an "extinction depth" is reached at which no water is removed by evaporation or plant transpiration. Evapotranspiration is closely correlated with the amount of solar radiation, which implies a strongly seasonal variation (high in summer, low in winter) (Stephens and Stewart, 1963).

To obtain an accurate simulation of transient water levels in southern Dade County with the regional flow model, a monthly varying, but spatially uniform, maximum evapotranspiration rate was specified. The seasonal variation of maximum evapotranspiration rates was as shown in the following table (values are in inches per day):

January	February	March	April
0.08	0.11	0.14	0.17
May	**June-October**	**November**	**December**
0.18	0.21	0.12	0.11

These rates closely resembled measured monthly average pan evaporation rates. An extinction depth of 20 ft was specified for the well-drained urban and agricultural parts of the region not regularly subject to inundation. In regularly inundated areas covered with a layer of peat or calcitic mud, an extinction depth of 5 ft was specified. In the present study area, only a northwestern corner is covered with peat.

The successful use of the 20-foot extinction depth in the noninundated areas included in the regional flow model was surprising, considering that only a few inches of soil overlay limestone bedrock in the area, and most tree roots are confined to the soil layer. Scattered solution holes exist and permit the rapid percolation of large amounts of rainfall, and the highly permeable aquifer drains rapidly to coastal discharge areas. Some fallen trees have been observed by the author to have roots that extend downward into apparent solution holes. However, large parts of the modeled area have been converted to farmland and have few trees. Use of shallower extinction depths than those cited for the calibration of the regional model produced unacceptable results. An examination of dry-season recessions in hydrographs from wells in southern Dade County showed no lessening of the recession rate even when water levels were as much as 12 ft below land surface.

Local Flow Patterns in the Biscayne Aquifer

The movement in the Biscayne aquifer of the brackish water that originates from the Grossman well is largely controlled by the natural gradients in the aquifer. The prior construction and calibration of the regional flow model (Merritt, 1995a) helped to provide an understanding of the magnitude and direction of flows in the aquifer and how they have changed with time and human intervention.

The regional flow model was used to simulate head variations in five successive water-management time periods (1945-52, 1953-61, 1962-67, 1968-82, and 1983-89) that correspond to distinct evolutionary stages in the development of the regional system of water management. Ground-water flow directions at two points in the study area during these time periods are shown in figures 8 and 9. The locations are at the site of the flowing Grossman well and at well S-196A in the southeastern part of the study area (figs. 2 and 3). Figures 8 and 9 show the superposition of a series of flow vectors computed by the regional flow model at 2-week intervals during each of the five water-management time periods. The lengths of the vectors are directly proportional to the flow rate.

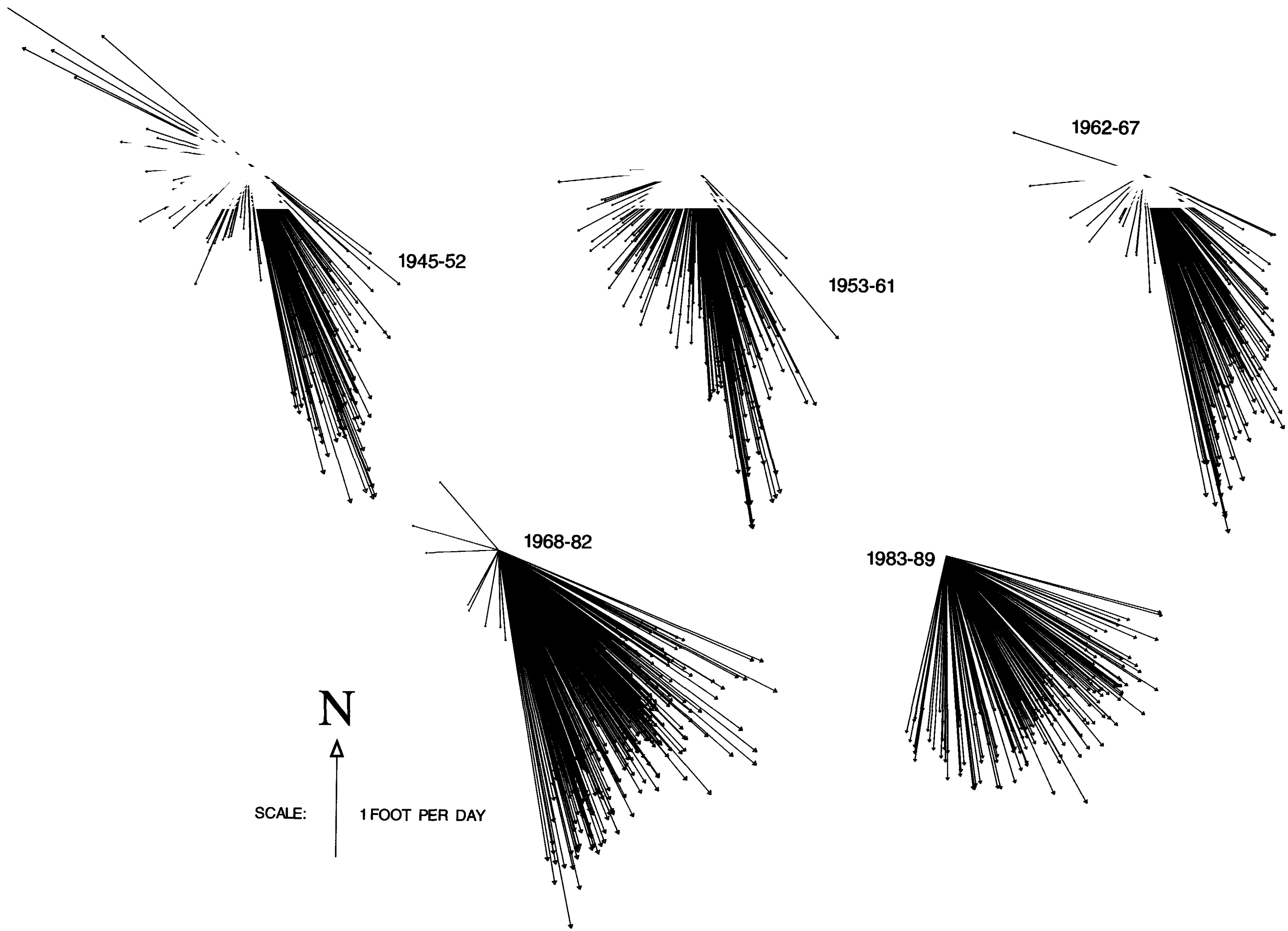

Figure 8. Superposition of vectors indicating simulated magnitude and direction of ground-water flow at the location of the Grossman well (S-524) at 2-week intervals during various water-management time periods.

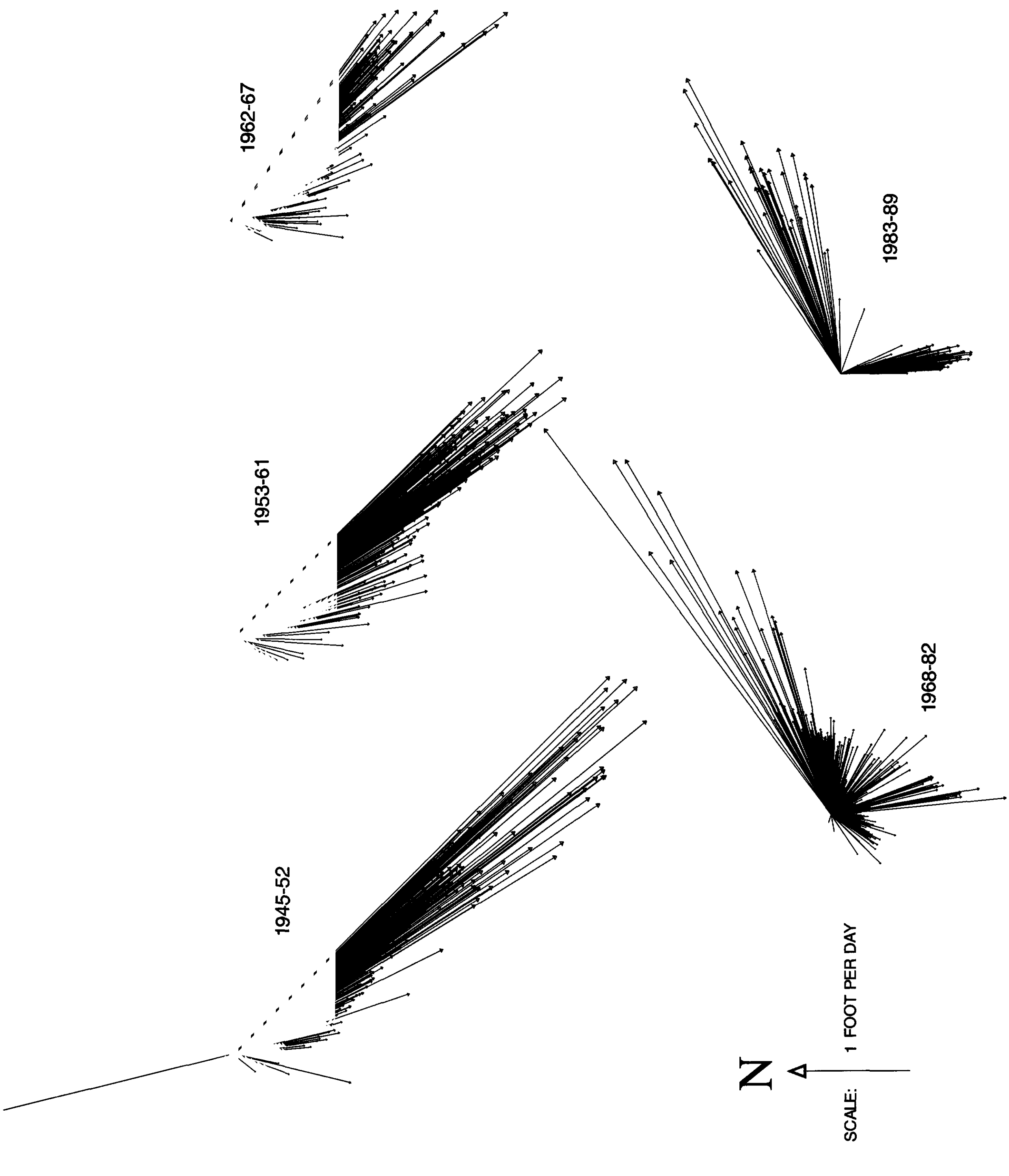

Figure 9. Superposition of vectors indicating simulated magnitude and direction of ground-water flow at the location of well S-196A at 2-week intervals during various water-management time periods.

In the 1945-52 and 1953-61 time periods, before construction of Levee 29 to the north and Black Creek Canal (C-2) to the east (fig. 1), the majority and longest of the vectors at the Grossman well point in a direction somewhat east of due south—the usual direction of ground-water flow at times of the year other than the period of highest water. The smaller number of shorter vectors pointing southwest and west represents the sluggish westward and southwestward flows that occur during the wet seasons when water-table altitudes are high. However, the westward flows were small in magnitude compared to southerly flows because the aquifer grades westward into materials of low permeability and because, before 1961, local northerly and southerly flows appeared to divide at the latitude of Grossman Hammock (Merritt, 1995a). Wet-season drainage in the vicinity of Chekika State Recreation Area was slight. By the time drainage had progressed inland to this area from the coast (and had become more rapid) during the dry season, the direction of flow had shifted to a southerly direction. Between 1945 and 1961, flow velocities at the location of well S-196A (fig. 9) were greater than at the Grossman well (fig. 8) and were in a more eastward direction.

The flow-vector patterns clearly suggest that transport of brackish water should be in a direction somewhat east of due south in these time periods, and that the small westward flows during the wet seasons might cause net flow to be more directly south. Most importantly, the seasonally varying flow directions would lead to diverging advection of chloride particles forming the plume, causing a spreading of the plume of brackish water analogous to the result of a dispersion process.

In the 1962-67 water-management time period, after construction of Levee 29 and Black Creek Canal (C-2), appreciable changes in the ground-water flow system were apparent. At the Grossman well, Black Creek Canal drainage caused dry-season flows to be more easterly (fig. 8). Severe flooding still caused slow westward movement, but normal high-water flows were southward. The flow direction at the Grossman well ranged from south-southeast to east-southeast. The most southerly flows were the most rapid and occurred when the water table was lowest. In this time period, seasonal drainage of the aquifer still began at the coasts and progressed gradually inland, so that the most rapid drainage of the farthest inland areas might not occur until late in the dry season (Merritt, 1995a). At the location of S-196A, flow directions were also more easterly than at the Grossman well (fig. 9), but velocities were reduced compared to those before 1962.

In the 1968-82 time period, ground-water flow directions at the Grossman well are nearly the same as in 1962-67 (fig. 8). However, because the most southerly flows no longer have the highest velocities, the net flow in the vicinity of the well should be slightly more easterly. Near well S-196A, flow directions are radically different (fig. 9). After 1967, S-196A was located a few hundred feet from Mowry Canal (fig. 3). All of the strong northeasterly and south-southeasterly flows correspond to periods of canal drainage during the high water events of 1968, 1969, and 1981. However, the majority of flows are less rapid and range in direction from southwest to northeast. These flows occurred during periods when the canal was inactive between closed control structures S-196 and S-167 (fig. 3) and when less local recharge of the aquifer occurred.

In the 1983-89 time period, ground-water flows at the Grossman well are relatively unchanged in magnitude in a southeasterly direction, but the more southerly flows are less rapid than before (fig. 8). At well S-196A, all ground-water flows are influenced by canal drainage, and their direction is southerly or northeasterly (fig. 9). In this time period, well S-196A is near the center of a region in which the water table has been raised by recharge from the canal system, particularly during regional high-water periods. The most rapid northeasterly flows all occur when downstream control structure S-167 is opened for drainage in the regional flow simulation. (S-196 upstream is simulated as always open.) Southerly flows correspond to periods when gate S-167 was closed and the canal recharged the aquifer in the vicinity of well S-196A.

Salinity of Water in the Biscayne Aquifer

In the present study, the significance of the chemistry of water native to the Biscayne aquifer resides in those characteristics that might affect the direction of flow of the brackish water in the aquifer or that would be useful in determining the areal extent of the brackish water. The different densities of the Upper Floridan aquifer and Biscayne aquifer waters could cause buoyancy stratification to occur at some undetermined distance from the source. The density of water is a function of the dissolved-solids concentration, and the dissolved-solids concentration correlates closely with specific conductance and with chloride concentration when chloride is one of the predominant ions.

The extent of movement of the brackish water would be most easily determined by the presence of a unique tracer. However, no observed constituent is known to be present in Upper Floridan aquifer water and absent from Biscayne aquifer water. Analysis of water samples from test holes drilled as part of the Surficial Aquifer System Study showed Biscayne aquifer water to be a calcium bicarbonate type (Sonntag, 1987). Water samples from the four test holes in the study area showed specific conductance to be generally about 500 μS/cm in the upper 50 to 75 ft of the Biscayne aquifer. The dissolved-solids concentration ranged from 250 to 350 mg/L, and the chloride concentration ranged from 10 to 20 mg/L. These concentrations are far less than those of water from the flowing well, which had a dissolved-solids concentration of about 3,000 mg/L and a chloride concentration of about 1,200 mg/L. Therefore, relatively high concentrations of either constituent served as an accurate tracer of the artesian well water entering the Biscayne aquifer.

MEASUREMENTS OF THE EXTENT OF THE PLUME OF BRACKISH WATER

Virtually no ground-water quality data from the study area predate late 1978, by which time the Grossman well had been flowing for 34 years. Data revealing the existence and showing the extent of the plume of brackish water in the Biscayne aquifer were first acquired in that year, and sporadic data collection by the USGS and DERM has continued until recently (1992). The data consist of chemical analyses of water samples from wells and measurements of conductivity or resistivity acquired during various surface-geophysical studies. The data-collection program has been conducted in three distinct phases preceding and following the plugging of the artesian well in April 1985. The first (1978-79) and third phases (1990-92) were conducted by the USGS. The second phase (1982-86) was conducted by DERM.

Data Collection, Phase 1, 1978-79

The areal extent of the region of the Biscayne aquifer contaminated by brackish water was determined in 1978-79 with a combination of surface-geophysical surveys and analyses of the quality of water in observation wells (Waller, 1982). In September 1978, wells were drilled by the USGS (fig. 3) and then sampled monthly for a period of 10 months. At four locations, clusters of two or three wells were drilled to different sampling depths to obtain information about the vertical distribution of the brackish water in the aquifer.

The surface-geophysical surveys were performed under contract by Technos, Inc., of Miami, Fla., in March 1979. Measurements of the conductivity of the subsurface were acquired with Geonics EM-34 equipment. The data were presented and interpreted by Technos, Inc. (1979) and by Waller (1982). The EM-34 conductivity measurements at 133 stations included shallow (0-25 ft) and deep (0-50 ft) measurements corresponding, respectively, to horizontal and vertical dipole orientations, each with a 10-meter spacing (figs. 10 and 11). The cited depth ranges are approximate depths of investigation. For the specified equipment, spacing, and dipole orientation, the measurements reflected conductivity of the subsurface within these depth ranges. Sets of measurements with different depths of investigation are often correlated to determine vertical variations in conductivity or to determine horizons at which conductivity changes occur as a result of vertical variations in rock type or native water quality.

As part of the present study, the EM-34 conductivity measurements have been reanalyzed with computer software to provide a more-detailed definition of the plume than reported earlier. The primary purpose of the reanalysis was to better define salinity variations in the zone of dispersion separating native water and the intruding brackish water. Computer-generated lines of equal specific conductance based on the EM-34 survey of shallow and deep measurements are shown in figures 10 and 11, respectively. The lines were generated using ARC/INFO[1] software to create triangulated irregular network (TIN) lattices.

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[1]Geographical information system developed by Environmental Systems Research Institute (ESRI), Redlands, Calif.

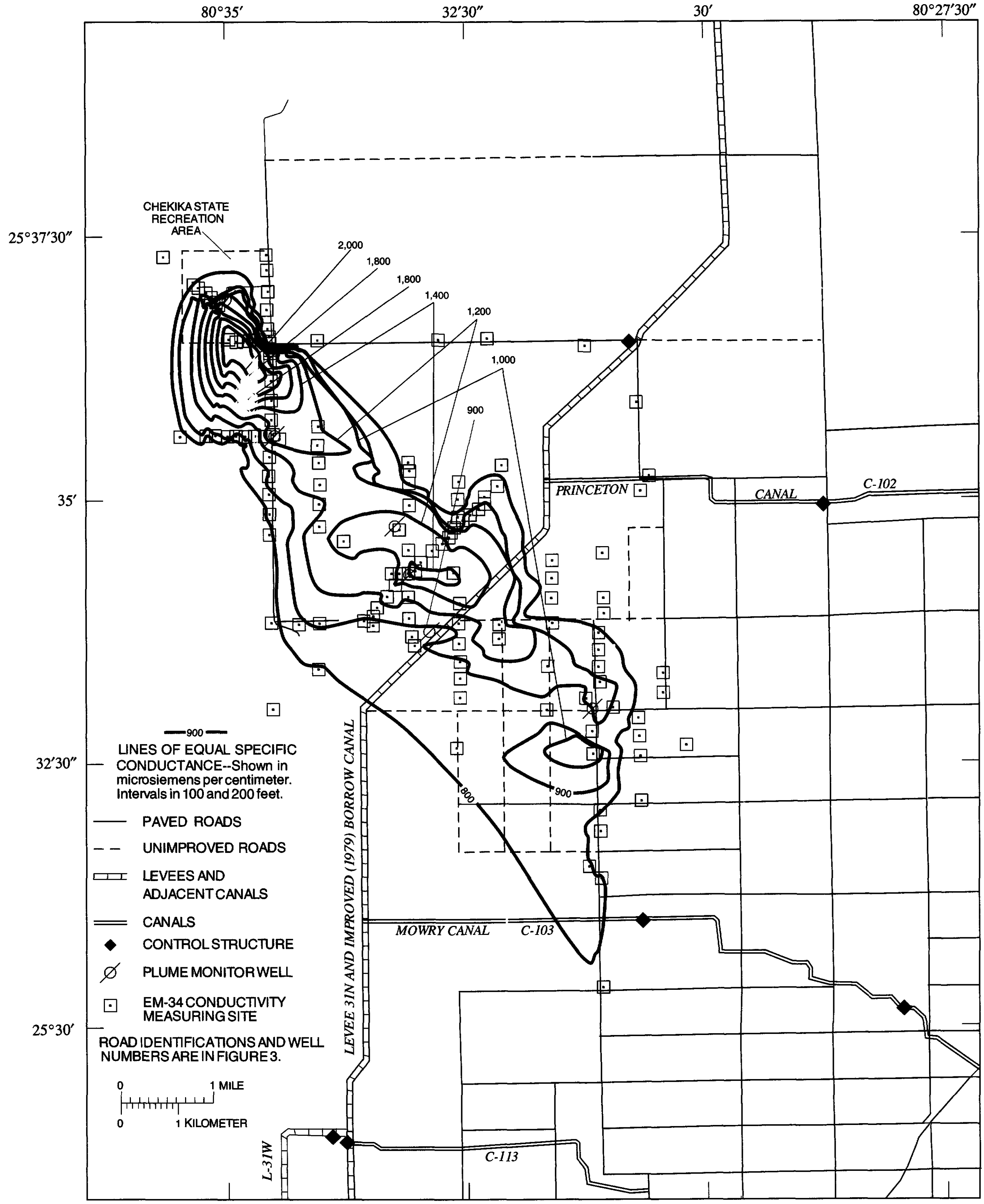

Figure 10. Computer-generated lines of equal specific conductance based on the EM-34 survey of March 1979, 10-meter horizontal dipole orientation.

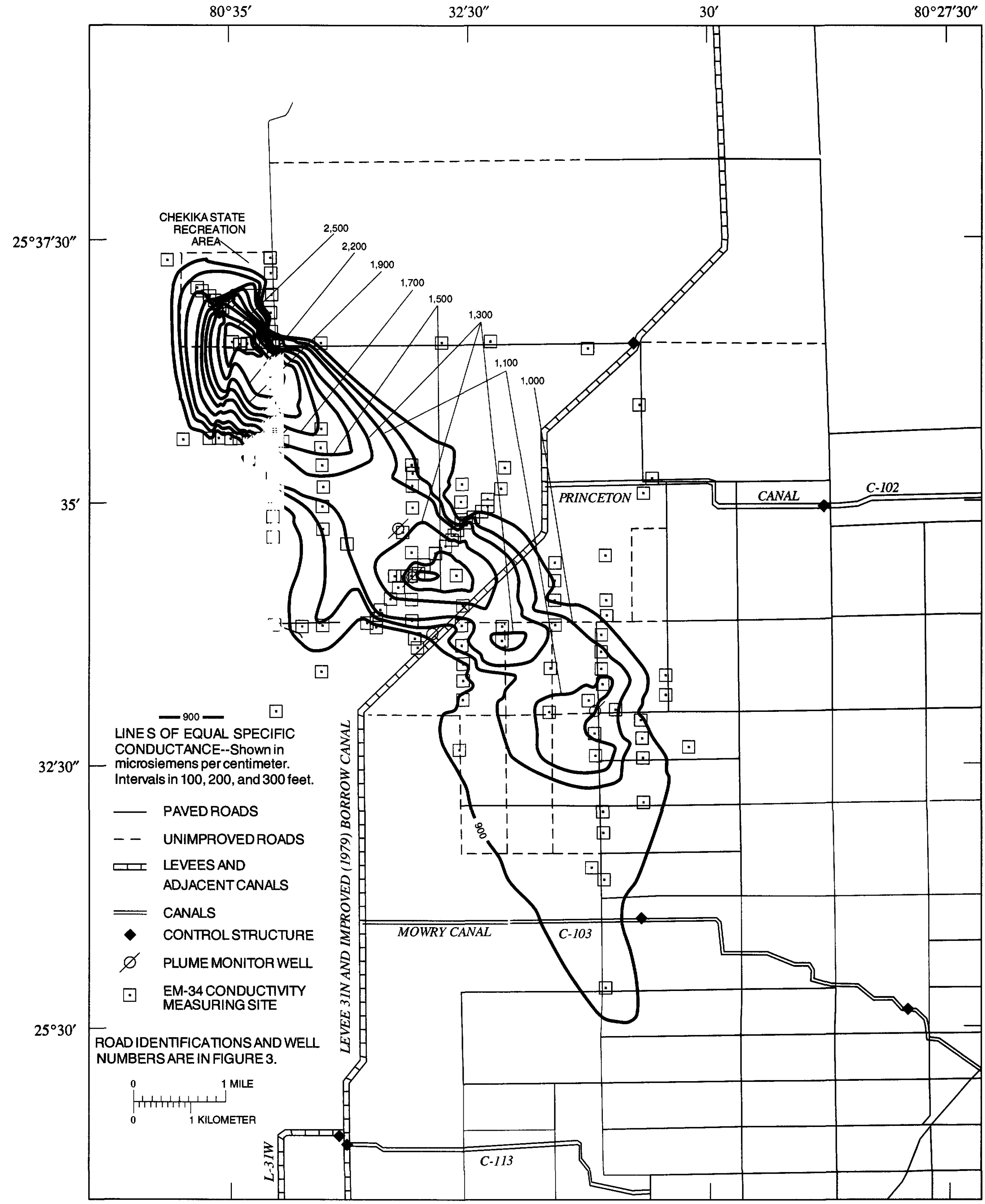

Figure 11. Computer-generated lines of equal specific conductance based on the EM-34 survey of March 1979, 10-meter vertical dipole orientation.

Seven shallow measurements in the depicted plume were removed as apparently erroneous. Actually, an EM-34 conductivity measurement substantially lower than surrounding measurements could simply show an area of low hydraulic conductivity not invaded, or only partially invaded, by brackish water flowing downgradient in adjacent rocks. However, such data points are not useful in showing the general areal extent of the brackish water. All measurements along Richard Road and Richmond Drive (figs. 3 and 10) were eliminated from the data set before the computer analysis. These values were anomalously large and appeared to indicate a northeasterly trending "lobe" of brackish water, as interpreted by Technos, Inc. (1979). To verify the EM-34 data, two wells were constructed along Richmond Drive near locations of high EM-34 measurements. Nine water samples acquired between September 1978 and May 1979 had specific conductance measurements that were similar to background (500 μS/cm) in the study area, and the apparent high conductivity lobe was attributed to measurement error, equipment problems, or some other unidentifiable cause.

Lines of equal specific conductance based on the EM-34 data (figs. 10 and 11) seem to show isolated pools of water characterized by high specific conductance, trending in a southeasterly direction from the site of the flowing artesian well. However, it is evident that these pools are located in areas where the coverage of measurement stations is most dense. In all likelihood, the lack of continuity of the 900, 1,000-, 1,200, and 1,400 μS/cm EM-34 conductivity lines (shallow measurements) along the southeasterly oriented major axis of the plume results from the lack of sufficient measurements along parts of the major axis of the plume where water with the highest specific conductance is located, and from the features of the contouring model used for generating the lines of equal specific conductance. The author, therefore, has redrawn the computer-generated lines of equal specific conductance based on the point data of the shallow measurements to show specific conductance to monotonically decrease in a southeasterly direction along the major axis of the plume (fig. 12). These lines are probably a better interpretation of the March 1979 EM-34 data and show the most probable distribution of the brackish water. The computer-generated lines based on the deep measurements (fig. 11) are similar and could have a similar interpretation.

The highest shallow EM-34 conductivity value was 2,300 μS/cm. (The artesian well water had a mean specific conductance of about 4,750 μS/cm.) Generally, the deep values were higher than the shallow ones. However, Technos, Inc. (1979), did not accept this as evidence that deeper rocks were invaded by higher chloride water than were more shallow rocks. Rather, Technos, Inc., accepted the conclusion that the specific conductance was approximately uniform vertically.

Support for the vertical uniformity hypothesis was provided by background EM-34 conductivity data (from areas where aquifer water seemed to be uncontaminated) and by water samples from the well clusters. Typical background shallow and deep EM-34 conductivity values were about 700 and 850 μS/cm, respectively. The specific conductance of water in the Biscayne aquifer was shown by Sonntag (1987) to be about 500 μS/cm in parts of central Dade County unaffected by the contamination from the flowing artesian well and did not exhibit appreciable vertical variations in the upper 50 ft of the aquifer. The higher background conductivity values measured by the EM-34 equipment are not statistically significant, although they might have been expected to be appreciably lower because the conductivity of solution-riddled limestone containing little or no clay should be quite low. Because the relation of the EM-34 conductivity measurements to specific conductance of water might have varied with depth, the two sets of EM-34 data are not considered to be evidence of an increase in specific conductance of water with depth. A comparison by Waller (1982) of selected EM-34 conductivity measurements and specific conductance of water samples at nearby well locations where the conductivity of aquifer water was slightly above the background level indicated a slight conductivity difference similar to that of background samples.

In the well clusters drilled during phase I data collection, individual wells were cased down to a short (0.5-2 ft) sampling interval. Some specific conductance measurements of water samples from these wells have been previously documented (Waller, 1982). These and additional data are presented in table 2. At three well cluster sites along the major axis of the plume, denoted well cluster B (wells G-3193 and G-3196), well cluster C (wells G-3195, G-3198, and G-3199), and well cluster D (wells G-3194 and G-3197) in succession toward the southeast, specific

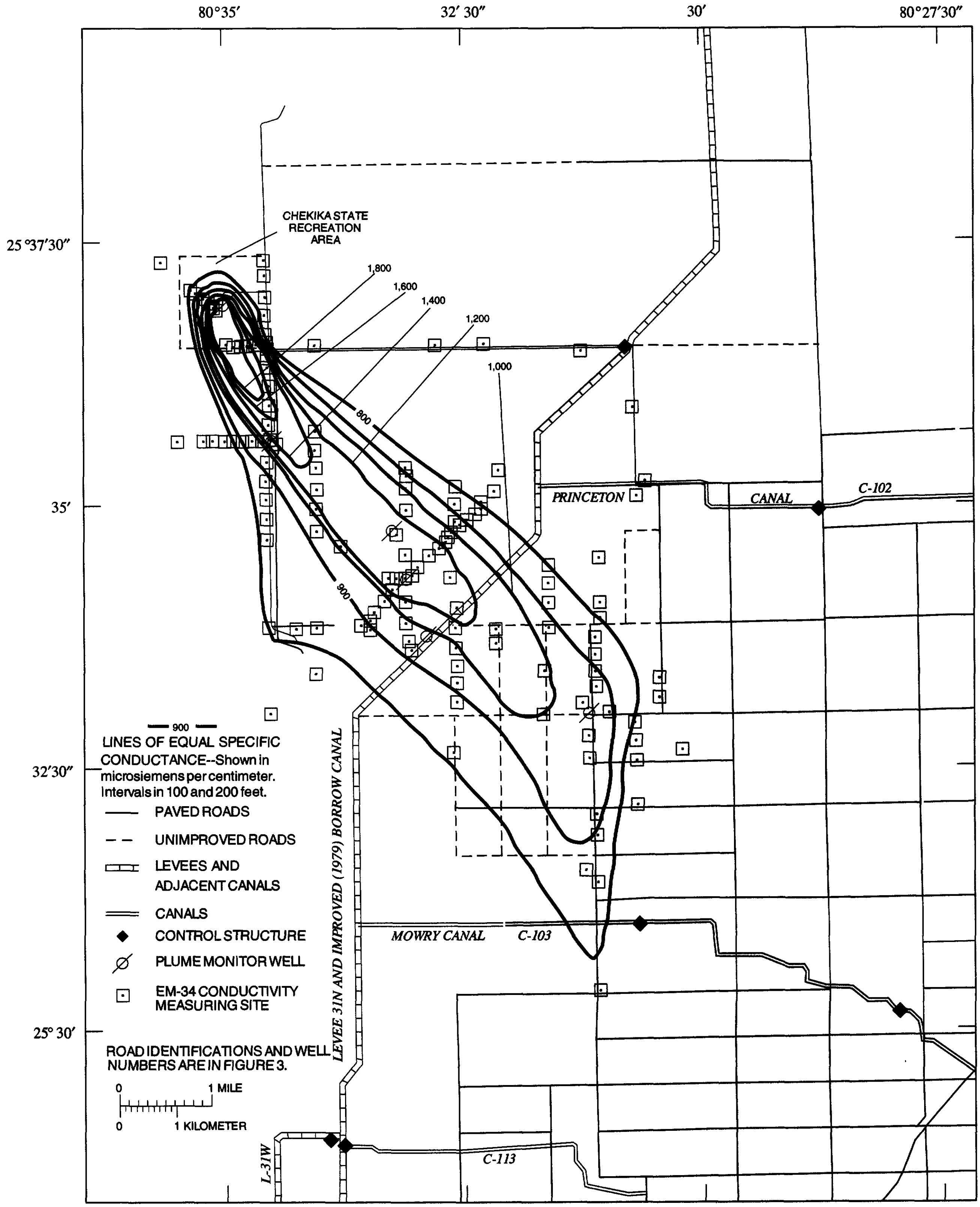

Figure 12. Redrawn lines of equal specific conductance based on the EM-34 survey of March 1979, 10-meter horizontal dipole orientation.

Table 2. Specific conductance and chloride concentration of water samples from wells used to monitor the plume of brackish water, 1976-79

[Well locations shown in figure 3. Specific conductance (SpCon) shown in microsiemens per centimeter and chloride in milligrams per liter. **Well G-3108:** First two samples were collected at 30 and 50 feet, respectively, during drilling of the well. ft, foot; --, no data]

Date	Well cluster B				Well cluster C					
	G-3193 (12 ft)		G-3196 (21 ft)		G-3195 (12 ft)		G-3196 (19 ft)		G-3199 (48 ft)	
	SpCon	Chloride	SpCon	Chloride	SpCon	Chloride	SpCon	Chloride	SpCon	Chloride
1-23-76	--	--	--	--	--	--	--	--	--	--
2-20-76	--	--	--	--	--	--	--	--	--	--
8-24-76	--	--	--	--	--	--	--	--	--	--
9-07-78	1,050	180	1,200	210	1,140	180	1,150	190	1,160	190
10-26-78	980	--	1,140	--	1,100	--	1,100	--	1,120	--
11-13-78	1,000	--	1,100	--	1,040	--	980	--	1,080	--
12-11-78	1,200	--	1,290	--	1,200	--	1,220	--	1,240	--
1-16-79	1,180	--	1,240	--	1,120	--	1,160	--	1,170	--
2-20-79	1,210	--	1,250	--	1,120	--	1,120	--	1,140	--
3-14-79	1,220	250	1,220	--	1,120	--	1,120	250	1,120	200
3-27-79	1,220	--	1,220	--	1,120	--	1,120	--	1,120	--
4-18-79	1,260	220	1,260	220	1,150	180	1,160	180	1,130	190
5-09-79	1,080	--	1,190	--	1,080	--	1,090	--	1,110	--
6-04-79	1,120	--	1,200	--	1,100	--	1,100	--	1,120	--
Mean......	1,138	217	1,210	215	1,117	180	1,120	207	1,137	193

Date	Well cluster D									
	G-3194 (11 ft)		G-3197 (21 ft)		G-3124 (10 ft)		G-3108 (70 ft)		G-1363 (33 ft)	
	SpCon	Chloride	SpCon	Chloride	SpCon	Chloride	SpCon	Chloride	SpCon	Chloride
1-23-76	--	--	--	--	--	--	615	41	--	--
2-20-76	--	--	--	--	--	--	590	43	--	--
8-24-76	--	--	--	--	--	--	590	52	--	--
9-07-78	650	80	780	82	--	--	--	--	--	--
10-26-78	700	--	720	--	--	--	--	--	--	--
11-13-78	700	--	718	--	--	--	--	--	--	--
12-11-78	770	--	690	--	--	--	--	--	--	--
1-16-79	720	--	740	--	--	--	--	--	--	--
2-20-79	720	--	720	--	--	--	--	--	--	--
3-14-79	700	--	710	74	880	130	720	80	560	24
3-27-79	1,210	--	720	--	--	--	--	--	--	--
4-18-79	740	75	740	76	--	--	--	--	--	--
5-09-79	710	--	--	--	--	--	--	--	--	--
6-04-79	--	--	--	--	--	--	--	--	--	--
Mean......	[1]712	78	726	77	880	130	629	54	560	24

[1]Mean does not include sample of March 27, 1979.

conductance measurements are appreciably higher than the background level of 500 µS/cm. The increase in mean specific conductance with depth is slight at the location of the well cluster C where the Biscayne aquifer is about 55-foot thick and the sampling points range in depth from 12 to 48 ft. The Biscayne aquifer thickness is nearly the same at the other well clusters where two wells at each site were completed to depths of 11 or 12 ft and 21 ft. At well cluster D, only a slight increase in specific conductance occurs with depth, but at well cluster B, the mean value at a depth of 21 ft is 7 percent greater than the mean value at a depth of 12 ft. The fact that the increase with depth at the latter site is greatest in the rainy months (May-October) and for a short period afterward and negligible in the dry spring months suggests that dilution by rainfall recharge might cause the depth variation observed at this location. Why this would not occur at the other well clusters is not known. If a thin layer of brackish water were present near the bottom of the Biscayne aquifer, it might not be detected by water samples from any of the wells in table 2.

Well cluster A (wells G-3204 at 13 ft deep and G-3205 at 44 ft deep) was located about 750 ft northeast of the Grossman well (figs. 3 and 4). Because the hydraulic gradient induced by the spillage of brackish water was small, and ground-water movement was generally to the southeast, well cluster A was near the northeastern edge of the plume. Shallow-well water samples (table 3) were only slightly more saline than background. Deep-well water samples were often as saline as the discharging brackish water, but their salinity varied substantially with time, possibly affected by rainfall. However, the downward hydraulic gradient induced by spillage from the nearby Grossman well was probably the primary cause of vertical stratification of salinity at this location. Well G-1502 (figs. 3 and 4), open between depths of 11 and 31 ft, was also sampled on October 27, 1978. The specific conductance and chloride concentration were 4,700 µS/cm and 1,200 mg/L, respectively.

Water in the Grossman Road borrow canal was sampled 22 times at a site near the location of well G-3124 (fig. 3). Flow in the canal was nearly always southward. The salinity of the water samples (table 4) was substantially higher than background. Because the Biscayne aquifer extends to land surface in the area, the 5 to 10 ft deep borrow canal penetrated flow pathways of the aquifer, intercepting the brackish water flowing from the Grossman well. Water from the Grossman well could not have reached the borrow canal by surface flow, except in the few instances when the entire area was inundated.

Table 3. Specific conductance and chloride concentration of water samples from wells northeast of the flowing Grossman well, 1978-79

[Well locations shown in figure 3. --, no data]

Date	Well cluster A			
	G-3204 (13 feet)		G-3205 (44 feet)	
	Specific conductance (microsiemens per centimeter)	Chloride (milligrams per liter)	Specific conductance (microsiemens per centimeter)	Chloride (milligrams per liter)
9-12-78	1,900	53	3,750	970
11-15-78	630	--	3,700	--
12-13-78	620	--	3,050	--
1-19-79	600	--	1,140	--
2-23-79	550	--	840	--
3-14-79	520	40	880	100
3-29-79	520	--	720	--
4-19-79	520	31	620	54
5-08-79	540	--	860	--
6-06-79	--	--	2,000	--
Mean	711	41	1,756	375

Table 4. Specific conductance and chloride concentration of water samples from a surface-water site southeast of the flowing Grossman well, 1978-79

[--, no data]

Date	Grossman Road borrow canal SW 184th Street	
	Specific conductance (microsiemens per centimeter)	Chloride (milligrams per liter)
4-25-78	1,580	310
5-18-78	1,700	--
6-14-78	1,820	--
7-11-78	1,200	--
8-13-78	1,700	--
9-19-78	720	--
10-11-78	1,280	240
11-20-78	950	--
12-18-78	1,400	--
1-17-79	1,540	--
2-14-79	1,480	--
3-14-79	1,160	--
4-23-79	1,350	240
5-30-79	970	--
6-20-79	1,930	--
8-30-79	1,790	--
10-15-79	1,020	170
11-19-79	1,400	--
12-26-79	1,260	--
1-30-80	1,330	--
2-20-80	1,430	--
4-24-80	1,160	--
Mean	1,371	240

Data Collection, Phase 2, 1982-86

Data collection by DERM included chemical analyses of water samples obtained from a network of wells, beginning in February 1982 and ending 22 months after plugging of the flowing artesian well in January 1987. Most of the wells were ones previously used by Waller (1982). Surface-resistivity surveys were performed in July 1986 and, together with results of the sampling program, are documented by Labowski (1988).

Data from the DERM sampling program (table 5) show some interesting contrasts with the earlier USGS data. Of the seven cluster wells (G-3193 to G-3199) located approximately on the axis of the plume in 1978-79, only well G-3195 was available for sampling after December 1982, the rest having been destroyed by farming activities or vandalism. The mean specific conductance and chloride concentration of water samples from well G-3195, between February 1982 and until the time (March 1985) when the Grossman well was plugged, were appreciably lower than in the 1978-79 period. In addition to data given in table 5, wells G-3193, G-3196, and G-3198 were sampled on February 26, 1982. Specific conductance values were 1,000, 1,000 and 800 µS/cm, respectively, and chloride concentrations were 160, 165, and 95 mg/L, respectively. Well G-3198 was sampled again on December 10, 1982. The specific conductance was 765 µS/cm and the chloride concentration was 118 mg/L. These values represent an appreciable decrease in salinity from the 1978-79 period. The salinity of water samples from G-3124 was generally lower, and the salinity of water samples from G-3108 and G-1363 was generally higher than that of the single sample taken from each well in the 1978-79 period. In addition, the average salinity of water samples from G-1363 increased in the period (1985-87) after the well was plugged.

Before the Grossman well was plugged, the salinity of water samples from well cluster A (wells G-3204 and G-3205) was generally similar to that of the 1978-79 sampling period. Salinity of water samples from well G-3205 continued to show high variability. On three occasions, the measured chloride concentration was higher than that of water flowing from the Grossman well; the reason for this is not known. After the well was plugged, salinity of water samples from wells G-3204 and G-3205 quickly approached background as the remnant plume moved downgradient toward the southeast.

Sampling from the southward-flowing Grossman Road borrow canal was expanded to four sites including SW 168th Street, SW 184th Street, SW 200th Street, and SW 216th Street (fig. 3). The salinity of water samples (table 5) collected from the northernmost site (SW 168th Street) was near background, indicating that the canal water was not contaminated by brackish water from the Grossman well at this location. However, the salinity of water samples collected from the site near well G-3124 (SW 184th Street) was at least as high as in the 1978-79 period, indicating that canal water at this location contained some of the brackish well water. The salinity of water samples collected from sites at SW 200th Street and SW 216th street was somewhat less, indicating that some dilution of the canal water by fresher ground water occurred as the canal water flowed south from SW 184th Street.

Table 5. Specific conductance and chloride concentration of water samples from wells and surface-water sites used to monitor

[Well locations shown in figure 3. Specific conductance (SpCon) shown in microsiemens per centimeter and chloride in milligrams per liter. ft, foot;

Date	Well cluster A				Well cluster C		Well		Well	
	G-3204 (13 ft)		G-3205 (44 ft)		G-3195 (12 ft)		G-3124 (10 ft)		G-3108 (70 ft)	
	SpCon	Chloride	SpCon	Chloride	SpCon	Chloride	SpCon	Chloride	SpCon	Chloride
Before Grossman Well Was Plugged										
2-26-82	--	--	750	90	800	100	740	100	--	--
8-06-82	600	50	2,700	800	800	100	800	130	950	110
12-10-82	600	70	4,350	1,500	770	170	600	100	920	130
3-25-83	590	60	4,600	1,300	770	120	550	70	850	130
7-21-83	630	70	3,500	950	790	110	590	70	880	120
11-22-83	550	70	4,100	1,950	690	110	490	60	780	110
3-01-84	530	70	1,220	330	690	90	500	50	790	110
6-18-84	600	60	2,600	750	700	90	600	80	850	110
8-02-84	580	70	3,540	1,000	700	80	510	60	780	100
11-30-84	570	60	2,600	730	600	60	450	50	720	90
2-17-85	520	80	650	130	650	100	510	50	90	140
Mean......	577	66	2,783	866	724	103	576	75	831	115
After Grossman Well Was Plugged										
3-19-85	530	70	560	90	680	130	580	120	830	180
4-04-85	530	50	580	70	660	90	1,000	90	810	100
4-19-85	650	--	680	--	800	--	750	--	980	--
5-06-85	540	--	580	--	660	--	650	--	800	--
5-22-85	540	60	570	70	680	90	660	--	830	120
6-18-85	550	--	610	--	680	--	740	--	920	--
7-19-85	580	--	520	--	680	--	660	--	850	--
8-09-85	570	--	630	--	680	--	610	--	940	--
9-20-85	650	--	620	--	680	--	580	--	820	--
10-28-85	640	--	580	--	680	--	560	--	820	--
11-22-85	550	50	550	50	600	60	500	50	750	70
2-04-86	500	40	500	50	600	70	550	70	750	100
3-28-86	500	40	550	50	650	70	600	90	800	100
5-29-86	520	50	520	60	650	100	680	130	800	75
8-07-86	500	50	500	50	630	80	600	90	800	110
1-16-87	--	50	--	50	--	100	--	100	--	110
Mean......	557	51	577	60	667	88	648	93	833	107

the plume of brackish water, 1982-87

--, no data]

Date	Well G-1363 (33 ft)		Grossman Road borrow canal							
			SW 168th Street		SW 184th Street		SW 200th Street		SW 216th Street	
	SpCon	Chloride	SpCon	Chloride	SpCon	Chloride	SpCon	Chloride	SpCon	Chloride
Before Grossman Well Was Plugged										
2-26-82	640	40	670	90	1,120	200	600	70	580	70
8-06-82	700	40	--	--	--	--	--	--	--	--
12-10-82	660	40	410	30	1,150	260	1,020	210	1,120	230
3-25-83	610	50	390	30	970	210	810	160	790	150
7-21-83	660	50	420	40	1,170	770	960	210	870	180
11-22-83	610	50	400	40	1,060	250	830	160	820	170
3-01-84	580	50	460	40	1,200	310	710	130	720	140
6-18-84	800	60	450	40	1,100	260	1,100	240	1,100	250
8-02-84	680	50	420	40	1,890	330	1,010	80	590	170
11-30-84	630	50	400	40	1,250	380	650	120	690	130
2-17-85	690	60	530	40	1,690	500	710	200	670	210
Mean ...	660	49	455	43	1,260	347	840	158	795	170
After Grossman Well Was Plugged										
3-19-85	730	130	570	--	2,000	--	740	--	620	--
4-04-85	--	90	--	90	--	210	730	130	650	140
4-19-85	870	--	620	--	2,300	--	930	--	750	--
5-06-85	690	--	490	--	1,020	--	720	--	620	--
5-22-85	730	70	490	70	1,980	560	820	160	610	130
6-18-85	750	--	460	--	1,900	--	680	--	1,060	--
7-19-85	740	--	480	--	2,050	--	1,340	--	1,380	--
8-09-85	810	--	450	--	1,880	--	1,300	--	1,250	--
9-20-85	760	--	420	--	--	--	--	--	820	--
10-28-85	790	--	450	--	1,600	--	1,190	--	1,080	--
11-22-85	700	60	400	30	1,300	280	1,250	290	1,150	250
2-04-86	700	60	500	40	1,700	420	750	130	450	150
3-28-86	700	70	400	30	--	310	1,500	350	850	160
5-29-86	700	70	450	40	1,800	420	700	110	700	120
8-07-86	650	60	400	40	1,120	260	1,100	230	1,000	230
1-16-87	--	60	--	40	--	250	--	100	--	100
Mean ...	737	74	470	48	1,720	339	984	188	865	160

Data Collection, Phase 3, 1990-92

In October 1990, 5 1/2 years after plugging of the artesian well, the USGS resampled the wells that remained among those used earlier to define the extent of the plume of brackish water and well S-196A with results given in the following table:

Well No.	Specific conductance (microsiemens per centimeter)	Chloride concentration (milligrams per liter)
G-3204	680	70
G-3205	640	60
G-3124	640	70
G-3108	900	140
G-1363	880	130
S-196A	680	60

In addition, the Grossman well borrow canal sites were revisited for the acquisition of water samples:

Surface-water site	Specific conductance (microsiemens per centimeter)	Chloride concentration (milligrams per liter)
SW 168 St.	500	50
SW 184 St.	760	80
SW 200 St.	720	80
SW 216 St.	640	70

Most of the salinity of the well water samples was only slightly higher than background, as were samples from the fountain outflow provided by the two local Biscayne aquifer wells drilled in July 1984, which had a specific conductance of 640 μS/cm and a chloride concentration of 60 mg/L. The fountain outflow continues to have a distinct sulfide odor, suggesting that some recirculation of brackish water spilled before 1985. The salinity of water samples from wells G-3108 and G-1363 was appreciably above background and higher than that of the 1982-87 sampling period. The dissolved-solids concentration in the water sample from well S-196A was near background.

Water samples from the Grossman Road borrow canal showed the same pattern as before, with the northernmost site (SW 168th Street) having background salinity and the other samples showing salinity elevated above background. However, the salinity of water samples from the three southernmost sites (SW 184th Street, SW 200th Street, and SW 216th Street) were substantially lower than that measured in the 1982-87 time period.

The most definitive salinity measurements should have been obtained from well G-3195, but this well could no longer be found after the conversion of a lime grove to a malanga field. For this reason, replacement wells were drilled at three sites in November 1991. The locations of the three wells (fig. 3, G-3469, G-3470, and G-3471) were chosen to lie more precisely on the axis of the plume as measured in 1979. Each well was drilled to 50 ft, and water samples were collected from the entire well after each 10 ft of penetration. Casing was then installed to 40 ft before collection of a final water sample. In each well, the specific conductance and chloride concentration of the water samples from the various lengths of open hole and from the completed well were nearly identical, consistent with earlier observations that little vertical stratification occurred. Additionally, a water sample was collected from a new recorder well (fig. 3, well G-3437) in January 1992 and again in March 1992. Average measured specific conductance and chloride concentration for wells G-3469, G-3470, G-3471, and G-3437 are given in the following table. The data for well G-3437 is represented by the sampling date of January 1992 in the table.

Well No.	Specific conductance (microsiemens per centimeter)	Chloride concentration (milligrams per liter)
G-3469	810	120
G-3470	850	130
G-3471	720	80
G-3437 (1/92)	510	50

Unlike the result of earlier measurements, the water sample from the most hydraulically upgradient well (G-3471) had a lower specific conductance and chloride concentration than water samples from downgradient wells G-3470 and G-3469. An effort was made to resample G-3469, G-3470, and G-3471 in May 1995. However, the locations of the wells were obscured by recent agricultural activity (G-3469) and by the use of areas surrounding the wells for debris storage and incineration following Hurricane Andrew in August 1992 (G-3470 and G-3471).

NUMERICAL SIMULATION OF THE PLUME OF BRACKISH WATER

The progressive development of the plume of brackish water was simulated for the purposes of: (1) demonstrating the use of computer simulation methods for assessing contamination in the Biscayne aquifer, and (2) providing the means for making predictions about the future movement and dispersal of the contaminant plume and its possible interaction with a proposed new well field. The principal difficulties involved in the simulation effort were as follows:

- Lack of reliable data describing the variation of the rate of discharge from the artesian well,
- Lack of data describing the plume before 1978 and the paucity of data thereafter,
- Need to adapt a computer code to represent the close hydraulic connection between surface water and ground water in the study area, and
- Lengthy computer processing times required for the simulations.

Results of the rate analysis have been briefly discussed, and available data describing the plume of brackish water have been presented. The remaining problems and resolution of the simulation objectives are discussed in the subsequent sections.

Simulation Code

The code selected for the simulation was the Subsurface Waste Injection Program (SWIP). This selection was made for two reasons: (1) the author's familiarity with details of the code, which permitted many complex modifications to be made with ease and confidence; and (2) the need for a three-dimensional solute-transport code for analysis of the plume of brackish water.

The SWIP code was developed by INTERCOMP Resource Development and Engineering, Inc. (1976), under sponsorship of the USGS and later revised for the USGS by the same firm renamed INTERA Environmental Consultants, Inc. (1979). Despite its intended use as a special package for waste-injection problems, the SWIP code received wider use within the USGS as a general-purpose three-dimensional simulator of solute- and thermal-energy transport in ground water. The code has been adapted for special purposes by various non-USGS public and private organizations. Some parts of the code have been used, with adaptation, as modules within a more recently developed USGS three-dimensional solute-transport code (Kipp, 1987).

The forms of the flow and solute transport equation solved by SWIP are as follows:

$$\underset{\sim}{\nabla} \bullet \underset{\sim}{K}(\underset{\sim}{\nabla} p - \rho \underset{\sim}{\nabla} z) = \frac{\partial}{\partial t}(\varnothing\rho) + q' \qquad (2)$$

and

$$\underset{\sim}{\nabla} \bullet C\ \underset{\sim}{K}(\underset{\sim}{\nabla} p - \rho \underset{\sim}{\nabla} z) + \underset{\sim}{\nabla} \bullet (\rho \underset{\sim}{E}) \bullet \underset{\sim}{\nabla} C = \frac{\partial}{\partial t}(\rho\varnothing C) + \Sigma q_i C_i \qquad (3)$$

where:

- $\underset{\sim}{K}$ is a hydraulic conductivity tensor (L/T),
- p is pressure (P/L^2),
- ρ is weight density (P/L^3),
- z is the coordinate in the vertical direction (L),
- $\varnothing$ is effective porosity (unitless),
- t is time (T),
- q' is a sum of fluid source and sink rates (P/L^3T),
- C is a unitless fraction ranging from 0 to 1 that represents the relative concentration of one of two fluids in a mixture, and
- q_i is a source or sink rate for fluid (P/L^3T) with concentration C_i.

P, L, and T indicate pound-force, length, and time units. $\underset{\sim}{\nabla} \bullet A$ denotes a divergence operator applied to vector A, and $\underset{\sim}{\nabla} A$ denotes the vector gradient of A. The forms of the diagonal (E_{ii}) and off-diagonal (E_{ij}) elements of the hydrodynamic dispersion tensor $\underset{\sim}{E}$ are as given by Kipp (1987):

$$E_{ii} = \alpha_l \alpha_t \frac{V_i^2}{V} + \alpha_t\ V + D_m$$
$$E_{ij} = (\alpha_l - \alpha_t)\frac{V_i V_j}{V} \qquad (4)$$

where:

- E_{ii} is the degree of dispersion in the *ith* coordinate direction related to the velocity of flow (V_i) in that coordinate direction,
- E_{ij} is the degree of dispersion in the *ith* coordinate direction related to the velocity of flow (V_j) in the *jth* coordinate direction,
- α_l is the longitudinal dispersivity (L),
- α_t is the transverse dispersivity (L), and
- V is the magnitude of the velocity (L/T) in the principal direction of flow,
- D_m is the molecular diffusivity (L^2/T).

The dispersion tensor operates on the concentration gradient vector $\underline{\nabla}C$, as implied by equation 3.

Solving the flow equation in terms of pressure enables the model to simulate flows caused by density gradients. The model accounts for fluid density and viscosity dependence on temporal changes of pressure, temperature, and solute concentration. Solution of equations for flow and solute and thermal-energy transport is by finite-difference techniques in which backward and central differencing in time and space are available as user options for solution of the equations for solute and thermal-energy transport. A Gaussian elimination technique and an iterative method are used to reduce the solution matrix size that results from the coupling of the three equations. The aquifer simulated can be fully confined or have a free surface, and the equations can be solved in either Cartesian or cylindrical coordinates.

Any fluids present in the aquifer or entering it in simulation scenarios are considered to be mixtures of the two fluids as described by the appropriate specification of C values. This approach works well for the problem of simulating the mixing of waters of different salinity which was the purpose of this study. C=0 was used to represent pure freshwater, and C=1 represented the most saline water in the modeled domain (the brackish water discharging from the artesian well). Values of density are associated by SWIP with the extreme values of solute fraction (C=0 and C=1) and are used in calculations of flows driven by density gradients and in adjusting hydraulic parameters.

The free-surface simulation capability was made part of the 1979 version of the code, but some minor errors had to be corrected by the author to make it work properly. The author has also modified the code to compute an evapotranspiration rate at all nodes designated as "recharge nodes." This function was coded implicitly to ensure stability (Trescott and others, 1976, p. 8). The author has made a number of additional mathematical and nonmathematical modifications to the code. Revisions or extensions of the mathematical procedures of the 1979 version of SWIP have been coded as options to preserve the original solution methodology.

As part of the construction of the model of regional flows in the Biscayne aquifer of southern Dade County (Merritt, 1995a) that provides boundary conditions for the plume simulation described herein, the code was modified to add representational options for the: (1) rewetting of dry nodes, (2) use of an upper layer of the model grid to represent overland sheetflow, (3) specification of control elevations to simulate the operation of control structures in thin strings of highly transmissive grid cells that are used to represent canals, and (4) specification of time-varying boundary conditions on the periphery of the modeled domain.

Other modifications made by the author consist of modified algorithms for the computation of vertical advective and dispersive fluxes of solute. The result of solute-transport computations in a particular physical representational problem is largely dependent upon the correct choice of numerical approximation methods and algorithm formulations for advective and dispersive transport and the avoidance of methods that would lead to erroneous or ambiguous results. A brief description of methods available in the modified version of the SWIP code, including standard and modified algorithms for representing vertical dispersion, and related restrictions on their use is presented in the following sections.

Numerical Dispersion and Oscillatory Behavior

When the user option of backward spatial differencing is selected for the advective terms, an error is introduced into the solution of the solute-transport equation that has the appearance of hydrodynamic dispersion. In one-dimensional computations, the degree of this first-order error, termed numerical dispersion, has been shown (Lantz, 1971) to be $U\Delta X/2$, where U is the fluid velocity and ΔX is the grid-cell dimension. The apparent dispersivity for the transport computation would be $(\alpha + \Delta X/2)$, where α is the dispersivity, a characteristic length used to represent the degree of physical dispersion that occurs in the aquifer. Lantz also shows in the one-dimensional case that backward differencing of the time derivative led to additional numerical dispersion of degree $U^2\Delta t/2\varnothing$, where Δt is the incremental time step and $\varnothing$ is the effective porosity. Thus, the actual degree of dispersion in the solute-transport solution would seem to be that which would be represented by a dispersivity of $(\alpha + U\Delta t/2\varnothing)$. In higher dimensions, the numerical dispersion terms are more complex but continue to influence the apparent degree of dispersion in the solution.

When central differencing in time or space is the chosen method, the corresponding finite-difference approximation is correct to the first order, and the first-order numerical dispersion terms are eliminated. Most of the apparent degree of dispersion in the transport solution depends on the dispersivities and is not determined by the local grid-cell size (given sufficiently fine discretization) or by a changing incremental time-step size. The different results obtained by use of the various optional approximation techniques have been illustrated with numerical examples in the discussion of numerical methods for solute-transport simulation (Merritt, 1993). Central-differencing approximations were used for the solute-transport computations in this study, and the apparent dispersivity in the solution is considered to be true mechanical dispersion lacking any appreciable component of numerical dispersion.

The formulation of the dispersion terms in the SWIP code suggests an interpretation of the dispersion process as an interchange of equal amounts of fluid between adjacent grid cells in the direction of flow, with the fluid received by each having the solute concentration (or fluid mix) of the nodal center of the other cell. Intuitively, this representation may be understood to work best when a region of changing concentration is finely subdivided into many grid cells in the direction of fluid movement. Alternatively, the representation might work best in regions where the spatial variation of concentration is "gradual" relative to the grid spacing. Similar advisement on finely discretizing the zone of concentration change is offered by Kipp (1987, p. 116-117).

The dispersion representation does not function as effectively when concentration changes are abrupt relative to the grid spacing in the direction of flow. In this case, specification of a large longitudinal dispersivity can cause the computed concentration variation to be distributed over a larger spatial volume than is realistic. Specification of a small longitudinal dispersivity might allow spatial oscillations to grow in the absence of the smoothing effect of dispersion (the "undershoot" and "overshoot" described by INTERCOMP Resource Development and Engineering, Inc., 1976). Spatial oscillations, when using central differences, indicate an incompatibility between the choice of longitudinal dispersivity and the grid dimensions. At times, the range of values that can be assigned to dispersivity might be restricted by a coarser than desired grid spacing mandated by the need for computational efficiency. Similarly, numerical oscillations at a grid node in sequential time steps indicate an incompatibility between the speed of solute movement and the time-increment sequence used to simulate it.

Numerical criteria for avoiding oscillatory behavior were developed by Price and others (1966) and are cited in the SWIP code documentation (INTERCOMP Resource Development and Engineering, Inc., 1976) and in the HST3D code documentation (Kipp, 1987, p. 114). Grid-cell dimensions and dispersivities chosen to realistically portray a zone of concentration change should be based upon physical measurements or the application of some physical conceptual model of the zone of dispersion based on data. In this study, the choice of grid-cell spacing and the longitudinal dispersivity, described in subsequent pages, is partly based on the reconstruction of the gradation of salinity in the plume as determined by the March 1979 surface-resistivity measurements (fig. 12).

Modified Dispersion and Advective Weighting Algorithms

A feature of the standard method of representing transverse dispersion in solute transport models such as SWIP is that the transverse dispersivity describes the degree of mechanical dispersion in a plane perpendicular to the direction of flow without distinguishing between transverse dispersion in the plane of flow (the bedding plane) or perpendicular to it (dispersion in the crossbed or vertical direction). However, macroscopic hydraulic properties might be different or have different degrees of spatial continuity along the different directional components of fluid flow paths. In rocks with solution porosity, transverse dispersion might be partly related to the tortuous orientation of solution features, but the extent to which this occurs might not be the same in the vertical direction as in the plane of flow.

When vertically adjacent layers are of different lateral hydraulic conductivity, the more permeable layer might be partially flushed by water of different quality than the other, perhaps as a result of flow from a recharge area or from an injection well that has not flushed the less-permeable zone to a similar extent. Usually the flow direction in the more permeable layer is nearly parallel to the interface between layers. Because of common data limitations and the need to spatially discretize hydraulic properties for application of finite difference approximations, the vertical transition of hydraulic properties and water quality is usually represented as a step function between adjacent layers of grid cells. In this case, use of central-difference approximations for vertical advective flux of solute across the interface between layers would imply that water flowing across the interface would have a solute composition that is a mixture of the two waters. However, a more realistic conceptual model of flux across the interface is of hydraulically driven seepage of water having the quality of that in the originating layer. Thus, an upstream (backward) advective weighting scheme would be more appropriate for representing the solute concentration of vertical advective flux.

When vertically adjacent layers contain waters of different quality, the vertical component of dispersion implied by the dispersion algorithm might be inappropriate because the transition of water quality does not occur gradationally across the thicknesses of several grid cells and is nearly perpendicular to the direction of flow. The nodal interchange representation in the vertical direction might not represent any known physical process. Providing a finer vertical discretization in the neighborhood of a vertical transition in water quality might not always be computationally efficient, and there might not be any data describing gradational hydraulic and water-quality variations. The degree of dispersion in the vertical direction can be made small by the specification of a low value for transverse dispersivity, but use of the small value might not be appropriate in the horizontal plane.

Further details concerning these problems are presented in a report by Merritt (1993). Also described in that report is another problem that occurs when there is a large difference in scale between the horizontal and vertical dimensions of grid cells. When transport processes occur over distances of several miles in aquifers a few tens of feet thick, computational economy might mandate that the ratio of average horizontal and vertical grid dimensions be two or more orders of magnitude. A large value for longitudinal dispersivity might be required to represent the degree of dispersion in the coarsely discretized horizontal plane. However, particularly if a smaller but still appreciable degree of vertical flow occurs, the component of simulated dispersion in the vertical direction related to the large value of longitudinal dispersivity might obscure actual vertical solute concentration variations.

Therefore, to provide the means for more realistic simulation of transport processes in the situations described, modified algorithms for representing vertical advective and dispersive fluxes of solute were encoded as options in the SWIP simulator. The modified algorithms implement the concepts described in the following statements:

- Mechanical dispersion in the vertical direction is identically zero between adjacent layers of different permeability [$(K_x(k) \neq K_x(k\text{-}1))$], where K_x is the hydraulic conductivity in the X-coordinate direction. Molecular diffusion between layers occurs as before. Between layers of similar permeability [$K_x(k) = K_x(k\text{-}1)$], mechanical dispersion in the vertical direction is scaled by a user-specified factor S ($0 \leq S$).
- Vertical advective flux of solute receives upstream weighting (backward differencing) across the boundary between layers of different permeability [$K_x(k) \neq K_x(k\text{-}1)$], regardless of which weighting is used in the rest of the spatial domain of the model.

These modified algorithms implement the conceptual view that solute flux across the boundaries between layers of different permeability occurs as molecular diffusion or as hydraulically driven seepage in which the water flux has the solute concentration of the source layer. The scaling factor is a user-specified parameter for problems where bedding effects or the horizontal discretization might cause incompatibility in the description of horizontal and vertical dispersive processes in a homogeneous layer. When the modified algorithms are not selected as an option by the model user, the standard (unmodified) algorithms for vertical dispersion of solute and the concentration-weighting of vertical advective flux of solute are used. These standard algorithms are as coded in the version of SWIP documented by INTERA Environmental Consultants, Inc. (1979).

Time-Step Restrictions

In early attempts to simulate transport of the intruding artesian water, increasing the time-step length beyond a certain limit caused divergence of the matrix inversion process when using the iterative solver, resulting in premature termination of the simulation. The situation was unrelated to the violation of time-step restrictions required to prevent oscillatory behavior. In fact, no unusual degree of oscillatory behavior was observed in the time steps immediately preceding the one in which divergence and the consequent run termination occurred.

A review of the formulation of the solution matrix helped to reveal the cause of this problem. Because the solution matrix before inversion contains diagonal elements with an inverse dependence on the time-step size, Δt, and off-diagonal elements with a linear dependence on fluid velocity, an ill-conditioned matrix (not diagonally dominant) can result when both fluid velocity and the computational time step are large. When the iterative matrix solver is used to invert this matrix, numerical roundoff causes the successive solution estimates to diverge and assume very large positive or negative values. Therefore, when flow velocities in the modeled domain fall within a certain range of magnitude, there is an upper limit for an allowable time-step length beyond which the iterative matrix solver does not perform successfully. If the prevailing flow velocities increase or decrease, the limiting time-step length also decreases or increases, respectively.

In the early simulation time periods of the present study that correspond to the period before canals were constructed in the study area (fig. 2), the maximum simulation time step that could be used varied from 1 to 3 days. The first 23 years of plume development had to be simulated with this time-step restriction; thus, very long computational (clock) times were required for these runs. The maximum usable time step was less in wet-season months of high aquifer recharge than in dry-season months.

At simulation times corresponding to the period when canals were present in the study area (canals were embedded in the model grid as strings of cells of high hydraulic conductivity) and when control structures were open to allow rapid canal flow (fig. 3), the maximum usable time step was only 0.15 to 0.25 day. This situation prevailed for several months during the 1968-82 time period and for all of the succeeding 1983-89 time period. Accordingly, the required computational (clock) times were even longer than for the early time periods.

The SWIP code also contains an optional direct, noniterative matrix solver. Tests showed that its use required substantially more computer-processing time than the iterative solver to invert the large three-dimensional matrix in the model of solute transport developed for this study. Whether similar time-step restrictions would be required using the direct solver was not studied. However, severely ill-conditioned matrices are difficult to invert with any available techniques, and it is likely that use of the direct solver would not have entirely removed the time-step restriction.

Use of backward-in-time differencing approximations was studied because this differencing method and the consequent larger apparent dispersion in the solution often permit use of time steps larger than those permitted by central differencing in time without causing spatial oscillations. However, the time-step restriction required to prevent ill-conditioning of the solution matrix was found to be virtually unchanged by use of the backward-in-time method.

Other Code Modifications

In initial attempts to simulate the transport of brackish water, divergence of the iterative matrix solver and premature run termination occurred after just a few computational time steps and with no prior indication of solution instability. The problem was independent of the previously cited time-step restrictions. An analysis revealed the difficulty to be related to the initialization of temporary matrix elements in the iterative solver when corresponding elements in the matrix to be inverted were zero, an indicator that the corresponding grid cell was dry. This situation had not occurred during use by the author of older versions of the model code because the occurrence of a dry cell was considered to be an error condition. The problem was easily corrected by using a larger initialization value.

Another modification was the coding of procedures to output pressure and concentration matrices at the end of various time periods for use as initial conditions at the beginning of the next time-period simulation. The normal use of restart records was not feasible because the designs of the sequential time-period models differed in many ways. Still another modification was a procedure to automatically reduce the maximum permitted time-step size when control structures in the canals opened. This was done to reduce the chance of premature run termination caused by the solution matrix becoming ill-conditioned when canal-water velocities greatly increased.

Design of Simulators

The simulators designed for each of the five water-management time periods (water years 1945-52, 1953-61, 1962-67, 1968-82, and 1983-89) delineated as part of the construction of the regional flow model (Merritt, 1995a) were independent, at least in a formal sense, although most elements of the model designs were common to all of them. The primary differences were the presence of canals and control structures in the study area in time period 4 (water years 1968-82) and time period 5 (water years 1983-89). In addition, significant changes in the magnitude and direction of regional flow (figs. 8 and 9) were caused by construction of canals and levees outside the study area at the beginning of time period 3 (water years 1962-67). Additional changes were caused when control structures began to be used for nearly year-round drainage during time period 5.

Relation Between Regional and Subregional Models

This study made use of a previously calibrated regional model of ground-water flow by using selected head values computed by the regional model as boundary conditions for subregional models of a smaller area (the study area) contained in the area of the regional model. The relation between the geographical areas contained in the regional flow model grid and the subregional model grid is shown in figure 13.

Many parameter values assigned to the subregional model of the study area were those also used in the corresponding part of the regional model grid. Land-surface elevations varied from 4.3 ft above sea level in the southwestern corner of the subregional model area to 10 ft above sea level in Grossman Hammock and in the part of the coastal ridge comprising the southeastern corner of the subregional model area. In comparison with land-surface elevations, water-table altitudes or surface-water stages computed by the regional flow simulation for the subregional study area varied from drought-induced lows of 0.3 ft below sea level in May 1965 and April 1971 near the southern and western boundaries to a high of 11.1 ft above sea level in the center of the eastern boundary in October 1947, when two hurricanes passed through the area. At this time, the simulated depth of inundation was as much as 4 ft south of the Grossman well and as much as 2.5 ft in the rocky glades in the northeastern part of the modeled area.

Subregional Grid Design and Boundary Conditions

The subregional area delineated in figure 13 was discretized into 37 columns and 36 rows as shown in figure 14. The artesian well was located in grid cell (7,10). The grid spacing is generally about 500 ft in the vicinity of the artesian well and increases with distance from the well to about 3,000 to 5,000 ft near the southeastern corner of the grid.

As in the regional flow model, tightly bunched pairs or trios of grid lines outline thin strings of grid cells used to represent canals and levees in later time periods (after 1961). Column 14, representing the Grossman Road borrow canal in rows 1 to 25, is too narrow to be shown at the scale portrayed in figure 14. The exact positions of canals, levees, and control structures in the grid designs for time period 4 (water years 1968-82) and time period 5 (water years 1983-89) are shown in figure 15.

To obtain specified but time-varying boundary conditions for the subregional model, the grid shown in figure 14 was embedded in the grid of the regional flow model, increasing the dimension of the regional grid from 32 × 36 to 58 × 55. As the transient regional simulations for the 5 water-management time periods were repeated using the denser grid, 10 selected heads along each boundary of the subregional model were stored. These heads were in either row 6 or column 12 of the original and redimensioned grids (fig. 13) and in either row 39 or column 47 of the redimensioned grid (within either row 21 or column 25 of the original grid). After reformatting, these transient heads were entered into the subregional model as specified time-varying monthly average boundary conditions, using the procedures developed for the regional flow model (Merritt, 1995a). Boundary pressures at the centers of exterior faces of all boundary grid cells were then computed by interpolation in time and space.

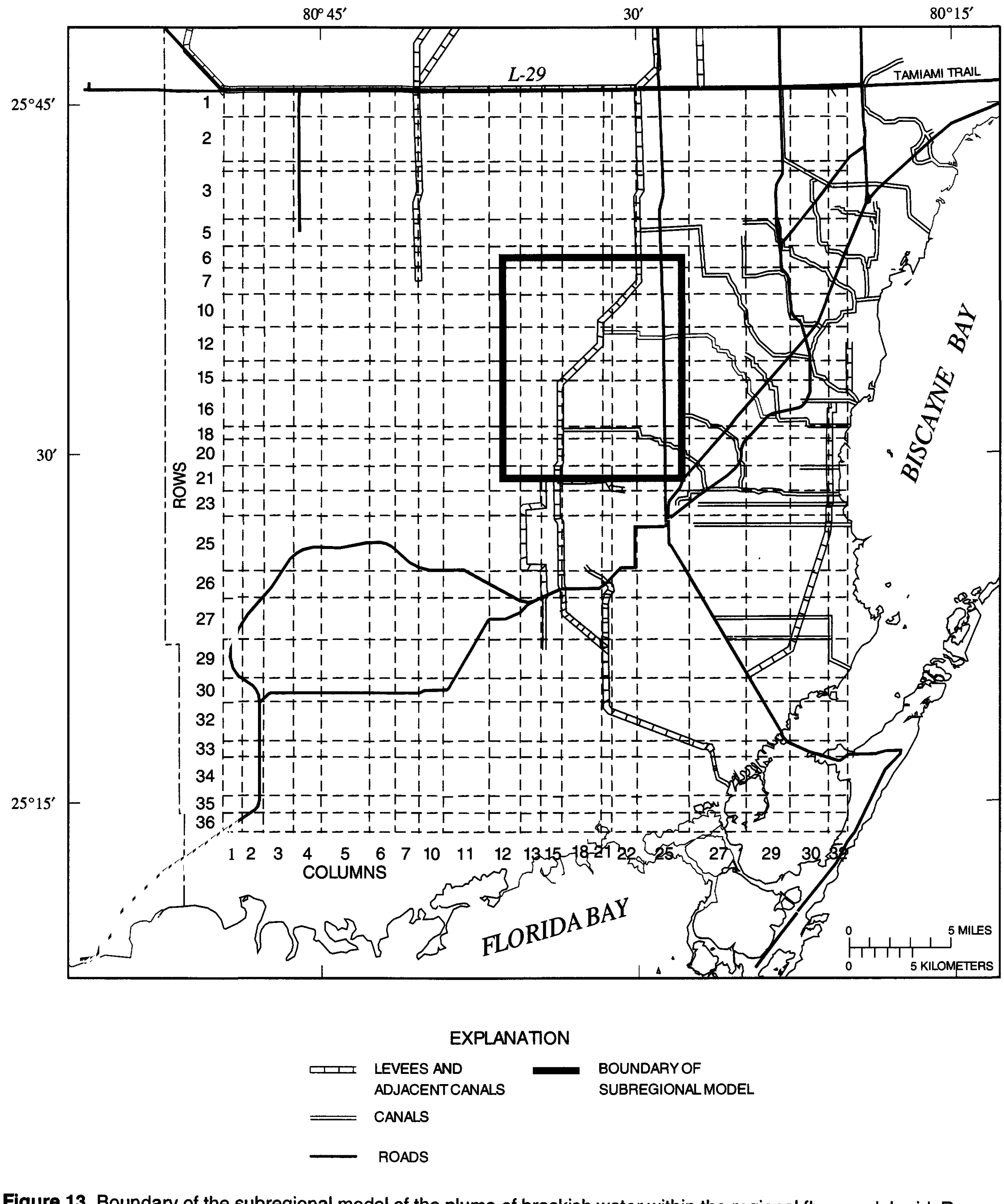

Figure 13. Boundary of the subregional model of the plume of brackish water within the regional flow model grid. Rows and columns not shown are too small in dimension to illustrate in this figure.

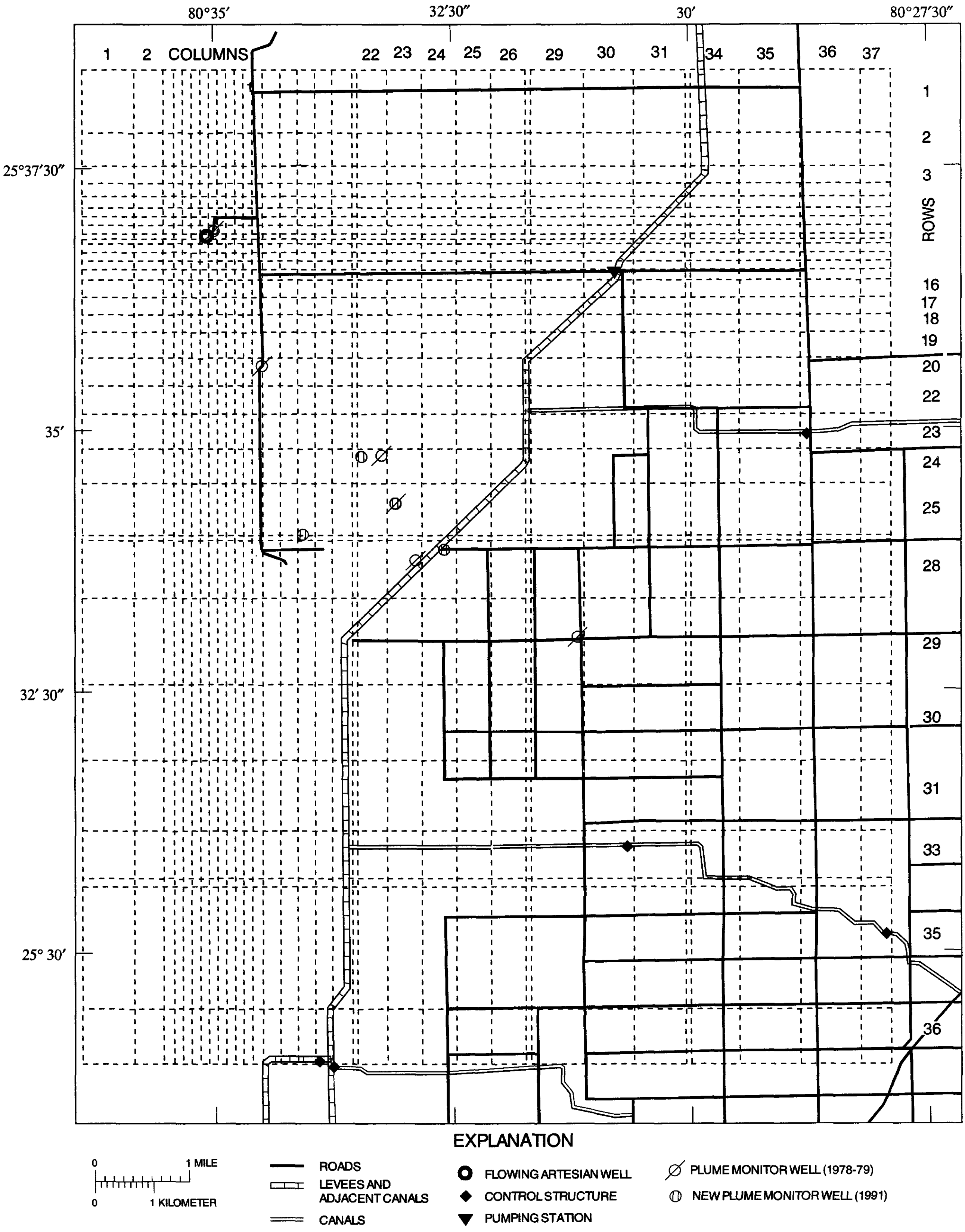

Figure 14. Horizontal discretization of the area contained within the subregional model of the plume of brackish water. Rows and columns not shown are too small in dimension to illustrate in this figure.

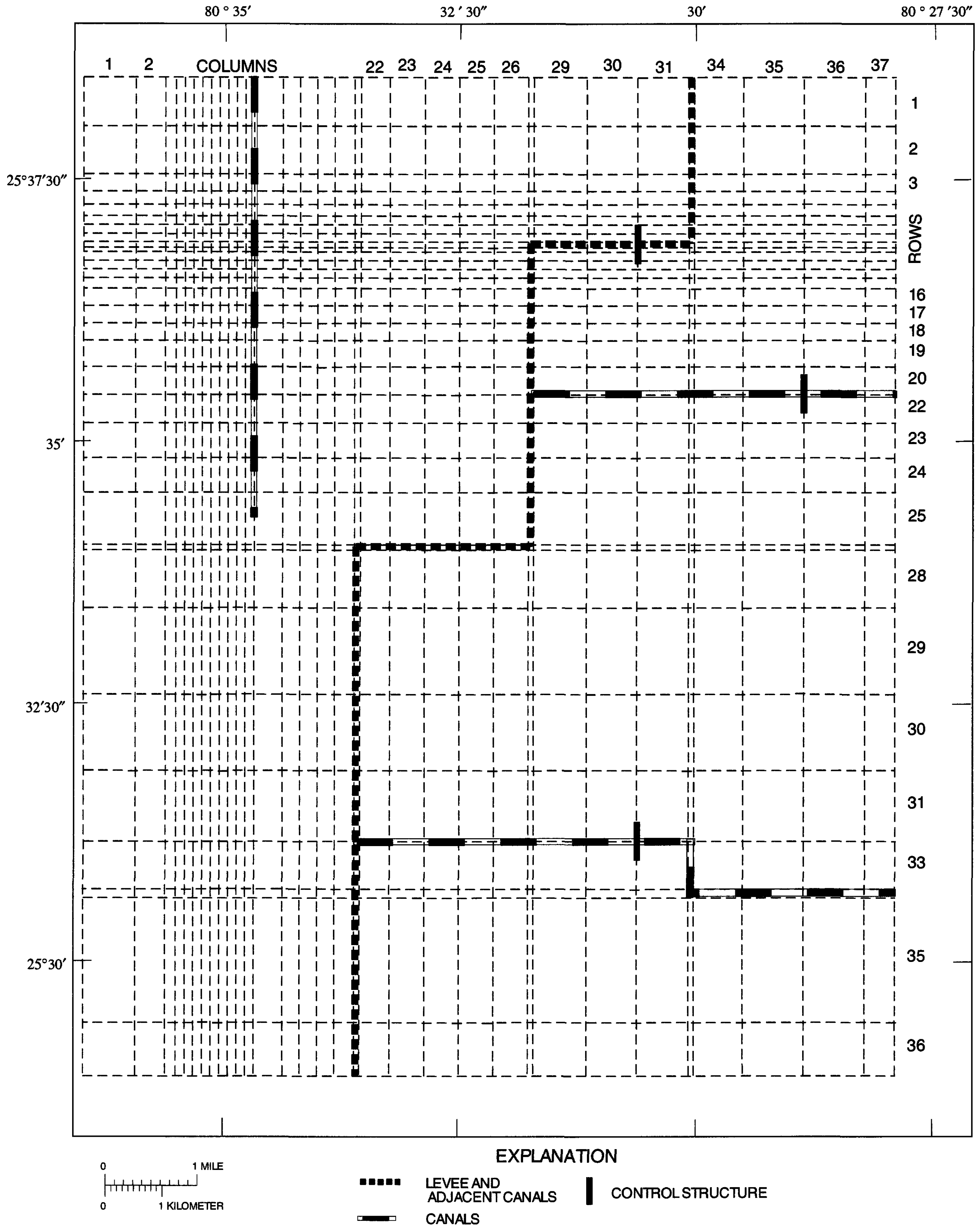

Figure 15. Grid cells used to represent canals, levees, and control structures at simulation times after 1967. Rows and columns not shown are too small in dimension to illustrate in this figure.

The vertical grid design was similar to that of the regional model. The upper layer, never fully saturated, represented overland sheetflow. In most of the modeled area, this layer was usually dry. Cells of the upper layer that were frequently partially saturated occurred primarily northwest, west, and south of the artesian well. When the simulated water table rose above land surface in large parts of the study area in response to heavy rainfall, rewetting procedures developed for the regional flow model were used to enable some dry cells of the overland flow layer to partially resaturate. Low values of hydraulic conductivity were assigned to certain cell strings of the top layer to represent levees.

Layer 2 represented the depth interval from land surface to sea level, as in the regional model. The thickness of this layer varied from 4.5 ft near the southwestern boundary of the grid to 10 ft in the southeastern part of the grid and in the small area representing Grossman Hammock. High values of hydraulic conductivity were assigned to certain cell strings in layer 2 to represent canals. Layer 2 was identified as a peat layer in the northwestern corner of the grid, an area where overland flow occurred regularly. Elsewhere, except for canal cells, layer 2 was considered an upward extension of layer 3, which represented the Miami Limestone. The fourth and bottom layer represented the Fort Thompson Formation. The thicknesses of grid cells in layers 3 and 4 were based on analyses of rock samples (Causaras, 1987) from test holes (G-3310, G-3314, and G-3315) drilled as part of the Surficial Aquifer System Study at locations shown in figures 3 and 6. A uniform thickness of 20 ft was assigned to layer 3; thicknesses ranging from 15 to 50 ft that generally increased southeastward were assigned to layer 4.

Flows were computed with the redimensioned regional model and the subregional model in each water-management time period to validate the process of using heads computed by the regional model as boundary conditions for the subregional model. This was done before attempting solute-transport computations. In each time period, all computed heads agreed within about 0.1 ft with those of the original regional model at grid cells corresponding to observation wells in the geographical area of the subregional model.

The point source of contamination, the spillage of brackish water from the flowing Grossman well, was represented as an injection well open to the 10-foot thickness of layer 2, the upper part of the Miami Limestone. This is consistent with the fact that much of the brackish water entered the aquifer through a 15-foot deep borrow pit, directly downward from the surface a short distance beyond the borrow pit, or through breaks in the liner of the shallow lake, although some brackish water might have entered the aquifer through breaks in the Grossman well casing at a greater depth.

Elimination of Surface Flow from Transport Solution Domain

Because rapid surface-water flows greatly restricted the maximum usable time-step size, and thereby greatly increased the required computer processing time, it was thought advisable to eliminate the surface-water grid cells in the overland flow layer and the strings of canal grid cells from the domain of the solute-transport computation (that is, delete equations corresponding to overland flow grid cells and canal grid cells from the solution matrix). This was considered consistent with the goal of the study, which was to simulate transport of the brackish water in the Biscayne aquifer. Simulation of transport of solute in surface-water bodies was considered beyond the scope of the study.

Elimination of the overland flow layer grid cells was achieved easily by specifying the appropriate value for a user option to indicate that the upper layer represented overland flow. Coefficient matrix elements corresponding to grid cells of the upper layer were then given negative values that served as a signal to the iterative solver to delete the corresponding equations from the solution. Overland flow layer cells were still included in the solution of the flow equation and could still be a source or sink of solute by advective and dispersive flux or by molecular diffusion in the solution of the solute transport equation. The sole effect of the code modification was that solute fraction values assigned to the overland flow layer as initial conditions could not be changed during subsequent solute-transport computations.

While elimination of the overland flow layer from the solute-transport solution had significant advantages from a computational standpoint, its hydrologic significance was important only during a few periods of unusually high water, which occurred with less frequency after Levee 29 (fig. 1) was completed north of the study area in 1961. Generally, overland sheetflow in the study area occurred only in a region northwest, west, and south of the site of the artesian well discharge, and normally did not occur in most of the area in which aquifer water was displaced by intruding brackish artesian water. The sheetflow layer was arbitrarily assigned an initial solute concentration value of zero, which had numerical consequences that will be discussed later.

Attempts were made to eliminate the thin strings of highly conductive grid cells representing canals from the solute transport solution for computation times when the canals were present in the study area (after 1968). This was not achieved even though several techniques were tested. Most of these techniques involved a search for grid cells with high hydraulic conductivity in the second and lower layers and the use of various strategies to eliminate the corresponding equations from the solution. However, the result of each attempt was to cause divergence of the iterative matrix solver as if the solution matrix had become ill conditioned. The effort to eliminate the canal cells was abandoned.

In some model analyses, canals were eliminated from both hydraulic and transport solutions. This was done by assigning aquifer hydraulic conductivity values to the canal grid cells. This had the undesirable side effect of also eliminating the local hydraulic influence of the canals in providing rapid recharge or drainage. However, the regional effect of the canal system was represented by the use of boundary conditions from the regional flow model in which the canal system was fully represented. The significance of this approach will receive more detailed discussion later in the report.

Retention of the canal cells in other analyses was found to have advantages for the study. First, the local hydraulic influence of the canals was represented. In addition, the behavior of the model in simulating the leaching of the plume or its dilution by canal recharge could be studied and compared with water-quality data to determine if it seemed to represent processes that actually occurred.

The computation of solute-transport equations in a grid domain that included canal reaches required stringent time-step restrictions, imposed by periodic high flow velocities in the canals. This was considered an acceptable tradeoff for being able to assess the simulated effect of canal flows on the plume of brackish water.

Inclusion of the canal cells in layer 2 solute-transport calculations had one disadvantage analogous to previously cited difficulties concerning the use of standard dispersion algorithms in computing dispersion between vertically adjacent layers having different hydraulic properties and water quality. As in the latter case, the nodal interchange representation of mechanical dispersion between aquifer and canal cells, occurring in a direction that is usually almost perpendicular to the prevailing flow direction and that crosses a discontinuity in solute concentration, might fail to represent any known physical process. Much smaller fluxes simulated as advective flow and molecular diffusion between canal and aquifer might be the only processes represented in the model that actually transfer solute in the real-world environment. Therefore, the model equations might overestimate the transfer of solute between aquifer and canal cells. This could lead to an overestimate of the effect of the canal in removing solute from the aquifer or in diluting its concentration in the aquifer.

Physical, Hydraulic, and Chemical Parameter Assignments

Monthly average rainfall and maximum evapotranspiration rates, rates of flow through pumping station S-331 (after its use began in 1983), and control elevations at canal structures (after their construction in 1967) were entered from an input file of monthly average boundary value assignments—the same procedure previously used in running the regional flow model. Values were the same in both regional and subregional models and included selected substitution of monthly rainfall values as described for the regional flow model (Merritt, 1995a). The evapotranspiration extinction depth was 20 ft, except in the northwestern corner of the modeled area where layer 2 represented peat and the evapotranspiration extinction depth was 5 ft.

Control elevation specifications were applied to pairs of adjacent grid cells in canal cell strings. When the upstream stage was less than the specified elevation, the intercell transmissivity was set equal to zero, which represented a no-flow condition at that location in the canal cell string. Control elevations for the two manually operated structures, S-196 and S-194, were given zero values in months when the structures were opened to reduce the effects of heavy rainfall, as was done in the regional model for time period 4 (water years 1968-82). Because these structures were simulated as always being open in time period 5 (water years 1983-89), zero control elevations were also used throughout this time period. Pumping rates at station

S-331 were not allowed to exceed monthly average values of 300 ft^3/s (cubic feet per second), as in the regional model.

Isothermal conditions at 75 degrees Fahrenheit were assumed to prevail in the Biscayne aquifer. Field measurements of the temperature of water samples from the first seven wells listed in table 2 ranged from 74 to 77 degrees Fahrenheit and did not seem to vary seasonally. This is consistent with the experience of USGS technical personnel who conduct regular reconnaissance of water quality in the study area. The effect of diurnal or seasonal temperature variations is restricted to an upper few feet. Because of the temperature uniformity, the viscosity of the native ground water was nearly uniform in the modeled region.

A solute fraction value of zero representing water with no dissolved solids and a corresponding weight density value of 62.2612 lb/ft^3 (pounds per cubic feet) at 75 degrees Fahrenheit was obtained from a standard handbook. A solute fraction value of 1.0 represented the discharging artesian water, which was assigned a weight density of 62.4108 lb/ft^3 at 75 degrees Fahrenheit based on an average dissolved-solids concentration of about 3,000 mg/L (table 1). Because the native Biscayne aquifer water has an average dissolved-solids concentration of about 300 mg/L, an initial solute fraction value of 0.10 was assigned to water in the modeled region. Rainfall recharge was assigned a solute fraction value of 0.002, representing a dissolved-solids concentration of 6 mg/L.

In initial attempts to simulate the plume, layer 4 (representing the Fort Thompson Formation) was assigned a horizontal hydraulic conductivity value of 40,000 ft/d in the horizontal plane. Layer 3 and most of layer 2 (representing the Miami Limestone) were both assigned a lower horizontal hydraulic conductivity value of 5,000 ft/d. Hydraulic conductivity was assumed to be horizontally isotropic. A 1:10 vertical to horizontal anisotropy ratio was used for all layers. Layers 3 and 4 were assigned effective porosity values of 35 percent, a value representative of the results of neutron porosity logging in the solution-riddled Upper Floridan aquifer. Layer 2, however, was assigned an effective porosity value of 20 percent, the estimated value of specific yield of the Biscayne aquifer. In layer 4, the plume of brackish water simulated for early 1979 generally resembled the one observed in March 1979 (fig. 11). However, the extent of the plume in layers 2 and 3 was less than observed because the lower hydraulic conductivity values assigned to these layers restricted flow. The computations showed a distinct vertical stratification of solute concentration that was at variance with the field measurements (table 2).

Subsequently, the model was revised to assume vertical uniformity of hydraulic properties in all layers corresponding to limestone of the Biscayne aquifer (the Miami Limestone and the Fort Thompson Formation). The chosen values were 30,000 ft/d for horizontal hydraulic conductivity and 20 percent (the specific yield estimate for surface rocks) for effective porosity. With these values, simulated chloride distributions resembled the measured plume in all aquifer layers of the model grid.

Dispersivities

Various dispersivity values were specified in a series of model runs to assess the influence of longitudinal and transverse dispersivities on the simulated development of the plume of brackish water. Results were compared with the plume observed in 1979 to determine the dispersivity values that best replicated the observed data. The analysis, therefore, served a purpose both as a sensitivity analysis and a preliminary calibration. Later computations through the 1979 water year lent support to the results of this procedure.

The most appropriate way to evaluate the results of these tests would be to compare chloride distributions simulated for March 1979 with the measurements of that date (fig. 11). However, the great amount of computer-processing time that was required to simulate 35 years of solute transport motivated the formulation of an alternative approach in which only the development of the plume until 1961 was simulated. The chloride distributions simulated for 1961 were examined to determine whether concentration gradients were qualitatively similar to those observed in March 1979. Simulations were also performed to determine whether the degree of transverse dispersion in the plane of flow should be differentiated from the degree of vertical transverse dispersion by using the modified vertical dispersion algorithm and a vertical scaling factor.

Comparing the simulated 1961 plume of brackish water with the measured 1979 plume was a more realistic procedure than might at first appear. The simulated 1961 plume represented an approximate steady-state condition after 17 years of brackish water transport under relatively stable hydraulic conditions. However, the general direction of flow near the discharging well changed at the end of the 1961 water year (fig. 8). As will presently be shown, a second plume then began to develop that, in March 1979, represented a second 17.5 years of brackish water transport under relatively stable hydraulic conditions, albeit different from those of the 1945-52 and 1953-61 water-management time periods. Computational efficiency was greater in the earlier time periods because of the lack of canals (so that larger time steps could be used), and results of the comparison tests seemed to be reasonably definitive in establishing qualitative differences between substantially different dispersion models (sets of dispersivities, choices of vertical dispersion algorithms, and vertical scaling factors).

Because the grid spacing near the origin of the brackish water was generally about 500 ft, 250 ft was the theoretical minimum value for the longitudinal dispersivity (α_l) for which all spatial oscillations could be avoided (INTERCOMP Resource Development and Engineering, Inc., 1976). Therefore, this value was the lower of the two values used in the comparison tests. The higher value used was 1,000 ft. The transverse dispersivity (α_t) was assigned values equal to the longitudinal dispersivity in some tests and a value of 0.1 ft in others. In the initial tests, the modified algorithms for vertical dispersion and vertical advective weighting described in a previous section were used. A vertical scaling factor of 0.01 was used when $\alpha_t = \alpha_l$, but vertical dispersion was not scaled when $\alpha_t = 0.1$ ft. Because layers 2, 3, and 4 are hydraulically uniform, except for a small area where layer 2 represents peat, the only result of the use of the modified dispersion and advective weighting algorithms was that: (1) vertical dispersive fluxes between the overland flow layer and layer 2 of the aquifer were eliminated, and (2) vertical dispersion between aquifer layers 2, 3, and 4 was scaled in some runs.

Results of the initial comparisons are illustrated in the sets of lines of equal chloride concentration simulated for October 1961 (fig. 16). Each set shows lines of 100, 200, 300, 400, and 500 mg/L chloride concentration. Lines of higher concentrations are difficult to show at this scale and are omitted even though solute fraction values equivalent to chloride concentrations as high as 1,200 mg/L were computed.

When $\alpha_l = \alpha_t = 1{,}000$ ft, the simulated October 1961 plume is rather rounded and does not extend very far downgradient (fig. 16*A*). This illustrates the influence of the relatively large degree of longitudinal dispersion and horizontal transverse dispersion that results from the specification of the large dispersivities. When $\alpha_l = \alpha_t = 1{,}000$ ft, the scaling factor of 0.01 means that the degree of vertical dispersion is approximately as if $\alpha_t = 10$ ft. This degree of dispersion, however, appears to cause sufficient vertical mixing that concentrations are vertically uniform and the extent of the plume is the same in the three aquifer layers. This is consistent with data measured in March 1979 that indicated vertical concentration uniformity. However, the measured plume was more elongated.

When α_l is maintained at 1,000 ft and α_t is reduced to 0.1 ft, the October 1961 lines extend farther downgradient because there is less dispersal of brackish water perpendicular to the direction of flow (fig. 16*B*). Lines are still somewhat rounded, owing to the high rate of longitudinal dispersion and the seasonal rotation of the average flow direction (fig. 8). Because the vertical scaling factor is unity, the degree of vertical dispersion between the aquifer layers is completely specified by the transverse dispersivity $\alpha_t = 0.1$ ft. However, vertical dispersive mixing apparently still causes concentrations to be vertically uniform and the extent of the plume is still the same in the three aquifer layers.

When $\alpha_l = \alpha_t = 250$ ft, the simulated plume is less dispersed to the north, east, and west of the source (fig. 16*C*) but extends farther downgradient than when $\alpha_l = \alpha_t = 1{,}000$ ft (fig. 16*A*). This is a demonstration of the reduced influence of dispersive flux relative to that of advective flux. The plumes are still the same in extent in all aquifer layers, showing that vertical mixing is sufficient to cause concentrations to be vertically uniform. The transverse dispersivity (α_t) of 250 ft is vertically scaled by a factor of 0.01 so that the degree of simulated vertical dispersion was approximately as if a transverse dispersivity of 2.5 ft had been specified.

When α_l is maintained at 250 ft and α_t is reduced to 0.1 ft and vertical dispersion is unscaled, the simulated October 1961 plume extends even farther downgradient than before (fig. 16*D*). The simulated distribution of brackish water is now qualitatively similar to the estimated distribution based on the March 1979 measurements (fig. 12). Compared to the case in which $\alpha_l = 1{,}000$ ft and $\alpha_t = 0.1$ ft (fig. 16*B*), the simulated lines of equal concentration are longer and narrower because the smaller α_l value reduces the degree of dispersion in the direction of flow as the average flow direction rotates seasonally.

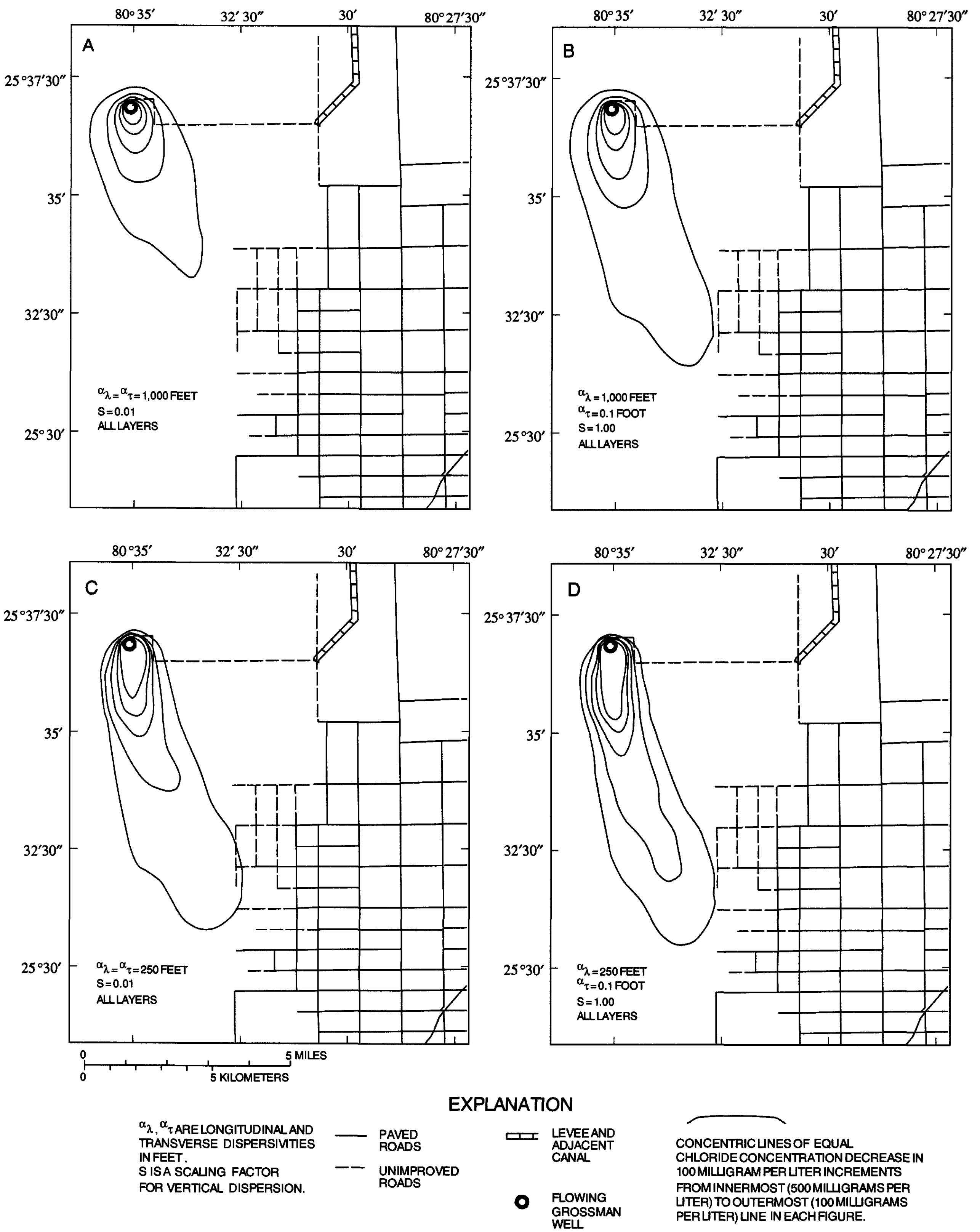

Figure 16. Simulated distributions of brackish water in October 1961 corresponding to various dispersion models.

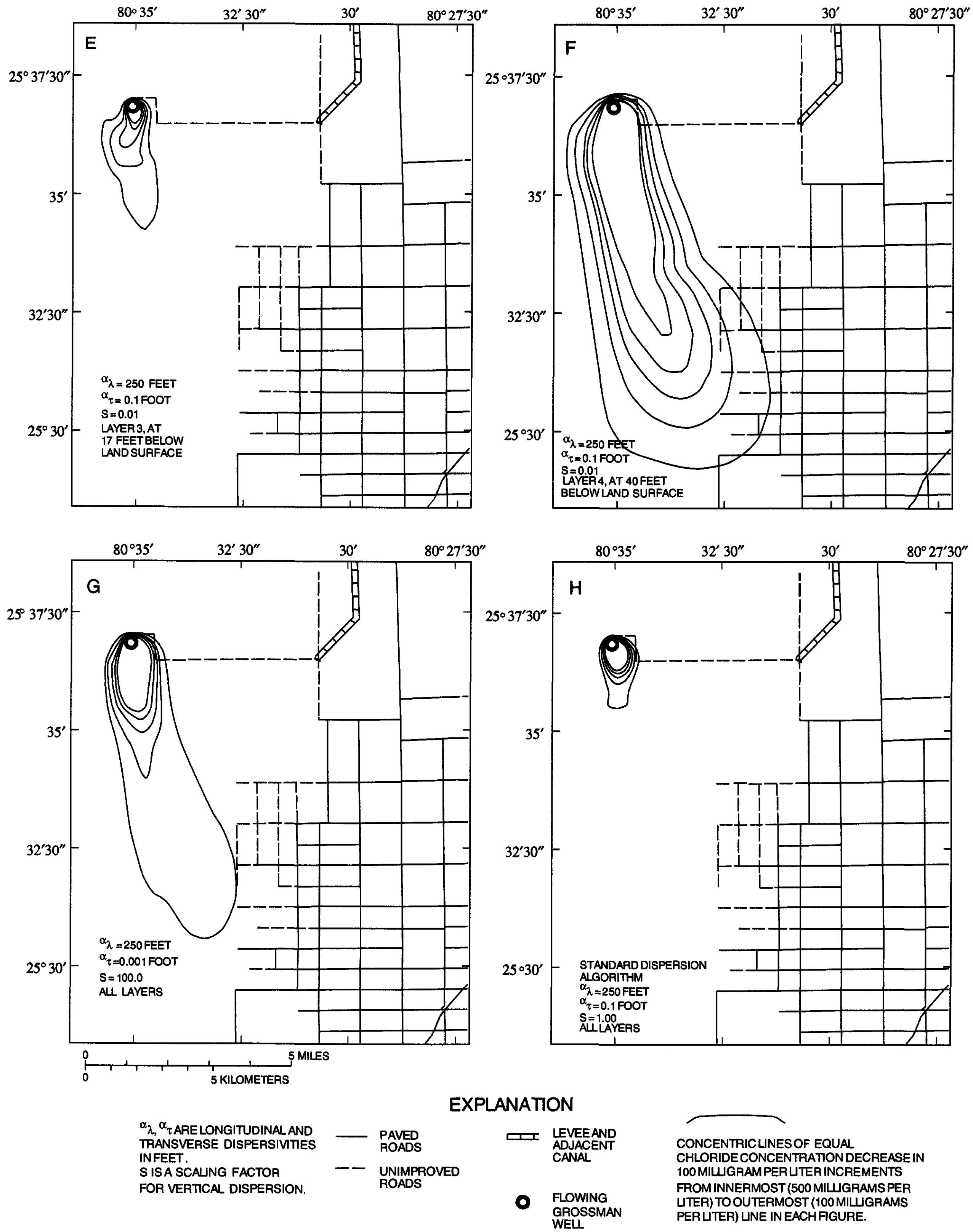

Figure 16.—*Continued.*

Even though vertical dispersion is unscaled and its degree is specified by a small transverse dispersivity (0.1 ft), the simulated vertical mixing apparently still causes the extent of the plume to be virtually the same in all aquifer layers. At this point, it is worthwhile to demonstrate that the uniform vertical distribution actually is caused by the small specified degree of vertical dispersion. To address this issue, the vertical scaling factor was reduced from 1.0 (no scaling) to 0.01. Thus, the degree of vertical dispersion was approximately as if the transverse dispersivity were $\alpha_t = 0.001$ ft. Results for layers 3 and 4 (figs. 16*E-F*) show that virtually all of the brackish water recharging the aquifer in layer 2 moves vertically downward, and downgradient advection occurs primarily in layer 4. The degree of vertical stratification is substantial. This means that the degree of vertical dispersion represented by the earlier specification of $\alpha_t = 0.1$ ft and no scaling was sufficient to cause solute concentrations to be vertically uniform, thereby preventing the stratification that is simulated when $\alpha_t = 0.001$ ft and little vertical dispersive mixing with rainwater percolating downward occurs.

Also of interest was the effect of further reducing transverse dispersion in the horizontal plane. To address this problem, the transverse dispersivity was reduced to 0.001 ft. However, because it was desired to preserve the vertical uniformity of solute concentration that occurred when $\alpha_t = 0.1$ ft (fig. 16*D*), a vertical scaling coefficient of 100.0 was also used. The longitudinal dispersivity (α_l) was 250 ft. Results (fig. 16*G*) were surprising in that simulated lines of equal chloride concentration are not appreciably narrowed in comparison with the case in which $\alpha_t = 0.1$ ft (fig. 16*D*). Apparently, when such a low value of transverse dispersivity is specified, the spread of brackish water perpendicular to the average flow direction is caused primarily by the seasonal changes in flow direction and longitudinal dispersion rather than by a classical process of transverse dispersion in the plane of flow. It is noted that the simulated lines of higher concentration are not as elongated when $\alpha_t = 0.001$ ft as when $\alpha_t = 0.1$ ft (fig. 16*D*). The reason for this difference is not known. Generally, given the specified value of longitudinal dispersivity (250 ft), it did not seem possible to simulate narrower and longer lines than the ones computed when $\alpha_t = 0.1$ ft.

As previously noted, use of the modified dispersion and advective weighting algorithms prevented dispersive flux of solute between the overland flow layer and the underlying aquifer layers. When vertical dispersion was unscaled, this was the only consequence of their use. Therefore, it was of interest to study the possibility that the standard algorithms of the version of SWIP documented by INTERA Environmental Consultants, Inc. (1979) could be used for the simulations of this study. The dispersivities used for the comparison test were $\alpha_l = 250$ ft and $\alpha_t = 0.1$ ft. No scaling factor for vertical dispersion was employed by the standard algorithms.

When the standard algorithms are used (fig. 16*H*), the simulated 1961 plume is substantially different from the 8-mile long plume simulated using the modified algorithms (fig. 16*D*). Using the standard algorithms, the lines of equal chloride concentration are confined to a small area of altitude 10 ft or more above sea level around the discharging artesian well (fig. 16*H*). This area is the only region that escaped inundation during the wet season of 1960. An inspection of solute concentrations computed using the standard algorithms for times earlier than the 1960 flooding shows a substantially more extensive distribution of brackish water in the aquifer than was present after the flooding. Therefore, when the standard algorithms are used, the model indicates that a substantial reduction in the extent of the plume occurred as a result of the flooding. Although data were not collected before 1979, it seems improbable that such a reduction in the extent of the plume actually did occur.

The simulated reduction of concentrations occurs because the standard method allows considerable vertical dispersion to occur between the overland flow layer, where concentrations are constrained to have a value of 0.0, and the uppermost aquifer layer. During simulated flooding, the large degree of vertical dispersion that occurs when $\alpha_t = 0.1$ ft reduces the simulated chloride concentrations to less than 100 mg/L in the aquifer layers wherever the overland flow layer is partially saturated. If the concentration of water in the overland flow layer had not been constrained to be zero, the resulting chloride distribution probably would still have been similar to that depicted in figure 16*H* because the chloride concentration of rapidly moving overland sheetflow during flood conditions probably would not have been appreciably raised above the background level by mixing or dispersing with the brackish water in the aquifer.

After Levee 29 was constructed north of the study area in 1961 (fig. 1), annual high water tables typically were lower than before. However, local inundation of marshy areas north and south of the flowing artesian well might have occurred in some later years, and substantial and widespread inundation did occur after heavy rains in August and September 1981. Chloride concentrations in water samples collected by DERM from wells G-3124 and G-3195 in February 1982 did not exceed 100 mg/L, which fails to conclusively establish whether or not an extensive plume existed on that date, as will be demonstrated by application of the model. However, it is likely that the elongated plume observed in March 1979 (fig. 12) and the one mapped by Labowski (1988) in July 1986 probably could not be simulated using the standard algorithms for vertical advective and dispersive flux in a setting where the aquifer was periodically overlain by a layer of surface flow. The process of vertical dispersion between the overland flow layer and the aquifer that is simulated by the standard algorithms probably does not actually occur or only occurs to a greatly reduced degree. It should be noted that even though the modified algorithms prohibit vertical mechanical dispersion of solute between flowing surface water and ground water, downward percolation of freshwater from the overland flow layer and upward ionic diffusion of chloride from parts of the aquifer invaded by the discharging artesian water are still simulated.

These qualitative comparisons indicated that the most realistic simulation of the measured plume of brackish water would be achieved by use of the modified dispersion and weighting algorithms with longitudinal and transverse dispersivities of $\alpha_l = 250$ ft and $\alpha_t = 0.1$ ft and with no scaling ($S = 1.00$) of vertical dispersion in the aquifer layers (fig. 16*D*). As previously noted, the only difference from the use of the standard algorithms is that vertical dispersion between the overland flow layer (when partially saturated) and the aquifer layers is not represented.

Progressive Development and Dispersal of the Plume of Brackish Water

The simulation of the movement and dispersal of the brackish water during consecutive water-management time periods is described in the next sections of this report. The model versions used to simulate the later time periods incorporate a representation of the effect of canal operation for recharge and drainage in the region. During the last water-management time period, the well discharge rate is changed to zero at a simulation time corresponding to March 1985 to represent plugging of the well. At subsequent computation times, the dissipation of the remnant plume is simulated.

Time Period 1, Water Years 1945-52

The simulated plume of brackish water is shown at simulation times representing 3.5, 5.5, 7.0, and 8.0 years following the drilling of the well and the beginning of the point-source contamination of the aquifer (fig. 17). As before, only 100, 200, 300, 400, and 500 mg/L lines of equal chloride concentration are shown because lines of higher chloride concentration cannot be clearly shown at this scale. Concentrations are nearly that of the discharging water (1,200 mg/L) within a short distance hydraulically downgradient of the well at all simulation times.

There are no field data to validate the distributions of brackish water simulated for times earlier than 1976. The computed distributions are considered partly validated, however, to the extent that the simulated evolution of the developing plume is substantiated by field data collected after 1976 and by the agreement of simulated and observed heads that determine the aquifer pore velocities for all simulation times.

Certain aspects of the depicted plume development are of interest. For instance, the simulated lines of equal chloride concentration for April 1948 and April 1950 are similar because significant augmentation of the plume in the intervening 2 years has not occurred. However, the lines for November 1951, 1.5 year later, show significant plume growth compared to April 1950. The explanation is that the simulated enlargement of the areal extent of the plume is controlled partly by variations in the rate of recharge by rainfall. Between April 1948 and April 1950, recharge from summer rainfall and from the tropical storms of 1948 and 1949 (133.5 in.) was slightly (7 percent) above normal for the area (62.25 in/yr). Flooding of the land area surrounding the site of the discharging well and downward percolation of freshwater restricted the simulated enlargement of the plume during this period. Between April 1950 and November 1951, the simulated enlargement of the plume was rapid because the amount of rainfall was below normal (50 in.) after November 1950. Lines of equal chloride

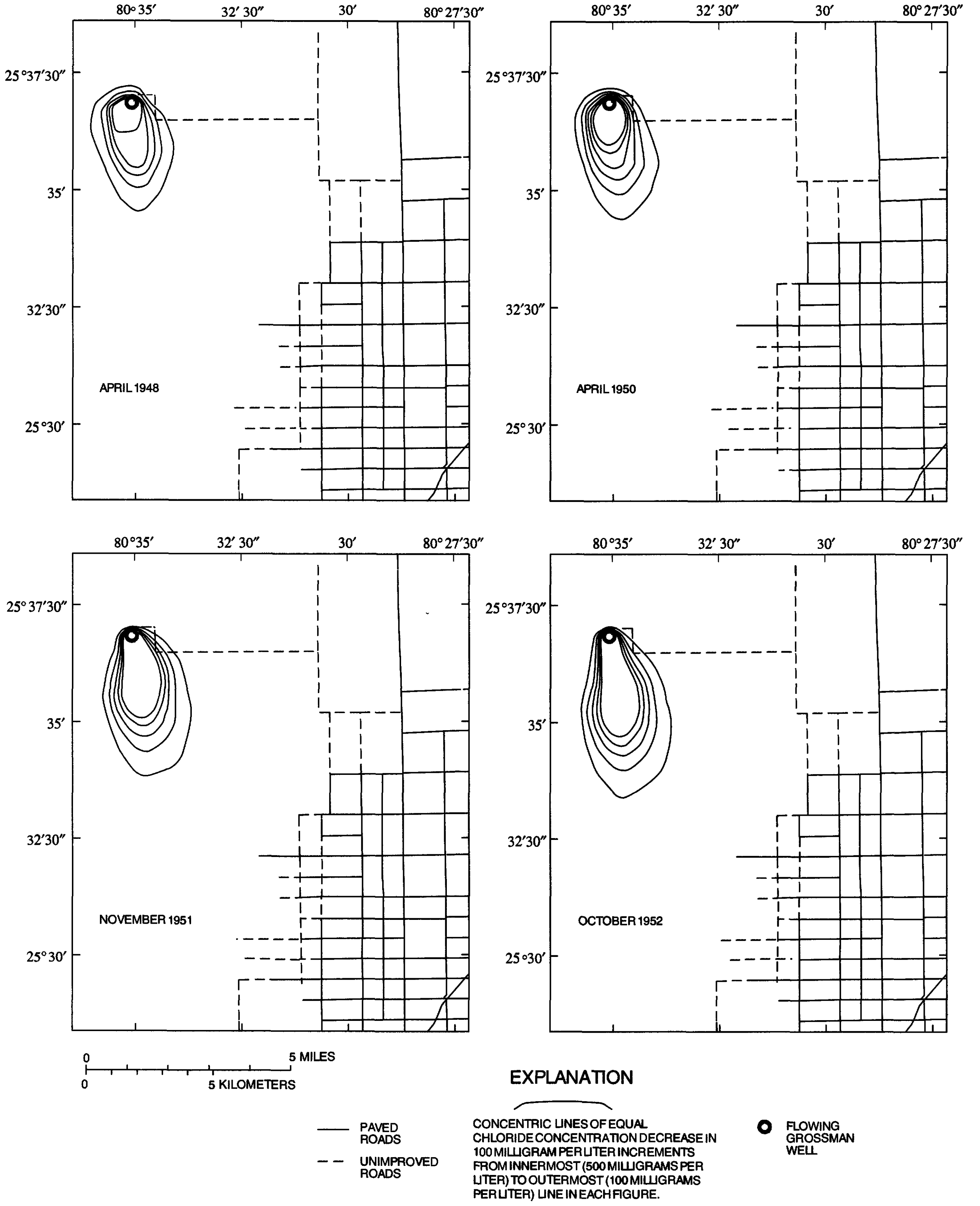

Figure 17. Simulated plume of brackish water at selected times during time period 1, water years 1945-52.

concentration for October 1952 show additional enlargement during a further period of slightly below-normal rainfall (57 in.).

Time Period 2, Water Years 1953-61

During time period 2 (water years 1953-61), the only existing canal-levee construction in the study area was the northern part of Levee 31N and the adjacent borrow canal east and northeast of the discharging well. The canal and levee had little effect on the flow regime in the region where aquifer contamination was occurring (fig. 8). During this time period, therefore, the hydraulic regime controlling the movement of the brackish water was basically unchanged from the previous time period.

Simulations of the extent of the plume at 10.5, 12.5, 15.0, and 17.0 years after the artesian well began to flow (fig. 18) show a steady increase of the area contained within the 100 mg/L line of equal chloride concentration. However, the region enclosed by the 200 mg/L line of equal chloride concentration decreases between November 1959 and October 1961, and the area contained within lines of higher chloride concentration decrease after April 1957. This is a further demonstration of the effect of higher-than-normal amounts of rainfall. The amount of rainfall (110 in.) was 11.6 percent below normal between April 1955 and April 1957, based on an annual average of 62.25 in. (fig. 7). Between April 1957 and November 1959, the amount of rainfall (205 in.) was 27.5 percent above normal, and between November 1959 and October 1961, the amount of rainfall (138 in.) was 15.7 percent above normal. The latter period included heavy precipitation from Hurricane Donna. The cited rainfall amounts were recorded at rainfall site 1 (fig. 1) at the Homestead Agricultural Experiment Station where well S-196A (figs. 2 and 3) is located.

As depicted by the model, freshwater recharge during periods of above normal rainfall seems to dilute the brackish water where it is present in high concentration. The concomitant enlargement of the lines of lower chloride concentration might represent the areal dispersal of the partially diluted water. The simulated degree of vertical transverse dispersion in the aquifer caused rainfall-diluted concentrations to be vertically uniform in the three aquifer layers.

Time Period 3, Water Years 1962-67

The north-south Grossman Road and the adjacent borrow canal (fig. 3) were constructed at the beginning of time period 3 (water years 1962-67). No new construction specifically for water-management purposes occurred in the study area during this period. However, the prevailing flow regime became more easterly (fig. 8) with the construction in 1962 of Levee 29 north of the study area and Black Creek Canal (C-1) east of the study area (fig. 1). The influence is evident in the computed lines of equal chloride concentration for April 1963 and October 1964 (fig. 19), which now bulge eastward. The 300-, 400-, and 500-mg/L lines of equal chloride concentration for April 1966 and October 1967 show two lobes divided by the Grossman Road borrow canal. Near its southern end, the simulated canal stage is slightly higher than the ground-water table, creating a hydraulic divide, and the canal is also simulated as channeling water of low chloride concentration southward from north of the source. The canal water increases in chloride concentration from contact with the plume in the adjacent aquifer, but is still lower in concentration than the aquifer water at the southern end of the canal where the canal water recharges the aquifer, causing the simulated two-lobe effect.

Time Period 4, Water Years 1968-82

Many canals and levees were present in the study area during time period 4 (water years). As shown in figures 3 and 14, Levee 31N and the adjacent borrow canal extended through the center of the study area in a generally south-southwestward direction. Princeton Canal (C-102) and Mowry Canal (C-103) extended eastward from the Levee 31N borrow canal. All three canals passed through sections of the contaminant plume. No pumping stations existed in the study area during the fourth time period, and the network of canals was operated for the sole purpose of flood control during periods of intense rainfall.

The periods of greatest rainfall were the wet seasons of 1968, 1969, 1981, and 1982. The wet season of 1981 culminated with about 20 in. of rainfall from Tropical Storm Dennis, followed by an equal amount of rainfall in the following month that was unrelated to the passage of tropical storms. Between the wet seasons of 1969 and 1981, control structures

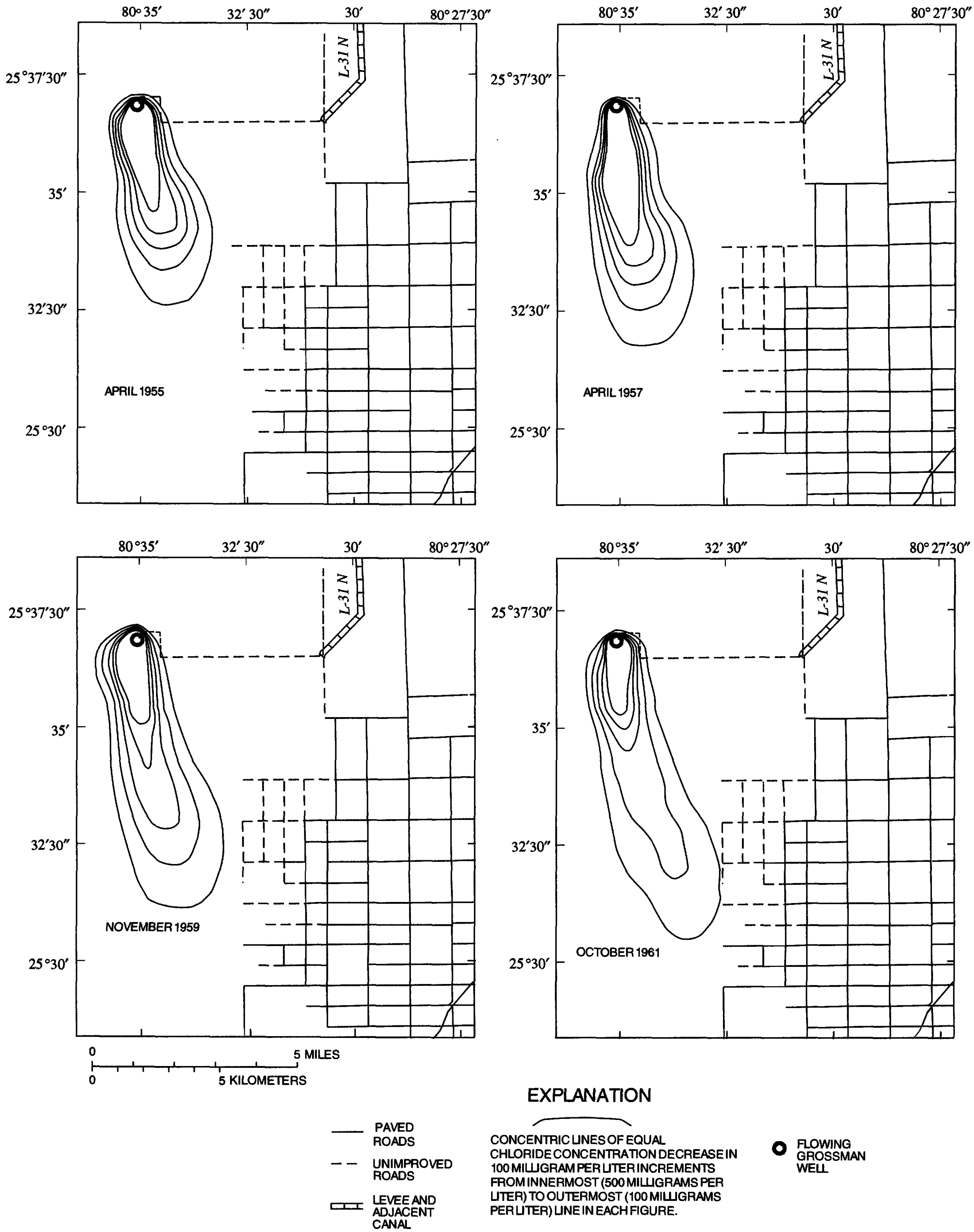

Figure 18. Simulated plume of brackish water at selected times during time period 2, water years 1953-61.

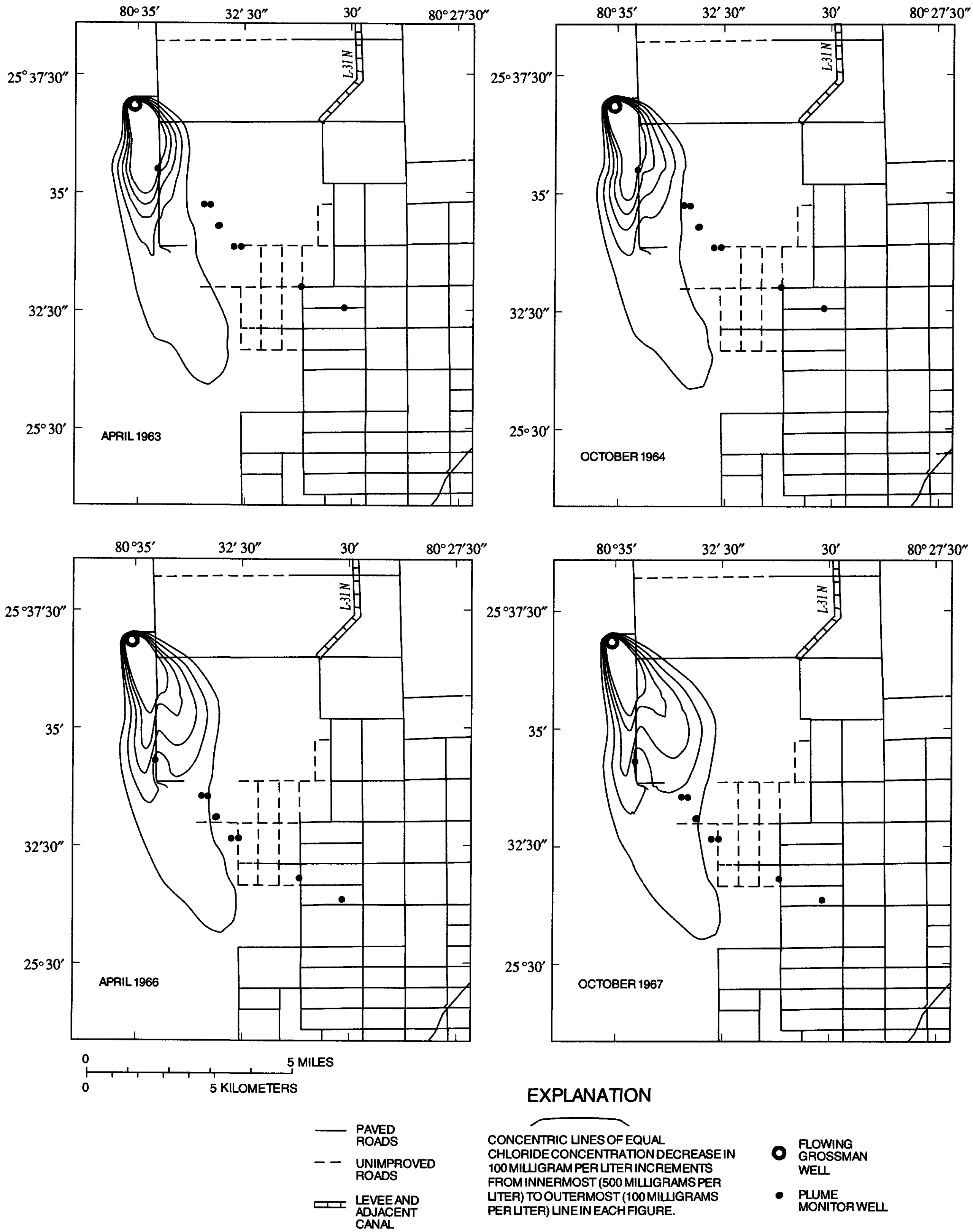

Figure 19. Simulated plume of brackish water at selected times during time period 3, water years 1962-67.

S-196, S-194, and S-173 were simulated as being open only for short periods in 1972, 1973, 1976, 1977, 1979, and 1980. Structures S-174 and S-176 in the Levee 31N borrow canal in the southern part of the study area (fig. 3) were simulated as being open for a few days in 1973, 1977, 1979, and 1980. All structures except S-173 were open for long periods of time during 1968, 1969, 1981, and 1982. When structures were closed, canal velocities were so low as to be virtually unmeasurable by standard USGS methods. When open, however, canal flow velocities could be as high as 5 ft/s (feet per second).

As explained previously, the method of representing mechanical dispersion in the model might have led to an overestimate of the rate at which canals removed solute (chloride) from the aquifer in the region of the contaminant plume. Additionally, recharge of the aquifer by canal water (and consequent dilution of brackish water in the aquifer) might have been overestimated by the assumption inherent in the construction of the regional flow model (Merritt, 1995a) that no plugging of canal walls occurred where the canal recharged the aquifer. Therefore, two scenarios were posed for simulating the movement of brackish water in this time period. The two scenarios were considered to represent extreme cases that overestimated and underestimated the influence of the canals on the plume. The true plume development was considered to have features that resembled one or the other simulation scenarios or were intermediate between them, as will be discussed later in greater detail.

In the first scenario, the canals (including the borrow canal along Grossman Road) were deleted from the simulation by assigning aquifer transmissivity values to the strings of canal cells. In the other scenario, the canals had the same high equivalent hydraulic conductivity values (2×10^8 and 3×10^8 ft/d) as in the regional flow simulation. In the latter scenario, when control structures were simulated as open, fresh canal water would be quickly routed from upstream to recharge the aquifer or routed downstream to drain the aquifer, and solute would either be diluted in the aquifer or would enter the canal cells to be quickly removed from the plume region. In both scenarios, however, boundary conditions were obtained from the regional flow model in which the canals were represented by assigning high equivalent hydraulic conductivity values to strings of canal cells. Therefore, the hydraulic influence of the canals in establishing regional flow patterns was represented in both scenarios. Only the local hydraulic influence of the canals and the representation of their influence on solute concentrations in the vicinity of the plume differed between the scenarios.

An assessment of the local hydraulic influence of the canal was made by studying the pattern of water flux near the east-west string of nodes (fig. 15, row 26 and columns 22-26) used to represent the Levee 31N borrow canal where it transected the plume hydraulically downgradient of the artesian well. (In reality, the canal transected the plume diagonally.) Simulated aquifer heads in column 24 north and south of the cell string (rows 25 and 28) were compared with the simulated stage in the canal.

When canal control structures were closed during this time period, the direction of flow in all aquifer layers, including layer 2 in which the canal cell string was present, was southward. The canal cell string drained water from aquifer cells on its northern side and recharged aquifer cells on its southern side. However, when structure S-196 in the Mowry Canal (fig. 3) was simulated as being open, simulated canal heads were below aquifer heads on the northern and southern sides, indicating drainage from both directions. The indicated drainage was stronger when structure S-176 in the Levee 31N borrow canal (fig. 3) was also simulated as open. Openings of S-176 were represented in the regional model as occurring during periods of intense wet-season rainfall, as occurred for lengthy periods in 1968, 1969, 1981, and 1982, and for shorter periods in 1972, 1973, 1975, 1976, 1977, and 1979. Recharge of the aquifer by the canal and flow northward from the canal cell string were indicated near the end of a period of record-low water-table altitudes in spring 1971.

Lines of equal chloride concentration in figure 20 depict the plume as simulated with the model version in which the canals were represented. Generally, the plume did not increase in extent during this time period, although the area enclosed by the 100 mg/L line of equal chloride concentration east of the Levee 31N borrow canal increased slightly until 1980. Apparently the loading of the aquifer by discharging brackish water is in approximate equilibrium with the counteracting processes of rainfall dilution, downgradient advection, hydrodynamic dispersion, and the effects of the canals transecting the plume.

A comparison of 1969 and 1971 lines of equal chloride concentration (fig. 20) with those for 1967 (fig. 19) indicates that the southern part of the 1967 plume has been drained or diluted by the lower reach of the Levee 31N borrow canal, represented as flowing rapidly when structures S-174 and S-176 were open for several months in 1968 and 1969. The simulated post-1962 southeastward trending lobe of the plume has increased in extent, whereas the lobe west of the Grossman Road borrow canal has diminished, indicating the continuing influence of canal and levee construction in 1962 in changing prevailing aquifer flow patterns. When canals were deleted from the model (fig. 21), the 1971 lines of equal chloride concentration encompassed an area that was more extensive to the southeast than shown in figure 20. However, the elongated lobe extending almost directly southward in 1967 (fig. 19) was reduced as the simulated movement of brackish water was in a more easterly direction. The leading part of the plume is depicted as more broadly distributed because it is formed from water moving in two different principal directions at different times.

The 1975 lines of equal chloride concentration (fig. 20, canals represented) indicate that all parts of the simulated plume were augmented after several relatively dry years with little use of the canals for drainage. However, a second set of lines for the same date based on computations without the canal representation (fig. 21) show an even more extensive plume. In this latter figure, the southerly part of the area enclosed by the 100 mg/L line of equal chloride concentration in 1967 still remains and has extended farther southward, but has also been augmented by the growing southeasterly directed lobe to form a single broad lobe of uneven forward extent.

Measured specific conductance and chloride concentration from well G-3108 in 1976 (table 2) were only slightly above background levels. A plot of simulated chloride concentrations (fig. 22) at grid locations corresponding to various monitor wells (canals represented) shows that simulated concentrations at the location of well G-3108 did not increase over background levels until about September 1976. The simulation, therefore, slightly underestimates the chloride concentration at this location in 1976. However, when canals were not represented, the concentration at well G-3108 is almost perfectly matched with field observations (fig. 22).

Lines of equal chloride concentration for March 1979 (fig. 20, canals represented) show the simulated plume at a time coinciding with the resistivity survey described by Waller (1982). The lobe of the plume west of the Grossman Road borrow canal is virtually nonexistent. An indentation in the 100 mg/L line of equal chloride concentration occurs along the Levee 31N borrow canal, showing the effect of the canal in moving fresher water south near the northern edge of the plume.

When the canals are deleted, the simulated plume in March 1979 (fig. 21) is more extensive, and its longitudinal axis extends in a more southerly direction than depicted by the model in which the canals are represented (fig. 20). Because the specified boundary heads are identical in both versions of the model, this shows the simulated effect of the canals in influencing the direction of flow in their vicinity and in diluting or removing some of the brackish water. The model version that contains the canal representation also simulated a slight degree of vertical stratification, and the extent of the plume in the upper layers is simulated to be somewhat more limited in extent. (The illustration is of concentrations in the lowest layer.) This shows that the simulated effect of the canals in diluting high chloride concentrations is strongest in the upper aquifer layer where the canals are represented in the grid.

Chloride concentrations of well water samples are compared in figure 22 with values simulated at grid nodes corresponding to the locations of the wells in the modeled area. (Bilinear interpolation procedures were used when well locations were not approximately coincidental with center of grid cells, and computed concentrations were omitted when they were at or below the background level of 20 mg/L.) It should be noted that simulating concentrations at fixed spatial locations in aquifers having secondary porosity might be difficult to achieve when local hydraulic properties do not match the spatially generalized properties specified for a larger modeled area that includes the location at which the comparison is made. Such was a conclusion of the effort to simulate injection, storage, and recovery of freshwater at Hialeah (Merritt, 1994b).

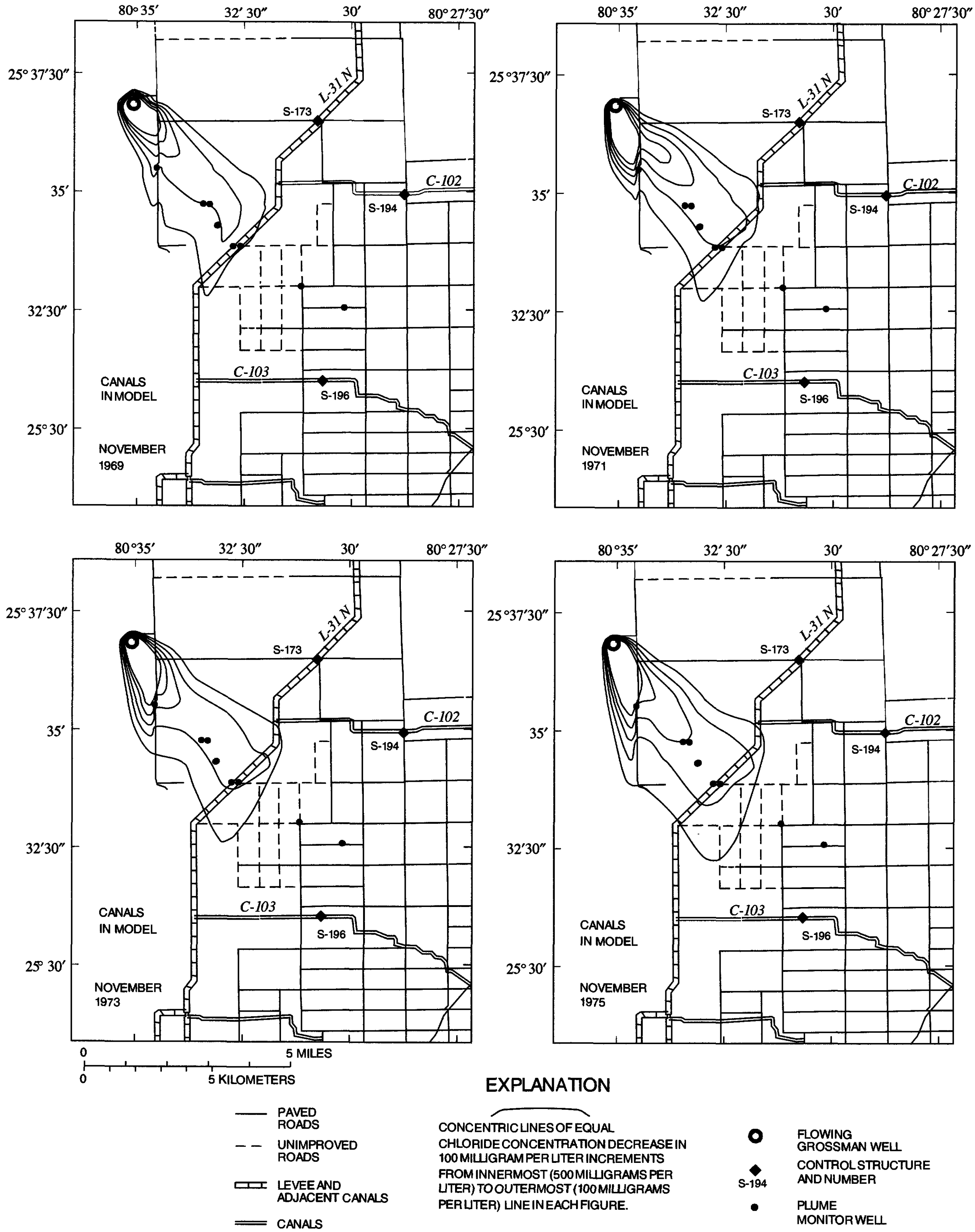

Figure 20. Simulated plume of brackish water at selected times during time period 4, water years 1968-82.

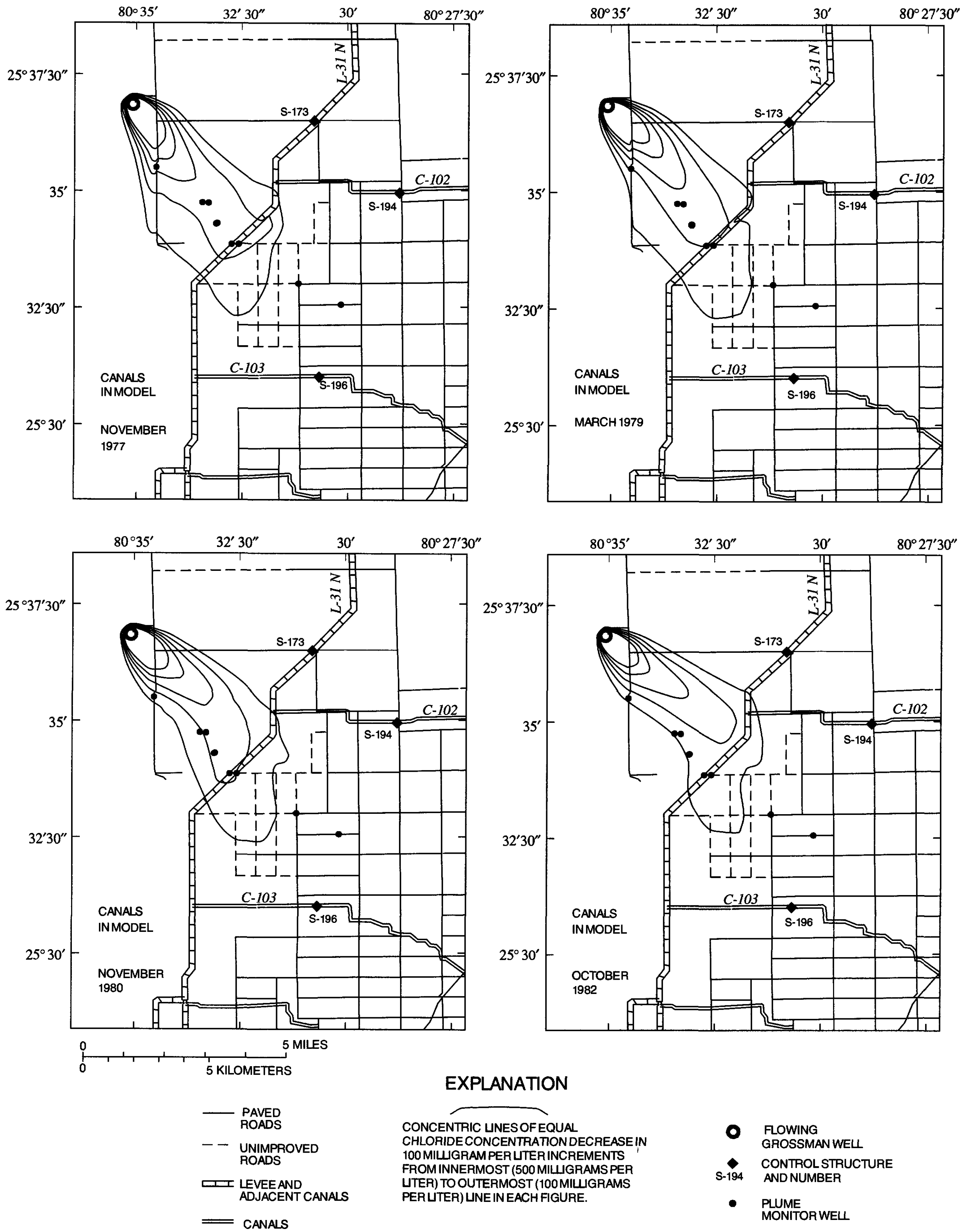

Figure 20.—*Continued.*

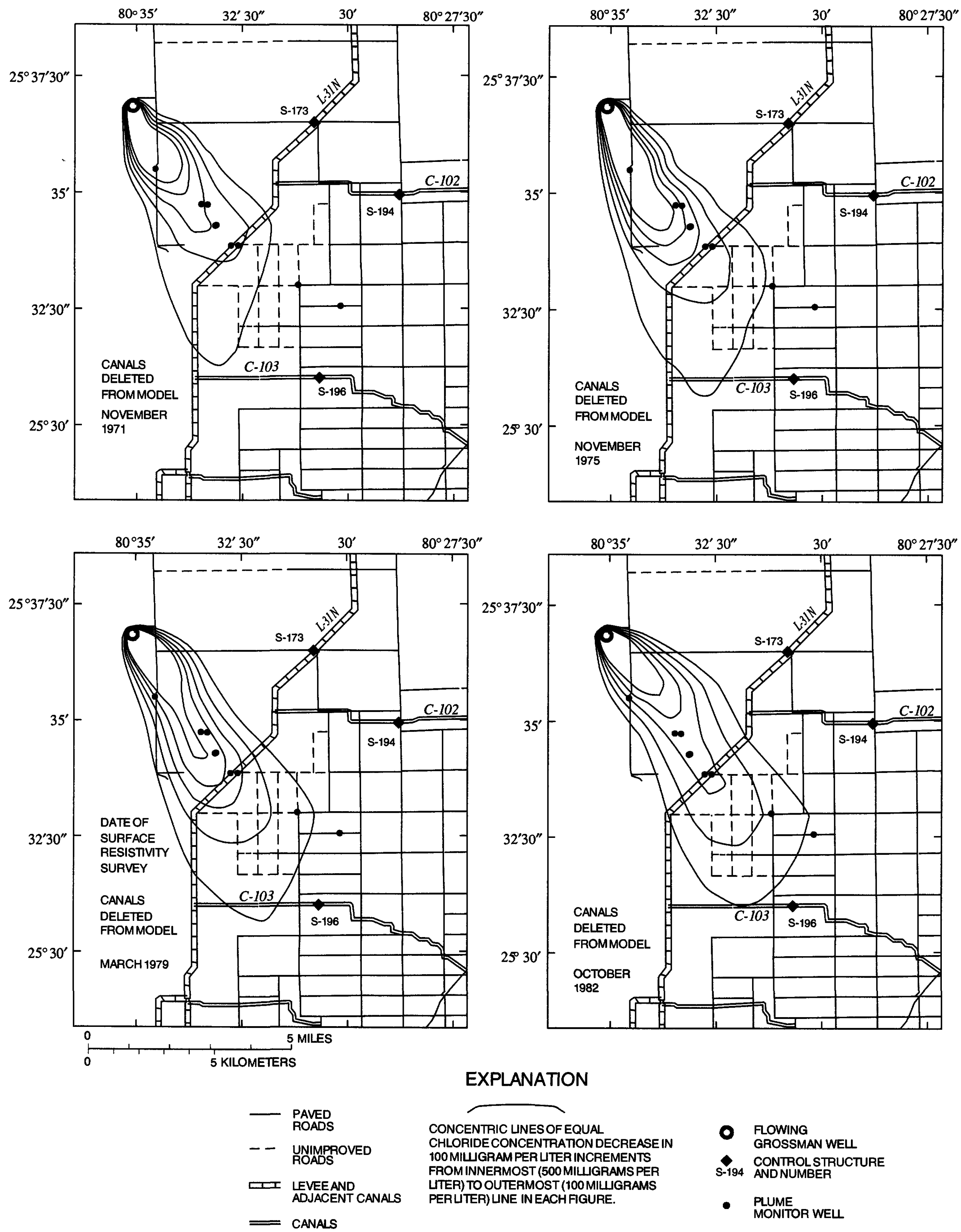

Figure 21. Simulated plume of brackish water at selected times during time period 4 (water years 1968-82) when representations of the canals are deleted from the model design.

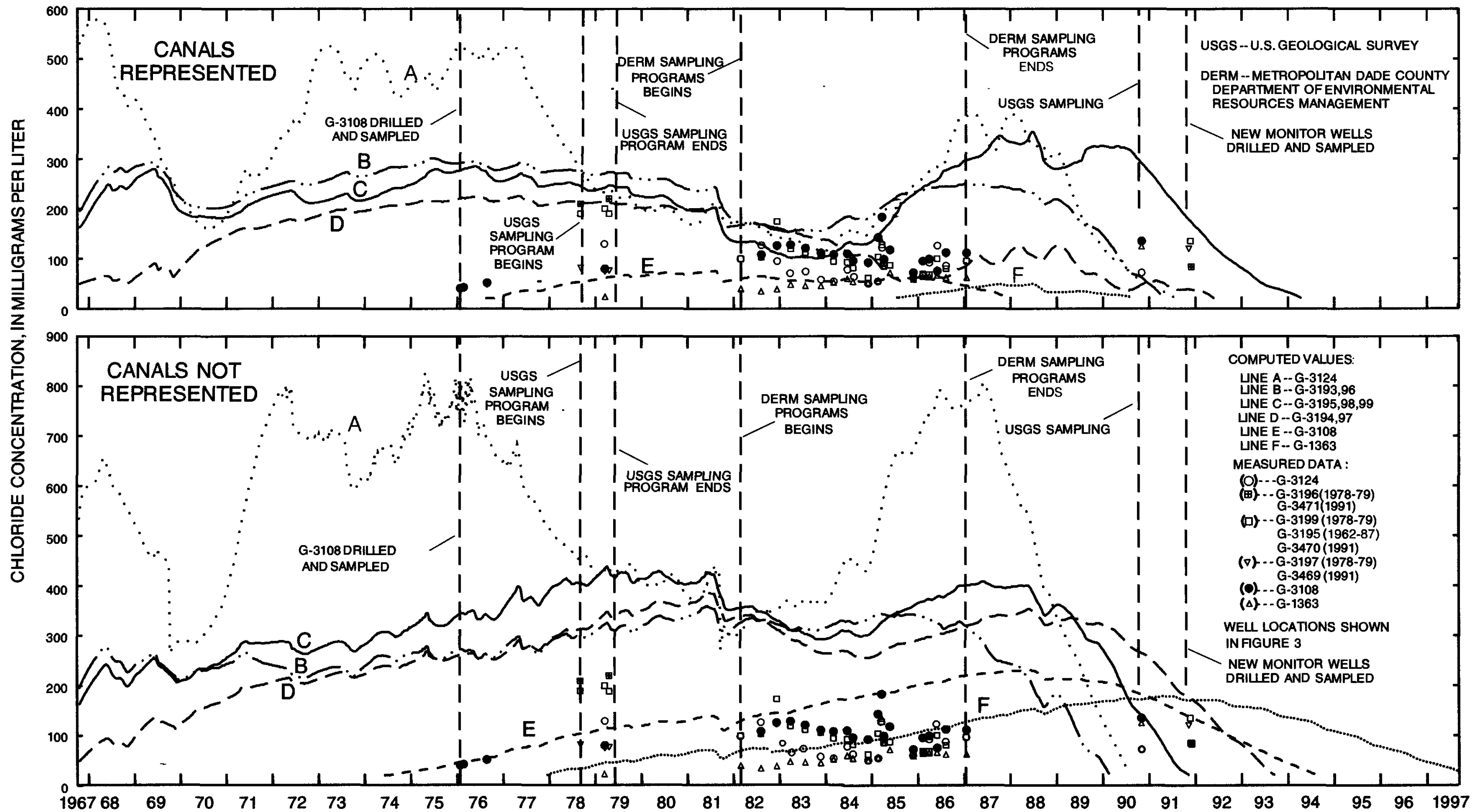

Figure 22. Simulated and observed chloride concentrations at various locations in the study area after 1967.

Simulations of solute distribution in aquifers with secondary porosity usually are only generally representative of an area and generally do not imply that there should be a precise match between simulated concentrations and water-quality data measured at point locations. Alternatively, such a precise match is not a complete test of the calibration of a model of solute distribution in aquifers having secondary porosity.

Additionally, lines of simulated equal chloride concentration (fig. 19) show that the proximity of wells (sampling sites) to the central (or longitudinal) axis of the plume vary as the simulated plume changes direction in response to variations in seasonal rainfall intensity and operation of the canal system for flood control. Because the rate of variation of concentration with orthogonal distance from the longitudinal axis of the plume is high, measured concentrations at individual well locations should be highly sensitive to changes in the orientation of the central axis of the plume, and simulated concentrations should replicate this sensitivity.

For these reasons, a comparison of simulated and observed chloride concentrations at well locations should not be expected to always show close agreement. Apparent close matches of simulated and observed chloride concentrations should probably be disregarded as coincidental. Instead, a general agreement between simulated and observed chloride concentration trends at groups of observation well locations would be considered the best test of the simulation.

When the canals are represented in the model, the general agreement between simulated and observed chloride concentrations in 1978-79 (fig. 22) is good at the locations of well cluster B (G-3193 and G-3196), well cluster C (G-3195, G-3198, and G-3199) west of Levee 31N, and well G-3108 hydraulically farther downgradient east of Levee 31N. A disparity between simulated and observed concentrations occurs at well cluster D (G-3194 and G-3197) just 400 ft west of the levee where measured concentrations were substantially less than the simulated ones and were no greater than measured concentrations at well G-3108 almost 2 mi downgradient. The reason for this disparity is unknown, although local water quality might be influenced by the dilution effect of recharge from the canal. The chloride concentration in water at well G-3124, about 30 to 50 ft west of the Grossman Road borrow canal and on the southern side of the plume in this simulation, was also overestimated by more than 80 percent.

When canals were deleted from the model, measured chloride concentrations at all well sites west of the levee were greatly overestimated. Lines of equal chloride concentration (fig. 21) show the wells to be near the central axis of the plume, a probable cause of the overestimate. Most likely, the better of the two simulations is the diminished and more easterly oriented plume (fig. 20) that results when the hydraulic influence of the canals is represented. When the canals are deleted, measured chloride concentrations at downgradient wells G-3108 and G-1363 are in good general agreement with computed ones, though slightly overestimated. The agreement was also generally good in the simulation in which the canals were represented, where measured chloride concentrations were slightly underestimated.

A comparison between the simulated lines of equal chloride concentration for March 1979 (fig. 20, canal represented) and the lines of equal specific conductance based on the EM-34 survey of March 1979 (fig. 11) indicates good general agreement with respect to the orientation of the longitudinal axis of the plume. Detailed comparisons of the extent and dispersal of the brackish water are not attempted because the two sets of data are collected by different methods that have different sources of error or bias.

The areas within the lines of equal chloride concentration simulated for November 1980 and October 1982 (fig. 20, canals represented), are slightly diminished in comparison with those simulated for March 1979. This represents the effect of heavy rainfall occurring in 1980, 1981, and 1982. The 200 mg/L lines of equal chloride concentration and higher now seem to extend more to the east than before, toward the upper end of Princeton Canal (C-102). Structures in the canal including S-194 (fig. 3) were open for several months in 1980 and for longer periods of time in 1981 and 1982 to permit drainage of floodwaters, and probably caused the redirection of flows indicated by the lines of equal chloride concentration. The area east of Levee 31N contained within the 100 mg/L line of equal chloride concentration seems to have diminished as a result of the more easterly flow direction of the brackish water.

West of Levee 31N, all observation wells are shown to fall along the simulated 100 mg/L line of equal chloride concentration on the southern edge of the plume, as the region of highest simulated concentration extends past the observation wells to the north. The low chloride concentrations simulated at the observation well locations (fig. 20, canals represented) generally match the data collected by DERM personnel at the end of the time period in late 1982. The August 1982 water sample concentrations (Labowski, 1988) do not differ from concentrations computed for wells G-3195, G-3124, G-3108, and G-1363 by more than 50 mg/L. Computed concentrations at the latter two locations are underestimates. When the canals were deleted from the model, concentrations at wells G-3195 and G-3124 were greatly overestimated (fig. 22). Lines of equal chloride concentration for 1982 from the simulation with canals deleted (fig. 21) show these wells to lie near the center of the longitudinal axis of the plume. Simulated concentrations at downgradient wells G-3108 and G-1363 are still within 50 mg/L of the measured concentrations but are now overestimates.

Generally, the computed chloride concentrations show a clear correlation with the amount of rainfall. Concentrations decrease abruptly following heavy rainfall in the summer of 1969 and the autumn of 1981 and increase gradually during the relatively dry years 1970-76 (fig. 22). The simulated concentration variation is the result of both dilution and the redirection of the plume by flow pattern changes that are natural or caused by canal drainage.

Time Period 5, Water Years 1983-89

During time period 5 (water years 1983-89), water managers operated pumping station S-331 during the wet summer months to drain a residential area to its north. By keeping open structures S-176, S-194, and S-196 (fig. 3) and other structures not in the study area, water managers caused the pumped water to be discharged through canals toward coastal outlets to the ocean. During the dry winter months, water was released through structure S-173 and through a siphoning system in S-331. The result of these practices, from the standpoint of modeling, is that water flowed rapidly through the canals at most times as a result of forced pumping or upstream releases. For this reason, structures S-176, S-196, and S-194 were represented in the model as always open and S-174 as frequently open. As previously noted, simulating rapid canal flows required that the simulation time-step length be less than 0.15 day to prevent solution matrices from becoming ill conditioned. The well discharge rate was changed to zero at a simulation time corresponding with March 1985 to represent plugging of the well.

As before two scenarios were considered, one in which the canals were represented (fig. 23) and one in which they were deleted (fig. 24). The hydraulic boundary conditions were the same for both scenarios. The effect of the canals on the water-table altitude and in draining or diluting the plume of brackish water was qualitatively different from that of earlier time periods as a result of the S-331 pumping and the permanent structure openings. As for time period 4 (water years 1968-82), an analysis was made of the relation of simulated canal stage to aquifer heads simulated on the northern and southern sides of the east-west string of grid cells (fig. 15, row 26 and columns 22-26) previously used to study head relations in time period 4. The analysis showed that flow in all aquifer layers, including layer 2 in which the canal was represented, was southward about 68 percent of the time between 1983 and 1989. During 18 percent of the time, the canal drained the aquifer in the region studied. During 14 percent of the time, the canal recharged the aquifer (the canal stage was greater than aquifer heads on the northern and southern sides of the east-west cell string).

Detailed analyses were made of solute (chloride) fluxes between aquifer and canal grid cells near the center of the same east-west canal string (fig. 15, row 26 and columns 22-26) where head relations were studied. On June 30, 1983, when the canal was simulated as draining the aquifer near the center of the east-west string of cells, large fluxes of solute from the aquifer into the canal augmented the load of solute carried by canal water in its southwestward direction. The largest aquifer solute fluxes were depicted as

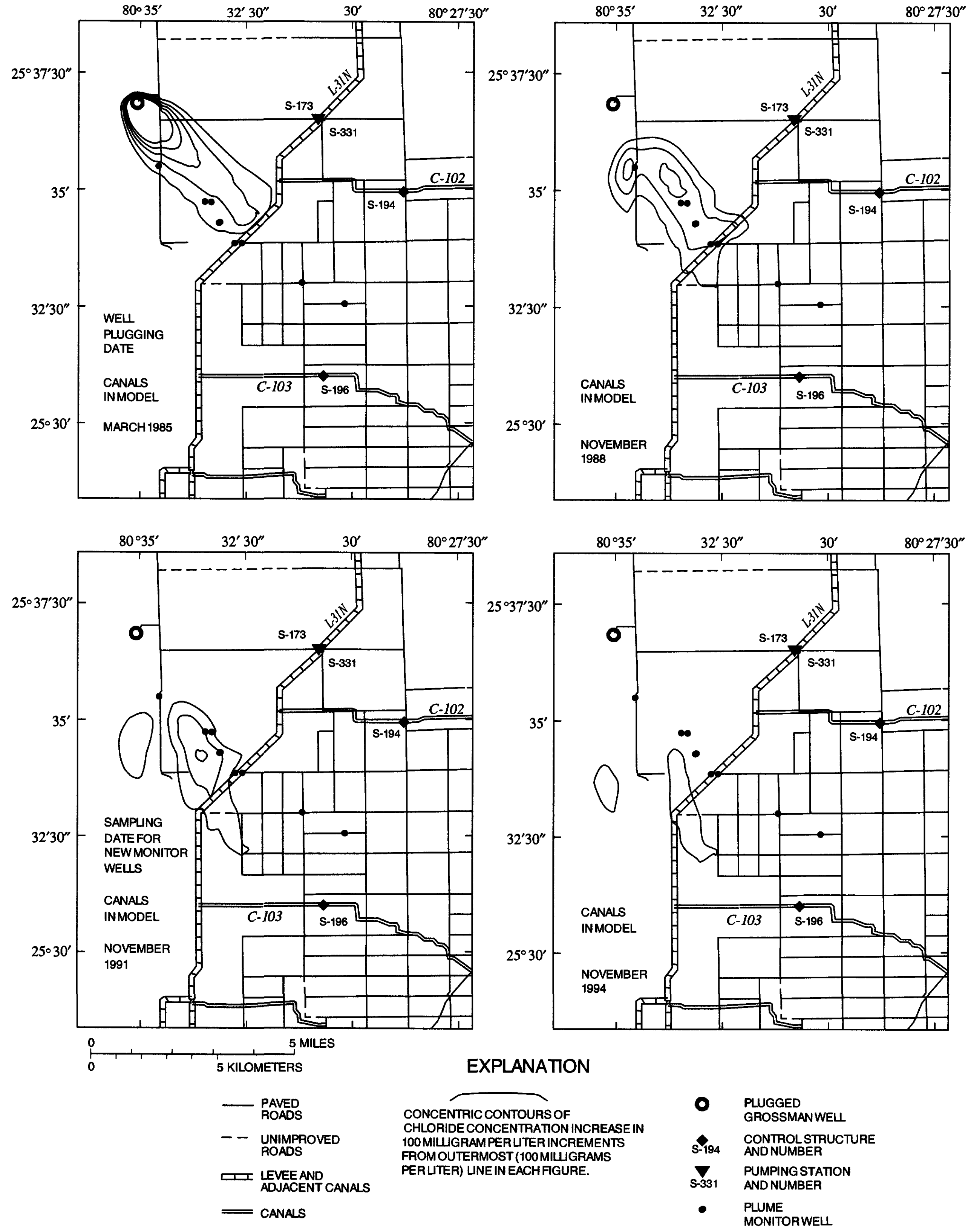

Figure 23. Simulated plume of brackish water at selected times during time period 5 (water years 1983-89) and at selected future times.

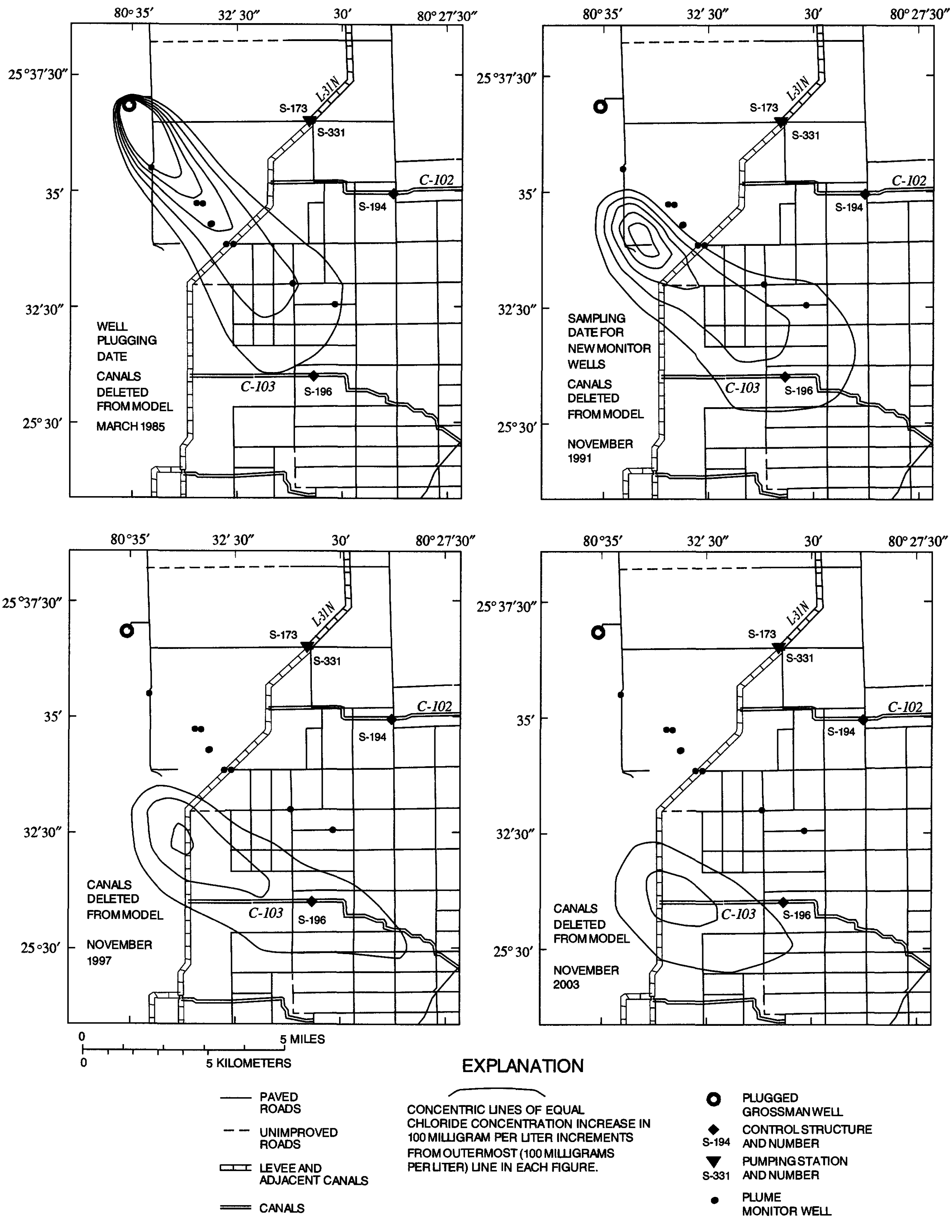

Figure 24. Simulated plume of brackish water at selected times during time period 5 (water years 1983-89) and at selected future times when representations of the canals are deleted from the model design.

moving southwest toward the canal on its northern side in aquifer layers 3 and 4. A large solute flux from below the canal upward into the canal cells was indicated. South of the canal, only slight solute fluxes in a southwestward direction were indicated.

On March 15, 1984, when simulated flow was southward past the canal in all aquifer layers, solute flux in the canal string was nearly as great as simulated in June 1983 but was not augmented by solute flux from the aquifer. The slight solute fluxes in the aquifer seemed to be virtually unaffected by the strong canal flows and were generally in a southwestward direction.

When canals are represented in the model, the simulated plume in March 1985, at the time the flowing well was plugged, is depicted as having been somewhat diminished in extent (fig. 23) from that shown for 1982 (fig. 20). The principal difference is that the area containing chloride concentrations higher than 100 mg/L does not extend past the Levee 31N borrow canal. As in 1982, the longitudinal axis of the plume is north of the observation wells located west of the levee, though the axis has rotated southward from its orientation in 1982.

In March 1985, the Levee 31N borrow canal was simulated as recharging the Biscayne aquifer. Solute fluxes in the second and third aquifer layers near the simulated east-west reach of the canal at the downgradient edge of the plume were directed away from the canal cells. Fresher canal water was simulated as moving northwest and downward into the aquifer from the canal to prevent brackish water from approaching the canal. Only in the fourth layer did water from the northwest flow under the canal cells. In the simulation, this underflow was sufficiently reduced in volume, and its chloride concentration sufficiently reduced by recharge from the canal, that chloride concentrations as high as 100 mg/L are only present northwest of the canal. The direction of ground-water flow near the canal was nearly parallel to the sides of the canal.

When canals are not represented in the model (fig. 24), the 100 and 200 mg/L lines of equal chloride concentration extend to the southeast a considerable distance beyond the actual canal location. In 1975 and 1979, the farthest extent invaded by water of more than 100 mg/L of chloride concentration is slightly east of due south, but by 1985 the more easterly movement of brackish water occurring since 1962 has caused the leading edge of the plume to have a more even appearance and to be broadly dispersed in an unusual way.

Before March 1985, the simulation containing the canal representation shows the longitudinal axis of the plume (fig. 23) to be north of the observation wells west of the levee. Simulated chloride concentrations generally agree with chloride concentrations measured at the wells (fig. 22). When the canal is not represented, the simulated longitudinal axis (fig. 24) approximately lies directly over the wells, and measured chloride concentrations are greatly overestimated. As to why measured chloride concentrations at all observation wells peak abruptly in March 1985 (the time of the well plugging), there is no obvious explanation.

Lines of equal chloride concentration for November 1988 (fig. 23, canals represented), 3 1/2 years after plugging of the well, show that the highest concentrations of the residual brackish water are located about 1 mi southeast of the plugged well. Simulated chloride concentrations are everywhere less than 400 mg/L. The observation wells west of the levee are just southeast of the highest concentrations, and this is reflected in the rise of simulated chloride concentrations with time shown in figure 22. However, chloride concentrations measured through January 1987 did not show any substantial change from 1982 or 1985 levels. Possibly, the actual movement of the rapidly diminishing mass of water with chloride concentrations greater than 200 mg/L was in a slightly different direction than simulated.

Potential Future Movement and Dispersal of Plume

A set of regional boundary pressure values and rainfall rates that were an average of values used during the 1983-89 water years was used in the regional flow model to provide average and representative boundary conditions for the subregional model of transport of brackish water after 1989. Average

1983-89 pumping rates for S-331 were used, and structures S-194 and S-196 were considered to remain continually open. The flow regime in the area of the plume computed by the regional model with average boundary conditions and rainfall had a seasonal pattern that was repeated almost identically each year after 1989.

When the canals are represented in the model, the simulated remnant plume drifts generally southward by 1991 and contains water of more than 300 mg/L of chloride concentration only in a small area (fig. 23). The two 100 mg/L lines of equal chloride concentration separated by a reach of the Grossman Road borrow canal are south of well G-3124. The simulated lines of equal chloride concentration for November 1994 show two small areas containing water of chloride concentration greater than 100 mg/L southwest of all observation wells located west of the levee. Simulated chloride concentrations at wells G-3124 and G-3196 decrease to background in early to mid-1991 (fig. 22). Computed chloride concentrations at wells G-3197 and G-3199 decrease to background in 1992 and 1994, respectively. The general indication is an irregularly distributed and diminishing volume of brackish water that moves past the various monitor wells during a period of 3 to 4 years.

The USGS sampling of 1990 confirms that near-background chloride concentrations prevail at well G-3124 (fig. 22). Water samples from wells G-3469, G-3470, and G-3471, drilled in 1991 near the former locations of wells G-3196, G-3199, and G-3197, respectively, contained chloride concentrations no higher than 135 mg/L, and the lowest chloride concentration (85 mg/L) was present in water samples from the northernmost well. Although the measured chloride concentration trends at the various wells vary from those of the simulated trends, the indicated pattern of diminishing chloride concentrations, with a breakthrough to background concentration occurring first at the northernmost observation site as the remnant plume moves south, is similar.

The principal discrepancy between simulated and observed concentrations occurs at wells G-3108 and G-1363, east of Levee 31N. Measured chloride concentrations exceed 100 mg/L at both wells in 1990, but the simulated chloride concentrations are less than 60 mg/L after 1982 at the two locations and are at background in 1990. This version of the model, therefore, fails to simulate the presence of brackish water in an extensive region east of the levee after 1989.

Estimated future canal-aquifer head relations near the center of the east-west cell string were studied as they were for time period 4 (water years 1968-82) and time period 5 (water years 1983-89). Southward flow in all aquifer layers, including the second layer in which the canal cell string was specified, was estimated to occur 62.5 percent of the average year. The canal was simulated as draining the aquifer in the remaining 32.5 percent of the year. The canal was not simulated as recharging the aquifer under average simulation conditions.

Another depiction of future plume movement is provided by the simulation in which the canals are not represented. The same pattern of southerly drift is evident (fig. 24), though the plume is more areally extensive and a region of chloride concentration higher than 200 mg/L is shown to persist beyond the year 2003. Brackish water is depicted as having drifted south of the observation wells west of the levee, except at well G-3197, by 1991. The pattern of native-water breakthrough at the wells is generally similar to and occurs within the same time period as that of the simulation with the canals represented, although computed concentrations at the various well locations are affected in a different sequence. However, the simulation lacking the canal representation slightly overestimates (by about 50 mg/L) the chloride concentrations measured at downgradient wells G-3108 and G-1363 in 1990, indicating the continued presence of brackish water during the mid-1990's. Most likely, the simulation that contains the canal representation underestimates the downgradient extent of the plume, and the simulation that lacks the canal representation overestimates the downgradient extent of the plume.

The predictive simulations must be qualified in that they are based on average hydraulic conditions prevailing during the 1983-89 water years, which strongly reflect the canal-levee system and control-structure operational procedures of that period. In actuality, water management in the study area has already changed appreciably with the construction in 1990 of structure G-211 in the Levee 31N borrow canal north of the study area. The structure is used to control southward canal flows to the vicinity of the residential area previously drained by use of pumping station S-331, and use of S-331 for pumping during the wet seasons has been almost entirely curtailed. However, releases through control structures are still frequently made to reduce water-table altitudes in areas used for agriculture. Whether this practice will continue after these areas are acquired by Everglades National Park is questionable. The effect of these changes in water management on the annual variation of the prevailing direction of ground-water flow, and on the degree of recharge and discharge occurring in Levee 31N borrow canal reaches farther south, might be to reduce the dilution of the remaining brackish water by the canal.

Effect of Proposed Well-Field Development

Although a single definitive depiction of the plume of brackish water was not achieved by the simulation effort, the two previously described simulations (canals represented and not represented) seem to have encompassed the most probable range of conditions that actually occur in the area. Therefore, an estimate of the effect of the proposed development of the West Well Field north of the study area (fig. 1) could be made by representing the well field in these two simulations. It is noted that the proposed West Well Field location has changed more than once since the site shown in figure 1 was considered. The current (1995) and probably final site is 6 or 7 mi north-northeast of the site depicted in figure 1. However, simulations based on the previously considered location are useful in generally demonstrating the effect of pumping at a site close to the remnant plume.

The rate of pumping from the new well field was planned to reach a daily average of 140 Mgal/d (million gallons per day), although this could also change after completion of an environmental impact statement by Dade County. With canals represented in the model, the plume of brackish water was simulated to be greatly diminished in 1991 and to be virtually nonexistent in 1994 (fig. 23). However, when the canals were not represented, a diminished plume remained in 2003 (fig. 24). Therefore, the hydraulic influence of the well field could be simulated in a "worst-case" scenario by using the model version lacking the canals to assess the effect of well-field pumping on the movement of the brackish water. This was done by representing the well field as located at the original proposed site and as pumping at a constant rate of 140 Mgal/d beginning in April 1992.

The hydraulic effect of this pumping scenario was previously studied by the author as part of the construction of the regional flow model (Merritt, 1995a). The well field was represented as a well at node (21,5) of the regional flow model (fig. 13). The simulated drawdowns in the region occupied by the plume in 1991 (fig. 24) were shown to be greatest in the northwestern corner of the remnant plume where they slightly exceed 0.25 ft. Because a large quantity of pumped water was simulated as being captured from the Levee 31N borrow canal, simulated drawdowns were greater than 1 ft only in a small area surrounding the well field.

Well-field pumping at the rate of 140 Mgal/d was simulated in the redimensioned regional flow model to provide a representative set of hydraulic boundary conditions for the subregional model (without canals) after April 1992. Results of the subregional simulation of the migration of the plume of brackish water during well-field pumping are shown as an overlay of 1997 chloride concentration lines on 1997 lines from the earlier simulation lacking the well-field influenced hydraulic boundaries (fig. 25). As suggested by the slight drawdown effect induced by the well field, the greatest difference in the position of brackish water is near the northwestern corner of the remnant plume. Even here, the position of the plume in 1997 has only been slightly altered. The conclusion is that if future hydrologic conditions are similar to those for 1983-89, a well field north of the study area at the originally proposed location would not reverse the direction of plume migration and would not pump brackish water originating as discharge from the Grossman well.

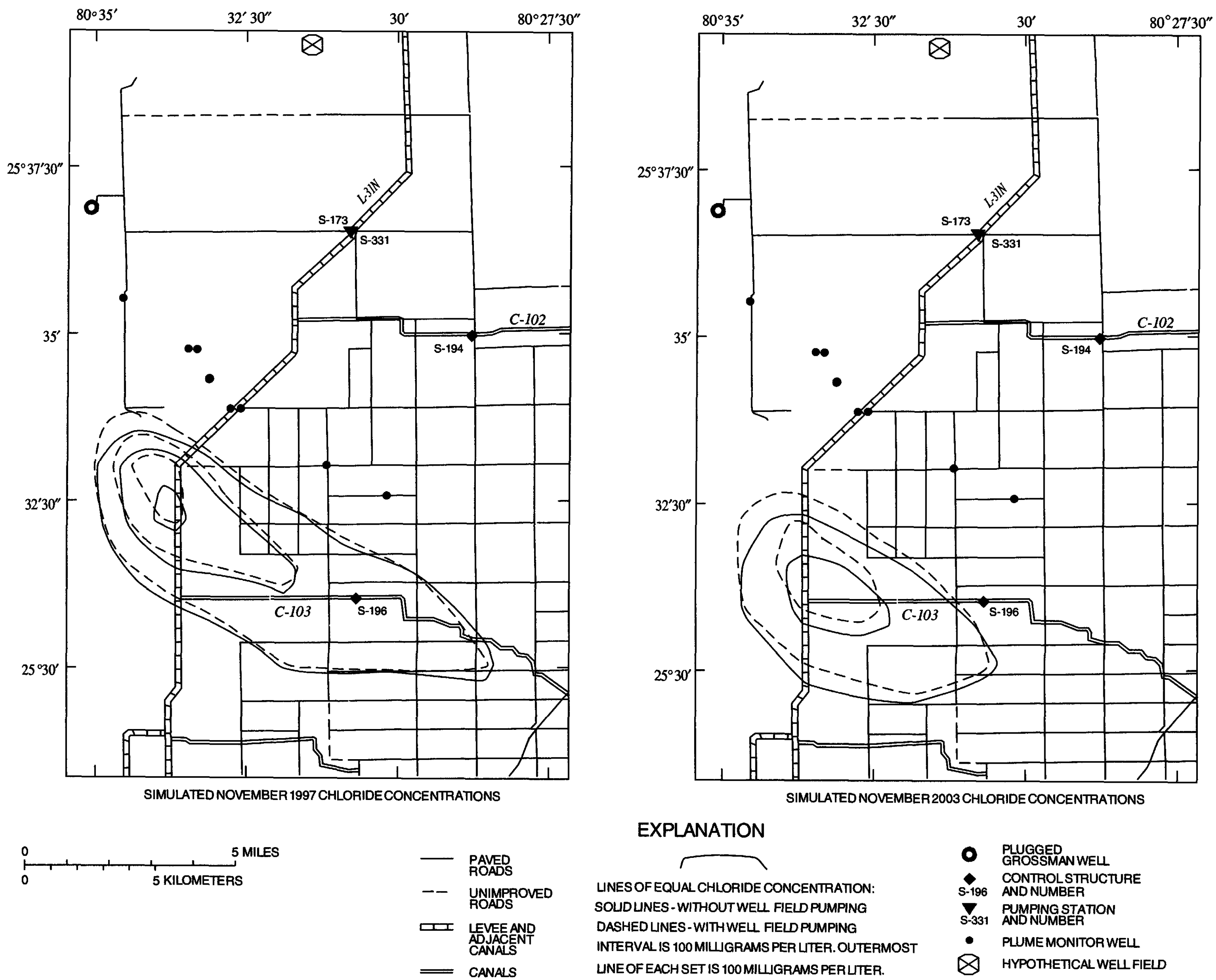

Figure 25. Simulated future rate of migration of the remnant plume (canals not represented) with and without representation of a well field north of the study area pumping 140 million gallons per day.

SUMMARY

The Biscayne aquifer in southern Dade County, Florida, extends to land surface and is easily recharged by abundant rainfall, making it a highly productive source of public supply. For these same reasons, it is also easily subject to pollution by contaminant spills. Concern about possible pollution of existing well fields has led Dade County officials to develop plans for the construction of a new inland regional well field, located west and hydraulically upgradient of urban development and bordering on wetlands of the Everglades. However, a contaminant threat to this proposed well field existed even at this location in the form of a plume of brackish water in the aquifer that originated from an artesian well in Chekika State Recreation Area that had been flowing since 1944. The well, which was open to permeable strata of the Upper Floridan aquifer of Eocene age, was plugged in 1985. The USGS, in cooperation with the Metro-Dade Department of Environmental Resources Management, began a study of the probable future movement and dispersal of the plume that included the use of numerical simulation techniques.

The artesian well was apparently the result of an abortive attempt at oil exploration in 1944. In December 1944, the rate of flow from the piece of 12-inch casing jutting out of the ground was measured to be 2,350 gal/min. Numerous analyses of constituent concentrations in the artesian discharge between 1944 and 1978 showed the average dissolved-solids and chloride concentrations to be 2,900 and 1,230 mg/L, respectively. The rate of flow from the well was measured to be 1,170 gal/min in 1964, 1965, and 1969. An analysis of the flow rate of the well using constant drawdown and numerical simulation approaches took into consideration changes in well design, the progressive drawdown in the aquifer, and the likely escape of part of the flow through rust holes in the casing. It was concluded that the true flow rate since the early 1960's was probably about 1,400 gal/min.

In the study area, the Miami Limestone and Fort Thompson Formation comprise the Biscayne aquifer, which extends from land surface to between 45 and 70 ft below land surface. The aquifer is vugular to cavernous throughout most of its thickness. Transmissivity is cited as greater than 1,000,000 ft^2/d, and the hydraulic conductivity is considered to be tens of thousands of feet per day. A value of 30,000 ft/d and an effective porosity value of 20 percent were used to calibrate a flow model of a large region that included the study area.

The quality of water in the Biscayne aquifer is relatively uniform throughout the study area. The water is a calcium bicarbonate type, and chloride and dissolved-solids concentrations in areas not influenced by the plume of brackish water range from 10 to 20 and 250 to 350 mg/L, respectively. The specific conductance of the water is about 500 μS/cm.

Rainfall in southern Dade County between 1940 and 1992 averaged about 62 in/yr. Summer (May-October) rainfall totals averaged about 75 to 80 percent of the annual totals. Maximum evapotranspiration rates were estimated indirectly through calibration of the regional flow model. The estimated maximum evapotranspiration rate ranged from a low of 0.08 in/d in January to a high of 0.21 in/d in June-October. Sections of the study area north, west, and south of the artesian well are subject to periodic inundation, and much of the study area is inundated during severe storm events. Since 1968, the study area has been transected by reaches of canals and levees used to control the water-table altitude in large parts of the county during floods and droughts.

At the location of the Grossman well (S-524), the general direction of flow in the Biscayne aquifer was somewhat east of due south between 1945 and 1961, based on an analysis of velocity vectors computed by the regional flow model. Weak westerly or southwesterly flows occurred during summer high-water periods. The seasonal variation of the flow direction would cause a lateral spreading of the plume of brackish water by divergent advection that would be analogous to the result of a dispersion process. During the 1962-67 time period, aquifer flows became more easterly at the Grossman well, and after 1967 the rate of dry-season southerly flows diminished.

The areal extent of the brackish water has been delineated twice by surface-geophysical surveys, and various observation wells have been used to obtain water samples for delineating local trends in water quality. Well water sample analyses between 1978 and 1992 indicated some quality changes when water samples were obtained at times several years apart. Water samples tended not to show appreciable vertical stratification of the brackish water. The more recent samples show that concentrations in water from upgradient wells have become less saline and some have approached background concentrations.

A numerical model was used to simulate the progressive development of the plume of brackish water in order to: (1) demonstrate the use of computer simulation methods for assessing contamination in the Biscayne aquifer, and (2) provide a means for making predictions about the future movement and dispersal of the contaminant plume and its possible interaction with a proposed new well field. The model is a three-dimensional, finite-difference simulator of solute and thermal transport in ground water and has the capability to perform free-surface calculations, which was needed for the simulation of chloride transport in the surficial Biscayne aquifer. Because of the unusual hydrologic conditions existing in Dade County, the code was modified to permit: (1) rewetting of dry nodes, (2) use of an upper layer of the model grid to represent overland sheetflow, (3) specification of control elevations to simulate the operation of control structures in the strings of highly transmissive grid cells that are used to represent canals, and (4) specification of time-varying boundary conditions on the periphery of the modeled domain. Central differencing approximation techniques (in time and space) were used in this study.

Five independent simulators were designed for each of five sequential water-management time periods (water years 1944-52, 1953-61, 1962-67, 1968-82, 1983-89). The principal changes in simulator design from one period to the next were the inclusions in the model domain of various canal and levee reaches and structures to control canal flows. The horizontal discretization of the subregional model was into 37 columns and 36 rows, and various thin strings of grid cells were used to represent canals and levees after 1961. The vertical discretization was into four layers, of which the uppermost represented seasonal overland sheetflow. Boundary conditions were obtained by embedding the subregional grid in the regional flow model, extracting heads from selected nodes along the subregional model boundary, and using the specified time-varying boundary value input feature to specify boundary pressure values for the subregional model.

The degree of hydrodynamic dispersion was user controlled in the model by the specification of values for longitudinal and transverse dispersivity and molecular diffusivity. A selection of dispersivity values that could be considered representative of the dispersion process in the Biscayne aquifer in the study area was accomplished by simulating the development of the plume of brackish water between 1945 and 1961 and making a qualitative comparison with the measured plume in 1979. Modified dispersion algorithms were used to eliminate all vertical dispersion between the overland sheetflow layer and the upper aquifer layer. A sensitivity analysis using standard algorithms that permitted such vertical dispersion had results that were unacceptable because every episode of local inundation caused simulated dilution of the plume to an unreasonably low concentration, except in a small area near the discharging well that was not inundated.

Longitudinal and transverse dispersivities of 250 ft and 0.1 ft produced a simulated plume qualitatively resembling the measured 1979 plume and were selected for use in the time-period simulations. The 0.1-foot transverse dispersivity value specified sufficient vertical dispersion in the aquifer layer that concentrations were vertically uniform. When the value was reduced to 0.001 ft, substantial vertical stratification occurred and most downgradient migration of brackish water occurred in the lowermost layer. On the other hand, reducing transverse dispersivity in the plane of flow to less than 0.1 ft did not produce a narrower plume. Apparently, the simulated horizontal dispersal of chloride normal to the average flow direction was caused primarily by seasonal variations in flow direction and the use of a large longitudinal dispersivity.

Simulations of the development of the plume of brackish water between 1945 and 1961, prior to the construction and the hydraulic influence of canals, were illustrative of the manner in which the model simulates the influence of the relative amounts of rainfall over periods of several months to several years. When specified rainfall amounts were below normal during an extended period, computed concentration levels increased at all points in the plume of brackish water and the areal extent of the simulated plume increased. During extended periods of above-normal rainfall, however, the area of the region of higher computed concentrations diminished. The area of the region of moderate levels of chloride concentration continued to increase, however, probably as a result of the dilution of the higher concentration water by rainfall.

Between 1961 and 1967, construction of canals and levees outside the study area caused the simulation of a more easterly flow regime near the discharging artesian well. Consequently, a new plume having a more easterly longitudinal axis was simulated, and the older more southerly oriented plume began to dissipate. Between 1968 and 1982, canals crisscrossed the area in which the aquifer was invaded by the brackish water. Flows in the canal system in this time period were usually negligible, as the system received use for flood control only in 1968-69 and 1981-82, and the full potential of the canal system to affect the plume was only realized in those years. Between 1983 and 1989, use of the canal system for water-management purposes increased in frequency. Because the interchange of solute between canals and the aquifer might be overestimated, two independent simulations were used after 1968. One incorporated the canals as previously described, and the other omitted the canal representation.

The simulation that included the canal representation depicted a diminution of the area occupied by water with a chloride concentration greater than 100 mg/L after 1968. This represented the simulated effect of the Levee 31N borrow canal in either draining the brackish water or in diluting it with fresh recharge. These simulations also depicted gradual changes in the orientation of the longitudinal axis of the plume. These changes were caused by long-term variations in the degree of use of canal control structures for drainage. Such variations in control-structure operation were related to long-term variations in the amount of rainfall.

When the canal representation was omitted from the simulation, the spatial extent of the plume of brackish water was greater and extended farther hydraulically downgradient to the southeast. The directional orientation of its longitudinal axis was more southerly than when canals were represented and underwent fewer and smaller changes that were caused by extended periods of above-normal and below-normal rainfall and by a gradual response to the post-1961 change in the general flow regime in the area.

In the simulation that included the canal representation, chloride concentrations at observation wells west of Levee 31N were simulated as varying primarily with the changing orientation of the longitudinal axis of the plume caused by operation of the canal system for drainage, a consequence of the high rate of decrease in concentrations with distance from the longitudinal axis of the plume. The simulated variation of the axial direction of the plume caused by canal drainage has the effect of making simulated concentrations show general agreement with measured ones.

Measured chloride concentrations at hydraulically downgradient observation wells (east of Levee 31N) are underestimated by the simulation containing the canal representation. They are overestimated by the simulation that lacks the canal representation, even though the directional orientation of the plume might be incorrect. Most likely, the former simulation underestimates the downgradient extent of the plume, and the latter simulation overestimates the downgradient extent of the plume.

Simulated concentrations in both versions of the model show abrupt responses to short periods of sustained intense rainfall, as occurred in summer 1969 and autumn 1981. In the period following plugging of the well, the simulation that incorporated the canal representation depicts a rapidly diminishing plume moving southward and a return to background concentrations of chloride between 1991 and 1994 at observation wells west of Levee 31N. Although some measured chloride concentration trends at individual wells in 1990-91 vary from those of the simulation, the general trend is in agreement with the simulation. Little of the plume is simulated as remaining at any location after 1994. When the canals are not represented in the model, the simulated return to background conditions at observation wells west of Levee 31N is similar to and occurs within the same time period as that of the simulation with canals. However, the southward-moving remnant plume is more areally extensive and persists beyond the year 2003.

Because the simulation that omitted the canals depicted a more extensive plume and indicated a longer time required for its dissipation than the simulation that incorporated the canals, and because the rate of southward drift was the same in both simulations, the former was used to pose a worst-case scenario to assess the effects of a proposed well field pumping 140 Mgal/d north of the artesian well source. Following modification of the regional flow model to provide revised subregional boundary conditions that reflected the well-field pumping, the subregional simulation of plume migration was repeated. The effect of the well field on hydraulic gradients near the location of the remnant plume after 1992 was minimal. The southward drift of the remnant plume was only slightly slowed, and there seemed to be no chance that wells in the proposed well field would pump the brackish water.

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