Hydrogeology and Simulation of Ground-Water Flow near the Lantana Landfill, Palm Beach County, Florida

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per year (ft/yr)	0.3048	meter per year
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer
acre	4,047	square meter
gallon per minute (gal/min)	0.06308	liter per second

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

ABBREVIATED WATER-QUALITY UNITS AND ACRONYMS USED IN REPORT:

µS/cm	microsiemens per centimeter at 25 degrees Celsius
mg/L	milligram per liter
dc	direct current
LWDD	Lake Worth Drainage District
PVC	polyvinyl chloride
PBCSWA	Palm Beach County Solid Waste Authority
SFWMD	South Florida Water Management District
USGS	U.S. Geological Survey
VES	vertical electric sounding

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By Gary M. Russell *and* Eliezer J. Wexler

Abstract

The Lantana landfill in Palm Beach County has a surface that is 40 to 50 feet above original ground level and consists of about 250 acres of compacted garbage and trash. Parts of the landfill are below the water table. Surface-resistivity measurements and water-quality analyses indicate that leachate-enriched ground water along the eastern perimeter of the landfill has moved about 500 feet eastward toward an adjacent lake. Concentrations of chloride and nutrients within the leachate-enriched ground water were greater than background concentrations. The surficial aquifer system in the area of the landfill consists primarily of sand of moderate permeability, from land surface to a depth of about 68 feet deep, and consists of sand interbedded with sandstone and limestone of high permeability from a depth of about 68 feet to a depth of 200 feet. The potentiometric surface in the landfill is higher than that in adjacent areas to the east, indicating ground-water movement from the landfill toward a lake to the east.

Steady-state simulation of ground-water flow was made using a telescoping-grid technique where a model covering a large area is used to determine boundaries and fluxes for a finer scale model. A regional flow model encompassing a 500-square mile area in southeastern Palm Beach County was used to calculate ground-water fluxes in a 126.5-square mile subregional area. Boundary fluxes calculated by the subregional model were then used to calculate boundary fluxes for a local model of the 3.75-square mile area representing the Lantana landfill site and vicinity. Input data required for simulating ground-water flow in the study area were obtained from the regional flow models, thus, effectively coupling the models. Additional simulations were made using the local flow model to predict effects of possible remedial actions on the movement of solutes in the ground-water system. Possible remedial actions simulated included capping the landfill with an impermeable layer and pumping five leachate recovery wells. Results of the flow analysis indicate that the telescoping grid modeling approach can be used to simulate ground-water flow in small areas such as the Lantana landfill site and to simulate the effects of possible remedial actions.

Water-quality data indicate the leachate-enriched ground water is divided vertically into two parts by a fine sand layer at about 40 to 50 feet below land surface. Data also indicate the extent of the leachate-enriched ground-water contamination and concentrations of constituents seem to be decreasing over time.

INTRODUCTION

The Lantana landfill is one of the principal point sources of contamination that could threaten the quality of water in the highly permeable surficial aquifer system in Palm Beach County (Vincent, 1984). The landfill in the east-central part of the county (fig. 1) encompasses about 250 acres of what once was a sand-and-shell quarry operation. When filling of the site began in 1968, some waste was disposed of below the shallow water table in rock pits excavated to about 20 ft below land surface. Numerous rock pits in the center of the landfill were used as sludge disposal basins (Florida State Board of Health, 1966). Later, landfill operating rules dictated that waste material be spread and

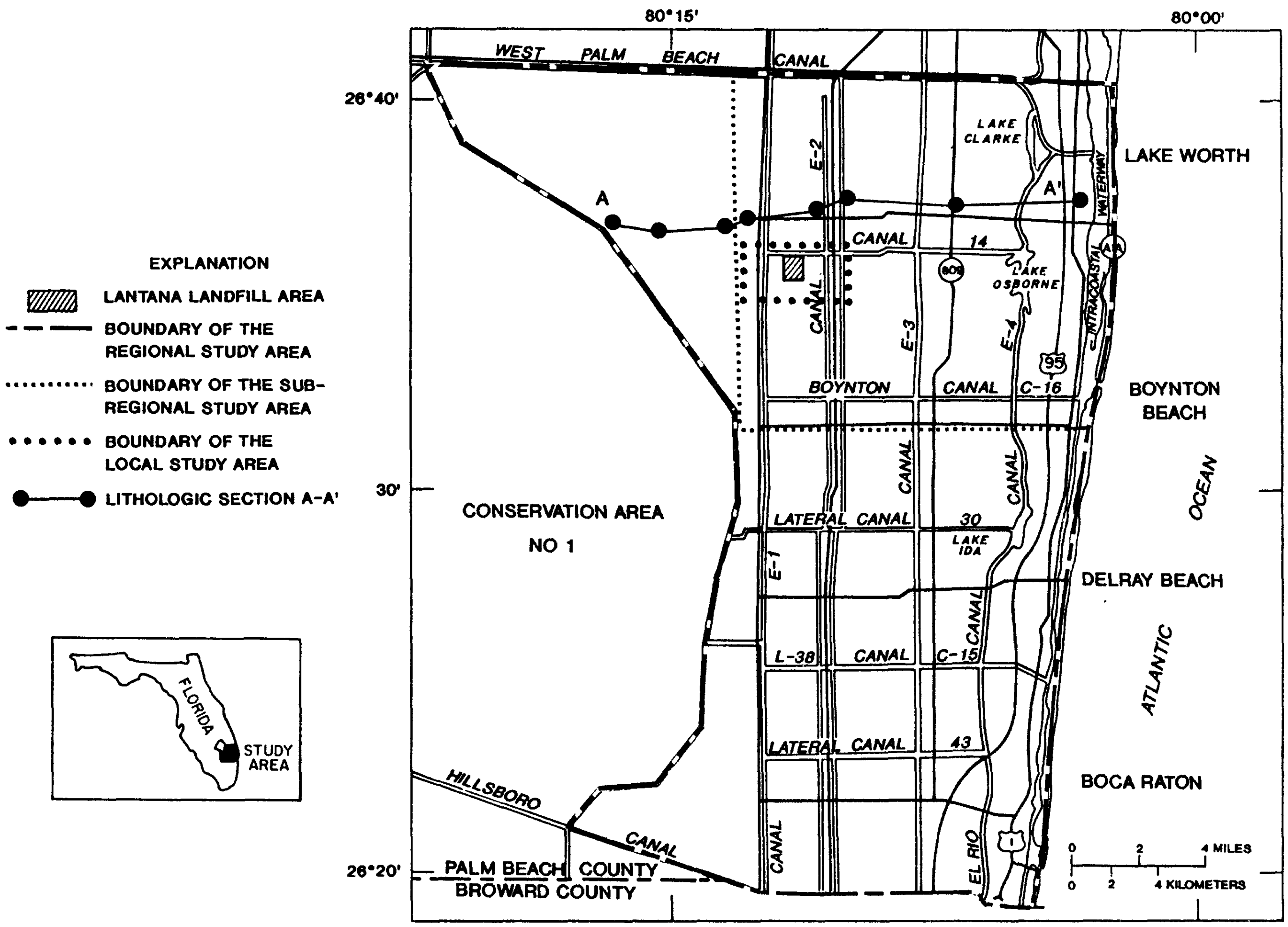


Figure 1. Location of the study areas in Palm Beach County, Florida.

compacted daily and covered with soil. Garbage and trash were compacted to elevations of 40 to 50 ft above original ground level. The landfill was closed in March 1987, and the surface has since been revegetated.

In 1984, the U.S. Geological Survey (USGS), in cooperation with the Palm Beach County Solid Waste Authority (PBCSWA), conducted a geophysical reconnaissance along the perimeters of 12 active and abandoned landfills in Palm Beach County, Fla. The reconnaissance at the Lantana landfill (fig. 1) revealed a low-resistivity area along the perimeter of the site (Russell and Higer, 1988). Additional studies, including the collection of surface-geophysical, water-quality, and lithologic data, were undertaken along the eastern perimeter of the landfill to delineate areas of potential contamination. Several observation wells and multipoint piezometers were installed along the perimeter of the landfill in areas of suspected leachate contamination and also in areas where no contamination was evident. Water samples were collected to determine concentrations of key constituents in the ambient water and in the leachate-enriched ground water.

Numerical models were also developed to determine the physical factors affecting ground-water flow and leachate movement and to determine the effects of possible remedial actions on the movement of landfill leachate. Inasmuch as a ground-water flow model was being developed by the South Florida Water Management District (SFWMD) for southeastern Palm Beach County, this cooperative study with the USGS, PBCSWA, and SFWMD provided an opportunity to study the feasibility of using results from large regional flow models to define conditions at the boundaries of finer scale flow models.

Purpose and Scope

The purposes of this report are to: (1) summarize data describing regional and local hydrogeology, (2) document results of additional analysis of water-quality data, (3) test the feasibility of using large-scale regional models to simulate boundary conditions and ground-water fluxes for smaller scale subregional and local flow models, and (4) assess the capability of a local flow model developed in this manner to simulate ground-water flow in the area of the landfill and to simulate the effects of possible alternative remedial actions at the landfill.

The first part of the report presents the results of the analysis to determine the extent of leachate movement from the eastern perimeter of the Lantana landfill in Palm Beach County. The results include geophysical, geologic, and hydraulic testing to determine aquifer properties. This part of the report describes the design and installation of a sampling network to determine water levels and water quality. The second part of the report describes the development and calibration of a local ground-water flow model of a landfill area based on simulated boundary conditions and ground-water fluxes derived from larger scale subregional and regional models. Simulation results from the local model are presented and evaluated.

Previous Investigations

The hydrogeology of southeastern Palm Beach County has been described by Parker and Cooke (1944), Parker and others (1955), Land and others (1973), Fischer (1980), Swayze and Miller (1984), and Shine and others (1989). Water quality at the landfill has been described by Post, Buckley, Schuh, and Jernigan, Inc. (1980; 1984; 1985) and Russell and Higer (1988). A quasi three-dimensional flow model was developed to represent the landfill by Post, Buckley, Schuh, and Jernigan, Inc. (1984; 1985).

Acknowledgments

The authors thank the Palm Beach County Solid Waste Authority for its cooperation in data collection at the site. Special thanks are extended to Mary Jo Shine of the SFWMD for providing data from the regional flow model of southeastern Palm Beach County and for the exchange of ideas and information regarding model development, data collection, and model calibration. The authors also extend thanks to Jeffrey Giddings of the SFWMD for providing data on withdrawals for public-water supply. The assistance of Engle Development Company for allowing access to adjacent property and the installation of monitoring wells is greatly appreciated.

Well-Construction Methods and Site Hydrogeology

Numerous ground-water sampling and direct-current (dc) resistivity sites were located along the eastern perimeter of the Lantana landfill during the study (fig. 2). Wells LW-1, LW-2, and LW-16 were installed prior to this study to depths of 25, 55, and 120 ft, respectively. These wells were used for water-quality monitoring. An additional 12 wells, PB-1508 through PB- 1519 (fig. 2), were constructed by the

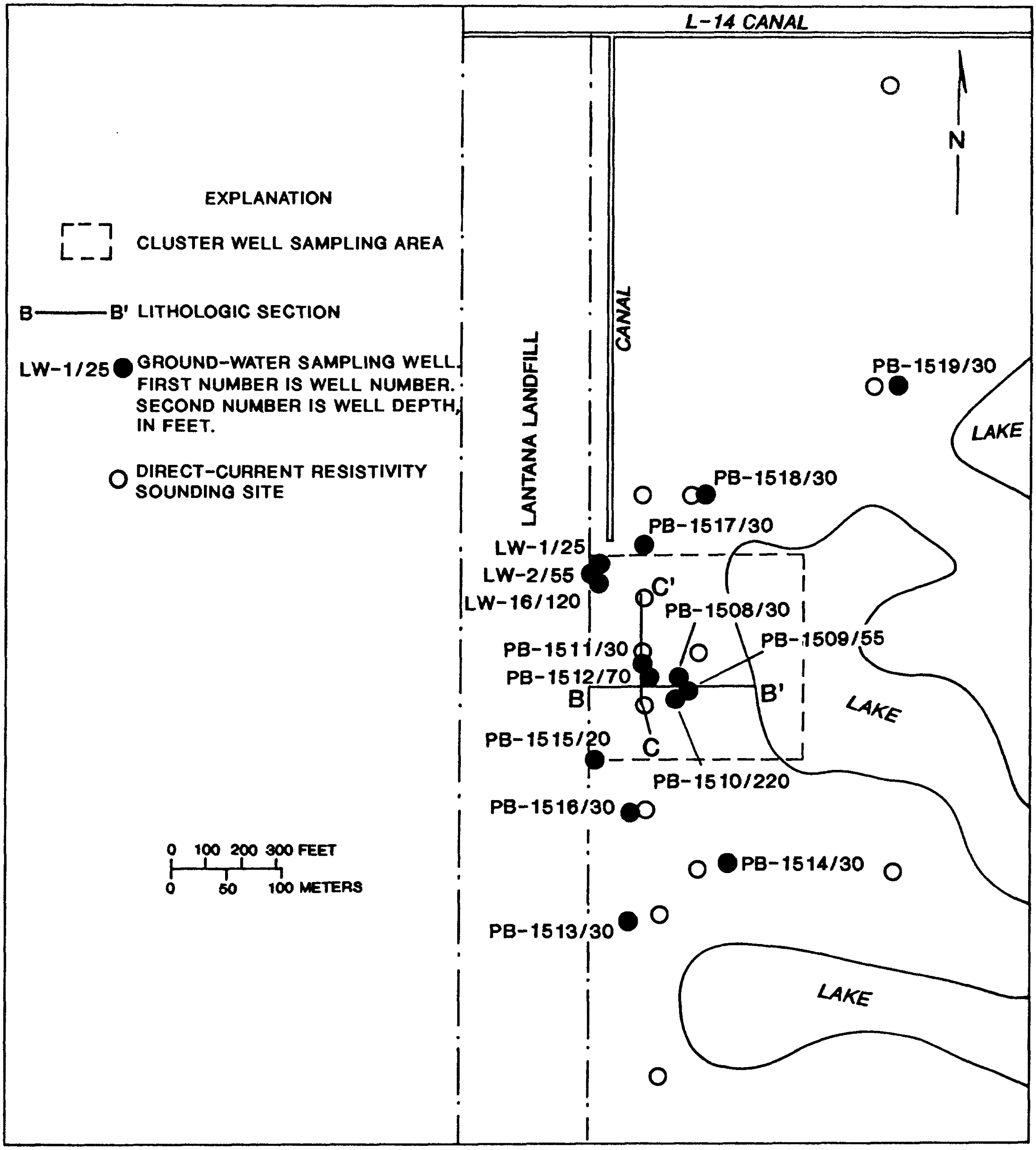


Figure 2. Location of ground-water sampling sites and direct-current resistivity sounding sites along the eastern perimeter of the Lantana landfill.

USGS in April 1985. Well PB-1510 was drilled by the reverse-air, dual-wall method to a depth of 220 ft. The remaining 11 wells were drilled by the cable-tool method to depths ranging from 20 to 70 ft. All wells, except for PB-1515, were constructed with a 2-in., clean-threaded, polyvinyl chloride (PVC) casing with a 3-ft long, 0.020-in. slot screen set at the desired depth. The screens were gravel packed and the casing was cement grouted. Well PB-1515 was constructed with a 4-in. PVC casing, slotted from 15 to 20 ft below land surface, and gravel packed. A continuous water-level recorder was installed in well PB-1515 to monitor water-level fluctuations in the surficial aquifer system. Samples were collected for water-quality analyses at all wells, except at PB-1515.

During the final data-collection effort of this study, cluster wells or multipoint piezometers were constructed to a maximum depth of 70 ft at 12 sites. Well sites were selected on the basis of information from surface geophysical studies and water-quality data, which had defined the areal and vertical extent of ground-water contamination and the direction of ground-water flow. These cluster wells consisted of 1-ft screens positioned at 5-ft intervals from 15 to 70 ft below land surface (fig. 3, cluster well sites 1 and 3-12). Cluster well 12 is near two existing wells, PB-1511 (30 ft deep) and PB-1512 (70 ft deep), and includes screens installed at depths of 20, 40, 50 and 60 ft below land surface. Cluster well 3 consists of six 1- in. PVC wells with 1-ft screens set at 10-ft intervals from 20 to 70 ft below land surface.

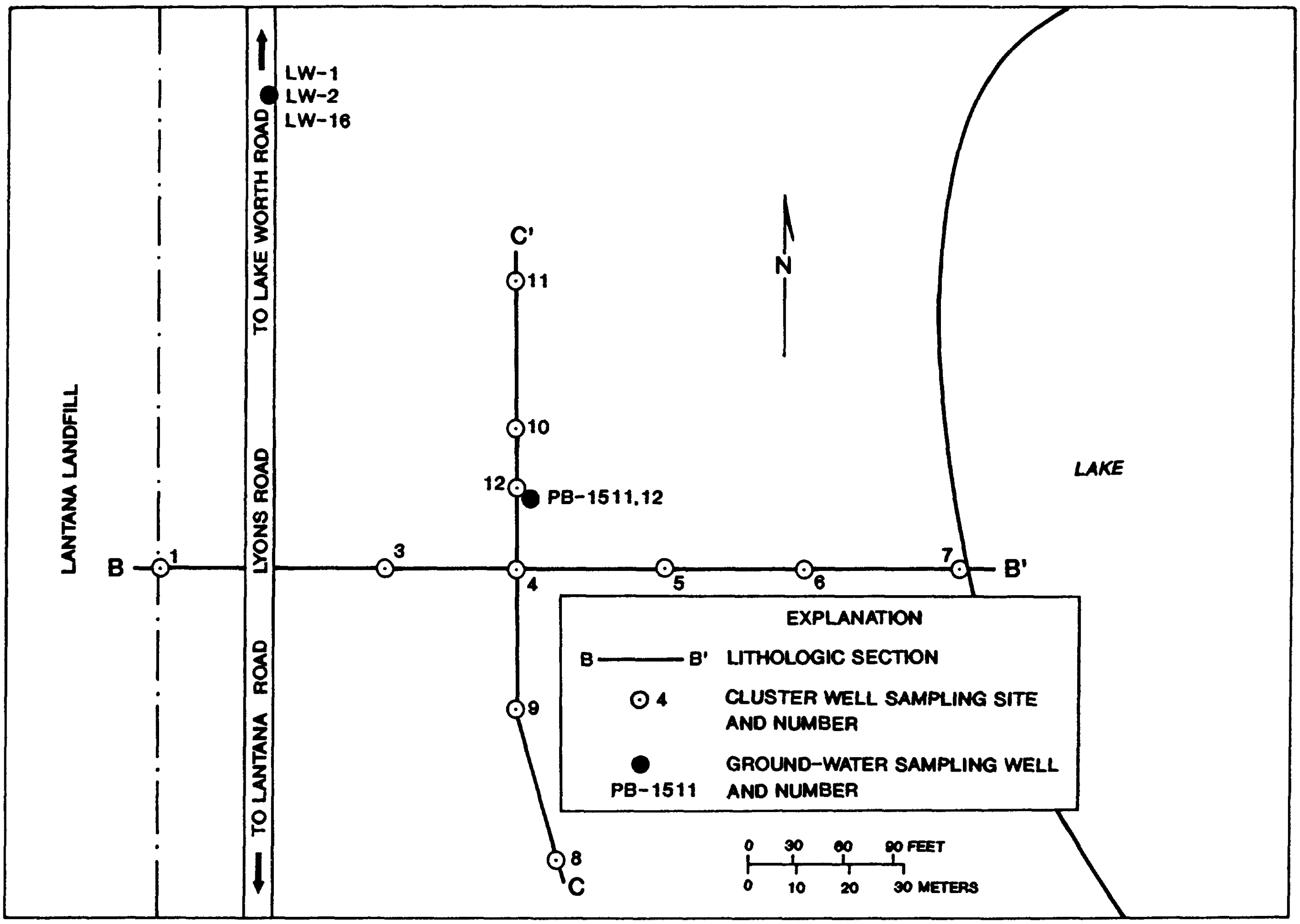


Figure 3. Location of cluster well sites and sections B-B′ and C-C′ along the eastern perimeter of the Lantana landfill.

HYDROGEOLOGY

Hydrologic features of the study area are determined by several factors including geology, climate, surface-water drainage, and ground-water flow. The primary sources of ground-water recharge are precipitation and canal infiltration. Downgradient inflow from adjacent parts of the aquifer add to the recharge. An extensive canal system maintains high canal water levels in the agricultural areas to the west (fig. 2) during the dry season (November-April).

Geologic Setting

Materials that form the surficial aquifer system in eastern Palm Beach County are comprised of several different stratigraphic units and were deposited in a variety of environments (Swayze and Miller, 1984, p. 10). A lithologic section of the surficial aquifer system in the study area is shown in figure 4. The lithology shown in this section, about 1 mi north of the landfill (fig. 1), is typical of subsurface lithology in southeastern Palm Beach County. The surficial aquifer system in the study area is comprised of part or all of the following formations, from land surface to the base of the aquifer system: the Pamlico Sand, Anastasia Formation, and Fort Thompson Formation of Pleistocene age, the Caloosahatchee Formation of Pliocene and Pleistocene age, and the Tamiami Formation of Pliocene age.

The upper part of the surficial aquifer system is primarily composed of quartz sand of the Pamlico Sand and varies in thickness from 0 to 50 ft. The Pamlico Sand occurs at or near the surface throughout most of the study area and consists of Pleistocene marine deposits that are younger than the Anastasia Formation (Parker and Cooke, 1944). Shell is often found in the Pamlico Sand and may occur in bedded layers or disseminated throughout the sand. Other less-common materials include silt, clay, and organic debris. Recently deposited organic soils may cover surficial sands of the Pamlico Sand in wetlands or in areas where plant growth has been persistent.

The Anastasia Formation varies in thickness from 0 to more than 200 ft and underlies the Pamlico Sand. The Anastasia Formation consists of sand, sandy limestone, sandstone, coquina, and shell. Lateral changes in lithology are difficult to predict, whereas vertical changes in lithology tend to progress downward from unconsolidated sand and shell, to calcareous sandstone, to biogenic limestone and coquina. Solution cavities are common in the limestone and coquina-dominated intervals. These solution zones commonly correspond to water-bearing intervals of the surficial aquifer system.

The Fort Thompson Formation varies in thickness from 0 to 40 ft and is present in the southern and western parts of southeastern Palm Beach County but does not underlie the Lantana landfill. To the east, the Fort Thompson grades laterally into the Anastasia Formation. In southeastern Palm Beach County, the Fort Thompson Formation consists of limestone, shells, sand, and marl that may grade vertically into the underlying Tamiami Formation or Caloosahatchee Formation.

The Caloosahatchee Formation varies in thickness from 0 to about 50 ft and consists of sandy, shelly marls with occasional stringers of well-consolidated sandy limestone. The Caloosahatchee Formation occurs only in the western part of the study area where it may directly underlie the Anastasia, Fort Thompson, or Pamlico Formations.

The upper part of the Tamiami Formation varies in thickness from 0 to 100 ft and consists of cavity-riddled sand and shell. The zone of dissolution that occurs within the upper Tamiami is a major water-bearing interval of the surfical aquifer system. The lower part of the Tamiami Formation consists of greenish clay marl, silty and generally very shelly sand, and calcareous marl. In places, this formation may be relatively impermeable and forms the lower boundary of the surficial aquifer system (Shine and others, 1989).

Well PB-1510 was drilled near the Lantana landfill (fig. 2) through the surficial aquifer system and into the underlying relatively impermeable units of the lower Tamiami Formation to provide detailed lithostratigraphic descriptions of the surficial aquifer system at the landfill. A detailed lithologic log was made from samples collected from the well (table 1). The upper geologic unit consists of fine sands of the Pamlico Sand (fig. 4). The underlying sand-and-shell strata of the Anastasia Formation and Tamiami Formation consist primarily of quartz sand and small marine shells, some of which have been cemented to form coquina or sandstone (fig. 4). Unconsolidated sand and shell are at land surface to a depth of about 68 ft. At depths of 68 to 130 ft, the Anastasia Formation consists mostly of sand interbedded with sandstone and limestone. No confining units were evident between the surficial sands and the Anastasia Formation. At this same interval (68-130 ft), the Anastasia Formation is cavity riddled and relatively permeable and grades into the Tamiami Formation at a depth of about 130 ft. At depths of 130 to about 195 ft, the upper Tamiami Formation is similar hydrologically to the Anastasia Formation in that the relatively high permeability within this interval is due to the postdepositional dissolution of calcareous material. At depths of 215 to 220 ft, the lower Tamiami Formation consists of a grayish-olive, sandy clay that is relatively impermeable and forms the lower boundary of the surficial aquifer system.

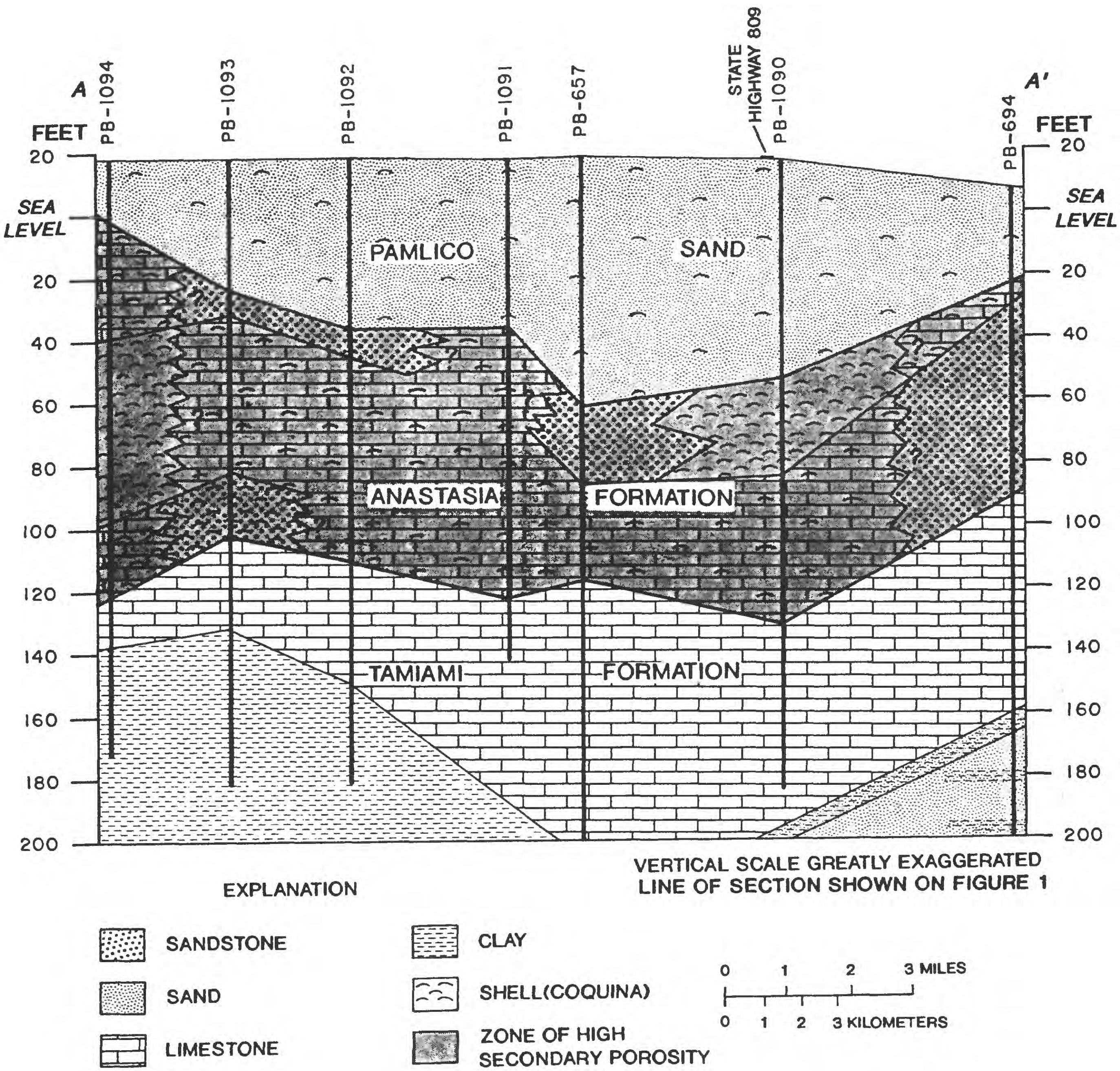


Figure 4. Lithologic section A-A′. (Modified from Swayze and Miller 1984.)

Table 1. Lithologic log of well PB-1510

Lat 26° 35'47", long 80° 11'17"
Sec. 32, T. 44S., R. 42E.

Thick-ness (feet)	Depth (feet below land surface)	Description
4	0 - 4	Fill.
2	4 - 6	Sand, dark-yellowish-brown (10 YR 4/2) to dusky-yellowish-brown (10 YR 2/2); quartzose, fine grained to silt, moderately sorted (fine), rounded to angular; about 1 to 3 percent heavy minerals, fine grained, subrounded to angular; about 5 percent shell fragments (very small), mollusks; about 20 percent organics; minor clay.
2	6 - 8	Shells and shell fragments, mollusks including Chione sp. and gastropods; about 30 percent sand as above; quartzose, medium grained to silt, moderately (fine) to poorly sorted; lacks organics; loosely to well cemented in places to very shelly sandstone.
6	8 - 14	Sand, very pale orange (10 YR 8/2) to pale-yellowish-brown (10 YR 6/2); quartzose, medium to very fine grained, moderately to well sorted (fine), angular to rounded; about 3 percent heavy minerals, fine grained to silt, well sorted (fine), subangular to rounded; about 1 to 3 percent shell fragments; about 1 to 3 percent organics.
2	14 - 16	Sand as above; less than 1 percent shell fragments.
2	16 - 18	Sand as above; quartzose, coarse to very fine grained, moderately sorted (fine); about 3 to 5 percent heavy minerals, medium grained to silt, moderately sorted (silt), angular; about 5 to 10 percent shell fragments; minor organics.
2	18 - 20	Sand as above; quartzose, medium to very fine grained, moderately to well sorted (fine); about 1 percent heavy minerals, fine to very fine grained, well sorted (fine to very fine).
6	20 - 26	Sand, dark-yellowish-brown (10 YR 4/2), very pale orange (10 YR 8/2), to pale-yellowish-brown (10 YR 6/2); quartzose, medium to fine grained, moderately to well sorted (fine), angular; about 1 to 3 percent heavy minerals and phosphorite, medium to fine grained, moderately sorted (fine), angular to rounded; about 1 percent shell fragments.
4	26 - 30	Sand, dark-yellowish-brown (10 YR 4/2); quartzose, coarse to very fine grained, well sorted (very fine to fine toward base), angular to rounded; about 1 percent heavy minerals, very fine grained, subangular to rounded; less than 1 percent shell fragments.
7	30 - 37	Sand as above; quartzose, medium to very fine grained, well sorted (very fine to fine toward base).
3	37 - 40	Sand as above; moderately sorted (very fine).
4	40 - 44	Sand as above; quartz, well sorted (fine); about 3 percent heavy minerals, fine grained to silt, well sorted (fine), angular.
3	44 - 47	Sand as above; quartzose, coarse to very fine grained.
7	47 - 54	Sand, pale-yellowish-brown (10 YR 6/2); quartzose, medium to fine grained, well sorted (fine to medium toward base), angular to subrounded; about 1 percent heavy minerals, fine to very fine grained, well sorted (very fine), angular to well rounded.
6	54 - 60	Sand as above; coarse to fine grained, well sorted (medium).
7	60 - 67	Sand as above; coarse grained to silt, well to moderately sorted (fine to very fine toward base).
1	67 - 68	Sand, pale-yellowish-brown (10 YR 6/2); quartzose, very coarse grained to silt, poorly sorted, angular to well rounded; about 25 percent phosphorite and heavy minerals, coarse to very fine grained, moderately sorted (very fine), subangular to well rounded; about 15 to 20 percent shell fragments, mollusks.

Table 1. Lithologic log of well PB-1510--Continued

Thick-ness (feet)	Depth (feet below land surface)	Description
6	68 - 74	Limestone, light-gray (N 7) to medium-gray (N 5); sandy, sparse biosparite, mollusks; about 30 percent quartz, medium to fine grained, well sorted (fine), subrounded to rounded; about 10 to 15 percent phosphorite and heavy minerals, fine to very fine grained, well sorted (fine), subangular to well rounded; well to very well cemented; moderately porous to porous toward base, moldic, vugs.
1	74 - 75	Sand as in 67 to 68 feet; phosphorite, moderately sorted (fine); about 35 percent shell fragments; loosely cemented in places into a sandstone.
5	75 - 80	Limestone as in 68 to 70 feet; grades to a sandstone in places; very loosely to well cemented at 79 and 80 feet; porous, vugs.
10	80 - 90	Shell fragments, very small to small; about 40 percent sand; quartzose, medium to very fine grained, moderately sorted (fine); about 15 to 20 percent phosphorite and heavy minerals, medium to fine grained, well sorted (fine), subrounded to rounded; loosely cemented into a sandstone; interbedded at 82 and 83 feet and 87 and 88 feet with a limestone; sandy, sparse biosparite; about 20 to 30 percent quartz, medium to very fine grained, moderately sorted (fine); about 10 percent phosphorite (same properties as in sand); grades into a sandstone in places at 87 and 88 feet; very well cemented; moderately porous, vugs.
5	90 - 95	Sand as above; loosely cemented in places into a sandstone; porous, interparticle and vugs.
5	95 - 100	Sand as above; light-olive-gray (5 Y 5/2); color is due to a silt coating around the grains; interbedded with sandstone at 97.5 to 100 feet; quartzose, coarse to very fine grained, moderately sorted (fine), subangular to rounded; about 10 percent heavy minerals and phosphorite, medium to fine grained, angular to rounded; about 30 to 35 percent shell fragments; about 20 percent sparite matrix; very well cemented; porous, vugs.
5	100 - 105	Limestone as in 75 to 80 feet; porous, interparticle and vugs.
5	105 - 110	Limestone, yellowish-gray (5 Y 8/1) to light-gray (N 7); sandy, packed biosparite, abundant in gastropods; about 35 percent quartz, fine grained, angular to subrounded; about 10 percent phosphorite and heavy minerals, medium to fine grained, well sorted (fine), angular to well rounded; grades into a sandstone at 105 and 106 feet and 108 to 109.5 feet; well cemented; porous, interparticle, moldic, and vugs.
5	110 - 115	Sandstone as above; loosely cemented; interbedded with limestone as above at 113 and 114 feet; barnacles.
5	115 - 120	Sandstone, yellowish-gray (5 Y 8/1) to light-gray (N 7); quartzose, medium to very fine grained, well sorted (very fine), angular to subangular; about 15 percent heavy minerals and phosphorite, medium to very fine grained, moderately sorted (very fine), subrounded to well rounded; about 25 to 30 percent shell fragments (small); about 10 percent sparite matrix; loosely to well cemented; porous, vugs and interparticle.
5	120 - 125	Sandstone, yellowish-gray (5 Y 7/2) to light-olive-gray (5 Y 5/2); quartzose, coarse to very fine grained, moderately to well sorted (fine), angular to subrounded; about 10 percent phosphorite and heavy minerals, coarse to very fine grained, moderately sorted (fine), angular to rounded; about 25 percent shell fragments, mollusks, echinoid spines, and abundant in foraminifers; about 5 to 10 percent poorly washed sparite matrix; moderately to well cemented; porous, vugs; grades into a limestone in places, sandy, sparse biosparite; very well cemented; moderately porous, vugs.
5	125 - 130	Limestone, yellowish-gray (5 Y 8/1); sandy, packed biosparite to poorly washed biosparite (coquinoid texture), barnacle fragments, mollusks, and benthic foraminifers; about 10 to 15 percent quartz, medium to fine grained, well sorted (fine), subangular to subrounded; about 10 percent heavy minerals and phosphorite, fine to very fine grained, well sorted (fine), angular to well rounded; moderately to well cemented; porous, vugs.

Table 1. Lithologic log of well PB-1510--Continued

Thickness (feet)	Depth (feet below land surface)	Description
5	130 - 135	Sandstone, light-olive-gray (5 Y 6/1); quartzose, coarse to very fine grained, moderately sorted (fine), angular to subrounded; about 10 percent phosphorite and heavy minerals, fine to very fine grained, well sorted (fine), angular to well rounded; about 40 percent shell fragments, barnacles, bryozoans, and mollusks; about 5 to 10 percent sparite matrix; grades into a limestone in places; loosely to moderately cemented; porous, interparticle and vugs.
8	135 - 143	Sandstone as above; about 15 percent phosphorite and heavy minerals, coarse to fine grained, moderately sorted (fine), subrounded to well rounded.
2	143 - 145	Limestone, light-olive-gray (5 Y 6/1) to light-gray (N 7); sandy, packed biosparite, bryozoans, barnacles, and mollusks; about 10 to 20 percent quartz, medium to fine grained, well sorted (fine), angular to rounded; about 15 to 20 percent phosphorite and heavy minerals, medium to fine grained, well sorted (fine), subangular to rounded; well cemented, friable; moderately porous, interparticle and moldic.
10	145 - 155	Limestone, light-olive-gray (5 Y 6/1); sandy, sparse to packed biomicrite, mollusks, barnacles and bryozoans; about 20 to 40 percent quartz, medium to very fine grained, moderately sorted (fine), angular to rounded; about 10 to 15 percent phosphorite and heavy minerals, medium to fine grained, well to moderately sorted (medium), subrounded to rounded; sandstone in places; loosely to moderately cemented.
5	155 - 160	Sandstone as above; quartzose, coarse to fine grained, well sorted (medium); minor hematite; about 20 to 25 percent shell fragments; about 5 to 25 percent micritic matrix; is a limestone in places as above; loosely to moderately cemented at 159 and 160 feet.
5	160 - 165	Limestone, yellowish-gray (5 Y 8/1) to light-gray (N 7) to medium-light-gray (N 6); sandy, packed biomicrite, mollusks; about 20 percent quartz, medium to fine grained, well sorted (fine), angular to subrounded; about 10 percent phosphorite and heavy minerals, medium to fine grained, moderately sorted (fine), angular to well rounded; loosely to well cemented at 164 and 165 feet.
5	165 - 170	Limestone as above; about 30 to 40 percent quartz; about 10 to 15 percent phosphorite and heavy minerals; sandstone in places; loosely to well cemented.
25	170 - 195	Limestone as above; about 20 to 30 percent quartz; about 10 percent heavy minerals and phosphorite; loosely to very loosely cemented.
5	195 - 200	Sand, very light gray (N 8) to yellowish-gray (5 Y 8/1); quartzose, medium grained to silt, well sorted (medium), angular to rounded; about 10 to 15 percent phosphorite and heavy minerals, medium to fine grained, well sorted (medium), angular to well rounded; about 35 percent shell fragments and detrital carbonate; loosely cemented in places into a silty, shelly sandstone.
5	200 - 205	Sand, very light gray (N 8) to yellowish-gray (5 Y 8/1); quartzose, medium to fine grained, well sorted (fine), angular; about 15 percent phosphorite and heavy minerals, coarse to fine grained, angular to well rounded; about 25 percent shell fragments; loosely cemented at 204 and 205 feet.
5	205 - 210	Sand as above; silty; about 30 percent shell fragments; loosely cemented in places at 205 to 207 feet.
5	210 - 215	Sand, light-olive-gray (5 Y 5/2); quartzose, fine grained to silt, moderately sorted (fine), angular to subrounded; about 10 percent phosphorite and heavy minerals, coarse grained to silt, moderately sorted (fine), angular to well rounded; about 35 percent shell fragments; about 5 percent lime mud; loosely cemented in places into very silty, shelly sandstone; slightly porous to relatively impermeable.
5	215 - 220	Silt, grayish-olive (10 Y 4/2); very sandy; about 20 percent phosphorite and heavy minerals, fine grained to silt, well sorted (fine), angular to rounded; about 10 to 20 percent lime mud; about 5 percent shell fragments; relatively impermeable.

Climate

The average annual rainfall within the study area is about 62 in/yr (W.J. Cogger, U.S. Geological Survey, written commun., 1991), with about 45 in/yr occurring during the wet season from May to October (Shine and others, 1989). Precipitation that is not returned to the atmosphere by evaporation and transpiration runs off into canals and discharges to the ocean or recharges the aquifer. The percentage of rainfall that reaches the aquifer is dependent on water-table depth, soil type, land cover, and infiltration capacity of soils. Recharge to the aquifer for this study was estimated to be between 50 and 75 percent of the average annual precipitation, depending on the degree of cultural development (Shine and others, 1989, p. 52).

Surface Water

The Lake Worth Drainage District (LWDD) in southeastern Palm Beach County operates an extensive network of canals and control structures. The district encompasses about 218 mi^2, extending from the West Palm Beach Canal south to the Hillsboro Canal (fig. 1). The western boundary of the district is irregular and is defined by the eastern levee of Conservation Area No. 1 to the south and by the E-1 canal to the north. The eastern boundary of the district is along the E-4 canal system that interconnects Lake Clarke, Lake Osborne, Lake Ida, and the El Rio Canal.

Water levels in the canal system are controlled primarily by water- management practices, which include maintaining high levels in the predominantly agricultural areas to the west during the dry season and low levels during the wet season. Water levels in the canals are maintained between 4.5 ft and 15.5 ft above sea level (W.J. Cogger, U.S. Geological Survey, written commun., 1991). There are eight intermediate stages, but most of the canal system is held at 15.5, 13, and 8.5 ft above sea level. Water levels are maintained at the 15.5-ft level by pumping from the Hillsboro Canal, and water is allowed to overflow and drain by gravity through each subsequent stage. The water levels in the canals vary according to the season but generally have been held within 1 ft of the desired elevation for the particular season during the past decade. Water is drained to the Intracoastal Waterway through automatic gates operated by the SFWMD. Drainage to the Intracoastal Waterway is controlled primarily by the L-38 Canal and the Boynton Canal (fig. 1). Many lateral canals drain directly into the E-4 canal system (W.J. Cogger, U.S. Geological Survey, written commun., 1991).

Ground-Water Flow

Ground water in the surficial aquifer system occurs under semiconfined or unconfined conditions. The water-table contour maps shown in figures 5 and 6 are based on water levels measured in April and November 1984, respectively (Miller, 1985a; 1985b). Water levels during this period were considered to be above average for the period 1970 to 1981 (Miller, 1988, p. 16). Seasonal variations in canal stage and aquifer recharge cause the altitude of the water table to fluctuate between 1 and 4 ft/yr. Extensive regulation of canal flows for flood control and agriculture tends to mask seasonal variations in ground-water levels (Miller, 1988). The altitude of the water table is usually highest in September and October and lowest in April and May.

The general direction of flow within the surficial aquifer system in southeastern Palm Beach County is eastward; however, water levels maintained in the canal system within the LWDD create local variations in the altitude of the water table and in the direction of ground-water flow.

Potentiometric data from shallow wells in the landfill area indicate that there is a slight eastward hydraulic gradient from the landfill toward the unnamed lake to the east (fig. 2). Differences in heads are about 0.3 ft over a distance of 300 ft (Russell and Higer, 1988). Water levels vary seasonally about 1 ft in this area; however, the hydraulic gradient probably remains nearly constant from dry season to wet season (Swayze and Miller, 1984).

Water-level data also indicate that the surficial aquifer system is separated into two hydrologic zones. Fine unconsolidated sands within the upper zone (0-68 ft) seem to restrict the movement of water downward to the lower consolidated zone (68-220 ft). Differences in water levels between shallow (25-30 ft) and intermediate (55 ft) wells averaged 0.08 ft higher for 1985. Differences in water levels between intermediate (55 ft) and deep (120-185 ft) wells averaged 0.38 ft higher for 1985, indicating that shallow wells have higher heads (Russell and Higer, 1988). The lithologic log of well PB-1510 (table 1) indicates that a confining layer does not exist in the surficial sands; however, water-level data indicate restricted movement into the lower zone.

Extent of Leachate-Enriched Ground Water

The areal and vertical extent of a leachate-enriched plume was delineated by surface-geophysical techniques. Water-quality analysis confirmed the degree of contamination.

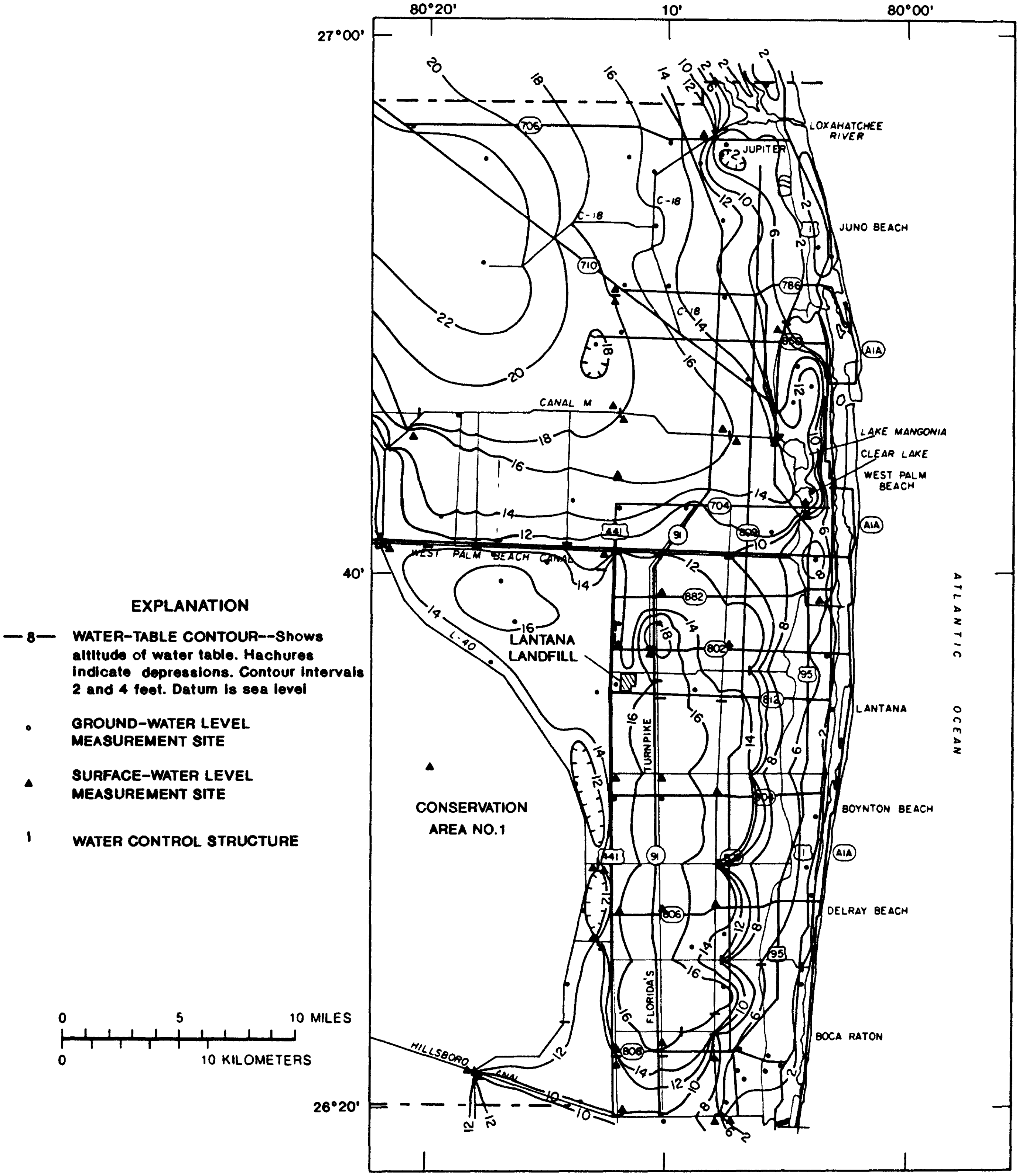


Figure 5. Altitude of water table of the surficial aquifer system in eastern Palm Beach County, April 1984. (Modified from Miller, 1985a.)

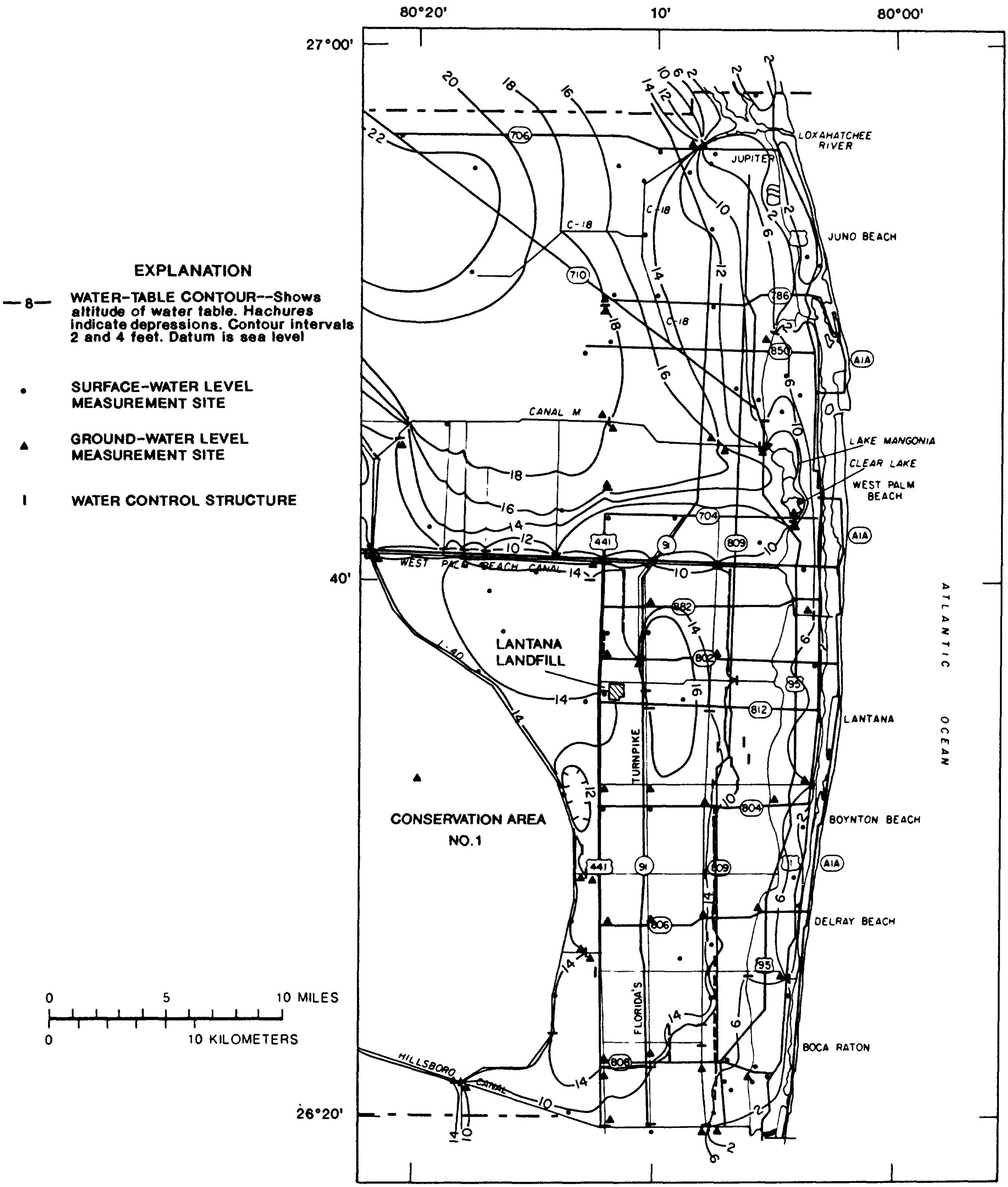


Figure 6. Altitude of water table of the surficial aquifer system in eastern Palm Beach County, November 1984. (Modified from Miller, 1985b.)

Surface Geophysics

A reconnaissance in 1984 using surface-geophysical methods identified the eastern perimeter of the Lantana landfill as an area of lower apparent earth resistivity. Geophysical surveys were conducted in February 1985 to define the possible extent of leachate-enriched ground water along the eastern perimeter of the landfill. Geophysical data were collected at 13 sites using a dc resistivity meter.

Resistivity is affected by moisture content, mineralogy, water quality, and physical characteristics of the surficial aquifer system. Lithologic units which have high porosity characteristically have lower resistivities; conversely, low-porosity units have higher resistivities. Clay minerals have low resistivities because they are electrochemically active and have large surface areas. Ground water with high mineralization has lower resistivities than water with low mineralization. Because the size of the study area is relatively small and the lithology is relatively uniform, abrupt changes in resistivity near the landfill probably are the result of variations in the degree of mineralization that represent corresponding changes in ground-water quality (Russell and Higer, 1988).

Most of the vertical electric soundings (VES's) in the resistivity surveys had the same general background profile, depicting three distinct layers within the surficial aquifer system (fig. 7). The dc resistivity soundings and water-quality data indicate that offsite movement of leachate has occurred along the eastern perimeter of the Lantana landfill. Downward movement of leachate may also have occurred into the high permeability zone of the surficial aquifer system (Russell and Higer, 1988).

A three-dimensional matrix was constructed (fig. 8) using information on layer resistivity, thickness, and depth produced from the interpreted VES's. The matrix represents the approximate study area from land surface to a depth of 200 ft. The major axis, aligned with the north arrow, represents the eastern perimeter of the landfill. Land-surface features, superimposed on figure 8, show the approximate location of the landfill to the west and the adjacent lakes to the east. The illustration shows the approximate location of a three-dimensional surface of apparent earth-resistivity of 30 ohm-meters during February 1985. All apparent earth-resistivity

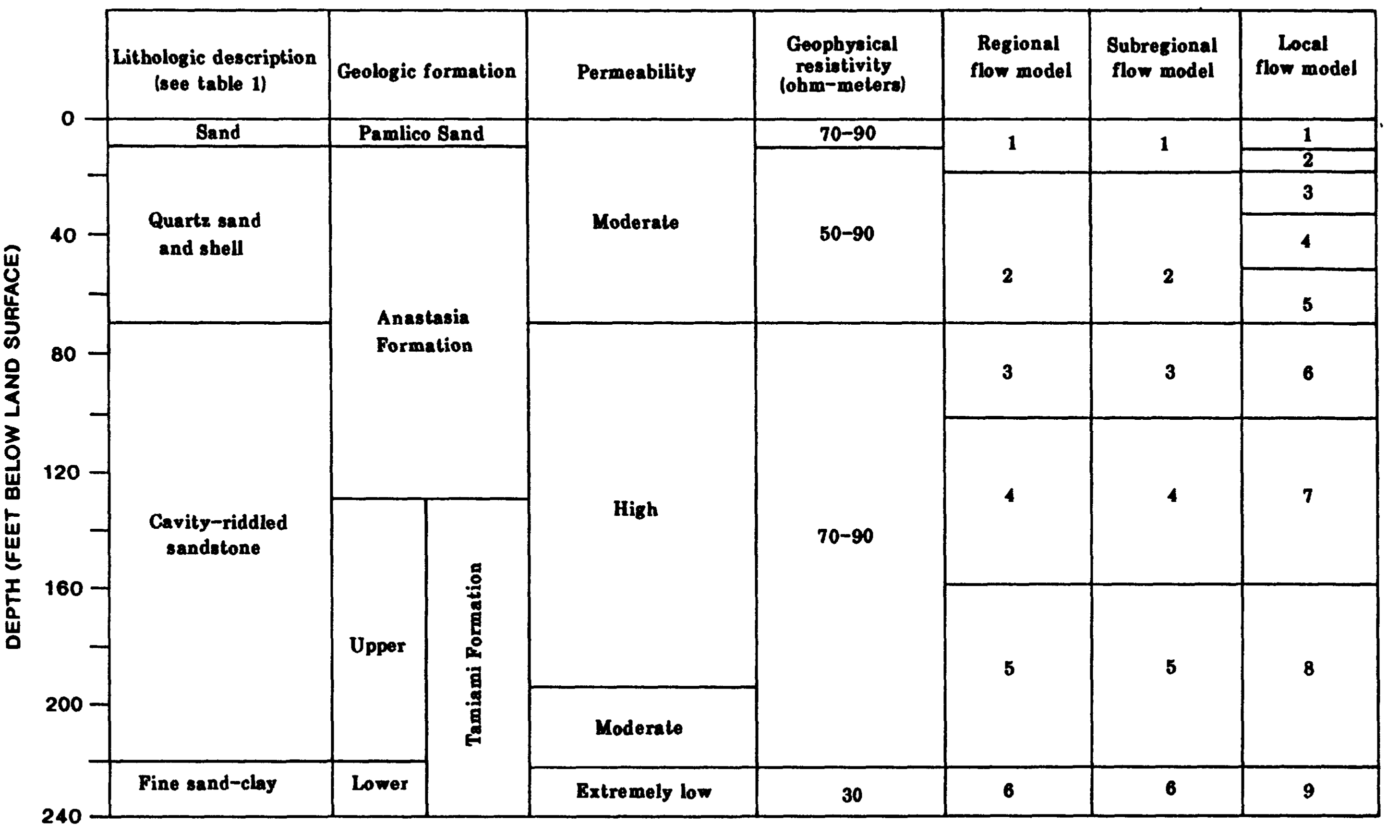


Figure 7. Correlation of lithologic and geologic units and model layers for the regional, subregional, and local ground-water flow models.

values are less than 30 ohm-meters between the landfill and the part of the aquifer delineated by the 30 ohm-meter surface. A 30 ohm-meter value was chosen as a convenient demarcation of the body of leachate-enriched ground water at this site where background resistivity is between 50 and 90 ohm-meters (fig. 7). The resultant three-dimensional surface shows the leachate-enriched ground water along the eastern perimeter of the landfill moving eastward toward the lake at a depth of about 30 ft.

Ground-Water Quality

Ground-water quality in the surficial aquifer system in Palm Beach County varies with location and depth. Factors that may affect water quality include composition of the aquifer, saltwater intrusion, residual seawater, and contamination. Generally, water in the surficial aquifer system is less mineralized along the coast than in areas farther inland. The water becomes highly mineralized toward the conservation areas to the west. Water-quality analyses available from well PB-1510 during drilling show a deterioration of water quality with depth. Chloride concentrations increased from about 70 mg/L at 140 ft to as much as 260 mg/L at 200 ft. Moderate permeabilities in this part of the surficial aquifer system have greatly retarded dilution of residual seawater by infiltration of rainfall and fresh surface water (Miller, 1988). Mineralization of the water also increases with depth (Miller, 1988).

Water samples were collected from 14 ground-water sites during May 1985 (fig. 2). Constituents analyzed were nutrients, carbon, major ions, and trace metals (Russell and Higer, 1988). Generally, water-quality constituents in the upper part (0-68 ft) of the surficial aquifer system decreased in concentration with distance from the landfill and with depth (Russell and Higer, 1988). Chloride concentrations greater than 20 mg/L and specific conductance values greater than 1,000 μS/cm, indicative of

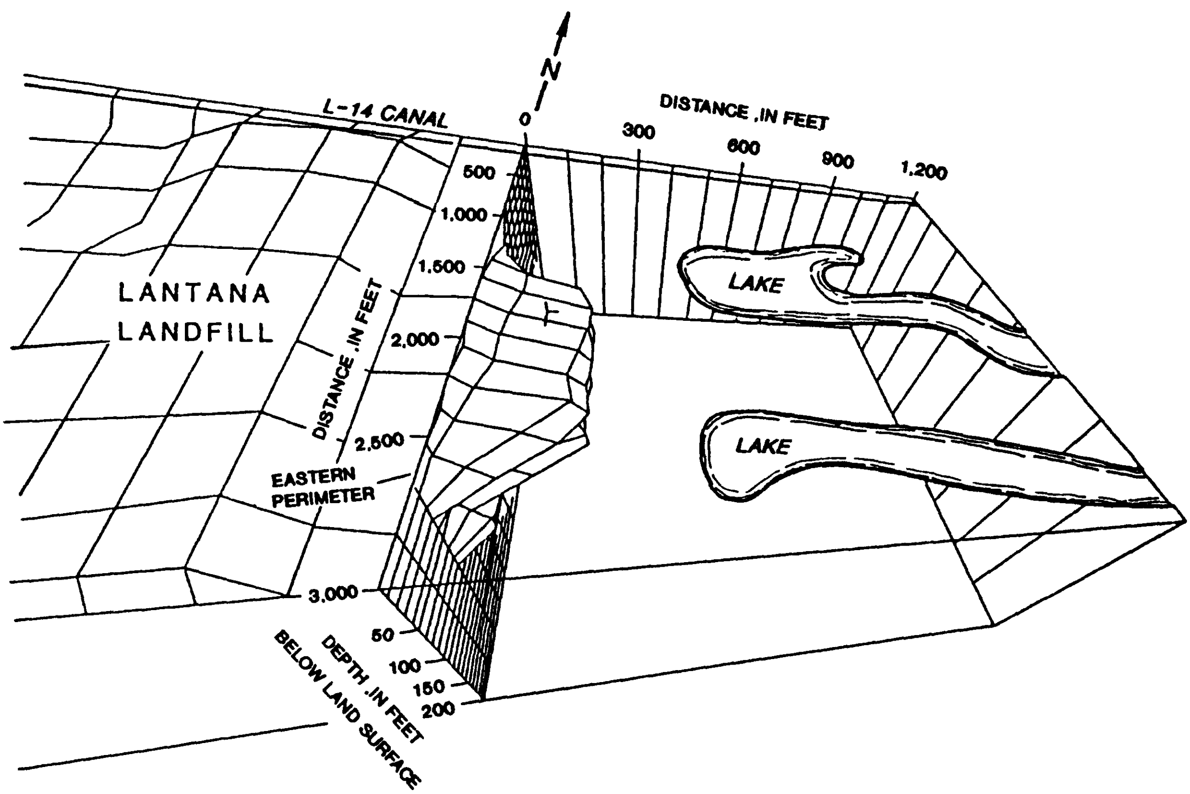


Figure 8. Approximate location of apparent earth-resistivity contours (30 ohm-meters) along the eastern perimeter of the Lantana landfill, February 1985. (Modified from Russell and Higer, 1988.)

leachate, were detected in water from shallow and intermediate depth wells along the eastern perimeter of the landfill. Chloride concentrations exceeded the background concentration of 20 mg/L (Land and others, 1973) in 11 wells and exceeded 50 mg/L in 6 wells.

Leachate is evident offsite in wells PB-1509 (55 ft deep) and PB-1512 (70 ft deep) where specific conductance measurements and chloride concentrations are somewhat higher than background levels (100 μS/cm and 20 mg/L). This may indicate some migration of leachate into the high permeability zone of the surficial aquifer system. Similar patterns are also evident for several other water-quality constituents (Russell and Higer, 1988).

Cluster well sites were selected on the basis of geophysical and water-quality data. Analysis of data collected at these sites was used to define the areal and vertical extent of the leachate-enriched ground water and direction of ground-water flow. Water samples collected from these cluster well sites were analyzed for specific conductance, pH, alkalinity, and chloride. These samples were collected from wells: (1) along the flow path of the leachate-enriched ground water (section B-B′) at 0, 156, 248, 351, 448, and 557 ft from the landfill; and (2) along a north-south transect (section C-C′) approximately parallel to and 248 ft from the eastern perimeter landfill, at 52, 98, and 200 ft north of the center of the leachate-enriched ground water, and at 96 and 200 ft south of the center (fig. 3).

Elevated specific conductance values, chloride concentrations, and alkalinity values were considered characteristic of the leachate plume and were used to delineate the area of contamination. Analysis of cluster-well data collected in July 1987 and May 1988 indicates that the plume of leachate-enriched ground water is divided vertically into two parts by a fine sand layer that seems to be continuous but occurs at depths ranging from about 40 to 50 ft (fig. 9a,b). The upper part of the plume, as identified by the 100-mg/L line of equal chloride concentration (fig. 9a,b), seems to have moved about 320 ft from the landfill (figs. 9-11, cluster well 5). The lower part of the plume seems to have moved about 550 ft from the landfill.

The areal extent of the leachate plume and the concentration of contaminants in ground water within the plume away from the landfill seem to have decreased in recent years. The area of leachate-enriched ground water away from the landfill was somewhat more concentrated in July 1987 than in May 1988 (figs. 9-11). Chloride concentrations within the leachate plume at a depth of about 40 ft at sites 4 through 10 were about 200 mg/L in July 1987 (fig. 9a) but decreased to about 100 mg/L in May 1988 (fig. 9b). The leachate plume may be dispersing in the surficial aquifer system; however, because of the complex nature of the flow system, it is not possible to determine if this is a temporary variation due to changes in recharge. Similar patterns exist for changes in specific conductance and alkalinity (figs. 10 and 11).

SIMULATION OF GROUND-WATER FLOW

In addition to delineation of the horizontal and vertical extent of the leachate-enriched ground water and determination of its chemical composition, methods of quantifying the physical factors affecting ground-water flow in the landfill vicinity were developed to help determine the movement of landfill leachate. Movement of conservative ground-water solutes, those that do not significantly enter into reaction with other ions, and move with the water with minor retardation or loss, is controlled by two physical processes--advection and hydrodynamic dispersion. Advection is the bulk movement of solutes in the direction of flow. Hydrodynamic dispersion is the mixing of solutes along a flow path due to the combined effects of molecular diffusion, velocity variations on the scale of pores, and velocity variations due to local variations in hydraulic conductivity (macrodispersion). Although accurate simulation of solute concentrations requires simulation of both advective and dispersion processes, determination of the advective movement of solutes alone can provide useful information where the ground-water flow system is complex or not well understood. Often, the general movement of ground water in an area may be known as a result of a regional flow analysis; however, because the area affected by solute movement is usually limited, knowledge of the local flow system is necessary in assessing the movement of contaminants.

The regional flow system in southeastern Palm Beach County has been the subject of numerous studies and generally is well understood. The hydrologic boundaries that affect regional ground-water flow in the region are distant from the Lantana landfill site. Simulation of both regional flow and local flow patterns at the landfill site with a single model was considered to be impractical. A relatively new technique was used in which three linked, three-dimensional, ground-water flow models representing the surficial aquifer system were developed to simulate transient ground-water flow at a regional, subregional, and local scale at the Lantana landfill. All models allow for simulation of water-table conditions, recharge and evapotranspiration, discharge to public-supply and irrigation wells, and leakage to or from canals.

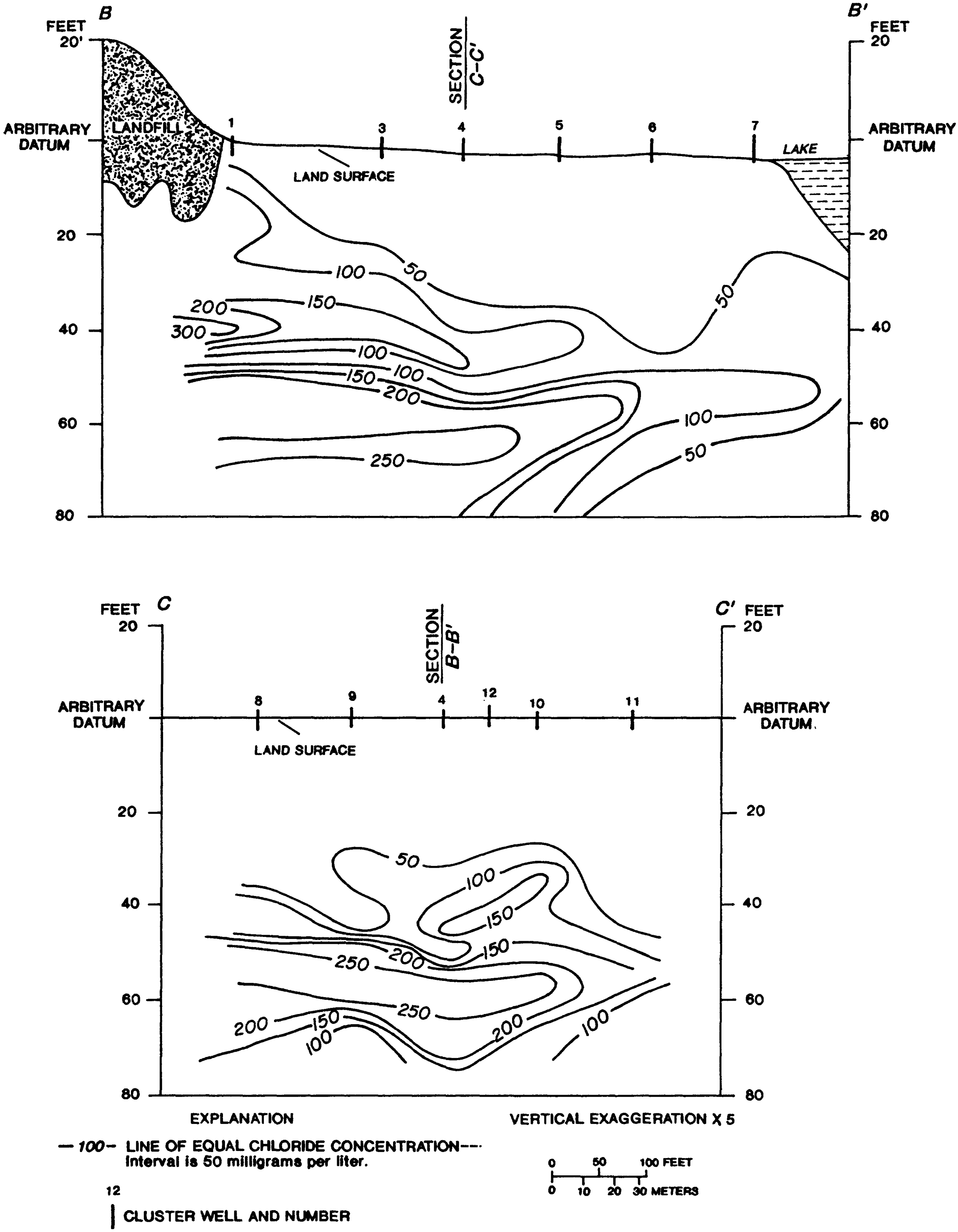
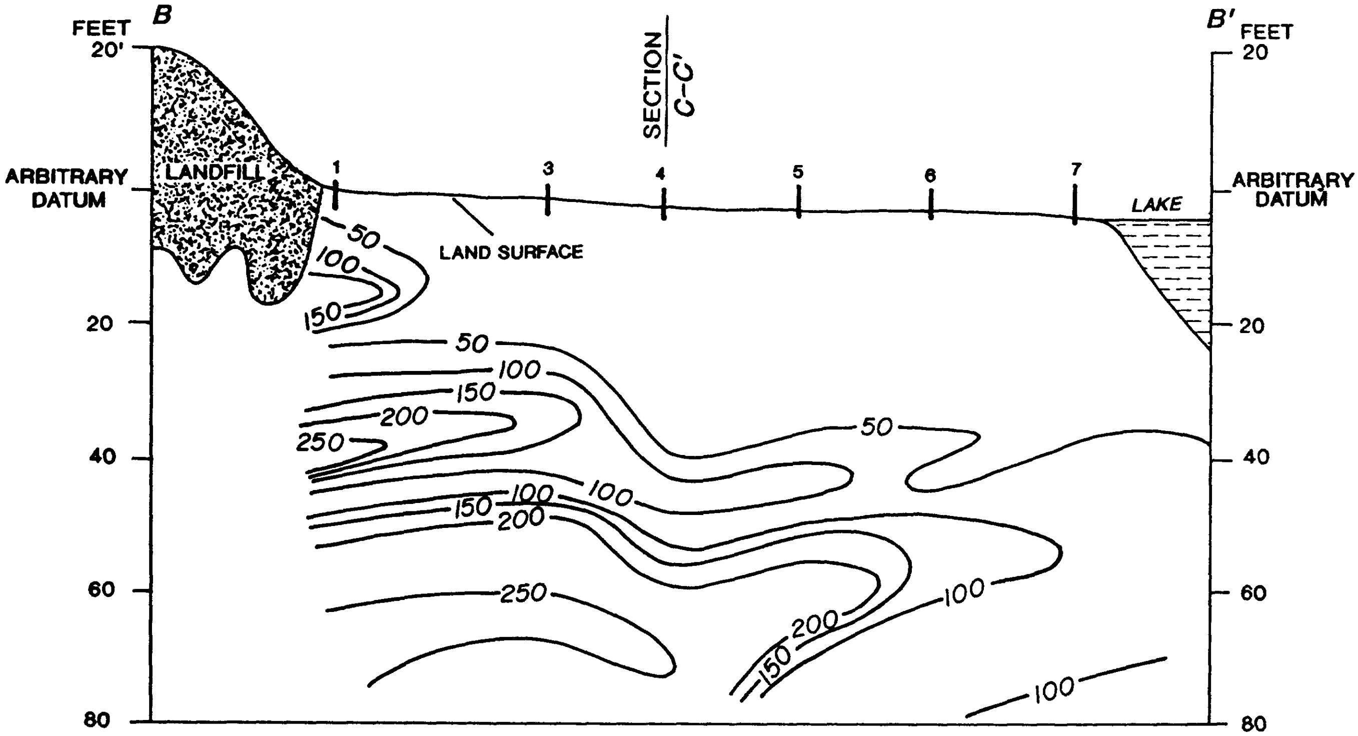
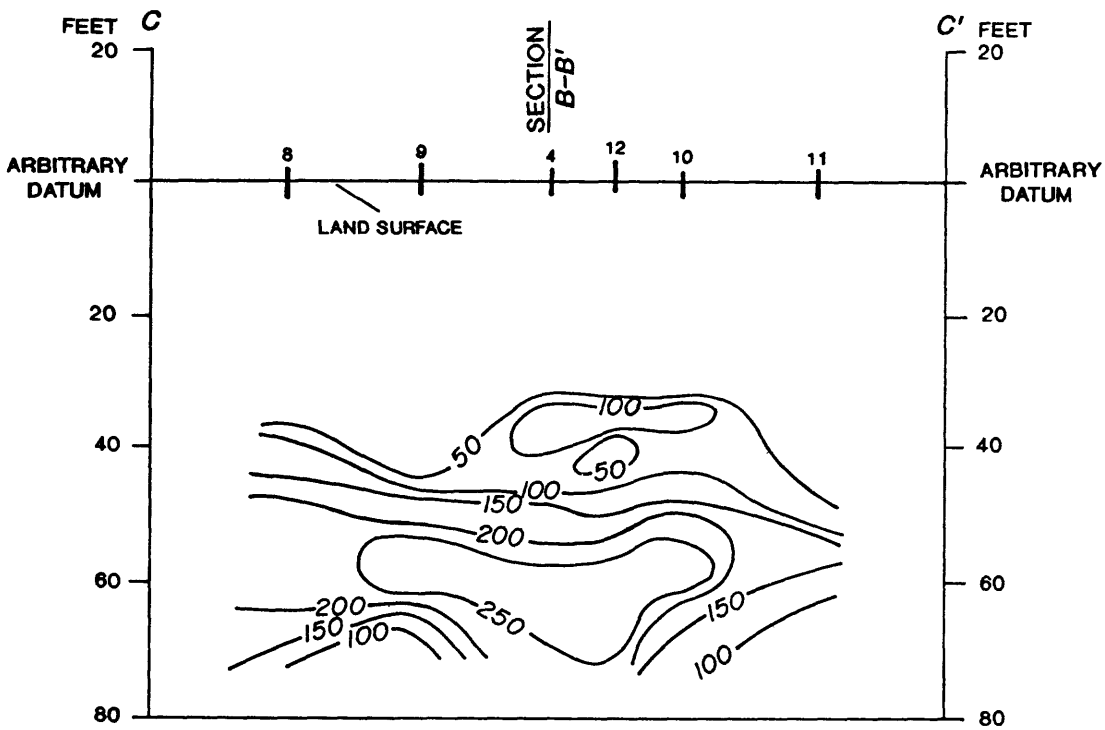


Figure 9a. Sections B-B′ and C-C′ showing lines of equal chloride concentration, July 1987.





EXPLANATION

VERTICAL EXAGGERATION X 5

—100— **LINE OF EQUAL CHLORIDE CONCENTRATION--Interval is 50 milligrams per liter.**

12 CLUSTER WELL AND NUMBER

0 50 100 FEET
0 10 20 30 METERS

Figure 9b. Sections B-B′ and C-C′ showing lines of equal chloride concentration, May 1988.

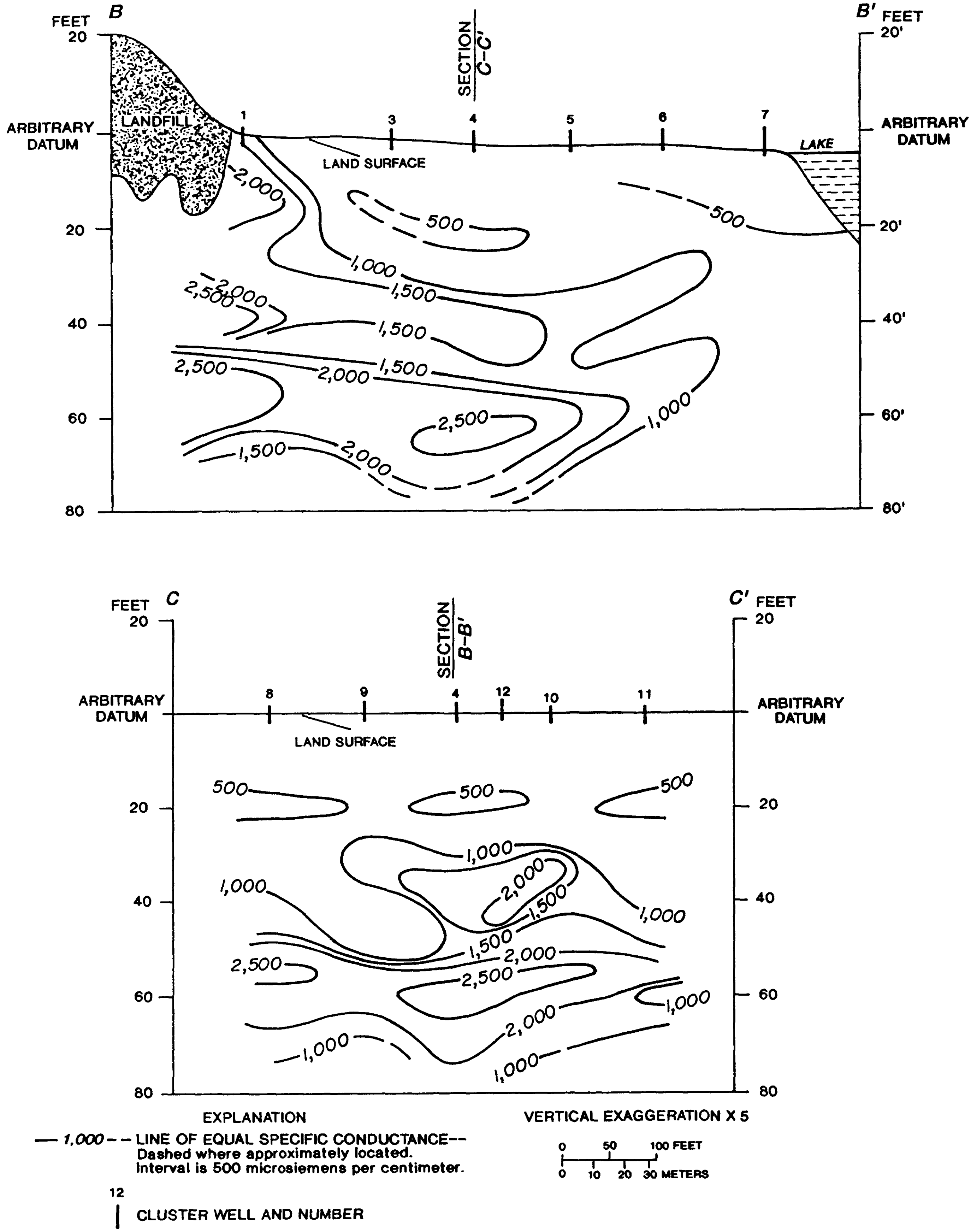


Figure 10a. Sections B-B′ and C-C′ showing lines of equal specific conductance, July 1987.

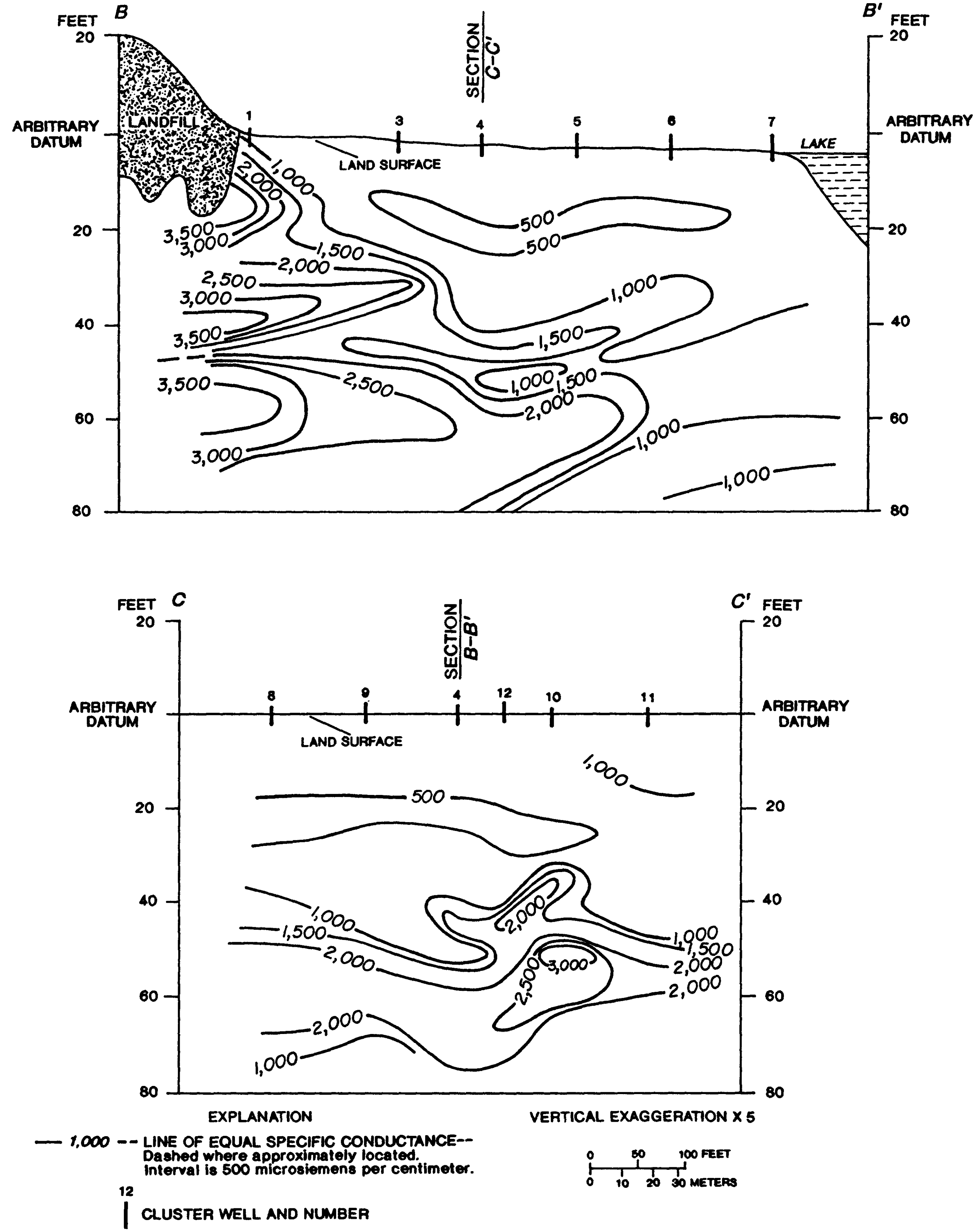


Figure 10b. Sections B-B′ and C-C′ showing lines of equal specific conductance, May 1988.

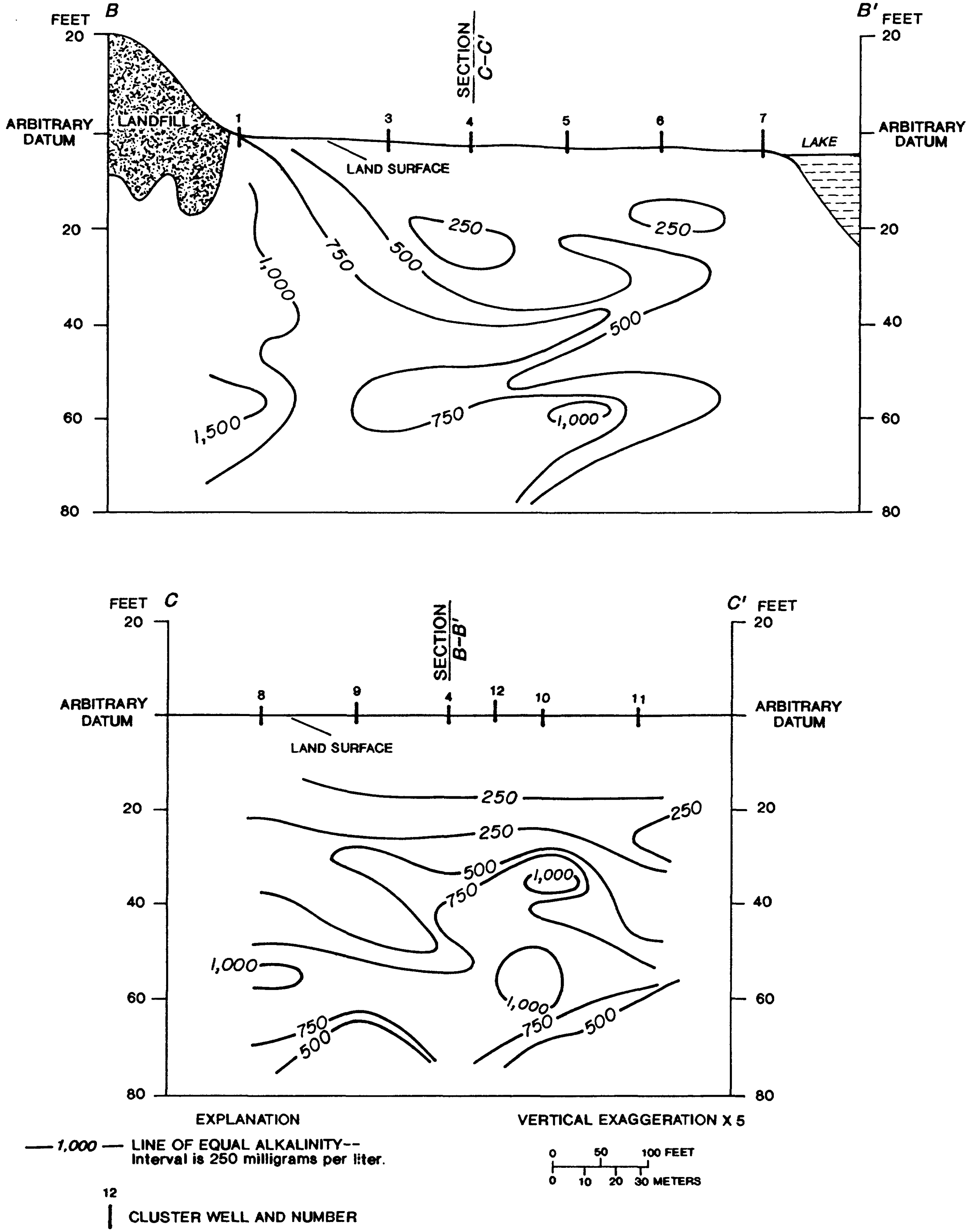


Figure 11a. Sections B-B′ and C-C′ showing lines of equal alkalinity, July 1987.

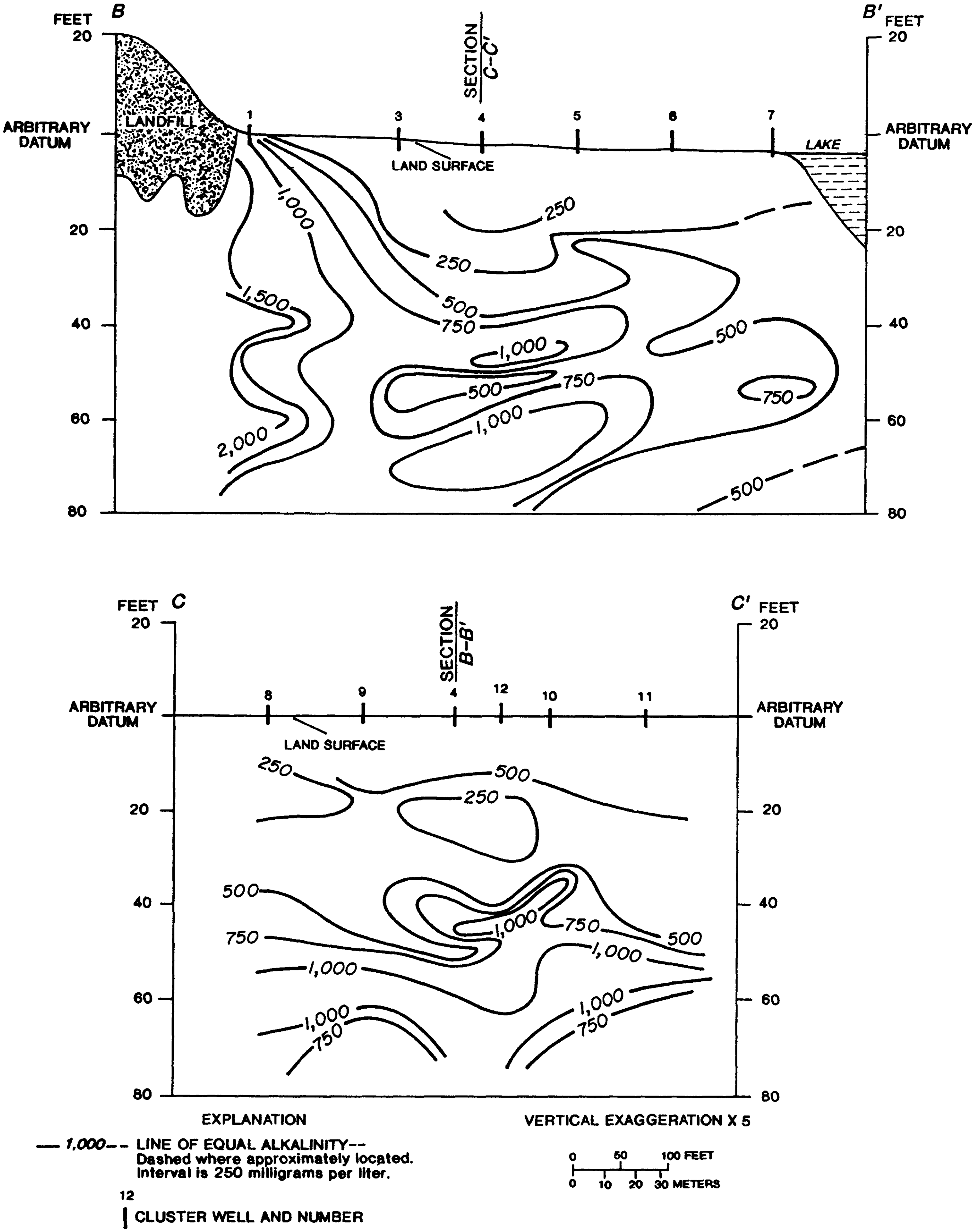


Figure 11b. Sections B-B′ and C-C′ showing lines of equal alkalinity, May 1988.

Ground-Water Flow Theory

The partial differential equation that governs three-dimensional (areal) ground-water flow in a heterogeneous anisotropic medium can be expressed as:

$$\frac{\partial}{\partial x}\left[K(xx)\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K(yy)\frac{\partial h}{\partial y}\right]\frac{\partial}{\partial z}\left[K(zz)\frac{\partial h}{\partial z}\right]$$

$$-W = Ss\frac{\partial h}{\partial t} \qquad (1)$$

where:

K(xx), K(yy), K(zz) are hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (Lt^{-1}),

h is the head (L),

W is a volumetric flux per unit volume and represents sources and/or sinks of water (t^{-1}),

S_s is specific storage of the porous material (L^{-1}), and

t is time (t).

Three types of boundary conditions are ssociated with equation 1. The first type, referred to as a prescribed-head boundary condition, is defined by:

$$h = H_1 \qquad (2)$$

where h is the head in the aquifer at a point on the boundary, and H_1 is a known value.

The second type, referred to as a prescribed-flux boundary condition, is defined by:

$$q_n = q_1, \qquad (3)$$

where q_n is the rate of flow normal to the boundary, and q_1 is a known value. A no-flow boundary, in which q_1 is equal to zero, can be used to represent streamline or impermeable boundaries.

The third type, referred to as a head-depndent flux boundary condition, is applied where flow across the aquifer boundary is dependent on the difference between the head in the aquifer and a known head on the opposite side of a semipermeable layer. The head-dependent flux boundary condition is defined by:

$$q_n = \frac{K'}{b'}(H_o - h), \qquad (4)$$

where q_n is the boundary flux, K' is the hydraulic conductivity of the semipermeable layer, b' is the thickness of the semipermeable layer, H_o is the known head on the opposite side of a semipermeable layer, and h is the head in the aquifer. Additional discussions on the ground-water flow equation and boundary conditions have been presented by Bear (1979, p. 117-123).

Equation 1 can be solved using analytical methods for idealized conditions only. For areas with irregularly shaped boundaries or with spatial variation in aquifer properties, numerical methods must be used. These methods involve determining a solution for the head values at a selected number of points within the area modeled rather than at all points. One technique, called the finite-difference method, involves dividing a map of the area modeled into a grid composed of smaller rectangular blocks or "cells." Points at the center of these blocks are called nodes.

The governing equations and boundary conditions can also be rewritten in terms of a mass balance of flows across the faces of each block and volumes of water in storage within the block. The partial derivatives in equation 1 are replaced by approximations involving either the differences in head values over finite intervals in time (time steps) or head differences between adjacent nodes. This substitution yields a system of simultaneous algebraic equations. Given appropriate boundary conditions, an approximation of the true aquifer heads can be determined by solving the finite-difference form of equation 1 for each node in the grid at the end of each time step.

The finite-difference method has been applied extensively in the simulation of ground-water flow. The theory and application of the method are described by Remson and others (1971), Bear (1979), and Wang and Anderson (1982). The computer code used in this study, developed by the USGS and described by McDonald and Harbaugh (1988), is referred to in this report as the MODFLOW model.

Regional Flow Model

The size of the regional flow model, which represents southeastern Palm Beach County, was determined by the location of the natural hydrogeologic boundaries nearest to the site. The boundaries include the West Palm Beach Canal to the north, the Hillsboro Canal to the south, Conservation Area No. 1 to the west, and the Intracoastal Waterway and Atlantic Ocean to the east (fig. 1). The water table is the upper boundary, and the clay unit that underlies the surficial aquifer system is the lower boundary.

The regional flow model for southeastern Palm Beach County was developed by SFWMD (Shine and others, 1989) using the MODFLOW code. This model represents the 500-mi^2 area with a finite-difference grid composed of 50 rows and 40 columns with square cells of 2,640 ft on a side. An areal representation of the regional flow model grid for southeastern Palm Beach County is shown in figure 12.

The regional flow model consists of six layers of varying thickness. The top two layers represent the surficial sands, the middle two represent the high permeability zone, referred to as the Biscayne aquifer by Shine and others (1989), and the lower two layers represent the lower permeability sand and shell and fine sand and clay units (fig. 7). Layers 2, 3, and 4 have the same number of active cells as layer 1; however, there are no prescribed-flux boundaries in these layers (Shine and others, 1989). An areal representation of the grid for layers 5 and 6 is shown in figure 13. The increased number of inactive cells in these layers represents the pinching out of the surficial aquifer system with depth in the western part of the model.

Prescribed-Head Boundaries

Prescribed-head boundary conditions (eq. 2) were applied to all cells in each layer along the western boundary of the study area to represent Conservation Area No. 1. The head values in this part of the model were set at 15.4 ft, which represents an average water level during the period November 1983 to May 1985 in the conservation area.

Prescribed-head boundary conditions were also applied in the uppermost layer of nodes along the eastern shoreline boundary. These head values were set to 0.0 ft to represent sea level.

Prescribed-Flux Boundaries—No Flow and Recharge

No-flow boundaries are automatically assigned at all external model boundaries and at the face of all cells adjacent to inactive cells by the MODFLOW code. A no-flow boundary was also applied to the base of layer 6 and represents the contact between the surficiall aquifer system and the underlying sequence of relatively impermeable clays, silts, and limestones of the lower Tamiami Formation.

The two major drainage canals along the northern and southern boundaries (West Palm Beach and Hillsboro Canals) were represented as line sinks for ground water, such that little or no lateral inflow occurs beneath the canals from outside the study area (Shine and others, 1989). Accordingly, no-flow boundaries were applied parallel to the canals along the northern and southern model boundaries. Discharge to the canals within the model area was simulated using head-dependent flux cells adjacent to the canals (described in the next section).

A freshwater-saltwater interface is present within the surficial aquifer system near the shore where freshwater in the aquifer system meets denser, saline ground water underlying the Intracoastal Waterway and the Atlantic Ocean. The actual position of the interface is not well known, but saltwater encroachment into the surficial aquifer system has occurred in the near-shore area (Shine and others, 1989). Accordingly, the interface is represented in layers 2 to 6 as a streamline or no-flow boundary in the cells along the shore where freshwater discharges upward along the interface to the Intracoastal Waterway or tidal canals. The coarseness of the areal discretization did not allow for representation of the sloping surface of the interface. Corresponding cells in layer 1 were treated as constant-head boundaries.

The water table was treated as a prescribed-flux boundary. Recharge to the water table was computed from monthly average precipitation, adjusted for losses because of runoff. Rates of recharge equal to 50 percent of precipitation were used in urbanized areas. Recharge rates equal to 75 percent of precipitation were applied in agricultural or nonurban areas (Shine and others, 1989). Local variations in precipitation were determined by interpolation of data from 24 rain gages in the area using kriging techniques.

Ground-water discharge from the surficial aquifer system as a result of evapotranspiration is significant because of the shallow depth to the water table in most of the area. Discharge from the aquifer system is calculated internally by the MODFLOW code, such that the rate of discharge has a maximum value when the water table is at or above land surface and decreases linearly to zero when the depth to water exceeds the extinction depth (McDonald and Harbaugh, 1988). The maximum rate of evapotranspiration in the SFWMD model was calculated monthly from long-term climatological data using the Penman method (Jones and others, 1984), and an extinction depth of 7.5 ft.

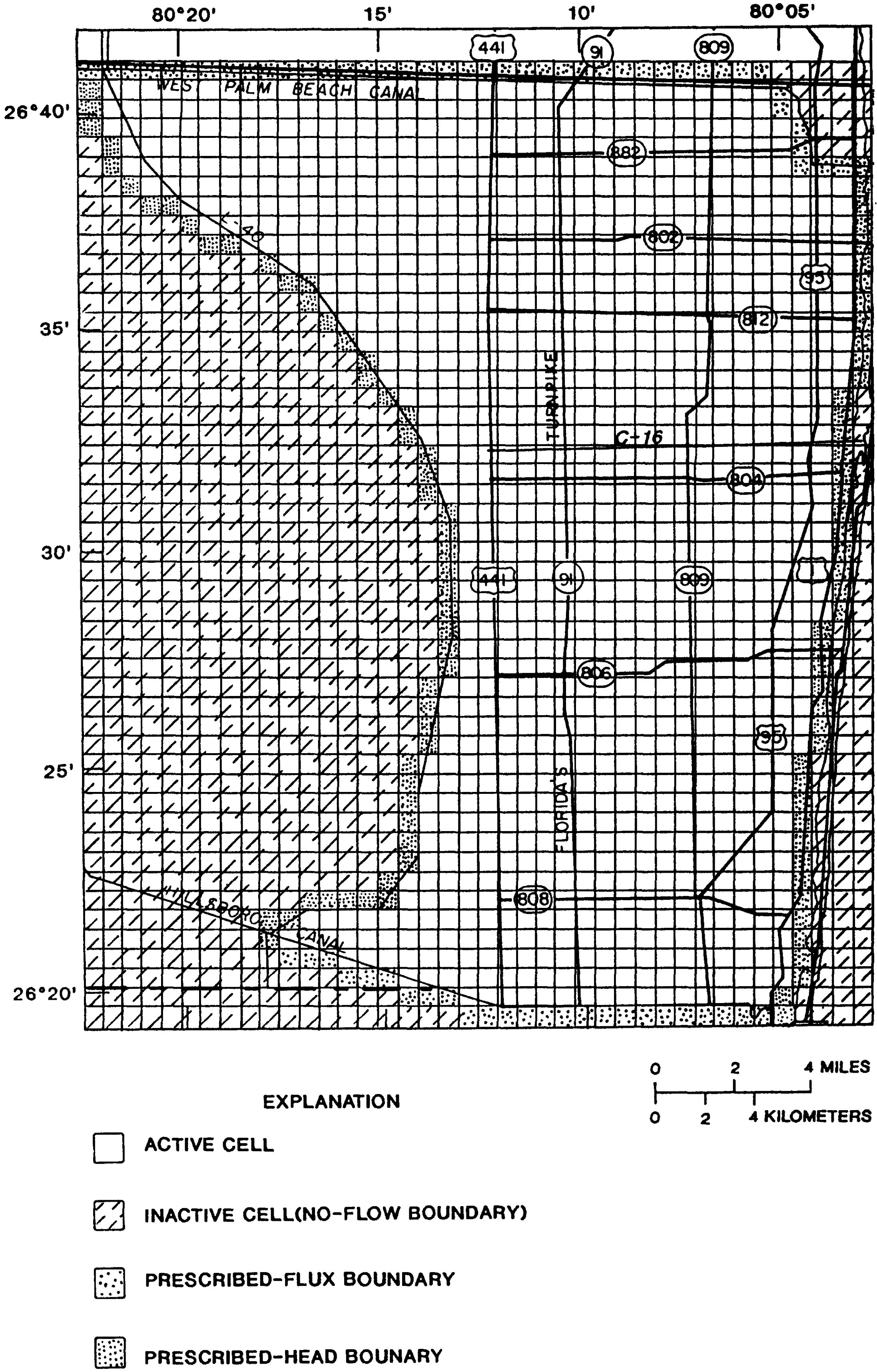


Figure 12. Model grid and layer 1 cell types for the 500-square mile area in southeastern Palm Beach County simulated by the regional flow model. (Modified from Shine and others, 1989.)

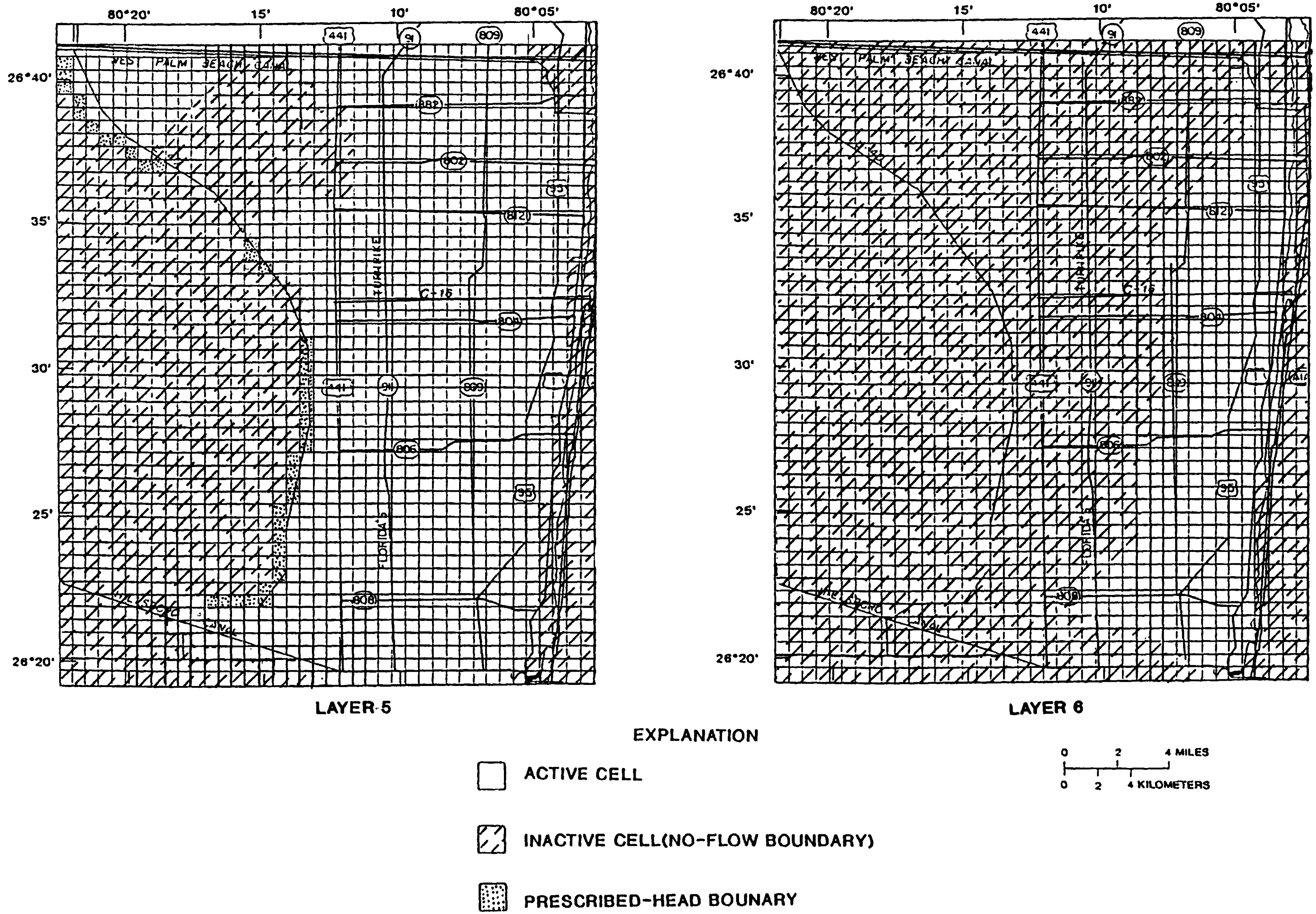


Figure 13. Southeastern Palm Beach County regional flow model grid for layers 5 and 6.

Head-Dependent Flux Boundaries

Discharge to the major canals (West Palm Beach and Hillsboro Canals) along the northern and southern boundaries was simulated using a head-dependent flux boundary--referred to as a general head boundary by McDonald and Harbaugh (1988). Flow across lower permeability material underlying the canal is dependent on the canal geometry, the controlled stage in the canal, the hydraulic conductivity (K') and thickness (b') of the bed materials, and the head in the surficial aquifer system beneath the canal. Stages in the canals are regulated and remain within 1 ft of the desired elevation during the year. Values for K'/b' are not well known and were adjusted over a range of accepted values during model calibration. Aquifer heads are calculated by the model as part of the solution procedure.

Leakage to or from the canals of the LWDD were treated in a similar manner, using the RIVER module of the MODFLOW model. Stages in the canal are regulated and remain within 1 ft of the desired elevation during the year. Values for K'/b' for these canals were also varied over a range of values during model calibration.

Discharge to drainage canals maintained by the Acme Improvement District was simulated using the DRAIN module of the MODFLOW model. Ground-water discharge is presumed to occur only when aquifer heads exceed the control elevations of the weirs on the canals.

Ground-Water Withdrawals

The principal stress on the surficial aquifer system is ground-water withdrawals for public-water supply and agricultural and nonagricultural irrigation. The location of wells and monthly pumping rates for public supply and agriculture were described by Shine and others (1989). Methods for calculating consumptive use were also described in that report.

Model Calibration

The regional flow model was calibrated by refining estimates of aquifer properties and canal-bed conductance to produce the best match between simulated and observed water-table altitudes during the period October 1983 through May 1985 (Shine and others, 1989). The steady-state calibration was based on the assumption that ground-water levels during the calibration period were in dynamic equilibrium, where there were no long-term trends in rainfall, pumpage, evapotranspiration, and canal levels. Input parameters varied during the calibration procedure were recharge, evapotranspiration, canal-bed conductances, aquifer hydraulic conductivities, and the horizontal-to-vertical hydraulic conductivity anisotropy ratio. Recharge, evapotranspiration, and canal-bed conductances were the only parameters that changed as a result of the calibration. A hydraulic conductivity value of 50 ft/d was used for the upper two sand layers and the lower two layers representing sand and shell and fine sands and clay. A hydraulic conductivity of 1,600 ft/d was used to represent the zones of shell and coquina in the lower two layers. A 1:10 ratio of vertical-to-horizontal hydraulic conductivity was assumed for all units. Canal-bed conductances were based on a thickness of 1 ft and a hydraulic conductivity of 0.5 ft/d. The results from calibration and sensitivity analysis are described by Shine and others (1989).

The SFWMD model seems to adequately simulate three-dimensional flow on a regional scale and match the observed water levels reasonably well. Calibrated steady-state heads in model layer 1 representing average annual conditions at the water table during the calibration period are shown in figure 14. Average water levels in all observation wells with surveyed elevations and more than one measurement during the calibration period are also illustrated. The shape of the simulated water table (fig. 14) is consistent with the average measured levels with no apparent areal trend in discrepancy (Shine and others, 1989, p. 95). The differences between simulated steady-state water levels and average measured water levels at each observation well are shown in figure 15. The regional flow mass balances for average annual conditions are given in table 2.

Adjustments to South Florida Water Management District Model

Several changes were made to the regional flow model to update the data for precipitation and ground-water withdrawals for the study period of March 1987 through July 1988. Several changes also were made to model boundary conditions. The boundary condition along the western edge of the area modeled was changed to reflect observed variations in water levels in Conservation Area No. 1, which varied from 12 to 17 ft. Similarly, prescribed-head values along the seashore were increased from 0.0 to 0.6 ft to reflect the observed mean tide levels in Palm Beach County (Schneider, 1973). These changes primarily affected heads near the eastern and western boundaries but were not sufficient to require recalibration of the model.

Revised Input Data Sets

Information on precipitation in southeastern Palm Beach County was retrieved from the SFWMD's hydrologic data base, which includes data from the National Oceanic and Atmospheric Administration rain gages and from gages maintained by other agencies (SFWMD, USGS, and LWDD). Data from the stations operating during the study

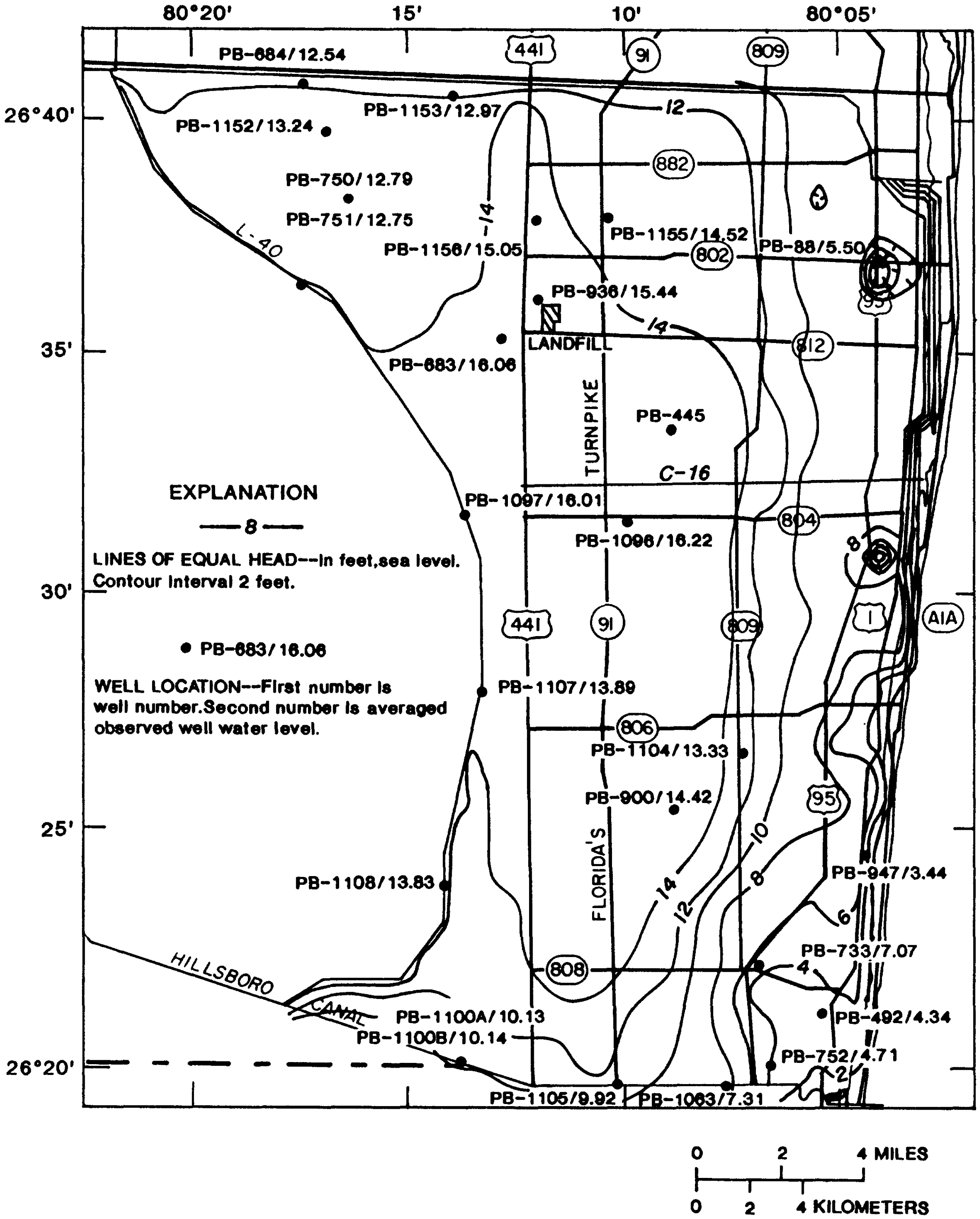


Figure 14. Simulated average annual water-table surface in southeastern Palm Beach County, based on heads from model layer 1. (Modified from Shine and others, 1989.)

period were supplied by W.J. Cogger (U.S. Geological Survey, written commun., 1991). Precipitation data for the period March 1987 to July 1988 were assigned to each grid cell by first applying the Theisen method (Linsley and others, 1975) to determine the area and, thus, the grid cells represented by each rain gage. The amount of precipitation assumed available for recharge was 50 percent in urban areas and 75 percent in nonurban areas as reported by Shine and others (1989). Rates of maximum evapotranspiration and the extinction depth were identical to those used in the regional flow model (Shine and others, 1989).

Data on pumping for public-water supply from March 1987 through July 1988 were supplied by SFWMD. Estimates of consumptive use of water were calculated using methods described by the South Florida Water Management District (1985). These methods estimate water use based on soil type, crop type and length of growing season, mean temperature, length of day, and other related factors. As reported by Shine and others (1989), these water-use estimates and data on farm acreage and irrigation efficiencies were used to estimate net values of agricultural pumping. Nonagricultural pumping used primarily for irrigating lawns and golf courses was calculated in a similar manner.

Results of Transient Simulations

Transient conditions were simulated for a 16-month period (April 1987 through July 1988) using the revised regional flow model. Initial heads were determined using the regional flow model to simulate steady-state conditions with stresses and boundary conditions of March 1987. Any errors introduced by assuming that steady-state conditions were in effect in March 1987, when the aquifer could still have been responding in a transient manner to previous stresses, were assumed to be insignificant by the

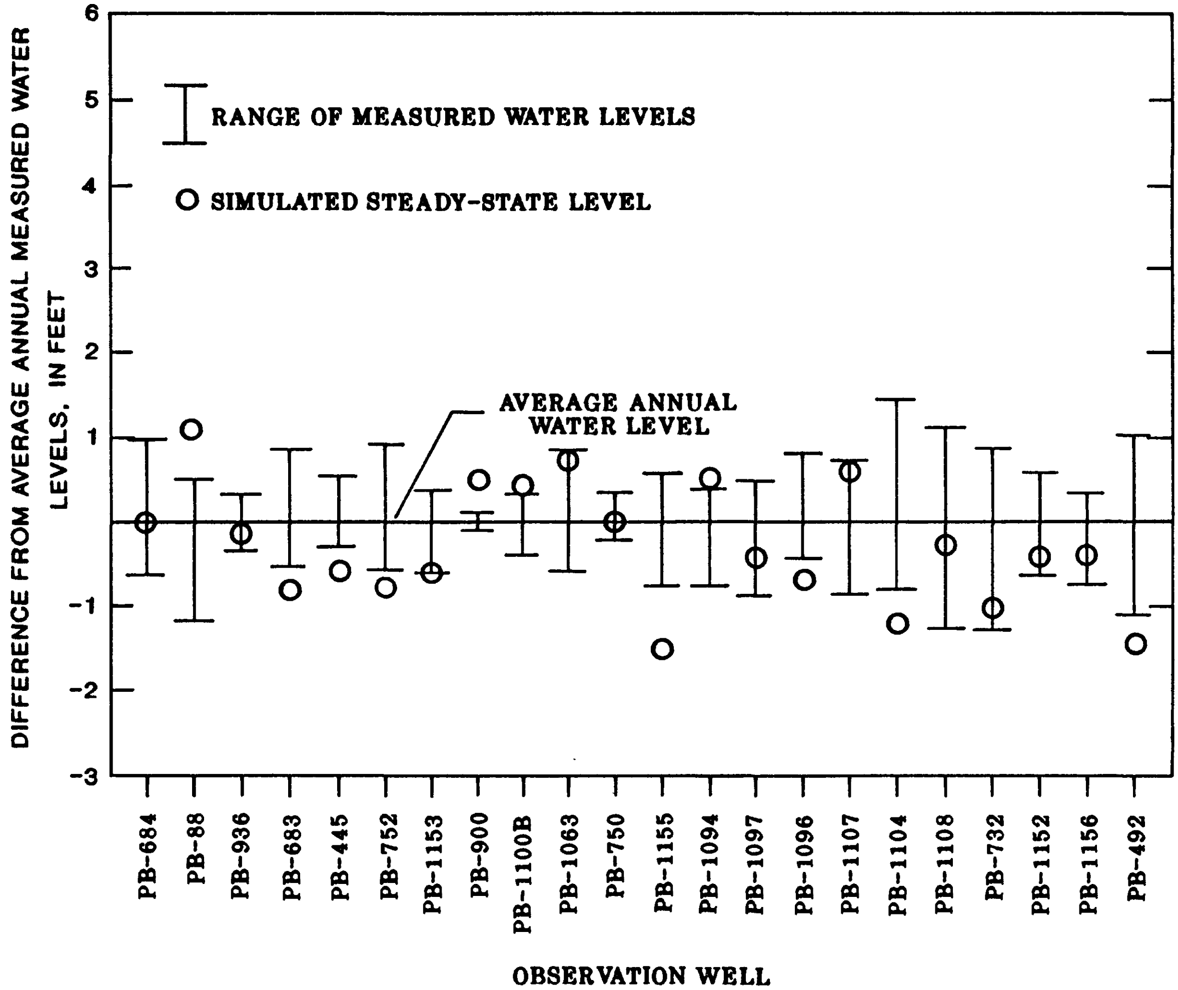


Figure 15. Simulated average annual heads and range of observed heads at observation wells, October 1983 to May 1985. (Modified from Shine and others, 1989.)

Table 2. Regional flow model mass balances for average annual conditions

[Data from Shine and others, 1989. All values in cubic feet per day X 10^3 rounded to nearest thousand, except where noted]

Budget component	In	Out	Net	In (percent)	Out (percent)
Water-Conservation Area No. 1	3,822	13	3,809	3.6	0.0
Intracoastal Waterway	0	315	-315	.0	.3
Acme Canals	753	848	-96	.7	.8
Lake Worth Drainage District Canals	22,111	23,033	-921	21.0	21.9
C-51 Canal	1	4,726	-4,725	.0	4.5
Hillsboro Canals	178	3,046	-2,869	.2	2.9
Rain infiltration	78,350	0	78,350	74.5	.0
Withdrawal from wells	0	23,867	-23,867	.0	22.7
Drainage canals	0	10	-10	.0	.0
Evapotranspiration	0	49,357	-49,357	.0	46.9
Change in storage	0	0	0	.0	.0
Total	105,215	105,214	1	100	100

end of June 1987, the first period for which observed water-level data are available. Simulated lines of equal head and observed water levels for June 1987, October 1987, March 1988, and May 1988 are shown in figures 16 to 19.

Water-level changes during March 1987 to March 1988 were simulated by the transient model. The simulated heads for October 1987 (fig. 17) and March 1988 (fig. 18) approximate end-of-wet-season and end-of-dry-season conditions, respectively (figs. 5 and 6). The shape of the simulated water tables is consistent with the shape of the observed water tables during wet and dry seasons. The simulated heads also match the observed water levels and are within about 0.5 ft of measured water levels in observation wells. There does not seem to be any areal trend in discrepancies between the simulated heads and observed water levels. Considering that the simulated heads are an averaged head over a period of several days, as compared to an instantaneous observed water-level measurement, the simulation results seem to adequately represent conditions in the aquifers. The regional flow model mass balances for transient conditions are given in table 3.

Subregional Flow Model

The accuracy with which numerical ground-water flow models can simulate the flow system in a given area depends in part on the dimensions of the finite-diference grid used to represent the modeled area. Because the cell size in the regional flow model was large (2,640 ft on a side), flow simulation results in the landfill vicinity were not to the scale needed for flow analysis in and adjacent to the landfill. Therefore, a subregional flow model was developed for the northeastern part of southeastern Palm Beach County (fig. 20). The total area of the subregional flow model is 126.5 mi^2. The subregion is bounded to the south by a line parallel to and 1.0 mi south of Boynton Canal and to the west by a line parallel to and about 1.3 mi west of Canal E-1 (fig. 1). The eastern, northern, upper and lower boundaries are the same as those in the regional flow model.

The subregional flow model is composed of square cells 528 ft on a side (each regional flow model cell was divided into 25 smaller cells). The grid contains 110 rows and 115 columns. The number of layers in the subregional flow model and the vertical discretization remained the same as those in the regional flow model.

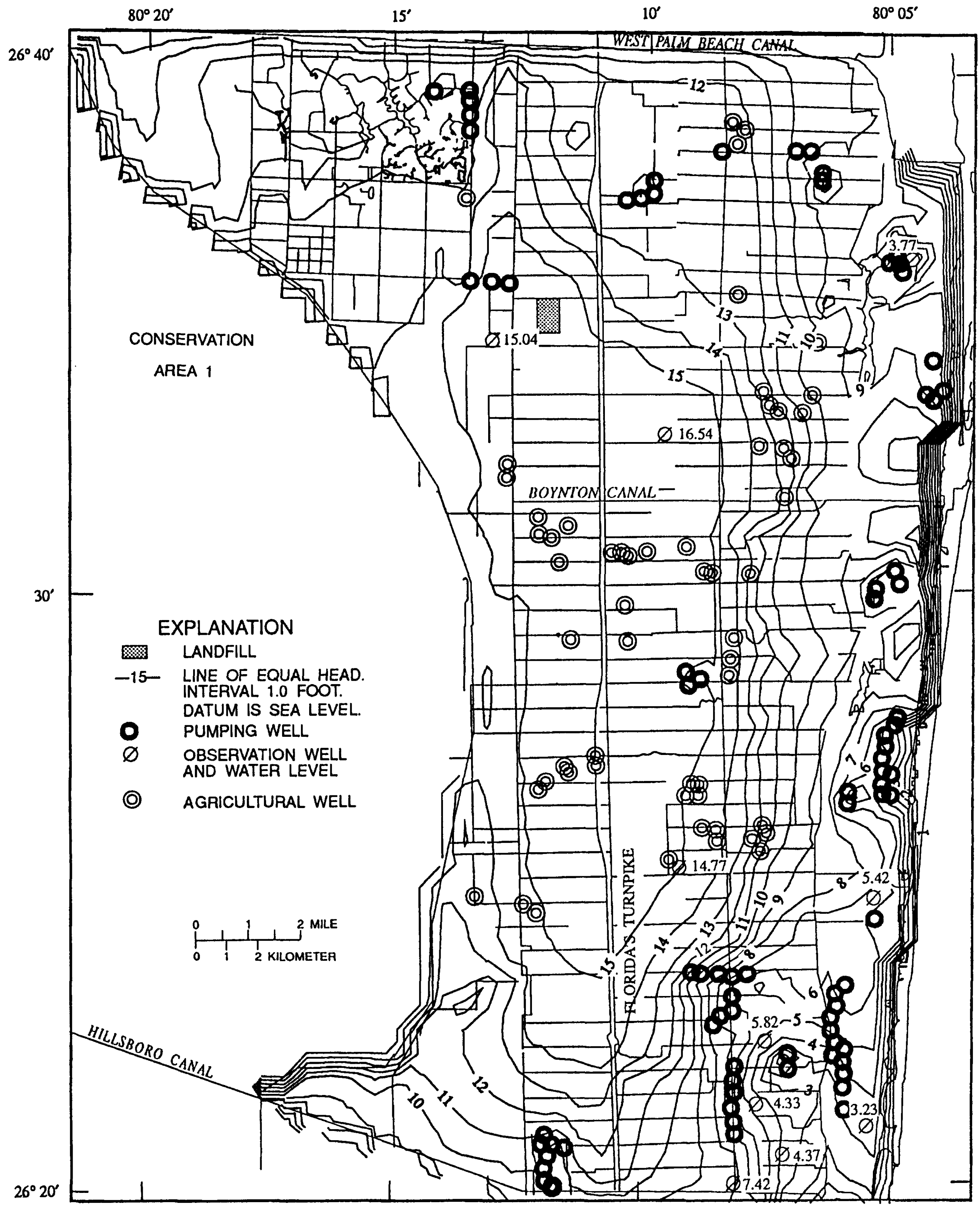


Figure 16. Simulated lines of equal head and observed water levels in layer 1 of the regional flow model for June 1987.

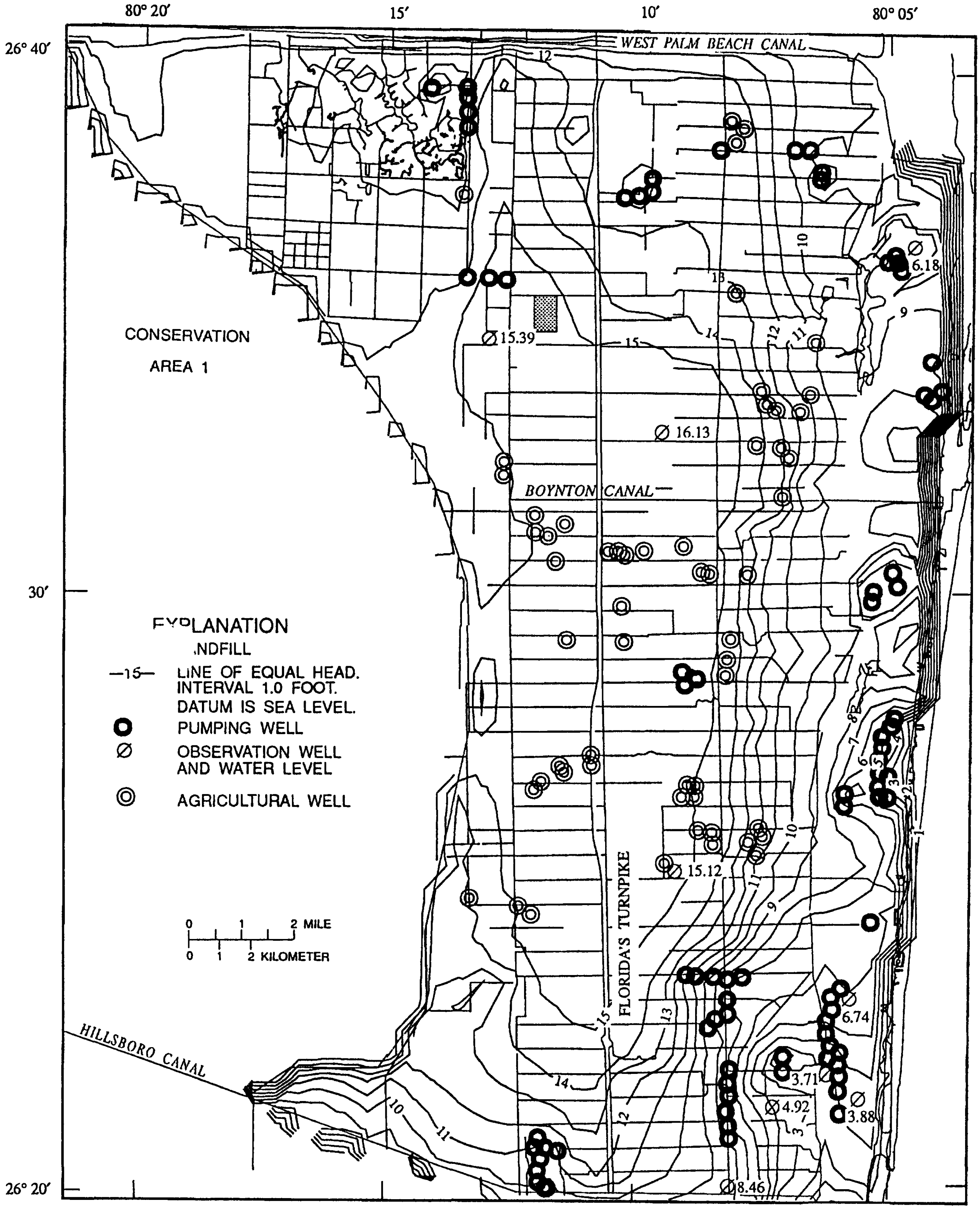


Figure 17. Simulated lines of equal head and observed water levels in layer 1 of the regional flow model for October 1987.

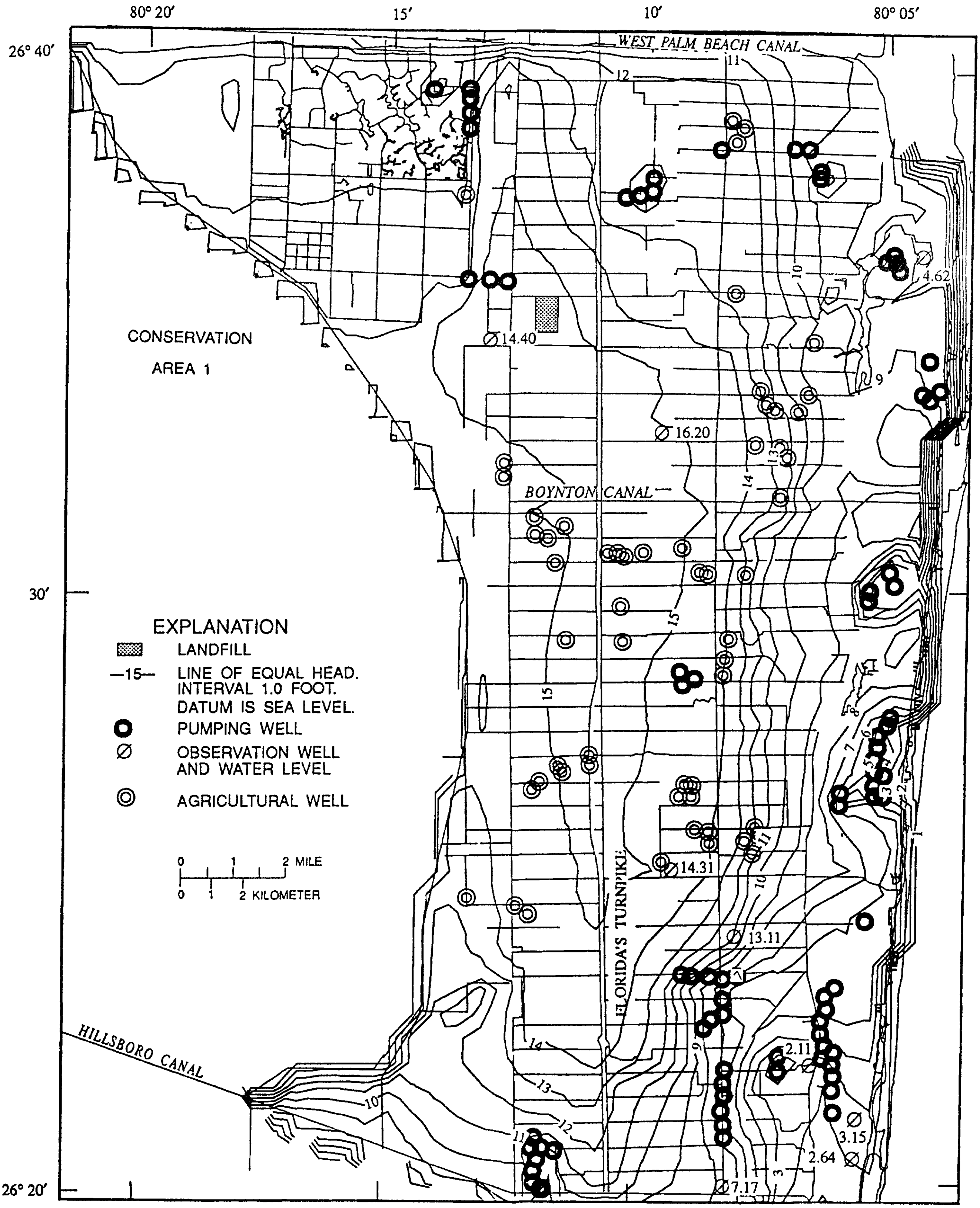


Figure 18. Simulated lines of equal head and observed water levels in layer 1 of the regional flow model for March 1988.

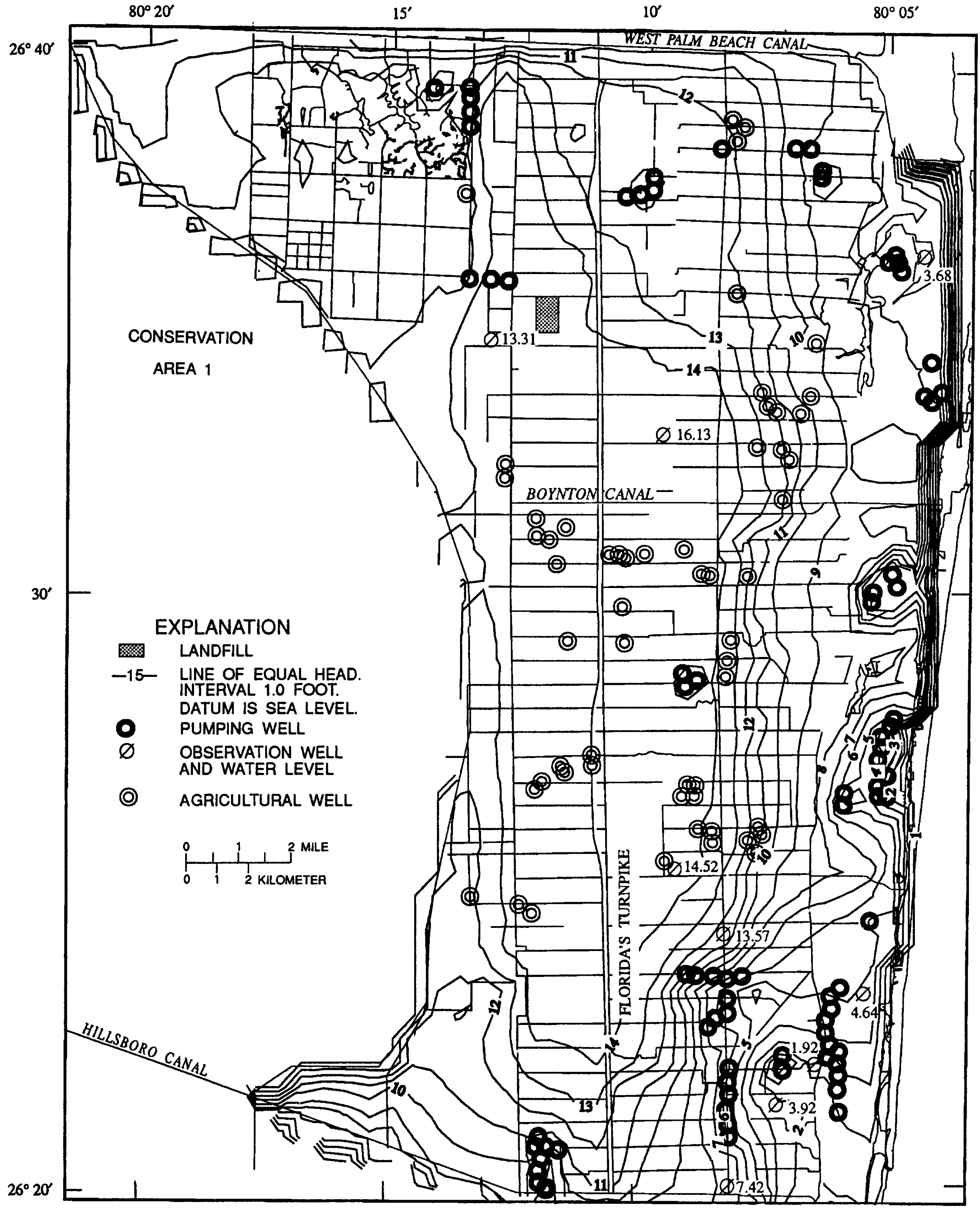


Figure 19. Simulated lines of equal head and observed water levels in layer 1 of the regional flow model for May 1988.

Table 3. Regional flow model mass balances for transient conditions

[All values in cubic feet per day x 10^3 rounded to nearest thousand, except where noted]

Budget component	In	Out	Net	In (percent)	Out (percent)
Flow across constant boundaries	0	33,000	-33,000	0.0	0.3
River leakage	2,338,000	2,380,000	-42,000	18.6	18.9
Rain infiltration	6,704,000	0	6,704,000	53.3	.0
Withdrawal from wells	0	1,593,000	1,593,000	.0	12.7
Evapotranspiration	0	5,955,000	-5,955,000	.0	47.4
Change in storage	2,746,000	1,698,000	1,048,000	21.8	13.5
Flow across head dependent boundaries	788,000	913,000	-125,000	6.3	7.3
Flow to surface-water drains	0	4,000	4,000	.0	.3
Total	12,576,000	12,576,000	-89	100.1	100.1

Revised Input Data Sets

Aquifer property data used in the subregional flow model and rates of recharge, potential evapotranspiration, and pumping rates were identical to those used in the regional flow model for transient simulations. Values for land-surface altitude, aquifer thickness, and basal altitude of the surficial aquifer system were interpolated from values used in the regional flow model. Land-surface altitude in blocks representing the Lantana landfill were later adjusted to better match the land-surface changes due to landfill construction. Input data sets defining the canal-bed conductance (product of the canal width, length of canal segment in each block, and K'/b') had to be extensively updated to reflect the change in the model grid size. Data sets that identify the location of pumping wells by cell location had to be revised for the same reason.

Many of the manmade lakes within the subregion were too small to be considered in the regional flow model but can influence flow patterns in the landfill area. Stages in most lakes are not controlled but vary as the water table rises or falls. The lakes were simulated in the subregional flow model by assigning a high horizontal hydraulic conductivity value to the upper layer cells representing the lake.

Output from the MODFLOW model includes flux across the faces of each cell in the grid. The regional and subregional flow models were effectively linked, using flux data generated by the regional flow model to specify flux values along the southern and western boundaries of the subregional flow model. These boundaries were selected at locations south and west of major canals, beneath which lateral flow is much reduced, so errors in the boundary fluxes due to the change in discretization would have minimal effects on the flow pattern in the vicinity of the landfill.

Because observed heads in the area of the subregional flow model are few, little attempt was made to calibrate the model by adjusting aquifer properties. Simulated water levels calculated with the subregional flow model match the limited observed data relatively well and provide much better representation of the water levels around the well fields and canals.

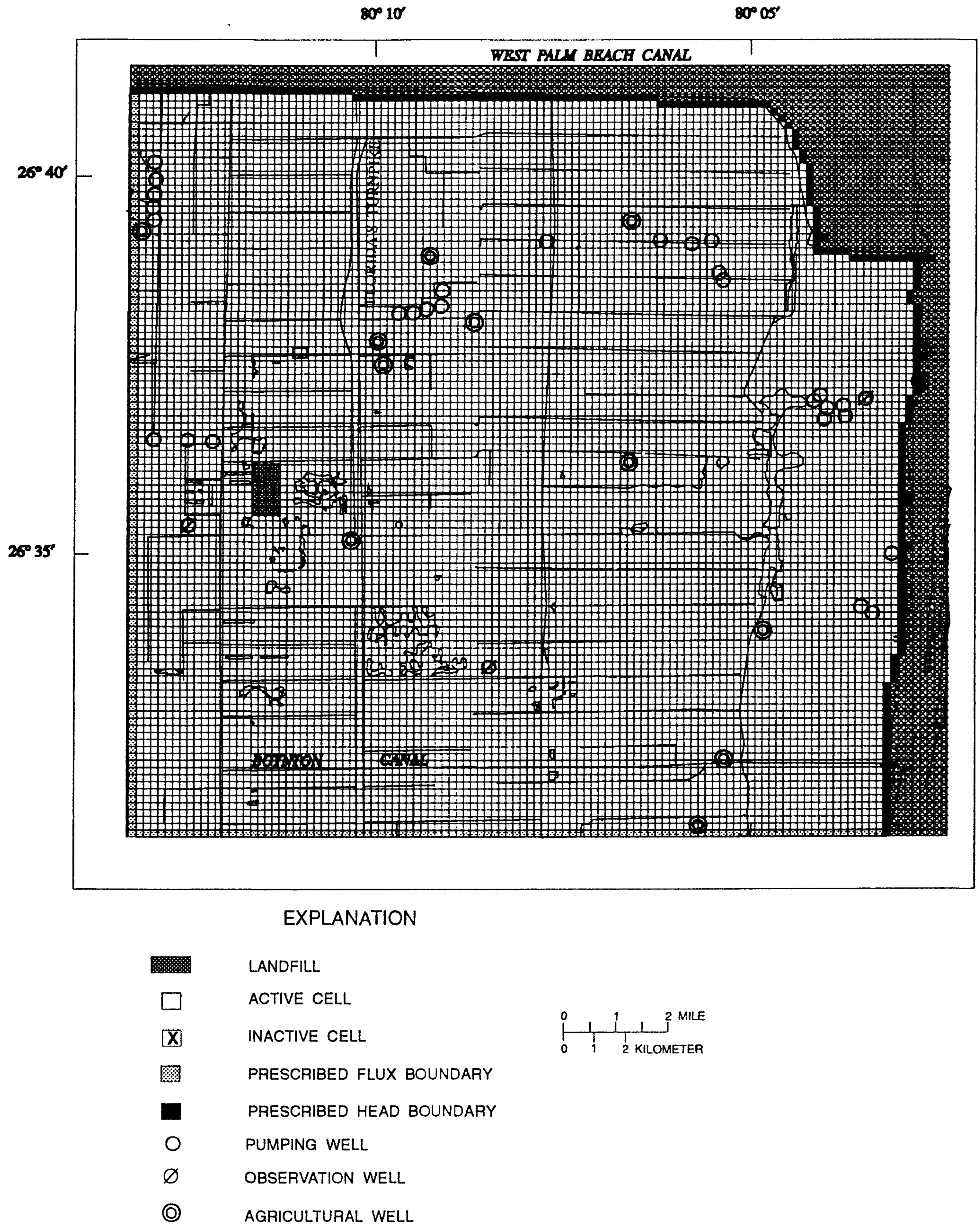


Figure 20. Model grid and layer 1 cell types for the 126.5-square mile area simulated by the subregional flow model.

Results of Transient Simulations

Simulated lines of equal head and observed water levels for June 1987, October 1987, March 1988, and May 1988 are shown in figures 21 to 24. The simulated heads in these illustrations reflect the finer discretization of the subregional flow model. The effects of the extensive canal network are apparent from the lines of equal head which indicate ground-water flow from the aquifer to the canals. The lowered water levels attributed to drawdown in the aquifer around well fields also are reflected by the lines of equal head. The water-table mound beneath the landfill site (fig. 21) is due in part to the decreased rate of evapotranspiration relative to the surrounding area because the depth to water over the landfill is greater than the extinction depth of the evapotranspiration in the model code. The simulated heads seem to match the few observed water levels reasonably well. Although the observed data are sparse, the observed water levels for the few wells for which data are available are within about 0.6 ft of the simulated levels (figs. 21-24). The subregional flow model mass balances for transient conditions are given in table 4.

Local Flow Model

Although simulation of the ground-water flow around the landfill seemed to be representative at the subregional scale, further refinement of the grid and input data sets was necessary to simulate vertical flow in the upper sand unit and ground-water interaction with the numerous lakes, ponds, and canals in the landfill vicinity. The subregional flow model was used to calculate ground-water fluxes and boundary conditions for a smaller grid local flow model of a 3.75 mi^2 area that includes the landfill and vicinity. Boundaries of the local flow model are shown in figure 25. The local flow model is composed of square cells each 132 ft on a side (each subregional flow model cell was divided into 16 smaller cells). The grid has 60 rows, 100 columns, and 8 layers. The upper sand units were subdivided into smaller units to allow simulation of flow patterns within sand layers that might be affected by the landfill leachate. Bottom elevations of the upper sand layers in the aquifer (model layers 1-5) were at 10, 20, 35, 55, and 70 ft below land surface. Beneath the landfill, layer 6 represents the most permeable unit of the aquifer (fig. 7). The bottom elevation of this unit remained at about 100 ft below land surface, the same as in the regional and subregional flow models. Bottom elevations of layers 7 and 8 in the lower part of the surficial aquifer system remained at about 130 and 220 ft below land surface (fig. 7).

Revised Input Data Sets

Aquifer properties and rates of recharge, potential evapotranspiration, and pumping rates used in the local flow model were identical to those used in the regional and subregional flow models. Land-surface altitude, aquifer thickness, and basal altitude of the surficial aquifer system were interpolated from values used in the subregional flow model. Input data sets defining canal-bed conductance were updated to reflect the change in the model grid size. The data set identifying the cell number location of the three nonagricultural pumping wells was also revised. All lakes in the landfill vicinity were represented by cells with very high horizontal hydraulic conductivity. Deeper lakes, such as the large lakes east and northwest of the landfill, are represented in two layers.

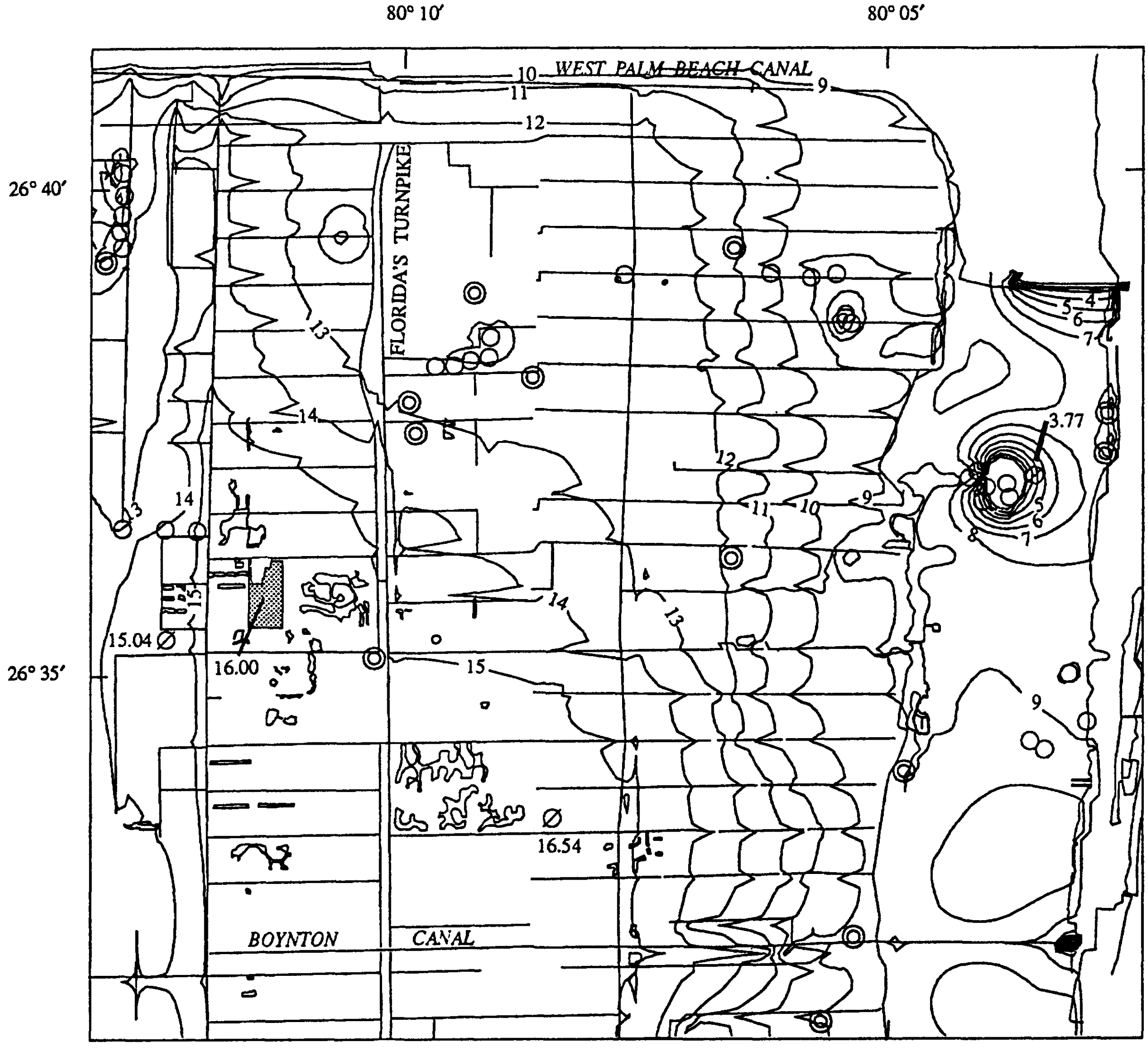
The subregional and local flow models were linked, using flux data generated by the regional flow model to specify flux values along all lateral boundaries of the local flow model. These boundaries were simulated at a great enough distance from the LWDD canals on the side opposite the landfill site to minimize the effects of boundary fluxes on the flow pattern in the vicinity of the landfill.

Results of Transient Simulations

Simulated lines of equal head in layer 1 at the landfill site for June 1987, October 1987, March 1988, and May 1988 are shown in figures 26 through 29, respectively. The lines of equal water-table altitude (figs. 26-29) closely match those of the subregional flow model (figs. 21-24), except that the local flow model produces a smoother water-table surface.

Lines of equal head in layer 6 for the same aforementioned periods are shown in figures 30 to 33, respectively. Heads in this layer are less influenced by the canals and lakes and more affected by regional flow patterns. Because the simulated heads in the layers underlying the landfill are generally lower than the water-table altitudes, leachate will move downward through the upper sand unit and then flow horizontally along the direction of regional flow (perpendicular to the lines of equal head). The local flow model mass balances for transient conditions are given in table 5.

Comparison between observed water levels and simulated lines of equal head may be used as an indication of model accuracy. Model output was available at the end of each 15-day period during the transient simulation, whereas observed water-level data were available about every 2 months. Observed data collected on May 2, 1988, were available for comparison to simulated lines of equal head for the end of April 1988 (fig. 34). Observed values in layers 1 and 6 are within 0.5 foot of the simulated output.



EXPLANATION

LANDFILL

—15— LINE OF EQUAL HEAD -INTERVAL 1.0 FOOT. DATUM IS SEA LEVEL.

PUMPING WELL

OBSERVATION WELL

AGRICULTURAL WELL

Figure 21. Simulated lines of equal head and observed water levels of the subregional flow model for June 1987.

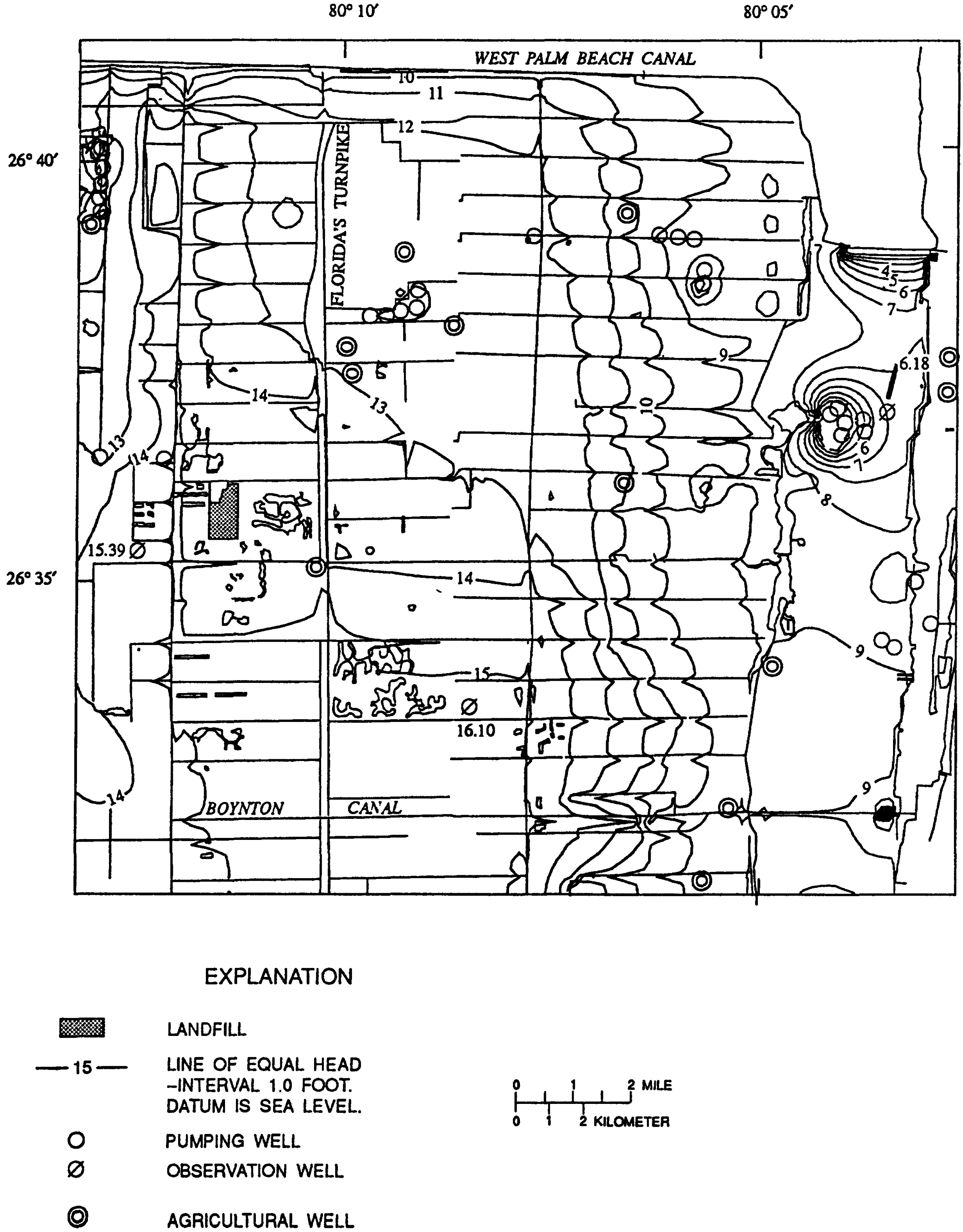
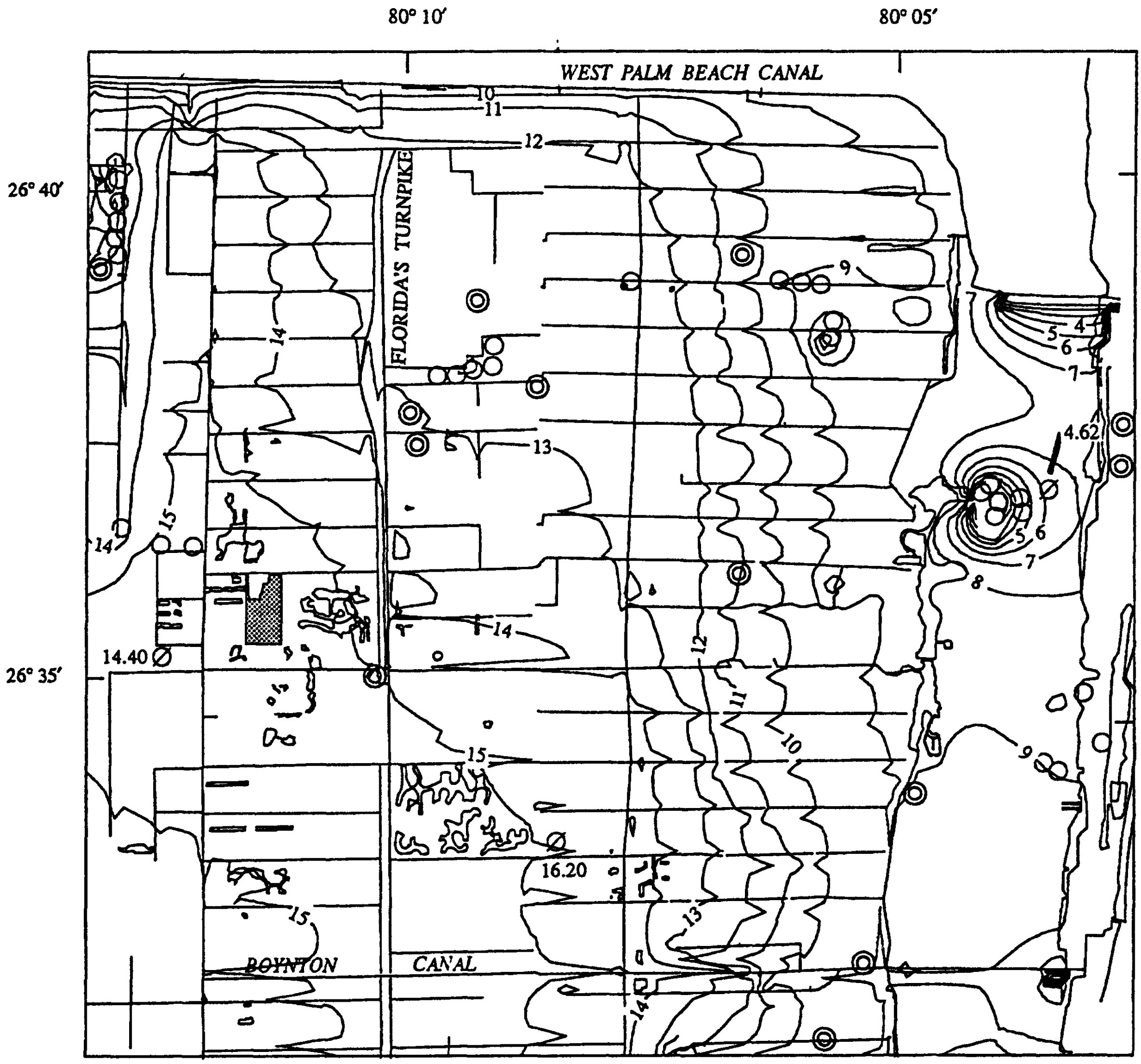


Figure 22. Simulated lines of equal head and observed water levels of the subregional flow model for October 1987.



EXPLANATION

LANDFILL

—15— LINE OF EQUAL HEAD --INTERVAL 1.0 FOOT. DATUM IS SEA LEVEL.

O PUMPING WELL

Ø OBSERVATION WELL

◎ AGRICULTURAL WELL

0 1 2 MILE
0 1 2 KILOMETER

Figure 23. Simulated lines of equal head and observed water levels of the subregional flow model for March 1988.

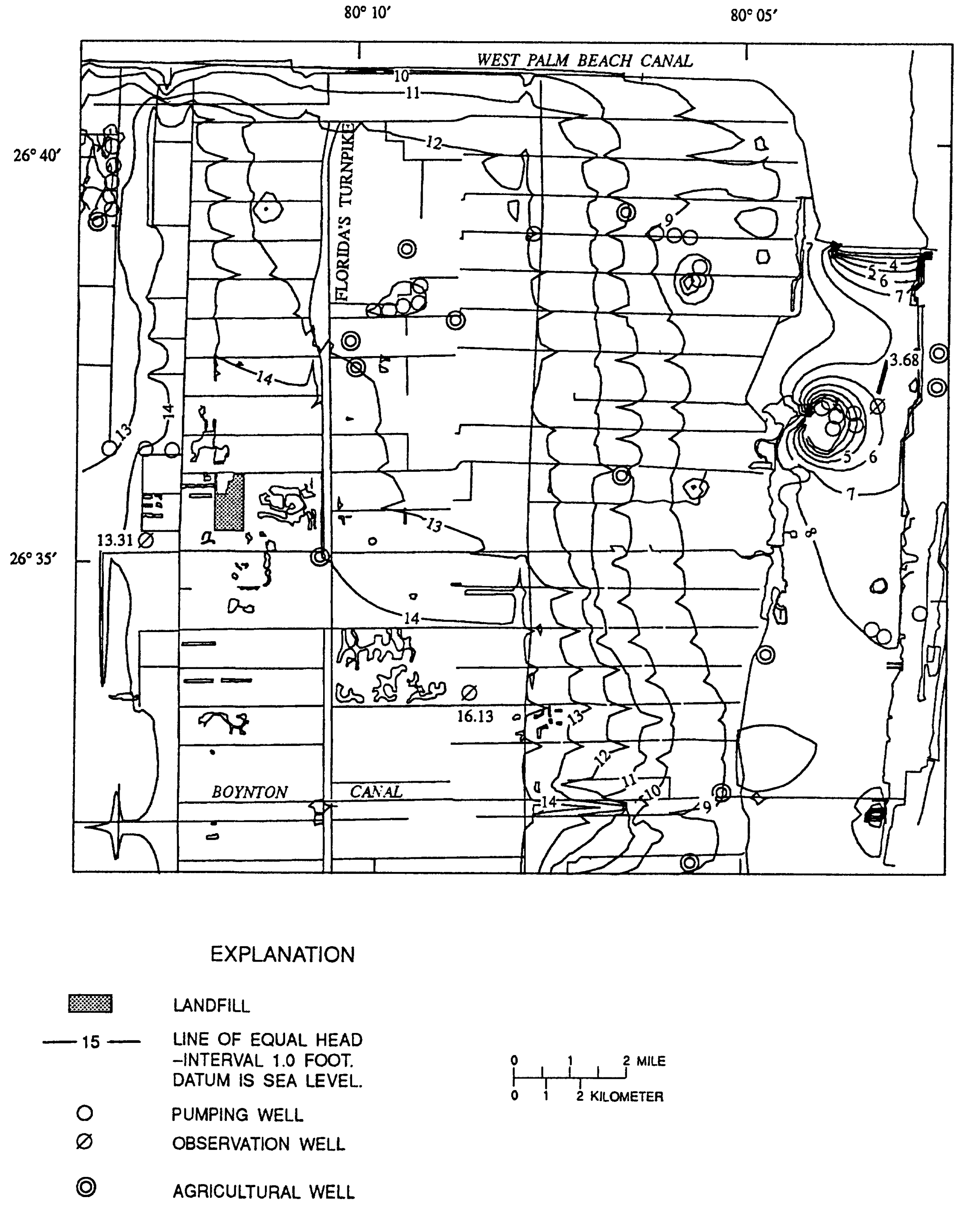


Figure 24. Simulated lines of equal head and observed water levels of the subregional flow model for May 1988.

Table 4. Subregional flow model mass balances for transient conditions

[All values in cubic feet per day x 10^3 rounded to nearest thousand, except where noted]

Budget component	In	Out	Net	In (per-cent)	Out (per-cent)
Flow across constant head boundaries.	52,000	16,700	35,300	0.4	0.1
River leakage	2,642,000	3,124,800	-482,800	18.8	22.2
Rain infiltration	8,625,000	0	8,625,000	61.4	.0
Withdrawal from wells	60,000	1,668,800	-1,608,300	.4	11.9
Evapotranspiration	0	6,699,000	-6,699,000	.0	47.7
Change in storage	2,655,500	1,600,000	1,055,500	18.9	11.4
Flow across head dependent boundaries	13,500	941,300	-927,800	.1	6.7
Total	14,048,000	14,051,000	-2,100	100.0	100.0

Table 5. Local flow model mass balances for transient conditions

[All values in cubic feet per day x 10^3 rounded to nearest thousand, except where noted]

Budget component	In	Out	Net	In (per-cent)	Out (per-cent)
Flow across constant head boundaries	0	0	0	0.0	0.0
River leakage	57,734	21,004	36,730	10.0	3.6
Rain infiltration	364,590	0	364,590	63.2	.0
Withdrawal from wells	27,221	94,813	-67,592	4.7	16.4
Evapotranspiration	0	390,230	390,230	.0	67.7
Change in storage	127,150	70,674	56,476	22.0	12.3
Total	576,695	576,721	-25	99.9	100.0

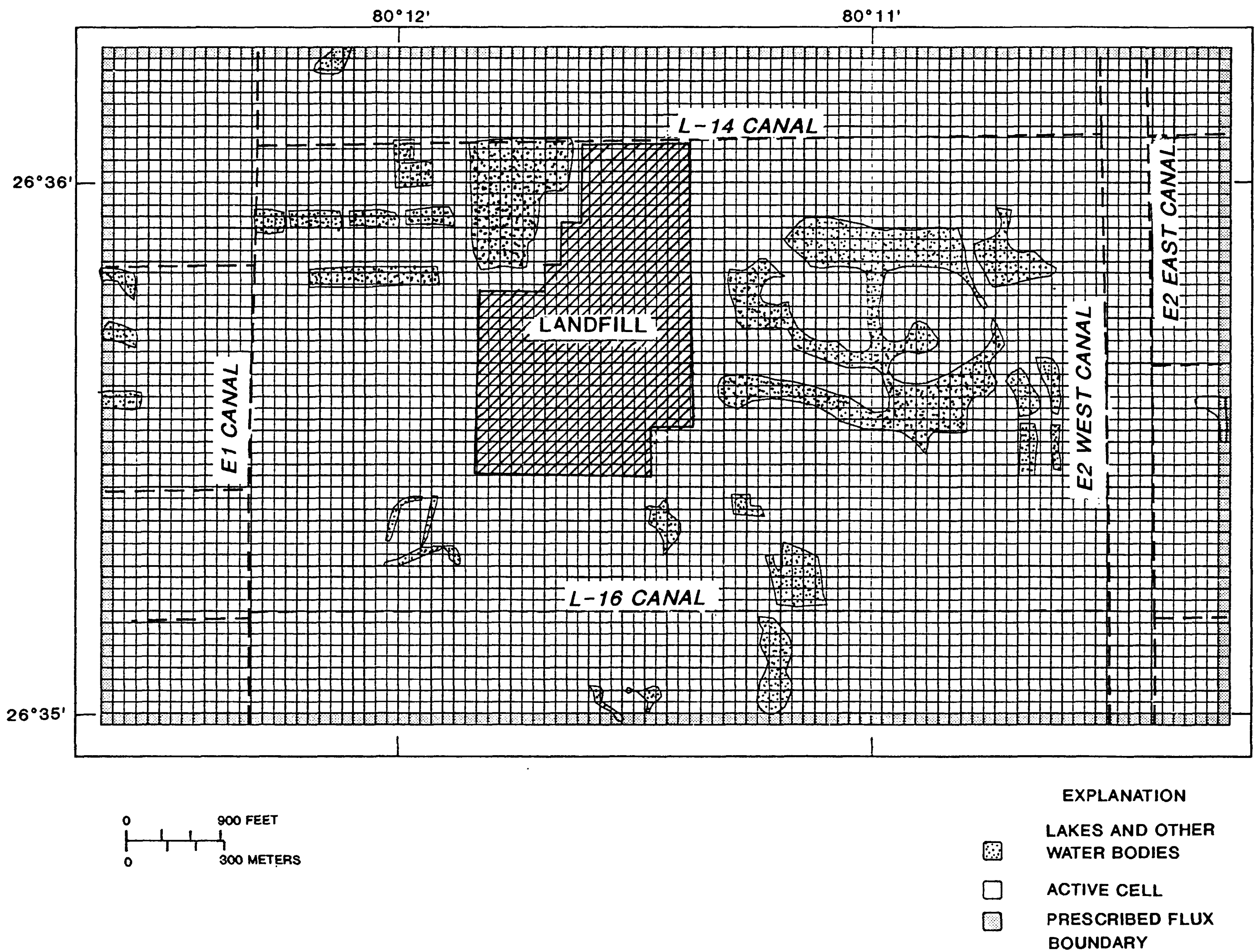


Figure 25. Model grid and layer cell types for the 3.75-square mile area simulated by the local flow model.

Predicted Effects of Possible Remedial Action

In addition to simulating the movement of water under natural ground-water flow conditions, the MODFLOW model can be used to evaluate the effects of alternative remedial actions. Several alternative hypothetical remedial strategies were examined with the MODFLOW model. The strategies included: (1) capping the landfill, (2) pumping recovery wells at various locations, and (3) varying pumping rates of recovery wells. Simulations of these strategies were intended for illustrative purposes only and should not be considered as recommendations nor endorsements of a particular option. The results are subject to the limitations imposed by the assumptions and simplifications discussed in the earlier sections on model development. In all predictive simulations, remedial actions were assumed to occur under steady-state conditions. Aquifer properties in these simulations were the same as in the previous simulations.

Alternative 1--Capping the Landfill

Capping the landfill with an impermeable surface would prevent further generation of leachate due to rainfall infiltration and reduce discharge of leachate to the surficial aquifer system. This occurred to some degree following landfill closure procedures that began in March 1987. Capping of the landfill was simulated to determine changes in local flow patterns and to estimate the time required for chloride concentrations in the leachate-enriched ground water to reach background levels under natural conditions. No other changes were made in the model for this simulation.

For simulation purposes, capping of the sanitary landfill was assumed to be complete at the end of 1987. Precipitation that would normally infiltrate the landfill

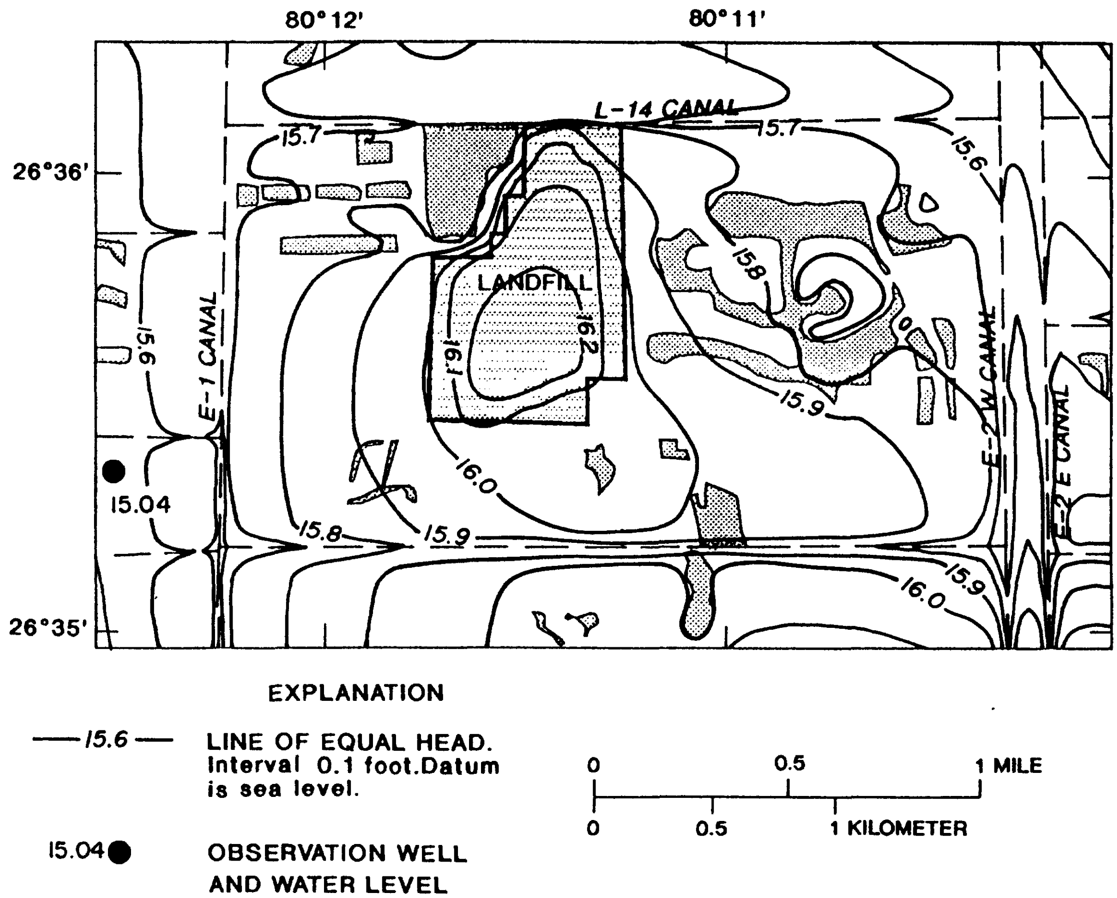


Figure 26. Simulated lines of equal head and observed water levels in layer 1 of the local flow model for June 1987.

was assumed to be diverted to a stormwater basin along the perimeter of the landfill. Changes in the ground-water flow system because of the diversion were calculated using only the local flow model, as no major changes in the boundary fluxes were expected. Results from the simulation are shown in figures 35 and 36.

Simulated lines of equal head under steady-state conditions in layer 1 without an impermeable cap on the landfill are shown in figure 35. The ground-water mound under the landfill is evident. The same steady-state conditions simulated for the same period with an impermeable cap on the landfill are also shown (fig. 35). The ground-water mound under the landfill is no longer evident in simulation results with the landfill capped. The absence of the ground-water mound beneath the landfill under capped conditions alters the ground-water flow pattern in layer 1. Along the eastern perimeter, where the leachate-enriched ground water exists, flow direction changes from due east with an uncapped landfill to north-northwest with the landfill capped.

Similar simulated lines of equal head in layer 6 are shown in figure 36. Simulated head changes under capped conditions are within 0.2 ft of steady-state conditions. Although not as dramatic as in layer 1, the flow direction in layer 6 has also shifted. Along the eastern perimeter of the landfill, the flow direction changes from northeast to more northerly.

Alternative 2--Capping the Landfill and Pumping Recovery Wells

The second remedial strategy analyzed included capping the landfill and pumping a line of five leachate recovery wells along the eastern perimeter of the landfill. In this simulation, the landfill was assumed to be capped and the production of leachate halted.

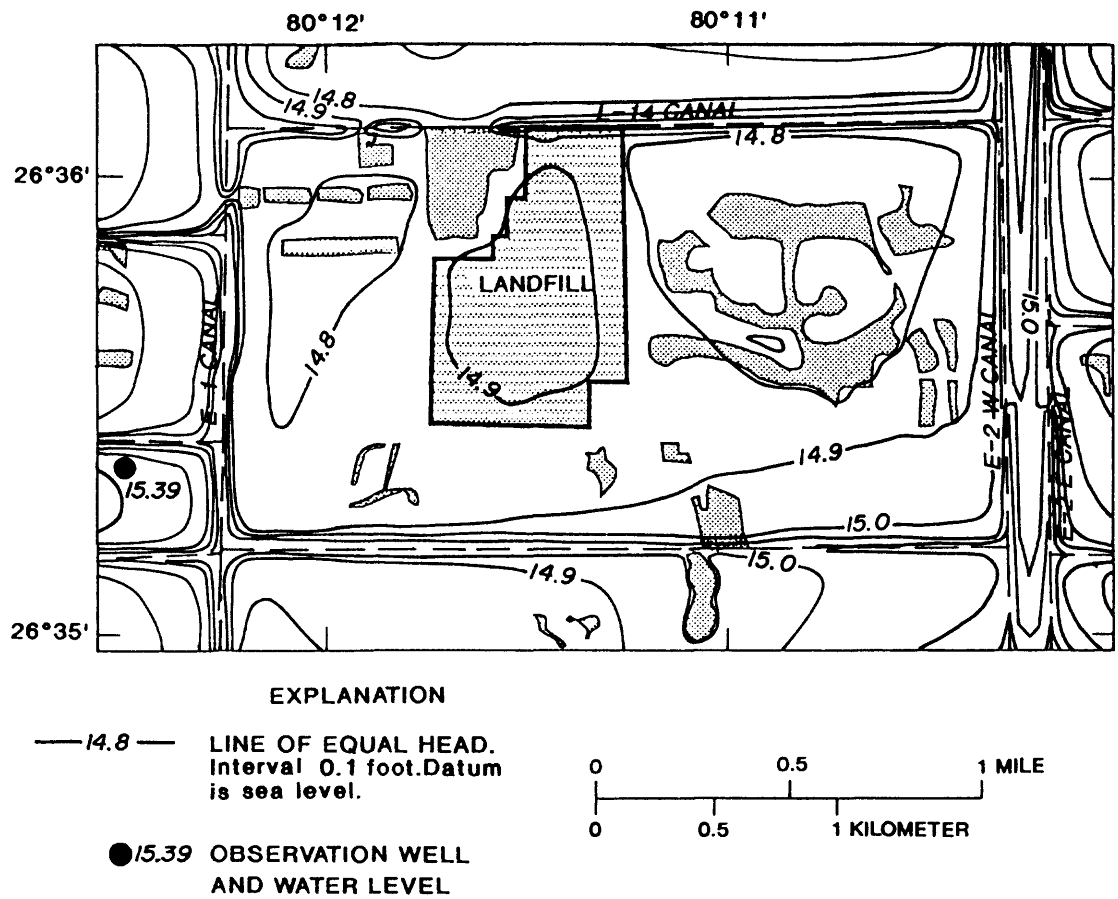


Figure 27. Simulated lines of equal head and observed water levels in layer 1 of the local flow model for October 1987.

A series of five wells were placed perpendicular to the centerline of the area of the leachate enriched ground water. Three wells pumped water from layers 4 and 5 at a rate of 25 gal/min each. Two wells pumped water from layer 6 at a rate of 75 gal/min each for 8 hours per day. Pumped water is assumed to be discharged as irrigation waters for the reclaimed landfill. Wells were placed at distances of about 528 ft along the perimeter of the landfill, and water was withdrawn from three layers.

Because the effect of pumping was likely to propagate to the local flow model boundaries, the simulation was first run using the subregional flow model. New values for boundary fluxes for the local flow model were generated. The local flow model was then run using the new boundary-flux values. The resulting water-table altitudes generated by the local flow model are shown in figure 37. The lines of equal head in layers 4 and 5 and in layer 6 indicate that ground water would flow from the surrounding surficial aquifer system to the leachate recovery wells, and, thus, would result in recovery of leachate-enriched ground water.

SUMMARY AND CONCLUSIONS

Direct-current resistivity soundings and water-quality data indicate that lateral movement of leachate of as much as 500 feet downgradient has occurred along the eastern perimeter of the Lantana landfill. Some vertical movement of the leachate may also have occurred into the lower zone of the surficial aquifer system to a depth greater than 70 feet.

Twelve cluster wells were constructed to depths of 70 feet. These cluster wells consisted of 1-foot sampling screens positioned at 5-foot intervals from 15 to 70 feet below land surface. Specific conductance

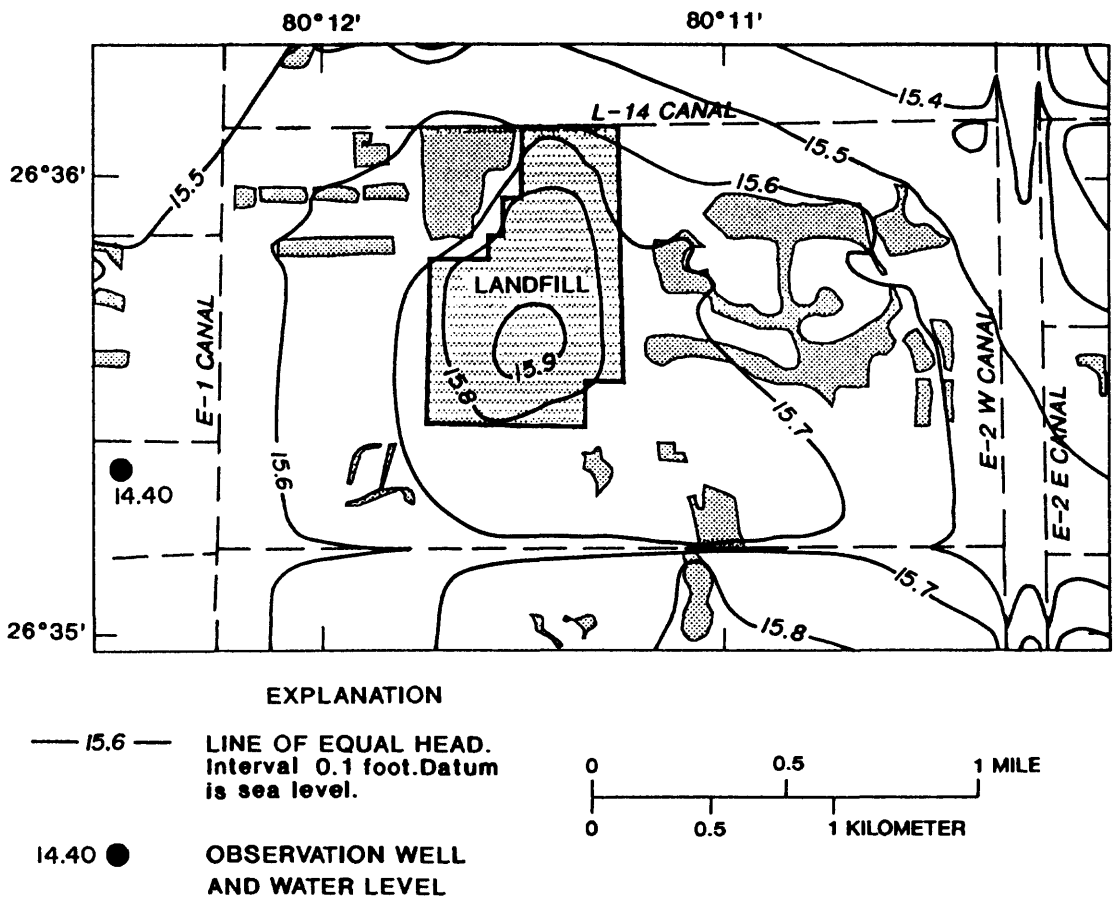


Figure 28. Simulated lines of equal head and observed water levels in layer 1 of the local flow model for March 1988.

values, chloride concentrations, and alkalinity values were used to trace the leachate-enriched waters. Data analysis indicates the leachate plume is divided vertically into two parts by a fine sand layer at about 40 to 50 feet below land surface. High concentrations of chloride and nutrients were detected within the leachate-enriched ground waters. Cluster well data indicate that the extent of the leachate plume and concentration of constituents seem to be decreasing over time.

As part of the hydrologic study of the Lantana landfill site, the feasibility of using large-scale regional ground-water flow models to simulate boundary conditions and ground-water fluxes for smaller scale subregional and local flow models was evaluated. This evaluation involved the development of three progressively finer grid models. The models were developed in three phases: (1) steady-state ground-water flow in the 500-square mile regional area encompassing the landfill was simulated using the MODFLOW code; (2) part of the finite-difference grid of the regional model was discretized more finely over a 126.5-square mile subregional area encompassing the site for more detailed ground-water flow simulations; and (3) part of the grid of the subregional model was discretized even finer over a 3.75-square mile area that included the landfill site for a more-detailed simulation of ground-water flow at the site. Values of prescribed head along the lateral boundaries of the fine-scale grid were interpolated from water-table altitudes generated in the larger scale model simulation. Hydraulic properties of the surficial aquifer system and confining unit were identical to those obtained through calibration of the larger scale model. Ground-water flow within the 3.75-square mile study area under steady-state conditions was simulated, and water-table altitudes, ground-water discharges, and head-dependent leakage rates at grid nodes were calculated.

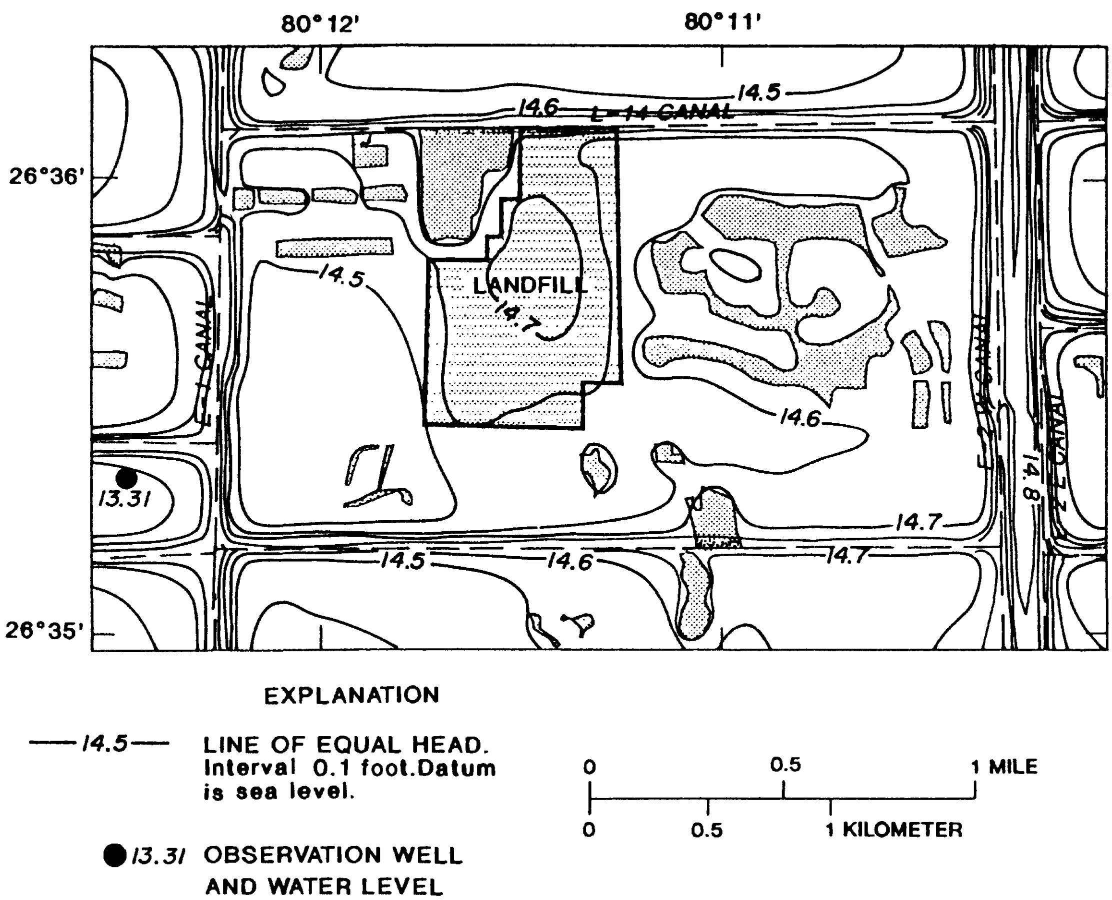
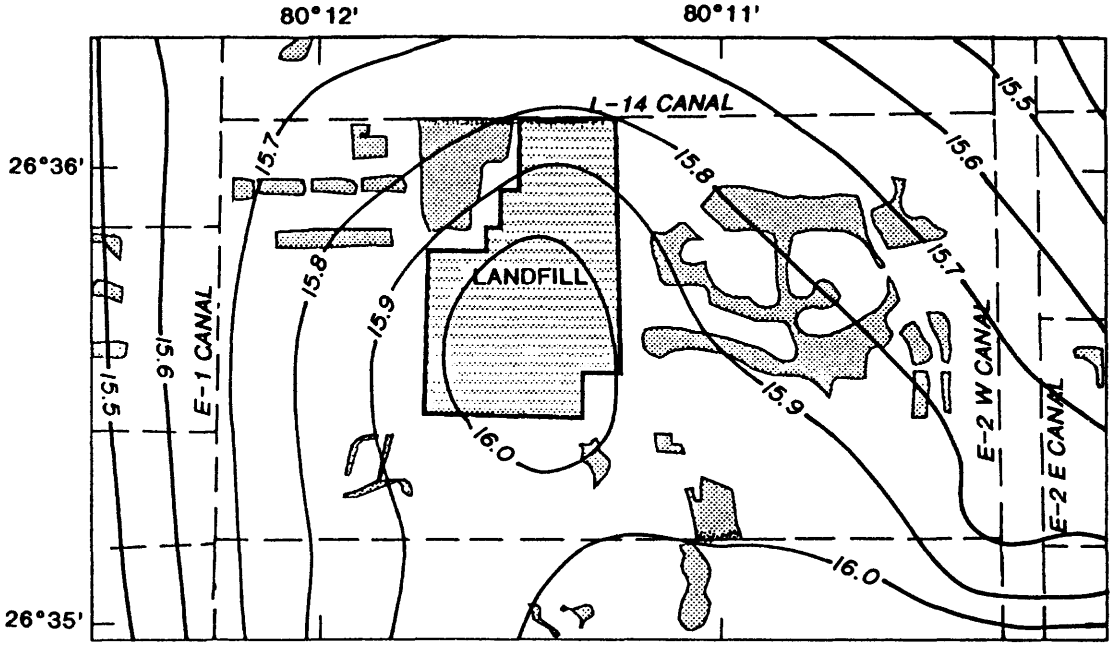


Figure 29. Simulated lines of equal head and observed water levels in layer 1 of the local flow model for May 1988.



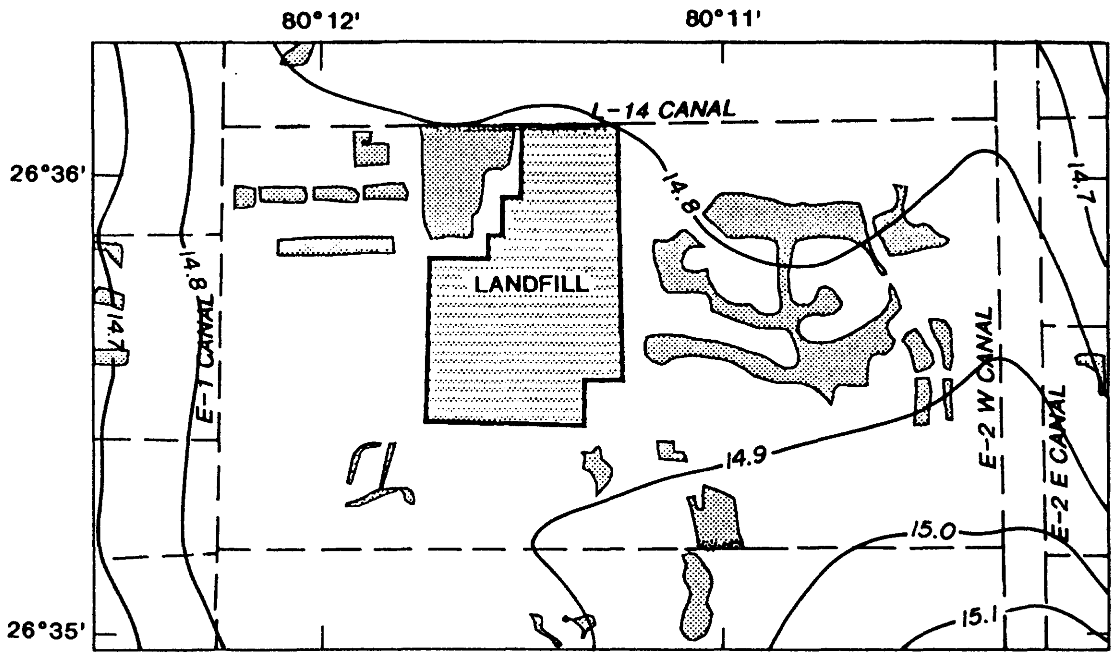
EXPLANATION

—— 15.5 —— LINE OF EQUAL HEAD. Interval 0.1 foot. Datum is sea level.

0 0.5 1 MILE

0 0.5 1 KILOMETER

Figure 30. Lines of equal head in layer 6 of the local flow model for June 1987.



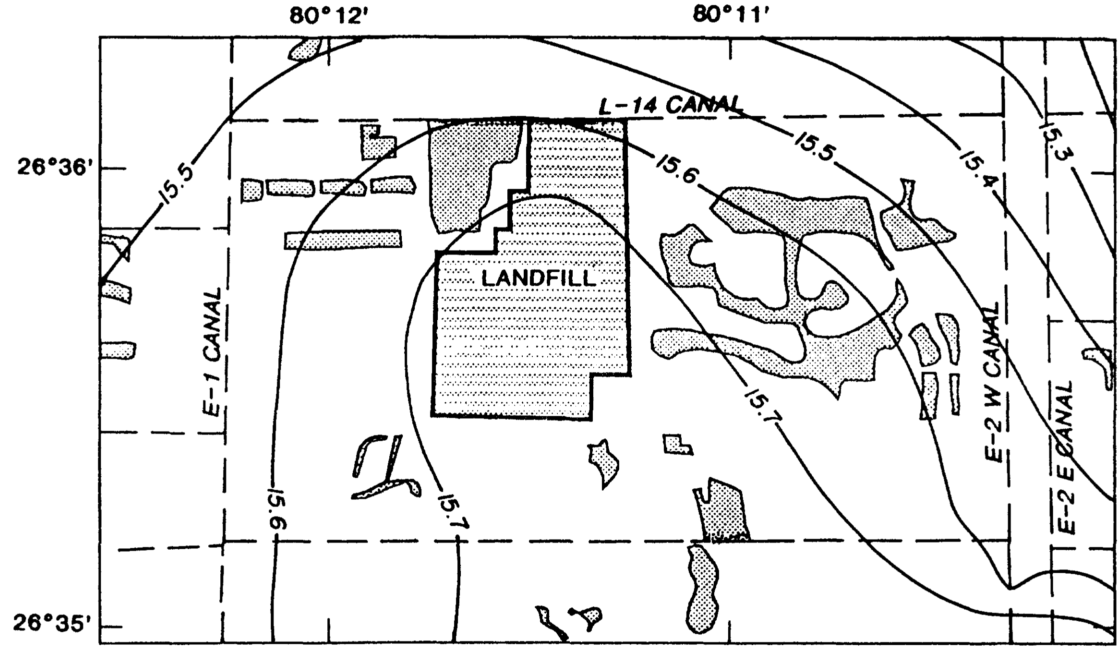
EXPLANATION

—— 15.0 —— LINE OF EQUAL HEAD. Interval 0.1 foot. Datum is sea level.

0 0.5 1 MILE

0 0.5 1 KILOMETER

Figure 31. Lines of equal head in layer 6 of the local flow model for October 1987.



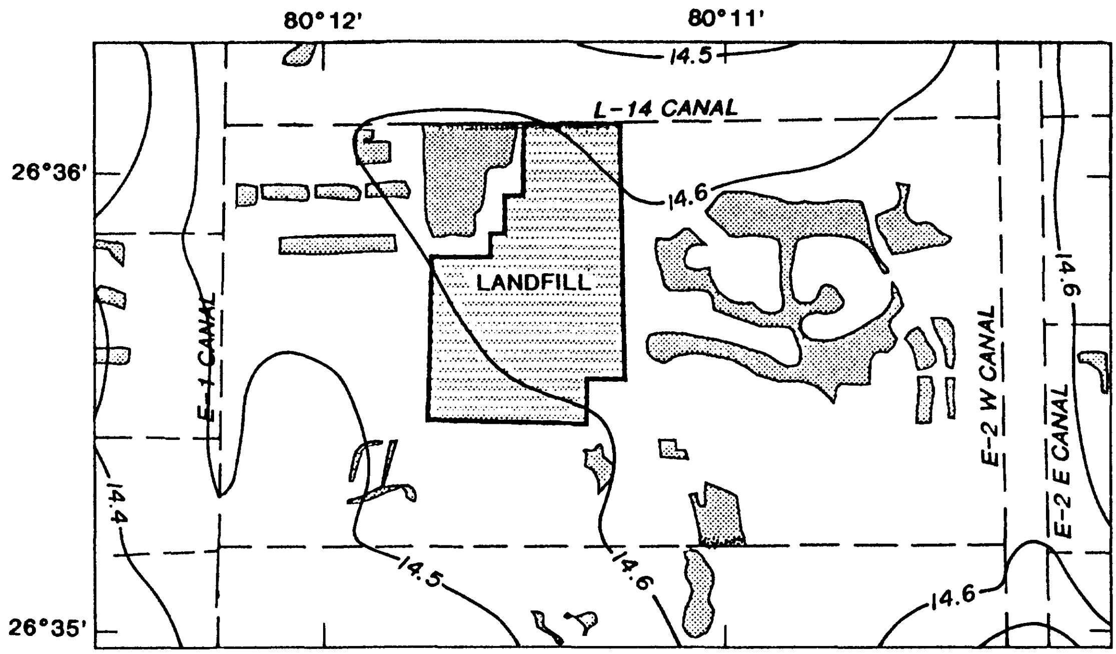
EXPLANATION

—— 15.6 —— LINE OF EQUAL HEAD. Interval 0.1 foot. Datum is sea level.

0 0.5 1 MILE

0 0.5 1 KILOMETER

Figure 32. Lines of equal head in layer 6 of the local flow model for March 1988.



EXPLANATION

—— 14.4 —— LINE OF EQUAL HEAD. Interval 0.1 foot. Datum is sea level.

0 0.5 1 MILE

0 0.5 1 KILOMETER

Figure 33. Lines of equal head in layer 6 of the local flow model for May 1988.

The effects of two possible remedial strategies on the movement of leachate downgradient of the landfill were simulated using the local flow model. The first simulation, which examined the effect of capping the landfill with an impermeable material, indicated that the cap would alter the natural ground-water flow patterns, changing the predominant direction of flow from east to north-northwest. The second simulation examined the effect of capping the landfill and pumping the five leachate recovery wells along the eastern perimeter of the landfill at a total rate of 300 gallons per minute for 8 hours per day. Simulation results indicated that pumping the recovery wells would facilitate removal of leachate-enriched waters from the surficial aquifer system and alter the direction of ground-water flow in the area of known leachate contamination.

Although few water-level measurements in the area of the local flow model were available for comparison with simulated water levels, the simulated levels were in good agreement with the few available measurements. The water levels simulated by the local flow model seemed reasonable and more accurately reflected the effects of pumping and local surface-water features on ground-water levels than did water levels simulated by the coarser grid subregional and regional models. Results of the simulations indicate that large-scale models can be used successfully in some instances to generate flux and boundary conditions for smaller scale local models needed to assess the possible effects of local management alternatives.

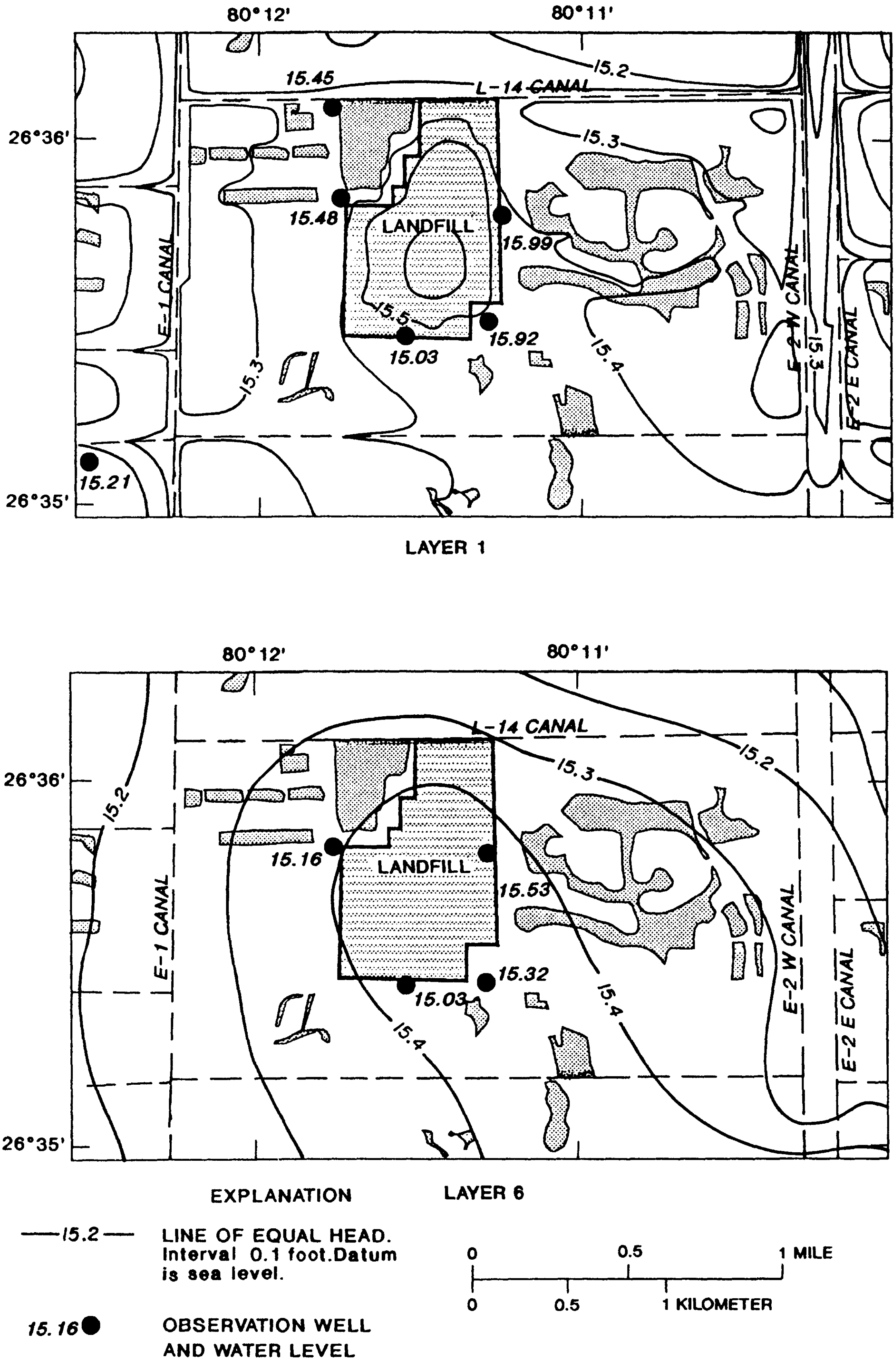


Figure 34. Simulated lines of equal head for April 1988 and observed water-level data for May 2, 1988, in layers 1 and 6.

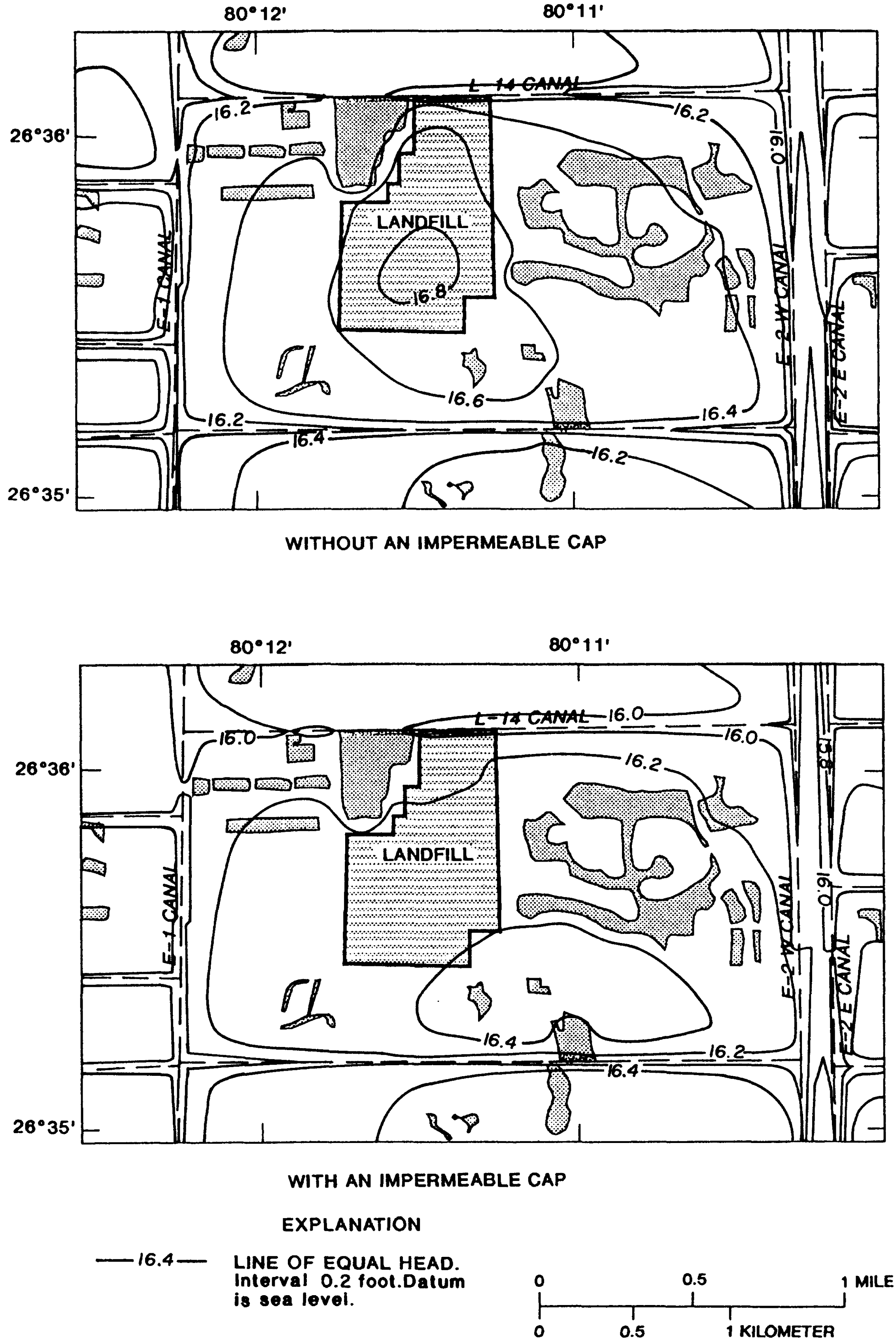


Figure 35. Simulated lines of equal head in layer 1 under steady-state conditions with and without an impermeable cap on the landfill.

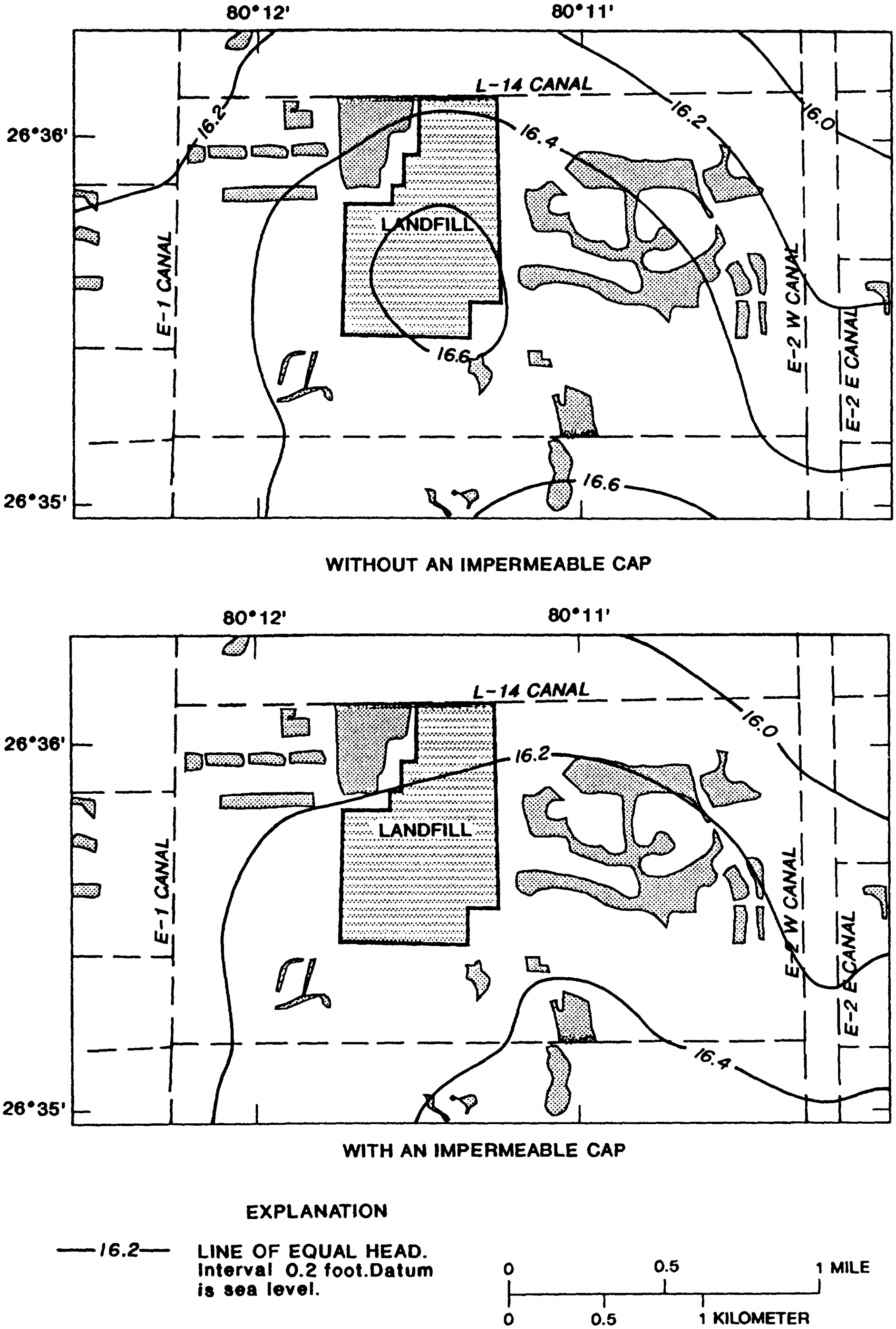


Figure 36. Simulated lines of equal head in layer 6 under steady-state conditions with and without an impermeable cap on the landfill.

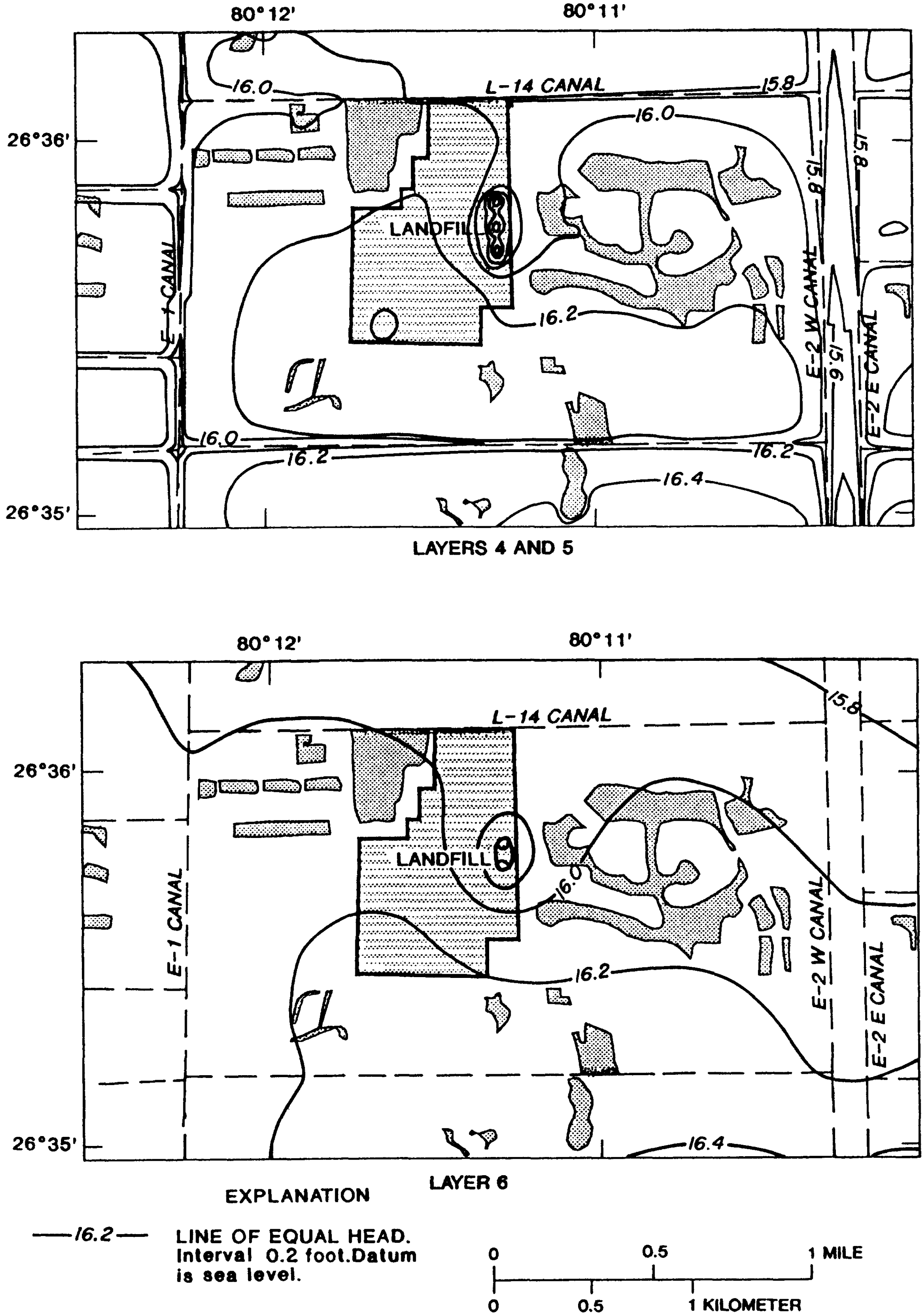


Figure 37. Simulated lines of equal head when the landfill is capped and five leachate recovery wells are pumped (three in layers 4 and 5 and two in layer 6.)

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