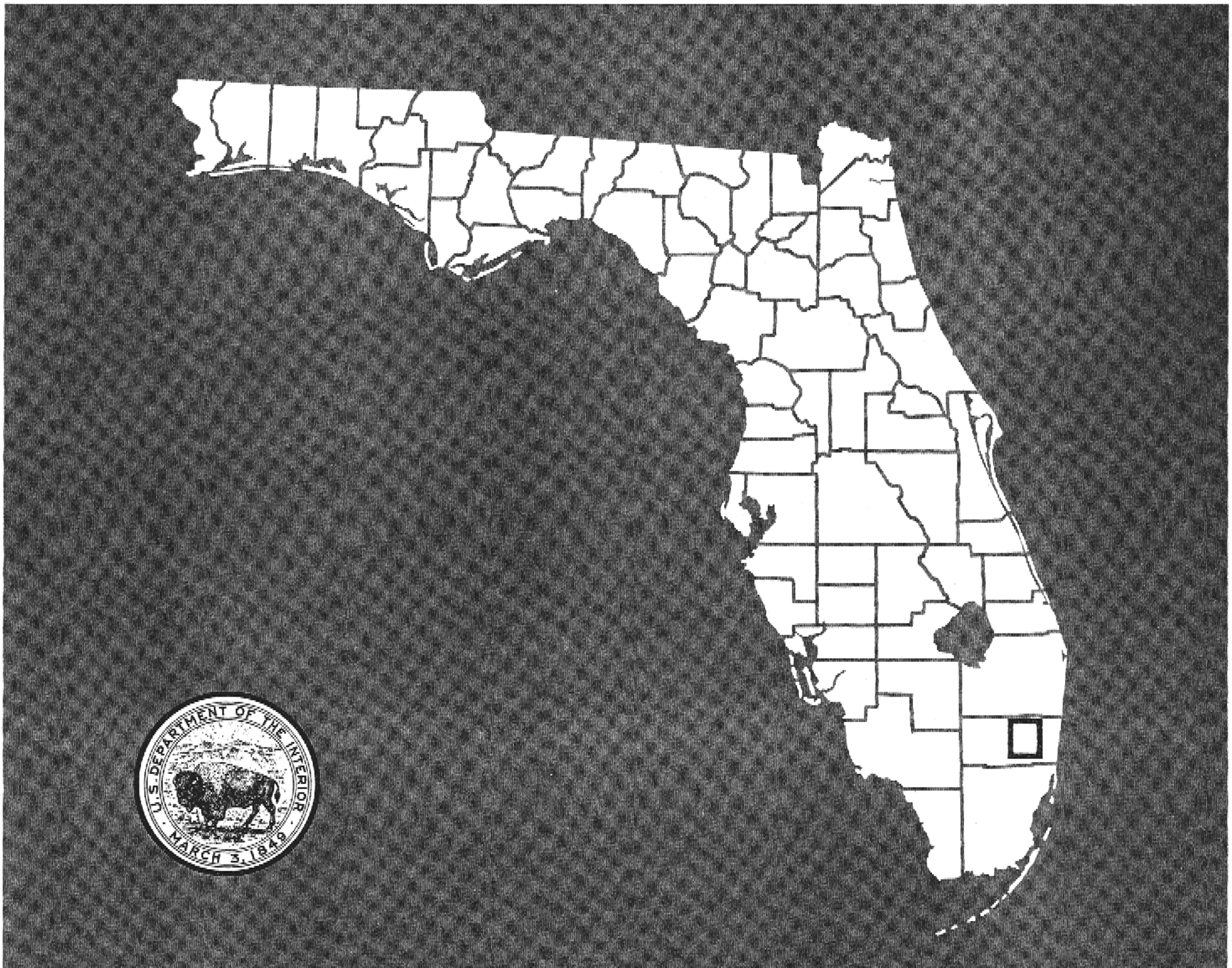
GROUND-WATER FLOW BENEATH LEVEE 35A FROM CONSERVATION AREA 2B, BROWARD COUNTY, FLORIDA

U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS REPORT 87-4280

Prepared in cooperation with the

SOUTH FLORIDA WATER MANAGEMENT DISTRICT



CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who may prefer to use metric (International System) units, rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
feet per foot (ft/ft)	1.0	meters per meter (m/m)
square foot (ft^2)	0.09294	square meter (m^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic feet per second per lineal foot [$(ft^3/s)/ft$]	0.0033	cubic meters per second per lineal meter [$(m^3/s)/m$]
cubic foot per second per mile [$(ft^3/s)/mi$]	0.0176	cubic meter per second per kilometer [$(m^3/s)/km$]
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon per minute (gal/min)	0.06308	liter per second (L/s)

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By Leo J. Swayze

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U.S. DEPARTMENT OF THE INTERIOR
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DEPARTMENT OF THE INTERIOR

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ABSTRACT

Conservation Area 2B is an area of recharge for the surficial aquifer system in Broward County. Water stored in the conservation area provides the hydraulic potential for downward flow to the high permeability zone of the Biscayne aquifer. A 5.64-foot head differential (average for the period of record) between water levels in Conservation Area 2B and water levels in the adjacent levee 35A borrow canal causes water to leak into the canal at an average rate of about 2.2×10^{-3} cubic feet per second per lineal foot of canal and accounts for a loss of 0.013 foot per day of surface water from Conservation Area 2B. Amounts of canal leakage and underflow are constantly changing and are dependent upon the head differential between Conservation Area 2B and the levee 35A borrow canal.

INTRODUCTION

Water-conservation areas within The Everglades in south Florida (fig. 1) are designed to store excess water during wet periods and release water during dry periods to provide supplemental water to the coastal areas, thereby retarding saltwater intrusion. The levees, which surround the water-conservation areas, prevent the overland flow of floodwater from The Everglades to the urbanized coastal areas. Excess water, which is impounded in the conservation areas for future use, becomes available for water management as direct release through control structures into canals or as uncontrolled seepage under levees into canals, which helps maintain water levels along the coastal areas during the dry season.

An important factor in determining which water-management practice to implement in southeast Florida is the hydraulic connection between surface water and ground water in the water-conservation areas and the ground water and canals adjacent to the conservation areas. Ponded water and shallow ground water in Conservation Areas 2A, 2B, 3A, and 3B (fig. 1) of the South Florida Water Management District constitute sources of recharge to the surficial aquifer system of southeast Florida during prolonged dry seasons. These sources of recharge will become increasingly important as water-use demands of the southeast coastal urban areas continue to expand. These urban areas withdraw nearly all their potable water from the Biscayne aquifer. Release of surface water to the coastal areas by way of the primary canal system during the dry season is generally adequate for water-supply replenishment and to retard saltwater intrusion.

The intent of this investigation was to collect and analyze data to determine hydraulic gradients and rates of seepage between conservation areas and perimeter canals. Four sites were selected for collection and evaluation

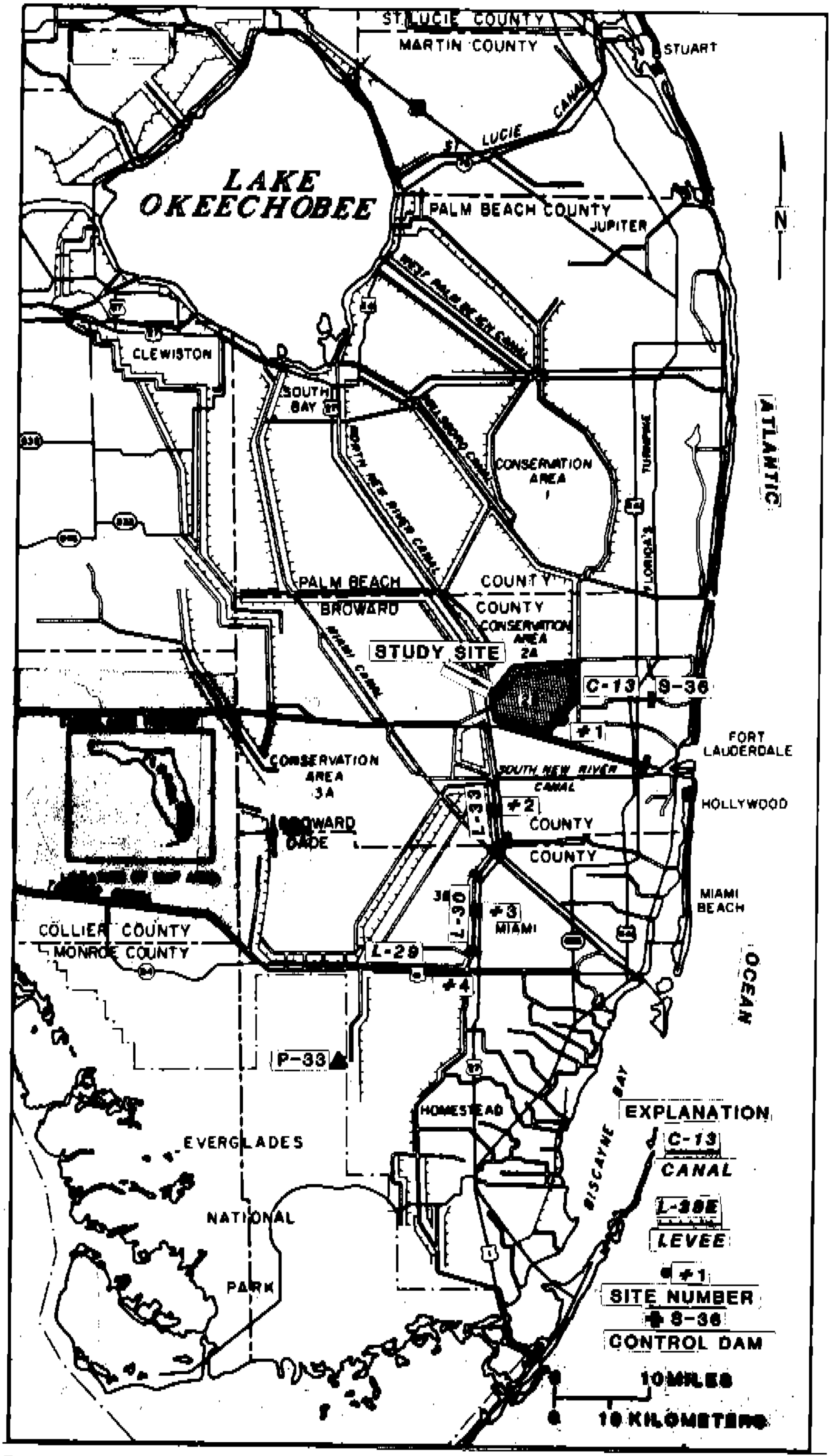

Figure 1.--Study site, water-conservation areas, levees, and canals in southeast Florida.

of data. The sites, from north to south, include levee 35A (site 1), levee 33 (site 2), levee 30 (site 3), and levee 29 (site 4) and are shown in figure 1. Multiple-depth wells were installed perpendicular to the levees. Water levels and flow measurements were made periodically from 1982 to 1984 to cover a wide range of hydraulic conditions created by seasonal variations in rainfall and water-management practices. Although four sites were established and data collection was attempted at all four, only site 1 yielded data from which seepage could be determined.

Purpose and Scope

The purpose of this report is to describe loss of water from Conservation Area 2B through ground-water flow. Head differentials between the area and the adjacent canal parallel to levee 35A are examined, ground-water flow patterns delineated, and a water budget described.

Previous Investigations

Klein and Sherwood (1961) calculated a seepage value of 540 $(ft^3/s)/mi$ length of levee 30 (L-30) when the head difference across the levee is 10 feet. Meyer (1971) calculated seepage values of 0.1 to 0.9 $(ft^3/s)/mi$ length of levee per foot of head along the southern shore of Lake Okeechobee. Leach and others (1972, p. 45-52) calculated a gross estimated eastward seepage of 180 ft^3/s, or 8 $(ft^3/s)/mi$ from Conservation Area 2 through levee 35 (L-35).

The U.S. Army Corps of Engineers (1952, p. 10) calculated a vertical hydraulic conductivity value of 1×10^{-4} ft/s for the top 3 feet of rock, underlying 2 to 4 feet of marly sawgrass peat at a levee test site on the northeastern corner of State Road 41 (Tamiami Trail) and State Road 27 (Krome Avenue). At that site, very little head loss occurred through the peat, indicating a high vertical hydraulic conductivity. Test results by the U.S. Army Corps of Engineers indicate that virtually no seepage occurs through a properly constructed levee. All seepage is by vertical flow through the surficial peat covering the bottom of the conservation areas and gradually changing to horizontal flow in deeper geologic layers of higher permeability.

Methods

Although four sites were chosen, levee 35A (L-35A), levee 33 (L-33), levee 30 (L-30), and levee 29 (L-29), only the L-35A site yielded data which could be analyzed for seepage. The main problem at the remaining three sites was the inability to measure the extremely low velocities in the perimeter canals. Low-velocity measurement techniques, such as the "float-stick" method, were attempted with no reproducible results; dye-tracer techniques were considered but eliminated because of dispersion problems. Low velocities in these canals were mainly caused by the large cross-sectional areas of the canals intercepting small quantities of ground-water seepage.

Site 1 was selected along a reach of the L-35A borrow canal for exploratory drilling and hydraulic testing. Multiple-depth wells were drilled along a line (Z-Z') perpendicular to L-35A and the canal as shown in figure 2. Geologic materials composing the Biscayne aquifer were collected and described, and the hydrologic and hydraulic properties of the aquifer and canals were defined (table 1).

Recording gages were installed to obtain continuous records of surface-water levels in the canal and the conservation area. Water levels in the wells were periodically measured during high- and low-water conditions to determine the head distribution in the surficial aquifer and the relation between surface-water and ground-water levels in the area.

Measurements of low flow, using the float stick method of measurement (W.A.J. Pitt, U.S. Geological Survey, written commun., 1969), were made in the L-35A borrow canal, about 1 mile upstream (southwest) and 1 mile downstream (northeast) of the line of wells (Z-Z'). Surface water flowing into the L-35A canal through the culvert from the secondary drainage canal was measured with a Price[1] AA velocity meter. The leakage of ground water into the L-35A canal was then determined by adding the measured upstream flow to the secondary canal flow and subtracting this total from the measured downstream flow value. Theoretically, seepage should vary in proportion to the water-table gradients or the head difference between the L-35A borrow canal and Conservation Area 2B.

GEOHYDROLOGY

The Biscayne aquifer, the most permeable part of the surficial aquifer system, is the sole source of fresh ground water in Broward County. It is chiefly composed of limestone, sandstone, and sand of marine origin, ranging in age from (oldest to youngest) Pliocene to Pleistocene. The aquifer generally is greater than 200 feet thick along the coast in Broward County (Sherwood and others, 1973). The thickness of the limestone sections and the permeability of the aquifer as a unit generally decrease to the north. The Biscayne aquifer also thins westward to about 70 feet in central Broward County and wedges out at land surface near the Collier-Broward County line. Most of the limestone beds in the Biscayne aquifer are capable of yielding large amounts of water to wells. Wells that tap the thick limestone in the deeper zones (depth of 100 feet or greater) near the coast commonly yield more than 1,000 gal/min. Most of the municipalities obtain water from this deep zone of the aquifer. Underlying the Biscayne aquifer is a 200-foot thick section of marl and clay of the Miocene Hawthorn Formation (Parker and others, 1955).

The surficial aquifer system at site 1 can be divided into five distinct layers based on lithology and hydraulic characteristics. A generalized lithologic section (fig. 3) was prepared using data (table 1) from a test well and drill cuttings from water-level observation wells drilled at site 1. The characteristics are as follows:

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[1] Use of the brand name in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

WELL GROUP	DEPTH, IN FEET BELOW LAND SURFACE
A	10
	20
	40
	80
B	10
	20
C	10
	20
	40
	56
D	10
	20
	30
	40
	60
	80
E	10
	20
	30
	40
	60
	84
F	10
	20
	30
	40
	60
	80
G	8
	30
	80

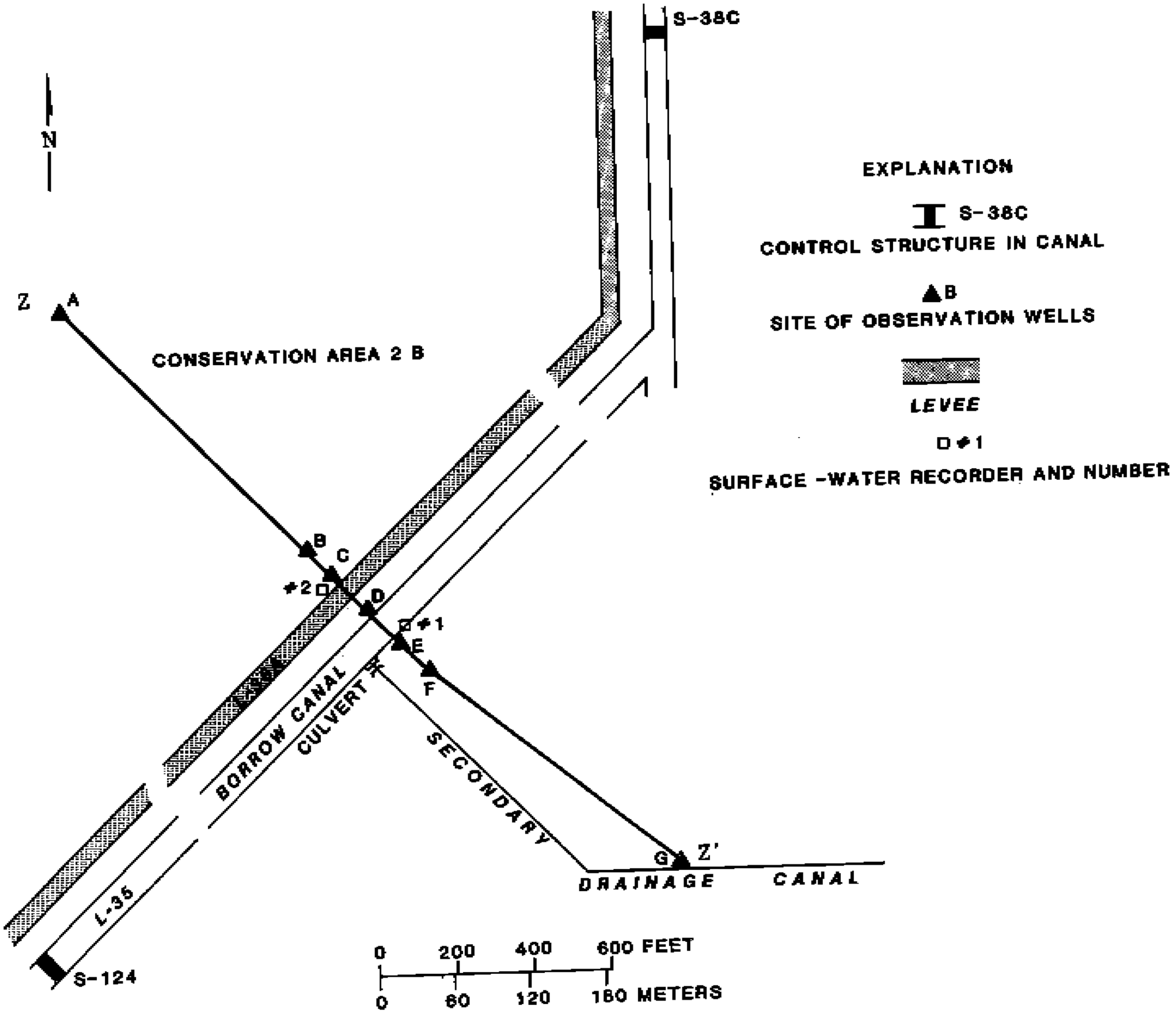

Figure 2.--Well locations and depths along the study area cross section (site 1).

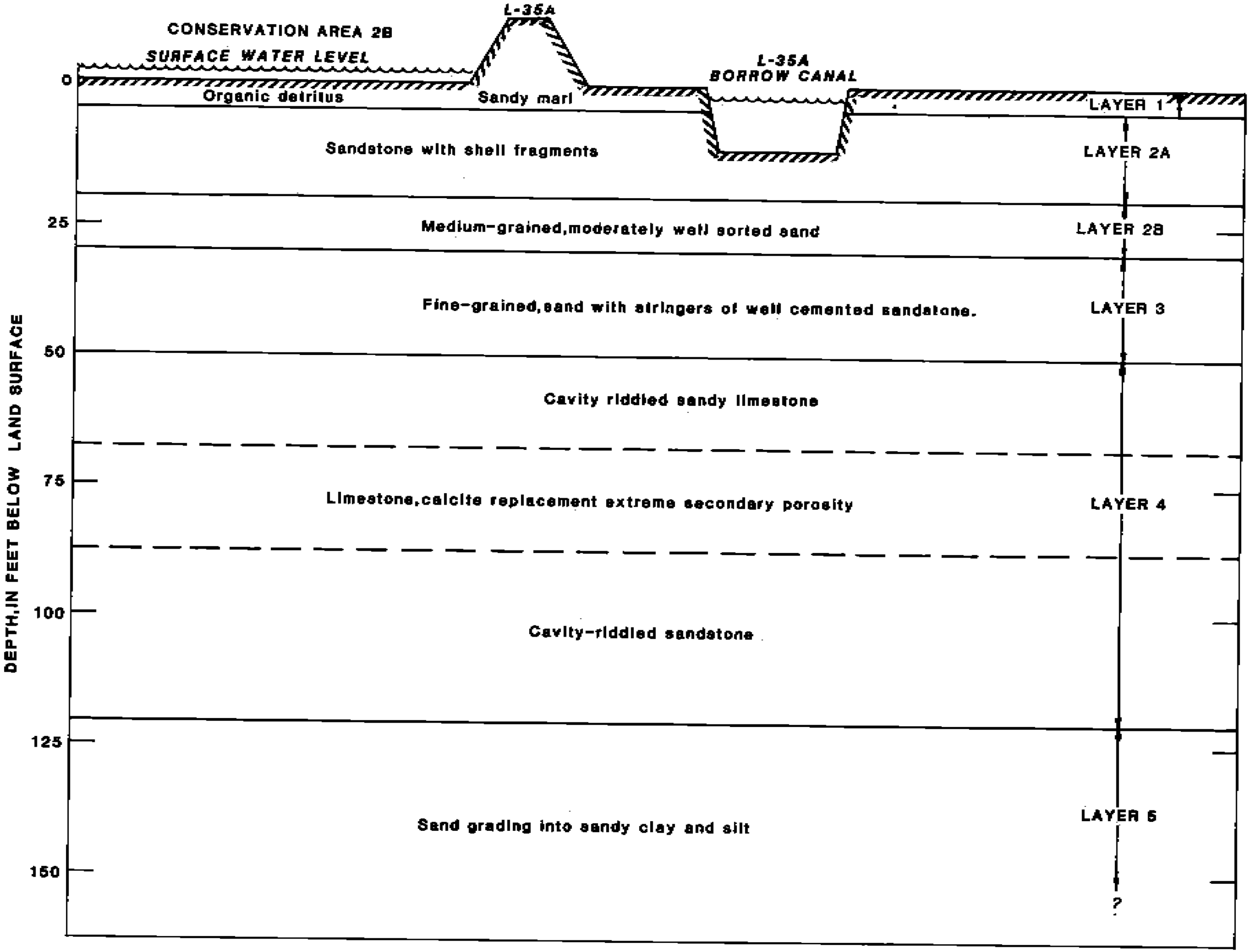

Figure 3.--Generalized lithologic section at site 1.

Table 1.--Lithologic log of a geologic test well at site 1

Depth (feet)	Description
0-2	Organic detritus (peat), dark-brown to black.
2-5	Sand, light-olive brown (5 Y 5/6); quartzose, fine grained, subangular to subrounded (claylike consistency.)
5-7	Sandstone, very pale orange (10 YR 8/2); rounded sand grains coated and moderately cemented with calcium carbonate; about 10 percent shell fragments with partial recrystallization to calcite.
7-10	Sandstone as above; contains about 50 percent shell fragments.
10-13	Sandstone as in 5 to 7 feet; well cemented.
13-16	Sandstone as above; about 10 percent shell fragments.
16-19	Sandstone as above.
19-22	Sandstone as above; moderately cemented with thin layer of high magnesium carbonate.
22-26	Sand, white (N 9); quartzose, medium grained, moderately well sorted, subangular to subrounded; about 3 percent phosphorite.
26-29	Sand, yellowish-gray (5 Y 8/1); quartzose, fine grained, moderately well sorted, subangular to subrounded; about 10 percent molluscan fragments.
29-32	Sand as above; about 5 percent small shell fragments; about 1 percent phosphorite.
32-36	Sand as above; thin layer of sandstone; well cemented with calcium carbonate.
36-39	Sand as in 29 to 32 feet.
39-42	Sand as above with sandstone nodules.
42-46	Sand as in 32 to 36 feet.
46-49	Sandstone, yellowish-gray (5 Y 8/1); well cemented with calcium carbonate containing about 50 percent molluscan fossil; cavities filled with sand as in 26 to 29 feet; about 1 percent phosphorite.
49-52	Sandstone as above.
52-56	Sandy limestone, yellowish-gray (5 Y 8/1) as in 46 to 49 feet; increasing content of molluscan shell fragments; some alteration to calcite; cavity riddled; some loose sand.
56-59	Sandstone, yellowish-gray (5 Y 8/1); well cemented with calcium carbonate; about 10 percent molluscan fragments; about 1 percent phosphorite; cavity riddled; thin section on file.
59-62	Limey sandstone, very pale orange (10 YR 8/2); well cemented with calcium carbonate; many molluscan casts; secondary porosity due to dissolution of original molluscan materials, cavity riddled; about 1 percent phosphorite.
62-66	Limey sandstone as above; extremely permeable; some calcite.
66-69	Limey sandstone as above; some sand-filling cavities.
69-72	Limestone (calcite), very pale orange (10 YR 8/2); fossiliferous micrite; about 1 percent sparite; extremely permeable due to cavities.
72-76	Limestone (calcite) as above.
76-79	Limestone (calcite) as above; about 10 percent sparite.
79-82	Limestone (calcite) as above; large molluscan fossils completely replaced by sparry calcite.
82-86	Limestone (calcite) as above.
86-89	Limestone (calcite) as above.
89-92	Sandstone, very light gray (N 8); about 5 percent molluscan shell fragments; about 1 percent phosphorite; cavity riddled, some sandfilling cavities; extremely permeable.
92-96	Sandstone as above; about 25 percent molluscan shell fragments; some sparry calcite.
96-99	Sandstone as above.
99-102	Sandstone, light-gray (N 7); about 50 percent shell hash; about 1 percent phosphorite; very loosely cemented.
102-106	Sandstone as above.
106-109	Sandstone as above; less cementation; echinoderm plates and spines, corals, and forams.
109-112	Sandstone as above; very little cementation; about 10 percent phosphorite.
112-116	Sandstone as above.
116-119	Sand, light-gray (N 7); quartzose; no cementation.
119-122	Sand as above.
122-126	Sand, yellowish-gray (5 Y 7/2); quartzose, fine grained, angular; grains are held together with a claylike consistency with particles of calcite.
126-129	Sand as above.
129-132	Sand as above.
132-136	Sand as above.
136-139	Sand as above.
139-142	Sandy clay, grayish-yellow-green (5 GY 7/2) as above; more claylike.

Layer 1 (0 to 5 feet): About 3 feet of organic detritus (peat), composed of decayed sawgrass and other varieties of Everglades plant life, overlying about 2 feet of sandy marl. This layer acts as a semiconfining layer hindering the vertical flow of surface water in the conservation area into the ground-water system.

Layer 2a (5 to 22 feet): About 17 feet of a moderately cemented sandstone, interspersed with as much as 50 percent shell fragments.

Layer 2B (22 to 32 feet): About 10 feet of a medium-grained, moderately well sorted sand.

Layers 2A and 2B are geologically dissimilar, but hydraulically they act as one continuous layer, as indicated by the equal distance separating contour lines (fig. 4). These layers are the main conductive paths for flow of ground water into the L-35A borrow canal.

Layer 3 (32 to 52 feet).--About 20 feet of fine-grained sand with stringers of well cemented sandstone of low permeability. This layer acts as a semiconfining layer to vertical ground-water flow into or out of layer 4.

Layer 4 (52 to 122 feet).--About 70 feet of sandstone and limestone (calcite), poorly cemented to well cemented and cavity riddled. This layer is highly permeable and is the main conductive path for ground-water flow in the regional ground-water system.

Layer 5 (122 - ? feet).--Sandy silts and clays. This layer acts as the lower confining layer of the surficial aquifer system.

ANALYSIS OF GROUND-WATER FLOW

Cross-sectional ground-water flow was analyzed by plotting field measurements of ground-water levels and contouring lines of equal potential (fig. 4). Flow directions are determined by drawing lines perpendicular to the equipotential lines. Ground water flows along these lines in the direction of decreasing potential. The driving force for ground-water flow at the study area is the potential created by the storage of water in Conservation Area 2B (a high potential) and the drainage of water east of the levee by the L-35A borrow canal (an area of lower potential). Several flowlines, A through G (fig. 4), illustrate the various paths of ground-water flow in the study area.

Flowline A is the most direct path water can flow to reach the canal from the conservation area. Surface water, near the levee, moves vertically through surficial layers of peat and sandy marls (layer 1) into layer 2 where it then moves horizontally toward and into the canal. West of the levee, the vertical gradients begin to take effect in layer 2. Surface water moving through surficial peat layers takes longer and deeper flowlines (B and C) before moving upward into the canal. At distances of about 1,000 feet or greater from the canal, recharging water from the conservation area moves down into the zone of high permeability (layer 4). This high permeability zone is the primary conducting layer of the regional ground-water flow system.

Drainage of water east of L-35A through the L-35A borrow canal creates a hydraulic stress across the semiconfining layer at the 32- to 46-foot interval (layer 3). This stress induces an upward leakage of ground water from the high permeability zone (layer 4) through the semiconfining layer. The effect of the semiconfining layer on ground-water flow is exemplified by the very close equipotential lines along flowline D beneath the canal and at point x on flowline E. This water then continues its upward flow through the low permeable sands of layer 3 and into the canal. Another effect of this upward leakage is the loss of water from layer 4, creating a flattening of the horizontal hydraulic gradients. Although there is an upward loss of some water out of layer 4, water is still available to underflow the canal (flowline F). This regional flow of ground water is then available for: (1) recharge of downgradient areas of ground-water withdrawal, such as well fields; (2) upward leakage to replace ground water in drained areas; or (3) ground-water discharge to the ocean. Flowline G represents a minor amount of ground water which flows westward into the L-35A borrow canal.

SEEPAGE ANALYSIS OF LEVEE 35A BORROW CANAL

The L-35A borrow canal intercepts part of the ground water which leaks under L-35A from Conservation Area 2B. It also serves as a main drainage canal for developed areas east of the canal. Water is drained, from housing developments to the east, into the L-35A borrow canal by a network of secondary canals. It is then diverted to the Atlantic Ocean by way of the Middle River Canal (C-13) through structure S-36 (see fig. 1).

Structure S-36 is equipped with tidally controlled gates which open and close automatically, depending upon the differences in surface-water elevations upstream and downstream of the gates. Because the downstream side of the structure is tidal, a tide cycle is generated in the Middle River Canal due to the opening and closing of the gates. This periodic effect (fig. 5) can be observed in the data collected at the L-35A borrow canal surface-water recorder site (fig. 2). Surface-water levels in the canal ranged from 8.67 to 10.47 feet datum[2] during the study period, indicating the controlled nature of the canal. Pool level in Conservation Area 2B ranged from 9.1 to 16.12 feet datum, which represents a more natural water system having more pronounced seasonal changes of water levels. A relation between the pool level in Conservation Area 2B and the water level in the L-35A borrow canal could not be established because of the extreme regulation of the canal.

Data collected from June 30, 1982, through November 4, 1983, at the L-35A study area are presented in table 2. A plot of the head differential between Conservation Area 2B and the measured ground-water inflow into the canal (in cubic feet per second) is shown in figure 6. According to the Darcy equation of ground-water flow, $q = K (dh/dl)$, discharge (q) is directly proportional to the hydraulic gradient (dh/dl). A plot of the head differential, the gradient between Conservation Area 2B and the L-35A borrow canal in relation to the ground-water inflow (Q) into the canal, should yield a straight line intersecting the point 0,0. Intersection of the line and the y-axis at a point

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[2] Arbitrary 10.00 foot datum set at top of culvert (fig. 2).

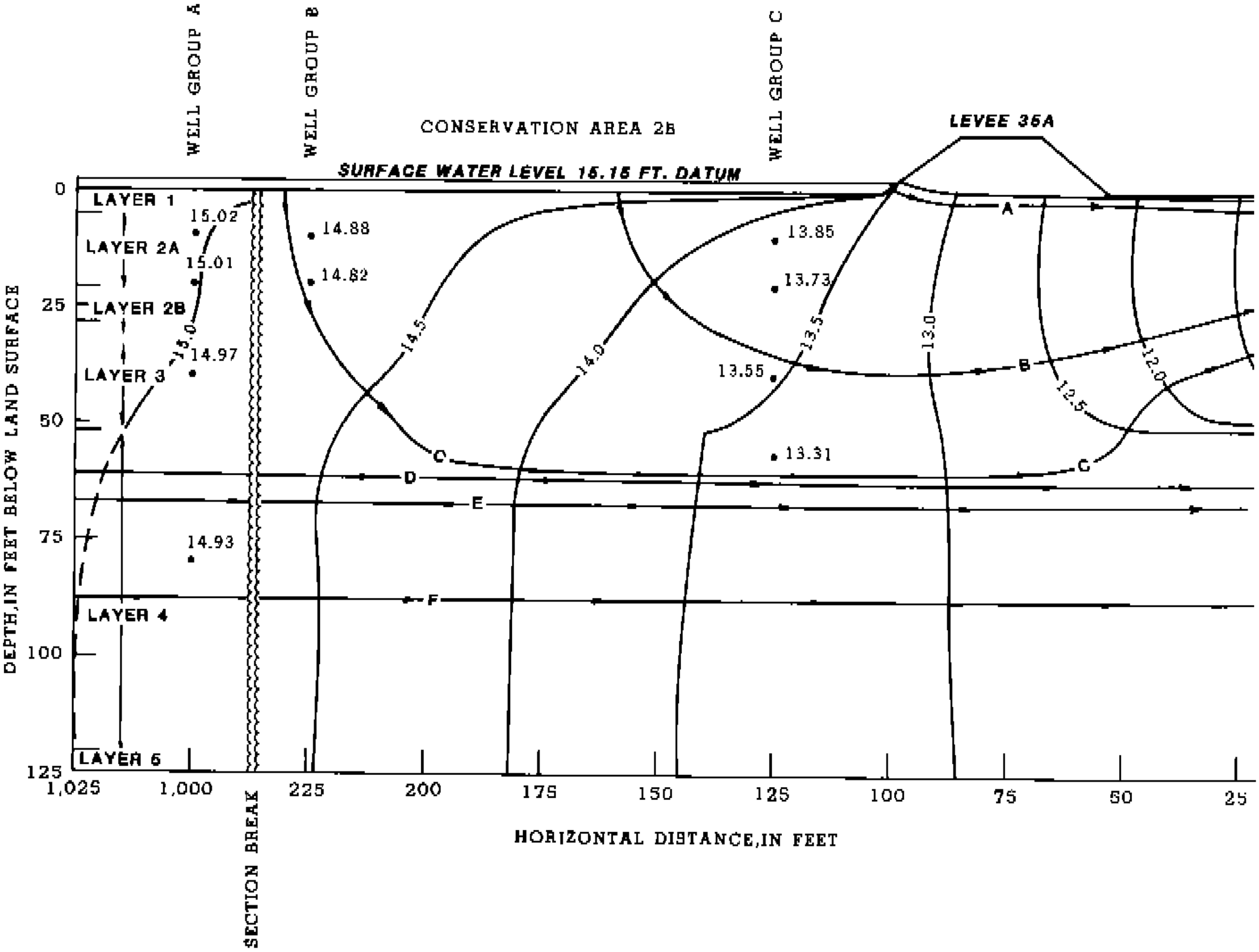
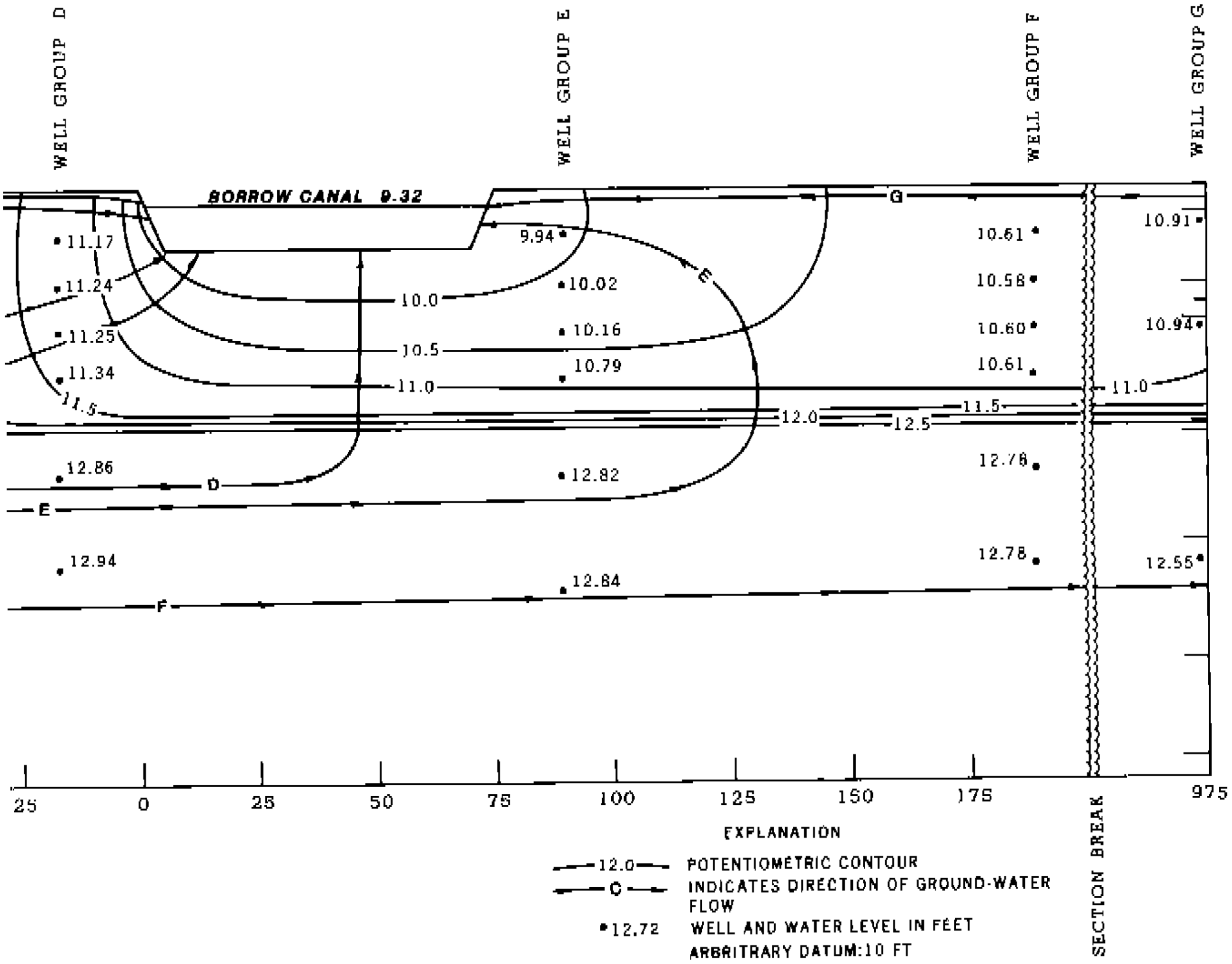


Figure 4.--Potentiometric contours and flow directions under the levee 35A, November 4, 1983.


WELL GROUP D
WELL GROUP E
WELL GROUP F
WELL GROUP G
BORROW CANAL 9.32
11.17
11.24
11.25
11.34
11.5
12.86
12.94
9.94
10.02
10.16
10.79
12.82
12.84
10.61
10.58
10.60
10.61
12.76
12.78
10.91
10.94
12.55
10.0
10.5
11.0
11.5
12.0
12.5
D
E
F
G
25
0
25
50
75
100
125
150
175
975
SECTION BREAK
EXPLANATION
12.0 POTENTIOMETRIC CONTOUR
C INDICATES DIRECTION OF GROUND-WATER FLOW
12.72 WELL AND WATER LEVEL IN FEET
ARBITRARY DATUM:10 FT

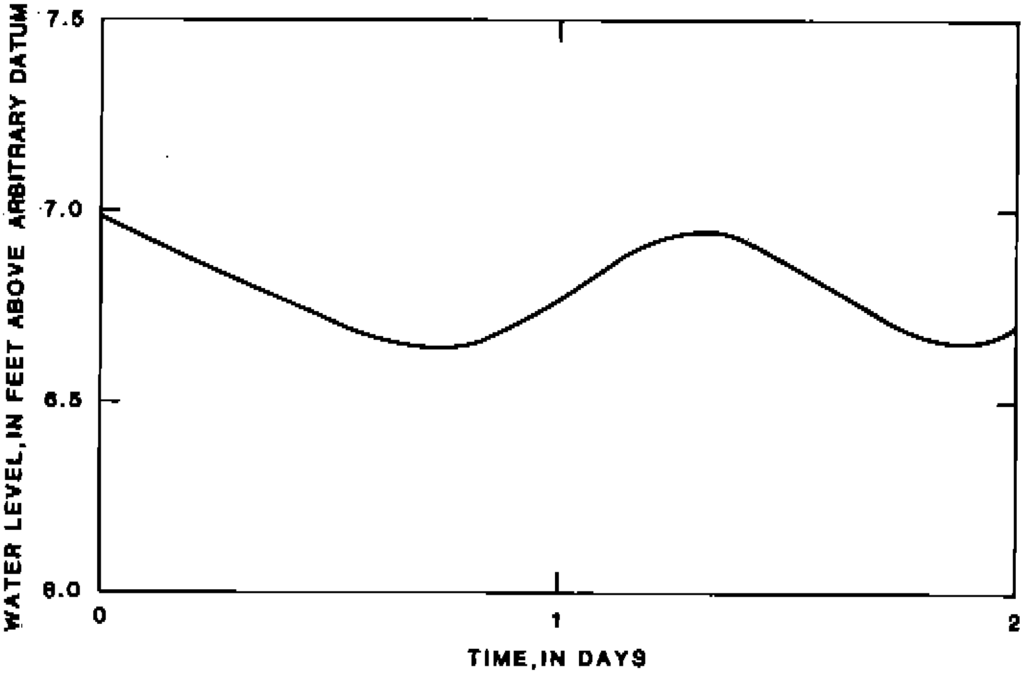


Figure 5.--Periodic surface-water levels observed in the levee 35A borrow canal at recorder No. 1.

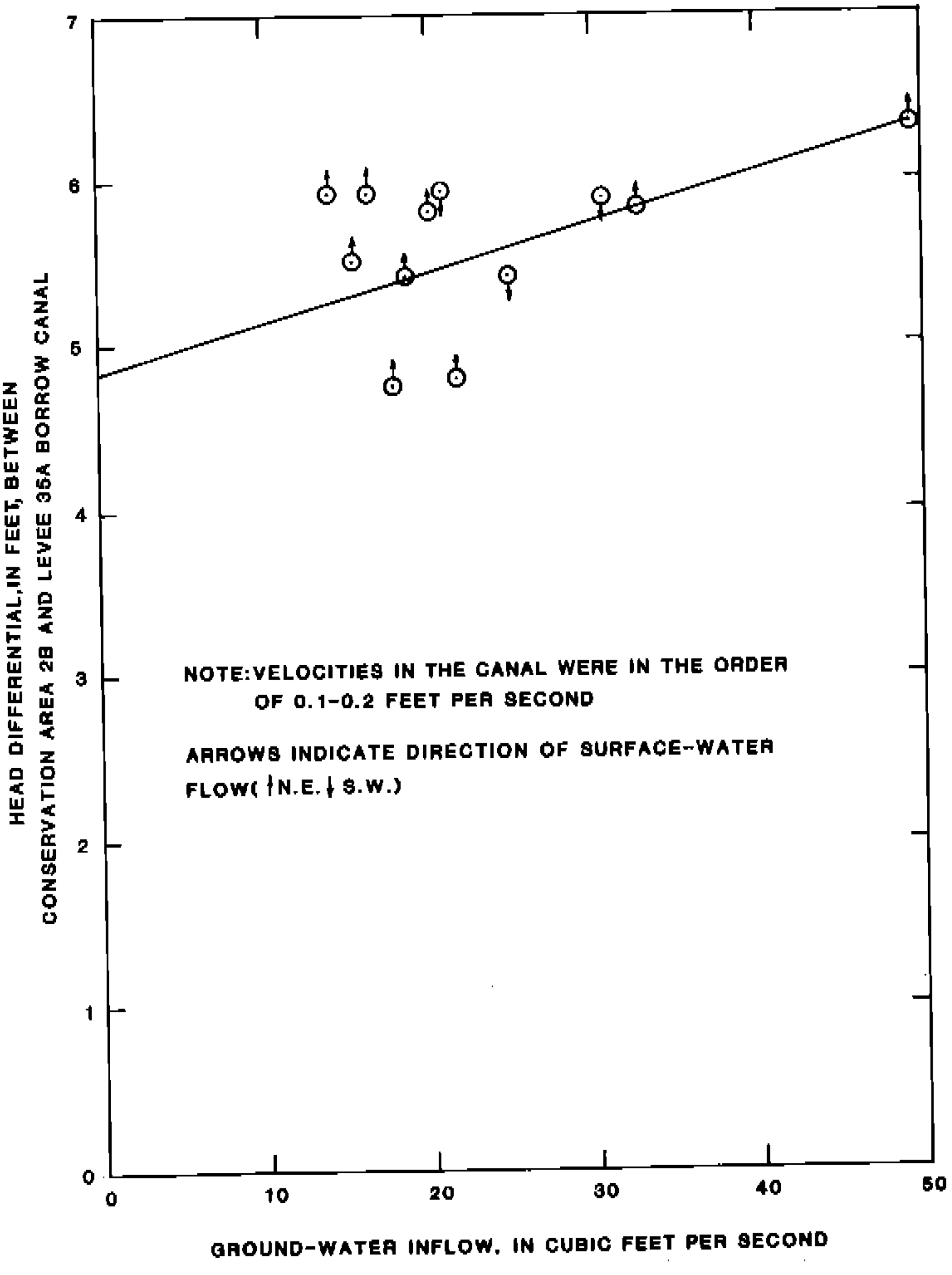


Figure 6.--Head differential between Conservation Area 2B and the levee 35A borrow canal in relation to ground-water inflow for a 2-mile reach of canal.

Table 2.--Water-level and flow data collected at levee 35A, June 30, 1982, through November 4, 1983

Date of measurement	Stage, in feet, arbitrary datum		Head differential, in feet	Flow, in cubic feet per second[1]	Cubic feet per second per foot of canal per foot of head
	Conservation Area 2B	Levee 35A borrow canal			
6/30/82	14.33	8.91	5.42	18.54	3.24×10^{-4}
7/27/82	14.65	9.87	4.78	17.80	3.52×10^{-4}
8/12/82	14.55	8.64	5.91	13.92	2.23×10^{-4}
9/8/82	14.73	9.22	5.51	15.31	2.63×10^{-4}
9/27/82	14.92	9.02	5.90	[2] [3]30.44	4.88×10^{-4}
12/21/82	14.71	8.78	5.93	[3]20.44	3.26×10^{-4}
1/19/83	14.25	8.82	5.43	[3]24.88	4.34×10^{-4}
2/9/83	14.43	9.64	4.79	21.49	4.24×10^{-4}
3/24/83	15.88	9.50	6.38	49.33	7.32×10^{-4}
5/24/83	15.13	9.30	5.83	20.05	3.25×10^{-4}
6/15/83	15.28	9.36	5.92	16.22	2.59×10^{-4}
11/4/83	15.15	9.32	5.83	32.46	5.27×10^{-4}
Average			5.64	21.40	3.90×10^{-4}

[1] This is the amount of ground water seeping into the measured 2-mile reach of canal.

[2] Normal flow direction is northeast and reverse flow is southwest; this occurs when structure S-124 is opened (fig. 7).

[3] Reverse flow.

other than (0,0) would indicate other sources (y value is negative) or losses (y value is positive) of water to the measured section of the canal. A positive head differential indicates leakage of ground water into the canal, zero head differential indicates no leakage, and a negative head differential indicates leakage out of the canal. The slope of this line is proportional to the hydraulic conductivity; that is, the flatter the line, the higher the aquifer hydraulic conductivity. As shown in figure 6, considerable scatter in the data is apparent as lower values of ground-water inflow were measured. This scatter or lack of direct relation may be due to the following factors:

- Average surface-water velocities in the L-35A borrow canal were on the order of 0.1 ft/s. With low velocity, a greater possibility for measurement error exists because of wind and wave action on the float stick. Efforts were made to minimize these problems. A float-stick measurement was attempted when the head differential was about 3 feet. Velocities were on the order of 0.04 ft/s, and large differences were observed in trying to duplicate measurements.

- Because of the cyclical nature of surface-water levels in the canal, the surficial aquifer system was in a constant state of flux; that is, steady-state conditions necessary for Darcy's law to be valid were never met. Also, bank and canal storage probably add considerable scatter to the data set.

Although the line intersects the y-axis at $y \approx 4.8$, field observations indicated no other losses of water were occurring in the measured section. Because data interpretation did not provide a strong linear relation, an average leakage value of 3.9×10^{-4} $(ft^3/s)/f_C/f_H$ (cubic feet per second per foot of canal per foot of head) was calculated at an average head differential of 5.64 feet (table 2) to yield an average leakage of 2.2×10^{-3} $(ft^3/s)/f_C$ (cubic feet per second per foot of canal) and was used for water budget calculations in the following section.

GROUND-WATER FLOW LOSSES - WATER BUDGET

A water budget attempts to quantify sources and sinks of water for a defined region. A water budget for Conservation Area 2B was prepared (fig. 7) in order to calculate the approximate leakage of surface water out of Conservation Area 2B into the high transmissive zone (layer 4) of the surficial aquifer (fig. 4). The water budget was calculated using hydrologic conditions which occurred prior to March 10, 1984. This date was chosen so that rainfall could be omitted from the water budget calculation. No appreciable amount of rainfall occurred for about 2 months prior to these data. The following section is a description of the sources and sinks of water to Conservation Area 2B and their volumetric rates per unit area.

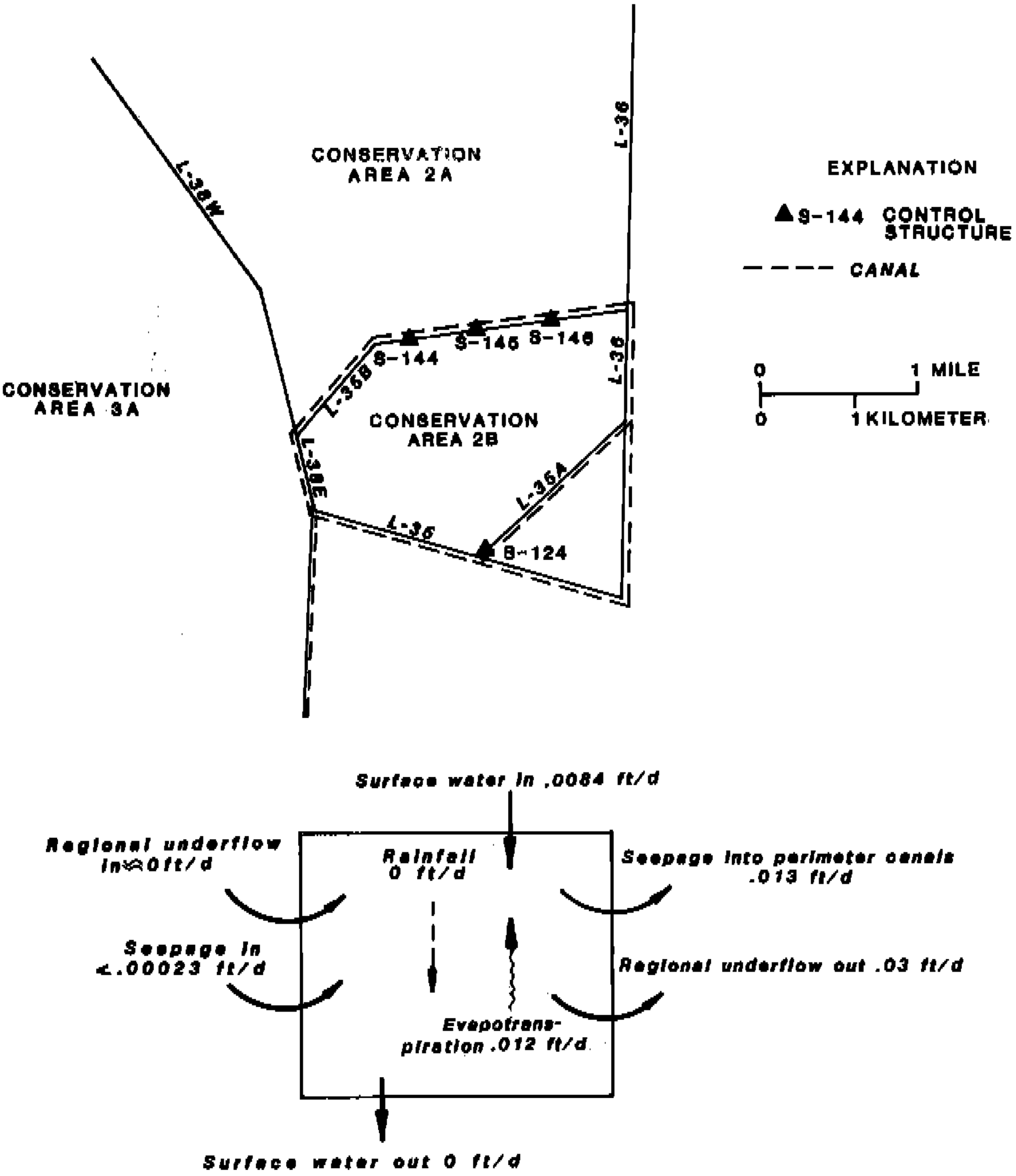


Figure 7.--Levees and control structures surrounding Conservation Area 2B and schematic representation of a water budget.

Sources

Water is input into Conservation Area 2B through four possible mechanisms as follows:

- Surface water is released from Conservation Area 2A into Conservation Area 2B through structures S-144, S-145, and S-146 (fig. 7). Flow through these structures was about 120 ft^3/s (J. Vearil, U.S. Army Corps of Engineers, oral commun., 1987). Based on an approximate total area of 44 mi^2 for Conservation Area 2B, the contribution of surface water from Conservation Area 2A is equivalent to a rise in stage of about 8.5×10^{-3} ft/d.

- Because of differences in surface-water levels between Conservation Areas 2A and 2B, ground water flows under levee 35B (L-35B) and seeps up into Conservation Area 2B. This value was not measurable; however, if an average leakage value of 3.9×10^{-4} $(\text{ft}^3/\text{s})/f_C/f_H$, as measured in the L-35A borrow canal, is applied to 10.5 miles of perimeter canal along L-35B, the volume of seepage under L-35B into Conservation Area 2B can be calculated as follows:

$$(3.9 \times 10^{-4}\ (\text{ft}^3/\text{s})/f_C/f_H)\ (86{,}400 \text{ seconds per day})\ (0.15 \text{ foot of head})\ (10.5 \text{ mi})\ (5{,}280 \text{ ft/mi}) = 279{,}936\ \text{ft}^3/\text{d}. \qquad (1)$$

  Based on an approximate total area of 44 mi^2 for Conservation Area 2B, the contribution of seepage from Conservation Area 2A would account for a rise in stage of about 2.3×10^{-4} ft/d. This value can be considered negligible for the water budget calculations.

- L-35B is located at the approximate western boundary of the Biscayne aquifer in an area where the high transmissivity zone (Biscayne aquifer), recognized in the lithologic section in figure 3, probably is not present (J.E. Fish, U.S. Geological Survey, oral commun., 1985). On a regional flow basis, the amount of ground water flowing under L-35B into the high transmissivity zone beneath Conservation Area 2B probably is minimal.

- Rainfall is a major source of recharge in south Florida. Because rainfall intensity is areally inconsistent, measuring its total influence over a 44-mi^2 area would be approximate. To alleviate this problem, a time period near the end of the dry season was chosen when no rainfall had occurred for several weeks.

Sinks or Water Losses

Water losses from Conservation Area 2B can be attributed to four mechanisms--evapotranspiration (ET), leakage into the perimeter canals, surface-water outflow, and downward leakage into the regional ground-water flow system. They are described as follows:

- An ET rate of 0.012 ft/d was obtained from data collected at surface-water gaging station P-33 in Everglades National Park during October 1966 (Kolipinski and others, 1967). Water levels and vegetative growth there are similar to Conservation Area 2B. The observed ET rate was measured during October, and calculations for this study were based on March data. However, graphs of mean monthly values of pan evaporation and ET for south Florida (Stewart and Mills, 1967) indicate that ET rates for these months can be considered equal.

- A value of leakage into the perimeter canals bordering L-35A was obtained from flow-measurement data (table 2). An average value of 3.9×10^{-4} $(ft^3/s)/f_C/f_H$ was applied to 15.6 miles of perimeter canals along L-35, L-35A, levee 36 (L-36), and levee 38E (L-38E) with a head differential of 5.64 feet (table 2, average for dry season). Total leakage into these canals amounted to 15,700,000 ft^3/d, or a 0.013-ft/d decline of water level over the total area of 44 mi^2 for Conservation Area 2B.
- No surface-water outflow can occur from Conservation Area 2B.
- Downward leakage of surface water into the regional ground-water flow system was not directly measurable; however, it can be calculated from the water-balance equation, using the above data for sources and sinks, if the rate of recession of surface water in Conservation Area 2B is known.

Evaluation of Water Budget

A recession rate of 0.03 ft/d was recorded (fig. 8) during February and the first 2 weeks of March 1984, a time period of no rainfall. The rate of recession in Conservation Area 2B is equal to the sources of water minus the sinks of water. Because the recession rate is known and all sources and sinks, except for underflow, have been measured, the underflow (downward leakage into the regional ground-water flow system) was calculated from the following equation:

$$\text{SOURCES} - \text{SINKS} = \text{RATE OF RECESSION (RR)} \qquad (2)$$

or

$$\begin{aligned}&(\text{SURFACE WATER IN} + \text{SEEPAGE IN} + \text{REGIONAL UNDERFLOW IN}\\ &+ \text{RAINFALL}) - [(\text{ET} + \text{SEEPAGE INTO PERIMETER CANALS})\\ &+ \text{REGIONAL UNDERFLOW OUT} + \text{SURFACE WATER OUT}] = \text{RR}.\end{aligned} \qquad (3)$$

Rearranging equation 3 yields:

$$\text{SOURCES} - \text{SINKS} - \text{RR} = \text{REGIONAL UNDERFLOW OUT}.$$

Substituting values, as described in the previous section, into equation 3 yields:

$$\begin{gathered}(0.0084 \text{ ft/d} + 0.00023 \text{ ft/d} + 0 \text{ ft/d}\\ + 0 \text{ ft/d}) - [(0.012 \text{ ft/d} + 0.013 \text{ ft/d})\\ + 0.03 \text{ ft/d} + 0 \text{ ft/d}] = \text{REGIONAL UNDERFLOW OUT}\end{gathered}$$

or

$$\text{REGIONAL UNDERFLOW OUT} = 0.046 \text{ ft/d or about } 56 \times 10^6 \text{ ft}^3\text{/d}.$$

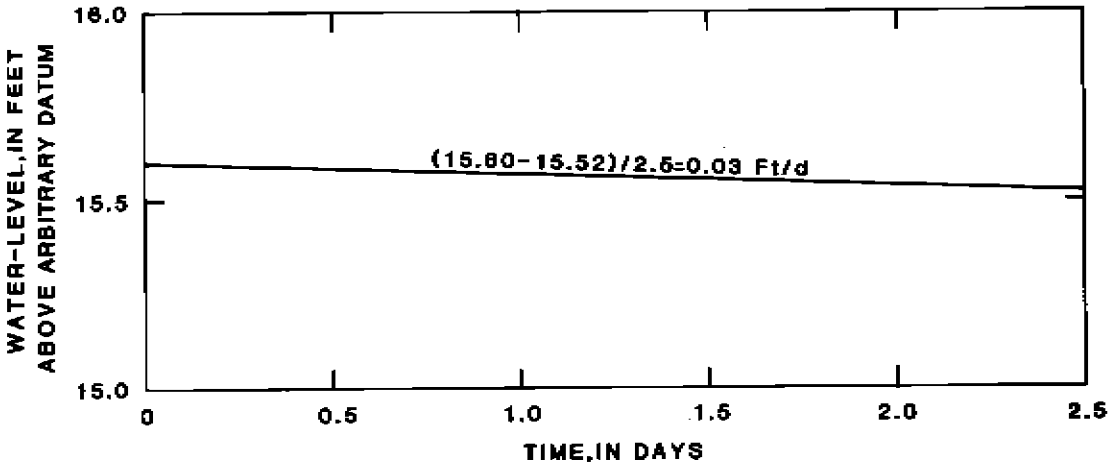


Figure 8.--Surface-water recession in Conservation Area 2B.

Because regional flow entering the system is considered negligible, downward leakage of surface water is the initial recharge for the beginning of regional flow in the high transmissivity zone. All other known losses of water have been accounted for, thus, this downward leakage can be considered the approximate amount of water available to recharge the regional flow system or the approximate amount of water flowing under the levee system in the high transmissivity zone.

GROUND-WATER FLOW LOSSES - DARCY'S LAW

Another method of determining the regional flow in the high transmissivity zone is use of Darcy's law:

$$Q = KIA$$

where Q is discharge, in cubic feet per day;
K is hydraulic conductivity, in feet per day;
I is hydraulic gradient, in feet per foot; and
A is area through which the discharge is occurring, in square feet.

Hydraulic conductivities near the study area were estimated by specific-capacity tests. Values measured were about 24,000 ft/d (J.E. Fish, U.S. Geological Survey, oral commun., 1985). Hydraulic gradients along the principal axis of the regional ground-water flow were determined from field measurements of hydraulic heads. The gradient between wells F-80 and G-80 (figs. 2 and 4) was about 2×10^{-4} ft/ft. The area through which the discharge is occurring was obtained through analysis of lithologic logs of various wells in the area. An average thickness of 40 feet was applied to 82,368 feet of levee to yield a flow area of about 3,300,000 ft^2. Substitution of these values into Darcy's equation, Q = KIA, yields:

$$Q = (24{,}000 \text{ ft/d}) \cdot (2 \times 10^{-4} \text{ ft/ft}) \cdot (3{,}300{,}000 \text{ ft}^2)$$

or approximately

$$Q = 16 \times 10^6 \text{ ft}^3\text{/d}.$$

The quantity of discharge as calculated using Darcy's law, (16×10^6 ft^3/d) is about 3.5 times less than the discharge calculated using the water budget method (56×10^6 ft^3/d). Although there is a reasonable comparison between calculated values of discharge, each method has its errors. Darcy's law is very site specific and does not consider the variability in hydraulic conductivities, potentiometric gradients, and aquifer thicknesses which occur over the study area. The water budget method yields the total amount of water available to recharge the regional ground-water system but does not consider the upward leakage of water east of the canal where the Darcy equation was applied. Because upward leakage has not been applied in the water budget method, it should give an erroneously high number as compared to the Darcy method. For these reasons, the two values, 16×10^6 ft^3/d and 56×10^6 ft^3/d, have been averaged to yield a final value of 36×10^6 ft^3/d.

CONCLUSIONS

Conservation Area 2B is an area of recharge for the surficial aquifer system in Broward County. Water stored in the conservation area provides the hydraulic potential for downward flow to the high permeability zone of the aquifer. Rates of seepage could not be related to hydraulic ground-water gradients as a result of the inaccuracy of measuring low surface-water flows in canals. A 5.64-foot head differential (average for the period of record) between water levels in Conservation Area 2B and water levels in the adjacent L-35A borrow canal causes water to leak into the canal at an average rate of about 2.2×10^{-3} $(ft^3/s)/f_C$ and accounts for a loss of 0.013 ft/d of surface water from Conservation Area 2B. The amount of ground-water flow is highly variable and is dependent upon seasonal changes of water levels in Conservation Area 2B.

Two methods were used to calculate the quantity of surface water in Conservation Area 2B flowing under the levee and entering the regional ground-water flow system. The first method was a water budget approach; the second was the application of Darcy's law to hydrologic variables measured in the field. These methods yielded comparable results of the same order of magnitude, 56×10^6 ft^3/d and 16×10^6 ft^3/d, respectively. An average value of 36×10^6 ft^3/d was determined to be representative of the system. Amounts of canal leakage and underflow are constantly changing and are dependent upon head differential between Conservation Area 2B and the L-35A borrow canal.

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