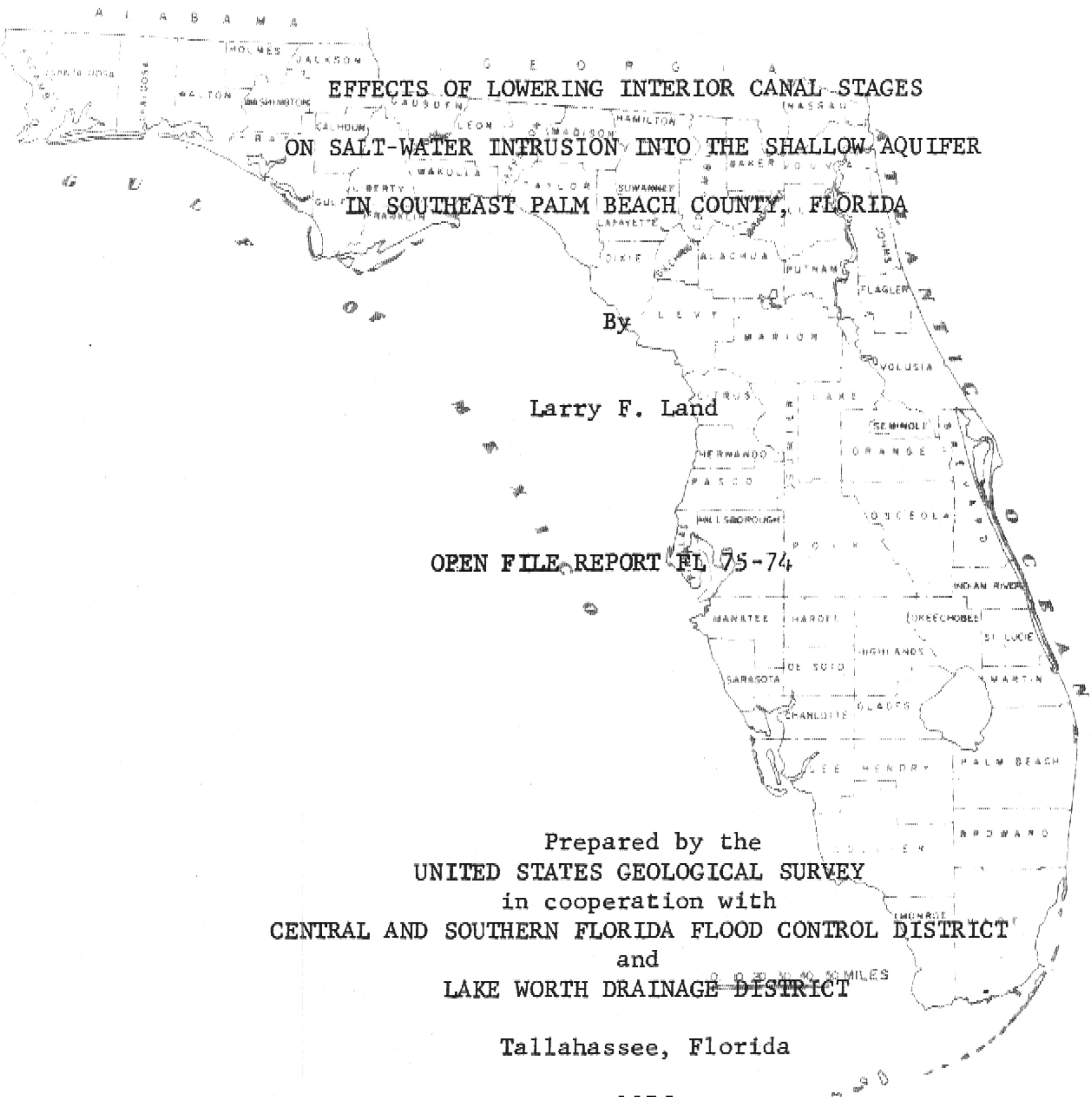
75-74 "EFFECTS OF LOWERING INTERIOR CANAL STAGES ON SALT WATER INTRUSION INTO THE SHALLOW AQUIFER ..." LFLand 75-74

UNITED STATES DEPARTMENT OF INTERIOR

GEOLOGICAL SURVEY




# EFFECTS OF LOWERING INTERIOR CANAL STAGES ON SALT-WATER INTRUSION INTO THE SHALLOW AQUIFER IN SOUTHEAST PALM BEACH COUNTY, FLORIDA

By

Larry F. Land

OPEN FILE REPORT FL 75-74

Prepared by the
UNITED STATES GEOLOGICAL SURVEY
in cooperation with
CENTRAL AND SOUTHERN FLORIDA FLOOD CONTROL DISTRICT
and
LAKE WORTH DRAINAGE DISTRICT

Tallahassee, Florida

1975

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CONTENTS

## ILLUSTRATIONS

## FACTORS FOR CONVERTING ENGLISH UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

| Multiply English units | By | To obtain SI units |
|---|---|---|
| | **Length** | |
| inches (in) | 25.4 | millimetres (mm) |
| | .0254 | metres (m) |
| feet (ft) | .3048 | metres (m) |
| miles (mi) | 1.609 | kilometres (km) |
| | **Volume** | |
| gallons (gal) | 3.785 | litres (l) |
| | 3.785 | cubic decimetres ($dm^3$) |
| | $3.785 \times 10^{-3}$ | cubic metres ($m^3$) |
| million gallons ($10^6$ gal) | 3785 | cubic metres ($m^3$) |
| | $3.785 \times 10^{-3}$ | cubic hectometres ($hm^3$) |
| | **Flow** | |
| cubic feet per second ($ft^3/s$) | 28.32 | litres per second (l/s) |
| | 28.32 | cubic decimetres per second ($dm^3/s$) |
| | .02832 | cubic metres per second ($m^3/s$) |
| gallons per minute (gal/min) | .06309 | litres per second (l/s) |
| | .06309 | cubic decimetres per second ($dm^3/s$) |
| | $6.309 \times 10^{-5}$ | cubic metres per second ($m^3/s$) |
| million gallons per day ($10^6$gal/d) | 43.81 | cubic decimetres per second ($dm^3/s$) |
| | .04381 | cubic metres per second ($m^3/s$) |

# EFFECTS OF LOWERING INTERIOR CANAL STAGES ON SALT WATER INTRUSION INTO THE SHALLOW AQUIFER IN SOUTHEAST PALM BEACH COUNTY, FLORIDA

By

Larry F. Land

## ABSTRACT

Land in southeast Palm Beach County is undergoing a large-scale change in use, from agricultural to residential. To accommodate residential use, a proposal has been made by developers to the Board of the Lake Worth Drainage District to lower the canal stages in the interior part of the area undergoing change. This report documents one of the possible effects of such lowering. Of particular interest to the Board was whether the lower canal stages would cause an increase in salt-water intrusion into the shallow aquifer along the coast.

The two main tools used in the investigation were a digital model for aquifer evaluation and an analytical technique for predicting the movement of the salt-water front in response to a change of ground-water flow into the ocean.

The method of investigation consisted of developing a digital ground-water flow model for three east-west test strips. They pass through the northern half of municipal well fields in Lake Worth, Delray Beach, and Boca Raton. The strips were first modeled with no change in interior canal stages. Then they were modeled with

a change in canal stages of 2 to 4 feet (0.6 to 1.6 metres). Also, two land development schemes were tested. One was for a continuation of the present level of land development, simulated by continuing the present pumpage rates. The second scheme was for land development to continue until the maximum allowable densities were reached, simulated by increasing the pumping rates.

The results of the test runs for an east-west strip through Lake Worth show that lowering part of the interior canal water levels 3 feet (1.0 metre), as done in 1961, does not affect the aquifer head or salt-water intrusion along the coastal area of Lake Worth. As a result, no effect in the coastal area would be expected as a result of canal stage lowering in other, interior parts of the study area.

Results from the other test runs show that lowering interior canal water levels by as much as 4 feet (1.2 metres) would result in some salt-water intrusion for either land development scheme. Salt-water intrusion is dependent on the location, and amount of water withdrawn, from well fields.

# INTRODUCTION

A large scale change in land use from agriculture to residential in the sandy flatlands area of southeast Palm Beach County, Florida, is causing the LWDD (Lake Worth Drainage District) to review their water management practices. Historically, canal water levels were maintained high for agricultural purposes. Now developers are submitting proposals to lower these interior canal water levels (see fig. 1) which in turn will provide some flood protection and lower the costs of development. Before the Lake Worth Drainage District or the CSFFCD (Central and Southern Florida Flood Control District) would give consideration to these proposals, these agencies entered into a cooperative program with the U.S. Geological Survey to determine whether large-scale lowering of water levels in canals would cause salt water to intrude farther inland into the aquifer. This determination is very important because several municipal well fields, each producing in excess of $5x10^6$ gal/day or 19,000 $m^3$/day, are within a few thousand feet of the Intracoastal Waterway -- the source of salt water -- and are vulnerable to this threat.

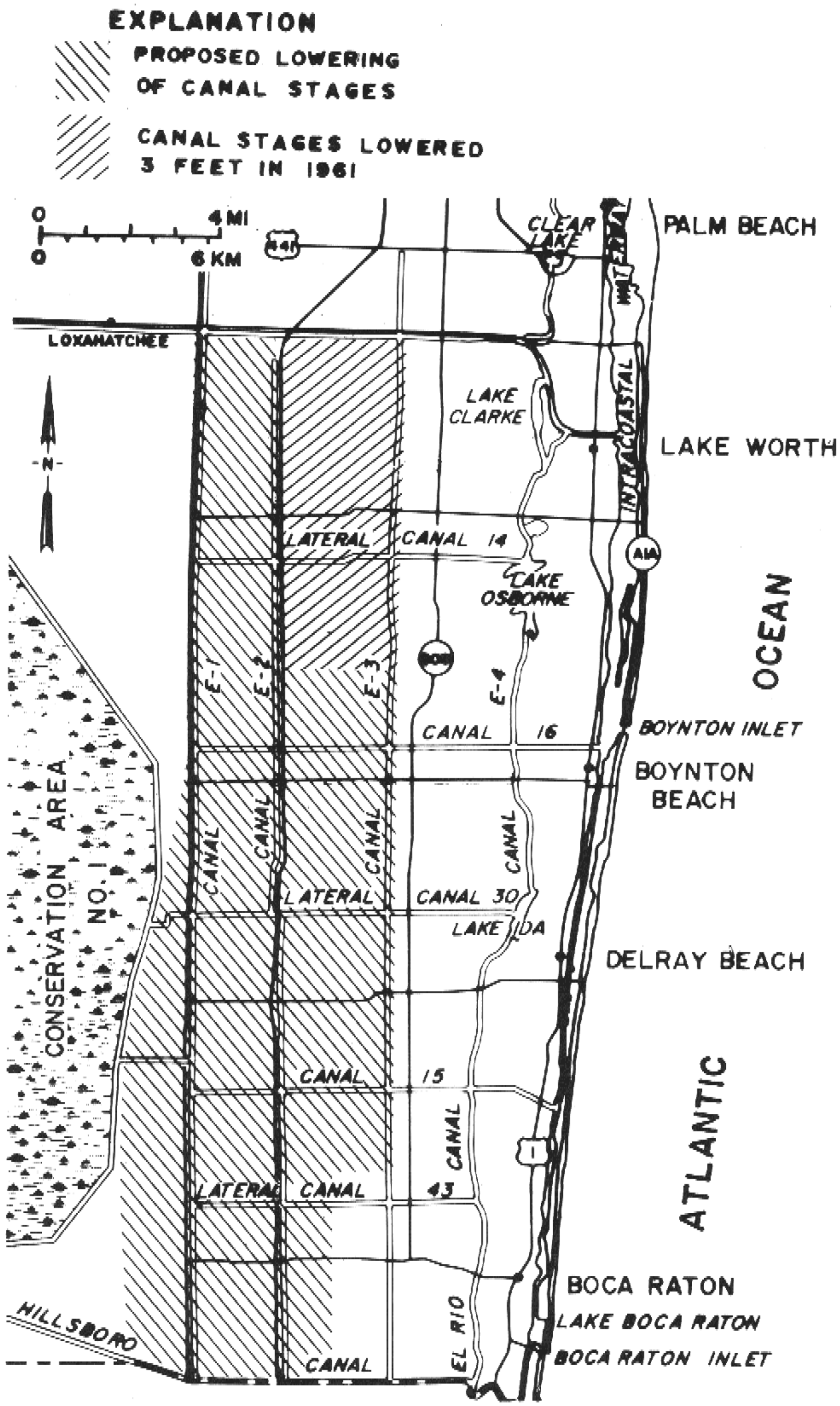


Figure 1.--Area proposed for lowering of canal water levels.

## Purpose and Scope

The purpose of this investigation was to determine the extent of salt-water intrusion that could be attributed to lowering interior canal water levels both with and without land development. The report does not evaluate nor predict the present or future hydrologic conditions of a particular well or group of wells nor does it recommend specific water management practices or well-field design criteria. However, it does provide some information on the effects of the location and size of new well fields on salt-water intrusion.

## Acknowledgments

The author thanks James H. Ransom, Manager, LWDD, for hydrologic information on the surface-water system in the project area; George F. Pinder, formerly with the U.S. Geological Survey, Reston, Virginia, and now associated with Princeton University, for his comments and guidance in designing the digital model and computing salt-water intrusion. The consultation and review by several staff members of the CSFFCD, and William E. Hill, P.E., consulting engineer for LWDD, is also greatly appreciated.

## General Features

The study covered the mainland area of southeast Palm Beach County as shown in figure 2. Almost all of the area between E-4 canal and Conservation Area No. 1 is extensively laced with canals containing control structures and pumps. In this area the land surface is generally between 15 and 20 ft (5 and 6 m) above msl (mean sea level) and the water table is within a few feet of the land surface. Between E-4 canal and the Intracoastal Waterway is an area generally known as the coastal ridge. Here, land surface ranges in elevation between 5 and 30 ft (2 and 9 m) above msl. Only major east-west canals cross the coastal ridge.

For purposes of this report, the interior is considered to be the area west of E-4 canal; the coastal area is considered to be the area east of this canal.

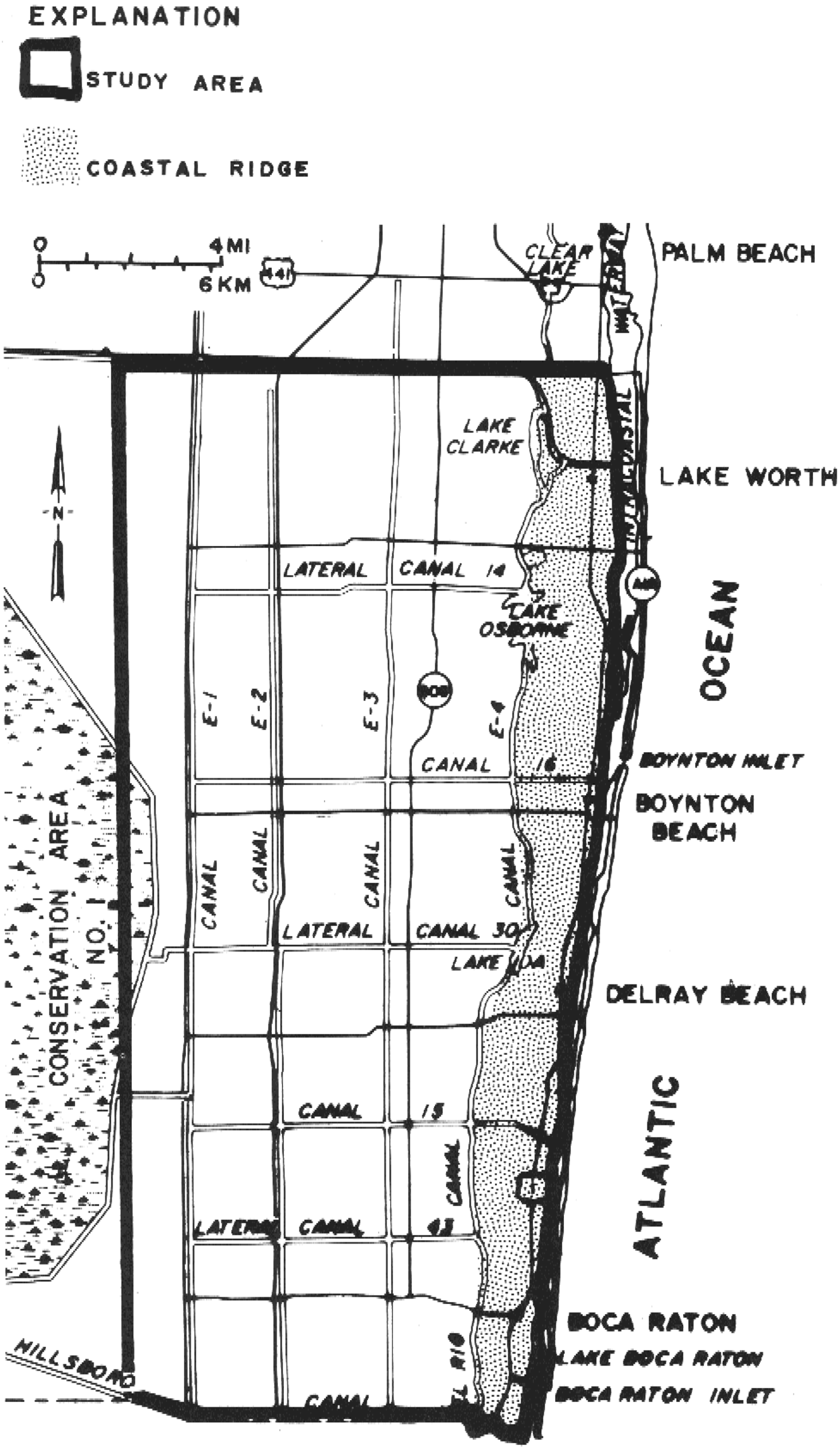


Figure 2.--Location of the study area and the coastal ridge in southeast Palm Beach County.

# DESCRIPTION OF THE GROUND-WATER SYSTEM

The ground-water system in southeast Palm Beach County is complex and has many local variations (Land, Rodis, and Schneider, 1973; Schroeder, Milliken, and Love, 1954; and Parker, Ferguson, Love and others, 1955). But generally the system includes a major water producing zone 40 to 90 ft (12 to 27 m) thick and beginning 40 to 100 ft (12 to 30 m) below land surface. This zone is composed of layers of sandstone, and limestone with mixtures of sand and broken shell that in places are cemented. The rock layers are generally solution riddled and therefore are highly permeable. The sediments above this major producing zone are composed mostly of sand in a wide range of sizes, thin beds of sandstone, and limestone all of which are relatively low in hydraulic conductivity. In most places a sandy muck bed, less than 5 ft (1.5 m) thick, is near the surface. The major producing zone is underlain by several hundred feet of almost impermeable marl, rock, and clay.

A ground-water system of this nature is referred to as a leaky artesian system in that water levels in the highly permeable (major water producing) zone would rise into the partly effective confining bed. For this report, "head" denotes the potentiometric surface of the zone having the high hydraulic conductivity and "water table" denotes the potentiometric surface in the overlying fine sands or confining bed.

The ground-water system and the canals are in hydraulic connection because the canals have been cut below the water table and into the leaky confining bed. Therefore, the canal stage reflects the general level of the water table in the vicinity of the canal. In other words, the water table is controlled by the canal's stage. A controlled canal is, for this report, considered to be a primary canal; an uncontrolled canal is considered to be a secondary canal. Figure 3 shows the present (1974) scheduled or planned elevation of the canal water levels in part of the primary canal network. In the past these water levels were generally maintained within half a foot of the scheduled elevation.

To illustrate the relation between water movement, water table, and head, a conceptual model of a small part of a typical section through the gound-water system under consideration is given in figure 4. The water table is assumed to fluctuate in response to rain, evapotranspiration, and leakage into or from the major producing zone. Horizontal ground-water movement is assumed to be negligible in the confining bed. It is assumed that rainfall follows a seasonal pattern and that evapotranspiration rate is directly proportional to the distance between the land surface and the water table. The rate of leakage is directly proportional to the difference between the elevations of the water table and the head in the major producing zone for a given thickness and

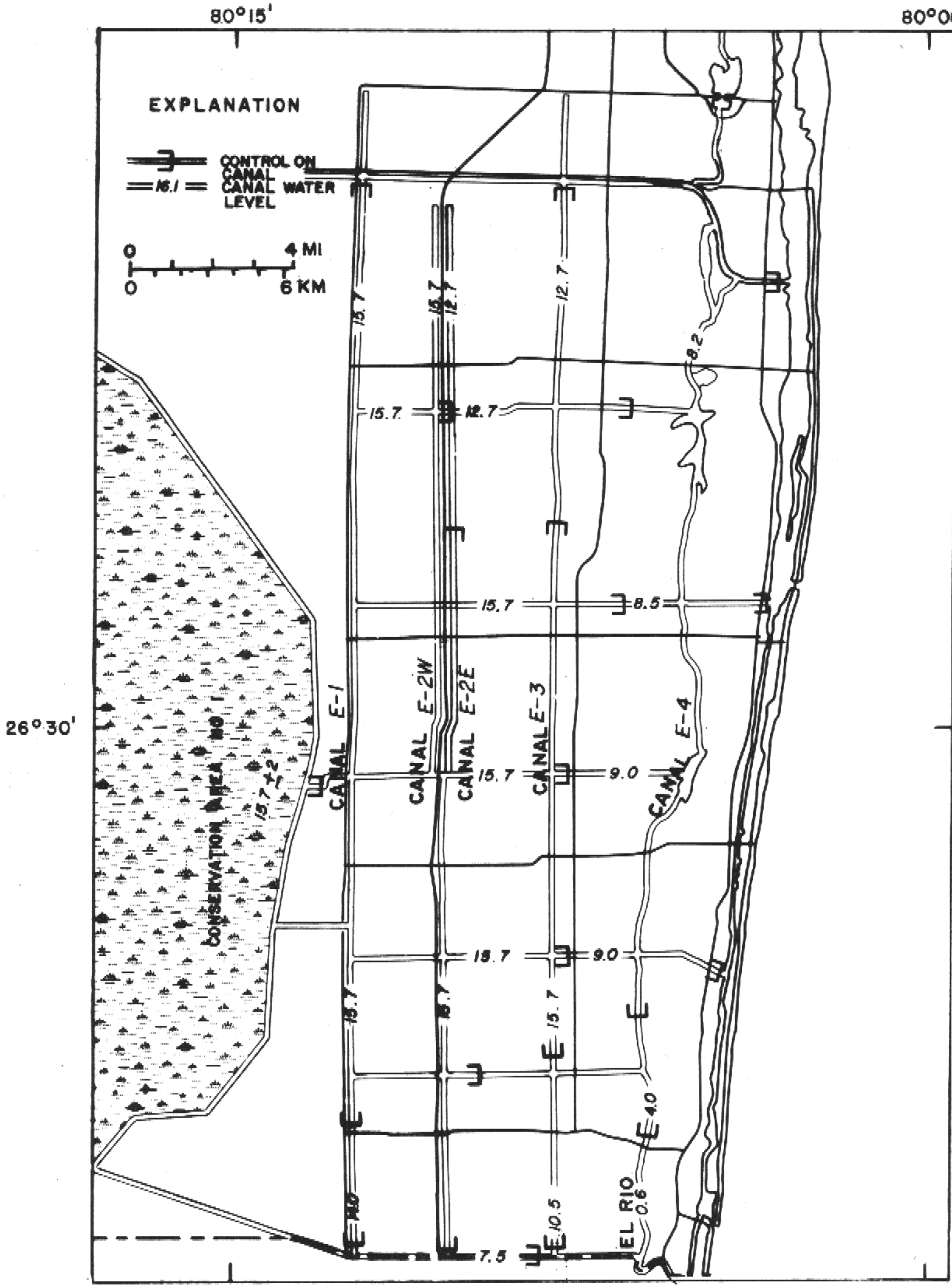


Figure 3.--Present (1974) scheduled water levels in part of the primary canal network.

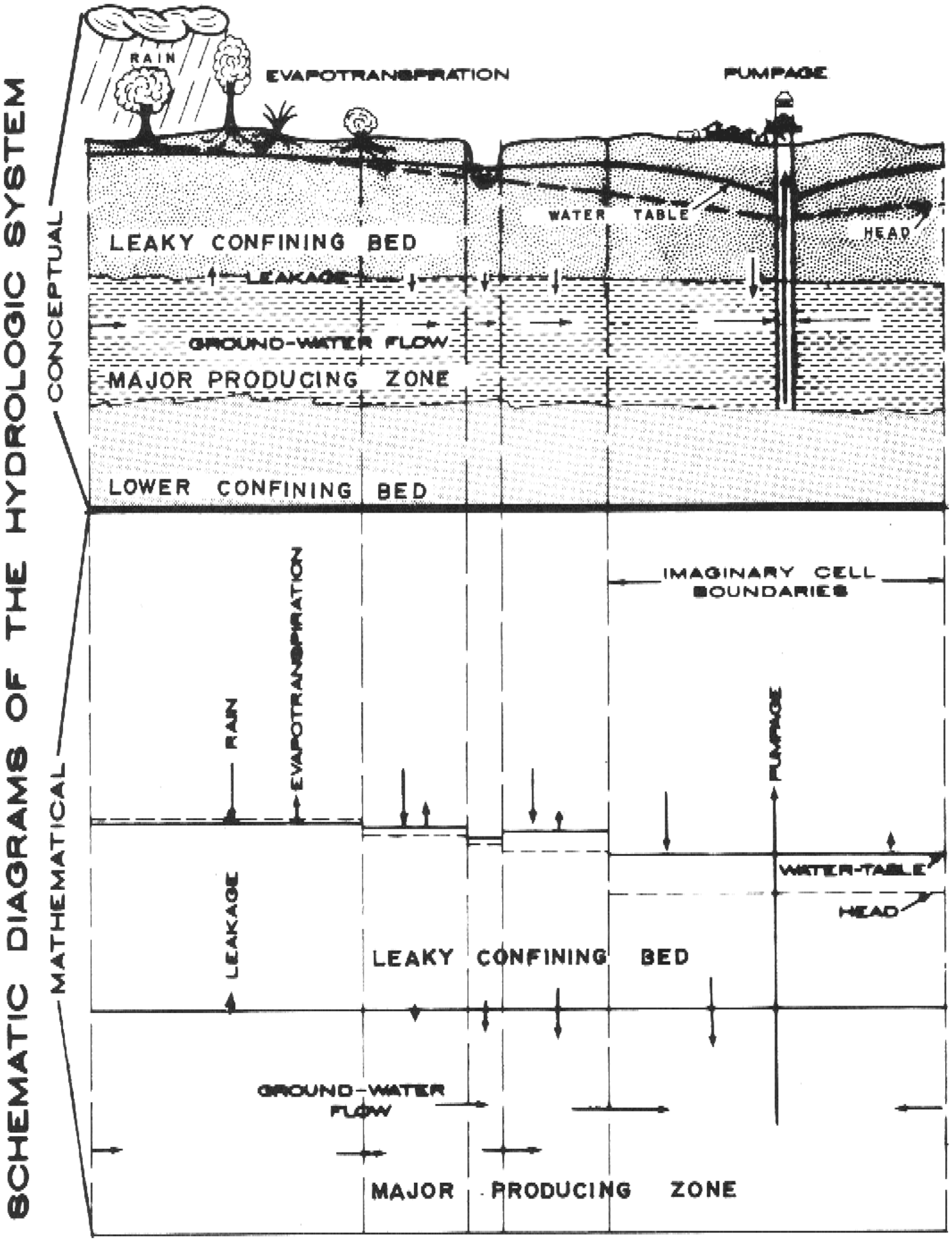


Figure 4.--Conceptual and mathematical schematic diagram of a partial and generalized hydrologic system. Length of arrows represent relative magnitude of flux.

hydraulic conductivity of the confining bed. In the immediate vicinity of a primary canal, the water table is assumed to have the same elevation as the fixed (scheduled) elevation of that canal's stage. To maintain the constant levels, water will most likely have to be imported or exported to balance losses or gains from the canals. The head in the major producing zone responds to horizontal ground-water movement, leakage into or from the upper confining bed, and pumpage. Leakage into or from the lower confining bed is considered negligible. Under stable and unstressed conditions the water table and the head elevations are very nearly the same.

An illustration of the digital (mathematical) model which corresponds to the conceptual model previously discussed is also given in figure 4. The model requires that the hydrologic system be uniform within each grid or cell. As a result the water table and head are constant within a cell; therefore, they step abruptly to the adjoining cell. The actual grid being modeled extends in all four horizontal directions from this generalized section.

In the study area the transmissivity at the shallow ground-water system is generally uniform north to south in the area west of the Canal E-4 system. The transmissivity, hydraulic conductivities, storage coefficient and specific yield values are derived from published reports (Land, Rodis, and Schneider, 1973; and McCoy and Hardee, 1972) and estimated from lithology and specific capacity tests. The highest transmissivity used is 500,000 (gal/d)/ft or 6,200 $m^2/d$ and occurs between Canals E-2 and E-3. The transmissivities decrease to about 200,000 (gal/d)/ft (2,500 $m^2/d$) west of Canal E-1. Along the coastal ridge the transmissivity gradually decreases from 400,000 (gal/d)/ft (5,000 $m^2/d$) in the vicinity of Boca Raton to 75,000 (gal/d)/ft (930 $m^2/d$) in the vicinity of Lake Worth. A gradual transition in transmissivities occurs in the area between the coastal area and Canal E-3.

The effective hydraulic conductivity of the upper leaky confining bed is approximately 0.5 ft/d (0.15 m/d) in the area west of E-3 Canal and 5 ft/d (1.5 m/d) along the coastal ridge. A gradual transition occurs between these two areas.

A storage coefficient of 0.0001 was used for the major producing zone and the leaky confining bed. A specific yield of 0.2 was used for the surficial water-table aquifer.

This being the case, only narrow east-west strips were modelled. The Intracoastal Waterway on the east and the Conservation Area No. 1 to the west are extensive enough to be considered constant-head boundaries; that is, the elevations of water-table and head in the aquifers at those locations do not change.

# METHOD OF INVESTIGATION

## General Approach

The procedure used in this investigation was to select and intensively study three east-west test strips (fig. 5.) These test strips range in width from 2.0 to 3.3 mi (3.2 to 5.3 km). The southern boundaries of the test strips pass through the center of municipal well fields located in Lake Worth, Delray Beach, and Boca Raton. Two of the test strips extend from the Intracoastal Waterway to the Conservation Area No. 1; the third extends from the Intracoastal Waterway to a point 12 mi (19.3 km) inland.

The Lake Worth test strip passes through an area where interior canal water levels had been lowered 3 ft (1 m), from 15.7 to 12.7 ft, (4.8 to 3.9 m) in 1961. Since no historical data are available to determine whether this stage change did or did not cause salt-water intrusion, modeling techniques were used to make a prediction. This prediction was then used to assess the effects of lowering canal stages on salt-water intrusion in other parts of the study area. The procedure consisted of making two model runs and comparing the resulting head distributions. One model run simulated the change in canal water levels as they occurred and the other simulated conditions as if there had not been a change in water levels. Pumpage was increased to account for land development that occurred during the test period.

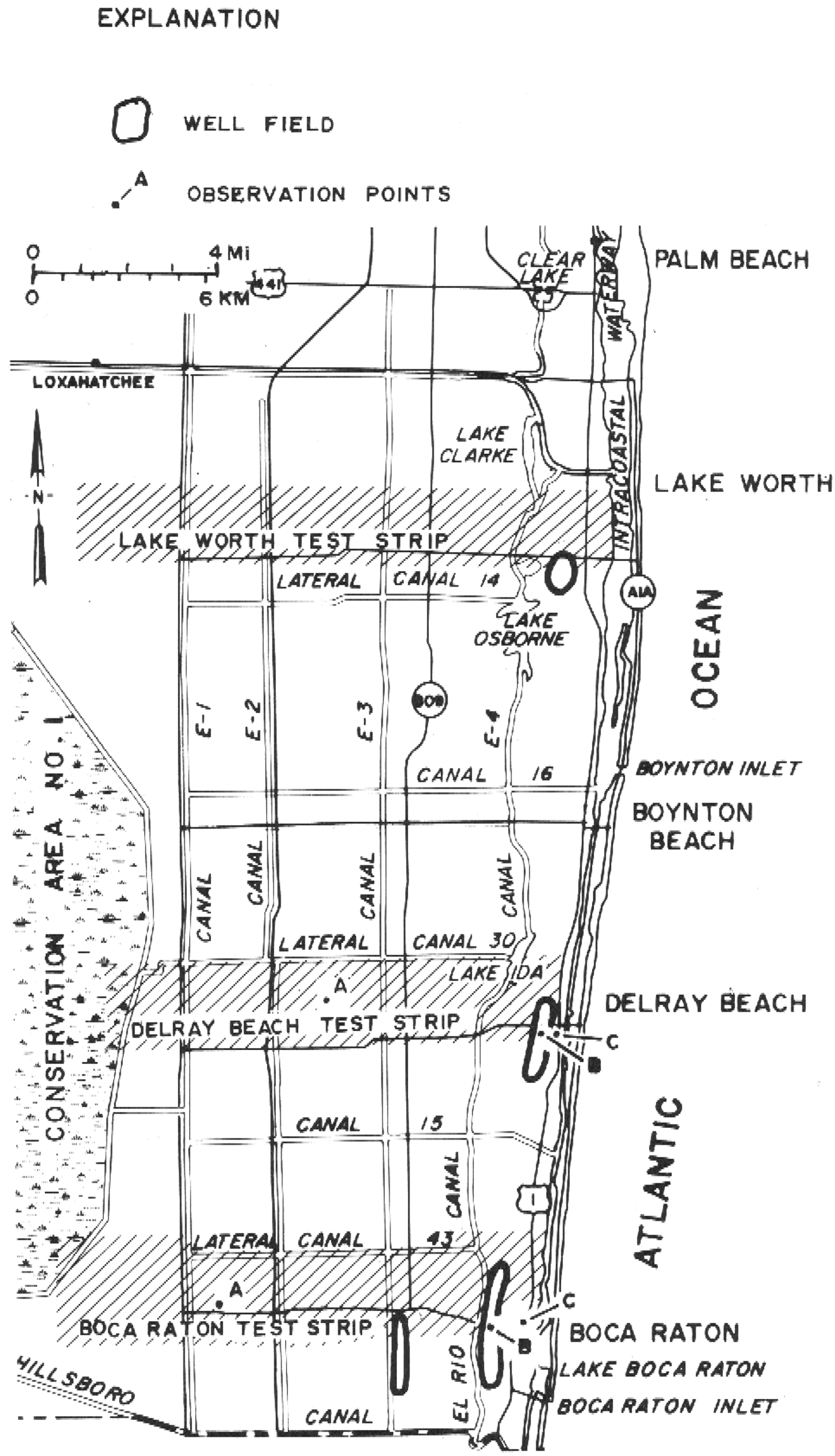


Figure 5.--Location of test strips and major well fields within the test strips.

The two test strips through Delray Beach and Boca Raton were modeled with the intent of predicting the effects of lowering canal water levels on salt-water intrusion for both the present stage of land development that is held constant and for an expansion of land development. The ground-water withdrawals were held constant in the first case and were increased to correspond to increased land development in the second case. The effects were predicted on the basis of comparing the resulting head distribution from model runs simulating a continuation of the present (1974) canal water levels with the resulting head distribution from model runs simulating the proposed canal water levels. The model runs were for a 12-year hypothetical period that began in 1974.

To simulate the present state of land development the annual withdrawal rate was held constant for the entire test period. To simulate an expansion of development, the annual withdrawal rate was increased in 1-year increments over a 9-year period and then held constant for 3 years. The maximum degree of development was considered to be the maximum population density suggested by a county land use plan (Palm Beach County Planning, Zoning and Building Department, 1972). Although development and the corresponding increase in withdrawal rates are not expected to be so rapid that the increase in withdrawal will reach a maximum by 1983, that increase reasonably represents the effects of land development on the hydrologic system.

## Technical Approach

The selected approach for determining the effects of lowering interior canal water levels on salt-water intrusion consists of two phases. The first phase simulates the ground-water system with a digital model capable of computing the head distribution that would result from an applied hydrologic stress. The second phase uses an analytical technique to compute the movement of the salt-water interface. The movement is dependent on the changes in the head along the Intracoastal Waterway which were computed by the digital model.

The digital model used in the first phase was developed and tested by the U.S. Geological Survey (Bredehoeft and Pinder, 1970; Trescott, Pinder and Jones, 1970). It provided a general procedure for predicting the response of a layered ground-water system to a pumping stress. The model was designed to simulate two-dimensional areal flow with an option for computing leakage from an adjacent aquifer for a third, vertical, dimension. To keep the original model as simple and economical as possible the potentiometric surface in the adjacent aquifer[1/] was held constant and the recharge rate was fixed at one value throughout the model run. To more accurately simulate the ground-water system being investigated, this model was modified to allow the water table to respond to seasonal rainfall, evapotranspiration, and leakage into and from the major producing



1/ The computer program has the capability of simulating either artesian or water-table conditions in the adjacent aquifer. In this report the adjacent aquifer is considered to be a water-table aquifer.

zone. Provisions were also made to vary pumping on a seasonal basis and to maintain water levels in canals at preselected constant values.

The data requirements for the digital model include the initial water table and head elevations, storage coefficients for both zones, hydraulic conductivity and thickness of the confining bed, transmissivity of the main aquifer and land elevations at each of 700 to 1,000 cells or nodes for each test strip. Average values for recharge, evapotranspiration and pumpage were also required. To make the application of modeling techniques feasible, the fitting procedure is used. This procedure uses the data base that is available and varies the poorly defined data until the computed water table and head at selected points matches the observed water table and head for the hydrologic event being simulated.

The second phase used an analytical technique for predicting the movement of the salt-water interface in coastal aquifers (Bear and Dagen, 1964, equation 30). This movement is computed on the change in the flow rate of ground water moving past the toe of the salt-water interface. The ground-water flow is computed by using the head distribution values from the digital model runs and Darcy's Law. The head distribution values are used to compute the head gradient at the toe of the interface. Multiplying head gradient by the transmissivity of the aquifer at that point yields ground-water flow at the toe of the interface.

## Assumptions Used in Digital Model Simulation

Following are the major assumptions used in setting up the digital model:

1) The hydrologic system within and adjacent to the test strips is adequately described by the model and the grid network;

2) The hydrologic system and its stresses on the north and south sides of the test strips are the same as in the test strip;

3) Water levels in Conservation Area No. 1 and the Intracoastal Waterway are constant and form constant-head boundaries;

4) Thirty-day time steps are sufficiently long for use in long-term model simulation; that is, steady state flow through the confined bed is established.

5) The timing and magnitude of the average seasonal rainfall pattern is satisfactorily represented by the sine curve shown in figure 6. End-of-month ratios were used;

6) Annual distribution of pumpage (fig. 6) is adequately represented using data from Boca Raton for the 5-year period from 1967-71 (Land, Rodis, and Schneider, 1973). End-of-month ratios were used;

7) Fifty percent of the average annual rainfall of 61.8 in (1,570 mm) is recharge to the ground-water system;

8) Evapotranspiration rate from the aquifer is equal to pan evaporation and is adequately described by a straight line function of depth to the water table; the rate varies from zero when the water

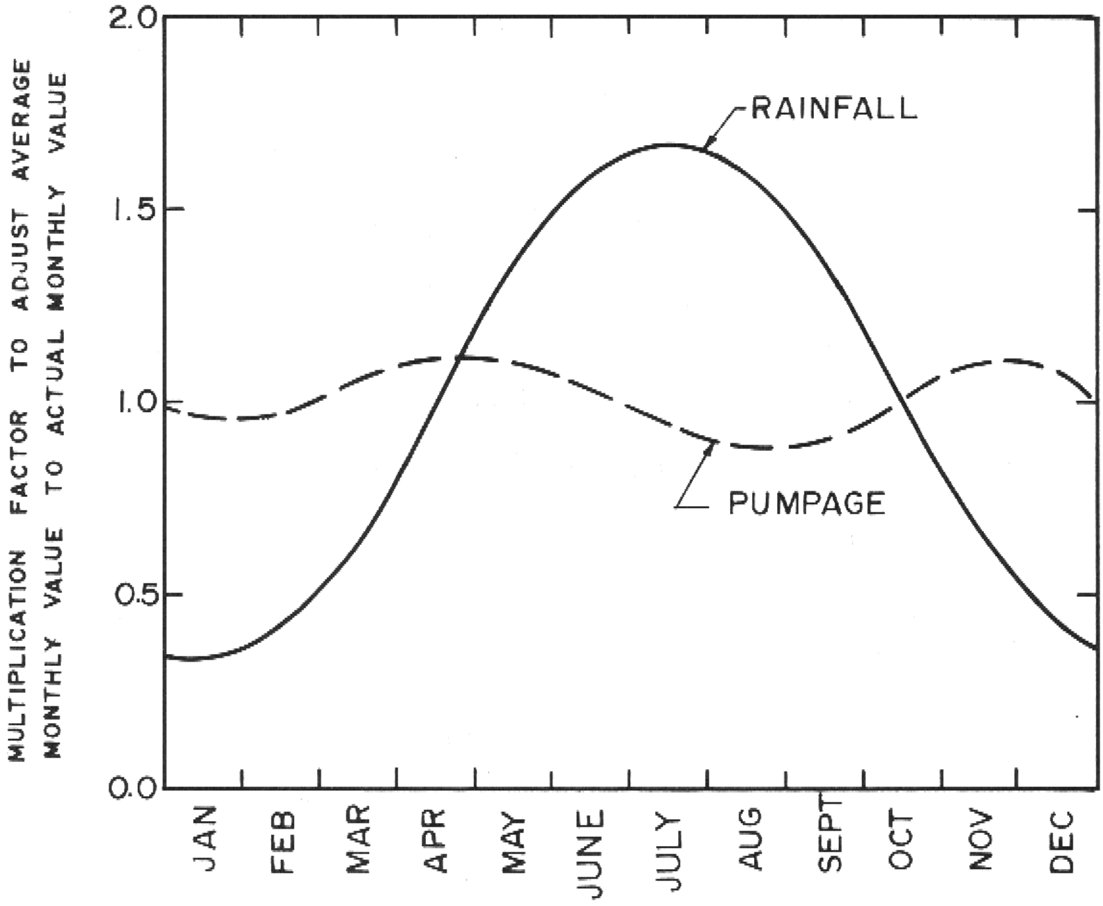


Figure 6.--Annual distribution of rainfall and pumpage used in digital model. (Rainfall from National Weather Service records for West Palm Beach, Fla. and pumpage from Boca Raton, Fla.

table is 7.5 ft (2.3 m) below land surface to 50 in (1270 mm) when the water table is at land surface;

9) Water levels in canals are maintained at scheduled or preselected levels;

10) The Palm Beach County Land-Use Plan, (Palm Beach County Planning, Zoning and Building Department, 1972), will be utilized and development will reach maximum density limits over a 9-year period;

11) Average occupancy per dwelling is 2.6 persons;

12) Consumptive daily water use (total water lost from the ground-water system) is 190 gallons (0.72 $m^3$) per person for estate and low housing densities, 175 gallons (0.66 $m^3$) for medium densities and 145 gallons (0.55 $m^3$) for high densities. Consumptive use for golf courses is 2 ft (0.6 m) per year over the irrigated area. Industrial and institutional consumptive water use is at the low density rate;

13) Land development does not affect aquifer recharge rates; and

14) Errors resulting from poorly defined data, or from averaging of data do not affect the comparability of the results when the same data are used for all model runs.

The only annual variables used in the model are canal water levels and pumpage; the total annual rainfall or its seasonal distribution are not changed from year to year for the purpose of simulating wet and dry years. In reality, development will most likely cause local changes in recharge; it will also affect the number and configuration of canals and lakes. No attempt was made to incorporate these changes into the test procedure.

# DESCRIPTION OF TESTS AND RESULTS

## Current (1974) Level of Land Development

The hydrologic data base for the study area consist of two recording observation wells in the vicinity of Lake Worth with approximately 20 years of record. A third recording observation well is in the vicinity of Boca Raton and has about 8 years of record. The data base also consisted of generalized water table maps for recent wet and dry seasons. Several water table maps for the ends of the wet and dry seasons were also available for the vicinity of Boca Raton's coastal well field. Keeping in mind the generalizations of the model as well as the specific and extreme hydrologic events available for fitting, a reasonably good calibration was obtained. In general, for years of approximately average rainfall, the computed water levels were within a half foot of observed water levels. In no case, did any unreasonable changes of transmissivity and storage coefficient values have to be made to obtain the selected calibration.

## Lake Worth Test Strip

In 1961, the stage in a section of the LWDD's canal system was lowered 3 ft (1 m) (fig. 2), from 15.7 ft (4.8 m) to 12.7 ft (3.9 m) above mean sea level. This stage has been maintained since that time. A 2.0-mi (3.2 km)-wide test strip, passing through the northern half of the Lake Worth well field, was selected to determine whether the 3-ft (1 m) decline in stage has, by itself, produced hydrologic conditions along the coast that would induce salt-water intrusion. For a location of the canal system in the Lake Worth test strip, see figure 7. During this 13-year span the hydrologic conditions have been substantially altered by a large increase in the withdrawal of fresh-water from the shallow ground-water system. Field data are not available to determine whether or not salt-water has moved in this test strip during this period.

To determine whether the stage decline produced salt-water intrusion, two simulation runs were made by using the digital model. Both runs provided the head distribution in the major producing zone at the end of 1973. For one of the runs, the canal stage was held at 15.7 ft (4.8 m) and for the other, 12.7 ft (3.9 m), 3 ft (1 m) lower, in that part of the strip shown in figure 1. In both runs, pumpage was increased by yearly increments to simulate the actual increase in water demand since 1961. This procedure isolates the effects of stage decline.

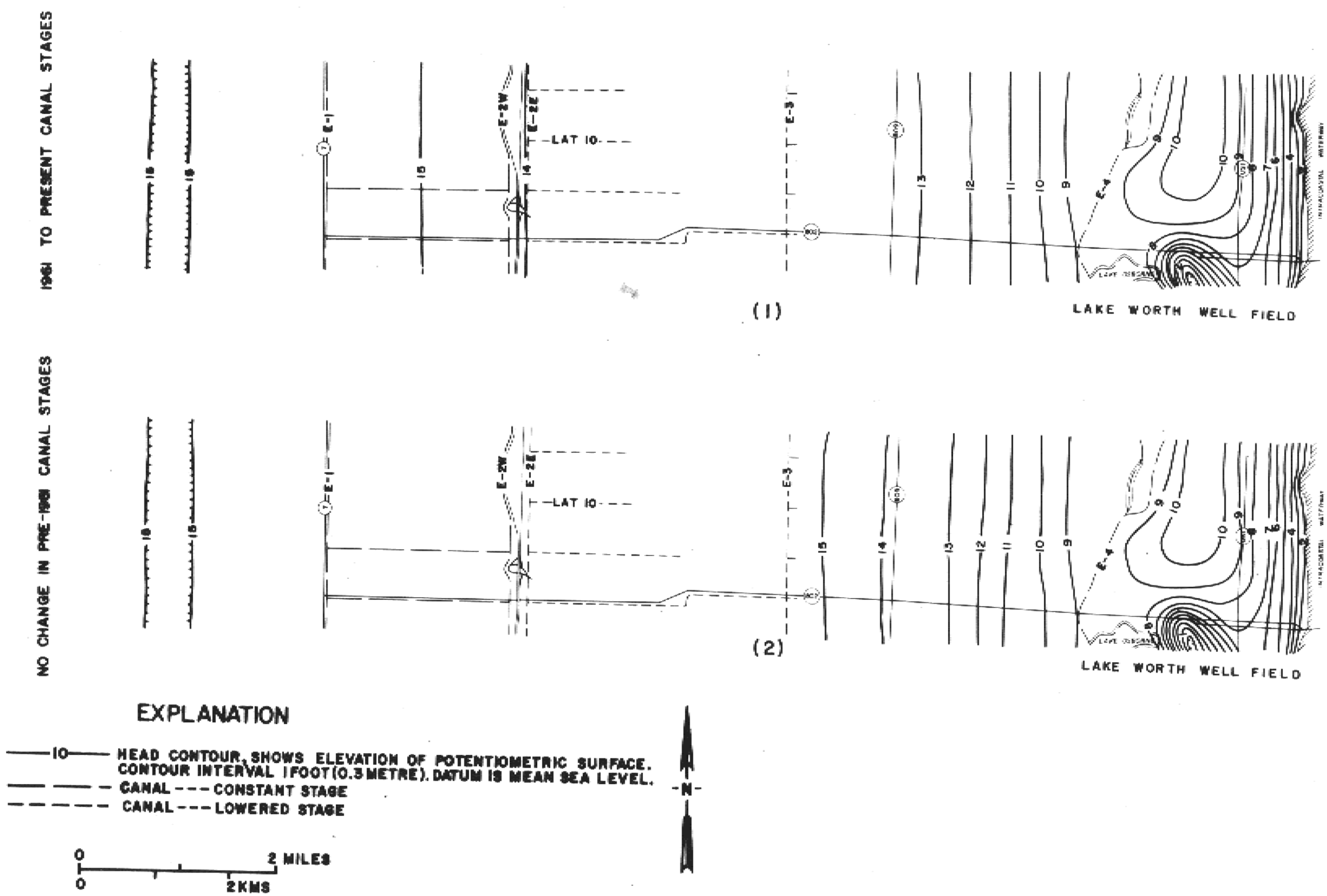


Figure 7.--Contours of the aquifer head for the Lake Worth test strip at the end of a 12-year test period (1961-1973) for 1) canal water level changes that actually occurred, and 2) a hypothetical no change in water levels.

As figure 7 shows, the head distribution in the coastal ridge in the major producing zone was the same for both runs. Therefore, it is concluded that lowering the canal stage did not alter the hydrologic conditions along the coast which would induce salt-water intrusion.

## Delray Beach and Boca Raton Test Strips

The Lake Worth test strip was selected and designed to predict, by digital modeling techniques, the effects of a decline in canal stage on salt-water intrusion where the interior canal water-levels had already been lowered. The Delray Beach and Boca Raton test strips were modeled with the intent of predicting how much, if any, salt-water intrusion would occur if water levels in selected interior canals were lowered 2 or 4 ft (0.6 and 1.2 m) in an area where historic canal stages have not been changed. The canals in the two test strips which are proposed to be lowered are shown by short dashed lines in figure 8. Also shown on these maps is the current estimated mean daily pumpage. The group of rather large pumping rates near the Intracoastal Waterway denotes the location of municipal well fields. For the entire Delray Beach test strip the present (1974) pumpage was estimated to be 478,000 $ft^3/d$ (13,500 $m^3/d$) or $3.6x10^6$ gal/d. Similar values for the Boca Raton test strip are 1,150,000 $ft^3/d$ (32,600 $m^3/d$) or $8.6x10^6$ gal/d.

The first step in the analysis is to make model runs with no change in canal water levels. For clarity such runs are called index runs. The head distribution resulting from these runs are the basis of comparison for model runs having the change in canal water levels. The resulting head (potentiometric surface of the major producing zone) distributions for the index runs are illustrated by contours in figure 9. This figure shows the head distribution for December 31


Figure 8.--Estimated distribution of present (1974) daily pumpage for the Delray Beach and Boca Raton test strips. A group of large values indicates location of a well field.

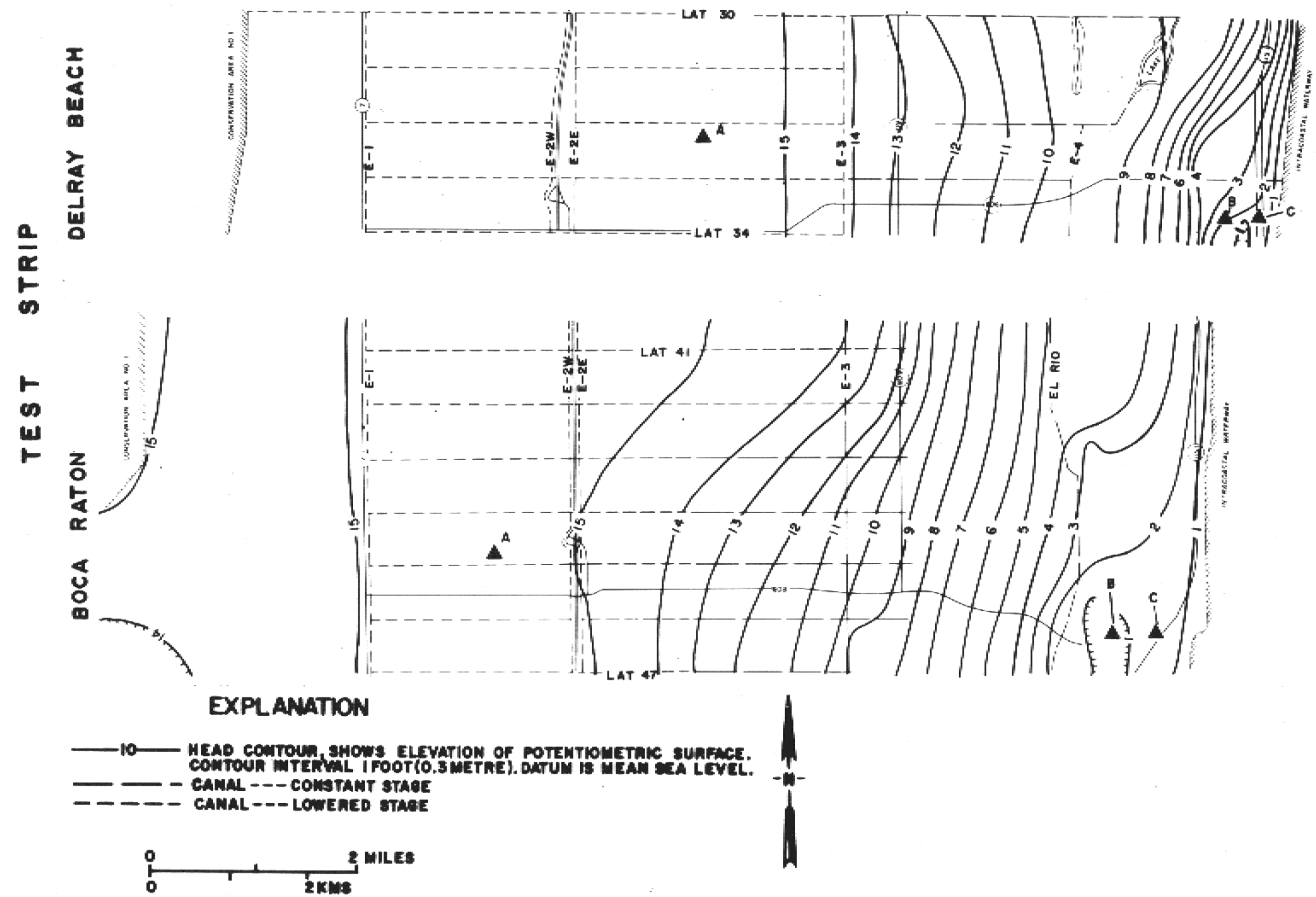


Figure 9.--Contours of the aquifer head in Delray Beach and Boca Raton test strips at the end of the 12-year test period for the index model run which had no change in interior canal water levels.

when conditions are approximately average for the year.

The second step is to make test (model) runs for the 2- and 4-ft (0.6-and 1.2-m) lowering of canal water levels in the selected network of canals. The resulting head distribution is shown in figure 10 for the Delray Beach test strip and in figure 11 for the Boca Raton test strip.

A comparison of the test runs for the Delray Beach test strip with the index run (fig. 9 with fig. 10) indicates that there is no difference in the head elevations east of Canal E-4. This analysis indicates that lowering canal water levels as much as 4 ft (1.2 m) would have no influence on the aquifer head along the coastal ridge. Since salt-water intrusion is directly related to the head of fresh water in the aquifer, no salt-water intrusion would result solely from lowering the selected interior canal water levels.

A comparison of the two test runs for the Boca Raton test strip with the index run (fig. 9 with fig. 11) indicates that only a minimal lowering of the aquifer head in the coastal area resulted. The computer printouts show that the drawdown was less than 0.05 ft (0.02 m). The inland constant-head source (Conservation Area No. 1) is relatively farther inland in the Boca Raton test strip. That, along with the higher transmissivities in the Boca Raton area and the lower stage in the Canal E-4 system near Boca Raton, appears to be the main reason for a detectable drawdown in the coastal area of Boca Raton. Upon applying

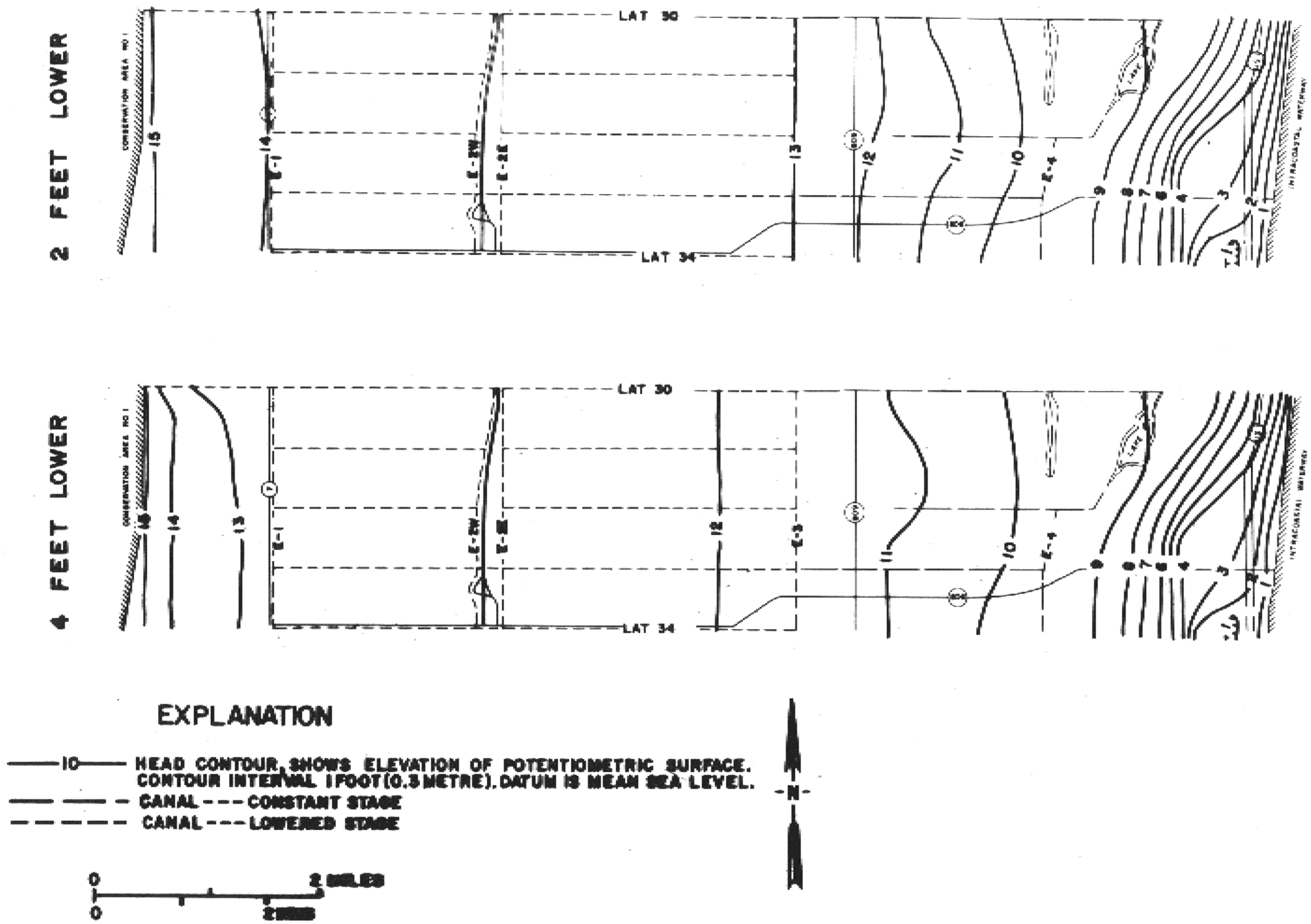


Figure 10.--Contours of the aquifer head for the Delray Beach test strip at the end of the 12-year test period that resulted from lowering interior canal water levels 2 and 4 feet. The current (1974) pumpage was held constant.

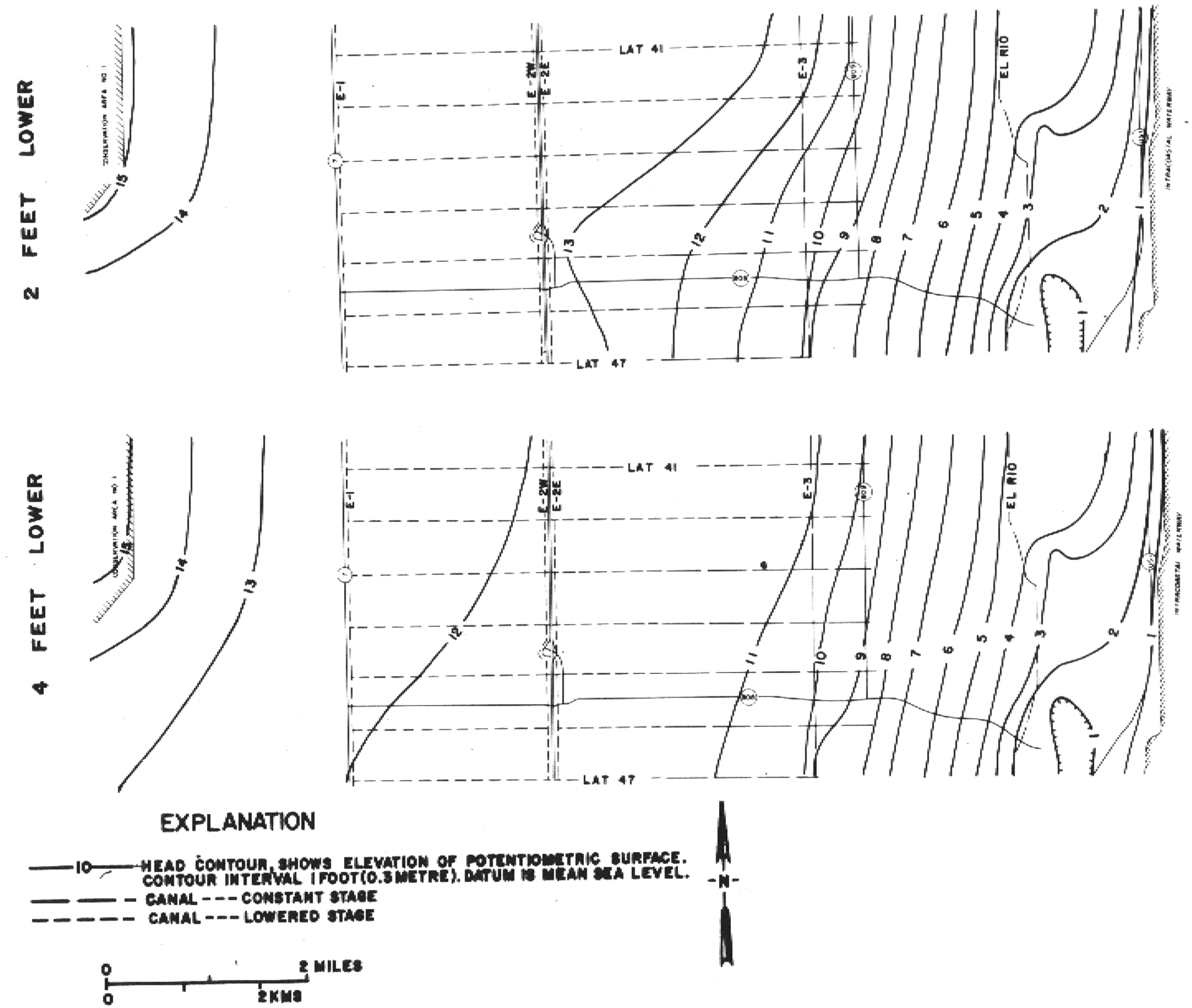


Figure 11.--Contours of the aquifer head for the Boca Raton test strip at the end of the 12-year test period that resulted from lowering interior canal water levels 2 and 4 feet. The current (1974) pumpage was held constant.

the analytical technique for computing salt-water intrusion, it was found that the amount of intrusion would not constitute a threat to the coastal well fields.

In summary, the results indicate that leakage from the El Rio Canal, E-4 Canal, and Lake Ida, combined with recharge from rainfall and the position of the interior canals between the Conservation Area and the coast were sufficiently large to eliminate, or very nearly eliminate, the effects of lowering the water levels in the selected interior canals on salt-water intrusion.

## After Full Land Development

The second phase of the investigation was to determine the effects of lowering interior canal water levels 2 or 4 ft (0.6 and 1.2 m) on salt-water intrusion that would occur with an expansion of land development. In reality this is the event that is most likely to occur. The test procedure, as explained earlier, is to gradually increase pumpage over a 9-year period, simulating land development, and to hold this pumpage constant for an additional 3 years. The estimated final distribution of pumpage after full land development is shown in figure 12. The estimated initial pumping rate is equal to the current (1974) pumpage and is shown in figure 8. Pumpage in the intermediate years is very generally increased linearly. All the actual daily pumpage is adjusted for seasonal effects by a multiplication factor and the average daily value. The final pumpage for the Delray Beach test strip is 3,560,000 $ft^3/d$ (100,800 $m^3/d$) or $26.7 \times 10^6$ gal/d. The final pumpage for the Boca Raton test strip is estimated to be 4,550,000 $ft^3/d$ (127,000 $m^3/d$) or $34 \times 10^6$ gal/d.

Again, the first step in the analysis is to make model runs with no change (index runs) in the interior canal water levels but with an increase in pumping rate from year to year. The resulting head distribution is illustrated by contours in figure 13. Again these contours represent the December 31 hydrologic conditions.

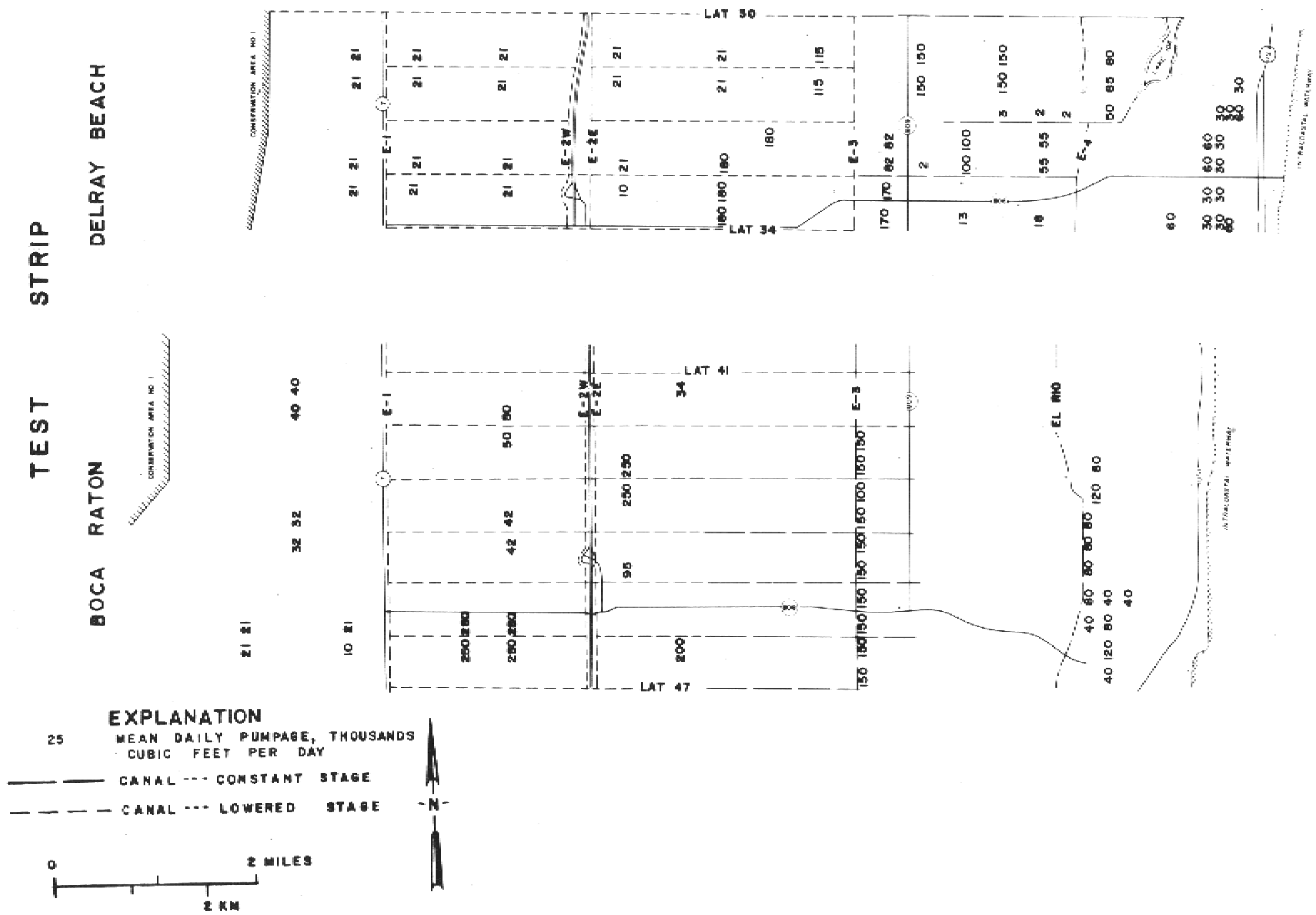


Figure 12.--Estimated distribution of pumpage after the land has been fully developed, Delray Beach and Boca Raton test strips. A group of large values indicates the location of a well field.

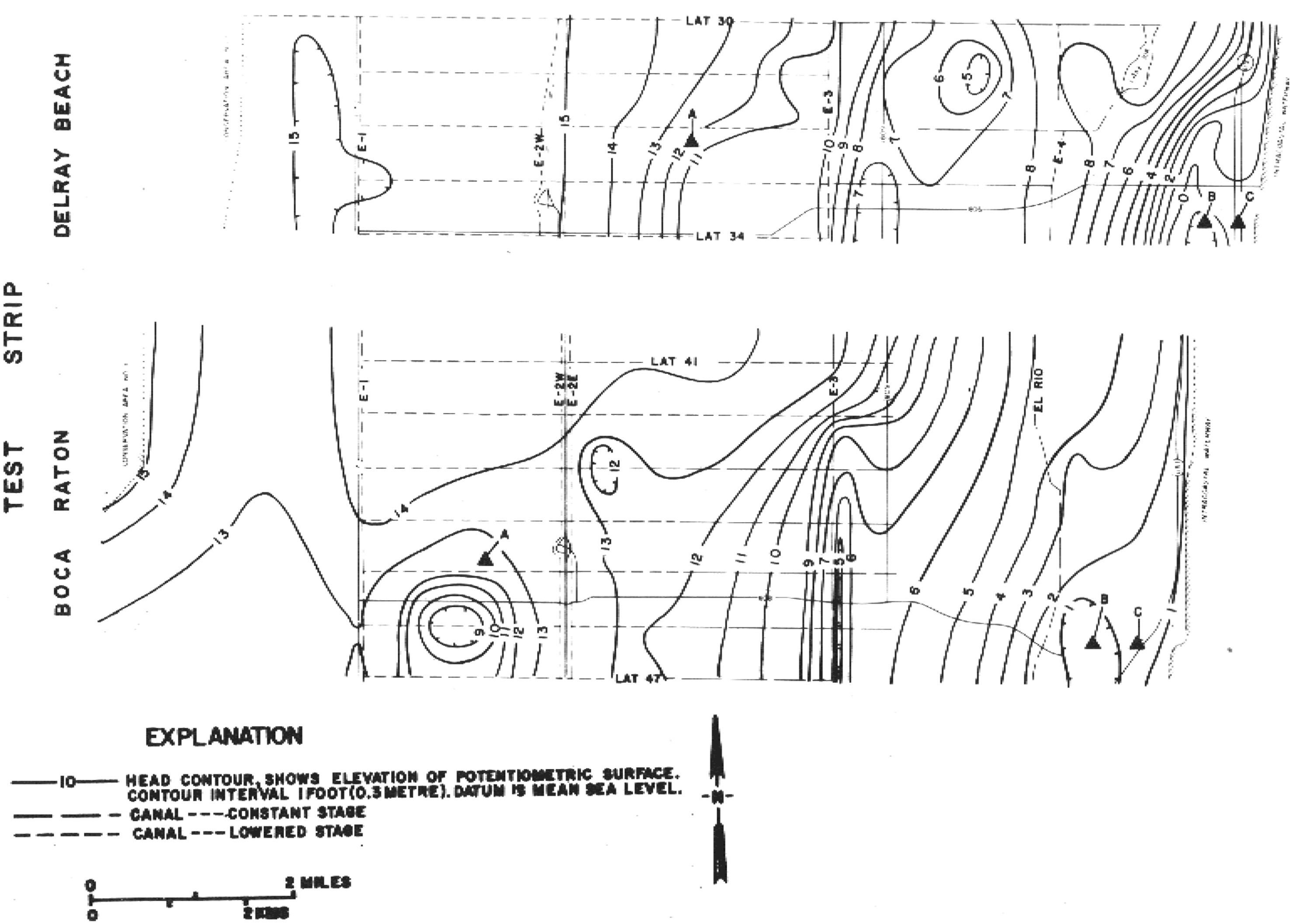


Figure 13.--Contours of the aquifer head that resulted from land development, Delray Beach and Boca Raton test strips. These are index model runs that have no change in interior canal water levels.

The second step is to make test runs for the identical pumpage used in the index run but for lower interior canal water levels. The resulting head distribution for a 2- and 4-ft (0.6- and 1.2-m) change is shown in figures 14 and 15 for the test strips through Delray Beach and Boca Raton, respectively. Again, these results show that the head in the coastal area of the Delray Beach area under full-development pumpage is not additionally affected by declines of as much as 4 ft (1.2 m) in interior canal water levels. The additional effects for the Boca Raton test strip are again so small (less than 0.05 ft or 0.02 m) that they must be determined from computer printouts.

The conclusion is that lowering the selected canal water levels in the interior would not contribute significantly to additional salt-water intrusion in the coastal area.

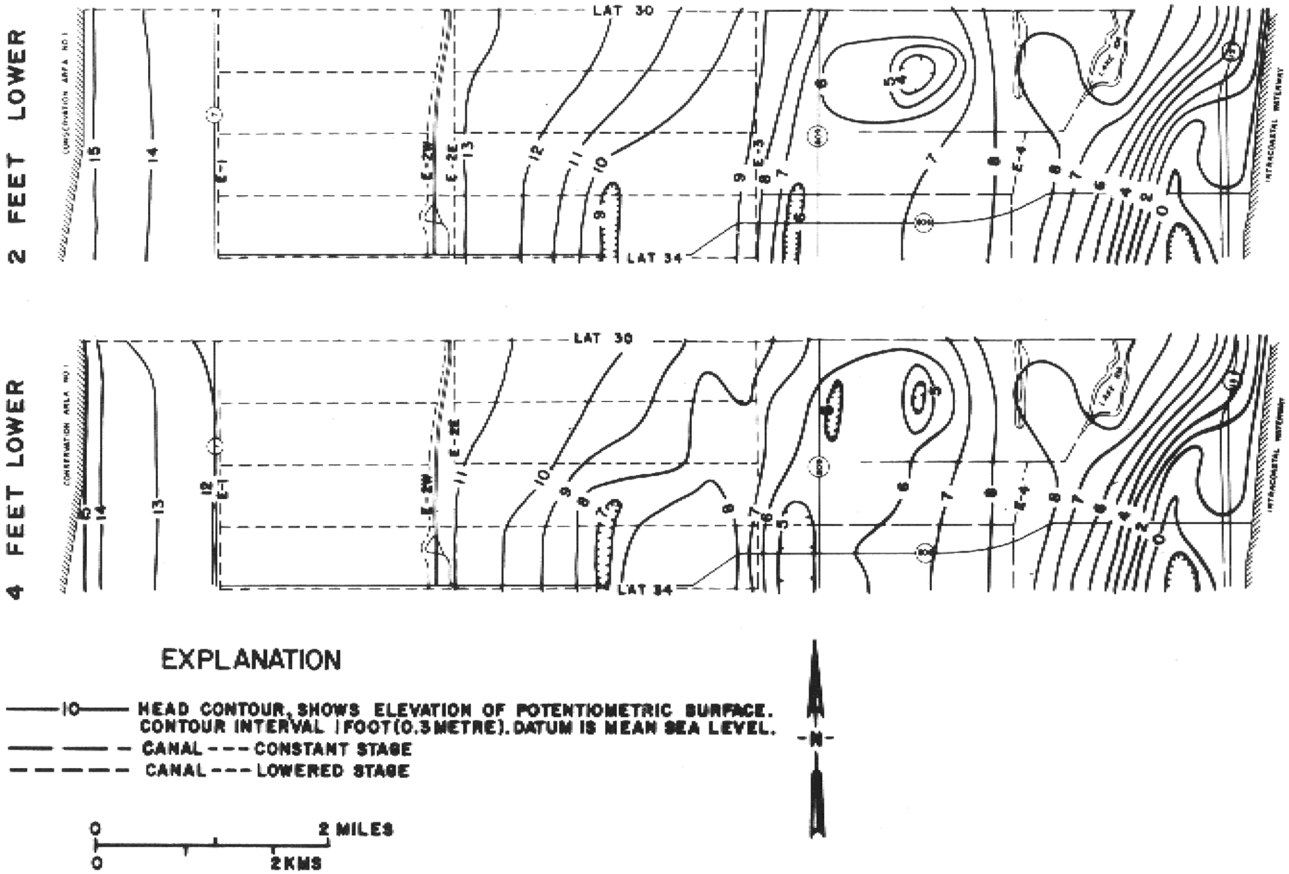


Figure 14.--Contours of the aquifer head for the Delray Beach test strip that resulted from land development and lowering interior canal water levels 2 and 4 feet.

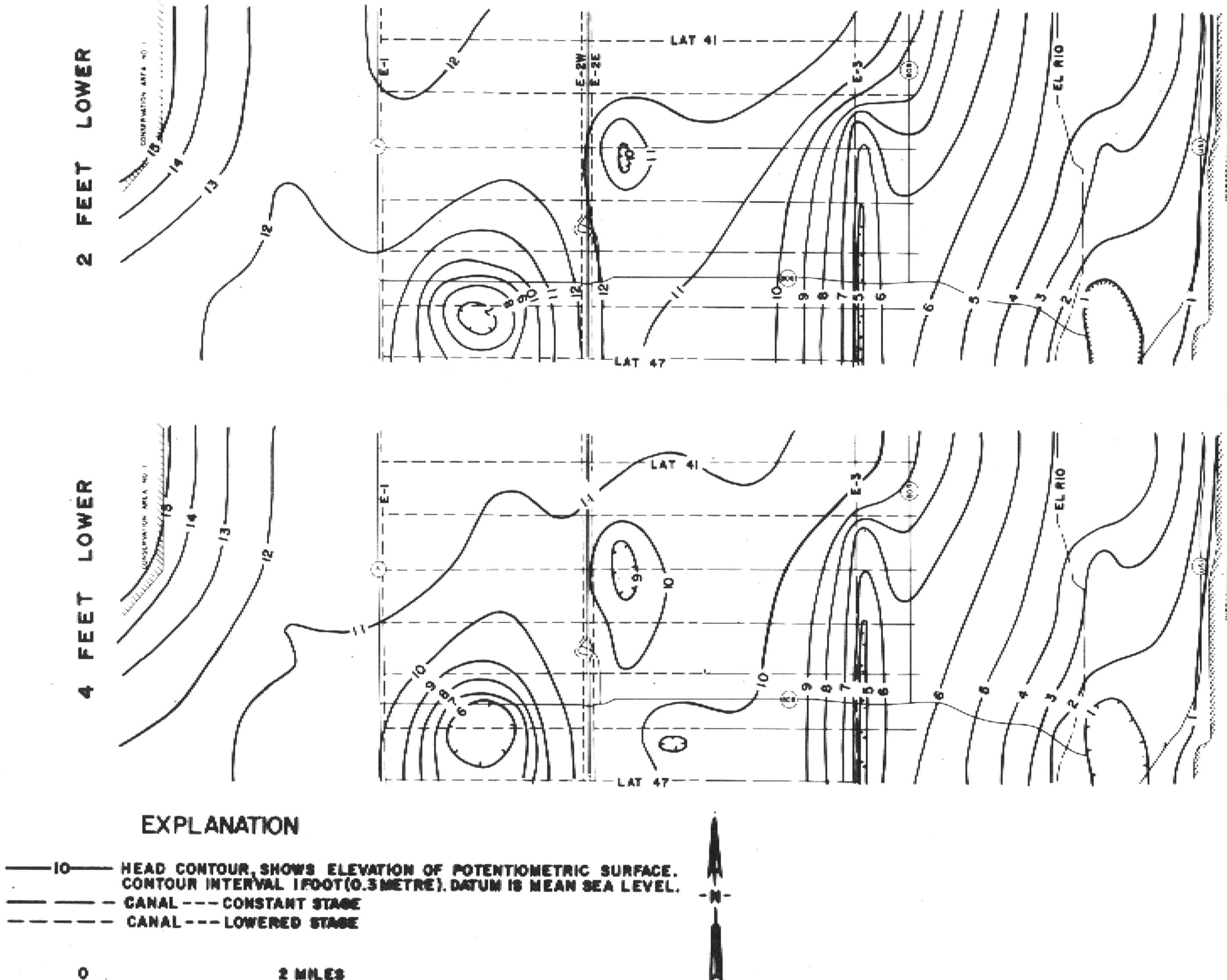


Figure 15.--Contours of the aquifer head for the Boca Raton test strip that resulted from land development and lowering interior canal water levels 2 and 4 feet.

# DISCUSSION

## Head Fluctuations

To illustrate how the head in the major producing zone along the coast would vary seasonally and throughout the 12-year test period, three observation points were selected in both the Delray Beach and Boca Raton test strips (fig. 2). Observation point A is in the interior and B is in the coastal area well field and C is approximately midway between the well field and the Intracoastal Waterway.

The model runs indicate a head decline of 1.7 and 3.4 ft (0.5 and 1.0 m) at observation point A for a 2- and 4-ft (0.6-and 1.2-m) decline in canal water levels. The seasonal variation of hydrologic conditions caused approximately a 0.5-ft (0.2-m) range in seasonal fluctuations. This indicates that the canals are generally effective in lowering the head but leakage from these canals and recharge from rainfall preclude a 1-for-1 change. Hydrographs of observation points B and C in the Delray Beach test strip are given in figures 16 and 17. At these two observation points the hydrographs are identical for all model runs having identical pumping rates. Lowering the interior canal water levels as much as 4 ft (1.2 m) did not affect the hydrographs at these observation points. For the Boca Raton test strip, hydrographs at observation point B and C are given in figures 18 and 19.

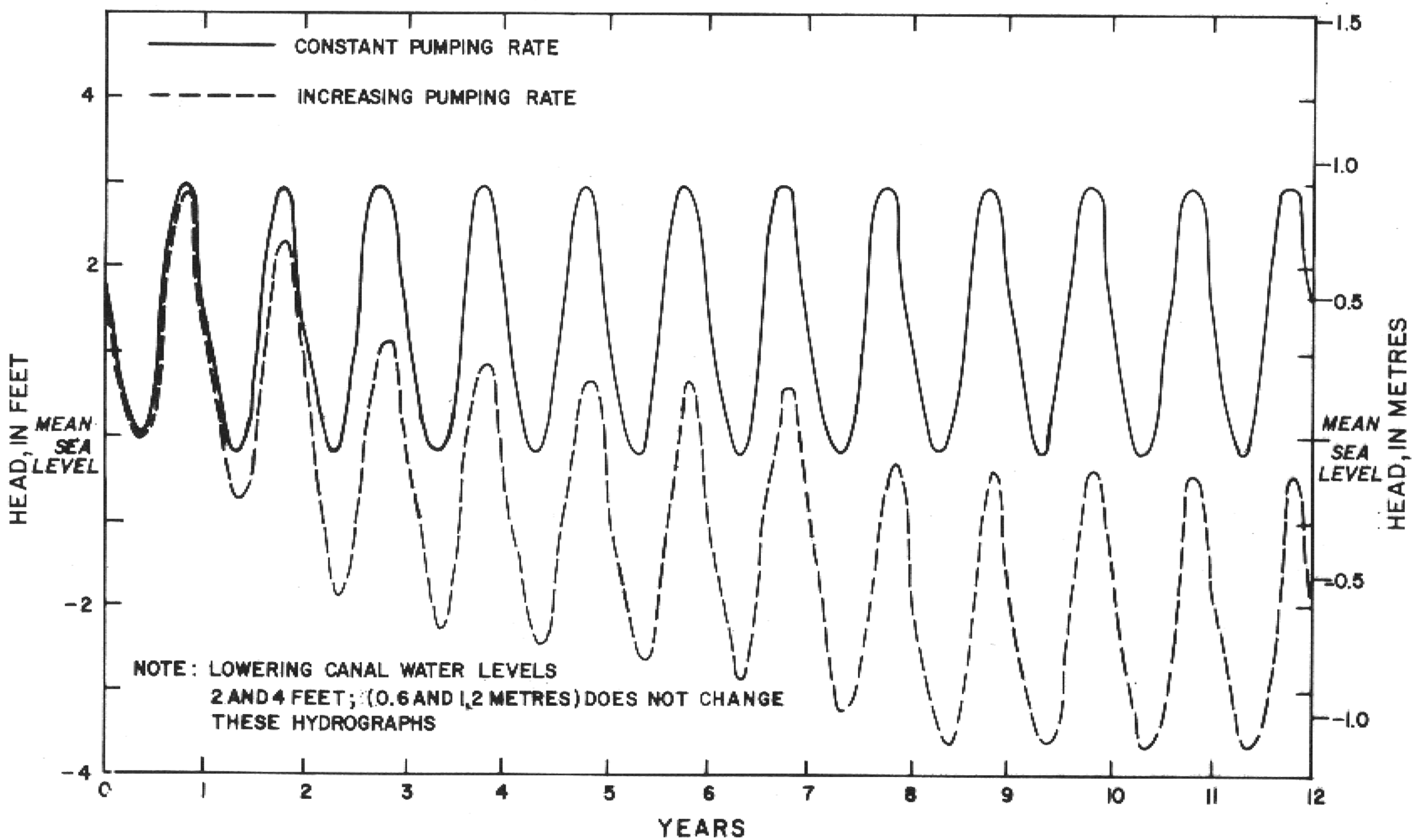


Figure 16.--Hydrographs of aquifer head at observation point B (in well field area) for Delray Beach test strip.

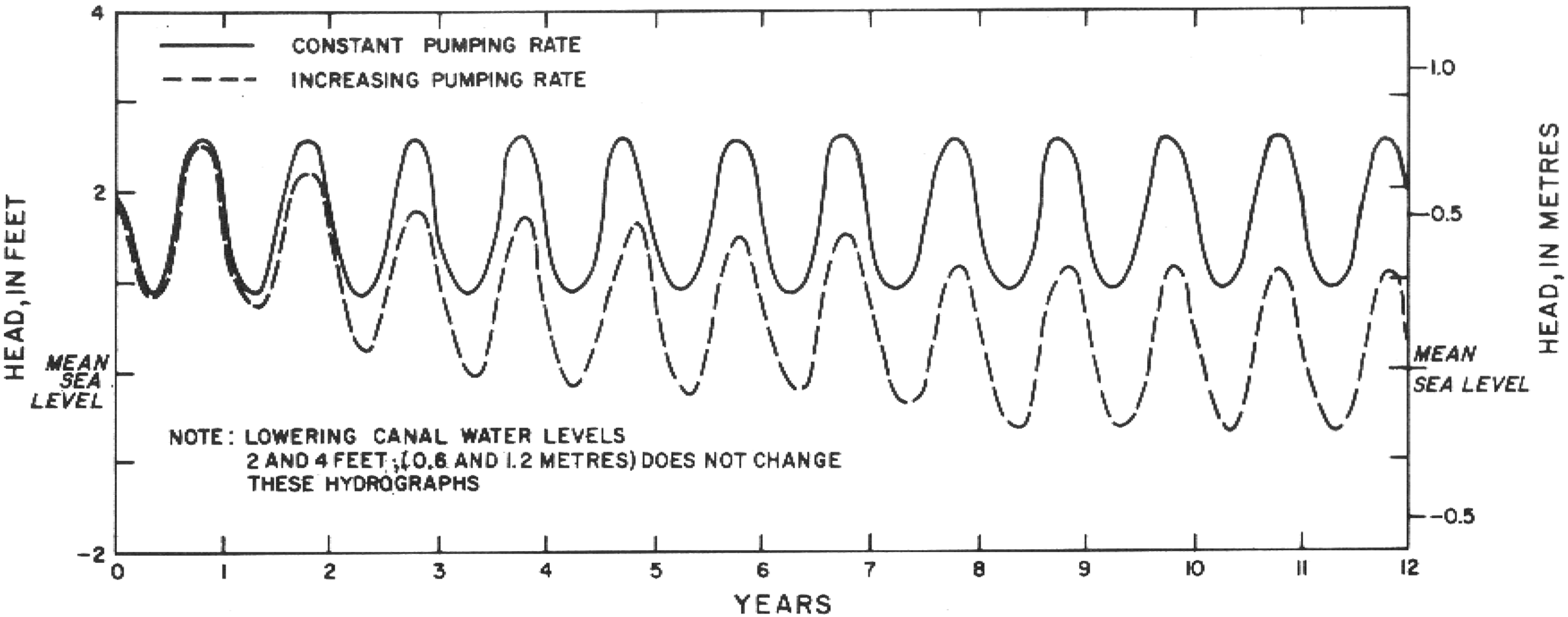


Figure 17.--Hydrographs of aquifer head at observation point C (midway between well field and Intracoastal Waterway) for Delray Beach test strip.

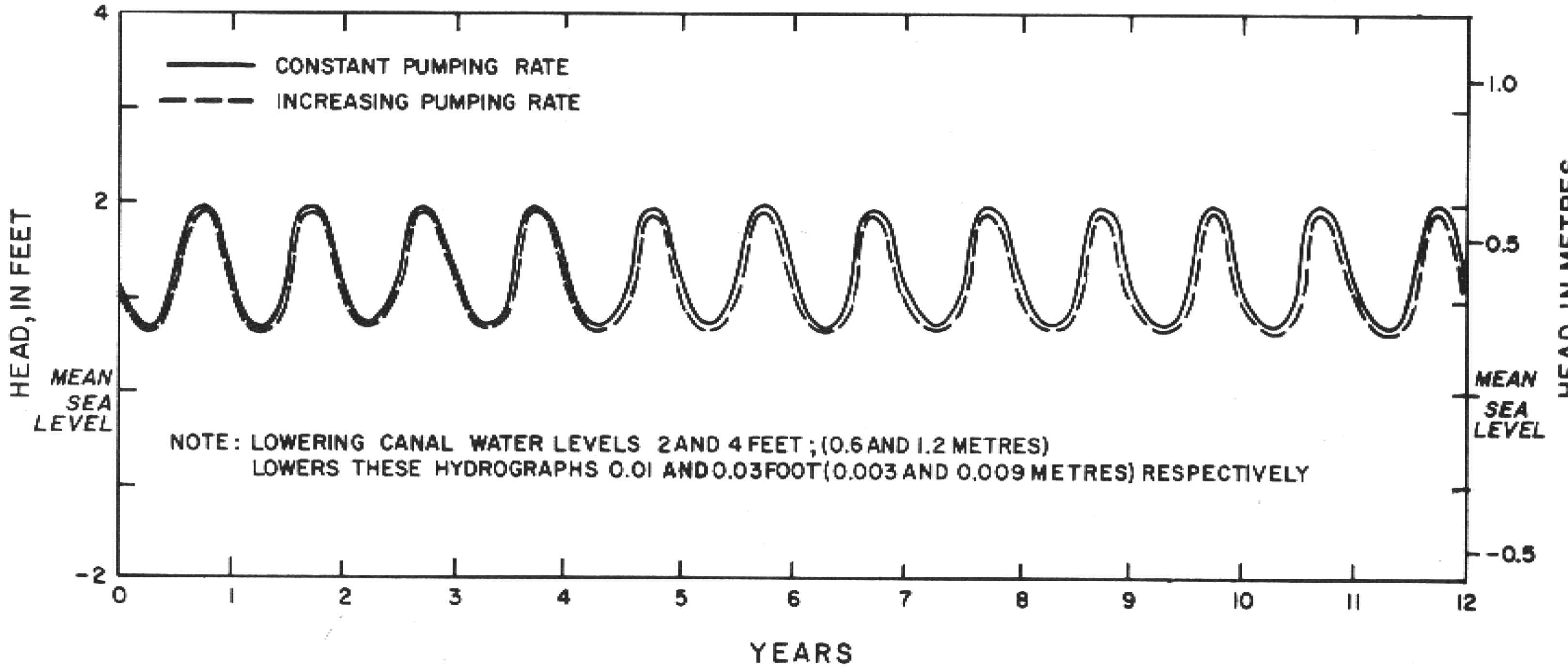


Figure 18.--Hydrograph of aquifer head at observation point B
(in coastal well field area) for Boca Raton test strip.

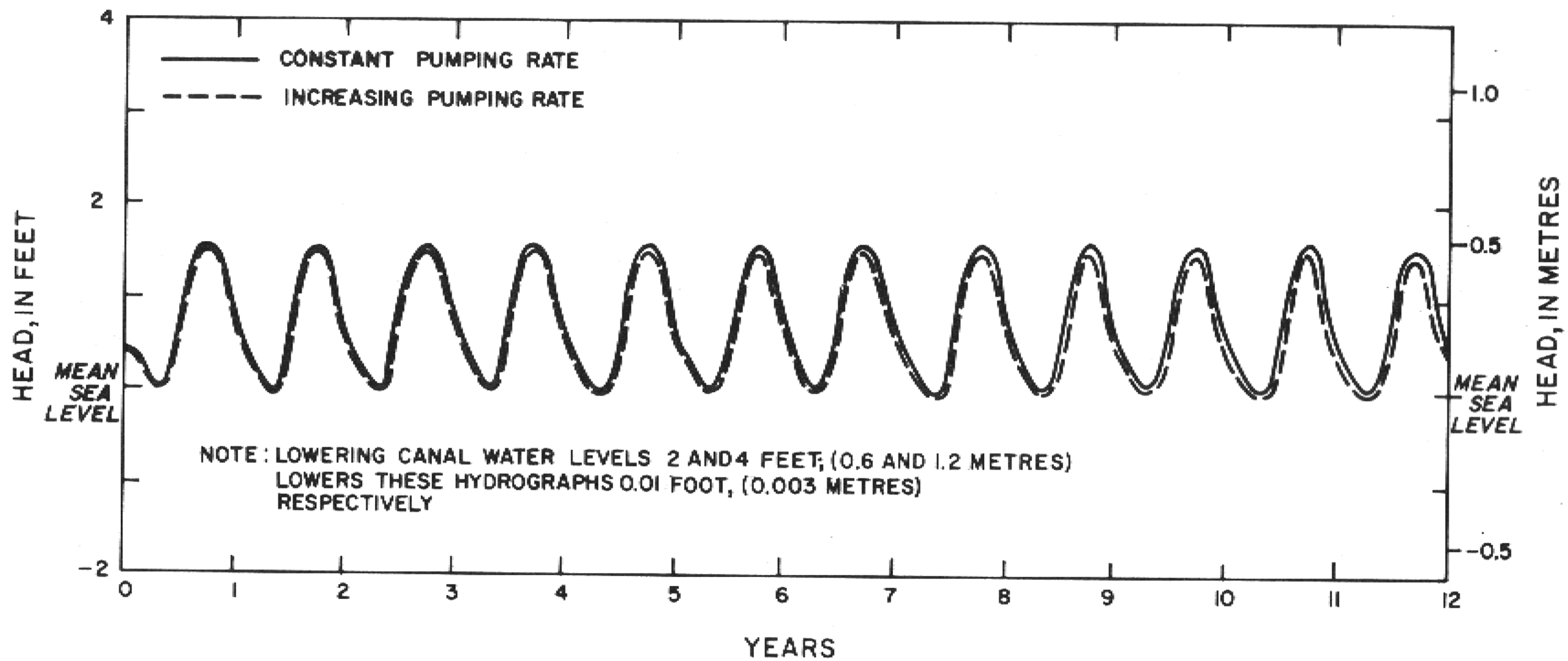


Figure 19.--Hydrograph of aquifer head at observation point C (midway between the coastal well field and Intracoastal Waterway) for the Boca Raton test strip.

## Effects of Lowering Canal Stages on Salt-water Intrusion

A study of the Lake Worth test strip indicates that a 3-ft (1-m) decline in interior canal stages in 1961 has not influenced the present (1974) position of the fresh-water-salt-water interface in this area. Studies of the Delray Beach and Boca Raton test strips indicate that if interior canal stages were lowered as much as 4 ft (1.2 m) salt water would not advance far enough inland to threaten any municipal well. In fact, salt water would advance only 125 ft (38 m) in the Boca Raton area and would not advance in the Delray Beach area for a stage change only, according to the modeling studies. A comparison of results from two ground-water withdrawal schemes, one for a continuation of the present level of land development and the other for an expansion of land development, shows that the amount of salt-water intrusion caused by a given decline in canal stage is independent of the withdrawal rates.

The head of the major producing zone in the vicinity of the coast, which ultimately determines the position of the salt-water front, appears to be sufficiently isolated from the surface-water system in the interior; therefore, a moderate stage decline in the selected interior canals will not contribute significantly to salt-water intrusion. The main reasons for the isolation are recharge from rainfall, leakage from the Canal E-4 system, the confining bed separating the canals from the major producing zone, the proximity of the Conservation Area, and the distance separating the stressed canal system and the coast.

## Effects of Additional Pumpage on Salt-water Intrusion

An insight into the effects of drilling and pumping additional wells at specific places on salt-water intrusion can be obtained by studying the contour plots in figure 9 to 11 and 13 to 15, the hydrographs in figures 16 to 19, and the estimated pumpage distribution maps in figures 8 and 12.

The pumpage distributions in figure 12 are for test purposes only. They may or may not be a reasonable estimate. The maps for the Delray Beach test strip show that all of the new land development in the Delray Beach area will be supplied with water from the same general area of their present well field. This area is inland from the Intracoastal Waterway at a distance of 2,000 to 4,000 ft (600 to 1,200 m). In contrast, these estimated pumpage distribution maps illustrate that Boca Raton's additional water requirements will be taken from a well field along Canal E-3 which is about 5 mi (8 km) inland. As expected, a long-term head decline occurred in Delray Beach's well field (fig. 16) and virtually no long-term decline occurred in Boca Raton's coastal ridge well field (fig. 18). For points midway between the well field and the Intracoastal Waterway, approximately the critical area where the head must be sufficiently high to control salt-water intrusion, the results were similar (figs. 17 and 19).

Using the analytical technique for predicting salt-water intrusion, it was found that the salt-water-fresh-water interface would advance into the Delray Beach well field before full development is reached. In Boca Raton the salt-water interface at a depth of 100 ft (30 m) would advance from approximately 800 ft (244 m) inland to 925 ft (282 m) after full land development. The nearest municipal well is approximately 5,000 ft (1,500 m) from the waterway. A possible salt-water threat to Boca Raton's coastal well field is from the tidal section of the El Rio Canal. No evaluation was made concerning the likelihood of a salt-water advance from this source because of the extremely complex nature of this system. However, the 125-ft (38-m) advance inland from the coast may also be a reasonable estimate for this area.

## Decision Making on Basis of the Modeling Predictions

In taking the results of the modeling into consideration as part of the data base for decision making, the modeling assumptions are here summarized:

1) The model was operated under the assumption that the canal stages would remain at fixed levels throughout the year. In reality, enough water may not be available in the Lake Worth Drainage District to maintain these stages when increased pumpage causes substantial leakage from the canals. This would most likely occur during the dry season or dry years.

2) Although the model varied the hydrologic conditions on a seasonal basis, long-term average hydrologic conditions were used as a base. During exceptionally dry and wet years the results could be somewhat different.

If land development continues until the maximum limit recommended by the Palm Beach County Land Use Plan is reached, the hydrologic system will become severely stressed. One limitation of the hydrologic system is the quantity of water available for use. For modeling purposes it was estimated that the consumptive use of water in the

Delray Beach test strip is equivalent to 28 in. (710 mm) of annual rainfall; almost half of the average annual rainfall. In the Boca Raton test strip the consumptive use was estimated at 22 in. (560 mm).

Furthermore, this report is not intended to suggest any changes in the operation of the canal system or any recommendations on obtaining additional water supplies for cities. The particular operating conditions were suggested by the cooperators. Such future operating decisions must be left to the water management agencies and the cities. Undoubtedly they will consider many factors other than those presented here.

## SUMMARY

A large-scale change of land use from agriculture to residential in the sandy flatlands of southeast Palm Beach County is causing the present (1974) water management practices to be reviewed by local agencies. One of the major changes under consideration is the lowering of interior canal water levels. Before these changes are implemented the effect on sea water intrusion must be known so that coastal well fields can be protected.

The hydrologic system in this flat and low lying area is characterized by a network of canals that cut into the shallow aquifer system. The hydraulic connection between the aquifer and the canals is only partially effective since the canals penetrate only a few feet of a 40- to 100-ft- (12- to 30-m)-thick zone of relatively low hydraulic conductivity. Immediately below this zone is a 40- to 90-ft- (12- to 27-m)-thick zone of high hydraulic conductivity. The latter zone functions as a leaky artesian aquifer.

A digital model was used to predict the response of the head in the major producing zone along the coast to lowering selected interior canal water levels. An analytical technique utilizing information computed by the digital model was used to predict the movement of the salt-water front.

The procedure used in this investigation was to study east-west test strips that pass through the northern half of the Lake Worth,

Delray Beach, and Boca Raton well fields. The Lake Worth test strip passes through an area where part of the interior canal water levels were lowered 3 ft (1 m) in 1961. Lacking historical data, modeling techniques were used to predict the effects of this action. These results were then extended to the study area where a similar, although more extensive, lowering of canal water levels is under consideration. The procedure used for the Delray Beach and Boca Raton test strips was to compare the results at the end of a 12-year test period of index model runs having no change in present canal water levels with test runs having the proposed changes of 2 and 4 ft (0.6 and 1.2 m). Two suites of model runs were made. One simulated a continuation of the current level of land development by maintaining the annual pumping rate constant and the other simulated an expansion of land development to the limits proposed by the Palm Beach County Land Use Plan. This was done by increasing pumpage in 1-year increments over a 9-year test period and holding the last 3 years constant.

Results of the model runs in the Lake Worth area indicate that the head in the coastal area was not affected by lowering part of the interior canal water levels 3 ft (1 m) in 1961. It is reasonable to assume that a similar decline in canal stage at the same relative distance between the constant head boundaries inland and the Waterway would not cause salt-water intrusion in other parts of the study area.

The results of the digital model runs in the study area show that lowering selected interior canal water levels as much as 4 ft (1.2 m) caused no effects on the head along the coastal ridge in the Delray Beach area and only a minimal effect in the Boca Raton area. The effects were identical whether land development was held constant or allowed to expand to the maximum limits. The higher transmissivity in the Boca Raton area, the size of Lake Ida, the distance to the conservation area, and the lower stage in the E-4 canal system near Boca Raton appear to be the main reasons for a detectable drawdown in the coastal area of Boca Raton and not Delray Beach.

The results from the test strips suggests that the lowering of the interior canal water levels alone will lower the aquifer head along the coastal ridge less than 0.05 ft (0.02 m). The resulting inland movement of the salt-water front will be minimal.

The movement of the salt-water front is highly responsive to the location and quantities of ground-water withdrawals; movement would be appreciable under full development if the increased withdrawals were taken from coastal ridge areas.

The principal factors affecting the aquifer head along the coastal ridge are eastward leakage from Canal E-4 and connecting canals and recharge from rainfall in the area east of the lowered canal stages. After full development the leakage will be of prime importance during the long dry season. The amount of water needed to meet expected demands is estimated to be 25 inches (640 mm) per year over the entire developed area. This is about 40 percent of the average annual rainfall.

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