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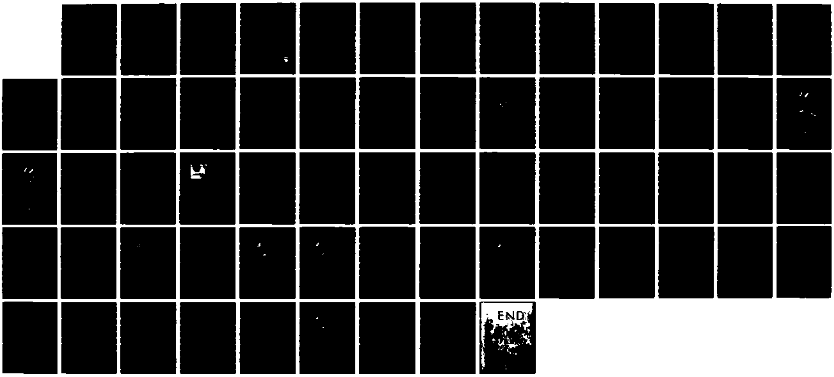

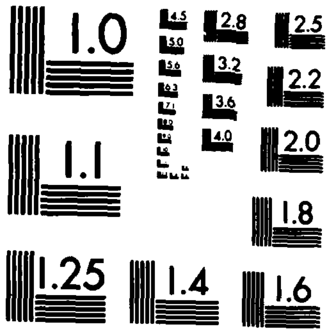

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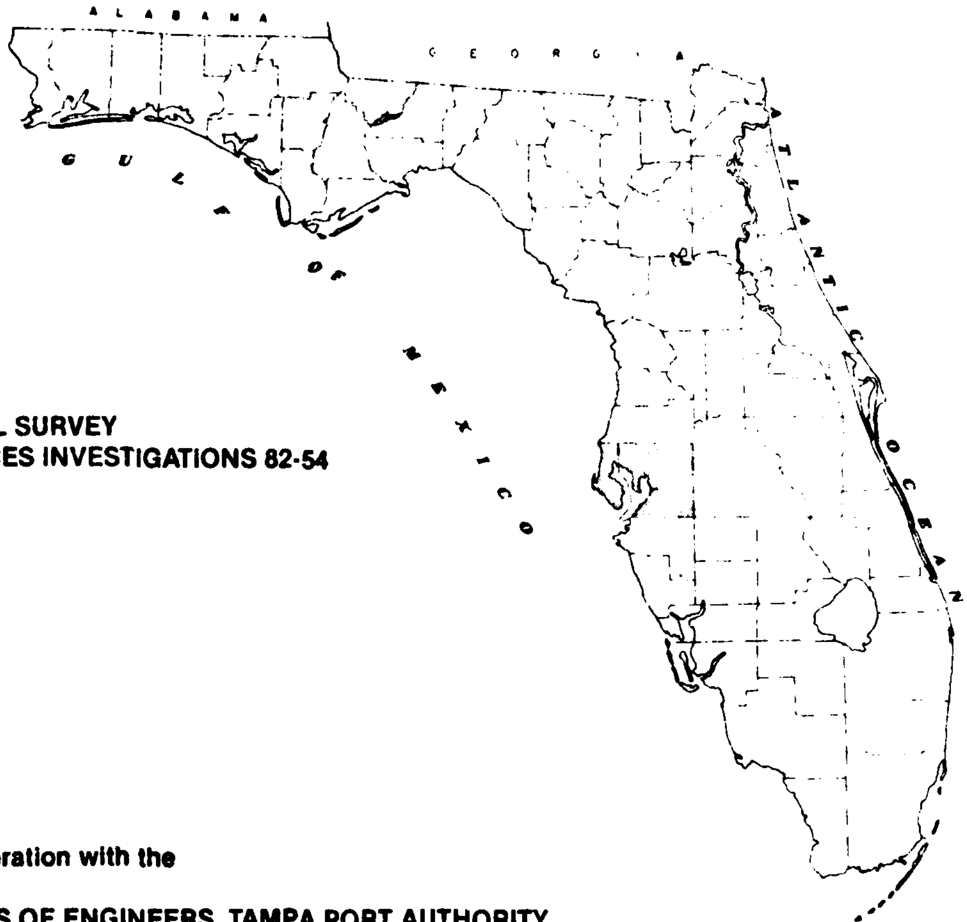
ASSESSMENT OF THE INTERCONNECTION BETWEEN TAMPA BAY AND THE FLORIDAN AQUIFER, FLORIDA



U.S. GEOLOGICAL SURVEY
WATER-RESOURCES INVESTIGATIONS 82-54

Prepared in cooperation with the

U.S. ARMY CORPS OF ENGINEERS, TAMPA PORT AUTHORITY,

and SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT

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Factors that control interflow between Tampa Bay and the Floridan aquifer are assessed, both qualitatively and quantitatively, with emphasis on the impact of harbor improvement. Hydrogeologic units underlying the 350-square-mile bay include the surficial-sand aquifer, upper sand and clay confining bed, and limestone of the Floridan aquifer. The surficial aquifer and upper confining bed have been eroded away in several areas along the northern coast of the bay to directly expose the Floridan aquifer to saltwater. There also, the top of the aquifer is, has been, or will be exposed to saltwater in numerous channels dredged in the bay.

Saltwater-freshwater relations indicate that the degree of bay-aquifer interconnection decreases from north to south. Saltwater intrusion is occurring along the coast of Tampa Bay, as indicated by reduction or reversal of potentiometric-surface gradients and increasing chloride concentrations in coastal monitoring wells.

A computer model of ground-water flow developed for a 97-square-mile area was interrogated under five options of channelization and pumping. Model results indicate that the total impact of channelization upon bay-aquifer interconnection are expected to be small and may be imperceptible when considered over the long term with other unknown changes in climate and development.

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ASSESSMENT OF THE INTERCONNECTION BETWEEN TAMPA BAY

AND THE FLORIDAN AQUIFER, FLORIDA

By C. B. Hutchinson

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 82-54

Prepared in cooperation with the

U.S. ARMY CORPS OF ENGINEERS, TAMPA PORT AUTHORITY,

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Tallahassee, Florida

1983

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JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

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Factors for converting inch-pound units to International System (SI) of metric units and abbreviation of units

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
foot per day per foot [(ft/d)/ft]	1	meter per day per meter [(m/d)/m]
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
mile (mi)	1.609	kilometer (km)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
billion gallons per day (Bgal/d)	43.81	cubic meter per second (m^3/s)

* * * * * * * * * * * *

National Geodetic Vertical Datum of 1929 (NGVD of 1929).--A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. The terms NGVD of 1929 and sea level appear in this report.

* * * * * * * * * * * *

EXPLANATION OF UNITS

Ground-water term		Original form		Reduced form
Transmissivity, *T*	=	$(m^3/d)/m$	=	m^2/d
	=	$(ft^3/d)/ft$	=	ft^2/d
Hydraulic conductivity, *K*	=	$(m^3/d)/m^2$	=	m/d
	=	$(ft^3/d)/ft^2$	=	ft/d

ASSESSMENT OF THE INTERCONNECTION BETWEEN TAMPA BAY AND THE FLORIDAN AQUIFER, FLORIDA

By C. B. Hutchinson

ABSTRACT

Rapid urbanization of the Tampa Bay area has placed heavy demands upon the coastal ground-water resources. Municipal, industrial, and agricultural pumping from the Floridan aquifer intercepts freshwater that would otherwise discharge to the bay. Where water-level gradients are reversed near the coast, salty bay water is leaking into the freshwater aquifer. Factors that control interflow between Tampa Bay and the Floridan aquifer are assessed, both qualitatively and quantitatively, with emphasis on the impact of proposed harbor improvement.

Hydrogeologic units of the Tampa Bay area include the surficial aquifer, upper confining bed, Floridan aquifer, and lower confining bed. The Floridan aquifer is the principal source of water supply. The general direction of ground-water movement is from the land toward the bay. Ground-water outflow to the bay averages about 100 million gallons per day and comprises about one-sixth the total discharge of the aquifer from the drainage basins surrounding the bay.

The surficial aquifer and upper confining bed have been eroded in several areas along the northern coast of the bay to directly expose the top of the Floridan aquifer to saltwater. In addition, the top of the aquifer is, has been, or will be exposed in numerous channels dredged in the bay for drainage, pleasure boating, and commercial shipping. In the southern part of the bay, the upper confining bed thickens to about 250 feet and forms a relatively effective barrier to bay-aquifer interflow.

Saltwater-freshwater relations indicate that the degree of bay-aquifer interconnection decreases from north to south. Chloride concentration of water from the upper part of the Floridan aquifer beneath the bay decreases from about 14,000 milligrams per liter in the north to about 1,300 milligrams per liter in the south. Saltwater intrusion is occurring along the coast of Tampa Bay, as indicated by reduction or reversal of potentiometric-surface gradients and increasing chloride concentrations in coastal monitoring wells. The rate of inland movement of the saltwater front is probably between 0.3 and 5 feet per day in the southern part of the Tampa Bay area and nil in the northern part of the bay area. A network of coastal monitoring wells could make it possible to detect the rate and extent of saltwater intrusion in the freshwater aquifer.

A computer model of ground-water flow developed for a 97-square-mile area was interrogated under five options of channelization and pumping. The greatest hydrologic effects are expected to occur near a 55-million-gallon-per-day pumping center about 1,500 feet north of the area where deepening of the Alafia River channel is expected to breach the upper confining bed. The Floridan

aquifer in this area already contains saltwater, but with the channel construction, the aquifer would be exposed directly to the bay. Under pumping conditions, the potentiometric surface is expected to rise about 5 to 10 feet in response to a net increase of 9.6 million gallons per day in downward leakage of saltwater in the vicinity of the channel. If pumping were to cease, upward leakage through the channel cut would increase about 4.1 million gallons per day above that computed for existing conditions with no pumping. The model analysis indicated that the hydrologic effects of widening and deepening the main ship channel and Big Bend channel would be relatively small compared to those estimated for the Alafia River channel. The total impact of channelization upon bay-aquifer interconnection is expected to be small and may be imperceptible when considered over the long term with other unknown changes in climate and development.

INTRODUCTION

Tampa Bay is the largest estuary on Florida's west coast. In terms of tonnage shipped, the port of Tampa ranked seventh in the nation during 1979, having shipped 49,830,441 tons of commerce (Tampa Port Authority, 1980). In addition to its importance for providing a sheltered harbor for shipping, Tampa Bay supports shellfish and recreational industries that contribute to the economy of the State.

The 20th-century population boom in Pinellas, Hillsborough, and Manatee Counties that surround the bay has placed heavy demands upon coastal ground-water resources. Municipal, industrial, and agricultural pumping from the Floridan aquifer intercepts freshwater that would otherwise discharge to the bay. Where water-level gradients near the coast are reversed, salty bay water is leaking into the freshwater aquifer. Knowledge of the direction, quantity, and quality of bay-aquifer interflow is needed for sound development and management of the bay and ground-water resources in the area. This knowledge will aid in assessment of the hydrologic effects of nearby ground-water development, ship-channel widening and deepening, and other bay area alterations, such as residential and industrial dredging.

This report presents the results of an 18-month investigation by the U.S. Geological Survey in cooperation with the U.S. Army Corps of Engineers, the Tampa Port Authority, and the Southwest Florida Water Management District. The objectives of the investigation were to assess (1) the factors that control the hydraulic interconnection between Tampa Bay and the Floridan aquifer, (2) the direction, rate, and quality of interflow between the bay and aquifer, and (3) the relative impacts of options for harbor improvement on bay-aquifer interflow. Evaluations are based on data obtained from State and Federal reconnaissance reports, consulting engineers' reports, published and unpublished geologic logs and water-quality analyses, and information supplied by the Corps of Engineers. A conceptual model of the bay-aquifer system is formulated as a basis for making quantitative estimates of interflow and for defining areas of existing and potential saltwater intrusion. The potential impact of harbor improvement is assessed through a digital model of ground-water flow.

Acknowledgments

Assistance and cooperation of engineering and technical personnel of organizations which provided information and aided in field work are sincerely appreciated. These organizations include the U.S. Army Corps of Engineers; Gardinier, Inc.; and the city of Tampa. The author is particularly grateful to M. I. Rorabaugh and C. S. Conover (U.S. Geological Survey, retired) for their helpful reviews of the manuscript and personal discussions concerning the hydrogeology of Tampa Bay.

Special acknowledgment is made to Mahesh C. Jindal, Hydrogeologist; Central Ground Water Board, Government of India; Chandigrah, 160019 (India), who constructed, calibrated, and interrogated the ground-water flow model used to assess the impact of harbor improvement on bay-aquifer interconnection. Mr. Jindal was sponsored by a United Nations Fellowship, granted for advancing the technologies of developing countries, to study Geological Survey methods of computer modeling of hydrologic systems. Mr. Jindal was assigned to the Survey's office in Tampa from October 1979 to April 1980.

Sources of Information

Numerous published reports describe the hydrogeology of the Tampa Bay area. These reports provided most of the data used in development of a conceptual model of the study area and in the evaluation of interconnection between Tampa Bay and the Floridan aquifer.

Reports by White (1958) and Stahl (1970) describe the geomorphology and origin of the bay. Mann (1972) discusses aspects of bay-aquifer interconnection in upper Old Tampa Bay. Goodwin (1977) assesses the surface-water hydraulics of part of the bay.

Hydrogeologic data are from ground-water reports by Heath and Smith (1954), Peek (1958; 1959), Menke and others (1961), Cherry and others (1970), Motz (1975), Geraghty and Miller, Inc. (1976), Seaburn and Robertson, Inc. (1976), Wilson and Gerhart (1980), Hickey (1982), and Ryder (1982); in map reports by Stewart and Hanan (1970), Duerr (1975), Buono and Rutledge (1979), and Buono and others (1979); and in files and reports of the U.S. Army Corps of Engineers (1969; 1975). Water-use data are from reports by Mills and others (1975), Leach and Healy (1980), Wilson and Gerhart (1980), and Hickey (1981) and in records of local water users. Maps of the potentiometric surface of the Floridan aquifer during dry and wet periods are from reports by Wolansky and others (1978a; 1978b). Chloride maps are from reports by Shattles (1965), Cherry (1966), Hickey (1981; 1982), and Causseaux and Fretwell (1982). Bay water quality was described in detail by Goetz and Goodwin (1980).

Description of the Area

Tampa Bay is a Y-shaped embayment with 110 miles of shoreline and an area of 350 mi^2 on the central Gulf Coast of the Florida Peninsula (fig. 1). An interbay peninsula separates the branches of the Y into Old Tampa Bay on the

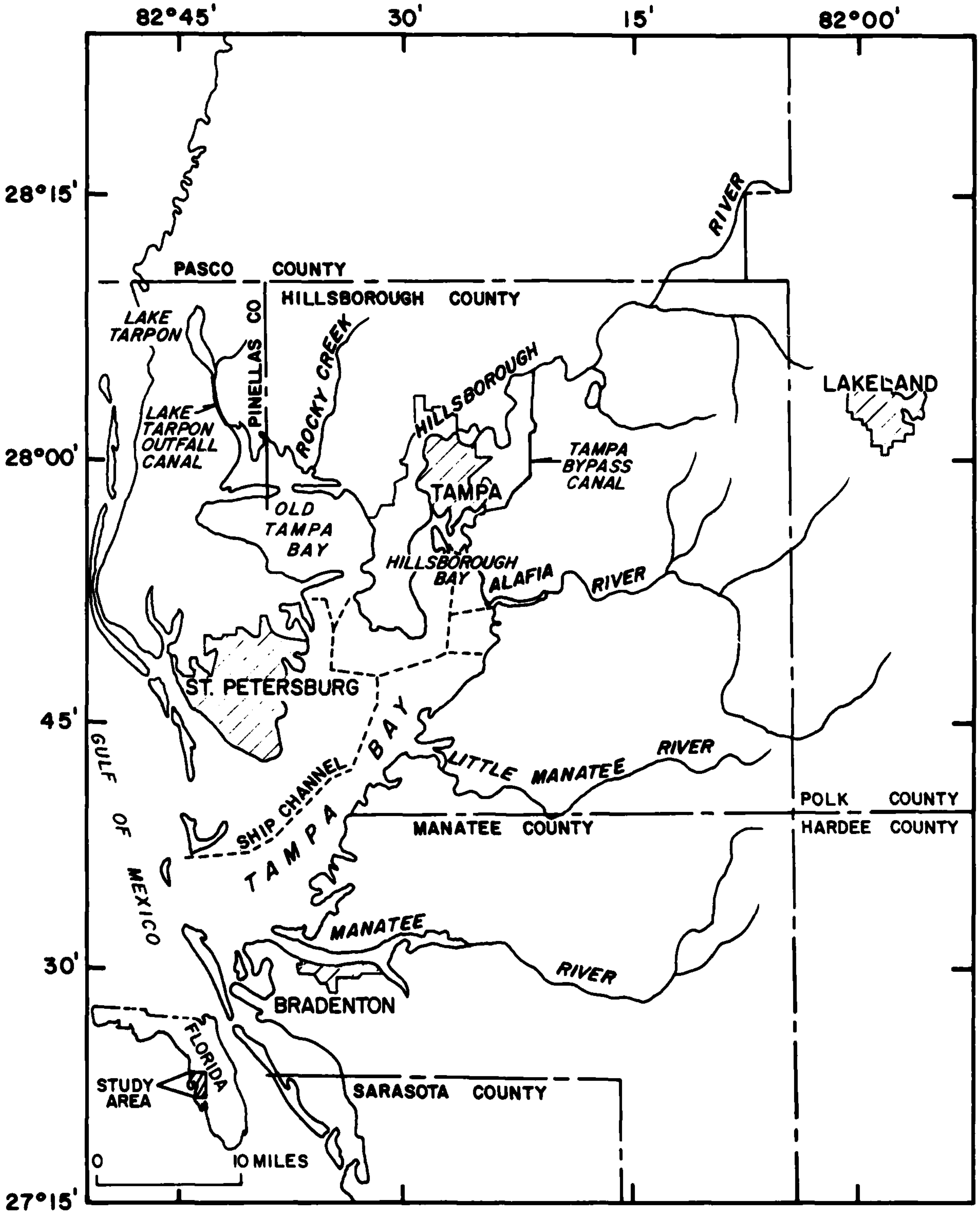


Figure 1.--Location of Tampa Bay.

northwest and Hillsborough Bay on the northeast. Tampa Bay is generally understood to refer either to the main stem south of the two branches or to the entire bay system. Unless otherwise qualified, the term "the bay," as used in this report, refers to the entire bay system. The average depth of the bay increases from about 12 feet in the branches to about 30 feet at the Gulf of Mexico. A main ship channel, about 400 feet wide and 34 feet deep, extends about 35 miles from the Gulf of Mexico to the port of Tampa in upper Hillsborough Bay. About 20 miles of ship channels lead from the main channel to ports in the bay. Work is in progress to widen the main ship channel to 500 feet and to deepen it to 43 feet, plus a 2-foot tolerance for overdeepening. Proposed improvements for the 3.5-mile-long Alafia River tributary channel, connecting the main channel with terminals at the mouth of the Alafia River, include deepening from 28 to 38 feet and widening from 200 to 430 feet. Another tributary channel, the Big Bend channel, 5 miles south of the Alafia River channel may also be deepened and widened.

The surface-water drainage area surrounding Tampa Bay is about 2,200 mi^2 (fig. 2). Major streams in the area and their average discharges are listed in table 1. The average discharge of the streams to the bay totals about 1,440 Mgal/d (14 in/yr over the drainage area and 84 in/yr over the 350-mi^2 bay). Typically, May is a low-flow period when streamflow is composed mainly of ground-water outflow from the underlying aquifers. Discharge of streams to the bay during May averages 382 Mgal/d (23 in/yr over the 350-mi^2 bay), or about one-fourth the average daily discharge, and is considered herein to approximate the minimum average daily base streamflow. In addition to the freshwater contribution by streamflow, about 55 inches of rain falls on the bay annually, about 78 Mgal/d (4.7 in/yr over the 350-mi^2 bay) of wastewater currently (1977) discharges to the bay (Tampa Bay Regional Planning Council, 1978), and about 100 Mgal/d (6.0 in/yr over the 350-mi^2 bay) of fresh ground water seeps to the bay. The combined freshwater contribution to the bay from streamflow, rainfall, sewage discharge, and ground-water outflow totals about 12.5 ft/yr.

The freshwater inflow to Tampa Bay causes a reduction of salinity in the estuary and establishes a horizontal increase in conductivity from the heads of Old Tampa and Hillsborough Bays to the Gulf of Mexico. A typical specific-conductance distribution, mapped by Goetz and Goodwin (1980), is presented in figure 3. The typical specific conductance range is 37.9 to 39.0 millimhos per centimeter (mmho/cm) in Old Tampa Bay and 32.9 to 36.9 mmho/cm in Hillsborough Bay, and gradually increases to 48.9 to 51.0 mmho/cm at the Gulf. Hillsborough Bay receives a relatively large quantity of surface-water inflow (772 Mgal/d from totals of Alafia and Hillsborough Rivers, Sulphur Springs, and Tampa Bypass Canal and not including a small quantity of ungaged streamflow, table 1), which causes dilution of the salty bay water. Old Tampa Bay has a larger surface area than Hillsborough Bay and receives significantly less surface-water inflow (63 Mgal/d from Rocky, Sweetwater, and Brooker Creeks and not including a small quantity of ungaged streamflow, table 1), yet specific conductance of the water there is only slightly higher than that of Hillsborough Bay. Dilution of water in Old Tampa Bay could be caused by fresh ground-water discharge upward through the bay bottom combined with the surface-water inflow and precipitation.

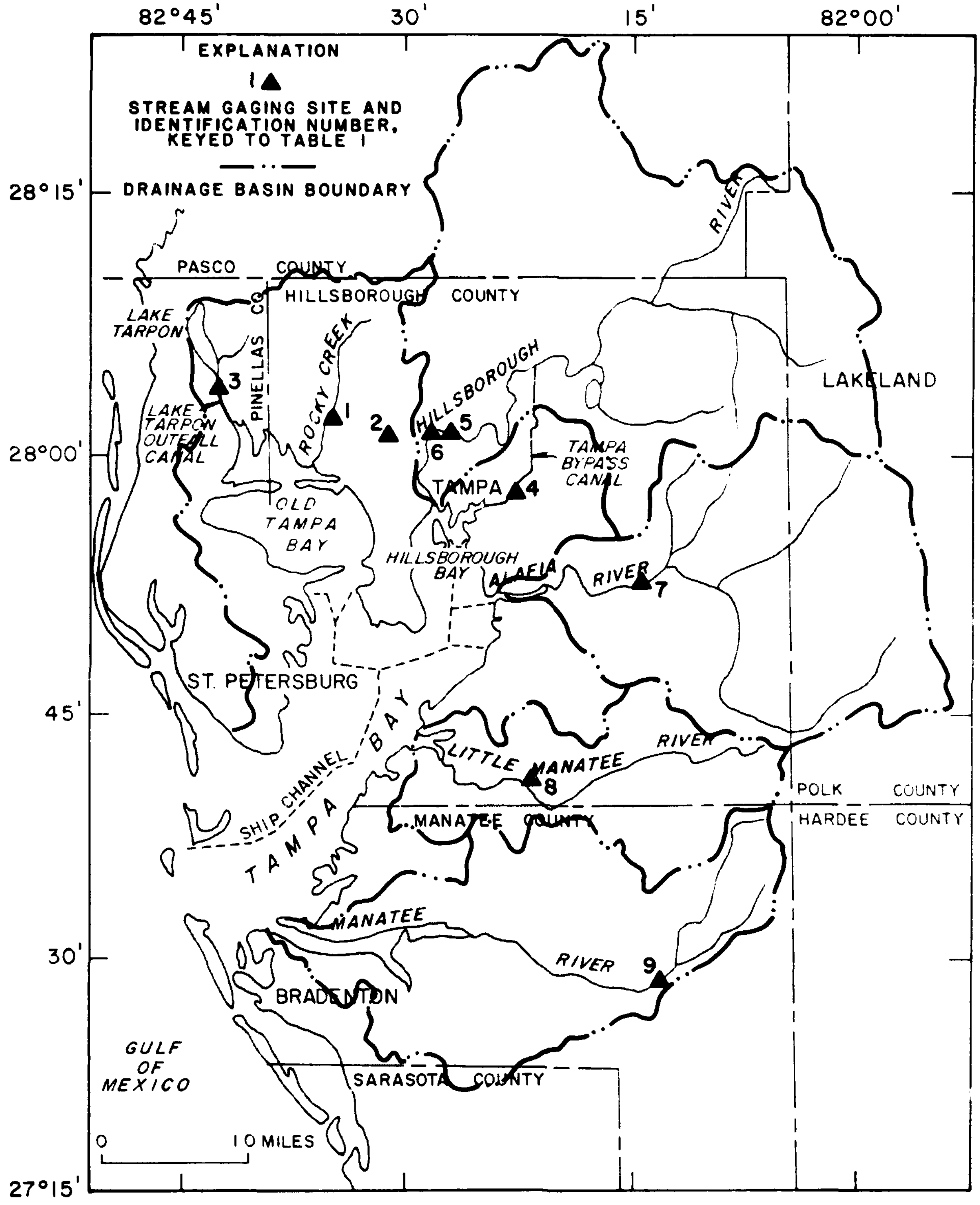


Figure 2.--Tampa Bay-area drainage network.

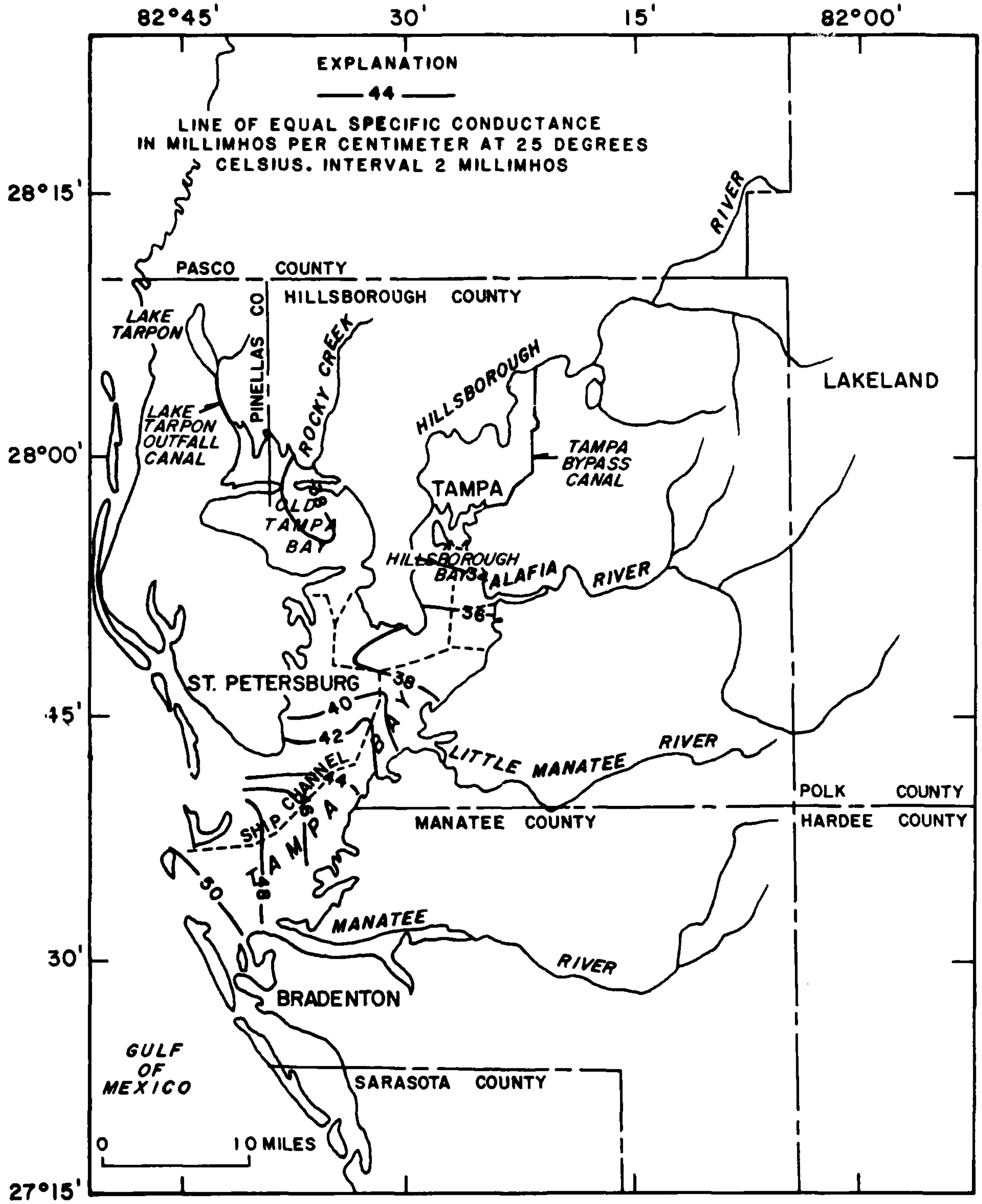


Figure 3.--Typical specific conductance distribution in Tampa Bay (from Goetz and Goodwin, 1980).

Table 1.--Surface-water discharge to Tampa Bay
(U.S. Geological Survey, 1978)

Site number 1/	Drainage basin	Period of record (years) 2/	Drainage area 3/ (mi^2)	Average discharge during May 4/ (Mgal/d)	Average annual discharge 4/ (Mgal/d)
	Tampa Bay and coastal areas				
1	Rocky Creek	24	45	8	30
2	Sweetwater Creek	26	25	4	14
3	Lake Tarpon Canal	3	65	2	19
4	Tampa Bypass Canal	19	39	31	37
	Ungaged area 5/	--	339	60	222
	Hillsborough				
5	Hillsborough River 6/	39	690	70	411
6	Sulphur Springs	18	--	17	27
	Alafia				
7	Alafia River	45	420	102	297
	Little Manatee				
8	Little Manatee River	38	211	31	155
	Manatee				
9	Manatee River	11	350	57	228
	Total		2,184	382	1,440

1/ See figure 2 for location.
2/ Period of record includes all measurements through 1977.
3/ Data from Conover and Leach (1975).
4/ Discharge is linearly adjusted to include ungaged drainage area in each basin.
5/ Discharge in ungaged basins is assumed to be directly proportional to discharge in gaged basins.
6/ Adjusted for diversions by city of Tampa.

HYDROGEOLOGY

The origin of Tampa Bay, whether structural or erosional, is not clear. White (1958) conjectured that Hillsborough Bay and lower Tampa Bay may have been formed as the valley of the Hillsborough River, and because Old Tampa Bay has no apparent relation to any large stream, it must have been connected by seaway to the Gulf of Mexico by way of the Lake Tarpon trough. It is peculiar, however, that these estuaries end abruptly with no gradation or preliminary narrowing.

Structurally, Tampa Bay is on the southwest flank of the peninsular arch and is southwest of the Ocala uplift. The peninsular arch, a 275-mile-long anticlinal fold formed during the Mesozoic Era, is the dominant subsurface structure and forms the axis of the Florida peninsula. The Ocala uplift is a gentle anticlinal flexure in north-central Florida, which is believed to have formed during late Oligocene and early Miocene time (Vernon, 1951). Axes of both structural features approximately parallel each other and trend northwest to southeast. Vernon (1951) mapped hundreds of fractures in Florida that roughly parallel or run perpendicular to the major structural features. Tampa Bay could possibly overlie graben features formed by this fracturing for it displays a striking persistence of northwest-southeast, northeast-southwest, and north-south alinements of coastline; however, a map of the top of the Floridan aquifer presented in this report does not indicate a depression in the underlying bedrock.

The Tampa Bay area is underlain by a sequence of sedimentary rocks whose texture and composition control the chemical content of the water contained and the rate of ground-water movement. The thickness, areal extent, and fracturing of the rocks will also influence the rate of ground-water movement. Hydrogeologic units discussed and evaluated in this report comprise the surficial aquifer, upper confining bed, Floridan aquifer, and lower confining bed (table 2). Units include carbonate and clastic rocks ranging in age from Holocene to Eocene.

Deposits of the surficial aquifer form a sand blanket that covers the area around and beneath the bay. As mapped by Wolansky and others (1979), the aquifer is as much as 70 feet thick in the ridge of central Pinellas County where it is probably composed of dune remnants. Beneath Tampa Bay, the aquifer is generally less than 40 feet thick (fig. 4) and contains seawater. Because of its low yield, the aquifer is not a major source of water supply even where it contains freshwater.

The upper confining bed separates the surficial aquifer from the Floridan aquifer and is the principal lithologic unit that separates the bay and aquifer. It consists of relatively impermeable, fine-grained deposits within the Hawthorn Formation and possibly includes clay at the top of the Tampa Limestone. The upper confining bed thickens from an average of about 25 feet in Old Tampa and Hillsborough Bays to about 250 feet in the southern part of Tampa Bay (figs. 4 and 5). Locally, the bed has been breached by erosion or channelization. For analytical purposes in this study, the vertical hydraulic conductivity of the upper confining bed (K') is estimated to average 2×10^{-2} ft/d, based on laboratory tests reported by Mann (1972), Cherry and Brown (1974), Sinclair (1974), Hutchinson and Stewart (1978), and Stewart and others (1978), and on aquifer tests reported by Motz (1975) and Hutchinson (1978). Because confining-bed thickness increases to the south, the regional leakage coefficient (K'/b') probably decreases to the south.

The Floridan aquifer is the principal source of water supply in the Tampa Bay area. Public supply and irrigation wells typically yield 1,500 gal/min and locally yield as much as 5,000 gal/min. The aquifer is more than 1,000 feet thick and includes the persistent carbonate sequence of the Tampa Limestone, Suwannee Limestone, Ocala Limestone, and Avon Park Limestone. Transmissivity of the freshwater part of the Floridan aquifer, computed from pumping tests primarily in well-field areas surrounding the bay, ranges from about 30,000 to 200,000 ft^2/d (Ryder, 1982). The least transmissive area is the upper freshwater-bearing unit of the aquifer in Pinellas County. The most transmissive

Table 2.--Hydrogeologic units beneath Tampa Bay

Hydrogeologic unit	Approximate range in depth below land surface or bay bottom (ft)	Approximate range in thickness (ft)	Physical character	Aquifer and yield characteristics	Formation	Geologic age
Surficial aquifer	0-70	0-70	Fine-coarse sand, interbedded with clayey sand, clay, and marl; poorly sorted.	Wells rarely yield more than 50 gal/min. Transmissivity commonly less than 1,000 ft^2/d. Good water quality.	Surficial sand	Holocene and Pliocene
Upper confining bed	25-275	0-250	Interbedded sandy limestone, marl, and clay; dolomitic phosphatic; fossiliferous.	Relatively impermeable, yields very little water to wells. South and east of Tampa Bay, wells tapping the limestone member yield up to 200 gal/min of good-quality water.	Hawthorn Formation	Miocene
Floridan aquifer	0-300	1,000-1,300	Limestone and dolomite.	Yields up to 5,000 gal/min. Transmissivity ranges from 30,000 to 200,000 ft^2/d. Water quality varies with depth and location.	Tampa Limestone	Miocene
					Suwannee Limestone	Oligocene
					Ocala Limestone Avon Park Limestone	Eocene
Lower confining bed	1,000-1,600	> 1,000	Gypsiferous and anhydritic limestone and dolomite.		Lake City Limestone	Eocene

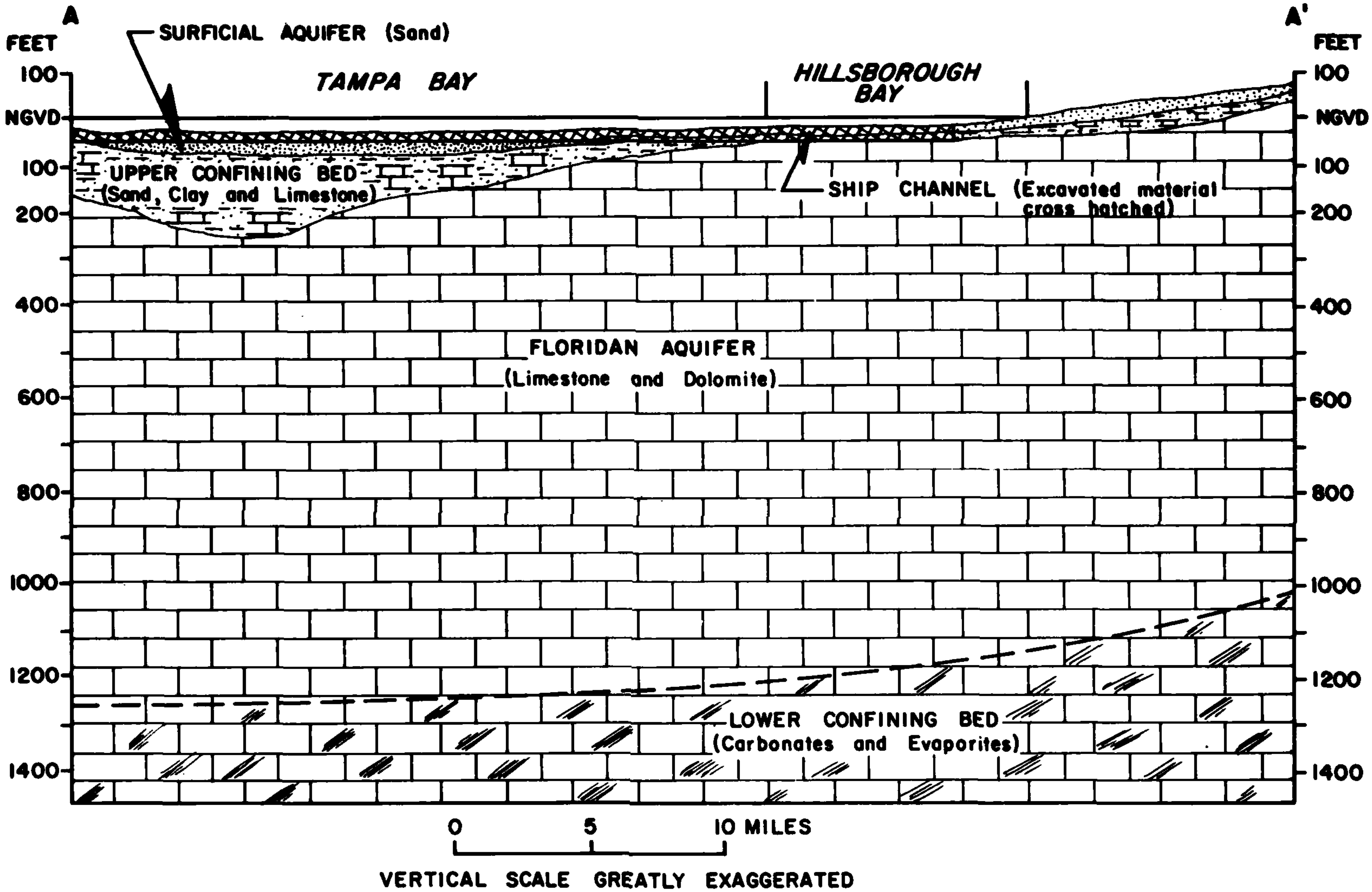


Figure 4.--Hydrogeologic section along the Tampa-Hillsborough Bay ship channel and northward (A-A' in figure 5).

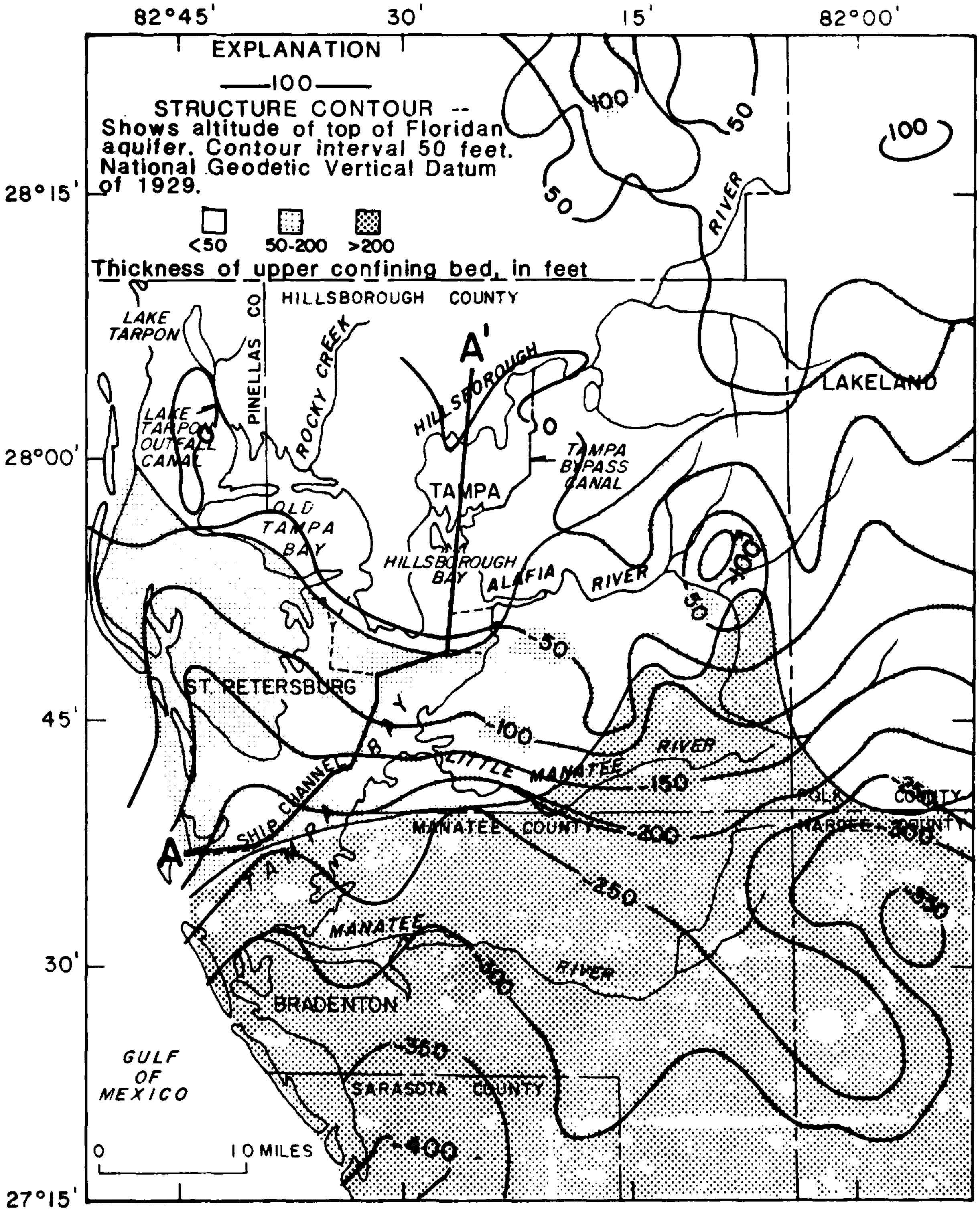


Figure 5.--Altitude of the top of the Floridan aquifer and thickness of the upper confining bed. (Contours are a compilation of maps produced by Peek, 1959; Buono and Rutledge, 1979; Buono and others, 1979; and Hickey, 1982.)

area occurs along the lower reach of the Hillsborough River. These extremes bracket the range in transmissivities used to compute the rate of ground-water outflow to Tampa Bay.

The concept of transmissivity zonation within the Floridan aquifer is gaining credibility, but the extent of the zones and the degree of interconnection are not completely documented. Although structural controls on aquifer permeability may be important, stratigraphic controls are certainly more obvious. Permeable zones in the limestone are apparently related more to horizontal zonation at erosional surfaces or stratigraphic breaks than to vertical zonation along fault planes. At four test sites in Pinellas County, Hickey (1981) recognized four permeable zones within the Floridan aquifer separated by less permeable zones. In southeastern Hillsborough and southwestern Polk Counties, Hutchinson (1978) separated the Floridan aquifer into upper and lower units on the basis of an areally extensive clay and chert layer as much as 100 feet thick at the base of the Tampa Limestone. In a 176-foot test well in Hillsborough Bay, Sinclair (1979) discerned a relatively permeable zone in the upper 20 feet of the Floridan aquifer, underlain by a 73-foot-thick section of low permeability similar to that described by Hutchinson. Proposed deepening of the main ship channel to 43 feet below sea level will cut into the permeable zone at the top of the Floridan aquifer in Hillsborough Bay (fig. 4). For analytical purposes in this study, the Floridan aquifer is considered to be vertically homogeneous, except in the Pinellas Peninsula where it is considered to be separated into upper and lower units by a less permeable zone within the Suwannee Limestone.

The lower confining bed of the Floridan aquifer is composed of limestone and dolomite with intergranular gypsum and anhydrite that probably comprise the Lake City Limestone. On the basis of visual examination and laboratory permeability tests of cores from Pinellas and Polk Counties, and from injection tests, flowmeter and temperature logs, and borehole television survey of wells in Pinellas County, the lower confining bed probably has a vertical hydraulic conductivity similar to or less than that of the clays of the upper confining bed (Hickey, 1981).

Transfer of water between Tampa Bay and the Floridan aquifer depends upon head differences in the two bodies and upon the thickness and hydraulic conductivity of the overburden deposits. Where the potentiometric surface of the aquifer is below sea level at the coast, seawater intrusion is inevitable. Conversely, where the head in the aquifer is above sea level, freshwater outflow occurs. Under the same head conditions, the rate of inflow or outflow would be greater where the confining bed is thin than where it is thick, given a constant hydraulic conductivity. Structural controls or interconnection, such as sinkholes or faulting that may breach the confining bed, are thought to be of minor significance.

For a given hydraulic gradient, large leakage through the bay bottom would occur in areas where the confining bed is absent or has been breached by natural phenomena, such as sinkholes or erosion, or by man-imposed conditions of dredging or channelization. Exposures of the Floridan aquifer occur only in the northern part of the Tampa Bay area (fig. 6). Four exposures along the shorelines of Old Tampa Bay and Hillsborough Bay were mapped by Carr and Alverson (1959), indicating that the top of the aquifer is very near land surface. Areas of possible exposure by channelization include the 130-foot wide by 15- to 20-foot deep Lake Tarpon Outlet Canal; the 200- to 400-foot wide by 20- to 30-foot deep Tampa Bypass Canal; the 500-foot wide by 43- to 45-foot deep proposed ship channel in Hillsborough Bay; the 430-foot wide by 38-foot deep Alafia River ship channel; and numerous fingered channels for housing developments along Old Tampa Bay.

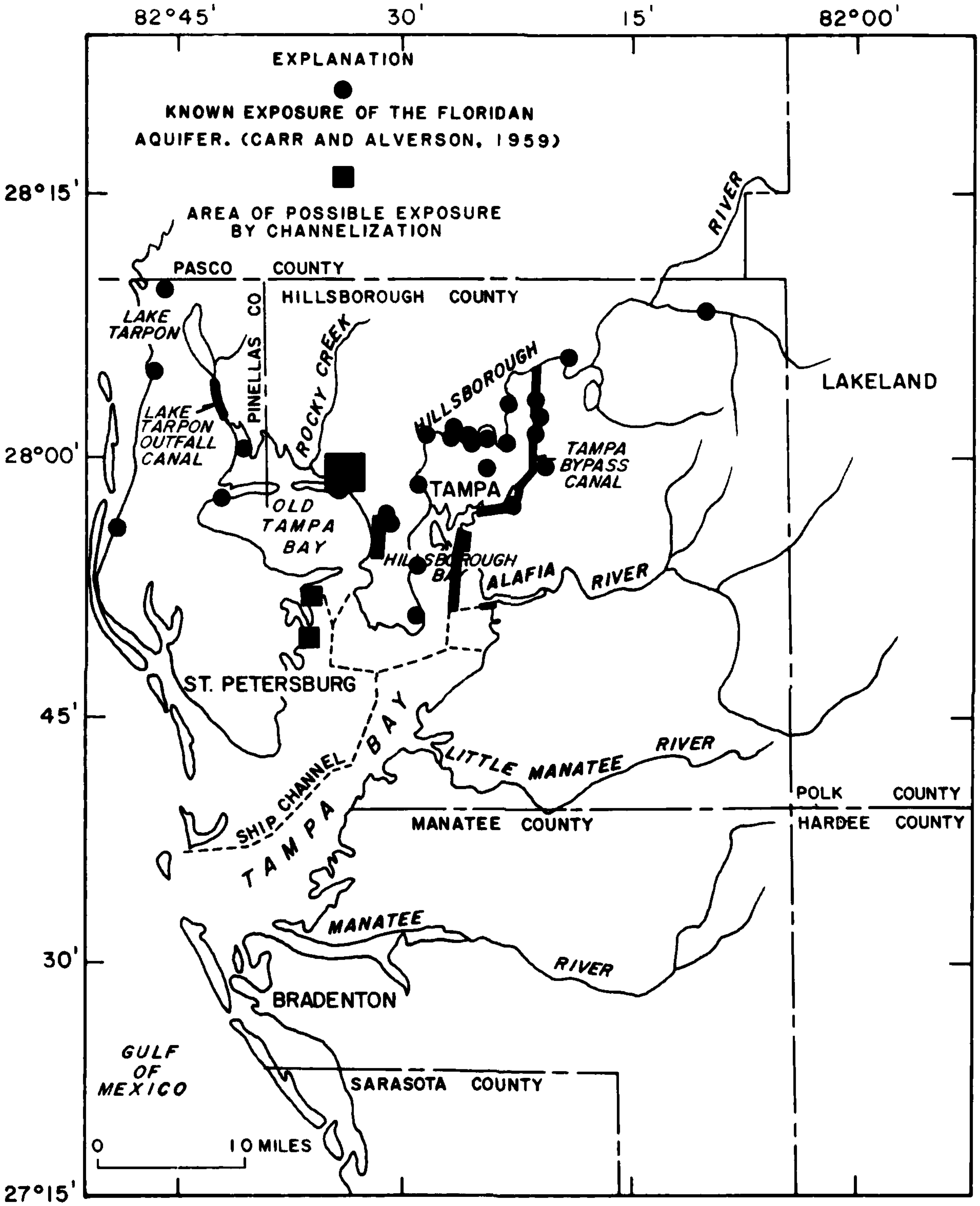


Figure 6.--Locations of known exposures of the Floridan aquifer and areas of possible exposure by channelization.

WATER USE

Both ground and surface water are used in the Tampa Bay area; use of ground water greatly exceeds use of surface water. Total water use during 1977 in Hillsborough, Manatee, and Pinellas Counties is estimated to have averaged about 420 Mgal/d (table 3). Use is greatest during the spring, as demand for irrigation water increases, and least during the rainy summer months, when irrigation ceases.

During 1977, pumpage from the Floridan aquifer for public, rural, industrial, and irrigation supplies totaled about 330 Mgal/d in the Tampa Bay area (table 3). Of this total, about 271 Mgal/d was freshwater. A total of about 59.3 Mgal/d was saline water pumped from wells at a phosphate processing plant (55 Mgal/d) at the mouth of the Alafia River, at a phosphate processing plant (1.3 Mgal/d) about 5 miles north of the Alafia River, and from wells at the city of Tampa incinerator (3 Mgal/d) about 10 miles to the north on Hillsborough Bay.

During 1977, use of fresh surface water totaled about 91 Mgal/d (table 3). Uses consisted primarily of diversion from the Hillsborough and Manatee Rivers to supply the city of Tampa and communities in Manatee County, respectively, and from springs tributary to the Alafia River for industrial purposes. In several areas, small amounts of water are withdrawn from streams and lakes for citrus-grove irrigation.

GROUND-WATER LEVELS AND MOVEMENT

The ultimate sources of freshwater recharge to the Floridan aquifer in the Tampa Bay area are vertical leakage through the confining bed and horizontal underflow from adjoining basins. Rain that falls over basins adjacent to Tampa Bay either runs off, is lost to evapotranspiration, or seeps to the water table in the surficial aquifer. Leakage from the surficial aquifer into the Floridan aquifer is controlled by the hydraulic conductivity of the intervening confining bed and the head difference between the water table and potentiometric surface. Underflow from adjoining basins is controlled by the regional gradient of the potentiometric surface and transmissivity of the aquifer. Once in the Floridan aquifer, water moves downgradient and eventually discharges through pumping wells, springs, or upward vertical leakage through the upper confining bed into the surficial aquifer, eventually discharging into Tampa Bay.

Figure 7 shows water-level fluctuations in the Floridan aquifer in six long-term monitoring wells adjacent to Tampa Bay. Seasonal and long-term trends shown in the top two hydrographs from wells north of Tampa Bay primarily reflect natural water-level conditions, whereas trends in the four wells along the east coast reflect pumping stresses imposed upon the natural trends. Natural seasonal fluctuations are 3 to 5 feet, and the long-term trend is one of slight decline that may be attributed to below average rainfall during 1965-75. Seasonal fluctuations in the stressed area have increased in amplitude from about 5 to 15 feet. The long-term trend in the annual peaks in the stressed area is one of decline of 5 to 10 feet during 1965-75 and one of a few feet of recovery during 1975-79 when rainfall returned to average. If a good interconnection

Table 3.--Water use in the Tampa Bay area, 1977
(compiled by Leach and Healy, 1980)

[GW - ground water used in Mgal/d; SW - surface water used in Mgal/d]

County	Public supply		Rural		Industrial		Irrigation		Subtotal		Total
	GW	SW	GW	SW	GW	SW	GW	SW	GW	SW	
Hillsborough	13.4	56.6	13.1	0	83.4	7.4	47.9	2.5	157.8	66.5	224.3
Manatee	0	22.4 1/	6.5	.2	3.4	0	41.0	2.2	50.9	24.8	75.7
Pinellas	88.7 2/	0	3.4	0	1.3	0	28.1	0	121.5	0	121.5
Subtotal	102.1	79.0	23.0	.2	88.1	7.4	117.0	4.7	330.2	91.3	421.5
Total	181.1		23.2		95.5		121.7		421.5		421.5

1/ Includes 5.7 Mgal/d exported to Sarasota County (A. D. Duerr, written commun., 1980).

2/ Includes 25.1 Mgal/d imported from Hillsborough County and 26.0 Mgal/d imported from Pasco County (A. D. Duerr, written commun., 1980).

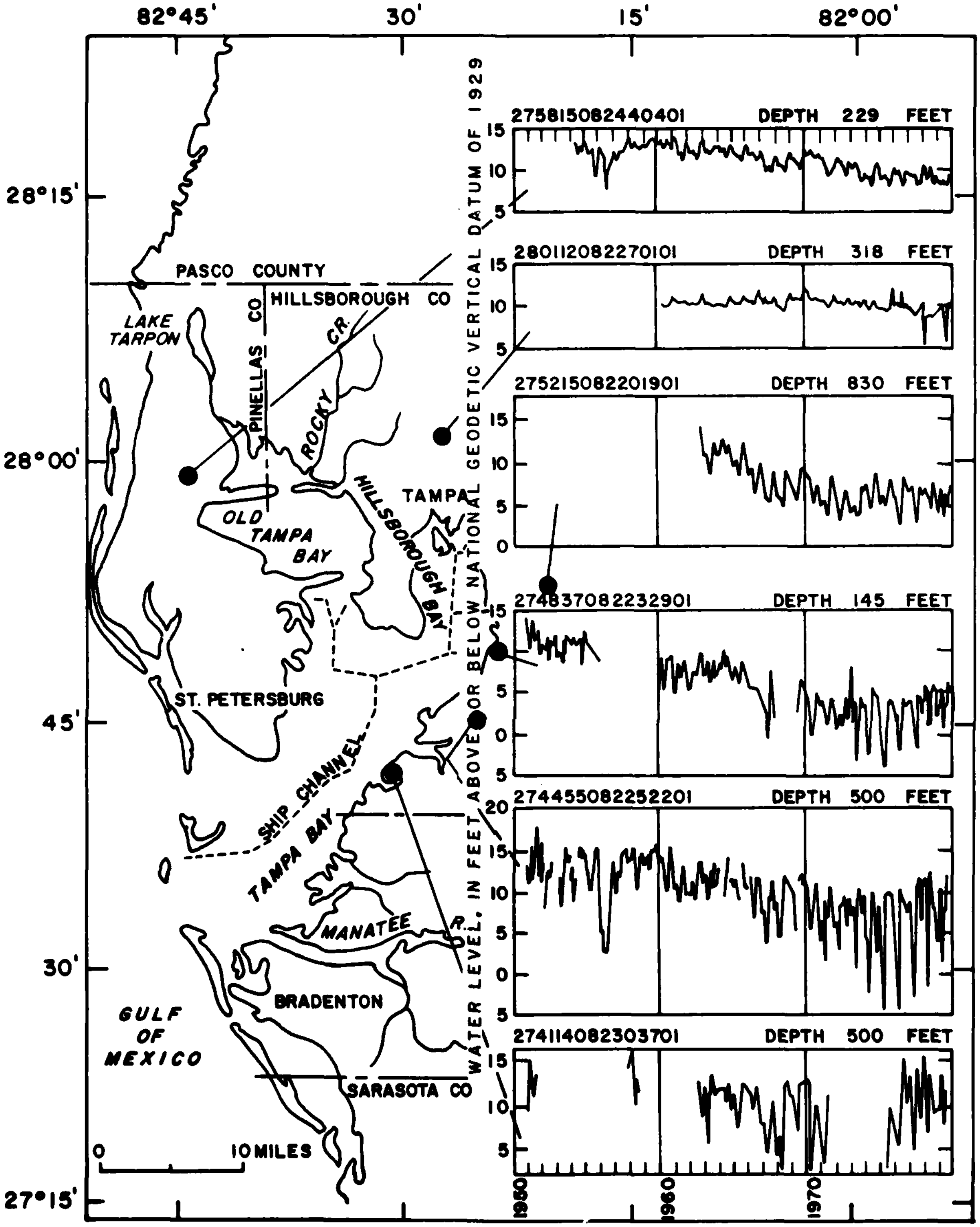


Figure 7.--Hydrographs of water levels in selected wells tapping the Floridan aquifer, 1950-79.

exists between Tampa Bay and the Floridan aquifer along the east coast of the bay, seasonal saltwater intrusion would occur because the potentiometric surface is frequently below sea level.

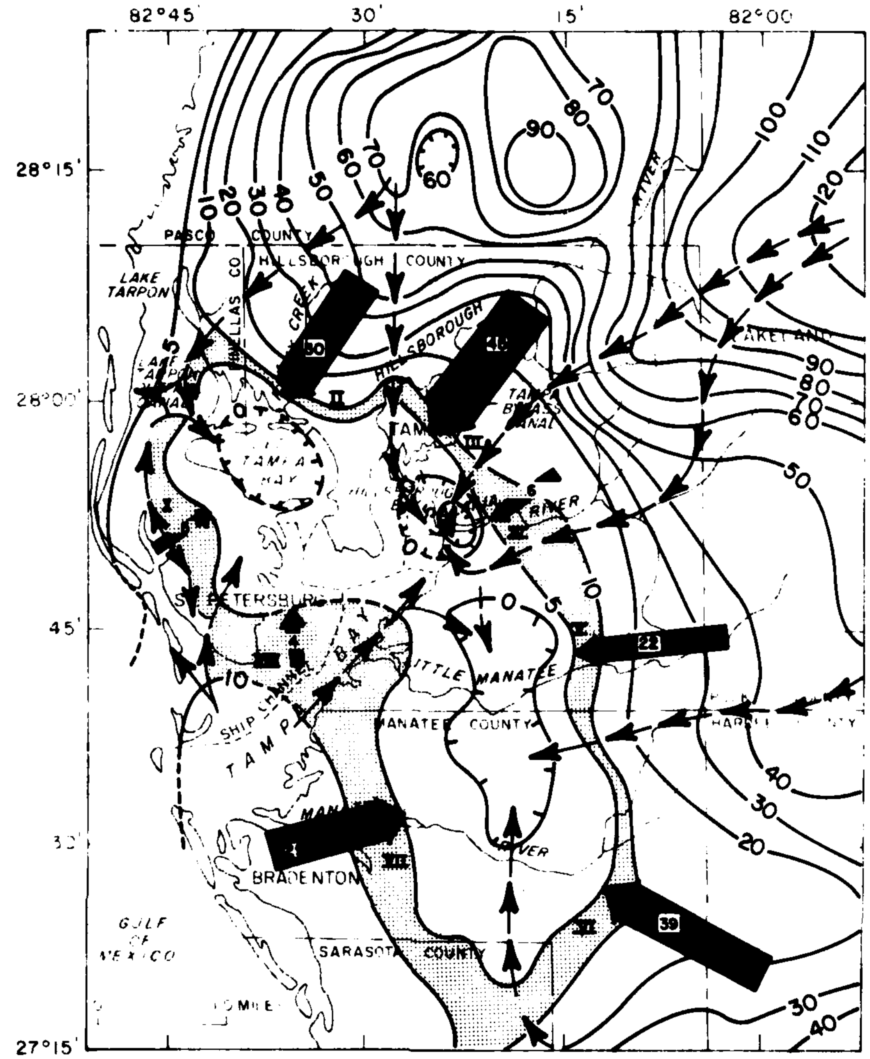
Twice yearly the U.S. Geological Survey prepares regional maps of the potentiometric surface of the Floridan aquifer. Figures 8 and 9 show the configuration of the potentiometric surface and direction and rate of ground-water movement in the Tampa Bay area during May and September 1978, which correspond to the ends of the dry and wet seasons, respectively (adapted from Wolansky and others, 1978a; 1978b).

The May 1978 map (fig. 8) depicts conditions when pumping stresses on the aquifer were high, primarily due to irrigation of citrus, truck crops, and lawns. Depressions in the potentiometric surface developed in several areas. The depression in Pasco County was a result of municipal pumping; the one at the mouth of the Alafia River was a result of industrial pumping; the one in southern Hillsborough and northern Manatee Counties was a result of agricultural pumping. The depression at Old Tampa Bay is evidence of natural discharge of ground water to the bay. The cones of depression at the Hillsborough-Manatee County line and beneath Hillsborough Bay indicate that all westward flow of freshwater is intercepted by pumping. At Hillsborough Bay, the cone of depression lies below sea level, thereby indicating that saltwater is seeping from the Bay to the Floridan aquifer.

Under the assumption that ground water moving toward the bay between two potentiometric-contour lines generally paralleling the coast will eventually discharge to the bay, flow-net analysis techniques (described by Walton, 1970, p. 188) were used to compute ground-water discharge to the bay. Table 4 lists the data and flow equation used in the computations. The rate of ground-water movement between the 10-foot and 5-foot contours (stippled area on fig. 8) totals about 180 Mgal/d, with about 90 Mgal/d moving toward Tampa Bay and about 90 Mgal/d moving toward the southern Hillsborough-northern Manatee County depression. Part of the water moving toward Hillsborough Bay is intercepted by pumping at the mouth of the Alafia River.

The September 1978 map (fig. 9) depicts conditions when pumping stresses on the aquifer were relatively small, primarily due to near-zero irrigation pumpage. Depressions remained in the potentiometric surface in Pasco County and at the mouth of the Alafia River due to continued municipal and industrial pumping; however, because agricultural pumping ceased in early summer, the large cone of depression along the Hillsborough-Manatee County line recovered, and ground-water gradients toward Tampa Bay were restored. The rate of ground-water movement toward the bay, between the 20-foot and 10-foot contours in Hillsborough and Manatee Counties and the 10-foot and 5-foot contours in Pinellas County (stippled area on fig. 9), totaled about 118 Mgal/d. The cone of depression caused by pumping saline water from industrial wells at the mouth of the Alafia River remained a major feature of the potentiometric surface.

Annual fresh ground-water leakage to Tampa Bay, as indicated by the May and September extremes, ranges between 5.4 and 7.1 inches over the 350-mi^2 bay area. Compared to contributions to the bay by rainfall (55 inches), streamflow (84 inches), and sewage effluent (4.7 inches), upward leakage through the confining bed is small and accounts for only about 4 percent of the total freshwater input to the bay. Compared to total aquifer discharge of about 812 Mgal/d (382 Mgal/d as base flow in streams, 330 Mgal/d as ground-water pumpage, and 100 Mgal/d as leakage), leakage from the Floridan aquifer to Tampa Bay accounts for about 12 percent of the aquifer's discharge.



EXPLANATION

——60——

POTENTIOMETRIC CONTOUR
Shows altitude of potentiometric surface of Floridan aquifer, May 1978. Contour interval 5 and 10 feet. National Geodetic Vertical Datum of 1929.

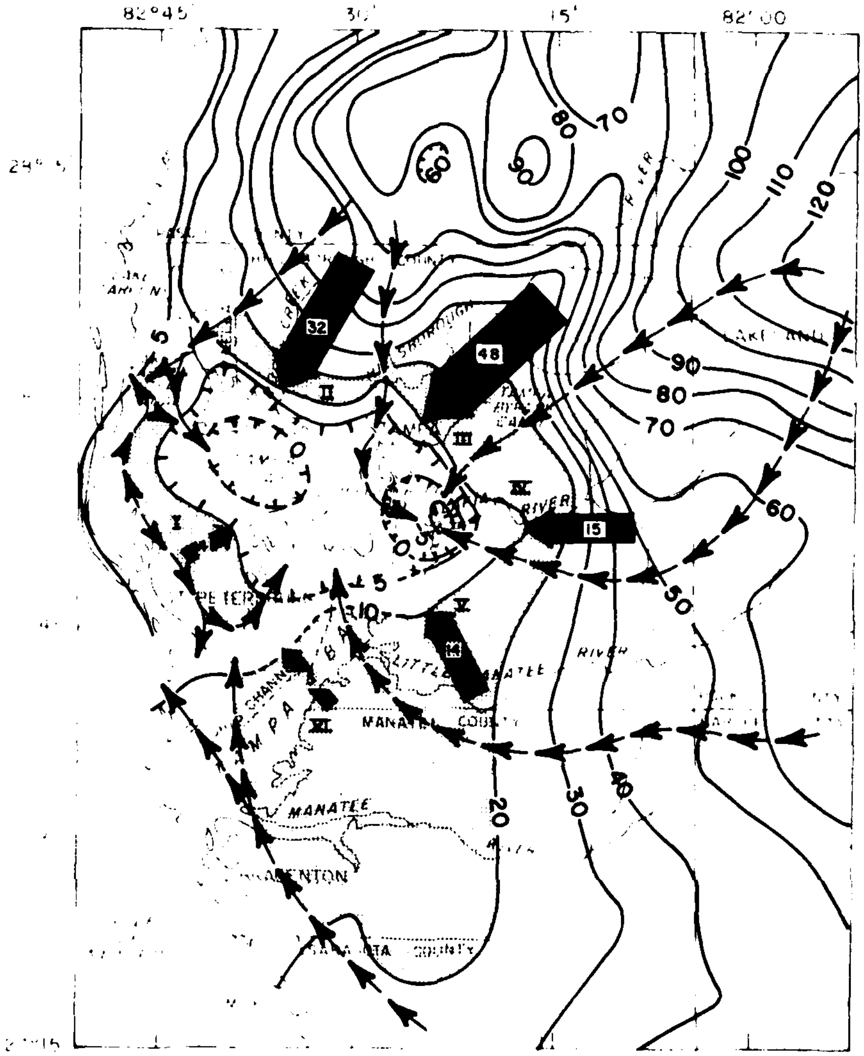
IV

FLOW LINE
Shows direction of ground-water movement. Roman numeral denotes number of flow zone between flow lines (see table 4).

50

FLOW RATE
Shows rate of ground-water movement in million gallons per day across stippled area and between adjacent flow lines. Size of arrow is proportional to flow rate.

Figure 8.--Potentiometric surface of the Floridan aquifer and direction and rate of ground-water movement, May 1978 (modified from Wolansky and others, 1978a).



EXPLANATION

—20—

POTENTIOMETRIC CONTOUR
Shows altitude of potentiometric surface of Floridan aquifer, September 1978. Contour interval 5 and 10 feet. National Geodetic Vertical Datum of 1929.

IV

FLOW LINE
Shows direction of ground-water movement. Roman numeral denotes number of flow zone between flow lines (see table 4)

15

FLOW RATE
Shows rate of ground-water movement in million gallons per day across stippled area and between adjacent flow lines. Size of arrow is proportional to flow rate

Figure 9.--Potentiometric surface of the Floridan aquifer and direction and rate of ground-water movement, September 1978 (modified from Wolansky and others, 1978b).

Table 4.--Flow-net analysis data for May and September 1978

Flow zone	(T) Transmissivity (ft^2/d)	(I) Potentiometric gradient (ft/mi)	(L) Length of flow zone (mi)	(Q) Discharge rate[1/] (Mgal/d)
		May 1978		
I	30,000	1.1	20	5
II	67,000	3.8	16	30
III	200,000	3.3	9	45
IV	100,000	1.2	7	6
V	100,000	1.6	18	22
VI	100,000	2.1	25	39
VII	100,000	1.1	35	29
VIII	67,000	.7	12	4
Total				180
		September 1978		
I	30,000	.9	20	4
II	67,000	4.3	15	32
III	200,000	2.9	11	48
IV	100,000	1.8	11	15
V	100,000	1.2	16	14
VI	100,000	.4	18	5
Total				118

1/ Discharge rates through each flow zone were computed by Darcy's formula: $Q = 7.48 \times 10^{-6}$ TIL. The method assumes strictly lateral flow through the aquifer and does not compensate for any vertical component of flow, which may be significant along the coast. Flow zones and potentiometric gradients were measured from figures 8 and 9. Estimates of transmissivity were based on aquifer tests in published and unpublished reports.

Computed ground-water discharges to Tampa Bay probably represent maximum amounts. As there is some indication of vertical hydraulic separation between the upper and lower parts of the Floridan aquifer (Sinclair, 1979; Hickey, 1981), discharge to the bay could be restricted to the upper part of the aquifer, and thereby be less than computed by flow-net analysis. Also, because of lack of control, the zero contour in the bay could easily have been mapped to fall along the shoreline. If so, a significant reduction in the computed discharge to the northern part of the bay would result. Broadening of the zero closed contour would indicate equilibrium between the potentiometric surface and sea level and, thus, zero discharge.

Relative magnitudes of hydraulic interconnection between the bay and aquifer can be defined on the basis of water levels and confining-bed thickness. Because leakage is inversely proportional to confining-bed thickness when hydraulic conductivity is constant, a poorer hydraulic interconnection will exist in the southern part of Tampa Bay where the confining bed is thick, and a better hydraulic interconnection will exist in Old Tampa and Hillsborough Bays where the confining bed is thin. These conditions are further substantiated by the potentiometric maps (figs. 8 and 9) that show heads in the aquifer much above sea level in the south where upward movement is impeded by the thick confining bed. In the north where the confining bed is thin, the potentiometric surface is at nearly the same altitude as the bay level, thus indicating a good hydraulic interconnection between the bay and aquifer.

SALTWATER-FRESHWATER RELATIONS

A saltwater-freshwater transition zone exists along the coast of Tampa Bay in the underlying Floridan aquifer. The theoretical position of this zone is describable in some areas by hydraulic relations, and its actual position may be delineated by water-quality sampling. If movement of the transition zone from its predevelopment position has occurred, the nature of the movement may be recent lateral saltwater intrusion along the coast, upconing of ancient saltwater that has never been flushed from the aquifer, or a combination of these processes.

Chloride concentrations of ground water in the Tampa Bay area vary widely. Inland, chloride concentrations range from 10 to 25 mg/L, which is considered to be the "background" range for fresh ground water unmixed with saltwater. Along the coast, at least part of the Floridan aquifer contains saltwater with chloride concentrations ranging from 14,000 to 19,000 mg/L. This range is approximately the same as that observed between Tampa Bay water and Gulf water. The inland limit of water with this concentration range is considered to be the saltwater front.

Figure 10 shows a conceptual view of saltwater-freshwater relations in the Tampa Bay area under predevelopment conditions with no channelization or pumping. The saltwater fronts in the Floridan and surficial aquifers are considered to be stationary interfaces with freshwater and transition water flowing seaward over them and static seawater below them. As shown by Hubbert (1940), the saltwater front must rise in the direction of freshwater flow, its elevation depending on the freshwater head on the interface itself. Because the equipotential lines are curved, the head on the saltwater front differs from that vertically above it. However, if vertical head gradients are small, the heads at the saltwater front will be about the same as the measured heads shown on the potentiometric-surface maps. Under this condition, the saltwater front dips landward at 40 times the gradient shown by the potentiometric-surface maps.

Under predevelopment conditions, water is recharged vertically to the Floridan aquifer inland, where the water table is above the potentiometric surface; moves horizontally through the Floridan aquifer toward the coast; and eventually discharges vertically near the coast, where the potentiometric surface is above the water table.

Under postdevelopment conditions, pumping may lower the potentiometric surface along the coast, thereby changing the equilibrium position of the saltwater front. Where the potentiometric surface is lowered below bay level along the coast, saltwater will leak downward into the Floridan aquifer.

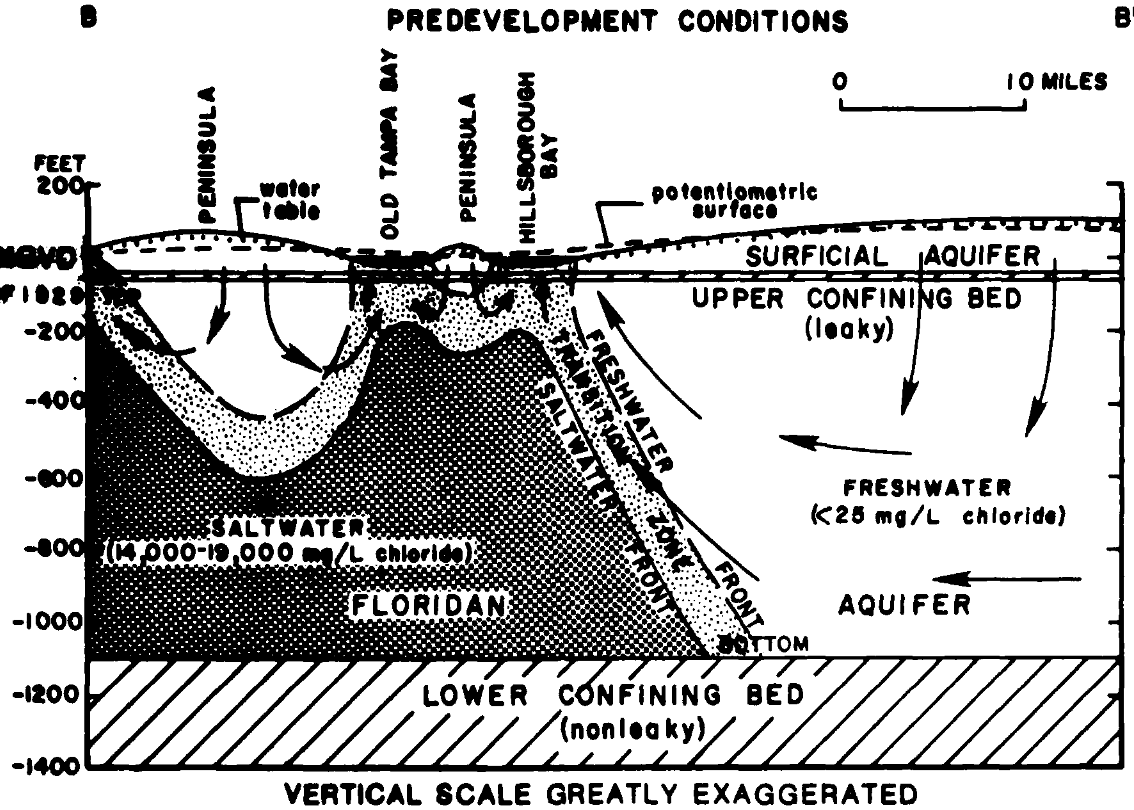


Figure 10.--Conceptual view of saltwater-freshwater relations in the Tampa Bay area under predevelopment conditions (B-B' in figure 11).

A well drilled into the transition zone can yield water ranging in quality from fresh to saline, depending upon well depth and pumping rate. Supply wells seldom tap only the lower part of the aquifer, and definition of the position of the deeper parts of the saltwater front on the basis of field sampling is virtually impossible. Also, because the front slopes, areal mapping of the position of any isochlor in the transition zone, such as the 250-mg/L chloride-concentration line, should be qualified with respect to representing "upper," "middle," or "lower" part of the aquifer to be meaningful.

Hydraulic Analysis

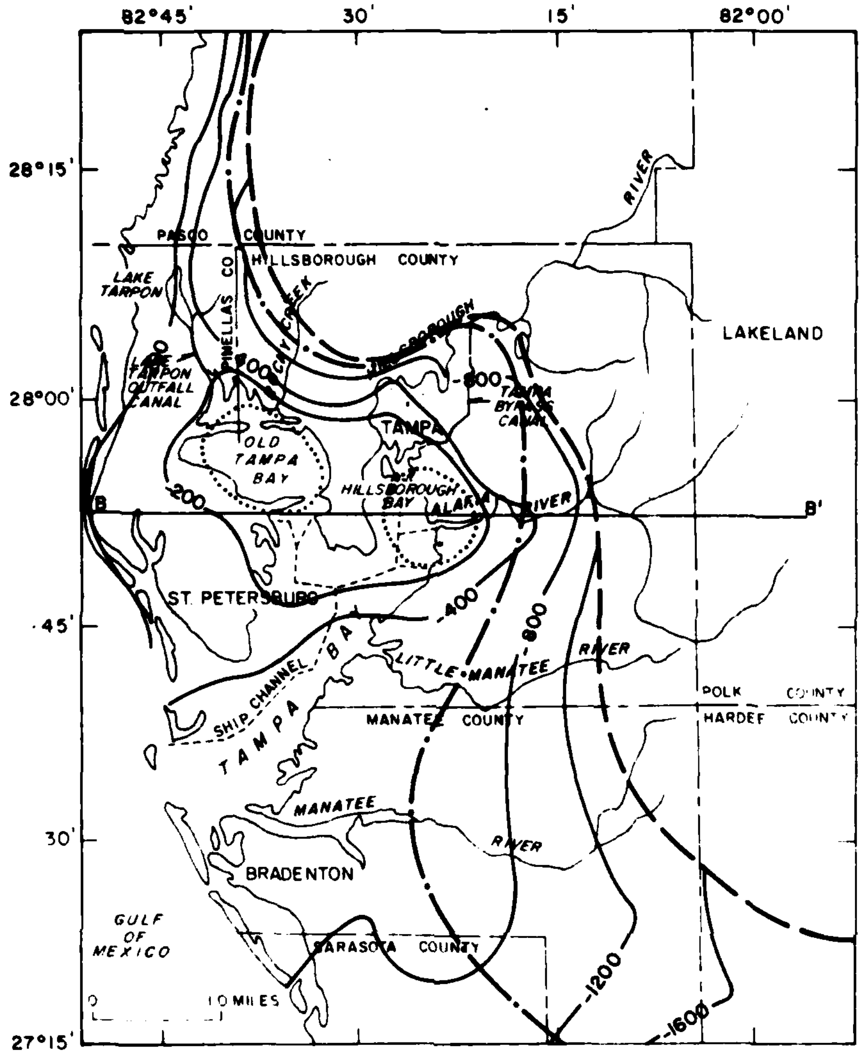
Based on the conceptual model of the ground-water flow regime, a theoretical equilibrium position of the saltwater front compatible with September 1978 potentiometric data was determined. It was assumed that vertical head gradients were small and that therefore the equilibrium position of the saltwater front could be estimated by applying Hubbert's relation to the September 1978 potentiometric-surface map (fig. 9) to generate contours of the theoretical interface elevation compatible with that head data. These contours were used together with contours of the top and bottom of the Floridan aquifer to define lines of intersection of the saltwater front with those aquifer boundaries. A similar analysis was carried out for predevelopment conditions using a potentiometric map developed by Johnston and others (1980) for the predevelopment period. The results of these analyses are summarized by figure 11, which shows altitude contours for the theoretical saltwater front associated with the 1978 potentiometric surface, lines of intersection of that surface with the top and bottom of the aquifer, and the line of intersection of the theoretical saltwater front for predevelopment conditions with the bottom of the aquifer.

In the northern part of the area, the saltwater front associated with the September 1978 potentiometric surface slopes downward to the northeast from less than 200 feet to more than 800 feet below sea level at an average gradient of about 150 ft/mi. In the southern part of the area, the front slopes downward to the southeast from about 400 to 1,600 feet below sea level at an average gradient of about 25 ft/mi.

The position of the bottom of the saltwater front calculated for September 1978 lies 5 to 10 miles inland north of Tampa Bay and 15 to 30 miles inland (from the Gulf of Mexico) east of Tampa Bay. The theoretical equilibrium position of the bottom of the front for predevelopment conditions lies about halfway between the coast and the 1978 theoretical position south of the Alafia River; north of the river, it converges with the 1978 theoretical position. Thus, the saltwater front probably has remained stable since the early 1930's in the northern area and has moved inland in the southern area. If the theoretical position of the bottom of the front were to reach an equilibrium position compatible with September 1978 potentiometric head values, the maximum intrusion would lie in the area of the Manatee River and southward where the predevelopment and September 1978 positions are farthest apart. In order for the interface to have reached the new equilibrium position in September 1978, it would have been necessary for the saltwater front to move 17 miles in 50 years in the area of the Manatee River, which represents a rate of about 5 ft/d.

Based on aquifer hydraulics, Wilson (1981) determined that the saltwater front is moving inland in the area of the Manatee River at an average rate of about 0.3 ft/d; in highly permeable zones, the rate might be as much as 4 ft/d. At these rates, the time required for the bottom of the saltwater front to move inland 17 miles along the Manatee River would range from 60 to 800 years. Development in this area has been in progress only for about 50 years, and it therefore appears unlikely that the saltwater front has stabilized; rather, the front is probably still in motion and lies somewhere between the predevelopment and theoretical 1978 equilibrium positions.

In figure 11, the saltwater front compatible with 1978 heads intersects the top of the Floridan aquifer in two circular lines of intersection, one in Hillsborough Bay and one in Old Tampa Bay. This implies that if an equilibrium position of the front compatible with 1978 heads were achieved, cones of static saltwater should extend upward from the regional saltwater front, intersecting the top of the aquifer in these two circular areas. As noted above, however, it appears very unlikely that a stationary saltwater front compatible with 1978 heads has yet been established in the aquifer. In the Hillsborough Bay area, the potentiometric surface appears to be below sea level at present; this implies that saline water from the bay is flowing downward through the confining materials, which in this area are thin and possibly breached by channelization. Thus, it is likely that saltwater is leaking into the aquifer from above in the Hillsborough Bay area, and that the upper part of the aquifer is in the process of becoming saline here. In the Old Tampa Bay area on the other hand, potentiometric heads appear to be about equal to sea level and there is probably very little flow between the bay and the aquifer.



EXPLANATION

——-800——

SALTWATER-FRONT CONTOUR
Shows theoretical altitude of the saltwater front that would be compatible with the September 1978 potentiometric heads if an equilibrium had been established. Contour interval 200 and 400 feet. Datum is National Geodetic Vertical Datum of 1929.

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TOP OF SALTWATER FRONT
Shows intersection between the top of the Floridan aquifer and the theoretical position of the saltwater front that would be compatible with the September 1978 potentiometric heads if an equilibrium had been established.

— — — —

BOTTOM OF SALTWATER FRONT

Shows intersection between the bottom of the Floridan aquifer and the theoretical position of the saltwater front that would be compatible with the September 1978 potentiometric heads if an equilibrium had been established.

—·—·—

BOTTOM OF PREDEVELOPMENT SALTWATER FRONT

Shows intersection between the bottom of the Floridan aquifer and the theoretical position of the saltwater front that would be compatible with predevelopment potentiometric heads (Johnson and others, 1980).

Figure 11.--Comparison of the theoretical equilibrium positions of the saltwater front compatible with potentiometric-surface maps for September 1978 and estimated predevelopment conditions.

Water-Quality Analysis

Accurate delineation of the saltwater front on the basis of water-quality sampling of existing wells is virtually impossible as very few wells tap discrete intervals in only the saltwater zone. A more common procedure has been to map the 250-mg/L line of equal chloride concentration, which lies within the transition zone, as the interface between potable and nonpotable water. Although most wells do not tap discrete depth intervals, the chloride gradient can be generalized using data from these wells. If data from shallow wells tapping only the upper part of the aquifer are used, the approximate isochlor trace in the upper part can be mapped, from which generalizations about the extent of saltwater intrusion and bay-aquifer interconnection can be made.

The position of the 250-mg/L line of equal chloride concentration (fig. 12) in the upper part of the Floridan aquifer (Causseaux and Fretwell, 1982) was determined by interpretation of chloride-concentration data for wells open only to the upper producing zone of the Floridan aquifer. Some data were collected prior to the 1970's; however, current conditions are presumed to be represented because of the relatively slow movement of the interface. Most data were collected at wells having open holes located within the upper 250 feet of the Floridan aquifer. Because of the southwestward dip of the aquifer, the depth to the top of the strata containing the mapped position of the interface is greatest in the southern part of the Tampa Bay area.

The map is generalized and serves principally to guide attention to regional differences in chloride distribution. Areas of probable landward intrusion of saltwater occur near the mouth of the Manatee River, at the mouth of the Hillsborough River, along the interbay peninsula between Old Tampa and Hillsborough Bays, along the Lake Tarpon trough extending northwest from upper Old Tampa Bay to the Gulf of Mexico, and at the southern tip of the Pinellas Peninsula.

The 250-mg/L line of equal chloride concentration lies near shore or just offshore along much of the eastern coast of Tampa Bay. According to the previous hydraulic analysis, this is the area of greatest potential for saltwater intrusion. The offshore position of the line in the southeastern part of Tampa Bay is not certain because of paucity of field data. A water sample from a flowing well (depth unknown) on the causeway between St. Petersburg and Bradenton had a chloride concentration of 1,300 mg/L (May 18, 1979). A sample collected from a 175-foot deep well in Hillsborough Bay had a chloride concentration of 14,000 mg/L (April 4, 1978). A comparison of the two samples suggests that the offshore distance of the 250-mg/L line increases from north to south. The position of the line, combined with geologic data, indicates that the degree of bay-aquifer interconnection decreases from north to south where the thick intervening confining bed impedes leakage.

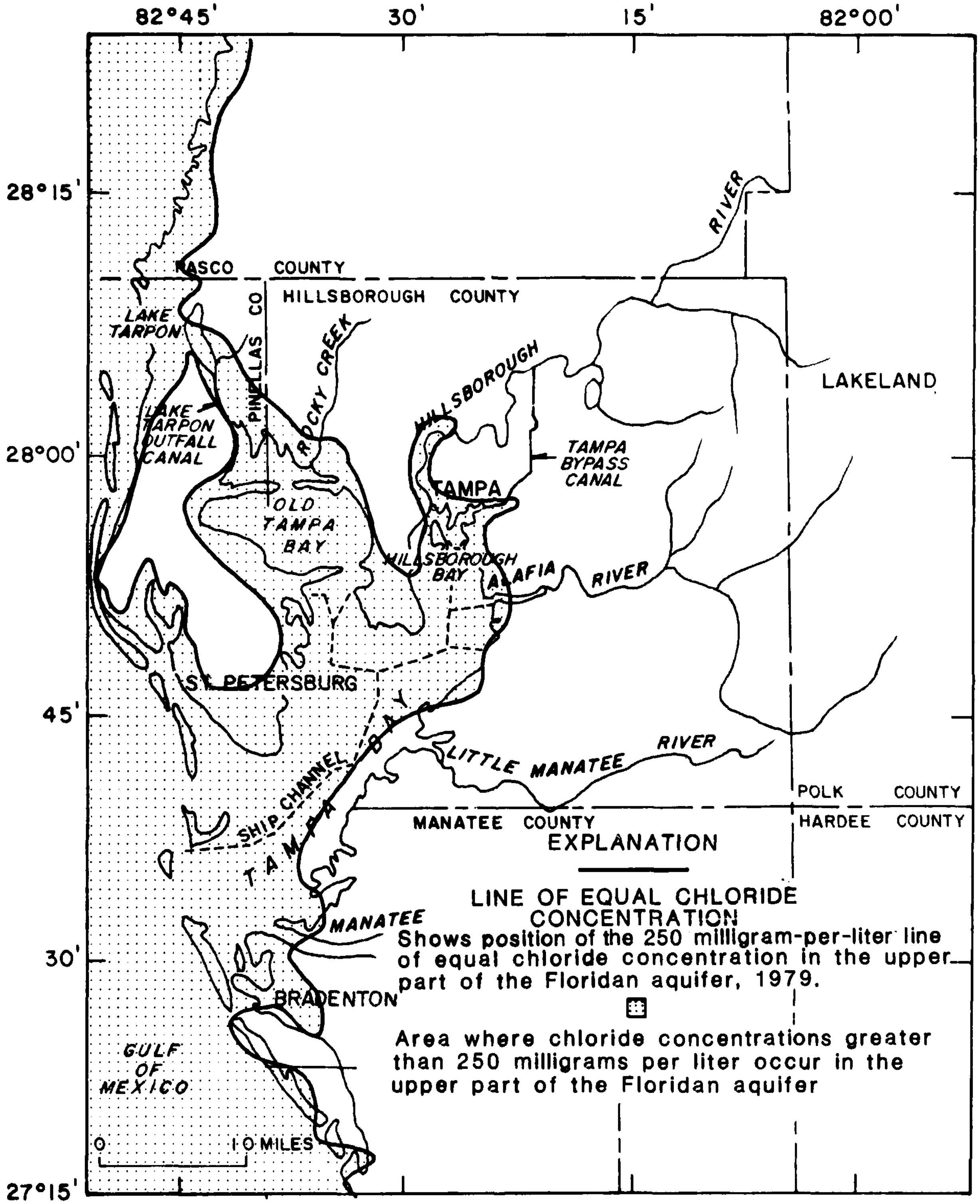


Figure 12.--Position of the 250-milligram-per-liter line of equal chloride concentration in the upper part of the Floridan aquifer (Causseaux and Fretwell, 1982).

Seasonal and long-term trends of chloride concentration in the Floridan aquifer can be determined using data from nonpumping monitor wells along the Tampa Bay coast (fig. 13). Wells 1 and 3 tap the freshwater zone (Cl < 25 mg/L), well 5 intersects the plane of the freshwater-transition zone (Cl = 20 to 50 mg/L), and wells 2 and 4 tap the transition zone (Cl = 25 to 19,000 mg/L). Amplitudes of seasonal changes are greater and long-term average trends are toward higher chloride concentrations as the saltwater front is approached. For example, at well 3, seasonal changes in the freshwater zone are less than 5 mg/L, and the long-term average trend is stable at 15 mg/L; at well 4, in the transition zone, seasonal changes are about 50 mg/L, and the 1970-79 average trend rises from about 77 mg/L to about 113 mg/L; and at well 2, in the transition zone, seasonal changes are about 2,000 mg/L, and the 1971-79 average trend rises from about 2,300 mg/L to about 3,600 mg/L. The trends in the five chloride-concentration hydrographs indicate that the saltwater front has either stabilized or is moving inland.

Theoretically, fluctuations in the potentiometric surface should cause movement of the saltwater front, and this movement should be reflected in changing chloride concentrations of water from coastal monitoring wells. In the previous section on hydraulic analysis, the potential for saltwater intrusion into the Floridan aquifer was shown to be greatest along the east coast of Tampa Bay where the potentiometric surface has been progressively lowered. The increasing chloride-concentration trend at well 4 corresponds with the areal potentiometric-surface decline, but chloride-concentration trends at wells 3 and 5 do not. Both wells 3 and 5 are deep enough to pierce the plane of the theoretical saltwater front (fig. 11, Cl = 14,000 to 19,000 mg/L), yet their chloride concentrations are less than 50 mg/L and stable. This indicates that the saltwater front has not reached an equilibrium position compatible with the 1978 potentiometric surface or that most of the pumped water comes from above the transition zone.

Additional insight into the correlation between chloride concentration and potentiometric surface is gained through an analysis of short-term microtrends in these parameters. Figure 14 shows the relations between chloride concentrations and water levels as observed at wells 2 and 4 during the period 1970-79. At both wells, little correlation exists between chloride concentrations and water levels, as seasonal peaks rarely coincide. If there were any correlation, highs in chloride value (troughs in the chloride curves of figure 14) would be expected to follow lows in water level. A visual analysis of harmonic trends indicates that chloride peaks lag 3 to 6 months behind water-level peaks, but this relation is also poor. Apparently, the actual rate of movement of the saltwater front is controlled by transmissivity and long-term head changes, whereas short-term fluctuations of the potentiometric surfaces reflect nearly instantaneous responses to pressure changes within the confined Floridan aquifer. Simply, pressure changes are reflected instantaneously, whereas actual movement of water takes a long time.

The decline in water levels caused by pumping in the Tampa Bay area has created the potential for saltwater intrusion into the freshwater aquifer. The effects of the increased ground-water withdrawals can be observed through a water-level and water-quality monitoring network. Installation of sets of shallow and deep monitor wells for obtaining water-level measurements and water samples for chemical analysis at multiple depths could be used to accurately determine the rate and extent of saltwater intrusion. The network could act as an early-warning device for detecting saltwater intrusion and serve as a base for possible later construction of a computer model of the saltwater-freshwater interface along the coast.

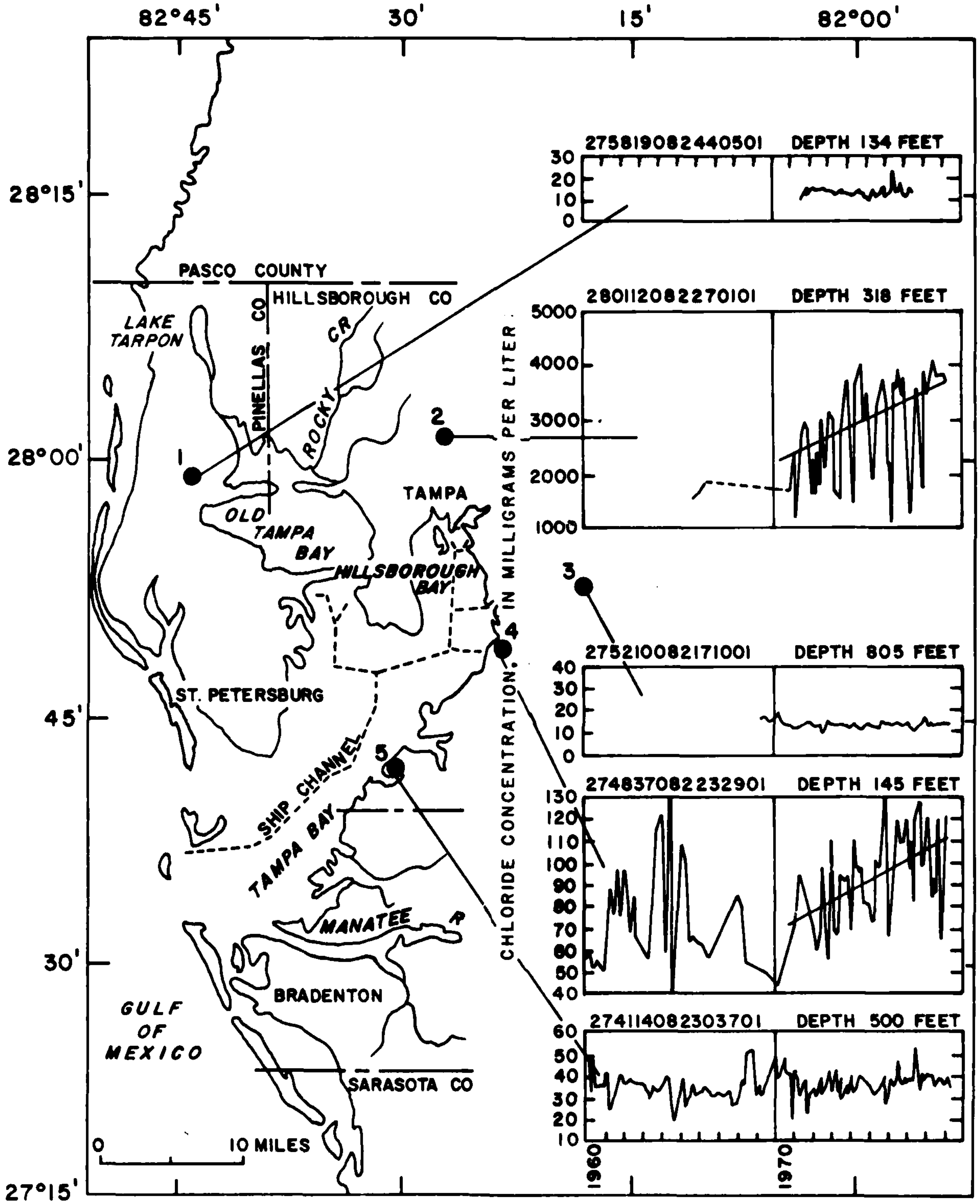


Figure 13.--Chloride concentrations in water from the Floridan aquifer from long-term sampling wells along the coast of Tampa Bay.

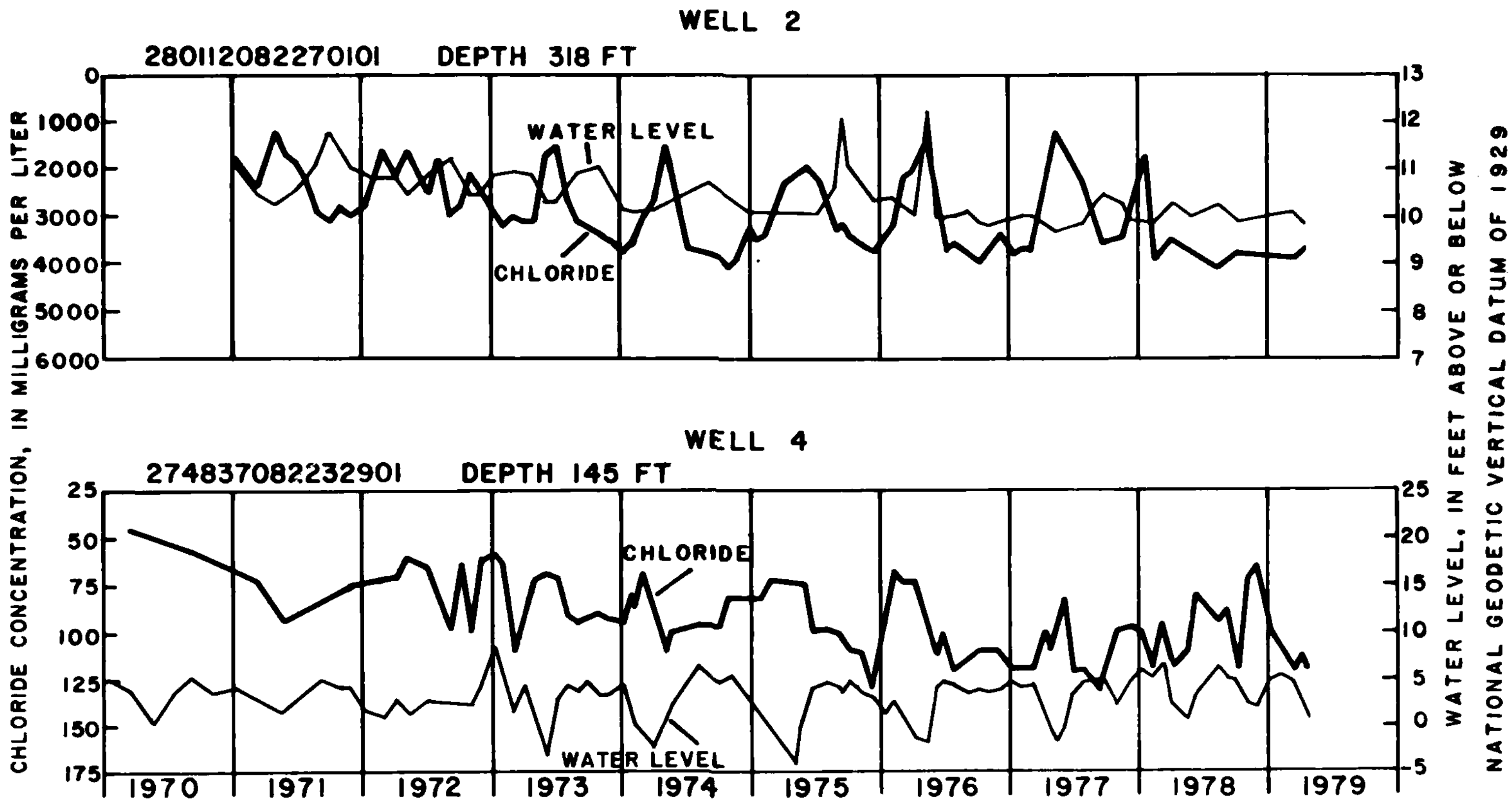


Figure 14.--Chloride concentrations and water levels in the Floridan aquifer, 1970-79 (see figure 13 for well locations).

IMPACT OF HARBOR IMPROVEMENT

One important aspect of the assessment of the hydraulic interconnection between Tampa Bay and the Floridan aquifer is to assess the impact, if any, of the harbor improvement project, particularly in Hillsborough Bay. There, channel deepening and widening in the 7.5-mile-long main ship channel and the 3.6-mile-long Alafia River channel will expose about 15.3 million ft^2 (0.55 mi^2, or about 0.2 percent of the 350-mi^2 bay) of the Floridan aquifer surface to salty bay water along some stretches and considerably thin the upper confining bed along other stretches. In addition, there are two pumping centers along the shore pumping 1.3 Mgal/d and 55 Mgal/d of saltwater within 3 miles of the main ship channel. The large 55 Mgal/d pumping center is about 1,500 feet north of the turning basin at the east end of the Alafia River channel. The smaller pumping center is at the head of Hillsborough Bay about 2,000 feet east of the proposed turning basin. The points of concern are the degree of impact of channelization on the water balance, its relation to nearby pumping, and its effect on the regional ground-water flow regime.

Two approaches were selected to determine the hydrologic effects of harbor improvement. First, a digital model of ground-water flow was utilized in the assessment of the Alafia River and main ship channels because channel deepening there will cut into the top of the Floridan aquifer where the upper confining bed is of variable thickness. Second, an analytical technique was utilized in the assessment of the Big Bend channel located about 5 miles south of the Alafia River channel because channel deepening there will only thin the uniformly thick upper confining bed. Because channelization will occur within or very near the area where the Floridan aquifer theoretically is filled with saltwater (fig. 11), it was assumed that the impact would not reach beyond this zone; therefore, the approaches need not consider variability in viscosity and density of bay-aquifer interflow or movement of the saltwater front.

Model Analysis of the Alafia River and Main Ship Channels

Estimates of the anticipated change in leakage due to dredging the Alafia River and main ship channels were calculated using a computer model of ground-water flow. The U.S. Geological Survey standard two-dimensional finite-difference model, developed by Trescott and others (1976), was selected for the analysis. The modeled area, shown in figure 15, occupies 97 mi^2 and centers on the main pumping center (55 Mgal/d) at the mouth of the Alafia River.

The model grid is alined orthogonally with the main ship channel. It comprises 884 nodes formed by the intersections of 26 vertical columns and 34 horizontal rows (fig. 16). A narrow 400-foot wide column coincides with the main ship channel. Widths of the columns expand laterally to reduce their number, thereby reducing computer storage requirements. A similar spacing of the rows was assigned so that a finer model grid would overlie the aquifer exposures in the turning basin at the northern end of the main ship channel and in the area of the Alafia River channel. Model conceptualization, calibration procedures, and sensitivity to errors in the input parameters are described in the "Supplemental Data" section.

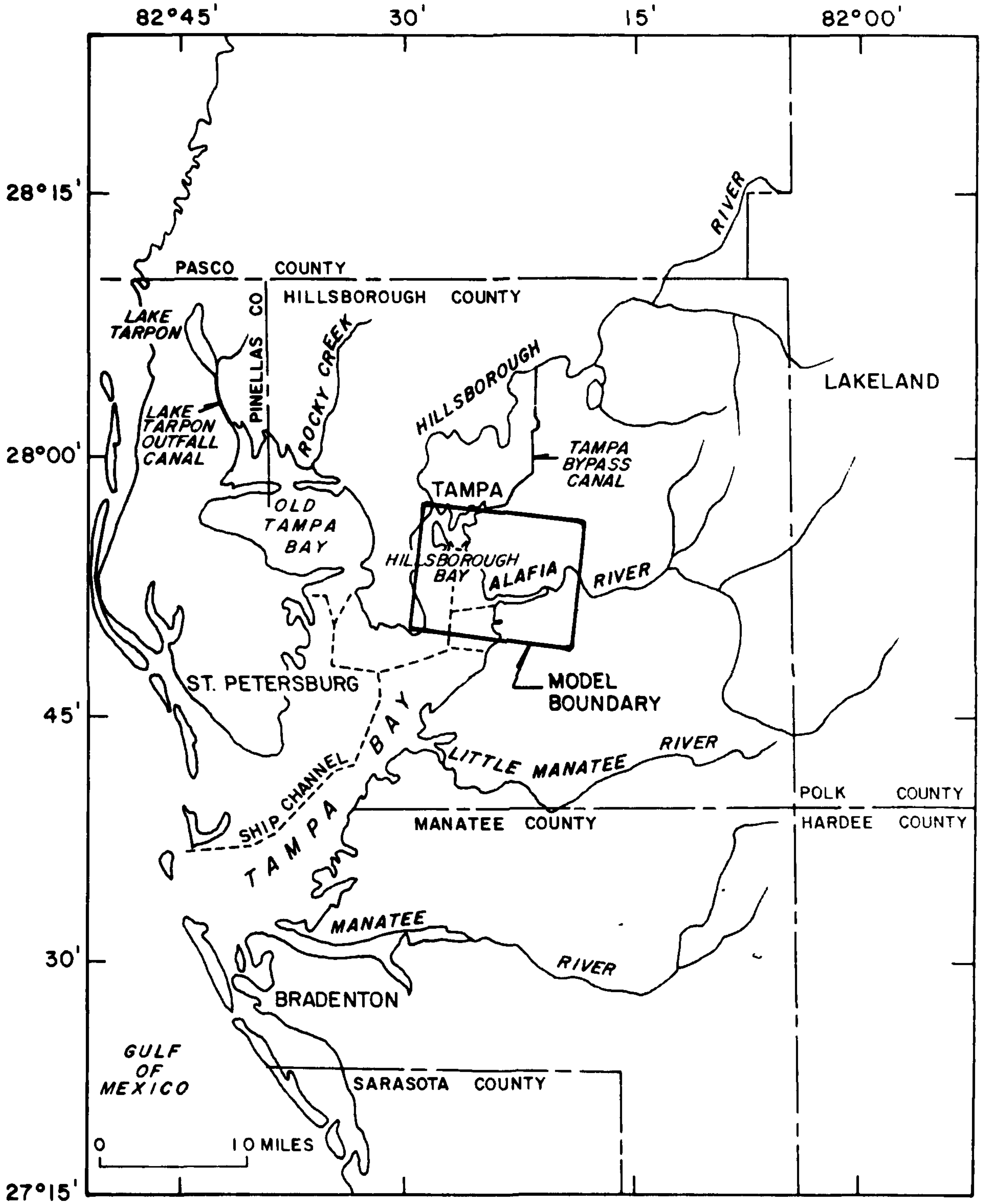


Figure 15.--Area selected for model analysis of the effects of harbor improvement on Tampa Bay-Floridan aquifer interflow.

Inflow, outflow, and water levels under five options of channelization and pumping were simulated through the model. They are:

1. Existing channels, with pumping.
2. Dredge main ship channel only, with pumping.
3. Dredge main ship channel and Alafia River channel, with pumping.
4. Existing channels, no pumping.
5. Dredge main ship channel and Alafia River channel, no pumping.

The no-pumping options were included to evaluate the potential impact of channelization should pumping for phosphate-processing cooling water eventually cease as the phosphate resource is depleted.

The water balance computed by the model for each option is presented in table 5. The water balance equates inflow and outflow as:

$$\underline{\text{Inflow}} \quad = \quad \underline{\text{Outflow}}$$

$$\text{Downward Leakage} + \text{Boundary Inflow} = \text{Upward Leakage} + \text{Boundary Outflow} + \text{Pumpage}$$

The following five sections concern changes in water balance under the modeled options of channelization. The sixth section concerns limitations of the model analysis.

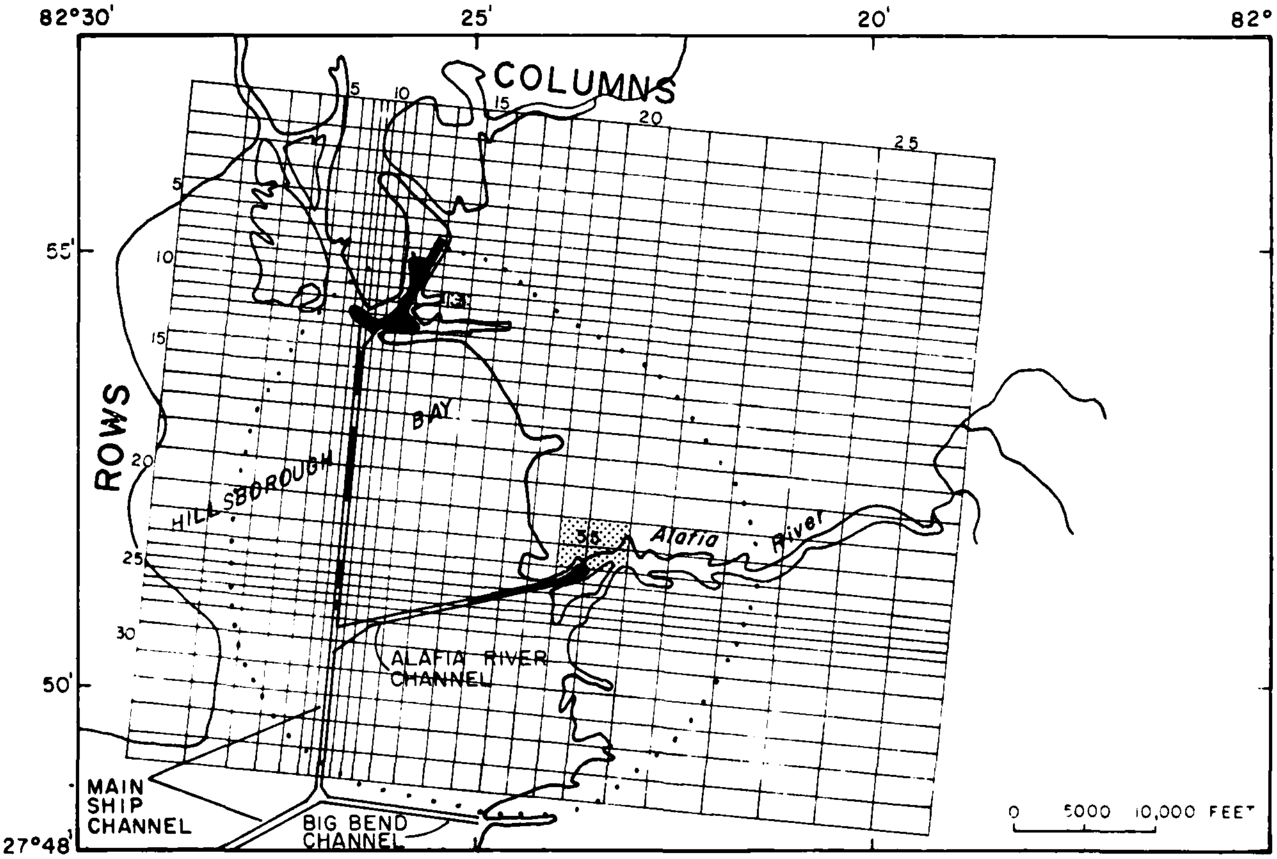
Existing Channels, with Pumping

The existing conditions of channelization and pumping are the basis for the steady-state calibration. Model computed inflows and outflows are balanced at 67.1 Mgal/d (table 5). Seventy-one percent of the inflow to the Floridan aquifer is by downward leakage and 29 percent is by boundary inflow. Outflow from the Floridan aquifer totals 84 percent as pumping, 10 percent as boundary outflow, and 6 percent as upward leakage.

Dredge Main Ship Channel Only, With Pumping

Deepening and widening the 7.5-mile-long main ship channel will expose about 0.4 mi^2 (11 million ft^2) of the Floridan aquifer surface to salty bay water. The altitude of the potentiometric surface in the channel nodes ranges from 1.0 foot above bay level to -0.9 foot below bay level. To simulate channel widening in the model, the vertical column of nodes containing the main channel was widened 100 feet and the width of adjacent columns were reduced 50 feet each. Deepening from 34 feet to 43 feet was simulated by thinning the confining bed by 9 feet in channel nodes, and where the confining bed is removed and the Floridan aquifer would be exposed, a constant head equal to bay level was assigned to the potentiometric surface. In the exposed areas, the channel actually will cut a maximum of about 5 feet into the top of the Floridan aquifer.

The simulation results indicate that, in the central part of the channel, the potentiometric surface would rise as much as 0.5 foot within 2,000 feet of the channel, but otherwise, the potentiometric surface would show a small rise



EXPLANATION

Area of the Floridan aquifer to be exposed by dredging.

55

Center of pumping from the Floridan aquifer. Number is pumping rate in million gallons per day.

TOP OF SALTWATER FRONT

Shows theoretical intersection of the saltwater front with the top of the Floridan aquifer. See figure 11.

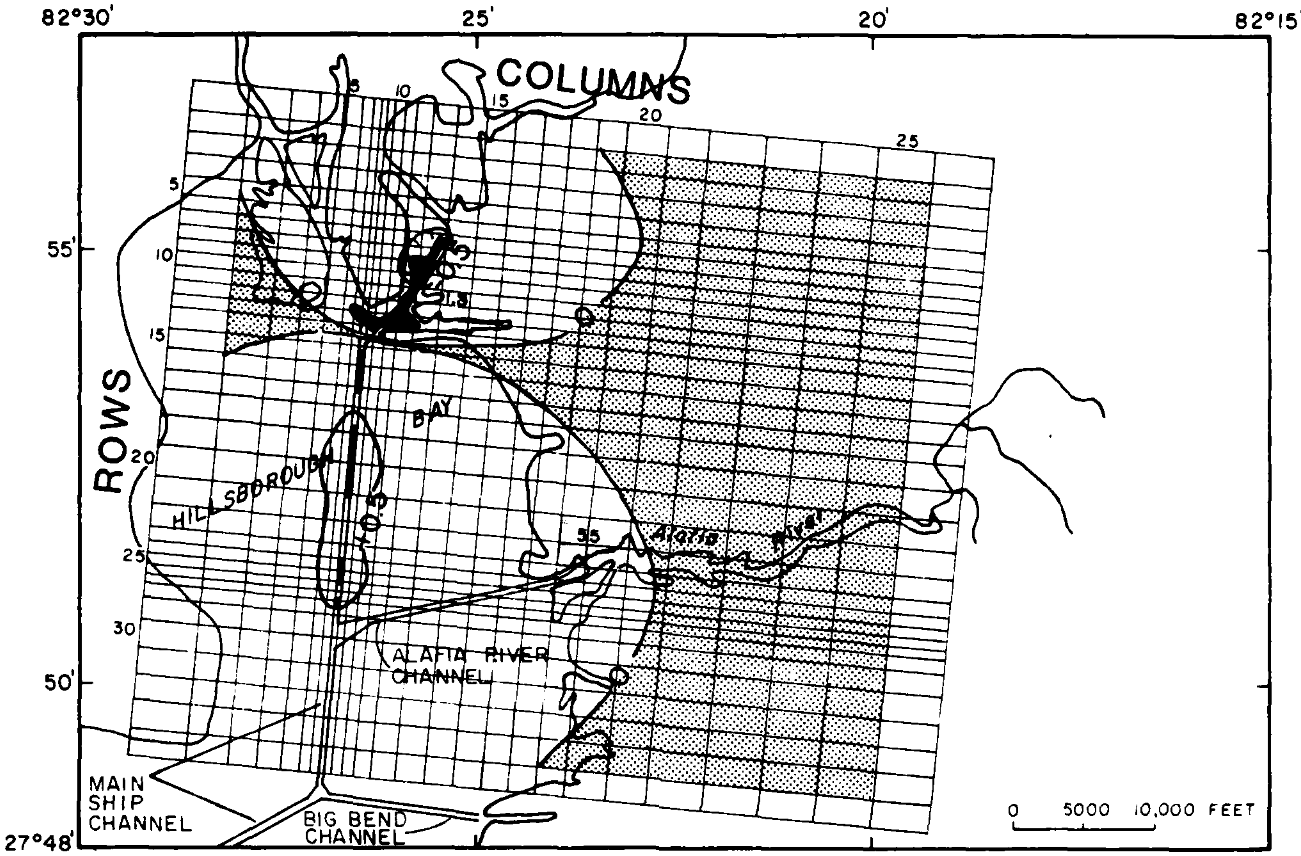
Figure 16.--Model grid and its relation to pumping centers, ship channels, and the saltwater front.

Table 5.--Model-computed water balance under options for harbor improvement

[Rates are in million gallons per day.]

	Existing channels with pumping (option 1)		Dredge main ship channel only, with pumping (option 2)		Dredge main ship channel and Alafia River channel, with pumping (option 3)		Existing channels no pumping (option 4)		Dredge main ship channel and Alafia River channel, no pumping (option 5)	
Inflows										
Downward leakage	47.7	71%	50.2	72%	57.3	78%	22.1	67%	22.7	63%
Boundary inflow	19.4	29%	19.1	28%	15.9	22%	11.1	33%	13.4	37%
Total	67.1		69.3		73.2		33.2		36.1	
Outflows										
Upward leakage	4.3	6%	6.5	9%	8.6	12%	19.8	60%	23.9	66%
Boundary outflow	6.5	10%	6.5	9%	8.3	11%	13.4	40%	12.2	34%
Pumpage	56.3	84%	56.3	81%	56.3	77%	0		0	
Total	67.1		69.3		73.2		33.2		36.1	

of less than 0.5 foot to a decline of about 0.5 foot at the north end of the channel (fig. 17). The flow through the system would increase 2.2 Mgal/d, or 5 percent above the present flow (table 5). Increased downward leakage of saltwater along the channel cut in the southern part of Hillsborough Bay would cause the potentiometric surface to rise to bay level there. Because the rise extends to the model boundary, boundary inflow would be decreased by 0.3 Mgal/d, thereby relieving stress on the inland freshwater resources. Increased upward leakage beneath the turning basin at the northern terminus of the main ship channel would cause a lowering of the potentiometric surface of about 0.5 foot to bay level there. Under the option where only the main ship channel is dredged, potentiometric-surface changes are generally less than 0.5 foot and change in total water balance is less than 3 percent. These changes are within the accuracy limits of the data and are relatively small when compared to tidal and seasonal water-level fluctuations and to the total water balance under existing conditions. Conclusions based on these results are that relatively small increases in outflow or inflow would result from widening and deepening the main ship channel and that the impact on landward freshwater resources would



EXPLANATION

——— -0.5 ———

LINE OF EQUAL WATER-LEVEL CHANGE
Shows model-simulated change in the potentiometric surface of the Floridan aquifer after dredging the main ship channel. Contour interval 0.5 foot.

■ Area of the Floridan aquifer to be exposed by dredging.

55 Center of pumping from the Floridan aquifer. Number is pumping rate in million gallons per day.

Area where potentiometric surface is not affected by channelization.

Figure 17.--Model-simulated change in the potentiometric surface of the Floridan aquifer due only to widening and deepening the main ship channel.

be negligible. The critical element in this analysis is probably that the relatively small head difference between the potentiometric surface and the bay level provides only a slight driving force for the transfer of water between the bay and aquifer.

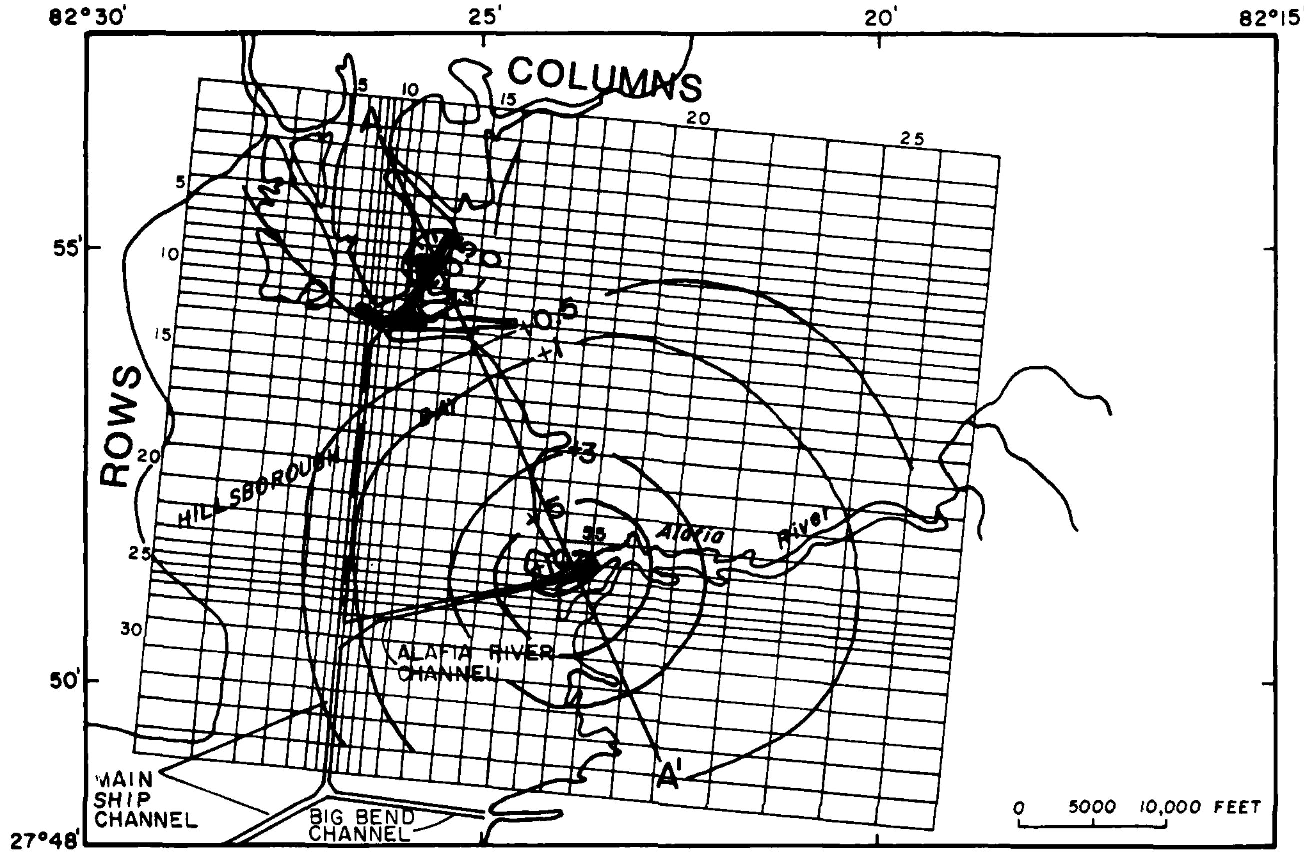
Dredge Main Ship Channel and Alafia River Channel, With Pumping

Proposed improvements of the 3.6-mile-long Alafia River channel include deepening from 28 to 38 feet, widening from 200 to 430 feet, and excavating a 1,200-foot diameter turning basin. Dredging would expose about 0.15 mi^2 (4.3 million ft^2) of the Floridan aquifer surface to salty bay water and would cut a maximum of 2 feet into the top of the Floridan aquifer. The steady-state potentiometric surface in the Alafia River channel nodes ranged from 0.6 foot below bay level at its intersection with the main ship channel to 9.6 feet below bay level at its eastern terminus. Widening of the Alafia River channel was not simulated in the model because the channel cut diagonally across several rows of nodes. Deepening was simulated by thinning the confining bed in nodes through which the diagonal cut. At the eastern terminus of the channel where the Floridan aquifer would be exposed, four nodes covering an area of 0.23 mi^2 (6.5 million ft^2) were assigned constant potentiometric heads equal to bay level.

The model-simulated change in the potentiometric surface that would result from dredging the main ship channel and the Alafia River channel is shown in figure 18. The potentiometric surface would rise about 10 feet at the eastern terminus of the Alafia River channel and fall about 0.5 foot at the northern terminus of the main ship channel. The impact of channelization would extend into the saltwater-freshwater transition zone as the rise in the potentiometric surface along the saltwater front would average about 1 foot. The potentiometric surface would rise 1 foot or more within a 33-mi^2 area, centered on the Alafia River channel. The balance of inflow and outflow, representing increased circulation of water between the bay and aquifer would increase 6.1 Mgal/d, or 9 percent above the water balance for existing conditions. Increased downward leakage along the channel cuts in the southern part of Hillsborough Bay would cause the potentiometric surface to rise. Because the rise extends to the model boundary, boundary inflow would decrease by 3.5 Mgal/d, thereby relieving stress on the inland freshwater resources. Increased upward leakage beneath the turning basin at the northern terminus of the main ship channel would cause a lowering of the potentiometric surface to bay level there. Boundary outflow would increase by 1.8 Mgal/d over existing conditions (table 5).

The potentiometric surface of the Floridan aquifer under existing and post-dredging conditions are compared in figure 19. The general configurations of the contours are similar. Channelization would serve principally to distort and reduce the size of the cone of depression caused by pumping 55 Mgal/d of saltwater at mouth of the Alafia River.

Dredging the Alafia River channel would have a significantly greater impact upon the interflow of water between Tampa Bay and the Floridan aquifer than would dredging the main ship channel only. The impact of channelization would be localized in the Hillsborough Bay area where exposing the top of the Floridan aquifer over a 0.55-mi^2 area would cause a change in water balance of 6.1 Mgal/d. This change is less than 1 percent of an estimated discharge of 812 Mgal/d from the Floridan aquifer and is small by comparison.



EXPLANATION

——-0.5——

LINE OF EQUAL WATER-LEVEL CHANGE

Shows model-simulated change in the potentiometric surface of the Floridan aquifer after dredging the Alafia River and main ship channels. Contour interval varies, in feet.

■

Area of the Floridan aquifer to be exposed by dredging.

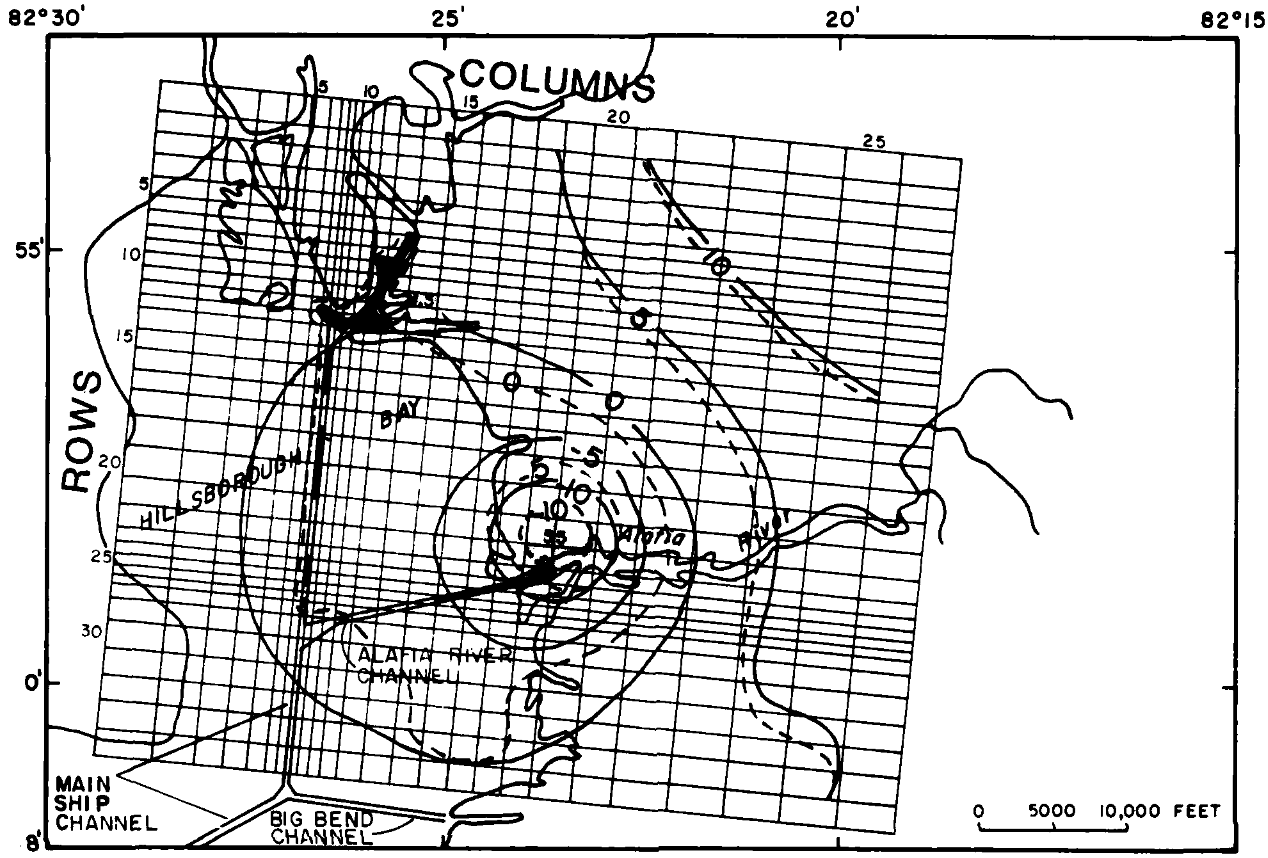
▦ 55

Center of pumping from the Floridan aquifer. Number is pumping rate in million gallons per day.

A———A'

Line of section for model-sensitivity analysis, see figure 23

Figure 18.--Model-simulated change in the potentiometric surface of the Floridan aquifer due to widening and deepening the main ship channel and Alafia River channel.



EXPLANATION

——5—— BEFORE DREDGING

---5--- AFTER DREDGING

POTENTIOMETRIC CONTOURS

Show altitude of model-simulated potentiometric surfaces of the Floridan aquifer before and after channel dredging. Contour interval 5 feet. National Geodetic Vertical Datum of 1929.

■ Area of Floridan aquifer to be exposed by dredging.

▦ 55 Center of pumping from the Floridan aquifer. Number is pumping rate in million gallons per day.

Figure 19.--Model-simulated potentiometric surfaces of the Floridan aquifer, before and after widening and deepening the main ship channel and Alafia River channel.

Channelization may be beneficial to the water resources of the area in that saltwater flow from the bay toward the saltwater pumping center at the mouth of the Alafia River would be increased, thereby reducing the bayward flow of freshwater resources from the east. The availability of freshwater for other uses would then be increased.

Channelization may be detrimental in that the outflow through the turning basin in the north part of the bay may increase the rate of bayward movement of inland freshwater resources. Also, because the increase in saltwater inflow would be directed toward the main pumping center, which produces cooling water for phosphate processing, temperature and turbidity of the well water there could change. Typically, the temperature of water in the Floridan aquifer is a constant 23°C, and temperature of water in Hillsborough Bay may range from 14°C to 30°C (Goetz and Goodwin, 1980); while turbidity of water in the Floridan aquifer is less than 1 JTU (Jackson Turbidity Unit), and turbidity in Hillsborough Bay may range from 2 JTU to 25 JTU (Goetz and Goodwin, 1980).

The reason for pumping cooling water from industrial wells, as opposed to the bay, is that temperature and turbidity of the ground water are constant. Cutting into the top of the Floridan aquifer, where a zone of relatively high permeability occurs, may upset this constancy. The potential for, or actual changes in, turbidity in ground water of west-central Florida have been reported at Sulphur Springs when dye was injected into a distant sinkhole (Stewart and Hanan, 1970); at Weeki Wachee Springs, possibly due to dredging at a nearby lake (Stallings, 1976); and in shallow wells near a sinkhole collapse along a lakeshore (Stewart, 1980). In each of these cases, solution features occur in the upper part of the Floridan aquifer, and they could be analagous to the zone of high permeability that will be breached by the proposed channels. On the other hand, the industrial wells are deep wells (1,000 feet) that may be deriving a major part of their discharge from highly transmissive deeper zones, which would not be directly exposed to inflowing bay water. Therefore, the temperature and turbidity of the resulting blend of water that would ultimately reach the wells may not be appreciably different from that prior to harbor improvement.

Existing Channels, No Pumping

If pumping were to cease, the total water balance would be reduced by 51 percent to 33.2 Mgal/d (table 5). The potentiometric surface would recover, resulting in large reductions of 33.9 Mgal/d in downward leakage and boundary inflow. Upward leakage and boundary outflow would increase 22.4 Mgal/d because pumping no longer intercepts water from its bayward course. By relieving pumping stresses, saltwater inflow to the aquifer would cease.

Dredge Main Ship Channel and Alafia River Channel, No Pumping

Once the harbor improvements have been made, the channels will remain indefinitely, but pumping for phosphate processing will eventually cease due to depletion of the phosphate ore. Upon cessation of pumpage, the potentiometric surface would recover and a new water balance would be established. The new water balance computed by the model is 36.1 Mgal/d, or 2.1 Mgal/d greater than that computed for existing channel conditions with no pumping. The larger water balance would primarily be due to increased upward leakage of 4.1 Mgal/d through the channel cut (table 5).

Figure 20 depicts model-simulated potentiometric surfaces of the Floridan aquifer under nonpumping conditions before and after channel dredging. The location of the 5-foot and 10-foot contours in the landward part of the modeled area are nearly identical. In Hillsborough Bay, the potentiometric surface would be about 1 foot lower under dredged channel conditions than under existing conditions. The largest differences occur at the channel cuts where increased upward leakage from the aquifer to the bay would cause a less than 1-foot maximum lowering of the potentiometric surface.

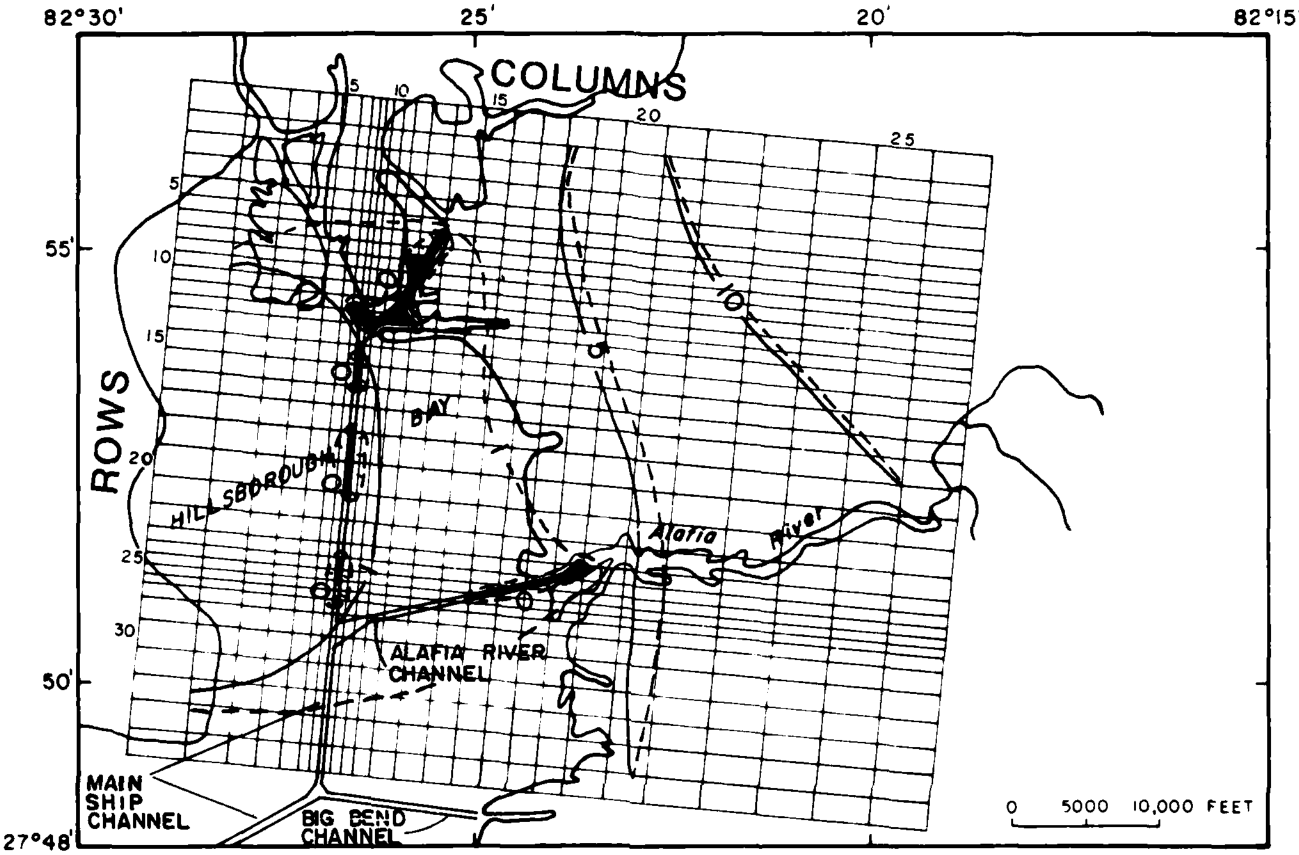
Limitations of the Model Analysis

Quantitative estimates of bay-aquifer interflow were obtained by simplifying the physical system into a form represented by the mathematical model. Five limitations of the model analysis have been recognized, which are related to conceptualization of the problem rather than to calibration technique:

1. Saltwater-Freshwater Head Relations.--The model assumes a uniform water quality, and, hence, a uniform distribution of fluid density and viscosity. Under actual field conditions, water density and viscosity are not uniform, and measured saltwater heads should be converted to equivalent freshwater heads. Equations for the conversion, formulated by Kohout (1960) and Lusczynski (1961), demonstrate that the computed freshwater head is always higher than the measured saltwater head.

   The concept that freshwater and saltwater zones in the same aquifer will respond differently to the same stress is not represented by the mathematical model. The convective-dispersive solute-transport equation probably best describes this type of movement; however, data to define the three dimensional properties of the aquifer in the area are very sparse, and the reliability of this type of model would be difficult to evaluate. Instead, modeling assumptions were made that head and water-quality changes would not occur beyond the zone encompassed by the top of the saltwater front and that there will be no movement of the saltwater front. As depicted in figures 11 and 12, the aquifer in the Hillsborough Bay and channelized areas contains mostly saltwater or transition-zone water. The aquifer probably contains a thin freshwater lens underlain by a thick saltwater wedge in the eastern quarter of the modeled area. The model simulations indicated that the greatest impacts of harbor improvement would occur in areas near the channels where the aquifer is filled with saltwater of uniform density; therefore, predictions of water-level and leakage-rate changes based on the model are probably realistic there.

   Saltwater-freshwater head relations increase in importance successively with each of the four predictive model runs. Under option 2, where only the main ship channel is dredged, new stresses (change in potentiometric head at the channel cut) on the aquifer system are



EXPLANATION

——5—— ---5---

BEFORE DREDGING | AFTER DREDGING

POTENTIOMETRIC CONTOURS

Show *altitude of model-simulated potentiometric surfaces* of the Floridan aquifer under nonpumping conditions before and after channel dredging. Contour interval variable, in feet. National Geodetic Vertical Datum of 1929.

■

Area of Floridan aquifer to be exposed by dredging.

Figure 20.--Model-simulated potentiometric surfaces of the Floridan aquifer under nonpumping conditions, before and after widening and deepening the main ship channel and Alafia River channel.

small, and heads in the landward freshwater and transition zones do not change significantly. Under option 3, where both the main ship channel and Alafia River channel are dredged, moderate new stresses on the aquifer system cause heads at the saltwater front and transition zone to rise slightly. In this case, errors probably are not significant because the density of water in the transition zone near the saltwater front is only slightly less than saltwater. Under options 3 and 4, where the large pumping stress is relieved, density considerations become significant because freshwater flow to the bay is restored. Under these options, the relative changes in impact on the aquifer system due to channelization may provide a realistic assessemnt of what will truly occur, but the absolute quantitative assessment of each option may contain significant errors.

2. Vertical Components of Ground-Water Flow.--Vertical components of ground-water flow affect water levels in coastal areas where upward discharge occurs within the freshwater zone. For example, in two adjacent piezometers of different depths within the freshwater zone, the water level in the deep piezometer will be higher than that in the shallow piezometer as long as the levels are above sea level. Because the model computes water levels on the basis of two-dimensional horizontal flow in the aquifer, its limitation in simulating a three-dimensional flow system must be recognized. The significance of the vertical component of ground-water flow may be determined through analysis of water levels in clustered piezometers of varying depth, but this information is not available. The potentiometric surface in the model is based on integrated water levels in wells that tap large thicknesses of the aquifer, thereby diminishing errors introduced by ignoring the vertical component of ground-water flow.

3. Partial Penetration of the Channel Cuts.--The channels barely penetrate the top of the Floridan aquifer, thus there would be strong convergence of flow in the Floridan aquifer beneath the channel cuts. By imposing a constant-head potentiometric surface over the exposures, the model exaggerates conditions by converting a shallow cut into a deep, fully penetrating one of equal capacity. Distances from the channels at which the effects of partial penetration are seen, depend upon aquifer thickness and layering and the ratio of vertical to horizontal hydraulic conductivity. The effects of partial penetration would be to reduce aquifer inflows and outflows; therefore, the total water balance computed by the model is maximized and "worst case" conditions are represented.

4. Channel Geometry.--The model grid does not exactly conform to the shape of the channels. The grid of the pre-harbor-improvement model contains a 400-foot wide column alined with the main ship channel. To simulate harbor-improvement conditions, the column was widened to 500 feet and the widths of the two adjacent columns were reduced by 50 feet. At the northern end of the main ship channel and along the Alafia River channel, however, the model grid is about 50 percent larger than the actual channel geometry, and additional errors in the computed leakage result from nonconformance of the channel and turning basins to the grid arrangement. Had the actual channel areas been represented in the model, the computed leakage rates might be as much as one-third lower.

5. Model Representation of Long-Term Average Conditions.--Because the storage coefficient was held at zero, calibration and interrogation of the model represent steady-state, or long-term average, solutions. The short-term transient changes to new conditions during channel deepening were not computed. The steady-state solutions represent the change in leakage that would ultimately result due to modification of the channel.

Analysis of Big Bend Channel

Big Bend channel lies just south of the modeled area (fig. 16). Big Bend channel is not expected to cut into the top of the Floridan aquifer, so its impact on bay-aquifer interflow is expected to be small; therefore, the model grid was not expanded to include the channel. The U.S. Army Corps of Engineers is studying the feasibility of widening the 2.2-mile-long channel from 200 to 460 feet, deepening it from 34 to 42 feet, and dredging a 1,500-foot diameter turning basin at its eastern terminus. The hydrologic effects of these improvements are one aspect of the Corp's feasibility study.

Lithologic information from logs of test borings in the channel (B. D. Kitching, Tampa Electric Co., written commun., 1980) indicates that the top of the Floridan aquifer lies about 70 feet below bay level; therefore, it would not be directly exposed to saltwater once the 42-foot deep channel has been dredged. The upper confining bed will be thinned from about 36 feet to about 28 feet over a 0.25-mi^2 area. Because the potentiometric surface of the Floridan aquifer lies about 3 feet above bay level (figs. 8 and 9), the rate of upward leakage from the aquifer to the bay will increase.

An estimate of the change in rate of upward leakage due to improvement of Big Bend channel was made through a form of Darcy's equation, which states:

$$Q = (7.48 \times 10^{-6})(k')(\frac{\Delta h}{b'})A$$

where: Q = rate of leakage, in million gallons per day;
k' = hydraulic conductivity of upper confining bed, in feet per day;
b' = thickness of upper confining bed, in feet;
Δh = head difference between potentiometric surface and bay level, in feet; and
A = area through which leakage occurs, in square feet.

Leakage will increase through the existing 200-foot wide channel and through a 130-foot wide strip of natural bay bottom on either side of the channel. Values for the components of the leakage equation are:

Component	Natural bay-bottom	Existing channel	Improved channel
k' (ft/d)	0.02	0.02	0.02
b' (ft)	58	36	28
Δh (ft)	3	3	3
A (ft^2)	4.79×10^6	2.32×10^6	7.11×10^6
Q (Mgal/d)	.04	.03	.11

Under current channel conditions, the upward leakage rate through the area to be improved is about 0.07 Mgal/d (total of natural bay-bottom and existing channel). The new rate with channel improvements will be about 0.11 Mgal/d, which represents an increase in upward leakage of 0.04 Mgal/d. The hydrologic effects of widening and deepening Big Bend channel seem small compared to those computed by the model for channels to the north. The low rates may be attributed to a combination of factors including a thick confining bed, low head difference, and small area to be channelized.

SUMMARY AND CONCLUSIONS

Assessment of the interconnection between Tampa Bay and the Floridan aquifer has been directed toward the following questions:

1. <u>What factors control the hydraulic interconnection between Tampa Bay and the Floridan aquifer?</u>--Factors controlling hydraulic interconnection include head relations between the bay and aquifer, thickness and permeability of intervening sand and clay deposits, and the degree of channelization. Where the potentiometric surface of the Floridan aquifer is below sea level, salty bay water leaks into the Floridan aquifer, and where head conditions are reversed, freshwater leaks from the aquifer to the bay. In the southern part of the bay area, sand and clay deposits are about 200 feet thick and form an effective seal against bay-aquifer interflow, as is evidenced by the presence of water beneath the bay with a lower chloride content than seawater and artesian heads that are well above sea level. A good hydraulic interconnection in the northern part of the bay area is indicated by high chloride concentrations, low head differences, and thin sand and clay deposits that have been breached naturally by limestone outcroppings along the shore and have been thinned or removed by channelization. Numerous shallow channels dredged for industrial and residential purposes likely increase bay-aquifer interflow; however, their impact seemingly has not been measureable. Widening and deepening of the main ship channel and Alafia River channel will breach the upper confining bed over a 0.55-mi^2 (15.3 million ft^2) area, thus providing a direct interconnection between Tampa Bay and the Floridan aquifer.

2. <u>What is the direction, rate, and quality of interflow between Tampa Bay and the Floridan aquifer?</u>--In the northern part of the bay area, ground-water outflow to the bay is perennial, and in the southern part of the area, seasonal changes of potentiometric-surface gradients cause reversal of flow to occur. Total ground-water outflow to the bay averages about 100 Mgal/d annually. In May 1978, a typical low-water period, outflow from the Floridan aquifer to the bay totaled 90 Mgal/d and occurred only in the northern part of the bay area. A large cone of depression along the Hillsborough-Manatee County line intercepted all outflow in the southern part of the bay area. In September 1978, a typical high-water period, landward gradients in the southern part of the area were reversed and total outflow to the bay was about 118 Mgal/d. Chloride concentration of water from the upper part of the aquifer decreases from about 14,000 mg/L in Hillsborough Bay southward to the mouth of Tampa Bay where

it is 1,300 mg/L. Saltwater intrusion is occurring at a number of areas along the coast of Tampa Bay, as indicated by reduction or reversal of potentiometric-surface gradients and increasing chloride concentrations in coastal monitor wells, but the rate of movement of the saltwater front could not be absolutely determined. Based on theoretical hydraulic analysis and observations of water-quality changes, the intrusion rate is probably between 0.3 and 5 ft/d in the southern part of the bay area and nil in the northern part. Sets of deep and shallow monitor wells could be installed in the Floridan aquifer along the coast of Tampa Bay to detect any saltwater intrusion into the freshwater aquifer. The most favorable sites appear to be south of the Alafia River between the bay and a seasonal cone of depression.

3. <u>What is the impact of harbor improvement on bay-aquifer interflow?</u>-- A computer model of ground-water flow was developed to estimate the hydrologic effects of proposed harbor improvement in Hillsborough Bay where the upper confining bed is expected to be greatly thinned or breached by dredging of shipping channels. The model was interrogated under five options of channelization and pumping. The greatest hydrologic effects should occur in the area where the Alafia River channel is expected to cut a maximum of 2 feet into the top of the Floridan aquifer, thereby exposing it directly to saltwater. The exposures are about 1,500 feet from a well field that pumps about 55 Mgal/d of saltwater. The potentiometric surface in the vicinity of the well field would rise about 5 to 10 feet in response to a net increase of 9.6 Mgal/d in downward leakage of saltwater in the vicinity of the channel. The increased leakage of saltwater through the channel cut would all be drawn into the pumping center, thereby reducing stress on nearby freshwater resources formerly drawn to the well field. Channelization eventually could possibly cause temperature and turbidity changes of the well water, which would be undesirable for current uses.

The model analysis indicated that the hydrologic effects of widening and deepening only the main ship channel, where dredging is expected to cut a maximum of 5 feet into the top of the Floridan aquifer, would be relatively small compared to those computed for both the main ship channel and Alafia River channel. A numerical analysis of the hydrologic effects of widening and deepening Big Bend channel, where the upper confining bed would be thinned but not breached, indicated that upward leakage would be increased by about 0.04 Mgal/d, a relatively small amount compared to increases by other channelization. The minimal impact of channel improvement at Big Bend is due to a combination of factors, including a thick confining bed, low head difference between the bay level and potentiometric surface, and relatively small area to be channelized compared to the entire bay area.

The changes in leakage caused by channelization should be relatively small when compared to the total flow regime of the Tampa Bay area. They may be imperceptible when considered with other unknown changes in climate and development.

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SUPPLEMENTAL DATA: MODEL CONCEPTUALIZATION, CALIBRATION, AND SENSITIVITY

The model grid comprises an orthogonal array of 34 horizontal rows and 26 vertical columns with each grid being rectangular, varying from 375,000 to 8,000,000 ft^2. The head-controlled-flux condition, utilized by Wilson and Gerhart (1980), combines features of the constant-head and constant-flux boundary conditions and allows both head and flow to vary at the model-grid boundaries. Under the steady-state condition, storage changes are not considered and all storage terms are set to zero.

A generalized conceptual model of the hydrogeologic system is shown schematically in figure 21. The Floridan aquifer is the principal source of ground-water supply in the area. It is confined on the top and bottom and is overlain by the unconfined surficial aquifer. The hydrologic model assumes that:

1. Ground-water movement in the Floridan aquifer is horizontal.
2. Water moves vertically into or out of the Floridan aquifer through the upper confining bed.
3. The confining layers have negligible storage.
4. Changes in ground-water storage in the Floridan aquifer occur instantaneously with changes in hydraulic head.
5. The Floridan aquifer is homogeneous and isotropic.
6. Physical parameters of the system do not change with time.
7. The head in the surficial aquifer and water levels in Hillsborough Bay do not change in response to any imposed stress.
8. Head changes in the Floridan aquifer caused by an imposed stress will eventually stabilize; that is, a condition of steady state will be reached.
9. Head-controlled-flux condition accurately represents the hydrologic boundaries of the aquifer.
10. Recharge occurs instantaneously.
11. Density of the ground water is the same as the bay water.
12. Channelization will not change the position of the saltwater-freshwater interface.

The mathematical model of the hydrologic system is based on the governing equations of ground-water flow that are approximated numerically by a finite-difference method. The resulting system of simultaneous equations is solved by the strongly implicit procedure.

Input parameters to the calibrated model included May-September 1978 average potentiometric-surface and water-table altitudes, uniform transmissivity of 100,000 ft^2/d, average pumping rate of 56.2 Mgal/d, confining-bed vertical hydraulic conductivity of 2.0×10^{-2} ft/d, variable confining-bed thickness of 4 to 90 feet (based on fig. 5 and a channel profile provided by the U.S. Army Corps of Engineers), head-controlled flux boundaries, and zero storage coefficient. The model was calibrated by adjusting confining-bed thickness until an acceptable match between the model-simulated potentiometric surface and the observed-average potentiometric surface was achieved (fig. 22). The calibrated model

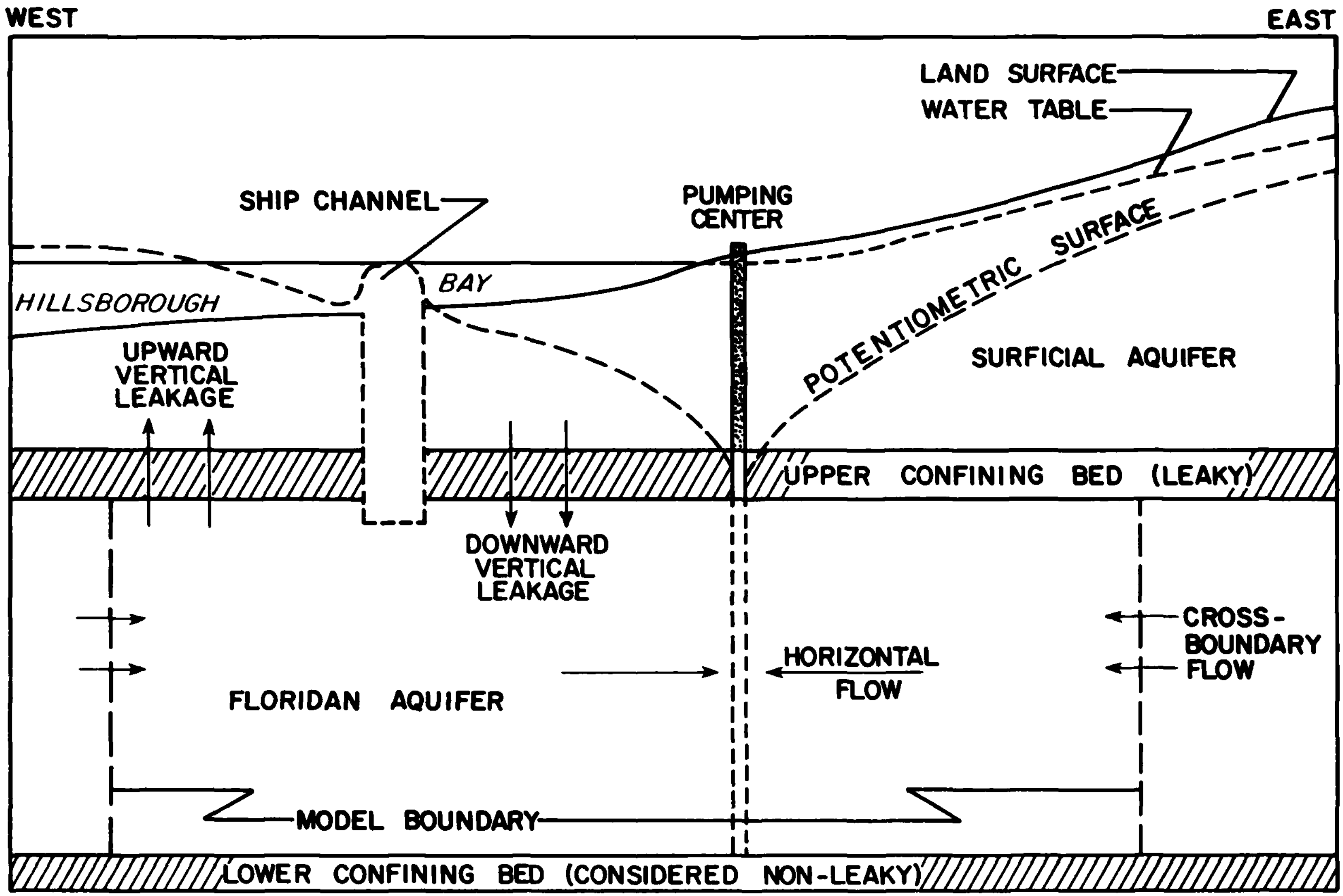
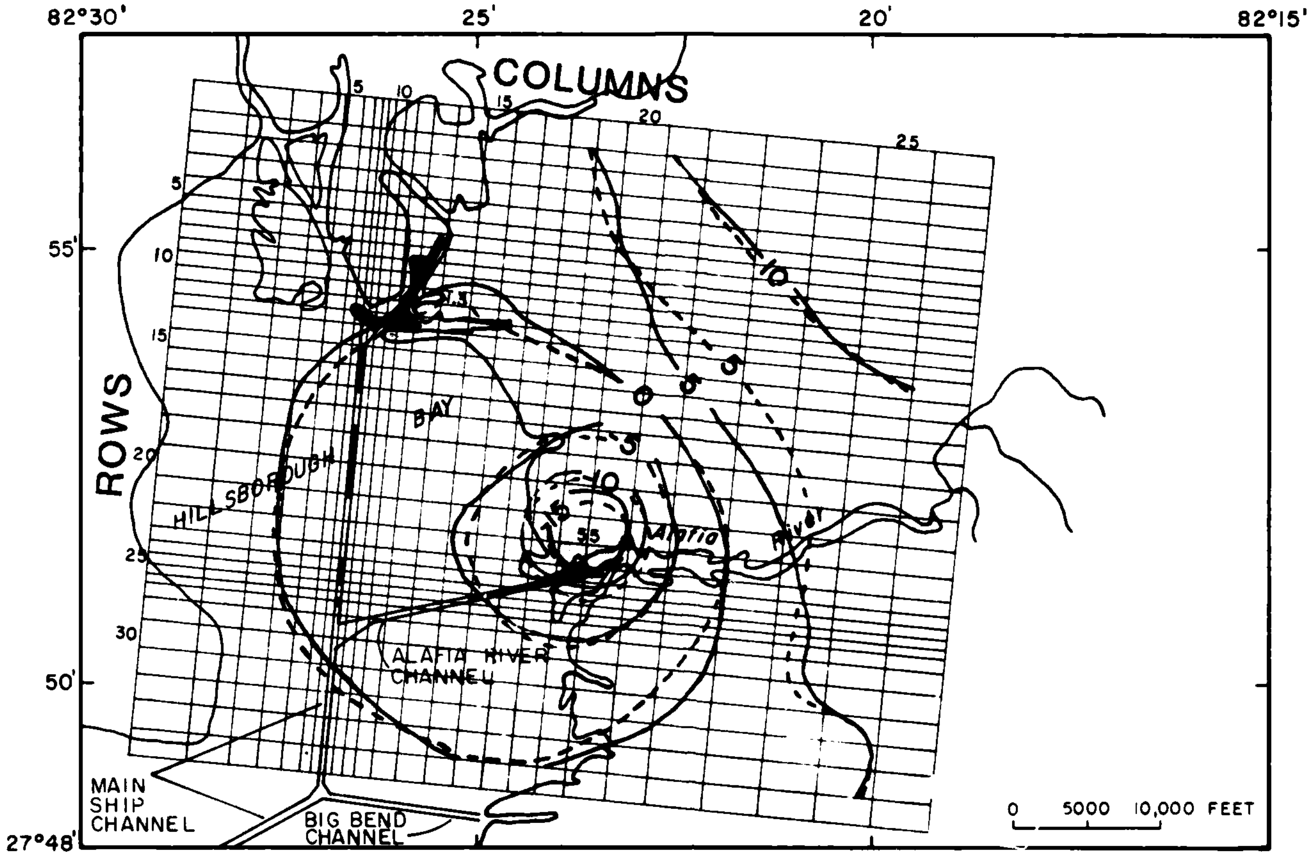


Figure 21.--Generalized conceptual model of the hydrogeologic system (from Wilson and Gerhart, 1980).



EXPLANATION

——5——

AVERAGE POTENTIOMETRIC CONTOUR

Shows altitude of May-September 1978 average potentiometric surface of the Floridan aquifer.

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SIMULATED POTENTIOMETRIC CONTOUR

Shows altitude of model-simulated potentiometric surface of the Floridan aquifer. Contour interval 5 feet. National Geodetic Vertical Datum of 1929.

Area of the Floridan aquifer to be exposed by dredging.

55

Center of pumping from the Floridan aquifer. Number is pumping rate in million gallons per day.

Figure 22.--Comparison of May-September 1978 average and model-simulated potentiometric surfaces, representing steady-state calibration.

was then interrogated to compute the change in leakage and water levels that should occur as a result of completely removing or thinning the confining bed to the level specified in the channel-deepening project.

Once the simulated potentiometric surface matched the actual average potentiometric surface, the model was considered to be calibrated. Over the 816 interior nodes (for example, excluding border nodes) the simulated potentiometric surface ranged from +4.2 feet above to -2.3 feet below the actual average steady-state potentiometric surface, with a mean of +0.2 foot. The standard deviation of the residuals was 0.7 foot, which indicates that the simulated potentiometric surface matched within a range between 0.9 foot above to -0.5 foot below the actual level at about 68 percent of the nodes. The correlation coefficient was 0.987, indicating a near perfect association between the two surfaces. The potentiometric surface simulated by the calibration run was used as the starting head upon which predictive model runs were based.

An important stage in the development of an accurate aquifer model is to compare the model response to a known stress other than that upon which the calibration was made. Since the aquifer response is a function of several parameters (transmissivity, confining-bed hydraulic conductivity, confining-bed thickness, recharge, boundary conditions, and so forth), it is possible that the wrong parameters may be varied to give an apparently adequate fit for the calibration. The model could then give totally inadequate results when used for predictive purposes. Because historical ground-water data for Hillsborough Bay were not available, model acceptance could not be evaluated.

A sensitivity analysis is often a more realistic approach for testing model accuracy. Separate model simulations are made with individual parameters varied in turn over the range in values within which they are known to occur. The model was not recalibrated each time parameter values were changed since this would be impractical in terms of time and cost. Exact values of head changes from sensitivity tests should be viewed critically, but relative changes can provide insight as to the manner in which any parameter may affect results of model simulation.

Model sensitivity was tested by varying transmissivity to ±50 percent and confining-bed hydraulic conductivity within a range of one order of magnitude. The effects on potentiometric-surface changes caused by the variations under the option of dredging the Alafia River and main ship channels, with pumping, are shown in cross section in figure 23. The section depicts the model-simulated potentiometric surface along a line through the main ship channel turning basin and the Alafia River channel (fig. 18).

The cross section representing head changes that correspond to transmissivity indicates that the model is most sensitive to transmissivity near the pumping center north of the Alafia River channel. The estimate of transmissivity was based on an analysis of 1955 aquifer-test data at the pumping center provided by the Gardinier Corporation. Because transmissivity is known most accurately in the area where the model is sensitive to this parameter, it is probably not an important source of error in the model calibration.

The cross section representing head changes that correspond to hydraulic conductivity of the confining bed indicates that the model is sensitive to this parameter in the southern area. In this area, there is either a large head difference between the potentiometric surface and the water table or bay level, or a thick confining bed. Since leakage rate is proportional to head difference and confining-bed thickness, the southern area can be expected to be sensitive to changes in the hydraulic conductivity parameter.

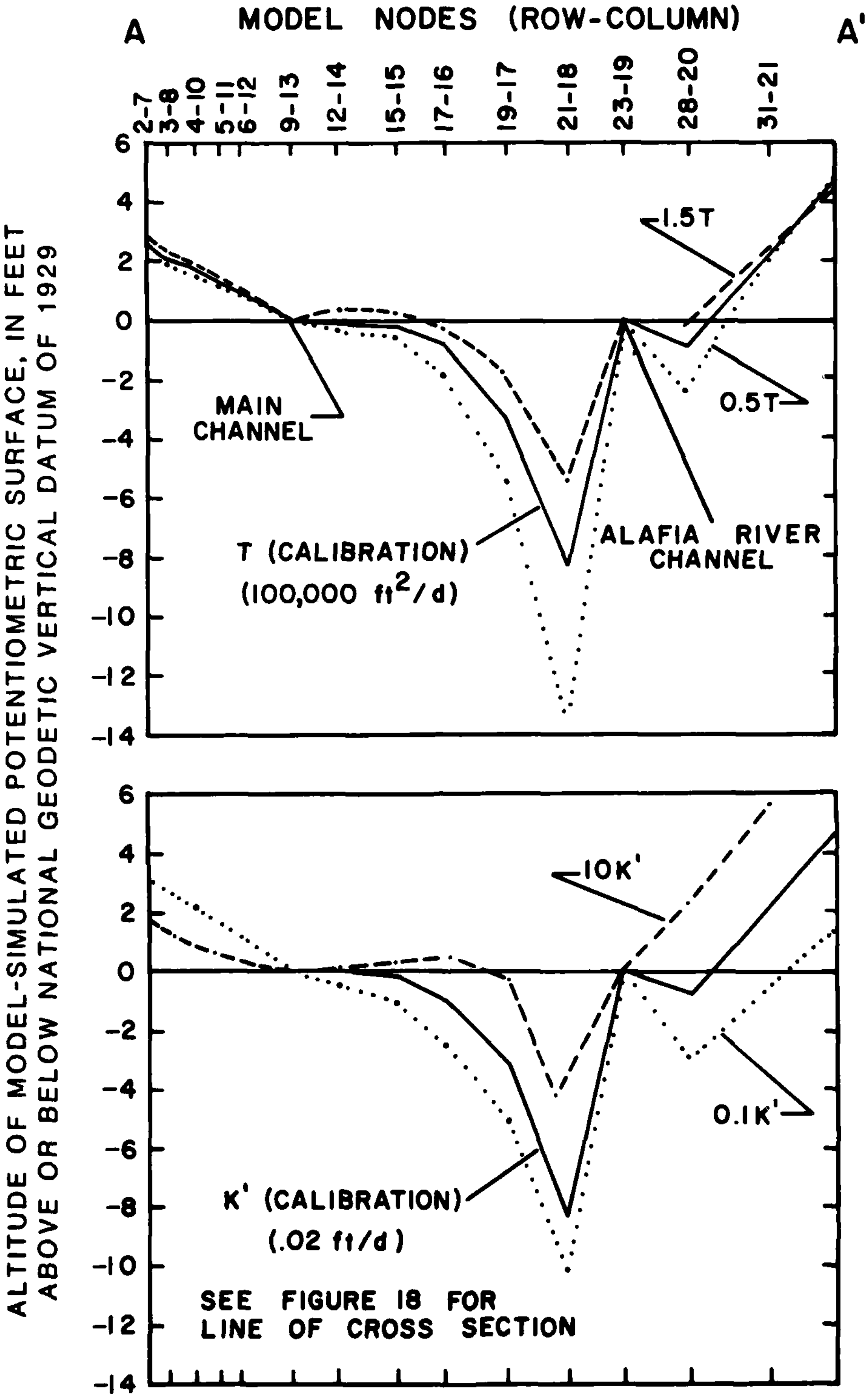

Figure 23.--Effects on potentiometric surface caused by varying model-input transmissivity (T) and hydraulic conductivity (K') parameters.

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