

Water-Resources Potential of the Freshwater Lens at Key West, Florida

By Donald J. McKenzie

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CONTENTS

Abstract	1
Introduction	1
Purpose and scope	2
Methods and procedures	2
Description of area	3
Geohydrologic setting	6
Characteristics of the freshwater lens	6
Rainfall recharge	6
Water-table fluctuations	7
Configuration of the freshwater lens and transition zone	8
Ground-water quality	14
Major inorganic constituents and physical properties	14
Nutrients	15
Trace elements	19
Synthetic organic compounds	21
Bacterial analyses	23
Summary and conclusions	23
Selected references	23

FIGURES

1. Map showing location of Key West and the Florida Keys	2
2. Map showing the island of Key West: (A) as it appeared in about 1850, and (B) as it appeared in 1988	4
3. Graph showing monthly rainfall for 1986-88, and long-term average monthly rainfall at Key West	5
4. Map showing location of wells, ground-water level recorders, and cored well sites at Key West	5
5. Map showing water-table elevations for the highest ground-water levels measured during the investigation, December 8, 1986	8
6. Map showing water-table elevations for the lowest ground-water levels measured during the investigation, June 24, 1987	9
7. Hydrograph of water-table fluctuations at wells MO-147 and MO-152 and the tide stages at Key West, December 10-13, 1986	9
8. Hydrograph of well MO-152 showing the times of specific conductance profile measurements in four wells, October 22-23, 1987	10
9-12. Depth profiles of specific conductance and associated concentrations of chloride at wells:	
9. MO-149	10
10. MO-152	11
11. MO-153	11
12. MO-155	11
13. Hydrologic cross section of Key West along line A-A' showing chloride concentrations in ground water, October 21-22, 1986	12
14-18. Maps showing:	
14. Lines of equal chloride concentration at a depth of 4 feet below the water table, October 21, 1986	13
15. Lines of equal chloride concentration at a depth of 4 feet below the water table, April 1, 1987	14
16. Surface-geophysical survey sites and lines of equal resistivity, November 20, 1986	15

17. Average concentrations of nitrate nitrogen in water from wells at depths of 2 to 15 feet below the water table at Key West, October 1986 through January 1988 19
18. Average concentrations of lead and iron in water from wells at depths of 2 to 5 feet below the water table at Key West, October 1986 through September 1987 21

TABLES

1. Lithologic log of wells MO-155 and MO-158 at Key West 7
2. Chemical and physical characteristics of Key West ground water at depths of 2 to 5 feet below the water table, October 21-22, 1986 16
3. Nutrient concentrations in Key West ground water at various well depths, October 1986 through January 1988 17, 18
4. Trace-element concentrations in Key West ground water at depths of 2 to 5 feet below the water table, October 1986 through April 1988 20
5. Synthetic organic compounds for which gas chromatograph/mass spectrometer analyses were determined 22

METRIC CONVERSION FACTORS

The inch-pound units used in this report may be converted to metric (International System) units by the following factors:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
square mile (mi ²)	2.590	square kilometer (km ²)
million gallons (Mgal)	3,785	cubic meter (m ³)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m ³ /s)

ADDITIONAL FACTORS

Multiply milliliter (mL) by 0.001 to obtain liter (L).

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows: °F = 1.8(°C) + 32

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

ADDITIONAL ABBREVIATIONS

micrograms per liter=μg/L
microsiemens per centimeter=μS/cm
milligrams per liter=mg/L

Water-Resources Potential of the Freshwater Lens at Key West, Florida

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Abstract

The island of Key West lies at the end of the Florida Keys, about 150 miles southwest of Miami. The public-water supply for the island is provided by the Florida Keys Aqueduct Authority Well Field near Miami. However, there are many privately owned wells on the island that tap the local fresh ground-water lens for potable and nonpotable water supply. The number of people who use water from the wells for drinking purposes is unknown.

From 1985 to 1988, the U.S. Geological Survey, in cooperation with the South Florida Water Management District, conducted an investigation to characterize the Key West freshwater lens. Observation wells were drilled to determine the extent of the lens and to characterize the water quality. Previous well logs and well-core data collected during the investigation showed the aquifer to be a highly permeable, porous, solution-riddled, oolitic limestone that allows rainfall recharge to quickly seep into the ocean and saltwater to easily intrude the aquifer.

The small freshwater lens (250 milligrams per liter of chloride concentration, or less) averages 5 feet in thickness below the center of the western half (Old Town) of the island. The lens contains about 20 million gallons of freshwater during the dry season and about 30 million gallons during the wet season. Underlying the freshwater lens is a transition zone of freshwater-saltwater mix that extends to the saltwater interface (19,000 milligrams per liter of chloride concentration), which is about 40-feet deep at the center of the lens. The water table fluctuates and the configuration of the lens constantly changes, largely as a result of tidal effects. Others events, such as rainfall, pumping, and evapotranspiration, are masked by the tidal effects.

The freshwater lens is a calcium bicarbonate water that grades to a sodium chloride type near the saltwater interface. Elevated concentrations of nitrate nitrogen were found in water samples from wells in the Old Town district. However, concentrations generally were not above the maximum contaminant level of 10 milligrams per liter for drinking water established by the Florida Department of Environmental Regulation. Water samples near an old landfill in the eastern half of the island had concentrations of iron (600-1,900 micrograms per liter) and lead (40-800 micrograms per liter) that exceeded maximum contaminant levels of 300 and 50 micrograms per liter. These

trace-element concentrations generally decreased with distance from the landfill.

Although the freshwater lens is a potential source of water for additional nonpotable water needs in Key West, any large-scale pumping could quickly exhaust the freshwater lens, and saline water could be rapidly drawn through the porous limestone aquifer. Water-quality data indicate that the lens is an unlikely source of potable water.

INTRODUCTION

Before 1940, the island of Key West received its drinking water from rainfall cisterns, domestic wells that tapped a freshwater lens below the island, and from "springs," which were solution holes in the limestone that gave access to the freshwater lens. Parker (1941, p. 6) reported that hundreds of shallow wells were used for potable water supply. During World War II, the U.S. Navy developed large parts of the island, and with the subsequent need for more freshwater constructed an aqueduct (18-inch diameter pipe) from the mainland. The water was pumped from a well field and treatment plant at Florida City (fig. 1) to Key West, and provided water to the other islands along the way. As of 1988, the Florida Keys Aqueduct Authority (FKAA) still used the same well field and treatment plant but used a larger (24- to 36-inch diameter) aqueduct pipe to provide 11 Mgal/d (million gallons per day) of water for the system. During the winter tourist season, Key West uses about 5 Mgal/d of that total. A reverse-osmosis plant on Stock Island, adjacent to the eastern part of Key West, produces desalinated water from wells for auxiliary use.

Although the local ground water is considered nonpotable by the Monroe County Health Authority (C.D. Pierce, Monroe County Public Works Department, oral commun., 1987), many residents use it in a dual water-supply system. The aqueduct water is used for cooking, bathing, and drinking, and the well water is used for such purposes as flushing toilets, washing clothes, and lawn irrigation. The number of people currently using well water for drinking purposes is unknown.

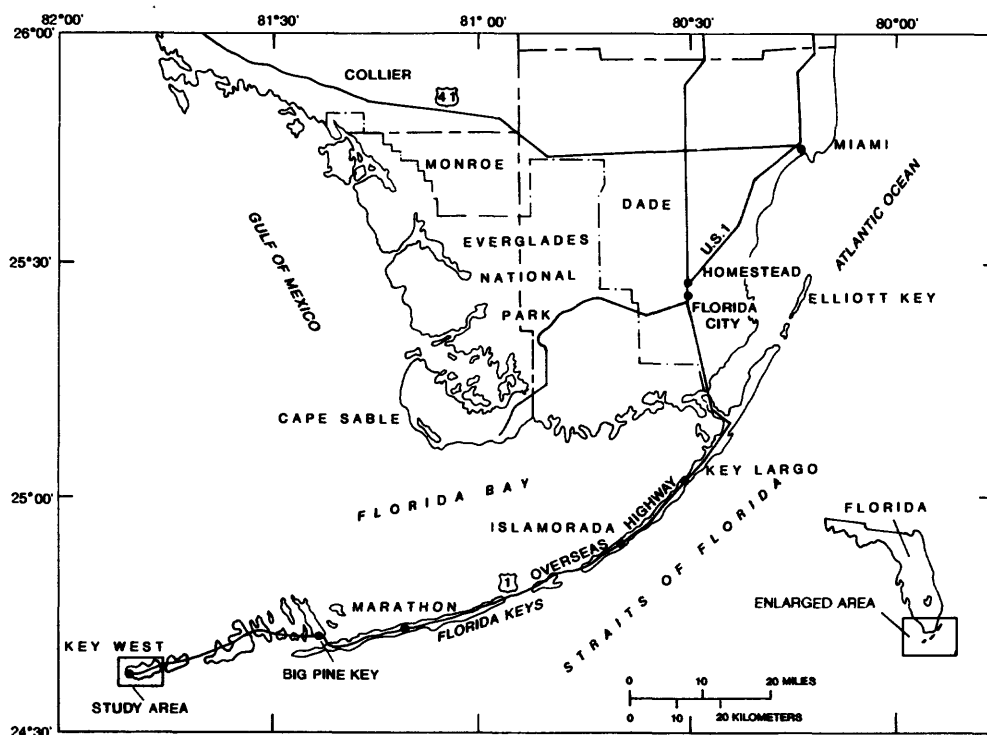


Figure 1. Location of Key West and the Florida Keys.

From 1985 to 1988, the U.S. Geological Survey, in cooperation with the South Florida Water Management District, conducted an investigation to evaluate the water-resources potential of the freshwater lens at Key West. Long-term ground-water data were not available for Key West, and a detailed evaluation of changes over time was not possible in this investigation. This investigation focused on the occurrence and quality of freshwater on the island and established a data base for future intensive studies of the water quality and hydraulics of the freshwater lens.

Purpose and Scope

This report presents the results of an investigation to evaluate the water-resources potential of the freshwater lens at Key West by: (1) determining the areal extent, thickness, and volume of the lens; and (2) characterizing the water quality of the lens.

The work included: test drilling with examination of drill cuttings to refine the geologic knowledge of the area; measuring water levels to depict the water-table gradient and determine the effect of rainfall recharge; collecting specific conductance and chloride concentration data to depict the configuration of the lens and the zone of freshwater-saltwater diffusion; constructing lines of equal chloride concentration to delineate the areal extent, thickness, and volume of the freshwater lens; and performing a surface-geophysical survey to augment the specific conductance and chloride

concentration data to further define the configuration of the lens. Results of this investigation are presented herein.

The Florida Secondary Drinking Water Regulations (Florida Department of Environmental Regulation, 1983) establishes a recommended limit of 250 mg/L (milligrams per liter) chloride concentration for potable water, which was used in this report to define freshwater. However, because domestic use of water from privately owned wells could include water of much higher chloride concentration, water sampling was extended into the transition zone, which underlies the freshwater lens.

Methods and Procedures

Observation wells were drilled to determine the general water quality and to describe the horizontal and vertical configuration of the lens. The wells were drilled using only local ground water and were cased only through the upper few feet above the water table. Polyvinyl chloride (PVC) casing was seated in the borehole, and the annular space was grouted. The top of the well casing was capped just below land surface, and the installation was protected by a water meter box set level with the ground surface.

After the wells were constructed, the elevations of the casing tops above sea level were measured using transit and rod standard leveling techniques. National geodetic surveys and local benchmarks of first-order accuracy were used. All ground-water level measurements are referenced to the casing tops.

The wells were left uncased below the water table so that a specific conductance probe (temperature compensated to 25 °C [degrees Celsius]) could be lowered into the well to profile the water column. The equipment used for the profiling was a Yellow Springs Temperature and Conductivity Meter 3000¹. The meter was calibrated in the laboratory and in the field using standard solutions supplied by the U.S. Geological Survey Quality of Water Service Unit in Ocala, Fla. The specific conductance probe was lowered down the well, and measurements were taken at major changes in specific conductance. As the probe was retrieved, readings were taken again and comparisons made with the descending measurements to determine any changes due to disturbance of the water column.

After the profiling of specific conductance, water samples were collected at specific conductance horizons, and chloride concentrations were determined using the Mohr titration method (Brown and others, 1970, p. 69). Water samples were collected by use of a low-volume peristaltic pump with a 1/4-inch Tygon tube lowered to the desired depth. This resulted in minimal disturbance of the water column.

A surface-geophysical resistivity survey was conducted to augment the chloride concentrations and specific conductance measurements and help define the configuration of the freshwater lens and the transition zone. The electromagnetic-16R (EM-16R) very low frequency (VLF) meter was used because of its ability to operate in an urban area with numerous electrical interferences.

Samples for inorganic chemical and physical elements were collected in the same manner as the chloride samples. The U.S. Geological Survey Quality of Water Service Unit in Ocala provided the analyses, using analytical methods described by Fishman and Friedman (1985).

Samples for synthetic organic compound analyses were collected with a peristaltic pump and Teflon hose. Samples for base-neutral and acid-extractable compounds were placed in glass containers (supplied by the Quality of Water Service Unit in Ocala), preserved with mercuric-chloride as a bactericide, and packed in ice as recommended by the U.S. Environmental Protection Agency (1980). Samples to be analyzed for volatile organic compounds were collected in 40-mL glass vials with a Teflon seal. Samples were shipped in ice for overnight delivery. Samples were analyzed using either the gas chromatograph/flame ionization detection (GC/FID) method or the gas chromatograph/mass spectrometer (GC/MS) method by laboratories of the U.S. Geological Survey. The analytical methods for the determination of organic substances are described by Wershaw and others (1983).

Coliform samples were collected by use of a peristaltic pump with a Tygon hose; a new length of hose was used for

each well. The samples were placed in sterile glass bottles, and within 2 hours, using the membrane filter technique, the necessary dilutions were made and the samples placed in portable incubators. Final incubation and bacterial colony counts were conducted at a U.S. Geological Survey laboratory.

Two continuous water-level recorders were installed, one near the northwestern coast adjacent to well MO-147 and another near the center of the island adjacent to well MO-152. The instruments were Stevens model 7000 digital tape recorders that automatically punch the ground-water levels on paper tape at hourly increments. The punched tapes were later translated to generate a ground-water hydrograph.

A tidal hydrograph was constructed from tide prediction tables published by the National Oceanic and Atmospheric Administration (1986), and comparison made of the tidal hydrograph with ground-water hydrographs of inland wells. The tidal range at Key West is about 1.5 feet. There is no significant difference between the tidal ranges on the Gulf of Mexico side and the Atlantic Ocean side of the island. The predicted tides differed from the actual tides by no more than about 0.09 foot during the investigation. The accuracy is within an acceptable range for comparison of the ground-water level and tide.

Discrete ground-water level measurements in all the wells were made monthly using a hand-held steel tape. Rain-fall data provided by the National Oceanic and Atmospheric Administration (NOAA) station at Key West were used to describe the response of the lens to rainfall recharge.

Description of Area

The island of Key West lies at the end of the Florida Keys, about 150 miles southwest of Miami on the Overseas Highway (fig. 1). At a latitude of 24°34' north, the island lies adjacent to the tropical Straits of Florida between the Atlantic Ocean and the Gulf of Mexico. The island is about 4 miles long and 1.5 miles wide, encompassing a residential area of about 4 mi² (square miles). The size and shape of the island have changed considerably since it was ceded by Spain to the United States in 1821. The island as it appeared in about 1850 and as it appeared in 1988 is shown in figure 2. (The original map is in the archives of the Key West Library.)

The ground elevation typically is 4 to 5 feet above sea level with a maximum elevation of 14 feet near the western end of the island. The average annual temperature is 24.6 °C, and the average annual rainfall is 39.4 inches. Most of the rainfall (75-80 percent) generally occurs during the wet season from May to November as shown in figure 3 (Sherwood and others, 1973, p. 8).

Key West had a permanent population of about 28,000 people in 1987-88, including U.S. Naval personnel (Rosemary Vogenet, Key West Planning Department, oral commun., 1989). In addition, about 1.5 million tourists visit

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

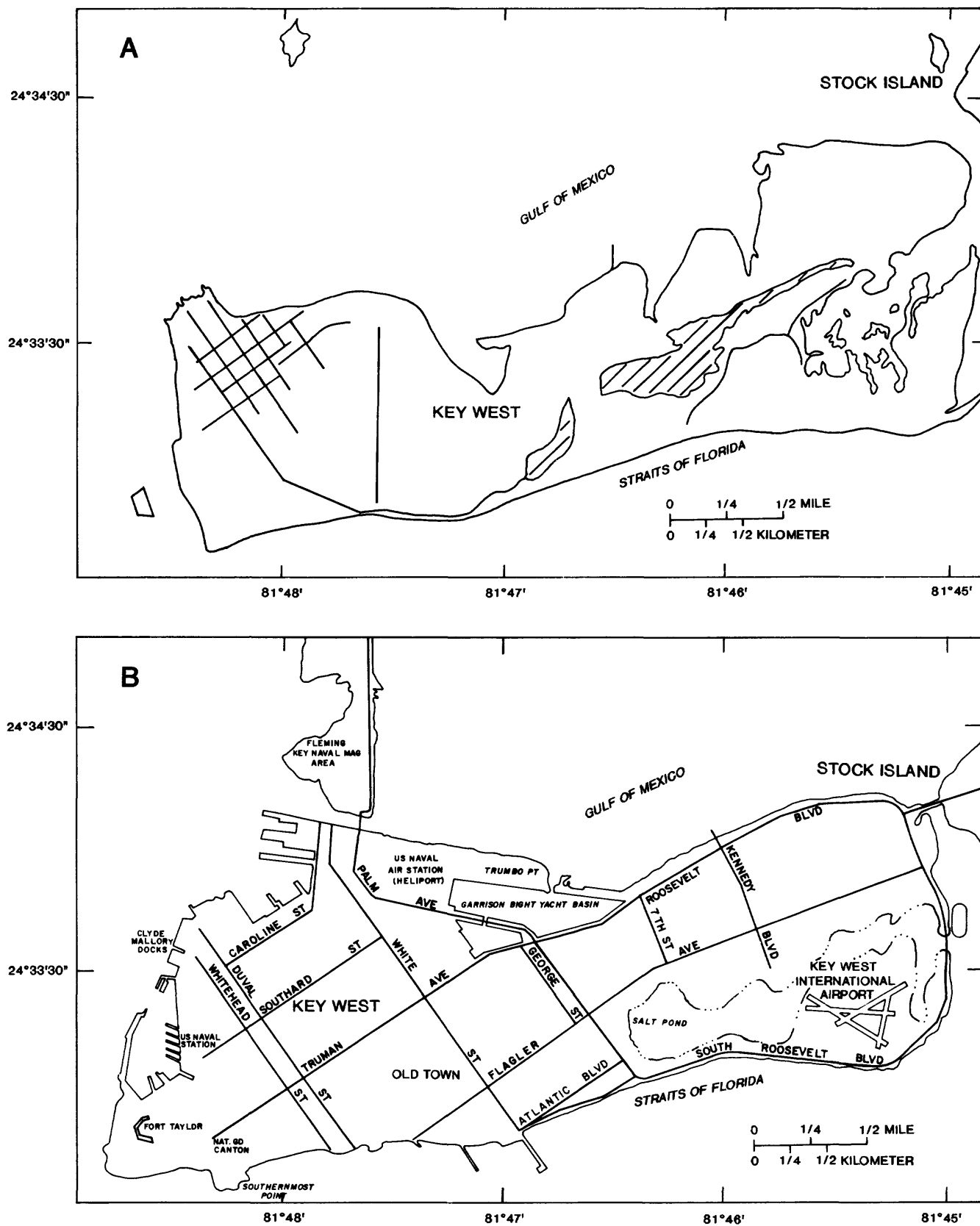


Figure 2. The island of Key West: (A) as it appeared in about 1850, and (B) as it appeared in 1988.

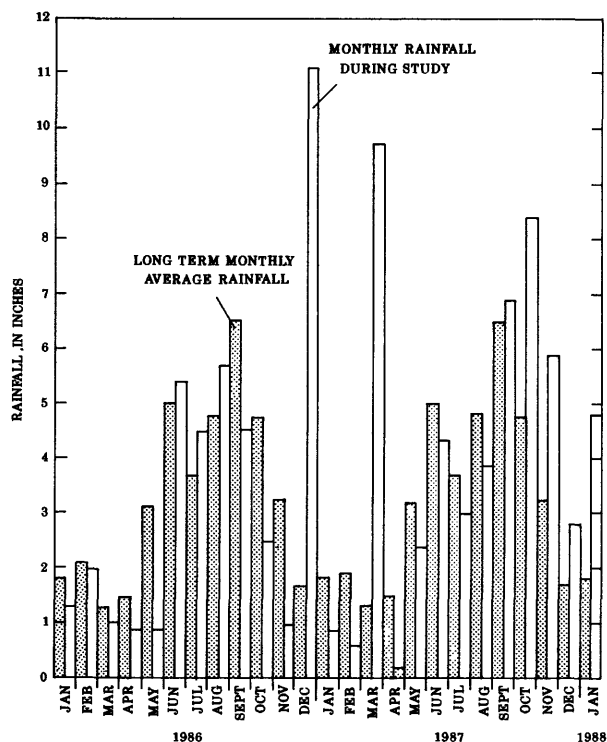


Figure 3. Monthly rainfall for 1986-88, and long-term average monthly rainfall at Key West.

the island each year, averaging about 4,100 individuals per day with a slight seasonal variation. The greatest population density is on the western part of the island where wooden single family residences predominate, many built during the 19th century. The area is locally referred to as "Old Town." Renovation and construction on much of the island is ongoing to accommodate an increase in tourism and new residents.

The observation wells drilled for this investigation (fig. 4) were concentrated in the western part of Key West, which is the largest area of natural land (oolitic limestone). Much of the eastern part of the island consists of large areas of artificially created land (fig. 2A-2B) with extensive areas of saltwater mangrove ponds; the freshwater lens is small or nonexistent there. The fill material generally was sand that was pumped from the adjacent shallow seabed, whereas some small inland areas were filled with domestic refuse. At present, a large sanitary landfill on Stock Island in the eastern part of Key West (fig. 4) receives the city's refuse.

Untreated domestic sewage is conveyed to the ocean through an outfall pipe to a deep trench, about 5,100 feet from the southwestern end of the island. The daily volume of sewage is 5.5 to 9.0 Mgal, depending on the amount of rainfall and seepage that enters the sewer pipes (Daniel J. Lagosky, City of Key West Sewer Department, oral commun., 1986). Some commercial developments, such as

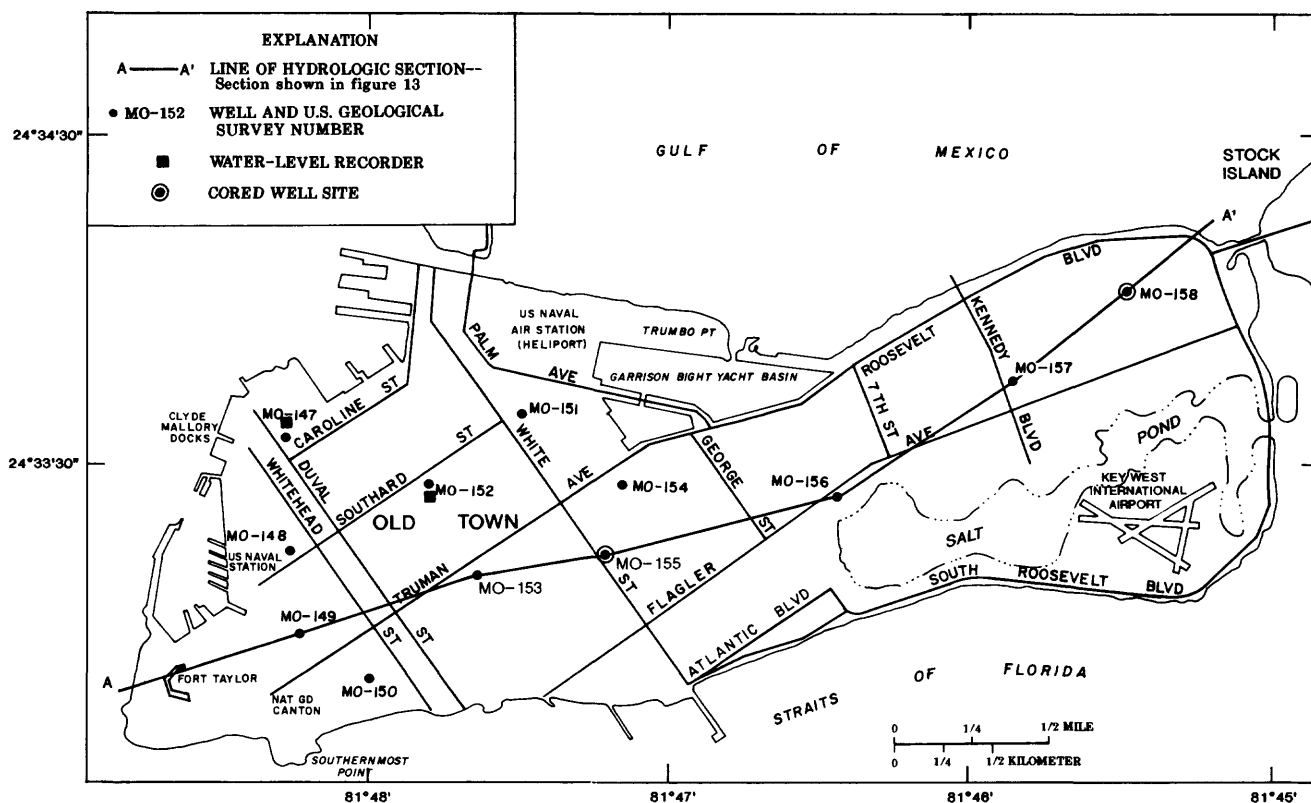


Figure 4. Location of wells, ground-water level recorders, and cored well sites at Key West.

condominium buildings, have individual package sewage-treatment plants and onsite effluent injection wells to a depth of 80 feet. The only known septic tanks are on the eastern part of the island near the Key West International Airport and on the northern part of the island near the Garrison Bight Yacht Basin (fig. 4). A sewage-treatment plant for the entire island is being constructed and is scheduled for completion in about 1990.

GEOHYDROLOGIC SETTING

The lower Florida Keys, from Big Pine Key to Key West, are a lithologic extension of the oolitic limestone that underlies Miami and other southeastern Florida coastal cities. The Miami Oolite of Pleistocene age was described by Parker and others (1955, p. 102) as honeycombed with solution holes, giving the rock an exceedingly high permeability. Parker and others further stated that many of the solution holes probably connect with channels open to the sea, allowing rainwater to rapidly escape to the sea and seawater to easily infiltrate the oolitic limestone of the island.

To substantiate and augment Parker's description of the oolitic lithology for Key West, two wells were cored to the saltwater interface—well MO-155 (40 feet deep) in the center of the western part of the island and well MO-158 (25 feet deep) on the eastern part of the island (fig. 4). Lithologic descriptions were made from microscopic examination and chemical testing of the well cuttings and cores. The lithologic logs for wells MO-155 and MO-158 are presented in table 1.

The oolitic limestone in Key West is pale orange, crystalline, porous to cavernous, with porosity increasing with depth, and contains an abundance of corals and other marine fossils indicating deposition in a marine environment. The oolite was the only rock type found in the cores of the two wells. Descriptions of the oolitic rock in the Lower Keys, similar to those of Parker and others (1955, p. 100), have been reported by Hoffmeister and others (1967, p. 186) and Mitchell-Tapping (1980, p. 118).

A lithologic log from the U.S. Geological Survey file for well MO-117 (W-265), drilled in 1938, indicates that oolite was penetrated to 200 feet. Beneath that was a white fossiliferous limestone with facies of gray shale, quartz sand, and loosely cemented coquina occurring to the bottom of the well at 2,000 feet. The exact location at Key West was not recorded. Another well (W-137), drilled in the 1920's, also has a lithologic log on file with the Survey that indicates a hard oolitic limestone, commonly with coral, to a total depth of 75 feet. The well was constructed on the western part of the island near well MO-148.

Fresh ground water (less than or equal to 250 mg/L of chloride) on islands, such as Key West, occurs in the form of a lens which floats on saltwater, the result of density differences. The lens is under water-table conditions, and the

surface is free to rise and fall. The freshwater head is greater in the center of the island where land-surface elevations are higher. Where the aquifer rock is a highly permeable oolitic limestone, as is the case at Key West, ground-water gradients typically are low. Ground water moves from the center of the lens to discharge along the beaches and salt ponds. Underlying the freshwater lens is a zone of mixed freshwater-saltwater, the transition zone that extends to the saltwater interface (19,000 mg/L of chloride).

CHARACTERISTICS OF THE FRESHWATER LENS

The highly permeable oolitic limestone extends throughout Key West and reaches a depth of about 200 feet. It is of sufficient extent at shallow depths in the western half of the island to contain a freshwater lens that is tapped by many domestic wells. The eastern half of the island has large areas of artificially created land and lacks sufficient aquifer material for a measurable freshwater lens.

Rainfall Recharge

Ground-water levels indicate that rainfall recharge quickly reaches the water table and rapidly seeps to the ocean (the amount of mixing in the transition zone is unknown). The greatest rainfall recorded during the investigation was 6.66 inches at the Key West International Airport on December 8, 1986. At well MO-152 near the center of the island, the water table rose 7.0 inches and then receded to the prepeak level about 1 hour after the peak was reached. The coastal well recorder (well MO-147) showed no effects from the rainfall of December 8.

The next greatest rainfall was 5.26 inches at the airport on March 6, 1987. The water table at well MO-152 rose about 8.5 inches and receded in 4 hours. The water-level recorder near well MO-147 recorded a 0.15-inch rise with a recession in 3 hours. The effect of the rainfall recharge on the water table is dependent on the volume and duration of the rainfall. This accounts for the differences between rise and recession rates of the ground-water levels during the storms of December 8, 1986, and March 6, 1987.

There were five other major rainfall events recorded during the investigation; rainfall varied from 3.47 to 1.47 inches. None of these events produced noticeable changes in recorded ground-water levels at wells MO-147 or MO-152.

Surface runoff and evapotranspiration affect the amount of rainfall that recharges the aquifer and subsequently influences the ground-water levels. There is little surface runoff to the ocean from unpaved areas because the island generally has low relief and the surface rock is highly permeable. About two-thirds of the stormwater runoff

(Daniel J. Lagosky, City of Key West Sewer Department, oral commun., 1986) from paved areas (about 20 percent of total area) is channeled into French drains (dry wells), and the rest is conducted by a separate system of stormwater sewers to an ocean outfall.

Water-Table Fluctuations

Fluctuations in the water table were monitored at two sites by automatic, continuous ground-water level recorders. Water-table fluctuations at well MO-152 near the center of

Table 1. Lithologic log of wells MO-155 and MO-158 at Key West

Description	Thick- ness (feet)	Depth (feet below land surface)
Well MO-155		
Limestone, very pale orange (10 YR 8/2); oosparite; moderately to well cemented; porous, vugs, and interparticle.	4	0 - 4
Limestone, very pale orange (10 YR 8/2); sparse oosparite, mollusks, framework organisms and serpulids; well cemented; porous to very porous, vugs.	4	4 - 8
Limestone, very pale orange (10 YR 8/2); fossiliferous, poorly washed oosparite; well cemented; porous to very porous, vugs.	4	8 - 12
Limestone, very pale orange (10 YR 8/2); biolithite; well cemented; porous, framework, at about 14 to 16 feet sparse oosparite; well cemented; very porous, vugs.	4	12 - 16
Cavern.	4	16 - 20
Limestone as in 12 to 16 feet.	0.5	20 - 20.5
Limestone, very pale orange (10 YR 8/2); oolite-bearing sparse to packed oosparite, abundant corals, serpulids and worm borings, and mollusks; well cemented; moderately porous to porous at 22 to 24 feet, framework and vugs.	3.5	20.5 - 24
Limestone as above; porous and cavernous at about 24 to 25 feet.	3	24 - 27
Limestone, very pale orange (10 YR 8/2); sparse to packed poorly washed biosparite, abundant corals; well cemented; very porous, vugs are coated with iron mineral.	1	27 - 28
Limestone, very pale orange (10 YR 8/2); sparse poorly washed oosparite to packed oosparite toward the base, abundant corals including <i>Monastrea</i> sp.; well cemented; porous to cavernous in places.	4	28 - 32
Limestone, very pale orange (10 YR 8/2); oolite-bearing packed sparite to packed sparite, abundant corals; well cemented; porous to cavernous.	4	32 - 36
Cavern.	4	36 - 40
Well MO-158		
Limestone, very pale orange (10 YR 8/2); sparse poorly washed oosparite, mollusks; moderately to well cemented; moderately porous to porous in places; vugs and interparticle.	2.5	2.5 - 5
Limestone as above; grades to a fossiliferous oosparite toward base; moderately porous (vugs) to porous and slightly porous at about 5 to 5.5 feet.	5	5 - 10
Limestone, very pale orange (10 YR 8/2); fossiliferous oosparite; well cemented; slightly porous to porous at about 14 to 15 feet, vugs.	5	10 - 15
Limestone, very pale orange (10 YR 8/2); sparse oosparite, benthic foraminifers and mollusks; well cemented; porous (vugs) to slightly porous at about 19.5 to 20 feet.	5	15 - 20
Limestone, very pale orange (10 YR 8/2); intraclastic-bearing sparse oosparite; well cemented; moderately porous to porous, vugs.	5	20 - 25

Old Town ranged from 0.8 foot above sea level on June 16, 1987, to 2.4 feet above sea level on March 6, 1987. Near the coast at well MO-147, the range was from 0.4 foot above sea level on June 16, 1987, to 2.2 feet above sea level on December 30, 1986. The high ground-water levels were of short duration and were the product of storms (discussed earlier) and tidal effects and were not representative of average conditions.

Ground-water levels in all of the observation wells were measured monthly with a hand-held steel tape. Measurements were completed in as short a period as possible to minimize the rapid changes in the ground-water levels caused by the semidiurnal tides. The highest water-table measurements were recorded on December 8, 1986, following a 6.66-inch rainfall. During the time required to make the steel-tape-measurements, the two automatic ground-water level recorders indicated a mean decrease of 0.25 foot. The lowest monthly measurements were made on June 24, 1987. During the hour required to make the tape measurements, there was a mean decrease of 0.08 foot indicated by the ground-water level recorders. Figures 5 and 6 depict the water table on these dates when the gradients were, respectively, about 4 and 1 ft/mi (foot per mile).

The close relation between water-table fluctuations at wells MO-147 (about 0.2 mile from the coast) and MO-152 (about 0.7 mile from the coast) and the tide stages is shown in figure 7. A comparison indicates the tidal signal typically reaches well MO-147 in about 30 minutes and well MO-152 in about 1.5 hours. The range in magnitude of water-table

fluctuations decreases from the coast to the inland area, a manifestation of decreasing tidal effects with increasing distance from the coast. The short lag time reflects the high permeability of the aquifer.

Configuration of the Freshwater Lens and Transition Zone

The constantly changing configuration of the freshwater lens and the transition zone of freshwater-saltwater mix is principally a manifestation of tidal effects. To appraise the magnitude of changes that occur in the lens and the transition zone, the water columns in four wells (MO-149, MO-152, MO-153, and MO-155) were measured for specific conductance and sampled for chloride concentrations during a tide cycle on October 22-23, 1987. The data were collected at high, low, and intermediate stages of the tide-influenced ground-water levels. Figure 8 shows the ground-water hydrograph of well MO-152 and the times of data collection at the four observation wells. Profiles of specific conductance and associated concentrations of chloride (A, high ground-water levels; B, low ground-water levels; and C, intermediate ground-water levels) for each of the four observation wells are shown in figures 9 to 12.

A well-defined relation between specific conductance and chloride concentration was established at Key West during the investigation and is given in the table below. Salinity, describing general dissolved salt content, is used in

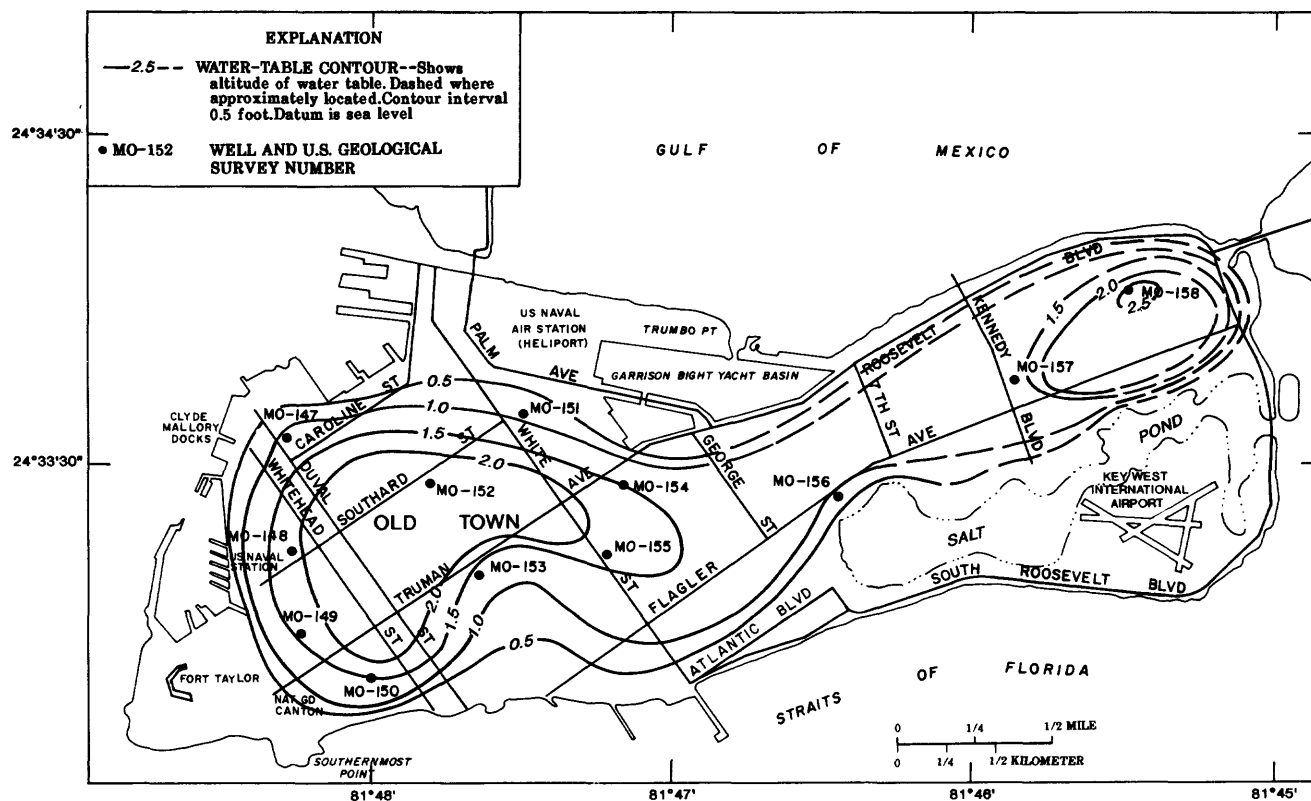


Figure 5. Water-table elevations for the highest ground-water levels measured during the investigation, December 8, 1986.

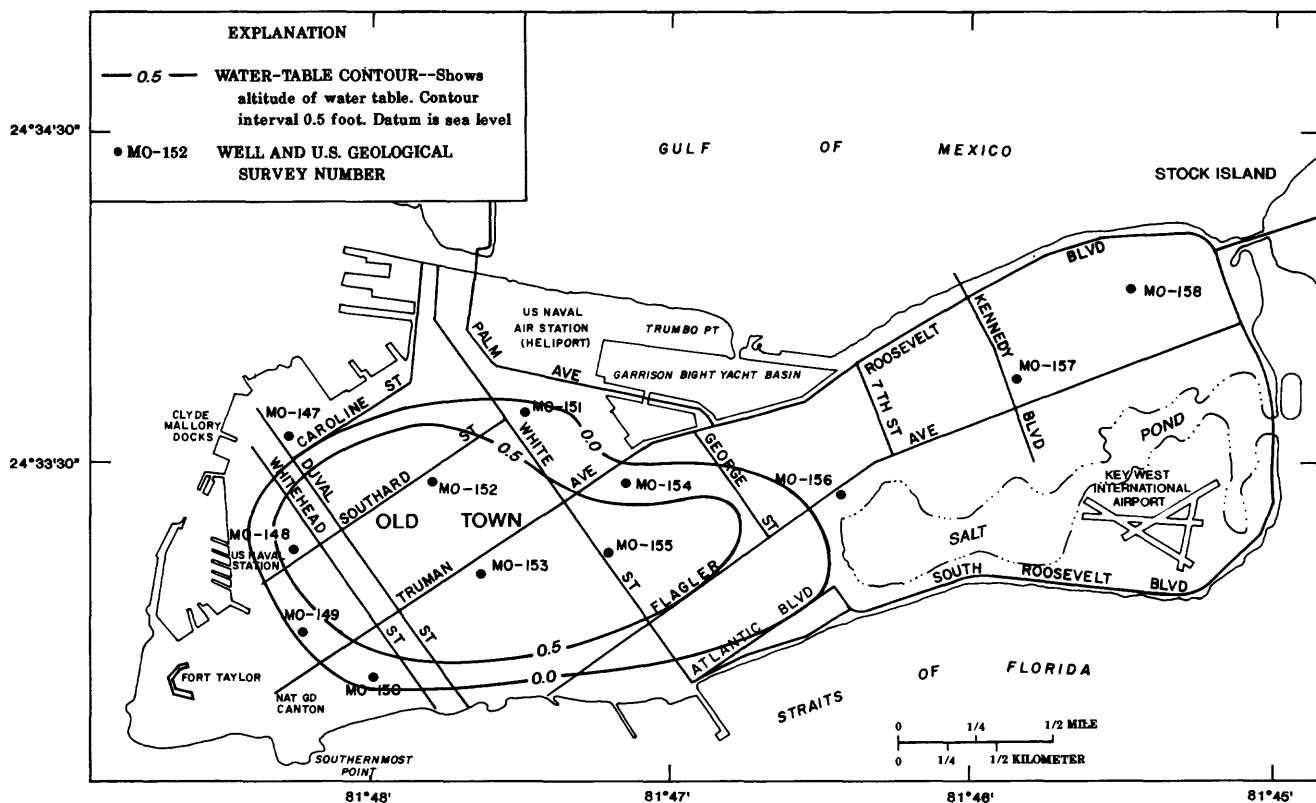


Figure 6. Water-table elevations for the lowest ground-water levels measured during the investigation, June 24, 1987.

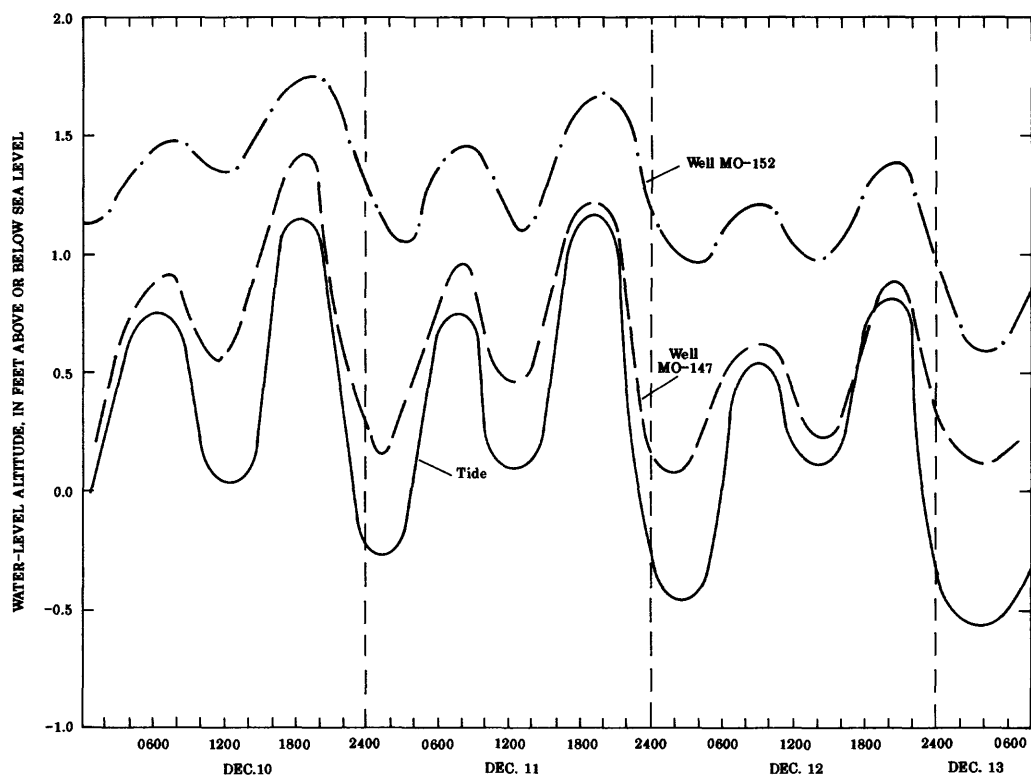


Figure 7. Water-table fluctuations at wells MO-147 and MO-152 and the tide stages at Key West, December 10-13, 1986.

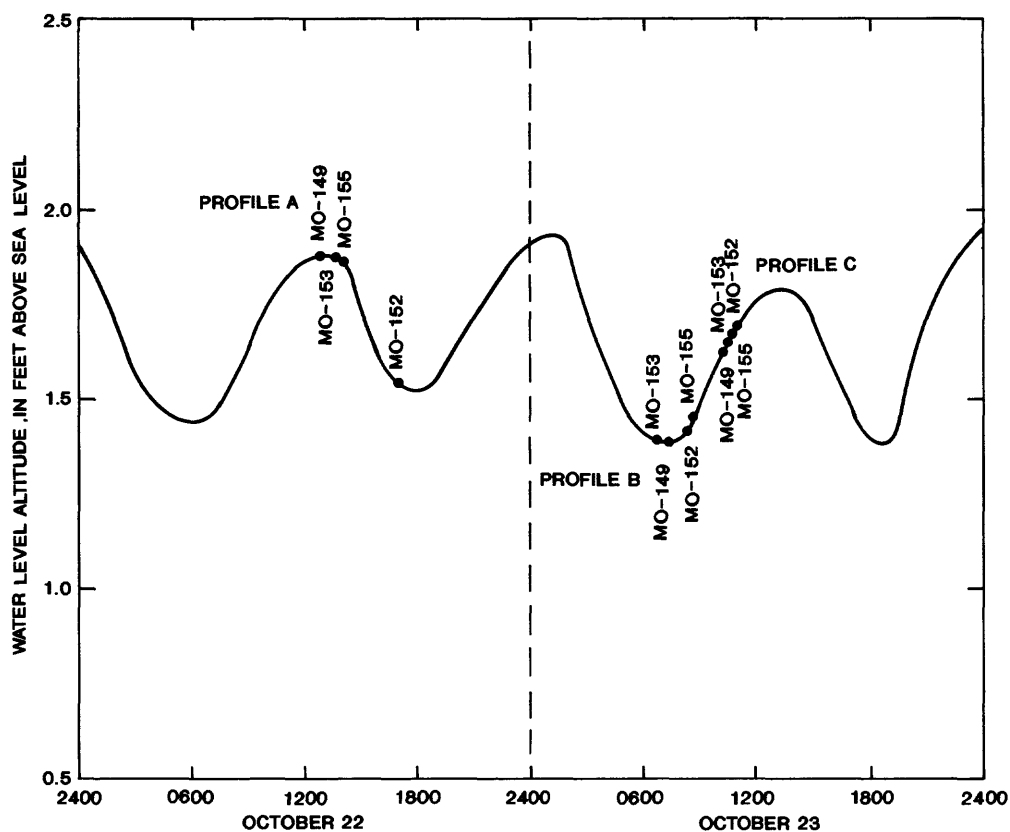


Figure 8. Hydrograph of well MO-152 showing the times of specific conductance profile measurements in four wells, October 22-23, 1987.

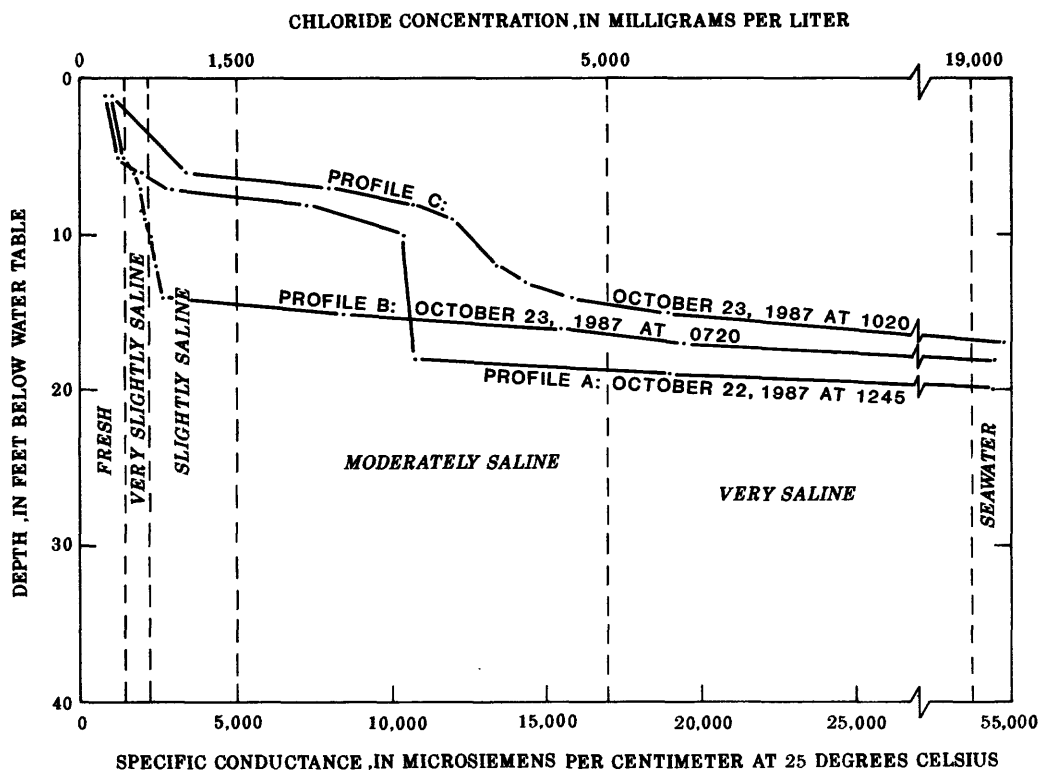


Figure 9. Depth profiles of specific conductance and associated concentrations of chloride at well MO-149.

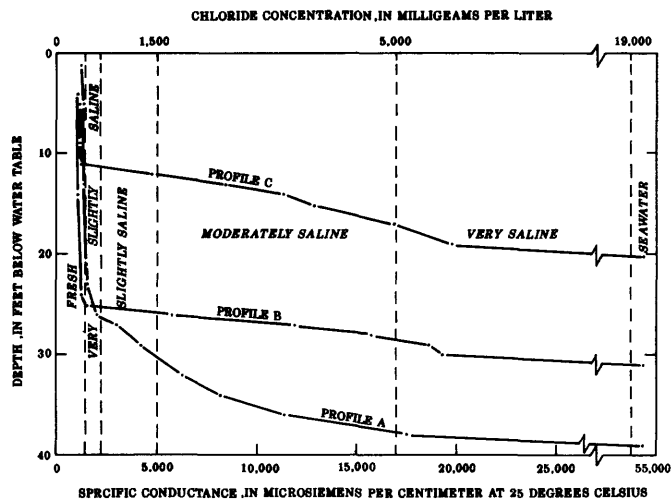


Figure 10. Depth profiles of specific conductance and associated concentrations of chloride at well MO-152.

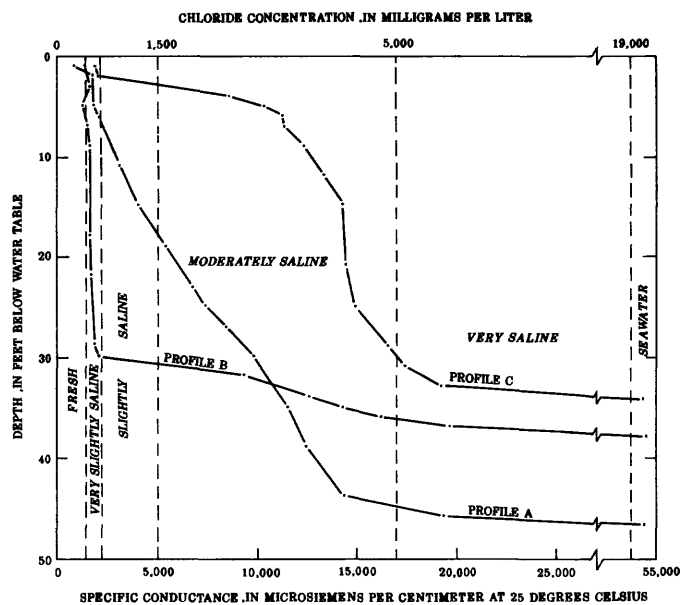


Figure 11. Depth profiles of specific conductance and associated concentrations of chloride at well MO-153.

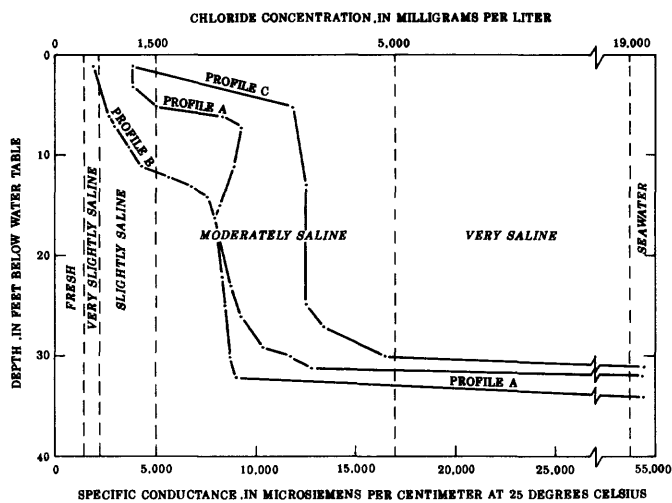


Figure 12. Depth profiles of specific conductance and associated concentrations of chloride at well MO-155.

the table to relate specific conductance and chloride concentration to water type. This information is also shown in the well water profiles (figs. 9-12).

Type of water	Specific conductance (microsiemens per centimeter)	Chloride (milligrams per liter)
Fresh	0 - 1,400	0 - 250
Very slightly saline	1,400 - 1,900	250 - 400
Slightly saline	1,900 - 5,000	400 - 1,500
Moderately saline	5,000 - 17,000	1,500 - 5,000
Very saline	17,000 - 52,000	5,000 - 19,000
Seawater	>52,000	>19,000

Wells MO-152, MO-153, and MO-155 are near the center of the lens in the vicinity of Old Town, whereas well MO-149 is in the western part of Key West in the vicinity of Fort Taylor, which is an artificially constructed land area. Because of the proximity of well MO-149 to the coast, water in this well is more saline at shallower depths than is water in the other three wells (fig. 9).

The distinctive characteristic of all four wells is that the freshwater and salinity zones measured by chloride and specific conductance constantly change with water-table fluctuations that are influenced by tides. The salinity of water in these wells (figs. 9-12) indicates that wide variations in specific conductance may occur within short time spans at each depth. For example, at well MO-153 on October 23, 1987, at a depth of 10 feet, the specific conductance was about 1,500 $\mu\text{S}/\text{cm}$ (microsiemens per centimeter) at 0730 hours; but 3 hours later, the specific conductance had increased to almost 13,000 $\mu\text{S}/\text{cm}$ (fig. 11).

All four wells show some similarity in specific-conductance profiles. Profile C shows the thinnest freshwater zone and was measured midway between high and low ground-water levels. Profile B was measured at low ground-water levels and has the thickest freshwater zone. Profile A was measured at high ground-water levels, and the specific conductance falls somewhere between the other two extremes, except at well MO-152 on October 22, 1987, at 1710 hours (fig. 10). This profile actually coincided with a low ground-water level (fig. 8) and reflects a thick freshwater lens like the B profiles which were also measured at low ground-water levels.

Although there probably is a precise relation among tide, ground-water levels, and lens thickness, it was not fully defined during these three measurements. The correlation of lens thickness with semidiurnal tidally induced fluctuation in ground-water levels, occurring in a solution-riddled, fissured aquifer, is beyond the scope of this investigation.

Because the water-table fluctuations and the configuration of the freshwater lens and transition zone are constantly changing, vertically and areally, only a generalized depiction of the lens and diffusion zones could be made. The specific conductance and chloride-concentration data collected during seven sampling events were used to construct a generalized cross section of the lens and transition zone along the length of the island (fig. 13). The measurements were made in May, August, and October 1986, and March and October 1987 (three sampling events in October), during high and low stages of the tide and ground-water levels.

The water table generally was 1 to 2 feet above sea level at the center of the lens. The freshwater lens ranged in

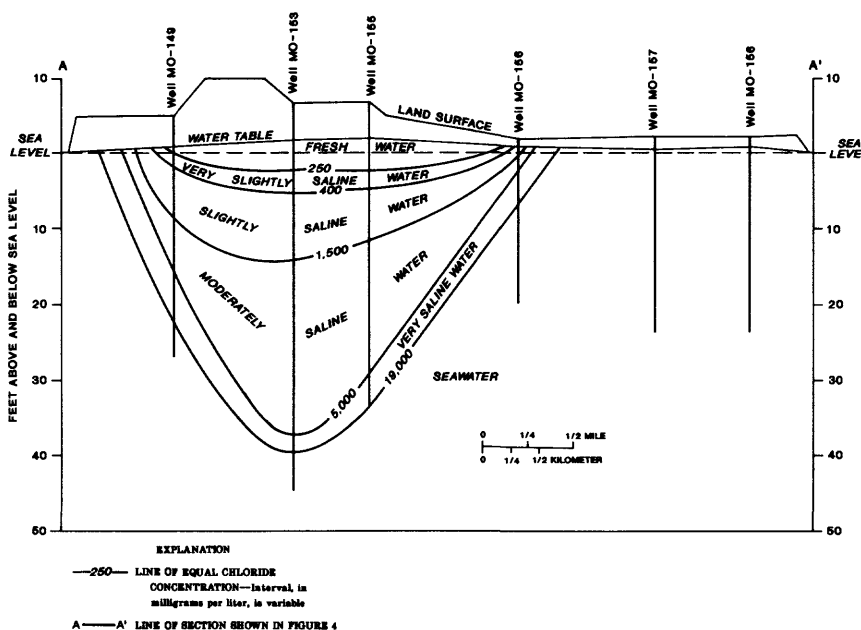


Figure 13. Hydrologic cross section of Key West along line A-A' showing chloride concentrations in ground water, October 21-22, 1986.

thickness from less than 1 foot to 9 feet, with an average thickness of 5 feet at the center of the lens near Old Town. The lens quickly thinned toward the coast. The very slightly saline zone. (chloride concentration of 250-400 mg/L) was usually about twice as thick as the overlying freshwater lens, ranging in thickness from 7 to 34 feet. The depth to the saltwater interface (chloride concentration of 19,000 mg/L) near the center of the island was about 40 feet.

To illustrate the areal extent and thickness of the freshwater lens and estimate the volume, lines of equal chloride concentration were constructed at 2-foot depth intervals to the bottom of the 250-mg/L chloride concentration zone. The surface area for each depth was calculated; a 0.20 storage coefficient, commonly used for the Miami Oolite (Parker and others, 1955, p. 281), was used; and the approximate volume was determined. The volume of the freshwater lens on October 21, 1986, near the end of the wet season, was about 30 Mgal and on April 1, 1987, near the end of the dry season, it was about 20 Mgal. Lines of equal chloride concentration at a depth of 4 feet below the water table for the two respective dates are shown in figures 14 and 15.

The volume of freshwater is affected by the amount of rainfall, seepage to the ocean, evapotranspiration, and withdrawal. Determining the volume of freshwater is further complicated by the constantly changing configuration of the lens and transition zone that is caused by the effects of the semidiurnal tide.

Surface-geophysical resistivity measurements were made to augment specific conductance and chloride-concentration data at the observation well sites. The EM-16R VLF system was selected because of its operational adaptability to a dense urban area with many magnetic interferences, such as overhead electrical wires and metal fences. The principal site requirement was that the surface be unpaved and soft enough to accept manually inserted probes.

VLF radio signals are transmitted from stations throughout the world. Each VLF radio signal induces electric and magnetic fields in the Earth that are related to its electrical properties. In surface-geophysical resistivity measurements, an instrument measures the ratio of the horizontal components of the electric and magnetic fields of a selected signal. It is calibrated to read directly the apparent resistivity and the phase angle. Because the phase angle measured at all stations was 45°, it is assumed that the apparent resistivity is equal to the true bulk resistivity of the Earth.

The apparent resistivity, measured in ohm-meters and equal to bulk resistivity, reflects the entire depth of penetration and not a particular depth as did the chloride concentration and specific conductance measurements. Because the shape of the lens and transition zone constantly changes, a general configuration is best reflected by the resistivity measurements: the lens is centered under the Old Town area and grades rapidly to saline and ocean water.

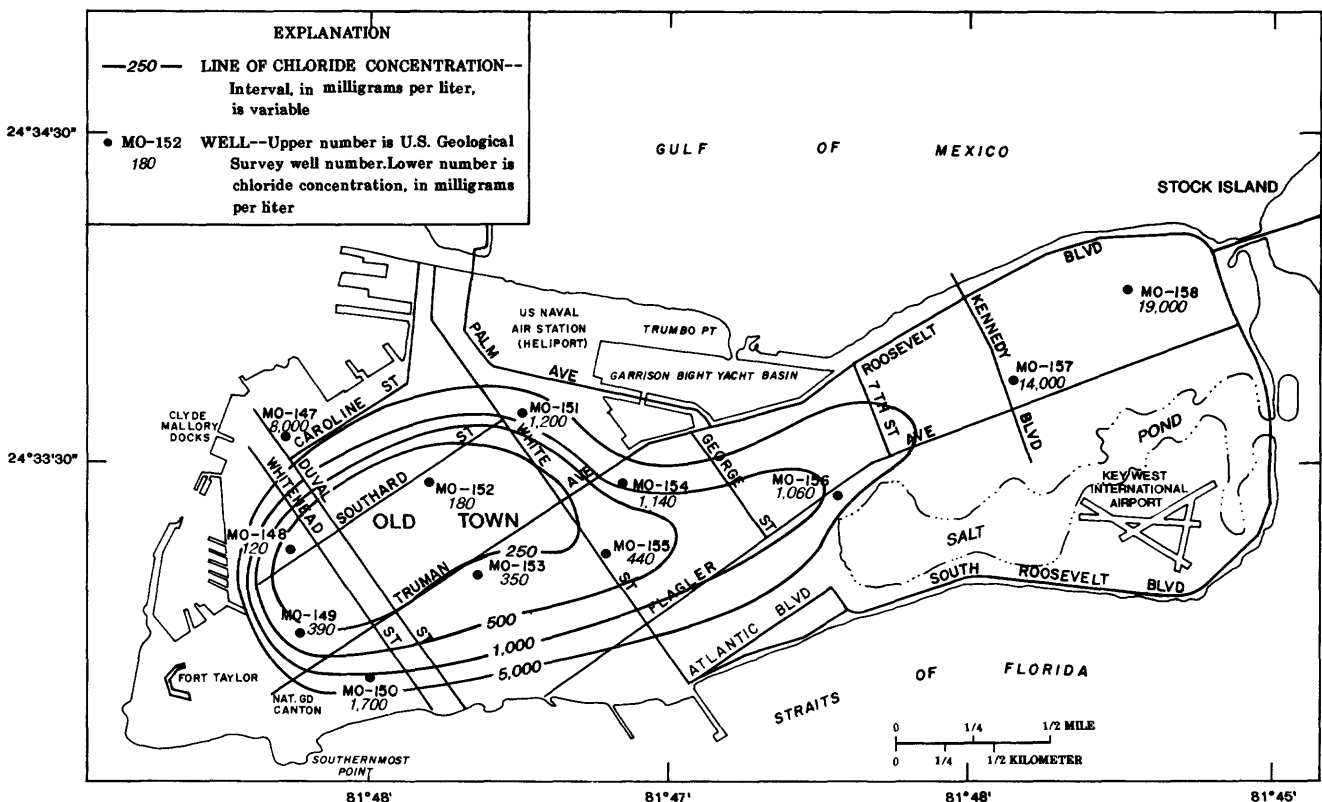


Figure 14. Lines of equal chloride concentration at a depth of 4 feet below the water table, October 21, 1986.

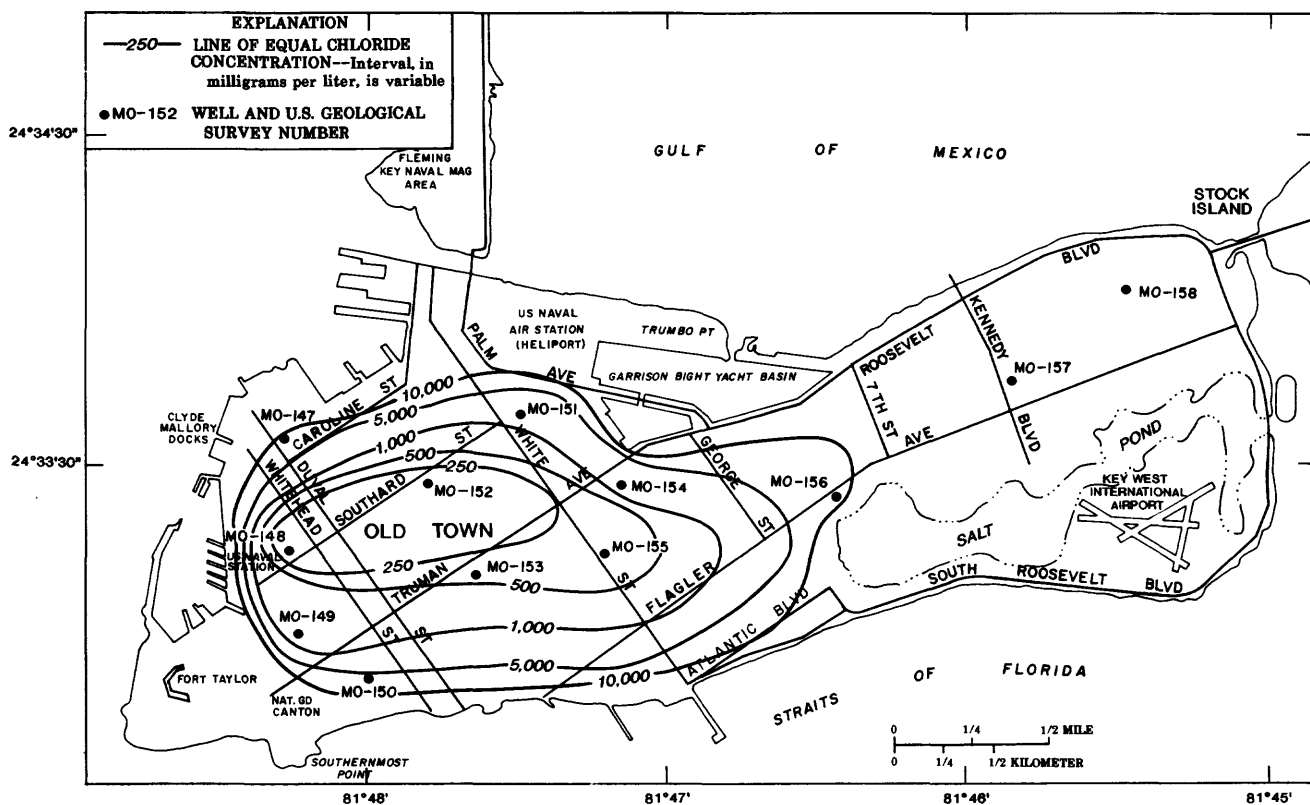


Figure 15. Lines of equal chloride concentration at a depth of 4 feet below the water table, April 1, 1987.

The surface-geophysical resistivity measurements using the EM-16R VLF meter were made during November 20-21, 1986. Measurements were recorded at 22 sites concentrated in the western half of the island. The approximate limits of the freshwater lens as defined by the 10 ohm-meter line of equal resistivity, located under the central part of the western half of the island, are shown in figure 16. The highest reading (13.5 ohm-meters) was obtained near the site of a former freshwater spring. The zones of freshwater and salinity defined by the resistivity lines in figure 16 and the chloride concentration lines in figures 14 and 15 are in general agreement.

GROUND-WATER QUALITY

The quality of ground water can be described in terms of its chemical constituents and physical and biological characteristics. The quality is usually defined according to its intended use: potable, recreational, agricultural, or industrial. The water is considered to be of poor quality or contaminated if a particular constituent exceeds the level or limit set for the

intended use. The contamination may be a health hazard, an esthetic degradation, or a threat to the aquatic environment.

Possible sources of ground-water contamination at Key West include many of those common to a modern urbanized society, including landfill disposal of household and industrial refuse (Stock Island); pesticide and fertilizer applications; stormwater runoff; and industrial enterprises (such as maintenance of airplanes and fuel storage tanks).

Major Inorganic Constituents and Physical Properties

The shallow ground water was sampled at depths of 2 to 5 feet below the water table on October 21-22, 1986, for major inorganic ions and related characteristics (table 2). The sampling depth was selected on the basis of salinity (or chloride concentration) at the time of collection; the objective was to obtain samples of the freshest water, the most likely to be withdrawn for domestic use. Sampling was conducted during various phases of the tide cycle and at various ground-water stages.

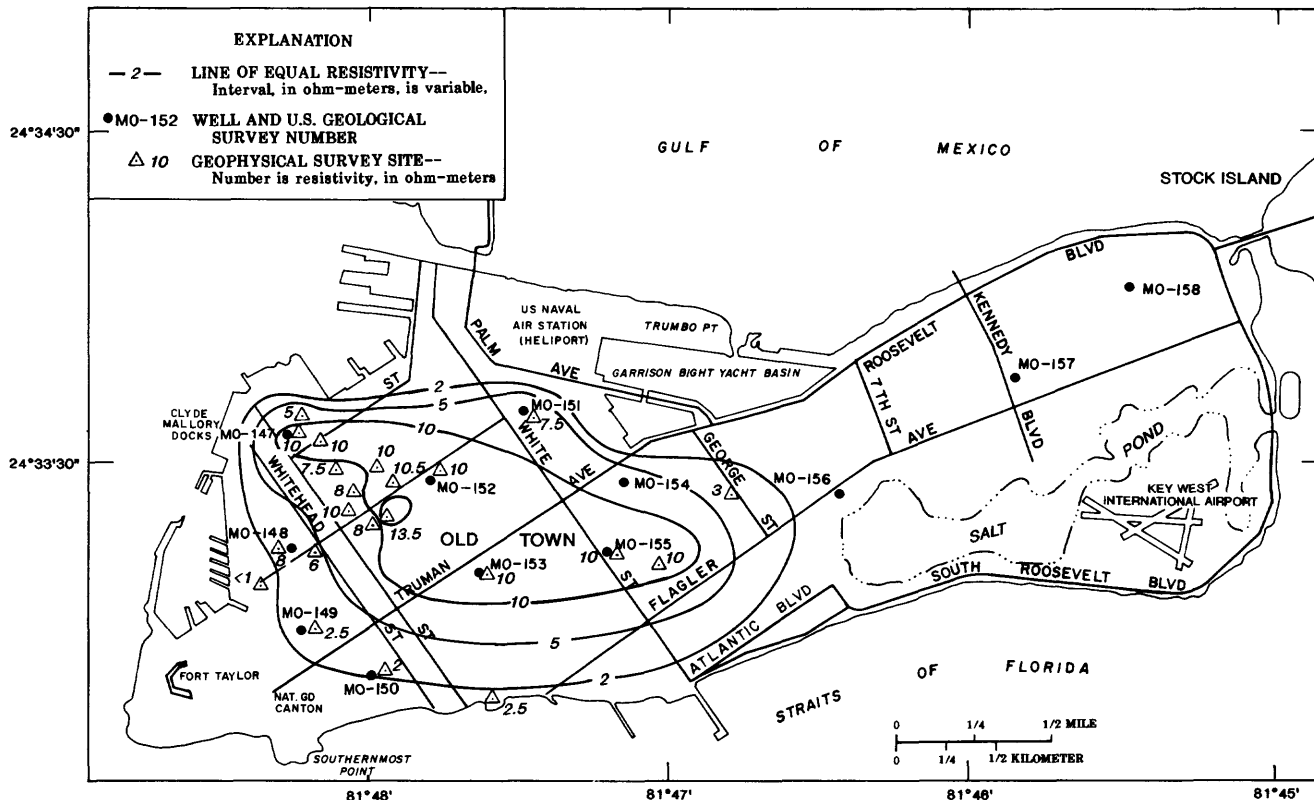


Figure 16. Surface-geophysical survey sites and lines of equal resistivity, November 20, 1986.

The analytical results of this sampling reconnaissance indicate that concentrations of major inorganic constituents generally increase with increases in chloride concentration. The chloride concentration is a good indicator of mixing in that chloride ions enter into few chemical or biochemical reactions, and are retained in solution through most of the processes which separate other ions (Hem, 1985, p. 120). A relation between chloride concentrations and other major constituent concentrations indicates that the major inorganic composition throughout the well water column likely results from a simple mixing of freshwater and saltwater. As mentioned earlier, the maximum contaminant level (MCL) for chloride is 250 mg/L. However, this is a consideration for taste rather than for human health. People and vegetation can tolerate even higher concentrations of chloride (National Academy of Sciences, National Academy of Engineering, 1974, p. 328; U.S. Environmental Protection Agency, 1986b, p. 206). As a result, water with chloride concentrations exceeding 250 mg/L is pumped from many domestic wells in Key West that tap various depths and areas of the ground water for household and lawn irrigation (Rosemary Vogenet, Key West Planning Department, oral commun., 1989).

Wells MO-148, MO-152, and MO-155, sampled during various phases of the tide cycle, yielded water with chloride concentrations ranging from 45 to 150 mg/L, which were among the lowest concentrations measured. The water in these wells was a calcium bicarbonate water (table 2). However, as the saltwater content increased and chloride concentrations exceeded 1,000 mg/L (as shown in some of the other well water samples), the water became a sodium chloride water with large amounts of magnesium, sulfate, and potassium.

Water in the Key West freshwater lens is similar to that in the Biscayne aquifer (Sonntag, 1987, p. 18) of adjacent Dade County in that these waters have similar major constituent concentrations. The freshwater lens has a slightly higher specific conductance and greater concentrations of dissolved solids and sulfate than water in the Biscayne aquifer.

Nutrients

Wells MO-147 to MO-158 were sampled in October 1986, March 1987, and September 1987, for organic

Table 2. Chemical and physical characteristics of Key West ground water at depths of 2 to 5 feet below the water table, October 21-22, 1986

[Concentrations are shown in milligrams per liter, except where noted; sampling depth is shown in feet below the water table; <, less than the value. Specific conductance for well MO-156 is a field value]

Well number	Sampling depth (feet)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Chloride (Cl)	Sulfate (SO ₄)	Silica (SiO ₂)	Potassium (K)	Fluoride (F)	Bicarbonate (HCO ₃)	Hardness (as CaCO ₃)
MO-148	4	90	11	29	45	48	6.0	3.3	0.5	244	273
MO-149	2	130	34	320	530	150	8.3	39	1.1	—	-
MO-151	4	200	240	1,900	3,700	460	9.3	78	1.6	301	1,501
MO-152	5	130	5.2	77	130	70	7.7	2.2	.7	330	351
MO-153	2	140	73	570	1,000	180	6.8	23	.6	352	654
MO-154	2	180	200	1,600	2,900	440	7.3	75	1.0	412	1,282
MO-155	2	110	17	65	150	45	6.4	5.2	.5	305	348
MO-156	4	450	1,400	12,000	20,900	2,699	1.9	500	1.6	—	6,899
MO-157	2	450	1,400	12,000	21,000	2,900	1.7	490	1.6	183	6,899

Well number	Sampling depth (feet)	Alkalinity (as CaCO ₃)	Dissolved solids	Chemical oxygen demand	Specific conductance (microsiemens per centimeter)	pH (standard units)	Color (platinum-cobalt units)
MO-148	4	200	408	<10	701	7.9	<5
MO-149	2	—	1,990	55	2,500	—	—
MO-151	4	247	7,490	32	11,600	7.8	10
MO-152	5	270	672	44	971	7.7	<5
MO-153	2	289	2,440	36	3,980	7.6	<5
MO-154	2	339	6,240	73	9,680	7.8	20
MO-155	2	250	620	<10	1,000	7.6	5
MO-156	4	232	41,199	250	52,000	7.4	20
MO-157	2	250	41,500	390	54,200	7.4	10

nitrogen, ammonia, nitrate, nitrite, phosphorus, and total organic carbon (TOC). Wells MO-148, MO-149, MO-153, and MO-154 were sampled a fourth time in January 1988 because of relatively high nitrate-nitrogen concentrations in the earlier samples. Wells MO-147 and MO-150 were sampled at a depth of 2 feet below the water table. The remaining wells were sampled at depths of 5 to 15 feet (5-foot depth intervals) below the water table, depending on salinity. The shallower part of the lens that is most likely to be tapped for domestic wells was emphasized for sampling.

Table 3 presents the results of the nutrient analyses of the samples collected at various well depths during the four sampling events. Of the nutrients analyzed, nitrate nitrogen was the most abundant with most samples having concentrations exceeding 1 mg/L; some samples had concentrations exceeding 5 mg/L. Nitrate-nitrogen concentrations that exceed 1 mg/L usually signify man's influence (National Academy of Sciences, National Academy of Engineering, 1974, p. 73), indicating sources such as fertilizer or domestic sewage. For comparison, nitrate-nitrogen concentrations in the Biscayne aquifer generally are less than 0.10 mg/L (Irwin and Healy, 1978, p. 35; Sonntag, 1987, p. 32). The average nitrate-nitrogen concentrations for each well site in Key West are shown in figure 17.

In the western half of the island, average concentrations of nitrate nitrogen in water samples from wells MO-147 to MO-155 ranged from 0.52 to 6.06 mg/L. The maximum nitrate-nitrogen concentration detected in any well was 11 mg/L (MO-149), which exceeded the MCL (10 mg/L) of the Primary Drinking Water Regulations established by the Florida Department of Environmental Regulation (1983). In the eastern part of the lens, nitrate-nitrogen concentrations were low, ranging from less than 0.01 mg/L to 0.34 mg/L in wells MO-156, MO-157, and MO-158. A water sample from well MO-158 had a total nitrogen concentration of 7.53 mg/L (primarily ammonia) in October 1986. The high ammonia concentration likely was a result of decomposing organic matter in a drainage ditch near the well.

No relation exists between nitrate nitrogen and the salinity of the sampled water (table 3), indicating that saltwater intrusion contributes little to the nitrate concentration. For example, in October 1986, well MO-148 had a nitrate-nitrogen concentration of 6.50 mg/L and a chloride concentration of 45 mg/L. At the same time, well MO-154 had a nitrate-nitrogen concentration of 5.35 mg/L and a chloride concentration of 2,900 mg/L.

Table 3. Nutrient concentrations in Key West ground water at various well depths, October 1986 through January 1988

[Concentrations shown in milligrams per liter; —, not sampled; <, less than the value]

Well number	Sampling depth (feet)	Date of sampling	Ammonia nitrogen	Organic nitrogen	Nitrite nitrogen	Nitrate nitrogen	Orthophosphate	Phosphorus as PO ₄	Total phosphorus	Chloride	Total organic carbon
MO-147	2	Oct. 1986	0.04	0.34	0.16	3.24	0.04	8.18	0.06	7,440	3.1
		March 1987	.04	.26	.05	2.45	.05	.15	.06	5,108	5.0
		Sept. 1987	.03	.47	<.01	6.6	.02	.06	.03	—	5.0
		Jan. 1988	—	—	—	—	—	—	—	—	—
MO-148	5	Oct. 1986	.03	.75	<.01	6.50	.02	.12	.04	45	2.0
		March 1987	.02	.45	<.01	7.4	.02	.06	.03	120	6.2
		Sept. 1987	.03	.52	<.01	5.8	.01	.03	.03	—	6.0
		Jan. 1988	.03	.79	.01	4.10	.01	.03	.04	—	—
	10	Oct. 1986	<.01	.33	<.01	6.70	.01	.123	.04	275	2.0
		March 1987	.02	<.20	<.01	4.4	.02	.06	.03	4,390	5.0
		Sept. 1987	.04	.28	<.01	9.4	.02	.06	.03	—	—
		Jan. 1988	.01	.40	<.01	4.00	.01	.03	.04	—	—
MO-149	5	Oct. 1986	<.01	.54	<.01	5.00	.02	.123	.04	500	8.0
		March 1987	.02	.68	<.01	11	.03	.09	.03	580	8.0
		Sept. 1987	.03	.23	<.01	.92	.13	.40	.14	—	7.0
		Jan. 1988	.01	.64	.01	9.00	.01	.03	.02	—	—
	10	Oct. 1986	—	—	—	—	—	—	—	600	—
		March 1987	.03	.60	<.01	.20	.02	.06	.02	1,550	11.0
		Sept. 1987	.04	.62	.09	9.31	.02	.06	.03	—	—
		Jan. 1988	.01	.66	.01	8.20	.02	.06	.03	—	—
	15	Oct. 1986	—	—	—	—	—	—	—	600	—
		March 1987	—	—	—	—	—	—	—	4,820	—
		Sept. 1987	—	—	—	—	—	—	—	—	—
		Jan. 1988	.04	.44	.01	3.40	.04	.12	.04	—	—
MO-150	2	Oct. 1986	.71	.99	<.01	.02	.02	2.48	.81	3,400	6.8
		March 1987	.03	1.97	.01	.49	.08	.24	.18	2,080	33.0
		Sept. 1987	.52	.88	<.01	<.01	.03	.09	.11	—	6.0
		Jan. 1988	—	—	—	—	—	—	—	—	—
MO-151	5	Oct. 1986	.02	.38	<.01	1.80	.02	.184	.06	950	7.1
		March 1987	.02	.25	<.01	.28	.05	.15	.06	1,360	9.0
		Sept. 1987	.03	.34	<.01	1.10	.02	.06	.08	—	6.5
		Jan. 1988	—	—	—	—	—	—	—	—	—
	15	Oct. 1986	.63	.67	.21	1.79	.02	.153	.05	2,965	6.8
		March 1987	.02	.31	.02	1.38	.02	.06	.02	2,614	6.8
		Sept. 1987	.04	.41	.04	1.96	.02	.06	.03	—	—
		Jan. 1988	—	—	—	—	—	—	—	—	—
MO-152	5	Oct. 1986	.03	.73	<.01	.95	.02	.153	.05	160	2.9
		March 1987	.02	.45	<.01	1.7	.01	.03	.02	180	7.0
		Sept. 1987	.02	.35	<.01	1.1	.02	.06	.05	—	5.0
		Jan. 1988	—	—	—	—	—	—	—	—	—
	10	Oct. 1986	2.80	.40	<.01	.02	.03	.15	.05	310	6.8
		March 1987	1.00	.60	.04	.30	.01	.03	.02	340	7.2
		Sept. 1987	.42	.68	.02	.43	.01	.03	.05	—	—
		Jan. 1988	—	—	—	—	—	—	—	—	—
	15	Oct. 1986	2.20	.20	<.01	<.02	.02	.092	.03	310	3.2
		March 1987	.70	.50	.12	.31	.01	.03	<.02	400	6.0
		Sept. 1987	.43	.57	.02	.43	.01	.03	.04	—	—
		Jan. 1988	—	—	—	—	—	—	—	—	—
MO-153	5	Oct. 1986	.02	.50	<.01	5.00	.02	.092	.03	400	3.8
		March 1987	.02	.25	.01	2.69	.01	.03	<.02	3,675	6.0
		Sept. 1987	.02	.26	<.01	4.6	.02	.06	.04	—	4.5
		Jan. 1988	.02	.56	.03	3.37	.02	.06	.05	—	—

Table 3. Nutrient concentrations in Key West ground water at various well depths, October 1986 through January 1988—Continued

Well number	Sampling depth (feet)	Date of sampling	Ammonia nitrogen	Organic nitrogen	Nitrite nitrogen	Nitrate nitrogen	Orthophosphate	Phosphorus as PO ₄	Total phosphorus	Chloride	Total organic carbon
MO-154	10	Oct. 1986	.03	.35	.03	2.57	.02	.092	.03	834	2.0
		March 1987	.02	.35	.01	2.79	.01	.03	<.02	5,120	6.2
		Sept. 1987	.03	.37	.01	3.99	.02	.06	.07	—	—
		Jan. 1988	.02	.56	.03	3.37	.02	.06	.05	—	—
	15	Jan. 1988	.02	.40	.03	2.97	.02	.06	.03	—	—
		Oct. 1986	.02	.25	.02	2.58	.02	.123	.04	853	2.0
		March 1987	.04	.43	.05	1.35	.03	.09	.05	5,300	7.0
		Sept. 1987	.06	.47	.01	3.19	.03	.09	.04	—	—
	5	Jan. 1988	.02	.60	.02	2.88	.02	.06	.03	—	—
		Oct. 1986	0.02	0.35	0.35	5.35	0.02	0.092	0.03	2,900	7.0
		March 1987	.03	1.27	<.01	.14	.02	.06	.06	1,140	12.0
		Sept. 1987	.04	1.16	.50	3.1	.03	.09	.06	—	12.0
		Jan. 1988	.01	.56	.01	1.60	.02	.06	.02	—	—
	10	Oct. 1986	.13	.34	.22	5.48	.03	.184	.06	6,603	4.0
		March 1987	.04	.33	<.01	3.40	.03	.09	.04	9,413	5.8
		Sept. 1987	.05	.27	.15	3.95	.04	.12	.05	—	—
		Jan. 1988	.02	.33	.01	3.80	.03	.09	.04	—	—
	15	Oct. 1986	—	—	—	—	—	—	—	11,500	—
		March 1987	—	—	—	—	—	—	—	11,784	—
		Sept. 1987	—	—	—	—	—	—	—	—	—
		Jan. 1988	.02	.27	.01	4.39	.04	.12	.04	—	—
MO-155	5	Oct. 1986	.02	.63	<.01	.84	.02	.31	.10	2,268	2.5
		March 1987	.02	1.18	<.01	.52	.02	.06	.29	500	6.0
		Sept. 1987	.03	<.17	.01	.53	.02	.06	.06	—	3.8
		Jan. 1988	—	—	—	—	—	—	—	—	—
MO-156	10	Oct. 1986	<.01	.27	<.01	1.40	.02	.123	.04	2,270	2.5
		March 1987	.02	.41	<.01	.66	.01	.03	.02	500	6.0
		Sept. 1987	.04	.26	<.01	1.10	.02	.06	.04	—	3.8
		Jan. 1988	—	—	—	—	—	—	—	—	—
	15	Oct. 1986	.01	.26	<.01	1.40	.02	.123	.04	2,270	2.0
		March 1987	—	—	—	—	—	—	—	540	8.0
		Sept. 1987	—	—	—	—	—	—	—	—	—
		Jan. 1988	—	—	—	—	—	—	—	—	—
	5	Oct. 1986	.58	.01	.01	.01	.03	—	.06	2,278	2.0
		March 1987	.03	.88	<.01	.34	.12	.37	.14	679	—
		Sept. 1987	.56	.40	.01	.02	.04	.12	.06	—	—
		Jan. 1988	—	—	—	—	—	—	—	—	—
MO-157	5	Oct. 1986	.46	.54	.01	.02	.02	.06	.10	12,800	4.5
		March 1987	.28	.82	<.01	.01	.01	.03	.09	1,060	14.0
		Sept. 1987	.48	.92	.01	.01	.04	.12	.12	—	3.8
		Jan. 1988	—	—	—	—	—	—	—	—	—
MO-158	10	Oct. 1986	.46	.26	<.01	.02	.04	.12	.08	19,000	2.5
		March 1987	.28	.52	<.01	.04	.01	.03	.07	19,120	6.2
		Sept. 1987	.42	.98	.01	.01	.03	.09	.23	—	—
		Jan. 1988	—	—	—	—	—	—	—	—	—
	15	Oct. 1986	—	—	—	—	—	—	—	19,000	—
		March 1987	.33	1.67	<.01	<.01	.01	.03	.10	14,120	<1.0
		Sept. 1987	.47	1.53	.01	.01	.04	.12	.13	—	—
		Jan. 1988	—	—	—	—	—	—	—	—	—
	5	Oct. 1986	6.50	1.00	<.01	.03	.08	.18	.06	19,000	19.0
		March 1987	1.80	.80	<.01	<.01	.06	.18	.07	19,000	1.0
		Sept. 1987	—	—	—	—	—	—	—	—	—
		Jan. 1988	—	—	—	—	—	—	—	—	—

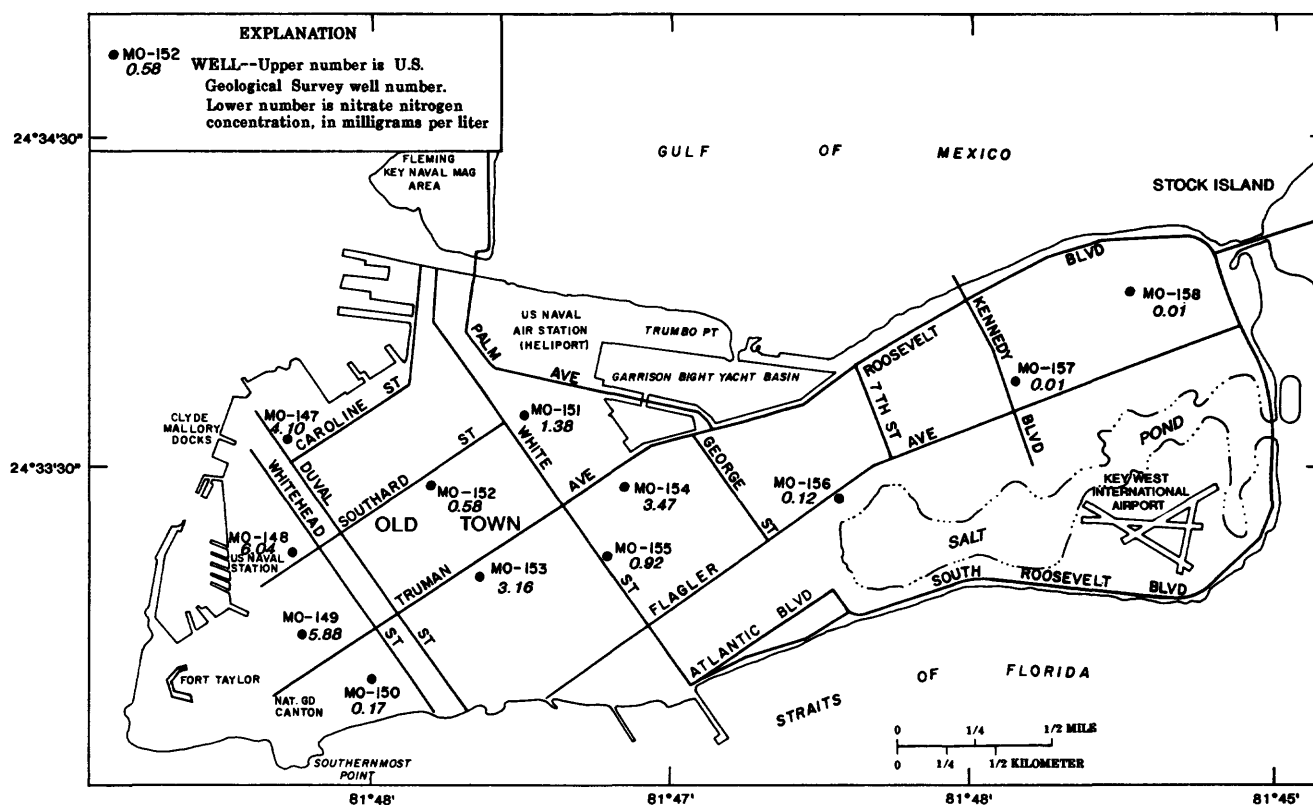


Figure 17. Average concentrations of nitrate nitrogen in water from wells at depths of 2 to 15 feet below the water table at Key West, October 1986 through January 1988.

Concentrations of the other nutrients sampled in the well waters were low in comparison to nitrate nitrogen. Nitrite nitrogen, organic nitrogen, and ammonia nitrogen concentrations were less than 1 mg/L in nearly all the samples, and total phosphorus concentrations averaged 0.06 mg/L. TOC concentrations ranged from less than 1.0 to 33.0 mg/L, with an average for all samples of 6.5 mg/L.

Trace Elements

Trace-element concentrations were determined for well waters at depths of 2 to 5 feet below the water table in October 1986, March 1987, September 1987, and April 1988. Trace elements that were analyzed are those commonly found in stormwater runoff or those that can be hazardous to human health when found in concentrations exceeding the MCL's of the Primary Drinking Water Regulations established by the Florida Department of Environmental Regulation (1983). The elements that were analyzed included arsenic, cadmium, chromium, iron, lead, mercury, selenium, and silver. Although iron is not considered hazardous, it was included in the analyses because it is a common and often undesirable constituent of

potable water. A MCL of 300 µg/L (micrograms per liter) for iron is included in the Secondary Drinking Water Regulations (Florida Department of Environmental Regulation, 1983). Table 4 presents the results of analyses of trace elements in unfiltered samples of Key West ground water.

All trace-element concentrations were less than the MCL's, except for total lead at wells MO-155 to MO-157 and total iron at wells MO-150 and MO-154 to MO-157. Lead concentrations equaled the MCL (50 µg/L) at well MO-155 in March 1987, and exceeded the MCL at well MO-156 (70 µg/L) in October 1986 and at well MO-157 (800 and 60 µg/L) in October 1986 and March 1987, respectively. Lead concentrations did not exceed the MCL in additional samples from wells MO-155 and MO-156 (table 4). In contrast, samples from well MO-157 had high lead concentrations during each sampling event; this well also had the highest iron concentrations of any of the wells sampled. The high concentrations of lead and iron in ground water at well MO-157 may be due to the fact that the well is located near an old landfill. Concentrations generally decreased with increasing distance west of the landfill site. Average concentrations of lead and iron at each well site for October 1986 through September 1987 are plotted in figure 18.

Table 4. Trace-element concentrations in Key West ground water at depths of 2 to 5 feet below the water table, October 1986 through April 1988

[Total concentrations shown in micrograms per liter; —, not sampled; <, less than the value; MCL, maximum contaminant levels for all the trace elements are included in the Primary Drinking Water Regulations, except for iron which is included in the Secondary Drinking Water Regulations (Florida Department of Environmental Regulation, 1983)]

Well number	Sampling depth (feet)	Date of sampling	Arsenic (As)	Cadmium (Cd)	Chromium (Cr)	Iron (Fe)	Lead (Pb)	Mercury (Hg)	Selenium (Se)	Silver (Ag)
MO-147	2	October 1986	—	—	—	—	—	—	—	—
		March 1987	—	—	—	—	—	—	—	—
		September 1987	—	1.0	4.0	70	<5	0.2	2.0	1.0
		April 1988	—	—	—	—	—	.1	—	—
MO-148	5	October 1986	4.0	<1.0	1.0	90	10	—	4.0	<1.0
		March 1987	5.0	1.0	<1.0	90	20	.5	6.0	2.0
		September 1987	—	<1.0	<1.0	80	10	—	<1.0	1.0
		April 1988	—	—	—	—	—	.1	—	—
MO-149	5	October 1986	—	—	—	—	—	—	—	—
		March 1987	16	<1.0	<1.0	70	20	.5	1.0	<1.0
		September 1987	—	<1.0	2.0	30	10	.1	5.0	1.0
		April 1988	—	—	—	—	—	.1	—	—
MO-150	2	October 1986	—	—	—	—	—	—	—	—
		March 1987	—	—	—	—	—	—	—	—
		September 1987	—	<1.0	<1.0	960	<5	—	<1.0	1.0
		April 1988	—	—	—	—	—	.2	—	—
MO-151	5	October 1986	1.0	<1.0	1.0	160	10	.1	2.0	<1.0
		March 1987	—	—	—	—	—	—	—	—
		September 1987	—	<1.0	<1.0	50	<5	—	2.0	1.0
		April 1988	—	—	—	—	—	.1	—	—
MO-152	5	October 1986	1.0	<1.0	<1.0	70	6	—	2.0	<1.0
		March 1987	1.0	2.0	<1.0	100	10	.2	2.0	1.0
		September 1987	—	<1.0	<1.0	120	20	—	1.0	1.0
		April 1988	—	—	—	—	—	.2	—	—
MO-153	5	October 1986	1.0	<1.0	1.0	110	20	<.1	3.0	<1.0
		March 1987	<1.0	<1.0	<1.0	80	10	.5	1.0	<1.0
		September 1987	—	1.0	<1.0	70	<5	—	<1.0	1.0
		April 1988	—	—	—	—	—	.1	—	—
MO-154	5	October 1986	<1.0	<1.0	.2	130	20	.1	<1.0	1.0
		March 1987	—	—	—	—	—	—	—	—
		September 1987	—	<1.0	2.0	360	30	—	<1.0	1.0
		April 1988	—	—	—	—	—	.1	—	—
MO-155	5	October 1986	2.0	<1.0	3.0	330	30	<.1	<1.0	1.0
		March 1987	3.0	<1.0	<1.0	320	50	1.1	<1.0	1.0
		September 1987	—	1.0	<1.0	120	9	—	<1.0	1.0
		April 1988	—	—	—	—	—	.1	—	—
MO-156	5	October 1986	1.0	2.0	5.0	740	70	.90	1.0	1.0
		March 1987	—	—	—	—	—	—	—	—
		September 1987	—	<1.0	1.0	350	10	—	<1.0	1.0
		April 1988	—	—	—	—	—	.1	—	—
MO-157	5	October 1986	1.0	<1.0	2.0	1,900	800	—	<1.0	2.0
		March 1987	1.0	1.0	<1.0	1,500	60	.8	<1.0	2.0
		September 1987	—	1.0	<1.0	600	40	—	<1.0	1.0
		April 1988	—	—	—	—	—	.1	—	—
MCL			50	10	50	300	50	2.0	10.0	50.0

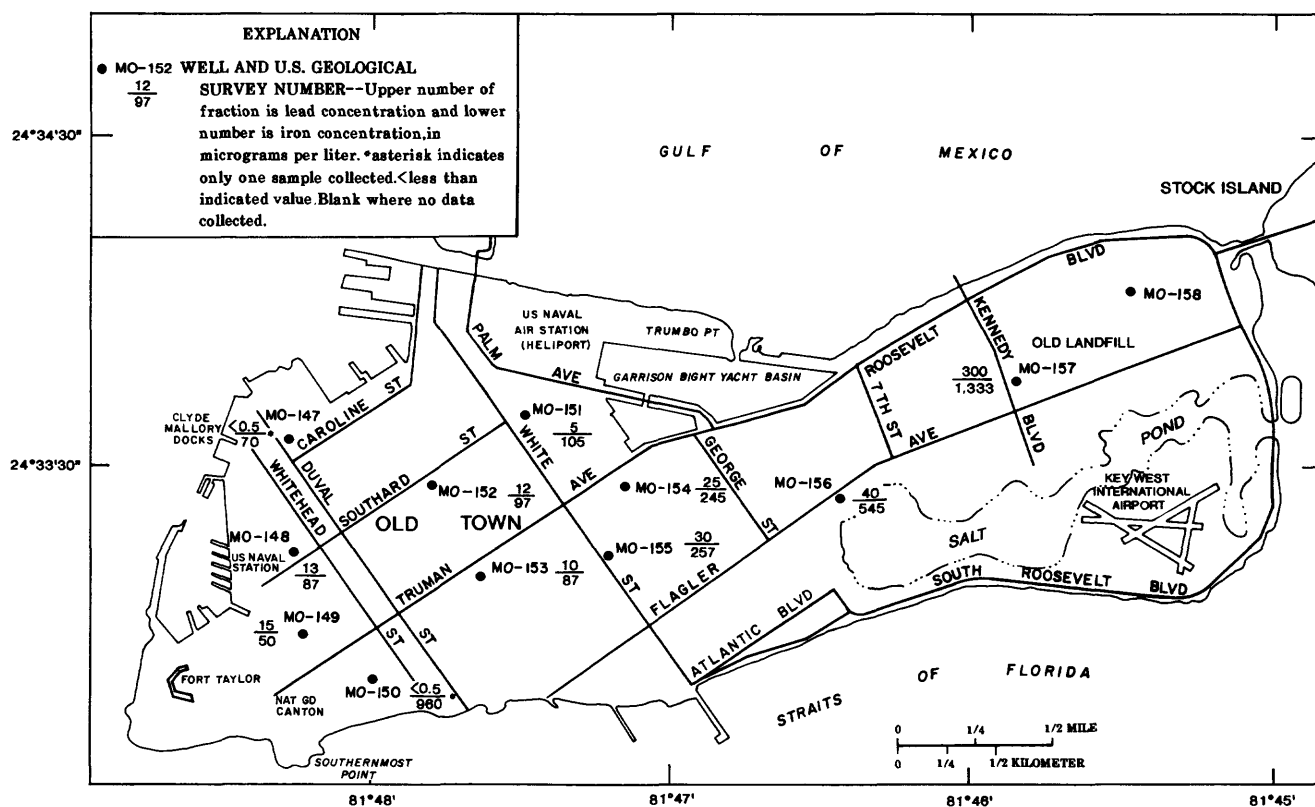


Figure 18. Average concentrations of lead and iron in water from wells at depths of 2 to 5 feet below the water table at Key West, October 1986 through September 1987.

Mercury concentrations in all the well waters ranged from less than 0.1 µg/L to as much as 1.1 µg/L. Although these concentrations do not exceed the MCL (2 µg/L) of the Primary Drinking Water Regulations (Florida Department of Environmental Regulation, 1983), the range of concentrations in Key West ground water was greater than the 0.0 to 0.3 µg/L range reported for the Biscayne aquifer in Dade County (Irwin and Healy, 1978; Irwin and Hull, 1979; Sonntag, 1987).

Synthetic Organic Compounds

On September 1, 1987, water samples were collected from wells MO-147 through MO-156 for GC/FID scan analysis. The GC/FID analysis, or FID scan, is a screening technique for the determination of synthetic organic compounds in water. The FID scan analysis provides semi-quantitative data without identification of specific compounds. The sensitivity of the FID scan is about 10 times greater for most compounds than the GC/MS method. Results of the FID scan indicated that all the samples contained detectable, but very low, concentrations of organic compounds. The highest relative magnitude of organic

compounds was found in water samples from wells MO-148 and MO-152 near the center of the freshwater lens.

A subsequent set of samples collected at the monitoring wells in December 1987 had the greatest occurrence of measurable organic compounds. Water samples were collected from wells MO-152, MO-153, MO-154, and MO-148 for a GC/MS analysis of selected pesticides and synthetic organic contaminants (commonly termed priority pollutants). The priority pollutants are compounds designated by the U.S. Environmental Protection Agency (1980) as a human health concern for the general public. The compounds include volatiles, acid and base-neutral extractables, and pesticides. A list of the compounds for which analyses were made and the laboratory analytical detection limits is given in table 5. The list also includes Florida Department of Environmental Regulation standards for seven pesticides.

Pesticides analyzed included carbamate insecticides, chlorophenol acid herbicides, organochlorine compounds, and organophosphorus insecticides. The only pesticides detected were two organochlorine compounds: DDT (0.003 µg/L) and its metabolite DDE (0.002 µg/L) at well MO-148. These concentrations only slightly exceeded the analytical detection

Table 5.—Synthetic organic compounds for which gas chromatograph/mass spectrometer analyses were determined

[Compounds were analyzed using laboratory standard solutions of known chemical composition. All concentrations are in micrograms per liter. Numbers in parentheses are water-quality standards from the Florida Department of Environmental Regulation, 1983]

Type and name of chemical	Detection limit	Type and name of chemical	Detection limit
<u>Volatiles</u>		<u>Base- neutral extractables</u>	
Benzene	0.20	Hexachloroethane	5.0
Bromoform	.20	Indeno(1,2,3-cd)pyrene	10.0
Carbon tetrachloride	.20	Isophorone	5.0
Chloroenezene	.20	Naphthalene	5.0
Chlorodibromomethane	.20	Nitrobenzene	5.0
Chloroethane	.20	N-Nitrosodi-N-propylamine	5.0
2-Chloroethylvinyl ether	.20	N-Nitrosodimethylamine	5.0
Chloroform	.20	N-Nitrosodiphenylamine	5.0
1,2-Dibromomethylene	.20	Phenanthrene	5.0
1,2-trans Dichloroethylene	.20	Pyrene	5.0
Dichlorobromomethane	.20	1,2,4-Trichlorobenzene	5.0
Dichlorodifluoromethane	.20		
1,2-Dichloroethane	.20	<u>Acid extractables</u>	
1,1-Dichloroethylene	.20	4-Chloro-3-methylphenol	30.0
1,2-Dichloropropane	.20	2-Chlorophenol	5.0
1,3-Dichloropropane	.20	2,4-Dichlorophenol	5.0
cis-1,3-Dichloropropane	.20	2,4-Dimethylphenol	5.0
trans-1,3-Dichloropropane	.20	4,6-Dinitro-2-methylphenol	30.0
Ethylbenzene	.20	4,6-Dinitro-orthocresol	30.0
Methyl bromide	.20	2,4-Dinitrophenol	20.0
Methyl chloride	.20	2-Nitrophenol	5.0
1,1,2-Tetrachloroethane	.20	4-Nitrophenol	30.0
Tetrachloroethylene	.20	Parachlorometacresol	30.0
Toluene	.20	Pentachlorophenol	30.0
1,1,1-Trichloroethane	.20	Phenol	5.0
1,1,2-Trichloroethane	.20	2,4,6-Trichlorophenol	20.0
Trichloroethylene	.20		
Trichlorofluoromethane	.20	<u>Pesticides</u>	
Vinyl chloride	.20	Aldrin	.001
		Ametryne	.1
<u>Mixtures</u>		Atrazine	.1
Polychlorinated naphthalenes	.1	Chlordane	.1
Polychlorinated biphenyls	.1	Cyanazine	.1
		DDD	.001
<u>Base-neutral extractables</u>		DDE	.00
Acenaphthene	5.0	DDT	.001
Acenaphthylene	5.0	Dieldrin	.001
Anthracene	5.0	Diazinon	.01
Benzo(a)anthracene	10.0	EDB	(0.02) .0
Benzo(a)pyrene	10.0	Endosulfan	.001
Benzo(g,h,i)perylene	10.0	Endrin	(0.2) .001
Benzo(k)fluoranthene	10.0	Ethion	.01
Benzo(b)fluoranthene	10.0	Ethyl trithion	.01
4-Bromophenyl phenyl ether	5.0	Heptachlor	.001
N-Butylbenzyl phthalate	5.0	Heptachlor epoxide	.001
875bis (2-Chloroethoxy)methane	5.0	Lindane	(4) .001
bis(2-Chloroethyl)ether	5.0	Malathion	.01
bis(2-Chloroisopropyl)ether	5.0	Methoxychlor(100)	.01
2-Chloronaphthalene	5.0	Methyl parathion	.01
4-Chlorophenyl phenyl ether	5.0	Methyl trithion	.01
Chrysene	10.0	Methomyl	2.00
1,2,5,6-Dibenzo(a,h)anthracene	10.0	Mirex	.01
Di-n-butyl phthalate	5.0	Parathion	.01
1,3-Dichlorobenzene	5.0	Perthane	.1
1,4-Dichlorobenzene	5.0	Prometon	.1
1,2-Dichlorobenzene	5.0	Prometryne	.1
Diethyl phthalate	5.0	Propazine	.1
Dimethyl phthalate	5.0	Propham	2.0
2,6-Dinitrotoluene	5.0	Sevin	2.0
2,4-Dinitrotoluene	5.0	Silvex	(10) .01
Di-n-octylphthalate	10.0	Simazine	.1
bis(2-Ethylhexyl)phthalate	5.0	Simetryne	.1
Fluoranthene	5.0	Styrene	.2
Fluorene	5.0	Toxaphene	(5) 1.0
Hexachlorobenzene	5.0	Trithion	.01
Hexachlorobutadiene	5.0	2,4-D	(100) .01
Hexachlorocyclopentadiene	5.0	2,4-DP	.01
		2,4,5-T	.01
		Xylene	.2

limit. Of the other organic compound groups, only dichlorobromomethane (1.8 µg/L) and chloroform (1.2 µg/L) at well MO-152 were detected. Both concentrations exceeded the analytical detection limit of 0.20 µg/L. There are no

drinking water MCL's for these four contaminants, but the U.S. Environmental Protection Agency (1986a; 1986b) recommends that ambient water concentrations be below detection for optimum defense of human health.

Bacterial Analyses

The high concentrations of nitrate nitrogen found in ground water during the sampling reconnaissance indicated the possible presence of sewage, which commonly contains high concentrations of nutrients and bacteria. It is possible that raw sewage may have been leaking from the network of underground pipes that transport the waste to the central outfall pipe. To assess this possibility, on January 27, 1988, wells MO-148, MO-152, MO-154, and MO-155, which had high nitrate-nitrogen concentrations and were located near the center of the lens, were sampled for the presence of total coliform, fecal coliform, and fecal streptococci bacteria. Water samples were taken at depths of 5, 10, and 15 feet below the water table.

The samples at a depth of 5 feet below the water table from wells MO-148, MO-152, and MO-153 were freshwater. The other water samples ranged from very slightly saline to slightly saline. Sodium chloride has an inhibitory influence on coliform bacteria, but the concentrations found in the sampled waters probably had little or no toxic effect on the bacteria (Salle, 1954, p. 221; U.S. Environmental Protection Agency, 1976, p. 45).

The results were inconclusive. The samples from well MO-154 showed the presence of fecal coliform at the 5-foot depth, but there was no indication of total coliform. The water samples from the 10-foot depth at well MO-148 produced a growth of unidentified bacteria. Coliform and fecal streptococci bacteria were not detected in any of the other samples.

SUMMARY AND CONCLUSIONS

Key West is underlain by oolitic limestone (Miami Oolite) that extends to a depth of about 200 feet. The oolitic limestone has a high permeability and is honeycombed with solution holes that allow rainwater to rapidly escape to the sea and seawater to easily infiltrate. There is a substantial amount of freshwater only in the western half of the island.

The freshwater floats in a lens-shaped configuration on the saltwater as a result of density differences. The freshwater lens (chloride concentration of 250 mg/L or less) is thickest, averaging about 5 feet, in the center of the Old Town area. Underlying the freshwater is the transition zone--a mix of freshwater and saltwater that increases in salinity vertically until the saltwater interface is reached at a depth of about 40 feet.

As a result of tidal effects, the water table fluctuates constantly. During the investigation, it ranged from 0.8 to 2.4 feet above sea level at the center of the island and from 0.4 to 2.2 feet above sea level near the coast. Tidal effects cause continual change, both vertically and areally, in the

configuration of the freshwater lens and salinity of the transition zone.

The amount of freshwater varies with rainfall, seepage to the ocean, evapotranspiration, and withdrawal. The effect of evaporation and withdrawals on water levels is largely masked by tidal influence. During the investigation, the estimated freshwater volumes varied from 30 million gallons in the wet season to 20 million gallons in the dry season. The water-table gradient varied from about 4 to 1 ft/mi.

The freshwater lens is a calcium bicarbonate water. Below the freshwater lens, the chloride concentration increases with depth, and the water becomes a sodium chloride water with large amounts of magnesium, sulfate, and potassium. Concentrations of most major inorganic constituents increase with salinity. The chemistry of the major inorganic constituents in the freshwater lens and transition zone is characterized by a simple mixing of freshwater and saltwater.

Nitrate-nitrogen concentrations ranged from less than 1 mg/L to as much as 11 mg/L, indicating the possible presence of sewage and the possibility of related bacterial contamination. Bacterial analyses were inconclusive, but fecal coliform was found in one of the four wells tested. The highest concentrations of nitrate nitrogen were found in the center and western part of the lens.

Lead concentrations equaled or exceeded the maximum contaminant level (50 µg/L) in water from three observation wells, and iron concentrations exceeded the maximum contaminant level (300 µg/L) in water from five wells. The highest concentrations of lead and iron were found in the eastern part of the lens near an old landfill, but the concentrations decreased with increasing distance west of the site.

A one-time sampling of well water for pesticides and synthetic organic compounds indicated the presence of DDT (0.003 µg/L), DDE (0.002 µg/L), chloroform (1.2 µg/L), and dichlorobromomethane (1.8 µg/L), all slightly exceeding the analytical detection limits. The compounds were found near the center of the lens.

Because the freshwater lens is very thin, from less than 1 foot near the edge to an average of about 5 feet near the center, any heavy pumping might quickly exhaust the freshwater supply and draw in saline water through the highly porous rock. The reconnaissance water-quality sampling also indicated that the lens water does not meet State drinking water standards for several constituents.

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