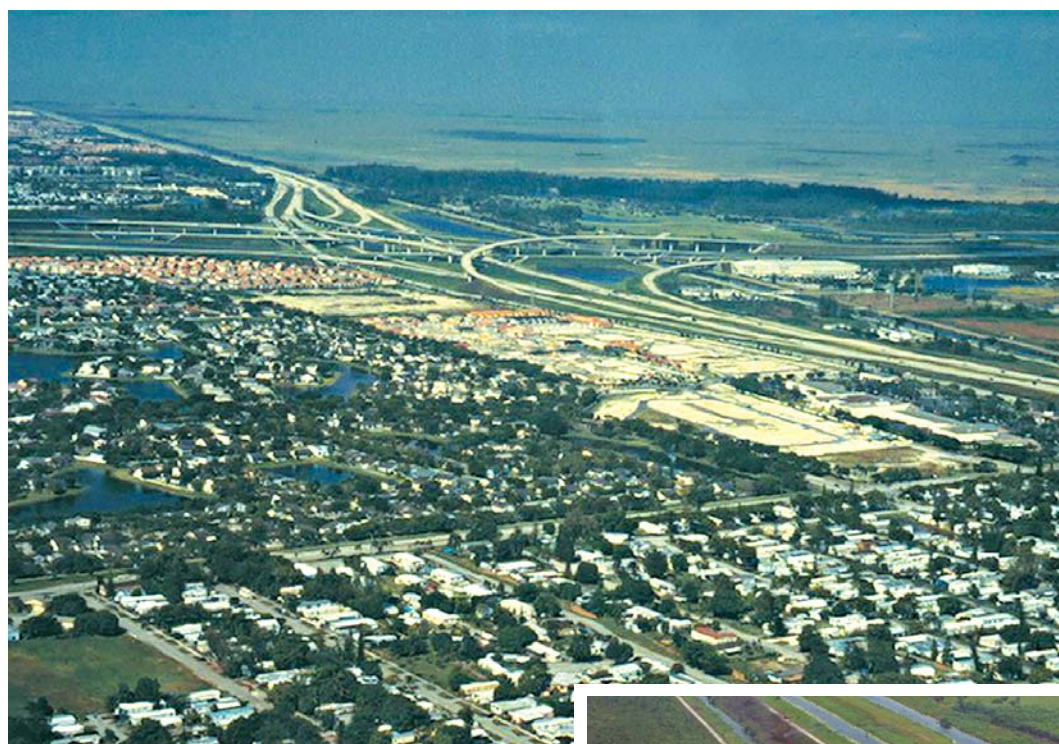


Quality of Ground Water in the Biscayne Aquifer in Miami-Dade, Broward, and Palm Beach Counties, Florida, 1996-1998, with Emphasis on Contaminants



Open-File Report 2004-1438

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By Anne Bradner, Benjamin F. McPherson, Ronald L. Miller, George Kish,
and Bruce Bernard

Open-File Report 2004-1438

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Conversion Factors and Datums

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
Flow rate		
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m³/s)
Mass		
ounce, avoirdupois (oz)	0.03527	grams (g)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the insert datum name (and abbreviation) here for instance, “North American Vertical Datum of 1988 (NAVD 88).”

Horizontal coordinate information is referenced to the insert datum name (and abbreviation) here for instance, “North American Datum of 1983 (NAD 83).”

Altitude, as used in this report, refers to distance above the vertical datum.

Acronyms and Additional Abbreviations:

DDE	DDE is an abbreviation of dichlorodiphenyldichloroethylene [2,2-bis(4-chlorophenyl)-1, 1-dichloroethene]. DDE is an environmental dehydrochlorination product of DDT (dichlorodiphenyltrichloroethane).
DDD	dichlorodiphenyldichloroethane
DDT	dichlorodiphenyltrichloroethane
EPTC	Eptam, Farmarox, Alirox
FDEP	Florida Department of Environmental Protection
kg/ha	kilograms per hectare
mg/L	milligrams per liter
µg/L	micrograms per liter
MCL	maximum contaminant level
MSMA	monosodium methane arsonate
MTBE	methyl tert-butyl ether
NAWQA	National Water Quality Assessment Program
NWQL	National Water Quality Laboratory
pCi/L	picocurie per liter
SFWMD	South Florida Water Management District
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VOC	Volatile organic compound

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By Anne Bradner, Benjamin F. McPherson, Ronald L. Miller, George Kish, and Bruce Bernard

Abstract

The high permeability of the sand and limestone sediments and shallow water table of the Biscayne aquifer make ground water vulnerable to contamination by human activities. To assess potential contamination in the aquifer, untreated ground water was sampled from 30 public-supply wells (40-165 feet deep) in Broward, Miami-Dade, and Palm Beach Counties, 32 shallow wells (10-50 feet deep) in a recently urbanized (residential and light commercial) part of Broward County, and 3 shallow reference wells in Broward County. Results from sample analyses indicate that major ions, pH, dissolved oxygen, nutrients, and trace element concentrations were generally within the range indicative of background concentrations, except for: (1) substantially higher bromide concentrations in water from public-supply wells in southern Miami-Dade County; (2) a few relatively high (greater than 2 milligrams per liter) concentrations of nitrate in water from public-supply wells near agricultural lands in Miami-Dade and southern Broward Counties; and (3) a few relatively high concentrations of arsenic (greater than 10 micrograms per liter) in water from some shallow urban wells near golf courses.

Pesticides were detected in every public-supply well, in most of the shallow, urban monitoring wells (78 percent), and in one reference well; however, no pesticide concentration exceeded any drinking-water standard. Fifteen different pesticides or their degradation products were detected. The most frequently detected pesticides were atrazine and tebuthiuron; less frequently detected were the herbicides diuron, fenuron, prometon, metolachlor, simazine, and 2,6-diethylaniline.

Volatile organic compounds (VOCs) were detected in most of the public-supply wells (77 percent) and shallow, urban wells (91 percent) and in two of the three reference wells. Thirty-two different VOCs were detected in ground water in the Biscayne aquifer, with *cis*-1,2-dichloroethene the most frequently detected VOC in the public-supply wells, followed by methyl *tert*-butyl ether (MTBE), 1,4-dichlorobenzene, and chloroform. Toluene, *p*-isopropyltoluene, and 1,2,4-trimethylbenzene were the most frequently detected VOCs in the shallow, urban wells. Concentrations of all VOCs were less than the maximum contaminant level (MCL) for public drinking water, except in two samples from public-supply wells near industrialized areas that had vinyl chloride concentrations (3 and 5 micrograms per liter) above the MCL of 1 microgram per liter.

Introduction

Southeastern Florida, including Miami-Dade, Broward, and Palm Beach Counties (fig. 1), has a population exceeding 5.0 million (University of Florida, 2001), of whom approximately 4.0 million rely on the Biscayne aquifer as a public-water supply (Marella, 2004). The aquifer also supplies water to the Florida Keys Aqueduct Authority, which pipes water from the mainland to the Florida Keys (Meyer, 1974). Total withdrawals from the Biscayne aquifer exceeded 875 million gallons per day (Mgal/d) in 2000, of which 700 Mgal/d were withdrawn for public supply (Marella, 2004). The Biscayne aquifer has been designated by the U.S. Environmental Protection Agency as a sole-source aquifer, meaning that this aquifer is the only viable ground-water source in this area.

2 Quality of Ground Water in the Biscayne Aquifer in Miami-Dade, Broward, and Palm Beach Counties, Florida

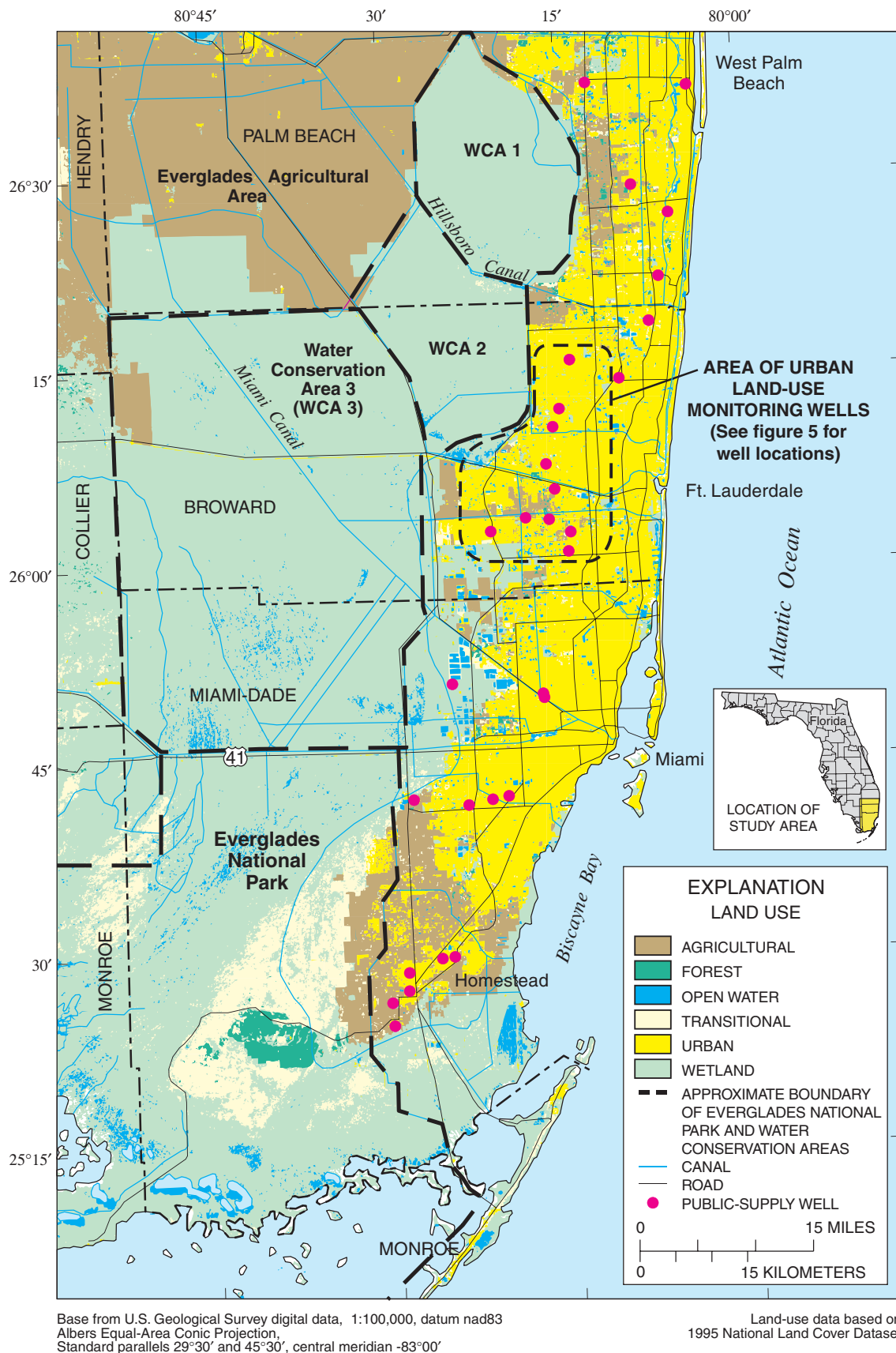


Figure 1. Locations of study area, land use, and wells sampled in southeastern Florida.

Land use in most of the eastern part of southeastern Florida is older residential, commercial, and industrial. Land use in the central and western parts is newer residential and light commercial. The developing western residential areas abut the Everglades (figs. 1 and 2), where water is impounded by the South Florida Water Management District (SFWMD) for dry-season releases. There are isolated agricultural areas in Broward and Palm Beach Counties too small to be shown on figure 1, but many are being converted into residential housing. There is a large agricultural area in southern Miami-Dade County (fig. 1) where primarily winter vegetables and nursery ornamentals are grown, with some citrus and tropical fruits. In western Palm Beach County, an expansive Everglades Agricultural Area is present.

Water quality of the shallow, highly permeable Biscayne aquifer is a major concern to water managers because of the vulnerability of the aquifer to contamination from the land surface and from septic tanks, and the dependency of a large segment of the population on this aquifer for their sole water supply. Steadily increasing water usage by a swelling population, and declining water levels caused by droughts and construction of drainage canals, have caused saltwater intrusion in the Miami area, which began as early as 1925 (Parker and others, 1955).

Purpose and Scope

In the 1990s, the U.S. Geological Survey (USGS) conducted a regional assessment of water quality in the Biscayne aquifer in Broward, Miami-Dade, and Palm Beach Counties, Florida, as part of the National Water Quality Assessment (NAWQA) Program (Haag and others, 1998). During the regional assessment, a survey of untreated ground water was conducted, in which water quality was sampled in 30 public-supply wells in the eastern parts of Miami-Dade, Broward, and Palm Beach Counties and in 35 wells within a nested urban land-use area in Broward County. Untreated ground-water samples were tested for major ions, selected trace elements, carbon, radon, and various nutrients. The purpose of this report is to summarize the results of that survey, which was conducted between 1996 and 1998. This report includes descriptions of the Biscayne aquifer and land use in the area, and water-quality results for the 30 water supply wells and 32 monitoring wells sampled in the study area.

Figure 1 shows the location of the study area, including the wells and land uses discussed in this report. The 30 public-supply wells are distributed throughout the area, from south of Homestead, north to West Palm Beach. The wells are located in urban areas on the higher



Figure 2. Photo showing urban sprawl adjacent to the Florida Everglades, Broward County, Florida.

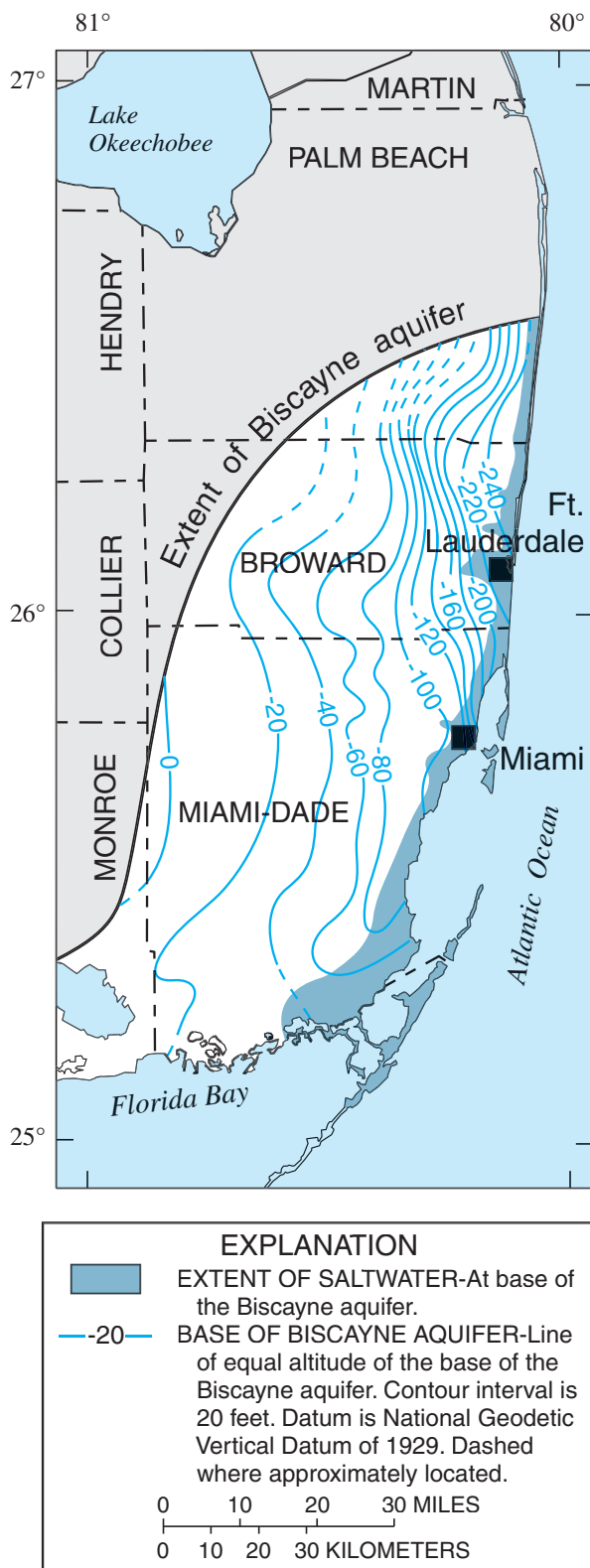


Figure 3. Location and depth of Biscayne aquifer, and area of saltwater intrusion into the Biscayne aquifer (modified from Miller, 1990).

elevations of the southeastern Florida coast, as well as in agricultural areas, primarily in the south near Homestead. The wells range in depth from 40 feet (ft) in the south to 165 ft in the north. The shallow, urban monitoring wells are nested within the western part of the populated eastern portion of Broward County (figs. 1 and 2), and represent an area of recently developed residential and light-commercial land use. The entire study area is underlain by the Biscayne aquifer and all wells sampled withdraw water from this aquifer.

Hydrogeology

The upper 3,000 ft of rock underlying south Florida is composed chiefly of limestone, dolomite, sand, clay, and shells. Shallow aquifers, including the Biscayne aquifer and localized aquifers that are part of the surficial aquifer system, yield practically all of the municipal and much of the irrigation water used in south Florida. The Biscayne aquifer is present in southeastern Florida, reaching a maximum thickness of 240 ft along the Atlantic Coast north of Fort Lauderdale, and thinning westward (fig. 3). Toward the west and north, the Biscayne grades into less productive sandy deposits that are part of the surficial aquifer system. The three northernmost public-supply wells (fig. 1) are within the transitional zone between the Biscayne and laterally-equivalent surficial aquifers, but were considered to be in the Biscayne aquifer for this study.

This report deals only with the Biscayne aquifer, which is unconfined in the study area. The Biscayne aquifer consists chiefly of highly permeable Pleistocene limestone and sand, overlain in some areas by a thin layer of peat and sand. The aquifer contains several lithologic units, which are generally thin and lens-like; the entire sequence of units (table 1) is not present in any one place. The aquifer extends beneath Biscayne Bay and the Atlantic Ocean. Because of the aquifer's high permeability and in response to the lowering of inland ground-water levels, saltwater has migrated inland (fig. 3) along the base of the Biscayne aquifer. The potable, high-yielding portion of the Biscayne aquifer is in consolidated limestone extending from land surface to a depth of approximately 50 ft in southern Miami-Dade County, deepening northward to 120 to 170 ft below land surface in southeastern Palm Beach County. A sequence of low-permeability, largely clayey deposits about 1,000 ft thick forms a confining unit that separates the Biscayne aquifer from the underlying, brackish-water Floridan aquifer system.

Table 1. Stratigraphic and hydrologic section for the Biscayne aquifer in southeastern Florida

Series	Stratigraphic and hydrologic units		Lithology and water-yielding characteristics	Thickness (feet)
Holocene	Organic soils	Confining unit	Peat and muck; water has high color content. Almost impermeable. Lake Flirt is shelly, calcareous mud.	0-18
	Lake Flirt Marl			
Pleistocene ¹	Pamlico Sand	Biscayne aquifer	Quartz sand; water high in iron. Low yields to domestic wells.	0-40
	Miami Oolite		Sandy, oolitic limestone. High yields.	0-40
	Fort Thompson Formation		Alternating marine shell beds and freshwater limestone. Generally high permeability. High yields.	0-150
	Anastasia Formation		Coquina, sand, sandy limestone, marl. Moderate to high yields.	0-120
	Key Largo Limestone		Coralline reef rock. High yields.	0-60
	Caloosahatchee Marl		Sand, shell, silt, and marl. Moderate yields.	0-25
Pliocene	Tamiami Formation	Confining unit	Limestone, clay, and marl. Occasional moderate yields in upper few feet. Remainder forms upper part of basal confining unit.	25-220

¹Stratigraphic units are equivalent in part. Order does not necessarily reflect relative age.

Modified from Miller (1990).

Although regional ground-water flow generally is toward the coast, locally, ground water flows toward canals and well fields. Minimum flows through canals are necessary to maintain water levels and to reduce saltwater intrusion, particularly during extended dry periods, and to maintain water levels in Everglades National Park. Recharge to the Biscayne aquifer is derived from rainfall and from water that leaks downward from the canals. Average annual rainfall is about 60 inches per year, most of which falls between June and September. During dry seasons, water in Lake Okeechobee and water-conservation areas to the north and west of the study area is conveyed south through canals by gravity and by pumps to recharge the Biscayne aquifer (Fish and Stewart, 1991; Merritt, 1996).

Background Water Quality

As early as 1928, evidence of saltwater intrusion prompted the construction of contour maps show water

levels and chloride concentrations near well fields and along the canals. Until the late 1970s, most water-quality studies of the Biscayne aquifer involved mapping the concentrations of anions, cations, and nutrients (Howie, 1987; Sonntag, 1987). Industrial contamination of well fields with VOCs in the 1970s spurred studies of public-supply wells by Vincent (1984) and the establishment of monitoring programs by the Florida Department of Environmental Protection (FDEP) and the U.S. Environmental Protection Agency (USEPA). Additionally, pesticide studies have been conducted on golf courses (Swancar, 1996), in agricultural areas (Baker, 1988), and in canals (Miles and Pfeuffer, 1997).

Study Procedures

We selected public-supply, urban, and reference wells for study in 1996, and then sampled the wells

between 1996 and 1998. The following sections describe procedures used to select sites and to collect water samples.

Site Selection

Thirty public-supply wells, 32 monitoring wells, and 3 reference wells were selected for sampling (figs. 4 and 5). The public-supply wells were selected to provide coverage over the study area and ranged from 40 ft deep in the southern part of Miami-Dade County to about 170 ft deep in southeastern Palm Beach County. The monitoring and reference wells were nested within a part of the study area, in the western portion of eastern Broward County (figs. 1 and 5). This area was selected because it represents recently developed residential and light-commercial land use; as part of the overall NAWQA Program, the water quality in this nested urban area can be compared with that in similar land-use areas nationwide (Squillace and Price, 1996). The 32 urban, monitoring well sites were selected randomly using a computer program developed for the NAWQA Program (Scott, 1990); 15 existing monitoring wells were used and 17 new wells were drilled at sites according to established protocols (Lapham and others, 1995). The monitoring wells ranged from 10 to 50 ft deep, had water levels ranging from about 2 to 19 ft below land surface, and were located in parks, roadsides, golf courses, parking lots, and residential lawns. The three reference wells were located in areas deemed to be little affected by land use, and were established to provide background water-quality information as part of the NAWQA protocol.

Sampling Protocols

Water-quality samples were collected, preserved in the field, and then shipped to the USGS National Water Quality Laboratory (NWQL) in Denver, Colo., for analysis following NAWQA protocols (Koterba and others, 1995). The sampling procedure involved sampling ground water at low flow rates (500 milliliters per minute) through a closed system. Samples were collected only after field measurements indicated that pH, dissolved oxygen, temperature, conductance, and turbidity had stabilized.

The monitoring wells were sampled using a Teflon and stainless-steel pump and Teflon tubing. For the high-volume public-supply wells, untreated water was sampled through cleaned tubing and Teflon fittings connected to a faucet at the well pump used by utilities

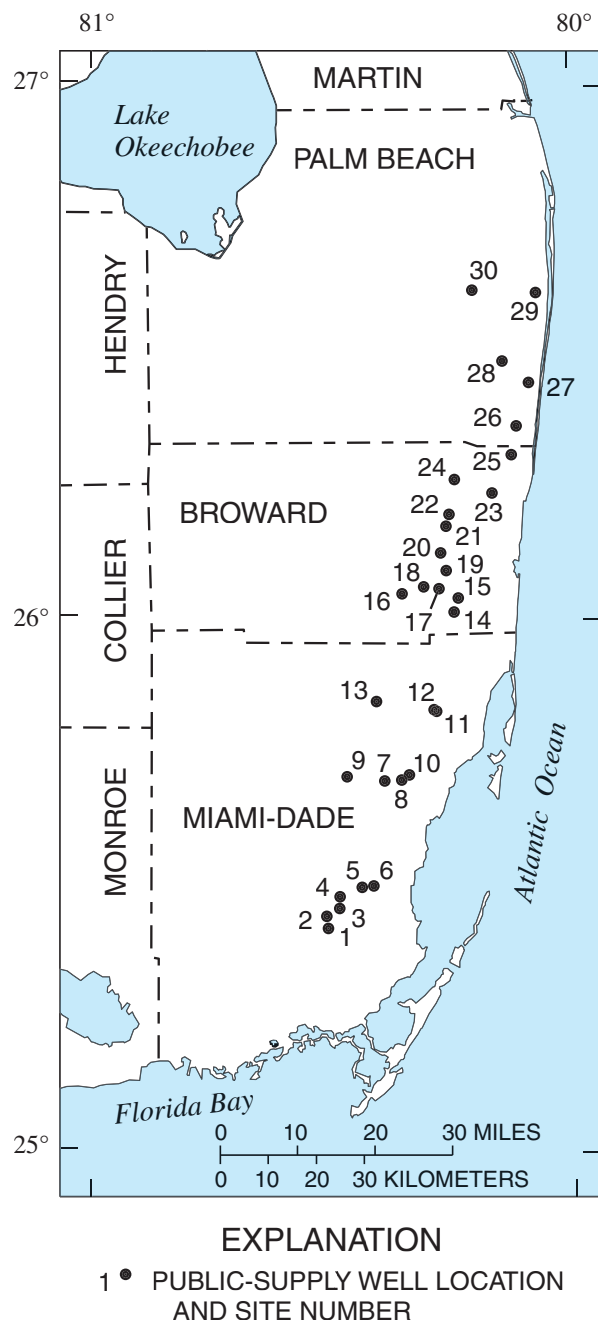


Figure 4. Location of public-supply wells sampled.

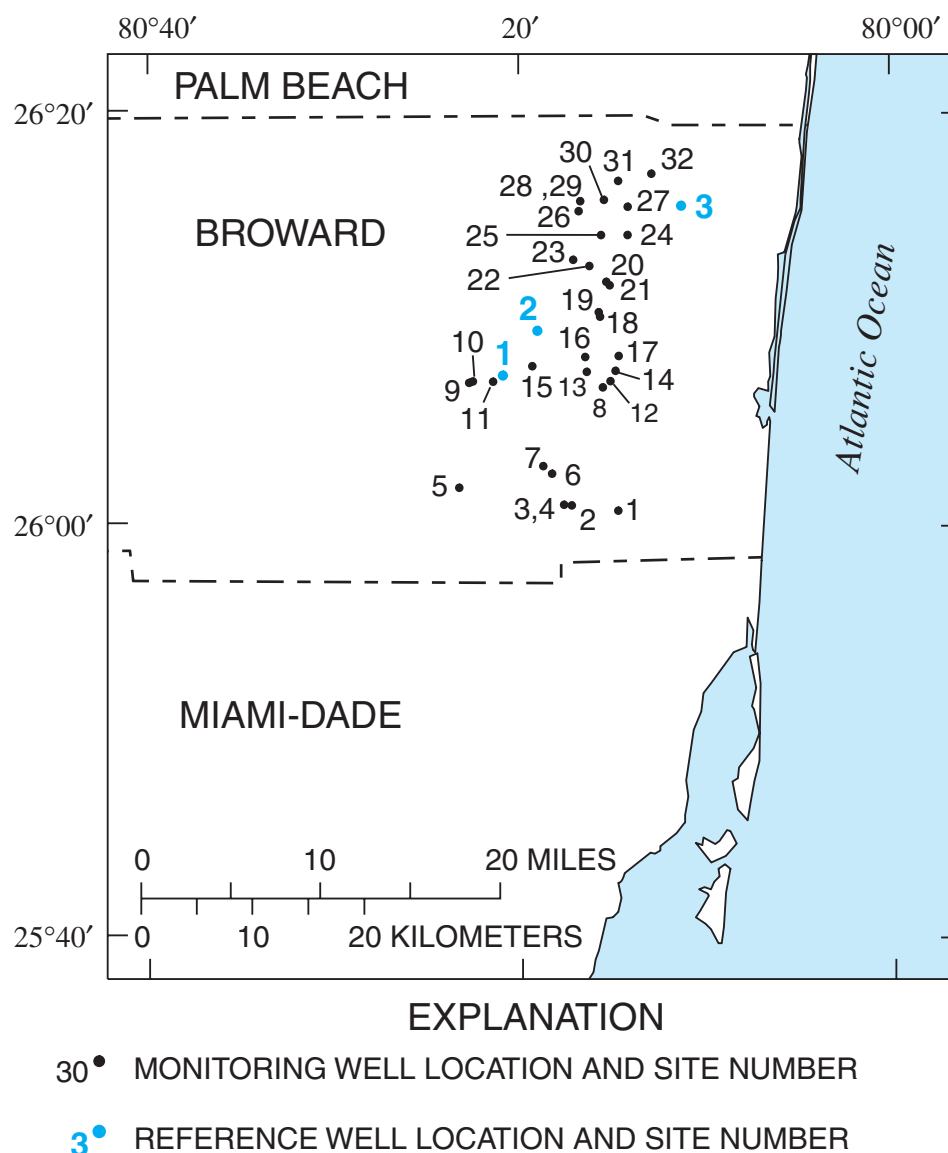


Figure 5. Location of monitoring and reference wells sampled.

personnel for sampling. Each well was being pumped at the time of sampling.

To meet established water-quality objectives of the NAWQA Program and to support other USGS water-quality investigations, the NWQL provided broad spectrum, low-level analyses for pesticides and VOCs (Zaugg and others, 1995; Connor and others, 1998). Other analytical procedures followed standard NWQL protocols (Koterba and others, 1995). Detections, as reported here, are a function of the laboratory's analytical methods and

their efficiency and limitations. Quality-control samples were collected in procedures outlined in Koterba and others (1995), and included field, laboratory, and solution blanks, sample replicates, and field spikes for VOCs and pesticides. None of the quality-control samples indicated field contamination, and the spiked samples showed reasonable recoveries of spiked analytes. The web site, <http://fl.water.usgs.gov/Sofl/gw/gwintro.html>, contains comprehensive water-quality results for this study.

Water Quality

In the following five sections, we summarize water-quality data collected from shallow wells in the Biscayne aquifer. The wells are located in urban and residential land use areas of southeastern Florida.

Water pH, Dissolved Oxygen, and Major Ions

The chemical composition of shallow ground water in the Biscayne aquifer varies with location and proximity to recharge from canal sources (Howie, 1987; Sonntag, 1987). The pH of samples collected for this study ranged from 6.2 to 7.7, with a median of 6.7 for monitoring wells and 6.9 for public-supply wells—higher than the pH of rainfall, which averages 5.1 in south Florida (Fernald and Purdum, 1998). These higher pH values in ground water are due to the buffering effect of the limestone as rainwater percolates down through the upper sediments. The median dissolved-oxygen concentration in water from all the wells was 0.15 milligrams per liter (mg/L).

The major ions in the shallow ground water of southeastern Florida reflect the composition and solubility of the carbonate rocks and organic soils of the area. In some parts of the area, saline residues from earlier invasions of sea water or recent influx of sea water also contribute to ionic composition (Parker and others, 1955). Concentrations of ions in shallow waters of the area vary with distance from the coast and with the season (Waller, 1982). For this study, the range and median values for major ion concentrations, including calcium, sodium, magnesium, and potassium, are listed in table 2. Concentrations generally were similar to previously reported values in the Biscayne aquifer (Howie, 1987; Sonntag, 1987).

Selected Trace Elements, Radon, and Carbon

Urban and agricultural activities are potential sources of trace element contamination—particularly arsenic, copper, and lead (De Carlo and Anthony, 2002). Urban activities, such as turf-grass maintenance in golf courses, have increased concentrations of arsenic in Florida's ground water through the use of the herbicide, monosodium methane arsonate (MSMA) (Swancar, 1996). Other potential sources of trace-element contamination in ground water include arsenic used in cattle dipping for disease control (Blasland, Bouck, and Lee, Inc., 1992), arsenic and copper used as fungicide on grapefruit and as a wood preservative (Sherwood and others,

1973), and lead used in gasoline and batteries (De Carlo and Anthony, 2002).

Arsenic concentrations in water from the shallow, urban monitoring wells ranged from less than 1 to 19 micrograms per liter ($\mu\text{g/L}$), with a median concentration of 2 $\mu\text{g/L}$. Water samples from monitoring wells located on golf courses had arsenic concentration higher than at other wells in the network (greater than 10 $\mu\text{g/L}$), although no samples exceeded the maximum contaminant level (MCL) of 50 $\mu\text{g/L}$. In contrast, the concentration of arsenic from the public-supply wells ranged from less than 1 to 3 $\mu\text{g/L}$, indicating that arsenic contamination from golf courses and other sources was diluted in the deeper public-supply wells by ground water from other land-use areas. About 34 percent of the monitoring wells contained water with copper concentrations above detection levels, with a maximum concentration of 4 $\mu\text{g/L}$ —considerably below the secondary drinking-water standard of 1,000 $\mu\text{g/L}$ (Florida Department of Environmental Protection, 2004, http://www.dep.state.fl.us/water/drinkingwater/sec_con.htm). Most of these detections were from shallow wells located near parks or golf courses. Only seven public-supply wells had water with detections of copper (maximum concentration of 6.3 $\mu\text{g/L}$), and these wells were located in or near large agricultural areas. Four ground-water samples in the network contained detectable concentrations of lead, and maximum concentrations of 5 $\mu\text{g/L}$ were below the MCL of 15 $\mu\text{g/L}$.

Bromide concentrations in water from the public-supply wells in southern Miami-Dade County were elevated above those in most other wells. Possible sources of high bromide concentrations include bromide-containing fumigants and seawater aerosols. Methyl bromide has been used as a fumigant in agricultural areas in southern Miami-Dade County near these public-supply wells (fig. 1). Additionally, these wells are within several miles of the coast and may be influenced by bromide-rich seawater aerosols.

The possibility of methyl bromide contributing measurable amounts of bromide ion to ground water in areas where it is applied was investigated. Methyl bromide is reported to decompose to bromide ion and methanol (GTZ, 2002). Bromide in excess of that expected from seawater can be computed using the bromide-to-chloride ratio (mass-to-mass) of 0.00353 for seawater and the chloride concentration in a water sample. For example, at public-supply well number 1 (fig. 4), which had the highest bromide ion concentration (0.71 mg/L), a value was computed of 0.61 mg/L of bromide in excess of that expected if seawater was the only source of bromide and chloride. This excess could

Table 2. Summary of major ions, selected trace elements, radon, organic carbon, and nutrient concentrations for 30 public-supply wells and 32 monitoring wells in the Biscayne aquifer

[Concentrations are dissolved, except radon; units are milligrams per liter except for arsenic and copper, which are micrograms per liter, and radon, which is picocuries per liter.]

Constituent	Well Type	Number of samples	Concentration		
			Minimum	Median	Maximum
Major Ions					
Calcium	Public supply	30	58	88.5	130
	Monitoring	32	36	120	160
Sodium	Public supply	30	12	25	42
	Monitoring	32	1.9	17.5	81
Magnesium	Public supply	30	2.5	4.1	8.5
	Monitoring	32	0.56	3.65	15
Potassium	Public supply	30	0.59	2.4	18
	Monitoring	32	0.70	2.75	13
Sulfate	Public supply	30	<0.1	17	84
	Monitoring	32	<0.1	16.5	66
Chloride	Public supply	30	17	39	67
	Monitoring	32	3.2	24.5	130
Silica	Public supply	30	2.7	8.0	15
	Monitoring	32	2.1	6.65	15
Trace Elements and Radon					
Arsenic	Public supply	30	<1.0	<1.0	3.0
	Monitoring	32	<1.0	2.0	19
Bromide	Public supply	30	0.024	0.077	0.71
	Monitoring	15	<0.01	0.03	0.11
Copper	Public supply	30	<1.0	<1.0	6.3
	Monitoring	32	<1.0	<1.0	4.0
Fluoride	Public supply	30	<0.10	0.23	0.37
	Monitoring	32	<0.10	0.30	0.41
Radon, in picocuries per liter	Public supply	30	202	421	901
	Monitoring	32	230	555	1,800
Carbon					
Dissolved organic carbon	Public supply	30	0.6	9.4	22
	Monitoring	32	1.9	11.5	36
Nutrients					
Nitrogen, nitrite	Public supply	30	<0.01	<0.01	0.087
	Monitoring	32	<0.01	0.01	0.30
Nitrogen, nitrite plus nitrate	Public supply	30	<0.01	0.025	5.99
	Monitoring	32	<0.01	<0.01	4.2
Nitrogen, ammonia	Public supply	30	<0.01	0.453	2.29
	Monitoring	32	<0.01	0.235	25
Nitrogen, ammonia plus organic	Public supply	30	<0.01	0.955	3.60
	Monitoring	32	<0.01	0.95	28
Phosphorus	Public supply	30	<0.01	<0.01	0.337
	Monitoring	32	<0.01	<0.01	0.295
Phosphorus, orthophosphate	Public supply	30	<0.01	0.024	0.47
	Monitoring	32	<0.01	0.02	0.239

result from the complete decomposition of 0.727 grams of methyl bromide under 1 square meter of soil in water 1 meter deep. One application of methyl bromide at the typical rate of 448 kilograms per hectare for nematode control (400 pounds per acre from Noling and Gilreath, 1998) would provide 44.8 grams per square meter to the soil. The decomposition and transfer of about 2 percent of the methyl bromide in this application to surrounding ground water could explain the excess bromide ion in the sample from well number 1.

Radon-222 is a radioactive gas that occurs naturally in ground water in areas that contain radionuclides of the uranium-238 radioactive decay series. Radon-222 is produced when radium-226 (a daughter of uranium-238) contained in water and aquifer materials undergoes nuclear decay. Uranium-238 commonly occurs in trace amounts in phosphatic deposits and limestone in Florida. Of the 65 Biscayne aquifer samples analyzed for radon-222, 56 (86 percent) exceeded the proposed 300 pico-curie per liter (pCi/L) MCL for drinking water (U.S. Environmental Protection Agency, 2004). Radon-222 activities ranged from 202 to 1,800 pCi/L, with a median activity of 440 pCi/L.

Dissolved organic carbon was consistently higher in the monitoring wells than in the public-supply wells. Most likely this is because organic deposits overlie the aquifer in many locations, and the monitoring wells are shallow and more likely to be influenced by factors at the surface.

Nutrients

Concentrations of nutrients generally are low in the Biscayne aquifer except near human sources, such as domestic waste and agricultural fertilizers. Concentrations of nitrite plus nitrate were low in most wells (commonly less than the 0.05-mg/L detection level), but occasionally were elevated above 2 mg/L (table 2). The higher values were found in public-supply wells in or near agricultural lands, although no well sample exceeded the MCL of 10 mg/L.

Concentrations of ammonia in ground water were relatively high compared to concentrations in other NAWQA study areas (McPherson and others, 2000). Median concentrations were less than 0.5 mg/L, but a few samples had concentrations up to 3 mg/L, and one monitoring well had a concentration of 25 mg/L. Water from this well contained hydrogen sulfide, which is indicative of a reducing environment that would favor conversion of organic nitrogen compounds to ammonia.

Phosphorus concentrations in ground-water samples ranged from less than 0.01 to 0.337 mg/L, with a median less than 0.01 mg/L (table 2). Highest concentrations were in the northern part of the study area, in southeastern Palm Beach County. Sources of the high phosphorus concentrations (those above the median value) may be fertilizers or naturally occurring phosphatic materials associated with the silts and clays. Phosphorus levels can be high in ground water where natural phosphates are present in the rock matrix, and could degrade the ecosystem by moving upward into surface-water bodies. West of the study area, substantial increases in the movement of phosphorus-laden surface water into the Everglades has been a major concern to land management and regulatory agencies in south Florida because of the potential for ecosystem degradation. Further investigation into the reason for the high phosphorus levels in ground water in the northern part of the study area is needed.

Pesticides

Historically, pesticides, including insecticides, herbicides, and fungicides, have been used to control insects, weeds, and fungi in agricultural areas. Expansion of the lawn care and golf industries in urban areas and the increased use of insecticides around homes have substantially increased the amount of pesticides used in the study area in recent years (Haag and others, 1998; Swancar, 1996). The legacy of banned pesticides or pesticides that are no longer used is still evident in some areas, based on the detection of the degradation products p,p'-dichlorodiphenyldichloroethylene (DDE) from the insecticide dichlorodiphenyltrichloroethane (DDT), used for mosquito control, 2,6-diethylaniline from the herbicide alachlor, used in agricultural areas, and the herbicide fenuron, used for weed control.

A total of 86 pesticides were analyzed in samples collected from the public-supply and monitoring wells (for a list of the pesticides analyzed, see McPherson and others, 2000); of these, 15 pesticides were detected in this study, 14 of which were detected more than once (fig. 6; table 3). At least one pesticide (generally atrazine or tebuthiuron) was detected in each of the 30 public-supply wells and in 78 percent of the 32 monitoring wells. Only one sample from the three reference wells had a pesticide detection (atrazine). Deethylatrazine, a degradation product of atrazine, also was detected frequently. No pesticide concentration exceeded the MCL.

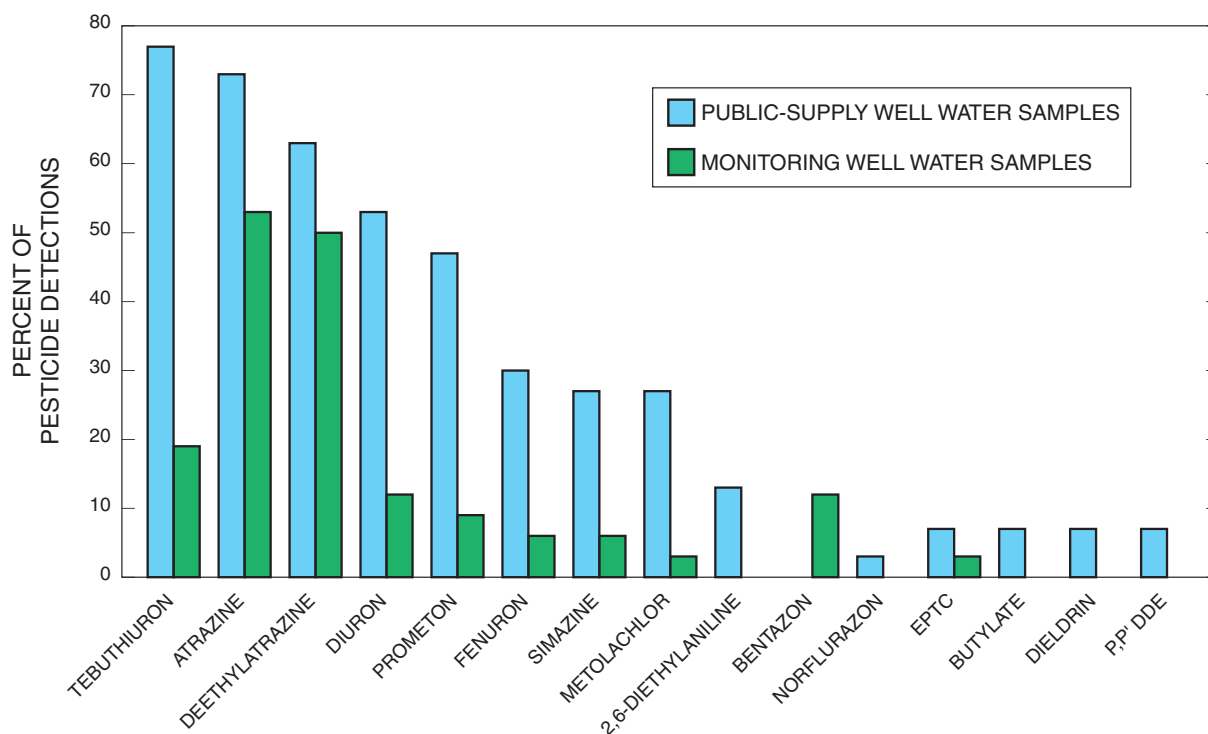


Figure 6. Pesticides detected in samples from the public-supply and monitoring wells in the Biscayne aquifer.

Regional patterns in pesticide distribution in ground water can be related to land use, solubility, transport, degradation characteristics of pesticides, and aquifer properties. Transported surface water also is a major source of pesticides in the study area. Pesticides such as atrazine, tebuthiuron, and diuron were detected frequently in canal waters that recharge the Biscayne aquifer (Miles and Pfeuffer, 1997). The detection of tebuthiuron and atrazine in ground-water samples indicates that the widespread use of herbicides—particularly tebuthiuron to control weeds in canals and rights-of-way (Miller and others, 1999) and atrazine to control weeds in agricultural and urban areas—has resulted in the transport of these pesticides into the Biscayne aquifer.

Fenuron and diuron were detected in public-supply wells in the northern part of the study area (figs. 7a and 7b, respectively). Fenuron has been used for control of woody plants and weeds, and diuron has been used commonly on sugar cane and citrus. Fenuron was detected in samples from two shallow monitoring wells. Although it is no longer on the list of approved herbicides in Florida, fenuron was once used in northern Broward and Palm Beach Counties. These detections

indicate that fenuron degrades slowly in ground water. Metachlor and simazine were detected in the mixed-agriculture areas of southern Miami-Dade County and occasionally in wells near other agricultural areas (figs. 7c and 7d, respectively).

Volatile Organic Compounds

VOCs are components of petroleum products and some man-made products such as solvents, refrigerants, and fumigants (Squillace and others, 1999). VOCs have chemical and physical properties that allow them to move freely between water and air (Bender and others, 1999). VOCs in rainfall may originate from vehicle and industrial emissions (Pankow and others, 1997). VOCs also can be formed in ground water in the presence of organic carbon and halogens (such as chlorine used to treat water supplies or degradation products of fumigants and fertilizers). The USEPA has established MCLs in drinking water for many VOCs because of human health concerns (Moran and others, 2002). Rowe and others (1997) summarized aquatic toxicity information and water-quality criteria for selected VOCs.

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Table 3. Summary of pesticide detections for 30 public-supply wells and 32 monitoring wells in the Biscayne aquifer

[Units are micrograms per liter; e, estimated*; GWGC, State of Florida ground-water guidance concentration; MCL, U.S. Environmental Protection Agency and State of Florida maximum contaminant level; <, less than; --, no applicable standard]

Constituent	Well type	Number of detections	Minimum reporting level	Concentration			GWGC or (MCL)
				Minimum	Median	Maximum	
Herbicides							
Tebuthiuron	Public supply	23	<0.01	<0.01	0.0197	0.69	490
	Monitoring	6	<0.01	<0.01	<0.01	*0.069	490
Atrazine	Public supply	22	<0.001	<0.001	0.009	0.113	3(MCL)
	Monitoring	17	<0.001	<0.001	0.0035	0.422	3(MCL)
Deethylatrazine	Public supply	19	<0.002	<0.002	0.0051	0.0259	--
	Monitoring	16	<0.002	<0.002	*0.005	0.387	--
Diuron	Public supply	16	<0.02	<0.02	0.0053	0.30	14
	Monitoring	4	<0.02	<0.02	<0.02	0.38	14
Prometon	Public supply	14	<0.018	<0.018	<0.018	0.0313	105
	Monitoring	3	<0.018	<0.018	<0.018	0.026	105
Fenuron	Public supply	9	<0.013	<0.013	<0.013	0.06	--
	Monitoring	2	<0.013	<0.013	<0.013	0.15	--
Simazine	Public supply	8	<0.005	<0.005	<0.005	0.0142	4(MCL)
	Monitoring	2	<0.005	<0.005	<0.005	0.006	4(MCL)
Metolachlor	Public supply	8	<0.002	<0.002	<0.002	0.042	1,050
	Monitoring	1	<0.002	<0.002	<0.002	0.014	1,050
2,6-Diethyl-aniline	Public supply	4	<0.003	<0.003	<0.003	0.0088	--
	Monitoring	0	<0.003	<0.003	<0.003	<0.003	--
Bentazon	Public supply	0	<0.014	<0.014	<0.014	<0.014	17.5
	Monitoring	4	<0.014	<0.014	<0.014	*0.15	17.5
Butylate	Public supply	2	<0.002	<0.002	<0.002	0.045	350
	Monitoring	0	<0.002	<0.002	<0.002	<0.002	350
Norflurazon	Public supply	1	<0.024	<0.024	<0.024	0.06	280
	Monitoring	0	<0.024	<0.024	<0.024	<0.024	280
Insecticides							
EPTC	Public supply	2	<0.002	<0.002	<0.002	0.0322	--
	Monitoring	1	<0.002	<0.002	<0.002	0.011	--
Dieldrin	Public supply	2	<0.001	<0.001	<0.001	0.002	0.1
	Monitoring	0	<0.001	<0.001	<0.001	<0.001	0.1
p,p' DDE	Public supply	2	<0.006	<0.006	<0.006	0.002	0.1
	Monitoring	0	<0.006	<0.006	<0.006	<0.006	0.1

* Estimated values below the usual reporting level are given for samples in which the compound's presence was verified from spectra. Values above the reporting levels are estimated if there are interferences, values below the lowest standard, or extraction recoveries less than normal.

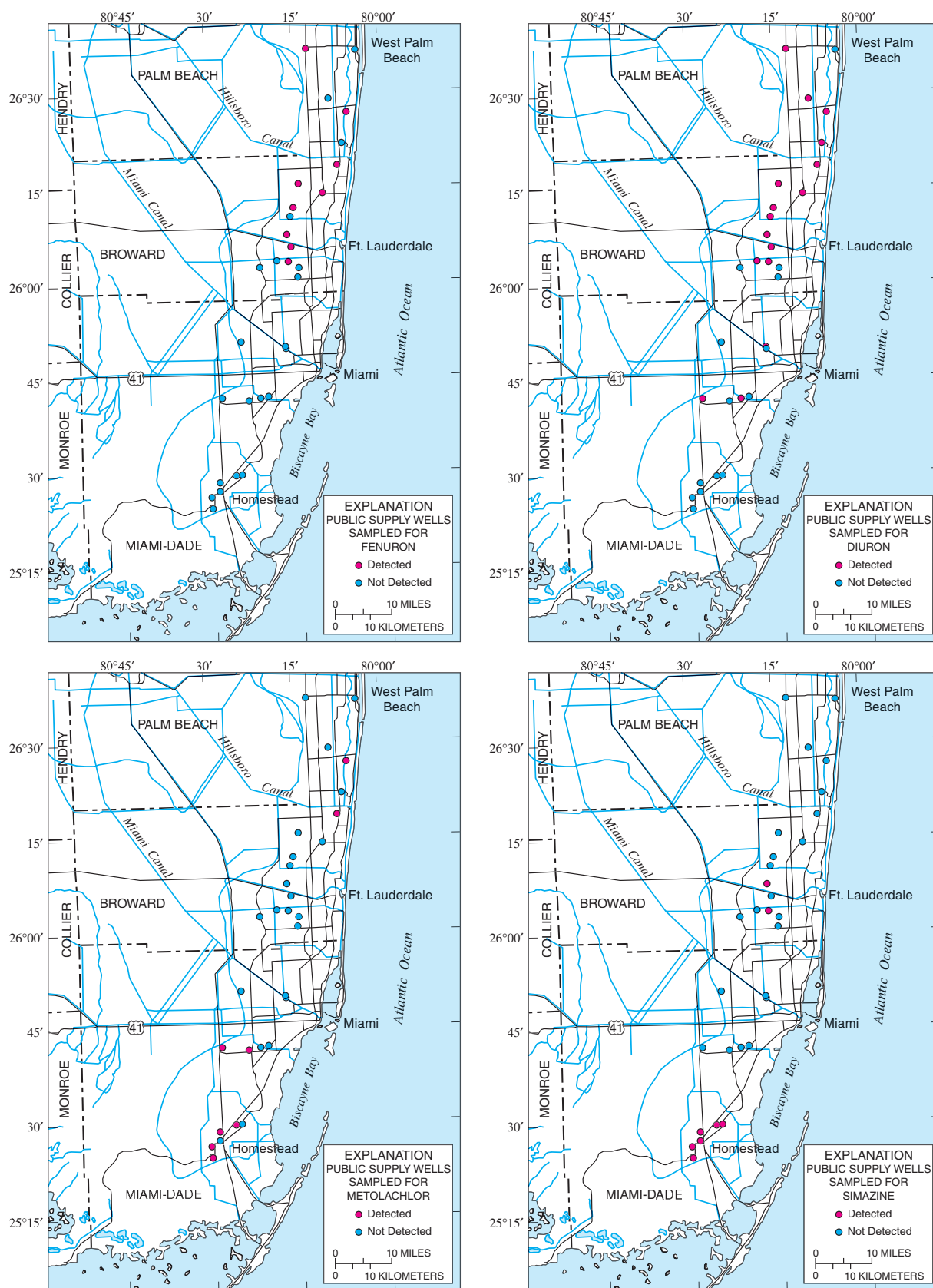


Figure 7. Regional patterns of occurrence of the pesticides (a) fenuron, (b) diuron, (c) metolachlor, and (d) simazine, detected in samples from public-supply wells in the Biscayne aquifer.

A review of VOCs detected in previous studies on public-supply wells and shallow, urban wells in south Florida indicated that few VOCs have been detected in shallow ground water, but many water-supply wells in the Dade, Broward, and Palm Beach Counties have had chemical contamination from VOCs (Vincent, 1984; Florida Department of Environmental Protection, 1999). Vincent (1984) reported that nearly 20 percent of samples from 250 public-supply wells (mostly in Miami-Dade County) contained detectable VOCs, mostly originating from industrial processes.

Since 1984, there have been three major actions taken to reduce VOCs in finished drinking water. First, cleanup of contaminated industrial sites has greatly reduced concentrations in untreated supply water from the well fields. Second, processing measures have been initiated, using air stripping or carbon filtration, to remove VOCs from untreated water in most of the contaminated water-treatment systems. Other water-treatment facilities remove organic carbon from the untreated supply water by reverse osmosis or other methods so that trihalomethanes are not formed when the water is chlorinated before its distribution to consumers. Third, most well fields now have delineated recharge protection zones and have monitoring programs and protection ordinances in place in those areas.

A total of 86 VOCs were analyzed in this study; 32 VOCs were detected (table 3; see McPherson and others, 2000, for a list of the analyzed VOCs). From 32 shallow monitoring wells, 29 samples (91 percent) contained one or more VOCs (fig. 8); from 30 deep public-supply wells, 23 samples (77 percent) contained one or more VOCs. Two reference wells contained low concentrations of two VOCs. One reason for the high number of detections is the use of new analytical methods with low reporting limits (Connor and others, 1998). Except for two samples from public-supply wells in a more industrialized area, concentrations of VOCs were all less than drinking-water standards. The two exceptions were vinyl chloride concentrations of 3 and 5 µg/L, which were above the MCL of 1 µg/L. The most common VOCs detected in ground-water samples for both surveys are shown in table 4 and figure 8. Acetone, methylethylketone, and tetrahydrofuran were detected in several of the laboratory blank samples. These compounds are common laboratory contaminants and are not included in the data table. Field solution blanks indicated that these compounds either were present in blank water or were detected in sporadic blanks in the laboratory, but not the samples. Carbon disulfide also was frequently detected, but is considered to be a naturally occurring

VOC because of the presence of hydrogen sulfide gas and the high organic carbon content of the ground water.

Cis-1,2-dichloroethene was the most frequently detected VOC in the public-supply wells. This compound and other VOCs, such as 1,4-dichlorobenzene, trichloroethylene, vinyl chloride, 1,1-dichloroethane, and chlorobenzene, were detected more commonly in the older and denser residential and industrial areas. In the 1984 USEPA study (Vincent, 1984) in this same area, the most frequently detected VOCs were *cis*-1,2-dichloroethene, 1,2-dichloroethane, trichloroethylene, vinyl chloride, and tetrachloroethylene. Although concentrations were less during the 1998 sampling period, the same VOCs persisted in the area of the Biscayne aquifer overlain by heavy industry and dense urban development.

Methyl *tert*-butyl ether (MTBE) was the second-most commonly detected VOC in the public-supply wells. MTBE is used as a gasoline additive in most states, including Florida, to increase the octane level, reduce vehicular carbon monoxide levels, and reduce ozone levels in urban air. MTBE was the second most frequently detected VOC in shallow ground water in urban areas in a study of 8 urban and 20 agricultural areas throughout the United States in 1993 and 1994, and has recently emerged as a possible risk to human health (Squillace and others, 1996). In south Florida's public-supply wells, MTBE detections occurred mostly in the heavily urbanized areas of Miami-Dade County and in agricultural areas in south Miami-Dade County where the wells are only about 40 ft deep (figs. 1 and 9).

Chloroform, bromoform, and other related VOCs were detected in water from public-supply wells in the mixed-agricultural area of southern Miami-Dade County. These VOCs probably are formed during degradation of the fumigant methyl bromide combined with chloropicrin, or fertilizers that contain chlorine. Chloroform also was detected in samples from some of the monitoring wells, probably resulting from the use of chlorinated drinking water as irrigation water or fertilizers containing chlorine. Tetrachloroethylene was detected in almost all the public-supply wells in the agricultural area of southern Miami-Dade County. Tetrachloroethylene is used as a solvent for degreasing and for dry cleaning.

Toluene, *p*-isopropyltoluene, and 1,2,4-trimethylbenzene were the most frequently detected VOCs in shallow ground water sampled from monitoring wells in the newer residential areas. These compounds may be from additives included in various pesticide sprays or from fuel or asphalt.

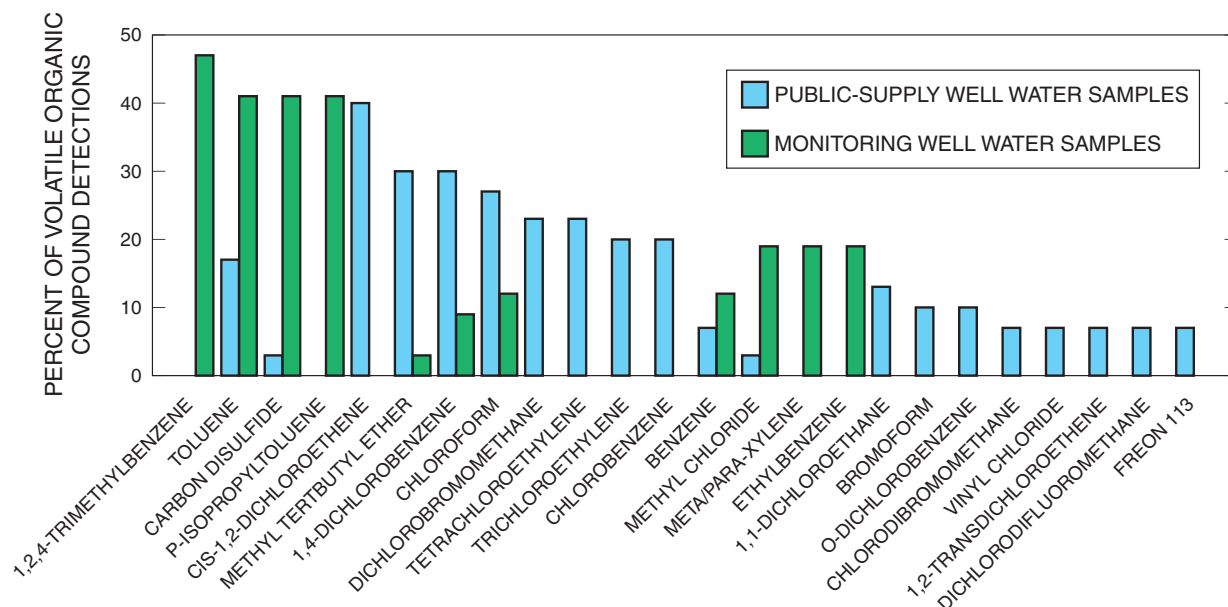


Figure 8. The most common volatile organic compounds detected in the Biscayne aquifer.

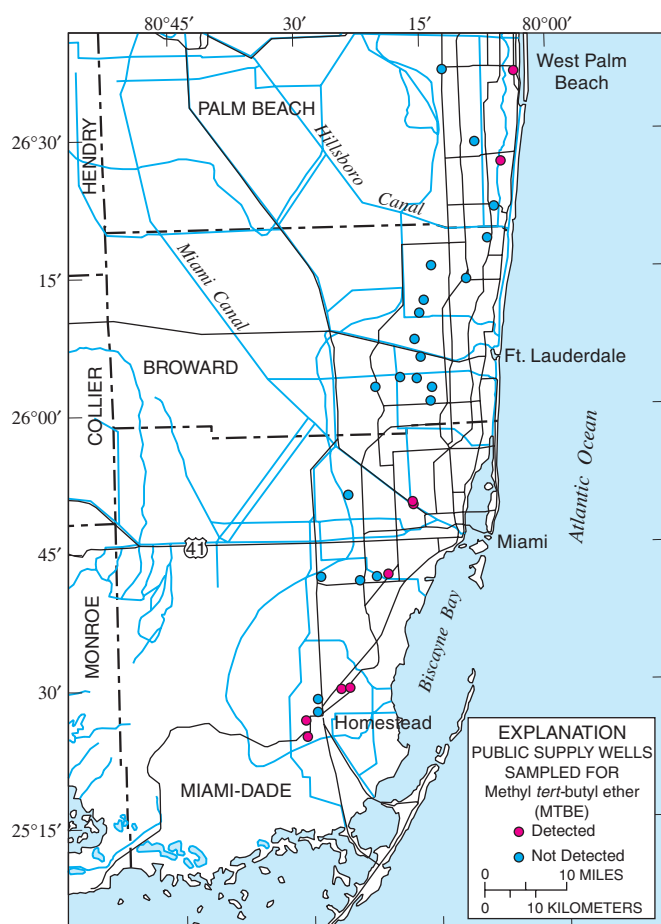


Figure 9. Regional patterns of methyl *tert*-butyl ether detected in samples from public-supply wells in the Biscayne aquifer.

Summary

This report summarizes the results of a survey of untreated ground water from: (1) 30 public-supply wells in Broward, Miami-Dade, and southern Palm Beach Counties, and (2) 32 shallow monitoring wells and 3 reference wells in an urban area of Broward County. The public-supply wells lie within the urban areas in the higher elevations of the southeastern coast of Florida, and in agricultural areas located mainly in the lower elevations of the southern part of the study area. The monitoring wells were nested in the western part of the populated area in eastern Broward County, in an urban area that contains recently developed residential and light-commercial land use. The study area overlies the Biscayne aquifer. The high permeability and shallow water table of the sand and limestone sediments make the ground water in the Biscayne aquifer vulnerable to contamination by human activities. Eighty percent of the population residing in the study area, as well as most of the population in the Florida Keys, is served by public-supply wells that tap the Biscayne aquifer. Total withdrawals from the Biscayne aquifer exceeded 875 million gallons per day in 2000, of which 700 million gallons per day were withdrawn for public supply.

Concentrations of calcium, magnesium, potassium, and sodium, as well as pH and dissolved oxygen measured for this study were typical of shallow ground water from the Biscayne aquifer. Bromide concentrations in water from public-supply wells in southern Dade County

Table 4. Summary of volatile organic compounds detected more than once in 30 public-supply wells and 32 monitoring wells in the Biscayne aquifer

[Units are micrograms per liter; e, estimated; HAL, health advisory level, 70-kilogram adult, lifetime, (U.S. Environmental Protection Agency, 2004); MCL, maximum contaminant level (U.S. Environmental Protection Agency, 2004); --, no applicable standard; <, less than; *, MCL for total xylenes. VOCs detected only once include dibromomethane, bromochloromethane, 1,1-Dichloroethylene, 1,2-Dichloropropane, 1,3-Dichlorobenzene, Methyl-tertpentyl-ether, chlorotoluene, ethylether, methyl-isobutyl-ketone, and o-xylene]

Constituent	Survey	Number of detections	Minimum re-reporting level	Concentration			HAL or MCL
				Minimum	Median	Maximum	
1,2,4-Trimethylbenzene	Public supply	0	<0.056	<0.056	<0.056	<0.056	--
	Monitoring	15	<0.050	<0.050	<0.050	*0.07	--
Toluene	Public supply	5	<0.038	<0.038	<0.038	*0.27	1,000MCL
	Monitoring	13	<0.050	<0.050	<0.050	0.29	1,000MCL
Carbon disulfide	Public supply	1	<0.080	<0.080	<0.320	*0.610	--
	Monitoring	13	<0.050	<0.050	<0.020	0.120	--
p-Isopropyltoluene	Public supply	0	<0.110	<0.110	<0.110	<0.110	--
	Monitoring	13	<0.050	<0.050	<0.050	1.0	--
cis-1,2-Dichloroethene	Public supply	12	<0.038	<0.038	<0.038	0.978	70MCL
	Monitoring	0	<0.038	<0.038	<0.038	<0.038	70MCL
Methyl tert-butylether	Public supply	9	<0.112	<0.112	<0.112	0.682	35HAL**
	Monitoring	1	<0.100	<0.100	<0.100	*0.010	35HAL**
1,4-Dichlorobenzene	Public supply	9	<0.050	<0.050	<0.050	*0.130	75MCL, 75HAL
	Monitoring	3	<0.050	<0.050	<0.050	*0.010	75MCL, 75HAL
Chloroform	Public supply	8	<0.052	<0.052	<0.052	1.12	80MCL, 70HAL
	Monitoring	4	<0.050	<0.050	<0.050	*0.080	80MCL, 70HAL
Dichlorobromomethane	Public supply	7	<0.048	<0.048	<0.048	0.337	100MCL
	Monitoring	0	<0.050	<0.050	<0.050	<0.050	100MCL
Tetrachloroethylene	Public supply	7	<0.038	<0.038	<0.038	*0.050	5MCL, 10HAL
	Monitoring	0	<0.050	<0.050	<0.050	<0.050	5MCL, 10HAL
Trichloroethylene	Public supply	6	<0.038	<0.038	<0.038	*0.34	5MCL
	Monitoring	0	<0.050	<0.050	<0.050	<0.050	5MCL
Chlorobenzene	Public supply	6	<0.028	<0.028	<0.028	0.53	100MCL
	Monitoring	0	<0.050	<0.050	<0.050	<0.050	100MCL
Benzene	Public supply	2	<0.032	<0.032	<0.032	*0.009	5MCL
	Monitoring	4	<0.050	<0.050	<0.050	*0.050	5MCL
Methyl chloride	Public supply	1	<0.254	<0.254	<0.254	*0.015	30HAL
	Monitoring	6	<0.200	<0.200	<0.200	*0.100	30HAL
Meta/Para-xylene	Public supply	0	<0.064	<0.064	<0.064	<0.064	10,000MCL*
	Monitoring	6	<0.050	<0.050	<0.050	*0.050	10,000MCL*

Table 4. Summary of volatile organic compounds detected more than once in 30 public-supply wells and 32 monitoring wells in the Biscayne aquifer—Continued

[Units are micrograms per liter; e, estimated; HAL, health advisory level, 70-kilogram adult, lifetime, (U.S. Environmental Protection Agency, 2004); MCL, maximum contaminant level (U.S. Environmental Protection Agency, 2004); --, no applicable standard; <, less than; *, MCL for total xylenes. VOCs detected only once include dibromomethane, bromochloromethane, 1,1-Dichloroethylene, 1,2-Dichloropropane, 1,3-Dichlorobenzene, Methyl-tertpentyl-ether, chlorotoluene, ethylether, methyl-isobutyl-ketone, and o-xylene]

Constituent	Survey	Number of detections	Minimum re- porting levels	Concentration			HAL or MCL
				Minimum	Median	Maximum	
Ethylbenzene	Public supply	0	<0.050	<0.050	<0.100	<0.020	700MCL, 700HAL
	Monitoring	6	<0.050	<0.050	<0.10	*0.010	700MCL, 700HAL
1,1-Dichloroethane	Public supply	4	<0.066	<0.066	<0.066	*0.34	--
	Monitoring	0	<0.050	<0.050	<0.050	<0.050	--
Bromoform	Public supply	3	<0.104	<0.104	<0.104	0.945	80MCL
	Monitoring	0	<0.003	<0.003	<0.003	<0.003	80MCL
o-Dichlorobenzene	Public supply	3	<0.048	<0.048	<0.048	*0.27	600MCL, 600HAL
	Monitoring	0	<0.050	<0.050	<0.050	<0.050	600MCL, 600HAL
Dibromochloro- methane	Public supply	2	<0.182	<0.182	<0.182	0.412	80MCL, 60HAL
	Monitoring	0	<0.100	<0.100	<0.100	<0.100	80MCL, 60HAL
Vinyl chloride	Public supply	2	<0.112	<0.112	<0.112	4.68	2MCL
	Monitoring	0	<0.100	<0.100	<0.100	<0.100	2MCL
1,2-trans-Dichloro- ethylene	Public supply	2	<0.032	<0.032	<0.032	*0.028	100MCL, 100HAL
	Monitoring	0	<0.050	<0.050	<0.050	<0.050	100MCL, 100HAL
Dichlorodifluoro- methane	Public supply	2	<0.096	<0.096	<0.096	*0.78	1,000HAL
	Monitoring	0	<0.200	<0.200	<0.200	<0.200	1,000HAL
Freon 113	Public supply	2	<0.032	<0.032	<0.032	*0.011	--
	Monitoring	0	<0.050	<0.050	<0.050	<0.050	--

* Estimated values below the usual reporting level are given for samples in which the compound's presence was verified from spectra. Values above the reporting levels are estimated if there are interferences, values below the lowest standard, or extraction recoveries less than normal.

** HAL value from Florida Department of Health, 2004

were elevated, possibly because of a breakdown of fumigants and pesticides used in that area. Nitrate concentrations in ground water were low (commonly not detected) in most wells, but were elevated at a few sites. Public water-supply wells located in or near agricultural land yielded water with detectable concentrations of nitrate. There were no specific land uses affecting concentrations

of nitrate in the shallow monitoring wells. Phosphorus concentrations in ground-water samples ranged from less than 0.01 to 0.34 mg/L, with a median of less than 0.01 mg/L; higher concentrations may come from fertilizer or may be a result of phosphatic material in the sandy limestone. Of the 65 Biscayne aquifer samples analyzed for radon-222, 56 (86 percent) exceeded the

proposed 300 picocurie per liter (pCi/L) maximum contaminant level for drinking water (U.S. Environmental Protection Agency, 2004). Radon-222 activities ranged from 202 to 1,800 pCi/L, with a median activity of 440 pCi/L.

Urban activities, such as turf-grass maintenance in golf courses, have increased concentrations of arsenic in ground water through the use of the herbicide MSMA. Some of the shallow monitoring wells located in golf courses had samples with concentrations that were higher than other wells in the network, although no samples exceeded the MCL of 50 mg/L. The values of arsenic in samples from the public-supply wells were lower than those from the shallow monitoring wells. Copper and lead concentrations were not substantially elevated in any of the samples.

Of the 86 pesticides analyzed in ground water from the Biscayne aquifer, both from the public-supply and from the monitoring wells, 15 pesticides were detected. One or more pesticides (generally atrazine or tebuthiuron) were detected in each of the 30 public-supply wells, and in 78 percent of the monitoring wells. One pesticide (atrazine) was detected in one of the samples from the three reference wells. No pesticide concentration exceeded any drinking-water standard.

Of the 86 different VOCs analyzed, 32 were detected. Most samples from the monitoring, public-supply, and reference wells had at least one VOC detection. Concentrations of VOCs in the samples were all less than drinking-water standards, except two samples from public-supply wells in an area near industrial development. These two samples had vinyl chloride concentrations (3 and 5 µg/L) that were above the MCL of 1 µg/L.

Cis-1,2-dichloroethene was the most frequently detected VOC in the public-supply wells. This compound and other VOCs, such as trichlorethylene, vinyl chloride, 1,4-dichlorobenzene, 1,1-dichloroethane, and chlorobenzene, were detected more commonly in the older and denser residential and industrial areas. MTBE, a VOC that is a possible risk to human health, was the second most frequently detected VOC in the public-supply wells.

Toluene, *p*-isopropyltoluene, and 1,2,4-trimethylbenzene were the most frequently detected VOCs in shallow ground water from monitoring wells within the newer residential areas. Although the specific source of these compounds is uncertain, they may come from fuels.

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