Retrospective Review of Watershed Characteristics and a Framework for Future Research in the Sarasota Bay Watershed, Florida

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Prepared in cooperation with the
Sarasota Bay Estuary Program

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Contents

Figures

Tables

Conversion Factors, Datums, Acronyms, and Abbreviations

Multiply	By	To obtain
	Length	
centimeters (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
centimeters per hour (cm/hr)	0.3937	inch per hour (in/hr)
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
liters per minute (L/min)	0.2642	gallons per minute (gal/min)
liters per second (L/s)	0.0228	million gallons per day (Mgal/d)
	Mass, hydraulic gradient, and density	
gram (g)	0.002205	pound (lb)
meter per kilometer (m/km)	5.27983	foot per mile (ft/mi)
grams per cubic centimeter (g/cm^3)	62.4298	pounds per cubic foot (lb/ft^3)
	Transmissivity*	
square meters per day (m^2/d)	10.76	square feet per day (ft^2/d)
	Load – application rate	
kilograms per year (kg/yr)	2.205	pounds per year (lb/yr)
kilograms per hectare per year [kg/ha/yr]	0.8921	pounds per acre per year [(lb/acre)/yr]
	Temperature	
Celsius (°C)	°F = (1.8 × °C) + 32	Fahrenheit (°F)
Fahrenheit (°F)	°C = (°F - 32)/1.8	Celsius (°C)

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Datums

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)
Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29)

Acronyms and Abbreviations

BMP	Best Management Practice
CCMP	Comprehensive Conservation and Management Plan
DCIA	Directly Connected Impervious Area
EMC	Event Mean Concentration
FY&N	Florida Yards and Neighborhoods Program
IMP	Integrated Management Practices
LID	Low-impact Development
NEXRAD	Next Generation Weather Radar System
SBEP	Sarasota Bay Estuary Program
SUNOM	Simplified Urban Nutrient Output Model
SWUCA	Southern Water Use Caution Area
SWFWMD	Southwest Florida Water Management District
TMDL	Total Maximum Daily Load
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
µg/L	micrograms per liter
mg/L	milligrams per liter

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Abstract

The U.S. Geological Survey, in cooperation with the Sarasota Bay Estuary Program, conducted a retrospective review of characteristics of the Sarasota Bay watershed in west-central Florida. This report describes watershed characteristics, surface- and ground-water processes, and the environmental setting of the Sarasota Bay watershed.

Population growth during the last 50 years is transforming the Sarasota Bay watershed from rural and agriculture to urban and suburban. The transition has resulted in land-use changes that influence surface- and ground-water processes in the watershed. Increased impervious cover decreases recharge to ground water and increases overland runoff and the pollutants carried in the runoff. Soil compaction resulting from agriculture, construction, and recreation activities also decreases recharge to ground water.

Conventional approaches to stormwater runoff have involved conveyances and large storage areas. Low-impact development approaches, designed to provide recharge near the precipitation point-of-contact, are being used increasingly in the watershed.

Simple pollutant loading models applied to the Sarasota Bay watershed have focused on large-scale processes and pollutant loads determined from empirical values and mean event concentrations. Complex watershed models and more intensive data-collection programs can provide the level of information needed to quantify (1) the effects of lot-scale land practices on runoff, storage, and ground-water recharge, (2) dry and wet season flux of nutrients through atmospheric deposition, (3) changes in partitioning of water and contaminants as urbanization alters predevelopment rainfall-runoff relations, and (4) linkages between watershed models and lot-scale models to evaluate the effect of small-scale changes over the entire Sarasota Bay watershed. As urbanization in the Sarasota Bay watershed continues, focused research on water-resources issues can provide information needed by water-resources managers to ensure the future health of the watershed.

Introduction

Comprehensive watershed planning is the key to successful multiple-use watershed management. Scientific tools available for watershed planning rely upon extensive, representative data collection programs that are well designed and well maintained. An understanding of the dynamics of the hydrologic system is necessary for efficient management of a watershed. The Sarasota Bay Estuary Program (SBEP) and its many partners have addressed and continue to address multiple-use issues to improve the health of the Sarasota Bay watershed in west-central Florida (fig. 1). The U.S. Geological Survey (USGS), in cooperation with the SBEP, initiated a study in 2003 in the Sarasota Bay watershed to provide information about the watershed characteristics that affect recharge to ground water and overland runoff to surface water. A thorough understanding of the watershed factors that affect the interaction between surface water and ground water in the Sarasota Bay watershed will enhance efficient use and management of the watershed.

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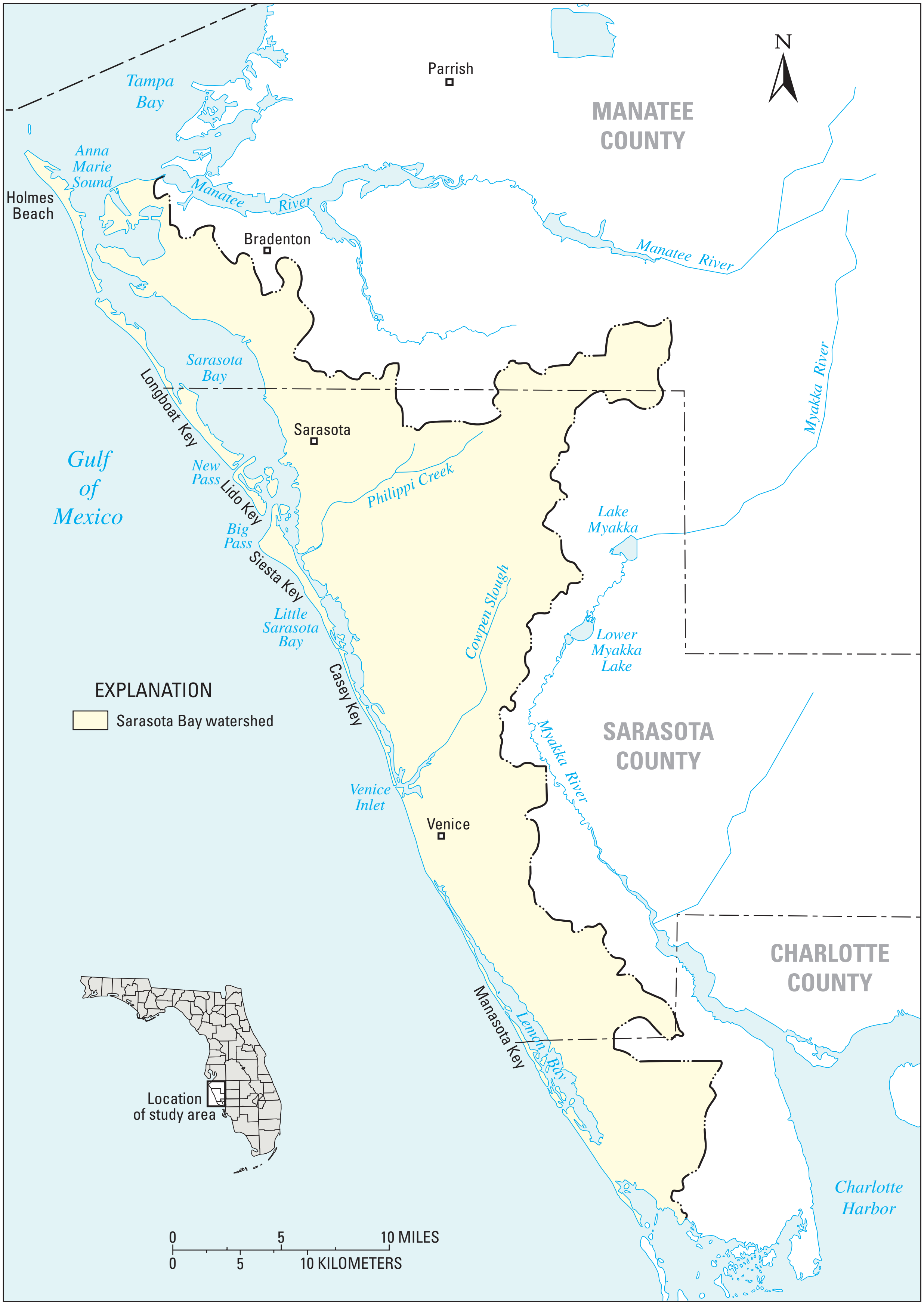


Figure 1. Location of the Sarasota Bay watershed in west-central Florida (modified from Sarasota Bay Estuary Program, 2005).

Purpose and Scope

The purpose of this report is to describe the watershed characteristics and the environmental setting of the Sarasota Bay watershed as they relate to surface-water and ground-water interactions. A comprehensive literature review of published reports about the Sarasota Bay watershed and applicable scientific literature regarding the potential influence of recharge to ground water and overland runoff to surface water on characteristics of the Sarasota Bay watershed form the basis of this report. Cultural practices and their influence on soil compaction and infiltration are emphasized. This report presents watershed science concepts that will enhance future approaches to modeling in humid, shallow water-table areas in urbanizing watersheds.

Historical Perspective of Sarasota Bay

Prior to 1800, the Sarasota area experienced little development or population growth. In 1842, the Armed Occupation Act encouraged homesteading in Florida by providing 160-acre parcels free to individuals who agreed to inhabit the land for 5 years. From 1868 to 1883, areas were cleared by settlers for orange groves and cattle. In 1870, the first settlement was established in Sarasota. Scottish settlers established a community in Sarasota in 1885 and were credited with building America’s first golf course in 1886. By 1898, cattle ranching had expanded and Sarasota cattle supplied beef for troops stationed in Tampa during the Spanish-American War. Development of the watershed remained relatively slow because transportation connecting Sarasota with other areas was limited to sailing ships or steamboats. During the period from 1900 to 1920, the town of Sarasota was incorporated, a railroad from Sarasota to Tampa was built, electric service was established, celery farmers began shipping their crop to northern markets, an air strip was built, and the Manasota Lumber Company saw mill began operation (Sarasota County History, 2005).

At the start of the Great Florida Land Boom in 1920, the population of Sarasota was about 2,150 (fig. 2). With substantial increases in businesses, schools, churches, hospitals, farming, cattle ranching, newspapers, homes, and apartments, by 1930, urban and agricultural development increased substantially as the population grew to 12,440 (fig. 2). From the 1930s to the 1950s, urban development continued and military bases were established (Sarasota County History, 2005). From 1950 to 2000, the population of Sarasota increased from 28,827 to 325,957 (U.S. Census Bureau, 2004). The growth in population brought increases in government services, housing developments, and infrastructure (for example, roads, utilities). Since the 1960s, conversion of agricultural land to urbanized land has continued to occur as the result of rapid population increases. Presently, the Sarasota Bay area is one of the most rapidly expanding urban areas in the Nation – primarily through residential and commercial development in the eastern part of Sarasota County.

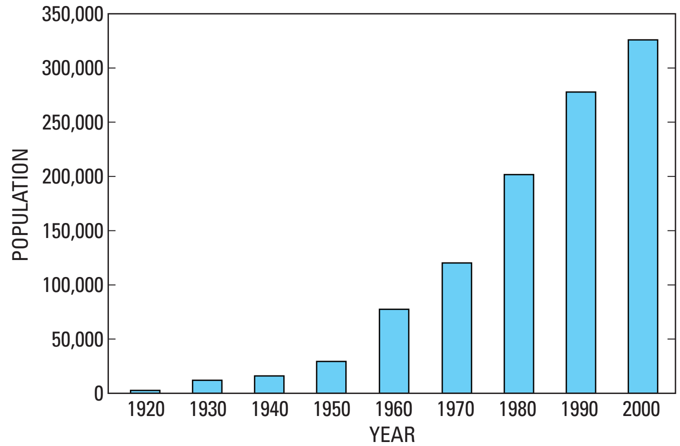


Figure 2. Population of Sarasota County from 1920 to 2000 (from U.S. Census Bureau, 2004).

Sarasota Bay National Estuary Program

The U.S. Congress named Sarasota Bay an estuary of national significance in the Water Quality Act of 1987. In 1995, the State of Florida and the U.S. Environmental Protection Agency (USEPA) approved the Comprehensive Conservation and Management Plan (CCMP) for Sarasota Bay. From 1995 to 2000, more than $200 million was committed to Sarasota Bay restoration. The CCMP consists of action plans designed to reduce nitrogen pollution from stormwater and wastewater, increase available habitat for fish and wildlife, and increase access to the bay and its resources (Sarasota Bay National Estuary Program, 2000).

Studies completed by the Sarasota Bay National Estuary Program in the early 1990s indicated that Sarasota Bay was more degraded than originally hypothesized (Sarasota Bay National Estuary Program, 2000). Nitrogen loading to Sarasota Bay in 1989, for example, had increased to 480 percent above predevelopment levels. In response to efforts by local, State, and Federal agencies, nitrogen pollution to Sarasota Bay decreased 47 percent between 1989 and 2000, to levels approximating 254 percent above predevelopment levels (Sarasota Bay National Estuary Program, 2000). The load reduction has been achieved as a result of (1) improved wastewater treatment, (2) reduced volume of wastewater discharge due to construction of reclaimed water systems, and (3) constructing stormwater treatment systems.

Recent estimates indicate that 56 percent of the remaining nitrogen load to Sarasota Bay is from stormwater (Sarasota Bay National Estuary Program, 2000). The Sarasota Bay community is addressing additional nitrogen reductions in stormwater through several integrated water-resource management approaches: (1) regional stormwater treatment systems (for example, Phillippi Creek), (2) stormwater reuse, and (3) regional educational programs to promote cultural change and water conservation such as the Florida Yards and Neighborhoods (FY&N) Program (Garner and others, 2001).

Acknowledgments

Gary Raulerson, Senior Environmental Scientist of the SBEP, is gratefully acknowledged for his guidance in developing this report. Dave Tomasko, formerly of the Southwest Florida Water Management District (SWFWMD), provided valuable insight and details about the effect of nitrogen loads on the watershed. Mark Shelby, formerly with the University of Florida Institute of Food and Agricultural Sciences, provided information about construction and landscaping practices.

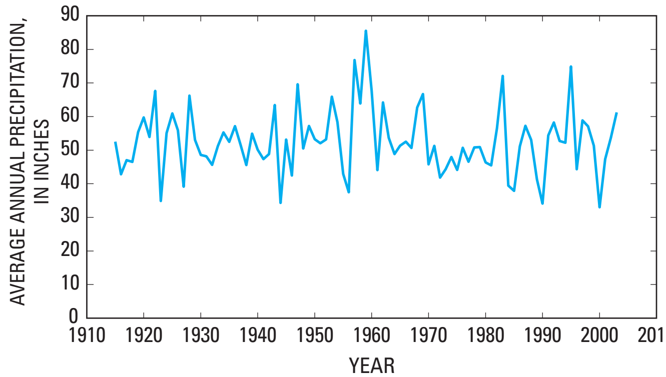


Figure 3. Average annual precipitation for Sarasota County from 1915 to 2003 (from the Southwest Florida Water Management District, 2005).

Environmental Setting of the Sarasota Bay Watershed

The Sarasota Bay watershed drains more than 200 mi^2 (518 km^2) within Manatee, Sarasota, and Charlotte Counties in west-central Florida (fig. 1). The watershed consists of five major embayments—Sarasota Bay, Roberts Bay, Little Sarasota Bay, Blackburn Bay, and Lemon Bay—and a series of creeks and bayous, inlets, upland drainage and barrier islands. Phillippi Creek is the primary tributary in the watershed. Many reaches of the creeks have been converted to ditches throughout the Sarasota Bay watershed to facilitate drainage of the relatively flat, low-gradient subbasins. Inlets between the barrier islands exchange water between Sarasota Bay and the Gulf of Mexico. Sarasota Bay extends north to south about 56 mi (90 km) and ranges in width from 300 ft (91 m) to 4.5 mi (7.2 km).

The hydrologic system is closely linked to the unique environmental setting of the area. Climate, geography, soils, hydrogeology, land cover, land use, and urbanization all affect water movement within the watershed.

Climate

The climate of west-central Florida is characterized by long, warm, humid summers and short, mild, dry winters. The monthly maximum temperatures range from about 92 °F (33.3 °C) in July and August to 71 °F (21.7 °C) in January, with a mean annual maximum temperature of 82 °F (27.8 °C). The monthly minimum temperatures range from about 72 °F (22.2 °C) in August to 48 °F (8.9 °C) in January, with a mean annual minimum temperature of 61 °F (16.1 °C) (Soil Conservation Service, 1991). Average annual precipitation within Sarasota County between 1915 and 2003 was 52.47 in. (133 cm); the maximum and minimum recorded annual precipitation was 85.54 in. (217 cm) for 1959 and 32.77 in. (83 cm) for 2000, respectively (fig. 3) (Southwest Florida Water Management District, 2005).

Precipitation events occur in somewhat predictable seasonal patterns; winter frontal storms move southeastward across the continental United States, whereas tropical storms and hurricanes move toward the west across the Atlantic Ocean, and local thunderstorms occur almost daily during the summer. Although seasonal patterns are somewhat consistent, the intensity and duration of individual storms are difficult to predict. Converging sea breezes, the proximity to the Atlantic high pressure system, the shape of the peninsula, and its subtropical latitude all provide conditions suitable for thunderstorm development during the summer months. During the wet season, daily and hourly precipitation varies substantially. Precipitation amounts for 2004 from a rainfall station in Sarasota County indicate that precipitation occurs almost daily during the rainy period from July to October, but that precipitation events are sparse from November through June (fig. 4) (Southwest Florida Water Management District, 2005).

West-central Florida receives about 60 to 100 precipitation events per year and about 20 of these events result in precipitation totals greater than 0.5 in. (1.27 cm), which typically generate runoff (Mark Ross, University of South Florida, oral commun., 2005). During the dry season, a relatively even rainfall pattern predominates, punctuated by occasional frontal storms. Annual precipitation amounts may be highly variable and deviations from normal precipitation may vary substantially (fig. 5). For example, in 1995 and 1996, the annual precipitation amounts in Sarasota County were 22.35 in. (57 cm) above normal and 8.22 in. (21 cm) below normal, respectively (Southwest Florida Water Management District, 2005).

Temperature changes in the Atlantic and Pacific Oceans strongly influence the climate of Florida. When the temperature of the Atlantic Ocean near the Equator is higher than normal, changing wind patterns bring less moisture to Florida from the Gulf of Mexico (Henry, 1998). The El Niño/Southern Oscillation is a disturbance between the ocean and the atmosphere in the equatorial Pacific Ocean resulting in global shifts in weather patterns (National Oceanic and Atmospheric Administration, 2007). El Niño and La Niña events are the extreme phases of the El Niño/Southern Oscillation climate cycle occurring in the tropical Pacific Ocean. Normally, warm ocean water in the western Pacific Ocean is pushed westward

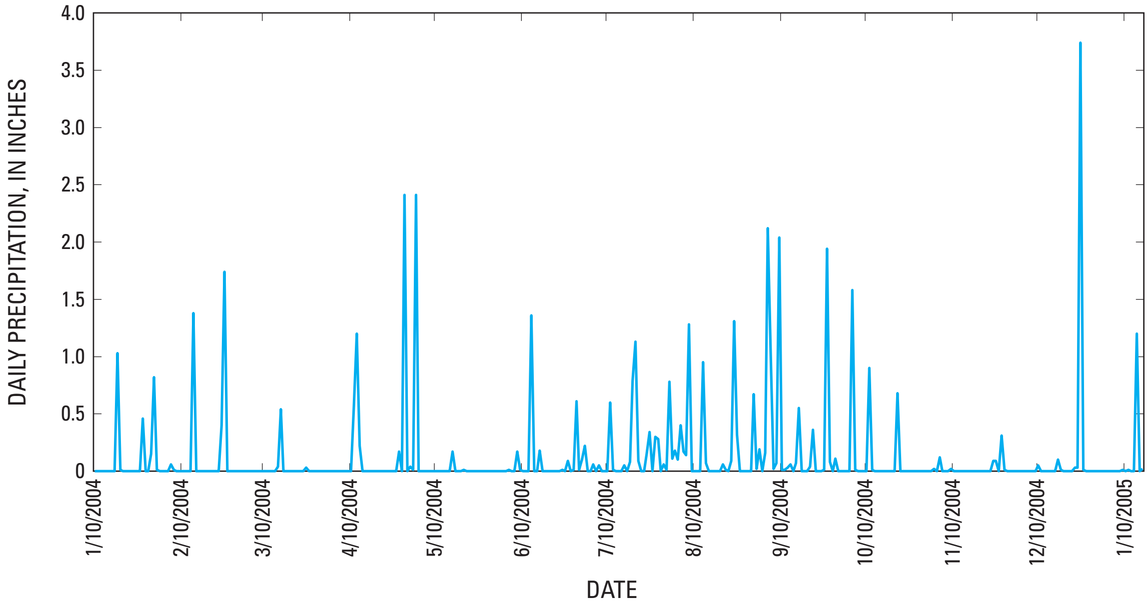


Figure 4. Daily precipitation in the Sarasota Bay watershed from January 10, 2004, to January 10, 2005 (from the Southwest Florida Water Management District, 2005).

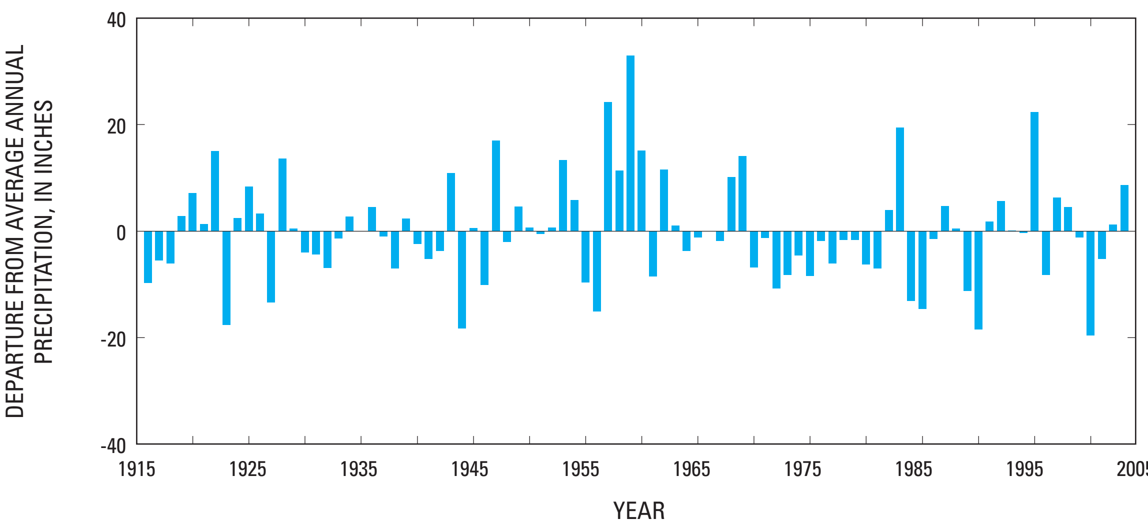


Figure 5. Departure from average annual precipitation in the Sarasota Bay watershed from 1915 to 2003 (from the Southwest Florida Water Management District, 2005).

by strong trade winds out of the east. Meanwhile, water upwelling from the cold ocean depths cools the water in the eastern Pacific Ocean. Every 2 to 7 years, the El Niño phase of the cycle occurs when the trade winds weaken and warm water from the western Pacific Ocean moves eastward. As the warm water enters the eastern Pacific Ocean, upwelling of cool, deep water is suppressed. El Niño events cause the following effects in Florida; greater than normal winter precipitation, more frequent, intense storms from the Gulf of Mexico, and less frequent hurricanes than normal years (Henry, 1998). The difference between precipitation during the 1998 El Niño year and the average monthly precipitation for the Sarasota Bay watershed is shown in figure 6. Precipitation was well above normal during January, February, and March of the El Niño year, followed by below normal precipitation from April to August (Southwest Florida Water Management District, 2005).

La Niña is the opposite phase of the cycle. During La Niña years, trade winds are stronger than normal, holding back the eastward advance of warm, western Pacific water, while permitting cool, deep Eastern Pacific water to move westward. La Niña events cause lower winter rainfall in Florida than during normal years. The recurrence and strength of El Niño and La Niña events and the frequency and intensity of rainy season thunderstorms and hurricanes add complexity to precipitation patterns.

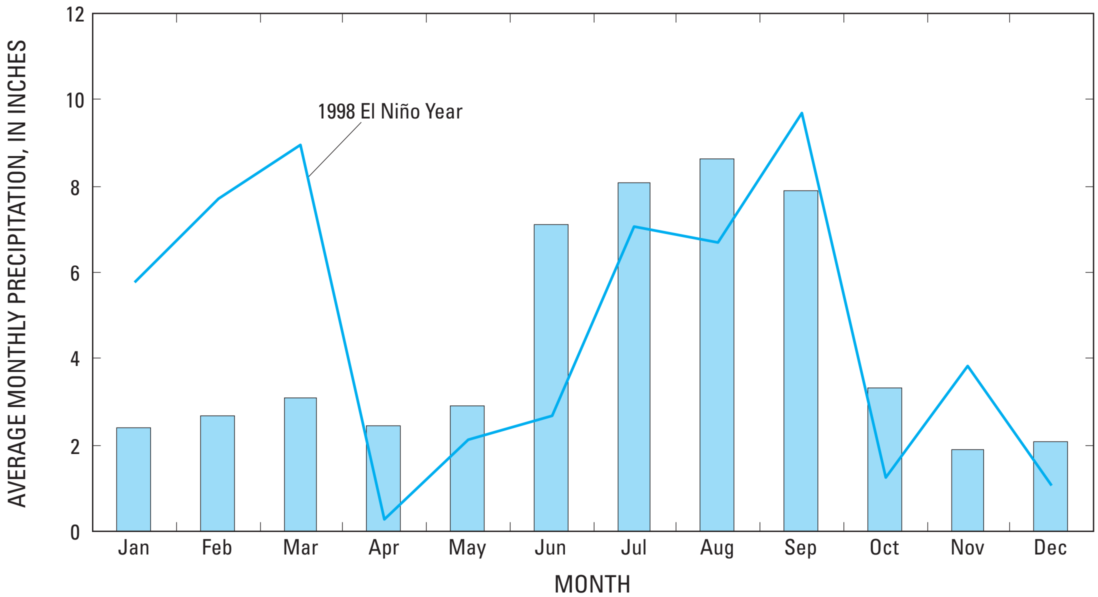


Figure 6. Average monthly precipitation from 1915 to 2003 and 1998 El Niño precipitation in the Sarasota Bay watershed (from Southwest Florida Water Management District, 2005).

Geography

The Sarasota Bay watershed drains northern and western Sarasota County and small parts of Manatee and Charlotte Counties (fig. 1). Most of the watershed lies within the Southern Gulf Coastal Lowlands, whereas the headwaters originate in the Desoto Plain (fig. 7) (White, 1970). Elevations within the watershed range from 0 ft along the coast to about 135 ft (41.1 m) above the National Geodetic Vertical Datum of 1929 (NGVD 29) in south-central Manatee County. The topography consists of a series of relict marine terraces (Campbell, 1985) and is characterized by (1) broad flatlands with many sloughs and swamps in lowland areas, and (2) gradually sloping scarps and terraces created by various Pleistocene sea-level stands in coastal areas. Seasonally dry upland areas consisting of palustrine forest, scrub-shrub, or palustrine emergent wetlands are scattered throughout inland areas (Knochenmus and Bowman, 1998). Four terraces exist within the watershed, but the scarps that separate them are poorly defined. From the coastline inland, the terraces are Pamlico (8-25 ft above NGVD 29), Talbot (25-42 ft above NGVD 29), Penholoway (42-70 ft above NGVD 29), and Wicomico (70-100 ft above NGVD 29) (Healy, 1975).

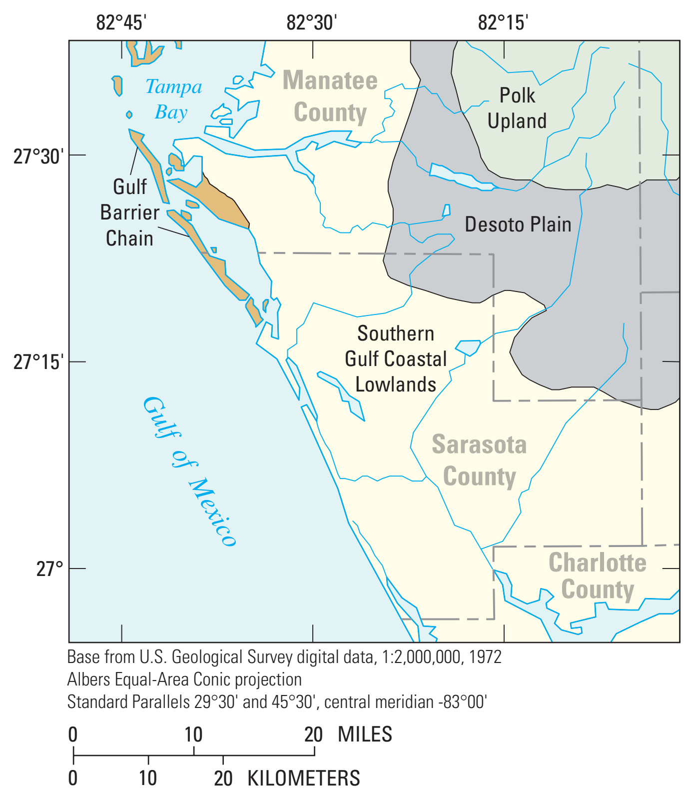


Figure 7. Geomorphological features in west-central Florida (from White, 1970).

Soils

Soils in the Sarasota Bay watershed are typically poorly to very poorly drained fine sands. The Soil Conservation Service (1991) grouped soils within the watershed into Flatwoods soils, Depressions soils, and Coastal Islands soils. Physical properties of the soil series within each soil group are listed in table 1.

Table 1. Physical characteristics of Flatwoods, Depressions, and Coastal Islands soils in the Sarasota Bay watershed.

[U.S. Department of Agriculture (1983, 1991). ft, feet; in., inches; g/cm^3, grams per cubic centimeter; >, greater than]

Soil series	Hydrologic soil group	Depth to high water table (ft)	Depth interval (in.)	Bulk density (g/cm^3)	Comments
			Flatwoods Soils		
Eau Gallie	B/D	-0.5 to -1.5			Poorly drained, sandy, siliceous, from marine sediments, acidic, spodic horizon, nearly level
			0 - 22	1.25 - 1.50	
			22 - 44	1.45 - 1.60	
			44 - 48	1.45 - 1.65	
			48 - 66	1.55 - 1.70	Clay content 13-31 percent
			66 - 80	1.45 - 1.55	
Holopaw	D	>2.0 to -1.0			Very poorly drained, loamy, siliceous, from marine sediments, acidic, spodic horizon, nearly level
			0 - 50	1.35 - 1.60	
			50 - 66	1.60 - 1.70	Clay content 13-28 percent
			66 - 80	1.50 - 1.60	
Myakka	D	-0.5 to -1.5			Very poorly drained, sandy, siliceous, from marine sediments, acidic, spodic horizon, nearly level on broad flatwoods
			0 - 24	1.25 - 1.45	
			24 42	1.45 - 1.60	
			42-80	1.48 - 1.70	
Pineda	B/D	0.0 to -1.0			Poorly drained, loamy, sandy, nearly level on low hammocks and in broad, poorly defined sloughs
			0 - 22	1.25 - 1.60	
			22 - 36	1.40 - 1.70	
			36 - 48	1.50 - 1.70	Clay content 10-25 percent
			48 - 80	1.45 - 1.60	
Pomello	C	-2.0 to -3.5			Moderately well drained, sandy, nearly level to gently sloping on low ridges and knolls on flatwoods
			0-48	1.35 - 1.65	
			48-80	1.45 - 1.60	
			Flatwoods Soils		
Delray	B/D	>2.0 to -1.0			Very poorly drained, loamy, sandy, from marine sediments, acidic, slope is less than 2 percent, found in depressions
			0 - 20	1.35 – 1.45	
			20 - 54	1.50 – 1.65	
			54 - 80	1.45 – 1.60	
Felda	D	>2.0 to -1.0			Poorly to very poorly drained, from sandy and loamy marine sediments, slope from 0 to 2 percent on low hammocks or flood plain
			0 - 22	1.40 – 1.55	
			22 - 60	1.50 – 1.60	
			60 - 80	1.45 – 1.55	
Floridana	D	0.0 to -1.0			Very poorly drained from sandy and loamy marine sediments; nearly level; found in depressions
			0 - 14	1.40 – 1.50	
			14 - 36	1.50 – 1.60	
			36 - 80	1.60 – 1.70	
Holopaw	D	>2.0 to -1.0			Very poorly drained, loamy, sandy, from marine sediments, acidic, spodic horizon, nearly level
			0 - 50	1.35 - 1.60	
			50 - 66	1.60 - 1.70	Clay content 13-28 percent
			66 - 80	1.50 - 1.60	

Table 1. (Continued) Physical characteristics of Flatwoods, Depressions, and Coastal Islands soils in the Sarasota Bay watershed.

Soil series	Hydrologic soil group	Depth to high water table (ft)	Depth interval (in.)	Bulk density (g/cm^3)	Comments
Coastal Island Soils					
Beaches	D	0.0 to -6.0	0 - 80	—	Tide and surf-washed sand and shell fragments along the Gulf of Mexico shoreline; nearly level to moderately sloping
Canaveral	C	-1.0 to -3.0	0 - 7	1.25 - 1.50	Somewhat poorly drained to moderately well-drained; formed in thick deposits of sand and fine shell fragments; nearly level to gently sloping from 0 to 5 percent on low, dune-like ridges
Kesson	D	0.0 to - 0.5			Deep, very poorly drained from marine deposits of sand and shell fragments; nearly level; flooded during normal high tides; upper layer of organic muck
			0 - 7	0.15 - 0.35	
			7 - 80	1.50 - 1.65	

Flatwoods occupy about 90 percent of the Sarasota Bay watershed. Soils of Flatwoods are nearly level, moderately to very poorly drained, and sandy to loamy. Soil series in this group include Eau Gallie, Holopaw, Myakka, Pineda, and Pomello. In the upper portion of the watershed, Flatwoods soils commonly have a spodic horizon (layer of accumulated minerals) generally 2-3 ft (0.61-0.91 m) below land surface. In some Flatwoods soils, the spodic horizon is chiefly hardpan, restricting the infiltration of water and subjecting the areas to seasonal flooding and drying.

Depressions soils are found in the north-central portion of the watershed and along sloughs. Soils in this group typically are very poorly drained and mucky, sandy, or loamy. Depressions soils have been used extensively for agriculture, principally celery. Poorly drained soils throughout the watershed enhance depressional storage of water in swamps, marshes, and ponds (Soil Conservation Service, 1991).

Coastal Islands soils are found on the barrier islands. Soils in this group are gently sloping, moderately to poorly drained, and sandy. Soil series of Coastal Islands include Beaches, Canaveral, and Kesson. Shell fragments are common and areas of very poorly drained sand are covered with a mucky layer.

Soil characteristics play an important role in the hydrologic regime of the Sarasota Bay watershed. Precipitation that occurs in the watershed may infiltrate directly into the soil and percolate to ground water, or it may flow over land toward depressional surface features such as swamps, ponds, and streams. The path taken depends upon physical and chemical characteristics of the soil, the intensity and duration of precipitation, slope, antecedent soil moisture conditions, depth to ground water, and cultural practices.

Water Use

In 2000, total water use in Sarasota County was 46.3 Mgal/d (2,028 L/s) with ground water accounting for 87.2 percent or 40.37 Mgal/d (1,769 L/s) of the total. About 69.5 percent was used for public supply, 17.3 percent for agriculture, 12.3 percent for recreational irrigation, 0.8 percent for commercial/industrial, and 0.1 percent for domestic (Marella, 2004).

The Upper Floridan aquifer is the principal source of water supply in Sarasota County, accounting for 67.5 percent of ground-water use in 2000 (R.L. Marella, U.S. Geological Survey, oral commun., 2007). About 32.4 percent of the total amount of ground-water withdrawn was from the overlying intermediate aquifer system and relatively little (0.1 percent) ground water was withdrawn from the surficial aquifer system (fig. 8) (Marella, 2004).

Ground-water use has remained relatively constant in Sarasota County since 1977 (fig. 9) but ground-water use by category has changed substantially. In 1977, ground-water withdrawals were 9.58 Mgal/d (420 L/s) for public supply and 22.65 Mgal/d (992 L/s) for agriculture. By 2000, ground-water withdrawals were 27.56 Mgal/d (1,207 L/s) for public supply and 6.88 Mgal/d (301 L/s) for agriculture (fig. 10).

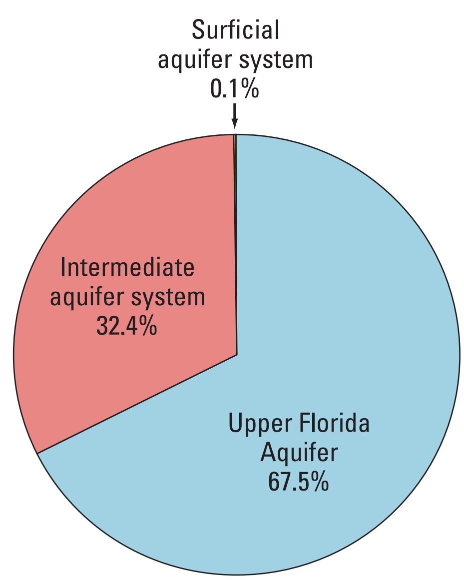


Figure 8. Ground-water use by aquifer in Sarasota County in 2000 (from Marella, 2004).

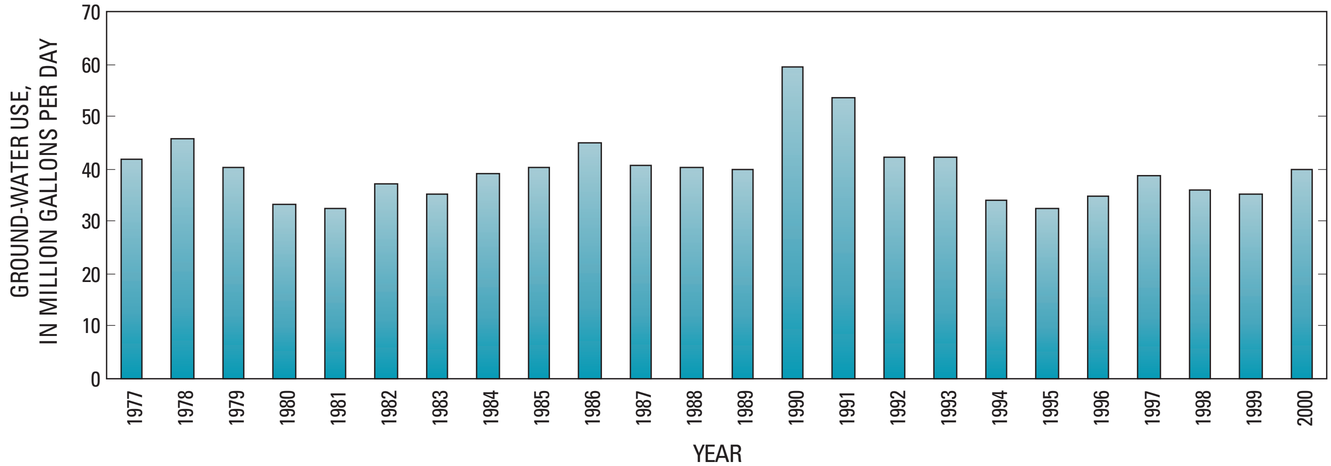


Figure 9. Annual ground-water use in Sarasota County from 1977 to 2000 (from Marella, 2004).

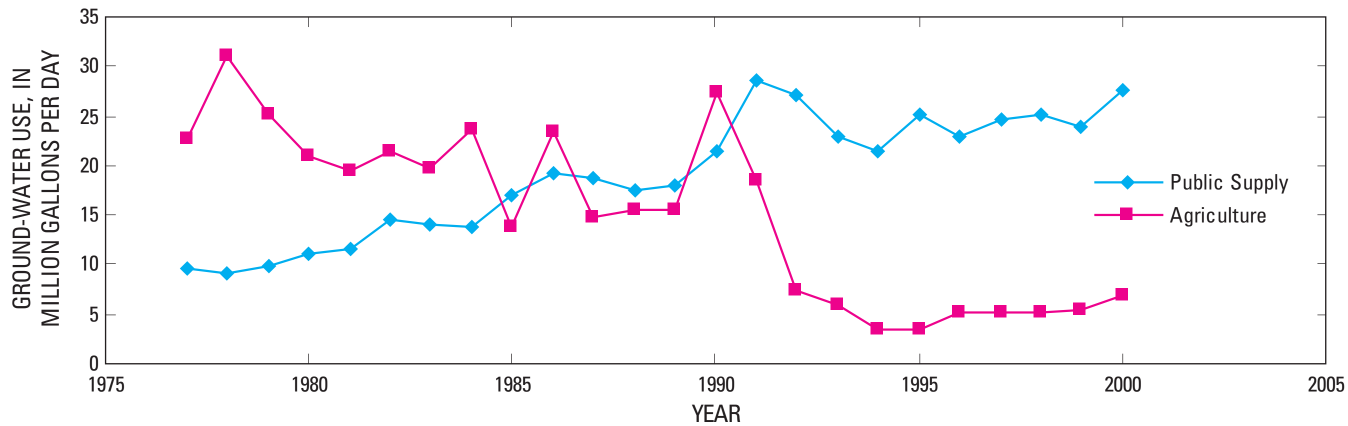


Figure 10. Ground-water use for public supply and agriculture in Sarasota County from 1977 to 2000 (from Marella, 2004).

Total withdrawals for public supply in Sarasota County are projected to increase to about 63 Mgal/d (2,760 L/s) by 2020 (Southwest Florida Water Management District, 1992). The increased demand for water in the region has resulted in a reevaluation of the surficial aquifer system for use as irrigation water or for blending with other water sources (Southwest Florida Water Management District, 1998). The surficial aquifer system is closely linked to the surface-water system (Winter and others, 1998), supplies water to depressional features and wetlands, and is vulnerable to contamination from the surface.

Hydrogeology

Ground water is an abundant but vulnerable resource in Florida. About 93 percent of Florida's population obtains drinking water from ground water (Berndt and others, 1998). In Sarasota County, more than 87 percent of the water used is obtained from ground-water sources and the demand for public supply is expected to increase by about 130 percent over the period 2000 to 2020 (Marella, 2004). Ground-water resources are vulnerable to contamination from land-surface activities and saltwater intrusion from over-pumping. Replenishment of ground-water resources depends upon the infiltration of rainfall into porous, sandy soils that eventually becomes part of the ground-water system (recharge). As urbanization continues, the landscape changes from naturally pervious soils to impervious surfaces, which results in a reduction of the volume of water reaching the ground-water system.

Beneath the shallow soils of the Sarasota Bay watershed, the ground-water system consists of a series of unconsolidated and consolidated marine sediments. The principal hydrogeologic units underlying Sarasota Bay watershed are, in ascending order, the Upper Floridan aquifer, intermediate aquifer system, and surficial aquifer system (fig. 11).

System	Series	Stratigraphic unit	General lithology	Hydrogeologic unit	
Quaternary	Holocene and Pleistocene	Unconsolidated to weakly indurated clastics and marine deposits	Fine to medium quartz and phospahtic sand, clayey sand, limestone, clay, and sand	Surficial aquifer system	
Tertiary	Pliocene	Undifferentiated deposits Tamiami Formation	Fossiliferous limestone and dolostone, clay, quartz and phospahtic sand, and sandy calcarious clay	Permeable Zone 1	Intermediate aquifer system
	Miocene	Peace River Formation	Fossiliferous limestone and dolostone, quartz and phospahtic sand, and clay	Confining unit	
		Arcadia Formation		Permeable Zone 2	
				Confining unit	
	Upper Oligocene	Tampa Member / Nocatee Member		Permeable Zone 3	
	Lower Oligocene	Suwannee Limestone	Fossiliferous limestone and dolostone, some clay and quartz sand; some traces of phosphate near top	Upper Floridan aquifer	

Figure 11. Stratigraphic, lithologic, and hydrogeologic units in west-central Florida (modified from Barr, 1996).

Upper Floridan Aquifer

In the Sarasota Bay watershed, the Upper Floridan aquifer consists of the Suwannee Limestone, which is composed of limestone and dolostone with some clay and quartz sand. The Upper Floridan aquifer provided 27.2 Mgal/d (1,192 L/s) for public supply in Sarasota County in 2000 (Marella, 2004).

Intermediate Aquifer System

The intermediate aquifer system overlies the Upper Floridan aquifer in the Sarasota Bay watershed. The intermediate aquifer system is a series of intercalated permeable zones and poorly permeable confining units consisting of sandy clay, clay, limestone, and dolostone of the Hawthorn Group (Barr, 1996). The permeable zones function regionally as a water-yielding hydraulic unit (Duerr and Wolansky, 1986); the intermediate aquifer system provided 13.1 Mgal/d (574 L/s) for public supply in Sarasota County in 2000 (Marella, 2004).

Surficial Aquifer System

In 2004, less than 1 percent of the ground-water use in Sarasota County was obtained from the surficial aquifer system (Marella, 2004). Because of the increase in the demand for water in the region, the surficial aquifer system is being reevaluated as a potential source of water for irrigation and for blending with other sources of water (Southwest Florida Water Management District, 1998). Most previous hydrogeologic investigations in southwest Florida have been focused on deeper zones used for water supply; hence, information about the hydrologic characteristics of the surficial aquifer system is limited. This section summarizes the available information about the hydrologic characteristics of the surficial aquifer system.

The surficial aquifer system overlies the intermediate aquifer system in the Sarasota Bay watershed and consists of undifferentiated surficial deposits that are predominantly fine- to medium-grained sand with some shell fragments, clay, and limestone. The surficial aquifer system is generally unconfined; lenses of sand, clayey sand, and limestone may contain water under confined conditions in some areas. The surficial aquifer system provided 0.04 Mgal/d (1.8 L/s) for public supply in Sarasota County in 2000 (Marella, 2004).

The average depth to the water table in the surficial aquifer system is generally less than 5 ft (1.5 m) in the Sarasota Bay watershed. In the higher elevations of the watershed, the water table may be greater than 5 ft below land surface; in areas of low topographic relief and near the coast, the water table can occur at land surface. Fluctuations of the water table are generally seasonal and vary within about a 5-ft (1.5 m) range. The seasonal low water table usually occurs during May or June, at the end of the dry season. The seasonal high water table usually occurs during the wet summer months. For the poorly drained Flatwoods soil group in the Sarasota Bay watershed, the depth to the high water table may be as little as 0.5 ft (0.15 m) below land surface or, in the case of the Holopaw soil series, the high water table may be above land surface.

Major sources of recharge to the surficial aquifer system in the watershed are (1) rainfall, (2) upward leakage where the elevation of the potentiometric surface of the intermediate aquifer system is higher than the water table, (3) infiltration of irrigation water, and (4) ground-water inflow from adjacent areas. Major types of discharge from the surficial aquifer system are (1) evapotranspiration, (2) seepage into streams, lakes, swamps, and canals, (3) pumping from wells, and (4) downward leakage where the elevation of the water table is higher than the potentiometric surface of the underlying aquifers (Duerr and Wolansky, 1986).

The hydraulic properties of the surficial aquifer system vary widely because of the heterogeneous nature of the aquifer material (such as grain size, sorting, and compaction) and the thickness of the unit. The SWFWMD (1988b) compiled hydraulic properties from aquifer tests of wells that penetrate sections of the surficial aquifer system. Transmissivities determined from these tests varied from 267-6,000 ft^2/d (25-557 m^2/d) and storage coefficients varied from 0.05 to 0.19 (table 2). The surficial aquifer system supplies limited water to wells in the Venice area and the yield of these wells generally is less than 50 gal/min (189 L/min) (Duerr and Wolansky, 1986).

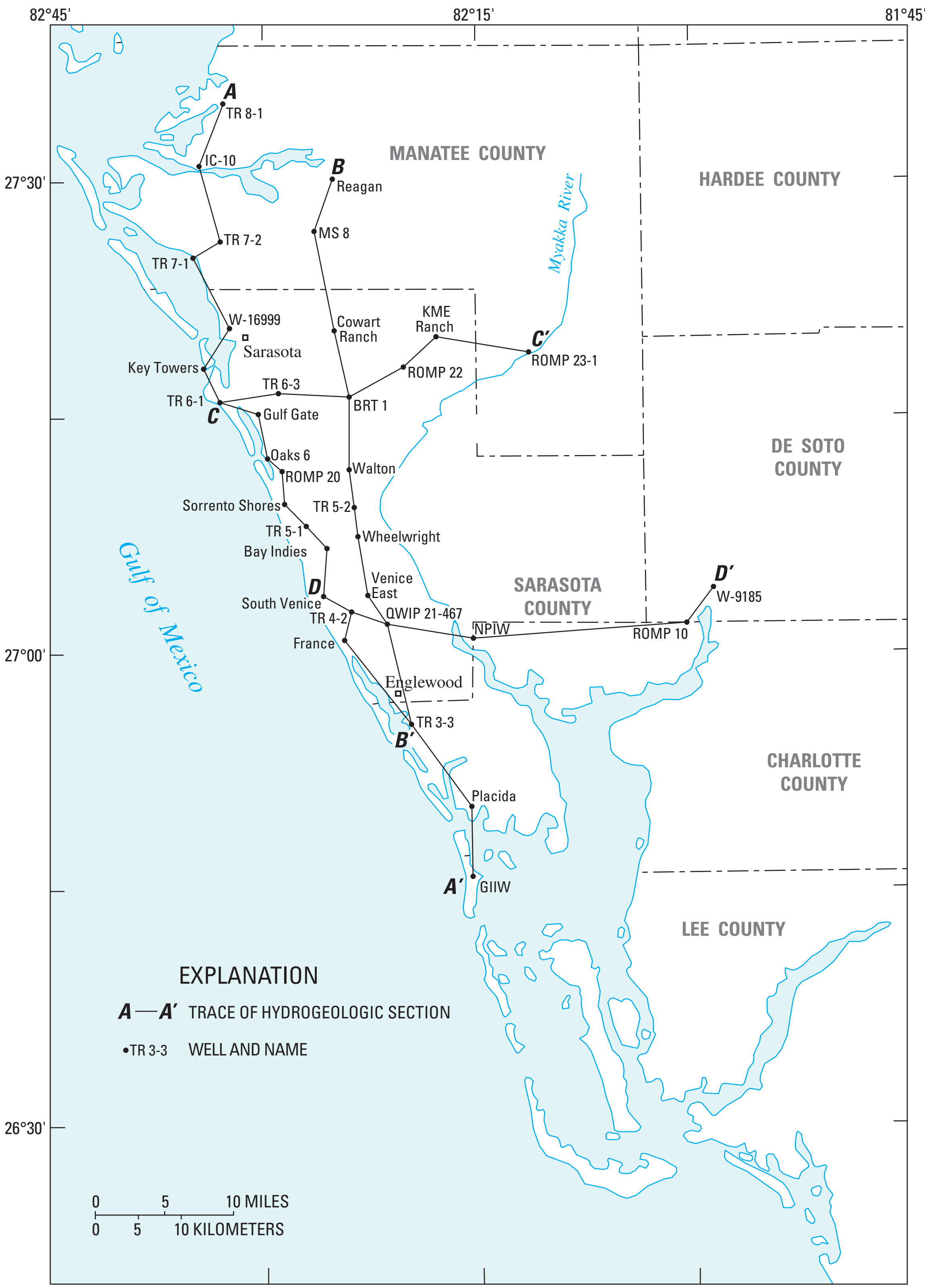
Table 2. Hydraulic properties of the surficial aquifer system in the vicinity of the Sarasota Bay watershed.

[From Southwest Florida Water Management District (1988). ft^2/d, feet squared per day; --, no data]

Transmissivity (ft^2/d)	Storage coefficient	Location
267	0.1	Southern Manatee County
600	0.05	Northeast Sarasota County
1,110	0.15	Central Sarasota County
1,805	0.19	Central Sarasota County
1,000	--	West-central Sarasota County
3,800	--	Southwestern Sarasota County
6,000	--	Southwestern Sarasota County

The locations of geologic sections used to characterize the thickness and extent of the surficial aquifer system in the vicinity of the Sarasota Bay watershed are shown in figure 12 (Barr, 1996). Within the Sarasota Bay watershed, the elevation of the top of the surficial aquifer system varies from less than 10 ft (3 m) above NGVD 29 near the coast to about 40 ft (12 m) above NGVD 29 in the extreme northeastern part of the watershed. The surficial aquifer system is thin and contiguous along the coast from Manatee County to Charlotte County (fig. 13). About 5-10 mi (8-16 km) inland from the coastline, the surficial aquifer system is thin from Manatee County through a portion of Sarasota County, but thickens near Venice and southward toward Engelwood (fig. 14) and eastward from Venice toward the Charlotte County boundary (fig. 15). In the northern portion of the watershed, the thickness of the surficial aquifer system increases slightly near the coastline (fig. 16). The saturated thickness of the surficial aquifer system varies from less than 10 ft (3 m) in the northern coastal area of the Sarasota Bay watershed to about 60 ft (18 m) in the southern area of the watershed, and is generally less than 20 ft (6 m) over most of the watershed (fig. 17) (Barr, 1996).

The direction of ground-water flow in the surficial aquifer system is from areas of higher elevation to areas of lower elevation (fig. 18); however, this pattern is interrupted locally where the aquifer discharges to streams, lakes, or low swampy areas. The interaction between ground water and surface water in coastal areas depends upon ground-water discharge from regional ground-water systems, local ground-water systems associated with scarps and terraces, evapotranspiration, runoff, and coastal flooding (Winter and others, 1998). Recharge to ground water occurs along a north-south orientation at the center of the peninsula, where the surficial aquifer system is thick and permeable, and the confining clays are thin (Purdum, 2002). As ground water travels from the middle of the peninsula to the coastline, overlying clays and low-permeability sediments confine the ground water (Purdum, 2002). Areas of regional recharge to ground water and discharge to surface water in the Sarasota Bay watershed are shown in figure 19. In coastal areas, the Upper Floridan aquifer is under sufficient artesian pressure to cause ground water to flow from wells or springs. Generalized patterns of vertical ground-water flow in the Sarasota Bay watershed are upward toward the surficial aquifer system (Knochenmus and Bowman, 1998). Greater hydrostatic pressure in the Upper Floridan aquifer creates the potential for ground water to move upward into the surficial aquifer system as shown for the well cluster TR 5-2 (fig. 20), which is near the middle of the line of cross section B–B' between the Walton and Wheelright wells (see fig. 12 for location of well). All ground-water levels at this well cluster show a seasonal fluctuation. In 1994 after the rainy season (October), the surficial aquifer system reached a high that was about 4.5 ft (1.4 m) above the low occurring near the end of the dry season (May and June).



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
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Figure 12. Locations of geologic sections in the study area (modified from Barr, 1996).

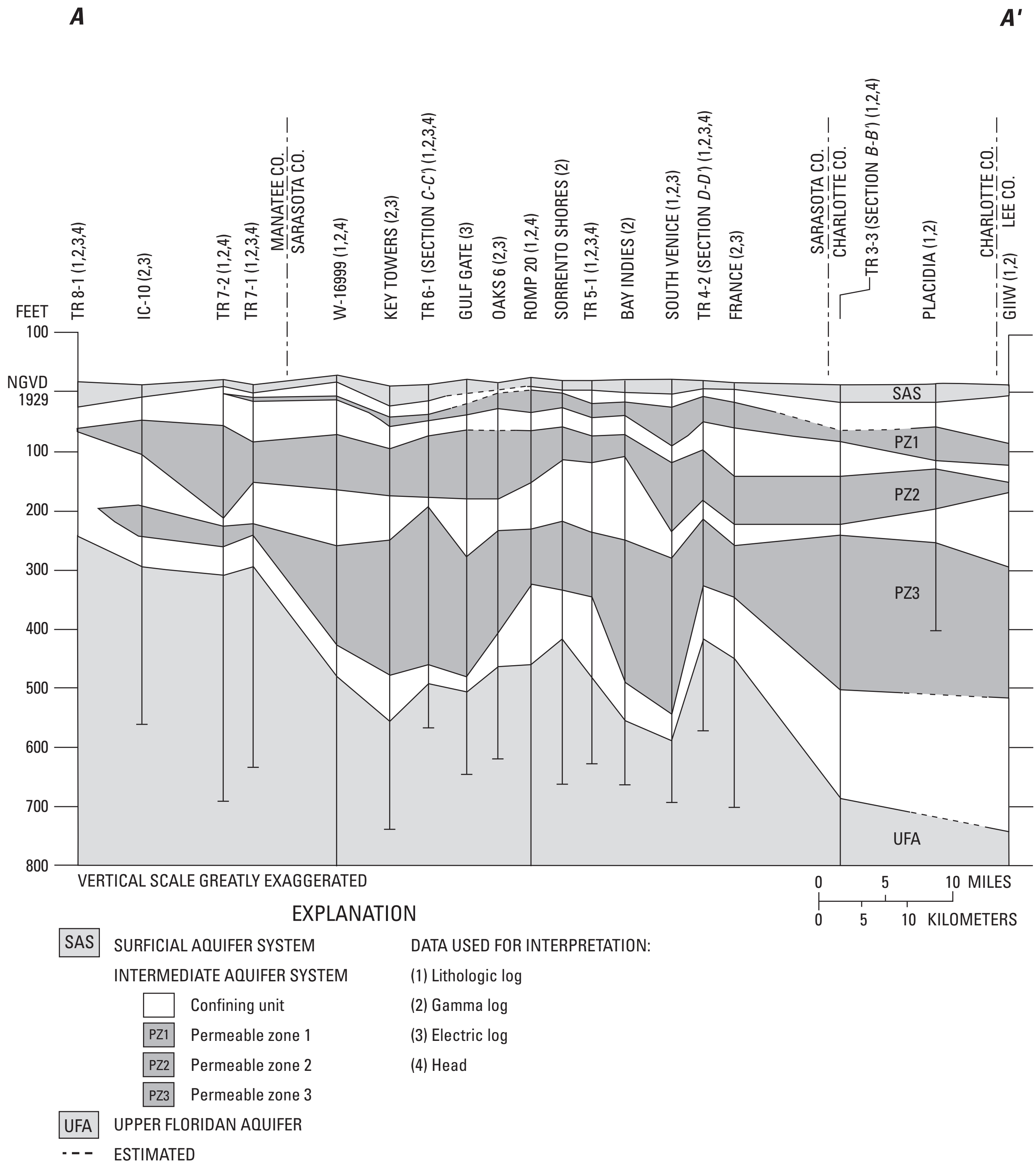


Figure 13. Geologic section *A–A′* (modified from Barr, 1996).

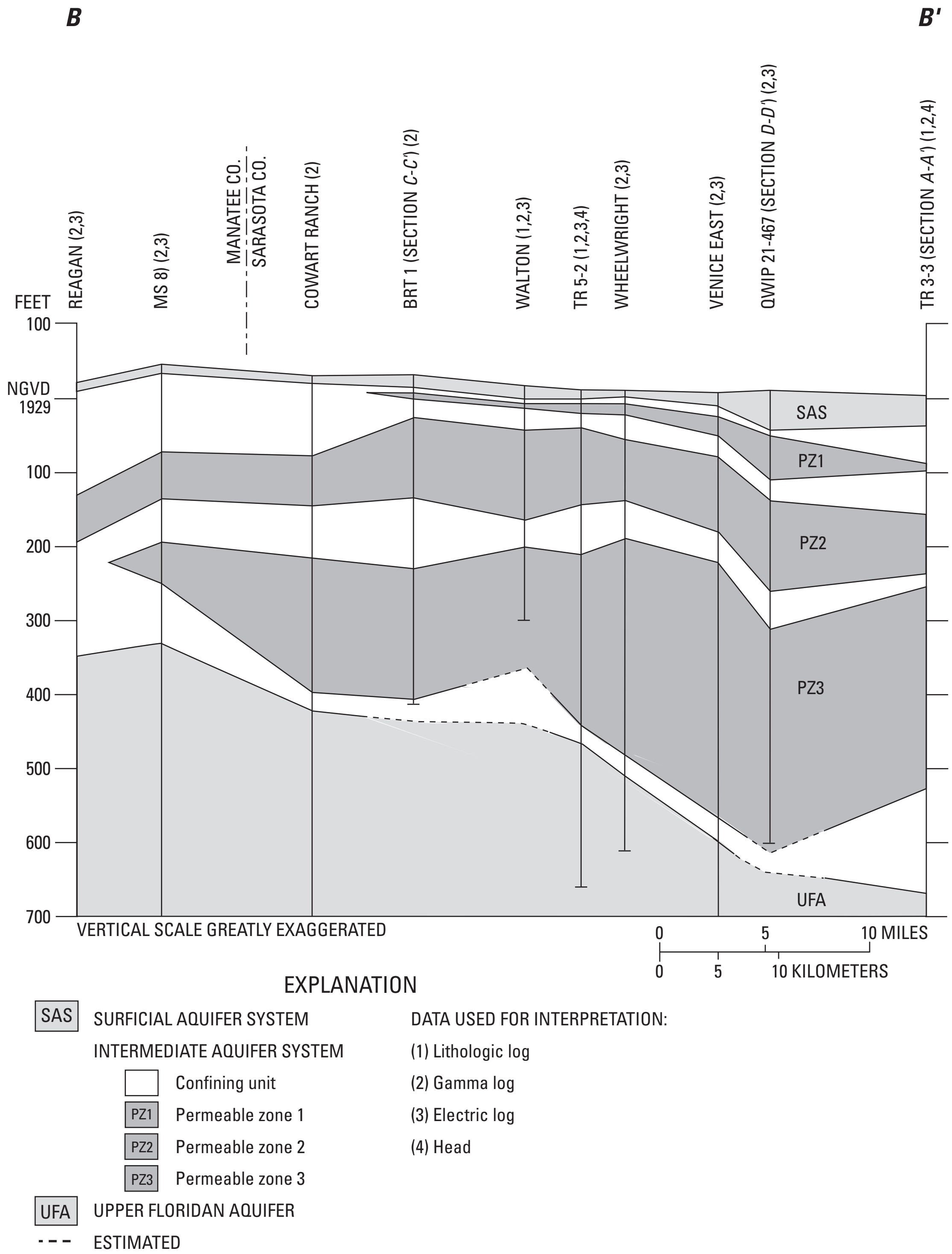


Figure 14. Geologic section *B–B′* (modified from Barr, 1996).

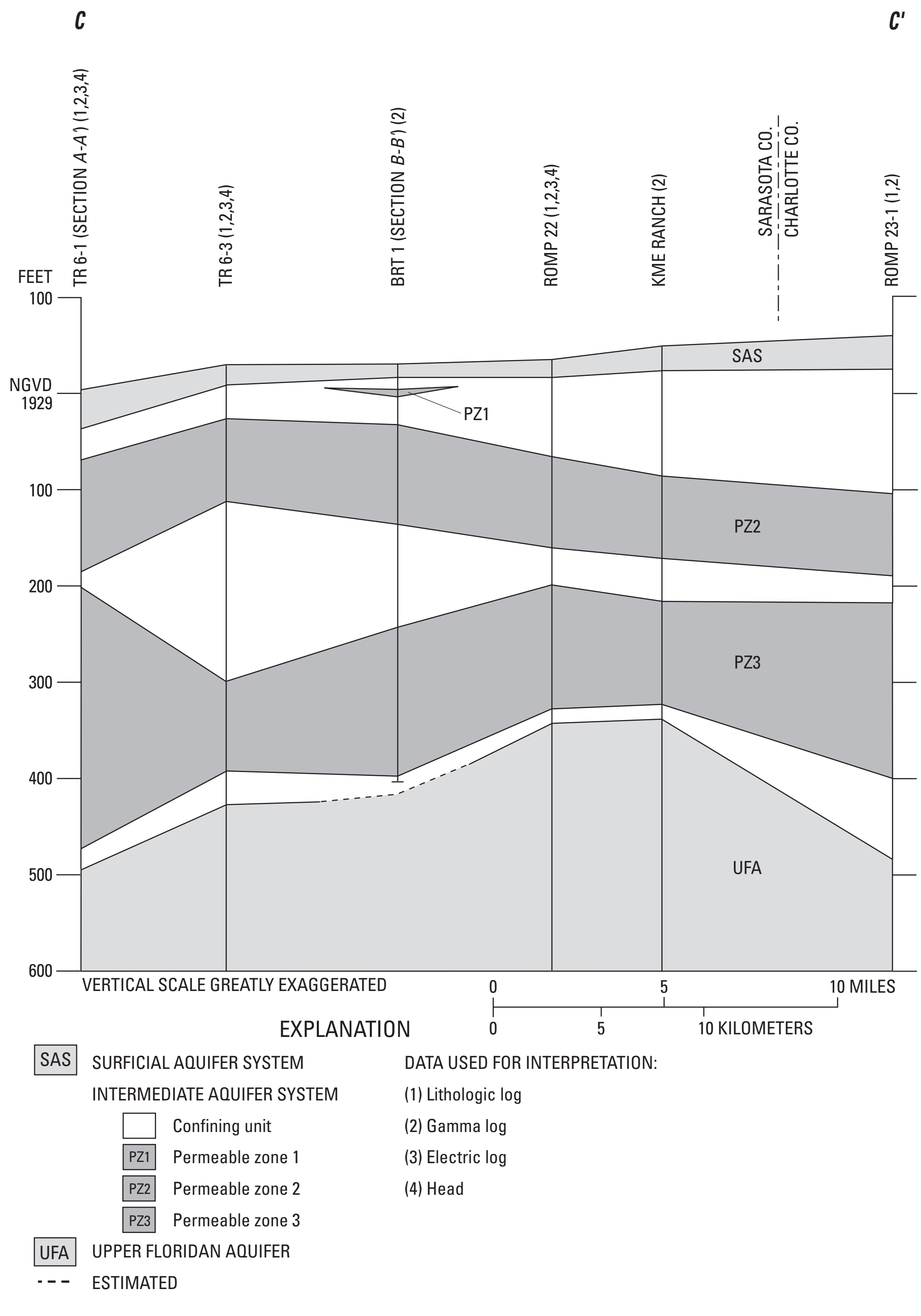


Figure 15. Geologic section *C–C′* (modified from Barr, 1996).

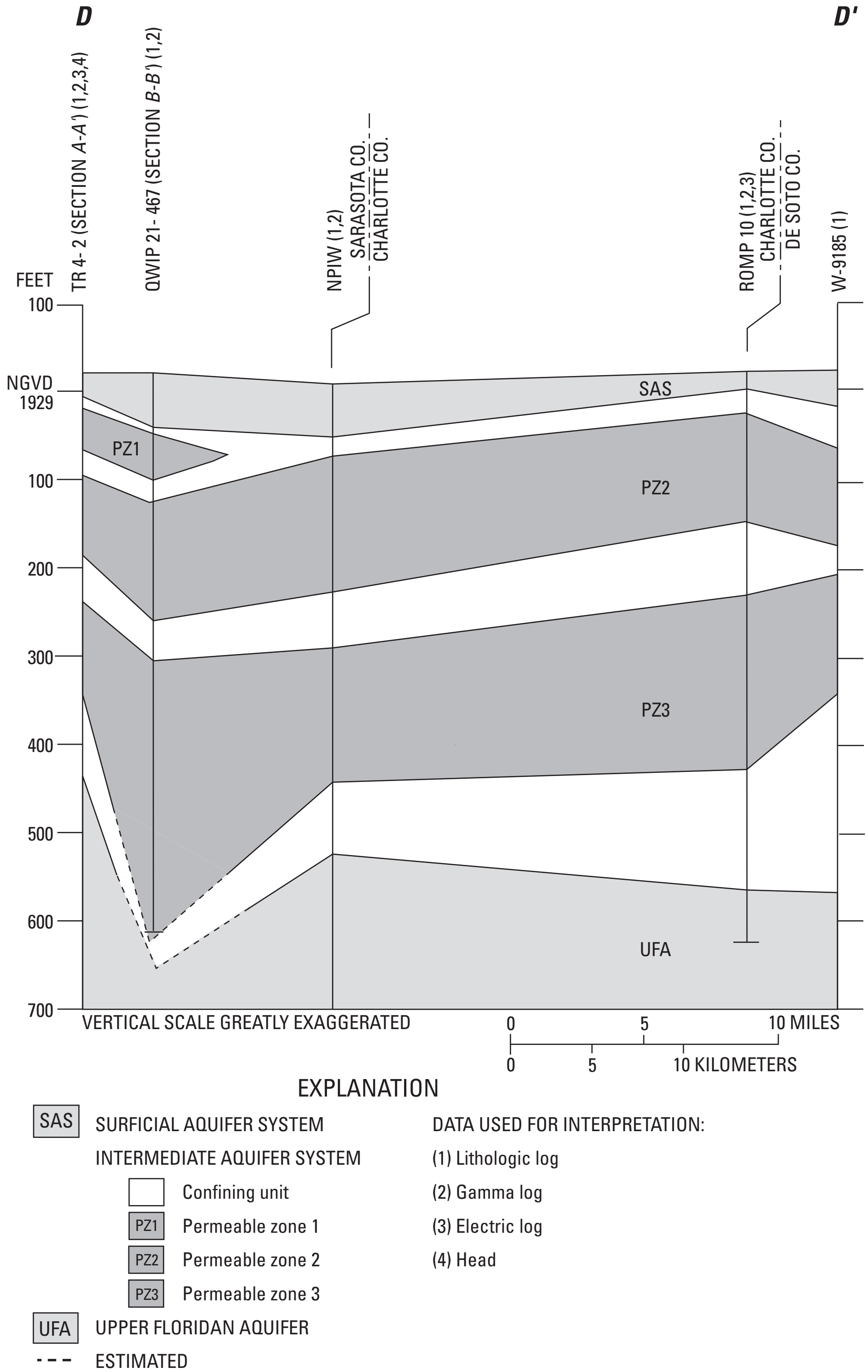


Figure 16. Geologic section *D–D′* (modified from Barr, 1996).

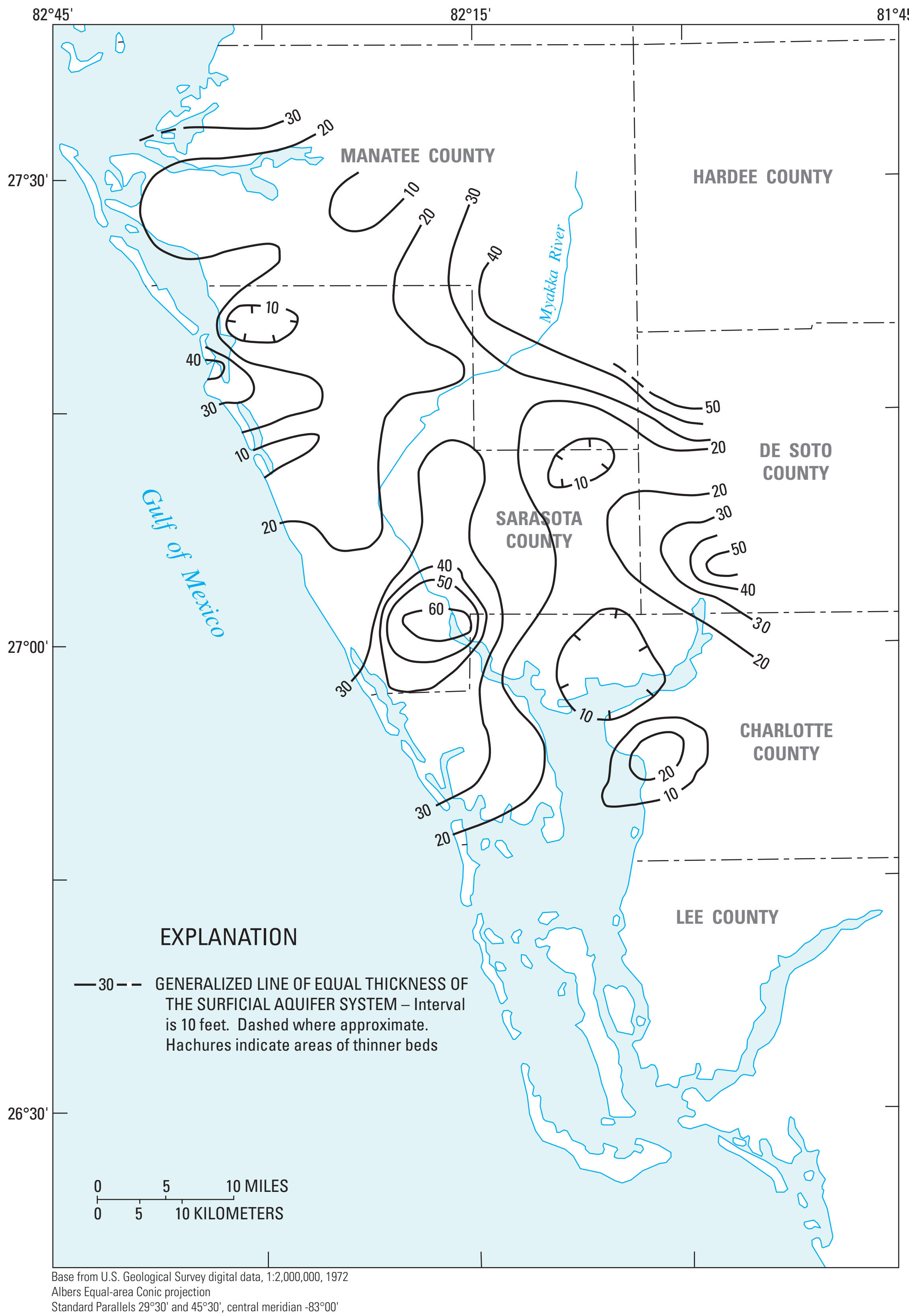


Figure 17. Generalized thickness of the surficial aquifer system in the study area (modified from Barr, 1996).

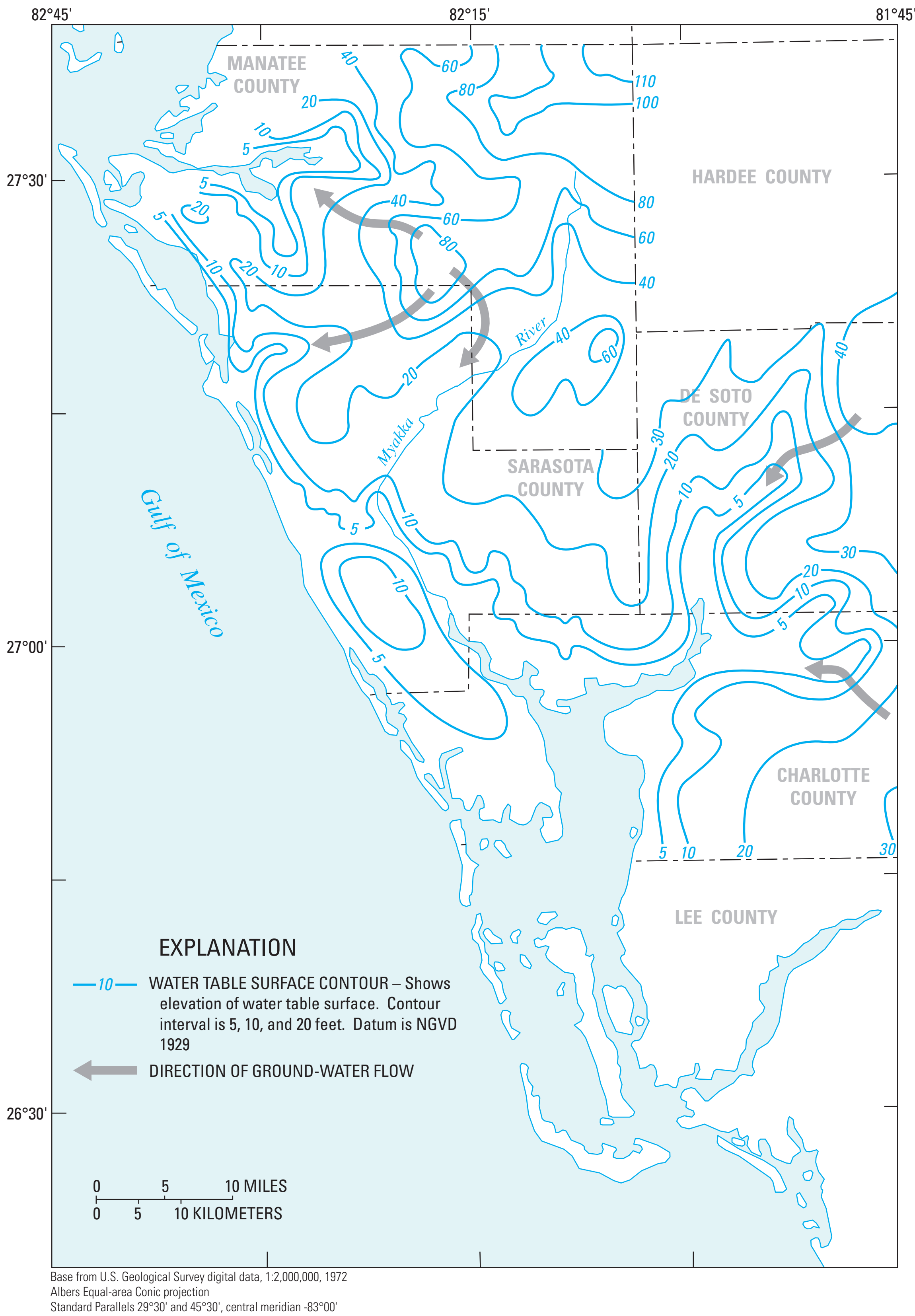


Figure 18. Generalized direction of flow in the surficial aquifer system in west-central Florida (modified from Berndt and others, 1998 and published with permission).

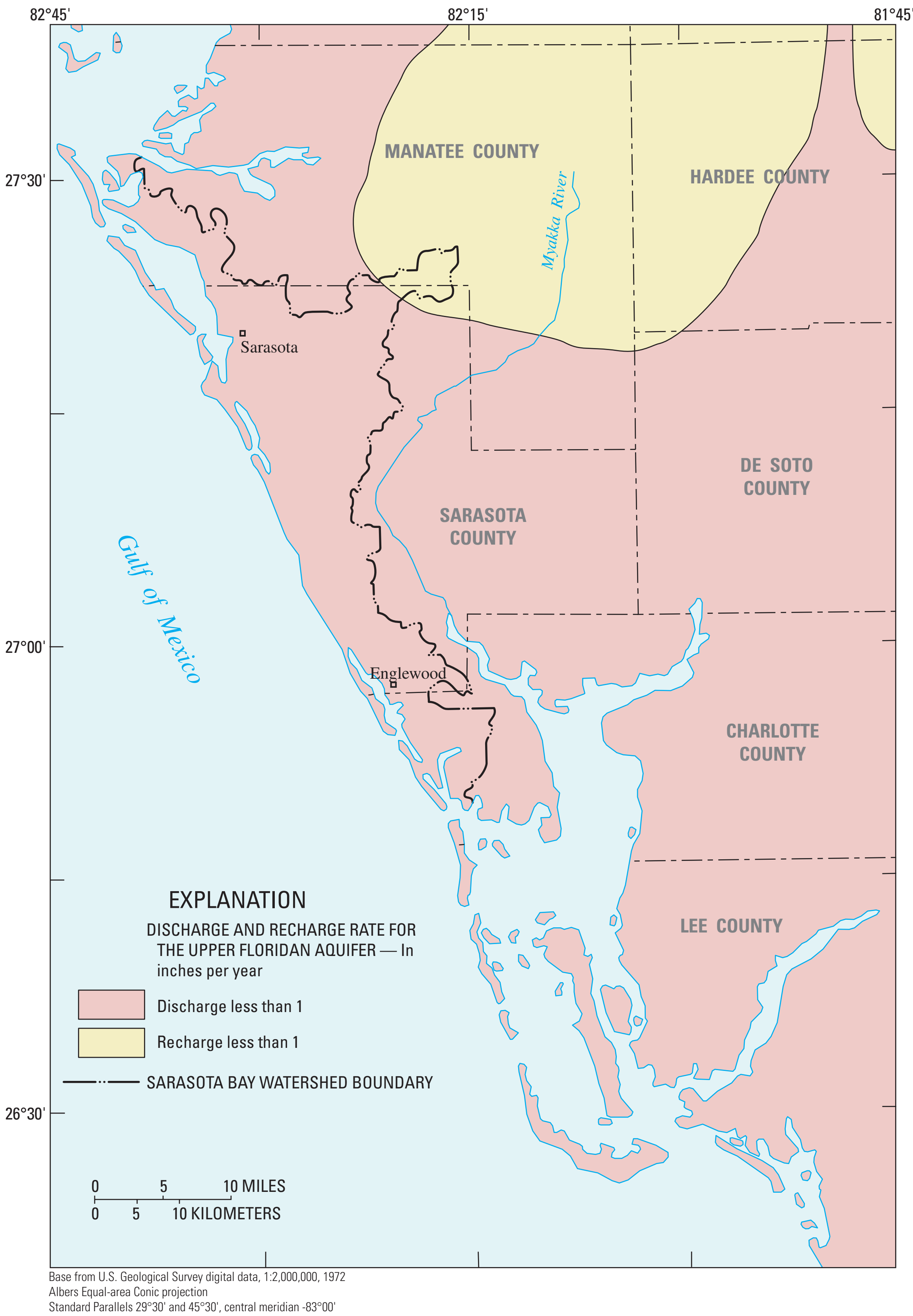


Figure 19. Generalized recharge/discharge areas of the Upper Floridan aquifer in west-central Florida (data from the Southwest Florida Water Management District, 2005).

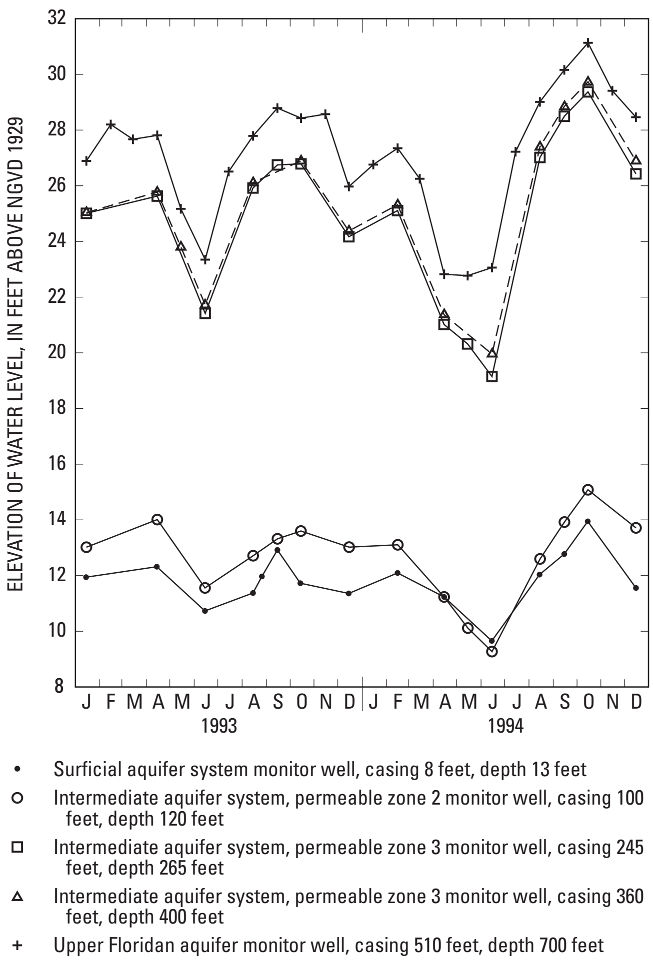


Figure 20. Elevation of water levels in the surficial, intermediate, and Upper Floridan aquifer systems in well cluster TR 5-2 near Walton for 1993-94, west-central Florida (modified from Barr, 1996; see fig. 12 for location of well).

Ground-water withdrawals have lowered potentiometric heads in the Upper Floridan aquifer from 30-50 ft (9-15 m) below predevelopment levels in the upper reaches of the Sarasota Bay watershed (Broska and Knochenmus, 1996). The decline in potentiometric heads increases the potential for recharge from the surficial and intermediate aquifer systems to the Upper Floridan aquifer. Ground-water withdrawals from major pumping centers in coastal areas of the southwestern part of the watershed have caused lateral saltwater intrusion and upconing into both the surficial and intermediate aquifer systems (Barr, 1996). Regional ground-water movement, ground-water withdrawals, and proximity to the coast have produced high chloride concentrations in the Upper Floridan aquifer (Barlow, 2003). The chloride concentrations in the surficial aquifer system exceed 5,000 mg/L near Venice, and exceed 1,000 mg/L near Englewood (fig. 21). A steady increase in saltwater intrusion has been associated with increased ground-water withdrawals, especially in the vicinity of operating well fields (Southwest Florida Water Management District, 1998).

Maintaining the surficial aquifer system at or near predevelopment water levels by increasing recharge from the surface can minimize saltwater intrusion and stabilize the ground-water supply. Recharge to the ground-water system also reduces pollutant loading to surface water by reducing the volume of runoff available to transport contaminants to surface-water bodies. Surface water that infiltrates through soils and becomes part of the ground-water system receives natural filtration.

One of the current challenges to the Sarasota Bay area and other coastal communities is to maintain a balance between (1) removing surface-water runoff rapidly to prevent flooding during heavy rainfall events in shallow water-table environments, (2) maintaining the ground-water supply as demand continues to increase, and (3) reducing pollutant loads to surface waters to maintain the health of Sarasota Bay.

Watershed Characteristics Influencing Recharge and Discharge

Recharge to ground water and overland runoff to surface water in the Sarasota Bay watershed are affected by soil characteristics (porosity, bulk density, penetration resistance, and infiltration rate), the water budget, urbanization and land use, land practices (construction, agriculture, and recreation), and infiltration and runoff.

Soil Characteristics

The water-holding potential and compaction of soils can be inferred or estimated by physical measurements of porosity, bulk density, penetration resistance, and infiltration rate.

Porosity, Bulk Density, and Penetration Resistance

Because soil consists of both solid particles and air spaces (voids), the volume of the voids determines the maximum space available for storing water. Porosity increases as the volume of the voids increases with respect to the total volume of solids. Porosity is the ratio of the volume of the voids to the total volume of soil expressed as a percent:

$$\text{Porosity } (n) = \left[\left(V(\text{total}) - V(\text{solids})\right) / V(\text{total})\right] \times 100, \quad (1)$$

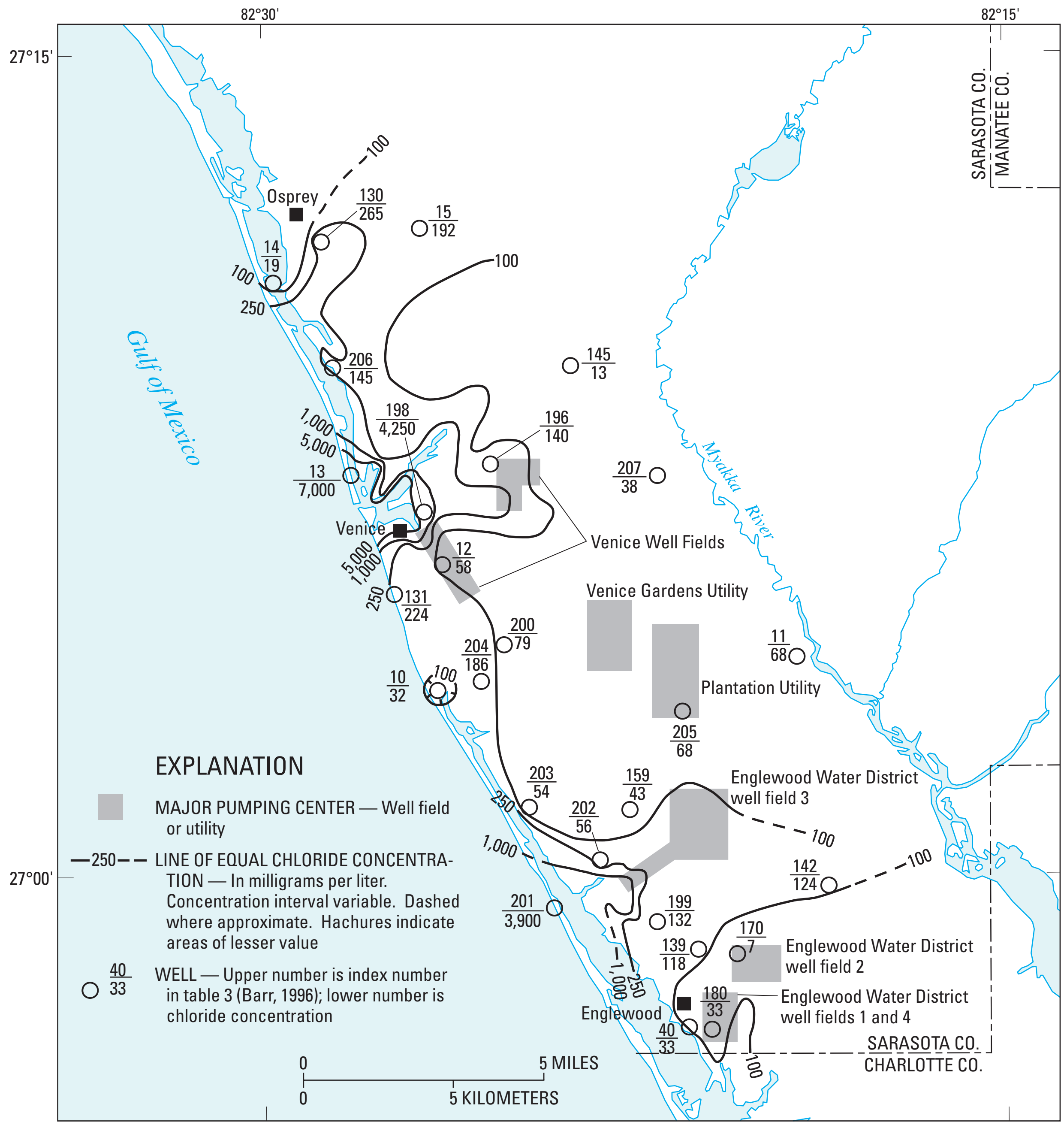
where

V(total)	is the total volume of soil,
V(solids)	is the volume of the solids, and
V(total) – V(solids)	is the volume of the voids.

Bulk density provides an estimate of soil density and is the weight of a known volume of oven-dried soil divided by the volume of the soil expressed as grams per cubic centimeter (Brady, 1990):

$$\text{Bulk density } (D_b) = \text{dry weight of soil} / \text{volume of soil}. \qquad (2)$$

Porosity and bulk density are closely related soil characteristics; as the volume of pore spaces increases, bulk density decreases (table 3). Bulk density measurements for peat typically range from 0.2-0.3 g/cm^3 (12.5-18.7 lb/ft^3), whereas the porosity of peat is about 92 percent (Schueler, 2000a). Glacial till, compressed beneath ice sheets during



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-area Conic projection
Standard Parallels 29°30' and 45°30', central meridian -83°00'

Figure 21. Generalized isopleths of chloride concentration in the surficial aquifer system (modified from Barr, 1996).

Table 3. Selected physical and hydrologic properties for selected earth materials.

[From Heath (1983) and Dragun (1988). ppv, percent per volume; g/cm^3, grams per cubic centimeter; in/hr, inch per hour; –, no data; <, less than; >, greater than]

Earth material	Porosity (ppv)	Specific yield (ppv)	Specific retention (ppv)	Bulk density (g/cm^3)	Infiltration rate (in/hr)
Peat	92	–	–	0.2 – 0.3	–
Average soil	55	40	15	–	–
Clay	50	2	48	1.0 – 1.2	<0.1 – 0.2
Sand	25	22	3	1.1 – 1.3	0.5 – >2.0
Gravel	20	19	1	–	–
Limestone	20	18	2	–	–
Sandstone	11	6	5	–	–
Basalt	11	8	3	–	–
Glacial till	10	–	–	1.6 – 2.0	–
Granite	0.1	0.09	0.01	–	–

the last Ice Age, exhibits a bulk density range of 1.6-2.0 g/cm^3 (99.9-124.9 lb/ft^3) and porosity range of 10 to 20 percent (Fetter, 1994). Bulk densities of Flatwoods soils in the Sarasota Bay watershed vary from 1.25-1.70 g/cm^3 (78.0-106.1 lb/ft^3) (Soil Conservation Service, 1991). Under natural conditions, bulk density generally increases with depth, a consequence of compression by the overlying soil and the scarcity of organic matter and biological activity (Schueler, 2000a). Measurements of bulk density can be used to estimate porosity and the effect of porosity on the water-holding capacity, infiltration, and root penetration of the soil (Schueler, 2000a).

Penetration resistance is a measure of the external force required to drive a probe a specific distance into the soil. Penetration resistance is a rapid field-based measurement frequently used as a surrogate for bulk density to measure compaction in altered soils.

Infiltration Rate

Infiltration rate is the rate at which water enters the soil and is related to porosity and bulk density. A double-ring infiltrometer is used typically to measure infiltration rate in units of inches per hour or millimeters per hour (Pitt and others, 1999). Infiltration rate is highest for sand at greater than 2.0 in/hr (5.1 cm/hr) and lowest for clay at less than 0.1-0.2 in/hr (0.25-0.51 cm/hr) (table 3). The infiltration rate is also related to bulk density for a particular soil. Smith and others (2001) observed that infiltration is greater than 14 in/hr (36 cm/hr) when the bulk density is less than 1.5 g/cm^3 (93.6 lb/ft^3), but as bulk density reaches 1.65 g/cm^3 (103.0 lb/ft^3), infiltration drops to less than 2 in/hr (5.1 cm/hr). As bulk density increases beyond 1.65 g/cm^3 (103.0 lb/ft^3), infiltration approaches zero. Infiltration is negligible on impervious surfaces (for example, sidewalks and parking lots) or when the rainfall exceeds the capacity of a pervious medium to hold or transmit water. In soils with frequent wetting and drying cycles, infiltration may be inhibited by a crust on the soil surface formed by the breakdown of soil structure by flowing water or raindrops (Natural Resource Conservation Service, 1996a).

In dry soils, infiltration begins rapidly but approaches a uniform, low rate as the soil becomes saturated. This relation was first described by Horton in the 1930s and is referred to as Horton infiltration (Freeze and Cherry, 1979). The initial precipitation rate is equal to the infiltration rate; as rainfall continues, infiltration decreases but reaches a constant rate. The water table is assumed to be deep and does not play a role in the infiltration rate. Runoff occurs when the precipitation rate exceeds the infiltration rate.

In humid, high water-table environments, the capacity of a pervious medium to hold or transmit water is affected by the proximity of ground water to land surface. Dunne infiltration (also described as saturation excess runoff) is most often ascribed to conditions in Florida, primarily during the rainy season. In Dunne infiltration, a dynamic water level is assumed; as rainfall continues, available pore spaces are filled. When all pore spaces are filled, no additional infiltration can occur. The precipitation becomes runoff because the surface is virtually impervious and no additional infiltration can occur (fig. 22).

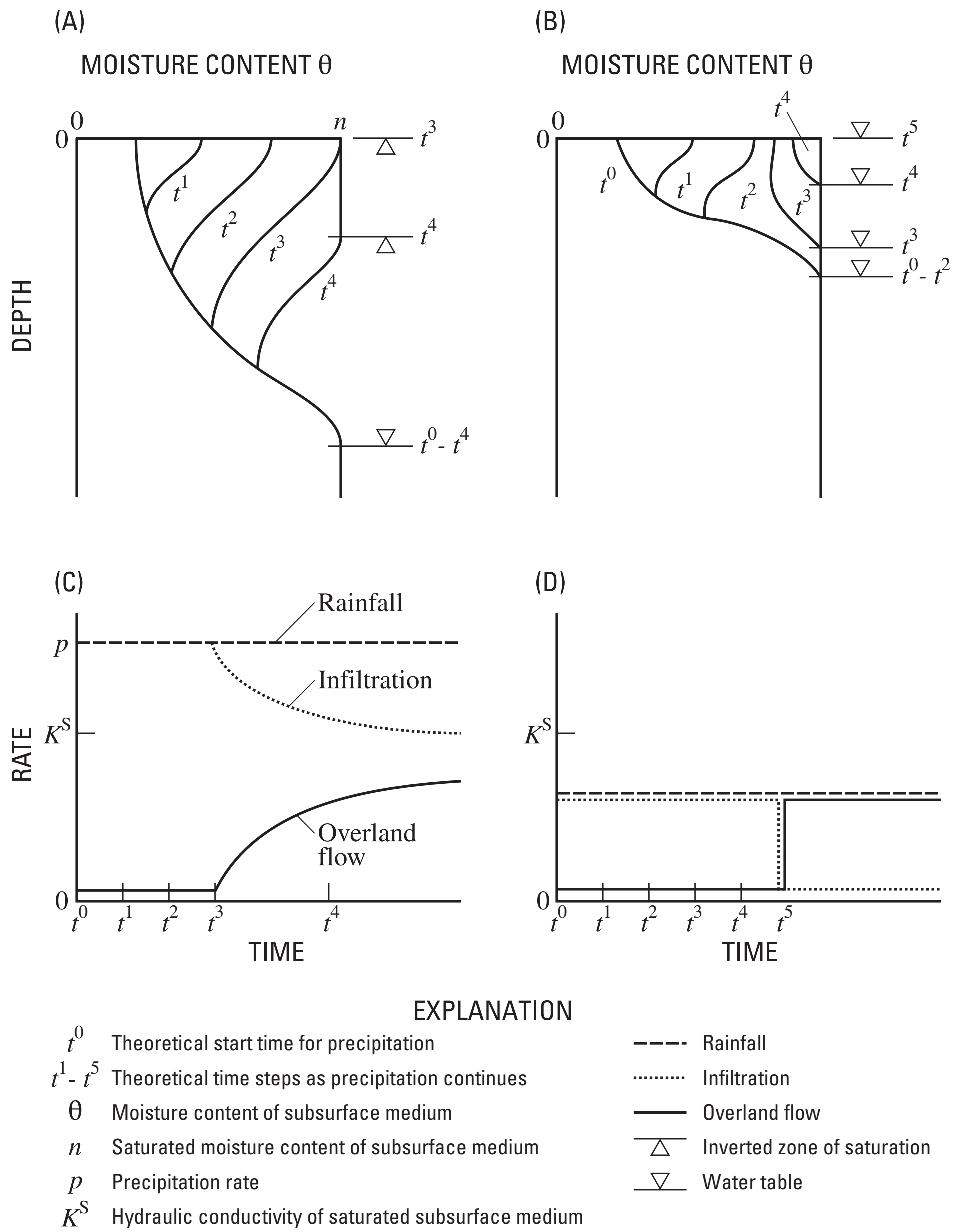


Figure 22. Relation between moisture content and soil depth: (A) Horton infiltration, (B) Dunne infiltration, (C) Horton runoff, and (D) Dunne runoff (reprinted from Freeze, 1980 and published with permission).

In Florida, Horton infiltration is likely to predominate in upland areas of Scrub and Sandhill ecosystems, typically along the ridge area of central Florida, whereas Dunne infiltration is predominant in high water-table areas, especially in discharge areas along or near the coastline of Sarasota Bay. Figure 22 shows the differences between Horton and Dunne infiltration, and table 4 describes the conditions under which Horton or Dunne infiltration predominates. In west-central Florida where the water table is at or near land surface, Dunne infiltration and saturation excess runoff may occur early during a rainfall event. Over the course of wet and dry seasons, both Horton and Dunne infiltration may occur.

Water Budget

Henry (1998) estimated a simple climatic water budget for Tampa that is used here to represent conditions in the Sarasota Bay watershed. The water budget considers only precipitation, potential evapotranspiration, actual evapotranspiration, and soil storage. Potential evapotranspiration is defined as the amount of water that would be lost from the soil if there was always sufficient water available for plants to transpire at their maximum rates. Actual evapotranspiration is the amount of water that would be lost based on the availability of soil moisture. Henry (1998) defines a soil-water

Table 4. Characteristics of Horton and Dunne mechanisms for infiltration and runoff.

[From Knighton (1998)]

Characteristic	Horton overland flow	Dunne overland flow
Rainfall	High rates, short duration	Light to moderate rate, long duration
Infiltration	Surface infiltration capacity	Transmissibility in lower soil horizons
Temporal distribution	Begins when rainfall intensity exceeds infiltration rate	Begins only when underlying soil layers are saturated
Spatial distribution	Semi-arid, poorly drained areas	Humid, high water-table areas

deficit as the difference between potential evapotranspiration and actual evapotranspiration. When precipitation exceeds actual evapotranspiration, soil storage increases (recharge); when precipitation is less than actual evapotranspiration, water stored in soil is reduced because of evaporation from soil and transpiration by plants. From September until mid-May, precipitation is generally less than evapotranspiration and water needs of plants are satisfied by utilizing soil moisture (fig. 23). By mid-January, much of the available soil moisture is gone and the system runs at a deficit until the summer rains begin. From about mid-May until September, precipitation contributes the bulk of the recharge to the system.

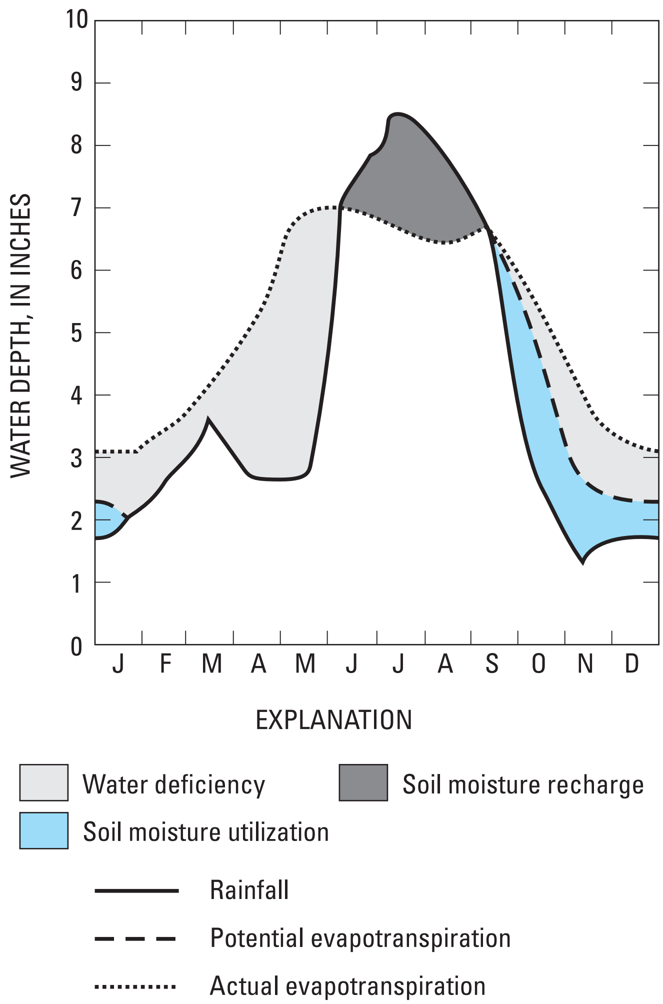


Figure 23. Average monthly water budget for west-central Florida (modified from Henry, 1998 and published with permission).

Urbanization and Land Use

Coastal areas of the Sarasota Bay watershed are characterized by high-density residential, recreational, and commercial development, whereas inland areas are characterized by agricultural land use (Knochenmus and Bowman, 1998). Population growth has affected the landscape by causing loss of habitat and natural vegetative cover, while simultaneously increasing the spatial extent of impervious surfaces (Sarasota Bay National Estuary Program, 2000). The increase in impervious cover alters the hydrology of the watershed and necessitates infrastructure changes to handle the increased runoff. Land practices that may affect hydrologic processes in the watershed include agriculture, construction, and recreation.

Land Practices

Most land practices tend to compact soil and reduce water movement through soils, either by design or as a consequence of using the land. Agricultural and construction practices affect the infiltration of rainfall to the ground water on a large scale. Recreational areas, often thought to provide pockets of increased infiltration in urbanized areas, may provide limited infiltration capacity during rainfall events. The concept of compaction and its effect on infiltration is well documented in the agricultural literature and provides the basis for understanding the effects of construction and recreational activities on soil structure and infiltration. These concepts applied to the Sarasota Bay watershed provide a useful framework for understanding runoff processes and their effects on recharge to and discharge from the surficial aquifer system.

Agriculture

Compaction is a common problem in agricultural soils. Compaction may damage the soil structure and (1) restrict rooting depth and growth, (2) decrease infiltration of water and nutrients reaching the plant roots, and (3) increase runoff and erosion (Peet, 1995; Natural Resource Conservation Service, 1996a; DeJong-Hughes and others, 2001). Major causes of compaction in agricultural soils are raindrop impact, tillage, and wheel traffic. Raindrop impact causes a crust to form at the soil surface. The crust is commonly less than 0.5 in. (1.27 cm) thick and can prevent the healthy propagation of seedlings (Natural Resource Conservation Service, 1996b). Surface hoeing is generally used to break up the crust (DeJong-Hughes and others, 2001). Tillage is the mechanical moving, turning, or stirring of the soil. Historically, tilling has been used to incorporate fertilizers, crop residues and pesticides, increase infiltration, control weeds, and reduce erosion (Harpstead and others, 1997). The use of certain types of conventional tillage over a number of years causes subsurface compaction, creating tillage pans or plow pans. This condition can be intensified when plowing occurs during wet conditions (McBride and others, 1997).

Hangen and others (2002) investigated infiltration patterns in silty loam that was subjected to conventional tillage (plowing and harrowing) and conservation tillage (minimal plowing and use of mulches). Tracers used during infiltration experiments showed much deeper water infiltration in the conservation tillage area. The study also quantified earthworm activity and macropores from crop stems and root channels. They concluded that deep percolation of water in the silty loam under conservation tillage was the result of an extensive macropore network that is often missing in conventionally tilled fields. Carmen (2002) investigated the effect of vertical load exerted by tires and vehicle speed on the compaction of loamy clay. At maximum tire load, bulk densities increased 40 percent above background values. Vertical load was the most significant contributor to increased soil compaction. A secondary factor was velocity of the vehicle. As speed increased, compaction was reduced because of decreased contact duration between the tires and the soil. Leskew (2002) studied subsoil compaction in Ontario, Canada, as the result of wheel traffic from heavy agricultural equipment in clays, clayey loams, and silty clays. About 50 to 70 percent of the agricultural land in four counties was affected by moderate to severe subsurface compaction. Leskew (2002) estimated an increase in phosphorus loading to the Great Lakes of 77,200-86,900 lb/yr (35,000-39,400 kg/yr) and increased soil erosion of 17 to 39 percent as the result of increased runoff caused by soil compaction. Meek and others (1992) developed a relation between infiltration, hydraulic conductivity, and bulk density for disturbed and undisturbed soils in a sandy loam. In disturbed soils, as bulk density increased from 1.6-1.8 g/cm^3 (99.9-112.4 lb/ft^3), infiltration decreased by 53 percent and hydraulic conductivity decreased by 86 percent.

Management practices to reduce soil compaction and increase infiltration in agricultural fields have focused on adding organic matter (Peet, 1995) and deep-rooted plants (Rosolem and others, 2002), minimizing tilling or wheel traffic in wet conditions (McBride and others, 1997), controlling traffic (limiting the number of passes of heavy equipment and using the same paths), and reducing the axle load of heavy equipment (Leskew, 2002).

Construction

Research from agricultural practices has direct application to the movement of heavy equipment and vehicles during the construction of home sites. Soil compaction resulting from construction practices is site specific, but development of large tracts of land can affect both ground-water recharge and stormwater runoff in the Sarasota Bay watershed. Soil compaction is desirable for most development projects (for example, highways, earth dams, levees, and building pads) and is often mandated by code. In construction engineering, compaction is defined as the process of making soil more dense by squeezing air out of the voids to increase strength, decrease permeability, decrease compressibility, and to help reduce the effects of frost heaving (Strata, Inc., 2002). The goal of compaction for construction is to “densify” or reduce the void ratio (increase the dry weight) of the soil by fracturing grains and by reorienting, bending, or distorting particles. Compaction is accomplished by applying tampers or hammers to mechanically compact or densify the soil. Water is often added to attain a specific moisture content to enhance the compaction process. The optimal water content to attain the highest level of soil compaction for an average soil (maximize the dry weight of a soil) is shown in figure 24. For dry soils, the unit weight increases as water is added and the water lubricates the soil

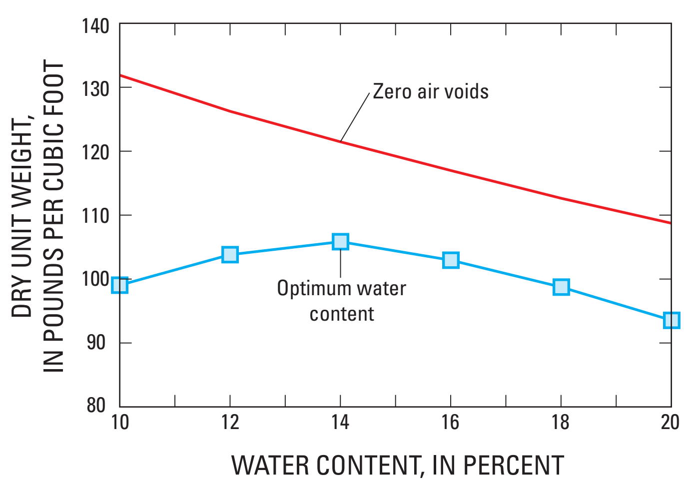


Figure 24. Generalized relation between compaction and moisture content of an average soil (modified from Goldsmith and others, 2001).

particles, making compaction easier. When water is added beyond the optimum water content, the void spaces become filled with water and compaction ceases.

Schueler (2000b) compared the bulk densities of mechanically compacted soils for common urban settings (table 5**).** The upper range of bulk density for all of the activities in table 5 is greater than 1.65 g/cm^3 (103.0 lb/ft^3), the bulk density at which infiltration is very slow (Smith and others, 2001). Table 6 provides bulk densities for a range of soil textures at which root growth may be affected; bulk densities ideal for root growth varied from less than 1.10 g/cm^3 (68.7 lb/ft^3) for clays to less than 1.60 g/cm^3 (99.9 lb/ft^3) for sands and loamy sands (Natural Resource Conservation Service, 1996b, 2000). Traditional large-scale land development practices may increase compaction over large areas. Infiltration may be restricted by compaction resulting from construction traffic and impervious structures (streets and driveways).

Regional recharge to ground water depends upon the pervious nature of the landscape. If pervious features are reduced, ground-water levels can be lowered and erosion and flooding can increase (Prince George's County, 1999). Conventional approaches convey and manage runoff generated by impervious surfaces in large facilities located at the base of drainage areas (U.S. Environmental Protection Agency, 2000a). Water is stored for a specific design volume and time to minimize flooding potential. In much of the Sarasota Bay watershed, the water table is close to land surface during certain times of the year. Home sites typically require fill to raise the level of land surface above the seasonal high water table to meet building codes (Mark Shelby, Sarasota County Agricultural Extension Service, oral commun., 2004). The fill brought to the site has undetermined soil characteristics and reworking of the soil alters its structure and infiltration characteristics. Determination of representative soil infiltration rates at home sites, therefore, is complicated by heterogeneous soil mixing during home construction. A study to evaluate soil compaction characteristics of reworked soils in residential neighborhoods in Sarasota County is currently being conducted (Sudeep Vyapari, University of Florida, oral commun., 2007).

Construction at a home site typically involves large vehicles delivering materials, pouring concrete slabs, hoisting structural framework, and so forth. The tire pressure exerted on the soil surface by vehicles may substantially increase surface and subsurface soil compaction. Site grading before final landscaping also increases compaction. Schueler (2000b) examined the practice of selective grading (the practice of grading limited areas) and determined that selective grading did not reduce soil compaction. Randrup and Dralle (1997) evaluated the influence of different types of landscaping on soil compaction at 17 construction sites in Denmark. They observed higher levels of compaction at all of the construction sites compared with the reference sites. Landscaping had no effect on compaction because construction traffic caused compaction before turf or landscaping beds were installed.

Because home lawns account for about 70 percent of the total turf area in urbanized landscapes, they represent substantial potential for infiltration (Schueler, 2000c). Legg and others (1996) deployed a rainfall simulator to observe infiltration from 20 residential lawns in Madison, Wisconsin. They observed that the infiltration rate for lawns from 1 to 3 years after establishment was 0.43 in/hr (1.1 cm/hr); whereas the infiltration rate for lawns greater than 7 years old varied from 1.69-2.13 in/hr (4.3-5.4 cm/hr). Similarly, Hamilton and Waddington (1999) evaluated infiltration rates in an urbanized area of central Pennsylvania. Infiltration rates were low for 67 percent of the lawns evaluated, and they concluded that infiltration rates were related to construction activities at each of the building sites; the highest infiltration rate was observed at a location that was not excavated prior to construction. Installation of turf over a graded, compacted soil had little effect on reducing compaction. Schueler (2000b) reported that bulk density decreased by only 0.20 g/cm^3 (12.5 lb/ft^3) over a 20-year period for lawns (listed as "Time" in table 7). Peet (1995) noted that the addition of organic matter to the soil improves soil structure, enhances aeration and increases pores spaces, and promotes the penetration of water and roots into the soil. Pitt and others (1999) amended compacted urban soils with organic matter, and over several years infiltration increased by 1.5 to 10 times above the precompost infiltration rate.

Subsequently, Schueler (2000b) noted that only compost amendments and reforestation offer the potential for substantial decreases in bulk density (table 7). Rosolem and others (2002), however, studied a variety of plants that could be used as cover crops to modify soil compaction by vigorous root growth and development of macropores. The grasses *Pennisetum americanum* (pearl mullet) and *Sorghum bicolor* (guinea-guinea sorghum) exhibited the highest root density and were recommended as possible cover crops for soils affected by compaction. Meek and others (1989) observed that infiltration rates under alfalfa cultivation doubled or tripled over a 3-year period, in both compacted and undisturbed soils. The alfalfa macropores allowed water to bypass the compacted surface layer. Shaw and Schmidt (2003) recommended northern climate plants with roots extending deep into the ground that aid infiltration by acting as pathways for the flow of water. Several of these plants reach west-central Florida through their native range:

Amorpha fruticosa (Indigo bush)
Asclepias tuberosa (Butterfly weed)
Cephalanthus occidentalis (Common buttonbush)
Eryngium yuccifolium (Rattlesnake master)
Euthamia graminifolia (Grass-leafed goldenrod)
Osmunda regalis (Royal fern)
Panicum virgatum (Switchgrass)
Pteridium aquilinum (Bracken fern)
Tradescantia ohiensis (Ohio spiderwort)
Schizachyrium scoparium (Little bluestem)
Sorghastrum nutans (Yellow indiangrass)

Table 5. Bulk density of common urban settings.

[From Schuler (2000b). g/cm^3, grams per cubic centimeter; %, percent]

Urban setting	Range of bulk density (g/cm^3)
Urban lawns	1.50 - 1.90
Crushed rock parking lot	1.50 - 2.00
Urban fill soils	1.80 - 2.00
Athletic fields	1.80 - 2.00
Building pads (85% compaction)	1.50 - 1.80
Building pads (95% compaction)	1.60 - 2.10
Concrete pavement	2.20
Quartzite	2.65

Table 6. Effect of bulk density on root growth for various soil textures.

[From U.S. Department of Agriculture (1996, 2000). g/cm^3, grams per cubic centimeter; <, less than; >, greater than]

Soil texture	Bulk density (g/cm^3)		
	Optimum for root growth	Impedes root growth	Restricts root growth
Sands and loamy sands	<1.60	1.69	>1.80
Sandy loams, loams	<1.40	1.63	>1.80
Sandy clay loams, clay loams	<1.40	1.60	>1.75
Silts, silt loams	<1.30	1.60	>1.75
Silty loams, silty clay loam	<1.10	1.55	>1.65
Sandy clays, silty clays	<1.10	1.49	>1.58
Clay (>45 percent clay)	<1.10	1.39	>1.47

In a similar way, the Florida Yards and Neighborhoods Program (FY&N) promotes appropriate plants, compost, and mulch to enhance infiltration and reduce runoff in neighborhood landscapes. The FY&N program was developed to provide special educational and outreach activities directed at the community for maintaining environmentally responsible landscapes. Among the objectives of the program are (1) reducing stormwater runoff and (2) decreasing nonpoint source pollution by promoting the value of mixed planting beds and soil amendments to conserve water and to enhance infiltration (Garner and others, 2001). Sarasota County enacted water efficient landscaping regulations in 2002 that embodies the principles of the FY&N program (Sarasota County Extension Service, 2006).

Table 7. Soil treatments to reduce bulk density.

[From Schuler (2000b). g/cm^3, grams per cubic centimeter]

Soil treatment	Change in bulk density (g/cm^3)
Tilling	-0.00 to -0.02
Soil loosening	-0.05 to -0.15
Selective grading	0
Soil amendment (fly ash)	-0.17
Soil amendment (compost)	-0.25 to -0.35
Time	-0.20
Reforestation	-0.25 to -0.35

Gregory (2004) evaluated how compaction affects infiltration rates in sandy soils of north-central Florida. Field experiments indicated that compaction substantially reduced the measured infiltration rates. Infiltration rates also were measured at three locations with installed pervious pavement. Infiltration rates on these pavements were highly variable depending upon the construction of the subgrade. Gregory (2004) concluded that substantial reductions in imperviousness at the lot scale for driveways (and parking areas) could be realized with appropriately engineered pervious surfaces.

Recreation

The Sarasota Bay watershed contains many recreational areas including golf courses, sports fields, camping areas, beaches, and trails for hiking or cycling. Research from other areas has indicated that soil compaction can occur in high-use recreational areas. Subsurface soils from 3.9-7.9 in (9.9-20.0 cm) deep along a pioneer trail in Iowa had substantially greater bulk densities than areas adjacent to the trail. The study concluded that the trail has been compacted for more than 150 years and that compaction persists today (Brevik and others, 2002). Similarly, Sharrat and others (1998) reported visibly evident soil compaction within wheel ruts of a pioneer trail used over 100 years ago in Minnesota. Bulk density and penetration resistance were 10 percent greater and infiltration was 50 percent lower within the trail than outside of the trail. An investigation of understory vegetation along a nature trail in Japan determined that substantially higher bulk densities and lower water content and porosities occurred along the nature trail than in the surrounding areas (Bhuji and Ohsawa, 1998). They also observed inhibited growth among woody shrubs and herbaceous plants, and deformed root growth in seedlings in the area of the compacted trail.

In a study of the soil characteristics of an urban park in Hong Kong, bulk densities (greater than 1.75 g/cm^3 or 109.2 lb/ft^3 in some locations), porosity, nutrient and water transmission, organic matter, pH, and cation exchange capacity were inadequate to maintain healthy vegetation in the park (Jim, 1998). Jim suggested that soil assessments and soil improvements should be an integral part of park maintenance. Stowell (1994) determined that turf grasses used for golf greens are subjected to sufficient soil compaction to prevent root penetration beyond depths of 2-3 in. (5.1-7.6 cm) below land surface.

Infiltration and Runoff

In 1979, Florida implemented a stormwater management goal for new developments to maintain post-development peak flow and pollutant loading at predevelopment levels (Livingston, 2004). To meet this goal, stormwater runoff in Florida is managed for the typical design storm through engineered conveyances and detention ponds sized for specific catchments. Detention ponds in Florida typically are wet detention ponds because the ground-water table is close to land surface for much of the year. Wet detention ponds are designed to store runoff during storm events and to release the water slowly from the pond. The Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service (SCS), runoff equation (eq. 3) is used in Florida to determine runoff for a particular catchment. The SCS method is commonly used in stormwater management because it is simple, yields consistent results, and is favored by regulatory agencies (Masek, 2002).

Runoff depth (Q) is estimated from a relation between precipitation (P), initial abstraction (Ia), and maximum potential soil retention (S):

$$Q = (P - Ia)^2 / (P - Ia + S). \quad (3)$$

Maximum potential soil retention in inches (S) is an empirical parameter based upon the runoff curve number (CN):

$$S = (1000 / CN) - 10, \quad (4)$$

and initial abstraction is:

$$Ia = 0.2 * S. \quad (5)$$

The runoff curve number, CN, is based on the relation between runoff, land cover, and soil condition. A runoff CN value that approaches 100 indicates increasing runoff. Table 8 provides a list of runoff CN values for a range of soil and land-cover conditions. Columns A through D represent different hydrologic soil groups (HSG) according to soil infiltration rates and drainage (Soil Conservation Service, 1986) (refer to table 1 for hydrologic soil group for soil series in the Sarasota Bay watershed). Soils in HSG “A” exhibit high infiltration rates and good drainage whereas soils in HSG “D” exhibit low infiltration rates and poor drainage. An example of a land cover and soil condition with a high runoff CN value (98) is a paved driveway (table 8). Nearly all of the precipitation that falls on a paved driveway becomes runoff. Soils in the Sarasota Bay watershed tend to be poorly drained (HSG B/D) with the seasonal high water table close to land surface for several months during the

Table 8. Runoff curve numbers by housing density and hydrologic soil group.

[From U.S. Department of Agriculture (1986). CN, runoff curve number (39-98); CN=39, least runoff; CN=98, most runoff; HSG, hydrologic soil group (A-D); HSG A; soils with rapid infiltration; HSG D; soils with slow infiltration; %, percent; <, less than; >, greater than]

Cover type	Increasing runoff curve number (CN) by decreasing infiltration (HSG)				Soil condition
	A	B	C	D	
Paved driveway	98	98	98	98	Impervious
Commercial district	89	92	94	95	85% impervious
Newly graded area	77	86	91	94	No vegetation
Housing lot (<1/8 acre)	77	85	90	92	65% impervious
Housing lot (1/4 acre)	61	75	83	87	38% impervious
Housing lot (1/2 acre)	54	70	80	85	25% impervious
Housing lot (2 acres)	46	65	77	82	65% impervious
“Poor” open lawn	68	79	86	89	50% grasses
“Good” open lawn	39	61	74	80	>75% grasses

rainy season. Compaction may act to further reduce infiltration. A “good, open lawn” contains at least 75 percent grass (Soil Conservation Service, 1986). In an area where soils are poorly drained (HSG D), a Myakka soil overlain by a good, open lawn may exhibit a runoff CN value of 80, according to table 8. Recreational areas with a good, open lawn, such as ball fields, trails and golf courses may have a higher than expected runoff CN value if these areas have been compacted by frequent foot or vehicle traffic. The degree of compaction and the influence of compaction on infiltration and runoff are unknown in the Sarasota Bay watershed.

Land cover is based on land-use categories described by the Soil Conservation Service (1986) and each land-use category has an assigned rainfall-runoff CN. The CN values are based on infiltration results from previous literature. Subsequent land practices may substantially alter infiltration characteristics and the runoff CN value originally assigned (Schueler, 2000a). In urban settings, soil is treated as a single soil type (urban soil), although infiltration characteristics vary dramatically in these soils and infiltration cannot be characterized adequately without site-specific measurements. Recognizing that urban soil characteristics are poorly understood or documented, the NRCS conducted an extensive research program to characterize urban soils in New York City. Infiltration rates in these urban soils varied substantially from site to site, prompting a new soil classification scheme for urban soils by the International Committee on Anthropogenic Soils (2003).

Hawkins and others (2002) determined that the value of 0.2 in eq. 5 was not corroborated for humid or arid environments using a least-squares fitting routine. In other words, the initial abstraction, Ia, is not fixed at 0.2 of the maximum potential soil retention, S, for all soil types. The study found that a value of 0.05 resulted in a better fit for data collected from more than 300 watersheds.

Golding (1997) challenged the use of the SCS method in Florida because of subjectivity in determining the runoff CN value. The runoff CN method for computing infiltration losses from rainfall using rainfall-runoff coefficients was developed to address deep water-table conditions in the Midwest; however, the method produces erroneous runoff estimates in shallow water-table environments (Masek, 2002). Research from several subbasins in west-central Florida indicates that widely used rainfall-runoff models produce large errors in predicting runoff, and adjusting runoff CN does not improve predictions substantially (Trommer and others, 1996a, b).

The runoff CN values are based upon Horton infiltration where substantial depth to the water table, substantial pore space for water storage, and constant rainfall intensity (rainfall rate) is assumed. Initially, the infiltration rate equals the rainfall rate. The infiltration rate decreases gradually to the hydraulic conductivity of the saturated zone as the soil column becomes partially saturated. With a constant rainfall rate, the gradual decrease in infiltration rate is accompanied by a gradual increase in the runoff rate. The mechanism, therefore, assumes that rate differences control runoff.

In Florida, Horton infiltration is likely to be limited to either upland areas of Scrub and Sandhill ecosystems, typically along the ridge areas of central Florida, or lowland areas only after extended periods of drought. In the headwaters area of the Sarasota Bay watershed, upland areas occupy a small portion of the DeSoto Plain where dry Flatwood and Sandhill ecosystems are present. In high water-table areas, especially in discharge areas along the Southern Gulf Coastal Lowlands, runoff processes are dominated by Dunne infiltration and by lateral subsurface return flow. Dunne infiltration assumes a dynamic water level; as rainfall continues, available pore spaces are filled and the water level continues to rise. No runoff occurs until the pore spaces are filled. When soil saturation is reached, the soil acts as an impervious surface and all of the precipitation becomes runoff.

Nachabe and others (2004) observed that rapid infiltration during intense rainfall events may trap air in soil pore spaces. In sandy soils, water can infiltrate pore spaces quickly, preventing air in pore spaces from escaping to the atmosphere. Where substantial trapped air exists in the soil profile, air counterflow and compression resist the downward flow of water (Wangemann and others, 2000). Taboada and others (2001) observed that pore air volume increased to 35 percent of the total soil volume during soil wetting but air did not escape at the soil surface. Consequently, hydraulic conductivity is reduced and runoff volumes may increase (Charbeneau, 2000).

Nachabe and others (2004) modified the equation for determining maximum potential soil retention (S) by developing an equation for soil water storage capacity (SWSC) as a function of water-table depth. Although detailed soil moisture data are needed to determine SWSC, Nachabe and others (2004) assert that soil storage capacity will be overestimated without an estimate based upon water-table depth.

Variations in topography, antecedent soil water content, soil moisture storage capacity, and rainfall intensity influence the spatial extent of areas where saturation excess runoff will occur. Hernandez and others (2003) indicated that these saturated areas, called variable source areas (VSAs), produce most of the runoff in shallow water-table environments. In areas with convex hillsides, runoff may consist of shallow subsurface flow (unsaturated throughflow) that discharges along the banks of the stream channel (fig. 25). In depressional storage areas (for example, wet detention ponds), contributing source areas may be larger than anticipated because of return flow. VSAs typically expand during the wet season and shrink during the dry season. Figure 26 depicts the variation in prestorm saturated source areas in March, April, and August 1973 for a small watershed in Vermont (Dunne and Leopold, 1978). The percentage of the saturated catchment area (A_S) varies from 51 percent in March to 15 percent in August. The expansion and contraction of VSAs define the hydroperiod in forested wetlands, which is an important consideration for ecological function in wetlands (Kautz, 1998).

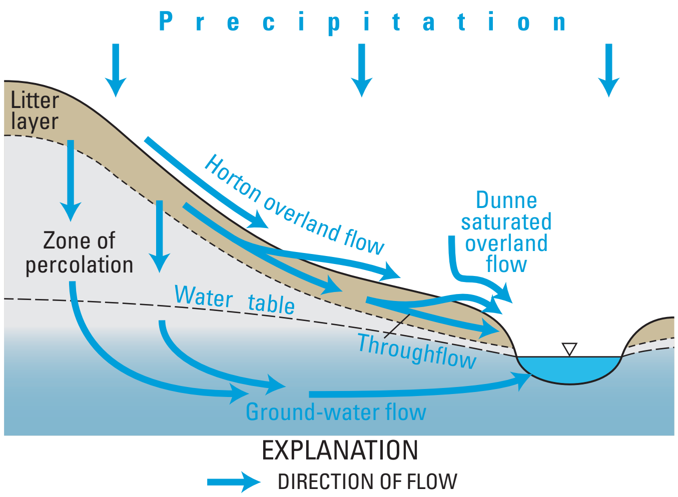


Figure 25. Potential routes of water movement (modified from Federal Interagency Stream Restoration Working Group, 1998).

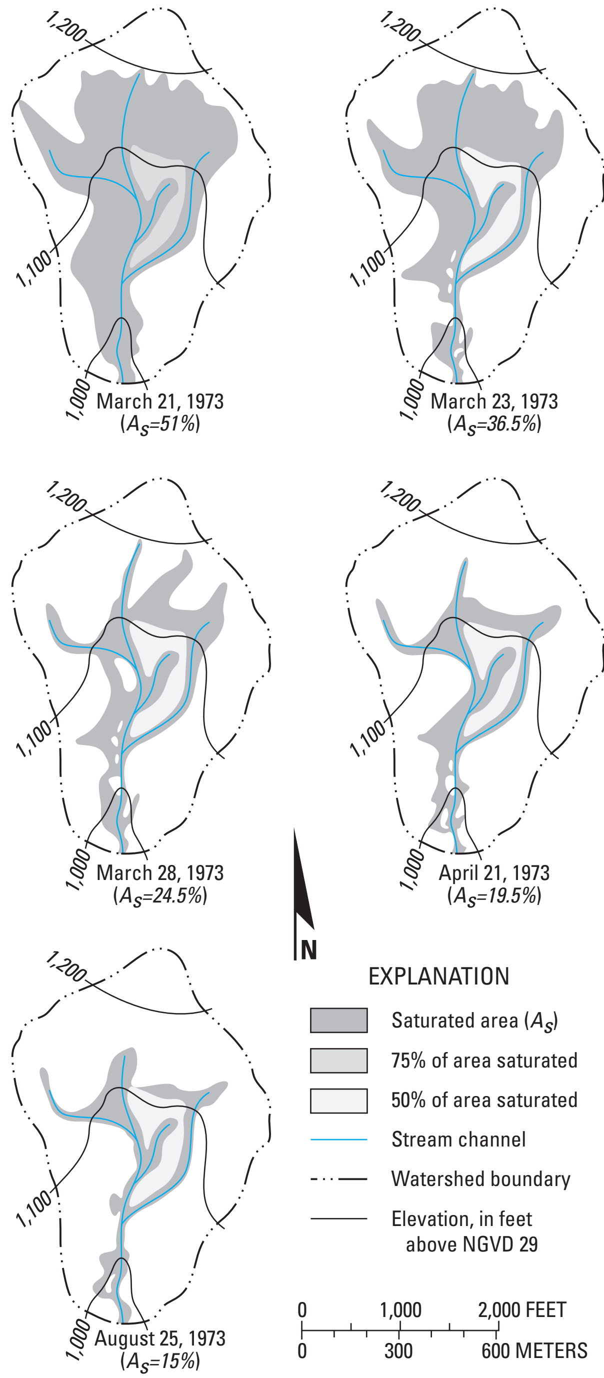


Figure 26. Examples of seasonal variation in saturated source areas for a catchment in Vermont (reprinted from Dunn and Leopold, 1978 and published with permission).

Accurate estimation of VSAs is particularly important for the design capacity of wet detention ponds in Florida. Schueler (2000d) explained that the performance of wet detention ponds designed to serve large catchment areas can be compromised by ground water entering the detention pond. Ground water may serve to dilute total nitrogen in wet detention ponds, but stormwater load removal may be decreased. Harper and others (2002) observed dry detention treatment in the Florida Keys to evaluate hydraulic performance and nutrient removal efficiency. Field observation indicated that lateral ground-water flow moved into the pond before actual runoff began. The concave depression formed by the dry detention pond decreased hydraulic performance and reduced nutrient removal efficiency.

Harper and Baker (2003a) evaluated alternative stormwater treatment options for achieving predevelopment pollutant loads in developed areas of southwest Florida. They concluded that wet detention in high water-table areas of Florida was an appropriate option because of efficient runoff storage capacity, ease of maintaining, and reasonable pollutant removal. Runoff is held for a designated period of time and is released slowly to ground water, surface water, or the atmosphere. Wet detention is the preferred option for runoff storage in Florida, but designs that incorporate modifications to the SCS method suggested by Nachabe and others (2003) may exhibit better hydraulic performance than conventional designs. The average antecedent dry periods between precipitation events in central and south Florida are 5.3 days during the dry season and 1.7 days during the wet season. Harper and Baker (2003a) indicated that nitrogen removal from a typical wet detention pond would achieve 70 percent removal after 150 days and 50 percent removal after 20 days. To achieve the removal efficiency goal of no net increase in loading (predevelopment loading conditions), options include wet detention systems in series, wastewater treatment approaches designed for stormwater, and reducing the volume of stormwater.

With urbanization, the hydrologic function of natural processes (depressional storage in swamps, cypress domes, and rapid infiltration in forested areas) is shifted toward designed engineering processes. Urban land-use practices tend to increase runoff and the likelihood of flooding by decreasing the perviousness of the land surface. Stormwater planning in west-central Florida makes use of traditional engineered structures to convey and store stormwater runoff and, with increasing frequency, incorporates lot-scale approaches that retain runoff close to rainfall point-of-impact. Engineered processes have been developed to address basin time-of-travel while attempting to retain precipitation close to where it falls on the land surface. These processes, designed and evaluated in other parts of the United States, are being applied to west-central Florida to enhance traditional stormwater management and retain runoff near its source.

Framework for Future Research in the Watershed

As urbanization in the Sarasota Bay watershed continues, focused research on water-resources issues will continue to provide information needed by water-resources managers to ensure the future health of the watershed. Conventional approaches are used to convey and manage runoff from developed areas to large detention or treatment areas. Finer-scale approaches to address sustainability, restoration, and low-impact development (portions of subdivisions, lots, impaired parcels, and so forth) are being used more frequently than in the past.

Low-Impact Development

Several approaches have been developed in other regions of the Nation to enhance infiltration and reduce runoff by modifying land practices. Prince George's County (1999) in Maryland developed Low-Impact Development (LID) guidelines to mimic the predevelopment site hydrology by using design features that store, infiltrate, evaporate, and detain runoff. These methods were designed to reduce runoff and ensure adequate ground-water recharge. In 2004, the Tampa Bay Regional Planning Council, Tampa Bay Estuary Program, and Florida Department of Environmental Protection co-sponsored a workshop on the application of LID approaches for Florida. Unanimous consensus at the workshop called for conducting research to determine what LID approaches would be best suited for Florida (Tampa Bay Regional Planning Council and others, 2004).

In an effort to restore predevelopment hydrologic processes, LID is designed to control stormwater volume at its source in discrete units throughout the watershed. Called the "distributed control approach," LID emphasizes materials such as native plants, soil, and gravel that can be integrated easily into the landscape to create distributed "microcontrol" systems to complement regional conveyance structures. LID limits clearing, grading, and construction easements, minimizes and disconnects impervious areas, avoids development in areas with high infiltration rates, and maintains existing topography and drainage divides. LID is not designed to replace conventional stormwater management approaches but rather attempts to enhance the efficiency of the conventional systems already in place.

The USEPA guidance on best management practices (BMPs) for stormwater states that preventing polluted runoff is less costly than treating it (U.S. Environmental Protection Agency, 2002). Swales, filter strips, and vegetated biofilters are recommended by the USEPA to keep runoff at its point-of-contact with the land surface (U.S. Environmental Protection Agency, 2004a, 2004b). Previously, the USEPA described LID practices applicable to retaining runoff close to its source including vegetative roof covers (green roofs), bioretention, grass swales, and permeable pavement (U.S. Environmental Protection Agency, 2000a).

Green roofs have been incorporated into building designs infrequently in Florida. Climatic conditions most favorable for green roofs are in areas that receive steady, light rainfall over an extended rainy season, typical of the northwestern United States. Conditions where the soil dries out completely for part of the year and where intense rainfall exceeds the soil storage capacity of green roofs for another part of the year present challenges to maintaining a green roof. However, experimental approaches on the campus of the University of Central Florida in Orlando (University of Central Florida, 2005) and at the Museum of Science and Industry in Tampa (W. Ostrenko, Museum of Science and Industry, oral commun., 2005) are being used to adapt green roof technologies for Florida. A new library planned for Sarasota County will serve as a pilot for the construction of a green roof (Whitt, 2006).

To increase infiltration and reduce runoff using "micro-control" strategies, Prince George's County (1999) developed microscale techniques called Integrated Management Practices (IMPs) and procedures, and criteria for selecting and designing the IMPs. Specific IMPs suggested by Prince George's County include: bioretention beds, dry wells, filter buffer strips, grassy swales, rain barrels, cisterns, and infiltration trenches.

Bioretention manages runoff by using an engineered planting bed and plant materials within a shallow depression to filter and retain stormwater. The bed is prepared by using in-situ soil with an infiltration rate greater than 0.5 in/hr (1.27 cm/hr) to a depth of 4 ft (1.2 m). Soil mixtures containing sand, loamy sand, and sandy loam with less than 10 percent clay are ideal for bioretention. Amending the soil with compost, although not specifically recommended by the IMPs, would increase biological activity and decrease bulk density. Pitt and others (1999) amended compacted urban soils with organic matter, and over several years, infiltration increased by 1.5 to 10 times the precompost infiltration rate. Because the water table is usually less than 5 ft (1.5 m) below land surface along the coastline, bioretention beds may have limited applicability to the Sarasota Bay watershed.

Dry wells, cisterns, and rain barrels are designed to capture runoff from roofs and permit the slow percolation of runoff to ground water. Dry wells may be appropriate for regions with deep water tables, but water-table conditions in the Sarasota Bay watershed would preclude their use. Additionally, these devices could inadvertently serve as conduits for movement of contaminants from land surface to ground water. Rain barrels and above-ground cisterns, advocated by the FY&N in Sarasota and Manatee Counties, are being used with increasing frequency as microscale detention devices for reuse of the collected water in the landscape (Garner and others, 2001).

Filter buffer strips, grassy swales, and infiltration trenches are vegetated areas of ground cover, shrubs, and trees designed to divert runoff to infiltration and restore infiltration rates to predevelopment natural ground cover levels. Grassy swales have been used extensively in the Sarasota Bay watershed and in most other areas of Florida as integral parts of stormwater management programs (E. Livingston, Florida Department of Environmental Protection, oral commun., 2004).

Rushton (2002) studied a low-impact design for reducing runoff in the parking lot of the Florida Aquarium in Tampa, Florida. A conventional asphalt system and a porous pavement system were installed side-by-side within the parking lot with drainage leading to separate, internally drained swales. The swales were directed to a series of wet detention ponds. The porous pavement system stored nearly all (greater than 99 percent) of the runoff generated during the study and pollutant removal efficiency was about 99 percent.

Caraco and others (1998) evaluated stormwater runoff, stormwater infiltration, and nutrient output from conventional and innovative site development plans for medium-density residential, low-density residential, retail shopping, and commercial office park sites in the Chesapeake Bay watershed. The conventional site design for each site was modified to incorporate narrow streets, small parking lots, open space options, short driveways, and open-channel drainage. The modified site characteristics were incorporated into the innovative redesign. Subsequently, a lot-scale model, the Simplified Urban Nutrient Output Model (SUNOM), was used to simulate nutrient export and runoff/infiltration characteristics for conventional and innovative site designs. SUNOM nutrient export rates were adjusted to include mean removal efficiencies of stormwater BMPs. The simulation showed that changes in site characteristics, principally impervious cover, resulted in less runoff, more infiltration, reduced nitrogen output, and reduced phosphorus output for medium-density residential, low-density residential, and commercial office park sites. Stormwater infiltration did not increase for the retail shopping site. Table 9 shows the projected changes in runoff characteristics for the four scenarios. Although the SUNOM model was applied to conditions in the Chesapeake Bay watershed, the principle of simulating changes in impervious cover to lot-scale nutrient runoff is applicable to the Sarasota Bay watershed.

Cheng and others (2004) conducted field monitoring to compare nitrogen output and hydrology from conventional and LID site designs in two small watersheds in Prince George's County, Maryland. The conventional design used a curb, gutter, and pipe stormwater conveyance system; whereas the LID design used grassy swales and bioretention areas. After 2 years of monitoring, total nitrogen loads decreased by 2.7 percent and nitrate-nitrite nitrogen loads decreased by 34.8 percent at the LID site compared with the conventional site. Average peak flow for the 2-year period at the LID site was 56 percent less than at the conventional site. Although basin characteristics were not described, expected streamflow velocities would probably be considerably higher than the velocities encountered in the Sarasota Bay watershed and the marked decreases in average peak flow and nitrate-nitrite nitrogen loads would likely be lower in the Sarasota Bay watershed because of the slower stream velocities and low relief.

The hydrologic analysis guidance for Prince George's County (1999) compared the calculation of a conventional runoff CN with a "custom-made LID" runoff CN. A composite runoff CN was achieved by segregating a 1-acre (0.4 ha)

Table 9. Percent change in simulated runoff characteristics of land-cover types from conventional BMPs to innovative design with BMPs from a study in the Chesapeake Bay watershed.

[From Caraco and others (1998). BMPs, best management practices]

Characteristic	Medium density residential housing	Low density residential housing	Shopping center	Office park
Impervious cover	-24	-35	-18	-22
Stormwater runoff	-25	-23	-17	-21
Stormwater infiltration	55	12	-2	42
Nitrogen output	-45	-46	-42	-45
Phosphorus output	-60	-50	-46	-47

residential lot into directly connected and unconnected impervious surfaces, open space, and wooded areas. The CNs obtained for the residential lot were: conventional (68), composite (63), and predevelopment (55). The composite curve number was subsequently used to determine detention storage requirements for the residential lot. Because watershed characteristics are considerably different in the Sarasota Bay watershed than in Prince George's County, Maryland, the approach for developing a custom-made LID runoff CN might not be applicable to conditions in west-central Florida. Developing lot-specific custom runoff CNs, however, would provide an improved understanding of runoff characteristics for Florida.

Gregory (2004) investigated lot-scale infiltration in areas of mixed forest and residential construction near Gainesville, Florida. Soils in these areas are sandy, loamy Paleudults (acidic, humid-region soils typically forming under pine forests [Buol and others, 1973]). A lot-scale model was developed to evaluate the effectiveness of several BMPs for reducing stormwater runoff by enhancing infiltration. Treatments modeled were (1) a conventional lot, (2) a predevelopment, high infiltration lot, (3) a pervious driveway, and (4) an engineered infiltration structure with runoff routed to it. Results indicate that predevelopment infiltration and an engineered infiltration structure resulted in a 50- to 92-percent reduction of lot-generated runoff. Gregory concluded that lot-scale infiltration could be an effective method for managing stormwater near the precipitation point-of-contact. Gregory's model has direct application to lot-scale efforts to improve infiltration in the Sarasota Bay watershed and may be a promising approach for evaluating infiltration using FY&N landscaping guidelines.

To reduce runoff, LID uses the hydrologic cycle as a design element to balance pervious and impervious cover. Figure 27 generalizes this balance showing the relative amounts of water moving to ground water and runoff with increasing percentages of impervious cover. In areas with natural ground cover, up to 50 percent of precipitation infiltrates into the ground water and 10 percent becomes runoff. As the percentage of impervious surface increases, either as impervious cover or compacted soils, infiltration decreases. In urban areas, impervious surfaces typically cover 75 to 100 percent of the land surface. Infiltration in these areas typically decreases to 15 percent whereas runoff increases to 55 percent (Federal Interagency Stream Restoration Working Group, 1998). In 14 watersheds located in west-central Florida, the average runoff for natural watersheds was 27 percent and the average runoff for urban watersheds was 41 percent (Trommer and others, 1996a).

Livingston (2003) indicated that stormwater volume must be reduced if post-development loading is not to exceed predevelopment loading. He suggested nonstructural controls, including LID, because structural controls alone will not protect the health of aquatic ecosystems. LID is not a replacement for conventional stormwater management, but instead, enhances stormwater management at or near the point at which rainfall reaches land surface.

Pollutant Loading and Watershed Modeling

Restoring the balance between predevelopment runoff and recharge assumes that runoff will be reduced to enhance recharge to ground water. Because ground water is the principal source of water in the Sarasota Bay watershed, enhancing recharge would help to maintain the ground-water supply. Restoring this balance is also important to reducing pollutants loadings in runoff that reach surface streams and Sarasota Bay.

In 1992, a point/nonpoint source pollution assessment of Sarasota County was conducted to evaluate nutrient inputs to Sarasota Bay (Camp Dresser & McKee, Inc., 1992). Pollutant loading rates were determined from available concentration and streamflow data; surface runoff was characterized by using event mean concentration data developed through the National Urban Runoff Program (U.S. Environmental Protection Agency, 1983). Available literature data for 17 land-use types were used in place of local monitoring for nonpoint loading factors including phosphorus, nitrogen, zinc, and lead.

Infiltration decreases and runoff increases as the amount of directly connected impervious area (DCIA) increases. The percentage of DCIA in the watershed was estimated for each urban land use from the National Urban Runoff Program (U.S. Environmental Protection Agency, 1983). Specific runoff loading estimates were made for golf courses, septic areas, canal communities, point sources, and rainfall. Wet- and dry-season results indicated that 60 percent of the annual loading occurred during the wet season (June-September), and 40 percent occurred during the dry season (October-May). The average annual loading of total nitrogen to the watershed was primarily from surface runoff (46 percent) and rainfall (27 percent). Baseflow, septic systems, and point sources each accounted for less that 10 percent of the total nitrogen loads. Loadings and flows were simulated as steady input values from the average annual results generated by a spreadsheet model using the WASP4 model (Southwest Florida Water Management District, 1992).

From the estimates for the Sarasota Bay watershed, the Sarasota Bay National Estuary Program projected annual loads to Sarasota Bay for total phosphorus, total nitrogen, lead, and zinc for a 20-year period from 1992 to 2012 (Heyl, 1992). The average annual total nitrogen load estimates were 933,750 lb/yr and 1,145,730 lb/yr (423,542 kg/yr and 519,694 kg/yr), for 1992 and 2012 respectively. Several management alternatives and land-use conditions were evaluated that could potentially affect the 20-year pollutant loading projections (table 10). Five of 14 build-out alternatives (build-out is an estimate of the total number of units that can potentially be built under land-use management plans) resulted in lower total nitrogen loads than the 1992 estimates; these five alternatives assumed the implementation of the Sarasota County advanced wastewater plan. The 30/70 (30 percent medium density and 70 percent open space) residential cluster development concept was determined to be the best alternative for reduction of

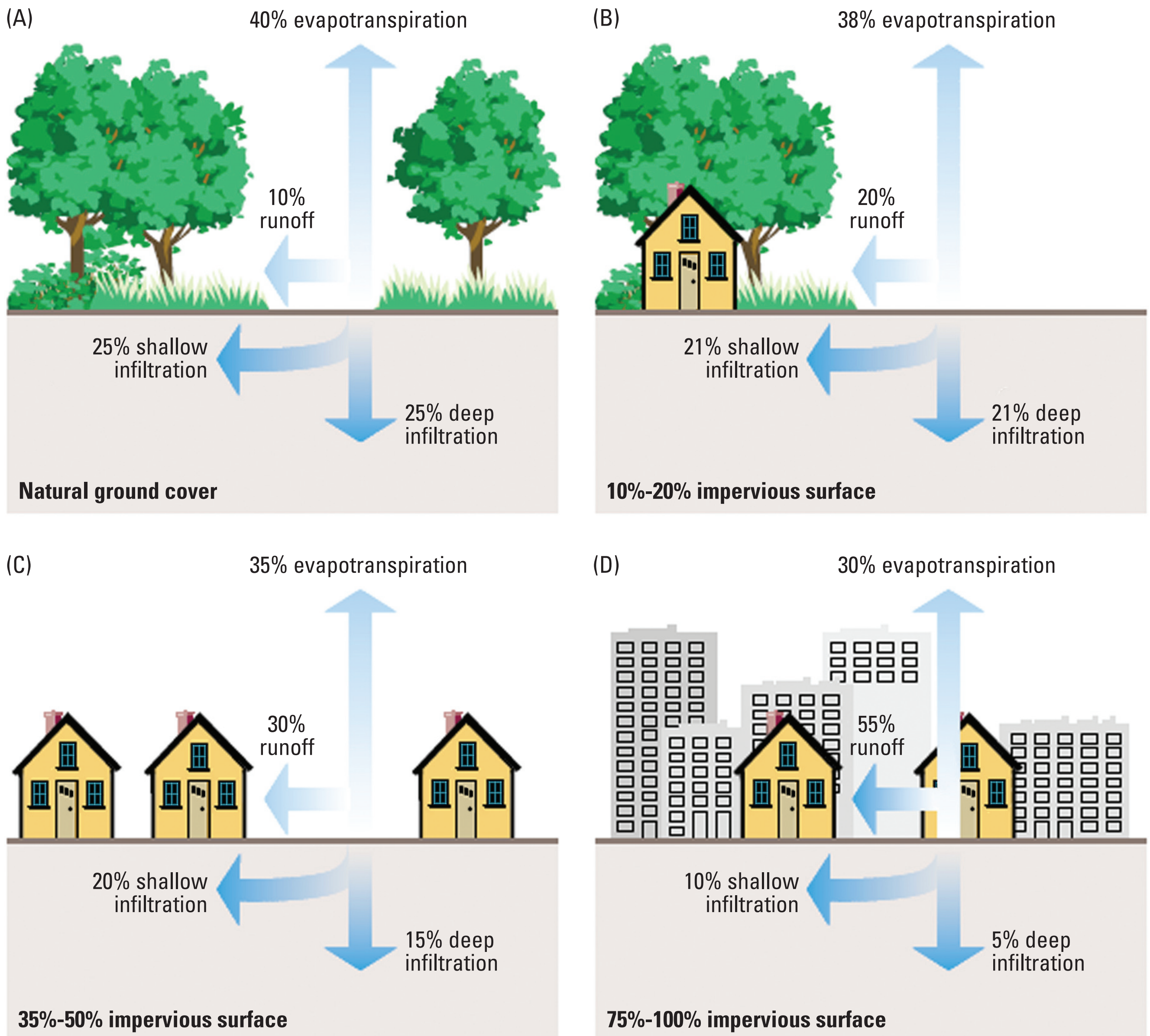


Figure 27. Examples of variation in runoff with increasing impervious surfaces: (a) natural ground cover, (b) 10-20 percent impervious cover, (c) 35-50 percent impervious cover, and (d) 75-100 percent impervious cover (from Federal Interagency Stream Restoration Working Group, 1998).

total nitrogen loads. At build-out, the 30/70 residential cluster concept results in a projected reduction of 89,490 lb/yr (40,592 kg/yr) of total nitrogen from the 1992 levels (Heyl, 1992).

The 1992 pollutant loading model relied on several simplifying assumptions because local, site-specific data were sparse.

- Total nitrogen loading from precipitation was distributed evenly over the 52-mi^2 (135 km^2) Sarasota Bay surface area. The loadings were based upon the total nitrogen concentration determined for Tampa Bay of 0.82 mg/L and an average precipitation of 54.6 in. (137 cm) or 337,000 lb/yr (152,860 kg/yr).

- Total nitrogen concentrations in runoff were estimated mostly from literature values for Florida from the 1983 National Urban Runoff Program.

- Runoff coefficients were estimated from the Soil Conservation Service (1986) hydrologic soil types and land-use groupings.

The simplifying assumptions used in the 1992 pollutant loading model permitted long-range projections using estimation techniques developed for broad, regional applications. Recent research has generated site-specific data, remote-sensing data, and Geographic Information System (GIS) methods to account for variability that had formerly been

Table 10. Total nitrogen loads to Sarasota Bay projected for 2012 for several land management alternatives in the Sarasota Bay watershed.

[From Heyl (1992). AWT, Advanced wastewater treatment; BMPs, best management practices; lb/yr, pounds per year; build-out, estimate of the total number of units that potentially can be built under the land-use management plans; %, percent]

Total nitrogen load (lb/yr)	Land management alternative[1]
933,750	1991 estimate
1,145,730	Uncontrolled build-out; no best management practices (BMPs); no advanced wastewater treatment (AWT)
1,064,620	Wet detention BMPs, as required by law; no AWT
914,860	Wet detention BMPs, as required by law and AWT
888,490	1-acre residential lot (80% pervious); commercial (40% pervious) plus BMPs and AWT
873,010	Residential cluster development (50% medium density-50% open space, 90% pervious); commercial (40% pervious) plus BMPs and AWT
855,360	2-acre residential lot (90% pervious); commercial (40% pervious) plus BMPs and AWT
844,260	Residential cluster development (30% medium density-70% open space, 90% pervious); commercial (40% pervious) plus BMPs and AWT

[1]Assumes all future development conforms to these land management alternatives.

limited to basinwide, evenly distributed estimates. Algorithms for predicting near-realtime precipitation from NEXRAD data have been developed and verified (Neary and others, 2004), and have been used in watershed modeling (Berne and others, 2005).

In the 1992 pollutant loading model, rainfall concentrations of nutrients from Tampa Bay were used to represent rainfall concentrations for the Sarasota Bay watershed resulting in overestimated atmospheric deposition of nutrients to the Sarasota Bay watershed (Southwest Florida Water Management District, 2002). Wet and dry atmospheric deposition of total nitrogen to the Sarasota Bay watershed was slightly more than half of the atmospheric deposition reported by Poor and others (2001) for Tampa Bay, or about 3.92 lb/acre/yr (4.4 kg/ha/yr) total nitrogen (N. Poor, University of South Florida, oral commun., 2004). Alexander and others (2001) used a spatially referenced regression watershed model (SPARROW) to predict the mean wet deposition of nitrogen to the Sarasota Bay watershed. They determined the wet deposition of total nitrogen to be 1.36 lb/acre/yr (1.53 kg/ha/yr) or slightly less than 40 percent of the total nitrogen deposition. Similar research by Poor and others (2001) in Tampa Bay indicated that wet deposition of total nitrogen in Tampa Bay accounted for 56 percent of the total nitrogen deposition for the period 1996 to 1999. The study also determined that a net flux of nitrogen from the water to the atmosphere, as ammonium, occurred during one summer when Tampa Bay warmed to 82.4 °F (28 °C). The 1992 pollutant loading model predicted atmospheric deposition as the second largest source of nitrogen to the Sarasota Bay watershed. NEXRAD data and nitrogen speciation/flux measurements can be used to provide a better means of understanding the variability of this substantial source of nitrogen to the Sarasota Bay watershed.

The soil storage capacity variable used in the 1992 pollutant loading model was based on the runoff numbers from the SCS method. Modifying watershed models to account for soil water storage capacity as a function of water-table depth will likely enhance the accuracy of runoff projections. The SWFWMD (2002) recommended updating the 1992 Sarasota Bay watershed pollutant loading model predictions by comparing the projections with current pollutant loading data.

Since the early 1990s, estimates of pollutant loads have been improved by comprehensive watershed models linking load estimates to dynamic processes within the watershed. In 1999, the USEPA recommended the use of watershed loading models to evaluate the effect of land-use practices on pollutant loading to water bodies (U.S. Environmental Protection Agency, 1999). Models were categorized as simple or complex, and the advantages and disadvantages of each of the groups were described.

Simple models, such as the watershed spreadsheet model, were recommended for gross, empirical estimates of pollutant loads when reliable data are relatively sparse. The 1992 Sarasota Bay watershed pollutant loading model is an example of this type of model. These models are of limited value for determining loads on a seasonal or finer scale and in evaluating the effect of control measures (U.S. Environmental Protection Agency, 1999).

Complex models utilize the current understanding of watershed processes affecting pollutant sources and sinks. Algorithms in complex models more closely simulate physical processes (infiltration, runoff, pollutant accumulation, ground-water/surface-water interaction) (U.S. Environmental Protection Agency, 1999). These models (1) can provide information on source loadings from specific parts of the watershed, (2) can predict the effect of different control practices, and (3) have greater spatial and temporal resolution. Complex models are appropriate for load estimates to: (1) provide explicit analysis of runoff and pollutant transport, (2) evaluate short-term processes lasting days or hours, and (3) optimize potential control scenarios. Predictions of variable flows and water-quality affected processes at numerous points within the watershed may be achieved using complex models (U.S. Environmental Protection Agency, 1999). Watershed models categorized into this group include:

- BASINS (Better Assessment Science Integrating Point and Nonpoint Sources)
- HSPF (Hydrologic Simulation Program—Fortran)
- SWAT (Soil and Water Assessment Tool)
- SWMM (Storm Water Management Model)
- SPARROW (SPAtially Referenced Regressions On Watershed Attributes)

BASINS is a multipurpose environmental analysis system developed to assist regional and local agencies with watershed and water quality-based evaluations by integrating data on water quality and quantity, land uses, and point and nonpoint source loading, thus providing the ability to perform preliminary assessments of watersheds (U.S. Environmental Protection Agency, 1999). BASINS consists of a series of interrelated components including: (1) data extraction tools for national databases; (2) assessment tools (TARGET, ASSESS, and Data Mining) for large and small-scale watershed characterization; (3) utilities for classifying digital elevation models, land use, soils, and water-quality observations; (4) an instream water-quality model, QUAL2E; (5) two watershed loading and transport models, Hydrological Simulation Program—Fortran (HSPF) and Soil and Water Assessment Tool (SWAT); (6) PLOAD, a simplified GIS-based model that estimates nonpoint pollutant loads on an annual average basis; (7) the Kinematic Runoff and Erosion Model (KINEROS), an event oriented, physically based model that may be used to determine the effects of various artificial features such as urban developments, small detention reservoirs, or lined channels on flood hydrographs and sediment yield; (8) Rosgen's Bank Erosion Hazard Index, which has been incorporated in the pollutant loading model as PLOAD-BEHI; (9) AQUATOX, which receives and automatically formats output from HPSF or SWAT to integrate watershed analysis with the likely effects on the aquatic biota in receiving waters; and (10) a Parameter Estimation (PEST) tool in WinHSPF (Windows version of HSPF) that automates the model calibration process and allows users to quantify the uncertainty associated with specific model predictions.

The HSPF model is used to calculate pollutant load and transport from complex watersheds to receiving waters (U.S. Environmental Protection Agency, 1999). HSPF provides capabilities for continuous and storm-event simulation. The model output includes a time series of the runoff flow rate, sediment load, nutrient and pesticide concentrations, and water quantity and quality at any location in the watershed. The Chesapeake Bay Program has used HSPF to model total watershed contributions of flow, sediment, and nutrients to the tidal region of the bay. Wicklein and Schiffer (2002) simulated hydrology and water quality of runoff using the HSPF model in central Florida. To characterize runoff, they examined six land-use types (agriculture, rangeland, forest, wetlands, rapid infiltration basins, and urban) for a complex stream system in the Reedy Creek Improvement District. For the period from 1990 to 1995, the model was calibrated for two subwatersheds and runoff was simulated for the remaining subwatersheds. Simulated time series for total phosphorus, phosphate, ammonia nitrogen, and nitrate nitrogen generally agreed with periodic data for the two subwatersheds. Simulation of hydrology and water quality of runoff for future land-use scenarios was then projected for 2008. The land-use scenarios assumed a decrease in forested areas by 50 percent and an increase in impervious areas by 300 percent. Simulated nutrient concentrations did not change substantially, but simulated loads for all constituents increased by 10 percent; nitrate-nitrogen loads increased by 17 percent. The HSPF model may also be used in conjunction with ground-water flow models to simulate surface-water and ground-water interactions.

SWAT is a watershed-scale model developed to predict the effect of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land use, and management conditions over long periods of time (Neitsch and others, 2005). Data inputs include weather, surface runoff, return flow, percolation, evapotranspiration, transmission losses, pond and reservoir storage, crop growth and irrigation, ground-water flow, reach routing, nutrient and pesticide loading, and water transfer. The model is physically based and does not rely on regression relations between input and output variables. This feature permits modeling of watersheds with minimal monitoring data (Neitsch and others, 2005).

The SWMM model simulates overland water quantity and quality produced by storms in urban watersheds for a wide range of watershed processes (U.S. Environmental Protection Agency, 1999). Model components include rainfall and runoff, water-quality analysis, and point-source inputs. Either continuous or storm-event simulation is possible, with variable and user-specified time steps (wet and dry weather periods). Input data requirements include rainfall hyetographs, antecedent conditions, land use, topography, soil characteristics, dry-weather flow, hydraulic inputs (gutters or pipes), pollutant accumulation and wash-off parameters, and hydraulic and kinetic parameters. Model output includes time series of flow, stage, and constituent concentrations at any location in the watershed.

The SPARROW model incorporates a statistical modeling approach that retains spatial referencing for illustrating predictions and for relating upstream nutrient sources to downstream nutrient loads (Smith and others, 1997). SPARROW is based on a digital stream-network data set that is composed of stream segments (reaches) that are attributed with travel time and connectivity information. Drainage-basin boundaries are defined for each stream reach in the network data set through the use of a digital elevation model (Preston and Brakebill, 1999). The application of SPARROW for watershed assessment offers three principal features. First, the statistical basis of SPARROW provides an objective means of identifying relations between stream-water quality and environmental factors such as contaminant sources in the watershed and land-surface characteristics that affect contaminant delivery to streams (Alexander and others, 2002). Second, SPARROW's spatially detailed network and travel-time data provide a means of estimating instream loss rates. These loss rates allow upstream watershed factors to be related to downstream loads in a more integrated manner than previously possible, and allow the simultaneous evaluation of many factors that affect loads including storage, denitrification, interbasin transfer, and ground-water/surface-water exchange (Alexander and others, 2002). Third, SPARROW provides a means of retaining detailed spatial information about all environmental factors considered in the regression model. Because the regression models are linked to spatial information, predictions and subsequent analytical results can be illustrated through detailed maps that provide information about nutrient loading at detailed spatial scales.

McMahon and Roessler (2002) used the SPARROW model to develop total nitrogen inputs and total nitrogen delivery and a total nitrogen budget for the Neuse River basin in North Carolina. SPARROW estimated nitrogen yield within 25 percent of the observed values at most of the 44 monitoring stations used to calibrate the model. Observed values consisted of water-quality data collected both by the USGS and the State of North Carolina. Soil drainage characteristics (specifically, ground-water recharge) and channel transport factors (aquatic processes in streams and reservoirs) both substantially influence the transport of total nitrogen at the reach and whole-basin scale. Total nitrogen losses associated with in-stream processes occurred at a rate of about 8 percent per mi (5 percent per km) in streams with a mean annual discharge less than 37 ft^3/s (1.04 m^3/s); losses in streams with greater discharge occurred at a rate of 0.3 percent per mi (2 percent per km). SPARROW included statistical uncertainty in nitrogen delivery estimates and the estimates were used to map the spatial probability distribution of stream reaches. McMahon and Roessler (2002) noted the flexibility of SPARROW to accept multiple model specifications that aid in the understanding of complex terrestrial-aquatic processes.

Sprague and others (2000) estimated nitrogen loads using observed concentration and streamflow data with the USGS ESTIMATOR model—a log-linear regression model that uses time, flow, and season terms to predict daily nutrient concentrations (Cohn and others, 1989). They obtained flow-adjusted concentrations to remove the bias of flow from the load estimates and applied the Kendall-Theil test to evaluate trends in nutrient loads. Sprague and others (2000) then used the Chesapeake Bay Watershed Model (WSM) to quantify nitrogen sources for 1995 and 1998 scenarios. The WSM is spatially and temporally variable and based on the HSPF model (Donigian, and others, 1994). Results from the WSM were used as input for the SPARROW model to determine the primary factors affecting the observed nutrient trends. Sprague and others (2000) found that cultural changes in nutrient sources and natural variations in streamflow were the major factors affecting the trends in nitrogen loads.

Revising the 1992 pollutant loading model predictions, as the SWFWMD has suggested, could involve the application of a detailed model (such as HSPF) to determine the spatial and temporal details of pollutant fate and transport and the application of SPARROW to assess the contribution of pollutant loads to the watershed by stream reaches. The accuracy of the multiple model approach could be refined by incorporating lot-scale models into the HSPF domain to elicit lot-scale inputs to pollutant loads in the watershed.

Jones, Edmund and Associates, Inc. (2006) developed a spatially integrated model for pollutant loading estimates (SIMPLE) to estimate pollutant loading for the Sarasota Bay watershed. SIMPLE is based upon previously developed models by Camp Dresser & McKee, Inc. (1992) and Harper and Baker (2003b) and includes functionality to permit user control of constituents, rainfall, and BMPs through an ArcMap interface. Baseflow contributions are inferred by data inspection and an average baseflow contribution factor of 0.0012 ft^3/acre (0.07 m^3/ha) was computed for the watershed. Pollutant loads were computed by multiplying runoff volumes by event mean concentrations (EMCs), similar to the procedures used by Camp Dresser & McKee, Inc. (1992) and Harper and Baker (2003b). Pollutant loads were estimated from the EMCs presented in Camp Dresser & McKee, Inc. (1992). Additional pollutant load estimates for (1) wetlands BOD (biochemical oxygen demand), TSS (total suspended solids), TP (total phosphorus), and TN (total nitrogen), (2) lead and zinc, (3) oil and grease, and (4) fecal coliform bacteria were obtained from other studies (Jones, Edmund and Associates, Inc., 2006).

The consistency of the estimation methods used in the 1992 and 2006 studies enabled a temporal comparison of the increase or decrease in pollutant loads reaching Sarasota Bay. In a complimentary approach, detailed field studies offer the possibility of measuring further reductions in pollutant loads caused by relatively small changes in watershed practices. The methods originally suggested by the USEPA for determining EMCs emphasized generalizing the EMCs to be applicable to many geographic areas (U.S. Environmental Protection Agency, 1983). The literature values determined in the National Urban Runoff Program were applied to watersheds to identify large-scale changes in pollutant loads with minimal data collection. Since 1983, changes in sampling methods and analysis have resulted in improved strategies for determining EMCs.

Event Mean Concentrations for Pollutant Loading Models

One way to characterize constituent concentrations and stormwater loads in streams and rivers involves using the EMC approach originally suggested by the USEPA through the Urban Stormwater Management Program (U.S. Environmental Protection Agency, 1983). Event mean concentrations have been used extensively to estimate runoff constituent loads to surface-water bodies; however, some EMCs are derived from literature values whereas others are derived from sparse data or limited storms (U.S. Environmental Protection Agency, 1999). Stormwater sampling strategies for characterizing the concentrations of constituents in runoff include grab, peak discharge, first-flush, composite, random, volume-weighted and flow-weighted sampling.

Chang and others (1990) sampled the first 0.5 in. (1.27 cm) of runoff for water-quality constituents to evaluate the first flush of stormwater runoff to streams. They found that although the first flush concentrations were elevated, the first 0.5 in. (1.27 cm) of runoff did not carry the majority of the storm load. As the amount of storm precipitation and the percent impervious cover increased, the percentage of constituent load in the first flush of runoff decreased (table 11). Precipitation falling on small, impervious catchments causes rapid changes in streamflow, dissolved constituents, and suspended solids and, therefore, a large number of samples are required to adequately characterize the stormwater loads (Breautt and Granato, 2000).

Stenstrom and others (2002) evaluated sampling errors resulting from the number of stormwater samples collected over the hydrograph during a typical storm. They found that a smaller percentage of error occurred with equal-volume or equal-rainfall sampling intervals than with equal-timing intervals or random timing. Error percentage also decreased as sample size increased. Automatic samplers were preferred over grab samples except in the case where sample contamination from carry-over is a concern.

Kayhanian (2002) studied the variability of EMCs for metal concentrations in stormwater as the result of sampling method (flow-weighted composite, first flush, all grabs, peak,

Table 11. Percentage of pollutant load contained in storm runoff for selected levels of impervious ground cover.

[Data from Chang and others (1990); in., inches; BOD, biochemical oxygen demand; COD, chemical oxygen demand; NH_3, ammonia nitrogen; NO_2+NO_3, nitrite plus nitrate nitrogen; TSS, total suspended solids]

Pollutant	Percentage of pollutant load					
	First 0.5 in. of runoff	Last 0.25 in. of runoff	First 0.5 in. of runoff	Last 0.75 in. of runoff	First 0.5 in. of runoff	Last 0.75 in. of runoff
	30 percent impervious cover[1]		50 percent impervious cover[2]		90 percent impervious cover[3]	
BOD	68	32	53	47	33	67
COD	77	23	57	43	48	52
NO_2+NO_3	62	38	56	44	40	60
NH_3	71	29	58	42	30	70
TSS	81	19	61	39	41	59
Copper	67	33	42	58	31	69
Fecal coliform bacteria	80	20	44	56	36	64

[1]0.75 in. average maximum runoff.

[2]1.25 in. average maximum runoff.

[3]2.25 in. average maximum runoff.

end, and random). Concentrations for copper, lead, and zinc showed considerable variability based upon the sampling method used (fig. 28), and the variability had a substantial impact on the calculation of annual loads. Othmer and Berger (2002) evaluated sampling methods for EMCs for solids, organic carbon, hydrocarbons, metals, and nutrients. They concluded that substantial variability between sampling methods indicated the need for establishing criteria for the collection of representative samples.

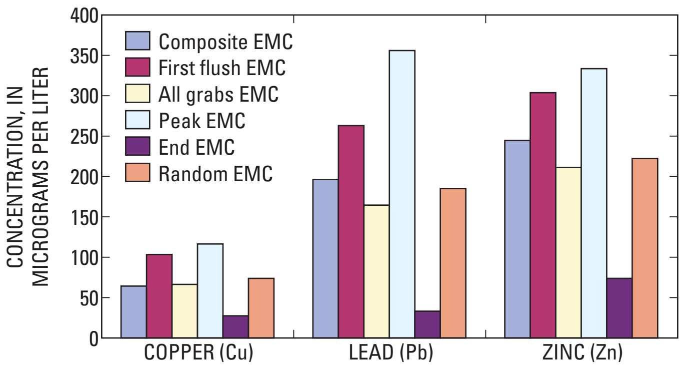


Figure 28. Variability in selected metal concentrations for different event mean concentration (EMC) sampling schemes (reprinted from Kayhanian, 2002 and published with permission).

Soller and others (2005) observed that pollutant concentrations in the first part of the wet season were up to 20 times higher than late season concentrations. They investigated pollutant loads from the first seasonal storm flows as an estimate of annual pollutant loads. Seasonal first flush did not consistently produce peak concentrations for total metals, dissolved metals, and anions because of variability in total flow, antecedent dry days, and season (Soller and others, 2005). EMCs from highway runoff decreased as total storm runoff increased, and increased as the number of dry antecedent days before a storm increased (Kim and others, 2005).

Continuous monitoring using in-stream sensors has been used as a surrogate to estimate pollutant concentrations and address the sample size errors described by Soller and others (2005). Regression equations for turbidity determined from nutrient and bacterial concentrations provided reliable estimates of nutrient and bacterial loads from continuous turbidity measurements (Rasmussen and others, 2005).

Research Topics

Management strategies for multiple uses of the water resources of the Sarasota Bay watershed will depend on continued research to understand the dynamics of the watershed's hydrology. Water movement and use within the watershed is complex and understanding water movement is paramount to refining strategies for balanced use of the resource. Important topics to consider for future research include:

- Determining the effect of lot-scale land practices on runoff, storage, and ground-water recharge including:
    - Compaction by construction traffic patterns and grading.
    - Retaining the original soil structure including organic and leaching horizons.
    - Infiltration specifications for fill used to raise the elevation in areas beyond the house foundation.
    - Infiltration for mixed-species planting beds in lot-scale landscapes.
    - Water and chemical needs for establishing and maintaining mixed species planting beds.
    - Engineered bioretention planting beds for reducing nutrient runoff.
    - Use of pervious materials (for sidewalks and driveways), disconnected impervious areas, swales, and other infiltration enhancements to reduce runoff.
    - Reducing the energy of runoff to streams to minimize transport and resuspension of contaminants (such as metals, pathogens, and endocrine disrupting compounds) from urban areas.
- Quantifying dry season flux of nutrients from atmospheric deposition to accurately determine atmospheric contributions.
- Quantifying changes in partitioning of water (infiltration, runoff, deposition, resuspension) and contaminants as urbanization alters predevelopment rainfall-runoff relations.
- Determining the variability in runoff pollutant concentrations and loads transported by streams.
- Using remote sensing and GIS to quantify spatial variability in watershed characteristics (such as soil moisture and precipitation) over large areas.
- Refining lot-scale hydrologic and hydraulic models.
- Evaluating sample-collection strategies to provide detailed environmental data for determining nonpoint inputs and loads.
- Developing watershed models that account for spatial variability, dynamic infiltration, and lot-scale hydrology.
- Developing the linkage between watershed models and lot-scale models to evaluate the effect of small-scale changes over the entire Sarasota Bay watershed.

Summary

Comprehensive watershed planning is the key to successful multiple-use watershed management. Scientific tools available for watershed planning rely upon extensive and representative data-collection programs that are well designed and well maintained. The Comprehensive Conservation and Management Plan developed by the SBEP provides the framework for long-term management of stormwater and wastewater, maintenance and restoration of habitats, and access to the natural resources of the Sarasota Bay watershed. This report summarizes characteristics of the Sarasota Bay watershed and factors influencing recharge to ground water and overland runoff to surface water in the watershed.

The Sarasota Bay watershed drains more than 200 mi^2 (518 km^2) within Manatee, Sarasota, and Charlotte Counties and empties into several embayments before flowing into the Gulf of Mexico. Climate, geography, soils, hydrogeology, land cover, land use, and urbanization all affect water movement within the watershed. The climate of west-central Florida is characterized by long, warm, humid summers and short, mild, dry winters. Precipitation is seasonal and nearly 60 percent of annual precipitation occurs during the wet season, from June through September. Average annual precipitation within Sarasota County between 1915 and 2003 was 52.47 in. (133 cm); the maximum and minimum recorded annual precipitation was 85.54 in. (217 cm) for 1959 and 32.77 in. (83 cm) for 2000, respectively.

The Sarasota Bay watershed lies within the Southern Gulf Coastal Lowlands where soils are poorly drained and the water table is near land surface. As the population of west-central Florida continues to grow, pasture and forested lands have been converted to urban or suburban use. The literature reviewed indicates that land conversion increases the impervious cover, which alters the hydrology of the watershed by increasing runoff and decreasing infiltration. Most land-use practices tend to compact soil and reduce water infiltration, either by design or as a consequence of using the land. Impervious cover and compaction disrupt the natural process of recharge to the surficial aquifer system and increase runoff. Enhancing recharge benefits the watershed by replenishing the ground-water system, encouraging natural filtration, and reducing the transport of pollutants in runoff.

Land practices that (1) reduce the removal of native soil horizons, (2) limit vehicular traffic during home site construction, (3) promote deeply rooted landscaping plants, and (4) add organic matter to the soil may enhance infiltration near the precipitation point-of-contact. Infiltration in the watershed does not occur exclusively by Horton infiltration, the infiltration mechanism employed by most rainfall-runoff models. Without accounting for Dunne infiltration, common in humid, high water-table areas, runoff CNs and runoff estimates may yield inaccurate results.

As urbanization in the Sarasota Bay watershed continues, conventional approaches used to convey and manage runoff to large detention or treatment areas are being augmented with integrated management practices to address sustainability, restoration, and low-impact development. Integrated management practices used or planned in the watershed include vegetative roof covers, bioretention, grass swales, and permeable pavement. These practices have been shown to reduce runoff and pollutant concentration in runoff and to increase infiltration.

Restoring the balance between predevelopment runoff to surface water and recharge to ground water assumes that runoff will be reduced to enhance ground-water recharge. Reducing pollutant loadings in runoff that reach surface streams and the Sarasota Bay is an important goal of the SBEP. Annual pollutant loadings to Sarasota Bay were estimated in 1992 and 2006 from simple pollutant loading models based on sparse and empirical data. Simple models are useful for annual estimates, but they are of limited value for determining loads on a seasonal or finer scale for evaluating the effect of control measures.

Complex models can provide information about (1) source loadings from different parts of the watershed, (2) effects of control measures, and (3) processes occurring at greater spatial and temporal resolution. Available complex watershed models include: BASINS (Better Assessment Science Integrating Point and Nonpoint Sources), HSPF (Hydrologic Simulation Program—Fortran), SWAT (Soil and Water Assessment Tool), SWMM (Storm Water Management Model), and SPARROW (SPA*tially* R*eferenced* R*egressions* O*n* W*atershed Attributes)*.

Improved methods for determining model inputs for event mean concentrations are available. Automated, discharge-weighted sampling produced fewer errors than random grab, seasonal first-flush, and hydrograph peak sampling strategies. Finer scale spatial and temporal data and modeling approaches have the potential to elicit detailed information about the watershed characteristics influencing (1) recharge to ground water and (2) discharge by overland runoff and pollutant loading to surface water in the Sarasota Bay watershed.

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