Hydrologic Conditions that Influence Streamflow Losses in a Karst Region of the Upper Peace River, Polk County, Florida

By P.A. Metz and B.R. Lewelling

Prepared in cooperation with the
Southwest Florida Water Management District

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre (ac)	4,047	square meter (m^2)
acre (ac)	0.4047	hectare (ha)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.003785	cubic meter per minute (m^3/min)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Temperature	
Celsius (°C)	°F = (1.8 × °C) + 32	Fahrenheit (°F)
Fahrenheit (°F)	°C = (°F - 32) / 1.8	Celsius (°C)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

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

*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.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Acronyms and Additional Abbreviations

AMO	Atlantic Multidecadal Oscillation
EM	electromagnetic
FDEP	Florida Department of Environmental Protection
GPS	global positioning system
µS/cm	microsiemens per centimeter
NOAA	National Oceanic and Atmospheric Administration
PDSI	Palmer Drought Severity Index
ROMP	Regional Observation Monitoring Program
SWCFGB	Southern West-Central Florida Groundwater Basin
SWFWMD	Southwest Florida Water Management District
USGS	U.S. Geological Survey
WWTP	Waste Water Treatment Plant (Bartow)

Juvenile alligator; Gator Sink Distributary
Photo credit: P.A. Metz, USGS

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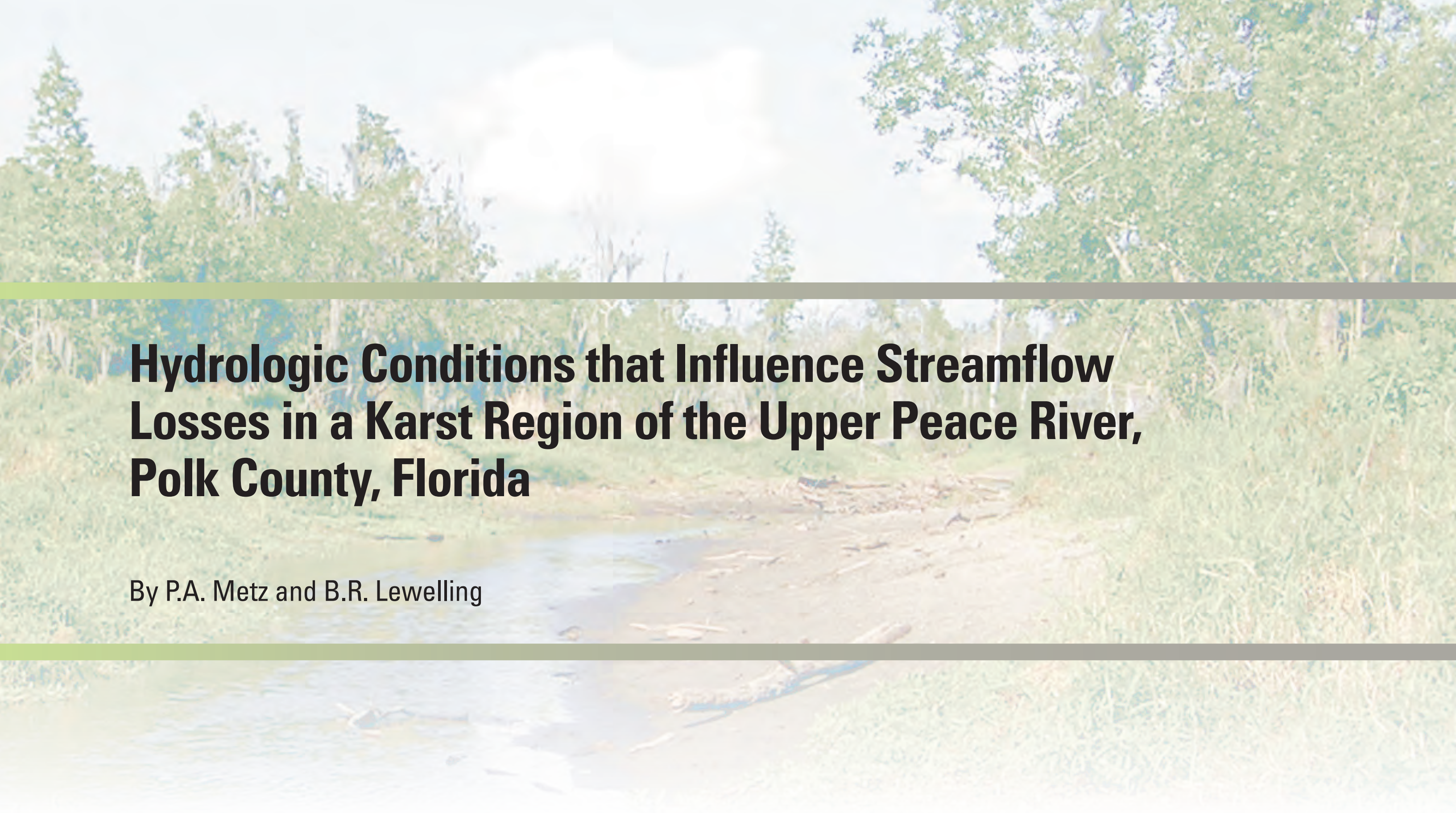


Hydrologic Conditions that Influence Streamflow Losses in a Karst Region of the Upper Peace River, Polk County, Florida

By P.A. Metz and B.R. Lewelling

Abstract

The upper Peace River from Bartow to Fort Meade, Florida, is described as a groundwater recharge area, reflecting a reversal from historical groundwater discharge patterns that existed prior to the 1950s. The upper Peace River channel and floodplain are characterized by extensive karst development, with numerous fractures, crevasses, and sinks that have been eroded in the near-surface and underlying carbonate bedrock. With the reversal in groundwater head gradients, river water is lost to the underlying groundwater system through these karst features. An investigation was conducted to evaluate the hydrologic conditions that influence streamflow losses in the karst region of the upper Peace River.

The upper Peace River is located in a basin that has been substantially altered by phosphate mining, changes in land use, and increases in groundwater use. These alterations have changed groundwater flow patterns and caused streamflow declines through time. Hydrologic factors that have had the greatest influence on streamflow declines in the upper Peace River include the lowering of the potentiometric surfaces of the intermediate aquifer system and Upper Floridan aquifer beneath the riverbed elevation due to below-average rainfall (droughts) and groundwater use, and the presence of numerous karst features in the low-water channel and floodplain that enhance the loss of streamflow. Other hydrologic factors that influence the decline in streamflow include changes in the natural drainage patterns of contributing streams to the upper Peace River, and altered surface sediments that affect surface runoff, infiltration, and baseflow characteristics.

During this study (2002-2007 water years[1]), streamflow was influenced by climatic conditions. The discharge in the river was greatest for the 2005 water year as a result of above-average rainfall that occurred over a 3-year period (2003-2005). Average annual discharge for the 2005 water year at the Peace River at Bartow gaging station was 545 cubic feet per second, more than double the long-term average of 227 cubic feet per second for the 68 years of record. The discharge in the river was lowest during the 2007 water year, when the cumulative rainfall deficit was almost 29 inches over a 2-year period (measured from the long-term average rainfall of 54 inches). Average annual discharge for the 2007 water year was only 18 cubic feet per second, and was the lowest on record for Peace River at Bartow.

Seepage runs conducted along the upper Peace River, from Bartow to Fort Meade, indicate that the greatest streamflow losses occurred along an approximate 2-mile section of the river, beginning about 1 mile south of the Peace River at Bartow gaging station. Along the low-water and floodplain channel of this 2-mile section, there are about 10 prominent karst features that influence streamflow losses. Losses from the individual karst features ranged from 0.22 to 16 cubic feet per second based on measurements made between 2002 and 2007. Along the upper part of this 2-mile section (in Reach 1), the largest and most consistent streamflow losses

[1]A 12-month period (October 1 through September 30), is typically used by the USGS for hydrologic data analysis. The water year includes parts of two calendar years; for example, the 2007 water year begins on October 1, 2006 and ends September 30, 2007.

occurred at the Ledges Sink, with measured losses ranging from 1 to 8 cubic feet per second. At the end of this 2-mile section (in Reach 2) is the most influential karst feature along the upper Peace River, Dover Sink, which had measured losses ranging from 2 to 16 cubic feet per second. The largest measured flow loss for all the karst features in Reaches 1 and 2 was about 50 cubic feet per second, or about 32 million gallons per day, on June 28, 2002.

Streamflow losses were related to the decline in the potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer below the riverbed elevation during below-average conditions along the upper Peace River. When groundwater levels were at their lowest level at the end of the dry season (May and June), there was an increased potential for streamflow losses. During this study, the largest streamflow losses occurred at the beginning of the summer rainy season when discharge in the river increased and large volumes of water were needed to replenish unfilled cavities and void spaces in the underlying aquifers.

The response of the river to changing groundwater levels was different in Reach 1 than in Reach 2. In Reach 1, the intermediate aquifer system is hydraulically connected to the river, and streamflow losses during below-average conditions were proportional to water-level changes in this aquifer. During the dry season in Reach 1, there was an increased potential for streamflow losses as aquifer levels declined, and as aquifer levels increased during the rainy season, streamflow gains were noted in Reach 1. However, in Reach 2 the relation between streamflow losses and aquifer level declines is more complex. In Reach 2, the upper Peace River is connected to both the intermediate aquifer system and the Upper Floridan aquifer through a large conduit system that is associated with Dover Sink. Because this conduit system is very large, it can accommodate a large proportion of flow from the river at multiple river stages.

The underlying geology along the upper Peace River and floodplain is highly karstified, and aids in the movement and amount of streamflow that is lost to the groundwater system in this region. Numerous karst features and fractured carbonates and cavernous zones observed in geologic cores and geophysical logs indicate an active, well-connected, groundwater flow system. Aquifer and dye tests conducted along the upper Peace River indicate the presence of cavernous and highly transmissive layers within the floodplain area that can store and transport large volumes of water in underground cavities. A discharge measurement made during this study indicates that the cavernous system associated with Dover Sink can accept more than 10 million gallons per day (16 cubic feet per second) of streamflow before the localized aquifer storage volume is replenished and the level of the sink stabilizes. Dover Sink stabilized when the pool of the sink rose to the level of the Peace River, which was about 87 feet above NGVD 1929, and water levels of the interconnected aquifers were about 78 feet above NGVD 1929.

Introduction

The upper Peace River from Bartow to Fort Meade, Florida, is described as a groundwater recharge area, reflecting a reversal from historical groundwater discharge patterns that existed prior to the 1950s (fig. 1; Lewelling and others, 1998). Historically, the floodplain along the upper Peace River contained artesian wells and a second magnitude spring (Kissengen Spring) that discharged an average of 20 million gallons per day (Mgal/d) into the Peace River (Peek, 1951; Stewart, 1966). However, hydrologic conditions began to change as early as the 1930s, with an increase in groundwater use for mining and agriculture (Peek, 1951). Because of this increased water use, a 40-foot (ft) decline in groundwater levels over a 20-year period resulted in the cessation of flow of the artesian wells and Kissengen Spring (Peek, 1951).

The upper Peace River is located in an area where the river and floodplain channels are characterized by extensive karst development where numerous fractures, crevasses, and sinks have been eroded in the carbonate river channel. Because of the reversal in groundwater head gradients, river water is lost to the underlying groundwater system through these karst features. A trend analysis of long-term streamflow data from the U.S. Geological Survey (USGS) Bartow gaging station shows a significant decline in streamflow during the 1940s, 1950s, and 1960s, whereas streamflow during the 1970s remained statistically unchanged (Hammett, 1990). Another trend analysis conducted from the 1970s to 2003 indicates a continuing decline in streamflow (Spechler and Kroening, 2007).

Over time, declines in streamflow and groundwater levels have been influenced by a number of factors. Losses have been attributed to the following: (1) long-term rainfall deficits and changes in wet season rainfall patterns (Basso and Schultz, 2003); (2) large groundwater withdrawals that have lowered the potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer beneath the riverbed (Peek, 1951); (3) changes in the natural drainage patterns of contributing streams to the Peace River resulting from agricultural, urban, and phosphate-mining development (Florida Department of Environmental Protection, 2007); (4) strip mining of phosphate that has altered the surface sediments, which affects surface runoff, infiltration, and baseflow characteristics of the basin (Lewelling and Wylie, 1993); and (5) numerous karst features that are found in the low-water channel and floodplain and have enhanced the loss of perennial flow (Patton and Klein, 1989).

The karst features along the upper Peace River play an important role in the loss of streamflow. A number of studies have documented these karst features, but little was known about the timing, duration, and the amount of streamflow that is lost to these features over varying hydrologic conditions. To gain a better understanding of the streamflow losses along the upper Peace River, the USGS, in cooperation with the Southwest Florida Water Management District

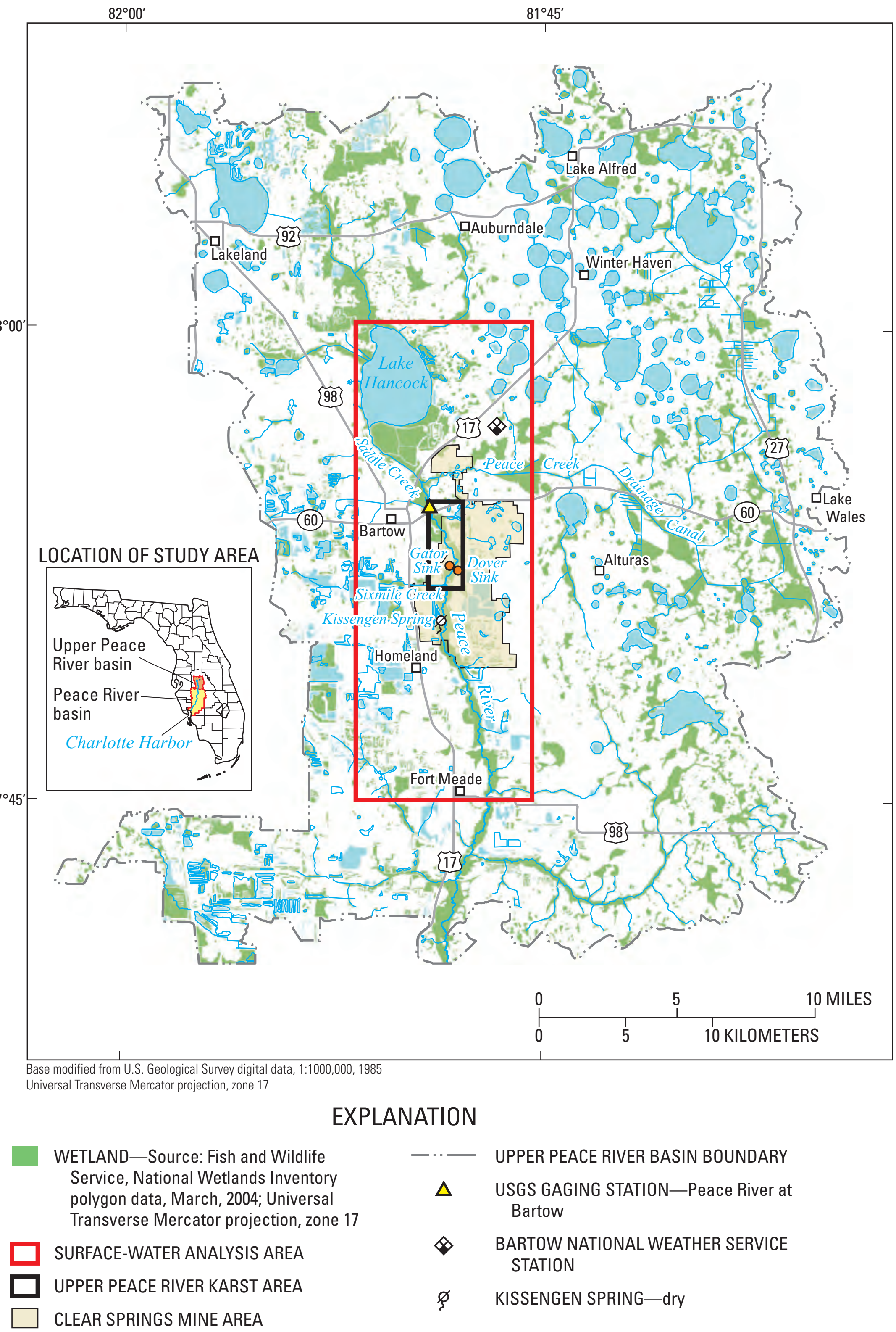


Figure 1. Location of the upper Peace River basin and the localized study areas along the upper Peace River, Polk County, Florida.

(SWFWMD), began a study in 2002 to assess the effects of karst development and groundwater conditions on streamflow losses. A broader understanding of the interaction between surface and groundwater watersheds and their relation to differing geologic settings is an important component of the USGS Strategic Plan. The data collected and knowledge gained during this investigation provide an understanding of the specific role that karst features play in streamflow losses in the upper reaches of the Peace River. These data and the results of this study also can be used to help determine the minimum hydrologic conditions needed to maintain continuous flow for the ecosystems associated with the upper Peace River (Southwest Florida Water Management District, 2002a).

Purpose and Scope

This report describes the hydrologic conditions that influence streamflow losses in a karst region of the upper Peace River in Polk County, Florida. For analysis purposes, the study area was composed of the larger upper Peace River basin and two smaller localized areas—the surface-water analysis area and upper Peace River karst area (fig. 1). The report provides the following information: (1) a historical retrospective of the hydrology and climate of the upper Peace River basin, (2) an analysis of land and groundwater use within the upper Peace River basin, (3) a description of the hydrogeologic framework and water chemistry of the geologic formations underlying the upper Peace River, (4) an inventory of prominent karst features along the upper Peace River karst area, (5) an analysis of the upper Peace River streamflow characteristics during the 2002 through 2007 water years, (6) documentation of streamflow losses to prominent karst features during the 2002 through 2007 water years, and (7) an analysis of the geologic and hydraulic connection between the upper Peace River and the underlying aquifers. Information used during this study consisted of hydrologic, lithologic, geophysical, and water-chemistry data collected from May 2002 to September 2007.

Methods of Investigation

During this investigation, the hydraulic connection between the upper Peace River and the underlying aquifers was defined using a number of hydrogeologic techniques. To define the rock formations and aquifer properties along the upper Peace River, wells were drilled in the surficial aquifer, intermediate aquifer system, and Upper Floridan aquifer at three sites along the Peace River floodplain between Bartow and the historic Kissengen Spring site. These wells provided the basis for the analysis of the hydrogeologic framework, hydraulic properties and groundwater flow patterns, and water chemistry.

To define the hydrogeologic framework, continuous geologic cores were collected from land surface to depths ranging from about 300 to 575 ft at the three well sites. These cores were collected and photographed by SWFWMD and described lithologically by the Florida Geological Survey in Tallahassee, Florida. To define the hydraulic properties and aquifer characteristics of the rock-bearing formations underlying the upper Peace River basin, aquifer performance tests, geophysical logging, and downhole video analyses were conducted at all three well sites by SWFWMD (Gates, 2009). These techniques helped determine the permeability of the aquifers, locations of cavities, solution conduits, fracture zones, the occurrence of clays, and other geologic features associated with the formations.

Borehole geophysical surveys were conducted at the three well sites to aid in the determination of aquifer properties. Geophysical logs collected included caliper, gamma, temperature, fluid conductivity, and fluid resistivity. In addition, electromagnetic (EM) flow and heat-pulse flowmeter logs were used to determine where flow zones are present within the hydrogeologic units at the well sites. Video logs also were obtained at a number of wells in the study area to visually inspect the aquifer within the borehole. The combined log information provided an understanding of well construction, contacts between hydrogeologic units, zones of inflow and outflow, chemical properties of water in the borehole, and locations of fractures and cavities. Individual log and borehole logging techniques are discussed in reports by Keys and MacCary (1971) and Keys (1990).

To understand the groundwater flow patterns along the upper Peace River, 12 continuous monitoring wells were used to define water-level trends in the surficial aquifer, intermediate aquifer system, and the Upper Floridan aquifer. In addition, wells located throughout the upper Peace River basin that were completed in the Upper Floridan aquifer were used to construct potentiometric-surface maps during wet and dry periods. Continuous water-level recorders also were placed on two prominent karst features, Dover and Gator Sinks, which were used to help understand the hydrologic responses of these features to streamflow losses.

To help determine the hydrologic relations between the river and the underlying aquifers, as well as the influence of the karst features, water levels were compared between hydrologic units. Linear regression analyses (coefficient of determination, r^2) also were used to help determine the strength of these water-level relations. A significant statistical relation indicates a high degree of interconnection between the river and the underlying aquifers or between aquifers ($r^2 = 1.00$).

Water-quality and stable isotopic samples were collected from the Peace River and from selected wells located in the intermediate aquifer system and Upper Floridan aquifer. Water-quality data were used to define the hydrochemical characteristics of the river water and the underlying groundwater system. Stiff diagrams (Stiff, 1951) were used to compare hydrochemical characteristics among sites. Stable isotopic samples (deuterium and oxygen-18) were used to help determine flow patterns between the river and the underlying groundwater system. The SWFWMD collected and analyzed the water samples for major ions, and the USGS collected and analyzed the water samples for isotopic composition. Each well was sampled four times for major ions and once for isotopic composition between May 2006 and March 2007. Established sampling protocols were used when collecting samples (Wilde and others, 1998; Southwest Florida Water Management District, 2006).

To evaluate streamflow conditions along the upper Peace River, 10 USGS continuous gaging-stations, located along the river and adjoining tributaries, were used to measure seasonal changes in flow. Hundreds of discharge measurements were made on the river and tributaries during the 2002-2007 water years to establish their respective stage-discharge rating curves. These stage-discharge rating curves are not stable, and are regularly adjusted, because the hydrodynamics of a stream or a river change constantly (Rantz and others, 1982). For example, flow along the upper section of the river was restricted by a large accumulation of aquatic vegetation that choked this section of the river during the summer months. Field observations indicated that herbicide spraying was used to remove the aquatic vegetation in Saddle Creek, Peace Creek Drainage Canal, and the upper Peace River during this period. In addition, stage-discharge relations changed substantially after trees downed by the 2004 hurricanes were cleared from the channels. Therefore, ratings were adjusted periodically based on field-discharge measurements.

Flow measurements were made using various methods depending on flow conditions. These methods included using portable flumes, a standard (type AA) current meter, a pygmy current meter, an acoustic Doppler velocimeter, and a high-water acoustic Doppler current profiler. All measurements were made using standard procedures and protocols (Rantz and others, 1982; Oberg and others, 2005). Surface and ground-water data are available in the annual USGS water data reports for southwest Florida (Kane and Fletcher, 2002a,b; Kane and others, 2003a,b; Kane, 2004a,b; 2005; Kane and Dickman, 2005; U.S. Geological Survey, 2006b; 2007b) and from the USGS National Water Information System database at *http://waterdata.usgs.gov/nwis*.

Data errors are inherent in discharge-rating curves (Rantz and others, 1982). Some of these errors may be caused by uncertainties associated with the measuring instruments, streamflow conditions, or human errors made while making the field measurements. Therefore, data derived from these curves should be used as a guide to understand variations in streamflow under varying hydrologic conditions, with the understanding that there is a degree of uncertainty and error associated with the discharge data. Typically, discharge measurements are subject to errors ranging from ±5 to 8 percent of the measured flow (Slade and Buszka, 1994). Measurements in the field are rated based on a scale of good (±5 percent error), fair (±8 percent error), and poor (>8 percent error). Measurements made at extremely high-flow conditions have a higher error associated with the measurements (±10 percent error). Most of the field measurements made during this investigation were rated as good to fair, and an error of ±5 to 8 percent should be considered as typical when evaluating the data presented in this report.

To help quantify current and historical streamflow characteristics of the upper Peace River, daily discharge-duration hydrographs at the Peace River at Bartow gaging station were used. These hydrographs were based on historical mean daily flows for each day of the year at Peace River at Bartow for the period of record (1940-2007 water years). In addition, discharge-duration curves for the 2003-2007 water years were used to compare streamflow conditions among the following gaging stations: Peace River at Bartow, Peace River near Bartow, and Peace River at Clear Springs. These graphs represent the percentage of time during which a given value of discharge at each gaging station was equaled or exceeded.

To define where streamflow losses and gains in the upper Peace River occurred, seepage runs were conducted along a 13-mile (mi) segment of the river, from Bartow to Fort Meade (fig. 1). The seepage runs were conducted as a series of synoptic streamflow measurements that were made at selected cross sections along the 13-mi length of the river. When the reaches of greatest streamflow losses were identified, the scope of subsequent seepage runs was narrowed to an approximate 3-mi karst region (fig. 1). The seepage runs were performed during the dry season, when rainfall was at a minimum and most streamflow was derived from groundwater seepage (baseflow) instead of runoff. Measurement errors and their relation to changes in streamflow during the time period of the seepage run were taken into consideration. An inherent error of ±5 to 8 percent, typical of measurements made in a natural stream environment (Rantz and others, 1982), was considered appropriate for the analyses of these seepage runs. Changes in discharge greater than this associated error (±5 percent) were considered as net changes. Net gains or losses within measurement error were not considered significant.

Prominent karst features in the low-water channel and floodplain were documented by global positioning system (GPS) latitude-longitude coordinates, and surface orientations and dimensions were measured. During the study, these features were found to be continuously changing because of scour and fill streamflow depositional processes, and photographs were taken to document these changes. For example, the effects of three major hurricanes passing through the area in 2004 caused some of the karst features to fill with sand, and in 2007 other observed karst features were enlarged due to increased scouring from river flow.

Several methods were used to quantify streamflow losses to the karst features. One method involved making discharge measurements in the channel directly above where the water flowed into the karst feature. The second method involved measuring discharge in the sections above and below the karst feature, and calculating the flow loss as the difference between these measurements. Measurements that bracket the karst features had the higher degree of uncertainty because of possible seepage losses through the riverbed between measurement sections.

Previous Investigations

Previous investigations have contributed to the understanding of the hydrogeology, water use, and karst development in the upper Peace River basin. Many studies that describe the general geology of central Florida have references to Polk County. Some of the early investigators include Matson and Sanford (1913), Stringfield (1936), Applin and Applin (1944), Cooke (1945), Vernon (1951), and Carr and Alverson (1959).

Stewart (1966) describes the geologic characteristics of Polk County and also provides detailed information pertaining to the hydrology. A section of Stewart's report also describes solutions features, cavities, and sinkholes in Polk County. Spechler and Kroening (2007) present an updated appraisal of the groundwater and surface-water resources of Polk County and describe the current hydrologic trends.

Updated descriptions of geology and hydrogeology of the Floridan aquifer system and the intermediate aquifer system in the study area are in reports by Ryder (1985) and Miller (1986). Scott (1988) describes the lithostratigraphy of the Hawthorn Group of Miocene age; Duerr and others (1988) define the hydrogeologic framework of the intermediate aquifer system; and Knochenmus (2006) evaluates the hydrogeologic framework, hydraulic properties, and chemical characteristics of the intermediate aquifer system. Especially pertinent to this study is the report by Gates (2009), which describes the aquifer properties at three monitor well sites along the upper Peace River that were drilled as part of this investigation.

Several investigators have discussed the karst hydrology of the upper Peace River basin. The study by Vernon (1951) suggests that the extensive fracturing in the rocks in Polk County greatly influences the groundwater hydrology. Stewart (1966) suggests that major cavernous development, which occurs along these fractures zones, enhances the water-transmitting ability of the underlying limestone. Sinclair and others (1985) characterizes the study area as being susceptible to sinkhole development and describes how various types of sinkholes form. Basso (2003) describes groundwater conditions and surface-water/groundwater interactions in the upper Peace River basin.

A number of investigations describe the locations of the karst features in the upper Peace River karst area and how these features affect the local hydrology. Patton (1981) and Patton and Klein (1989) mapped more than 90 sinkholes and discuss sinkhole formation and its effect on Peace River hydrology. McQuivey and others (1981) presented an experiment where rhodamine dye was injected into a major sink (Dover Sink), and described how the dye traveled south through an area where the intermediate aquifer system and Upper Floridan aquifer are interconnected. Lewelling and others (1998) documented that the greatest streamflow losses in the entire Peace River basin occur in the upper reaches of the Peace River. Knochenmus (2004) documented the upper Peace River karst features and defined the flow losses during a low-water period.

Numerous reports discuss water use and the effects of groundwater pumping in Polk County. Peek (1951) related the cessation of flow of Kissengen Spring to the excessive use of groundwater for mining operations. Kaufman (1967), Robertson and Mills (1974), and Hutchinson (1978) describe the effects of groundwater pumping in the upper Peace River basin. The first inventory of well records and other water-resource data in Polk County was presented in a report by Stewart (1961). Current groundwater withdrawals and trends in groundwater use in Polk County are discussed in reports by Marella (2004), Marella and Berndt (2005), and Spechler and Kroening (2007).

Brown and Tighe (1991) and Lewelling and Wylie (1993) discuss the effects of mining on the hydrology of the Peace River basin. The Peace River Cumulative Impact Study by Florida Department of Environmental Protection (2007) assesses the cumulative impacts of certain anthropogenic and natural stresses on historical changes in streamflow in the Peace River, and discusses rainfall and streamflow trends in the upper Peace River basin.

Upper Peace River Basin Characteristics

The Peace River is formed by the merging of Saddle Creek and the Peace Creek Drainage Canal, which both rise in the uplands of east and central Polk County (fig. 1). From the confluence of these streams, the river flows southward for 105 mi to Charlotte Harbor. The upper Peace River basin, as described in this study, extends south from an area near Lake Alfred to near Fort Meade (fig. 1). The upper basin drains about 790 square miles (mi^2), and encompasses an area about one-third of the size of the entire Peace River basin.

The upper Peace River basin partly resides within the Polk Upland, which is a poorly drained plateau that contains flatwoods, wetlands, and lakes (White, 1970; Brooks, 1981) (fig. 2). Adjacent to the upper Peace River and within the described basin are the Winter Haven Ridge and three northwest to southeast trending ridges: the Lake Henry, Gordonville, and Lakeland Ridges (White, 1970; Brooks, 1981). The easternmost extension of the upper Peace River basin is the Lake Wales Ridge, which is the highest and longest of the ridges that are present on the Florida peninsula. These ridges are remnant shoreline features and are the dominant landforms in the upper Peace River basin (Schmidt, 1997). These sandy ridges are internally drained with rapid recharge, and are prone to sinkhole development (Brooks, 1981). Land-surface elevation ranges from about 80 ft near Fort Meade to about 305 ft above NGVD 1929 along the Lake Wales Ridge.

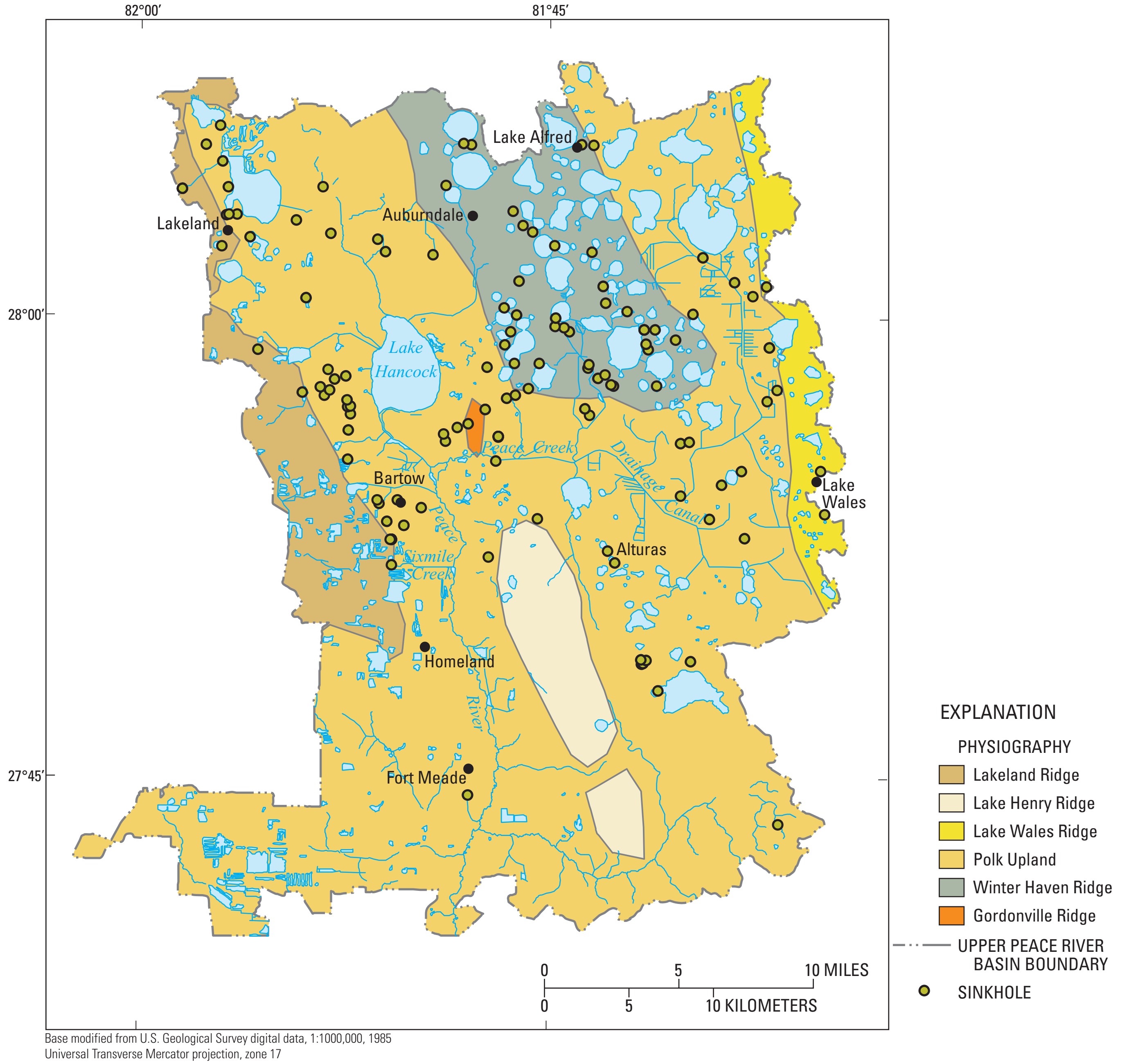


Figure 2. Physiographic subdivisions and location of sinkholes in the upper Peace River basin.

Sinkholes are prevalent throughout the upper Peace River basin and are in various stages of development, including ancient stable depressions and those formed recently. More than 140 sinkholes have been documented in the upper Peace River basin (fig. 2), and more than 90 sinkholes, fractures, and crevasses (not shown in fig. 2) have been documented along the upper Peace River floodplain (Patton, 1981). Karst features identified along the Peace River bed are discussed in a subsequent section (Karst Features along the Upper Peace River).

The sinkholes in the upper Peace River basin range in size from 10 to greater than 100 ft in diameter, and in depth from 5 to 200 ft below land surface. The shallow depressions usually contain swamps or cypress domes, whereas deeper depressions extending as much as 200 ft below land surface commonly infill with sand and water and form sinkhole lakes. The numerous closed basin lakes and sinkholes of the Winter Haven and Lake Wales Ridges indicate solutional activity in the geologic past. Collectively, the sandy ridges interspersed with sinkhole-formed lakes produce a setting capable of storing and recharging rain and shallow groundwater to deeper aquifers. Recharge is greater than 10 inches per year (in/yr) along the Lakes Wales and Winter Haven Ridges but is lower along the upper Peace River basin (0 to 5 in/yr) due to increased confinement between the surficial aquifer and Upper Floridan aquifer (Aucott, 1988; Yobbi, 1996).

Climate

Warm, wet summers and relatively mild, dry winters and springs characterize the subtropical climate of the study area. Rainfall varies seasonally, and more than half the annual rainfall typically occurs during the summer months (June through September). Rainfall can be unevenly distributed throughout the study area during the summer rainy season, because it is derived from localized, convective thunderstorms. Winter rainfall is more evenly distributed, because storms generally come from frontal air masses that move from north to south across the State.

The long-term (1900-2007) average annual rainfall from the National Weather Service Bartow station is about 54 in. (National Oceanic and Atmospheric Administration, 2007). Rainfall was summarized by water years in this study so that comparisons could be made between rainfall and streamflow. Yearly rainfall and the departure from the long-term average rainfall by water year are shown in figures 3A and 3B, respectively. The lowest rainfall recorded was about 32 in. in the 1950 water year, and the greatest was about 83 in. in the 2003 water year. Some of the lowest annual rainfall totals for the 107-year period of record occurred during this investigation; rainfall at the Bartow station was about 40 and 37 in. in water years 2006 and 2007, respectively.

Hydrologic conditions in the study area are directly related to seasonal variations in rainfall. For example, at the beginning of the rainy season, a large percentage of the rainfall is incorporated into surface and groundwater storage (Basso and Schultz, 2003). At the end of the rainy season, surface- and groundwater levels are high and much of the rainfall goes directly to runoff (Ross and others, 2001). On average, monthly rainfall at Bartow is lowest in November, followed by December, January, and April, whereas monthly rainfall is highest in July, followed by June, August, and September. Analysis of the last 11 years of rainfall record (1997-2007) indicates a reduction in rainfall during June and also during the latter part of the rainy season (September).

Assessing the long-term regional rainfall cycles gives insight to natural and anthropogenic hydrologic changes in streamflow and groundwater levels (Basso and Schultz, 2003). One such climatic cycle, the Atlantic Multidecadal Oscillation (AMO), helps describe the historical climatic changes of the study area (Gray and others, 1997; Landsea and others, 1999; Enfield and others, 2001). The AMO is defined by the warming or cooling surface temperatures of the oceans that affect rainfall patterns (Gray and others, 1997). The warm and cool phases of the AMO are shown in figure 3B. Research also suggests that during periods of cooler ocean temperatures in the Pacific Ocean, less rainfall occurs during the winter-early spring season across peninsular Florida and, conversely, warmer ocean temperatures in the Atlantic Ocean produce more summer rainfall (Enfield and others, 2001; Basso and Schultz, 2003; Kelly, 2004).

The 5-year moving average of the departure of rainfall from the period of record indicates a trend in the AMO and its relation to rainfall within the study area (fig. 3B). For example, during the warm AMO period from 1925 through 1969 (fig. 3B), there were periods of above-average rainfall and concurrent increases in tropical storm activity. During the cool AMO period from 1970 through 1995 (fig. 3B), periods of below-average rainfall were concurrent with decreased tropical storm activity (Gray and others, 1997; Landsea and others 1999). The current (1996-present) warm AMO phase is characterized by increased tropical storm activity in peninsular Florida.

Climatic conditions had a major influence on the hydrology of the study area, and the period of this investigation (2002-2007 water years) can be summarized as one of climatic extremes. In 2002, a severe drought was already underway, with a cumulative rainfall deficit of more than 31 in. for the 1999-2002 water years. Conditions changed between the 2003 and 2005 water years, with a cumulative rainfall excess of more than 43 in. for this period (fig. 3B). During a 6-week period from August through September 2004, three major hurricanes (Charley, Frances, and Jeanne) crossed the study area. However, climatic conditions again changed between 2006 and 2007, with below-average rainfall leading to another drought period. During the 2006 and 2007 water years, the cumulative rainfall deficit was almost 29 in., causing reduced streamflow in the upper Peace River. During these water years, a majority of the rainfall deficit occurred during the spring and summer months.

The Palmer Drought Severity Index (PDSI) for the Bartow station was used to evaluate the climatic conditions of the study area from October 2000 to September 2007. The PDSI is a measure of dryness, and is based on a model of soil moisture that accounts for rainfall and temperature (Palmer, 1965). This index uses zero as the normal value, whereas droughts are shown as negative numbers with -4 (and below) as the extreme drought condition, and wet periods are shown as positive numbers with +4 (and above) as the extreme. Weekly PDSI readings averaged to monthly conditions show the severity of the drought in 2000 that continued into the summer of 2002 for the Bartow area (fig. 4). The PDSI indicates wet conditions from July 2002 to August 2005, and moderate drought conditions from September 2005 to September 2007 (fig. 4).

In addition to rainfall, evaporation also plays an important role in the hydrology of the study area. Evaporation rates are high in Florida, and are greater than in most other areas of the country (Farnsworth and others, 1982). High evaporation rates in this subtropical climate are primarily due to high solar radiation and water temperatures. Long-term

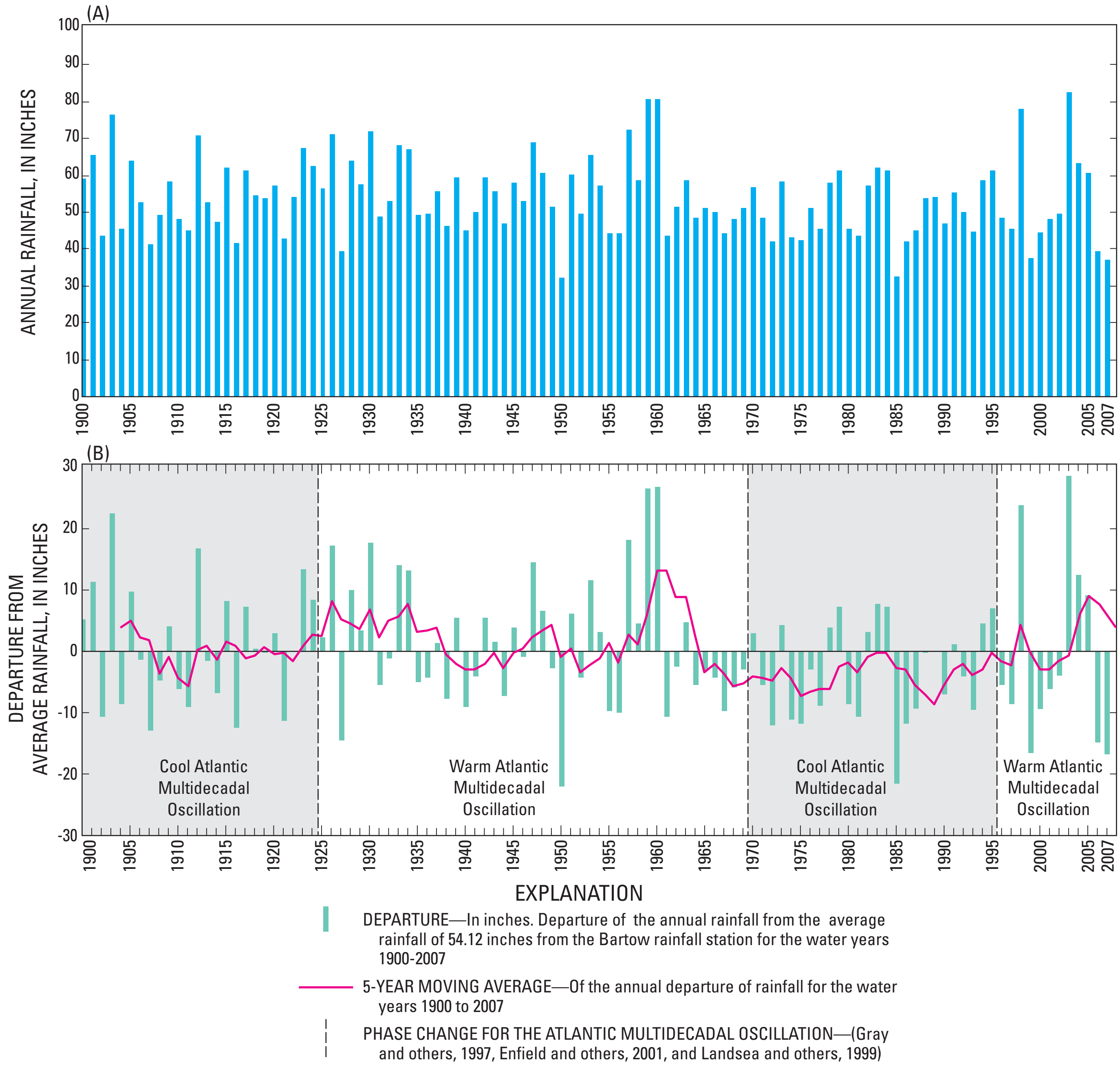
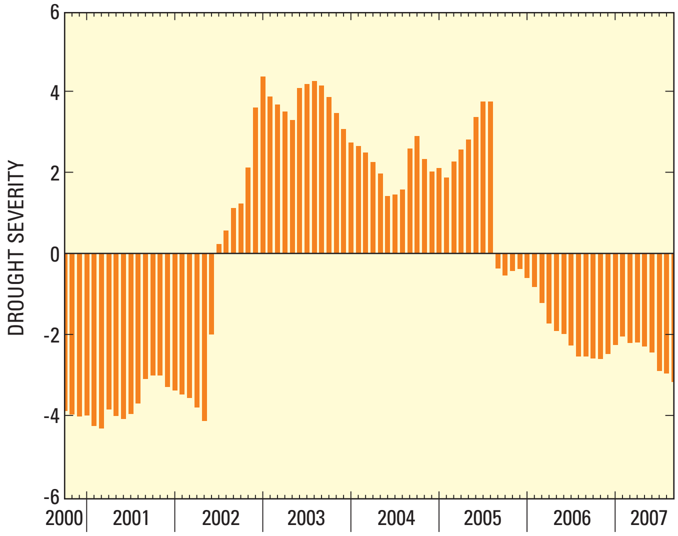


Figure 3. (A) Annual rainfall at Bartow, Florida (1900-2007), and (B) rainfall departure, 5-year moving average of this departure, and changes in the Atlantic Multidecadal Oscillation (location of weather station is shown in fig. 1).

estimates of annual shallow lake evaporation range from 48 to 59 in. in central Florida, and can vary depending on climatic conditions (Farnsworth and others, 1982; Lee and Swancar, 1997; Amy Swancar, USGS, written commun, 2008). Many clay-settling areas exist along the upper Peace River as a result of phosphate-mining extractions, and the clay-lined bottoms of these areas limit their recharge capacity. Water in these ponds typically evaporates instead of recharging the groundwater system, which is a loss of water from the upper Peace River basin that did not occur before mining operations began.



EXPLANATION

4.00 or more	Extremely wet	-0.50 to -0.99	Incipient dry spell
3.00 to 3.99	Very wet	-1.00 to -1.99	Mild drought
2.00 to 2.99	Moderately wet	-2.00 to -2.99	Moderate drought
1.00 to 1.99	Slightly wet	-3.00 to -3.99	Severe drought
0.50 to 0.99	Incipient wet spell	-4.00 or less	Extreme drought
0.49 to -0.49	Near normal		

Figure 4. Palmer Drought Severity Index for the study area for the 2001 to 2007 water years.

Hydrography

The upper reach of the Peace River, near the confluence of the Peace Creek Drainage Canal and Saddle Creek, is characterized by a narrow and shallow streambed that contains shifting sand and sluggish, tannic-colored streamflow. Pond cypress trees line the banks at the confluence, but after a short distance the banks are marked by large piles of mined tailings from previous phosphate-mining operations. For the next 13 mi downstream, numerous elevated clay-settling areas border the area alongside the floodplain, and surface-water drainage to the upper Peace River is limited to phosphate-mine outfalls, stormwater ditches, or reclaimed stream channels.

Historically, a number of streams contributed to the flow in the upper reaches of the Peace River. However, much of the predevelopment drainage system has been altered by phosphate mining and agricultural activities. Maps of the upper Peace River basin created during 1850-1855 show the natural streams prior to their alteration by phosphate mining (fig. 5). The original stream channels are shown for Saddle Creek, Peace Creek, Bear Branch, Sixmile Creek, Cedar Branch, Hamilton Branch, Barber Branch, and an unnamed tributary. These streams show dendritic drainage patterns and channels that are longer than their current configurations.

Figure 6 compares the present and historical hydrography, contrasting the extent of altered stream patterns. Peace Creek, which is now referred to as Peace Creek Drainage Canal, has been substantially altered to accommodate urban and agricultural runoff and flood control. Channelization of Peace Creek has caused sluggish flows or stagnation during medium to low-flow conditions, because the natural streambeds were replaced by wide, flat ditches or canals that have little to no gradient. Saddle Creek, Sixmile Creek, Cedar, Bear, Hamilton, and Barber Branches, as well as an unnamed tributary (now referred to as Phosphate Mine Outfall CS-8), were altered and reclaimed by the phosphate-mining process. The meandering natural streambeds with sloping gradients were typically replaced by flat ditches and clay-settling areas that can store large quantities of water. Runoff is typically stored in these clay-settling areas before discharging to the river. As a result of these impoundments and changes in the natural dendritic flow patterns of these streams, the amount of flow contributing to the upper Peace River has been reduced (Florida Department of Environmental Protection, 2007).

Land Use

Land use within the upper Peace River basin is diverse and continues to change as the population grows and the economy evolves (fig. 7). Major land-use categories in the upper Peace River basin include extracted mined lands (36 percent), agriculture (26 percent), urban development (12 percent), wetlands and forests (11 percent), water bodies (11 percent), and industrial and commercial (4 percent) (Southwest Florida Water Management District, 2007).

Polk County is the eighth most populous county in the State, and 2005 population estimates indicate that the population is expected to increase in the foreseeable future (Office of Economic and Demographic Research, 2005). The largest population in the upper Peace River basin occurs in the northern part of the study area, with Lakeland and Winter Haven being the largest cities in the county. Urban growth is greatest around these cities, with development extending beyond the city boundaries. Municipalities located near the upper Peace River include Bartow, Homeland, and Fort Meade (fig. 7).

Polk County had the second largest amount of agricultural land in the State in 2005, estimated at 626,634 acres (ac) (Polk County Farm Bureau, 2005). In 2004, Polk County ranked first in the State in the amount of commercial citrus groves and fourth in the number of beef and dairy cattle. In the upper Peace River basin, more than 125,000 ac is designated as agricultural land. The largest agricultural land-use categories include tree crops (citrus) and cropland and pastureland (Southwest Florida Water Management District, 2007)

About 15 percent of the area of Polk County has been mined for phosphate rock, and the county ranks first in the State (2005) for phosphate production (Polk County Department of Economic Development, 2005). Phosphate has been mined within the upper Peace River basin since the late 1800s. In 1881, the first discovery of phosphate deposits occurred in the Peace River bed near Fort Meade. This discovery initiated the mining of the largest identified deposit of phosphate rock in the world, known as the "Bone Valley Deposit" (Florida Institute of Phosphate Research, 2006b). The phosphate deposits found in the river are called river pebbles and were extracted from bars of coarse pebbles in and along the upper Peace River during the late 1800s. When these deposits began to be depleted and its extraction became too costly, prospecting for land-pebble deposits was initiated in 1890 along the headwaters of the Peace River near Bartow (Lanquist, 1955).

Phosphate mining for land pebbles played an important role in the development of many of the cities and towns located along the upper Peace River, such as Bartow, Homeland, and Fort Meade. During the 1920s, 1930s, and 1940s, phosphate mining was concentrated near the cities of Bartow and Fort Meade. Mining operations expanded to areas near Homeland by the 1950s, and to the Clear Springs and Kissengen Spring area by the 1960s. Much of the area around the upper Peace River was mined before the State of Florida required mandatory land reclamation in 1975; therefore, some of the land surrounding the upper Peace River has not been reclaimed (Michelle Harmeling, FDEP, Bureau of Mine Reclamation, written commun., 2008).

Phosphate mining for land pebbles involves using huge draglines and buckets to remove vegetation and overburden that is about 30 to 40 ft thick in the study area (Brown, 2005). Draglines and buckets are used to create cuts in the landscape that are 200 to 300 ft wide and up to several thousand feet long (Yon, 1983). The dragline digs out what is known as the matrix, which consists of phosphate rock, sand, and clay. The matrix is then dumped in a pit where high-pressure water guns create a slurry by a process called beneficiation. This slurry is then pumped to the beneficiation plant for further processing (Florida Institute of Phosphate Mine Research, 2006b). At the plant, the phosphate is separated from the sand and clay, the clay is then pumped to a clay-settling area, and the sand is typically pumped back to the site during reclamation. The postmined landscape is generally a combination of water-filled troughs and steep-sloped piles of sand and clay. The topography is often described as resembling a "moonscape" (Brinkmann and Koenig, 2007).

Slurry created by hydraulic pressure (above) then piped to beneficiation plant (below).

Altered landscape created by phosphate mining.

Phosphate mining for river pebbles along the Peace River, late 1800s.

Historical photos from the State Library and Archives of Florida; Department of Commerce collection.

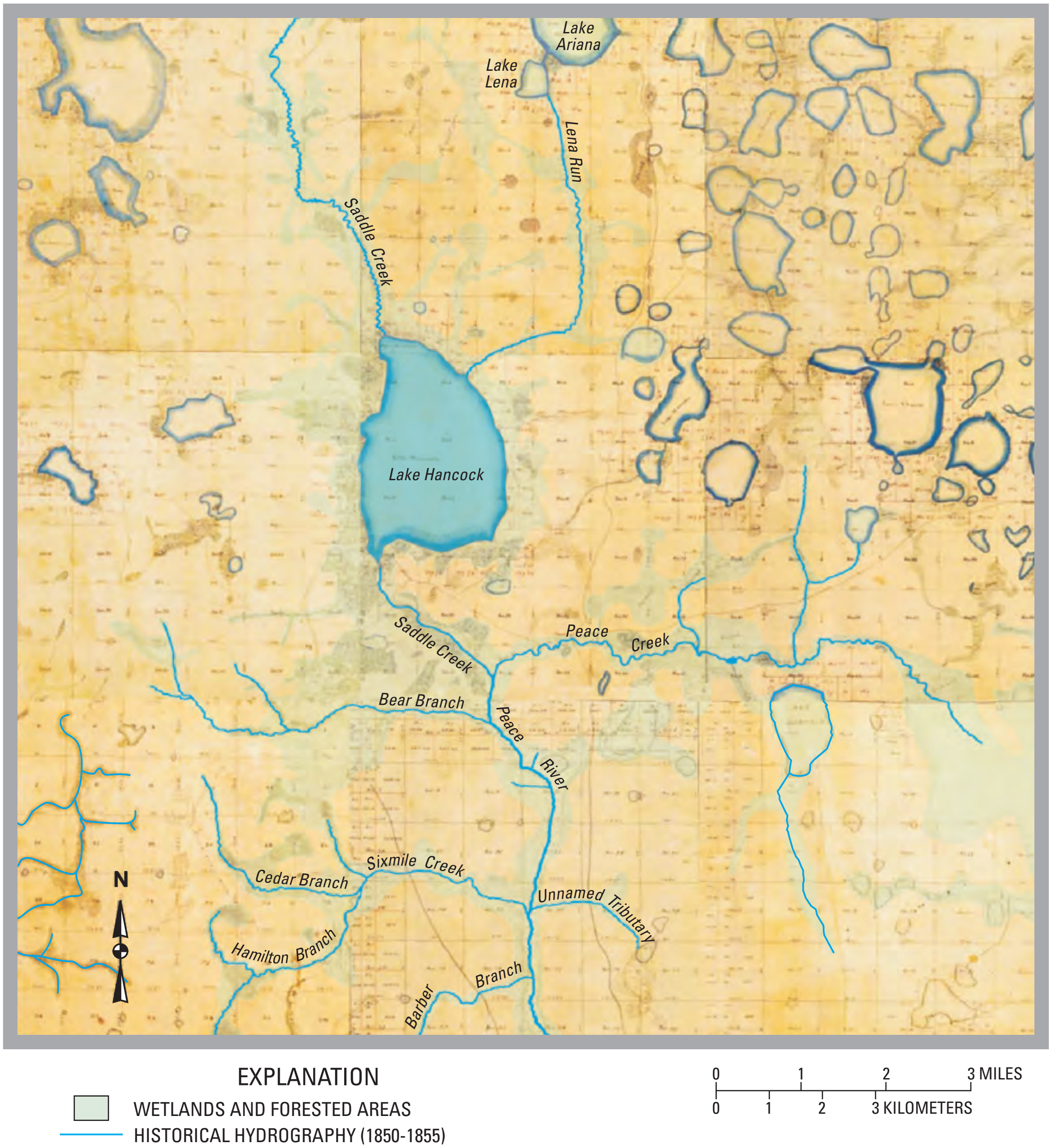


Figure 5. Historical hydrography (1850-1855) of the upper Peace River basin (base maps from the Florida Department of Environmental Protection, 2003).

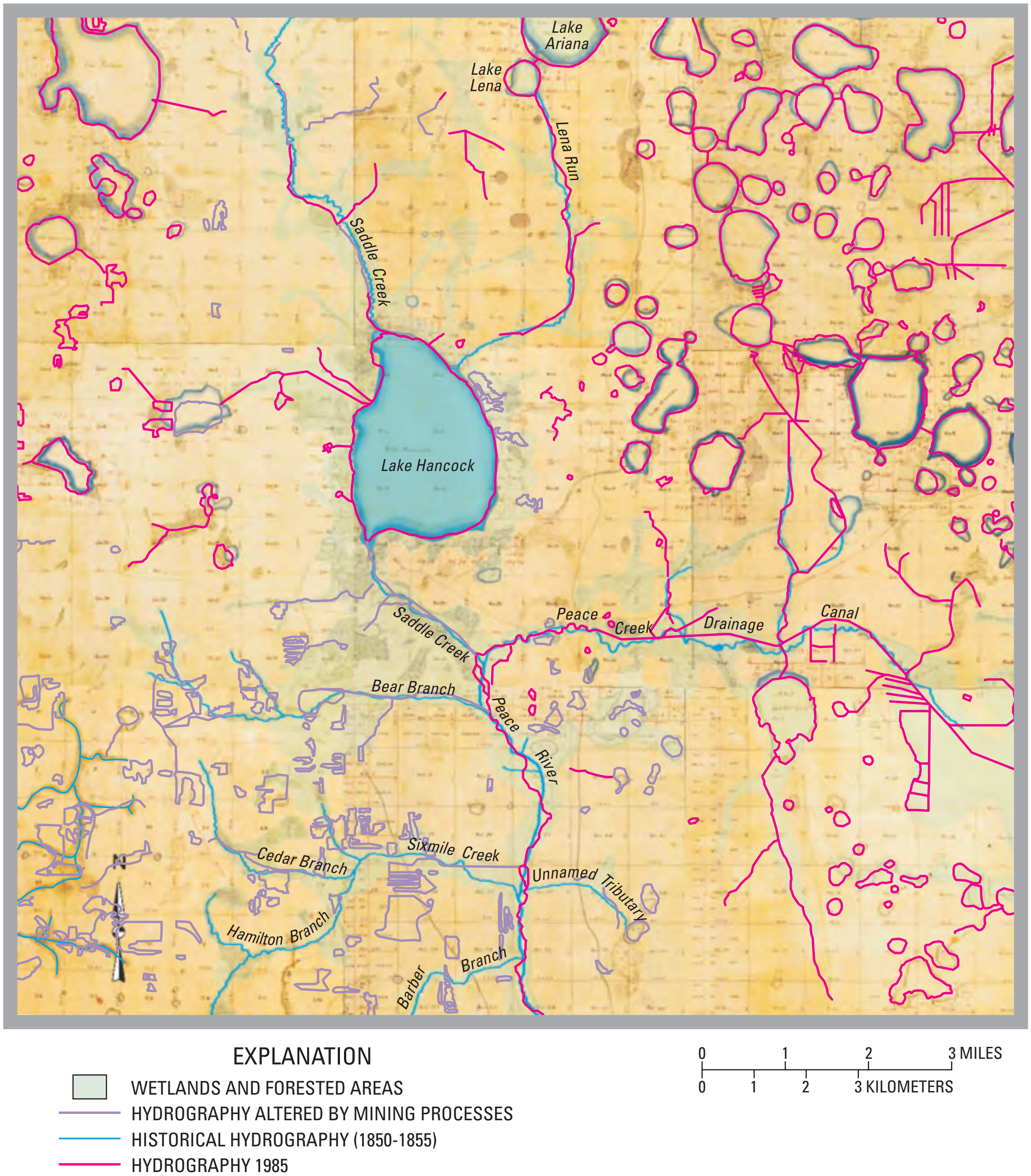


Figure 6. Historical (1850-1855) and current (1985) hydrography of the upper Peace River basin (base maps from the Florida Department of Environmental Protection, 2003).

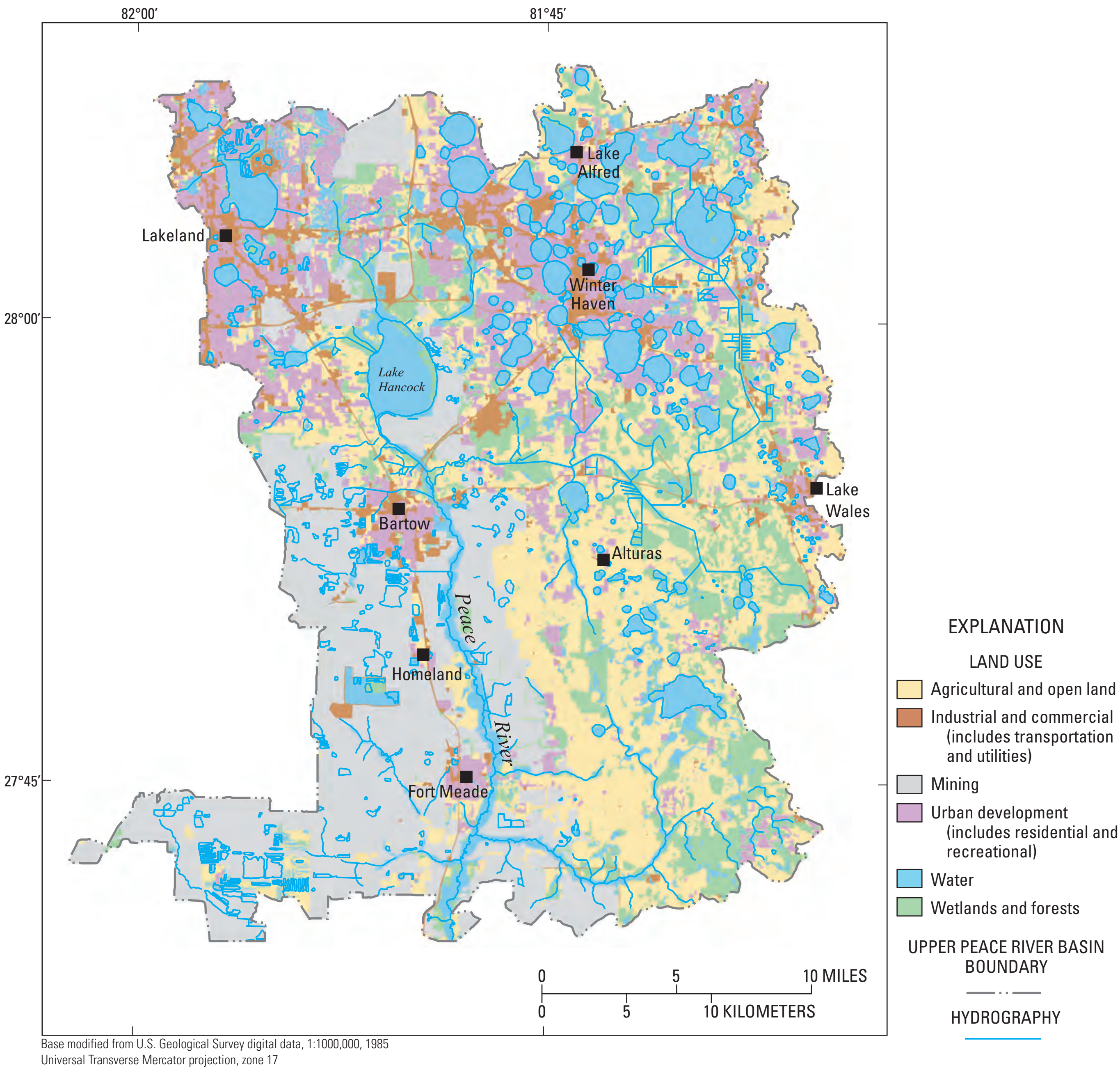


Figure 7. Land use in the upper Peace River basin, 2005.

Within the upper Peace River basin, the dominant reclaimed landforms produced during surface mining are clay-settling areas that can cover hundreds of acres and exceed 40 ft in depth. Many of these clay-settling areas line both sides of the upper Peace River floodplain from the cities of Bartow to Fort Meade. Typically, a reclaimed clay-settling area is built by constructing a high perimeter dam around a mined area, forming a containment to hold the clay-waste slurry (Lewelling and Wylie, 1993). During construction of the clay-settling area, most of the disturbed overburden that was removed from the mined pit is used to build the perimeter dam to provide more volume for clay storage. The clay slurry that is separated from the phosphate matrix during the beneficiation process is pumped into the clay-settling area to dewater, settle, and consolidate. These clay-settling areas possess entirely different physical properties, in terms of water storage and transmission, than the landscape prior to mining (Brickmann and Koenig, 2007).

Soils

The surface soils of the upper Peace River basin are composed of fine sands along the ridges and uplands, fine sands and loams along the riverine floodplain, mucky fine sand in depressional areas, altered soils in urban areas, and sandy-clay soils in mined areas (Southwest Florida Water Management District, 2002b; fig. 8). About 54 percent of the upper Peace River basin is underlain by upland soils that are moderately sloping and excessively to moderately well drained, which allows for rapid infiltration. Soils of the riverine floodplain and in depressional areas are frequently flooded, have little to no slope, and have a high water table (where present); these soils are moderately to poorly drained, providing moderate infiltration. The depressional and frequently flooded areas make up about 10 percent of the upper Peace River basin.

Mined soils border both sides of the Peace River floodplain and make up the remaining 36 percent of the upper Peace River basin (fig. 8). The sandy-clay soils of mined sites, or arents, are less pervious because of the increase in clay content at the surface horizons that tends to limit surface infiltration (Lewelling and Wylie, 1993). Postmining areas contain a large amount of clay waste byproduct, which typically occupies about 40 to 60 percent of the postmined landscape (Yon, 1983). Arent soil types include haplaquents, hydraquents, udorthents, gypsum-land complex, and urban-land complex. Because of the low hydraulic conductivity of clay, groundwater recharge and movement through a clay-settling area can be substantially less than soils under natural conditions.

The floodplain of the upper Peace River near the confluence of Saddle Creek and Peace Creek Drainage Canal, and along sections of the river within the Clear Springs Mine area, was mined before 1975 when mandatory reclamation was instituted. Field observations indicate that during low- to- moderate rainfalls, water tends to pond on these unreclaimed impervious soils and evaporation is assumed to be the major avenue of water loss from these areas. Additionally, shrinkage of the consolidating clays can cause depressional surface features to form, increasing ponding and evaporation, and reducing runoff (Lewelling and Wylie, 1993). During higher rainfall events, however, water tends to run off as sheetflow. Additional research is needed to understand how these altered soil characteristics affect drainage patterns in the upper Peace River basin.

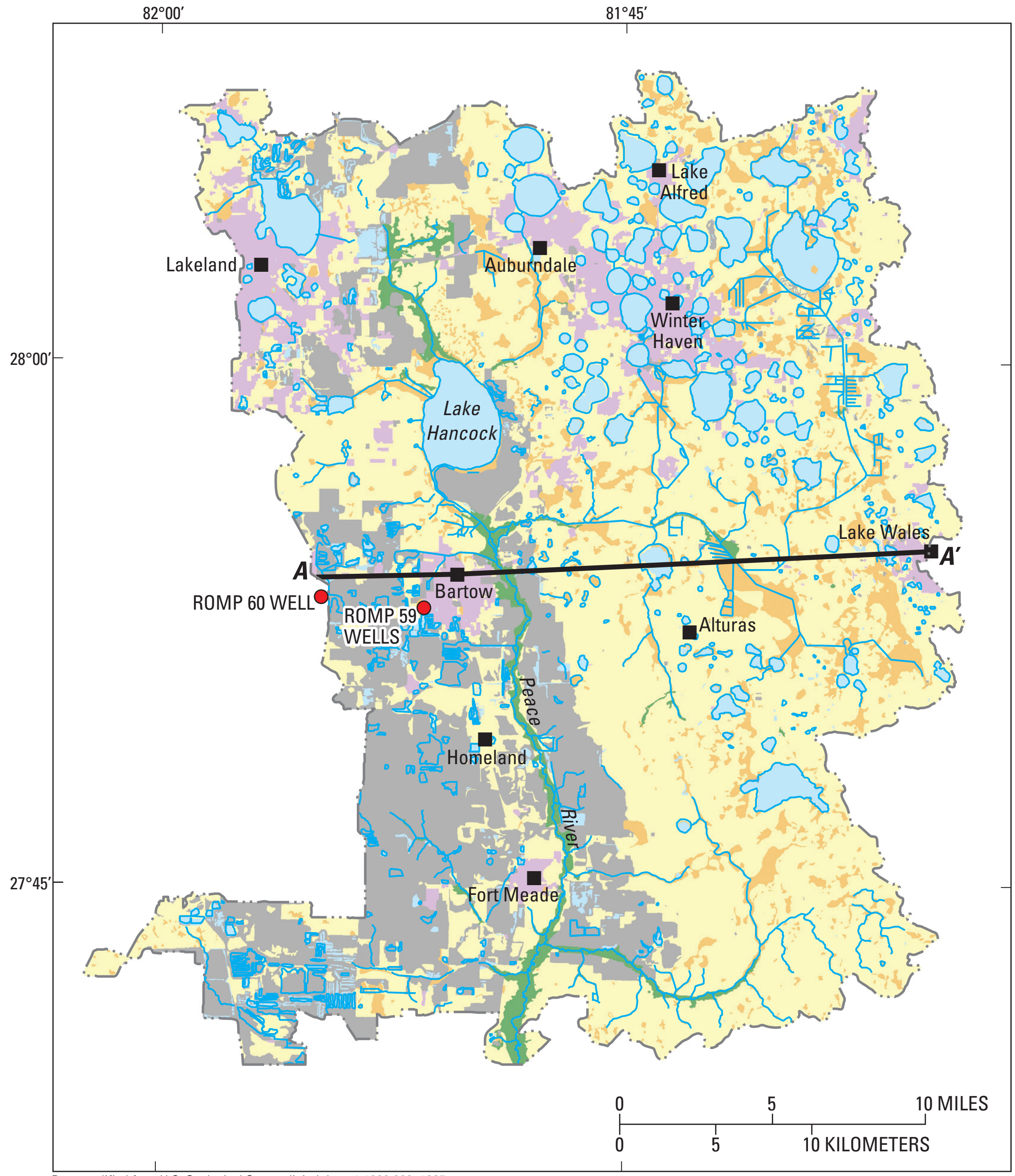
Groundwater Use

The upper Peace River basin is located in the Southern West-Central Florida Groundwater Basin (SWCFGB), about 5,000-mi^2, which relies heavily on groundwater for water supply (Southwest Florida Water Management District, 1988; Barcelo and Basso, 1993) (fig. 9A). During the study period, groundwater withdrawn for water supply from this groundwater basin ranged from about 480 (2005) to 642 (2006) Mgal/d (Mike Kelley, SWFWMD, written commun., 2009) (fig. 9B).

Groundwater use in Polk County totaled 212 Mgal/d in 2005, of which 98 percent was from the Upper Floridan aquifer (Marella, 2009). The total groundwater withdrawn from the upper Peace River basin during 1992-2005 averaged about 113 Mgal/d (Mike Kelley, SWFWMD, written commun., 2007) (fig. 9C). The greatest amount of groundwater withdrawn in the upper Peace River basin was during years of below-average rainfall in 1992, 1998, and 2000. The least amount of groundwater withdrawn was during years of above-average rainfall in 2003-2005 (fig. 3B).

The major groundwater-use categories for the 1992-2005 period are shown in figure 9D. The largest average groundwater use during this period was for agriculture (44.7 Mgal/d), public supply (38.6 Mgal/d), industrial/commercial (19.0 Mgal/d), mining (6.7 Mgal/d), and recreation (3.7 Mgal/d). Pumpage was constant for most purposes from year-to-year, except for agriculture and mining. Agriculture exceeded all other uses between 1992 and 2002, reaching a maximum during 2000 because of a severe drought that increased the need for irrigation. Agricultural water use declined from a high of 61 to 20 Mgal/d in 2000 and 2005, respectively, as a result of a number of wet years (2003-2005) that reduced the need for irrigation. In addition, in 2004 Hurricanes Charley and Frances passed directly through the study area, causing citrus tree loss and the resultant decrease in irrigation. Groundwater use for mining declined from 16.7 to less than 0.5 Mgal/d in 1992 and 2005, respectively (fig. 9D) as operations moved to areas south and west of the upper Peace River basin.

In 2005, major use categories were public supply (39 Mgal/d), agriculture (20 Mgal/d), industrial/commercial (16 Mgal/d), recreational (3 Mgal/d), and mining (0.5 Mgal/d) (fig. 9D). The spatial distribution of this pumpage by groundwater-use categories for the year 2005 is shown in



Base modified from U.S. Geological Survey digital data, 1:1000,000, 1985
Universal Transverse Mercator projection, zone 17

EXPLANATION

SOIL TYPE

- Fine sand
- Mucky fine sand
- Water
- Fine sand to sandy clay loam (frequently flooded)
- Urban land complex
- Arents (soil alterations due to urban and mining alterations which includes a sandy and clayey substratum, gypsum land, clayey haplaquants and hydraquents, excavated udorthents, and an urban land and water complex)

UPPER PEACE RIVER BASIN BOUNDARY

A—A′ LOCATION OF PROFILE LINE SHOWN IN FIGURE 21

Figure 8. Generalized soil types in the upper Peace River basin.

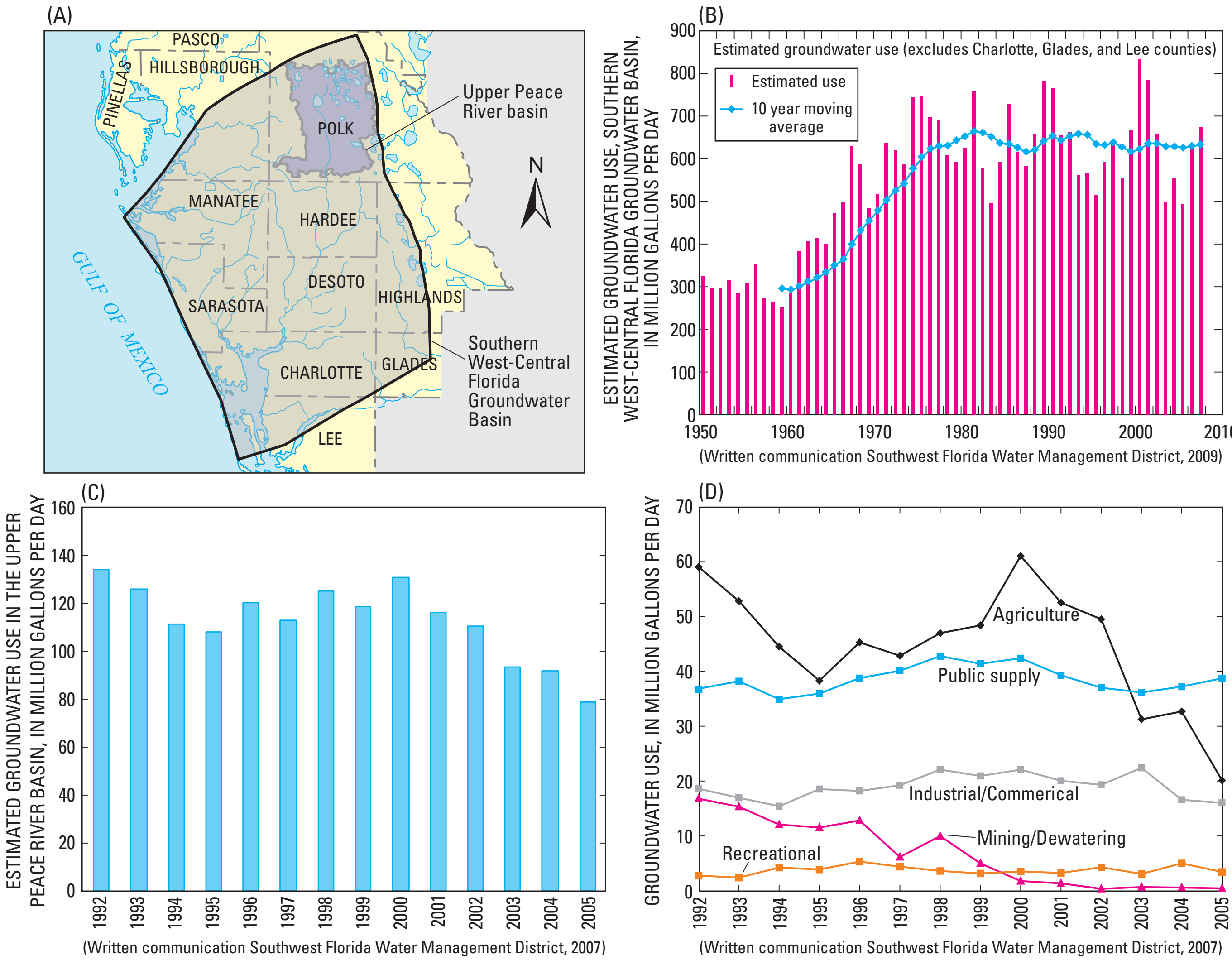


Figure 9. (A) Location of the Southern West-Central Florida Groundwater Basin, (B) estimated groundwater use in the Southern West-Central Florida Groundwater Basin and (C) in the upper Peace River basin, and (D) estimated groundwater use by category in the upper Peace River basin, 1992 through 2005.

figure 10 (Mike Kelley, SWFWMD, written commun., 2007). In addition, the amount of groundwater withdrawn during 2005 for the individual wells is shown in figure 10.

Public supply was the largest groundwater use during 2005, because agricultural use was lower during this wet year. Public-supply wells are concentrated near larger cities such as Lakeland, Bartow, Auburndale, and Winter Haven. Public-supply wells usually are concentrated in clusters and pumpage for individual wells ranges from less than 0.0001 to 1.4 Mgal/d (fig. 10). Agriculture was the second largest groundwater user in 2005, with more than 600 wells used for irrigation (2005) throughout the upper Peace River basin (Mike Kelley, SWFWMD, written commun., 2007). Citrus irrigation dominates this groundwater use at 92 percent of all agricultural-use categories (row crops, sod and plant nursuries, and pasture). Groundwater withdrawals from individual citrus irrigation wells ranged from 0.00001 to 0.40 Mgal/d in 2005. Industrial and commercial was the third largest use category, with phosphate and citrus processing using the majority of this water, and use ranged from 0.002 to more than 5 Mgal/d. The largest amount of groundwater withdrawn (5 Mgal/d) in the upper Peace River basin in 2005 was for a phosphate processing plant, which is considered industrial use. Recreational groundwater use included lawn, garden, and golf course irrigation and augmentation of lakes; water withdrawn from the individual wells ranged from 0.0002 to 0.23 Mgal/d in 2005.

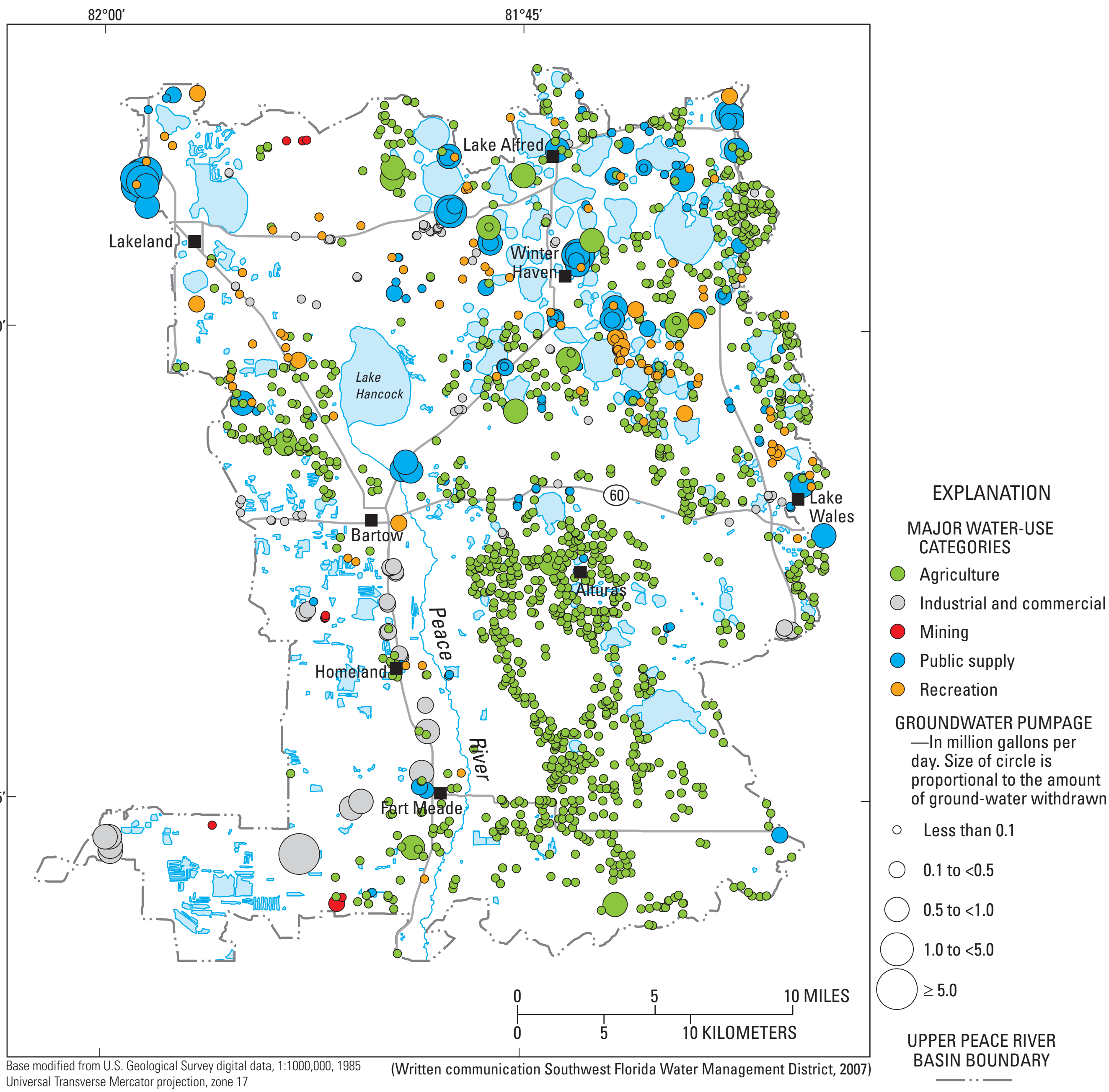


Figure 10. Major water-use categories and pumpage distribution for groundwater withdrawn from the Upper Floridan aquifer in the upper Peace River basin, 2005.

Geologic Framework

Many investigators have contributed to the understanding of the geologic framework of the study area. Prior to this study, however, limited information was available about the geology immediately adjacent to the Peace River and how the geology affects hydrologic conditions along the river. This investigation focuses on the geology that spans from the Eocene through Holocene ages, including from oldest to youngest, the Avon Park Formation, Ocala Limestone, Suwannee Limestone, Hawthorn Group, and undifferentiated surficial deposits. The stratigraphic units, hydrogeologic units, and generalized lithologic descriptions are presented in figure 11.

The geologic units along the upper Peace River consist of sand, clay, marl, phosphate grains and pebbles, and carbonate rocks that were deposited primarily in an open or restricted marine environment. Deposition of each formation was followed by a period of erosion that resulted in the development of solution cavities and formational surface irregularities. Carbonates are susceptible to postdeposition erosional processes that include weathering, dissolution, and fracturing, which enhances the permeability within and between these units. Of particular interest to this study are the Suwannee Limestone, the Hawthorn Group, and undifferentiated surficial deposits, because these formations have the greatest potential for interaction with the upper Peace River. A geologic cross section along the upper Peace River from north to south is shown in figure 12.

SERIES	STRATIGRAPHIC UNIT	GEOLOGY AND LITHOLOGY	HYDROGEOLOGIC UNIT
Holocene and Pleistocene	Undifferentiated surficial deposits	Sand and fossil fragments	Surficial aquifer system (surficial aquifer)
Pliocene	Undifferentiated surficial deposits; Cypresshead Formation	Sand, silt, and clay	Intermediate aquifer system[1]: Confining unit
Miocene	Hawthorn Group: Bone Valley Member; Peace River Formation	Sand, clay, marl, phosphate grains and pebbles, limestone and dolostone. Fossils common.	Intermediate aquifer system[1]: Zone 2, upper Arcadia aquifer
Miocene	Hawthorn Group: Arcadia Formation		Intermediate aquifer system[1]: Confining unit
Miocene	Hawthorn Group: Arcadia Formation; Tampa Member / Nocatee Member		Intermediate aquifer system[1]: Zone 3, lower Arcadia aquifer
Miocene	Hawthorn Group: Tampa Member / Nocatee Member		Intermediate aquifer system[1]: Confining unit
Oligocene	Suwannee Limestone	Limestone, sandy limstone and sand. Phosphatic in part. Dolostone beds and fossils common.	Floridan aquifer system: Upper Floridan aquifer: Upper permeable zone
Eocene	Ocala Limestone		Floridan aquifer system: Upper Floridan aquifer: Semiconfining unit
Eocene	Avon Park Formation		Floridan aquifer system: Upper Floridan aquifer: Lower permeable zone
Eocene	Avon Park Formation	Limestone and dolostone with some intervals containing inclusions of gypsum and anhydrite	Floridan aquifer system: Middle confining unit; Middle semiconfining unit
Eocene	Oldsmar Formation		Floridan aquifer system: Lower Floridan aquifer
Paleocene	Cedar Keys Formation	Limestone and dolostone with beds of gypsum and anhydrite	Sub-Floridan confining unit

[1]A proposed revision by DeWitt and Mallams (2007) and Mallams and DeWitt (2007) replaces zone 2 and zone 3 from Knochenmus (2006) with the upper and lower Arcadia aquifers, respectively. This revision also proposes to rename the intermediate aquifer system in southwestern Florida to the Hawthorn aquifer system (excluding the upper and lower confining units). There is not a current consensus, however, on the use of “Hawthorn aquifer system,” so in this report only the proposed upper and lower Arcadia aquifer names are used.

Figure 11. Relation of stratigraphic and hydrogeologic units (modified from Barr, 1992; Tihansky and others, 1996; O’Reilly and others, 2002; Sepulveda, 2002; Basso and Hood, 2005; Knochenmus, 2006; DeWitt and Mallams, 2007; Mallams and DeWitt, 2007; and Spechler and Kroening, 2007).

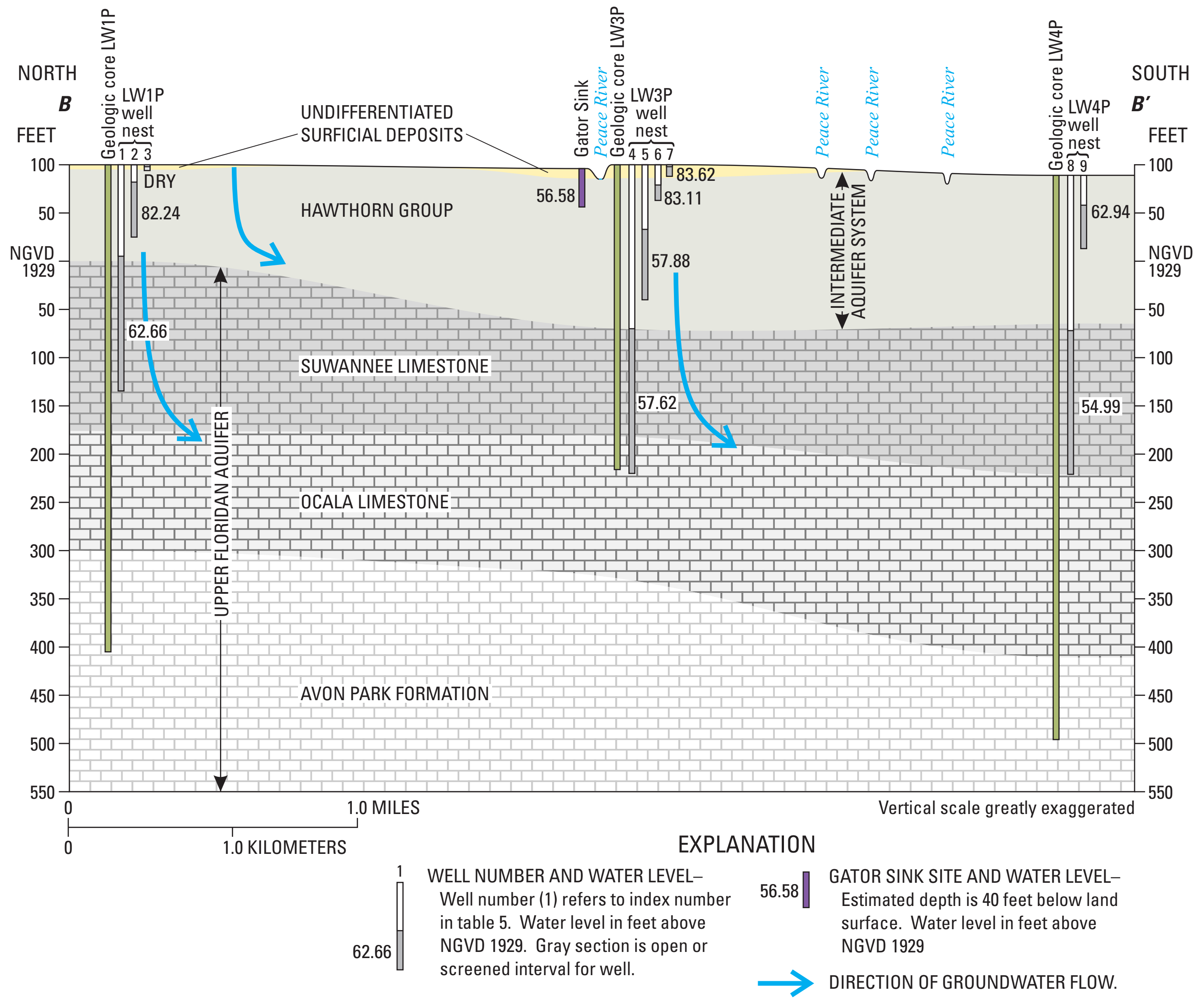


Figure 12. Geologic cross-section along the upper Peace River and water levels for study wells that indicate recharging conditions (June 1, 2007) (line of geologic section is shown in fig. 13B).

The lowermost geologic units of interest in the study area are composed of a thick sequence of carbonate rocks that vary in composition based on their depositional history (Randazzo and Jones, 1997). The Avon Park Formation is characterized by alternating layers of soft to well-indurated fossiliferous limestone that typically is highly fractured and cavernous (Stewart, 1966). Above the Avon Park Formation is the Ocala Limestone, which contains two distinct geologic units. The lower unit contains limestone and dolomite and is characterized as granular, well-indurated, dense, and fossiliferous. The upper unit is composed of soft, pure limestone that contains numerous fossils and is poorly indurated. The Suwannee Limestone of Oligocene age overlies the Ocala Limestone and is composed of interbedded, sand-size limestone grains and soft calcareous mud and sand. This limestone also is fossiliferous and contains abundant bryozoans, small mollusks, and large echinoids (Stewart, 1966).

Overlying these carbonate units is a sequence formed under a variety of depositional environments that produce a complex geologic assemblage of carbonates and siliciclastic sediments during the late Oligocene to Miocene (Randazzo and Jones, 1997). These environments of deposition included open marine, shallow water, coastal marine, fluvial, and estuarine (Gilboy, 1985). This complex sequence of sedimentary deposits forms the highly heterogeneous Hawthorn Group (Missimer, 2002).

Within the study area, the Hawthorn Group contains the Arcadia and the Peace River Formations. The Arcadia Formation underlies the Peace River Formation and consists primarily of carbonates with some siliciclastic sediments (Scott, 1988). Carbonates of the Arcadia Formation are sandy, phosphatic, and in some places clayey. The Arcadia Formation includes two members, the Tampa Member and the Nocatee Member. The Peace River Formation consists of beds of green-gray clay and dolomitic clayey sand to sandy clay that contain abundant pellets and fine pebble-sized phosphate (Scott, 1988). The Peace River Formation includes the Bone Valley Member, which is characterized by a mixture of phosphate gravel, sand-sized phosphate, quartz sand, and clay (Scott, 1988). The sediments that overlie the Peace River Formation consist of undifferentiated surficial deposits of the Pleistocene and Holocene series. These sediments consist of fine-to medium-grained quartz and phosphatic sands, silt, and clay. Undifferentiated surficial deposits have been disturbed over much of the upper Peace River basin during mining of the phosphate-rich Bone Valley Member.

Geologic Cores

Continuous geologic cores were collected at three sites along the upper Peace River within a span of about 3.5 mi (figs. 12 and 13). The cores were collected by the wire-line coring method; a detailed description of the method is presented in Gates (2009). The three core sites are the LW1P site located at the Bartow Waste Water Treatment Plant (WWTP), the LW3P site located at the Clear Springs Mine dragline crossing, and the LW4P site located near the historic Kissengen Spring. Continuous cores extended into the Avon Park Formation at the LW1P and LW4P sites and into the Ocala Limestone at the LW3P site.

Analysis of the cores indicates that the geology varies along the upper Peace River, especially within the Hawthorn Group, which is in direct contact with the river. The multiple interbedded layers of carbonate and siliciclastic sediments indicate a complex erosional and depositional history that occurred during the late Oligocene and Miocene time period. Cores show a wide variety of weathered carbonate rocks, interlayered with siliciclastic sediments. The core lithologies include sand and clay, dolomite or dolostone, and limestone that were further identified as packstone, mudstone, wackestone, grainstone, and calcilutite. Most of the limestone identified was rich in calcareous mud and is classified as a mudstone and wackestone (Dunham, 1962).

The top of the Avon Park Formation was detected at about 400 ft below land surface at the LW1P site and at 500 ft below land surface at the LW4P (Kissengen Spring) site. The top of Avon Park Formation consisted of medium-grained, poorly indurated limestone in a calcilutite matrix. The dominant fossils identified in these rocks included the foraminifera *Dictyoconus americanus* and the echinoid *Neolaganum dalli*. Cores extended 105 ft into the Avon Park Formation at LW1P and 85 ft at LW4P, and the limestone varied from grainstone, packstone, mudstone, to wackestone.

The Ocala Limestone, as described from the cores, varied from highly weathered, poorly indurated, calcareous mud to moderate -to well-indurated mudstone and wackestone. The fossil that defines the Ocala Limestone, *Lepidocyclina ocalana*, was present in most core samples. Calcareous mud was more prevalent at the LW1P site than at LW4P site, where the lower section contained many layers of well-indurated limestone (Gates, 2009). The average thickness of the Ocala Limestone, based on the two core sites (LW1P and LW4P), was about 160 ft.

Geologic core samples.

Overlying the Ocala Limestone is the Suwannee Limestone, which in cores was composed of highly weathered, friable limestone and dolostone that was poorly consolidated, calcareous and chalky, and contained some clay stringers and numerous fossils at varying depths. A majority of the limestone identified in the Suwannee Limestone was rich in calcareous mud and was identified as mudstone and wackestone. The average thickness of the Suwannee Limestone, based on the three cores, was about 130 ft.

The Hawthorn Group that overlies the Suwannee Limestone is composed of the Arcadia and Peace River Formations. The Hawthorn Group contains less limestone and more siliclastic sediments than the underlying Suwannee Limestone. The Hawthorn Group is exposed at places along the streambed and is in direct connection with the river. The cores that penetrated the Hawthorn Group are described as sequences of weathered dolomite that is fractured and contains pinpoint vugs, voids, and numerous fossils casts and molds that aid in the development of secondary porosity within this unit. Interspersed within the Hawthorn Group are sequences of stiff clays, sands, phosphate pebbles and grains, and thin layers of weathered limestone.

The Hawthorn Group has an average thickness of about 130 ft based on the three cores. The Arcadia Formation has an average thickness of about 120 ft, and is composed mostly of fossiliferous dolostone that contained numerous fossil

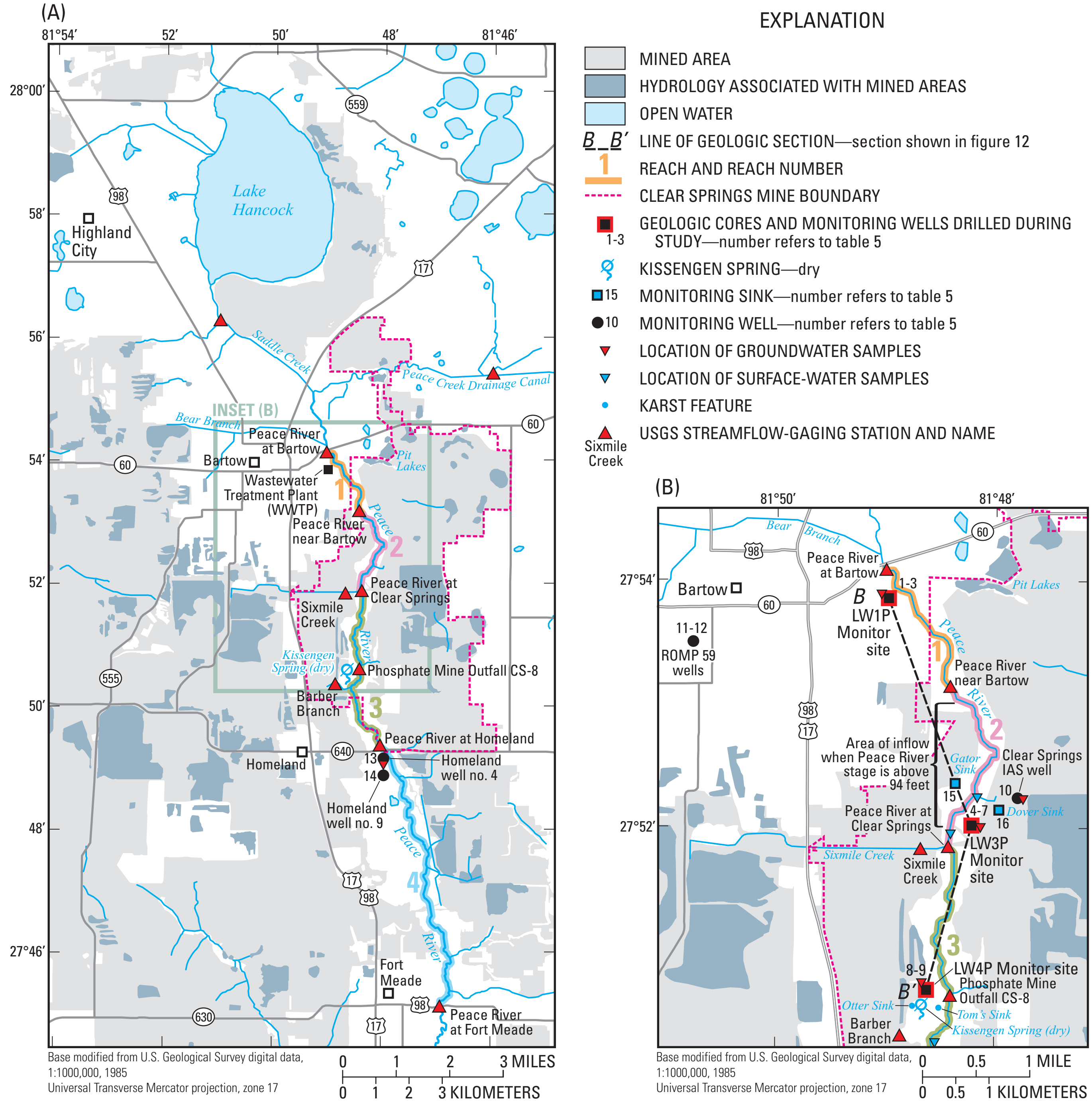


Figure 13. Location of (A) stream gaging stations, (B) geologic cores, sinks, and groundwater monitoring and water-quality sampling sites.

molds and casts. The Peace River Formation is thin, with an average thickness of only 10 ft. This formation is composed mainly of limestone that contains vugs, fossil molds, and fossil dissolution cavities.

The undifferentiated surficial sediments are the uppermost formation in the cores. These sediments consist of quartz and phosphatic sands, silt and organics, and varying amounts of clay. This unit is thin, with an average thickness of about 6 ft (LW1P and LW3P). Surficial deposits were absent at the LW4P site (Kissengen Spring).

Karst Development

Sinkholes are common throughout this mantled karst landscape and contribute to the highly variable geologic framework of the area. Sinkholes form when limestone dissolves and cavities develop in the subsurface limestone. As the cavities expand, the overlying sand and clay subside into the solution openings, forming a depression in the land surface. The more than 90 sinkholes documented by Patton (1981) were along about a 6-mi reach of the high and low-water channel of the upper Peace River, and most of the sinkholes were located along the upper half of this reach. Over half of these sinkholes were larger than 10 ft in diameter, with 10 percent exceeding 40 ft in diameter.

Although sinkholes develop naturally, their unusual density along the upper Peace River can be explained, in part, by the increased use of groundwater in the area (Kaufman, 1967; Patton, 1981; Sinclair, 1982; Newton, 1986; Shock and Wilson, 1996; Tihansky, 1999). Many of these sinkholes may have been formed after abrupt declines in groundwater levels during the 1940s through 1975, when large volumes of groundwater were pumped for phosphate mining. A large decline in groundwater levels removes the hydraulic support of overburden sediments lying above cavities, which results in the formation of sinkholes (Newton, 1986). Similar large-scale clustered sinkhole developments have been documented near well fields where large volumes of groundwater have been withdrawn for public supply (Sinclair, 1982; Tihansky, 1999; Metz and Sacks, 2002). In addition, changes in the Upper Floridan aquifer from discharge to recharge conditions may be related to the increased karst activity.

Karst solution features as described in this investigation consist of piping features, fissures, cracks, crevices, conduits, cavities, karst windows, sinks, and fractures in the limestone or dolomite bedrock. The two most important factors in development and expression of karst features are the amount of precipitation in the region and the solubility of the bedrock (Weary and others, 2008). Karst development occurs as a result of chemical dissolution of the soluble layers in the limestone and dolomite by slightly acidic water (a pH below 7.0).

The karst landscape is formed by circulating acidic waters that enlarge the natural fractures and pores within the limestone or dolomite, thus increasing the permeability of the rock. This enhanced secondary porosity allows for the movement of even larger volumes of water, which in turn dissolves more limestone and dolomite. Eventually, the openings and passageways coalesce to form conduits and or cavities that continue to enlarge by further solution development. Groundwater flow velocities typically are much greater in these karst conduit systems than in porous media (Ryder, 1985).

Limestone starts to dissolve at a pH below 7.0, and acidic industrial wastewaters may have accelerated the dissolution of the rocks underlying the upper Peace River during the early 1950s when some of the tributaries to the upper Peace River were contaminated by acid mine waste (Lanquist, 1955). The Florida State Board of Health collected 156 samples for pH determinations from 1950 to 1953 at the Bear Branch bridge on U.S. Highway 17, which flows into the Peace River about 326 ft above the State Road (SR) 60 bridge. The pH values of the tributary water ranged from 2.2 to 4.9, and averaged 4.6 (Lanquist, 1955). The Florida State Board of Health also collected 162 water samples for pH determinations from the Peace River at Bartow during this same time period. The pH of the river water ranged from 4.8 to 7.7, averaging 6.5. The USGS collected 200 river samples at the Peace River at Bartow gage between 1963 and 1999. The pH of these samples ranged from 5.6 to 10.0, averaging 6.9.

Important factors for determining the potential effects of these acidic waters on the river and karst dissolution are the residence time and the amount of flow in the river. During one of the years when acid mine waste was discharged (1950 water year), rainfall was the lowest amount for the 107 years of record (32 in.) and the discharge in the river was below average for most of the year. When rainfall and discharge in the river are low, there is an increased potential for limestone dissolution, because less discharge equates to less dilution of the acidic waters. In addition, reduced discharge indicates that streamflow is slower in the upper Peace River, increasing the time of contact with the dissolving limestone. Low pH water in the river may have enhanced limestone dissolution during this period, but the extent of this dissolution is difficult to quantify.

Limestone outcrop along the dry river bottom downstream from Ledges Sink. Photo credit: P.A. Metz, USGS

Hydrogeology

The principal hydrogeologic units in the study area are, in descending order, the surficial aquifer, intermediate aquifer system, and Upper Floridan aquifer (fig. 11). The uppermost unit, the surficial aquifer, is an unconfined sand and clayey sand aquifer. Underlying this unit is the mixed carbonate and siliciclastic intermediate aquifer system, which contains a number of water-bearing units. The lowermost unit, the Upper Floridan aquifer, is a highly productive carbonate aquifer and is the principal source of freshwater in west-central Florida (Miller, 1986).

Surficial Aquifer

The surficial aquifer is a permeable hydrogeologic unit, contiguous with land surface, that principally consists of unconsolidated to poorly indurated clastic deposits (fig. 11; Southeastern Geological Society, 1986). This unit is commonly referred to as the surficial aquifer system where more than one permeable zone is present or where the deposits are interbedded. In this report, the deposits are considered to form a single homogeneous aquifer, and are referred to as the surficial aquifer.

The surficial aquifer is recharged by rainfall that infiltrates the permeable deposits and percolates downward to the water table. The surficial aquifer is an important component of the groundwater system, because it provides the means for the temporary storage of infiltrating water that eventually percolates down to the underlying aquifers or moves laterally to areas of discharge.

In some areas of the upper Peace River basin, the surficial aquifer does not exist, because the surface sediments have been removed by strip mining for phosphate. Where the surficial aquifer is present, the thickness is variable in the upper Peace River basin, ranging from less than 10 ft to more than 200 ft along the sandy Lake Wales Ridge (Spechler and Kroening, 2007). Beneath the ridges of the upper Peace River basin (Lake Henry, Gordonville, Lakeland, and Lake Wales Ridges; fig. 2), the surficial aquifer has a large storage capacity and provides substantial recharge to the underlying aquifers. Along the Peace River floodplain, however, the surficial aquifer is thin to nonexistent, limiting the amount of infiltration and recharge. Where the water table is present along the floodplain, the depth to the water table is about 5 to 10 ft below land surface. During extended dry periods, the surficial aquifer may go dry. The surficial aquifer has a low specific capacity along the upper Peace River floodplain. A specific-capacity test was performed at the LW3P well on February 7, 2007. The well was constructed to a depth of 12 ft below land surface with 7 ft of open screen. The well was pumped dry during the test at a rate of less than 1 gallon per minute (gal/min). The calculated specific capacity was 0.3 gal/min per foot of drawdown (Gates, 2009).

Intermediate Aquifer System

The intermediate aquifer system includes all water-bearing units (aquifers) and confining units between the overlying surficial aquifer and the underlying Upper Floridan aquifer (Duerr and others, 1988). Within the study area, the intermediate aquifer system consists of three or more hydrogeologic units (fig. 11): (1) a clayey and pebbly sand, clay, and marl upper confining unit that separates the uppermost water-bearing unit in the intermediate aquifer system from the surficial aquifer; (2) one to two water-bearing units composed primarily of carbonate rocks, sand, and discontinuous beds of sand and clay; and (3) a sandy clay and clayey sand lower confining unit that lies directly over the Upper Floridan aquifer (Ryder, 1985). The thickness of the intermediate aquifer system from the three cores ranged from about 100 ft to less than 170 ft. The thickness of the intermediate aquifer system in the upper Peace River basin ranges from about 100 to 300 ft (Spechler and Kroening, 2007).

Slug tests were performed to determine the horizontal hydraulic conductivity of the confining and water-bearing units (aquifers) of the intermediate aquifer system. Slug tests provide a localized estimate of hydraulic conductivity or transmissivity in the near vicinity of a well. Slug test procedures and results are discussed in Gates (2009). Slug tests performed on the upper confining unit indicate that the unit has a low horizontal hydraulic conductivity value of about 0.3 foot per day (ft/d) (Gates, 2009).

Underlying the upper confining unit are two water-bearing units called the upper and lower Arcadia aquifers (DeWitt and Mallams, 2007) (fig. 11). This aquifer nomenclature is a proposed revision by DeWitt and Mallams (2007) and Mallams and DeWitt (2007) that replaces zone 2 and zone 3 from Knochenmus (2006) with the upper and lower Arcadia aquifers, respectively. This revision also proposes to rename the intermediate aquifer system in southwestern Florida to the Hawthorn aquifer system (excluding the upper and lower confining units), in keeping with aquifer naming guidelines in Laney and Davidson (1986). There is not a current consensus, however, on the use of “Hawthorn aquifer system,” so in this report only the proposed upper and lower Arcadia aquifer names are used.

Slug tests of these aquifers indicated an increase in the horizontal hydraulic conductivity compared to the overlying confining unit that ranged from 2 to 42 ft/d. Transmissivities of the upper Arcadia aquifer reported from aquifer performance tests at wells LW1P and LW4P were 5,000 to 125,000 feet squared per day (ft^2/d), respectively (Gates, 2009). The wide range of transmissivity values for the intermediate aquifer system indicates its formational heterogeneity.

The area of greatest transmissivity occurs within the upper Arcadia aquifer (zone 2; fig. 11) at the LW4P (Kissengen Spring) well. During coring at this well, a large cavity was detected between 40 and 55 ft below land surface. This cavity also was encountered at approximately the same depth while drilling two nearby monitor wells and a water-supply well. The cavity appears to be horizontally extensive across the 100-ft wide well site, which is located about 100 ft northeast of the historical Kissengen Spring site. The high transmissivity value of 125,000 ft^2/d for the intermediate aquifer system occurred within the depth interval from 30 to 76 ft below land surface. The high transmissivity and presence of large conduits indicate an active cavernous flow system within the upper intermediate aquifer system in this part of the upper Peace River floodplain. Figure 14 shows a nearby outcrop of the Arcadia Formation that depicts the secondary porosity of the weathered carbonate unit.

The lower confining unit lies at the base of the intermediate aquifer system and, to some extent, hydraulically separates the intermediate aquifer system from the Upper Floridan aquifer (fig. 11). The lower confining unit has a low vertical hydraulic conductivity and, consequently, retards interaquifer flow. Slug tests limited to the lower confining unit were performed at all three sites drilled for this study, and indicate horizontal hydraulic conductivity values that ranged from about 0.003 to 0.7 ft/d (Gates, 2009).

Within the study area, the intermediate aquifer system is used as a source of water for irrigation and public and domestic supply. Wells open to the intermediate aquifer system commonly yield less than 300 gallons per minute (gal/min) (Wilson, 1977). The yield to wells and total withdrawals of water from the intermediate aquifer system is much less than those for the underlying Upper Floridan aquifer, and represents only 1 percent of the groundwater withdrawn in Polk County.

Upper Floridan Aquifer

The Floridan aquifer system, as defined by Miller (1986), is a vertically continuous sequence of carbonate rocks of generally high permeability (fig. 11). In the study area, the Floridan aquifer system consists of two aquifers: the Upper Floridan aquifer, which generally contains freshwater, and the Lower Floridan aquifer, which contains highly mineralized water. The Upper Floridan aquifer consists of the Suwannee Limestone, the Ocala Limestone, and the Avon Park Formation of the Oligocene and Eocene series. The top of the Upper Floridan aquifer in the study area coincides with the top of the Suwannee Limestone. The base of the aquifer is defined as the first occurrence of vertically persistent intergranular evaporites in the Avon Park Formation (Miller, 1986). The thickness of the Upper Floridan aquifer is about 1,000 ft within the study area (Basso, 2003).

The Upper Floridan aquifer consists of limestone and dolomite that have solution-enlarged fractures. The Upper Floridan aquifer is the most productive and widely used aquifer in the Southern West-Central Florida Groundwater Basin, and supplies more than 10 times the amount of water that is pumped from the intermediate aquifer system (Metz and Brendle, 1996). The Upper Floridan aquifer is used extensively for irrigation, industrial and commercial, public, recreational, and domestic supplies; large capacity wells can yield up to 5,000 gal/min (Southwest Florida Water Management District,

Figure 14. Secondary porosity of the Arcadia Formation within the intermediate aquifer system (Gator Sink). Photo credit: P.A. Metz, USGS

1994). Some of the wells in the study area that are completed in the Upper Floridan aquifer also are open to the intermediate aquifer system (Metz and Brendle, 1996).

Aquifer performance tests were conducted at the LW1P and LW4P wells to determine the hydraulic properties of the Upper Floridan aquifer. The aquifer performance tests were conducted in the open intervals between 95 to 235 ft below land surface at the LW1P well, and between 151 to 310 ft below land surface at the LW4P well. Both of these test intervals coincide with the Suwannee Limestone, which, as described from the cores, is composed of highly weathered, poorly indurated, silt-size limestone and calcareous mud and sand. Transmissivity values within this unit ranged from 13,000 ft^2/d at the LW4P well site to 56,000 ft^2/d at the LW1P well site (Gates, 2009).

The geophysical logs for the three monitor well sites drilled for this project are shown in figures 15 through 17. Analysis of the gamma log indicates high levels of gamma activity in the Hawthorn Group within the intermediate aquifer system because of the clay matrix that surrounds the dominate rock type within this unit. Below the intermediate aquifer system, there is a decrease in clay content and a resultant decrease in gamma activity, which denotes the top of the Upper Floridan aquifer. The top of the Upper Floridan aquifer, as determined from the gamma logs, is about 105 ft below land surface at the LW1P well (fig. 15), 170 ft below land surface at the LW3P well (fig. 16), and 160 ft below land surface at the LW4P well site (fig. 17).

In addition to gamma logs, caliper and video logs were used to delineate the contacts between hydrogeologic units and locations of fractures and cavity zones. Contacts between units are generally more weathered and fractured than within units and are commonly indicated by an increase in the borehole diameter, as shown in the caliper log. The three caliper logs

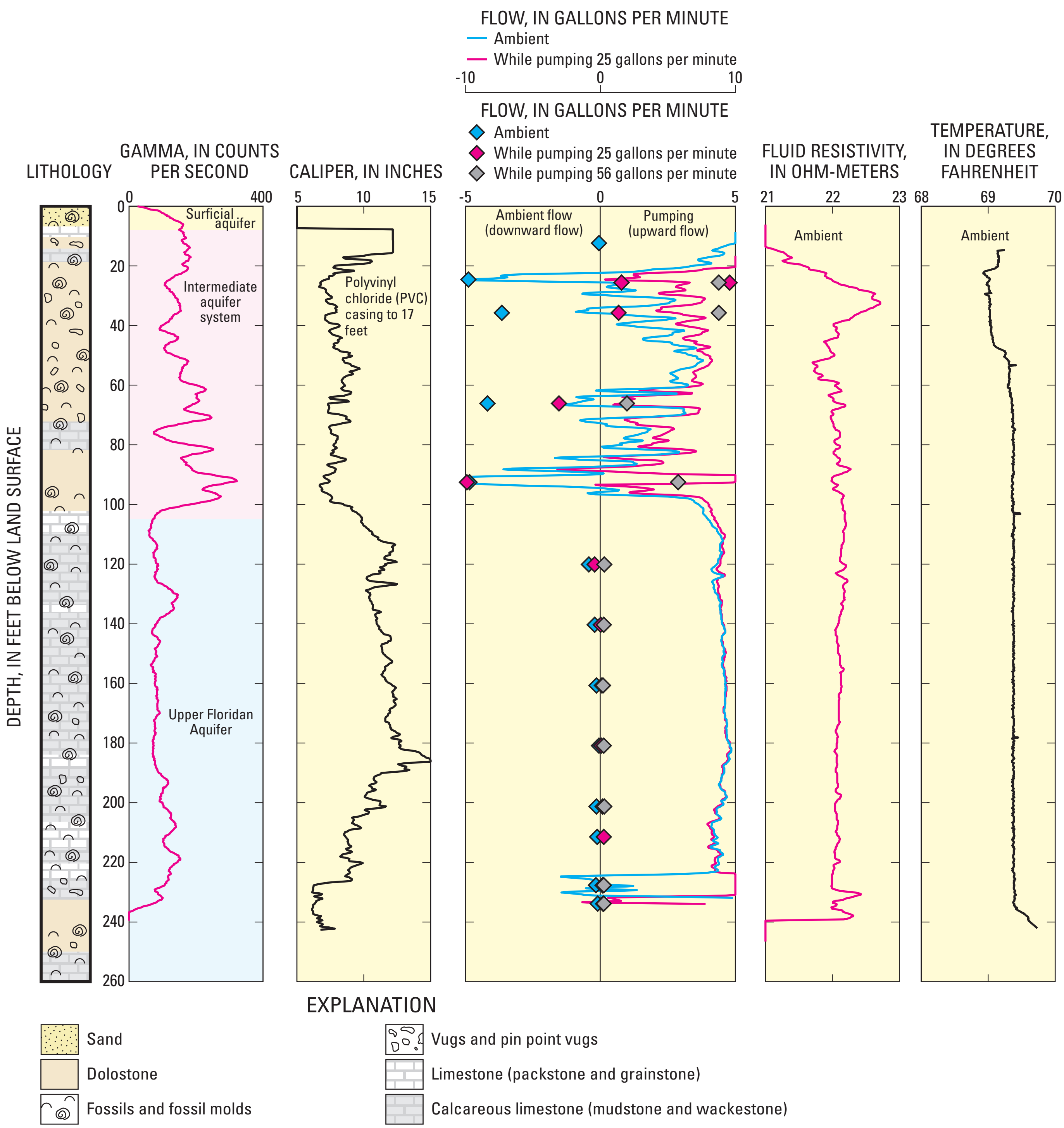


Figure 15. Geophysical logs for well site LW1P.

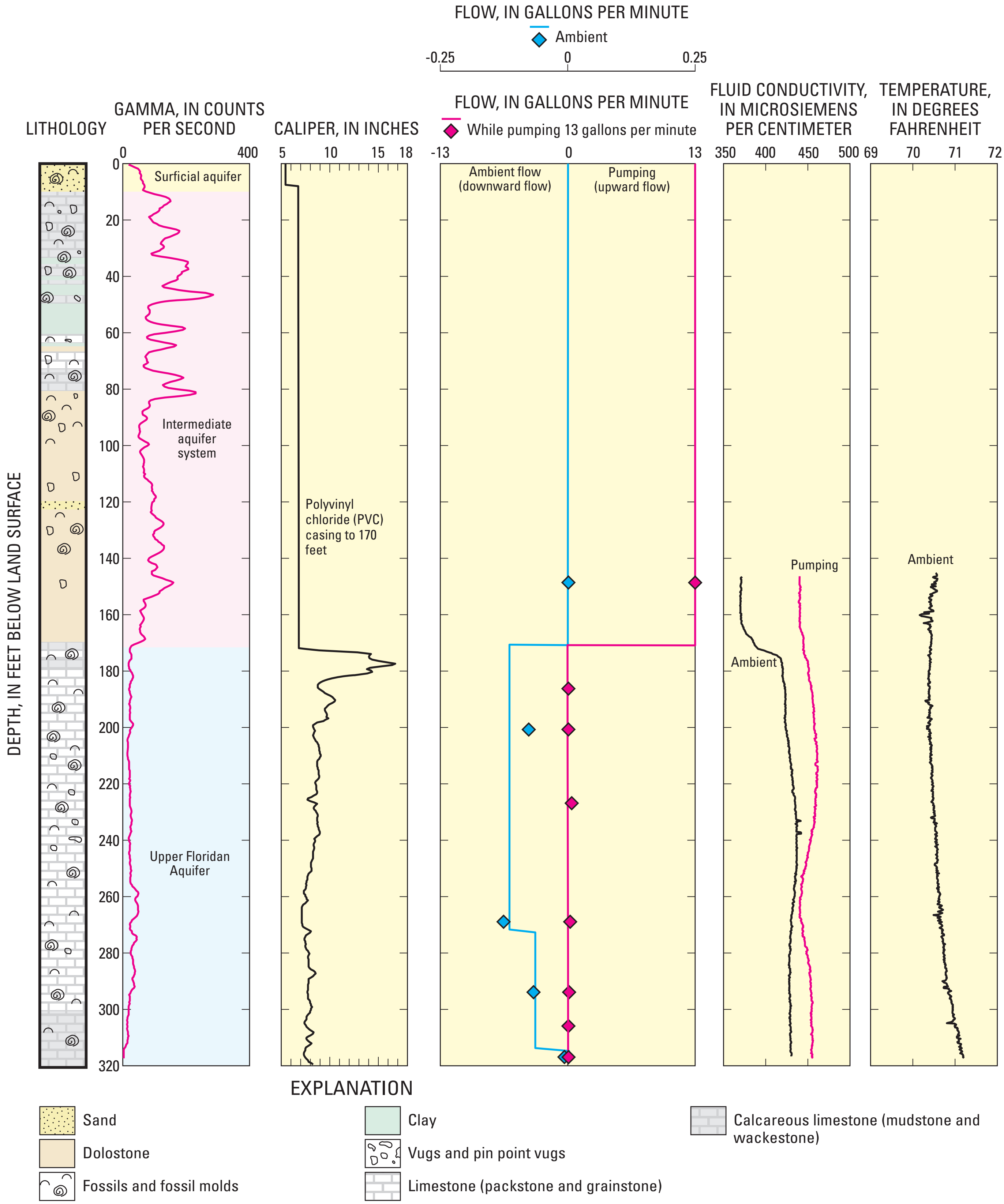


Figure 16. Geophysical logs for well site LW3P.

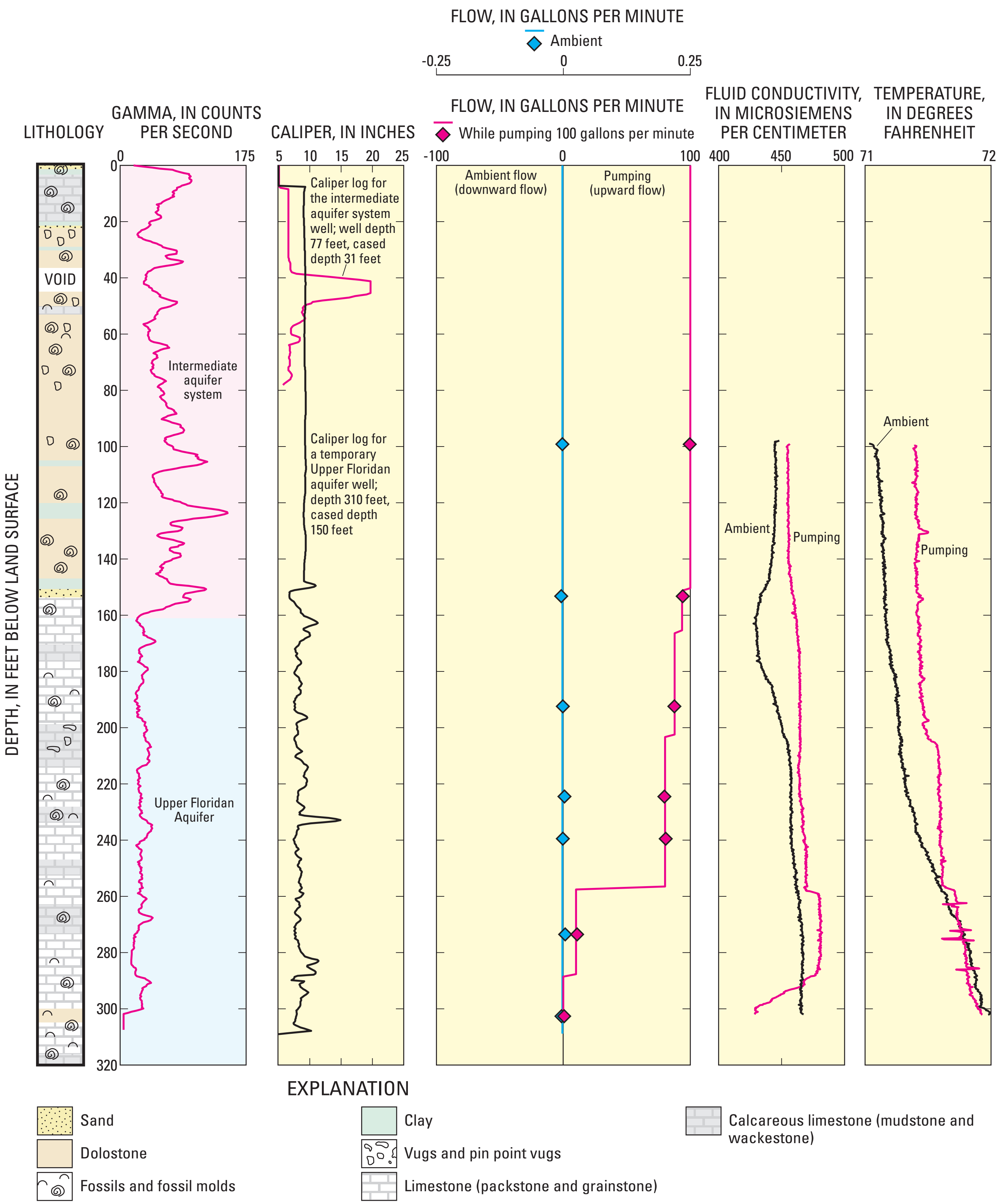


Figure 17. Geophysical logs for well site LW4P.

indicate an increase in the caliper trace at the top of the Upper Floridan aquifer, which signifies a weathered fractured zone. A downhole video camera was used to verify these zones.

Confirming the results of the drilling cores, the caliper log for the intermediate aquifer system well at the LW4P site (fig. 17) indicated a large cavity at a depth of 38 to 53 ft below land surface. A downhole video camera was then used to identify the extent of the pervasive cavity at a similar depth for three nearby temporary wells used during drilling and two nearby monitor wells. All logs indicated that a cavity exists at this depth over a distance of at least 100 ft. Near the LW4P site is the extinct Kissengen Spring, the newly formed Otter Sink, and Tom's Sink (fig. 13B), which may also be part of this fracture system. Numerous casts, molds, vugs, and fractures were visible in the video logs.

Results from the flowmeter logs during ambient conditions indicate downward flow in the boreholes for the LW1P and LW3P wells, and no detectable flow in the LW4P well borehole. Flowmeter logs during pumping conditions indicate that flow moved up the boreholes and exited the borehole at formation contacts. Results from EM flow logs at LW1P indicate that water moves downward within the borehole during non-pumping conditions. During pumping conditions, flow was observed at permeable zones within the hydrogeologic units. For example, EM flow logs at the LW1P well, which has an open interval of 17 to 235 ft below land surface, indicate that most flow in the borehole occurs at discrete zones located 20 to 25, 60 to 70, and 90 to 100 ft below land surface. A comparison of geologic cores and EM flow logs indicates that these flow zones are in areas where the carbonates are fractured and weathered.

Potentiometric Surface

Predevelopment water levels are considered to be the levels of the potentiometric surface of the Upper Floridan aquifer prior to any groundwater usage (Johnston and others, 1980). Predevelopment levels ranged from 120 ft in the northern part of the upper Peace River basin to 80 ft in the southern part (fig. 18A). Prior to development, regional groundwater flow through the upper Peace River basin was mostly from the north toward the south-southwest. Current potentiometric-surface levels (May 2007) indicate a range from 120 ft in the northern part to 50 ft in the southern part of the basin, with the largest declines occurring in the west-central part of the upper Peace River basin near Bartow (fig. 18B). The current regional groundwater flow paths (May 2007) have shifted to a more westerly direction through the basin compared to the predominate north-south trending predevelopment flow paths.

Potentiometric-surface maps of the intermediate aquifer system are difficult to construct, because existing control wells are finished in multiple aquifers producing composite potentiometric-surface levels. Water levels in the intermediate aquifer system in the study area also are more localized and are influenced by the heterogeneous geology and by several topographic highs, including the Lake Wales Ridge to the east

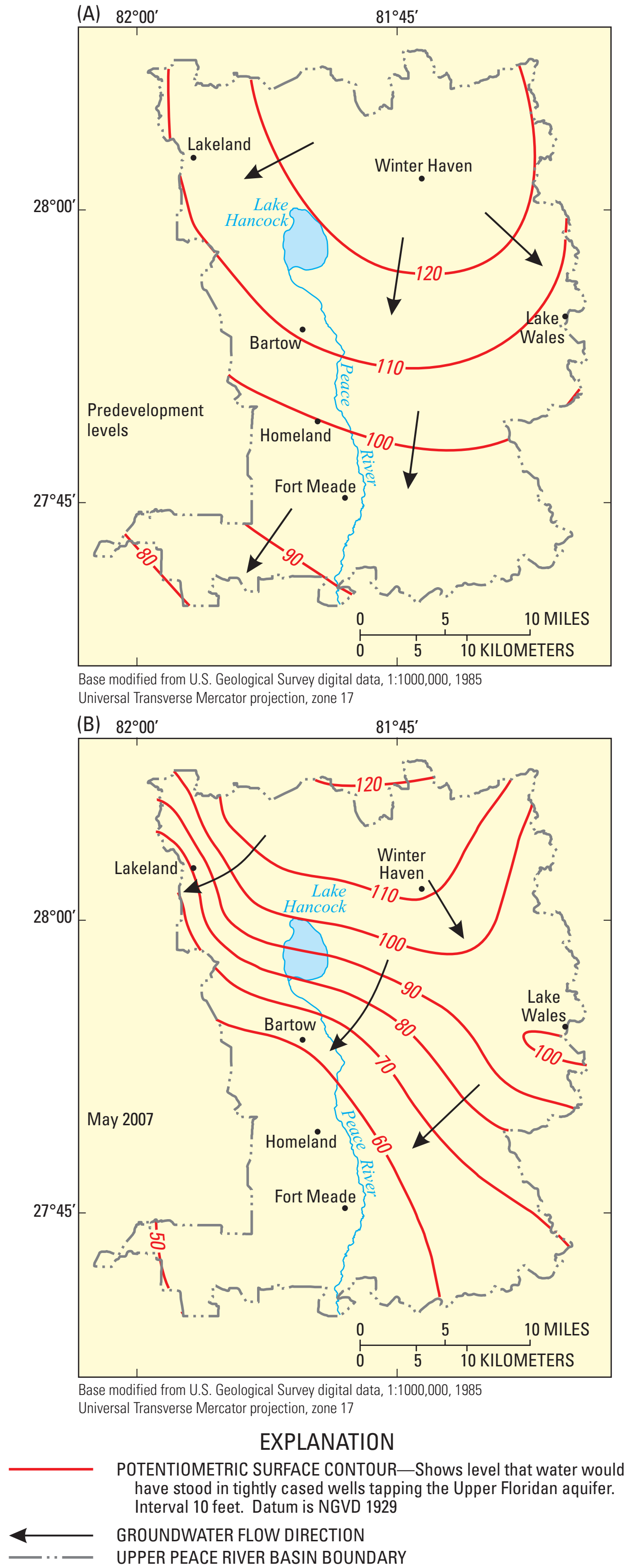


Figure 18. (A) Predevelopment (modified from Johnston and others, 1980) and (B) May 2007 potentiometric-surface levels (modified from Ortiz, 2008a) and regional groundwater flow patterns of the Upper Floridan aquifer within the upper Peace River basin.

Otter at Otter Sink. Photo credit: P.A. Metz, USGS

and Lakeland Ridge to the west (fig. 2). Based on wells open only to the lower Arcadia aquifer in the vicinity of the upper Peace River, groundwater flow generally moves from the nearby ridges toward the river.

Long-Term Trends in Groundwater Levels

In the upper Peace River basin, the groundwater levels in the Upper Floridan aquifer have declined (currently about 50 ft) from predevelopment levels because of historical groundwater use. Long-term water-level records indicate that the declines started in the late 1930s when large quantities of groundwater were used for phosphate-mining processes (Peek, 1951; Hutchinson, 1978; Lewelling and others, 1998). This large potentiometric-surface decline resulted in the cessation of flow from Kissengen Spring and minor springs that discharged from the Upper Floridan aquifer and intermediate aquifer system (Peek, 1951; Stewart, 1966; Lewelling and others, 1998) (fig. 19A). In addition, artesian wells at the headwaters of the Peace River near Saddle Creek ceased to flow in the late 1950s (Stewart, 1966).

A hydrograph of the Upper Floridan aquifer Regional Observation Monitoring Program (ROMP) well ROMP 60 shows that the long-term decline in water levels continued into the mid-1970s (fig. 19B; location of well is shown in fig. 8). The peak of phosphate production in the upper Peace River basin occurred during the mid-1970s, when groundwater pumpage for phosphate mining was estimated to be about 270 Mgal/d (Spechler and Kroening, 2007). An increase in water levels after the mid-1970s coincided with the period of time when the phosphate-mining industry started water-conservation practices (Spechler and Kroening, 2007).

Statistical analysis of the water levels in the Upper Floridan aquifer shows about a 20-ft rise in levels from the mid-1970s to 2007. This rise may be a result of a combination of factors that include the reduction in groundwater pumpage for phosphate during the past decades, climatic conditions, and improved conservation by agriculture. Although mining in the area has declined, an increase in population and agricultural expansion since the 1970s has resulted in a redistribution of some of the pumping stresses (Spechler and Kroening, 2007).

A hydrograph of the intermediate aquifer system ROMP 59 well also shows a continued steady recovery in water levels from the mid-1970s to 2007 (fig. 19C; location of well is shown in fig. 8). Water-level trends for the intermediate aquifer system, however, are not as dramatic as those observed in the Upper Floridan aquifer. The range of water-level fluctuations is about 8 to 10 ft for the less productive intermediate aquifer system, whereas the Upper Floridan aquifer has a much larger range, fluctuating as much as 40 ft between wet and dry seasons because of nearby pumpage. Based on statistical analysis, water levels in the intermediate aquifer system experienced a recovery of about 10 ft from the mid-1970s to 2007. This rise is likely the result of decreased pumpage from the Upper Floridan aquifer, which in turn causes reduced leakage from the intermediate aquifer system (Knochenmus, 2006).

The cumulative groundwater withdrawals in the 5,000-mi^2 Southern West-Central Florida Groundwater Basin influence the groundwater levels in the upper Peace River basin because of the regional flow regime of the Upper Floridan aquifer. Water-level difference maps were created based on predevelopment minus the May 1975, May 2007, and September 2007 levels to evaluate the decline in groundwater levels across the regional Southern West-Central Florida Groundwater Basin and the localized upper Peace River basin. The May 1975 map was used, because groundwater pumpage for phosphate mining in the upper Peace River basin was at its highest level during this period. The 1975 difference maps of the regional groundwater basin show that the greatest declines (greater than 50 ft) occurred in the central and southwestern half of the upper Peace River basin and extended to Hillsborough, Manatee, and Hardee Counties (fig. 20A).

The May 2007 difference map of the regional Southern West-Central Florida Groundwater Basin shows a rise in groundwater levels in the upper Peace River basin from the May 1975 levels. The lowest levels for the May 2007 difference map (greater than 50 ft) are located in Hillsborough, Manatee, and Hardee Counties (fig. 20B). Water-level difference maps for the upper Peace River basin for the current May and September 2007 levels (fig. 20C, D), indicate that the greatest declines are centered on the upper reaches of the Peace River near Bartow to Fort Meade (May 2007). The September 2007 difference map shows a water-level rise of about 10 to 20 ft from the May 2007 map near the Bartow to Fort Meade area.

The decline in the potentiometric surfaces of the Upper Floridan aquifer has affected the interactions between the Peace River and the underlying groundwater system. Figure 21 illustrates the level of the potentiometric surface of the Upper Floridan aquifer above the riverbed elevation when the area had flowing wells and springs. The area along the upper Peace River is now a recharge area where

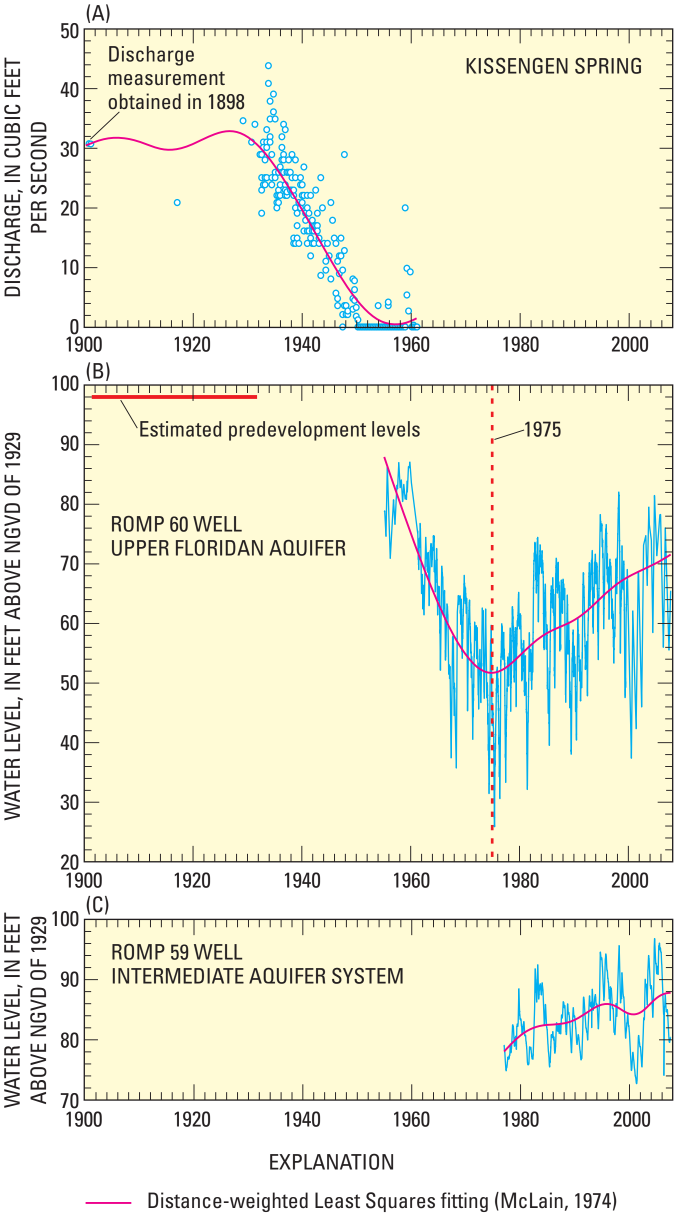


Figure 19. (A) Long-term discharge from Kissengen Spring, and long-term water levels in observation wells tapping the (B) Upper Floridan aquifer and (C) intermediate aquifer system (location of Kissengen Spring and wells are shown in figs. 13 and 8, respectively).

the potentiometric surface of the Upper Floridan aquifer is below the riverbed elevation, and river water flows downward through karst features to the underlying aquifers. During May 1975, when groundwater use for mining processes was at its highest level, the potentiometric surface of the Upper Floridan aquifer was as much as 50 ft below the riverbed elevation near Bartow (fig. 21). The May and September 2007 conditions indicate a rise in aquifer water levels above the 1975 levels, but levels remain as much as 30 ft and 20 ft below the riverbed elevation, respectively (fig. 21).

Streamflow

Data collected at 10 USGS continuous gaging stations located along the upper Peace River and contributing tributaries (fig. 22) were used to (1) quantify flow under varying hydrologic conditions; (2) determine historical changes in flow; (3) quantify river flow losses and gains; (4) understand anomalies in flow conditions, such as reversals in flow, and (5) determine losses or gains from any unknown sources. There were five main-channel stations along the upper Peace River (fig. 22); Peace River at Bartow (site 1), Peace River near Bartow (site 7), Peace River at Clear Springs (site 11), Peace River near Homeland (site 16), and Peace River at Fort Meade (site 31). The inflow tributary gaging stations were Saddle Creek at Structure P-11 (site A), Peace Creek Drainage Canal near Wahneta (site B), and three phosphate-mine outfalls; Sixmile Creek (site 12), Phosphate Mine Outfall CS-8 (site 14), and Barber Branch (site 15) (fig. 22).

River Channel Characteristics Affecting Upper Peace River Flows

The upper Peace River was subdivided into four principal study reaches based on their unique hydrologic and karst characteristics (fig. 22). A physical description of the Peace River channel and associated tributaries and distributaries along Reaches 1 through 4 follows.

Reach 1 begins at the Peace River at Bartow gaging station (site 1) at SR 60 and extends downstream 1.8 mi to the Peace River station near Bartow gaging station (site 7) (fig. 22). Saddle Creek (site A) and Peace Creek Drainage Canal (site B) drain the headwaters of the upper Peace River watershed, and inflows from these creeks largely determine the quantity of flow entering the upper part of Reach 1. The lower part of Saddle Creek drains Lake Hancock, and has been completely channelized from the lake outfall to its confluence with the Peace River and the Peace Creek Drainage Canal. A control structure (P-11) that regulates discharge from Lake Hancock is located about 2.3 mi upstream from the confluence of Peace Creek Drainage Canal and Saddle Creek. Peace Creek Drainage Canal also has been channelized in areas for flood control and, during higher flows, water from this canal moves into low-lying overbank areas.

The effect of these altered streams has the largest impact on Peace River flows during low-flow conditions, when the tributary inflows are most needed to sustain flows in the river. For example, when the control structure at Saddle Creek is closed, backwater from the Peace Creek Drainage Canal can flow up into the altered low-gradient channel of Saddle Creek. Because of the large storage capacity of this 2.3-mi dredged channel, a substantial volume of water from the Peace Creek Drainage Canal is stored in the Saddle Creek channel when P-11 is closed. As a result of channelization and increased storage, flows from these creeks to Reach 1 have been reduced during

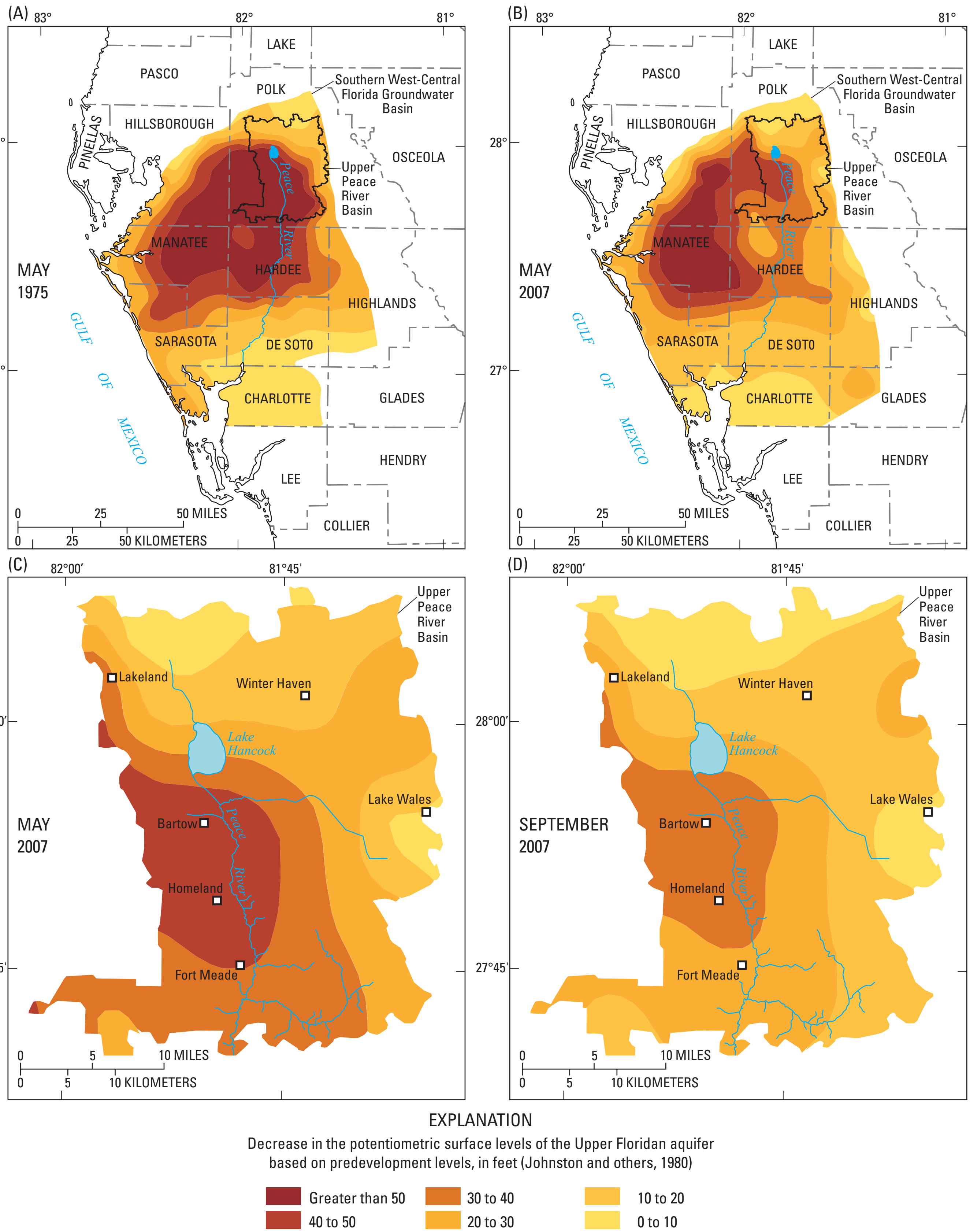


Figure 20. Changes in the potentiometric surface of the Upper Floridan aquifer between predevelopment (modified from Johnston and others, 1980) and (A) May 1975 (modified from Mills and Laughlin, 1976) and (B) May 2007 levels (modified from Ortiz 2008a) for the Southern West-Central Florida Groundwater Basin, and between predevelopment and (C) May 2007 and (D) September 2007 levels (modified from Ortiz 2008b) for the Upper Peace River basin.

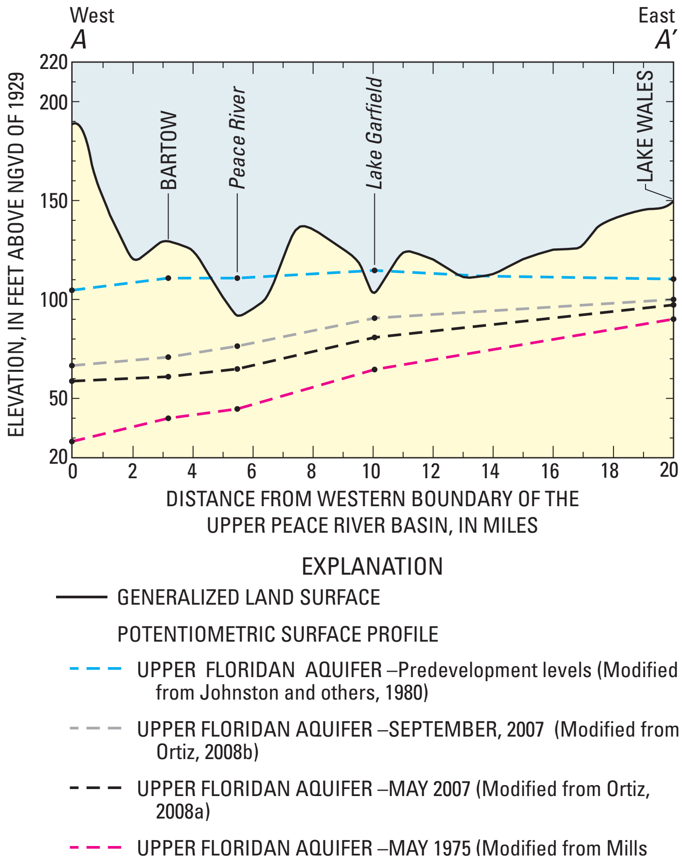


Figure 21. Comparison of potentiometric-surface profiles of the Upper Floridan aquifer for predevelopment and recent conditions (location of section *A-A′* is shown in fig. 8).

low-flow conditions. Similar conditions have been observed at other Peace River tributary sites, where the flat, low-gradient ditches pond water rather than flow during low-flow conditions.

Downstream from the confluence of these creeks, the Peace River channel along Reach 1 is characterized as sandy and gently meandering, and varies in width from about 30 to 100 ft. This poorly incised channel transitions into a broad, heavily wooded high-water channel (floodplain) with banks rising from about one to several feet in height. The extent of areal inundation of the high-water channel is generally restricted to a floodplain corridor, bordered on both sides by elevated phosphate-mined landforms (Lewelling, 2003). Numerous cypress trees line the edges of the low-water channel and, at several locations, the exposed roots of long-decayed cypress trees are associated with observed cracks or openings that drain river water into the underlying aquifer. Karst features are located along this reach and have been observed to persistently drain river water to the underlying aquifers. Intermittent exposures of karstified limestone layers are present in the channel bed along the lowermost sections of the reach. During most low-flow conditions, flow is perennial along the upper section of Reach 1. The reach becomes dry only during prolonged droughts, such as in 2000-2002.

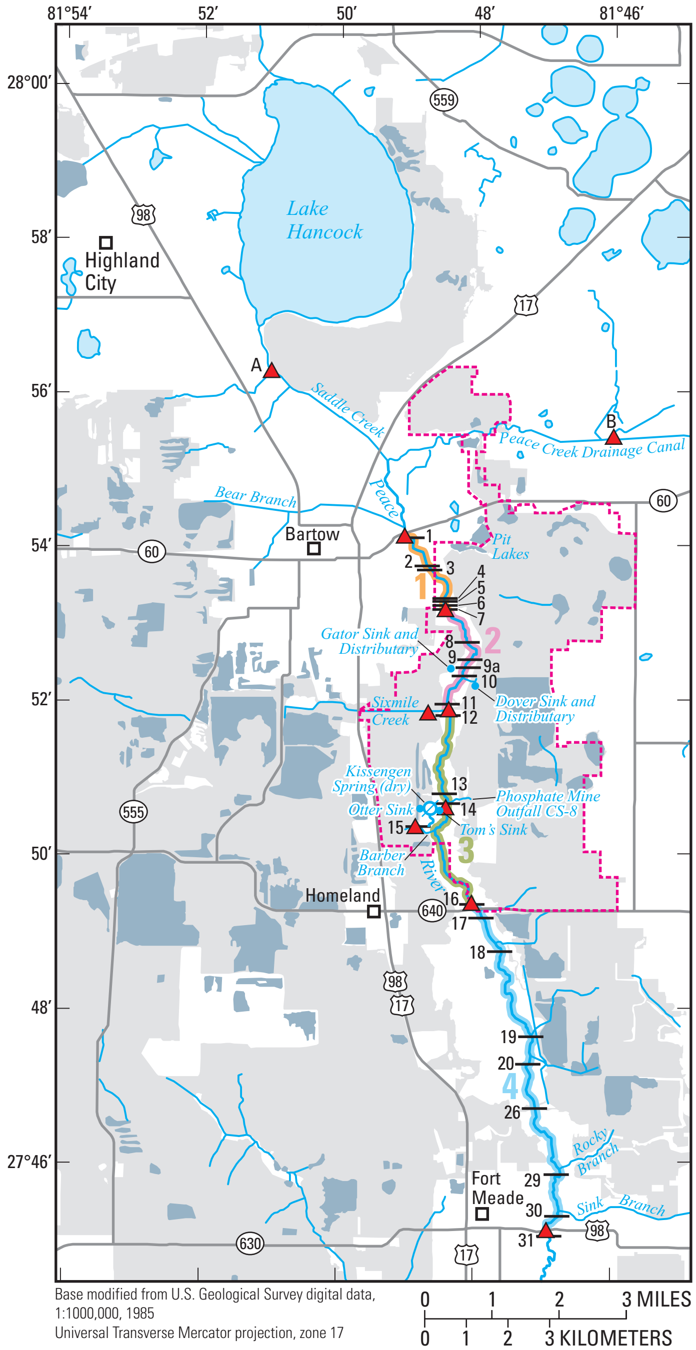
Surface-water inflows into Reach 1 include two poorly incised drainage channels located on the eastern side of the Peace River floodplain and immediately downstream from the Peace River at Bartow station (site 1). These channels can drain to or receive water from a series of interconnected phosphate-mine pit lakes during high-flow conditions. During dry periods when flows in the Peace River at the Bartow station are about 50 cubic feet per second (ft^3/s) or less, these channels typically do not convey any water between the pit lakes and the river. Two urban storm drainage ditches, one directly north and the other about 1,200 ft south of the Bartow WWTP, discharge flows into the Peace River. These ditches discharge to the Peace River only during intense storm events.

Reach 2 begins at the Peace River near Bartow gaging station (site 7) and extends 1.9-mi downstream to the Peace River at Clear Springs gaging station (site 11) (fig. 22). Except for several limited areas of limestone outcrops, most of the channel bed is overlain by a thick layer of shifting sand. The Peace River consistently goes dry in Reach 2 during low-flow conditions because of a number of karst features in the channel that intercept and drain the surface-water flow. An approximate 1,700-ft-long section of channel at the lower end of Reach 2 generally remains ponded. The ponding in this section may indicate an impermeable sediment layer in the channel bed or a lack of karst features that can drain surface-water flow.

There are no tributaries, channels, or ditches contributing flow to the Peace River along Reach 2. The broad floodplain of the Peace River along this reach is almost entirely bordered by elevated phosphate clay-settling landforms that confine high-flow discharge within the floodplain boundaries.

Located along Reach 2 are two distributary channels (Dover Sink Distributary and Gator Sink Distributary) that drain river water from the main channel under certain hydrologic conditions (fig. 22). The Dover Sink Distributary is an approximate 500-ft-long channel that winds through the floodplain and connects to Dover Sink. The poorly incised Gator Sink Distributary is about 200 ft upstream from the Peace River confluence with the Dover Sink Distributary. Gator Sink Distributary winds through the wooded floodplain and drops several feet in elevation before it reaches Gator Sink, which is about 800 ft west of the river. Also located in Reach 2 are two phosphate-mined pit lakes that accept backwater from the Peace River during high-flow conditions.

Reach 3 begins at the Peace River at Clear Springs gaging station (site 11) and extends 3.9 mi downstream to the Peace River near Homeland gaging station on the SR 640 bridge (site 16) (fig. 22). Reach 3 is defined by a poorly incised low-water channel, and this reach has not been observed dry during low-flow conditions. The extent of areal inundation of the high-water channel is generally restricted to the broad floodplain corridor, bordered on both sides by elevated reclaimed phosphate-mined landforms.



EXPLANATION

- MINED AREA
- HYDROLOGY ASSOCIATED WITH MINED AREAS
- OPEN WATER
- 1 REACH AND REACH NUMBER
- CLEAR SPRINGS MINE BOUNDARY
- KISSENGEN SPRING—dry
- —1 LOCATION OF DISCHARGE MEASUREMENT SITES DURING SEEPAGE RUNS AND NUMBER
- KARST FEATURE
- USGS STREAMFLOW GAGING STATION

Site number	River mile	Location
A		Saddle Creek at Structure P-11 (gaging station)
B		Peace Creek Drainage Canal (gaging station)
1	0	Peace River at Bartow (gaging station)
2[1]	0.8	Above Wabash Complex
3	0.9	Below Wabash Complex
4	1.3	Upper dragline crossing; Cook's Ripple
5	1.6	Above Ledges; Fricano Fracture
6	1.7	Below Ledges
7	1.8	Peace River near Bartow (gaging station)
8	1.9	Below diffuse zone and Midway
9	2.1	Below Elephant Graveyard
9a	2.6	Below Crevasses
10	2.8	Dover Sink and Dover Sink Distributary
11	3.7	Peace River at Clear Springs (gaging station)
12	3.8	Sixmile Creek (gaging station)
13	4.9	Above Kissengen Spring
14	5.2	Phosphate Mine Outfall CS-8 (gaging station)
15	5.7	Barber Branch (gaging station)
16	7.2	Peace River near Homeland (gaging station)
17	7.3	Department of Environmental Protection ditch
18	7.8	Below Juvenile Detention Center
19	9.5	Mobil Outfall 3W Cut
20	9.9	Camp Meeting Branch
26	10.8	Below Mobil bridge
29	11.9	Rocky Branch
30	12.6	Sink Branch
31	13.0	Peace River at Fort Meade (gaging station)

[1] Site 2 used as alternate discharge measurement section for site 1 during low-flow conditions

Figure 22. Locations of stream Reaches 1-4 and discharge measurement sites on the Peace River and tributaries during seepage runs.

Three phosphate-mine outfall gaging stations are located along Reach 3: Sixmile Creek (site 12), Phosphate Mine Outfall CS-8 (site 14), and Barber Branch (site 15; fig. 22). These outfalls generally supply water to Reach 3, except under extremely dry conditions. These three channels have been altered by strip mining for phosphate. The channels have been generally reclaimed as broad linear ditches. The contributing drainage areas for these channels are dominated by interconnected, reclaimed linear pit lakes and clay-settling areas, which are surrounded by various types of reclaimed landforms.

Reach 4 begins near the Homeland gaging station (site 16) at the SR 640 bridge, and extends 5.4 mi downstream to the Peace River at Fort Meade gaging station (site 31) (fig. 22). The channel along Reach 4 is generally more incised than the upstream reaches and, during moderate-flow conditions, the reach can exhibit multiple braided channels in places. Most of the riverbed is sandy, except for limited areas of karst outcroppings and remnants of phosphate-mining pebbles. Inflows into Reach 4 are predominately from numerous reclaimed phosphate-mined channels and outfall structures associated with the clay-settling landforms that border much of the floodplain (high-water channel) corridor. Discharges from the largest reclaimed channels, Rocky Branch and Sink Branch, generally produce the largest inflows. Discharge at these outfalls was not monitored continuously, although periodic flow measurements were made on these tributaries.

Streamflow Conditions (2002-2007 Water Years)

Streamflow conditions for the upper Peace River during this investigation (2002-2007 water years) can be summarized as a period of extremes, and climatic conditions were a dominant control on these varying conditions. Rainfall deficits or excesses (measured from the long-term average rainfall of 54.12 in.) were a major influence on streamflow in the study area, as shown in figure 23. Below-average streamflow conditions occurred during the 2002, 2006, and 2007 water years

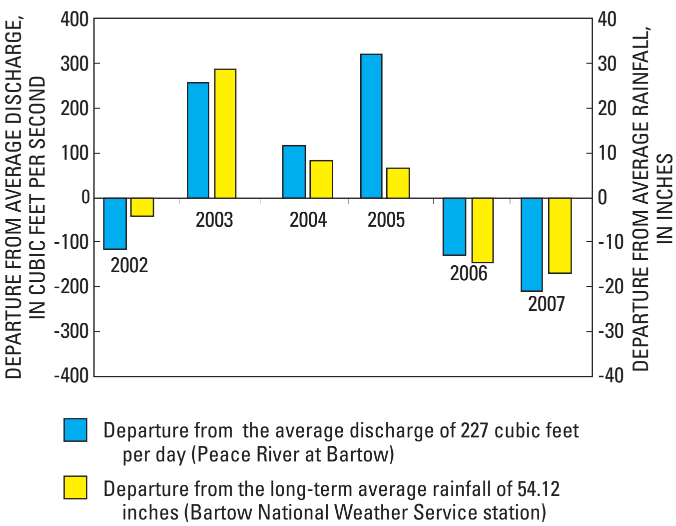


Figure 23. Departure from the average discharge and rainfall for the 2002-2007 water years.

when rainfall deficits occurred, and above-average streamflow conditions occurred during the 2003-2005 water years when rainfall excesses occurred.

Discharge hydrographs for four streamflow sites on the Peace River and at the three mine outfall stations for the 2002-2007 water years are shown in figures 24 through 29 (locations of stations are shown on fig. 22). Three main-channel sites, from the Peace River at Bartow to the Peace River at Clear Springs gaging stations, are located in the area of greatest observed streamflow losses. The discharge hydrographs illustrate the change in flow over varying hydrologic conditions and streamflow losses, and also indicate overbank storage between Peace River gaging stations. Streamflow statistics for the upper Peace River and the tributary sites for the 2002-2007 water years are shown in table 1.

Prior to the beginning of this study, a severe drought affected most of Florida from 1998 to 2002 (Verdi and others, 2006). During 2000 to 2002, the streamflow gage at the Peace River at Bartow (site 1) recorded periods of zero-flow for the first time in its 68-year history. Zero-flow periods occurred for 37 days between May and June, 2000; 25 days between May and June, 2001; and 6 days in May 2002. Although another severe drought during the 2006-2007 water years caused below-average streamflow conditions in the study area, the Peace River at Bartow gaging station did not reach zero flow.

During the study period (2002-2007 water years), the lowest annual mean discharge occurred during the 2007 water year, when a 2-year (2006-2007) cumulative rainfall deficit of almost 29 in. reduced streamflow in the upper Peace River (fig. 23). The annual mean discharge was only 18 ft^3/s for the 2007 water year, which was the lowest annual discharge for the 68-year period of record at the Peace River at Bartow gaging station. Rainfall for the 2007 water year was 37 in. and was the third lowest in the 107 years of record, which accounts for the streamflow reductions in upper Peace River. Below-average conditions also existed in the 2002 and 2006 water years at this station, when the mean annual discharge was 110 and 99 ft^3/s, respectively. For comparison, the period of record mean discharge record at this station is 227 ft^3/s.

A trend analysis of long-term streamflow data from the Bartow gaging station shows a significant decline in streamflow during the 1940s, 1950s, and 1960s, and statistically unchanged streamflow during the 1970s (Hammett, 1990). Another trend analysis conducted for 1970s to 2003 data indicates that a decline in streamflow continues through this time period (Spechler and Kroening, 2007). Over time, declines in streamflow have been influenced by a number of factors attributed to (1) rainfall deficits that affect annual surface- and groundwater storage conditions, (2) surface-water inflows and baseflow declines, and (3) large groundwater withdrawals that have lowered the potentiometric surfaces of the intermediate aquifer system and Upper Floridan aquifer beneath the riverbed, which results in a loss of river water to karst features that drain to the underlying aquifers.

During below-average streamflow years (2002, 2006, and 2007 water years), flow was observed draining into various karst features as flow in the channel progressed downstream from the Peace River at Bartow station (site 1, start of Reach 1). A comparison of discharge hydrographs between the upstream site (Peace River at Bartow; site 1) and the downstream site (Peace River near Bartow; site 7), mostly showed lower discharge at the downstream site (figs. 24-29). This difference reflects the loss of streamflow to the various sinks in this reach. This condition was most pronounced during periods when aquifer levels were low (figs. 24B-29B).

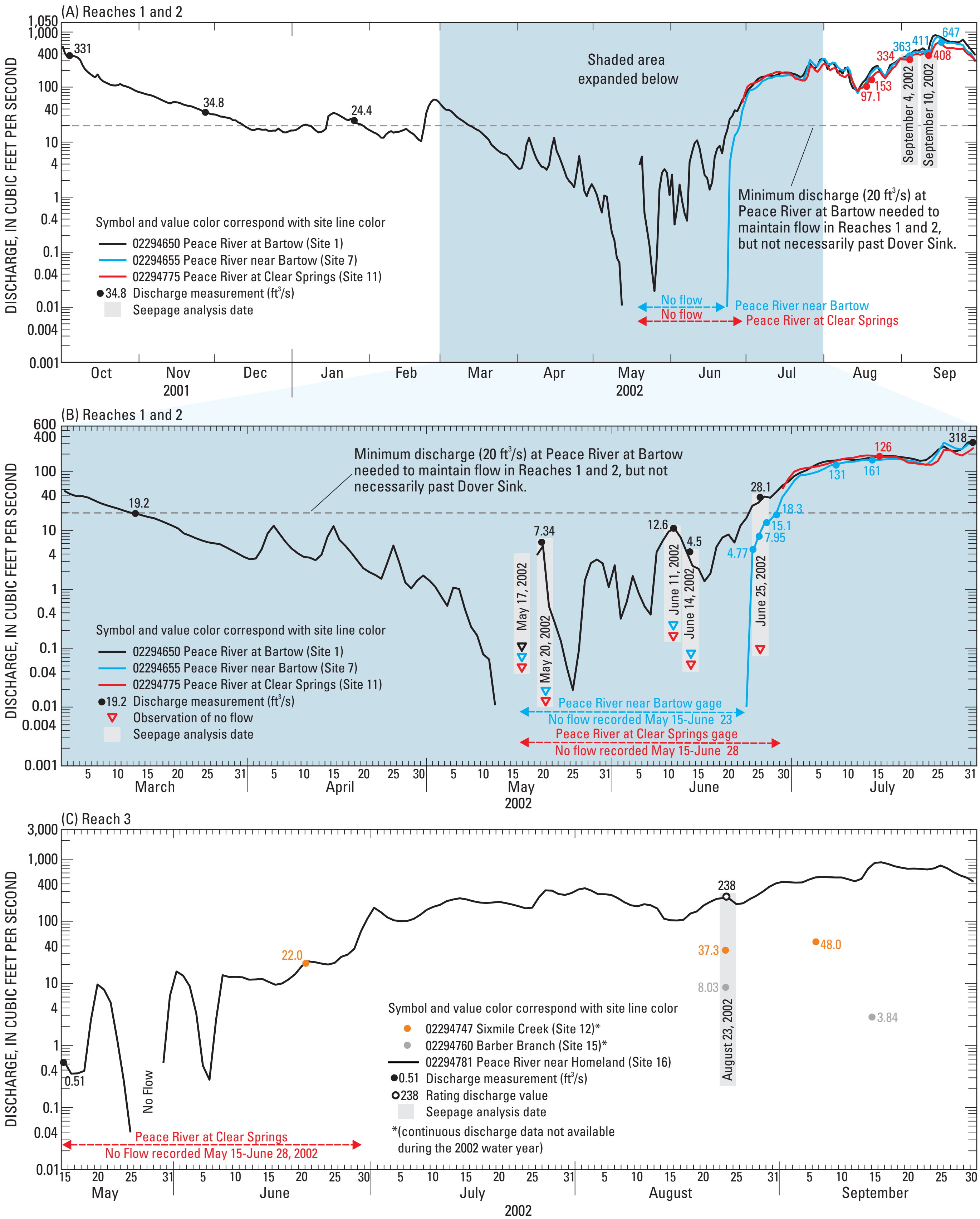


Figure 24. Daily mean discharge for Reaches 1 and 2 for the (A) 2002 water year, (B) the 2002 low-flow period, and (C) daily mean discharge for Reach 3 for the partial 2002 water year.

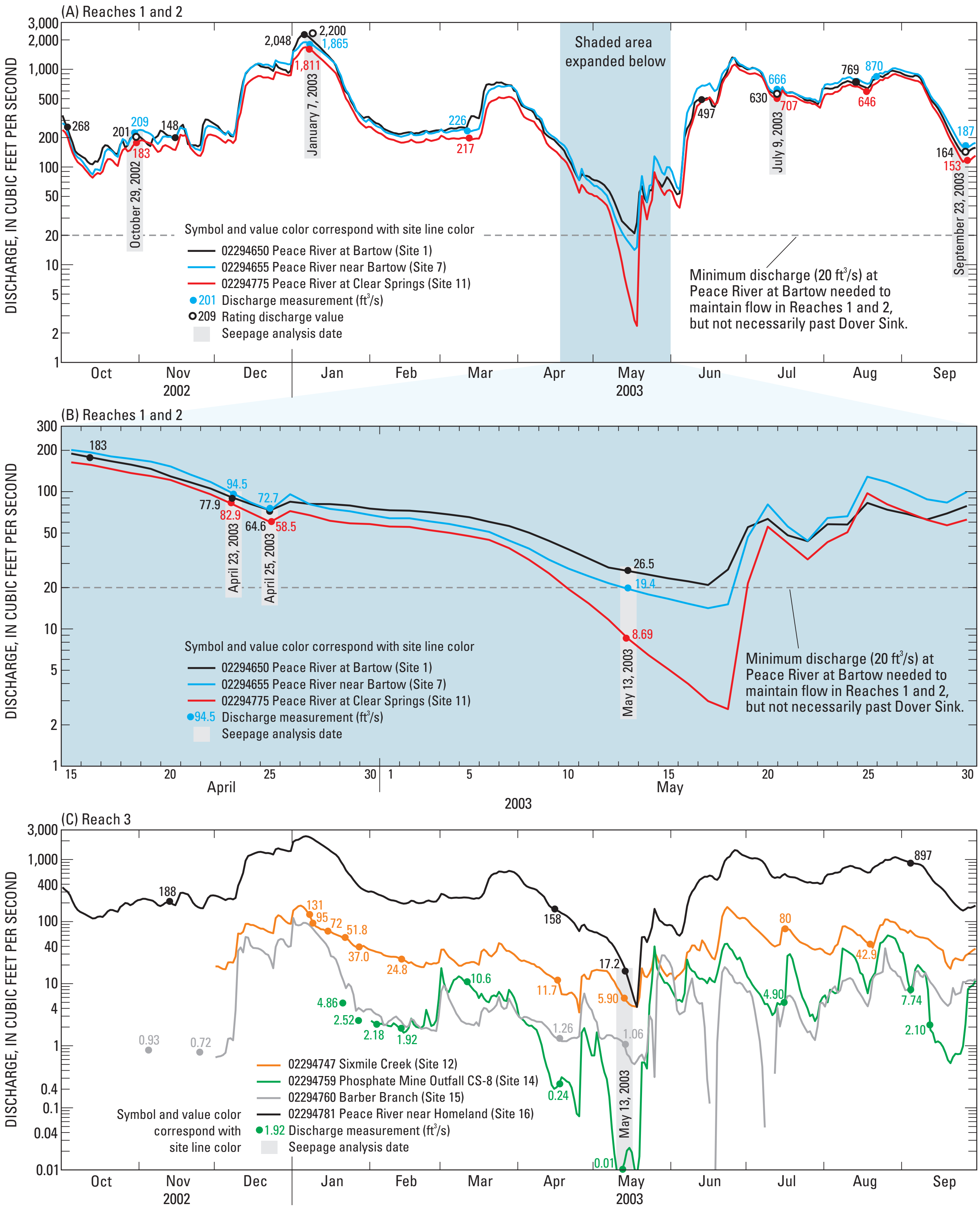


Figure 25. Daily mean discharge for Reaches 1 and 2 for the (A) 2003 water year, (B) the 2003 low-flow period, and (C) daily mean discharge for Reach 3 for the 2003 water year.

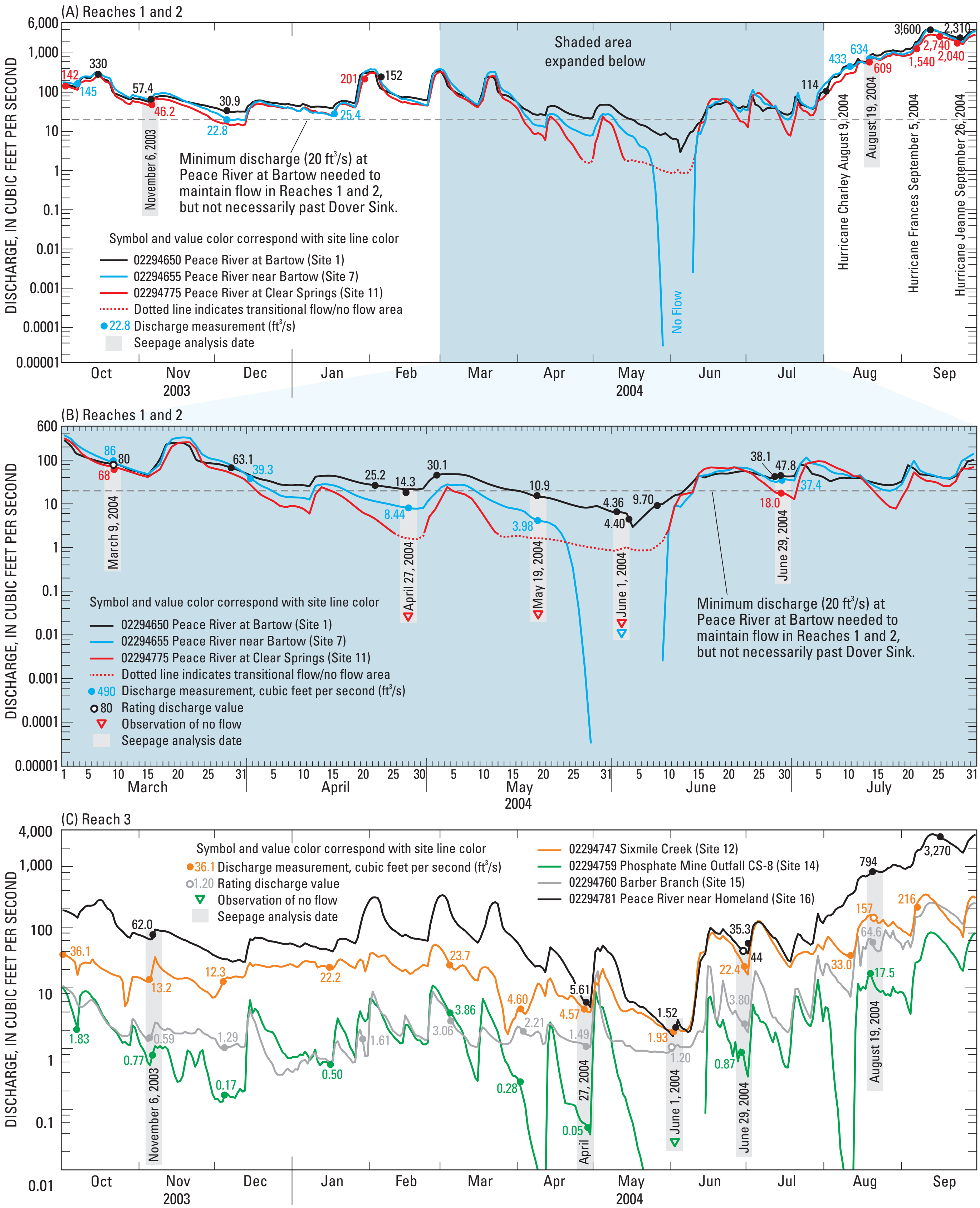


Figure 26. Daily mean discharge for Reaches 1 and 2 for the (A) 2004 water year, (B) the 2004 low-flow period, and (C) daily mean discharge for Reach 3 for the 2004 water year.

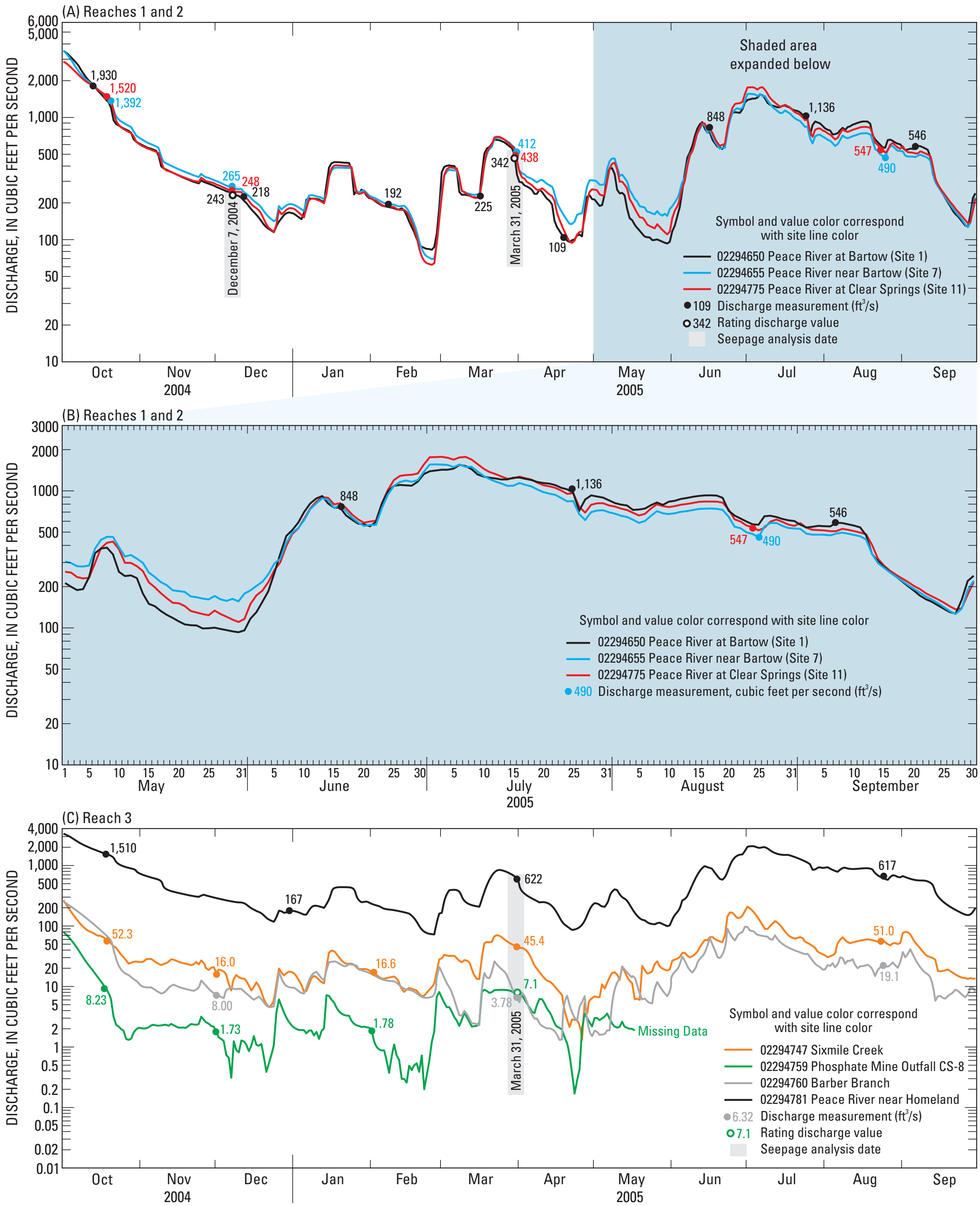


Figure 27. Daily mean discharge for Reaches 1 and 2 for the (A) 2005 water year, (B) a high-flow period during 2005, and (C) daily mean discharge for Reach 3 for the 2005 water year.

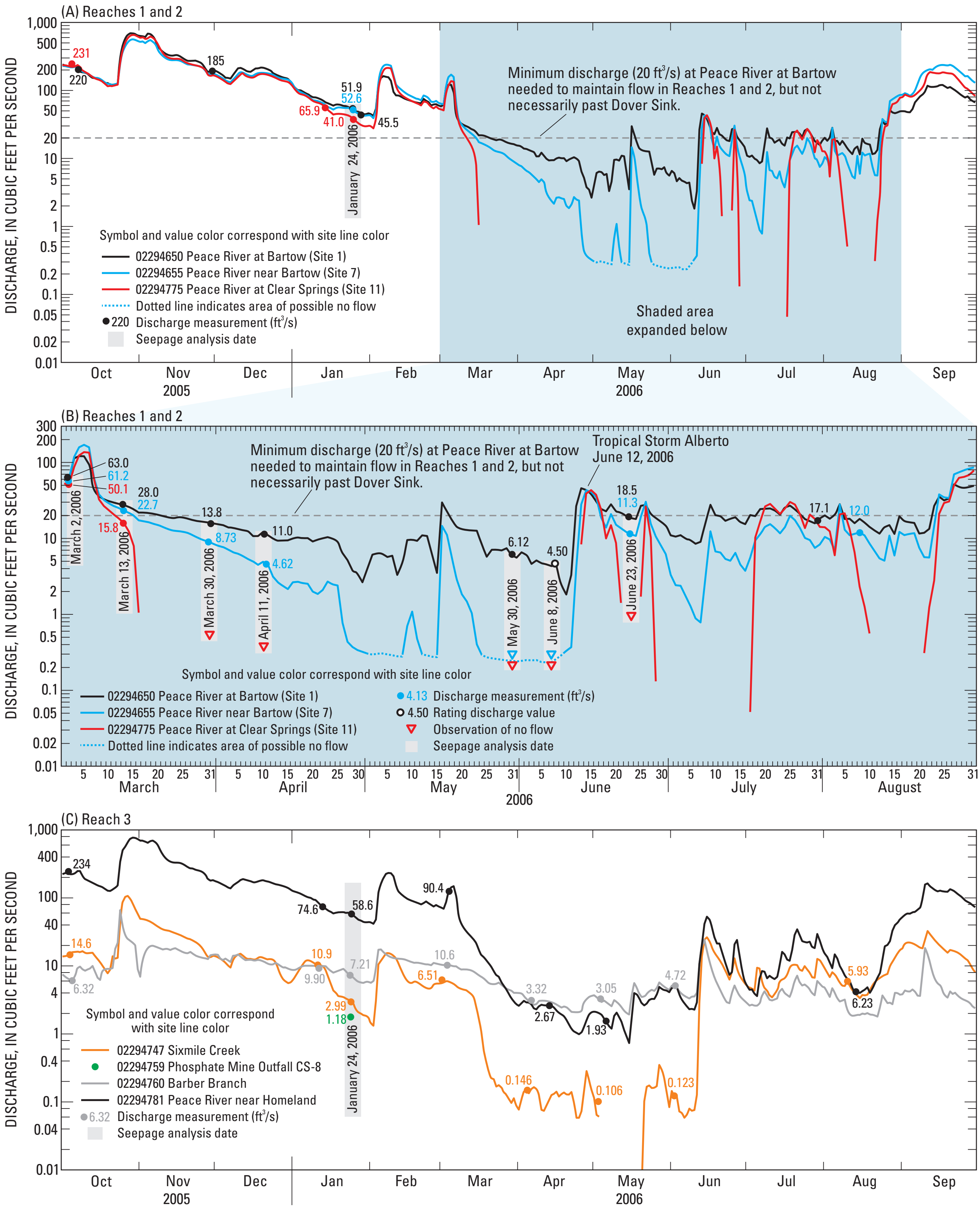


Figure 28. Daily mean discharge for Reaches 1 and 2 for the (A) 2006 water year, (B) the 2006 low-flow period, and (C) daily mean discharge for Reach 3 for the 2006 water year.

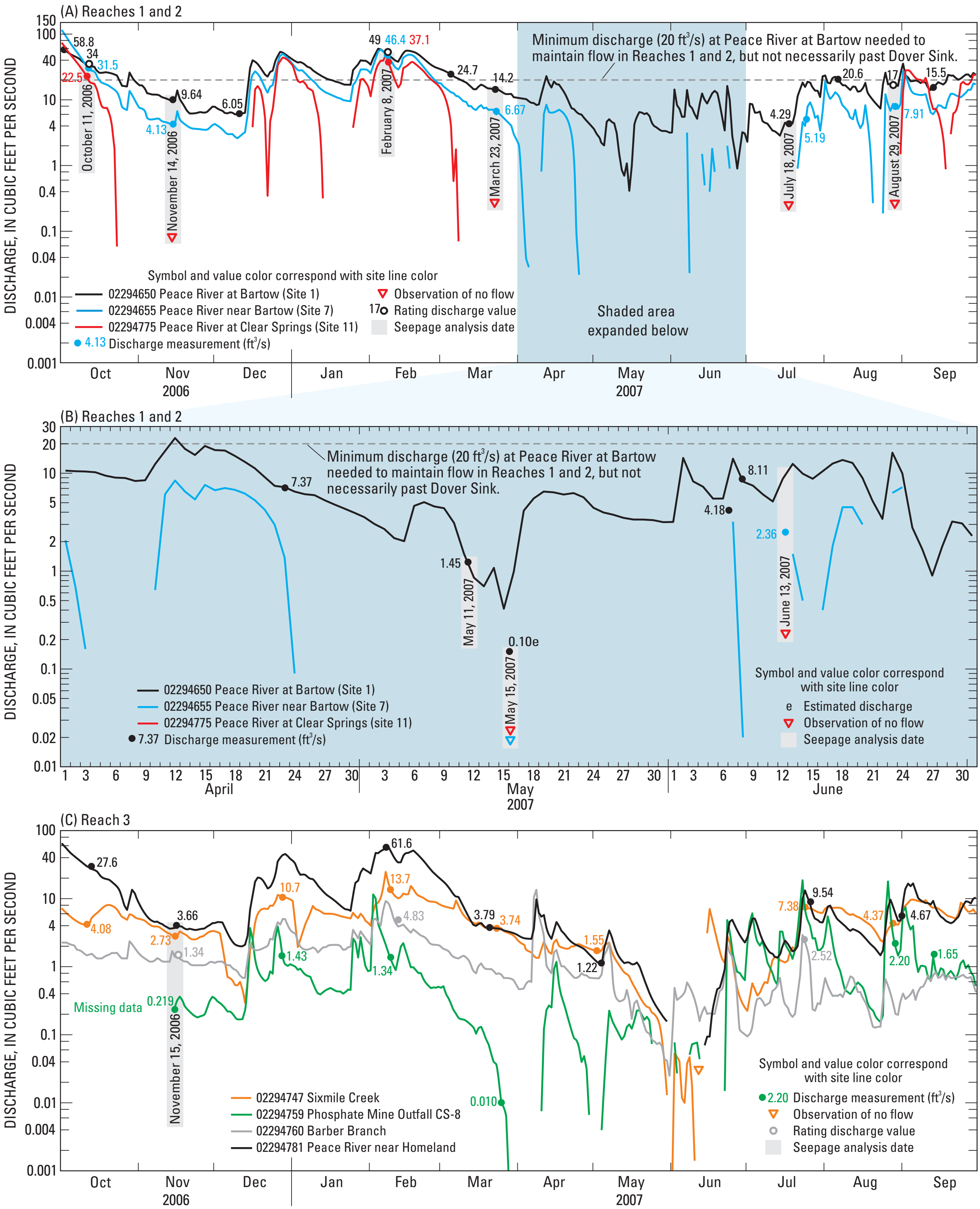


Figure 29. Daily mean discharge for Reaches 1 and 2 for the (A) 2007 water year, (B) the 2007 low-flow period, and (C) daily mean discharge for Reach 3 for the 2007 water year.

Table 1. Streamflow statistics for the upper Peace River and tributaries for the 2002-2007 water years.

[Streamflow statistics based on computed discharge from rating curves. ft^3/s, cubic feet per second; e, estimated; –, missing or no data; *first zero flow day in year]

Sites (fig. 22)	Station	Water year	Annual mean discharge (ft^3/s)	Maximum daily mean discharge (ft^3/s)	Maximum daily mean discharge Date	Minimum daily mean discharge (ft^3/s)	Minimum daily mean discharge Date	Number of zero flow days	Number of days of record
Site A	Saddle Creek at Structure P-11 Station number: 02294491 Period of record: 44 years December 1963-September 2007 Period of record mean discharge: 65 ft^3/s Mean discharge for May 2002-September 2007: 101 ft^3/s	2002	50	604	09-13-2002	0.00	01-03-2002*	183	365
		2003	190	936	01-04-2003	5.7	06-03-2003	0	365
		2004	131	1,620	09-11-2004	0.00	06-13-2004*	14	365
		2005	155	1,310	10-01-2004	0.00	02-18-2005*	9	365
		2006	23	238	11-04-2005	0.03	05-30-2006	0	365
		2007	0.46	28	06-17-2007	0.00	08-11-2007*	25	365
Site B	Peace Creek Drainage Canal Station number: 02293987 Period of record: 16 years March 1991-September 2007 Period of record mean discharge: 101 ft^3/s Mean discharge for May 2002-September 2007: 132 ft^3/s	2002	51	283	10-01-2001	0.81	05-14-2002	0	365
		2003	202	705	01-03-2003	12	10-22-2002	0	365
		2004	113	977	09-10-2004	3.3	06-03-2004	0	365
		2005	288	892	10-01-2004	36	02-19-2005	0	365
		2006	63	528	10-26-2005	1.7	06-10-2006	0	365
		2007	15	73	02-03-2007	3.1	05-14-2007	0	365
Site 1	Peace River at Bartow Station number: 02294650 Period of record: 68 years October 1939-September 2007 Period of record mean discharge: 227 ft^3/s Mean discharge for May 2002-September 2007: 292 ft^3/s	2002	110	881e	09-14-2002	0.00	05-13-2002*	6	365
		2003	483	2,240	01-05-2003	21	05-17-2003	0	365
		2004	344	4,010	09-11-2004	2.9	06-04-2004	0	366
		2005	545	3,520	10-01-2004	83	02-25-2005	0	365
		2006	99	693	10-28-2005	1.8	06-10-2006	0	365
		2007	18	62	10-01-2006	0.41	05-15-2007	0	365
Site 7	Peace River near Bartow Station number: 02294655 Period of record: 5.38 years Mean discharge for May 2002-September 2007: 287 ft^3/s	2002	–	820	09-15-2002	0.00	05-15-2002*	39	139
		2003	492	1,890	01-05-2003	14	05-17-2003	0	365
		2004	324	4,090	09-12-2004	0.00	05-27-2004*	14	365
		2005	545	3,530	10-01-2004	69	02-25-2005	0	365
		2006	97	563	10-29-2005	0.23	06-06-2006	0	365
		2007	12	115	10-01-2006	0.00	04-04-2007*	82	365
Site 11	Peace River at Clear Springs Station number: 02294775 Period of record: 5.38 years May 2002-September 2007 Mean discharge for May 2002-September 2007: 263 ft^3/s	2002	–	643	09-15-2001	0.00	05-15-2002*	45	139
		2003	444	1,850	01-06-2003	2.6	05-18-2003	0	365
		2004	264	2,950	09-12-2004	0.85	06-01-2004	0	365
		2005	545	2,870	10-01-2004	62	02-25-2005	0	365
		2006	92	661	10-29-2005	0.00	03-17-2006*	119	365
		2007	5	74	10-01-2006	0.00	10-23-2006*	175	365
Site 16	Peace River near Homeland Station number 02294781 Period of Record: 5.38 years May 2002-September 2007 Mean discharge for May 2002-September 2007: 298 ft^3/s	2002	112	893	09-16-2002	0.00	05-26-2002*	4	365
		2003	503	2,380	01-06-2003	4.2	05-18-2003	0	365
		2004	304	3,400	09-13-2004	1.6	06-01-2004	0	365
		2005	599	3,360	10-01-2004	73	02-25-2005	0	365
		2006	103	771	10-29-2005	0.73	05-15-2006	0	365
		2007	11	65	10-01-2006	0.00	05-31-2007*	14	365
Site 31	Peace River at Fort Meade Station number: 02294898 Period of record: 33.3 years June 1974-September 2007 Mean discharge for May 2002-September 2007: 343 ft^3/s	2002	132	973	09-25-2002	0.19	05-18-2002	0	365
		2003	584	2,040	01-06-2003	8.8	05-18-2003	0	365
		2004	327	2,450	09-13-2004	4.2	06-07-2004	0	365
		2005	695	2,390	10-01-2004	43	02-24-2005	0	365
		2006	119	850	10-30-2005	1.7	05-08-2006	0	365
		2007	22	134	02-03-2007	0.01	06-01-2007	0	365

Table 1. Streamflow statistics for the upper Peace River and tributaries for the 2002-2007 water years—Continued

[Streamflow statistics based on computed discharge from rating curves. ft^3/s, cubic feet per second; e, estimated; –, missing or no data]

Sites (fig. 22)	Station	Water year	Annual mean discharge (ft^3/s)	Maximum daily mean discharge		Minimum daily mean discharge		Number of zero flow days	Number of days of record
				(ft^3/s)	Date	(ft^3/s)	Date		
Site 12	Sixmile Creek	2002	–	–		–	–	–	–
	Station number: 02294747	2003	–	181	01-04-2003	3.4	04-25-2003	0	304
	Period of record: 4.83 years	2004	42	346	09-10-2004	1.7	03-27-2004	0	365
	Mean discharge for December 2002-September 2007: 28 ft^3/s	2005	40	267	10-01-2004	1.3	04-26-2005	0	365
		2006	11	107	10-27-2005	0.00	05-04-2006*	14	365
		2007	4	25	02-07-2007	0.00	05-29-2007*	16	365
Site 14	Phosphate Mine Outfall CS-8	2002	–	–		–	–	–	–
	Station number: 02294759	2003	–	60	08-26-2003	0.01	05-15-2003	0	242
	Period of record: 3.17 years	2004	6	82	09-12-2004	0.00	04-10-2004*	23	365
	Mean discharge for February 2003-May 2005 and November 2006-September 2007: 5.2 ft^3/s	2005	–	79	10-01-2004	e0.17	04-23-2005	0	229
		2006	–	–		–	–	–	–
		2007	–	19	07-23-2007	0.00	03-28-2007*	39	320
Site 15	Barber Branch	2002	–	–		–	–	–	–
	Station number: 02294760	2003	–	114	01-01-2003	0.00	06-17-2003*	5	304
	Period of record: 4.83 years	2004	20	253	09-12-2004	0.37	12-26-2003	0	365
	Mean discharge for December 2002-September 2007: 13.2 ft^3/s	2005	25	250	10-01-2004	1.3	04-17-2005	0	365
		2006	8	66	10-24-2005	1.8	08-22-2006	0	365
		2007	1	13	04-08-2007	0.03	05-31-2007	0	365

During this study, the Peace River near Bartow station (site 7) had more zero-flow days than the upstream Peace River at Bartow (site 1), with 39 zero-flow days out of the 139 total recorded days in 2002 (May 15 to September 30), 14 days in 2004, and 82 days in 2007 (table 1). In most cases, the zero-flow days recorded at the Peace River near Bartow (site 7) indicated that the flow in Reach 1 terminated at a large sink (Ledges Sink), located about 700 ft upstream from the gaging station.

Streamflow losses also occurred downstream from Peace River near Bartow gaging station (site 7) as flow progressed into Reach 2. A comparison of streamflow hydrographs between the upstream Peace River near Bartow station (site 7) with the downstream Peace River at Clear Springs gaging station (site 11) indicated that discharge at the downstream site was reduced or absent, reflecting the loss of water through the karst features in Reach 2 (figs. 24B-29B). Zero-flow days were reported at the Peace River at Clear Springs (site 11) for 45 days in 2002, 119 days in 2006, and 175 days in 2007 (table 1).

During below-average streamflow and groundwater conditions, and when the discharge at the Peace River at Bartow (site 1) was about 20 ft^3/s or less, all of the flow in the river drained into various karst features in the channel and flow usually ended within Reach 2 (Dover Sink) (figs. 24B, 26B, 28B, and 29B). During the 2006-2007 water years, the number of zero-flow days progressively increased, indicating a decline in floodplain storage along the upper Peace River. During these low-flow conditions, streamflow losses to the various karst features in the upper two reaches either reduced or eliminated the Peace River flow contributions into Reach 3.

During the 2006-2007 water years, the Peace Creek Drainage Canal (site B, fig. 22) supplied the largest amount of tributary flow to the upper Peace River. The mean discharge for the Peace Creek Drainage Canal for those years was 63 and 15 ft^3/s, respectively, compared to the period of record mean discharge of 101 ft^3/s (table 1). The mean discharge for Saddle Creek (site A, fig. 22) during the 2006-2007 water years was 23 and 0.46 ft^3/s, respectively, compared to the period of record mean discharge of 65 ft^3/s (table 1). Saddle Creek had a number of zero-flow days during the study period (2002, 2004, 2005, and 2007; table 1) which were often the result of closing the gate at the P-11 Structure.

Of the three phosphate mine outfalls sites, Sixmile Creek (site 12) supplied the most flow to Reach 3. But during the below-average 2006-2007 water years, Sixmile Creek supplied only 11 and 4 ft^3/s of mean discharge, respectively, compared to the period of record mean discharge of 28 ft^3/s (table 1). During the 2006-2007 water years, Sixmile Creek and Phosphate Mine Outfall CS-8 also had a number of zero-flow days (table 1). Discharge hydrographs for the three outfall tributaries and the Peace River near Homeland (site 16) are shown in figures 25C-29C. Hydrographs of the phosphate-mine outfalls illustrate the limited amount of inflow to the upper Peace River during low-flow conditions (figs. 28C and 29C). Discharge hydrographs for these sites indicate that the flows were “flashy” and that discharge receded rapidly after peak discharge events.

For the study period, streamflow was greatest during the 2003-2005 water years, when above-average precipitation fell in the study area. Most of the excess rainfall was during the 2003 water year when there was an increase of 29 in. above the long-term average (54 in.) rainfall (fig. 23). In addition to excess rain in 2003, three hurricanes crossed over the upper Peace River basin during a 6-week period from August through September 2004, producing about 24 in. of rain in the basin. The combined effects of two of these hurricanes resulted in the second greatest discharge for the period of record at Peace River at Bartow (4,010 ft^3/s) on September 11, 2004 (table 1). These storms caused considerable flooding, and high-to-medium streamflow persisted into the following 2005 water year. The greatest annual mean discharge (545 ft^3/s) for the study period occurred during the 2005 water year, which is more than double the long-term mean discharge (227 ft^3/s) (table 1). During the 2005 water year, Saddle Creek and Peace Creek Drainage Canal supplied a substantial amount of flow to the upper Peace River, with the annual mean discharges of 155 and 288 ft^3/s, respectively.

During high-flow periods, a large loss in flow was observed between the upstream and downstream gaging stations between Reaches 1 and 2 of the upper Peace River. This large volume loss between stations was typically the result of floodplain storage rather than losses to karst features. The upper Peace River channel is poorly incised along much of Reaches 1-2, and the transition of flow from the low-water to high-water channel generally occurs at a discharge of about 100 ft^3/s at Peace River at Bartow (site 1). The land-surface elevation contours of 88, 90, 92, and 94 ft above NGVD 1929 (shown in (figs. 30A-D) reflect potentially inundated areas along the upper Peace River with increasing river-stage levels. The river-stage levels for Peace River at Bartow, Peace River near Bartow, and Peace River at Clear Springs for the study period are shown in figure 31, as well as the respective river level ranges for when the Peace River is in the main channel.

In Reach 1, when river levels were greater than about 91.50 ft above NGVD 1929 at Peace River at Bartow, water drained into a series of interconnected pit lakes by way of a pair of small ditches along the eastern floodplain (fig. 30). At higher river stages in Reach 2 (greater than 91.0 ft above NGVD 1929) large storage losses occurred as river water drained into pit lakes along the western floodplain. The small size of the upper pit lake (about 14 ac) limits the amount of water that can be stored, whereas the much larger lower pit lake (about 40 ac) has the capacity to store large volumes of river backwater (fig. 30). The backwater conditions to the pit lakes occurred during extreme high-water conditions in 2003, 2004, and 2005 (fig. 31).

Discharge-Duration Hydrographs and Curves

Daily discharge-duration hydrographs for the Peace River at Bartow gaging station for the 68 years of record (1940-2007 water years) are shown in figure 32. The 90th to 100th percentile (maximum discharge) reflect very wet conditions, the 25th to 75th percentiles indicate normal conditions, and the 10th to 0th percentiles (minimum discharge) indicate very dry conditions. The minimum, maximum, average, and median


Low water levels hinder feasibility of canoeing and maintenance of healthy ecosystems. Note high water-level marks on trees located downstream of Peace River at Wabash (site 2). High water-level marks are the result of high flows during the 2005 water year. Photo credit: P.A. Metz, USGS

discharge values for the 0^{th} through 100^{th} percentiles are shown in figure 32. The discharge-duration hydrographs indicate that the greatest flows generally occur during the rainy season in June, September, and October (fig. 32). In addition, notable high flows occur in March. The lowest flows occur at the end of the dry season from May into June. The 0^{th} percentiles (zero flow periods) for the 68 years of record occurred during May and June of 2000-2002.

The annual (2002-2007) discharge-duration curves obtained at the Peace River at Bartow station and their relations to the long-term 68-year discharge-duration curve indicate that the 2002, 2006, and 2007 water years were below the long-term duration curve throughout most of the range of hydrologic conditions (figs. 33A, E, and F). Discharge-duration curves for the 2003 and 2005 water years at the Peace River at Bartow station indicate relatively high, stable discharge throughout most of the range of flows and suggest that most of the water may have been derived from floodplain storage (figs. 33B and D). Duration curves for the 2004 water year at the Peace River at Bartow station show a mixed ranged of hydrologic conditions (fig. 33C). The relatively flat slope of the duration curve during 2007 water year indicates persistent and steady low flow that was confined to the low-water channel (fig. 33F). The steep slope and abrupt ending at the low end of the duration curves indicates streamflow declines and periods of no flow.

A comparison of duration curves for the three gaging stations along Reaches 1 and 2 (sites 1, 7, and 11; fig. 22) shows streamflow gains, losses, or constant discharge conditions for the 2003-2007 water years (fig. 33B-F). Duration curves for the 2004 water year show a mix of hydrologic conditions, with flow losses and gains between gaging stations. For the 2003 and 2005 water years, the three gaging stations showed constant discharge conditions for most of the water year, except at the low end of the duration curve. Duration curves for the 2006-2007 water years illustrate flow losses between sites, with flow losses in Reach 1 not as extensive as in Reach 2 (figs. 33E-F).

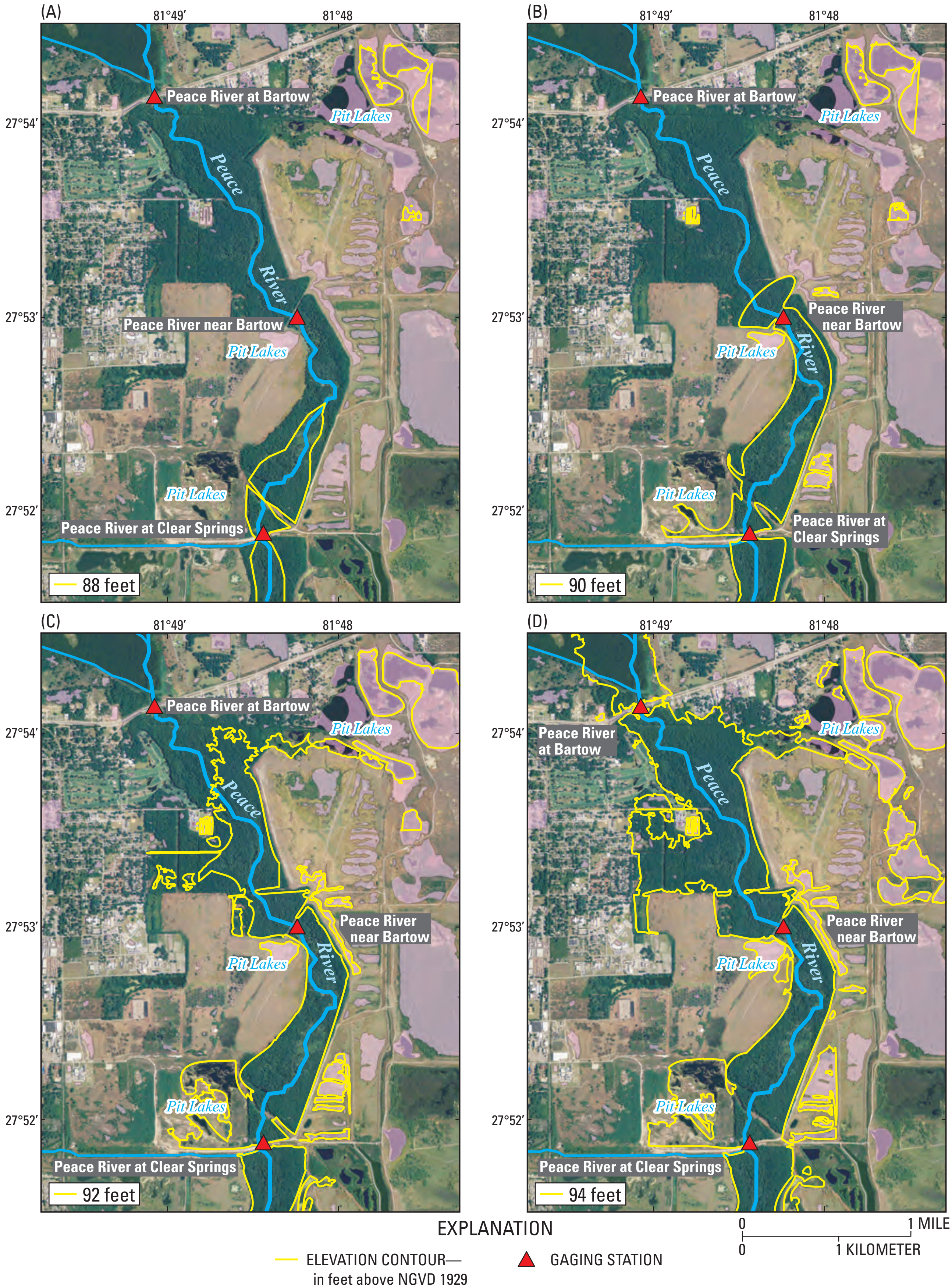


Figure 30. Land-surface elevation contours along the upper Peace River at (A) 88 feet, (B) 90 feet, (C) 92 feet, and (D) 94 feet above NGVD 1929.

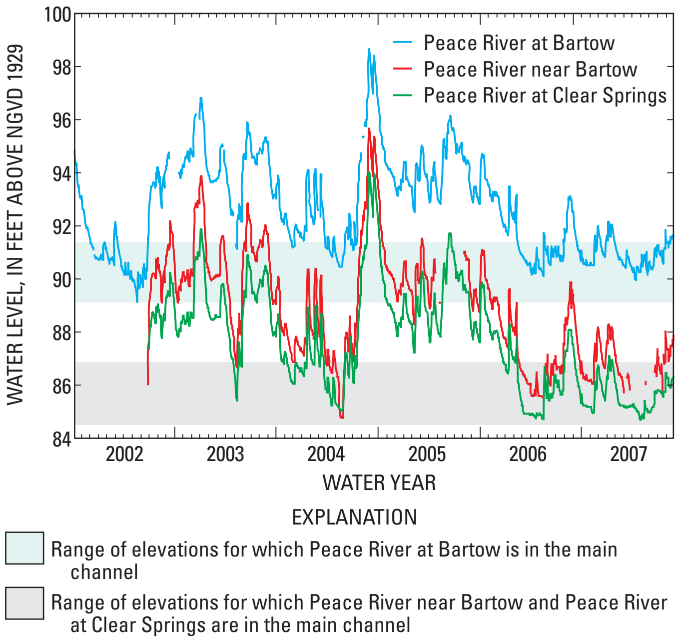
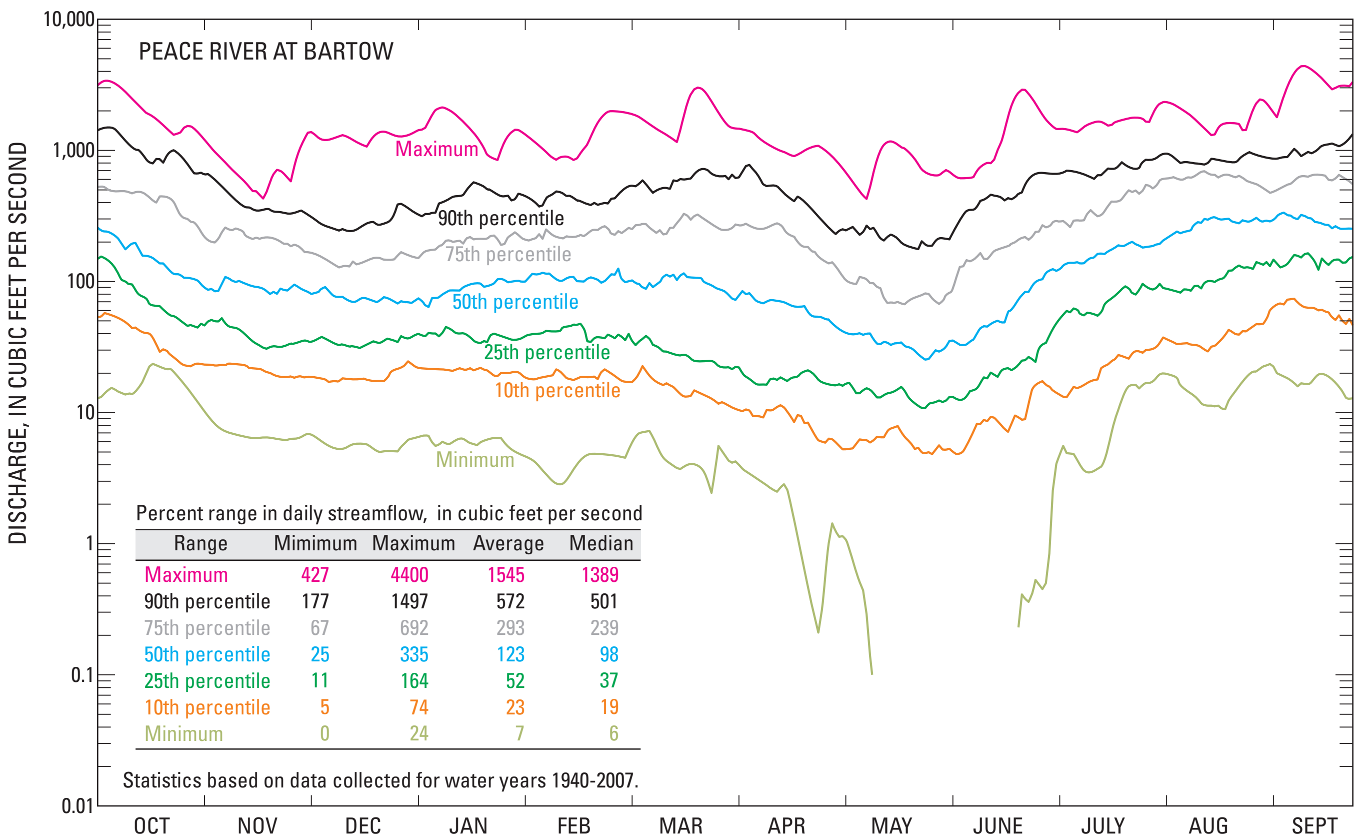


Figure 31. Approximate range of water-level elevations for which the upper Peace River is within the main channel.



Range	Mimimum	Maximum	Average	Median
Maximum	427	4400	1545	1389
90th percentile	177	1497	572	501
75th percentile	67	692	293	239
50th percentile	25	335	123	98
25th percentile	11	164	52	37
10th percentile	5	74	23	19
Minimum	0	24	7	6

Figure 32. Daily flow-duration hydrographs for Peace River at Bartow, water years 1940 through 2007.

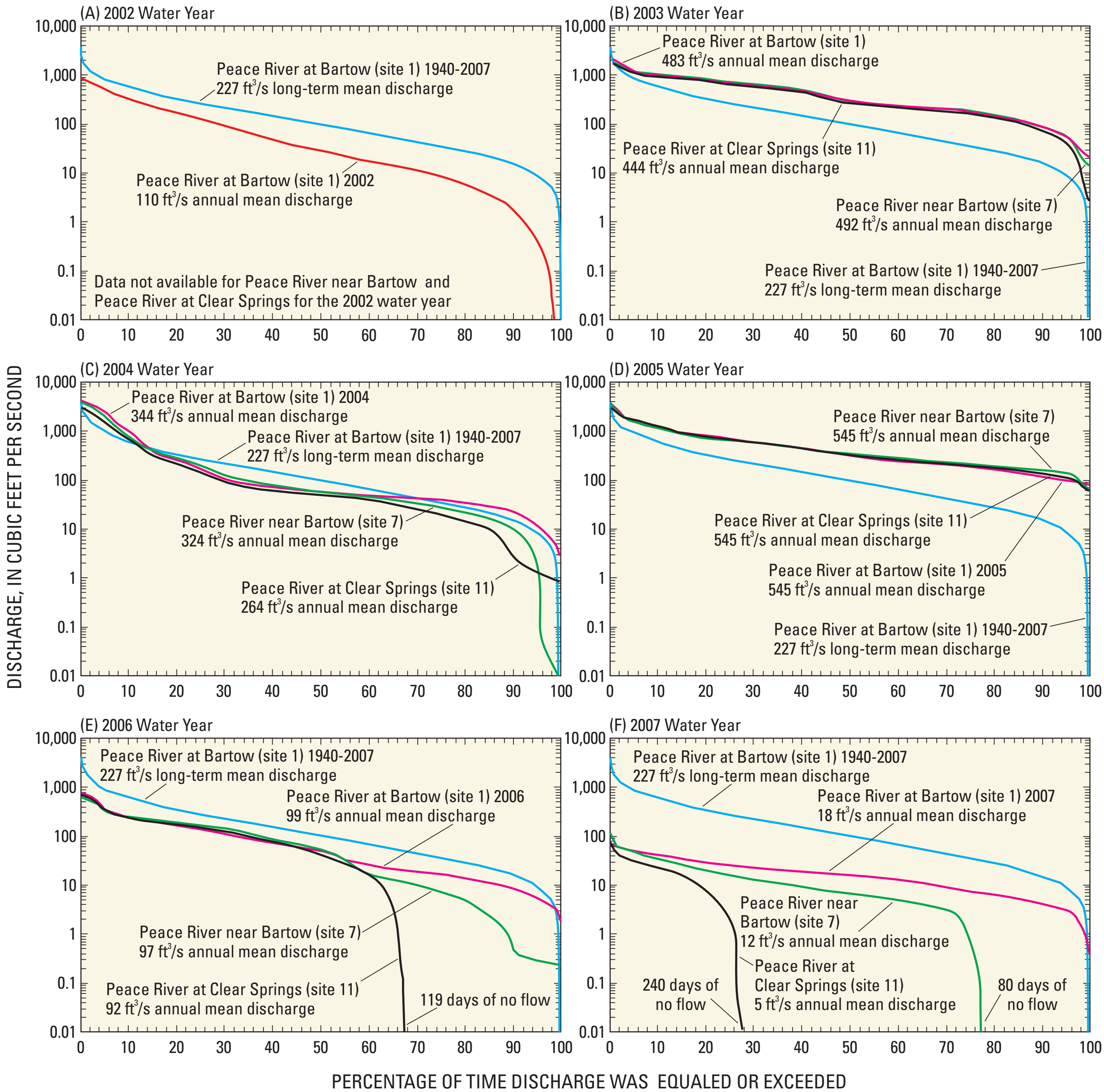


Figure 33. Discharge-duration curves for the Peace River at Bartow, Peace River near Bartow, and Peace River at Clear Springs gaging stations for the (A) 2002, (B) 2003, (C) 2004, (D) 2005, (E) 2006, and (F) 2007 water years, with a long-term comparative curve for the Peace River at Bartow gaging station for the 1940-2007 water years.

Effects of Karst Development on Streamflow Losses

The area along the upper Peace River is characterized as a carbonate karst terrain that has distinctive karst features and a hydrology defined by the combination of high rock solubility and well-developed secondary porosity (Ryder, 1985). A number of prominent karst features are located along the upper Peace River in the high-water floodplain and along the existing low-water channel. Depending on Peace River stage and groundwater conditions, these karst features can act as conduits for flow to the underlying aquifers. Seepage runs, in conjunction with monitoring of aquifer levels, were used to describe the timing, volume of water exchanged, and effects of karst development on streamflow losses along the upper Peace River.

Seepage Investigations

Seepage runs were conducted to determine where the greatest streamflow losses occurred along the upper Peace River from Bartow to Fort Meade (Reaches 1-4; fig. 22). Streamflow gains and losses, in cubic feet per second, along the Peace River were calculated using the following equation:

$$Q_s = Q_d - Q_u - Q_t, \quad (1)$$

where

Q_s = gain (positive) or loss (negative) in streamflow between adjacent sites;

Q_d = streamflow at downstream site;

Q_u = streamflow at upstream site; and

Q_t = total streamflow for all tributaries between upstream and downstream sites.

Seepage runs were performed during baseflow conditions, when rainfall was at a minimum and most streamflow was derived from groundwater seepage, rather than from runoff. During these seepage runs, a net increase in stream discharge along the reach was interpreted as a gain in groundwater discharge into the river. Conversely, a net reduction along the reach was a loss of river water into the aquifers. If stream discharge remained constant along a particular reach, then the river neither gained water from, nor lost water to, the underlying aquifers. Figures 34 and 35 show the losses and gains during seepage investigations along Reaches 1-4 and Reaches 1 and 2, respectively. Table 2 indicates the computed and measured discharge at selected sites and total streamflow losses along Reaches 1 and 2 during below-average flow conditions.

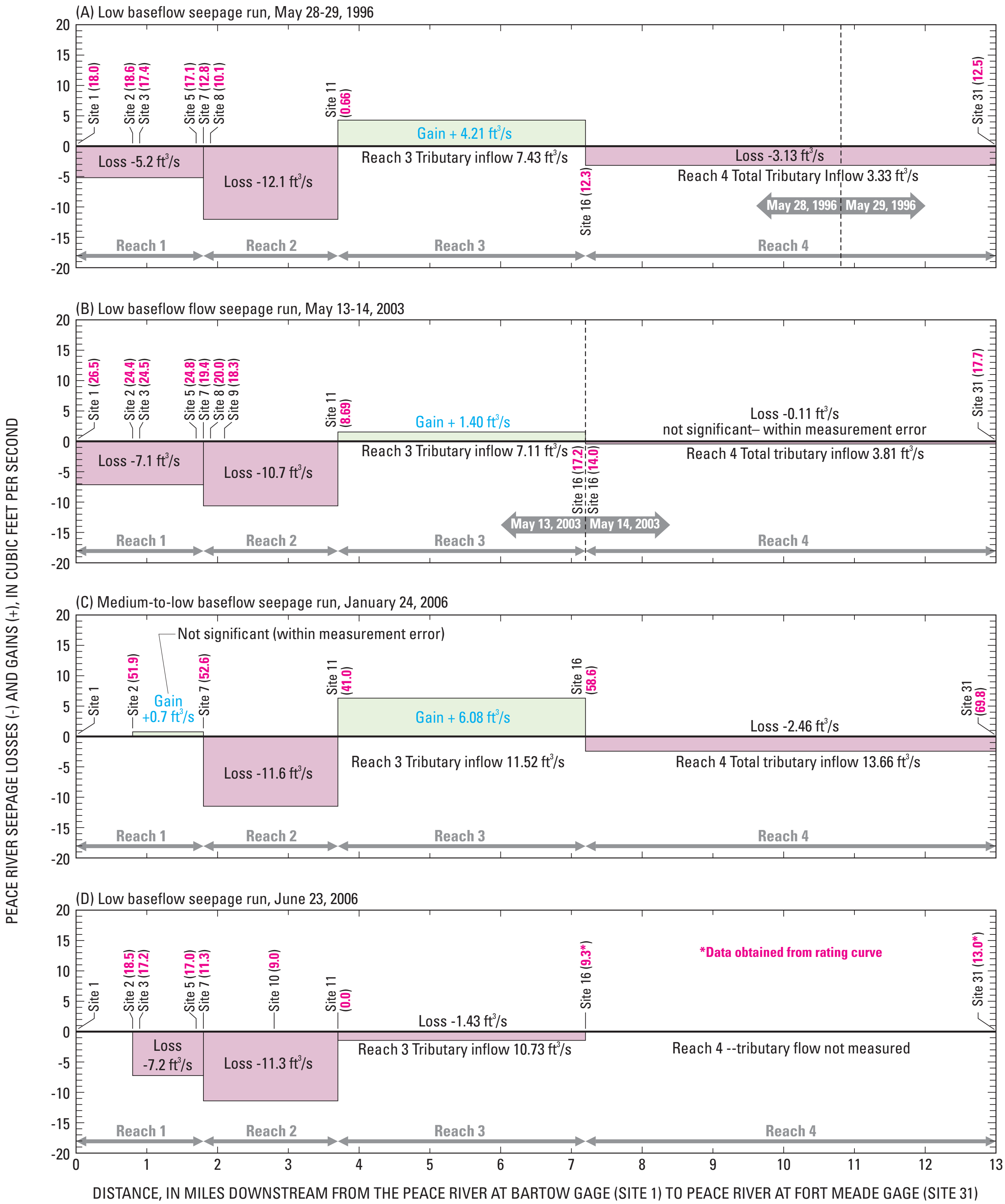
During this investigation, two seepage runs (May 13-14, 2003, and January 24, 2006) were conducted along Reaches 1-4 from Peace River at Bartow station (site 1) to Peace River at Fort Meade station (site 31) (fig. 22). In addition, results of a previous seepage run (May 28-29, 1996) conducted along Reaches 1-4 were used for comparison to the current seepage results.

The May 1996 and May 2003 seepage analyses indicate that the largest streamflow losses occurred along Reaches 1 and 2 between Peace River at Wabash (site 2) and Clear Springs station (site 11) where the most prominent karst features are located. For the two seepage runs, the cumulative losses along Reaches 1 and 2 were similar (-17.3 ft^3/s in May 1996 and -17.8 ft^3/s in May 2003). Streamflow losses in Reach 1 during May 1996 and May 2003 were -5.2 and -7.1 ft^3/s, respectively, and were -12.1 and -10.7 ft^3/s in Reach 2, respectively (fig. 34A, B). A comparison of these two temporally spaced, low-flow seepage runs suggests that the relation between the river and groundwater during low-flow conditions did not change significantly over the 7-year period along Reaches 1 and 2.

Reach 3 had the largest measured seepage gains of all the reaches. Seepage gains in Reach 3 were 4.21, 1.40, and 6.08 ft^3/s, for May 1996, May 2003, and January 2006, respectively (fig. 34A-C). Tributary flow is greatest along this reach, and some of these gains may be the result of ungaged inflows or other lateral flows that drain slowly to the river during low-flow conditions. Reach 3 ponds along most of the reach during low-flow conditions, which may reflect the lack of karst features along this reach.

Reach 4 had streamflow losses of -3.13, -0.11 (loss within measurement error and not considered significant), and -2.46 ft^3/s during the May 1996, May 2003, and January 2006 seepage runs, respectively (fig. 34A-C). There are a number of mine outfalls and two tributaries (Rocky and Sink Branch) that contribute flow to this section of the river. The losses during May 1996 (-3.33 ft^3/s) and January 2006 (-2.46 ft^3/s) seepage runs may indicate the occurrence of karst features in this reach, but no discernable features were located.

Results from the January 2006 (fig. 34C) seepage run indicated that in Reach 1, the river gained about 0.7 ft^3/s, but this gain was within the margin of error of the measurement and was not considered significant. This reach typically exhibits water losses during lower stream levels. Reach 1 has no natural tributaries, but receives flow from two poorly incised channels that can receive water from and lose water to a series of phosphate-mining pit lakes (fig. 22). These pits are located on the eastern side of the Peace River floodplain and immediately downstream from the Bartow gaging station, and inflows were not monitored during this study. Flows to or from these pit lakes can occur when streamflow at the Peace River at Bartow station is about 50 ft^3/s or more. Discharge measured on January 24, 2006, at the Peace River at Wabash (site 2) and near Bartow (site 7) was 51.9 and 52.6 ft^3/s, respectively (table 2). The seepage loss in Reach 2 (between site 7 and site 11) was -11.6 ft^3/s (fig. 34C). Losses in Reach 2 were similar to the losses documented in May 1996 and May 2003 (-12.1 and -10.7, respectively).



EXPLANATION

Site 2 (**18.5**) STREAMFLOW SITE NUMBER AND SEEPAGE DISCHARGE MEASUREMENT (**IN RED**)—Measurement sites are shown in figure 22.

Figure 34. Comparison of flow losses and gains for seepage runs conducted during (A) May 1996, (B) May 2003, (C) January 2006, and (D) June 2006 from the Peace River at Bartow to the Peace River at Fort Meade gaging stations.

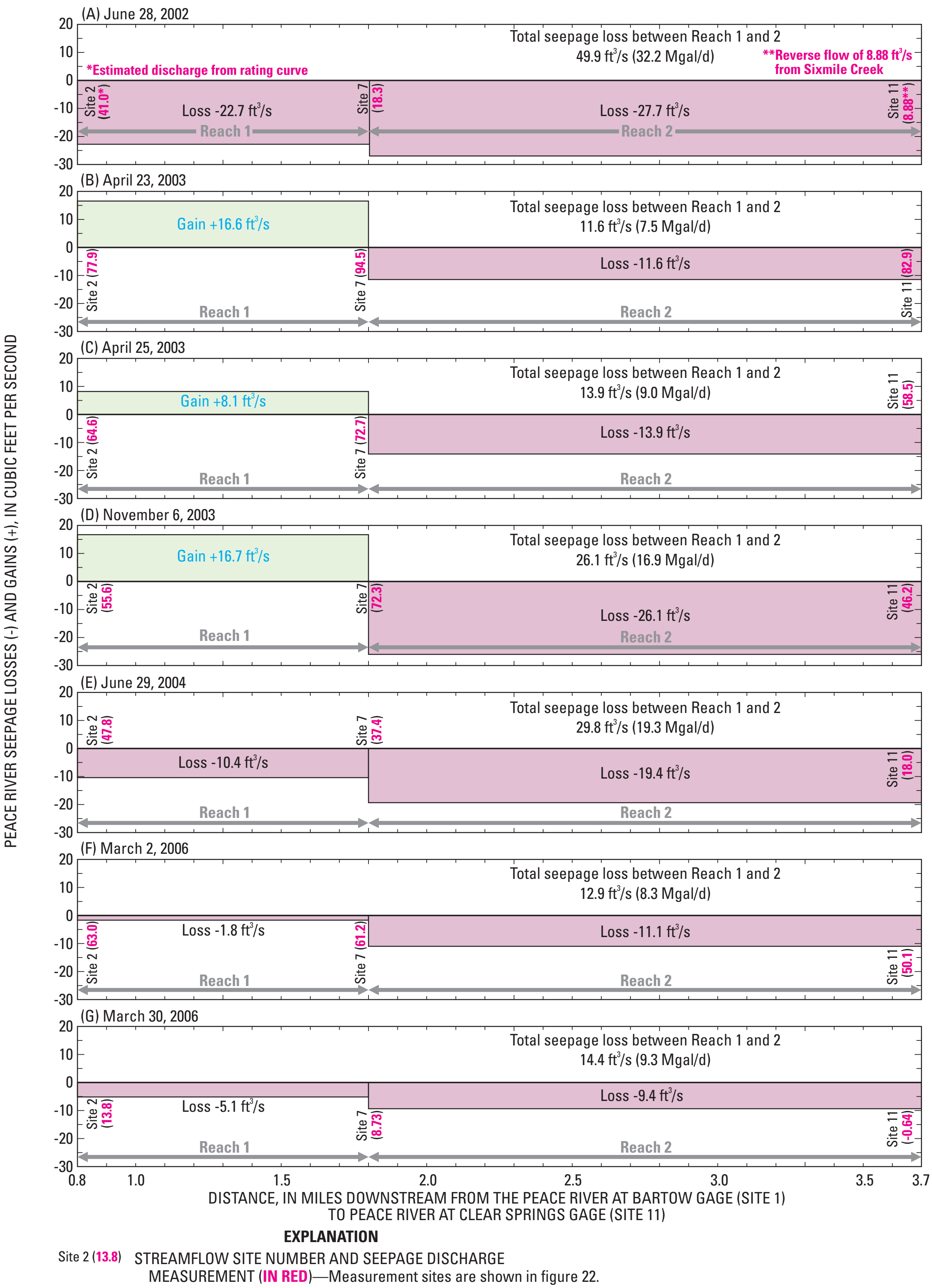


Figure 35. Streamflow losses along Reaches 1 and 2 from the Peace River at Wabash (site 2) to the Peace River at Clear Springs gaging stations (site 11).

Table 2. Computed and measured discharge at selected sites and total streamflow losses along Reaches 1 and 2 during below-average flow conditions.

[Sites shown in fig. 22. Discharge in cubic feet per second (ft^3/s). USGS discharge measurement error estimated at ±5 to 8 percent. Numbers shaded in blue represent instantaneous discharge obtained from the rating curve at Peace River at Bartow. Numbers shaded in yellow indicate flow reversal originating from Sixmile Creek. –, site not measured; e, estimated; 0, zero flow was observed. Below average flow conditions reflect periods when streamflow was less than 100 ft^3/s at Peace River at Bartow. During below average conditions, streamflow measurements for the Peace River at Bartow (site 1) were made at Peace River at Wabash (site 2)]

Date	Instantaneous and measured discharge (cubic feet per second)												Total loss
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 9a	Site 10	Site 11	
	Reach 1							Reach 2					
							2002 Water Year						
5/17/2002	0	0	0	0	0	0	0	0	0	0	0	0	0
5/20/2002	–	7.34	2.52	0.22	0.2	0	0	0	0	0	0	0	-7.34
6/11/2002	–	12.6	7.7	–	1.8	1.18	0	0	0	0	0	0	-12.6
6/14/2002	–	4.5	1.24	0.79	0.19	0	0	0	0	0	0	0	-4.5
6/19/2002	7.7	–	–	–	–	–	–	–	–	–	–	2.50	[1]-10.2
6/20/2002	9.8	–	–	–	–	5.54	0	0	0	0	0	5.06	[2]-14.9
6/24/2002	24	–	–	–	12.2	4.71	0	0.85	0	0	0	2.91	[3]-26.9
6/25/2002	–	28.1	22.6	–	–	–	7.95	5.37	2.0	0	0	0	-28.1
6/26/2002	37	–	–	–	–	–	15.1	–	–	3.02	0	0	-37.0
6/28/2002	41	–	–	–	–	–	18.3	–	–	–	3.82	8.88	[4]-49.9
							2003 Water Year						
4/23/2003	–	77.9	–	–	–	–	94.5	–	–	–	–	82.9	[5]-11.6
4/25/2003	–	64.6	–	–	–	–	72.7	–	–	–	–	58.5	[6]-14.2
5/13/2003	26.5	24.4	24.5	–	24.8	–	19.4	20.0	18.3	–	–	8.69	-17.8
							2004 Water Year						
11/06/2003	57.4	55.6	–	–	–	–	–	–	–	–	–	46.2	-11.2
3/09/2004	81	–	–	–	–	–	86.3	–	–	–	–	68.2	[7]-18.1
4/27/2004	–	14.3	–	–	–	–	8.44	–	–	–	–	0	-14.3
5/19/2004	–	10.9	–	–	–	–	3.98	–	–	–	–	0	-10.9
6/01/2004	–	4.36	–	–	–	–	0	0	0	0	0	0	-4.36
6/29/2004	–	47.8	–	–	–	–	37.4	–	–	–	–	18.0	-29.8
							2006 Water Year						
1/24/2006	–	51.9	–	–	–	–	53.7	–	–	–	–	41.0	[8]-12.7
3/02/2006	–	63.0	–	–	–	–	61.2	–	–	–	–	50.1	-12.9
3/13/2006	–	28.0	–	–	–	–	22.7	–	–	–	–	15.8	-12.2
3/30/2006	–	13.8	–	–	–	–	8.73	–	–	–	–	0.64	[9]-14.4
4/11/2006	–	11.0	–	–	–	–	4.62	–	–	–	1.44	0	-11.0
5/18/2006	17	–	–	–	–	–	–	–	–	–	2.34	0	-17.0
5/30/2006	–	6.12	–	–	–	–	–	–	–	–	–	0	-6.12
6/8/2006	4.4	–	–	3.0e	–	0.50e	0	0	0	0	0	0	-4.40
6/12/2006	27	–	–	–	–	–	–	–	–	–	16.1	0	-27.0
6/23/2006	–	18.5	17.2	–	17.0	–	11.3	–	–	–	9.00	0.83	[10]-19.3
							2007 Water Year						
10/11/2006	34	–	–	–	–	–	31.5	–	–	–	–	22.5	-11.5
11/14/2006	–	9.64	–	–	–	–	4.13	–	–	–	0.71	0	-9.64
2/08/2007	49	–	–	–	–	–	46.4	–	–	–	–	37.1	-11.9
3/23/2007	–	14.2	–	–	–	–	6.67	–	–	–	3.04	0	-14.2
5/11/2007	–	1.45	–	–	–	–	0	–	–	–	0	0	-1.45
5/15/2007	–	0.10e	0	0	0	0	0	0	0	0	0	0	-0.10e
6/13/2007	13	–	–	–	–	–	2.36	–	–	–	0	0	-13.0
7/18/2007	–	4.29	–	–	–	1.5e	0	0	0	0	0	0	-4.29
8/29/2007	17	–	–	–	–	–	7.91	–	–	–	2.5e	0	-17.0

[1]Flow loss of 7.7 ft^3/s and reverse flow of 2.50 ft^3/s from Sixmile Creek to Dover Sink for a total flow loss of -10.2 ft^3/s for Reaches 1 and 2.

[2]Flow loss of 9.8 ft^3/s and reverse flow of 5.06 ft^3/s from Sixmile Creek to Dover Sink for a total flow loss of -14.9 ft^3/s for Reaches 1 and 2.

[3]Flow loss of 24 ft^3/s and reverse flow of 2.91 ft^3/s from Sixmile Creek to Dover Sink for a total flow loss of -26.9 ft^3/s for Reaches 1 and 2.

[4]Flow loss of 41 ft^3/s and reverse flow of 8.88 ft^3/s from Sixmile Creek to Dover Sink for a total flow loss of -49.9 ft^3/s for Reaches 1 and 2.

[5]Gain of 16.6 ft^3/s in Reach 1 and a flow loss of -11.6 in Reach 2.

[6]Gain of 8.1 ft^3/s in Reach 1 and a flow loss of -14.2 in Reach 2.

[7]Gain of 5.3 ft^3/s in Reach 1 and a flow loss of -18.1 in Reach 2.

[8]Gain of 1.8 ft^3/s in Reach 1 and a flow loss of -12.7 in Reach 2.

[9]Flow loss of 13.8 ft^3/s and reverse flow of 0.64 ft^3/s from Sixmile Creek to Dover Sink for a total loss of -14.4 ft^3/s for Reaches 1 and 2.

[10]Flow loss of 18.5 ft^3/s and reverse flow of 0.83 ft^3/s from Sixmile Creek to Dover Sink for a total loss of -19.3 ft^3/s for Reaches 1 and 2.

A comparison of seepage runs was conducted on May 1996 (fig. 34A) and June 2006 (fig. 34D) when the discharge in the river at the beginning of Reach 1 was 18.6 and 18.5, respectively. These seepage runs indicated that during below-average streamflow and groundwater conditions, and when the discharge at Peace River at Bartow was less than about 20 ft^3/s (±5 to 8 percent error), all of the flow in the river drained into various karst features and flow usually ended within Reach 2. During the 2007 water year, the annual mean discharge was only 18 ft^3/s and for most of the water year, the flow ended at various karst features in Reaches 1 and 2.

A number of smaller seepage runs (about 3 mi) were conducted once the area of greatest streamflow losses was identified. Both streamflow losses and gains were noted in Reach 1 during below-average conditions, whereas losses consistently occurred in Reach 2 (fig. 35; table 2). Flow losses for the combined reaches ranged from 0.1 to about 50 ft^3/s and were dependent on the amount of discharge in the river and water levels in the aquifers. The greatest flow loss for Reaches 1 and 2 of about 50 ft^3/s (32 Mgal/d) was measured on June 28, 2002 (fig. 35A; table 2). This large loss occurred at the beginning of the summer rainy season when discharge in the river increased and large volumes of water were needed to replenish unfilled cavities and void spaces in the underlying aquifers.

Karst Features along the Upper Peace River

Based on the series of seepage runs, an approximate 2-mi section of the upper Peace River was determined to be a highly karstified region where numerous features were located that were capable of draining the river water (fig. 36). Surveys were conducted when the riverbed was dry to locate the karst features. These surveys indicated that a number of prominent karst features were located in both the low- and high-water channels (Knochenmus, 2004). Most of the high-water (floodplain) karst features showed evidence of surface-water inflows. Locations of these karst features were documented and dimensions and surface orientations were measured. Not all of the karst features along the upper Peace River were located, because they were inaccessible or covered by vegetation; therefore, additional buried features probably exist. Locations of the most prominent karst features for Reaches 1 and 2 are shown in figure 36, and the names, dimensions, and a brief description of the karst features for Reaches 1 through 4 are listed in table 3.

The karst features that were located in Reaches 1 and 2 consist of a variety of erosional features, such as cracks in the river channel limestone bedrock (Crevasses and Ledges Sinks): a large conduit system at the base of a highly fractured outcrop or swallet (Dover Sink); holes in the bedrock due to cypress root growth (near Wabash Complex); a series of interconnected karst windows (Catacombs Nos. 1-9); vertical pipes (Fricano Fracture, Wabash Sink, and Cook’s Ripple); and buried sinks or collapsed channel bedrock that subsequently infilled with sediments (Catfish, Midway, and Elephant Graveyard Sinks). Some of the prominent karst features found in the upper Peace River karst area are shown in figure 37. After the initial survey, several more prominent features were located, including Catfish Sink (Reach 2), Liz Sink (Reach 2) and Tom’s Sink (Reach 3). Otter Sink, adjacent to Kissengen Spring (Reach 3), developed and expanded during the course of this investigation. The prominent karst features located along Reach 3 are shown in figure 22.

During this investigation, most karst features were altered to some degree due to depositional processes, such as scouring and sediment infilling. During 2002, many karst features were exposed and could be easily identified. However, subsequent field surveys after the 2004 hurricane season and the high-water period of 2005 indicated that some karst features had silted in and had become unidentifiable. Midway Sink, Elephant Graveyard, Fricano Fracture, Harley, and Jackson Sinks were no longer exposed, and Ledges, Cook’s Ripple, and Crevasses Sink became partially silted in. Rainfall and streamflow were below average during the 2006-2007 water years, and the stream channel was dry during much of this time. This condition led to increased scouring by wind and the energy from infrequent streamflow events, which removed sediment and re-exposed some of the features. Dover Sink has undergone the most significant changes, which will be discussed in more detail in a later section.

Streamflow Losses to Karst Features

The following section describes the characteristics of karst features in Reaches 1 and 2 and the measured streamflow losses to the karst features. Streamflow losses to the karst features in Reaches 1 and 2 are listed in table 4. These karst features are characterized in an upstream to downstream order, and streamflow losses are expressed as negative values (-), to contrast with gains to the river from tributary inflows, which are expressed as positive values (+). Measurable streamflow losses were not observed in the low-water channel along Reach 3, although a limited description of the high-water channel karst features that are present along this reach is included in table 4. Karst features were not identified in Reach 4.

Some of the most influential karst features located in and along the Reach 1 channel bed include the Wabash Sink, Cypress Root Sink, Cook’s Ripple, Fricano Fracture, Ledges Sink, and the adjoining Catacombs Complex, which is located in the floodplain (fig. 38A-F). During different time periods of this investigation, flow in the river was observed terminating at the following sinks: Wabash Sink, Cypress Root Sink, Cook’s Ripple, Fricano Fracture, and Ledges Sink. In Reach 1, the largest loss of water from the river to the groundwater system persistently occurred at Ledges Sink, a fracture in the riverbed.

The Wabash Complex consists of several small karst features (Wabash Sink, Corbett Sink, and Cypress Root Sink), and it is the first notable karst complex in the long series

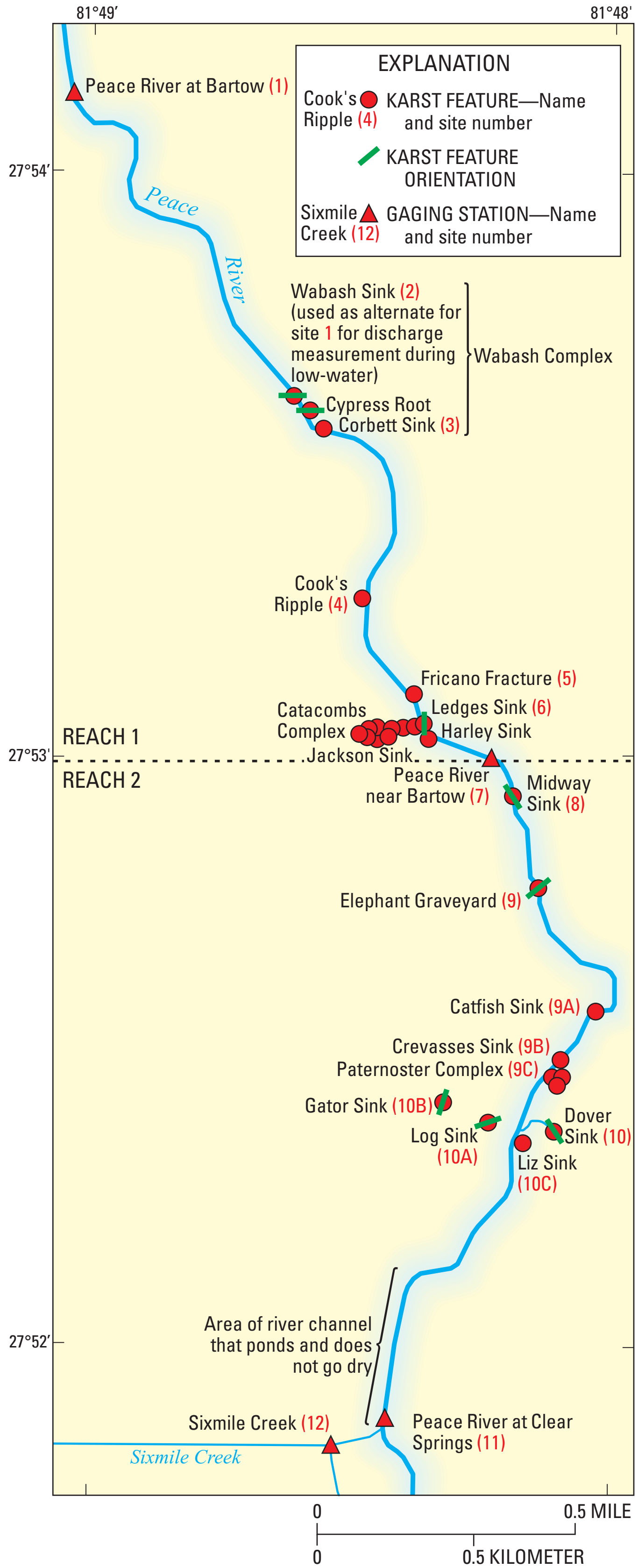


Figure 36. Location of karst features in Reaches 1 and 2.

of features that line the low-water channel along Reach 1 (fig. 36, site 2; fig. 38A-B). The complex spans a section of about 450 ft along the Peace River channel, which is located about 690 ft east of the Bartow Waste Water Treatment Plant. Wabash Sink, the most active sink in the complex, is a vertical pipe karst feature located at the eastern edge of the low-water channel. During low-flow conditions, river water that flows into this vertical pipe creates a circular whirlpool, which formed this conduit into its round vertical shape. A number of flow measurements were made at this feature during 2002-2006, and losses ranged from -0.30 to -5.50 ft^3/s (table 4).

Cook's Ripple is a karst feature located in the western edge of the channel bed, about 0.5 mi downstream from Wabash Sink (fig. 36, site 4; fig. 38C). The feature is a vertical pipe that drains a relatively small amount of flow from the Peace River at low river stages. Flow in the low-water channel is diverted to Cook's Ripple by a narrow distributary channel; however, under higher flow conditions, the distributary channel and feature are inundated. Flow that enters this vertical pipe also creates a circular whirlpool, indicating downward flow. Although this site has been infilled with sand since the initial survey of 2002, the amount of diffuse inflow into this sink does not appear to have diminished based on subsequent field observations. In 2002, measured flow losses to this feature were -0.45 and -2.30 ft^3/s (table 4).

Fricano Fracture is a small vertical pipe located at the eastern edge of the low-water channel and 0.2 mi downstream from Cook's Ripple (fig. 36, site 5; fig. 38D). Water that flows down the pipe also creates a small circular whirlpool, further indicating downward flow. This sink became filled with silt following the 2004 hurricanes and subsequent high-water period. Two measurements were made at this sink in 2002 when the flow in the channel ended at this site; measured losses were -0.22 and -0.19 ft^3/s (table 4).

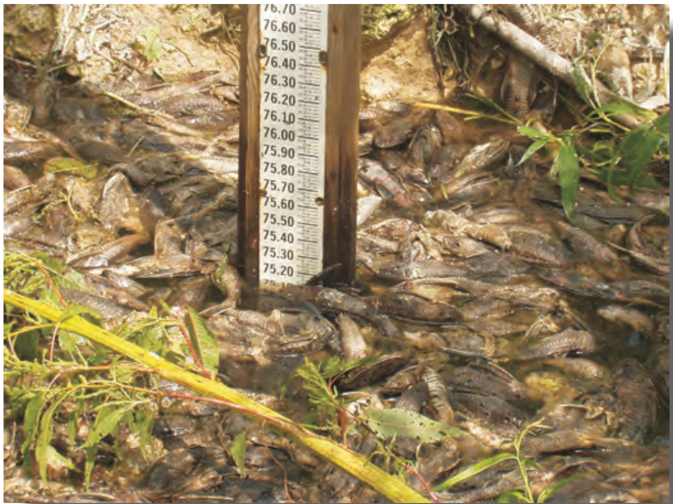
Ledges Sink is the most prominent karst feature along Reach 1 and, depending on hydrologic conditions, this sink can drain a large volume of water from the stream channel (fig. 36, site 6; fig. 38E). Ledges Sink is a fracture in the limestone bedrock that is exposed in the riverbed. This feature is located near the edge of the channel about 1.6 mi downstream from the SR 60 bridge at Bartow. The fracture is about 26 ft long and is oriented in a north-south direction. The fracture displaces the limestone bedrock slightly and elevates it above the channel bed. This displacement allows river water to flow directly under this limestone bedrock ledge. Discharge measurements to this feature were made under various flow conditions from 2002 to 2006, and losses ranged from -1.18 to -7.49 ft^3/s (table 4). Field observations indicated that when the flow at the Peace River at Bartow gaging station (site 1) was about 10 ft^3/s, the upper Peace River flow typically terminated at this sink.

Table 3. Location and description of major karst features along the upper Peace River.

[Features are listed from north to south, ddmmss.s, degrees, minutes, and seconds; No., number; ft, feet; E, east; W, west; N, north; S, south]

Karst feature[1]	Latitude ddmmss.s	Longitude ddmmss.s	Length (feet)	Width (feet)	Description
Wabash Sink	275336.2	814838.6	26	17	Vertical pipe; formed near cypress tree roots
Cypress Root Sinks	275334.0	814836.0	5	5	Two sinks in channel; formed by cypress roots
Corbett Sink	275334.0	814837.0	39	39	Sink located off the low-water channel about 50 ft
Cooks Ripple	275315.0	814828.9	15	10	Vertical pipe; small channel diverts flow to feature
Fricano Fracture	275307.0	814823.0	3	2	Vertical pipe located on eastern side of channel
Harley Sink	275302.0	814821.0	4	4	Vertical pipe: infilled with sediments after 2004 hurricanes
Ledges Sink	275300.2	814822.8	26	10	Crack in river channel bedrock; next to Catacombs
Catacombs No. 1	275303.8	814824.4	38	30	Karst window; 8 ft deep; most noticeable flow
Catacombs No. 2	275303.0	814825.7	35	20	Karst window; 4 ft deep; noticeable flow
Catacombs No .3	275303.7	814824.4	36	24	Karst window; 7 ft deep; reduced flow
Catacombs No. 4	275303.2	814825.3	28	17	Karst window; 4.5 ft deep
Catacombs No. 5	275302.8	814826.8	16	14	Karst window; root formed sink; 6 ft deep
Catacombs No. 6	275302.6	814825.8	17	18	Karst window; root formed sink; 5 ft deep
Catacombs No. 7	275302.1	814826.7	15	15	Karst window; root formed sink; 4.5 ft deep
Catacombs No. 8	275302.0	814827.2	22	15	Karst window; sounds of water in sink; about 12 ft deep
Catacombs No. 9	275302.8	814826.8	14	16	Karst window; two sinks close together; about 15 ft deep
Jackson Sink	275300.0	814822.0	5	3	Vertical pipe; infilled with sediments after 2004 hurricanes
Midway Sink	275254.0	814806.0	22	9	Collapsed channel bedrock, infilled with sediments in 2005
Elephant Graveyard Sink	275248.0	814807.0	8	8	Collapsed channel bedrock, infilled with sediments in 2005
Catfish Sink	275236.6	814806.6	50	25	Buried sink; traps aquatic life during low-flow periods
Crevasses Sink (E-W)	275229.0	814809.0	26	2	Crack in river channel bedrock; about 5 ft deep
Crevasses Sink (N-S)	275229.0	814809.1	9	2	Crack in river channel bedrock; about 7 ft deep
Paternoster Complex	275228.0	814805.0	70	62	Three sinks in high-water floodplain
Gator Sink	275226.0	814819.0	90	72	Large round sinkhole; river water is diverted to sink during higher flows
Log Sink	275223.0	814814.0	66	44	Drains river water during medium to high flows
Dover Sink	275222.0	814806.0	91	55	Swallet; drains largest volume of flow of all sinks
Liz's Sink	275220.8	814808.7	23	60	Collapsed limestone in high-water channel; evidence of inflow
Kissengen Spring	275033.3	814839.3	95	126	Dry; ponds during wet periods due to backwater from river
Otter Sink	275032.7	814841.5	30	20	Next to Kissengen Spring; developed during study
Tom's Sink	275032.8	814830.1	50	50	Collapsed limestone in high-water channel; evidence of inflow

[1]Locations of features are shown in figs. 13B and 36.



During receding flow periods a large number of fish die off, as shown here at Dover Sink, August 2, 2007.
Photo credit: Charles Cook, FDEP

(A) Crevasse or crack (Crevasses Sink)

Photo credit: Charles Cook, FDEP

(B) Swallet or sink (Dover Sink)

Photo credit: Charles Cook, FDEP

(C) Root-filled cavity (near Wabash Complex)

Photo credit: P.A.Metz, USGS

(D) Karst window (Catacombs No.3)

Photo credit: P.A.Metz, USGS

(E) Vertical pipe (Fricano Fracture)

Photo credit: Lari Knochenmus, USGS

(F) Buried sink (Catfish Sink)

Photo credit: Charles Cook, FDEP

Figure 37. Examples of karst features along the upper Peace River.

Table 4. Discharge measurements of streamflow losses to karst features in Reaches 1 and 2 along the upper Peace River.

[Discharge in cubic feet per second; –, no measurement; **bold** numbers indicate the difference in discharge measured upstream and downstream of a karst feature; shaded numbers indicate that upstream flow ended at a karst feature]

Site number (fig. 36)	Karst feature name	Station number[1]	Measurement date	Upstream discharge	Downstream discharge	Streamflow loss or gain to karst feature
2	Wabash Complex	02294648	5/20/2002	7.34	2.52	**-4.82**
			6/11/2002	12.6	7.70	**-4.90**
			6/14/2002	4.5	1.24	**-3.26**
			6/25/2002	28.1	22.6	**-5.50**
			4/25/2003	64.6	65.2	[2]**+0.60**
			5/13/2003	24.4	24.5	[2]**+0.10**
			6/04/2003	52.2	51.9	**-0.30**
			6/23/2006	18.5	17.2	**-1.30**
4	Cook's Ripple	02294665	5/20/2002	2.52	0.22	**-2.30**
			6/14/2002	1.24	0.79	**-0.45**
5	Fricano Fracture	02294670	5/20/2002	–	–	-0.22
			6/14/2002			-0.19
6	Ledges Sink	02294672	6/11/2002	–	–	-1.18
			6/20/2002	–	–	-5.54
			6/24/2002	12.2	4.71	**-7.49**
			5/13/2003	24.8	19.4	**-5.40**
			6/23/2006	17.0	11.3	**-5.70**
8	Midway Sink	02294692	6/24/2002	–	–	-0.85
			6/25/2002	5.37	2.0	**-3.37**
9	Elephant Graveyard Sink	02294695	6/25/2002	–	–	-2.0
			5/13/2003	20.0	18.3	**-1.70**
9B	Crevasses Sink	02294700	6/26/2002	–	–	-3.02
10B	Gator Sink	2752260814819	7/03/2002	–	–	[3]-1.38
			8/13/2002	–	–	[3]-3.20
10	Dover Sink	02294705	6/19/2002	–	–	[4]-2.50
			6/20/2002	–	–	[4]-5.06
			6/24/2002	–	–	[4]-2.91
			6/28/2002	–	–	[5]-12.7
			5/18/2006	–	–	[6]-2.34
			6/12/2006	–	–	[7]-16.1
			6/23/2006	–	–	[8]-9.83

[1]Station number corresponds to downstream order number or latitude and longitude in degrees, minutes, and seconds.

[2]Streamflow gain most likely the result of inherent discharge measurement error of 5 to 8 percent.

[3]Discharge measured at Gator Sink Distributary.

[4]Total discharge source is from Sixmile Creek.

[5]Discharge source is 8.88 ft^3/s from Sixmile Creek and 3.82 ft^3/s from the Peace River.

[6]Total discharge source is from the Peace River.

[7]Total discharge source is from the Peace River during Tropical Storm Alberto.

[8]Discharge source is 0.83 ft^3/s from Sixmile Creek and 9.00 ft^3/s from the Peace River.

Underlying Ledges Sink is a large cavity that receives the inflow from the river. Barr (1992) documented this feature as an open swallow hole in the riverbed with an underlying cavern large enough to accommodate several standing individuals. This open swallow hole is no longer visible in the riverbed because of infilling of channel sediments. Currently (2008), the water flows downward into the cavern and moves in a westerly direction through a series of contiguous karst features that are termed the Catacombs Complex. These features are located in the high-water channel and are composed of about 9 interconnected karst windows in which flow can be observed moving from one sink to another.

The flow entering Ledges Sink reappears in the floodplain about 75 ft west of the river edge within the Catacombs Complex (fig. 36; fig. 38F). Flow is often visible in a large cavernous area called Catacombs No. 1, which is about 30 by 38 ft. The visible flow in the deepest part of the karst window is about 8 ft below land surface, and can be observed moving swiftly at a velocity of about 1 ft/s. The flow from Catacombs No. 1 moves in a westerly direction to a series of smaller karst windows where velocities decline substantially. The length of the complex from Catacombs No. 1 to the termination of the sinks is about 450 ft. The smaller sinkholes appear to have been created by a loss of support of the underlying limestone, as well as by tree roots that have broken through the limestone bedrock. All streamflow losses to the Catacombs Complex are considered to be the same as the losses at Ledges Sink, because these features are interconnected.

The most influential karst features located in Reach 2 include the following: Midway, Elephant Graveyard, Catfish, Crevasses, Dover, and Gator Sinks (fig. 36). Some of the prominent karst features in Reach 2 are shown in figure 39. During this investigation, Reach 2 experienced the greatest number of days when the riverbed went dry, and the largest volume of streamflow losses recorded along the upper Peace River. During different time periods in this investigation, flow in Reach 2 was observed terminating at the following sinks: Elephant Graveyard, Crevasses Sink, and Dover Sink.

Midway Sink and Elephant Graveyard are first in the series of sinks located along Reach 2 (fig. 36, sites 8 and 9). Midway Sink and Elephant Graveyard are located about 230 and 1,500 ft south of the Peace River near Bartow gaging station, respectively. Midway Sink is a collapsed feature located near the edge of the low-water channel that contains small fractures at its base (fig. 39A). Elephant Graveyard is downstream from Midway Sink, and consists of a series of limestone outcrops and depressions in the low-water channel bed. The area between these two sinks also had observable diffuse seepage losses, but these were not measured directly. Therefore, the diffuse losses were included in the flow losses for Elephant Graveyard. Measurements made at Midway Sink were -0.85 and -3.37 ft^3/s, and measurements made at Elephant Graveyard

(A) Wabash Sink (part of Wabash Complex) — Photo credit: P. A. Metz, USGS

(B) Cypress Root Sink (part of Wabash Complex) — Photo credit: Charles Cook, FDEP

(C) Cook's Ripple — Photo credit: Lari Knochenmus, USGS

(D) Fricano Fracture — Photo credit: Lari Knochenmus, USGS

(E) Ledges Sink — Photo credit: P. A. Metz, USGS

(F) Catacombs No. 1 — Photo credit: P. A. Metz, USGS

Figure 38. Karst features in Reach 1 along the upper Peace River.

(A) Midway Sink

Photo credit: Charles Cook, FDEP

(B) Catfish Sink

Photo credit: P. A. Metz, USGS

(C) Crevasses Sink

Photo credit: Lari Knochenmus, USGS

(D) Gator Sink

Photo credit: P. A. Metz, USGS

(E) Gator Sink Distributary

Photo credit: P. A. Metz, USGS

Figure 39. Karst features in Reach 2 along the upper Peace River.

Photo credit: P.A. Metz, USGS

Vultures await their meal of snakes and fish stranded at Catfish Sink.

Photo credit: Charles Cook, FDEP

were -1.70 and -2.0 ft^3/s (table 4). Sediment deposition caused by the high flows from the hurricanes of 2004 buried these sinks, and they could not be identified until 2008. Because of the deposition and high- or no-flow conditions, flow measurements were not conducted at these sites after 2003.

Located 0.4 mi south of Elephant Graveyard is a diffuse seepage feature named Catfish Sink (fig. 36, site 9a; fig. 39B). This feature was discovered late in the investigation (2006), and flow measurements were not obtained at this site. The large volume of water that flowed down the dry channel bed from Tropical Storm Albert (June 12, 2006) filled this sink at a rate of about 2 to 3 ft^3/s within 30 minutes. However, typical diffuse seepage losses are probably less than 1 ft^3/s during varying hydrologic conditions based on measured streamflow losses along this reach. During receding flow periods, a large accumulation of dead catfish and debris usually settles over this feature.

The Crevasses Sink is a series of solution fractures in the limestone river bedrock located about 600 ft downstream from Catfish Sink (fig. 36, site 9b; fig. 39C). The longest fracture is about 26 ft long and is oriented in an east-west direction, spanning most of the low-water channel. An adjacent smaller fracture, about 9 ft long and oriented in a north-south direction, is located at the western edge of the channel. This feature is similar to Ledges Sink, consisting of a large exposed fracture in the channel bed and a large underlying cavity that receives flow from the river and drains into the underlying aquifers. Crevasses Sink receives water from the stream channel on a continual basis, but at a lower rate than the

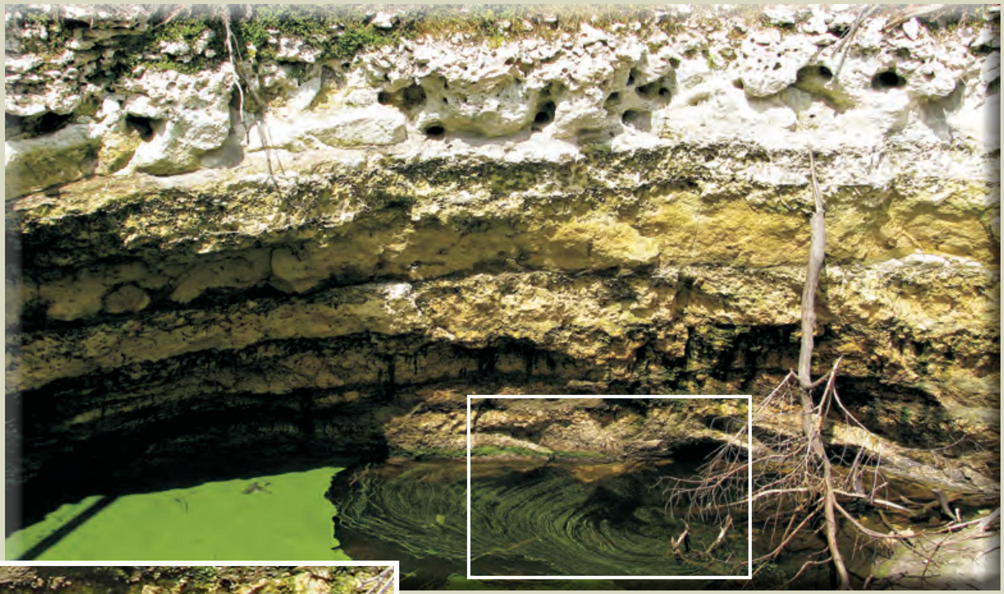


Photo credit: P.A. Metz, USGS

Gator Sink—A strong current of flow enters the western wall of the sinkhole; note the movement of duck weed on the water surface from the inflow (above).

Sinkhole wall, showing the sequence of sand, clay, dolomite, and limestone (right).

Photo credit: P.A. Metz, USGS

similar Ledges Sink. A number of field observations during 2006-2007 indicated that flow from the upper Peace River terminated at this sink. Measured flow loss at Crevasses Sink during June 26, 2002 was -3.02 ft^3/s (table 4).

Gator Sink is one of the largest of the documented sinkholes and has a **“**classic**”** circular shape. The sinkhole is 90 ft long, 72 ft wide and 40 ft deep (fig. 36, site 10b; fig. 39D). The beginning of the distributary to Gator Sink is located about 880 ft downstream from Crevasses Sink on the western edge of the floodplain. The sink is located about 800 ft west of the river’s edge, where a poorly incised distributary channel drains water from the Peace River at a river stage elevation of about 88 ft above NGVD 1929. As the river rises, flow in this distributary eventually drains into Gator Sink (fig. 39E).

When the storage capacity of Gator Sink is reached and the water level continues to rise, the sink overflows, inundating the surrounding floodplain. Two discharge measurements were made in July and August of 2002 at the Gator Sink Distributary, with flows draining into the sink at -1.38 and -3.20 ft^3/s (table 4).

The steep vertical walls of Gator Sink contain, from top to bottom, a sequence of sand, clay, dolomite, and limestone of the Peace River and the Arcadia Formations (see photos on p. 61). The lower sequence of limestone and dolomite forms a wall containing cracks, fractures, holes, and vugs. Depending on hydrologic conditions, these fractures and cavities occasionally transmit water to the sink. During low-flow periods when the bottom of the western wall of the sink was exposed, a strong current of flow could be observed moving into the sink about 30 ft below the land surface. A dye test conducted during this study indicates that some of the river water that flows into Ledges Sink and the Catacomb Complex moves southward about 0.75 mi (in less than 1 day) within the shallow karst floodplain geology to Gator Sink, then drains into the sink through the eroded western wall.

Other karst features located in the high-water channel of Reach 2 include the Paternoster Complex (consisting of three sinks), Log Sink, and Liz Sink (fig. 36). Evidence of seepage flow has been observed around each of these sinks, but the actual losses are unknown. A number of undiscovered sinks probably exist within the high-water channel along Reach 2, but dense vegetation makes these sinks difficult to locate.

Dover Sink, located in the eastern floodplain about 0.6 mi upstream from the Clear Springs gaging station (fig. 36, site 10), had the largest streamflow losses of all the karst features along the upper Peace River. Flow from the Peace River has eroded an approximate 500-ft-long distributary channel to Dover Sink (fig. 40A, 41D). The dimensions of Dover Sink are about 55 by 91 ft, and the size is continuously changing because of depositional and erosional processes. The bottom elevation of Dover Sink is presently about 13 ft below the elevation of the confluence of the Peace River and the distributary channel (fig. 40B). This steep elevation change allows large volumes of water to drain into the sink. At the bottom of the sink, the flow moves through a horizontal erosional crack in the wall of the Arcadia Formation.

Rhodamine dye, as seen through a karst window (Catacombs No. 1). Photo credit: P.A. Metz, USGS

Observations made during this study indicate that an extensive interconnected series of cavities exists beneath the walls of Dover Sink that can store large volumes of water. During the dry season, large unfilled cavities exist in the karst system that is connected to Dover Sink. When the rainy season returns, river water flows into Dover Sink and replenishes these void spaces in the underlying aquifers.

The interconnected karst system associated with Dover Sink is estimated to store more than 10 Mgal in a day before the level in the sink stabilizes. This estimate was based on (1) a discharge measurement of 16.1 ft^3/s made on June 12, 2006 (table 2; site 10) at Dover Sink Distributary after a storm event while aquifer levels were low; (2) a hydrograph of water levels of Dover Sink during this time period; and (3) streamflow conditions at the downstream Peace River near Clear Springs gaging station. Once the local aquifer storage volume was replenished, the pool surrounding Dover Sink and the distributary rose to the level of the Peace River at about 87 ft above NGVD 1929, and aquifer levels of the underlying interconnected aquifers were about 78 ft above NGVD 1929. A number of discharge measurements were made in the Dover Sink Distributary, and flow losses into Dover Sink ranged from -2.34 to -16.1 ft^3/s (table 4).

Dover Sink exhibited the most structural changes of all the karst features observed during the period of investigation. The series of photographs in figure 41 shows Dover Sink over a range of hydrologic conditions. At the beginning of the study in 2002, the Dover Sink Distributary channel was mostly a sand-filled waterway with small remnant lenses of the Bone Valley Formation exposed in the distributary channel and exposed rocks of the Arcadia Formation in the main sink (fig. 41A). After the hurricanes in 2004 and high-water period in 2005, sediment accumulated in Dover Sink and covered much of the exposed rock (fig. 41B). Intermittent flows during 2006-2007 caused greater flow velocities in the distributary channel that washed away overlying sediments, exposing large limestone boulders of the Arcadia Formation (fig. 41C). This erosional exposure created a cascading waterfall effect at the approach to Dover Sink (fig. 41D). As a result of several high-water events at the end of the 2007 water year, sediment again accumulated and covered some of the exposed rocks (fig. 41E). The photograph in figure 41F shows Dover Sink in a ponded condition after the interconnected karst aquifer system was replenished.

At the beginning of this investigation (2002), water entered the groundwater system from Dover Sink through a horizontal erosional crack at the bottom wall of Dover Sink. By the end of the study (2007), however, the force of moving water had scoured and enlarged the opening in the wall, which then measured about 3 ft in diameter. This enlarged opening allowed large quantities of water, sediment, aquatic life, and debris to flow into the conduits and cavities associated with the underlying aquifers.

In addition to the erosion of sediment and carbonate bedrock in the distributary channel, about 2 ft of erosion occurred along the Peace River channel bed at its confluence with Dover Sink Distributary. Over time, the erosion in the channel has aided in the diversion of flow from the Peace River to Dover Sink. Elevation profiles of the Peace River channel and Dover Sink Distributary are shown in figure 42. In addition to the erosion of the channel, sand also was deposited downstream from the confluence of the distributary, which aided in the diversion of flow to the sink. Based on elevation profiles, the extent of this erosional activity begins upstream near Crevasses Sink and ends about 200 ft downstream from the confluence of Peace River and Dover Sink Distributary (fig. 42).

About 0.7 mi downstream from Dover Sink is Sixmile Creek, which is a phosphate-mine outfall tributary to the Peace River (fig. 36, site 12). The area around the confluence of Sixmile Creek and Peace River has never been observed to go dry, but it does pond during low-flow conditions. As Sixmile Creek discharges into this ponded area of the river, the river rises enough for a gradient to form, causing an unusual case of flow reversal along the river. The water from this ponded area travels north about 1,500 ft and eventually discharges into Dover Sink. However, a fraction of the discharge in the ponded area still flows in the southward downstream direction. Figure 43A is a photograph showing the input from Sixmile Creek flowing north and the Peace River flowing south, with both flows merging into Dover Sink Distributary. A number of discharge measurements were made to document this reversal of flow, which ranged from 0.83 to 8.88 ft^3/s (table 2). A discharge hydrograph shows the periods when the discharge at Sixmile Creek is greater than discharge from Peace River at Clear Springs (flatline indicates no flow; fig. 43B). During these peak discharge events for Sixmile Creek, flow was observed moving north toward Dover Sink.

Although there were no notable karst features in the low-water channel of Reach 3, there were several karst features of interest in the high-water channel. These features are Otter and Tom's Sinks, which are located near the historic Kissengen Spring (fig. 22). Otter Sink formed in 2002 and drains river water during periodic seasonal floodplain inundations. A small amount of flow is lost when backwater from the Peace River flows up the 0.5-mi inactive spring run and floods the remnant spring pool of Kissengen Spring. During the 1960s, a large clay plug was placed in Kissengen Spring to limit flow exchange (Jackson, 2008). Currently (2009), flows travel up the inactive spring run and are scouring out a new channel to Otter Sink where observed streamflow losses to this sink are about 2 to 3 ft^3/s (Charles Cook, FDEP, written commun., 2009).

Located in the floodplain about 800 ft east of Kissengen Spring and 400 ft west of Peace River, Tom's Sink was discovered through aerial photo examination in 2008 (Tom Jackson, written commun., 2008). The aerial photo indicates that the flow to this sink has eroded an approximate 300-ft-long distributary, extending from the sinkhole to the relict Kissengen Spring run channel. During July 2008, flow was observed draining into Tom's Sink (Charles Cook, FDEP, written commun., 2008). Flow losses to these high-water

(A)

Images from U.S. Geological Survey digital orthophoto quadrangle data, photographed in 2004
Universal Transverse Mercator Projection, Zone 17

(B)

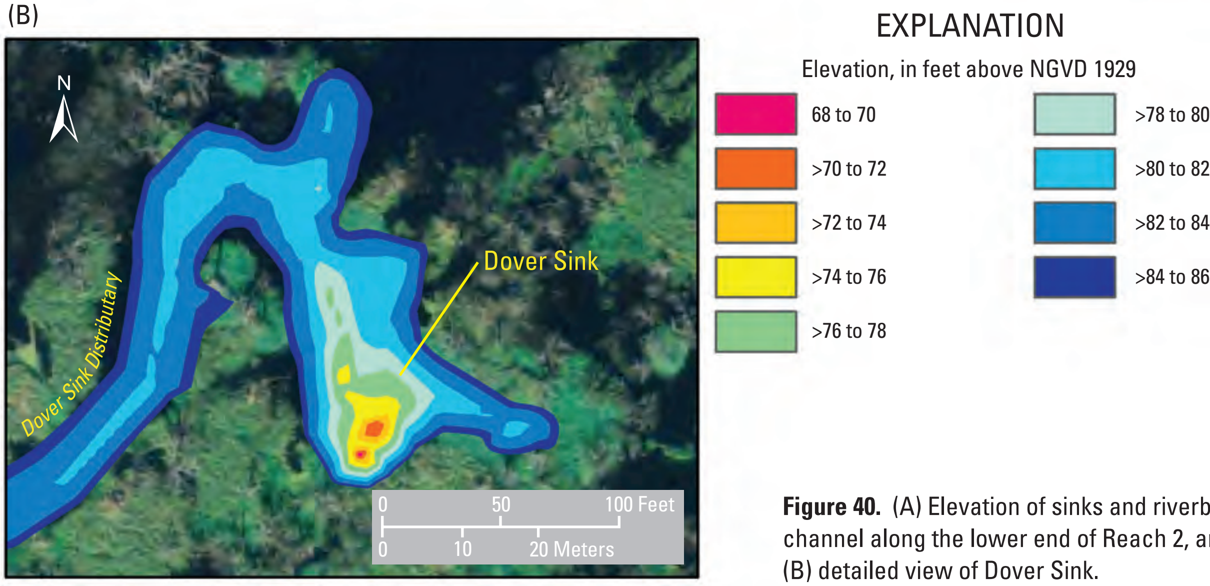


Figure 40. (A) Elevation of sinks and riverbed channel along the lower end of Reach 2, and (B) detailed view of Dover Sink.

(A) Exposed rocks, 2002

Photo credit: Lari Knochenmus, USGS

(B) Sediment and fish accumulation, 2006

Photo credit: P. A. Metz, USGS

(C) Storm event at Dover Sink, 2006

Photo credit: P. A. Metz, USGS

(D) Continued scouring of Dover Sink Distributary channel, 2007

Photo credit: Charles Cook, FDEP

(E) Infilling and scouring at Dover Sink, 2008

Photo credit: Charles Cook, FDEP

(F) Dover Sink ponded, 2008

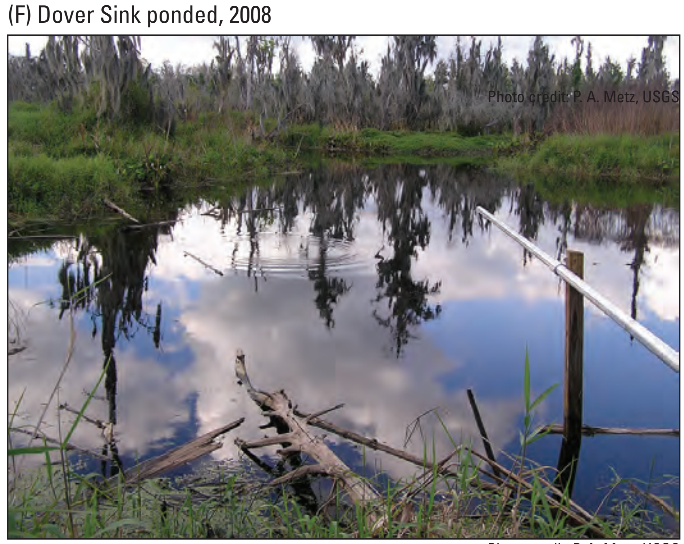


Photo credit: P. A. Metz, USGS

Figure 41. Changing hydrologic conditions at Dover Sink.

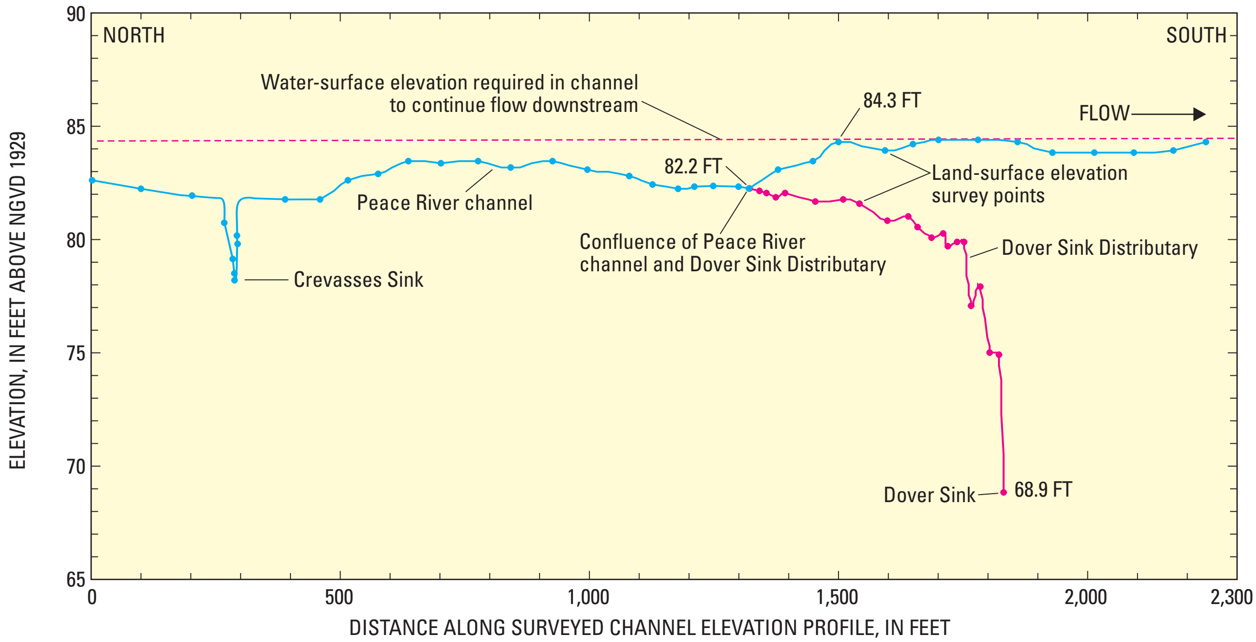


Figure 42. Topographical profile of Peace River channel and Dover Sink Distributary.

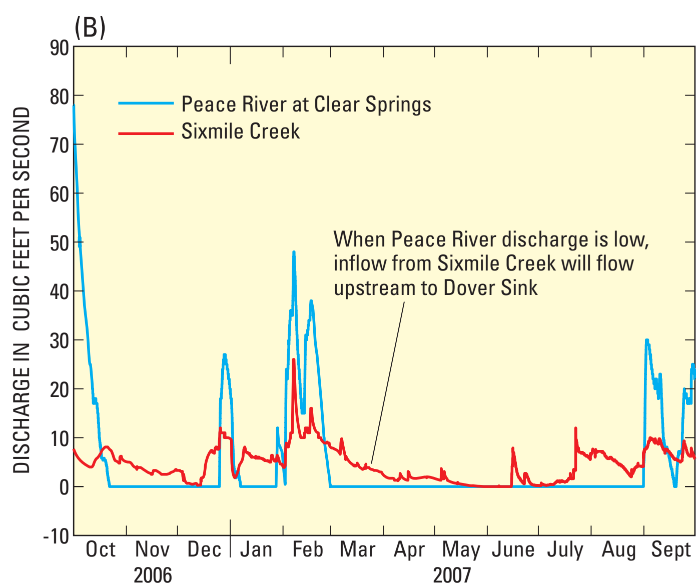


Figure 43. (A) Inflow to Dover Sink Distributary from two sources—from Peace River flowing south and Sixmile Creek flowing north—and (B) comparison of discharge from Peace River at Clear Springs and Sixmile Creek (location of gages shown in fig. 13).

channel sinks are currently unknown. Both Otter Sink and Tom's Sink recharge the underlying aquifer during periods of floodplain inundation, and probably influence water levels in the Kissengen Spring area LW4P monitor wells (fig. 13B).

Effects of Groundwater Conditions on Streamflow Losses

Within the upper Peace River karst area, streamflow losses are dependent on a number of hydrologic conditions. The elevations of the potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer are two of the most important factors that influence streamflow losses along the upper Peace River. As water-level differences increase between aquifer units during dry periods because of pumpage or hydrologic stresses, water stored in the intermediate aquifer system drains downward into the Upper Floridan aquifer. This in turn creates a potential for river water to drain into empty void spaces or cavities in the intermediate aquifer system. During these low-water periods, the small amount of water in the stream channel can be observed flowing into the various sinks until the upper reaches of the river become dry. During high-water periods, as water-level differences decrease between the river and the underlying aquifers and the storage in the aquifers is replenished, the potential for streamflow losses declines.

To understand these processes, analyses were made to determine if streamflow losses were proportional to the decline in the potentiometric surface below the elevation of the riverbed. Groundwater conditions were analyzed separately for Reaches 1 and 2 because of the different hydrologic conditions that exist in these reaches. For Reach 1, groundwater conditions were defined as the vertical distance of the potentiometric surface below the riverbed elevation, using water levels from the Upper Floridan aquifer and the intermediate aquifer system measured at the LW1P site. Because groundwater-level data were absent during much of the study period near Reaches 1 and 2, data from the ROMP 59 Avon Park and Hawthorn wells were used to extrapolate water-level conditions as necessary. For Reach 2, groundwater conditions were defined using only the Upper Floridan aquifer (LW3P), because the Upper Floridan aquifer and the intermediate aquifer system are hydraulically connected along this reach.

Streamflow losses were calculated from discharge measurements made during the study period at the three upstream gaging stations that spanned Reaches 1 and 2 (sites 1, 7, and 11; fig. 22). Discharge measurements selected for this analysis included synoptic seepage run measurements made between these stations during baseflow conditions. Under certain circumstances, continuous daily discharge data could be used for this analysis, but much of the continuous record is complicated by effects of overbank storage, rainfall and surface inflows, and zero-flow days. The continuous record was only used to determine streamflow losses when these complicating factors were not observed.

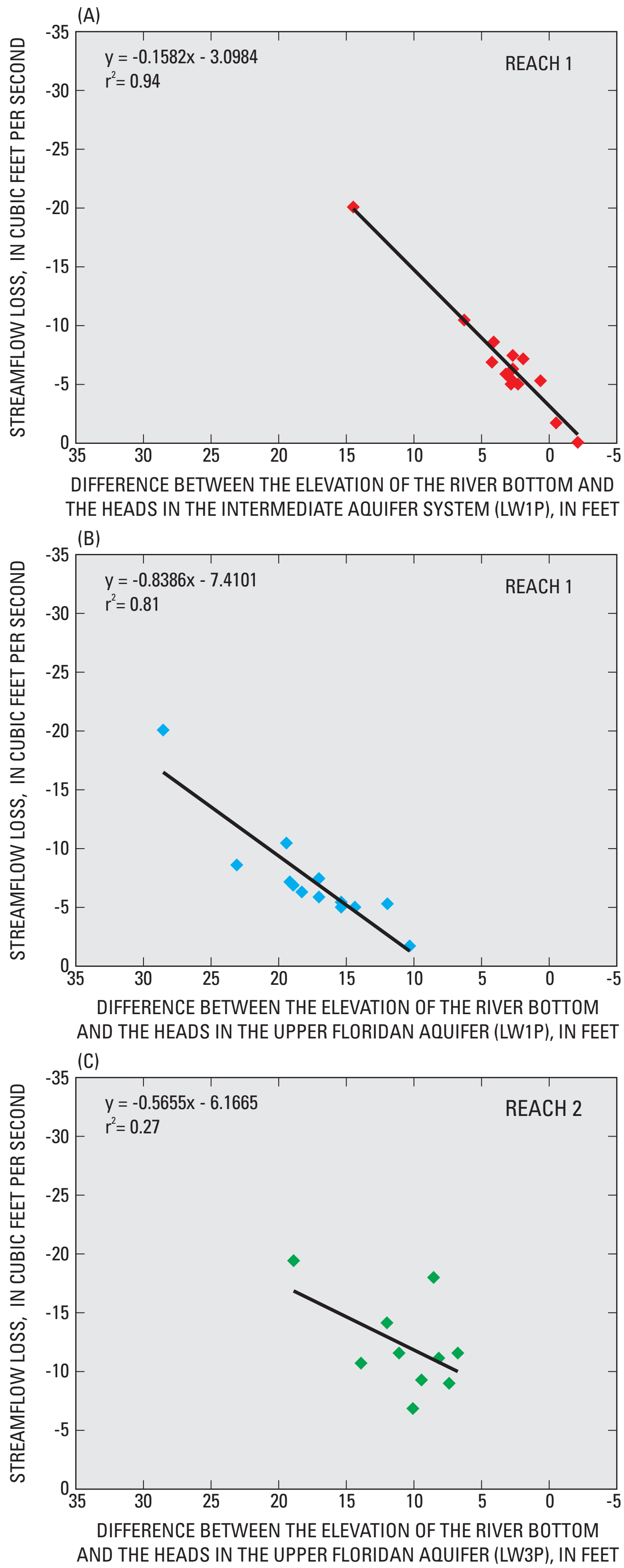


Figure 44. Relation of streamflow losses to aquifer water levels in Reaches 1 and 2 during seepage measurements.

In Reach 1, the intermediate aquifer system is hydraulically connected to the river and streamflow losses during baseflow conditions were strongly correlated to water-level changes in this aquifer (r^2 = 0.94; fig. 44A). During the dry season when groundwater levels were at their lowest, the water-level difference between the elevation of the riverbed and the intermediate aquifer system was 14.5 ft, and streamflow losses were greatest (-20 ft^3/s). During the wet season when water levels in the intermediate aquifer system were at their highest level, there was a reduced potential for streamflow losses. During these increased water-level periods, streamflow gains were noted in the river.

In Reach 1, there also was a good relation between streamflow losses and the vertical distance between the riverbed elevation and the potentiometric surface of the Upper Floridan aquifer during seepage runs (r^2 = 0.81; fig. 44B). This relation reflects the influence that the Upper Floridan aquifer has on the intermediate aquifer system. As water levels decline in the Upper Floridan aquifer because of pumpage or hydrologic stresses, these declines affect water levels in the intermediate aquifer system and, consequently, influence streamflow losses.

In Reach 2, there was not a significant linear relation between streamflow losses and the vertical distance between the riverbed and the Upper Floridan aquifer levels during seepage runs (r^2 = 0.27; fig. 44C). In Reach 2, the relation between streamflow losses and aquifer level declines is more complex. In this reach, the upper Peace River is connected to both the intermediate aquifer system and the Upper Floridan aquifer through a large conduit system. Because this conduit system is very large, it can accommodate a large proportion of flow from the river at multiple river stages.

Groundwater Flow Patterns Surrounding the Upper Peace River

The groundwater flow patterns surrounding the upper Peace River are influenced by recharge conditions, inflow from the river, and regional groundwater withdrawals. Water levels collected from a network of wells, sinks, tributaries, and phosphate-mine outfalls along an approximate 5-mi reach of the upper Peace River provide the basis for relating groundwater flow patterns to streamflow losses along the upper Peace River. To help define groundwater flow patterns, continuous water-level data were collected from a network of two surficial aquifer wells, four intermediate aquifer system wells, three Upper Floridan aquifer wells, and two major sinks (Gator and Dover Sinks) (fig. 13B). A well nest was installed at each of the geologic core sites (LW1P, LW3P, and LW4P) to determine the vertical component of flow within an aquifer or between aquifer units (fig. 13B).

Groundwater data were collected by the USGS at the LW1P well nest site from May 2005 to September 2007 and at the LW3P and LW4P well nest sites from July 2006 through September 2007. Supplemental groundwater data also were obtained from the SWFWMD, who continued monitoring at these sites after September 2007. Table 5 lists the index number for each well, location by latitude and longitude (ID number), well name, well depth and cased interval, hydrogeologic unit, and the summary of data collected at each well.

Because well nests near the river were not installed until later in the study, data from the ROMP 59 Avon Park and Hawthorn wells were used to help determine current and long-term trends in the study area (table 5, figs. 13 and 45). Linear regression analyses show a significant correlation between water levels in Upper Floridan aquifer wells at the study sites (LW1P, LW3P, and LW4P) and ROMP 59 Avon Park well (fig. 45). Based on the record at the ROMP 59 Avon Park well (1997-2007 water years), groundwater levels collected at LW1P from April 2005 through March 2006 were considered above average (high-water analysis period; fig 45) whereas water levels for the 2007 water year were considered below average (low-water analysis period; fig. 45).

Hydrographs that show the relations between water levels in the river; the underlying aquifers at LW1P, LW3P, and LW4P monitoring sites; and Dover Sink are shown in figure 46A-F. Comparison between water levels in the upper and lower aquifers within the intermediate aquifer system show that the hydraulic connection between (and within) these units varies between locations. Three wells were completed in the upper Arcadia aquifer (LW1P IAS UA, LW3P IAS UA, and LW4P IAS UA), and one well was completed in the lower Arcadia aquifer (LW3P IAS LA, fig. 46A). Water-level comparisons between sites for the upper Arcadia aquifer (LW1P IAS UA and LW3P IAS UA) showed good agreement (r^2 = 0.73; fig. 46A). Water-levels in the lower Arcadia aquifer at the LW3P well site (LW3P IAS LA) and upper Arcadia aquifer at the LW4P well site (LW4P IAS UA) were strongly correlated (r^2 = 0.98; fig. 46A), indicating a strong hydraulic connection between aquifers. Comparison between the upper and lower Arcadia aquifer levels at the LW3P well site (LW3P IAS UA and LW3P IAS LA) indicated a good connection (r^2 = 0.73; fig. 46A), although not as strong as the other sites.

Variable relations between aquifers within the intermediate aquifer system and between well sites indicate the complexity of the geology in the intermediate aquifer system. The intermediate aquifer system contains interbedded carbonates and siliciclastic sediments that contribute to the heterogeneity of this unit, and localized differences in groundwater levels. In addition, the Arcadia Formation contains weathered dolomite that is fractured and has pinpoint vugs, voids, and numerous fossils casts and molds that aid in the development of secondary porosity. This porosity strengthens the hydraulic connection between these aquifers (fig. 14). Although the confining units of the intermediate aquifer system impede downward flow into the Upper Floridan aquifer, the hydraulic connection between aquifers increases when the confining units are thinner, more permeable, breached by sinkholes, and contain sand-filled piping features, or cavities and conduit systems.

Table 5. Characteristics and data summary for wells and sinks located along the upper Peace River.

[BLS, below land surface; SWFWMD, Southwest Florida Water Management District; HTRN, Hawthorn; IAS, intermediate aquifer system; LA, lower Arcadia aquifer; LH, Lower Hawthorn, No.; number; NRSD, nonartesian sand aquifer; SA, surficial aquifer; SUW and SWNN, Suwannee; UA, upper Arcadia aquifer; UFA, Upper Floridan aquifer; UH, Upper Hawthorn; CON, continuous; REC, recorder; QW, water quality; –, no data]

Index No.[1]	USGS identification No.	SWFWMD well or sink name[2]	USGS abbreviated name	Hydrogeologic unit	Total depth BLS (feet)	Total cased interval BLS (feet)	Diameter, (inches)	Data summary
1	275336081484401	LW1P UFA	WWTP-LW1P SWNN	UFA	235	95	6	CON REC, QW
2	275336081484402	LW1P IAS UA	WWTP-LW1P HTRN	IAS (UA)	75	18	6	CON REC, QW
3	275336081484403	LW1P SA	WWTP-LW1P NRSD	SA	6	2	6	CON REC, QW
4	275156081481901	LW3P UFA	Clear Springs SUW	UFA	320	170	6	CON REC, QW
5	275156081481902	LW3P IAS LA	Clear Springs LH	IAS (LA)	140	67	6	CON REC, QW
6	275156081481903	LW3P IAS UA	Clear Springs UH	IAS (UA)	37	21	6	CON REC, QW
7	275156081481904	LW3P SA	Clear Springs SA	SA	12	2	6	CON REC, QW
8	275034081483901	LW4P UFA	Kissengen Spring SUW	UFA	310	151	6	CON REC, QW
9	275034081483902	LW4P UA	Kissengen Spring UH	IAS (UA)	76	31	6	CON REC, QW
10	275220081480101	Clear Springs IAS	Clear Springs IAS	IAS (LA)	143	62	6	CON REC, QW
11	275314081514201	ROMP 59 AP	ROMP 59 Avon Park	UFA	1,050	200	12	CON REC
12	275314081514202	ROMP 59 HTRN	ROMP 59 HTRN	IAS	142	122	6	CON REC
13	274908081480901	Homeland No. 4	Homeland No. 4	IAS (LA)	202	56	24	CON REC
14	274841081480901	Homeland No. 9	Homeland No. 9	UFA	746	–	6	CON REC
15	275226081481900	Gator Sink	Gator Sink	IAS (LA)	–	–	–	CON REC
16	02294705	Dover Sink	Peace River Distributary at Dover Sink	IAS (LA)	–	–	–	CON REC, QW

[1]Index numbers refer to wells and sinks shown in fig. 13B.

[2]Well name used in this study.

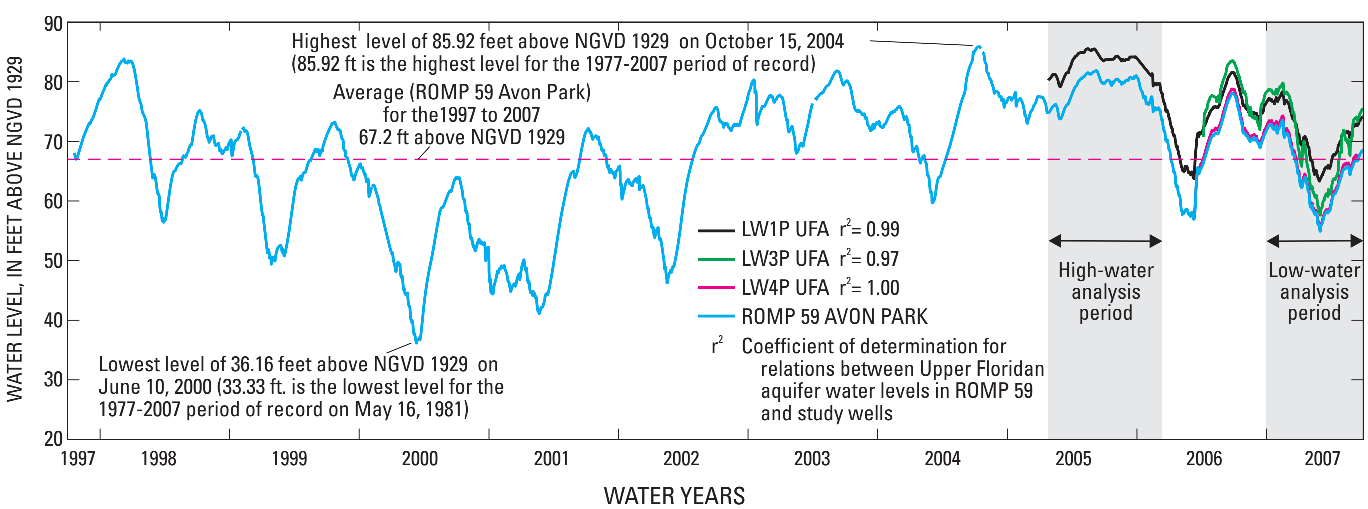


Figure 45. Long-term hydrograph for ROMP 59 Avon Park Upper Floridan aquifer well and hydrographs for the study period for Upper Floridan aquifer wells at LW1P, LW3P, and LW4P monitor sites (location of wells shown in figs. 8 and 13B).

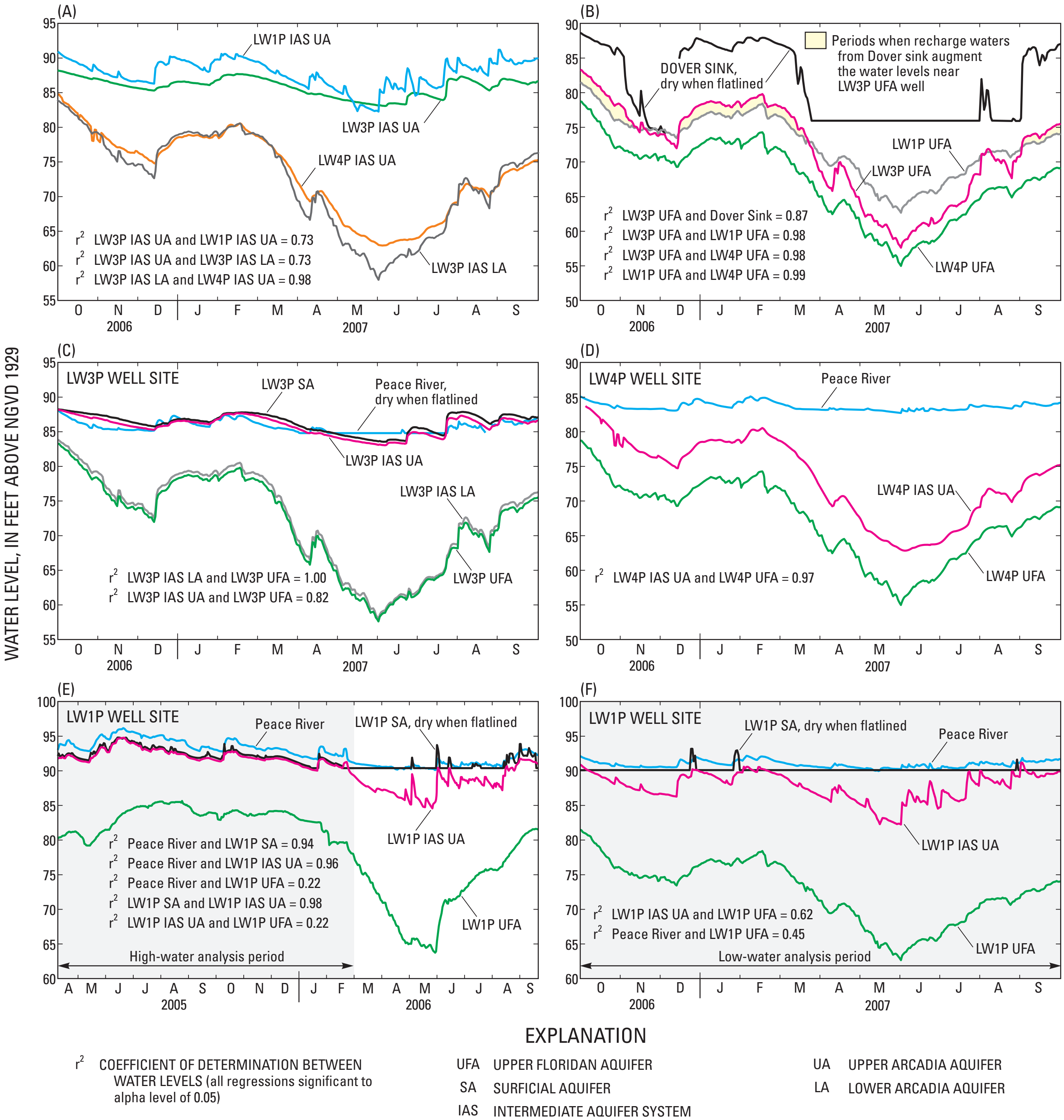


Figure 46. Comparison of the Peace River stage and water levels in monitor wells completed at different depths in the intermediate aquifer system and Upper Floridan aquifer (location of wells are shown in fig. 13B and well depths and cased intervals are shown in table 5).

A comparison of water levels in the three Upper Floridan aquifer wells (LW1P UFA, LW3P UFA, and LW4P UFA) indicated significant relations between all well sites (r^2 = 0.98-0.99; fig. 46B). The significant relations between these well sites indicate a good lateral connection and the regional nature of this unit. The lateral head gradient in the Upper Floridan aquifer decreases from north (LW1P) to south (LW4P), at about 0.70 foot per mile (ft/mi).

The differences between the elevation of the river bottom and water levels in the underlying aquifers were greatest during the dry season (May through June). The largest daily difference between the river bottom elevation and the Upper Floridan aquifer water levels occurred on June 1, 2007, with differences of 26.34 ft at well LW1P, 25.38 ft at well LW3P, and 26.01 ft at well LW4P. Substantial streamflow losses occur at the end of the dry season, when large volumes of water are often required to replenish the underlying storage of the intermediate aquifer system and Upper Floridan aquifer. At the three well sites, recharge conditions existed for most of the study period (fig. 12). An exception to this overall pattern occurred at the LW1P site when intermediate aquifer system levels were higher than surficial aquifer levels for a brief period in 2005.

The water-level differences at the well sites and linear relations between aquifers yield insight into the degree of confinement or interconnection between the intermediate aquifer system and the Upper Floridan aquifer. Differences between these water levels may indicate the localized nature of the confining unit sediments or the influence of karst features. For example, permeable sediments or secondary porosity associated with a karst environment will enhance the downward movement of recharge waters, resulting in a smaller water-level difference between aquifers.

At both LW3P and LW4P well sites (2007 water year) a strong connection exists between the intermediate aquifer system and Upper Floridan aquifer, as indicated by significant linear relations between water levels (r^2 = 1.00 for LW3P wells and r^2 = 0.97 for LW4P wells; fig. 46C-D). In addition, the smaller average water-level differences between the intermediate aquifer system and Upper Floridan aquifer at these sites (0.67 ft for LW3P wells, and 6.0 ft for LW4P wells) indicate a better hydraulic connection between aquifer units. The LW3P well site is in an area where prominent karst features (Dover Sink and Gator Sink) are located (fig. 13B), which is evidence of the cavernous karst conduit system that facilitates water movement between the aquifer units. The LW4P well site also is in an area where an extensive cavernous system exists that is associated with the dry Kissengen Spring.

In contrast, there is less connection between the intermediate aquifer system and Upper Floridan aquifer at the LW1P well site (2007 water year), as indicated by a weaker relation between water levels (r^2 = 0.62; fig. 46F). This relation may indicate there is more confinement at this site, which limits the connection between the intermediate aquifer system and Upper Floridan aquifer. Geologic cores and aquifer tests analyzed during the study indicate that a thick, low permeability layer exists between the two aquifers at the LW1P site. In addition, a relatively large average water-level difference (15 ft) between the intermediate aquifer system and the Upper Floridan aquifer was noted at this site, which indicates more confinement.

During above-average water-level conditions (high-water analysis period, April 26, 2005 to March 2, 2006; fig. 46E), the aquifers at the LW1P well site show different relations between one another and the river compared to below-average water-level conditions (low-water analysis period, October 1, 2006 to September 30, 2007; fig. 46F). During the high-water analysis period, there were significant relations between river levels and the surficial aquifer (r^2 = 0.94), between the river levels and the upper Arcadia aquifer (r^2 = 0.96), and between the upper Arcadia aquifer and surficial aquifer (r^2 = 0.98). The average river stage for this time period was 1.6 ft higher than surficial aquifer levels, indicating lateral recharge to that aquifer. The hydraulic connection between the river, surficial aquifer, and upper Arcadia aquifer can be attributed to the widespread karstified geologic framework of the Arcadia Formation. Geologic cores from the LW1P well indicate that the Arcadia Formation contains sections of fractured dolomite at depths ranging from 16 to 26 ft and from 50 to 75 ft, which enhance the hydraulic connection between the river, the surficial aquifer, and the intermediate aquifer system.

As water-level differences increase between units, there is an increased potential for downward recharge from the overlying hydrologic units at the LW1P site. During high-water analysis period (fig. 46E), there were no significant relations between river stage and the Upper Floridan aquifer (r^2 = 0.22), and between the intermediate aquifer system and Upper Floridan aquifer (r^2 = 0.22) at the LW1P well site. In contrast, statistical relations indicate an increased potential for downward flow during the low-water analysis period (fig. 46F). During this time, water-level relations between the river stage and the Upper Floridan aquifer improved slightly (r^2 = 0.45) compared to the high-water period (r^2= 0.22). Relations also improved between the intermediate aquifer system and the Upper Floridan aquifer at LW1P during the low-water period (r^2 = 0.62) compared to the high-water period (r^2= 0.22), indicating a higher degree of interconnection during low-water periods.

Flow Patterns Derived from Chemical Constituents and Isotopic Tracers

Information on groundwater flow patterns along the upper Peace River also can be derived using chemical and isotope-tracing methods. Water quality in the river is influenced by rainfall, groundwater and surface-water inflows, and land-use practices. Water quality in the underlying aquifers is controlled by the lithology and mineralogy of the particular unit, residence time of water in contact with the aquifer matrix, and recharge from the overlying aquifer and the river. These variations in water chemistry between the river, the intermediate aquifer system, and Upper Floridan aquifer

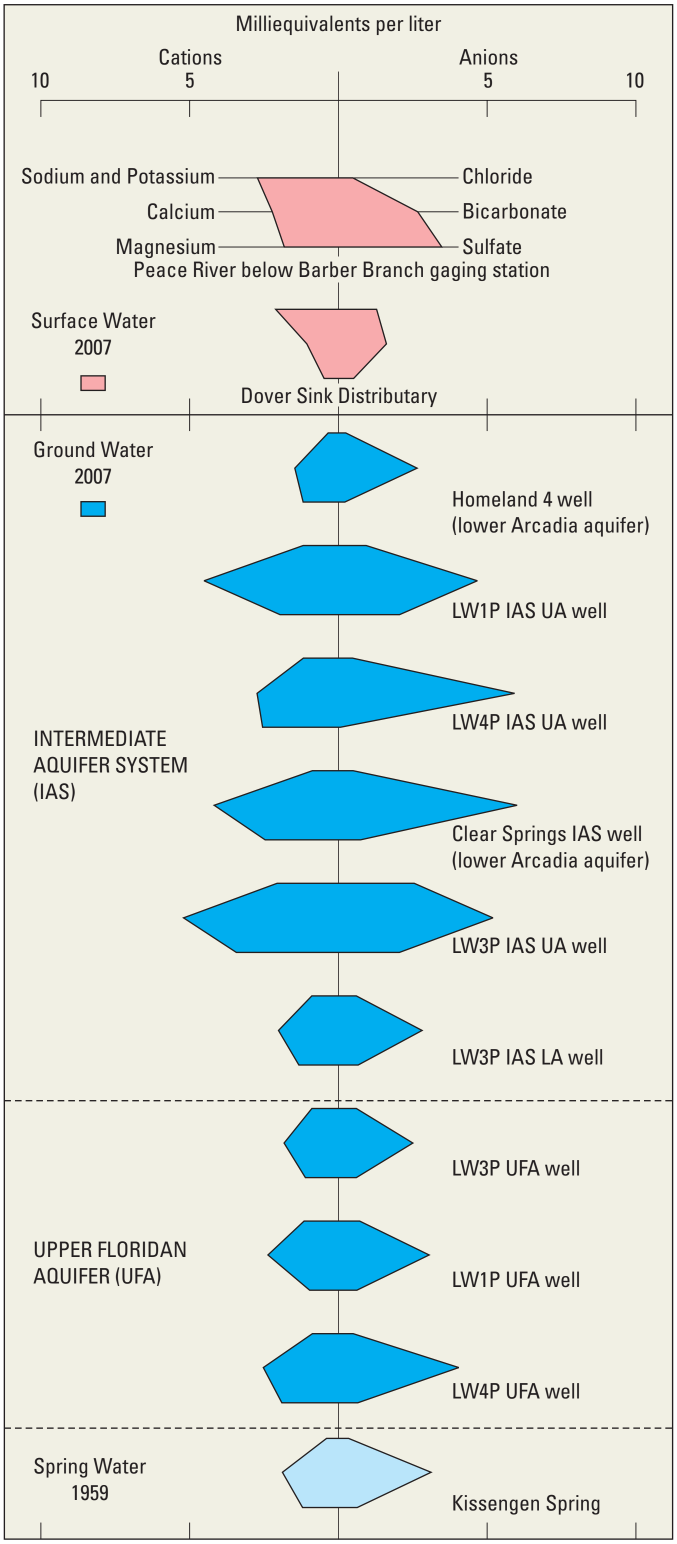


Figure 47. Stiff diagrams for surface-water and groundwater sites along the upper Peace River (location of sampling sites are shown in fig. 13B and well depths and cased intervals are shown in table 5).

provided insight into the multiple flow processes occurring along the upper Peace River. Stiff diagrams of water-chemistry data collected during this study show the variability of water in the river and the two aquifers (fig. 47).

River samples collected north of Sixmile Creek, Phosphate Mine Outfall CS-8, and Barber Branch had lower concentrations of dissolved constituents than water collected downstream from these mine-outfall sites (fig. 13B). As discussed in previous sections, the study area is lined by clay-settling ponds and mine-outfall sites, and water samples collected during this study varied chemically depending on their proximity to these sites. A river sample was collected at the Dover Sink Distributary during a low-flow period (mean discharge of 14 ft^3/s at Peace River at Bartow on March 23, 2007) when inflows to the upper Peace River were only derived from Peace Creek Drainage Canal. During this time, the remaining flow from the upper Peace River drained into Dover Sink. The Stiff diagram of the Dover Sink Distributary indicates that the water was slightly enriched in sodium, potassium, chloride, and bicarbonate, and was not influenced by mine drainage (fig. 47). The river-water sample was characterized by a high color content, and the specific conductance and pH were 397 microsiemens per centimeter (µS/cm) and 7.4, respectively.

Water samples collected downstream from the Peace River below Sixmile Creek are influenced by mine outfalls. During low-flow conditions, the mine outfalls are the primary source of inflows to this reach of the river. A surface-water sample collected downstream from Barber Branch had a higher ionic-strength than the upstream Dover Sink Distributary site. The water in this section of the river was influenced by the mine outfalls of Sixmile Creek, Phosphate Mine Outfall CS-8, and Barber Branch. Measured specific conductance and pH values were 690 µS/cm and 7.9, respectively. River water downstream from Barber Branch contained significantly higher concentrations of calcium, sulfate, and magnesium than water collected at Dover Sink Distributary (fig. 47). When river water flows north from Sixmile Creek and drains into Dover Sink, this inflow water is more enriched in calcium, sulfate, and magnesium than inflow water from Peace Creek Drainage Canal.

Stiff diagrams also show the variability in chemical constituents between the intermediate aquifer system and the Upper Floridan aquifer. The water chemistry of the intermediate aquifer system and the Upper Floridan aquifer was dominated by calcium carbonate. In addition, the intermediate aquifer system had increased concentrations of magnesium due to the dissolution of dolomite in the carbonate aquifer. Both aquifers contain water that is predominantly a calcium-bicarbonate water type, but the intermediate aquifer system contains water with higher concentrations, on average, of sulfate, potassium, bicarbonate, and chloride than water in the underlying Upper Floridan aquifer. In some cases, the upper Arcadia aquifer contained water with higher concentrations of calcium, bicarbonate, and sulfate than water in the lower Arcadia aquifer.

River and spring flow are influenced by groundwater conditions. Stages of riverflow, from flowing to dry (top and bottom); and mud puddle at inactive Kissengen Spring (center). Photo credit: P.A. Metz, USGS

There are several reasons for the chemical enrichment of the shallower part of the intermediate aquifer system: (1) the study wells are located in areas where the surficial aquifer is thin or absent and recharge waters have been affected by mining practices; (2) the wells are located in an area where there is extensive karst development that provides preferential recharge pathways from the surface to the underlying aquifer; and (3) the wells are located near mine-outfall pits that breach the upper confining layers. Some or all of these factors may influence the water chemistry of the intermediate aquifer system within the study area.

One of the wells sampled from the intermediate aquifer system (Homeland No. 4 well; 650 ft west of Peace River) is located in an area that has previously been mined (near several dredged pit lakes) but away from extensive karst development (fig. 13A). A Stiff diagram for this well indicates that the water is a calcium-bicarbonate type, but with lower levels of sulfate, magnesium, potassium, and chloride than wells closer to the river (fig. 47). This well is deeper (202 ft; table 5) than any of the other intermediate aquifer system wells sampled during this study, which also may explain the reduced influence of water from the mined areas.

Stiff diagrams of the three water samples collected from the Upper Floridan aquifer show similar chemical patterns. However, water samples at the LW4P UFA well had slightly higher magnesium and bicarbonate concentrations than samples from the other Upper Floridan aquifer wells, indicative of the chemical influence of water from the intermediate aquifer system (fig. 47). Hydrologic data, aquifer tests, and geophysical logs indicate a strong connection between the intermediate aquifer system and the Upper Floridan aquifer in this area, and the chemical data validates the downward movement of this water. For the LW3P well site, waters from the intermediate aquifer system (LW3P IAS LA) and the Upper Floridan aquifer (LW3P UFA) show almost identical chemical signatures, indicative of a strong hydrologic connection between these sites. The relation between water levels in these two wells corroborates the strong hydrologic connection between aquifers (r^2= 1.00).

A Stiff diagram also was constructed from historical water-quality data collected at Kissengen Spring in 1959, and is considered to represent the groundwater flow patterns in the study area under discharging conditions. A water sample was collected when the spring flow was measured at 9 ft^3/s, just before the spring ceased to flow in 1960 (Stewart, 1961). The chemical signature of the spring water indicates a chemical pattern similar to that of the water collected from the wells tapping the Upper Floridan aquifer and the lower Arcadia aquifer (fig. 47).

The naturally occurring stable isotopes deuterium and oxygen-18 also were measured in water samples collected from the river and seven wells in the study area to help determine flow paths between the river and the underlying aquifers. Differences in the enrichment of the isotopes by evaporation can give an indication of the water pathway. For example, river water derived from surface inflows has more opportunity to evaporate than does groundwater; therefore, the river water will have a heavier signature (larger δ value) than groundwater. The samples were collected during March 23-26, 2007 when groundwater levels were declining and sink features were draining the river water to the underlying aquifers. During this sampling, upper Peace River flow ended at Dover Sink and the estimated discharge to the sink was about 2 ft^3/s.

There was little isotopic variability between samples from the LW3P UFA, Clear Springs IAS, and LW1P UFA wells (fig. 48A), which may indicate that recharge waters in these areas were from a similar source and that the underlying aquifers are affected by the same flow processes (fig. 48A). Although isotopic samples were not collected at a surface-water site near the LW1P well, the isotopic composition would probably be similar to that of samples from Dover Sink Distributary because of the close proximity of the well and distributary (3.0 mi) and the short amount of time required for a particle of water to travel (less than 1 day) from the well to the distributary.

The percentage of river water in groundwater was used to help determine flow paths to the underlying aquifers. The percentage of river water (x) in the groundwater near the river was calculated using $\delta^{18}O$ as the conservative tracer in the following equation:

$$x = (\delta_{gw} - \delta_{mw}) / (\delta_{rw} - \delta_{mw}), \qquad (2)$$

where δ is the oxygen-18 value for the groundwater sample (gw), meteoric water (mw), and river water (rw). The $\delta^{18}O$ for river water used in the calculations was from Dover Sink Distributary (Peace River), and is assumed to be representative of river water recharging the groundwater. The meteoric water end member is water uninfluenced by recharge from the river. Several meteoric end members were considered in the calculations: (1) volume-weighted mean $\delta^{18}O$ of rainwater at a site in Polk County (Sacks, 2002); (2) water from the intermediate aquifer system unaffected by river recharge (ROMP 45 Hawthorn; Sacks and Tihansky, 1996); and (3) water from the Upper Floridan aquifer unaffected by river recharge (ROMP 45 Suwannee; Sacks and Tihansky, 1996).

Results for the end member analysis using the rainwater and the intermediate aquifer system water were similar, showing little variability (average difference less than 1 percent). A separate meteoric water end member analysis was conducted for the Upper Floridan aquifer, because groundwater in this area was recharged thousands of years ago, under different climatic conditions, and can have naturally elevated $\delta^{18}O$ values (Plummer and Sprinkle, 2001). Therefore, the meteoric water end member for Upper Floridan aquifer samples influenced by Peace River recharge could be a mix of this older groundwater and recent recharge. However, because of the current recharge setting, the deeper groundwater was not considered to influence water from the intermediate aquifer system.

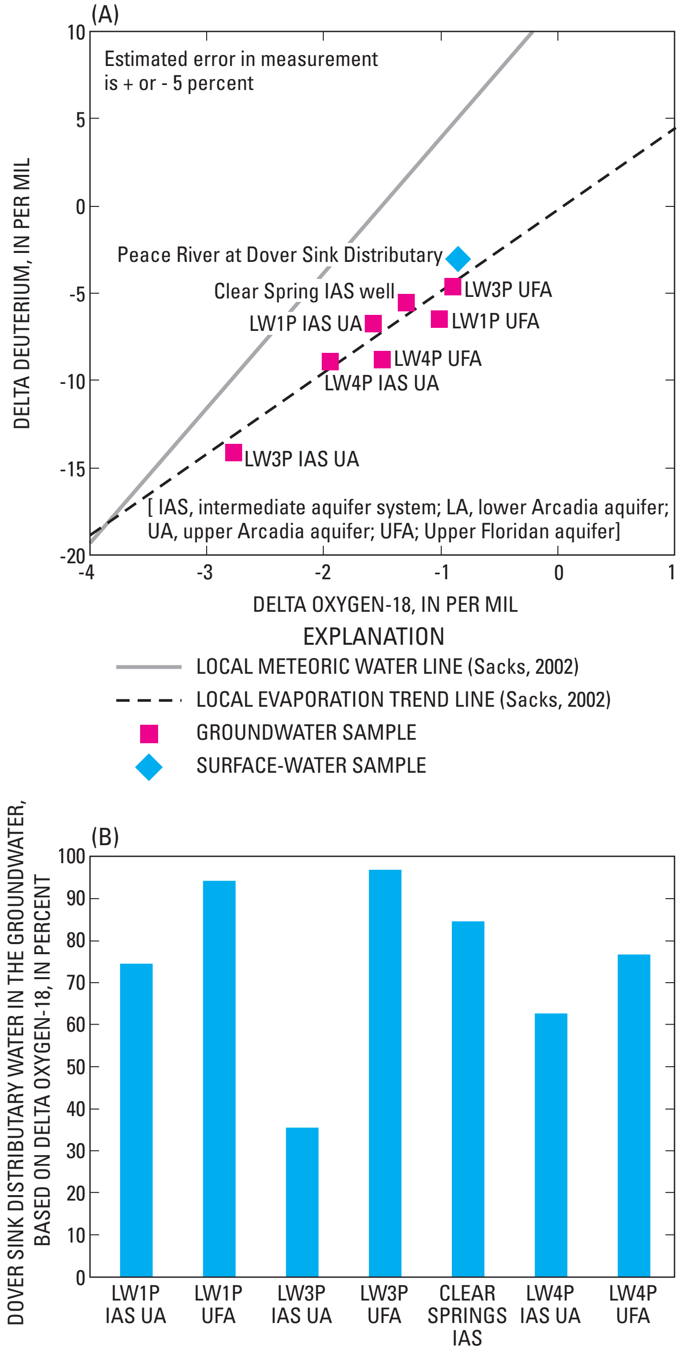


Figure 48. (A) Delta deuterium in relation to delta oxygen-18 in Peace River surface water and groundwater at selected well sites and (B) the percentage of river water in groundwater using delta oxygen-18 (location of sampling sites are shown in fig. 13B, and well depths and cased intervals are shown in table 5).

Results of this analysis indicate that the percentage of river water in the intermediate aquifer system ranged from 33 to 85 percent (fig. 48B). There was a high fraction of river water in the groundwater at the Clear Springs IAS well (85 percent) and LW1P IAS UA (74 percent), indicating a direct connection with the Peace River and the open interval of these wells. The lowest fraction (38 percent) of recharge water from the Dover Sink was LW3P IAS UA (upper Arcadia aquifer). This well is only completed to 37 ft and indicates that Dover Sink is not as well connected to a shallow part of the aquifer.

For Upper Floridan aquifer water, the percentage of river water ranged from 52 to 89 percent, using the old groundwater meteoric end member, and from 77 to 98 percent, using the recent rainwater meteoric end member. Regardless of the meteoric water end member, the river water is distinctly identifiable in the deeper aquifer. Samples from LW3P UFA and LW1P UFA contained the highest percentage of river water of all samples (98 to 94 percent, respectively; fig. 48B).

Influence of Large Karst Features on Flow Patterns and Streamflow Losses

An important characteristic of the geology underlying the upper Peace River is the capacity to store large volumes of water in the underground cavities within the floodplain and surrounding area. The geology of this area is highly karstified, as evidenced by numerous karst features and fractured carbonates and cavernous zones identified in geologic cores and aquifer tests. Geologic logs, aquifer and dye tests, and video logs indicate that there are several layers within the floodplain geology that are cavernous, highly transmissive, and have the ability to transport large volumes of water at a rapid rate. The following hydrograph analysis illustrates how karst features provide the hydrologic connection between the river and the underlying aquifers.

Water levels at two sinks (Gator Sink and Dover Sink; fig. 36), located in the floodplain of the highly karstic region of Reach 2, were monitored to determine how these features influence groundwater flow patterns. Dover Sink is the most influential karst feature within the upper Peace River karst area, and accounts for the most streamflow losses from the river. Gator Sink is less influential than Dover Sink in terms of streamflow losses, but accepts river flow during high stages. Gator Sink also receives groundwater flow from localized floodplain storage during low-flow conditions that travels through Ledges Sink and the Catacombs Complex.

A hydrograph of Clear Springs IAS well shows the simultaneous response of the intermediate aquifer system to recharge through Dover Sink (fig. 49A-B). This well is located 500 ft east of Dover Sink and is 143 ft deep, cased to 62 ft. Water levels in the sink and well are highly correlated ($r^2 = 0.94$, fig. 49A), indicating a good hydraulic connection between the two sites that is consistent with the fractured karst hydrology of the upper Peace River karst area. Prolonged dry periods deplete much of the water stored within the cavernous system that underlies the upper Peace River. Recharge waters rapidly fill the cavities through localized sinks when rainfall occurs.

Geophysical well logs and slug tests performed at the nearby LW3P IAS LA well indicate that the Clear Springs IAS well is open to geologic sections that are highly transmissive.

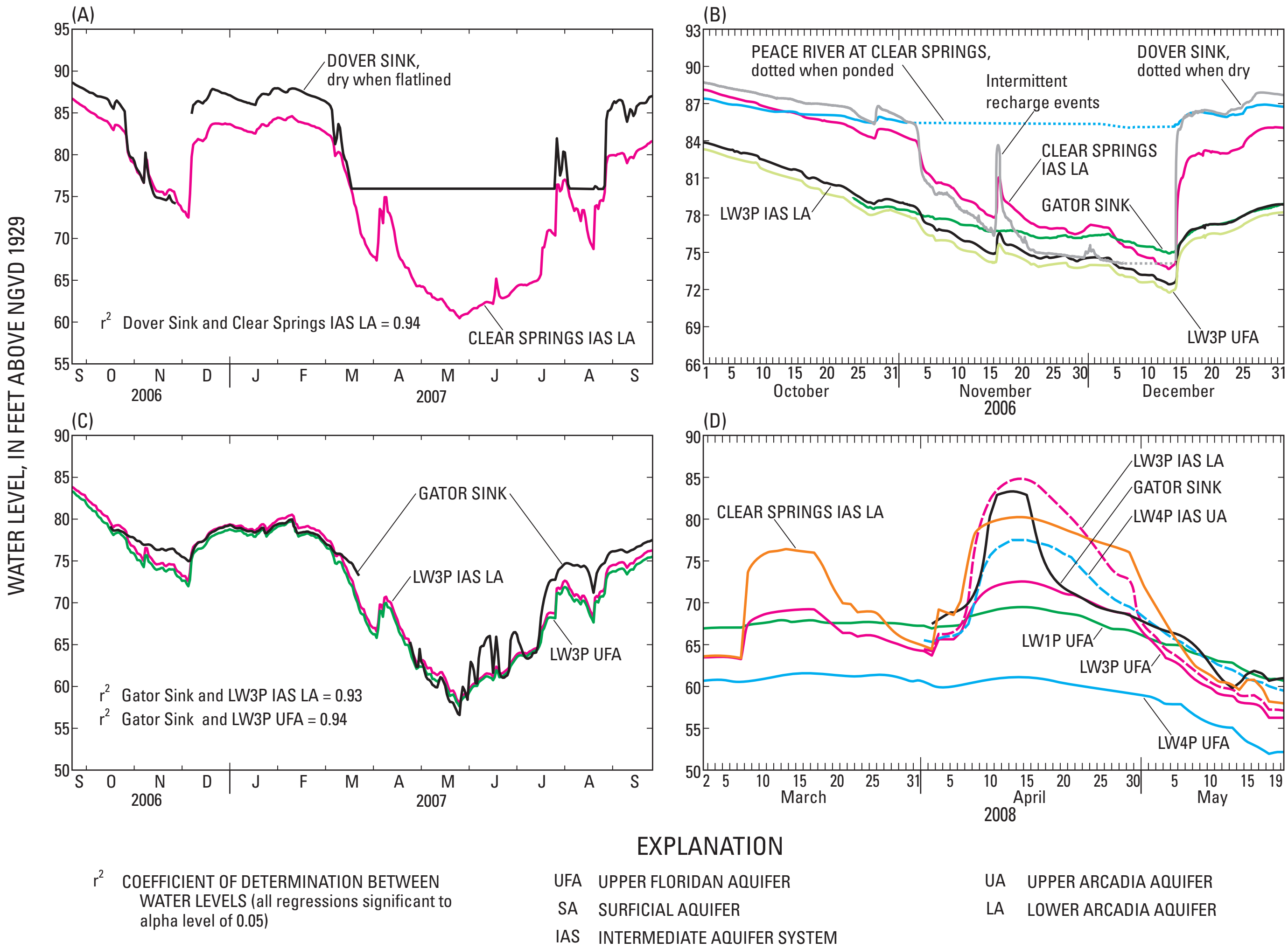


Figure 49. Comparison of water levels in wells and sinks within the upper Peace River karst area (location of wells and sinks are shown in fig. 13B and well depths and cased intervals are shown in table 5).

These sections are located in the intermediate aquifer system and are composed of fractured dolomite at depths of 30 to 60 ft and 90 to 100 ft below land surface. In addition to the fractured dolomite, large volumes of water have been observed to drain into Dover Sink, suggesting that a large cavernous conduit system exists. Based on measurements presented previously, the cavernous system associated with Dover Sink can store up to 10 Mgal/d under certain conditions.

The existence of a highly transmissive, cavernous conduit system was documented during a dye test conducted by McQuivey and others (1981). A dye tracer injected into Dover Sink was detected in a water sample collected from an Upper Floridan aquifer well located about 1 mi south of the injection site. The peak concentration of the dye arrived within 8 hours after injection, indicating a substantial hydraulic connection between Dover Sink and the Upper Floridan aquifer well. During this dye test, water moved at a rate of about 0.25 ft/s, which is similar to the velocity of a slow moving stream. Estimated velocities of regional groundwater flow in the Upper Floridan aquifer are substantially lower (2.0 x 10^{-7} ft/s; Plummer, 1977).

Part of the water captured by Dover Sink migrates to the LW3P well site located about 1,000 ft south of the sink. Hydrographs in figures 46B and 49B indicate that the recharge water from Dover Sink augments Upper Floridan aquifer water levels at the LW3P well site. The effects of recharge water can be observed when aquifer levels at the LW3P UFA well rise above those of the LW1P UFA well (fig. 46B). The LW1P well site is upgradient from the LW3P well site and, therefore, water levels are typically higher near the LW1P well site. When Dover Sink is dry, the water levels in the LW3P UFA well return to more typical gradient conditions where they are lower than those in the LW1P UFA well. Water-level fluctuations in the wells near Dover Sink demonstrate the rapid movement and extent of the recharge waters.

Hydrographs of Gator Sink, LW3P IAS LA, and LW3P UFA wells indicate a high degree of interconnection between the sink, the intermediate aquifer system, and the Upper Floridan aquifer (fig. 49C). For the May through July 2007 period, figure 49C indicates that water levels at Gator Sink were higher and fluctuated more than those of the underlying aquifers, with water levels in the sink fluctuating as much as 6 ft on an approximate weekly basis. During these water-level fluctuations, groundwater was observed seeping into the northwestern side of the sink through cracks and fissures. These unusual fluctuations were found to be related to streamflow losses that occurred at the upstream Ledges Sink and Catacombs Complex, as well as recharge water from a sprayfield located 0.5 mi west of Gator Sink. Both of these recharge sources eventually drain into Gator Sink. During low-flow conditions, Gator Sink is a low point in the surrounding floodplain that preferentially recharges the groundwater system.

Hydrographs from Gator Sink and a number of wells along the river illustrate a large pulse of water that was introduced into the groundwater system in response to a large rain event that occurred on April 1, 2008 during the dry season (fig. 49D). The elevation in the Peace River was high enough (greater than 88 ft above NGVD 1929) for river water to travel down Gator Sink Distributary and fill Gator Sink. The hydrographs in figure 49D show the large rise in the water levels of Gator Sink, with this water eventually draining into the underlying aquifers. Data from the nearby LW3P IAS LA well indicate that water levels in the lower Arcadia aquifer rose about 20 ft during this event (fig. 49D). The hydrographs also illustrate that, although the storage capacity of the underground cavities in the intermediate aquifer system was temporarily met, the water stored in these cavities continued to drain downward into the underlying Upper Floridan aquifer because of the large water-level difference between these two aquifers that created the potential for downward flow.

Summary and Conclusions

The upper Peace River from Bartow to Fort Meade, Florida, is described as a groundwater recharge area, reflecting a reversal from historical groundwater discharge patterns that existed prior to the 1950s. Historically, the area along the river contained artesian wells and a second magnitude spring (Kissengen Spring) that discharged an average of 20 Mgal/d (31 ft^3/s) into the Peace River. However, groundwater levels began to decline as early as the 1930s with an increase in groundwater use for mining and agricultural purposes. Due to this increased water use, a 40-ft decline in groundwater levels over a 20-year period has resulted in the cessation of flow of the artesian wells and Kissengen Spring, and flow now moves downward from the surface into the underlying aquifers.

Over time, declines in streamflow have been influenced by a number of factors, and these losses have been attributed to the following: (1) rainfall deficits; (2) large groundwater withdrawals that have lowered the potentiometric surfaces of the intermediate aquifer system and Upper Floridan aquifer beneath the riverbed; (3) changes in the natural drainage patterns of contributing streams to the Peace River; (4) altered surface sediments that affect surface runoff, infiltration, and baseflow characteristics of the basin; and (5) numerous karst features found in the low-water channel and floodplain that have enhanced the loss of streamflow. A trend analysis of long-term streamflow data from the USGS Bartow gaging station shows a significant decline in streamflow during the 1940s, 1950s, and 1960s; during the 1970s, streamflow remained statistically unchanged. Another trend analysis conducted using 1970s to 2003 data indicates a continued decline in streamflow during this period.

The upper Peace River is located in a basin that has been substantially altered by phosphate mining. Phosphate-mined land makes up the largest land-use category in the upper Peace River basin. Previously mined areas contain a large amount of clay-waste byproduct, which typically occupies about 40 to 60 percent of the postmined landscape. Because of the low hydraulic conductivity of clay, groundwater recharge and movement through a clay-settling area, or other altered landscape associated with mining, is substantially less than it was during predevelopment conditions.

The amount of flow derived from contributing tributaries has declined in the upper Peace River, because much of the natural drainage system of these tributaries has been altered by phosphate mining or agricultural activities. One of the largest tributaries is the Peace Creek Drainage Canal, which has been greatly altered by mining, and urban and agricultural development. Other tributaries such as Saddle Creek, Six-Mile Creek, Cedar, Bear, Hamilton, and Barber Branches, and Phosphate Mine Outfall CS-8 have all been altered as a result of phosphate mining. The meandering reaches and sloping gradients were replaced by flat ditches and clay-settling ponds that could store large quantities of water. Therefore, a component of the inflow to the upper Peace River has been lost because of altered drainage patterns, impoundment of water into clay-settling areas, and losses from these ponds due to evaporation.

The groundwater and surface-water interactions along the upper Peace River have been substantially altered because of groundwater use. Groundwater use has created a long-term decline in the potentiometric surface of the Upper Floridan aquifer that has affected interactions between the Peace River and the underlying groundwater system. When the potentiometric-surface levels of the underlying aquifers are lower than the elevation of the Peace River channel bed and floodplain, the potential for downward flow or recharge is initiated, which causes streamflow declines. When groundwater use for mining processes was at its greatest during May 1975, the potentiometric surface of the Upper Floridan aquifer was as much as 50 ft below the elevation of the riverbed along the upper Peace River.

As mining extraction processes have changed and mine operations have moved to areas south and west of the upper Peace River basin, groundwater use for mining has declined. The May 2007 potentiometric-surface map of the Upper Floridan aquifer indicates a rise in aquifer water levels from the 1975 levels, but levels remain as much as 30 ft below the Peace River floodplain elevation. Although groundwater levels have increased since the days of intense mining operations, the levels have not fully recovered, because there has been a redistribution of some of the pumping stresses due to population growth and agricultural expansion in the Southern West-Central Florida Groundwater Basin.

The upper Peace River is in a region where the river and floodplain are characterized by extensive karst development with numerous fractures, crevasses, and sinks that have been eroded in the limestone bedrock. With the reversal in groundwater head gradients, river water drainage into the underlying groundwater system through these karst features constitutes much of the streamflow loss in this region. Seepage runs were conducted along a 13-mi segment of the Peace River, from Bartow to Fort Meade, to define where the greatest streamflow losses occurred. Based on these seepage runs, the greatest streamflow losses occurred along an approximate 2-mi section of the river, located about 1 mi south of the Peace River at Bartow gaging station. About 10 karst features were responsible for the greatest streamflow losses along these reaches. Losses from individual karst features ranged from 0.22 to 16 ft^3/s based on measurements made between 2002 and 2007.

Along the upper part of this 2-mi section (in Reach 1), the largest and most consistent streamflow losses occurred at the Ledges Sink, with measured losses ranging from 1 to 8 ft^3/s. Located at the end of this 2-mi section (in Reach 2) is Dover Sink, which was the most influential karst feature along the upper Peace River and had measured losses ranging from 2 to 16 ft^3/s. The largest measured streamflow loss for all the karst features in Reaches 1 and 2 was about 50 ft^3/s (32 Mgal/d) on June 28, 2002.

During this study (2002-2007 water years), streamflow was influenced by climatic conditions. The discharge in the river was greatest for the 2005 water year as a result of above-average rainfall that occurred over a 3-year period (2003-2005). Average annual discharge for the 2005 water year at the Peace River at Bartow gaging station was 545 ft^3/s, more than double the long-term average of 227 ft^3/s for the 68 years of record. The discharge in the river was lowest during the 2007 water year when the cumulative rainfall deficit was almost 29 in. over a 2-year period. Average annual discharge for the 2007 water year was only 18 ft^3/s, and was the lowest on record for Peace River at Bartow.

Streamflow losses were related to the decline in the potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer below the riverbed elevation during below-average conditions along the upper Peace River. When groundwater levels were at their lowest level at the end of the dry season (May and June), there was an increased potential for streamflow losses. During this study, the largest streamflow losses occurred at the beginning of the summer rainy season when discharge in the river increased and large volumes of water were needed to replenish large unfilled cavities and void spaces in the underlying aquifers.

The response of the river to changing groundwater levels was different in Reach 1 than in Reach 2. In Reach 1, the intermediate aquifer system is hydraulically connected to the river, and streamflow losses during below-average conditions were proportional to water-level changes in this aquifer. During the dry season in Reach 1, there was an increased potential for streamflow losses as aquifer levels declined, and as aquifer levels increased during the rainy season, streamflow gains were noted in Reach 1. In Reach 2, the upper Peace River is connected to both the intermediate aquifer system and the Upper Floridan aquifer through a large conduit system that is associated with Dover Sink. Because this conduit system is very large, it can accommodate a large proportion of flow from the river at multiple river stages.

The underlying geology along the upper Peace River and floodplain is highly karstified and aids in the movement and amount of streamflow that is lost to the groundwater system in this region. Numerous karst features and fractured carbonates and cavernous zones observed in geologic cores and geophysical logs indicate an active, well-connected, groundwater flow system. Aquifer and dye tests conducted along the upper Peace River indicate the presence of cavernous and highly transmissive layers within the floodplain area that can store and transport large volumes of water in underground cavities. A discharge measurement made during this study indicates that the cavernous system associated with Dover Sink can accept more than 10 Mgal/d (16 ft^3/s) of streamflow before the localized aquifer storage volume is replenished and the level of the sink stabilizes. Dover Sink stabilized when the pool of the sink rose to the level of the Peace River, which was about 87 ft above NGVD 1929, and water levels of the interconnected aquifers were about 78 ft above NGVD 1929.

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