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Scientific Investigations Report 2010-5189

U.S. Department of the Interior
U.S. Geological Survey

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KEN SALAZAR, Secretary

U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2010

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
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)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Seepage	
cubic foot per second per mile [(ft^3/s)/mi]	0.0176	cubic meter per second per kilometer [(m^3/s)/km]
	Leakance	
foot per day per foot [(ft/d)/ft]	1	meter per day per meter
	Storage	
cubic foot per square mile (ft^3/mi^2)	0.01095	Cubic meter per square kilometer (m^3/ km^2)

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

°F=(1.8×°C)+32

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

DEM	Digital elevation model
in/wk	inches per week
LIDAR	Light detection and ranging
NED	National Elevation Dataset
ROMP	Regional Observation and Monitor-well Program
SWFWMD	Southwest Florida Water Management District
USGS	U.S. Geological Survey
NEXRAD	Next-Generation Radar (WSR-88D Weather Radar)
NOAA	National Oceanographic and Atmospheric Administration

Acknowledgments

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Effect of Groundwater Levels and Headwater Wetlands on Streamflow in the Charlie Creek Basin, Peace River Watershed, West-Central Florida

By T.M. Lee, L.A. Sacks, and J.D. Hughes

Abstract

The Charlie Creek basin was studied from April 2004 to December 2005 to better understand how groundwater levels in the underlying aquifers and storage and overflow of water from headwater wetlands preserve the streamflows exiting this least-developed tributary basin of the Peace River watershed. The hydrogeologic framework, physical characteristics, and streamflow were described and quantified for five subbasins of the 330-square mile Charlie Creek basin, allowing the contribution of its headwaters area and tributary subbasins to be separately quantified. A MIKE SHE model simulation of the integrated surface-water and groundwater flow processes in the basin was used to simulate daily streamflow observed over 21 months in 2004 and 2005 at five streamflow stations, and to quantify the monthly and annual water budgets for the five subbasins including the changing amount of water stored in wetlands. Groundwater heads were mapped in Zone 2 of the intermediate aquifer system and in the Upper Floridan aquifer, and were used to interpret the location of artesian head conditions in the Charlie Creek basin and its relation to streamflow. Artesian conditions in the intermediate aquifer system induce upward groundwater flow into the surficial aquifer and help sustain base flow which supplies about two-thirds of the streamflow from the Charlie Creek basin. Seepage measurements confirmed seepage inflow to Charlie Creek during the study period.

The upper half of the basin, comprised largely of the Upper Charlie Creek subbasin, has lower runoff potential than the lower basin, more storage of runoff in wetlands, and periodically generates no streamflow. Artesian head conditions in the intermediate aquifer system were widespread in the upper half of the Charlie Creek basin, preventing downward leakage from expansive areas of wetlands and enabling them to act as headwaters to Charlie Creek once their storage requirements were met. Currently, the dynamic balance between wetland storage, rainfall-runoff processes, and groundwater-level differences in the upper basin allow it to generate approximately half of the streamflow from the Charlie Creek basin. Therefore, future development in the upper basin that would alter the hydraulic connectivity of wetlands during high flow conditions or expand recharging groundwater conditions could substantially affect streamflow in Charlie Creek. LIDAR (Light detection and ranging) based topographic maps and integrated modeling results were used to quantify the water stored in wetlands and other topographic depressions, and to describe the network of shallow stream channels connecting wetlands to Charlie Creek and its tributaries over distances of several thousand feet. Peak flows at all but one streamflow station were underpredicted in MIKE SHE simulations, possibly because the hydraulics of surface channels connecting wetlands to stream channels were not explicitly simulated in the model. Explicitly simulating the smaller channels connecting wetlands and stream channels should improve the ability of future watershed models to simulate peak flows in streams with headwater wetlands.

The runoff potential was greater in the lower half of the Charlie Creek basin than in the upper half, and the streambed of Charlie Creek had greater potential to both directly gain streamflow from groundwater and lose streamflow to groundwater. Charlie Creek is more incised into the surficial aquifer in the lower basin than in the upper basin, and the streambed intersects the top of the intermediate aquifer system at two known locations. Groundwater levels in the intermediate aquifer system varied widely in the lower half of the basin from artesian conditions inducing upward flow toward the surficial aquifer and streams, to recharging conditions allowing downward flow and stream leakage. Recharge areas were greatest in May 2004 when rainfall was at a seasonal low and irrigation pumping was at a seasonal high. Recharge conditions in May 2004 extended to beneath the streambed and included areas where fractured carbonate rocks at the top of the intermediate aquifer system crop out in the streambed, increasing the possibility for flow between the stream and aquifer. Groundwater withdrawals from wells open to the intermediate aquifer system exclusively, or to both the Upper Floridan aquifer and intermediate aquifer system, increased the occurrence of recharging conditions in Lower Charlie Creek subbasin as well as in Buckhorn Creek subbasin.

Agricultural irrigation water returning to the stream as runoff or base flow sustained flow in the Oak Creek tributary during a dry season when flow ceased in the two other main tributaries to Charlie Creek. With the exception of Little Charley Bowlegs Creek, dissolved minerals in agricultural return water increased the specific conductance of water in streams monitored in the Charlie Creek basin, particularly Oak and Buckhorn Creeks.

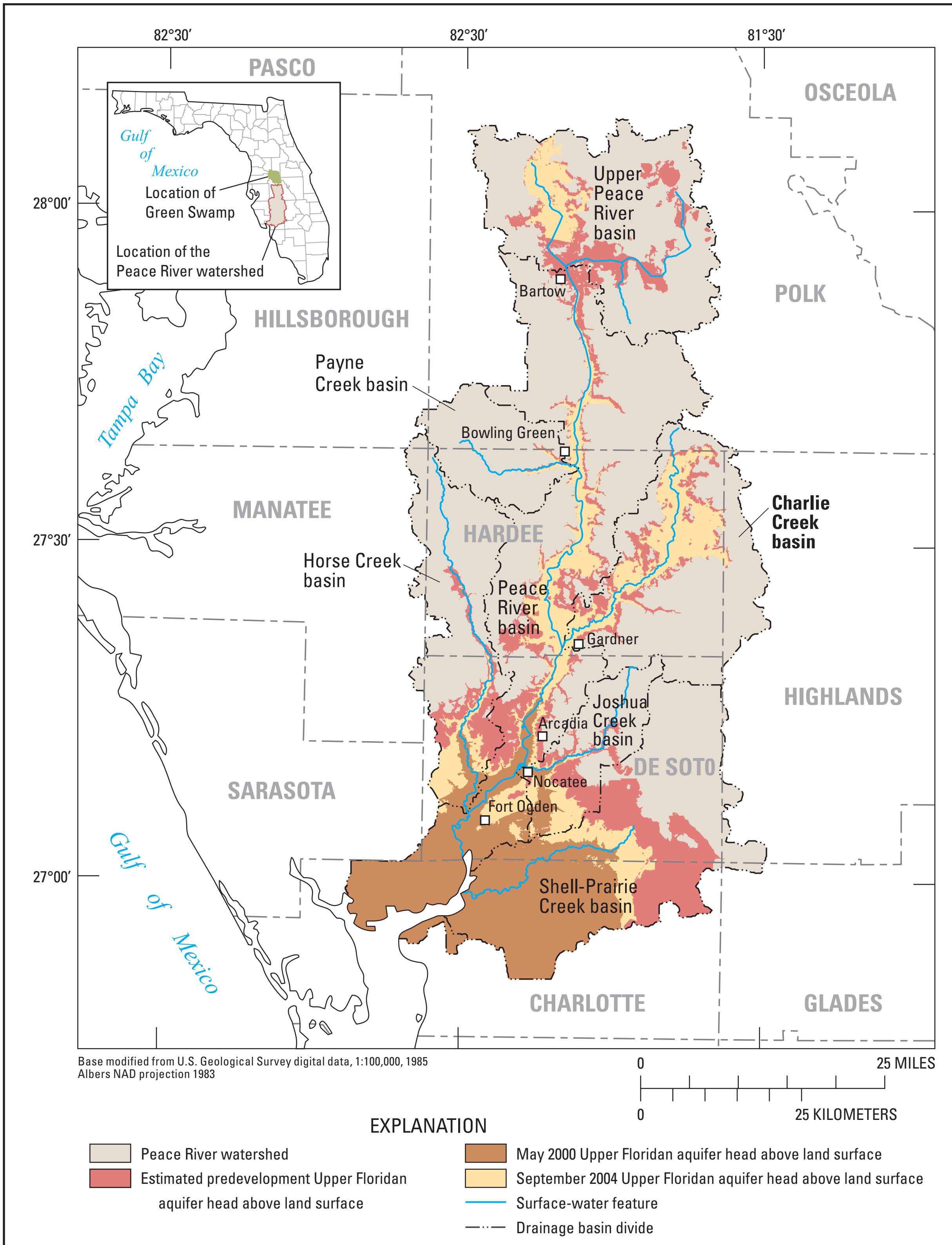

Figure 1. The Peace River watershed and its principal basins in west-central Florida. Map shows areas of artesian groundwater flow for estimated predevelopment groundwater levels in the Upper Floridan aquifer, and for recorded periods with very low (May 2000) and very high (Sept. 2004) groundwater levels in the Upper Floridan aquifer.

Introduction

Understanding the hydrology of tributary streams in central Florida is challenging because it requires quantifying the effects of two complex watershed processes on streamflow: the storage and overflow of water from headwater wetlands, and the interaction between groundwater and streams. Consequently, it remains difficult to predict streamflow losses that will occur when (1) an undeveloped landscape is altered by surface mining or other land-use changes that eliminate wetlands or alter their previous drainage patterns, or (2) groundwater levels are lowered substantially by pumping. It also remains difficult to determine how those losses will affect dry-season base flows and wet-season peak flows. In the mantled karst terrain of central Florida, peak streamflows generated by the runoff from tropical storms and hurricanes often include runoff routed through wetlands. These wet-season peak flows can be followed during drier months by base flows sustained solely by groundwater inflow (seepage). The first-order streams present in the headwaters of basins, where incipient streamflow begins, are particularly susceptible to dry climatic conditions and may intermittently dry out. In contrast, the successively higher-order streams (second, third, and so forth), created by the confluence of lower-order streams, rarely go dry. Seasonally-flooded depressional wetlands are a characteristic landscape feature in central Florida, and the overflow from wetlands generates streamflow in first-order streams. Depressional wetlands in the expansive, wetland-rich “Green Swamp” region of central Florida form the headwaters of four major rivers, including the Peace River—the largest river in west-central Florida in both magnitude of discharge and basin area (Fernald and Purdum, 1998). Like a fractal pattern that remains evident when viewing a whole image at a variety of scales, smaller networks of depressional wetlands form the headwaters of smaller tributaries in the Peace River watershed, including those in the Charlie Creek basin (fig. 1).

Tributary flows typically receive increased attention by water managers and the public when flows decline in the major rivers they drain into. For this reason, the hydrologic character of tributary streams is of particular interest in the Peace River watershed (Florida Department of Environmental Protection, 2007). Streamflow along upper reaches of the Peace River has declined over the past several decades, concurrent with declining outflow from its headwaters in the Upper Peace River basin— the largest in area of the Peace River’s six main tributary basins (fig. 1) (Florida Department of Environmental Protection, 2007; Metz and Lewelling, 2009).

Factors affecting tributary streamflow in the Peace River basin need to be characterized in order for Federal, State, and local agencies to effectively manage and preserve the hydrologic conditions and landscape features necessary to maintain streamflow. Surface strip-mining for phosphate has altered the topography and eliminated numerous wetlands and first-order streams in the Payne Creek basin and in the Upper Peace River basin (fig. 1) (Florida Department of Environmental Protection, 2007). Groundwater levels in underlying aquifers have been lowered by pumping, which has led to substantial streamflow losses, particularly in the Upper Peace River basin where karst features (sinkholes) are present along the stream channel (Metz and Lewelling, 2009). Farther downstream in the Peace River watershed, the groundwater used to irrigate extensive areas of citrus and agricultural crops has increased flows in the tributaries of Joshua Creek, Horse Creek, and Shell-Prairie Creeks (fig. 1 and table 1). By comparison, the landscape and streamflows in the Charlie Creek basin have remained relatively unaltered. Assuming that hydrologic processes were comparable in all basins prior to development, the hydrologic processes still occurring in the Charlie Creek basin provide a useful tool for understanding those processes altered or lost in other basins of the Peace River watershed.

Of the six main tributary basins in the Peace River watershed, the Charlie Creek basin has the greatest streamflow, and its historical basin and streamflow characteristics are the least altered. The Charlie Creek and Horse Creek basins have the lowest percentages of native land converted to phosphate mining, urbanization, or intensive agriculture since the 1940s (Florida Department of Environmental Protection, 2007). The Charlie Creek basin has the smallest loss of natural stream channels due to these conversions (table 1). The Charlie Creek basin is predominantly a landscape of pasture, open lands, forested wetlands, and citrus groves, although the relative proportion of these land uses and other physical features vary in different areas of the basin. Although streamflow leaving the Charlie Creek basin has been measured since 1951, little is known about which areas of the basin generate most of this flow, as well as the relation between wetlands, karst hydrogeology, and streamflow generation in Charlie Creek. For example, it is unclear what percentage of total streamflow originates in the headwater wetlands, what percentage is generated as runoff from areas bordering the main channel of the stream, and how the efficiency of streamflow generation differs between these regions. Artesian groundwater flow conditions existed in all basins of the Peace River watershed prior to development (Bush and Johnston, 1988) and may be better preserved in the contemporary Charlie Creek basin than in other basins in the Peace River watershed (fig. 1). However, the importance of hydrogeologic conditions, and particularly the prevalence of artesian head conditions, in maintaining streamflows in different areas of the Charlie Creek basin also is unclear.

To gain a better understanding of the natural hydrologic conditions affecting streamflow generation from a tributary basin in southwest Florida, the U.S. Geological Survey (USGS), in cooperation with the Southwest Florida Water Management District (SWFWMD), began a study in 2003 to characterize the hydrology of the Charlie Creek basin. Knowledge gained from the study will aid the establishment of State-mandated minimum surface-water flows and groundwater levels for Charlie Creek and neighboring basins, and contribute to our understanding of how surface mining and other land-use alterations can affect streamflow in similar watersheds.

Table 1. Physical characteristics of the principal tributary basins of the Peace River watershed in west-central Florida.

[All data from Florida Department of Environmental Protection (2007). %, percent; ft^3/s, cubic foot per second; in., inch; in/yr, inch per year; Mgal/d, million gallons per day; mi, mile; <, less than; Q_{10}, flowrate exceeded by 10 percent of the daily flow values; Q_{50}, flowrate exceeded by 50 percent of the daily flow values; Q_{90}, flowrate exceeded by 90 percent of the daily flow values]

Tributary basin name	USGS streamflow monitoring station name	USGS station identifier	USGS Gaged basin area, mi^2	USGS Average daily streamflow (1980-2005), ft^3/s	USGS Annual average runoff (1980- 2005), in.	Trend in base flow Kendall Tau (at Q_{10}, Q_{50}, Q_{90})	Mined land use, %	Citrus and intense agriculture, %	Improved pasture open land, %	Wetlands and forested uplands, %	Estimated loss of stream channel (1940-1999), %	Estimated groundwater pumping (1997-1999), Mgal/d (in/yr)
Peace River Headwaters	Peace River at Bartow, FL	02294650	390	195.4	6.8	Declining	9	14	15	23	60	151 (8.1)
Payne Creek	Payne Creek near Bowling Green, FL	02295420	121	124.1	13.9	Increasing[1]	63	10	8	16	52	24 (4.1)
Charlie Creek	Charlie Creek near Gardner, FL	02296500	330	254.8	10.5	No trend	<1	19	45	36	5	62 (3.9)
Joshua Creek	Joshua Creek at Nocatee, FL	02297100	132	117.6	12.1	Increasing Q_{50} and Q_{90}	<1	31	41	24	24	36 (5.7)
Horse Creek	Horse Creek near Arcadia, FL	02297310	218	203.5	12.7	Increasing	6	10	37	46	18	37 (3.6)
Shell-Prairie Creek	Prairie Creek near Fort Ogden, FL	02298123	233	227.1	13.2	Increasing	<1	31	25	42	20	55 (4.9)

[1] No trend statistics. Graphical evidence only due to gap in record.

Purpose and Scope

The purpose of this report is to characterize how streamflow in the Charlie Creek basin is affected by hydrologic processes, primarily (1) seasonal-flooding of headwater wetlands, and (2) groundwater interactions with Charlie Creek, its tributaries, and headwater wetlands. Field data were collected in the Charlie Creek basin from April 2004 through January 2006 and include streamflow, groundwater elevation, and rainfall. Daily streamflow was monitored during 2004-2005 at five streamflow gaging stations in the basin—two along the main stem of Charlie Creek and three along its main tributaries. The flows within these subdivided areas of the basin were related to the physical characteristics such as vegetation and topography, as well as the hydrogeologic framework and stream/groundwater interactions in the subbasin.

This report consists of two parts; the first describes the hydrogeologic framework of the overall basin and the various subbasins in detail, including hydrostratigraphy, groundwater flow patterns, and groundwater/stream interactions. The second part presents results of the numerical model used to simulate the coupled surface and groundwater flows in the subbasins using the hydrogeologic framework, climate data, and physical data (soils, topography, land use and cover, groundwater use) as input. Daily streamflow was simulated at the five stream gaging locations and calibrated to the observed flows. Modeling results also generated water budgets for the entire basin and individual subbasins. Differences in water-budget components between subbasins were related to the hydrogeological and physical differences between the subbasins.

Description of Study Area

The 330-mi^2 Charlie Creek basin occupies the eastern third of Hardee County, overlapping into southern Polk, western Highlands, and northern DeSoto Counties (fig. 1). It drains the east-central portion of the Peace River watershed. The Charlie Creek basin is in the mid-peninsular physiographic zone of White (1970), and it includes parts of three subdivisions: the Polk Upland, the De Soto Plain, and the Lake Wales Ridge. The majority of the basin lies within the De Soto Plain—a relict submarine shoal or plateau that is flat except in areas eroded by stream channels (White, 1970). The northern drainage divide is in the adjacent Polk Upland and the eastern drainage divide is along the Lake Wales Ridge where the elevation of land surface can exceed 180 ft above NGVD 1929. The lowest areas are along the stream channels and in wetland depressions, with elevations as low as 20 to 30 ft above NGVD 1929 in the stream channel at the most downstream end of the Charlie Creek basin (fig. 2). Away from the ridges and stream channels, much of the Charlie Creek basin ranges in land-surface elevation from 85 to 95 ft above NGVD 1929.

Three principal hydrogeologic units are present in the Charlie Creek basin. From shallowest to deepest they are the surficial aquifer, the intermediate aquifer system, and the

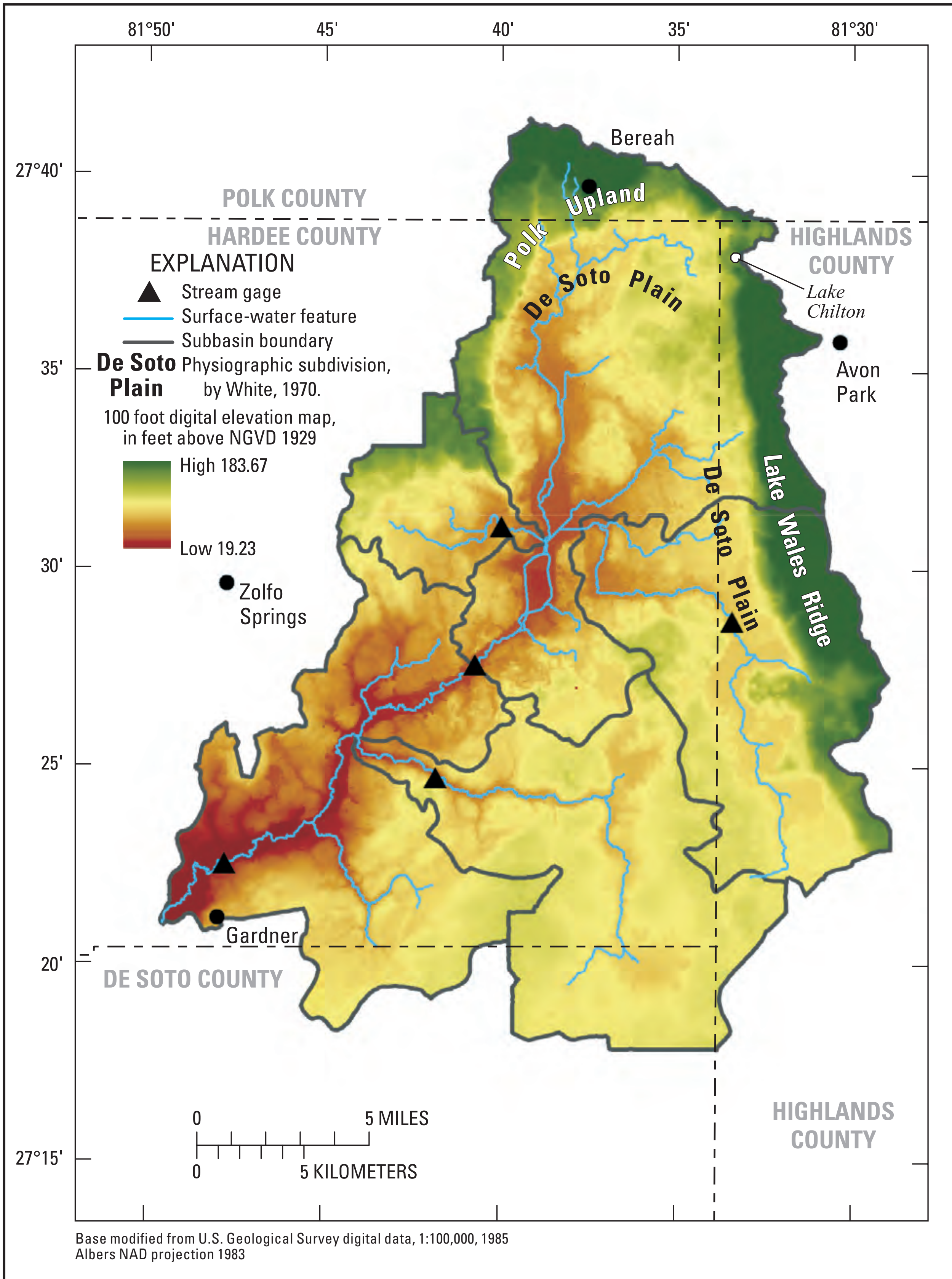

Figure 2. Land surface elevations in the Charlie Creek basin.

Pine flatwoods have been cleared and maintained as rangeland, pasture, and open land used for grazing cattle. (Photograph by T.M. Lee, USGS.)

Upper Floridan aquifer. The stream channel of Charlie Creek predominantly lies in the sandy deposits of the surficial aquifer, but in some areas may erode into the clay- and carbonate-rich layers at the top of the intermediate aquifer system. Only groundwater in the surficial aquifer and intermediate aquifer system has the potential to interact with Charlie Creek and its tributaries. The deeper Upper Floridan aquifer is the principal source of irrigation water and potable water in the basin. Although groundwater in the Upper Floridan aquifer does not interact directly with Charlie Creek, hydraulic heads in this aquifer affect Charlie Creek indirectly by governing the direction and magnitude of vertical flow occurring in the surficial aquifer and intermediate aquifer system.

The climate in the study area has distinct wet and dry seasons, with heavy rains from local convective and tropical storms during summer through early autumn, and a drier season from late fall through late spring with rainfall from frontal systems associated with continental air masses (Chen and Gerber, 1990). The average annual rainfall in the study area is 49.09 in., based on long-term (1949-2005) data from the Avon Park, Florida climate station (National Oceanographic and Atmospheric Administration, 2005). Monthly rainfall in the Charlie Creek basin was below average between January and June of 2004 (fig. 3A). Three named hurricanes raised the monthly total rainfall in August and September of 2004, and the 2004 annual total, above long-term averages. Hurricane Charley made landfall on August 13, 2004, followed by Hurricanes Frances and Jeanne on September 5 and 26, 2004, respectively (National Oceanographic and Atmospheric Administration, 2008) (fig. 3B). Monthly rainfall in the basin during 2005 was mostly at or above average. June was the wettest month in 2005 due to unnamed tropical storms that deposited 15.98 in. of rainfall, 7.73 in. greater than average. Hurricane Wilma made landfall in southern Florida on October 24, 2005 and outer bands of rain affected the Charlie Creek basin.

The Charlie Creek basin was subdivided into five smaller subbasins for this study, and streamflows exiting these subbasins were monitored for approximately 21 months (U.S. Geological Survey, 2007). The five subbasins include the subbasins of three tributary streams: Buckhorn Creek, Little Charley Bowlegs Creek, and Oak Creek (fig. 4). In addition, two more subbasins encompass the main Charlie Creek channel: Upper Charlie Creek subbasin and the Lower Charlie Creek subbasin. The northern half of the Charlie Creek basin is comprised of the three northernmost subbasins: Upper Charlie Creek, Buckhorn Creek, and Little Charley Bowlegs Creek. The collective outflow from these basins is measured at the USGS streamflow station Charlie Creek near Crewsville (fig. 4). The collective surface-water outflow of all five subbasins is measured at the Charlie Creek near Gardner streamflow station, in the Lower Charlie Creek subbasin (fig. 4). Streamflow generated by the two subbasins constituting the lower half of the Charlie Creek basin, Lower Charlie Creek and Oak Creek, was determined by subtracting flow at the Charlie Creek near Crewsville station from flow at the Charlie Creek near Gardner station. The northern or upper half of the basin makes up 57 percent of the gaged area of the Charlie Creek basin. The area below the Charlie Creek near Crewsville station composes the remaining 43 percent. About 2 percent of the Charlie Creek basin is located downstream from the Charlie Creek near Gardner station and is ungaged (fig. 4). The physical characteristics of the five component subbasins, and the upper and lower halves of the basin, are summarized in table 2.

Historically, the landscape in Charlie Creek basin was extensive pine flatwoods. This terrain was lowered by erosion and karst subsidence into areas occupied by stream channels and depressional wetlands. Forests adapted to withstand inundation occupy lower, flood-prone areas of the Charlie Creek basin (Abrahamson and Hartnett, 1990; Ewel, 1990). Much of the pine flatwoods have been cleared and maintained as rangeland, pasture, and open land used for grazing cattle (fig. 5).

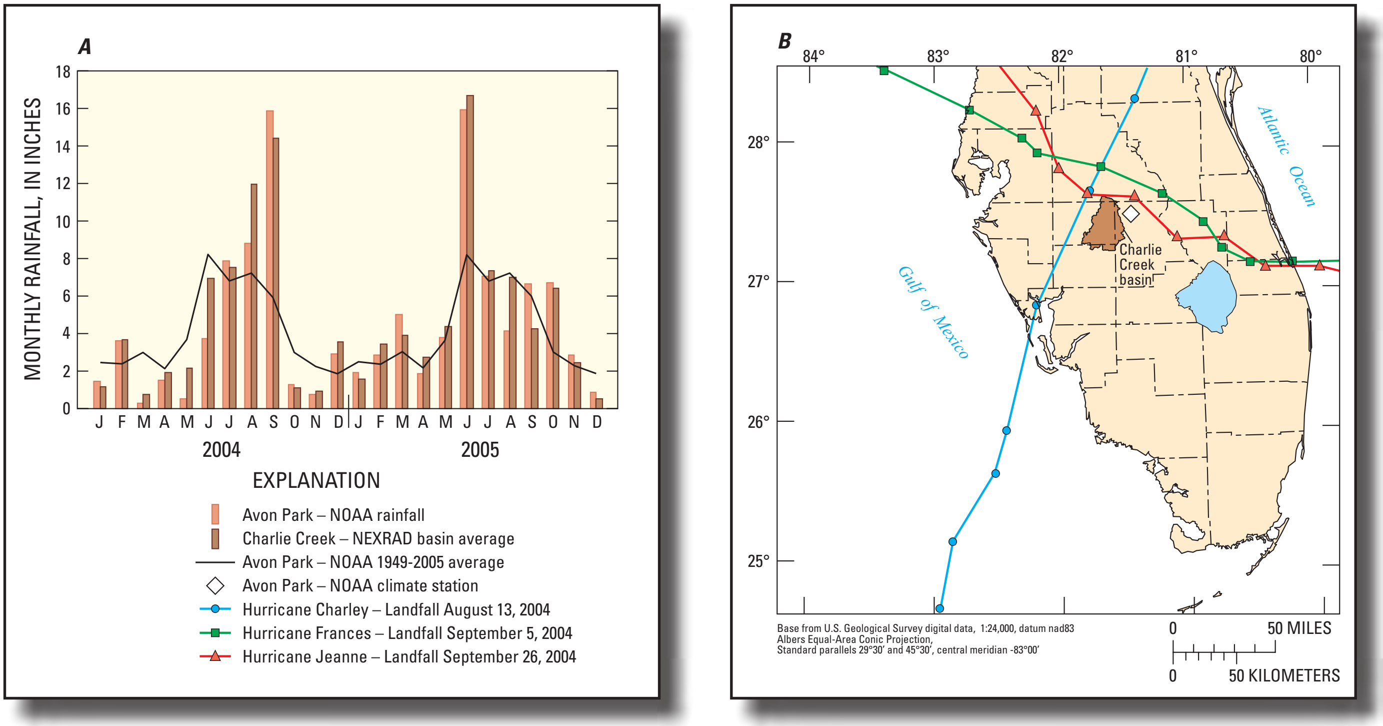

Figure 3. *A*, NEXRAD basin-wide average monthly rainfall totals during 2004-2005, and the long-term rainfall average at the NOAA Climate Station in Avon Park, Florida, and *B*, paths of hurricanes Charley, Frances, and Jeanne during 2004. NEXRAD is (Next Generation Radar); NOAA is National Oceanic and Atmospheric Administration.

An exception is the preserved upland forests within Highlands Hammock State Park in the Little Charley Bowlegs subbasin. Based on 2005 land use data, 46 percent of the Charlie Creek basin is pasture, open lands, and rangeland, and probably is not irrigated (table 2). Together with citrus production and wetland areas, these three land use categories represent the largest percentage of the land use in the basin. Irrigated citrus crops account for about 16 percent of the land area of the basin on average, but range from less than 6 percent of the land area of the Little Charley Bowlegs subbasin to 27 percent of the Buckhorn Creek subbasin. Forested and non-forested (marsh) wetlands occupy the largest percentage of area in the Little Charley Bowlegs subbasin (27 percent), and the smallest percentage of the Buckhorn Creek subbasin (11 percent).

Streamflow generated by the Charlie Creek basin has remained relatively unchanged during the past half century with no statistically significant trend ($\alpha = 0.05$) from 1951 to 2008 in the annual median, minimum, maximum, and percentile flows at P90, P75, P25, and P10 (where P90 indicates a flow rate exceeded 90 percent of the time). This is consistent with results reported by Florida Department of Environmental Protection (2007). Streamflow has been monitored in Charlie Creek near its confluence with the Peace River since May 1950 at the USGS streamflow station at Charlie Creek near Gardner, Florida (U.S. Geological Survey, 2007).

Streamflow measured at the five streamflow stations in the basin varied with the size of the gaged subbasin area and other factors discussed herein (U.S. Geological Survey, 2007). The tributary subbasins of Oak Creek and Little Charley Bowlegs Creek are the most similar in size and are each almost four times larger than the Buckhorn Creek subbasin (table 2). Streamflow measured in Oak Creek was the greatest of the three tributary stations, perhaps because its gaged area was larger than that of Little Charley Bowlegs Creek subbasin. Buckhorn Creek had less flow than the other two tributaries, but peak flows were pronounced at Buckhorn Creek, approaching or exceeding the maximum flows observed for Little Charley Bowlegs Creek and Oak Creek (fig. 6A).

Occasionally, minimal or no streamflow exited the subbasins of the three tributary streams or the Upper Charlie Creek subbasin. Streamflow duration curves based on flows between April 2004 and December 2005 show that Buckhorn Creek and Charlie Creek near Crewsville flowed during about 90 percent of the study period (fig. 6B). Buckhorn Creek had the most days with no flow during the study (58), followed by 54 no-flow days at Charlie Creek near Crewsville. All no-flow periods occurred during the spring and early summer of 2004. Little Charley Bowlegs Creek had more flow during this period with only 24 no-flow days, indicating that for 30 days streamflow either went into storage or was otherwise lost before reaching the Charlie Creek near Crewsville station. In contrast, Oak Creek had continual flow during the study, but the flattened slope at the declining end of the duration curve and specific conductance results presented later in the report suggest that water from crop irrigation during the dry season augmented the smallest streamflows in this subbasin (fig. 6B). The streamflow duration curve for Charlie Creek near Gardner shows continual flow exiting the basin from October 2002 through December 2005, including the model simulation period.

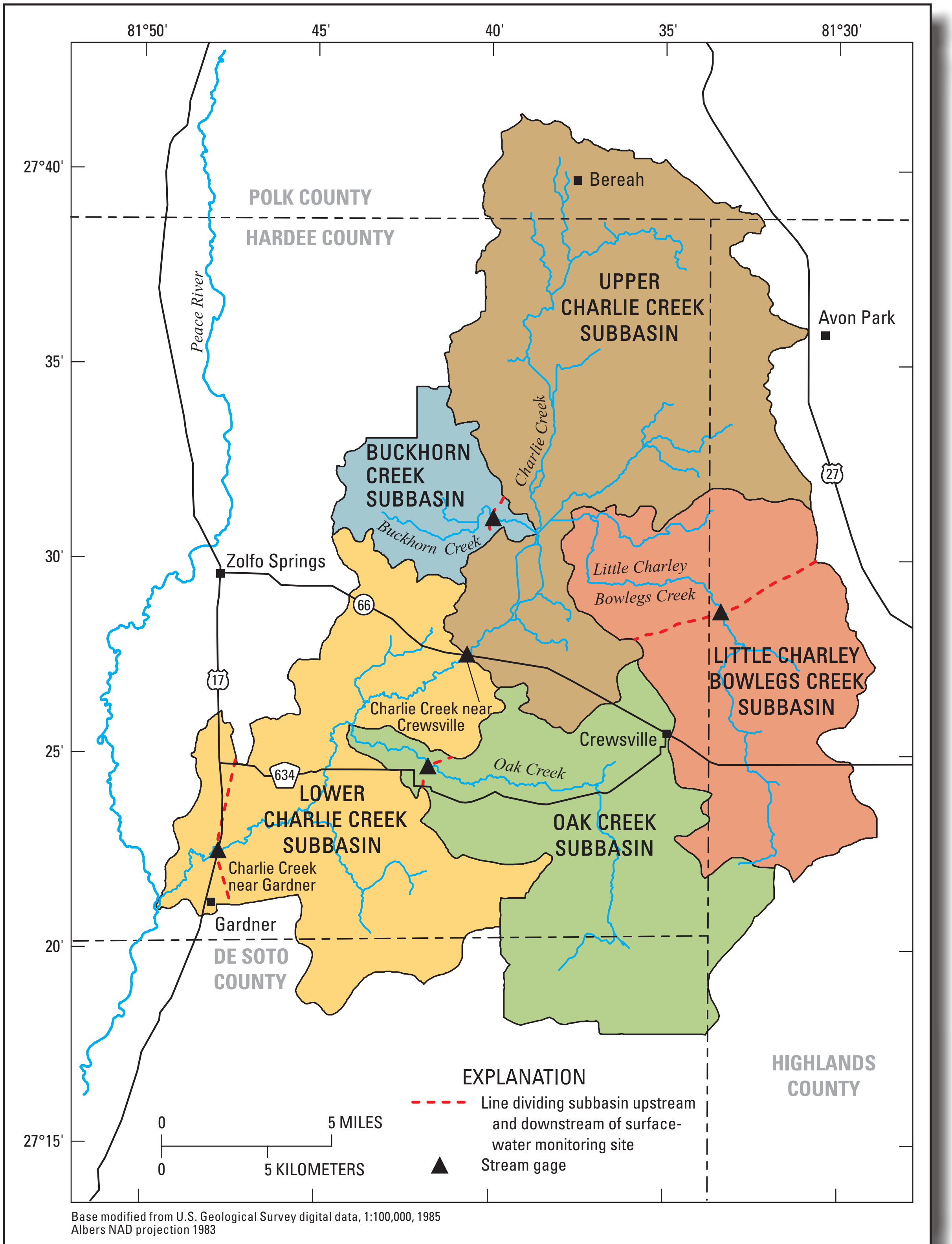

Figure 4. Charlie Creek basin, its five principal subbasins, and the location of streamflow monitoring stations used for this study.

Table 2. Physical characteristics of subdivided areas within the Charlie Creek basin.

[NA, not applicable; IAS, intermediate aquifer system; UFA, Upper Floridan aquifer; ft^3/mi^2, cubic foot per square mile; mi^2, square mile; mi/mi^2; mile per square mile; %, percent]

Basin or subbasin name	USGS streamflow monitoring station name	Station identifier	Sub-basin area (mi^2)[1]	Gaged subbasin area		Pasture, open lands, and range-land area (%)[2]	Wet-land area (%)[2]	Citrus area (%)[2]	Upland forest area (%)[2]	Depres-sion storage, million ft^3/mi^2	Area with B/D soil type (%)[3]	Stream length/ basin area (mi/mi^2)[4]	Artesian flow area (%)			
				(mi^2)	(%)								IAS, May 2004	UFA, May 2004	IAS, Sept. 2004	UFA, Sept. 2004
Buckhorn Creek Subbasin	Buckhorn Creek near Griffins Corner, FL	02296057	18.4	17.4	95	48	11	27	5.3	2.61	81	0.45	1	2	6	22
Little Charley Bowlegs Subbasin	Little Charley Bowlegs C AB CT[5] near Sebring, FL	02296222	65.2	42.8	66	37	27	6.7	19	3.18	69	0.43	23	2	39	18
Upper Charlie Creek Sub-basin	NA	NA	108.7	132.0	121	42	20	17	11	3.32	62	0.52	41	13	52	39
Oak Creek Subbasin	Oak Creek near Gardner, FL	02296389	67.7	65.0	96	53	18	20	5.9	2.99	76	0.31	2	0	6	1
Lower Charlie Creek Subbasin	NA	NA	74.1	68.9	93	54	17	16	8.8	2.05	72	0.50	3	7	25	30
Upper half of Charlie Creek Basin	Charlie Creek near Crews-ville, FL	02296260	192.3	192.3	100	41	22	15	13	3.20	66	0.48	31	8	44	30
Lower half of Charlie Creek Basin	NA	NA	141.9	133.8	96	53	18	18	7.4	2.50	74	0.41	3	4	16	17
Charlie Creek Basin	Charlie Creek near Gardner, FL	02296500	334.1	326.1	98	46	20	16	11	2.90	69	0.43	19	7	32	25

[1]Charlie Creek subbasins derived from Southwest Florida Water Management District (SWFWMD) (accessed June 2006, at *http://www.swfwmd.state.fl.us/data/gis/layer_library/category/physical_sparse*).

[2]Land use and land cover data from SWFWMD for 2005.

[3]Soils shapefile provided by SWFWMD accessed June 2006, at *http://www.swfwmd.state.fl.us/data/gis/layer_library/category/physical_dense*).

[4]Hydrography stream lengths and depression storage estimates derived using hydrology modeling tools in ArcMap from a 5-ft LIDAR digital elevation model resampled to 100 ft.

[5]C AB CT abbreviation for "Creek above control."

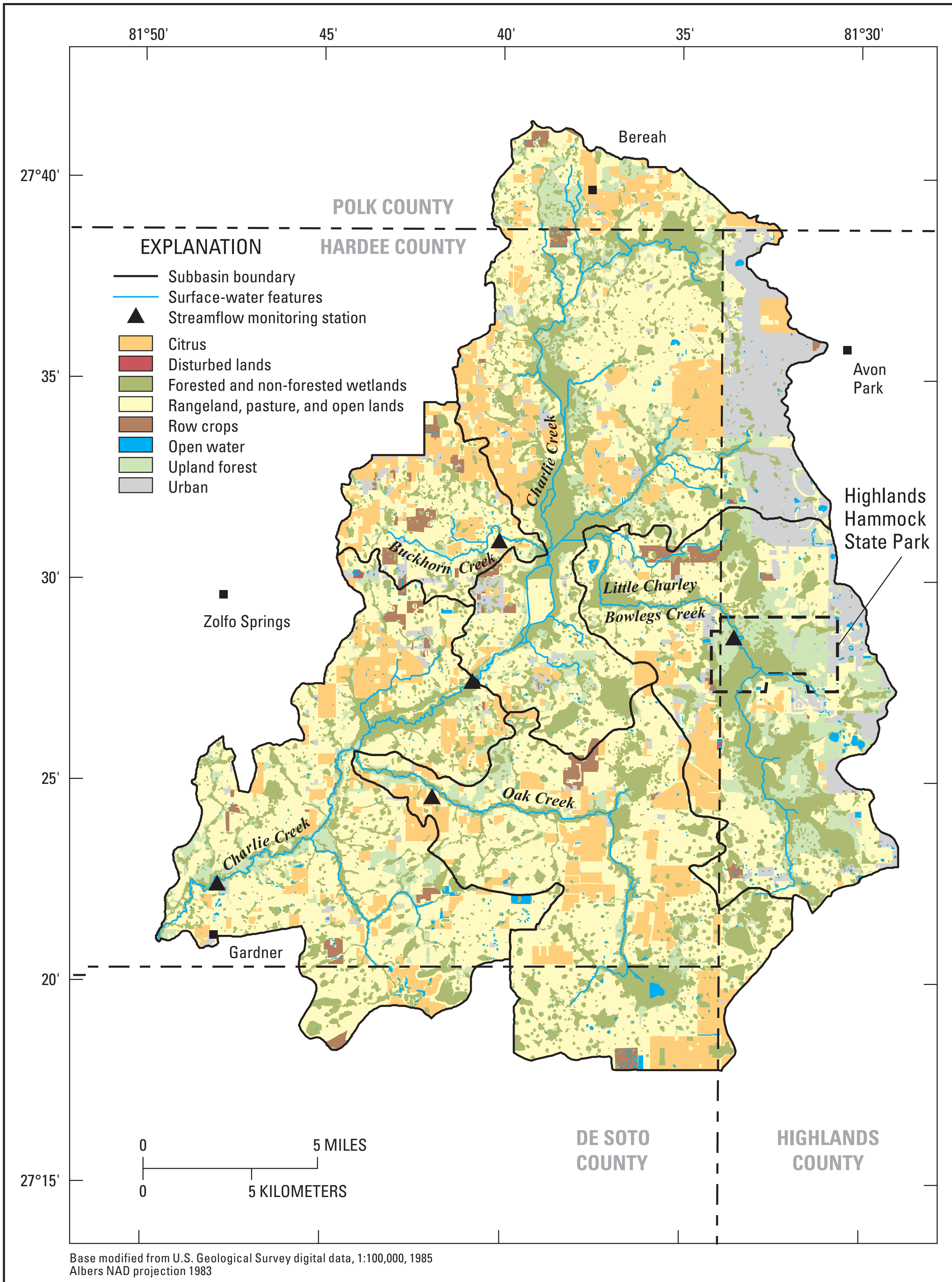

Figure 5. Generalized land use and land cover in the Charlie Creek basin.

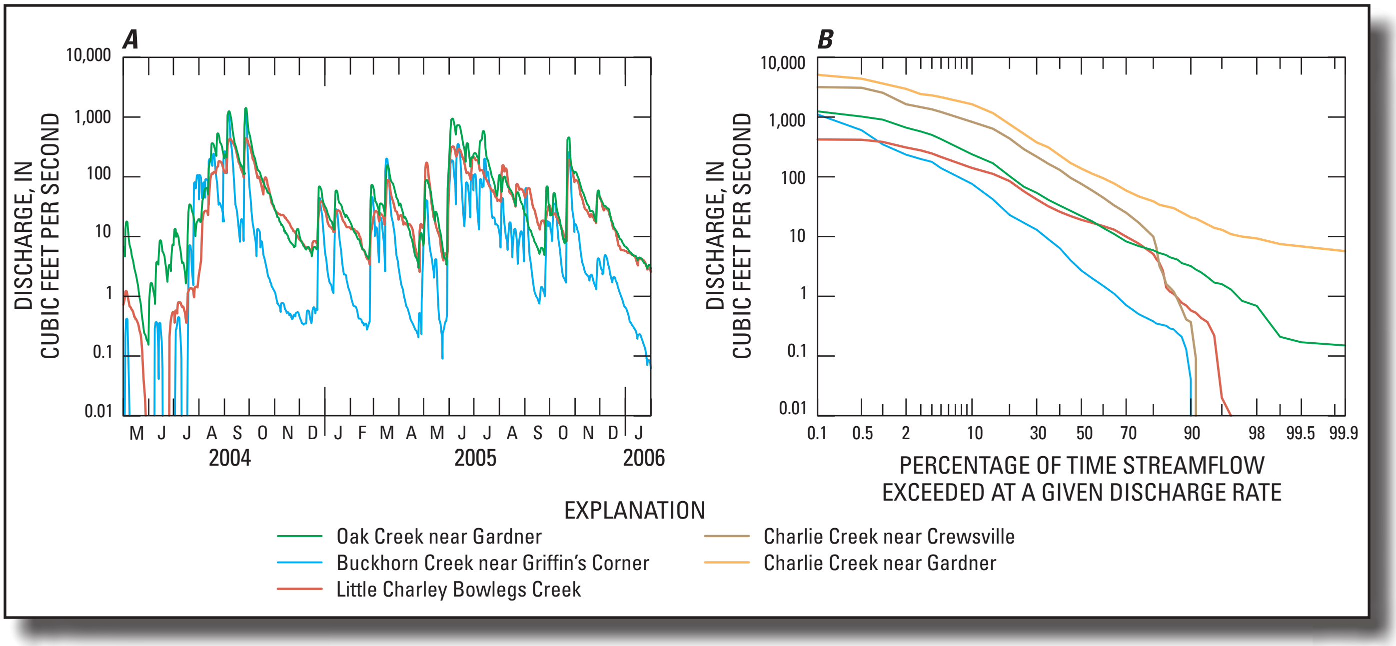

Figure 6. *A,* Streamflow hydrographs for the three tributaries to Charlie Creek, and *B,* duration curves for streamflows measured at Oak Creek, Little Charley Bowlegs Creek, Buckhorn Creek, and Charlie Creek near Crewsville, Florida from approximately April 2004 through December 2005, and for Charlie Creek near Gardner, Florida from October 2002 through December 2005.

Methods of Investigation

The hydrogeologic characterization of the Charlie Creek basin focused on understanding the stratigraphy of the intermediate aquifer system in the basin, and relied on published lithologic logs and measured surface-water and groundwater levels. Water-budget components used for the hydrologic characterization of the basin were measured, derived from remote-sensing data, or derived from MIKE SHE simulated flows.

Hydrogeologic Characterization

Specific approaches used to define the hydrogeologic setting in the Charlie Creek basin include describing the stratigraphic and hydrogeologic units, quantifying groundwater pumpage, examining lateral and vertical flow within and between aquifers, and defining the interaction between the groundwater and streams.

Basin Stratigraphy

Information on the depth and thickness of hydrogeologic units was compiled from 43 well logs obtained from the Florida Geological Survey (2008) and the Southwest Florida Water Management District (LaRoche, 2007), and from maps by Arthur and others (2008). Hydrogeologic cross sections through the Charlie Creek basin were constructed from these data to illustrate the spatial variability in thickness and depth of the units.

Basin Topography and Hydrography

Land-surface elevation within the Charlie Creek basin was interpreted from LIDAR data provided by the SWFWMD (A. Karlin, Southwest Florida Water Management District, written commun., 2008; Petrie and Toth, 2009). The LIDAR data are collected with aircraft-mounted lasers and the method provides land-surface elevations with a vertical precision of approximately 6 in. (Habib, 2009). Raw data acquired from this airborne technique consist of densely clustered elevation points that are typically averaged over different-sized areas. LIDAR data used in this study were spatially averaged to provide elevation values for raster grid cells with x- and y- horizontal dimensions equal to 5 ft. The resulting digital elevation model (DEM) of the basin topography was used for most analyses in the study except the integrated modeling. The MIKE SHE integrated model used a DEM based on LIDAR data averaged over a raster grid with a 300-ft cell size. The land-surface elevations of the entire Peace River watershed, shown in figure 1, are from the National Elevation Dataset (NED) from the USGS National Map Seamless Server (***http://seamless.usgs.gov/index.php***, accessed April 15, 2009). The horizontal resolution for 1/3 arc second elevation grids downloaded from this site is approximately 10 m (32.8 ft). The vertical accuracy of the NED is 8.00 ft (Maune, 2007).

Historical land-surface elevations have been altered by phosphate mining in limited areas of Horse Creek, and extensive areas of Payne Creek and Upper Peace River basins. These changes limit the ability to represent the predevelopment artesian head conditions in these basins in figure 1.

The hydrography, or locations of stream channels, within the Charlie Creek basin was derived from an analysis of the LIDAR data averaged over 100-ft grid cells. First, the flow direction within each grid cell was determined by comparing its elevation to that of adjacent cells. A flow accumulation grid was then derived using the flow direction in adjacent cells to resolve the down-slope direction. The complete analysis generated an interconnected network of stream channels based on the elevation dataset (Olivera and Maidment, 1999).

Groundwater Monitoring Network

Hydrogeologic data were collected from 29 shallow monitoring wells drilled for the study, as well as from existing wells and stratigraphic logs (figs. 7 and 8, and app. 1). At two locations along the main channel of Charlie Creek, shallow wells were drilled along transects crossing the stream (fig. 8). Wells on either side of the stream were used to measure the elevation of the adjacent water table. The northern, or upstream, transect of wells was near the Charlie Creek near Crewsville streamflow gage and the downstream transect was near the Charlie Creek near Gardner gage (figs. 4 and 8). The two transects were about 14 river miles apart.

At each of the three main tributaries, Buckhorn, Little Charley Bowlegs, and Oak Creeks, a single well, or (in some places) two wells completed at different depths in the surficial aquifer, were drilled near the gaging station and used to monitor the water-table elevation near the stream. Water levels in all of these wells were measured monthly from June or July 2004 until early February 2006. The water-table elevation also was monitored continuously in wells 17, 25, and 50, which are located in the three tributary subbasins, to assess changes in groundwater storage in the Charlie Creek basin (fig. 8 and app. 1).

Groundwater levels were obtained at three locations from existing wells tapping the surficial aquifer, the intermediate aquifer system, and the Upper Floridan aquifer to examine vertical head differences. These wells are maintained and monitored by the SWFWMD as part of the Regional Observation and Monitor-well Program (ROMP), and have a “ROMP” prefix as part of the site name (for example, LaRoche, 2007). At the three closest sites to the Charlie Creek basin, ROMP 26, 30, and 43, multiple wells were drilled to different depths using strict protocols, allowing water levels to be measured in the surficial aquifer and in discreet permeable units within the intermediate aquifer system and Upper Floridan aquifer. Only one of these well sites, ROMP 43, is inside the Charlie Creek basin, and it was under construction during the study (fig. 8). At this site, water levels were periodically measured for wells completed in the surficial aquifer, Zone 2 and Zone 3 of the intermediate aquifer system, and the Upper Floridan aquifer. Water levels also were monitored continuously for these same aquifers and zones during the study at two other sites (ROMP 26 and ROMP 30), just outside the Charlie Creek basin to the south and west (fig. 8). All three of these sites were considered upland sites, as they were not immediately adjacent to a stream.

Mapping and Spatial Analysis of Potentiometric Levels in Confined Aquifers

Potentiometric surface maps of the Upper Floridan aquifer within the Charlie Creek basin were constructed for May and September of 2004 and 2005 using data collected from Upper Floridan aquifer wells. Groundwater-level data were collected as part of the semi-annual, synoptic mapping by the USGS of the regional potentiometric surface of the Upper Floridan aquifer in west-central Florida (for example, Ortiz, 2006). The May measurement date typically captures the lowest annual water levels near the end of the dry season when groundwater pumping is highest; conversely, the September measurements typically capture the highest annual groundwater levels near the end of the wet season. The May and September 2005 maps were supplemented by water-level data from four wells in the Charlie Creek basin.

Potentiometric surface maps of the intermediate aquifer in the Charlie Creek basin also were constructed for May and September of 2004 and 2005. The potentiometric surface was mapped locally within the basin using well-construction information and lithologic data to identify which permeable zone(s) the intermediate aquifer system wells were open to. Several of the monitor wells used for mapping the intermediate aquifer system in the Charlie Creek basin were part of the regional monitor-well network operated by the USGS (Ortiz, 2006). Measurements collected from seven existing intermediate aquifer system wells were added to the map in 2005. Information provided by these additional wells guided the placement of equipotential contour lines interpreted from the 2004 data (which involved fewer wells), especially in the north and east part of the basin.

Potentiometric surface maps for both aquifers were converted to raster data, permitting a spatial analysis of aquifer heads in the basin. Potentiometric surfaces were subtracted from one another to quantify the vertical head differences between the intermediate aquifer system and Upper Floridan aquifer throughout the basin. In addition, the 5-ft LIDAR-based elevation model of the land surface was subtracted from the potentiometric surfaces to determine where aquifer heads exceeded the elevation of land surface. Areas of a confined aquifer where the elevation of the potentiometric surface is above land surface elevation have artesian head conditions, and groundwater here would flow freely out of uncapped wells tapping these aquifers (Bear 1979; deMarsily 1986). Potentiometric surface maps and the LIDAR DEM also were used to calculate the head difference of the intermediate aquifer system above or below the streambed elevation of Charlie Creek and its tributaries, and to infer the relative potential for interaction between groundwater and streams.

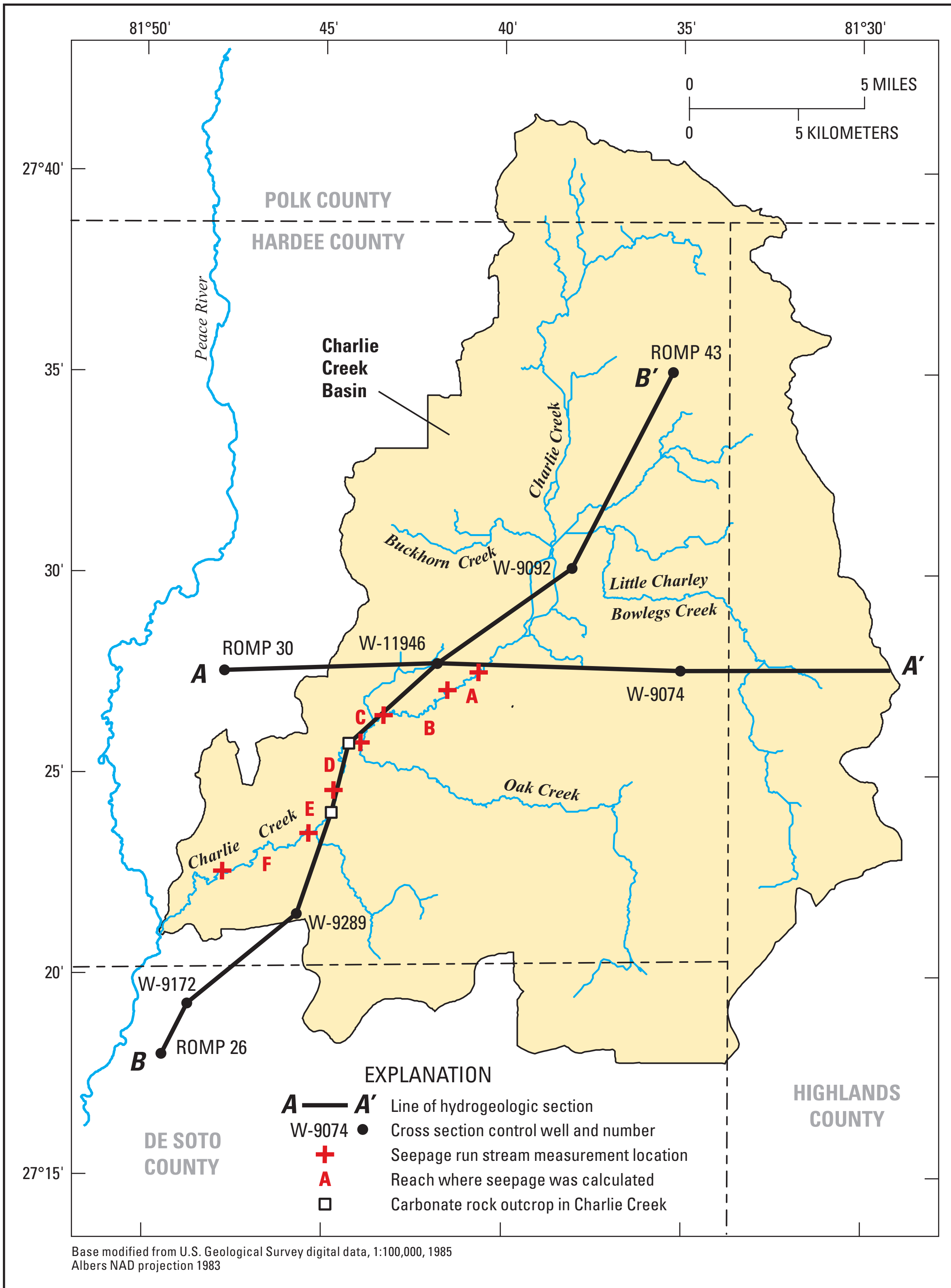

Figure 7. Location of geologic cross sections, carbonate rock outcrops in the Charlie Creek stream channel, and seepage-run measurement sites in the Charlie Creek basin.

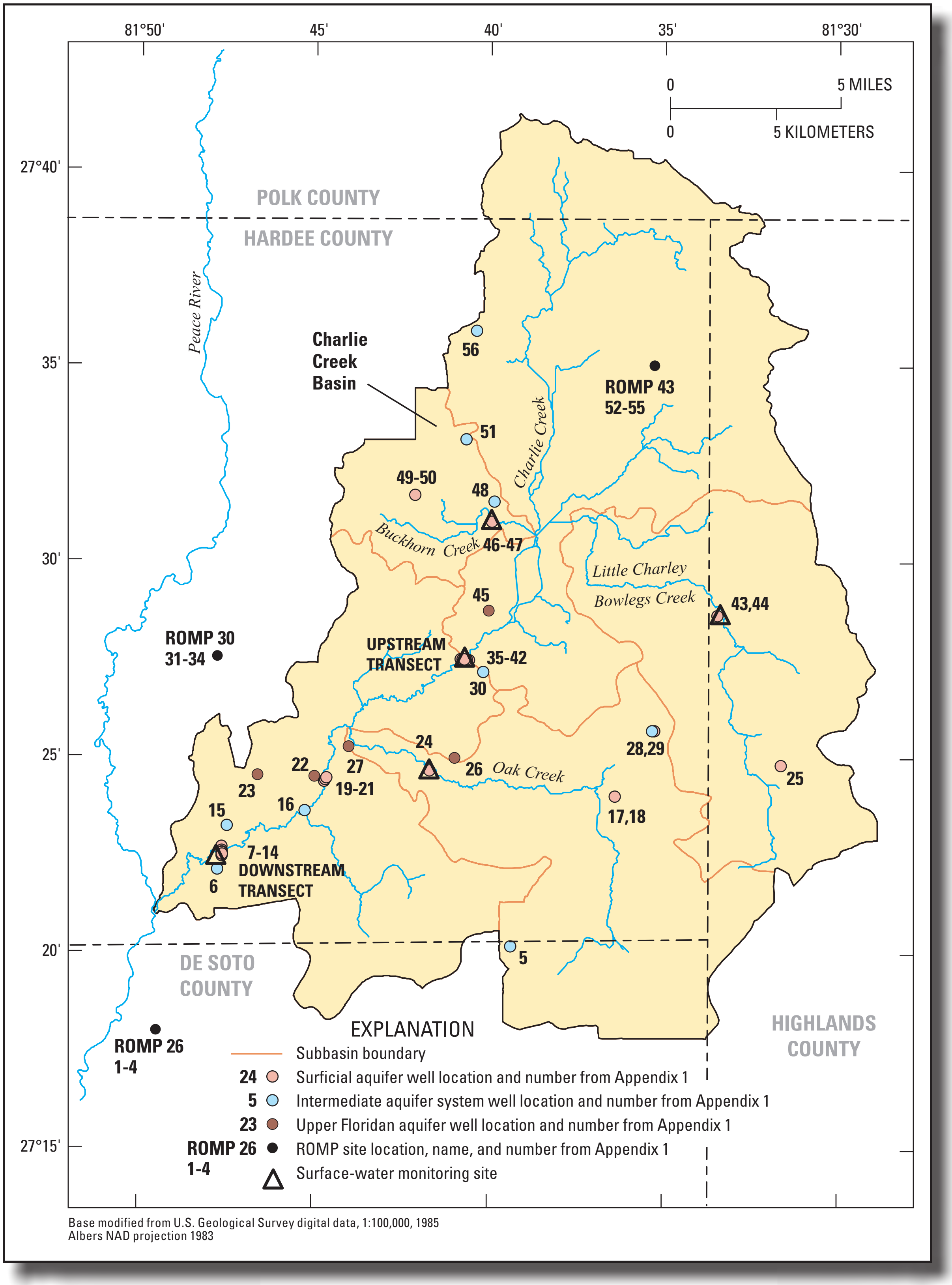

Figure 8. Location of the groundwater monitoring sites, streamflow monitoring stations, and well transect sites in the Charlie Creek basin.

Seepage Runs

A direct method for determining areas where groundwater is entering or leaving a stream is called a "seepage run." Seepage runs are typically done during dry periods when surface inflows are minimal and stream stage is stable. Over a short period of time when stream stage is constant, streamflow is measured at various cross sections along the channel, as well as at any tributaries entering the stream between the measured sections. Gains in streamflow that are not explained by tributary inflows are attributed to groundwater seeping into the channel. Streamflow losses not accounted for are attributed to water seeping out of the channel into the aquifer. Seepage was estimated as:

$$Q_s = Q_d - Q_u - Q_t \qquad (1)$$

where

Q_s is seepage, or the gain (positive) or loss (negative) in streamflow for the reach between two measured sections;

Q_d is streamflow at the downstream section;

Q_u is streamflow at the upstream section; and

Q_t is total streamflow from all tributaries between the upstream and downstream sections. All of the streamflow values are in units of cubic feet per second.

An estimate of the error in the calculated seepage was directly computed for each stream reach. As seepage is a residual term (streamflow difference minus inflows), small uncertainties (or errors) in streamflow measurements can greatly affect the uncertainty in the calculated seepage. The uncertainty or error in seepage was computed as the square root of the sum of the squared individual errors:

$$e_{Qs} = [(e_{Qd})^2 + (e_{Qu})^2 + (e_{Qt})^2]^{1/2} \qquad (2)$$

where e is the estimated error in the terms in equation (1), in cubic feet per second. Streamflow measurement errors were assumed to be 5 to 10 percent, depending on flow and conditions. The uncertainty for Q_s calculated from equation 2 should be considered a maximum possible error because it assumes that all of the errors are in the same direction and do not cancel each other. Most seepage run analyses do not consider individual estimates of error and do not discuss the error relative to the calculated seepage (Lewelling and others, 1998; Trommer and others, 2007; Metz and Lewelling, 2009). The analysis described herein attempts a more thorough approach to interpreting seepage run results. Further discussion of error analysis in hydrologic studies is provided in Winter (1981). Whenever calculated seepage in a reach was less than 10 percent of the average streamflow in that reach, the seepage value was less than the estimated error and was not considered significant. This approach is more conservative than that of Trommer and others (2007), who considered seepage results statistically significant when differences in streamflow between upstream and downstream sections were greater than 5 percent of the average streamflow in the reach (after Hortness and Vidmar, 2005), or greater than 0.5 ft^3/s. Other studies (Lewelling and others, 1998) used an even less conservative approach that considered errors in seepage results to be comparable to errors in the discharge measurement (5-8 percent) regardless of the magnitude of the seepage. But the error in seepage can be the same magnitude or greater than the calculated seepage, especially when seepage values are small. In this study, errors in seepage estimates are presented along with the seepage values to allow a more rigorous interpretation of seepage results. Addressing the larger errors in residual terms such as seepage helps ensure the interpreted values are valid (Winter, 1981).

All seepage runs were made along the main channel of Charlie Creek within the Lower Charlie Creek subbasin. Measurements were made on February 18, 2005; May 26, 2005; December 29, 2005; and January 23, 2006 (app. 2). Seepage was estimated along six reaches, located between the gage at S.R. 66 (Charlie Creek near Crewsville; close to the upstream transect site) and the gage at U.S. 17 (Charlie Creek near Gardner; close to the downstream transect site) (figs. 4 and 7). Surface inflows were measured at up to 11 tributaries between these sites. Seepage was normalized to the length of the stream reach to allow seepage rates to be compared. Seepage also was estimated for combined reaches, and for the entire run using equation 1.

Hydrologic Analysis

Measured and model-simulated values were used to quantify the hydrologic characteristics and water-budget components of the five subbasins of Charlie Creek. Model-derived characteristics included the volume of surface water stored in land surface depressions over time and the rate of groundwater exchange between the surficial aquifer and deeper aquifers. Directly measured characteristics included stream discharge and specific conductance, and basin groundwater levels. Rainfall and evapotranspiration rates were quantified using remotely-sensed data and were used in both the numerical model and the arithmetic water-budget calculations.

Integrated Modeling of Surface Water and Groundwater

The rainfall-runoff response and streamflow in Charlie Creek and its tributaries were simulated using MIKE SHE, a numerical model that simulates coupled groundwater and surface-water flow processes. Remotely-sensed imaging of the physical features of the land surface, as well as energy and water fluxes above the land surface, provide the model with input variables for rainfall, evapotranspiration, basin topography, hydrography, soils, and land cover that are spatially distributed across the Charlie Creek basin.

The uniform spatial distribution of data permits the basin to be subdivided into smaller areas that can be compared and contrasted to one another in an equivalent manner.

Model discretization, assignment of hydraulic properties, and model boundary conditions are described herein and provide the spatial and temporal framework necessary for solving finite-difference approximations to surface-water and groundwater flow equations. MIKE SHE is a well-established numerical code that has been applied in hundreds of studies worldwide (Graham and Butts, 2006). The theory and governing equations in the MIKE SHE model are fully described in DHI Water and Environment (2008a, b). The numerical model developed is used to evaluate subbasin water budgets and factors contributing to differences in major water-budget terms between subbasins.

Modeling Approach

Integrated surface-water/groundwater models are useful for analyzing water-resources problems in complex watersheds because they allow the dynamic coupling of evapotranspiration, surface runoff, streamflow, unsaturated zone flow, and groundwater flow processes. A fully integrated surface-water/groundwater approach was used because it was important to simulate the surface-water/groundwater interactions and quantify differences in surface-water characteristics between the Charlie Creek subbasins.

Representing the physical processes of infiltration, depression storage, unsaturated flow, and the exchange of water between the surficial aquifer, surface water, and underlying aquifers, was considered critical to understanding streamflow in the Charlie Creek basin. The topographic relief is low and water-table elevations are high and variable in much of the Charlie Creek basin. As a result, soil saturation and runoff are important processes, and parts of the watershed can rapidly change from infiltration to runoff conditions as the water table changes and/or rainfall intensity increases. Because the Charlie Creek basin has low topographic relief, water may accumulate at land surface to sufficient depth to allow runoff to be driven by water-surface gradients rather than topographic gradients. Consequently, spatial differences in rainfall may result in topographic gradients driving runoff in one portion of a surface-water subbasin and water-surface gradients driving runoff in another portion of the same subbasin.

MIKE SHE was developed specifically to simulate fully coupled surface-water and groundwater flow and transport processes using a spatially-distributed, physically-based approach or a hybrid, lumped conceptual and distributed physically-based approach (Graham and Butts, 2006). MIKE SHE includes a number of self-contained modules to represent rainfall, snow-melt, canopy interception, overland flow, saturated-unsaturated flow, evapotranspiration, irrigation, and channel flow processes. A variety of numerical approaches are available in MIKE SHE for simulating individual hydrologic/hydraulic processes; these allow models to vary in complexity from simplified lumped-parameter process representations to spatially-distributed, physically-based process representations.

Spatial Discretization and Assignment of Model Parameters

The modeled area corresponds to the surface-water basins contributing flow to the Charlie Creek near Gardner gage and delineated by the Florida Department of Environmental Protection (FDEP, ***http://ca.dep.state.fl.us/www.dep.state.fl.us/metadata.jsp?layer=dep.drainage_basins_areas***, accessed December 10, 2008). The numerical approaches used in MIKE SHE require that the basin area be represented as layered, square grids of model cells. Specifically, the model domain was represented spatially as a grid with 490 rows and 390 columns of square cells, each with dimensions of 300 × 300 ft. Line segments representing the location of stream channels are linked to the x-y coordinates of the grid. The surficial aquifer was represented as an unconfined aquifer using a single model grid layer. The bottom elevation of the surficial aquifer was calculated using an interpolated surface of the top of the Hawthorn Group that was developed from well log data collected by the Florida Geological Survey (Scott, 1988; Arthur and others, 2008). The exchange of groundwater between the surficial and Upper Floridan aquifers was represented in the model using a linear head-dependent flux boundary with a constant leakance value of 8.64×10^{-6} (ft/d)/ft, representing the vertical hydraulic properties of the Hawthorn Group based on data in Knochenmus (2006). This leakance value results in a net vertical flux of approximately 1 in/yr from the surficial aquifer to the Upper Floridan aquifer.

Surficial aquifer properties were distributed based on hydrologic soil groups (app. 3). A thickness-weighted arithmetic mean was used to calculate representative horizontal hydraulic conductivities and specific yield for each hydrologic soil group. The saturated vertical hydraulic conductivity is identical in the surficial aquifer and the overlying unsaturated zone. A thickness-weighted harmonic mean was used to calculate representative saturated vertical hydraulic conductivities for hydrologic soil groups.

The LIDAR data provided in 5-ft grid cells by the SWFWMD were resampled, or averaged spatially, to the 300 × 300-ft grid-cell size used in the model. Resampling was accomplished by calculating the mean topographic elevation within each grid cell. The topographic data represent the elevation of the overland flow plane and the top elevation of the surficial aquifer in the model. The elevation gradient between adjacent grid cells was used in combination with simulated overland water-surface depth to calculate the overland flow between adjacent cells.

The main channels of Little Charlie Bowlegs Creek, Buckhorn Creek, Oak Creek, and Charlie Creek were explicitly represented in the one-dimensional, streamflow routing component of the model. Creek segments were conceptualized as triangular channels with maximum top-widths and depths based on a GIS analysis of the Charlie Creek watershed

Charlie Creek in the Lower Charlie Creek subbasin. (Photograph by T.M. Lee, USGS.)

(B. Dixon, University of South Florida, written commun., 2008). The bed elevations for creek cross sections at junctions between segments were developed from the 5-ft LIDAR data. Bed elevations between junctions were linearly interpolated between bed elevations defined at the start and end of creek segments. A uniform Manning's *n* roughness coefficient of 0.03, representative of a weedy earth channel, was assigned to all creek segments (***www.engineeringtoolbox.com/mannings-roughness-d_799.html***, accessed Nov. 19, 2009). The weir at the Little Charlie Bowlegs Creek gage was explicitly defined in the model, based on leveling data collected during installation of the gage. The weir crest is 90 ft wide and at an elevation of 76.8 ft NGVD 1929. There are two, 2-ft diameter culverts adjacent to the weir that allow discharge when the stage in Little Charlie Bowlegs Creek is above 75.3 ft NGVD 1929.

Surface-water/groundwater exchange between the creek segments and the surficial aquifer are controlled in the model by the simulated creek-wetted perimeter and the specified creek-bed leakance coefficient in each grid cell. A constant leakance coefficient of 0.432 (ft/d)/ft was specified for all creek segments. Leakance values are based on an estimated creek sediment thickness ranging from 1 to 2 ft and typical vertical hydraulic conductivity values for sandy clay surficial aquifer sediments (0.01 to 2.0 ft/d) in west-central Florida (Sinclair, 1974).

The land-use and land-cover characteristics of the modeled area were obtained from the 2006 SWFWMD shapefile library (***http://www.swfwmd.state.fl.us/data/gis/layer_library/category/physical_dense***, accessed May 13, 2008) (fig. 5). The spatial distribution of different types of land cover and land use were used as a template to define the spatial characteristics of other model parameters, namely those related to vegetation, overland flow processes, or irrigation rates. Vegetation parameters that have been related to land use/land cover include the leaf area index, root depth, and crop coefficients used to scale reference evapotranspiration rates to vegetation-specific rates. The methods for distributing the overland flow parameters and irrigation rates over the model domain are described in further detail in appendix 3.

Unsaturated flow in the Charlie Creek basin was simulated using a simplified water-balance approach. In the model, the unsaturated zone extends from the land surface to the water table with the maximum thickness defined by the root depth. Unsaturated zone parameters were distributed according to hydrologic soil groups and developed from laboratory analyses of representative soil profiles (Carlisle and others, 1988). Unsaturated parameters that have been related to hydrologic soil groups include saturated hydraulic conductivity and the water content at the wilting point, field capacity, and saturation. Thickness-weighted parameters were used to calculate representative properties used by the simplified water-balance approach.

Temporal Discretization and Boundary Conditions

Daily values of boundary input variables were used by the model to simulate sub-daily water fluxes and streamflow values. Model time-step lengths were adjusted based on changes in streamflow or rainfall intensity, with maximum time-step lengths of 30 minutes for the stream-flow and overland routing component, 12 hours for the unsaturated component, and 24 hours for the groundwater component. Hydraulic head or flux boundary conditions were provided at the daily time step for the complete simulation period from October 2002 through December 2005. The specified flux conditions applied to the upper model boundary were derived from daily values of rainfall and potential evapotranspiration. Overland water depths at the edge of the model domain were specified to be zero and time-invariant for all external overland cells. Specifying a zero depth still allows overland flow out of the model boundary when the water-surface elevation gradient between the active model domain and model boundary would allow discharge to occur. The daily average observed stage at the Charlie Creek near Gardner streamflow gage was applied as a water-level boundary at the downstream end of Charlie Creek. No other boundary conditions were specified for the creek segments. Dynamic lateral inflows (runoff and base flow) to stream segments were calculated by the model.

Groundwater flux was set to zero along the lateral boundaries of the surficial aquifer, which correspond to surface-water subbasin divides. Along these divides, the water table is expected to have the highest elevations in the subbasin and therefore these areas correspond to groundwater flow divides. Heads in the Upper Floridan aquifer were specified as the lower boundary condition for the model and these heads were varied to reflect the effect of groundwater withdrawals on the potentiometric surface.

Hydrologic Input Variables in the Model

Rainfall and potential evapotranspiration rates derived from satellite-based remote-sensing techniques were used in the model because of the increased spatial resolution of these datasets compared to data collected at widely-spaced weather stations. Daily rainfall data used as input to the model were based on WSR-88D (NEXRAD) radar reflectance data calibrated to data from raingages (Hoblit and others, 2003). NEXRAD rainfall data were obtained from the SWFWMD (2005) and are spatially distributed to a 2 × 2-km (1.24 × 1.24-mi) grid.

Daily potential evapotranspiration rates were calculated from satellite-based solar radiation data using the Priestley-Taylor method—a technique that uses the concept of the theoretical lower limit of evaporation from a wet surface (Holmes and others, 2008; Jacobs and others, 2008; U.S. Geological Survey, 2009). Potential evapotranspiration estimates were spatially distributed to the 2 × 2-km cell dimensions of the NEXRAD grid.

Groundwater used to irrigate agricultural land use/land cover types in the basin was represented in the model as coming from external sources, as the effect of pumping in the basin already was reflected in the potentiometric levels specified as the Upper Floridan aquifer model boundary. There are substantial groundwater withdrawals in the Charlie Creek basin from the Upper Floridan aquifer to meet local irrigation demands. Irrigation water demands were calculated for each model time step and irrigation water was applied to those areas defined as agricultural land-use/land cover types until the simulated evapotranspiration was equal to the potential evapotranspiration rate.

Spatially-distributed Upper Floridan aquifer water levels were developed for each grid cell using May and September potentiometric surface maps for 2002 through 2006 (Knochenmus and others 2003; Blanchard and others 2003, 2004; Blanchard and Seidenfeld 2005; Ortiz and Blanchard 2006; Ortiz 2006, 2007). Daily Upper Floridan aquifer water levels were linearly interpolated from May and September potentiometric surface elevations developed for each grid cell.

Model Calibration and Error

The model was calibrated using daily streamflow values published by the USGS for the five Charlie Creek subbasins. Initially, model calibration focused on getting the basin and subbasin water budgets within expected ranges for watersheds in central Florida (Swancar and others, 2000; Knochenmus and Yobbi, 2001; Spechler and Halford, 2001; Sumner, 2001; Knowles and others, 2002). Vegetation-specific crop coefficients were the primary parameters adjusted to achieve evapotranspiration and runoff rates within expected ranges.

Overland roughness coefficients, surficial aquifer hydraulic conductivity, simplified water balance approach parameters, and leakance coefficients representing the vertical hydraulic properties of the Hawthorn Group were adjusted to improve the match between simulated and observed streamflow while maintaining an average surficial aquifer to Upper Floridan aquifer exchange of 1 in/yr. During model calibration, it was assumed that land use/land cover based parameters could be developed that were applicable to the entire Charlie Creek basin. No attempt was made to develop land use/land cover based parameters for individual subbasins to improve model performance.

Qualitative and quantitative measures were used to assess model performance. Quantitative measures of model performance included the mean error and the Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970). The mean error, *ME*, is calculated as:

$$ME = \frac{\sum_{n=1}^{nobs}(o_n - s_n)}{nobs} \qquad (3)$$

where *nobs* is the number of observations at the respective streamflow gage during the simulation period, o_n is the observed daily streamflow (in cubic feet per second), and s_n is the simulated daily streamflow (in cubic feet per second) for the same day. The mean error is a measure of model bias, and a value close to zero indicates little model bias at the evaluated location.

The Nash-Sutcliffe coefficient, *NS*, is calculated as:

$$NS = 1 - \frac{\sum_{n=1}^{nobs}(o_n - s_n)^2}{\sum_{n=1}^{nobs}(o_n - \bar{o})^2} \qquad (4)$$

where $\bar{o}$ is mean observed streamflow (in cubic feet per second) for the simulation period and all other terms are as previously defined. The Nash-Sutcliffe coefficient is a measure of the percentage of the data variance explained by the hydrologic model. Model accuracy increases as the coefficient approaches 1, with $NS = 1$ indicating perfect model predictions. A zero or negative Nash-Sutcliffe coefficient indicates model predictions that are as accurate as, or less accurate than, the mean of the observed data, respectively.

Model performance also was assessed by comparing the distribution of simulated values to the distribution of observed flow values using the percentile flow method. Daily streamflow values, either simulated or observed, are ranked from largest to smallest and five values, or “breaks,” are identified that divide the entire range of flow values into 10th, 25th, 50th, 75th, and 90th percentile categories. The 10th percentile category, or the uppermost 10 percent of either observed or simulated flows, contains the largest flow values, including peak flows. The value representing the break for the 10th percentile flows is denoted P10, and all values equal to or greater than this value are in the 10th percentile range. By comparison, P_{50} is a lesser flow rate equaled or exceeded by half of the values in the distribution and, by definition, is the median value. P90 is the smallest value used to characterize the distribution of flow values, those equaled or exceeded by 90 percent of the record. Simulated and observed P90 values were compared to assess the ability of the model to simulate the smallest stream discharges, typically base flow.

Observed and Simulated Water Budgets for the Basin

Water budgets were calculated for individual subbasins, and for the collective upper and lower halves of the Charlie Creek basin, using the observed and simulated streamflows. As noted earlier, the upper half of the basin contains the headwaters area of Charlie Creek (Upper Charlie Creek subbasin), and two tributary basins (Little Charley Bowlegs and Buckhorn Creek subbasins). The lower half of the basin includes the Lower Charlie Creek subbasin and the largest tributary subbasin, Oak Creek. Water-budget results are presented for June 2004 through December 2005, the only period with concurrent streamflow measurements for all five subbasins, as well as for 2003, the model year for which streamflow was known only at the outlet of the basin. The observed water-budget period from June 2004 through December 2005 was wetter than average. The model was used to simulate 2003, a relatively dry year, to infer the effect of dry conditions on basin and subbasin water budgets.

Assuming each subbasin defines a control volume, the comprehensive water budget was calculated from *simulated* results using:

$$Rai - ET \pm OL_L - Ro + I \pm GW_L \pm GW_V \pm AC \pm \Delta S_S \pm \Delta S_{GW} - Err = 0 \qquad (5)$$

where

Rai	is rainfall,
ET	is evapotranspiration,
OL_L	is overland flow across subbasin boundaries,
Ro	is runoff to the stream,
I	is irrigation,
GW_L	is lateral groundwater flow across subbasin boundaries,
GW_V	is the vertical groundwater exchange between the surficial aquifer and the Upper Floridan aquifer,
AC	is aquifer-creek exchanges,
ΔS_S	is the change in overland (depressional and canopy) storage in the surface water system,
ΔS_{GW}	is the change in groundwater storage in the surficial aquifer, and
Err	is the simulated model error.

All terms in the equation are in volumetric units of cubic feet, and water budgets were calculated for monthly time periods.

The observed water budgets include only rainfall, net precipitation, and runoff (observed streamflow) in each subbasin. Rainfall was defined as the cumulative rainfall in a basin computed from the spatially-distributed NEXRAD rainfall data. Net precipitation for a subbasin was calculated as the difference between cumulative rainfall and cumulative evapotranspiration losses from the subbasin. The cumulative evapotranspiration losses were computed using methods described in the modeling methods section herein. Stream discharge measurements were made according to USGS protocols (Rantz and others, 1982; Oberg and others, 2005), and specific conductance of the stream was monitored at each of these sites using USGS field methods (Wagner and others, 2006). Daily stream discharge values and specific conductance values are available from the USGS online at ***http://waterdata.usgs.gov/fl/nwis/***.

Gaged streamflows were analyzed further to estimate the base flow contribution to the total streamflow in Charlie Creek. Base flow is streamflow not associated with overland runoff from rainfall events but, rather, water that enters the stream channel more gradually and continually between rainfall events. Base flow magnitude was estimated using graphical and digital filter techniques applied to daily streamflow values (Rutledge, 1998; Eckhardt, 2005). In both techniques, filtering is used to estimate base flow by removing the streamflow component associated with overland runoff from rainfall events. The origin of the base flow is then deduced from what is known about the physical setting of the stream channel. For streams that fully penetrate the thickness of a non-leaky surficial aquifer, base flow generally is groundwater discharge to the stream channel. In the Charlie Creek basin, some stream channels do not fully penetrate the surficial aquifer, and the terrain is relatively flat with many depressional wetlands that store runoff. For these reasons, base flow estimates may include the effects of delayed runoff from wetlands, or agricultural runoff, in addition to groundwater discharge.

The numerous years of streamflow data needed to characterize long-term average base flow for the entire Charlie Creek basin were available at the Charlie Creek near Gardner gage, but not for individual subbasins. To allow comparisons between subbasins, base flow estimates were made using the observed streamflow record from 2005. These base flow estimates were compared to ones derived from streamflows simulated in the MIKE SHE model for the 3-year period from 2003 through 2005.

Hydrogeologic Framework of the Charlie Creek Basin

This section details the hydrogeologic framework within the Charlie Creek basin and relates the groundwater levels and flow direction in the underlying aquifers to streamflow in Charlie Creek and its tributaries. The general hydrogeologic framework of Hardee and DeSoto Counties including the Charlie Creek basin has been described by Wilson (1977), Duerr and Enos (1991), Metz (1995), and Knochenmus (2006). The relation between stratigraphic and hydrogeologic units in the Charlie Creek basin is summarized in figure 9.

Hydrogeologic Units

Three principal hydrogeologic units are present in the Charlie Creek basin: the surficial aquifer, the intermediate aquifer system, and the Upper Floridan aquifer. The intermediate aquifer system received detailed analysis in this study because the impermeable and permeable layers that compose this hydrogeologic unit are more limited in their spatial extent than the units that compose the Upper Floridan aquifer. This spatial variability can cause localized differences in its interaction with the overlying surficial aquifer, or with stream channels that have eroded into the top of the intermediate aquifer system. The Upper Floridan aquifer does not interact directly with Charlie Creek, but hydraulic heads in this aquifer can affect Charlie Creek indirectly by affecting vertical groundwater exchange with the intermediate aquifer system.

Surficial Aquifer

The surficial aquifer comprises undifferentiated beds of sand, clay, and fossil fragments of Holocene to Pliocene age, and it is unconfined, with the water table at the top of the saturated sediments (fig. 9). Surficial deposits range in thickness from 0 to 150 ft in the Charlie Creek basin (figs. 10 and 11). The surficial aquifer is thickest in ridge areas along the eastern basin divide and thin or absent in the stream channel of lower Charlie Creek. Localized phosphate-rich beds also are present, because surficial aquifer deposits include reworked sediments from the underlying Peace River Formation. Clay content generally increases with depth, and the phosphate-rich beds, along with the upper part of the Peace River Formation, form a confining unit between the surficial aquifer and intermediate aquifer system.

Although the surficial aquifer is not a major water-supply source for the area, it is important for storing water that recharges deeper aquifers or discharges into streams, wetlands, and lakes. Reported hydraulic conductivity of the surficial aquifer in the study area ranges from 1 to 34 ft/d. Transmissivity values increase with aquifer thickness, and probably range from around 10 to 1,000 ft^2/d (Wilson, 1977; LaRoche, 2007).

Intermediate Aquifer System

The intermediate aquifer system is a heterogeneous unit, consisting of interbedded phosphate-rich sands, clays, and carbonates of the Hawthorn Group and, to a lesser extent, overlying undifferentiated surficial deposits (fig. 9). The Hawthorn Group sediments are mostly of Miocene age, but range from late Oligocene to early Pliocene age. The heterogeneity of the unit is the result of changing depositional environments as sea level and ocean circulation patterns fluctuated when the Hawthorn Group was deposited (Scott, 1988; Knochenmus, 2006; Arthur and others, 2008). This heterogeneity means the beds have varying permeability. As a result, the intermediate aquifer system contains several permeable zones separated by zones of lower permeability. The unit also acts as a confining unit, limiting water exchange between the overlying surficial aquifer and the underlying Upper Floridan aquifer. In the study area, the Hawthorn Group is composed of the Peace River and Arcadia Formations.

The shallower Peace River Formation is thinner and overlies the Arcadia Formation (fig. 9). The Peace River Formation is predominantly siliciclastic, consisting of sands, phosphate-rich sediments, and clays, although localized carbonate beds

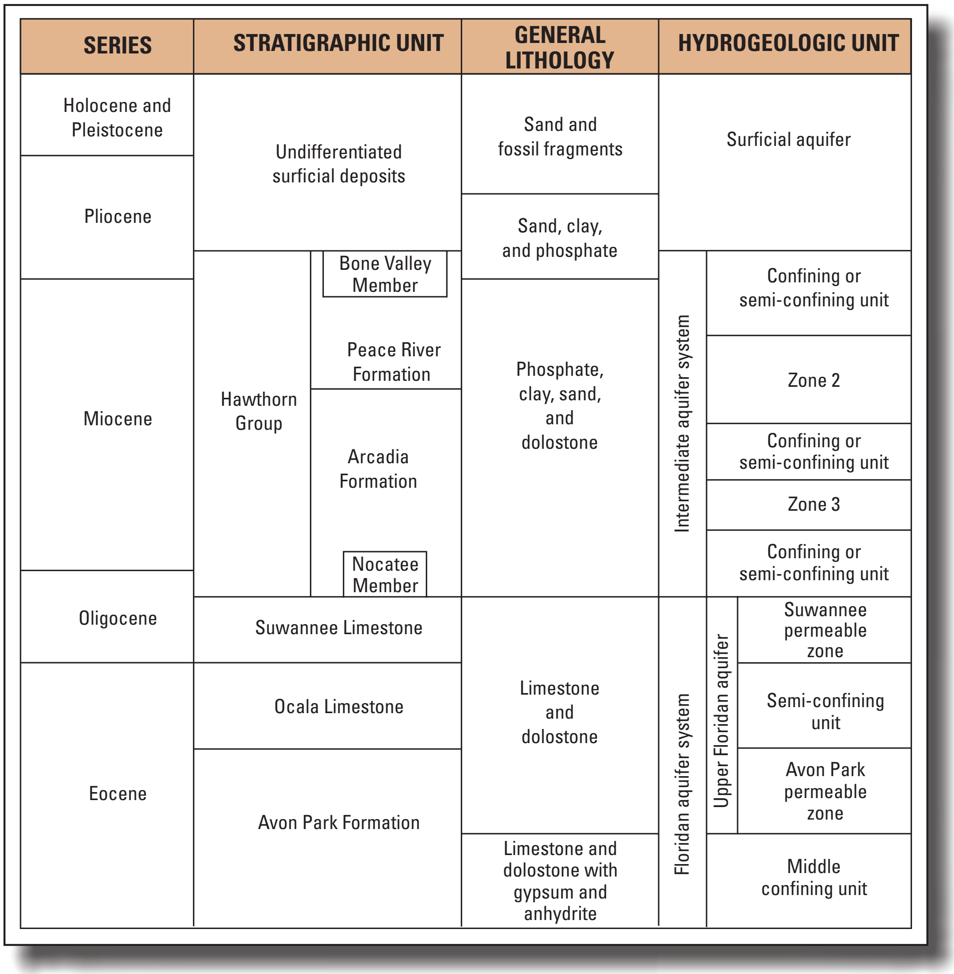

Figure 9. Relation between stratigraphic and hydrogeologic units in the Charlie Creek basin modified from Metz and Lewelling (2009).

are present (Scott, 1988; Arthur and others, 2008). In the Charlie Creek basin, the Peace River Formation ranges from 20 to 70 ft thick and averages 45 ft in thickness (based on 17 lithologic logs). The top of the unit ranges from land surface in the western part of the basin to 150 ft below land surface in the southern part of the basin (77 ft above to 58 ft below NGVD 1929 for 22 logs). Beds dip steeply to the east just beyond the eastern edge of the basin boundary, toward a trough in the surface of the Peace River Formation beneath the Lake Wales Ridge (Arthur and others, 2008) (fig. 10). Fractured carbonate rock in the Peace River Formation crops out in the streambed of Charlie Creek above and below its confluence with Oak Creek, at elevations of 32.5 and 42.6 ft above NGVD 1929 (figs.11 and 12), and creates a small cataract at low streamflow (fig. 12a). The elevation of these outcrops is consistent with the elevation of carbonate beds from the Peace River Formation at two nearby wells (38 and 39 ft above NGVD 1929). The Bone Valley Member of the Peace River Formation is present in the extreme northwest corner of the Charlie Creek basin. This unit has economically valuable phosphate deposits, and has been mined extensively to the northwest of the study area.

The Arcadia Formation underlies the Peace River Formation, and its lowermost sediments form the Nocatee Member in the study area (fig. 9). The undifferentiated Arcadia Formation is primarily a carbonate unit, with varying amounts of sand, clay, and phosphate grains (Scott, 1988; Arthur and others, 2008). It contains the most permeable beds in the intermediate aquifer system in the study area. The unit is 140 to 340 ft thick in the Charlie Creek basin (based on 14 well logs). The top of the Arcadia Formation ranges from 66 to 175 ft below land surface (36 ft above to 88 ft below NGVD 1929, based on 17 logs), with the depth increasing from west to east across the basin (fig. 10).

The Nocatee Member of the Arcadia Formation is predominantly a siliciclastic unit, with interbedded sands, clays, and carbonates (Scott, 1988; Arthur and others, 2008). This lower-permeability unit forms the lowermost confining bed between the intermediate aquifer system and the Upper Floridan aquifer. The Nocatee Member ranges from 20 to 100 ft thick in the Charlie Creek basin (based on 14 logs), and is 215 to 400 ft below land surface (104 to 315 ft below NGVD 1929).

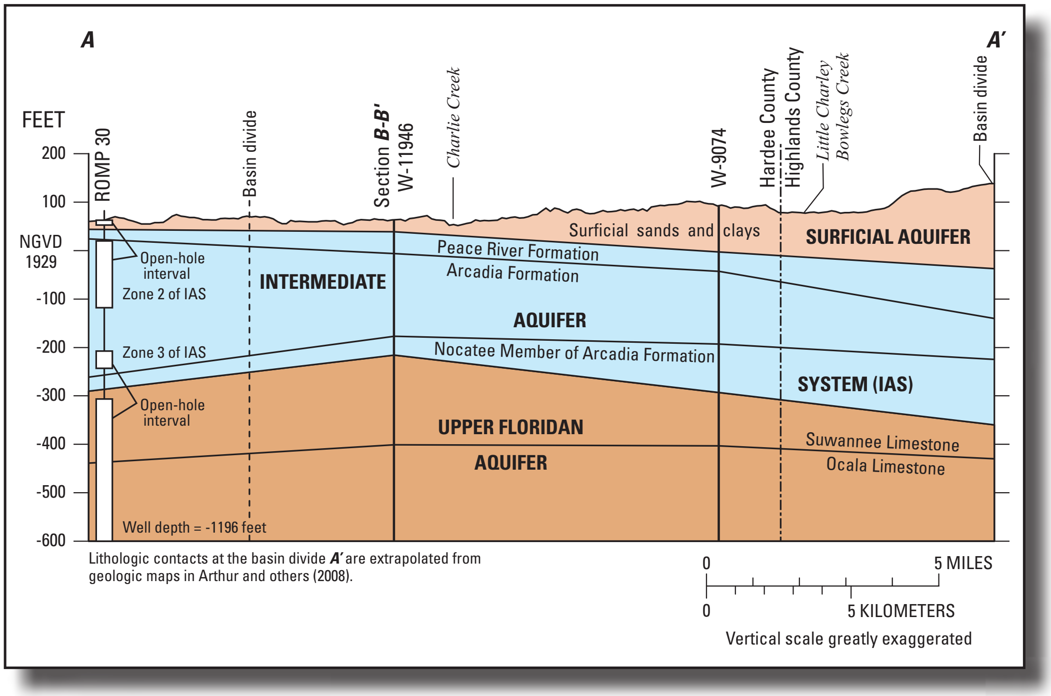

Figure 10. Generalized hydrogeologic section *A–A′* in and near the Charlie Creek basin (section location shown in fig. 7).

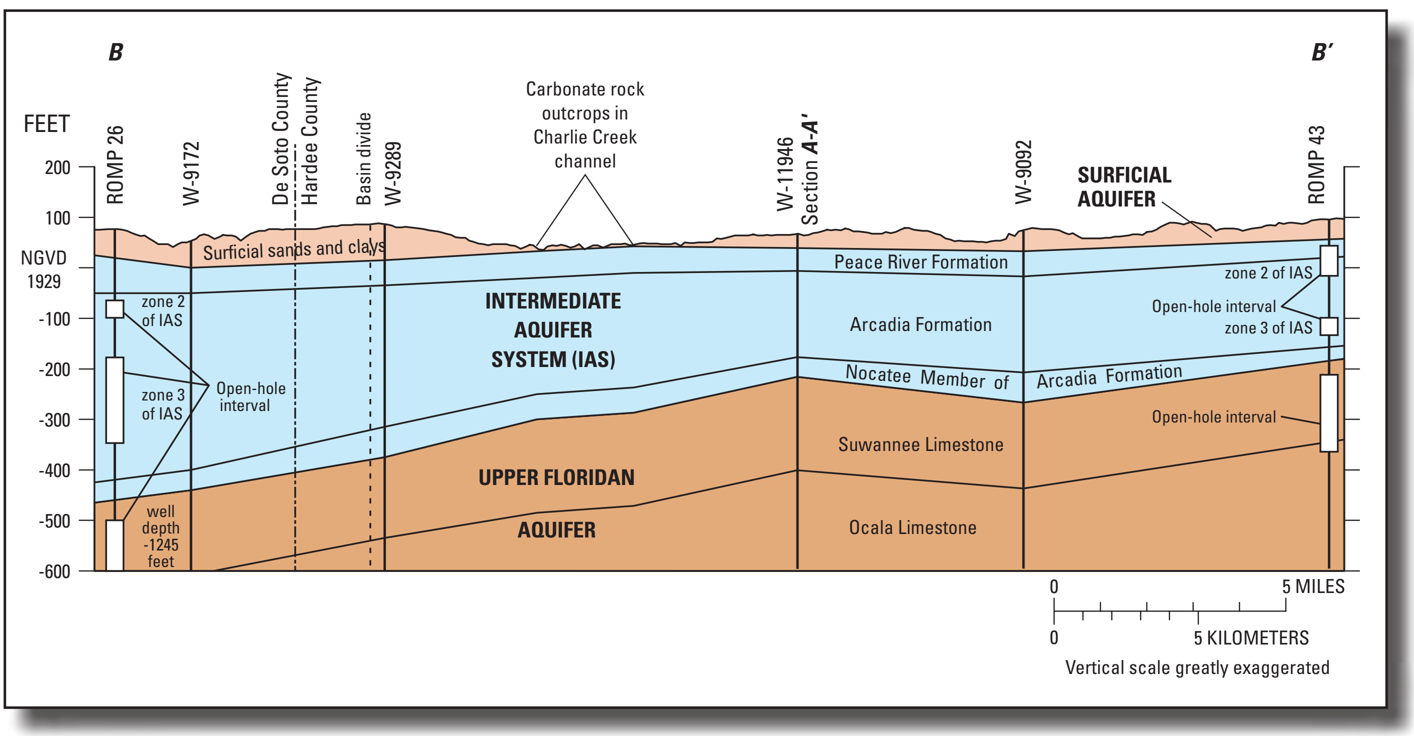

Figure 11. Generalized hydrogeologic section *B–B′* in and near the Charlie Creek basin (section location shown in fig. 7).

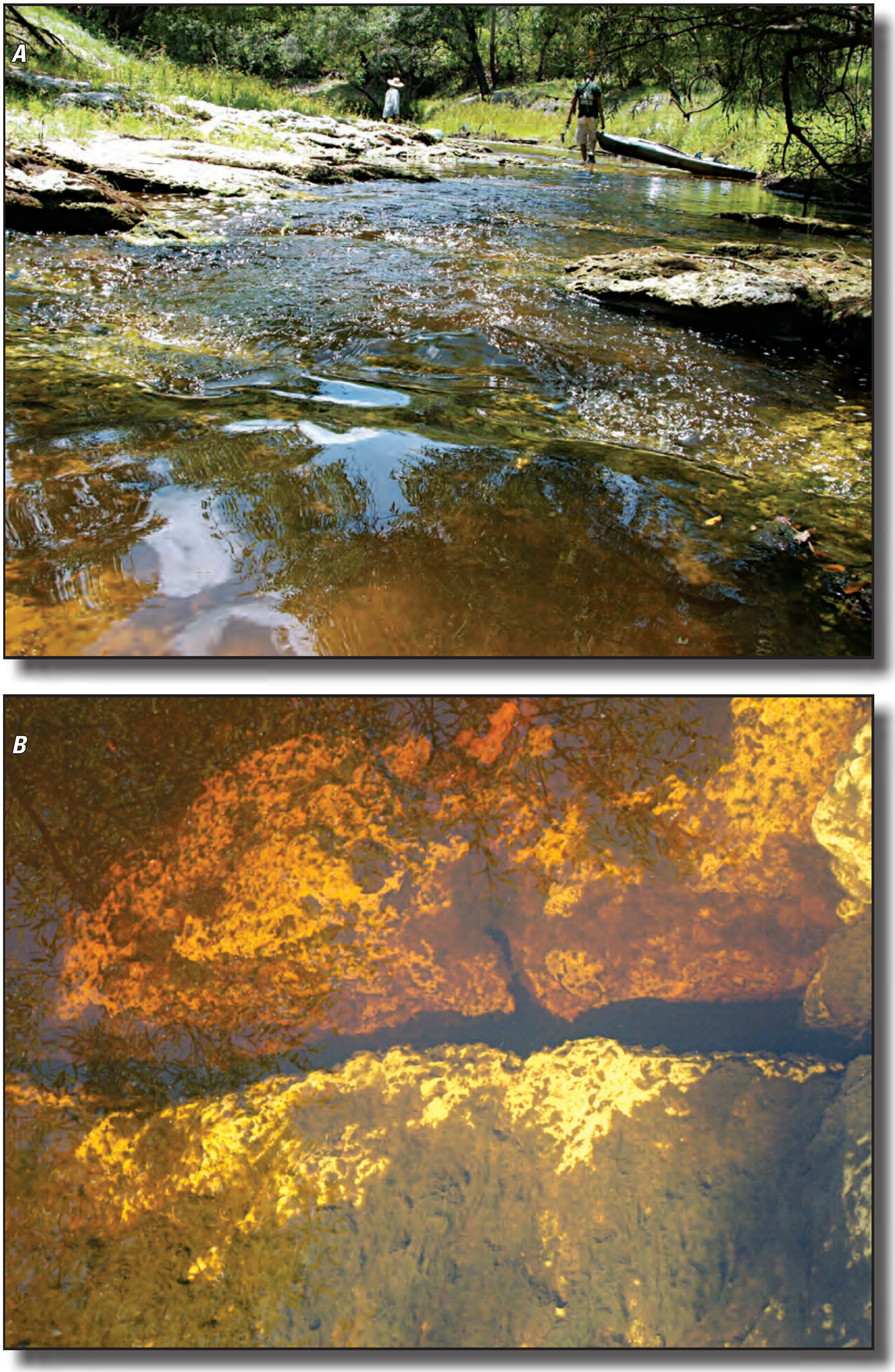

Figure 12. Fractured carbonate rock exposed in the bed of Charlie Creek at the southernmost of the two outcrops shown in figure 7. The photo in B was taken looking down at the rocks through the water. (Photograph by T.M. Lee, USGS.)

Permeability in the intermediate aquifer system varies greatly because of its heterogeneity. In the study area, two regionally extensive permeable zones are present: Zones 2 and 3 (fig. 9). Nomenclature for these permeable zones varies in previous reports, and nomenclature used in this report follows Knochenmus (2006). Zone 2 is in the lower Peace River Formation and upper Arcadia Formation, and also is referred to as the upper Arcadia aquifer (LaRoche, 2007; Gates, 2009, Metz and Lewelling, 2009). Zone 3 is in the lower part of the undifferentiated Arcadia Formation, and also is referred to as the lower Arcadia aquifer (LaRoche, 2007). Lateral continuity and flow within these permeable zones is not well understood. Zone 2 appears to be present throughout the Charlie Creek basin, and is the most regional and hydraulically isolated of the permeable zones (Basso, 2003; Knochenmus, 2006). Zone 3 thins out considerably or is not present in the eastern and northern part of the Charlie Creek basin (Knochenmus, 2006), but appears to be present in the rest of the basin.

Limited data are available concerning the thickness and hydraulic properties of the permeable zones in the intermediate aquifer system in the Charlie Creek basin. At ROMP 43, in the northern part of the Charlie Creek basin, wells were recently installed and aquifer performance tests were conducted in both zones (LaRoche, 2007). Zone 2 is about twice as thick as Zone 3 at that site (64 and 37 ft, respectively) and between 52 and 116 ft below land surface (46 ft above to 18 ft below NGVD 1929); Zone 3 is between 196 and 233 ft below land surface (98 to 135 ft below NGVD 1929). Hydraulic conductivity in Zones 2 and 3 were similar (average of 8 and 11 ft/d, respectively). Because Zone 2 was thicker than Zone 3, however, its transmissivity values were twice that of Zone 3 (800 and 400 ft^2/d, respectively). Permeable zone information also is available for two monitoring well sites just outside the Charlie Creek basin. At those sites (ROMP 30 and ROMP 26; fig. 8), Zone 2 was 125 and 40 ft thick, respectively, and Zone 3 was 36 and 175 ft thick, respectively. No data on hydraulic properties were available for permeable zones at these sites.

Upper Floridan Aquifer

The Upper Floridan aquifer is a vertically continuous sequence of carbonate rocks of generally high permeability underlying the intermediate aquifer system (Southeastern Geological Society, 1986). In the study area, the Upper Floridan aquifer consists of carbonate rocks of the Suwannee Limestone of Oligocene age, and the Ocala Limestone and Avon Park Formation, both of Eocene age (fig. 9). The top of the Upper Floridan aquifer deepens from north to south in the Charlie Creek basin. The top of the Upper Floridan aquifer ranges from less than 150 ft below NGVD 1929 at the northern part of the basin, to more than 375 ft below NGVD 1929 at the southern part of the basin (Arthur and others, 2008; Florida Geological Survey, 2008). The base of the Upper Floridan aquifer consists of vertically persistent evaporites (anhydrite and gypsum), which infill porosity in carbonate rocks in the lower Avon Park Formation. This low permeability zone forms the middle confining unit, separating the Upper Floridan aquifer from the Lower Floridan aquifer. The middle confining unit was found at 1,580 ft below land surface (1,480 ft below NGVD 1929) at ROMP 43 in the northern part of the Charlie Creek basin (LaRoche, 2007).

The Upper Floridan aquifer is the most productive aquifer in the study area and consists of two water-bearing zones: the shallower Suwannee permeable zone and the deeper, more transmissive, Avon Park permeable zone (fig. 9). At ROMP 43, the hydraulic conductivity of the Suwannee permeable zone is about 90 ft/d, whereas the hydraulic conductivity of the Avon Park permeable zone is about 4 times greater, or approximately 400 ft/d (LaRoche, 2007). This translates into an even greater transmissivity because of the greater thickness of the Avon Park permeable zone (13,000 ft^2/d and 300,000 ft^2/d for the Suwannee and Avon Park permeable zones, respectively). The higher permeability of the Avon Park permeable zone is due to fractures and well-developed secondary porosity. These two zones are separated by the Ocala Limestone, which has lower permeability due to its fine-grained texture (LaRoche, 2007).

Groundwater Use

Charlie Creek basin is a region of moderate groundwater withdrawals and use, flanked by regions with greater groundwater withdrawals. Pumping in the surrounding regions has the potential to lower Upper Floridan aquifer heads in the Charlie Creek basin. Most notably, a large region-wide depression in the potentiometric surface of the Upper Floridan aquifer forms during the dry season in southern Hillsborough and central Manatee Counties, about 25 mi west of the Charlie Creek basin, where heads are regularly below NGVD 1929 (Southwest Florida Water Management District, 1993: Duerr, 2001; Ortiz, 2006). These potentiometric lows are caused by high rates of groundwater pumping, primarily for agricultural use. The pumping magnitude depends upon climatic conditions and seasonal pumping rates, and is typically greatest during the spring (Southwest Florida Water Management District, 1993) (fig. 13). The estimated groundwater pumpage in the Charlie Creek basin in 1997-1999, when normalized to inches per year over the basin area, was the lowest of all basins in the Peace River watershed except for Horse Creek basin (table 1). Smaller subbasins immediately surrounding Charlie Creek to the north, west, and east have roughly twice the annual groundwater withdrawal rate, per area, of the Charlie Creek basin (Southwest Florida Water Management District, Data & Maps, 2008, ***http://www.swfwmd.state.fl.us/data/gis/layer_library/category/physical_sparse***, accessed March 8, 2008; Mike Kelley, Southwest Florida Water Management District, written commun., 2007).

Virtually all water used in the Charlie Creek basin during the study period was groundwater, based on pumping estimates from wells and surface-water bodies with water-use permits (Mike Kelley, Southwest Florida Water Management

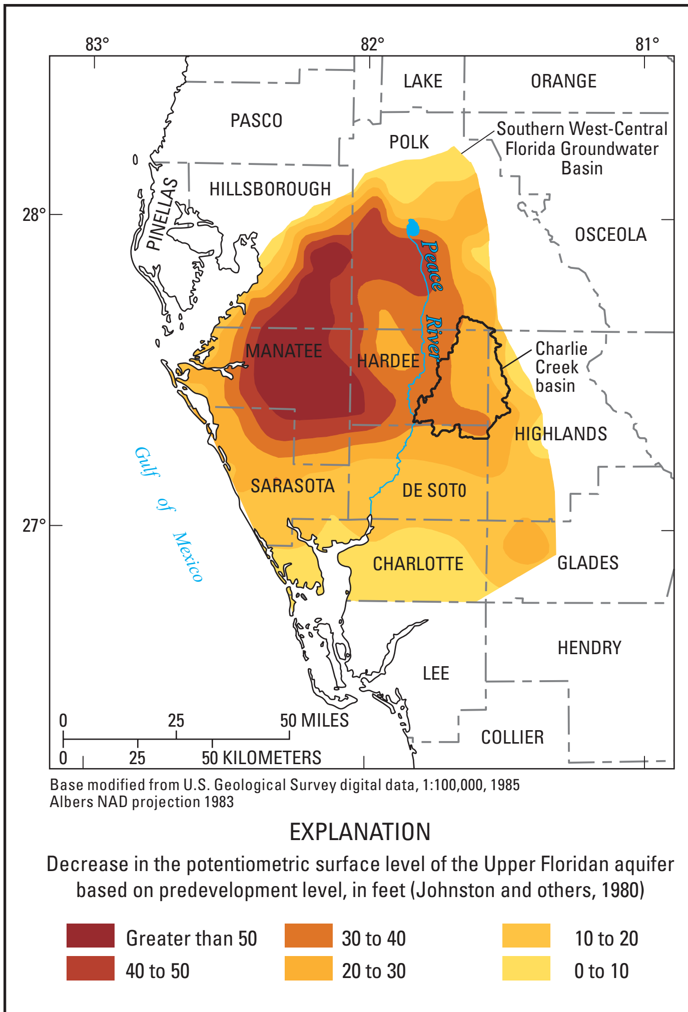

Figure 13. Decrease in the potentiometric surface of the Upper Floridan aquifer from predevelopment levels to May 2007 for the Southern West-Central Florida Groundwater Basin (modified from Metz and Lewelling, 2009).

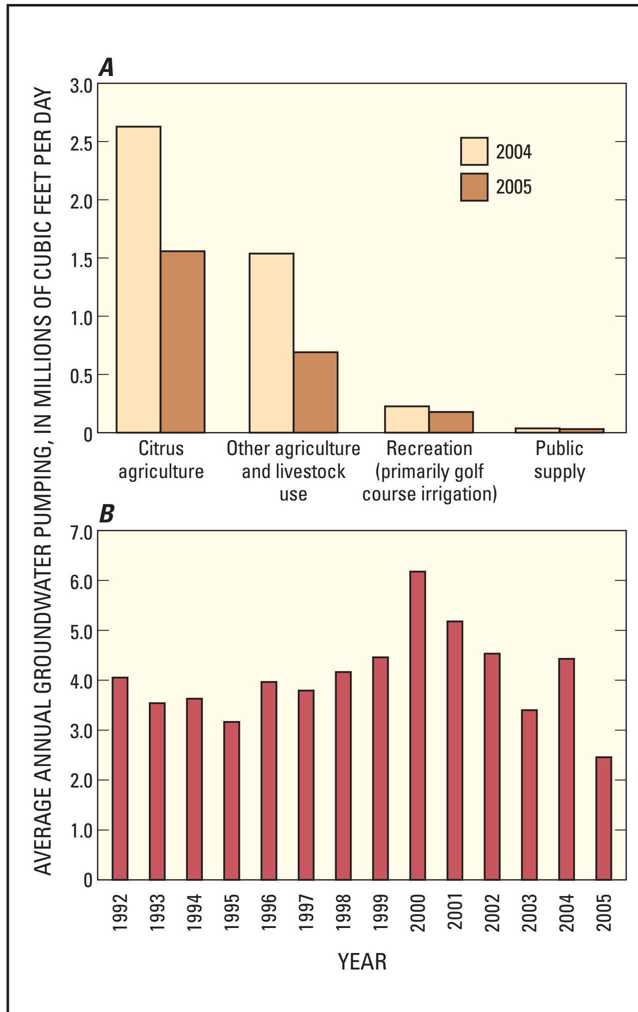

Figure 14. Estimated ground-water pumping in the Charlie Creek basin *A,* by use category for 2004 and 2005, and *B,* as annual averages from 1992 to 2005.

District, written commun., 2007). For example, 99.5 percent of water used in 2004 and 2005 was groundwater, when over 2,200 wells in the Charlie Creek basin had groundwater use permits. The intermediate aquifer system and Upper Floridan aquifer are both used as a water-supply source. The majority (57 percent) of wells with groundwater use permits are open to both aquifers. Pumping from these wells accounted for 56 percent of the groundwater use for 2004 and 2005. Of the remaining 44 percent of water pumped, 39 percent was solely from the Upper Floridan aquifer, and 4 percent was from wells completed in the intermediate aquifer system. Less than 1 percent of groundwater pumped was from wells completed in the surficial aquifer.

More than 90 percent of the groundwater was used for agriculture (including livestock), with the majority used for citrus irrigation (59 and 63 percent for 2004 and 2005, respectively) (fig. 14A). Most of this water (58 percent in 2004-2005) was pumped from the Upper Charlie Creek and Lower Charlie Creek subbasins. However, the Buckhorn Creek subbasin had the greatest volume of groundwater pumped relative to its size, and had more water pumped exclusively from the intermediate aquifer system than did other basins (table 3). Expressed as pumpage per surface area, total groundwater withdrawals from Buckhorn Creek subbasin were about 1.6 times greater than the average of the other four subbasins in 2004-2005. The Buckhorn Creek subbasin also had a greater percentage of its basin used for citrus agriculture than the other four subbasins (table 2). Little Charley Bowlegs Creek subbasin, which had the lowest percentage of its basin used for citrus agriculture, also had the least groundwater pumping relative to its size in 2004 and 2005 (table 3).

Water use in the Charlie Creek basin during 2005 was almost half that of 2004 (fig. 14A and table 3). Agricultural pumping was lower in 2005 because the 12.2 in. of precipitation received during the spring growing season from March through May was several inches above the long-term average for those months, compared to the drier spring of 2004 when the basin received only 4.8 in., half of the long-term average. Rainfall data for Hardee County and the long-term average are based on records from 1915 to 2008 (*http://www.swfwmd.state.fl.us/data/wmdbweb/rainfall_data_summaries.php*, accessed May 15, 2009).

Although annual rainfall for both years was above average, most of the rainfall in 2004 was due to tropical storms and hurricanes in August and September. For the 14 years (1992-2005) with available groundwater-use data, groundwater pumpage was greatest in 2000 (table 3) and the largest groundwater withdrawals occurred in the 4 years from 1999 to 2002 (fig. 14B), followed by 2004; withdrawals were lowest in 2005.

Aquifer Potentiometric Levels

The groundwater conditions in the Charlie Creek basin vary due to elevation changes in the potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer. A concurrent response in the overlying surficial aquifer brings the water table closer to or farther from the land surface and changes the potential for both runoff from rainfall and groundwater inflow to streams. Collectively, these changes affect the potential for groundwater inflow to Charlie Creek.

Upper Floridan Aquifer

During the 2004-2005 study period, heads in the Upper Floridan aquifer in the Charlie Creek basin were lowest in May 2004 and highest in September 2004. The potentiometric surface consistently sloped downward from the northeast toward the southwest, with heads in May 2004 decreasing from more than 70 ft above NGVD 1929 in the northeastern part of the basin to less than 40 ft above NGVD 1929 in the southwestern part (fig. 15). In September 2004, heads were about 15 ft higher overall and ranged from about 90 ft above NGVD 1929 in the northeastern part of the basin to about 50 ft above NGVD 1929 in the southwestern part. Water levels in two wells in the central part of the Charlie Creek basin were 17.6 and 20.4 ft higher in September 2004 than in May 2004. Groundwater flow paths had a slightly more westerly component in May 2004 than in September 2004 because of a regional low in the potentiometric surface west of Charlie Creek. The Upper Floridan aquifer levels changed more between September 2004 and May 2004 in the western part of the basin than in the northern and eastern parts.

Heads in the Upper Floridan aquifer were considerably higher during the study period than during the preceding

Table 3. Groundwater use in subdivided areas of the Charlie Creek basin.

[UFA, Upper Floridan aquifer; IAS, intermediate aquifer system; in, inch; mi^2, square mile]

Basin or subbasin	Groundwater pumping (in/yr)[1]			Groundwater pumping, in inches over subbasin, in 2004, from wells open to:[2,3]			
	2000	2004	2005	IAS only (in)	IAS and UFA (in)	All wells open to IAS (in)	UFA only (in)
Buckhorn Creek subbasin	4.09	3.13	1.65	0.22	2.06	2.28	0.63
Little Charley Bowlegs subbasin	1.75	1.36	0.78	0.01	0.88	0.89	0.46
Upper Charlie Creek subbasin	2.86	2.11	1.32	0.03	0.92	0.95	1.15
Oak Creek subbasin	3.37	1.94	1.13	0.10	0.99	1.09	0.85
Lower Charlie Creek subbasin	3.47	1.93	1.15	0.14	1.14	1.28	0.58
Upper half of Charlie Creek basin	2.60	1.95	1.17	0.04	1.01	1.05	0.87
Lower half of Charlie Creek basin	3.42	1.94	1.14	0.12	1.06	1.19	0.71
Charlie Creek Basin	2.95	1.94	1.16	0.08	1.03	1.11	0.80

[1]Groundwater pumping data from M. Kelley (Southwest Florida Water Management District, written commun. 2007).

[2]The sum of ‘UFA only’ and ‘All wells open to IAS’ can be less than ‘Groundwater pumping (in/yr) in 2004’ due to pumping from the surficial aquifer system or from wells without depth information.

[3]Depth to aquifers generalized for each subbasin from Arthur and others (2008).

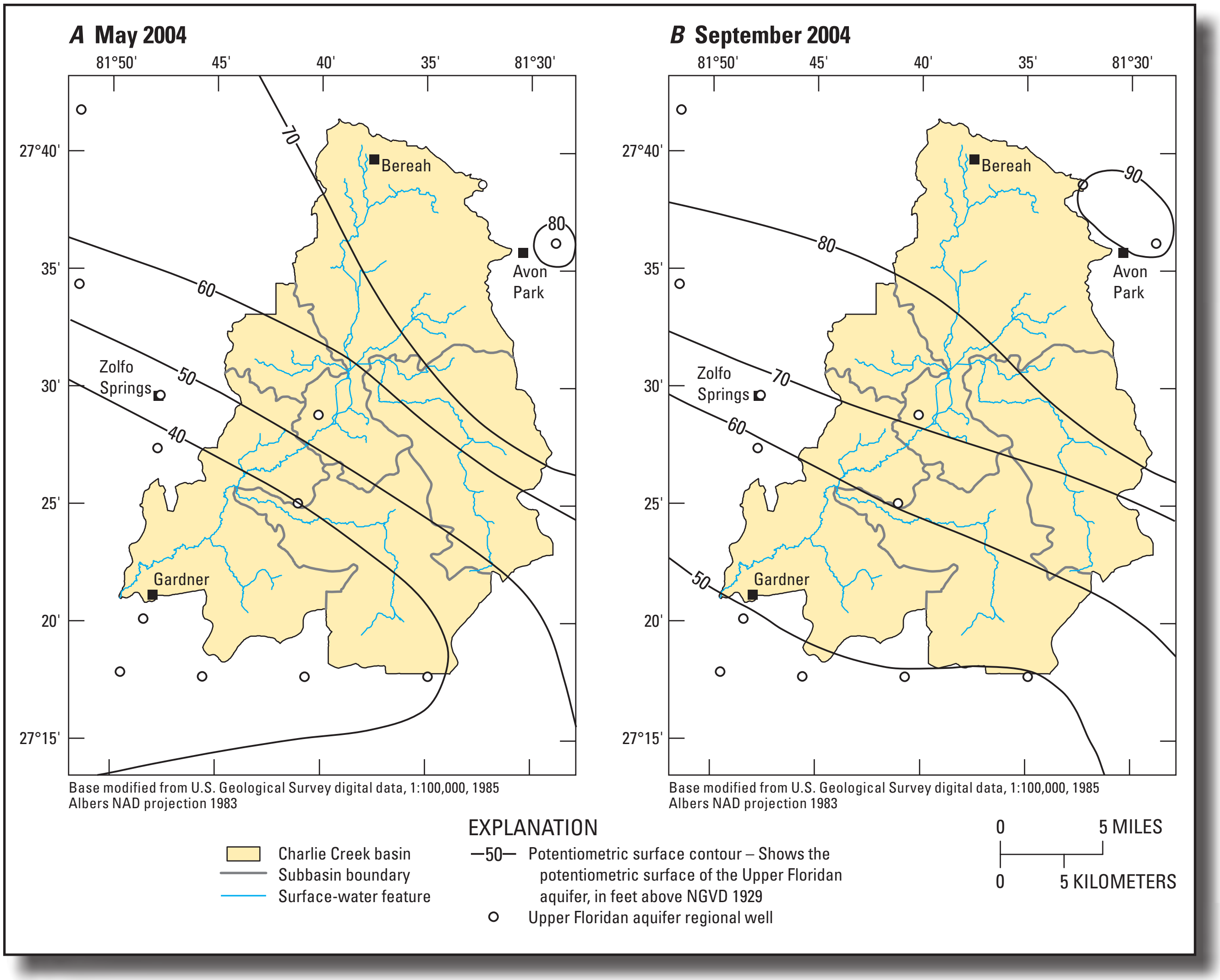

Figure 15. Potentiometric surface of the Upper Floridan aquifer for *A,* low (May 2004) and *B,* high (September 2004) conditions for the 2004-2005 study period.

several years, when a regional drought resulted in greater groundwater withdrawals and less recharge. During May 2000, heads in the Charlie Creek basin were as much as 40 ft below those observed in September 2004 (Duerr, 2001). May 2000 potentiometric contours focus flow lines toward the depressed potentiometric surface west of the Charlie Creek basin, where minimum heads were more than 20 ft *below* NGVD 1929. In May 2000, heads in the southwestern part of the Charlie Creek basin were lowered comparatively more than heads in the northern part of the basin. May 2000 heads in the Charlie Creek basin ranged from greater than 60 ft above NGVD 1929 in the northern part of the basin to less than 20 ft above NGVD 1929 in the southwestern part.

Two Upper Floridan aquifer wells in the Charlie Creek basin (wells 26 and 45; app. 1) with more than 20 years of data were evaluated for long-term trends (fig. 16). Potential trends were evaluated for the entire period of record for both wells, with wet and dry seasons analyzed separately. No statistically significant trends were observed for the dry season data or for all data grouped together (*t*-statistic on slope of the regression line, $\alpha = 0.05$). A statistically significant declining trend was noted for well 26 for the wet season ($p = 0.01$; $R2 = 0.27$), although data are missing for 9 of the 34 years of record.

Intermediate Aquifer System

There are enough data available to construct potentiometric surface maps for permeable Zone 2 of the intermediate aquifer system in the Charlie Creek basin for the study period. Potentiometric surface maps constructed for Zone 2 relied on data from wells either open only to Zone 2, or open to both Zones 2 and 3. Wells open to both zones were included for two reasons. First, it was assumed that the composite intermediate

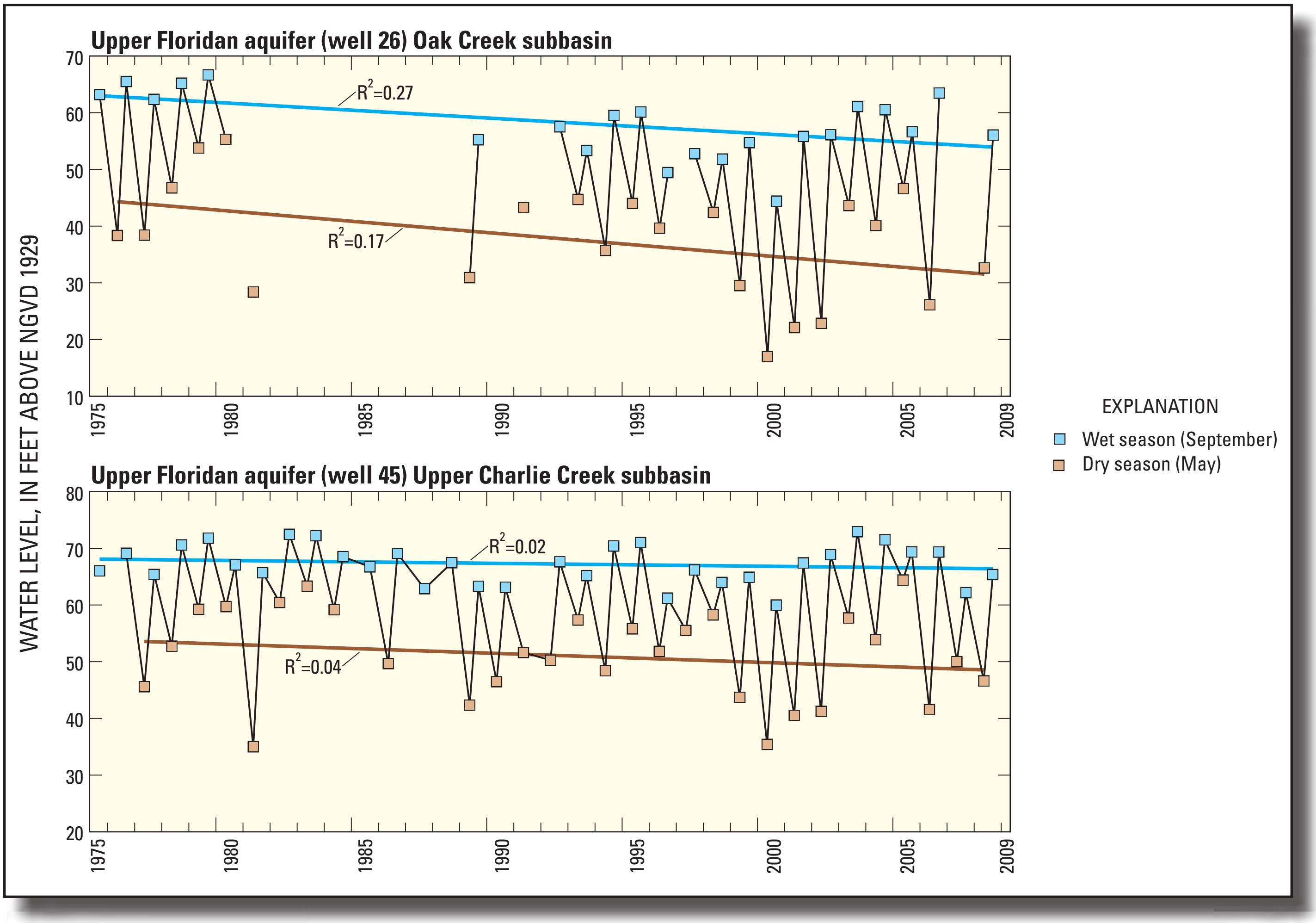

Figure 16. Wet and dry season water levels in two Upper Floridan aquifer wells in the Charlie Creek basin from 1975 to 2008. Well locations shown in figure 8.

aquifer system head would be more similar to Zone 2 in areas where that zone is thick (north and east part of the basin). Second, heads in both zones are similar at two ROMP sites just south and west of the Charlie Creek basin (median difference less than 1 ft, based on daily data from 2004-2005). Therefore, composite heads in the southern and western parts of the basin were assumed to be similar to those in the uppermost permeable zone (Zone 2) in the intermediate aquifer system. The 10-ft contour interval used for the maps should allow for minor errors inherent in both assumptions. Permeable Zone 2 is referred to simply as the intermediate aquifer system hereafter.

During the study period, heads were lowest in the intermediate aquifer system in May 2004 and highest in September 2004, as was the case in the Upper Floridan aquifer (fig. 17A-B). For both conditions, heads were highest in the northern part of the basin and lowest in the southwestern part of the basin, near the mouth of Charlie Creek. Heads in May 2004 ranged from less than 40 ft above NGVD 1929 in the southwestern part of the basin to greater than 110 ft above NGVD 1929 in the northern part. Similar to the Upper Floridan aquifer, heads in the intermediate aquifer system in September 2004 were about 10 to 15 ft higher than in May 2004, and ranged from about 50 ft above NGVD 1929 in the southwestern part of the basin to more than 120 ft above NGVD 1929 in the northern part.

During the regional drought in May 2000, heads in the intermediate aquifer system were much lower than during the study period. The water level in well 30 in the central part of the Charlie Creek basin (fig. 8) was 39 ft lower in May 2000 than in September 2004. Heads during May 2000 ranged from about 20 ft above NGVD 1929 in the southwest part of the basin to more than 80 ft above NGVD 1929 in the northern part.

Of the three wells in the intermediate aquifer system in the Charlie Creek basin with long-term record (wells 56, 30, and 5 shown on fig. 17), two have about 20 years of water-level data (wells 5 and 30). No long-term trends in water levels were observed for well 30 in the central Charlie Creek basin ($\alpha = 0.05$) (fig. 18). The water-level responses in well

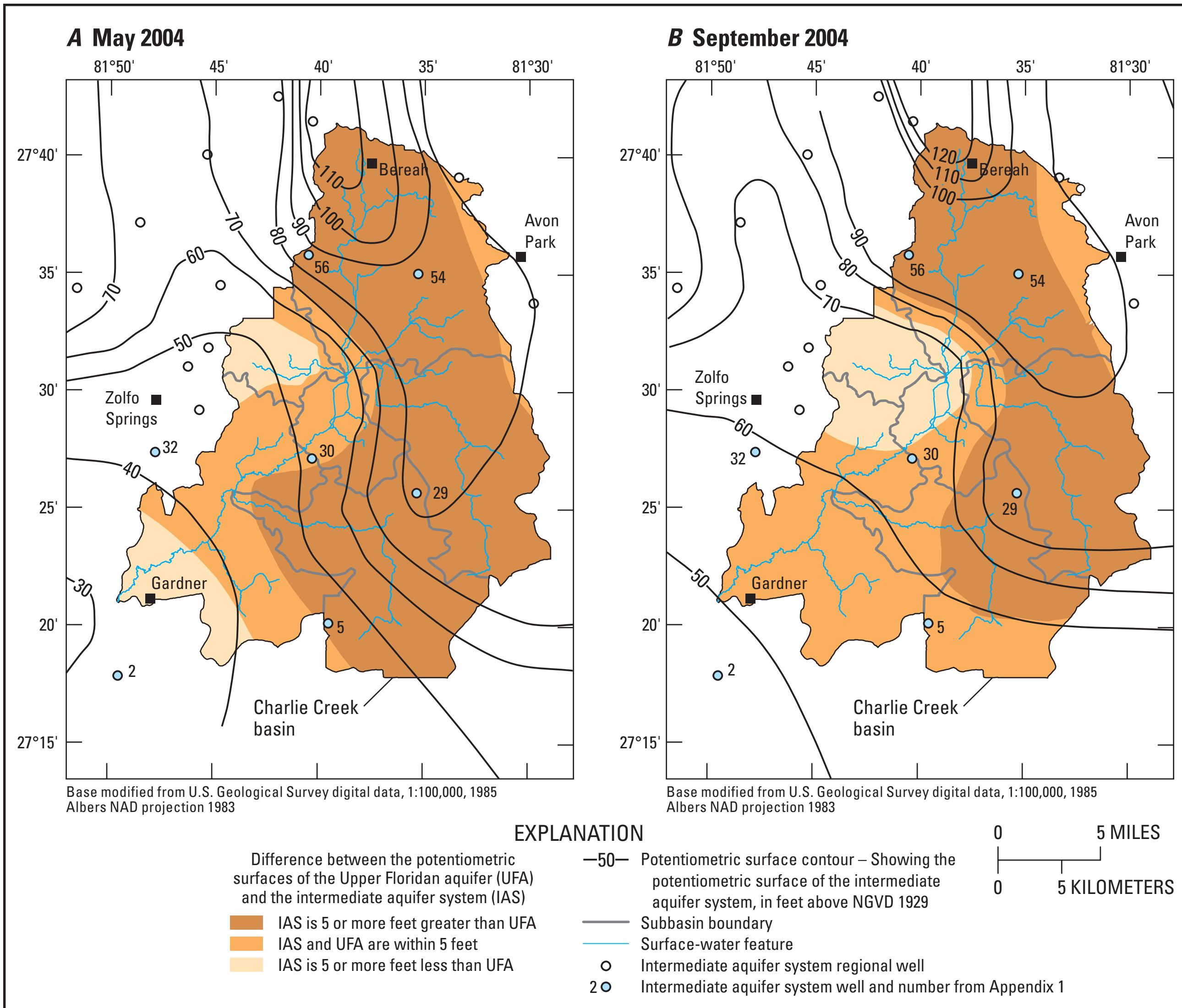

Figure 17. Potentiometric surfaces of the intermediate aquifer system for *A,* dry (May 2004) and *B,* wet (Sept. 2004) conditions during the study, also showing areas where the intermediate aquifer system heads are greater and less than heads in the Upper Floridan aquifer.

56 in the northern basin were similar to well 30, but the short record prevented the interpretation of trends. However, a statistically significant declining trend was noted for dry-season water levels ($p = 0.02$) for well 5 in the southern part of the basin. For that well, no significant trends were observed for the wet season, or for all of the data considered together.

Head Differences between the Intermediate Aquifer System and Upper Floridan Aquifer

A potential for downward flow from the intermediate aquifer system (Zone 2) to the Upper Floridan aquifer existed over about 80 percent of the Charlie Creek basin during both May and September of 2004. In the remaining 20 percent of the basin, the heads in the Upper Floridan aquifer were above those in the intermediate aquifer system. Because the contour lines cannot be positioned precisely due to limited data, figure 17 illustrates areas where the vertical head difference between aquifers was greater than 5 ft. The majority of the basin, 67 and 50 percent for May and September 2004, respectively, still displayed heads in the intermediate aquifer system that were 5 ft or more higher than heads in the underlying Upper Floridan aquifer. The downward flow potential between the two aquifers existed in the eastern and central parts of the

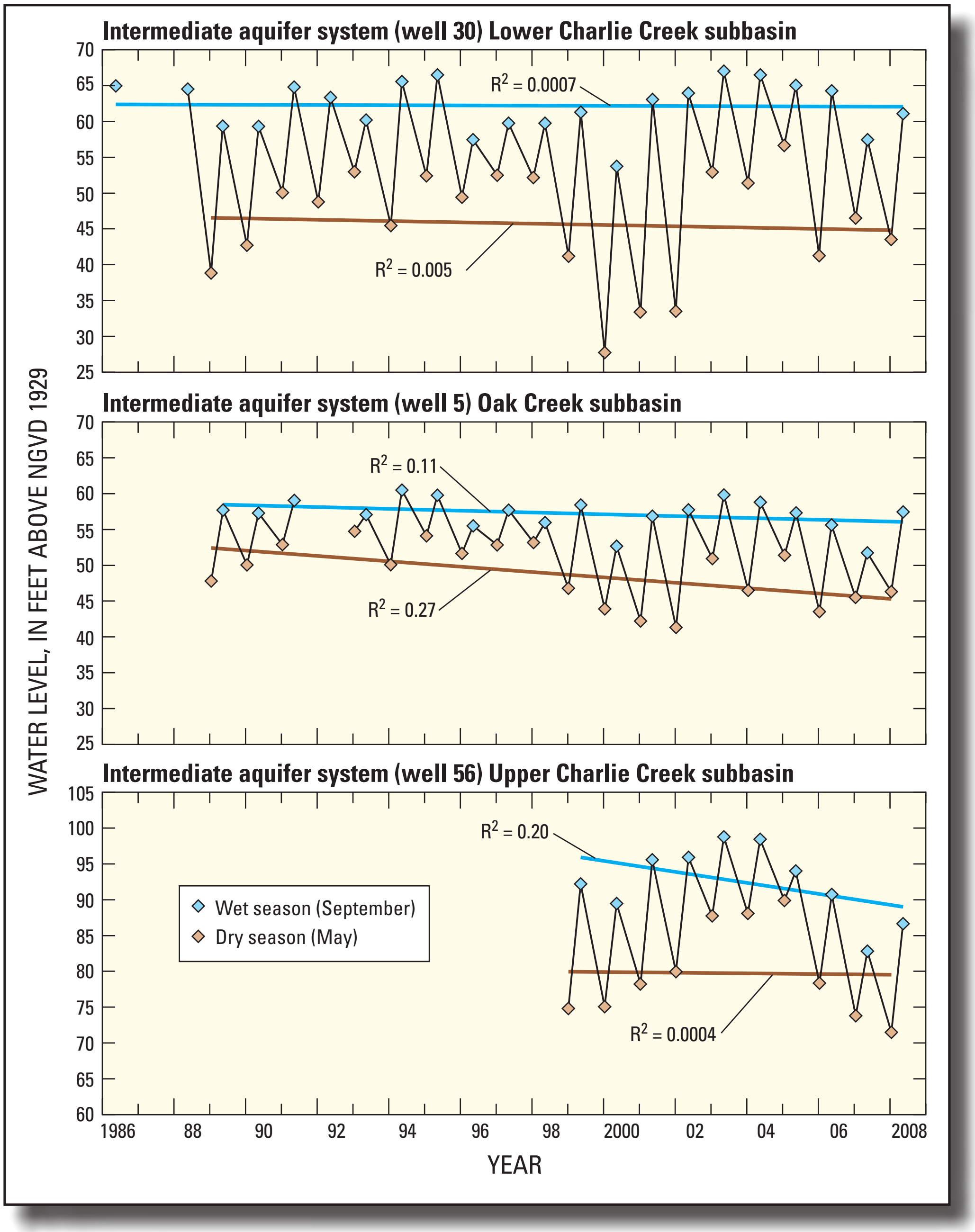

Figure 18. Wet and dry season water levels in three intermediate aquifer system wells in the Charlie Creek basin from 1986 to 2008. Well locations are shown in figure 8.

basin, which corresponds to much of the upper Charlie Creek and Little Charley Bowlegs subbasins, and parts of Oak Creek subbasin. Only about 10 percent of the basin had an upward head difference of more than 5 ft. These conditions existed in the west-central part of the basin, centered over much of Buckhorn Creek basin, in May and September 2004. In May 2004, the southwest part of the Charlie Creek basin showed a similar potential for upward flow from the Upper Floridan aquifer toward the intermediate aquifer.

The spatial extent of the downward flow potential between the intermediate and Upper Floridan aquifers was considerably larger during May 2000, when groundwater levels were extremely low because of an extended drought and increased pumping. During this period, 93 percent of the basin had a downward head difference between the aquifers, compared to 80 percent during 2004. However, the percentage of the basin with a downward head difference of more than 5 ft in May 2000 was comparable to that in May 2004, at 65

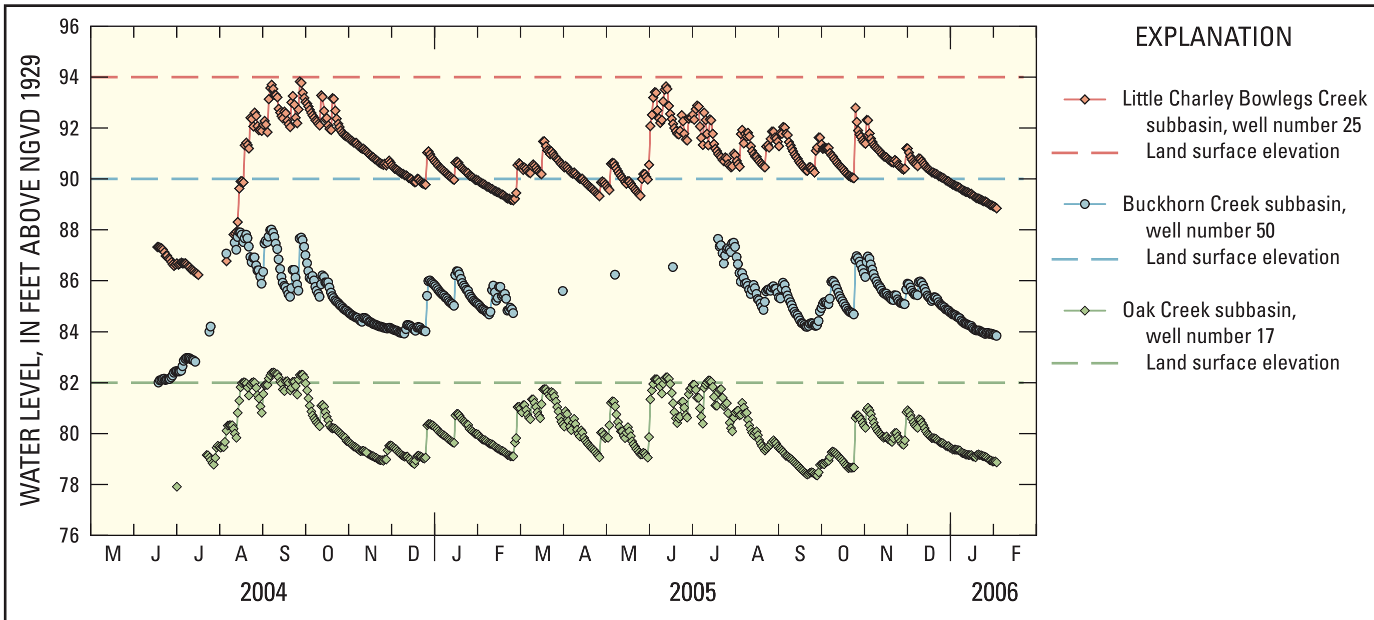

Figure 19. Daily average water levels in the surficial aquifer at upland wells in the three tributary subbasins. Well locations are shown in figure 8.

and 67 percent, respectively. Only 7 percent of the basin had an upward head difference in May 2000, and less than 1 percent of the basin had an upward head difference greater than 5 ft. This suggests that the Upper Floridan aquifer was drawn down to lower levels during the drought than the intermediate aquifer system.

Surficial Aquifer

The water table in the surficial aquifer of Charlie Creek was not mapped due to sparse data; however, the water table is assumed to generally reflect land surface topography, with higher elevations in upland areas and lower elevations near streams. For the network of surficial aquifer wells monitored for this study, water-table elevations ranged from a low of 25 ft above NGVD 1929 near Charlie Creek at the downstream well transect to a high of 97 ft above NGVD 1929 at ROMP 43. The highest water-table elevations in the basin were inferred from lake stages to be along ridge areas near the eastern and northern basin divide. For example, the average stage of Lake Chilton, at the northeastern basin divide (fig. 2), was 112 ft above NGVD 1929 during 2004-2005, indicating a slightly higher water table in that area than at ROMP 43 (fig. 8). The greatest water-table depths also were inferred to be in these areas where ridge elevations can exceed 150 ft above NGVD 1929. The lowest measured water-table elevations were in the southwestern part of the basin near Charlie Creek, where flow is toward stream channels. At upland sites, the water table fluctuated between 3 and 7 ft during the study. In monitoring wells near streams, the range was greater (7-12 ft), reflecting, in part, the bank storage caused by peak streamflows. The relation between the water table and the streams is described later in the discussion of groundwater interactions with Charlie Creek. The water table in monitoring wells ranged from at land surface during wet periods to greater than 10 ft below land surface during drier periods.

Water-table elevations were continuously monitored near the centers of the three tributary subbasins and showed similar temporal patterns (fig. 19). As with the potentiometric surface, the water-table elevations at the three sites decreased from the north and east toward the southwest and were highest in the Little Charley Bowlegs subbasin (typically above 90 ft NGVD 1929) and lowest in the Oak Creek subbasin, as indicated by water levels in wells 25 and 17, respectively (fig. 8 and app. 1). The lowest water-table elevations were recorded at the beginning of the data collection period, in mid-June to early July 2004 (fig. 19). The highest water-table elevations were generally in September 2004, following a wet rainy season and heavy rainfall from Hurricanes Charley, Frances, and Jeanne. The water table remained relatively high during 2005 compared to the low levels recorded at the beginning of the study. Rainfall was above average during the spring of 2005 (fig. 3), resulting in higher water-table elevations than during the drier spring of 2004. When the water table was highest, the water levels in wells 25 and 17 approached land surface (fig. 19).

Temporal Changes in Vertical Head Differences between Aquifers

Vertical head differences between aquifers indicated the surficial aquifer continually recharged the underlying intermediate aquifer system at the three ROMP sites (fig. 20). However, the flow direction varied over time between zones within the intermediate aquifer system, and between the intermediate and Upper Floridan aquifers. Heads in the surficial aquifer were higher than in Zone 2 of the intermediate aquifer system at all three sites, although the difference ranged from a median value of 2.2 ft at ROMP 43 to 24.9 ft at ROMP 26, possibly indicating greater confinement between these aquifers at ROMP 26 (fig. 20).

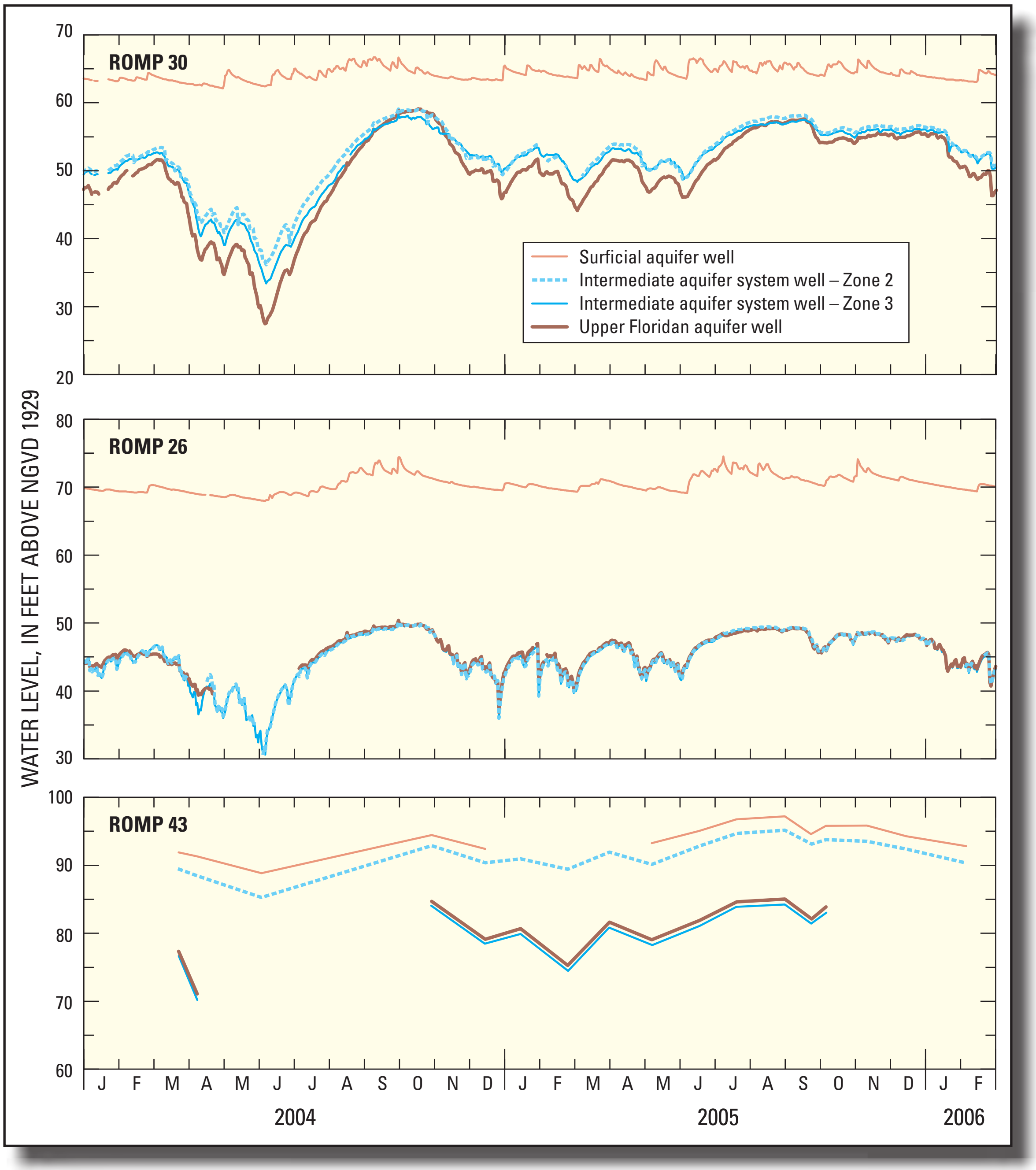

Figure 20. Water levels in wells in the surficial aquifer, Zones 2 and 3 of the intermediate aquifer system, and the Upper Floridan aquifer at ROMP 30, ROMP 26, and ROMP 43.

At all three ROMP sites, groundwater in Zone 2 of the intermediate aquifer system predominantly flowed downward toward Zone 3. Heads in Zone 2 of the intermediate aquifer system were higher than in Zone 3 for the majority of the study period, but the magnitude of this difference varied considerably between sites (median 0.1 to 11.5 ft; fig. 20). At ROMP 26 and ROMP 30, the median downward head difference between the zones was less than 1 ft, and the direction occasionally reversed to an upward head difference. In contrast, heads in Zone 2 were always substantially higher than in Zone 3 at ROMP 43. Leakance estimates at ROMP 43 were two orders of magnitude lower for Zone 2 than for Zone 3, indicating that Zone 3 has a stronger hydraulic connection to the Upper Floridan aquifer than to Zone 2 of the intermediate aquifer system (LaRoche, 2007). Leakance estimates were not available for the other sites.

At two of the three ROMP sites, ROMP 26 and ROMP 43, heads in Zone 3 were similar to those in the Upper Floridan aquifer and typically slightly lower (median 0.3 and 0.6 ft lower, respectively, fig. 20), suggesting substantial hydraulic connection between Zone 3 of the intermediate aquifer system and the Upper Floridan aquifer and indicating the potential for upward discharge. This may be the result of local groundwater pumping from wells open to both aquifers. Because the Upper Floridan aquifer has a considerably higher transmissivity than the intermediate aquifer system, the Upper Floridan aquifer is expected to have less drawdown than the intermediate aquifer system for a given withdrawal rate. At ROMP 30, the head in Zone 3 was typically greater than the Upper Floridan aquifer (median difference 1.8 ft), indicating predominantly downward recharge into the Upper Floridan aquifer; however, reversals did occasionally occur at this site.

Groundwater and Stream Interactions

The changing groundwater levels in the basin determine the interaction of Charlie Creek with groundwater. This section examines in greater detail the groundwater heads controlling lateral and vertical flow patterns in the aquifers adjacent to and beneath Charlie Creek and its tributaries, and then describes the measured contribution of seepage to Charlie Creek. The specific conductance of streamflow in different areas of the basin is described and provides further evidence of the interaction between the stream network and the watershed.

Artesian Flow Conditions in the Basin

Groundwater in both the Upper Floridan aquifer and the intermediate aquifer system (Zone 2) exhibited artesian head conditions in areas of the Charlie Creek basin. Artesian head conditions exist where the potentiometric surface of groundwater in the aquifers is higher than land surface elevation, allowing groundwater to flow upward and out of any uncapped wells at land surface (***http://ga.water.usgs.gov/edu/gwartesian.html***). Artesian flow conditions in the intermediate aquifer system are of greater interest than those in the Upper Floridan aquifer in the Charlie Creek basin because groundwater leaks between the intermediate aquifer system and the overlying surficial aquifer. Prior to this study, only data for the potentiometric surface of the Upper Floridan aquifer were available and, therefore, could be used to infer areas of artesian flow conditions in the intermediate aquifer system. Heads mapped in the intermediate aquifer system during this study were higher than those in the Upper Floridan aquifer over the majority of the Charlie Creek basin. As a result, areas of artesian flow conditions in the intermediate aquifer system covered a larger area than those in the Upper Floridan aquifer basin-wide, but exceptions occurred in two subbasins (fig. 21).

Artesian head conditions in an aquifer cause the water level in a well to rise above land surface. (Photograph on left by A.M. Cressler, USGS; photograph on right by USGS.)

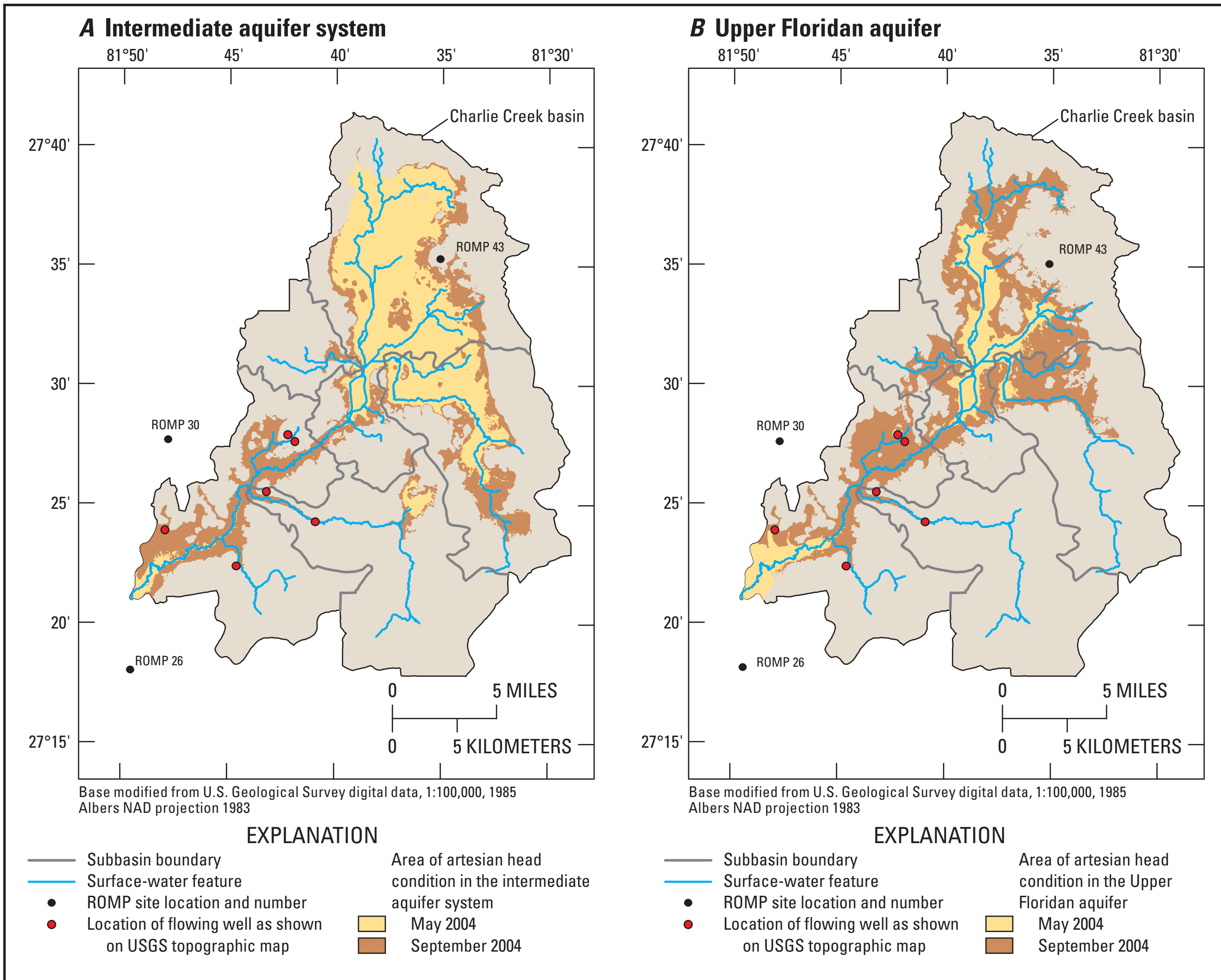

Figure 21. Artesian flow conditions in *A,* the intermediate aquifer system and *B,* the Upper Floridan aquifer in the Charlie Creek basin for low (May 2004) and high (Sept. 2004) head conditions during the 2004-2005 study period.

In the Buckhorn Creek and Lower Charlie Creek subbasins, the area of artesian flow conditions in the Upper Floridan aquifer was larger than that of the intermediate aquifer system at both low and high water-level conditions (fig. 21A and B). This result is consistent with the fact that the potentiometric surface of the intermediate aquifer system was more than 5 ft below the potentiometric surface of the Upper Floridan aquifer near Buckhorn Creek subbasin during May and September 2004 (fig. 17), as well as in the southern end of the Lower Charlie Creek subbasin for May 2004. These relative head positions indicate that groundwater could flow upward from the Upper Floridan aquifer toward the intermediate aquifer system; however, flow in the intermediate aquifer may not move upward into the surficial aquifer.

Groundwater pumping from the intermediate aquifer system in these two areas probably explains the lower heads in this aquifer relative to the Upper Floridan aquifer. In 2004, comparatively more groundwater was pumped in the Buckhorn Creek and Lower Charlie Creek subbasins than any other subbasins of Charlie Creek, from wells open exclusively to the intermediate aquifer system (0.22 in/yr and 0.14 in/yr, respectively), or to both the intermediate aquifer system and Upper Floridan aquifer (2.28 in/yr and 1.28 in/yr, respectively) (table 3). In contrast, groundwater withdrawals from the intermediate aquifer system were lowest in the northern subbasins (Little Charley Bowlegs and Upper Charlie Creek), where artesian flow conditions were extensive; withdrawals in the Oak Creek subbasin were only slightly greater (table 3). This comparatively greater pumping stress on the intermediate aquifer system in the southern and western regions of the Charlie Creek basin during the study could explain the lower heads in the intermediate aquifer system compared to the Upper Floridan aquifer in these parts of the basin (fig. 17).

Currently, no ROMP sites are within any of the areas of artesian flow mapped for this study. Therefore, vertical head differences between aquifers were not available to confirm whether (1) upward flow occurred between all three aquifers, or (2) water flowed from both the surficial aquifer and Upper Floridan aquifer into the intermediate aquifer system. During the highest water-level conditions of this study, the expanding areas of artesian flow approached the ROMP 43 site, but never reached it (fig. 21). Six flowing wells, originally shown on USGS 1:24,000-scale quadrangle maps from the 1950s, are located in the lower parts of Charlie Creek or Oak Creek subbasins within, or very near, mapped areas of artesian conditions for both aquifers in September 2004 (fig. 21). However, these wells were outside the areas of artesian conditions for both aquifers for May 2000 and May 2004. The six flowing wells are all clearly within the areas of artesian head conditions associated with the predevelopment potentiometric surface of the Upper Floridan aquifer (Ryder, 1985).

Delineating the areas of the Charlie Creek basin that have artesian conditions, and the duration of these conditions, helps define where the surficial aquifer and its embedded streams and wetlands have the potential to gain water from or lose water to the underlying intermediate aquifer system. The quantity of water exchanged between these aquifers can be small because the rate of water movement is typically slowed by clay layers within the intermediate aquifer system. However, artesian conditions contribute flow to the surficial aquifer, and moreover, prevent water from leaking downward out of wetlands, streams, and the surficial aquifer, especially through preferential flow paths.

The Upper Peace River basin provides an extreme example of a setting where artesian flow conditions below the stream have been largely lost (fig. 1). In areas of the Upper Peace River basin, heads in the intermediate aquifer system can be tens of feet below the elevation of the Peace River streambed, and water leaking through karst features in the streambed periodically leaves sections of the river dry (Metz and Lewelling, 2009). If the confining clays between the surficial and intermediate aquifer system become breached by subsidence, erosion, or mining, more permeable carbonate rocks can become exposed, creating preferential paths for groundwater flow. The creation of preferential flowpaths could also be accelerated if overlying clayey sand sediments become dry, shrink, and ravel down into karst solution openings (Metz and Lewelling, 2009).

In the Charlie Creek basin, the distribution of recharge and artesian flow conditions varied seasonally and annually. In the upper half of the basin, artesian flow conditions in the intermediate aquifer system were relatively consistent during the study, ranging from 31 to 44 percent of the total area in May and September of 2004, respectively (table 2). Most of the expansion in September 2004 resulted from artesian conditions advancing upstream along Little Charley Bowlegs Creek tributary and downstream along Charlie Creek in the Upper Charlie Creek subbasin, as well as spreading into headwater wetlands and areas bordering the stream channel (fig. 21A).

In contrast, artesian conditions in the lower half of the basin underwent a more extreme change. In May 2004, artesian conditions in the intermediate aquifer system were present in only 3 percent of the Lower Charlie Creek subbasin, subjecting most of the lower channel of the creek to potential recharge conditions, with only a small area at the downstream end of Charlie Creek exhibiting artesian flow conditions (fig. 21A). By September 2004, artesian flow conditions in the intermediate aquifer system expanded to encompass 25 percent of the Lower Charlie Creek subbasin (table 2), including all of the area below the main channel of Charlie Creek and the adjacent riverine floodplain, and extending upstream along small tributaries and Oak Creek—the principal tributary in the lower basin (fig. 21A). In May 2004, artesian head conditions in the intermediate aquifer system were present in only 2 percent of the Oak Creek subbasin, and were absent beneath the stream channel of Oak Creek—as was the case along the lower channel of Charlie Creek. Instead, artesian conditions encompassed a roughly circular area of isolated wetlands in the Oak Creek subbasin and an associated tributary flowing into Oak Creek about halfway up its reach (fig. 21A and fig. 5). The wetter conditions of September 2004 expanded the size of the artesian flow conditions around this wetland area. During the drought in May 2000, artesian conditions in the intermediate aquifer system existed in only 2 percent of the entire Charlie Creek basin, in the headwaters of the Upper Charlie Creek subbasin.

In the upper half of the Charlie Creek basin, areas with artesian flow conditions in the Upper Floridan aquifer differed substantially from those in the intermediate aquifer system, and the size of artesian flow areas in the Upper Floridan aquifer were not a consistent predictor of its size in the intermediate aquifer system (fig. 21B). In May 2004, artesian conditions in the Upper Floridan aquifer encompassed about 8 percent of the upper half of the Charlie Creek basin while artesian conditions in the intermediate aquifer system encompassed nearly 4 times that amount, or 31 percent of the upper basin (table 2). In September 2004, the two areas were more similar in relative size; artesian conditions in the Upper Floridan aquifer encompassed 30 percent of the upper half of the basin, and artesian conditions in the intermediate aquifer system encompassed about 1.5 times that amount, or 44 percent of the upper basin.

In the lower half of the Charlie Creek basin, areas of artesian flow predicted from the two aquifers were more comparable, but the Upper Floridan aquifer heads typically implied larger areas of artesian flow than the intermediate aquifer system heads. Individual subbasins had greater disparities, but in most cases the areas were closer in relative size during the wet season than during the dry season. In contrast with the study period, during the drought in May 2000 artesian conditions in the Upper Floridan aquifer were nearly

Table 4. Differences between head in the intermediate aquifer system and the overlying streambed elevation for subbasins in the Charlie Creek basin.

[All values shown except percentages are in feet. Positive elevation differences indicate upward flow conditions; negative differences indicate downward flow conditions. %, percent]

Elevation difference statistic	Stream					
	Charlie Creek, Upper Channel[1]	Charlie Creek, Lower Channel[2]	Oak Creek	Buckhorn Creek	Little Charley Bowlegs Creek	All stream channels in Charlie Creek basin
			May 2004			
Average	6	3	-14	-14	-1	-2
Minimum	-52	-8	-37	-33	-25	-52
Maximum	25	16	2	6	11	25
% positive	81%	69%	1%	12%	46%	48%
% negative	19%	31%	99%	88%	54%	52%
			September 2004			
Average	18	19	-5	-1	10	10
Minimum	-33	6	-28	-17	-16	-33
Maximum	38	33	18	16	20	38
% positive	94%	100%	39%	44%	89%	78%
% negative	6%	0%	61%	56%	11%	22%
			May 2000			
Average	-7	-16	-30	-31	-24	-19
Minimum	-44	-29	-41	-57	-50	-57
Maximum	14	0	-18	-6	-5	14
% positive	25%	0%	0%	0%	0%	9%
% negative	75%	100%	100%	100%	100%	91%

[1] Upstream from streamflow monitoring station near Crewsville, including Bee Branch.

[2] Downstream from streamflow monitoring station near Crewsville, main channel only.

absent from the entire Charlie Creek basin. For predevelopment groundwater levels, the artesian flow area estimated in the Upper Floridan aquifer covered about 35 percent of the entire basin (Ryder, 1985), compared to 25 percent of the basin in September 2004 (figs. 1A and 21B).

Vertical Flow Potential between Streams and the Intermediate Aquifer System

The potential for upward and downward groundwater flow along the stream network changed substantially between the low and high head conditions during the study (May and September 2004, respectively), and relative to the historically low head conditions of May 2000 (fig. 22).

For the histroically low head condition in May 2004, about half (52 percent) of the total length of Charlie Creek and its tributaries had a downward head difference, and the intermediate aquifer system heads were an average of 2 ft below the corresponding elevations of Charlie Creek and its tributaries (fig. 22A; table 4). Of the streams with an upward head difference, the upward head difference was greater and covered more of the stream network in the Upper Charlie Creek subbasin than the Lower Charlie Creek subbasin (81 percent, compared to 69 percent). For Little Charley Bowlegs Creek subbasin, about half the stream length was subject to an upward head difference and the average intermediate aquifer head was 1 ft below the channel. Tributary streams in the Buckhorn Creek and Oak Creek subbasins were dominated by downward head differences. Heads in the intermediate aquifer system were an average of 14 ft below the streambed elevations in both subbasins, and only a small percentage of the length of either Buckhorn Creek or Oak Creek experienced an upward head difference (12 and 1 percent, respectively).

For the high head condition observed in September 2004, the vast majority of the streams in the Charlie Creek basin

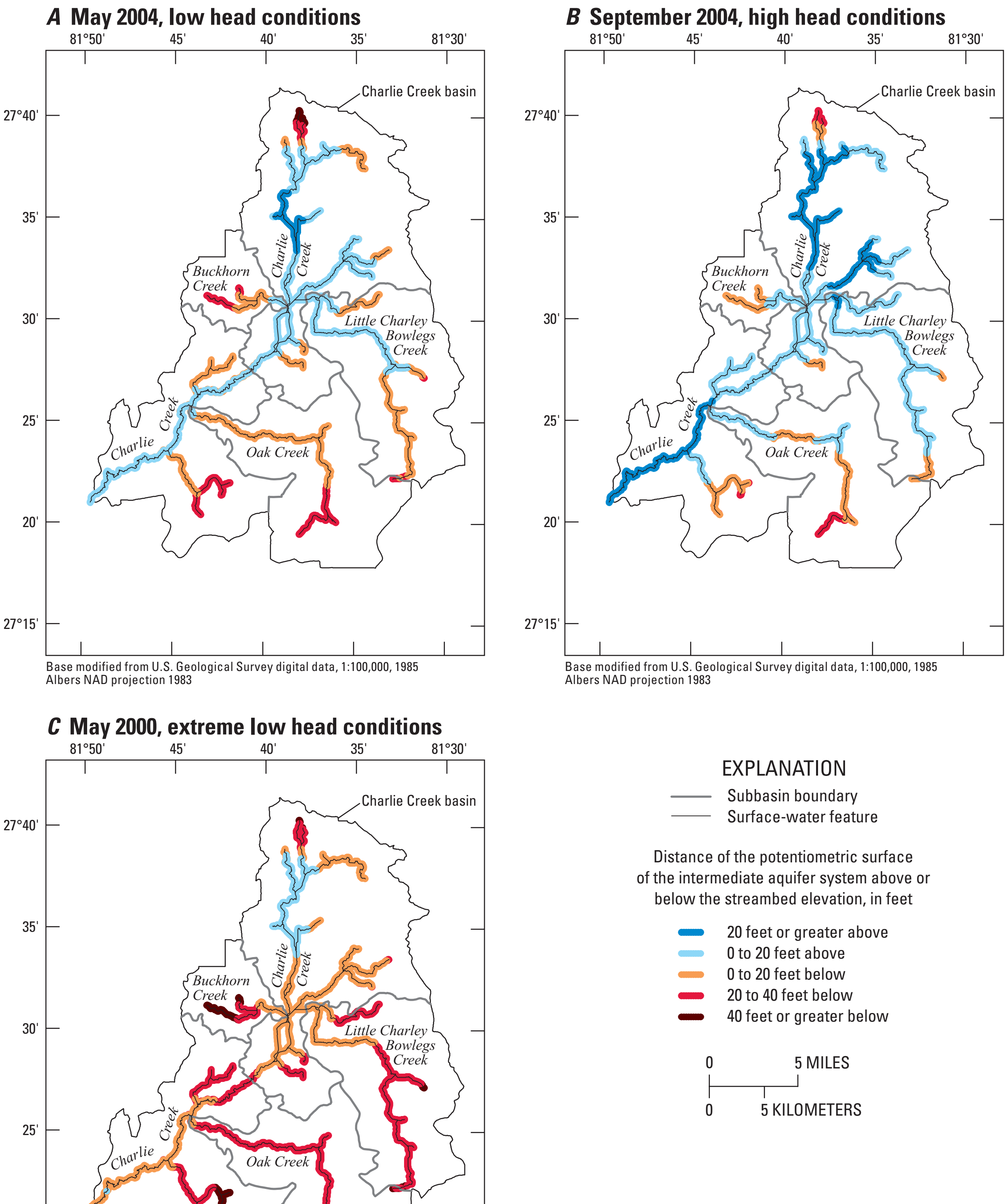

Figure 22. Difference between head in the intermediate aquifer system and streambed elevation for Charlie Creek and major tributaries, for *A,* low (May 2004) and *B,* high (Sept. 2004) head conditions during the 2004-2005 study period, and for *C,* very low head conditions (May 2000).

experienced upward head conditions (78 percent of all stream channels) and heads in the intermediate aquifer system averaged 10 ft above the average streambed elevation in the basin (fig. 22B; table 4). Upward head conditions were concentrated along the main channel of Charlie Creek: 100 percent of the main channel of Charlie Creek in the Lower Charlie Creek subbasin experienced upward head conditions averaging 19 ft above the streambed. In the headwaters-dominated Upper Charlie Creek subbasin, 94 percent of all stream channels experienced upward head conditions that averaged 18 ft above the streambed. Of the three tributary streams, the majority of Little Charley Bowlegs Creek was affected by upward head differences, whereas the percentage of stream channels experiencing upward head differences in the Oak Creek and Buckhorn Creek subbasins increased to 39 and 44 percent, respectively.

The historically low head conditions of May 2000 provided the greatest potential for water in Charlie Creek and its tributaries to leak downward (fig. 22C). Intermediate aquifer system heads averaged 19 ft *below* the bed elevation of the stream network over the entire basin (table 4). Intermediate aquifer system heads averaged 16 ft below the streambed elevations in the Lower Charlie Creek subbasin compared to 7 ft below in the Upper Charlie Creek subbasin. The largest downward head differences were in Buckhorn Creek and Oak Creek subbasins, which averaged about 30 ft below the stream channel. The only place in the entire basin with an upward head difference was at the headwaters wetland area of the Upper Charlie Creek subbasin (fig. 22C).

For all three conditions depicted in figure 22, Oak Creek was the subbasin with vertical head differences that most consistently allowed for downward recharge between the stream and intermediate aquifer system. Alternatively, the Lower Charlie Creek and Little Charlie Bowlegs Creek subbasins exhibited the largest swings in vertical head differences, from large upward head differences to large downward ones. These changes altered conditions in the Lower Charlie Creek subbasin the most, with 100 percent of the main channel experiencing an upward potential for groundwater flow in September 2004, and 100 percent experiencing downward leakage potential in May 2000 (table 4). The complete head reversal and loss of artesian head conditions in the Lower Charlie Creek subbasin did not occur in the other subbasins for these two periods. The larger than expected change in the Lower Charlie Creek subbasin is probably attributable to groundwater pumping effects on the intermediate aquifer system within and outside the subbasin, lowering heads comparatively more in this subbasin than others during the May 2000 drought.

Stream Interactions with the Surficial Aquifer

The surficial aquifer contributed groundwater directly to Charlie Creek and its tributaries whenever the water table in the adjacent surficial aquifer was higher than the stream stage. Vertical groundwater flow patterns were described at two cross sections through Charlie Creek and used to examine seasonal changes in these patterns at different locations in the basin. Groundwater levels in the surficial aquifer were taken from transect wells at each cross section. Heads in the deeper intermediate aquifer system and Upper Floridan aquifer were interpolated at each location from potentiometric surface maps.

Charlie Creek

Charlie Creek almost continually received groundwater inflow from the surficial aquifer during the study period, but the magnitude of the inflow gradients differed at the downstream transect location compared to the upstream location. Groundwater levels measured approximately monthly in transect wells were plotted on a cross section through the stream channel. The conditions shown in figures 23 and 24 are close to the lowest and highest head conditions observed in the intermediate aquifer system and Upper Floridan aquifer for the study period. The dates representing the lowest and highest measurable head conditions are July 1, 2004, and October 28, 2004, respectively, and bracket the hurricanes of August and September 2004. Although intermediate aquifer system heads in the basin were actually highest in September 2004 (fig. 25), many of the wells were flooded that month as a result of high stream stage.

The stream profile near the upstream transect is broad and shallow, and the stream probably receives less groundwater inflow here than at the more deeply incised downstream site. Compared to the downstream transect, the slope of the water table toward the stream was lower at the upstream transect, and was sometimes away from the stream (fig. 23). The median lateral gradient of the water table at the upstream site was 0.0023 (for wells 1, 2, 5, 6, and 8), an order of magnitude lower than at the downstream site. The upstream site also experienced upward head gradients within the surficial aquifer near the stream less frequently compared to the downstream site. The median vertical gradient was 0.042 (for wells 3 and 4), which also is an order of magnitude lower than at the downstream site. In July and October 2004, heads in the intermediate aquifer system exceeded the stream stage elevation by 6 and 17 ft, respectively.

Recharging conditions probably occurred at the upstream site when the stream stage rose above the adjacent water table. At lower stream stages, however, the water table sloped toward the stream, and very small upward head gradients were present in the surficial aquifer. Groundwater inflow was probably minimal during the low water-level conditions of July 1, 2004, when the stream had stopped flowing, and the stream stage and adjacent water-table were low (fig. 23A). However, peak streamflows occurring while the water table was low probably resulted in recharge to the surficial aquifer. For example, around August 10, 2004, stream stage rose higher than the adjacent water table and flooded wells near the stream channel. The stage peaked at even higher elevations during the next 2 months, flooding monitoring wells and recharging the surficial aquifer (fig. 25A).

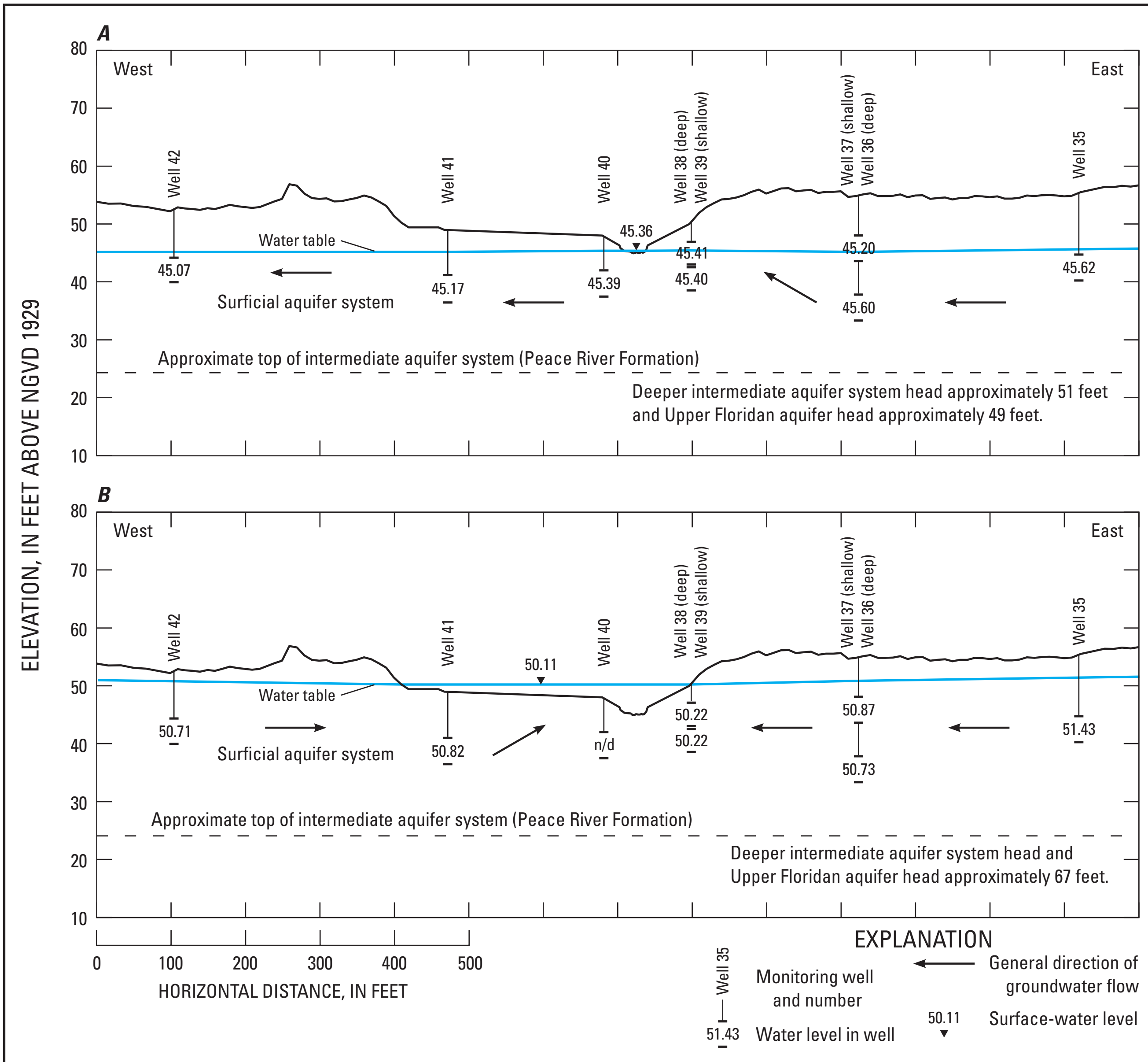

Figure 23. General groundwater flow direction around Charlie Creek at the upstream transect site for *A,* July 1, 2004, and *B,* October 28, 2004.

At the downstream transect, groundwater flow was characterized by upward flow in the surficial aquifer near the stream and fairly steep lateral gradients toward the stream (fig. 24). The water table consistently sloped toward the stream during all observations, with steeper slopes on the south bank of the river. Both lateral and vertical head gradients were lowest at high stream stage, but were still toward the stream. The highest lateral and vertical gradients were on September 22, 2005, following the end of the rainy season, when the stream stage receded much faster than the adjacent water table.

The upward flow potential from the intermediate aquifer system also tended to be greater at the downstream transect compared with the upstream transect. When the potentiometric head of the intermediate aquifer system was near the seasonal low on July 1, 2004, the head at the downstream transect was about 19 ft higher than the stream stage (fig. 24A). When the potentiometric head was near its highest level on October 28,

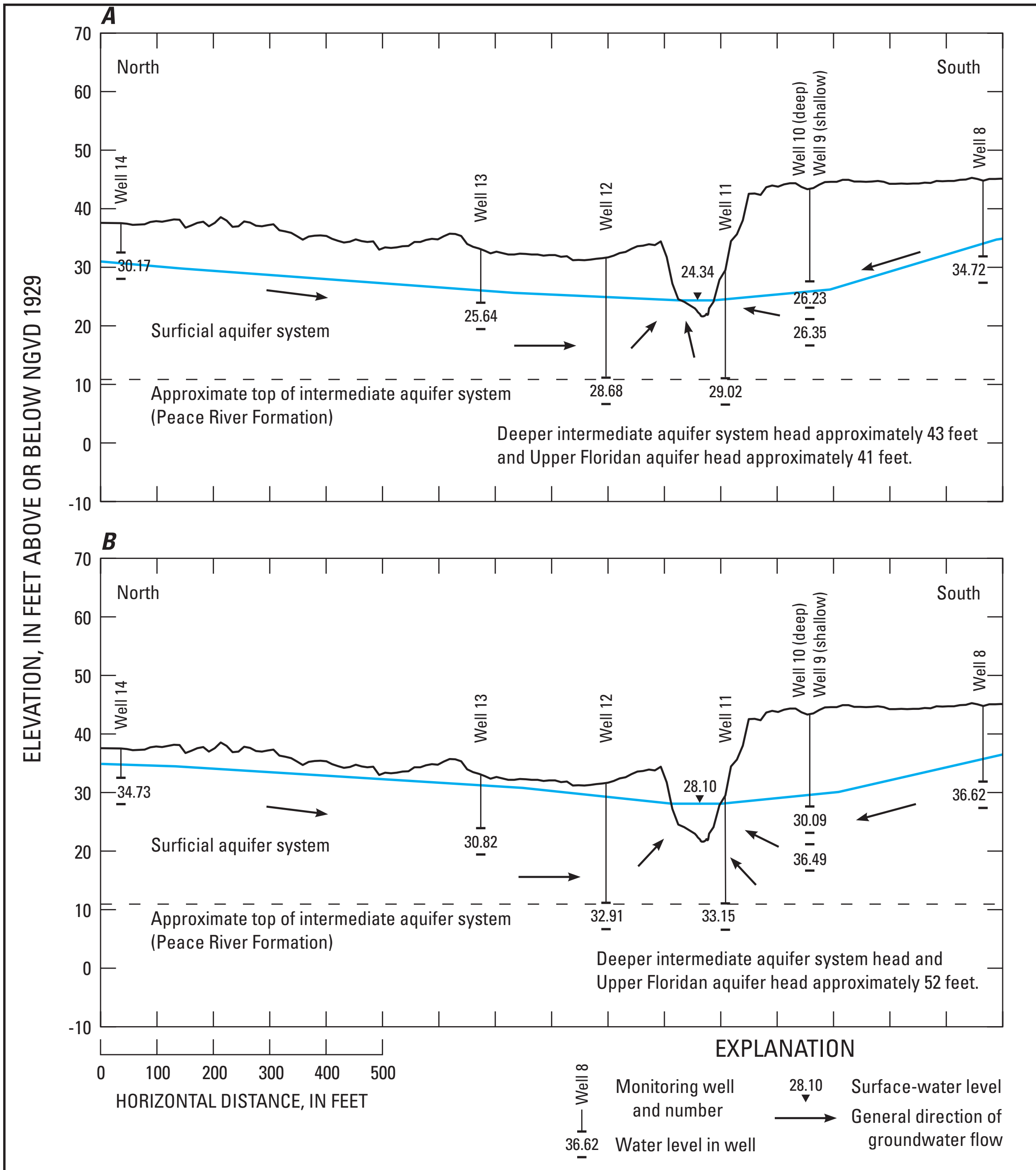

Figure 24. General ground-water flow direction around Charlie Creek at the downstream transect site for *A*, July 1, 2004, and *B*, October 28, 2004.

2004, the head in the intermediate aquifer system was about 24 ft higher than the stream stage (fig. 24B). These were larger upward head differences than at the upstream transect for the same dates. Greater lateral and vertical head gradients at the more incised, downstream transect site existed throughout the study (fig. 25B).

Tributaries

The three Charlie Creek tributaries also showed the potential to receive groundwater inflow from the surficial aquifer. Buckhorn Creek showed a potential to gain from, and lose to, the surficial aquifer. Groundwater levels measured in a deeper well in the surficial aquifer near the Buckhorn Creek

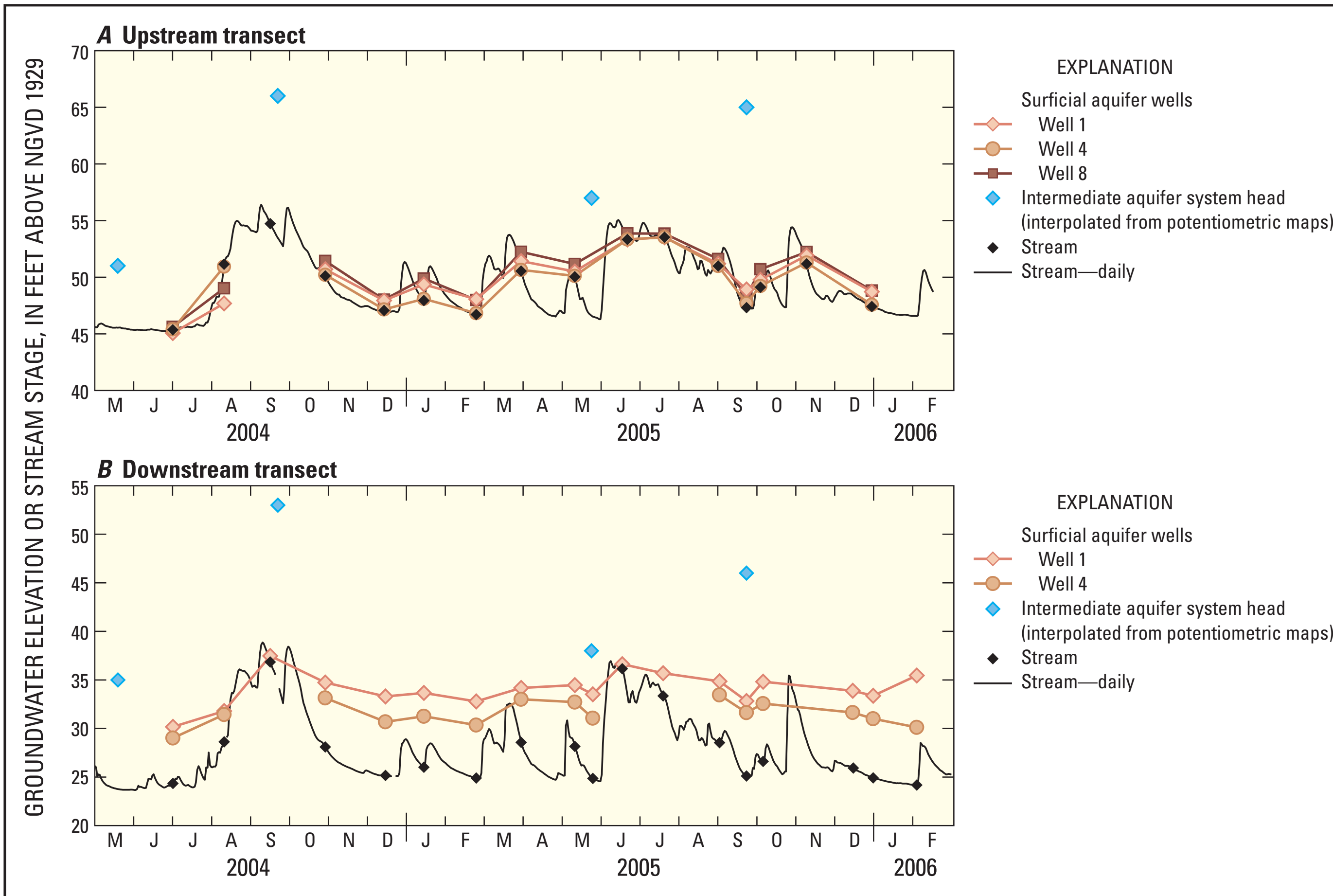

Figure 25. Water levels in representative wells and Charlie Creek at the *A*, upstream and *B*, downstream well-transect sites.

gage consistently had a higher head than the shallow well, indicating upward flow in the surficial aquifer (figs. 8 and 26A). A fairly steep upward gradient was present between the two surficial aquifer wells (median 0.61), with a slightly lower upward gradient between the deeper well and the stream (median 0.17). During this time, the head in the intermediate aquifer system near this site was higher than stream stage and the head in surficial wells (fig. 26A), indicating the potential for upward flow. Although flow potential between the wells was upward, the water level in the shallow surficial aquifer well was usually lower than the stream stage, possibly due to evapotranspiration from shoreline vegetation depressing the water table near the stream. Water levels in the shallow well were higher than stream stage for several months following the recession of peak flood flows in September 2004, probably due to the effects of bank storage. Water levels in the deep surficial aquifer well were higher than the stream stage for all observations except in early August of 2004 and possibly May 2004. Measurements were not available in May 2004 to establish whether downward head conditions existed in the surficial aquifer, but the intermediate aquifer system head was below the stream stage in Buckhorn Creek, indicating the potential for downward flow.

Upward flow also occurred consistently in the surficial aquifer near Little Charley Bowlegs Creek (fig. 26B). Like Buckhorn Creek, the deeper surficial aquifer well at Little Charley Bowlegs Creek had a greater head than the shallow surficial aquifer well, indicating a potential for upward flow. The median vertical gradient between surficial aquifer wells (0.052) was an order of magnitude less at this creek than at Buckhorn Creek, but the vertical gradient between the deep surficial aquifer well and the stream was similar to that for

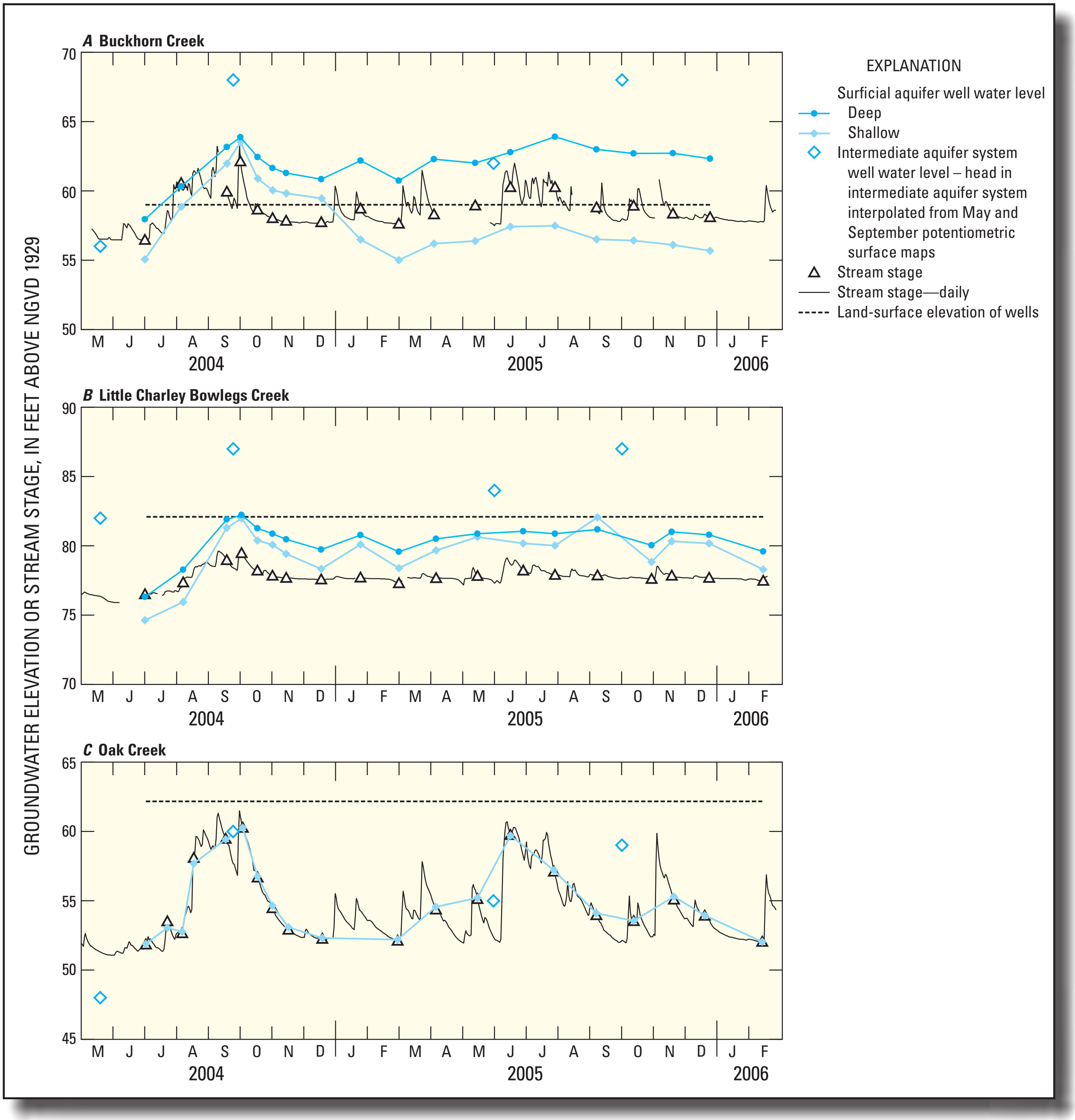

Figure 26. Water levels in the stream and adjacent surficial aquifer system at *A,* Buckhorn Creek, *B,* Little Charley Bowlegs Creek, and *C,* Oak Creek.

Buckhorn Creek (median 0.12). The water level in the shallow surficial aquifer well was most frequently greater than the stream stage, except in late June and early August 2004, when the water level was lower (fig. 26B). The median lateral head gradient between the shallow well and the stream was 0.0095, which is greater than at the upstream transect on Charlie Creek, and indicates inflow. Heads in the intermediate aquifer system near Little Charlie Bowlegs Creek were consistently higher than the stream stage and water levels in the surficial wells, indicating upward flow toward the surficial aquifer.

There was only one well at Oak Creek, and, consequently, the vertical flow direction within the surficial aquifer could not be determined (fig. 26C). The single surficial aquifer well was at a depth similar to the deep wells at the other tributary sites. The vertical head gradient between the stream and well was about an order of magnitude lower than at the other sites (median 0.0095). The groundwater level was similar to stream stage (median difference 0.07 ft) and slightly above it about 80 percent of the time. Reversals in flow occurred during high stage, when stream water was probably recharging the surficial aquifer. The head in the intermediate aquifer system near the Oak Creek gage was below stream stage in May 2004, and on the other three measurement dates the upward head difference between the intermediate aquifer system and stream stage was less than at the two other tributaries (fig. 26C).

Seepage Inflow to Charlie Creek

Seepage runs quantified the groundwater inflow to Charlie Creek implicit in the groundwater flow patterns. Groundwater inflow was greater than outflow during the seepage runs, as indicated by seepage gains for all significant seepage values. May 26, 2005, was the only date when the seepage gains measured within five of the six river reaches were large enough to be interpreted discretely and without being summed over multiple reaches (table 5). For that date, reaches with the greatest seepage corresponded to areas where the intermediate aquifer system head was highest above the streambed (fig. 27A). Seepage inflow had to be interpreted over combined stream reaches for the other three seepage-run dates because otherwise seepage inflow was not significantly greater than the potential seepage error.

Seepage errors for stream reaches with significant seepage, where the seepage rate was greater than 10 percent of the average streamflow in the reach, ranged from 30 to 58 percent, with a median of 53 percent. In contrast, stream reaches where seepage magnitudes were less than 10 percent of the average streamflow had errors ranging from 100 to over 5,000 percent because the quantity of seepage between sections was small compared to streamflow. Results from this study indicate that the uncertainty in seepage estimates is potentially much higher than percentage errors associated with the discharge measurements alone.

Table 5. Seepage run results with error estimates for 2005-2006 measurement dates.

[Locations of seepage run reaches are provided in figure 7 and appendix 2. Negative values indicate seepage loss from stream. (ft^3/s)/mi, cubic foot per second per river mile; --, data not available]

Reach	Reach length (miles)	February 18, 2005		May 26, 2005		December 29, 2005		January 23, 2006	
		Seepage (ft^3/s)/mi	Error (ft^3/s)/mi	Seepage (ft^3/s)/mi	Error (ft^3/s)/mi	Seepage (ft^3/s)/mi	Error (ft^3/s)/mi	Seepage (ft^3/s)/mi	Error (ft^3/s)/mi
A	1.3	0.57	0.60	-0.18	0.40	0.09	1.70	-0.37	0.70
B	3.4	0.61	0.35	0.70	0.20	-0.10	0.70	-0.13	0.30
C	1.4	0.58	0.95	1.19	0.60	1.00	1.80	0.06	0.70
D	2.3	0.40	0.74	1.16	0.60	-0.93	1.30	0.47	0.50
E	1.7	0.79	1.18	--	--	1.34	1.90	0.51	0.80
F	4.1	0.24	0.54	[1]1.0	0.35	0.81	0.90	0.78	0.40
A-C	6.1	0.59	0.16	0.62	0.13	0.19	0.40	-0.14	0.15
D-F	8.1	0.40	0.23	1.04	0.22	0.43	0.40	0.63	0.18
A-F	14.2	0.49	0.11	0.86	0.12	0.33	0.22	0.30	0.10

[1] No measurement made at upstream section, so combined reaches E and F.

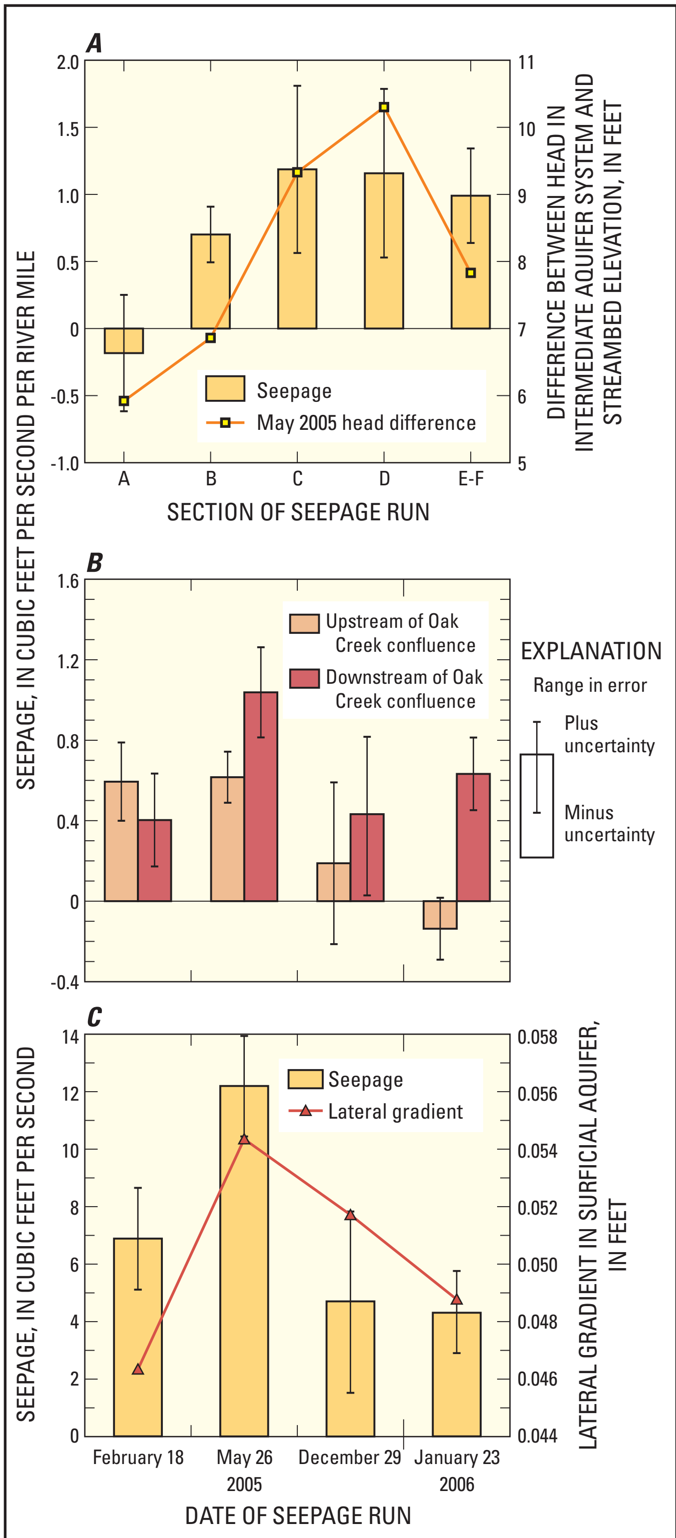

Figure 27. Groundwater inflow to Charlie Creek for *A,* different stream reaches during May 2005, *B,* all four seepage runs for sections upstream and downstream of the confluence with Oak Creek, and *C,* all seepage runs for the entire stream reach.

Seepage quantities were consistently significant when the individual reaches of Charlie Creek were combined and considered as two larger reaches located upstream and downstream of the confluence with Oak Creek (A-C and D-F on fig. 7, fig. 27B and table 5). Average seepage for all four runs for the downstream reach (0.63 (ft^3/s)/mi) was about twice that of the upstream reach (0.31 (ft^3/s)/mi), confirming the greater importance of groundwater inflow along the downstream reach of the stream. Seepage values for the upstream reach (A-C) were greater than the estimated error for February and May 2005, but were less than the error for December 2005 and January 2006 seepage runs, and there was a possibility of negative seepage (leakage) in January. The downstream reach (D-F) had seepage values greater than the estimated error for all four seepage runs, with the greatest amount of seepage in May 2005 [8.4 ft^3/s or 1.04 (ft^3/s)/mi] (fig. 27B).

Seepage inflow was greatest when vertical and lateral gradients were largest in the shallow groundwater near the stream. These larger gradients probably resulted in more groundwater inflow from the surficial aquifer. Total seepage over the entire reach (A-F) ranged from 4.3 to 12.2 ft^3/s (table 5), with an average seepage of 7.1 ft^3/s (or [0.50 (ft^3/s)/mi]) for the four runs. Errors estimated for the entire reach were all less than calculated seepage, and ranged from 14 to 68 percent. The largest seepage inflow was on May 26, 2005, and the smallest was on January 23, 2006 (fig. 27C).

Although seepage inflow was related to vertical and lateral head gradients in the surficial aquifer, the seepage rates measured during this study did not appear to be correlated to the upward head differences between the intermediate aquifer system and the stream channel. In fact, the smallest upward head difference of the four seepage runs occurred in May 2005, coinciding with the largest measured seepage. Larger upward head differences would be expected to result in more upward flow potential from the deeper aquifer. However, the inability to discern any relation may be a consequence of the relatively high intermediate aquifer system heads during all four seepage runs. For example, heads at the ROMP 30 Zone 2 well, if used as an overall index of conditions, ranged between 49.4 and 56.4 ft for the seepage runs. Yet heads in the intermediate aquifer system at this site can be considerably lower. The lowest heads measured at the ROMP 30 site during the study were more than 13 ft lower than those measured during the seepage runs (36 ft NGVD 1929 in early June 2004), whereas the lowest heads on record were about 30 ft lower (21 ft NGVD 1929 in May 2000). Seepage runs conducted along Charlie Creek during periods when heads are lowest in the intermediate aquifer system could yield lower seepage inflow values, and possibly outflow values.

Seepage inflow is an important contributor to flow in Charlie Creek, particularly along its lower reach. On average, seepage determined from the four seepage runs accounted for 20 percent of the total outflow from the basin (measured at the Charlie Creek near Gardner gage on the same date), and 30 percent of the average flow along the combined A-F reach. Seepage into Charlie Creek (per river mile) measured during this study was greater than seepage measured during December 1993 for a 43-mi reach of Horse Creek, another tributary to the Peace River with a basin about two-thirds the size of Charlie Creek (table 1) (Lewelling, 1997). Total seepage into Horse Creek during the high base-flow conditions in December 1993 was about one quarter of the seepage into Charlie Creek measured in this study during periods of greatest seepage, although seepage accounted for a similar fraction of downstream flow for both streams. During a low base flow seepage run in May 1994, Horse Creek had a net loss of river water to groundwater (Lewelling, 1997).

Seepage data from previous studies in the Peace River basin are only roughly comparable to Charlie Creek because of different climate and groundwater pumping conditions than those during this study. Seepage inflow estimated for some reaches of the lower Peace River in Hardee County in April 1988 was 1.5 (ft^3/s)/mi (Duerr and Enos, 1991), slightly greater than that estimated for the entire reach of Charlie Creek in May 2005 [(12.2 ft^3/s or 0.86 (ft^3/s)/mi] (table 5). Seepage along other reaches of the lower Peace River in 1988, however, was up to four times greater than the greatest observed seepage at Charlie Creek during this study. Although seepage to other streams in the Peace River basin varied widely in magnitude, it generally represented a similar fraction of downstream flow (18 to 39 percent).

Stream Specific Conductance

Surface-water specific conductance provided an additional line of evidence for interpreting the flow paths and sources of water in Charlie Creek and its tributaries. Continuous specific conductance, measured at all five streamflow gages (fig. 4), varied considerably over time at each site and was negatively correlated with streamflow ($\alpha = 0.05$). Specific conductance also varied considerably between stream sites (fig. 28A), being lowest at Little Charley Bowlegs Creek (median 95 µS/cm) and highest at Buckhorn and Oak Creeks (median 396 and 311 µS/cm, respectively). The highest value observed was 863 µS/cm at Oak Creek, and the lowest value was 60 µS/cm at Little Charley Bowlegs Creek. The specific conductance of Charlie Creek was between those of its tributaries, with median values increasing from 169 µS/cm at the upstream gage to 211 µS/cm at the downstream gage.

Differences in agricultural land use in the basin appear to be an important factor controlling the specific conductance of stream water. Little Charley Bowlegs Creek had the smallest percentage of citrus agriculture in its basin (5 percent upstream of the gage), and the lowest median specific conductance (fig. 28B). In contrast, Buckhorn Creek had the greatest percentage of citrus agriculture in its basin (26 percent upstream of the gage) and the highest median specific conductance. The percentage of citrus agriculture in the Charlie Creek basin overall was between these extremes at 16 percent.

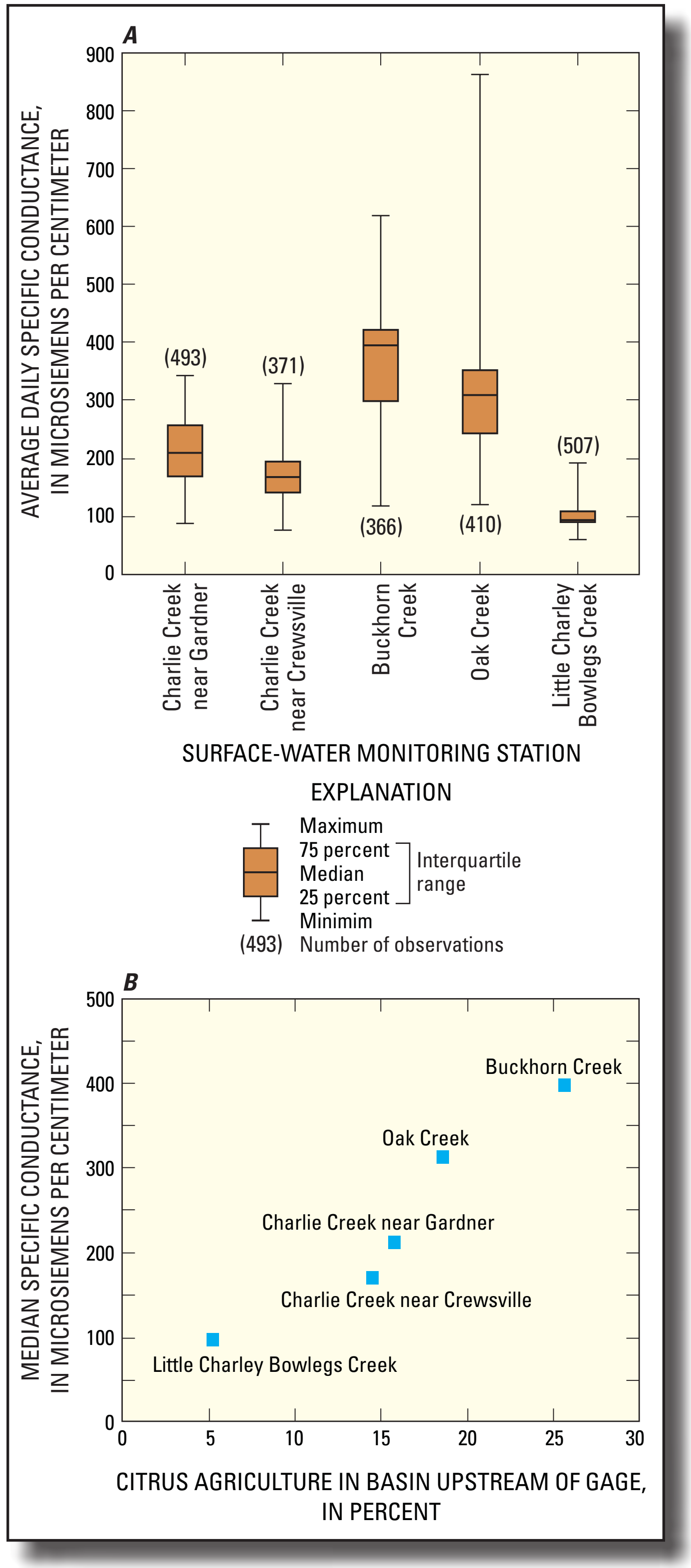

Figure 28. *A,* The range of daily values of specific conductance at the five streamflow stations in the Charlie Creek basin, and *B,* the relationship between the median specific conductance in the steams and the percent of the gaged basin in citrus agriculture in 2005.

Specific conductance is a general estimate of dissolved constituents in the water. Citrus agriculture has been associated with higher concentrations of many dissolved constituents in the surficial aquifer due to applications of fertilizers, salts, and pesticides (Stauffer, 1991; Sacks and others, 1998). Whether agricultural chemicals enter streams in the Charlie Creek basin mostly through the shallow groundwater or through drainage ditches fed by shallow groundwater and runoff is not known. Shallow groundwater quality was not sampled for this study. During seepage runs, however, the specific conductance in several small streams and ditches that drained agricultural areas was elevated (greater than 300 µS/cm), which is typical for agricultural runoff (app. 2).

Hydrologic Analysis of the Charlie Creek Basin

The prominent hydrologic processes in the Charlie Creek basin are examined herein by comparing the magnitude of the water-budget components within and among the subbasins. Simulated streamflows are addressed first, as the ability of the model to accurately simulate observed streamflows can greatly affect the accuracy of the other model-derived water-budget components. The water-budget results, whether derived from the model or calculated, are used individually and collectively to address (1) whether hydrologic characteristics are distinctively different in the subbasins; (2) which physical

Drainage from this citrus grove will eventually flow to a tributary in the Lower Charlie creek subbasin. (Photograph by T.M. Lee, USGS.)

characteristics (land cover, physiography, hydrogeologic framework) contribute to the observed differences in streamflows; and (3) which factors in the landscape of the basin are most responsible for maintaining the magnitude and timing of the streamflow of Charlie Creek.

Simulated Streamflow in Charlie Creek and its Tributaries

Global mass-balance errors in the numerical simulation of the Charlie Creek basin were small, indicating that the model was numerically stable. The model-generated discrepancies between total inflows and total outflows for all subbasins evaluated were always less than 0.4 percent of the sum of inflows (rainfall, irrigation, and lateral flow terms).

For the five subbasins, the model typically was able to accurately simulate the observed timing of streamflow responses to daily rainfall as well as the receding limb of the hydrograph between streamflow peaks (figs. 29-33). As expected in a watershed without significant anthropogenic surface-water discharges, streamflow peaks were associated with rainfall events. The magnitude of the simulated peak streamflow, however, was typically substantially less than observed streamflow during extreme rainfall events, most markedly for the three streamflow peaks following the rainfall from Hurricanes Charley, Frances, and Jeanne in August and September 2004. Underpredicting extreme events is a common shortcoming of regional scale integrated surface-water/groundwater flow models (Refsgaard, 1997; Vázquez and others, 2002; Interflow Engineering, 2008).

Overall, the simulated streamflow was closest to the observed streamflow at Little Charley Bowlegs Creek, the only tributary with a flow-control structure (weir), followed by Charlie Creek at the two streamflow stations: Charlie Creek near Crewsville and Charlie Creek near Gardner (figs. 29, 31, and 33). The mean error for the overall simulation period ranged from 7.47 ft^3/s to 57.43 ft^3/s, and was 15 percent or less of the daily average streamflow measured at the Charlie Creek near Crewsville, Charlie Creek near Gardner, and Little Charley Bowlegs Creek stations (table 6). The mean errors were a larger percentage of the daily average flow simulated at the two tributary gages, Buckhorn Creek near Griffins Corner and Oak Creek near Gardner. The mean errors for these two tributaries were small, however, relative to the peak streamflows at these stations. Nash-Sutcliffe statistics for the five simulated streamflows ranged from 0.35 to 0.80 and indicated the model was a better predictor of daily streamflow than mean streamflow (table 6). Streamflows predicted in Charlie Creek at the Crewsville and Gardner streamflow stations, and at Little Charley Bowlegs Creek gage, had the highest Nash-Sutcliffe correlation values of the five subbasins: 0.78, 0.69, and 0.80, respectively.

Peak flows simulated for the second and third hurricanes in August and September 2004 were well below observed values at Buckhorn Creek, which is the smallest of the three tributary subbasins and the tributary with the lowest daily average flow (fig. 30). The large peak flows followed by extremely low base flows typical of this basin were difficult to simulate. As a result, predicted flows for Buckhorn Creek had the lowest Nash-Sutcliffe value and the second largest mean error of the five subbasins (table 6).

Overall cumulative percent errors in streamflow for the 2003-2005 period ranged from 3.7 to 60 percent at the five stations, with Oak Creek having the greatest error (table 6). Annual cumulative percent errors varied at the five streamflow gages in the Charlie Creek basin, but were lowest in 2004 at the two streamflow gages along Charlie Creek. Large negative cumulative percent differences for the Buckhorn Creek near Griffins Corner gage were a result of underpredicted peak streamflows during the 2004 wet season. Large positive cumulative percent differences for the Oak Creek near Gardner gage resulted from overpredicting streamflows that were less than about 200 ft^3/s (fig. 32).

Comparing the simulated and observed streamflow distributions generally indicated that peak flow values were underpredicted by the model, and lesser flows were overpredicted. The simulated P10 flow value was 16 to 33 percent lower than the P10 value for the observed streamflows for all gages except Oak Creek near Gardner; for that gage, the model overpredicted peak flows, and the simulated P10 was larger than the observed P10 by 38 percent (table 7). In contrast, the model typically overpredicted the P25, P50, P75, and P90 for all subbasins, and the percentage differences generally increased as the observed percentile flow values decreased. The underprediction of peak events (P10) and overprediction of moderate and low flows (P25, P50, P75, and P90) indicates there was a temporal displacement in simulated runoff in the model. That is, water not simulated to arrive fast enough to contribute to the peak flow was distributed into the lower flow events. This result suggests the connectivity between surface-water features in the model may not be sufficient to adequately represent runoff processes for the full range of rainfall conditions observed in the Charlie Creek basin. In contrast, the model does not adequately account for processes in the Oak Creek basin that diminish the observed streamflow peak. Although model simulations generally underpredicted peak streamflows, the Nash-Sutcliffe statistic and cumulative streamflow comparisons indicated the model was a good overall predictor of hydrologic responses in the Charlie Creek basin.

In this study, overland and channel roughness coefficients generally have the greatest direct effect on simulated streamflow because rainfall is prescribed and infiltration and evapotranspiration are solved for implicitly. The weighted roughness coefficients used in the model are effective parameters that attempt to characterize the flow resistance across the model cell. Decreasing the effective roughness speeds the arrival of runoff from the basin to the stream, increasing peak streamflow and shortening the duration of high flow events. Conversely, increasing the effective roughness of model cells slows the arrival of runoff from the basin, decreasing total

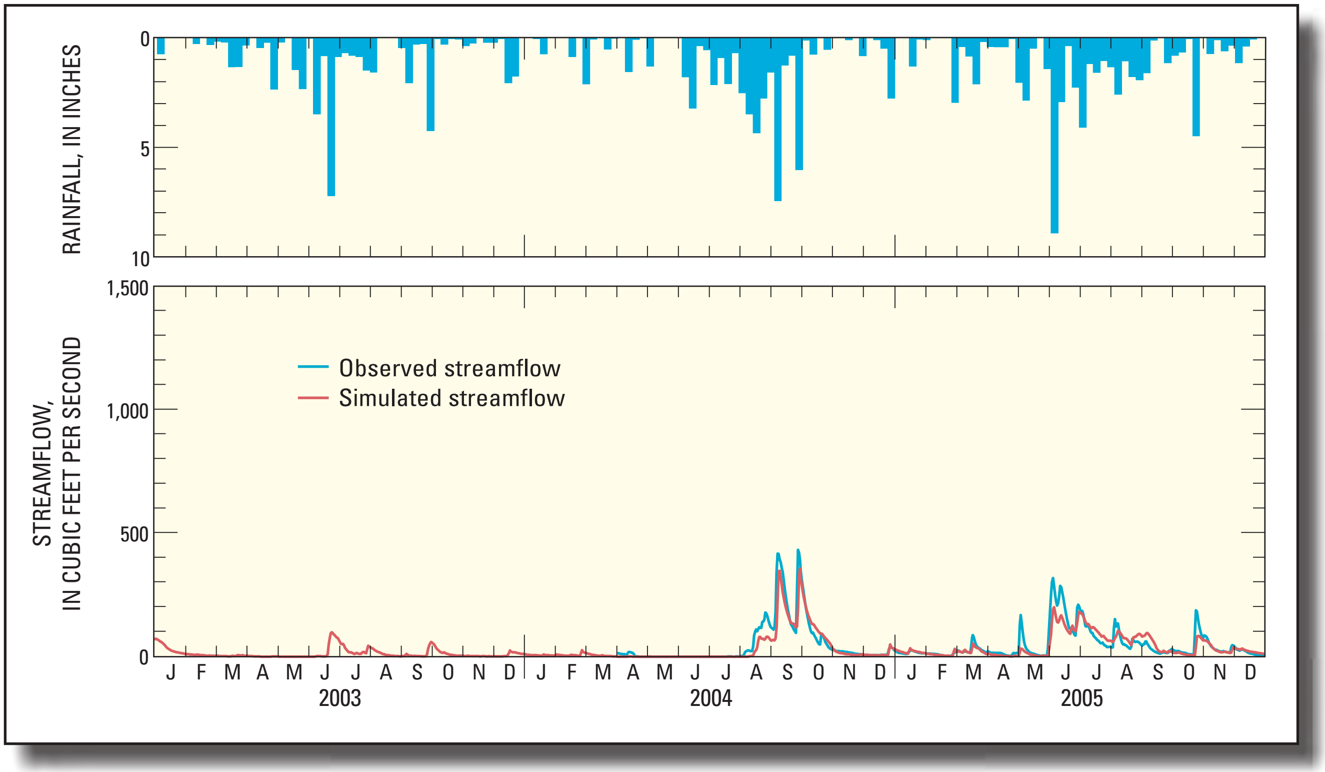

Figure 29. Observed and simulated streamflow at Little Charlie Bowlegs Creek near Sebring, Florida, and weekly total NEXRAD (Next Generation Radar) rainfall at the pixel closest to the streamflow monitoring station, 2003 to 2005.

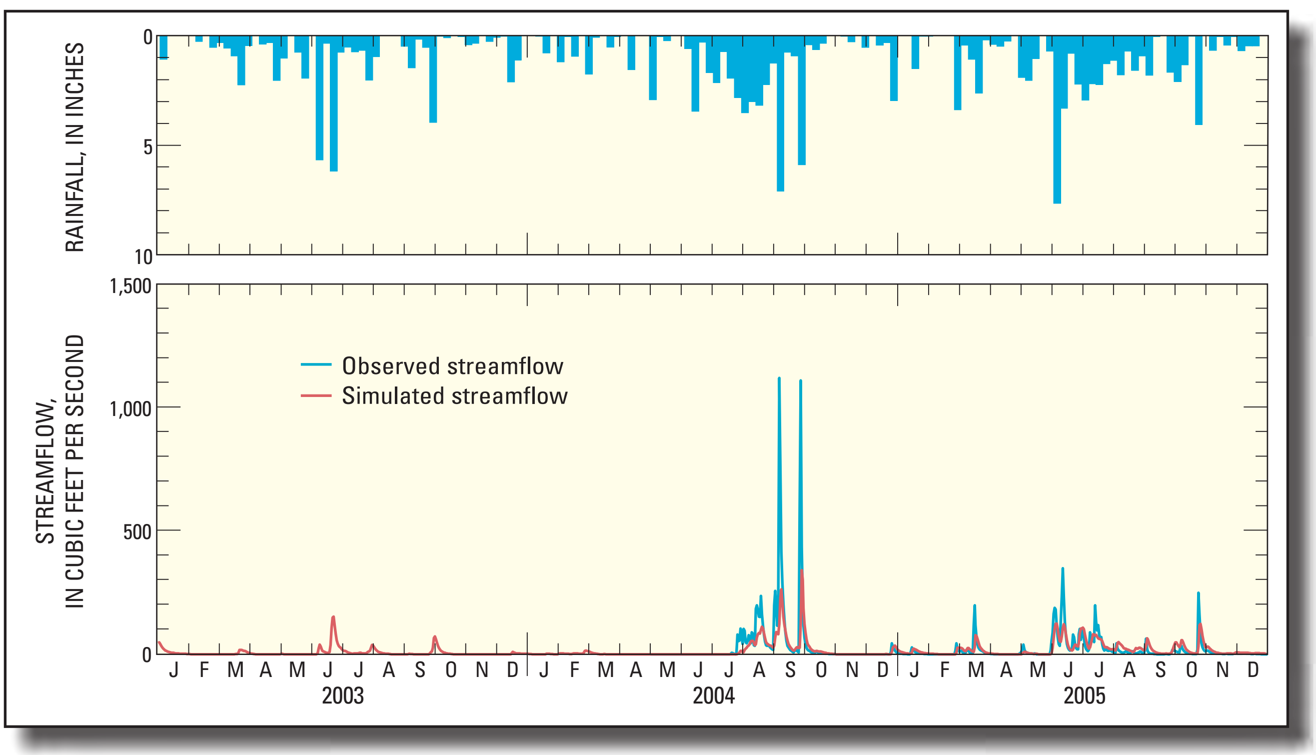

Figure 30. Observed and simulated streamflow at Buckhorn Creek near Griffins Corner, Florida, and weekly total NEXRAD (Next Generation Radar) rainfall at the pixel closest to the streamflow monitoring station, 2003 to 2005.

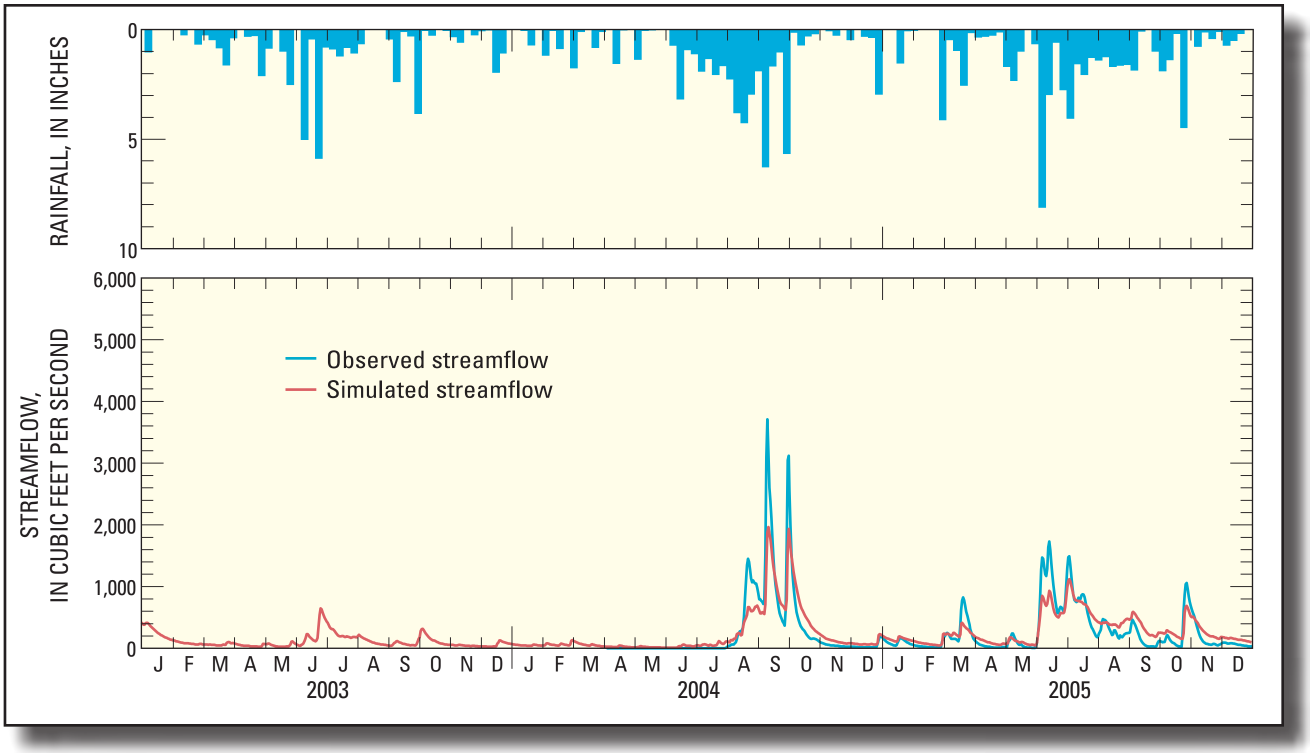

Figure 31. Observed and simulated streamflow at Charlie Creek near Crewsville, Florida, and weekly total NEXRAD (Next Generation Radar) rainfall at the pixel closest to the streamflow monitoring station, 2003 to 2005.

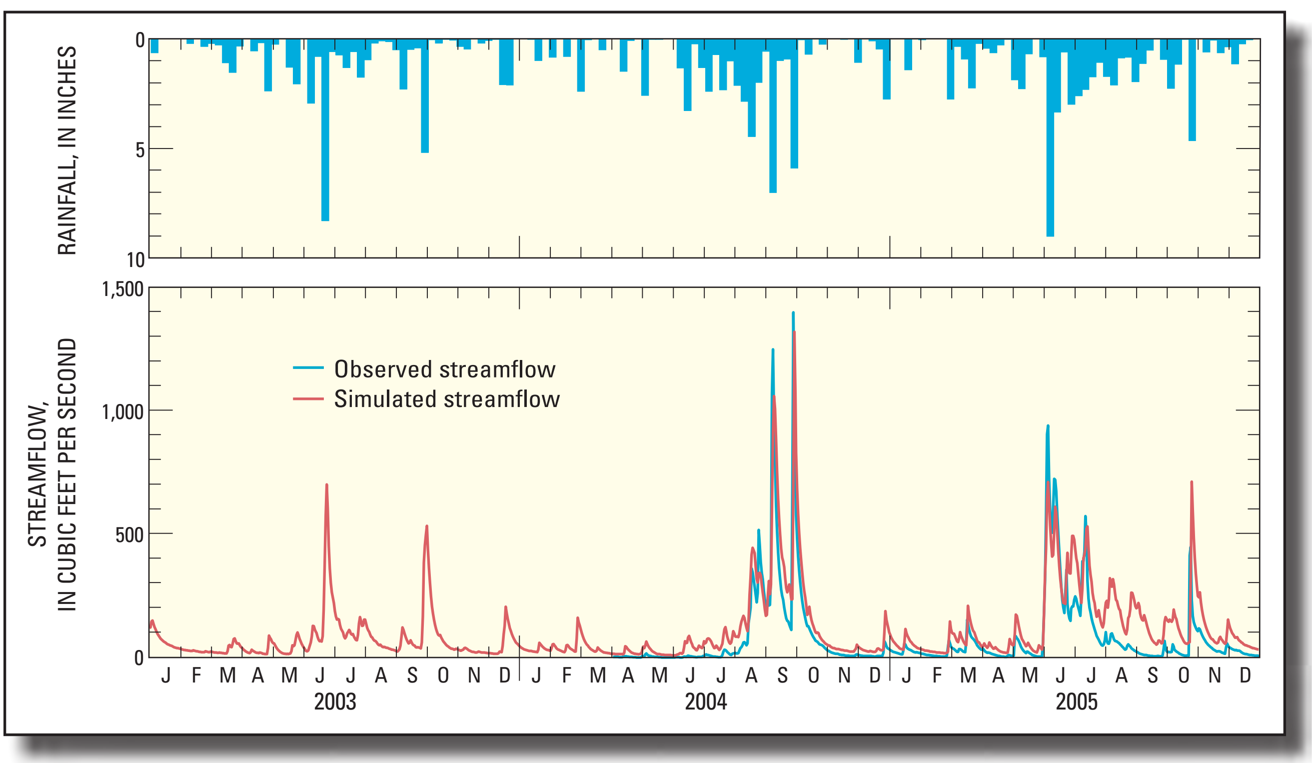

Figure 32. Observed and simulated streamflow at Oak Creek near Gardner, Florida, and weekly total NEXRAD (Next Generation Radar) rainfall at the pixel closest to the streamflow monitoring station, 2003 to 2005.

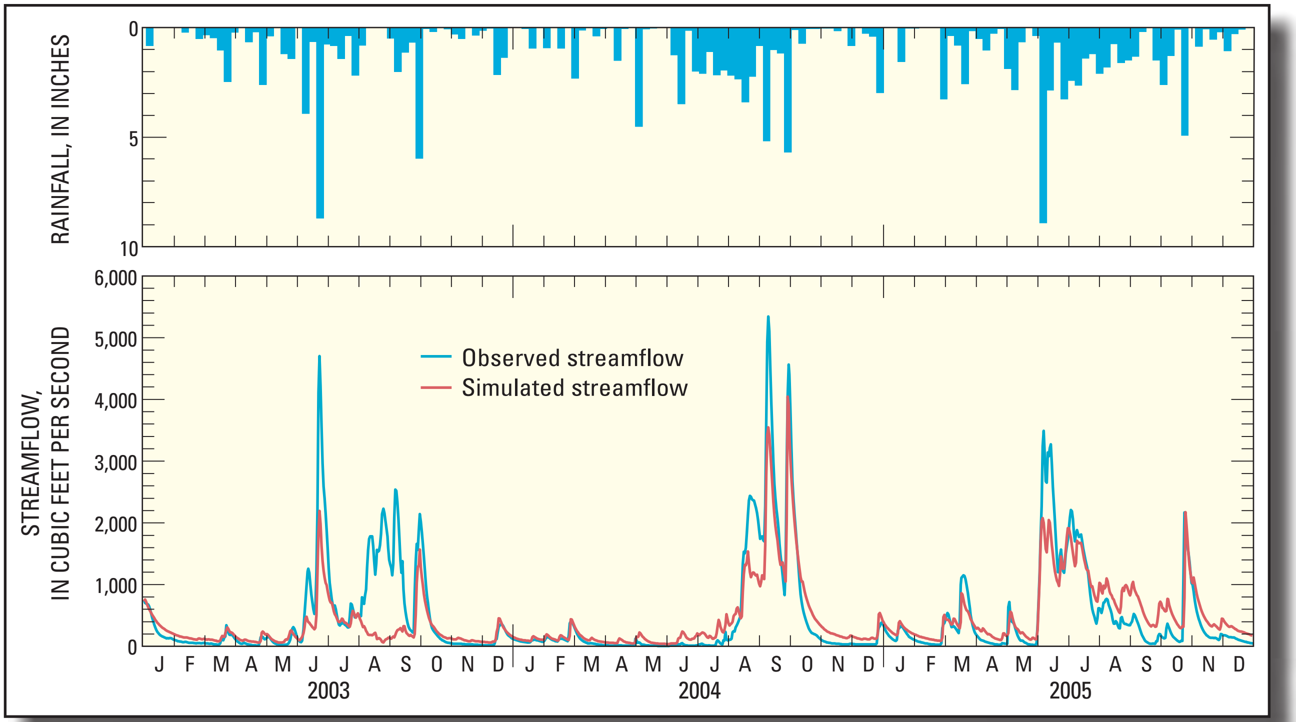

Figure 33. Observed and simulated streamflow at Charlie Creek near Gardner, Florida, and weekly total NEXRAD (Next Generation Radar) rainfall at the pixel closest to the streamflow monitoring station, 2003 to 2005.

Table 6. Summary calibration statistics for the simulated streamflows at five streamflow stations in the Charlie Creek basin.

[--, no value; ft^3/s, cubic foot per second; (-), dimensionless]

USGS streamflow station	Number of observa-tions	Mean error, (ft^3/s)	Mean gaged streamflow, (ft^3/s)	Nash-Sutcliffe, (-)	Cumulative percent errors			
					Overall	2003	2004	2005
Little Charlie Bowlegs Creek near Sebring	638	7.78	50.70	0.80	-15	--	-20	11
Buckhorn Creek near Griffins Corner	608	7.47	28.64	0.35	-26	--	-47	4.3
Charlie Creek near Crewsville	638	-10.39	277.71	0.78	3.7	--	-4.6	11
Oak Creek near Gardner	638	-51.98	85.83	0.65	60	--	44	75
Charlie Creek near Gardner	1186	57.43	492.47	0.69	-9.8	-43	-1.5	15

and peak streamflow but prolonging the duration of high flow events. Roughness coefficients used in the model are representative of land-use/land cover types in the basin and the stream characteristics.

Measurements of runoff from smaller areas of the Charlie Creek basin that have a uniform land use/land cover also would improve the ability to develop effective overland and stream roughness coefficients and to simulate streamflow in the model. For example, Variano and others (2009) used the tracer sulfur hexafluoride to evaluate surface-water flow dynamics and develop site-specific roughness coefficients at two sites in the Everglades. Results of this study indicated roughness coefficients in the study area exceeded typical overland values (for example, Chow (1959)).

Simulated streamflows probably also were affected by not modeling the flow in selected small channels carrying the spillover from wetlands and other depressional features across the landscape to the larger stream channels. These smaller stream features are not explicitly represented in the model using a 300 ft grid resolution, but are hypothesized to be important factors affecting the total and peak downstream flow during high-intensity events. In the current model, the effect of flow in small stream channels on the runoff from a model cell has been represented in the effective overland roughness coefficients. Measuring the magnitude of streamflow in these small channels during high-intensity events would improve the ability to calibrate effective overland roughness coefficients and simulate streamflow in the model.

Basin and Subbasin Water Budgets

Basin and subbasin water budget components were evaluated using both model-derived fluxes from the MIKE SHE simulation of streamflow in the basin and calculated water-budget components. The modeling results quantified components of the water budget that could not be directly measured, focusing on groundwater exchange between the surficial aquifer and deeper aquifers, exchange between groundwater and streams, and the volume of surface water stored in topographic depressions in the terrain (table 8). Four categories of water-budget components were then compared between subbasins: the climate-driven fluxes of rainfall and evapotranspiration, surface water stored overland in topographic depressions in the landscape, groundwater exchanges, and observed streamflow.

Rainfall and Evapotranspiration Differences between Subbasins

Rainfall and evapotranspiration were the two largest water-budget components in the Charlie Creek basin, and differences between subbasins in the amount of rainfall received were generally greatest over shorter time periods. Weekly rainfall totals differed by as much as 40 percent between subbasins, whereas the largest annual difference in rainfall between subbasins (6.47 in. in 2003) (table 8), was only 15 percent of the basin-wide annual rainfall. Subbasin differences in annual rainfall were considerably less in the following years, equaling 3 percent and 6 percent of the basin-wide total in 2004 and 2005, respectively. For the week with the greatest amount of rainfall (Sept. 1-7, 2004), the cumulative rainfall at individual 2 × 2-km (1.24 × 1.24-mi.) pixels ranged from about 3.3 to 9.5 in. (fig. 34A), whereas the spatially-averaged rainfall for the 5 subbasins ranged from 5.10 to 7.23 in. A difference in the subbasin rainfall of 2 in. or more in a week should affect the magnitude of streamflow generated by subbasins. This temporal variability in rainfall may average out over the year and exert a comparable effect on the capacity of subbasins to generate annual streamflow. Annual rainfall totals for the five subbasins ranged from 55.23 to 57.43 in. for 2004, and from 58.53 to 62.09 in. for 2005 (table 8). Over the annual time period, however, the total rainfall at individual pixels varied from about 48 to 65 in. (fig. 34B).

Differences in the spatially-averaged rainfall rates decreased for larger subbasin areas. For the upper half of the Charlie Creek basin, for example, the spatially-averaged rainfall was 56.68 in. for 2004, of which 42.36 in. occurred during the wet season between July and December 2004. Average rainfall for the lower half of the Charlie Creek basin was about 2 percent less during 2004 and totaled 55.33 in., with 38.77 in. occurring in the wet season.

Differences in evapotranspiration between subbasins were much less than rainfall. Potential evapotranspiration rates increased southward across the Charlie Creek basin by a little

Table 7. Observed percentile-flow values and the error in the simulated percentile-flow values for the five streamflow stations in the Charlie Creek basin.

[Error computed as ((simulated-observed)/observed); negative errors indicate simulated flow values were less than observed flow values; ft³/s, cubic foot per second; %, percent]

Streamflow station name	P_{10} observed flow (ft³/s)	Simulated P_{10} error (%)	P_{25} observed flow (ft³/s)	Simulated P_{25} error (%)	P_{50} observed flow (ft³/s)	Simulated P_{50} error (%)	P_{75} observed flow (ft³/s)	Simulated P_{75} error (%)	P_{90} observed flow (ft³/s)	Simulated P_{90} error (%)
Little Charlie Bowlegs Creek near Sebring	147	-16	59	15	19	-8.4	7.6	-55	0.62	-73
Buckhorn Creek near Griffins Corner	79	-20	17	60	2.7	120	0.51	-41	0.06	-52
Charlie Creek near Crewsville	847	-18	294	42	76	120	17	310	0.39	7,900
Oak Creek near Gardner	248	38	68	150	22	210	7	420	3.2	550
Charlie Creek near Gardner	1,660	-33	524	-2.5	137	63	48	160	22	300

Table 8. Simulated water-budget components for the Charlie Creek subbasins for 2003-2005.

[All values are shown in inches per year. ET, evapotranspiration; UFA, Upper Floridan aquifer]

Basin or subbasin	Rain-fall	ET	Overland boundary flow	Runoff	Irriga-tion	Lateral ground-water flow	Surficial aquifer exchange with UFA	Surficial aquifer exchange with creeks	Canopy/ overland storage change	Sub-surface storage change	Error	Stream-flow	Runoff and base flow	Stream storage change
2003														
Little Charlie Bowlegs Creek near Sebring	41.88	-38.16	-0.59	-3.60	1.54	-0.12	-1.20	-3.42	1.48	1.99	-0.19	-4.18	-7.02	2.84
Buckhorn Creek near Griffins Corner	41.62	-35.16	-2.69	-1.32	5.68	-0.05	-0.78	-10.43	0.95	1.97	-0.22	-5.69	-11.74	6.06
Charlie Creek near Crewsville	40.87	-37.01	0.20	-4.99	2.83	0.01	-0.63	-5.64	1.94	2.23	-0.19	-9.90	-10.63	0.73
Oak Creek near Gardner	44.86	-36.46	0.14	-4.49	3.48	0.03	-1.22	-7.99	0.86	0.61	-0.18	-15.52	-12.48	-3.04
Charlie Creek near Gardner	47.34	-36.44	-0.06	-6.15	3.14	0.03	-0.73	-8.92	0.85	0.72	-0.23	-17.91	-15.07	-2.85
Total	43.20	-36.83	-0.12	-4.76	3.01	0.00	-0.85	-6.76	1.38	1.54	-0.20	-11.73	-11.52	-0.21
2004														
Little Charlie Bowlegs Creek near Sebring	55.62	-38.24	-1.88	-9.45	1.60	-0.12	-1.21	-3.89	-0.90	-1.39	0.15	-10.52	-13.34	2.82
Buckhorn Creek near Griffins Corner	57.43	-35.78	-5.46	-4.32	5.86	-0.05	-0.79	-13.74	-1.29	-1.73	0.13	-11.99	-18.06	6.07
Charlie Creek near Crewsville	56.93	-37.04	0.14	-12.08	2.92	0.01	-0.59	-6.99	-1.22	-1.92	0.18	-17.91	-19.07	1.15
Oak Creek near Gardner	55.23	-37.24	0.10	-10.30	3.59	0.03	-1.27	-9.14	-0.29	-0.65	0.06	-23.07	-19.44	-3.63
Charlie Creek near Gardner	55.40	-37.40	-0.01	-9.86	3.25	0.03	-0.74	-9.41	-0.53	-0.62	0.10	-22.61	-19.28	-3.33
Total	56.12	-37.25	-0.46	-10.50	3.11	0.00	-0.85	-7.88	-0.85	-1.31	0.13	-18.64	-18.38	-0.26
2005														
Little Charlie Bowlegs Creek near Sebring	59.07	-39.84	-2.73	-12.45	1.56	-0.14	-1.27	-4.99	0.48	0.23	-0.08	-13.87	-17.45	3.58
Buckhorn Creek near Griffins Corner	58.53	-36.89	-7.96	-3.88	5.58	-0.07	-0.73	-15.91	0.47	0.75	-0.11	-16.16	-19.79	3.63
Charlie Creek near Crewsville	61.03	-38.57	0.49	-17.03	2.84	0.01	-0.59	-9.02	0.41	0.34	-0.10	-23.90	-26.05	2.15
Oak Creek near Gardner	60.54	-38.11	-0.04	-13.09	3.54	0.05	-1.32	-12.05	0.08	0.34	-0.05	-29.58	-25.14	-4.44
Charlie Creek near Gardner	62.09	-38.25	0.09	-14.13	3.22	0.03	-0.76	-12.62	0.00	0.24	-0.09	-30.66	-26.75	-3.91
Total	60.76	-38.49	-0.57	-14.33	3.04	0.00	-0.87	-10.22	0.27	0.33	-0.09	-24.73	-24.55	-0.18
2003 - 2005														
Little Charlie Bowlegs Creek near Sebring	52.19	-38.75	-1.73	-8.50	1.57	-0.12	-1.23	-4.10	0.36	0.28	-0.04	-9.52	-12.60	3.08
Buckhorn Creek near Griffins Corner	52.52	-35.95	-5.37	-3.17	5.71	-0.06	-0.77	-13.36	0.04	0.33	-0.06	-11.28	-16.53	5.25
Charlie Creek near Crewsville	52.94	-37.54	0.28	-11.37	2.86	0.01	-0.60	-7.21	0.38	0.22	-0.04	-17.24	-18.58	1.34
Oak Creek near Gardner	53.54	-37.27	0.07	-9.30	3.54	0.03	-1.27	-9.72	0.22	0.10	-0.06	-22.72	-19.02	-3.70
Charlie Creek near Gardner	54.94	-37.36	0.01	-10.05	3.20	0.03	-0.74	-10.32	0.10	0.11	-0.07	-23.73	-20.36	-3.36
Total	53.36	-37.52	-0.39	-9.86	3.05	0.00	-0.86	-8.29	0.27	0.19	-0.05	-18.37	-18.15	-0.22

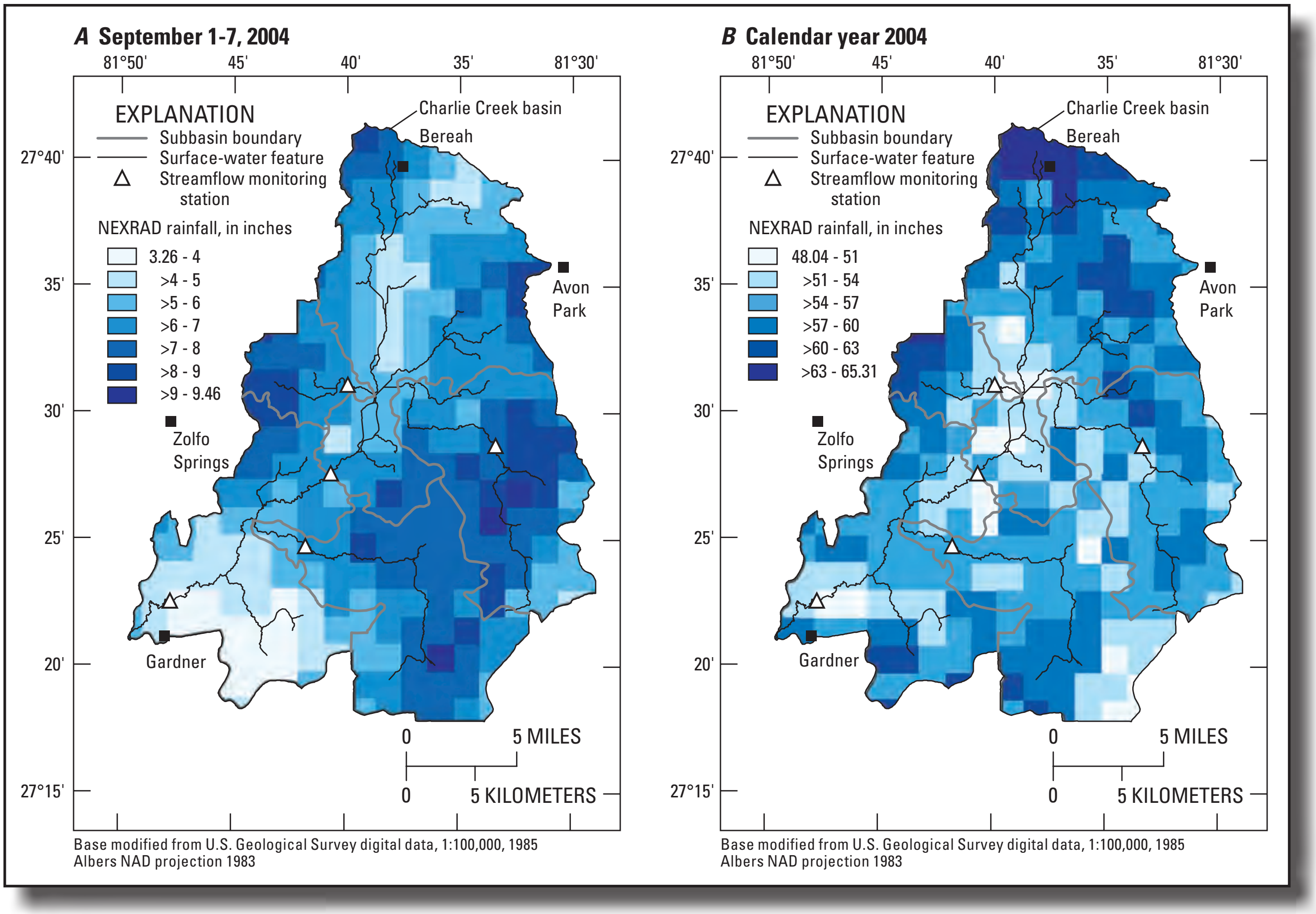

Figure 34. NEXRAD (Next Generation Radar) rainfall totals in the Charlie Creek basin for *A,* the week with the greatest rainfall in 2004 (Sept. 1-7), and *B,* the 2004 calendar year.

over an inch due to the increase in available solar energy with decreasing latitude (fig. 35A). Simulated evapotranspiration had far greater spatial variability than potential evapotranspiration, however, because its rates were determined by land use/land cover across the basin and vegetation-specific parameters (fig. 35B; app. 3).

The upper basin had slightly greater simulated evapotranspiration rates than the lower basin because it contained a greater proportion of wetlands and open water land use/land cover types (22 percent) than the lower basin (18 percent) (table 2). For example, the median, spatially-averaged, simulated evapotranspiration rate was slightly higher (0.71 in/wk) in the upper half of the basin than in the lower half (0.69 in/wk). Simulated evapotranspiration rates in the subbasins composing the lower basin were slightly less variable overall than the upper half (fig. 36). Average simulated evapotranspiration rates were highest for the land use/land cover classifications that define wetlands and open water (53.1 in/yr), and row crops (46.8 in/yr). The remaining land use/land cover classifications in the basin result in simulated evapotranspiration rates that ranged from 29.7 to 35.7 in/yr during 2003-2005 (table 9). Year-to-year differences in evapotranspiration rates were higher for the wetlands and open water (3.55 in/yr) and row crops (7.25 in/yr) landuse/land cover classifications (table 9).

Wetland Water-Storage Differences between Subbasins

Although the overall topography in the basin directed runoff toward Charlie Creek and its tributaries, isolated wetlands and other naturally occurring topographic depressions intercepted and stored runoff overland in the landscape, removing it from the cumulative streamflow. Each of the subbasins to Charlie Creek stored overland water, and the area of the basin covered with water varied substantially from the dry season to the wet season (fig. 37). The amount of water stored above land surface at any given time was simulated in the MIKE SHE model by routing the inflows and outflows across each model cell and storing accumulated water as standing water above the model cell when inflows exceeded outflows.

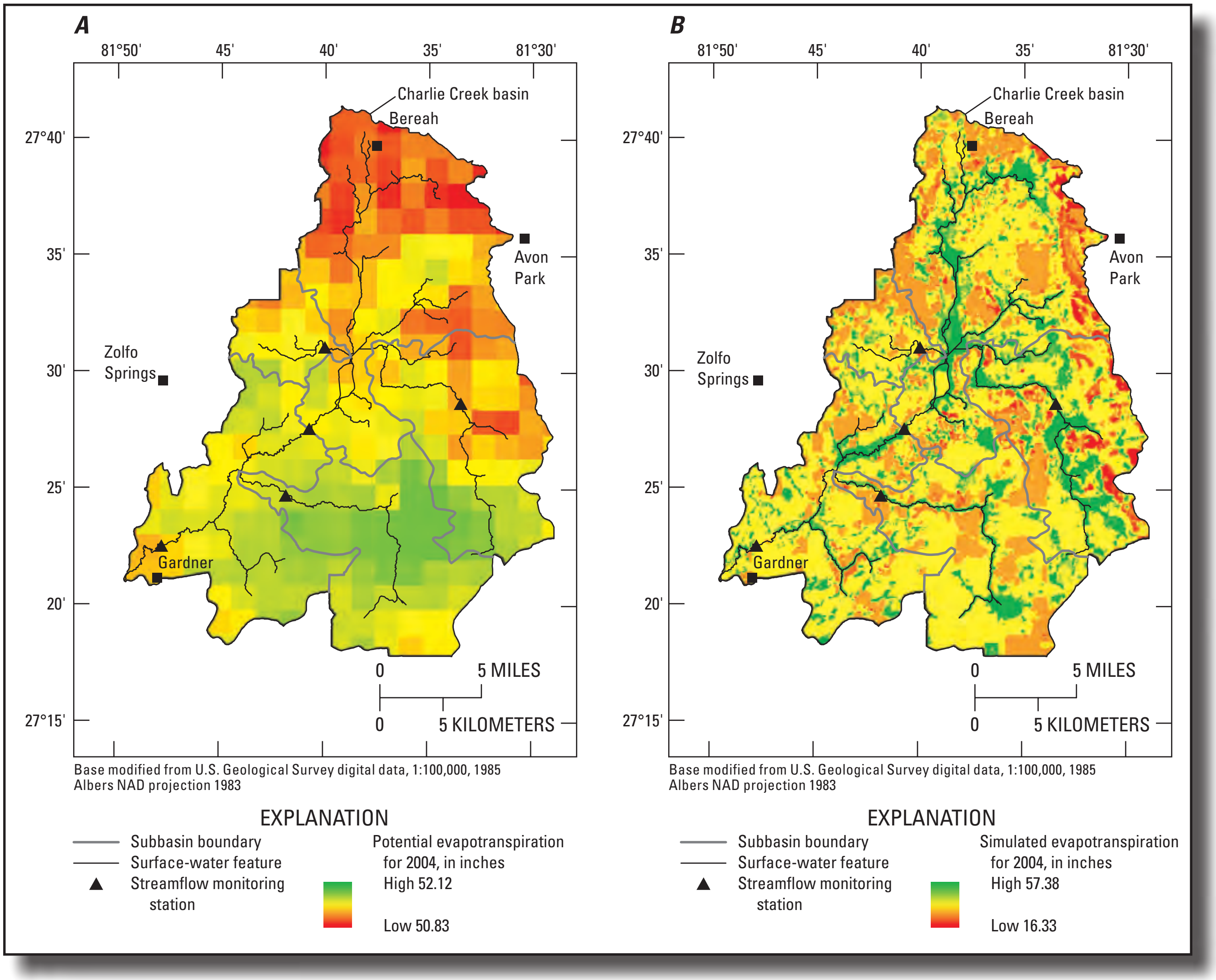

Figure 35. Annual *A,* potential evapotranspiration and *B,* simulated evapotranspiration in the Charlie Creek basin for 2004.

Table 9. Simulated annual evapotranspiration rates for the land uses and land covers represented in the model.

[All values in inches per year]

General land use/ land cover classification	2003	2004	2005	Average
Wetlands and open water	52.0	51.8	55.4	53.1
Upland forest	34.7	35.6	35.6	35.3
Pasture and rangeland	34.6	35.1	35.7	35.1
Citrus	29.9	30.9	31.0	30.6
Row crops	43.8	45.5	51.1	46.8
Urban	30.9	29.7	33.2	31.3
Average	36.8	37.3	38.5	37.5

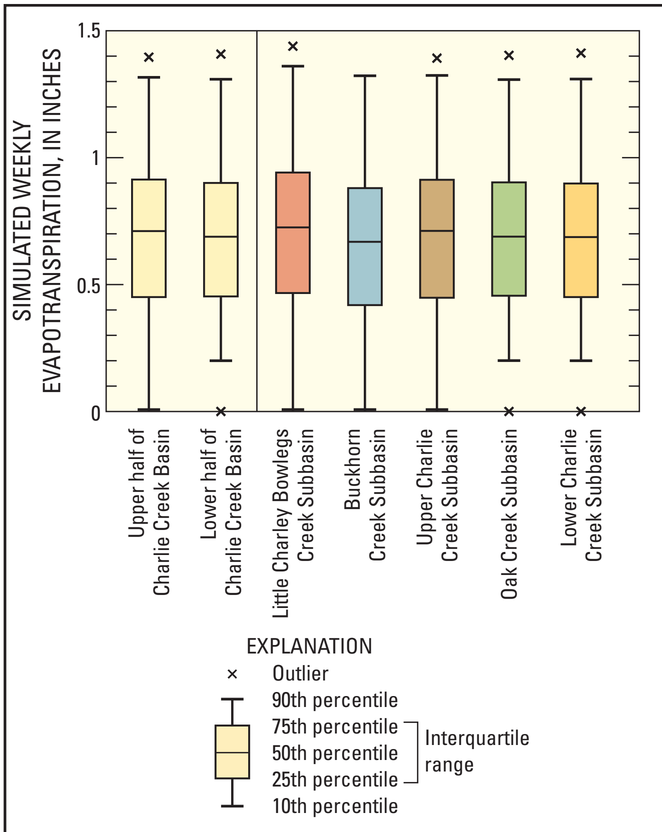

Figure 36. Simulated range of weekly evapotranspiration rates for the five subbasins and for the upper and lower halves of the Charlie Creek basin from October 2002 through December 2005.

Surface-water flow into model cells representing local land-surface depressions is one process that results in surface-water storage. The standing water depth can increase until it rises higher than an adjacent model cell.

Areas of the basin having the greatest standing water depths generally corresponded to areas with a land use/land cover classification of forested and non-forested wetlands or open water (figs. 5 and 37). For September 8, 2004, a day following Hurricane Frances and during the week with the greatest rainfall during the 2004 wet season, the maximum water depth simulated in the model was about 14 ft, with about 21.9 percent of the upper half of the basin and 16.2 percent of the lower half of the basin predicted to have standing water depths of more than 1.0 ft (fig. 37B). Nearly two-thirds of this area was classified as wetlands. In contrast, for the week that had the most rainfall during the dry season of 2004, 6.1 percent of the upper basin and 3.9 percent of the lower basin had water stored above land surface. The majority of this water (75 percent) was stored in wetlands (fig. 37A).

The volume of water stored daily within each subbasin was expressed as an equivalent water depth over the sub-basin area (fig. 38). The Upper Charlie Creek subbasin stored a greater volume of water per unit area of basin than any other subbasin. The Upper Charlie Creek and Little Charlie Bowlegs subbasins both consistently stored more water per unit area than the other three subbasins, and Buckhorn Creek and Oak Creek stored the least. Overall, substantially more water was stored in the upper half of the Charlie Creek basin per unit area than in the lower half.

A tropical storm floods the pasture near the Buckhorn Creek streamflow station. (Photograph by T.M. Lee, USGS.)

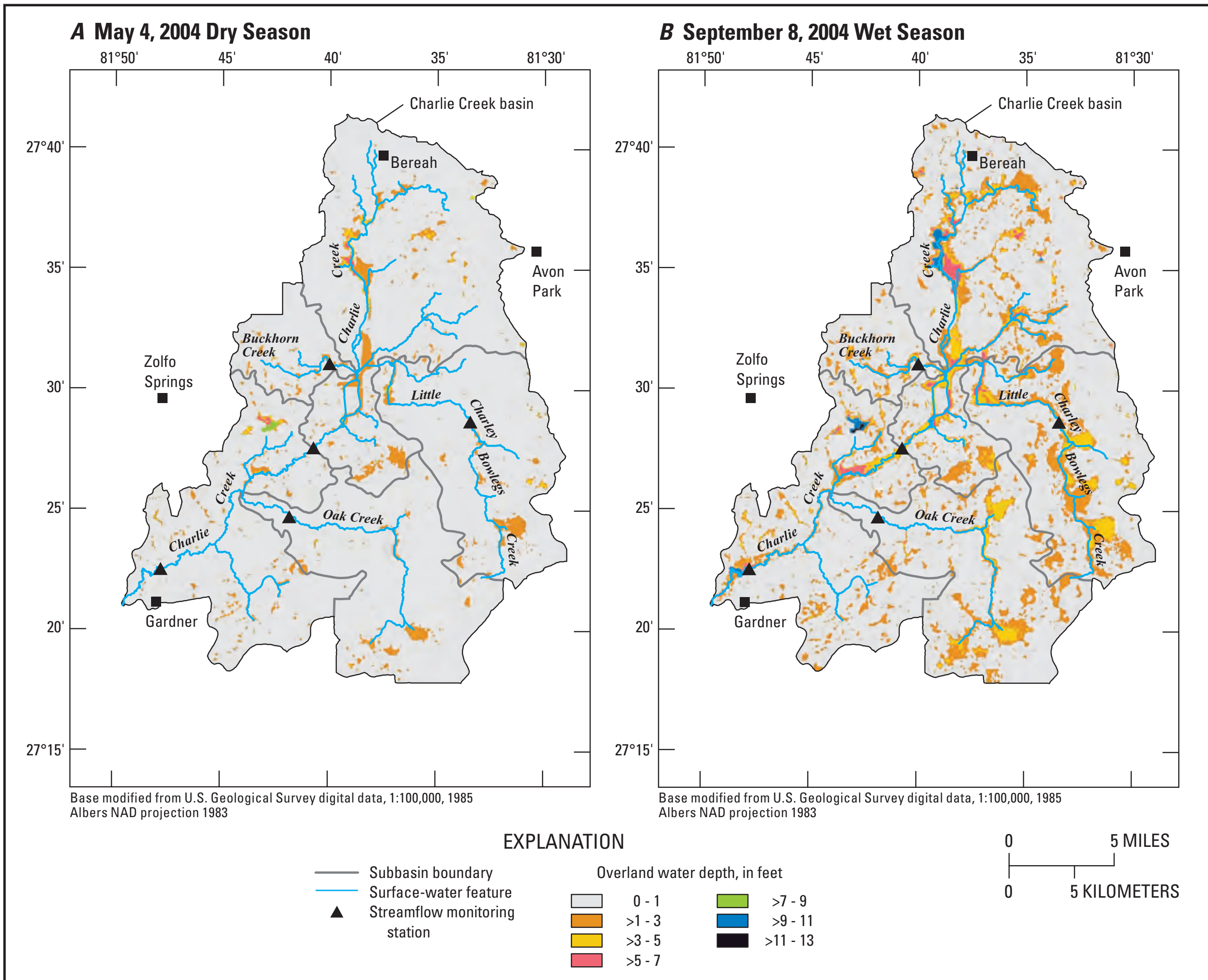

Figure 37. Simulated depths for water stored above the land surface in the Charlie Creek basin for *A,* May 4, 2004, and *B,* September 8, 2004.

The wetlands and landscape depressions that store water in the Charlie Creek basin are shown more clearly on a 5-ft LIDAR DEM than on the digital elevation model used in MIKE SHE, which resampled the original LIDAR data to a 300-ft horizontal resolution (fig. 39). The higher resolution reveals the shallow swales and channels that convey the outflow from the filled wetland depressions to the streams. Some of these channels have been ditched to accelerate the drying out of wetlands, while other channels have remained undeveloped. Whereas the larger horizontal dimension used in the model preserves the physical function of many of the wetland depressions, it may not account for small-scale drainage features that convey water from the wetlands to Charlie Creek and its tributaries. In this study, using the 5-ft resolution data in MIKE SHE made model simulation times unacceptably long, although the approach should be suitable to much smaller basins.

During extremely wet conditions, the water flowing from the surface depressions to the stream channels may originate 0.5 mi or more from the stream (fig. 39). This connectivity would accelerate the delivery of runoff from the basin to the stream, increasing the peak streamflow generated by the basin. These channels represent the first-order streams in the Charlie Creek watershed that, by definition, have no other streams feeding into them, thus representing the headwaters where flow originates. In MIKE SHE, and most regional-scale watershed models, lower order conveyance features are not explicitly represented. Instead, the part of the cell typically contributing runoff to adjacent cells, and ultimately to downstream creek segments, is assigned effective parameters that represent weighted roughness coefficients characteristic of the flow resistance. Because extremely high-intensity events are relatively infrequent, effective parameters developed for long-term simulations generally undersimulate peak flow events.

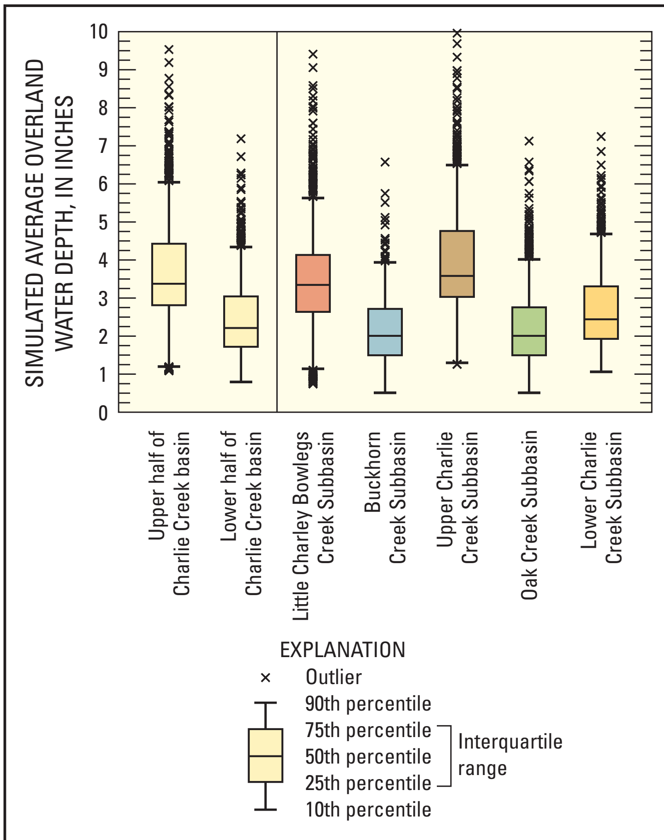

Figure 38. Simulated range in the spatially-averaged, daily water depth stored above land surface for the five subbasins, and for the upper and lower halves of the Charlie Creek basin, from October 2002 through December 2005.

Groundwater Flow Differences between Subbasins

The simulated groundwater exchange between the surficial and Upper Floridan aquifers varied by subbasin and season (fig. 40). Areas of the basin with upward groundwater discharge resembled the areas where artesian head conditions were mapped in the Upper Floridan aquifer (fig. 21B). Downward recharge from the surficial aquifer to the Upper Floridan aquifer was the predominant groundwater flow process simulated within the Charlie Creek watershed during this study, occurring over 80 to 91 percent of the total basin (table 10). The area of recharge and the total recharge volume (8,907 ac-ft) were greatest during the first half of 2004 (January-June), when the downward head differences between the surficial aquifer and the Upper Floridan aquifer were greatest. The potentiometric level of the Upper Floridan aquifer rose following the hurricanes in August and September 2004, and recharge during the second half of 2004 (July-December) decreased to its lowest level during the study (6,659 ac-ft). The recharge volume increased moderately to 7,796 ac-ft during the first half of 2005 and did not change substantially during the second half of 2005 (table 10).

Small channels carry flow from wetlands into Charlie Creek. (Photographs by T.M. Lee, USGS.)

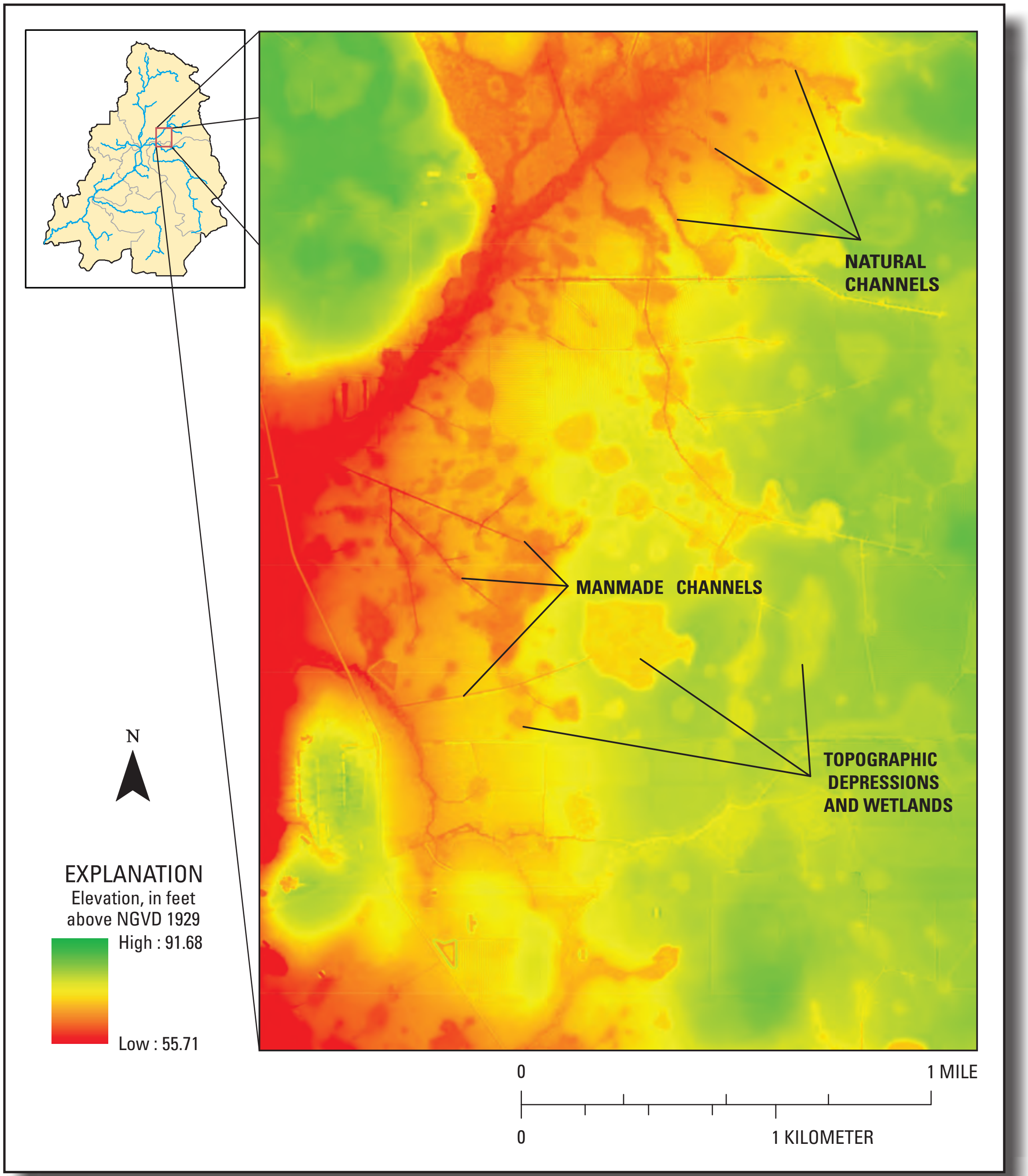

Figure 39. Microtopographic features in the upper part of the Charlie Creek basin, including wetlands and shallow topographic depressions and the surface channels connecting them to streams.

In the second half of 2004, as areas of the basin with downward recharge became areas with upward discharge, the magnitude of discharge changed by a greater percentage than the amount of land area converted. The area of groundwater discharge more than doubled in the second half of 2004, from 9 percent to nearly 20 percent of the basin, however the magnitude of groundwater discharge more than tripled, from 169 to 532 ac-ft (figs. 40A and B; table 10). During the first half of 2005, when the area of discharge decreased by about 30 percent, the discharge volume declined by about 40 percent.

The largest areas of simulated upward flow from the Upper Floridan aquifer to the surficial aquifer were in the Upper Charlie Creek subbasin where water flows upward below the creek, and below the network of topographic depressions, wetlands, and first-order streams described in the previous section (fig. 40). Upward discharge also occurred over smaller areas in the three tributary subbasins, occurring near the confluence of Buckhorn Creek with Charlie Creek during the wet season of 2004 and in 2005 (fig. 40B and D).

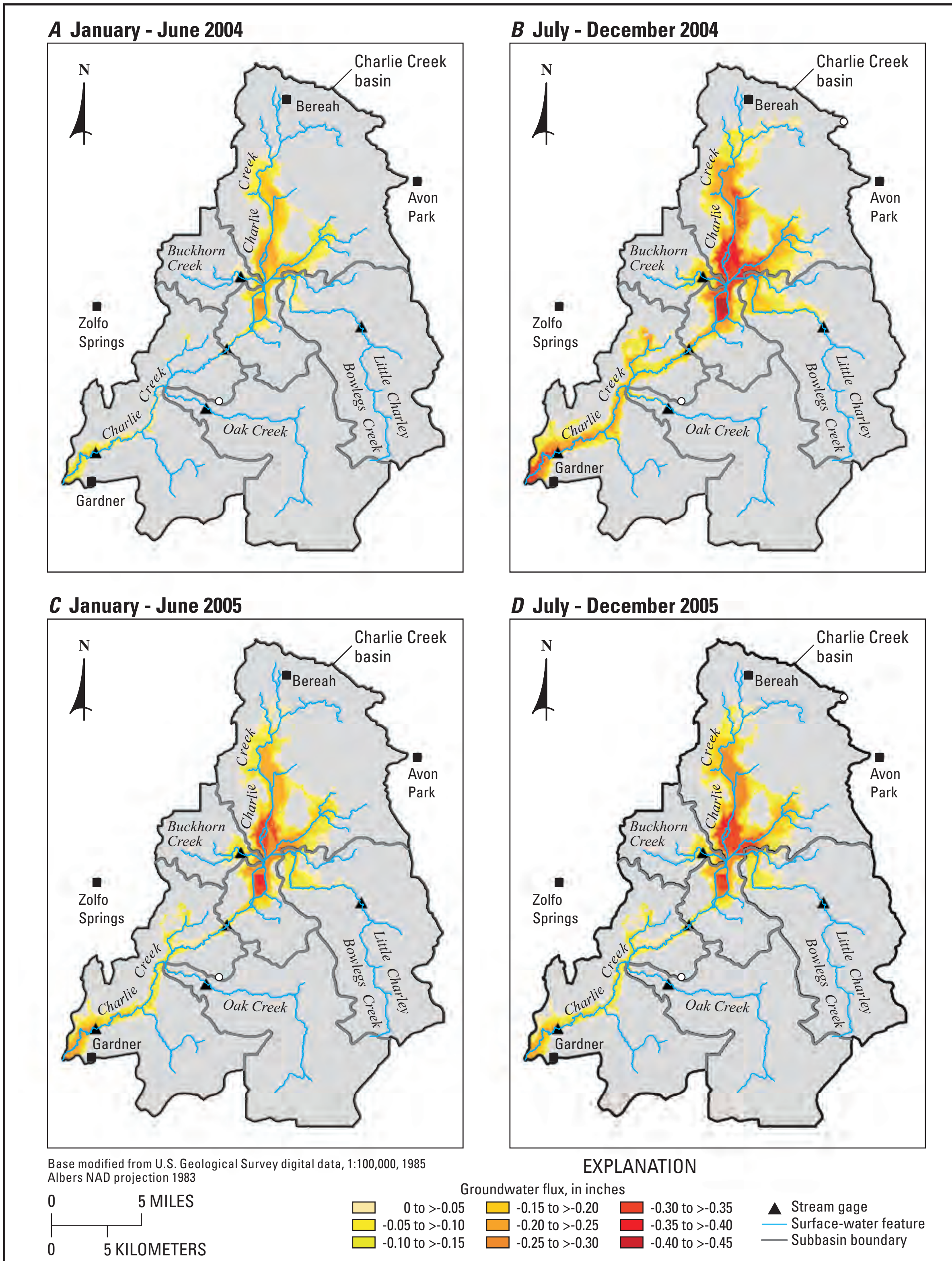

Figure 40. Simulated cumulative groundwater flux from the Upper Floridan aquifer to the surficial aquifer for *A,* January through June 2004, *B,* July through December 2004, *C,* January through June 2005, and *D,* July through December 2005.

Table 10. Simulated percentage of the Charlie Creek basin where the surficial aquifer is recharging downward or receiving upward groundwater discharge, and the groundwater volumes for 6-month periods in 2004 and 2005.

[ac-ft, acre-feet; %, percent]

Period	Percentage of Charlie Creek Basin		Volume , ac-ft	
	Downward (Recharge) (%)	Upward (Discharge) (%)	Recharge	Dis-charge
Jan-Jun 2004	91	9	8,907	169
Jul-Dec 2004	80	20	6,659	532
Jan-Jun 2005	86	14	7,796	322
Jul-Dec 2005	86	14	8,048	351

This same transition to wetter conditions expanded the area of upward discharge in the Little Charley Bowlegs subbasin. Upward discharge was negligible beneath the Oak Creek subbasin, even during the wet season of 2004. Groundwater discharge conditions changed the most in the Lower Charlie Creek subbasin.

Overall, upward groundwater discharge into the surficial aquifer was more extensive in the upper half of the basin than in the lower half (fig. 40; table 10). During the high groundwater conditions between July and December 2004, discharge from the Upper Floridan aquifer was simulated in 25 percent of the upper basin and only 10 percent of the lower basin. Similarly, during low water conditions from January to June of 2004 and 2005, upward discharge from the Upper Floridan aquifer was simulated in 12.5 and 18 percent of the upper half of the basin, but only 2 and 6 percent of the lower half of the basin, respectively.

Using the higher potentiometric surface of the intermediate aquifer system as the boundary condition to the model should both expand the area of upward flow and increase the upward discharge rates in the basin compared to areas delineated by the Upper Floridan aquifer heads. The surficial aquifer that interacts with streams in the Charlie Creek basin also receives water from the intermediate aquifer system, which had a potentiometric surface more than 5 ft higher than the Upper Floridan aquifer in much of the northern and eastern basin during the study (fig. 17). At present, only the potentiometric surface of the Upper Floridan aquifer is routinely mapped to compare past and present hydrologic conditions in the Charlie Creek basin. For this reason, head conditions in the Upper Floridan aquifer were used in the MIKE SHE model. As a result, the model probably simulates comparatively less upward flow into the surficial aquifer than it would if intermediate aquifer system heads were used. Upward potential for flow from the intermediate aquifer system covered approximately 50 percent more area in the upper half of the Charlie Creek basin in September of 2004, and over three times more area in May 2004, than areas inferred from Upper Floridan aquifer heads (table 2).

In the headwater regions of Charlie Creek and its tributaries, artesian head conditions in the intermediate aquifer system may be more important in preventing downward flow than generating upward flow. By preventing downward leakage, artesian head conditions maintain water in the surficial aquifer, elevating the water table. This, in turn, maintains water in wetlands, increasing the frequency of spillover from wetlands into first-order streams. Elevated water-table conditions also increase the potential for groundwater in the surficial aquifer to return to stream channels as base flow.

Base flow contributed the majority of the total annual streamflow in the Charlie Creek basin whether estimated from observed or simulated daily streamflows (table 11). Base flow analysis of observed streamflow records from 1952 to 2003 using the PART model (Rutledge, 1998) indicated that 73 percent of the annual average daily flow at Charlie Creek near Gardner was base flow. On average, the mean annual streamflow of 10.86 in/yr (264 ft^3/s) over that period included 7.94 in/yr of base flow (table 11). Yearly base flow during this 52-year period ranged from 1.99 in/yr in 1981 to 19.85 in/yr in 1998. Groundwater discharge from the surficial aquifer is probably the primary contributor of base flow to Charlie Creek. Base flow also could include gradual surface-water inflows from wetlands and groundwater discharge from the intermediate aquifer system.

During 2005, the year with concurrent streamflow observations at all stations, base flow contributed the majority of the observed annual flow at all stations except Buckhorn Creek near Griffiths Corner (table 11). The Buckhorn Creek subbasin was notable for its comparatively low proportion of base flow. Base flow estimated from the observed streamflows using two techniques ranged from 37 to 44 percent of the annual total streamflow, making Buckhorn Creek the only tributary in the Charlie Creek basin dominated by runoff. Little Charley Bowlegs Creek had the largest base flow contribution to streamflow (66-81 percent of the total flow), and only slightly less of the total flow at Oak Creek was base flow (61-74 percent) (table 11). Base flow accounted for 63 to 79 percent of the total annual flow leaving the upper half of the Charlie Creek basin, and a similar fraction (65-75 percent) of the flow exiting the basin at Charlie Creek near Gardner station (table 11).

Base flows also were derived from the model-simulated daily flows for 2005, and contributed a comparable percentage of the total streamflow at the five stream gages as base flows computed from observed daily streamflows (table 11). However, the absolute magnitude of simulated base flow differed from observed amounts, particularly at the Oak Creek near Gardner station, due to discrepancies between simulated and observed streamflows.

Table 11. Baseflow contributions to streamflow in the Charlie Creek basin in 2005 based on measured and simulated streamflow.

[Values in parentheses are for 52 years of record (1952-2003). Baseflow estimated from measured streamflow using RDF, Recursive Digital Filter (Eckhardt, 2005) and PART computer program (Rutledge, 1998). Baseflow estimated from model simulated streamflow using RDF. mi^2, square mile; in/yr, inch per year; ft^3/s, cubic foot per second; %, percent]

USGS streamflow monitoring station name	Gaged drainage area (mi^2)	Average stream-flow (ft^3/s)	Average stream-flow (in/yr)	PART base flow (in/yr)	PART base flow index (%)	RDF base flow (in/yr)	RDF base flow index (%)	MIKE SHE simulated stream-flow for 2005 (in/yr)	MIKE SHE simulated base flow for 2005 (in/yr)	MIKE SHE simulated base flow index (%)
Buckhorn Creek near Griffins Corner, FL	17.4	19.8	15.5	5.7	37	6.8	44	16.2	9.0	56
Little Charley Bowlegs C AB CT near Sebring, FL	42.8	49.4	15.7	12.7	81	10.3	66	13.9	10.0	72
Charlie Creek near Crewsville, FL	192.3	268	19.0	14.9	79	11.9	63	21.0	15.9	76
Oak Creek near Gardner, FL	65.0	80.9	16.9	12.5	74	10.3	61	29.6	20.1	68
Charlie Creek near Gardner, FL	326.1	515 (264)	21.4 (10.9)	16.2 (7.9)	75 (73)	13.9	65	24.8	18.3	74

Runoff and Streamflow Differences between Subbasins

The five subbasins yielded substantially different amounts of runoff, or streamflow per square mile of gaged area, based upon the observed streamflows during the study. For the 19-month period from June 2004 through December 2005, Little Charley Bowlegs Creek subbasin generated the least runoff of the five subbasins (29.5 in., table 12). The result is consistent with more rainfall stored in depressions in this subbasin, which has the largest percentage area of wetlands and a weir controlling streamflows. Oak Creek, the tributary subbasin in the lower half of the Charlie Creek basin, generated the next lowest runoff value, greater than that of the Little Charlie Bowlegs subbasin, and less than that of the Upper Charlie Creek subbasin. The lower runoff from these three subbasins may reflect their similar depression storage: 2.99 million ft^3/mi^2 in Oak Creek compared to 3.18 and 3.32 million ft^3/mi^2, respectively, for Little Charlie Bowlegs subbasin and Upper Charlie Creek subbasin (table 2). Oak Creek subbasin also has a wetland area comparable to that of the Upper Charlie Creek subbasin (20 percent). Lower runoff from the Oak Creek subbasin compared to the Upper Charlie Creek subbasin may reflect more water being lost as recharge to deeper aquifers, as Oak Creek subbasin consistently had the smallest percentage area of artesian head conditions.

With the exception of the Lower Charlie Creek subbasin, the magnitude of measured runoff was broadly comparable in the other four subbasins between June 2004 and December 2005 (29.5-39.2 in.). Runoff from the three tributary subbasins and Upper Charlie Creek subbasin represented roughly one third (28-37 percent) of the total rainfall (table 12). Buckhorn Creek, which had the lowest percentage of wetland area and the next-to-lowest depression storage of the five subbasins, yielded both the most runoff (39.2 in.) and the most efficient runoff (37 percent of the rainfall).

The distinctively greater runoff from the Lower Charlie Creek subbasin compared to the other four subbasins indicates that there are hydrologic characteristics unique to this subbasin. Lower Charlie Creek subbasin produced approximately twice the runoff of the other four subbasins, and runoff was equivalent to 60 percent of the total rainfall (table 12). Runoff may have been magnified by the smaller depression storage in this basin, which is roughly two-thirds that of the other subbasins (table 2). Runoff may have been highly efficient in this subbasin whenever rainfall was falling on saturated land surfaces, or flooded areas. The Lower Charlie Creek subbasin has the lowest land-surface elevations, and lowest relief of the five subbasins (fig. 2).

Greater streamflow generation in the Lower Charlie Creek subbasin also could reveal the contribution of comparatively greater groundwater discharge from the surficial aquifer and intermediate aquifer system along this more incised section of Charlie Creek. Artesian head conditions in the intermediate aquifer system increased by a greater percentage in this subbasin (from 3 to 25 percent) than in any other between

Table 12. Runoff from subdivided areas of the Charlie Creek basin.

[mi^2, square mile; ft^3/s, cubic foot per second; in., inch; NA, not applicable]

Basin or subbasin	Streamflow station name	Gaged subbasin area (mi^2)	Average daily discharge for June 2004–Dec. 2005 (ft^3/s)	Total runoff for June 2004–Dec. 2005 (in.)	Total rainfall for June 2004–Dec. 2005 (in.)	Runoff, in percentage of rainfall
Buckhorn Creek subbasin	Buckhorn Creek near Griffins Corner, FL	17.4	30.2	39.2	105.9	37
Little Charlie Bowlegs Creek subbasin	Little Charley Bowlegs C AB CT near Sebring, FL	42.8	55.6	29.5	106.6	28
Upper Charlie Creek subbasin[1]		132.0	221	38.0	109.4	35
Upper half of Charlie Creek basin	Charlie Creek near Crewsville, FL	192.3	307	36.2	NA	NA
Oak Creek subbasin	Oak Creek near Gardner, FL	65.0	94.5	33.0	105.8	31
Lower Charlie Creek subbasin[1]		68.9	191	62.9	105.7	60
Lower half of Charlie Creek basin[1]		133.8	286	48.4	NA	NA
Charlie Creek basin	Charlie Creek near Gardner, FL	326.1	592	41.2	107.3	38

[1] Runoff from the subbasin computed by difference

May and September 2004 (table 2). In addition, the increased area was largely below and bordering the stream (figs. 21 and 22). Carbonate rocks also were exposed in the streambed only in this subbasin, potentially allowing direct inflow from the intermediate aquifer system. However, unless upward flows included undocumented spring flow, or flow from uncapped artesian wells, it is unlikely that groundwater discharge from the intermediate aquifer system alone could explain the greater streamflow generated by this subbasin.

The greater runoff potential of the Lower Charlie Creek subbasin probably helps maintain the continual streamflow observed downstream at the Charlie Creek near Gardner station. In contrast, the entire upper half of the Charlie Creek basin, upstream of the Charlie Creek near Crewsville station, can generate no streamflow. In 3 of the 5 years between 2004 and 2008 (including a break in the record in 2006), streamflow measured at the Charlie Creek near Crewsville station was zero from 1 to 54 days (table 13).

Hydrologic Differences between the Upper and Lower Parts of the Charlie Creek Basin

The traits of the individual subbasins create hydrologic differences between the upper and lower halves of the Charlie Creek basin. Analysis of the simulated water budgets for all of 2004 and for just the wet season from July to December 2004 indicate substantial differences between the upper and lower halves of the Charlie Creek basin for selected water-budget components. Water-budget components computed for the entire Charlie Creek basin show that the majority of changes in annual rainfall, runoff, base flow, and storage took place during the wet season between July and December 2004 (fig. 41). To contrast their differences, water-budget terms for the upper and lower halves of the basin also are shown as inches of departure from the basin-wide values (fig. 42).

During the wet season of 2004, the change in total water storage, which is dominated by the change in surface water storage, was greater in the upper half of the basin (1.38 in.) (fig. 42A) than in the overall basin, and less in the lower half of the basin (-1.99 in.) (fig. 42B). Evapotranspiration rates in the upper and lower basins were only slightly above and below the basin-wide average, respectively. Rainfall departures show that the upper basin received more rainfall than the lower basin, yet generated less base flow than the lower half,

Table 13. Average annual streamflow and the number of days with no flow at streamflow stations in the upper and lower reach of Charlie Creek.

[ft^3/s, cubic foot per second]

Year	Upper Reach Charlie Creek near Crewsville			Lower Reach Charlie Creek near Gardner		
	Flow, ft^3/s	Observations (days)	No-flow days	Flow, ft^3/s	Observations (days)	No-flow days
2004	290	275	54	568	366	0
2005	268	365	0	515	365	0
2006	49.3	155	0	107	365	0
2007	12.7	365	1	337	365	0
2008	73.4	363	44	146	366	0

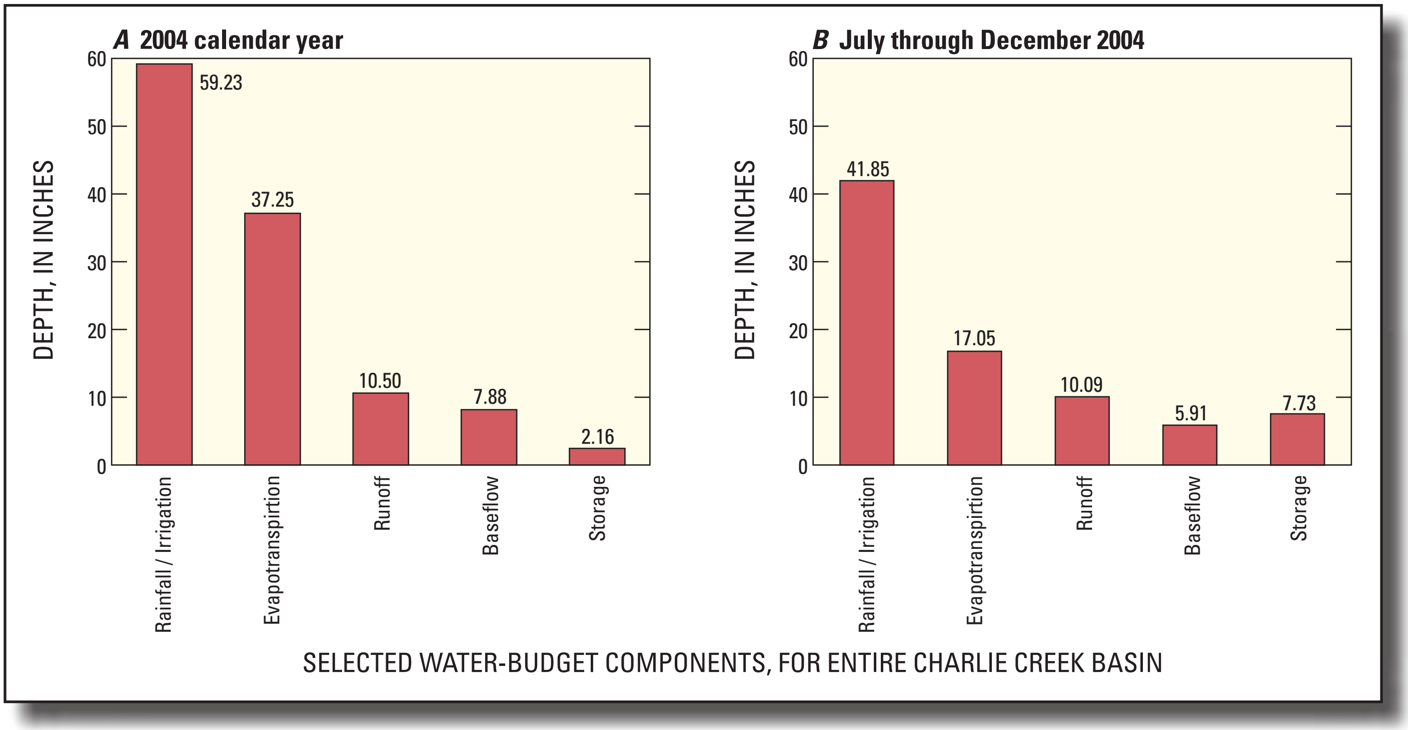

Figure 41. Selected water-budget components for the entire Charlie Creek basin for *A,* the 2004 calendar year, and *B,* for the wet season of July through December 2004.

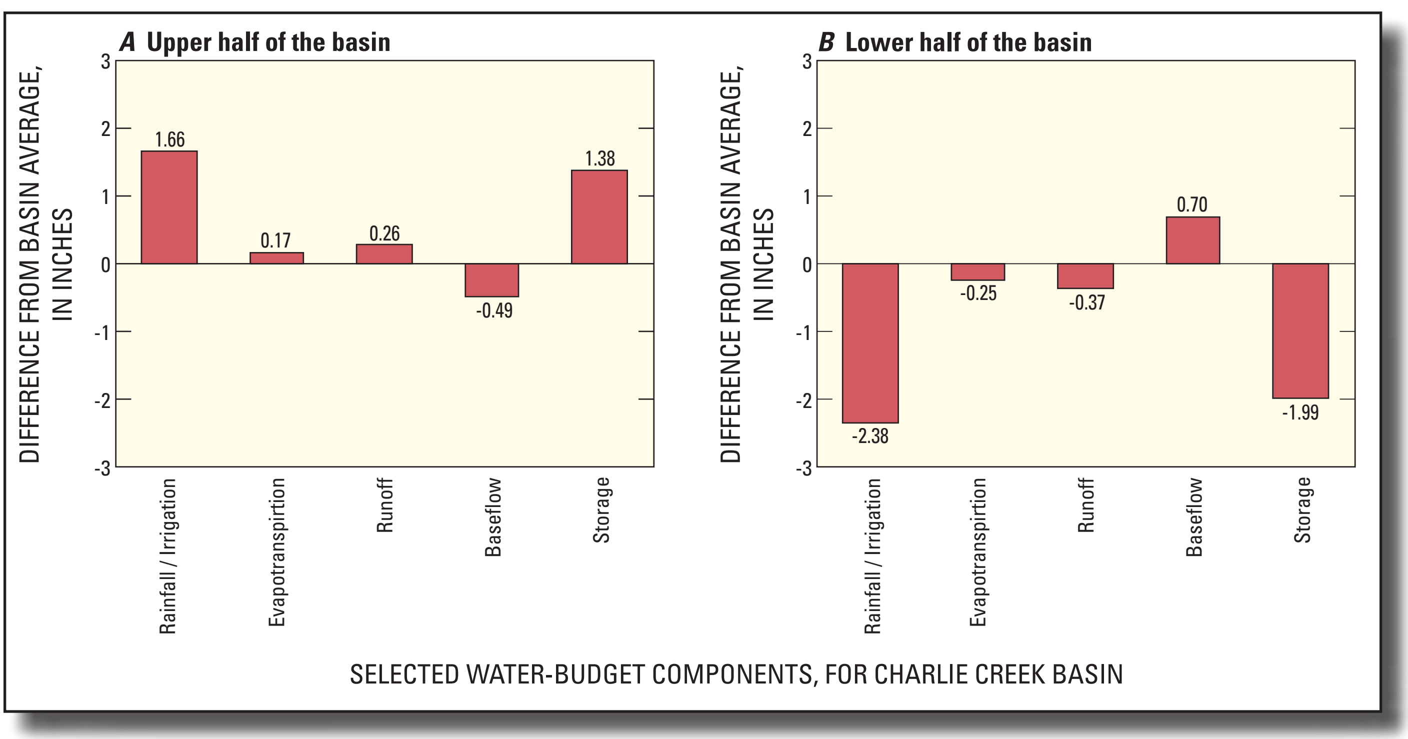

Figure 42. Differences between water-budget terms spatially-averaged for the entire Charlie Creek basin during the wet season in 2004 and their spatially-averaged value in the *A,* upper half and *B,* lower half of the Charlie Creek basin for the same period.

probably due to greater surface storage of water in wetlands in the upper basin. Taken together, simulated overland water depths, vertical groundwater flow, base flow, and water budget results indicate differences in hydrologic response between the upper and lower basin.

Graphing the cumulative simulated daily streamflow against the available water (the sum of rainfall and irrigation minus evapotranspiration) for the upper and lower basins highlights differences in the temporal response of runoff from these basins (fig. 43). Streamflow for the upper basin is the simulated streamflow at the Charlie Creek near Crewsville gage, and streamflow for the lower basin is the difference between streamflows simulated at the Charlie Creek near Gardner gage and the Charlie Creek near Crewsville gage. Over the simulation period from January 2003 to December 2005, the slope of net available water to net streamflow is less than 1 for the upper half of the basin and approximately 1 for the lower half of the basin. The period from October to June is typically a period when stored water contributes to streamflow in both the upper and lower halves of the basin, making the slope greater than 1. The period from June to October is characterized by an initial period with a slope less than 1 (water going into storage or recharging the surficial aquifer) followed by a period with an approximate slope of 1, where available water generally goes directly to streamflow. The upper basin was generally characterized by a longer period of time with a slope less than 1 from June to October, especially from June to October 2004.

Temporal variations in overland water depths (figs. 37 and 38), water budget results (figs. 41 and 42), and the comparison of available water and net streamflow (fig. 43) suggest that wetland storage and hydraulic connectivity between wetlands and tributary streams are controlling factors for rainfall-runoff processes for the upper half of the Charlie Creek basin. During the dry season, water is depleted from storage by evapotranspiration processes and vertical groundwater flux to the intermediate and Upper Floridan aquifers. During the wet season, available water initially replenishes depleted storage and some streamflow from areas near major conveyance features. As the wet season continues, wetland storage can reach capacity and allow runoff to be delivered from a large percentage of the upper basin. The lower basin behaves similarly during the dry season, but during the wet season available water is converted to net streamflow more quickly here than in the upper basin. During dry seasonal conditions, the upper half of the basin can generate little or no flow for days or weeks. Development that lowers groundwater levels in the upper half of the basin below current levels could increase the number of no-flow days at the Charlie Creek near Crewsville gage.

Although wetland storage is a controlling factor in the hydrology of the upper basin, streamflow from the upper half of the basin still accounts for approximately 40 to 50 percent of the annual flow discharging from the Charlie Creek basin. The upper basin contributed from 0 to 100 percent of the daily flow exiting the basin between 2004 and 2008 (fig. 44). This means that the overflow of water from wetlands is an important component of the Charlie Creek basin water budget, and an important source of streamflow to the Peace River and ultimately, Charlotte Harbor.

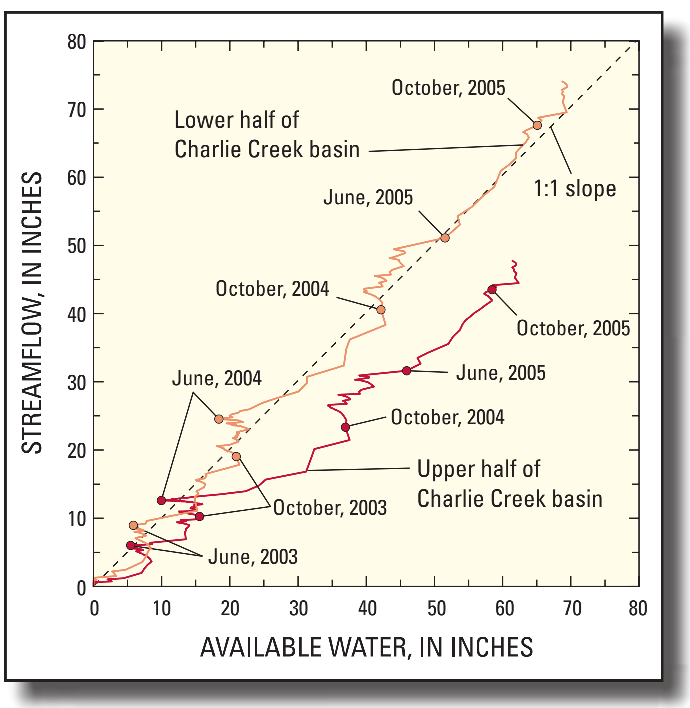

Figure 43. Relationship between the cumulative daily values of available water and streamflow for the upper half and the lower half of the Charlie Creek basin.

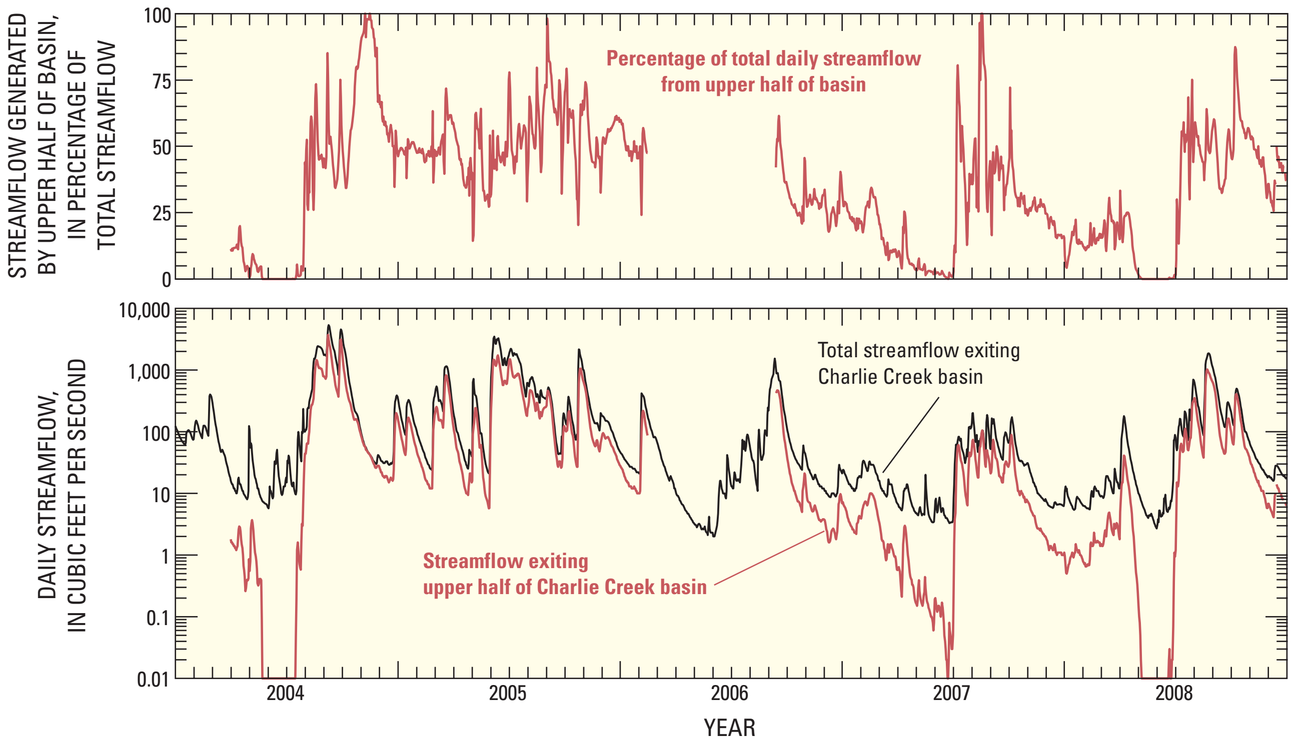

Figure 44. Percentage of the daily streamflow at Charlie Creek near Gardner generated by the upper half of the basin from January 2004 to December 2008.

Summary and Conclusions

The Charlie Creek basin was studied to better understand how groundwater levels in the underlying aquifers and storage and overflow of water from headwater wetlands preserve the streamflows exiting this least-developed tributary basin of the Peace River watershed. The hydrogeologic framework, physical characteristics, and daily streamflow were described and quantified for five subbasins of the 330-square mile Charlie Creek basin, allowing the contribution of its headwaters area and tributary subbasins to be separately quantified. Stream-water specific conductance was monitored to interpret the concentration of dissolved minerals in streams in the basin. A MIKE SHE model simulation of the integrated surface- and groundwater flow processes in the basin was used to simulate daily streamflow observed over 21 months in 2004 and 2005 at five streamflow stations, and to quantify the monthly and annual water budgets for the five subbasins including the changing amount of water stored in wetlands.

Study results suggest that agricultural land-use practices have increased the specific conductance of stream water in the Charlie Creek basin. The specific conductance of stream water monitored at five stream gages was positively correlated to the percent of citrus land use in the area upstream of the gage.

Study results further indicate that mapping the potentiometric surface of groundwater in Zone 2 of the intermediate aquifer system is necessary to understand the hydrogeologic setting of Charlie Creek and the association between groundwater levels and streamflow in different parts of the basin. Groundwater levels in the intermediate aquifer system affect the groundwater exchanges that occur in the overlying surficial aquifer, streams, and wetlands, and therefore, are an important indicator of hydrologic conditions in the Charlie Creek basin. The potentiometric surface of the intermediate aquifer system was mapped over time for this study and used in geospatial analyses, along with refined LIDAR-based land surface elevations and the potentiometric surface of the Upper Floridan aquifer, to derive three new mapping products for the Charlie Creek basin. The maps depict (1) the vertical flow direction and head differences between the intermediate aquifer system and the Upper Floridan aquifer in the basin, (2) the changing location of artesian head conditions and recharging head conditions in the basin over time, and (3) the vertical distance of the potentiometric surface in the intermediate aquifer system above and below the streambed of Charlie Creek and its tributaries over time.

Downward recharge between the surficial aquifer, intermediate aquifer system, and Upper Floridan aquifer prevailed over most of the Charlie Creek basin. Upward groundwater flow from the Upper Floridan aquifer to the intermediate aquifer system was attributed to a higher concentration of wells pumping from the intermediate aquifer system in two areas of the basin.

Artesian head conditions in the intermediate aquifer system were an important source of upward flow to the surficial aquifer in the vicinity of headwater wetlands and stream channels. Artesian head conditions in the intermediate aquifer system generally covered a larger area of the Charlie Creek basin than artesian conditions defined by heads in the Upper Floridan aquifer. The discrepancy in the size of the two areas was greatest when groundwater levels reached a seasonal low. Mapping areas of artesian head conditions helped to describe their location relative to streams, wetlands, stratigraphic units, ROMP wells, flowing wells, sinkholes, and geologic outcrops.

Activities that lower or eliminate artesian head conditions in the intermediate aquifer system in the Charlie Creek basin have the potential to decrease the magnitude of streamflow. In the upper part of the basin, artesian head conditions in the intermediate aquifer system were consistently associated with wetland-dominated headwater regions of Charlie Creek where they generated upward flow into the surficial aquifer and prevented water in the surficial aquifer and wetlands from recharging downward. Both processes should prolong wetland flooding, and increase peak streamflows and total runoff by increasing the frequency with which water overflows wetlands into streams, compared to an analogous setting where the surficial aquifer leaks downward. The loss of artesian head conditions in the intermediate aquifer system in the upper part of the basin would be expected to reduce streamflow by lowering wetland water levels, increasing depression storage, and reducing the frequency with which water stored in wetlands spills over to streams.

In the lower half of the Charlie Creek basin, artesian head conditions in the intermediate aquifer system were smaller in area and tended to closely border the main channel of the creek. Charlie Creek is more deeply incised into the surficial aquifer in the lower basin than in the upper basin, and the streambed intercepts the top of the Peace River Formation at two locations. At these locations, fractured carbonate rocks crop out in the streambed and may provide preferential groundwater flow paths. Heads in the intermediate aquifer system have the potential to directly affect streamflow in these areas, although no conclusive evidence was found of a direct exchange in this study. Both outcrops are in the stream reach that had the largest measured seepage inflows during the May 2005 seepage run, and base flow and seepage inflows measured during low-flow periods were greater in the lower part of the Charlie Creek basin than in the upper part. Artesian head conditions in the intermediate aquifer in the Lower Charlie Creek subbasin also cause slow upward movement of water into the surficial aquifer below the stream, raising or maintaining the water-table near the stream compared to recharging conditions. The Lower Charlie Creek subbasin generated nearly twice as much runoff as the other four subbasins of the Charlie Creek basin. One cause of this higher runoff efficiency is speculated to be rain falling on flooded or saturated land areas adjacent to the creek channel during peak streamflows.

Artesian head conditions in the intermediate aquifer system appeared to be more vulnerable to pumping effects in the Lower Charlie Creek subbasin than any other subbasin during the study. Pumping from wells open to the intermediate aquifer system in the Lower Charlie Creek subbasin has the potential to reduce the magnitude and duration of artesian head conditions and to increase periods of recharging conditions below the stream, especially during drought years such as 2000. In addition, groundwater levels in the Upper Floridan aquifer in the Lower Charlie Creek subbasin appear to be subject to lowering by pumping that occurs outside and mostly west of the Charlie Creek basin.

Depression storage associated with headwater wetlands affected the hydrology of the upper half of the Charlie Creek basin, causing it to generate less streamflow per unit area and less base flow per unit area on an annual basis than the lower half of the basin. Periodically, during drier months when streamflow in the downstream reach was being sustained by base flow, the upper part of the basin generated no streamflow at all. Yet the upper half (57 percent) of the basin generated about 52 percent of the total streamflow exiting the Charlie Creek basin during this study. The shallow channels connecting wetlands to Charlie Creek are expected to deliver runoff faster and with greater efficiency than sheetflow across the land surface. The absence of features in the MIKE SHE model to simulate the flow in these smaller channels probably explains why the model consistently underpredicted peak flows during extreme events at four of the five streamflow stations.

Measuring the intermittent streamflow in small channels draining wetland-dominated landscapes would improve model calibration of runoff quantities from the headwaters area of Charlie Creek and similar basins. The LIDAR-based topographic map of the Charlie Creek basin indicates that shallow channels can hydraulically connect the overflow from depressional wetlands back to the stream channels over distances of half a mile or more. Small channels delivering overflow from wetlands back to streams extend farther distances than are routinely considered when buffering stream channels and wetlands from upland alterations. The loss of wetlands and the channels connecting them to streams due to phosphate mining or other landscape alterations could decrease peak streamflows generated by the basin.

Currently, there is a dynamic balance between wetland storage, rainfall-runoff processes, and groundwater-level differences in the upper basin that allow it to account for approximately half of the streamflow from the Charlie Creek basin. Therefore, any future development in the upper basin that would alter the hydraulic connectivity of wetlands during high flow conditions or reduce groundwater levels could substantially affect streamflow in Charlie Creek. Numerous wetlands and stream channels have been lost due to phosphate mining in other areas of the Peace River watershed (Florida Department of Environmental Protection, 2007). If wetland hydraulic connectivity is completely lost in the upper basin of Charlie Creek, it is possible that streamflow from Charlie Creek to the Peace River would decline substantially, affecting the ability of the lower Peace River to meet minimum flows and levels. Additional groundwater withdrawals from the Upper Floridan aquifer to meet future water demands in this area would likely (1) increase water-level differences between the surficial aquifer and the Upper Floridan aquifer, (2) increase the potential for downward groundwater flow, (3) reduce the percentage of the basin where the intermediate aquifer system discharges upward into the surficial aquifer, and (4) decrease surficial aquifer groundwater levels. The model used to simulate surface and groundwater interactions in the Charlie Creek basin demonstrated the linkage between Upper Floridan aquifer water levels, upward groundwater discharge, base flow, and streamflow.

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Appendixes

Appendix 1

Table 1–1. Characteristics of wells used in the study.

[DDMMSS, latitude or longitude presented with degrees as first two digits, minutes as second two digits, and seconds as last two digits; SA, surficial aquifer; IAS, intermediate aquifer system; UFA, Upper Floridan aquifer; --, data not available; ~, approximately]

Well number	Abbreviated well name	Latitude (DDMMSS)	Longitude (DDMMSS)	Land elevation, ft above NGVD of 1929	Well depth (feet)	Casing depth (feet)	Aquifer	Measurement frequency
1	ROMP 26 SA well	271757	814930	75	15	10	SA	continuous
2	ROMP 26 Hawthorn well (Zone 2 and Zone 3 of IAS)	271757	814930	75	180	140	IAS	continuous
3	ROMP 26 Tampa well (Zone 3 of IAS)	271757	814930	75	430	255	IAS	continuous
4	ROMP 26 Avon Park well	271757	814930	75	1320	580	UFA	continuous
5	Amoco 2 Oil Test Well	272015	813927	94	312	--	IAS	semiannual
6	Brookside Bluff Trailer Park, #1 well IAS[1]	272211	814750	120	--	--	IAS	semiannual
7	Brookside Bluff Trailer Park, #2 well IAS[1]	272226	814737	46	12.6	8.1	SA	~monthly
8	Downstream Transect well 8	272228	814737	46	18.4	13.9	SA	~monthly
9	Downstream Transect well 6	272231	814738	44	20.7	16.2	SA	~monthly
10	Downstream Transect well 7	272231	814738	44	27.3	22.8	SA	~monthly
11	Downstream Transect well 4	272232	814738	30	23.65	19.15	SA	~monthly
12	Downstream Transect well 3	272234	814738	33	26.2	21.7	SA	~monthly
13	Downstream Transect well 2	272236	814738	34	14.1	9.6	SA	~monthly
14	Downstream Transect well 1	272242	814738	38	10.4	5.9	SA	~monthly
15	Bryan Hodge IAS well[1]	272318	814734	50	--	--	IAS	semiannual
16	Paulson Residential IAS well[1]	272341	814521	55	--	--	IAS	semiannual
17	Bentley Shallow SA well	272402	813624	82	10.7	3.5	SA	~monthly
18	Bentley Deep SA well	272402	813624	82	19.1	4.5	SA	continuous
19	Westby well 1	272423	814444	41	19	14.3	SA	~monthly
20	Westby well 2	272426	814443	43	18.7	15.2	SA	~monthly
21	Westby well 3	272428	814443	44	19.7	14.95	SA	~monthly
22	Sunny South UFA well[1]	272436	814504	66	1400	--	UFA	semiannual
23	Hwy 634 roadside well[1]	272437	814642	65	241	--	IAS	semiannual
24	Oak Creek SA well	272442	814143	62	23	18.5	SA	~monthly
25	Sebring SA well	272452	813141	94	--	--	SA	continuous
26	Marrls Floridan well nr Gardner	272509	814104	82	1100	--	UFA	semiannual
27	Messana UFA well[1]	272521	814406	56	1100	--	UFA	semiannual
28	Crewsville SA well	272538	813508	90	26	6	SA	~monthly
29	Crewsville Upper Intermediate well[1]	272538	813508	90	115	96	IAS	~monthly

Table 1-1. Characteristics of wells used in the study. —Continued

[DDMMSS, latitude or longitude presented with degrees as first two digits, minutes as second two digits, and seconds as last two digits; SA, surficial aquifer; IAS, intermediate aquifer system; UFA, Upper Floridan aquifer; --, data not available; ~, approximately]

Well number	Abbreviated well name	Latitude (DDMMSS)	Longitude (DDMMSS)	Land elevation, ft above NGVD of 1929	Well depth (feet)	Casing depth (feet)	Aquifer	Measurement frequency
30	Wilbur Robertson Hawthorn well	272715	814016	75	343	103	IAS	semiannual
31	ROMP 30 SA well	272728	814747	70	15	10	SA	continuous
32	ROMP 30 Arcadia well (Zone 2 of IAS)	272728	814747	70	180	55	IAS	continuous
33	ROMP 30 Tampa well (Zone 3 of IAS)	272728	814747	70	316	280	IAS	continuous
34	ROMP 30 Avon Park well	272728	814747	70	1266	380	UFA	continuous
35	Upstream Transect well 8	272729	814036	56	15.3	10.8	SA	~monthly
36	Upstream Transect well 7	272730	814039	55	21.5	17	SA	~monthly
37	Upstream Transect well 6	272730	814040	55	11	6.5	SA	~monthly
38	Upstream Transect well 4	272730	814042	50	11.1	6.6	SA	~monthly
39	Upstream Transect well 5	272730	814042	50	7	2.5	SA	~monthly
40	Upstream Transect well 3	272730	814043	48	10.7	6.2	SA	~monthly
41	Upstream Transect well 2	272730	814046	49	12.7	8.2	SA	~monthly
42	Upstream Transect well 1	272730	814050	53	12.8	8.38	SA	~monthly
43	Little Charley Bowlegs Creek Shallow SA well	272840	813329	82	10	5.5	SA	~monthly
44	Little Charley Bowlegs Creek Deep SA well	272840	813329	82	25.9	21.4	SA	~monthly
45	Peace River Ranch Floridan well nr Crewsville	272855	814007	76	1163	141	UFA	semiannual
46	Buckhorn Creek Shallow SA well	273104	813958	59	9	4.5	SA	~monthly
47	Buckhorn Creek Deep SA well	273104	813958	59	18	13.5	SA	~monthly
48	Stevens / Crazy Cow IAS well[1]	273135	813958	68	120	--	IAS	semiannual
49	Prescott Shallow SA well	273143	814210	90	9.7	3.5	SA	~monthly
50	Prescott Deep SA well	273143	814210	90	23.4	4.5	SA	continuous
51	Rest Haven IAS well[1]	273310	814047	123	--	--	IAS	semiannual
52	ROMP 43 MW-1 SA well	273501	813519	98	12	2	SA	~monthly
53	ROMP 43 MW-2 Upper Arcadia well (zone 2 of IAS)[1]	273501	813519	98	116	52	IAS	~monthly
54	ROMP 43 MW-3 Lower Arcadia well (zone 3 of IAS)	273501	813519	98	233	196	IAS	~monthly
55	ROMP 43 43 MW-4 Suwannee well[1]	273501	813519	98	464	306	UFA	~monthly
56	John White Hawthorn well nr Wauchula	273555	814030	117	270	63	IAS	semiannual

[1] Water level only measured for 2005 potentiometric surface maps.

Appendix 2

Table 2-1. Discharge and specific conductance measurements for the four seepage runs.

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter; --, no data; REW, right edge of water looking downstream; LEW, left edge of water looking downstream]

Site description[1]	February 18, 2005		May 26, 2005		December 29, 2005		January 23, 3006	
	Discharge (ft^3/s)	Specific conductance (µS/cm)	Discharge (ft^3/s)	Specific conductance (µS/cm)	Discharge (ft^3/s)	Specific conductance (µS/cm)	Discharge (ft^3/s)	Specific conductance (µS/cm)
Charlie Creek at Highway 66 Bridge	14.30	201	8.34	222	32.30	170	12.50	202
Inflow downstream of Highway 66 Bridge (LEW)	0.14	--	0.00	--	0.47	184	0.17	--
Charlie Creek on Robertson property downstream of HWY 66 (A)	15.20	196	8.09	222	32.89	--	12.19	211
Inflow on D&H Ranch from Citrus Grove (LEW)	0.75	347	0.82	348	0.71	337	0.59	326
Charlie Creek on Faulkner Property (D&H Ranch) (B)	18.00	--	11.27	261	33.25	197	12.35	224
Inflow across from D&H Ranch (REW)	--	--			1.89	--	1.25	486
Charlie Creek above Oak Creek (C)	18.80	--	12.90	287	36.52	206	13.68	252
Inflow Oak Creek above Charlie Creek confluence (LEW)	7.57	--	8.83	315	10.37	271	4.59	280
REW Tributary #1 downstream of Oak Creek	--	--	--	--	--	--	0.02	405
REW Tributary #2 downstream of Oak Creek	--	--	--	--	--	--	0.05	430
Charlie Creek at Highway 634 (D)	27.30	--	24.40	298	44.75	220	19.42	274
Inflow along Highway 634 (REW)	0.01	442	--	--	0.26	--	0.06	--
Inflow Unnamed tributary creek north of limestone rapids (REW) Westby	0.12	--	0.03	--	--	--	--	--
Inflow through Taylor Property (LEW) "Badlands Northernmost"	0.54	--	--	--	--	--	0.50	--
Inflow through Westby property (LEW) "Badlands Middle"	--	--	--	--	0.78	--	1.26	276
Fish Branch Tributary across from Paulson Property (LEW)	1.10	284	1.00	302	1.70	252	--	--
Charlie Creek at Paulsen Property (E)	30.43	276	--	--	49.82	233	22.13	--
Inflow on Bryan Hodge Property (REW)	--	--	--	--	0.03	--	0.02	--
Inflow just North of DOT transect wells (LEW)	--	--	0.03	--	0.03	--	0.02	--
Charlie Creek at Hwy 17 near Gardner (F)	31.40	297	31.20	295	53.19	--	25.32	--

[1] (A), (B), (C), (D), (E), and (F) refers to the downstream measurement section for this reach.

Appendix 3

Detailed Hydrologic Modeling Methods

Hydrologic soil groups were used to assign soil properties as part of the simplified water-balance approach used to represent flow and evapotranspiration in the unsaturated zone (app. 3, table 1). Soil horizon thickness, soil moisture, and hydraulic conductivity data from Robbins and others (1984) and Carlisle and others (1988) were used to develop representative soil properties for hydrologic soil groups A, B, C, D, W, and B/D present in the study area. A thickness-weighted arithmetic mean was used to calculate representative water contents at the wilting point, field capacity, and saturation for hydrologic soil groups. A thickness-weighted harmonic mean was used to calculate representative saturated vertical hydraulic conductivities for hydrologic soil groups.

The soil classes contributing to the hydrologic soil groups A, B, C, D, W, and B/D in the study area are described below.

- Archbold sand is the predominant soil classification in hydrologic soil group A, composing 34 percent of this hydrologic soil group, and data from Carlisle and others (1988) were used to develop representative soil parameters.
- Hydrologic soil group B is composed solely of Jonathan sand, and data from Robbins and others (1984) were used to develop representative soil parameters.
- Zolfo fine sand is the predominant soil classification in hydrologic soil group C, composing 41 percent of this hydrologic soil group, and data from Robbins and others (1984) were used to develop representative soil parameters.
- The Bradenton-Felda-Chobee soil association is the predominant soil classification in hydrologic soil group D, composing 48 percent of this hydrologic soil group, and data from Carlisle and others (1988) were used to develop representative soil parameters.
- Soil parameters from hydrologic soil group D were used for hydrologic soil group W.
- Myakka fine sand is the predominant soil classification in hydrologic soil group B/D, composing 18 percent of this hydrologic soil group, and data from Carlisle and others (1988) were used to develop representative soil parameters.

A sinusoidal pattern was used to assign leaf area indices and root depths for non-agricultural land use/land cover types throughout the year. A constant leaf area index and root depth was used for citrus. Spring and winter row crops were simulated by assigning two periods with large leaf area indices and root depths. Maximum crop coefficients for agricultural crops were assigned based on data from Allen and others (1998). Crop coefficients for non-forested wetlands, forested wetlands, and open water were adjusted to constrain annual evapotranspiration rates to be no greater than long-term evaporation rates observed at Lake Starr (57.29 in/yr, A. Swancar, U.S. Geological Survey, written commun., 2009). Crop coefficients for upland forests, pasture/open lands, rangeland, and utilities/communications facilities were adjusted to reflect the observed seasonal ratio of actual evapotranspiration to reference evapotranspiration at a pasture evapotranspiration station located in Pasco County, Florida (A. Swancar, U.S. Geological Survey, written commun., 2008) (app. 3, table 3). Irrigation was enabled for agricultural areas, with crop demand calculated using the crop stress factor approach that applies irrigation to meet daily crop-specific evapotranspiration rates.

Overland flow parameters that have been related to land use/land cover include overland roughness coefficients (app. 3, table 2) and separated overland flow areas. Separated overland flow areas were defined for agricultural land uses (citrus and row crops) to represent perimeter berms around farm fields used to manage surface-water discharge. Land use/land cover data distributed model parameters are comparable to parameters used in an integrated surface-water/groundwater model developed for the upper Myakka River watershed (Interflow Engineering, 2008).

Table 3-1. Unsaturated and saturated hydraulic properties applied to various hydrologic soil groups represented in the model.

[ft/d, feet per day]

Hydrologic soil group	Saturated horizontal hydraulic conductivity (ft/d)	Saturated vertical hydraulic conductivity (ft/d)	Specific yield (-)	Water content at saturation (-)	Water content at field capacity (-)	Water content at wilting point (-)
A	19.53	19.44	0.39	0.40	0.033	0.0082
B	20.52	3.00	0.37	0.40	0.083	0.032
C	7.43	6.55	0.38	0.40	0.065	0.017
B/D	6.58	1.50	0.35	0.39	0.13	0.040
D–W	2.13	0.17	0.25	0.38	0.23	0.13

Table 3-2. Manning's roughness coefficient and vegetation parameters applied to the various types of land uses and land covers represented in the model.

General land use/ land cover classification	Overland Mannings M[1] coefficient (-)	Minimum leaf-area index (unitless)	Maximum leaf-area index (unitless)	Minimum root depth, (inches)	Maximum root depth, (inches)
Non-forested wetlands	1.43	2	4.8	6	24
Open water	20	0	0	0	0
Upland forests	1.67	3.4	5.5	60	60
Pasture/ open lands	4.17	2	4	36	60
Rangeland	2.5	3	4.8	36	60
Citrus	5.88	4.5	4.5	60	60
Urban	6.67	1	2	24	24
Row crops	5.88	0	2.7	0	8.1
Forested wetlands	1.25	3	7	24	60
Disturbed land	10	1	1	12	12
Utilities/communications	4.17	2	4	36	60

[1] Mannings M is the reciprocal of Mannings n

Table 3-3. Monthly vegetation crop coefficients applied to various types of land uses and land covers represented in the model.

General land use/ land cover classification	Month of the year											
	1	2	3	4	5	6	7	8	9	10	11	12
Non-forested wetlands	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Open water	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Upland forests	0.8	0.8	0.8	0.8	0.8	0.8	0.5	0.5	0.5	0.8	0.8	0.8
Pasture/open lands	0.8	0.8	0.8	0.8	0.8	0.8	0.5	0.5	0.5	0.8	0.8	0.8
Rangeland	0.8	0.8	0.8	0.8	0.8	0.8	0.5	0.5	0.5	0.8	0.8	0.8
Citrus	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Urban	0.8	0.8	0.8	0.8	0.8	0.8	0.5	0.5	0.5	0.8	0.8	0.8
Row crops	1	1.15	1.15	1.15	1.15	1	1	1	1.15	1.15	1.15	1.15
Forested wetlands	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Disturbed land	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Utilities/ communications	0.8	0.8	0.8	0.8	0.8	0.8	0.5	0.5	0.5	0.8	0.8	0.8

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