Analysis of Long-Term Trends in Flow from a Large Spring Complex in Northern Florida

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Abstract

Nonparametric regression analysis of historic flow and rainfall data was used to estimate declining flows in a river draining a large spring complex in northern Florida, USA. The analysis indicated that flow declined by an estimated 23 percent from 1900 to 2009. The rate of decline appeared to increase over time, from about 0.8 cubic foot per second per year during the period from 1930-1970, to about 1.1 cubic feet per second per year over the period from 1970-2009. The estimated decline for the period prior to 1980 is consistent with evidence indicating groundwater withdrawals to the east of the study area have diverted groundwater that formerly flowed toward the Ichetucknee River under predevelopment conditions.

INTRODUCTION

The Ichetucknee River is a tributary to the Suwannee River and drains an area of karst topography in northern peninsular Florida, USA. Flow in the 5.2-mile long river is sustained by 8 named springs and spring complexes that discharge groundwater from the highly transmissive Floridan aquifer system. The purpose of this paper is to describe a long-term trend of declining flow in the Ichetucknee River, and changes in the groundwater flow system in the vicinity of the river that have most likely contributed to this trend.

REGIONAL GROUNDWATER FLOW SYSTEM

Groundwater in the Floridan aquifer system generally flows toward the Ichetucknee River from the region north and east of the springs. This pattern of flow is evident in potentiometric-surface maps of conditions prior to the initiation of substantial groundwater withdrawals from the Floridan aquifer system in the late 1800s (predevelopement conditions), as well as conditions subsequent to groundwater development, in May 1980 (Johnston and others, 1980; Johnston and others, 1981; figs. 1 and 2, respectively). These two potentiometric-surface maps were chosen because they are the only maps that had been published for the entire Floridan aquifer system, and therefore make it possible to evaluate patterns of the groundwater flow system over large areas that could affect the discharge of groundwater to the Ichetucknee River. The flow lines shown in figures 1 and 2 are drawn so that (1) they are directed from areas of higher water levels toward areas of lower water levels, and (2) points of intersections between the flow lines and equipotential (contour) lines in the potentiometric surface form right angles. In addition to representing directions of groundwater flow, the flow lines can also be used to define the approximate location of important boundaries within the groundwater flow system, as well as the areas that contribute groundwater flow to springs and rivers.

A key feature in the regional groundwater flow system of the Floridan aquifer system in northern Florida is the groundwater flow line that runs roughly northwest to southeast and defines the boundary between groundwater flowing eastward (toward the Atlantic Ocean) and westward (toward the Suwannee, Santa Fe, and Ichetucknee Rivers) (figs.1 and 2). The boundary is formed by two flow lines. The first originates on a high, dome-shaped area of the potentiometric surface of the Floridan aquifer system, near the city of Valdosta, in southern Georgia. The second flow line originates on another high, dome-shaped area of the potentiometric surface of the Floridan aquifer system east of the Ichetucknee River, near Keystone Heights, Florida. These flow paths meet at one or more points where groundwater flow direction diverges and splits (stagnation

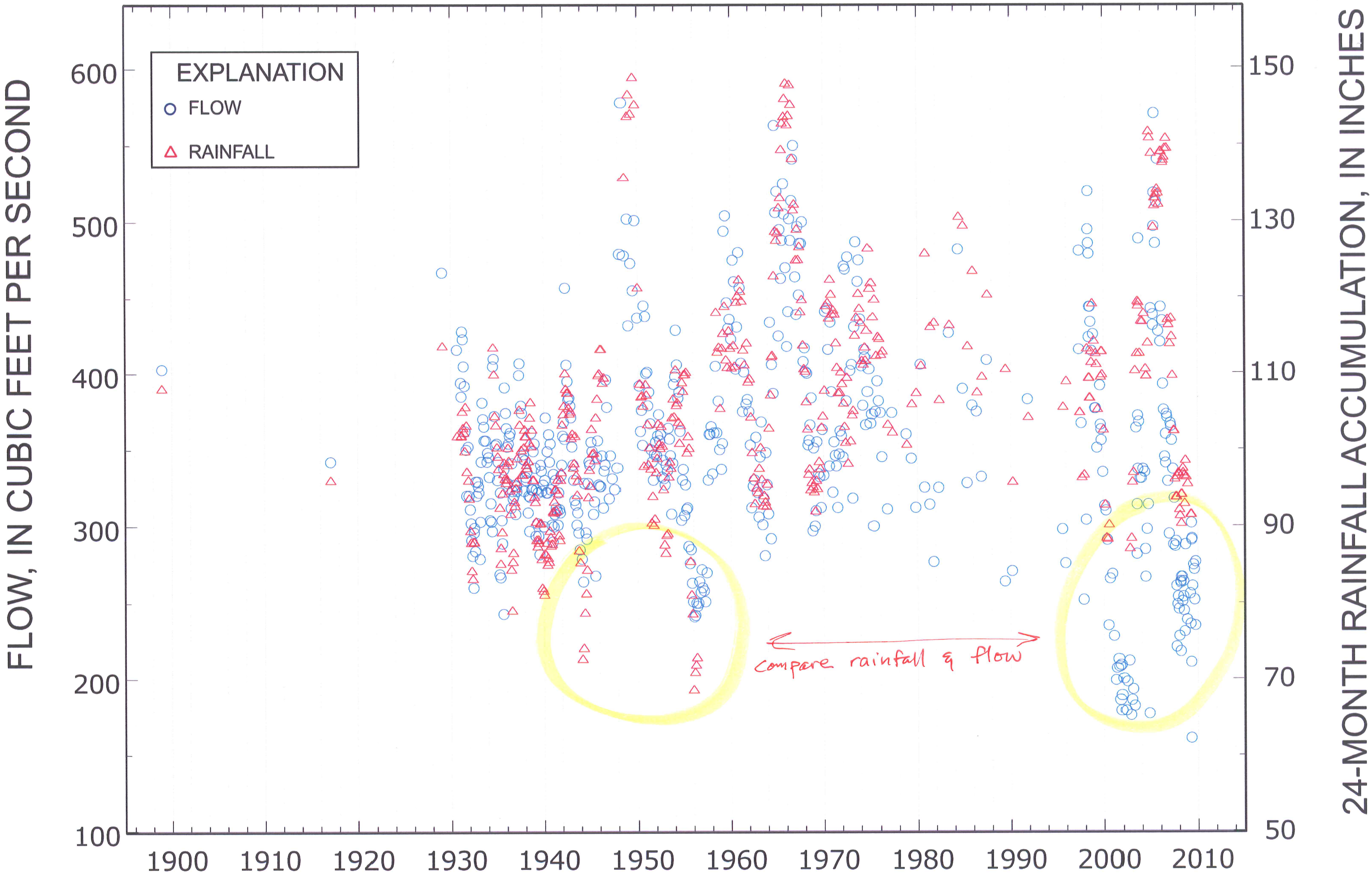

Figure 5. Time series of historic stream-flow measurements in the Ichetucknee River at USGS gaging station 02322700, and associated values of 24-month antecedent rainfall accumulations from the National Weather Service Weather Station, Lake City 2 E (COOP ID 084731).

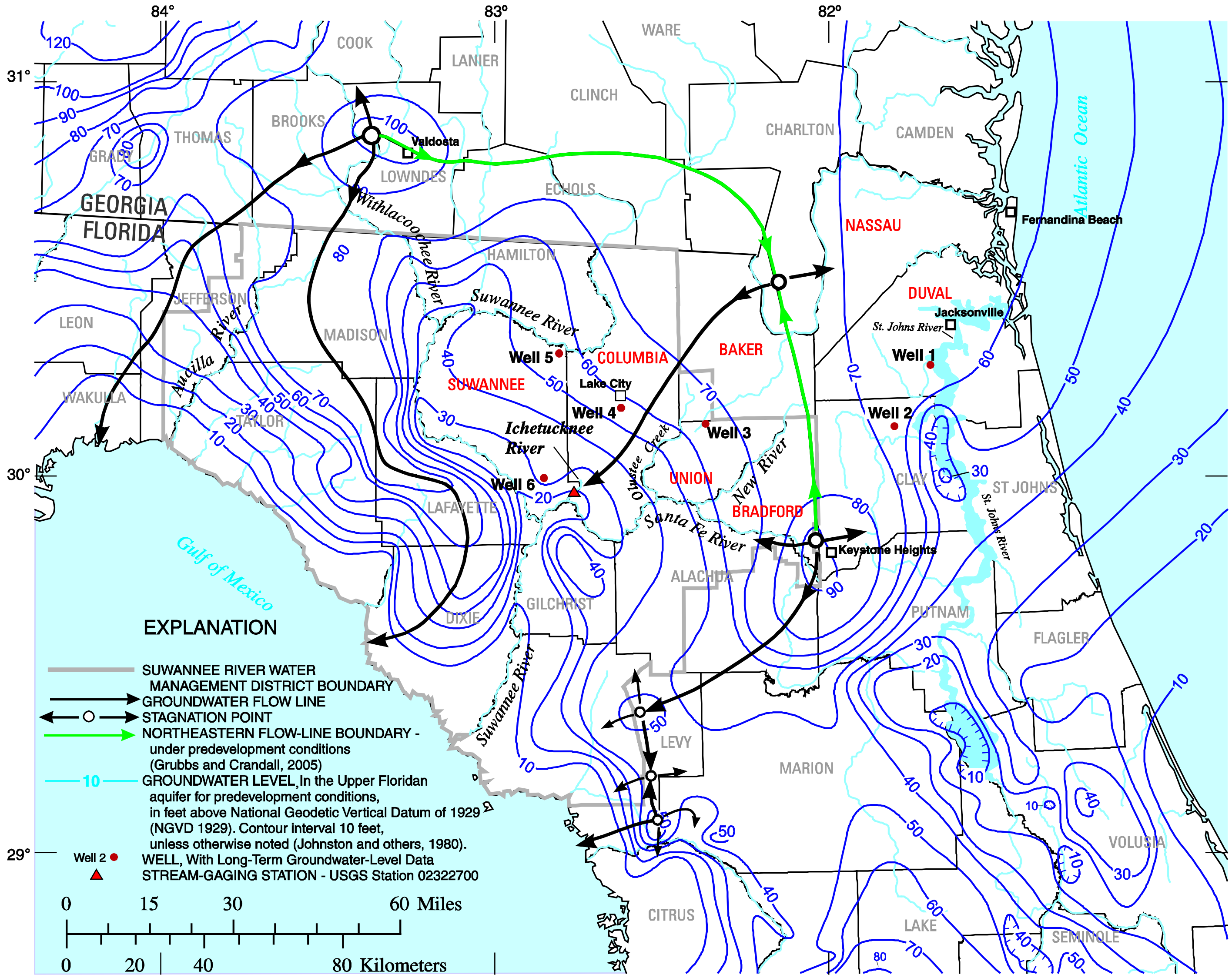

Figure 1. Estimated potentiometric surface of the Upper Floridan aquifer during predevelopment conditions, including key flow line boundaries (contour lines are from Johnston and others, 1980; modified from figure 19 in Grubbs and Crandall, 2005).

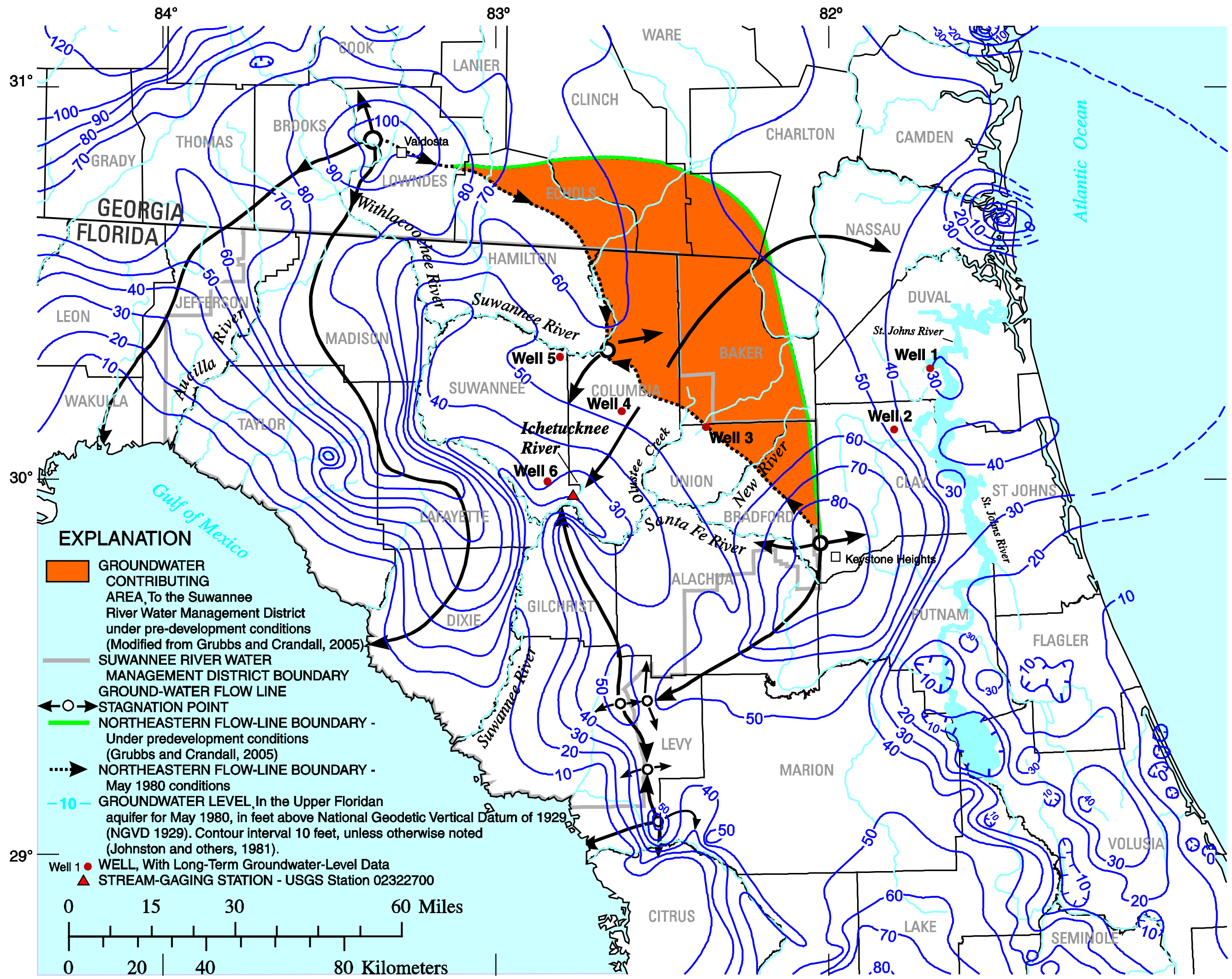

Figure 2. Potentiometric surface of the Upper Floridan aquifer during May 1980 showing: (1) key groundwater flow lines, (2) the northeastern flow-line boundary, and (3) the estimated area where groundwater flow has been diverted away from the Suwannee, Ichetucknee, and Santa Fe Rivers (contour lines are from Johnston and others, 1981; modified from figure 18 in Grubbs and Crandall, 2005).

point) into eastward- and westward-directed flow paths. In this paper, this divide is referred to as the northeastern flow-line boundary.

The location of the northeastern flow-line boundary is evident in the potentiometric-surface map representing predevelopment conditions, as well as in maps made subsequent to groundwater development. The configuration of the potentiometric-surface map corresponding to predevelopment conditions (Johnston and others, 1980) suggests that the northeastern groundwater flow boundary passed through an area near the eastern boundaries of Baker and Bradford Counties in Florida (fig. 1; Grubbs and Crandall, 2007, fig. 19, page 26) prior to groundwater development. This area coincides with the Trail Ridge, a physiographic feature with the highest elevation in the area between the Suwannee and the Atlantic Ocean.

The configuration of the May 1980 surface suggests that the northeastern groundwater flow boundary migrated westward after development of the groundwater flow system (fig. 2; Grubbs and Crandall, 2007). This movement is consistent with the historic patterns of groundwater development (2011, http://fl.water.usgs.gov/infodata/wateruse/counties.html), in which groundwater withdrawals have been substantialy larger to the northeast (in Duval and Nassau Counties) than in the four counties closest to Ichetucknee Springs (Columbia, Union, Baker, and Suwannee) (fig. 3). Comparison of the two potentiometric-surface maps also indicates that groundwater-level declines between predevelopment conditions and May 1980 were negligible near the Ichetucknee River, but became more pronounced toward the northeast. For example, the maps indicate that groundwater levels fell by approximately 10-12 feet in Baker and northern Union Counties, approximately 25 feet in eastern Duval and Nassau Counties, and by as much as 90 feet near Fernandina Beach, where paper mills withdrew approximately 50 cubic feet per second (ft^3s^{-1}) from the Floridan aquifer system in 2000 (Richard Marella, U.S. Geological Survey, written commun., 2010). This geographic pattern of groundwater-level decline and groundwater withdrawals suggest that larger withdrawals, by lowering groundwater levels over a larger area, shift the northeastern flow-line boundary and create a larger contributing area to capture greater amounts of groundwater recharge. Westward migration of the boundary has also resulted in a contraction of the area of westward-flowing groundwater toward the Suwannee, Ichetucknee and Lower Santa Fe Rivers (fig. 2). It should be noted that this area where the groundwater contributing area has changed (fig. 2) was originally delineated in figure 18 in Grubbs and Crandall (2007). The area shown in figure 2 differs from that originally shown in figure 18 in Grubbs and Crandall (2007) because it reflects corrections that were made to the contour lines that were shown in the original figure.

The declines in groundwater levels of the Floridan aquifer system observed at individual wells are consistent with the differences seen in the predevelopment and May 1980 potentiometric-surface maps. Data from selected wells (fig. 4) indicate that average-annual groundwater levels declined by 2 to 10 feet in wells east and west of the northeastern groundwater flow divide from 1960 to 1980, and by approximately 4 to 12 feet in these same wells from 1960 to 2009. Longer-term data from well 1 near the metropolitan area of Jacksonville indicated a decline of more than 30 feet from 1930 to 2009. Kendall's tau tests (Conover, 1980) for negative correlations between groundwater-levels and time were significant for all of the time series shown in figure 4, with the highest levels of significance (p-value < 0.0001) associated with wells 1-5 (well 6 had a one-sided p-value of 0.048). The computed values of Kendall's tau also became progressively more negative (and increased in absolute value) for wells closer to Duval and Nassau Counties, indicating a closer correspondence between groundwater level and time as one moves from the Ichetucknee River toward these two counties.

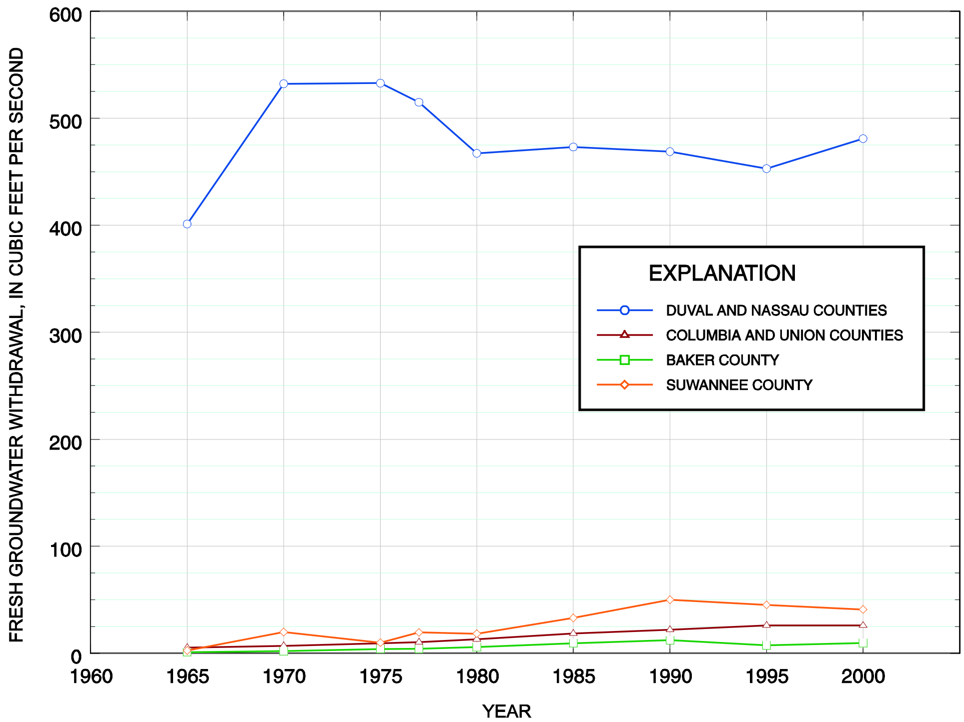

Figure 3. Time-series of historic groundwater withdrawals from selected counties in northern peninsular Florida, 1965-2000.

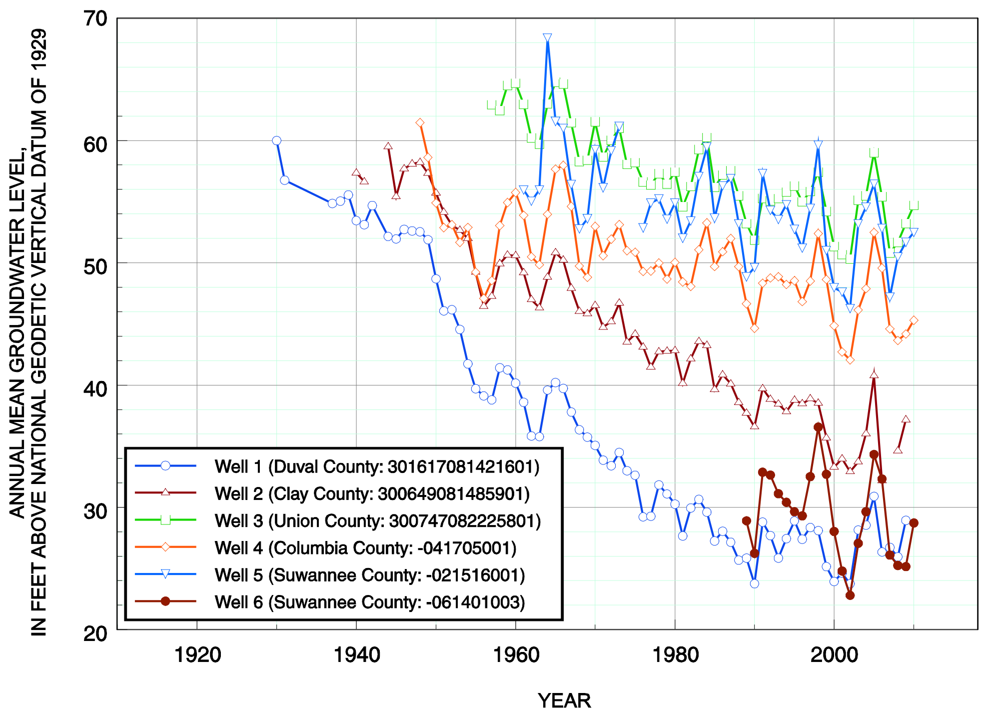

Figure 4. Time-series of groundwater levels from selected wells in northern peninsular Florida.

TRENDS IN THE FLOW OF THE ICHETUCKNEE RIVER

Between December 1898 and September 2009 the U.S. Geological Survey (USGS) made 538 individual field measurements of flow at a cross section of the Ichetucknee River downstream from its major springs, where it passes under the bridge at U.S. Highway 27 (USGS station 02322700). Comparison of time-series plots of the flows measured at this cross section and rainfall totals accumulated at Lake City (National Weather Service coop station 084731) for the 24 month period prior to (and including) the month during which each flow measurement illustrate the relation between river flow, rainfall, and time (fig. 5). As expected, measured flows generally increased with increasing antecedent rainfall totals, and decreased as these rainfall amounts decreased. For example, flows in the river generally increased as conditions became wetter from late 1963 to late 1965, and subsequently decreased as conditions became drier from late 1965 to late 1968. In addition, periods of extreme low flow coincided with periods of deficient rainfall in the mid 1950s, 2000-2003, and 2007-2009. Evidence for a possible relation between time and flow is suggested by noting that the average flow from 1930-1965 (346 ft^3s^{-1}) was higher than the average flow for the period after 1970 (326 ft^3s^{-1}), even though the average 24-month rainfall accumulation for measurements made in the earlier period was lower than that of the later period (100 inches versus 111 inches, respectively). Similarly, the low flows during dry periods in 2000-2003 and 2007-2009 were generally lower than those during the dry period in the mid 1950s, even though the 24-month antecedent rainfall totals in the 2000-2003 and 2007-2009 dry periods were much higher than the rainfall totals during the mid 1950s (fig. 5). These observations suggest that flow in the Ichetucknee River may have declined over time from causes that are unrelated to rainfall.

To assess the significance of the time trends in the flow in the Ichetucknee River while controlling for the effects of rainfall, a multivariate, locally-weighted scatterplot smoothing, (LOWESS; Cleveland and others, 1988) regression model was created to estimate flow in the Ichetucknee River at U.S. Highway

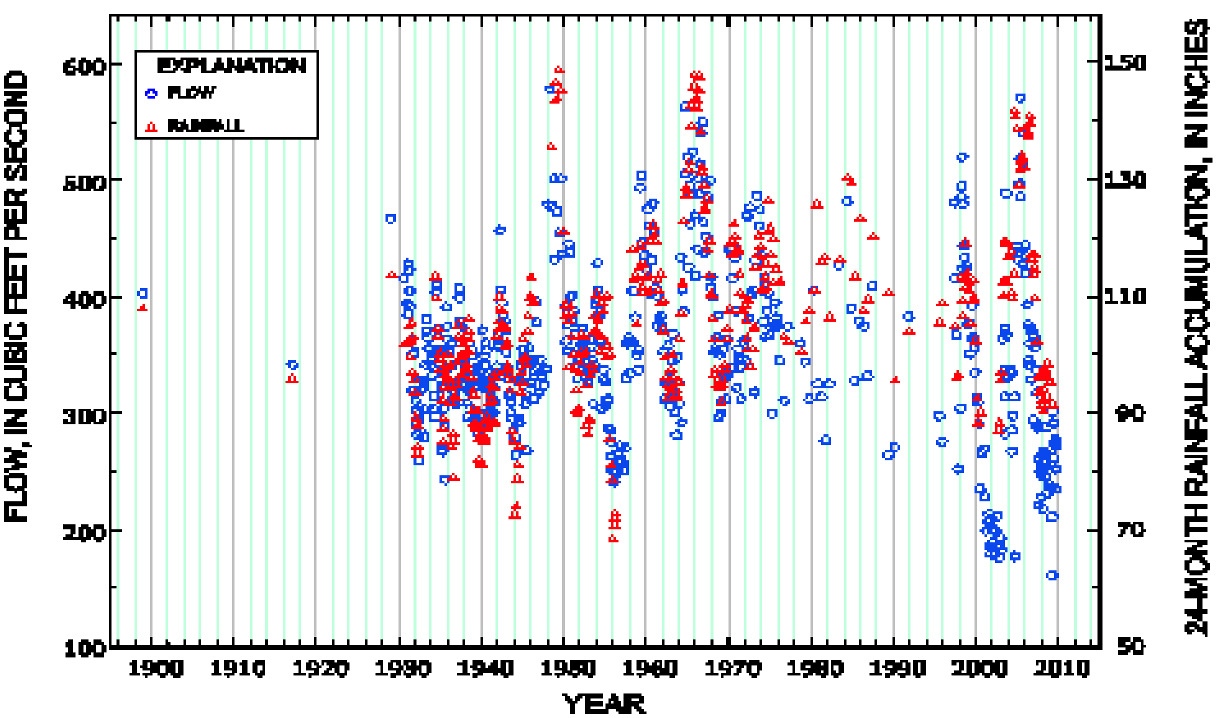

Figure 5. Time series of historic stream-flow measurements in the Ichetucknee River at USGS gaging station 02322700, and associated values of 24-month antecedent rainfall accumulations from the National Weather Service Weather Station, Lake City 2 E (COOP ID 084731).

27 as a function of two explanatory variables: time and 24-month antecedent rainfall. LOWESS regression was chosen because it requires no prior assumptions about the form of the relation between the response and explanatory variables, such as whether the relation is linear or nonlinear. The data used to fit the model were obtained by grouping the individual flow measurements by the year in which each measurement was made, and then computing the average of the flows, 24-month rainfall accumulations, and dates associated with each measurement made in a given year. This was done to obtain more reliable estimates of the model error and confidence limits for the flow values produced by the model. The overall model fit was highly significant (p-value < 0.001). Nested F-tests indicated that, although both explanatory variables were significant at a confidence levels of 0.96 or better, the addition of the explanatory variable associated with the 24-month rainfall accumulation was responsible for a greater degree of model improvement (p-value < 0.007) than that associated with time (p-value < 0.04).

The regression model made it possible to evaluate the magnitude and significance of the time trend over selected time intervals by using it to estimate river flow at the beginning and end of a given time interval (using the same antecedent rainfall amount for computing both estimates), then computing changes in flow over the interval as the difference between the two estimates. Table 1 shows the results from an analysis of changes in the Ichetucknee River flow under conditions of typical rainfall (24-month rainfall accumulation was set equal to the median of 24-month rainfall accumulation values used to fit the regression model). In this analysis, the estimated flow declined by 92 ft^3s^{-1} from 1900 to 2009 (table 1). The analysis also suggests that the stream-flow losses have probably accelerated over time. For example, the estimated slope of the trend for the period between 1930 and 1970 was about -0.8 cubic foot per second per year (downward), but steepened to about -1.1 cubic feet per second per year in the period between 1970 to 2009.

DISCUSSION

The estimated decline in the flow of the Ichetucknee River from 1900 to 1980 is approximately 60 ft^3s^{-1} (table 1), with a 95 percent confidence interval of 23 to 96 ft^3s^{-1}. The configuration of the May 1980 potentiometric surface and a more recent detailed study of the surface in the vicinity of the Ichetucknee River (Sepulveda and others, 2006) suggest that the area contributing groundwater to the river during this period was probably located within an area roughly comprising the southern half of Columbia County and perhaps half of Union County. The estimated total fresh groundwater withdrawals from the Floridan aquifer system in these two counties was 13 ft^3s^{-1} in 1980 (2011, http://fl.water.usgs.gov/infodata/wateruse/counties.html). Thus it seems unlikely that estimated decline in the flow of the Ichetucknee River from predevelopment conditions to 1980 can be explained entirely by groundwater withdrawals within the post-development groundwater contributing area to the river. The most likely alternative explanation is that estimated flow declines were caused by the westward migration of the northeastern groundwater flow boundary (and the concurrent contraction of the groundwater contributing area to the Ichetucknee River).

This explanation is also consistent with estimates of the magnitude of groundwater flow that was diverted from the river in response to the contraction of its contributing area, computed as the product of change in the size of the contributing area and groundwater recharge rate to the Floridan aquifer system. The potentiometric-surface maps suggest a plausible range of approximately 450 to 850 square miles for the reduction in the size of the groundwater contributing area to the Ichetucknee River from predevelopment conditions to May 1980. Recharge rates of approximately 1 to 1.8 inches per year over an area of this magnitude are sufficient to produce a flux of 60 ft^3s^{-1}, and are also consistent with plausible rates of recharge (for example, Sepulveda, 2002) in this area where groundwater flow directions have been reversed. Therefore it seems likely that some (if not most) of the estimated reductions in flow in the Ichetucknee River from predevelopment

conditions to 1980 resulted from changes in the groundwater flow system arising from withdrawals outside of the area that contributed groundwater to the river in and prior to 1980.

Table 1. Estimated Changes in Flow in the Ichetucknee River at USGS Station 02322700 for Typical Rainfall Conditions and Selected Time Intervals.

[Unit abbreviations: ft^3s^{-1}, cubic feet per second; $ft^3s^{-1}yr^{-1}$, cubic feet per second per year]

Time Interval	Time Span (Δt), in years	Estimated Decline in Flow (ΔQ), in ft^3s^{-1}	Standard Error of ΔQ, in ft^3s^{-1}	Lower limit of 95% confidence interval for ΔQ, in ft^3s^{-1}	Upper limit of 95% confidence interval for ΔQ, in $ft^3s^{-1}yr^{-1}$	Estimated Rate of Decline in Flow, in $ft^3s^{-1}yr^{-1}$
1900-2009	119	92	20	52	132	0.84
1930-1970	40	31	11	10	53	0.78
1970-2009	39	42	11	20	65	1.08
1900-1980	80	60	18	23	96	0.74
1980-2009	29	32	11	10	55	1.12

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