Groundwater abstraction impacts on spring flow and base flow in the Hillsborough River Basin, Florida, USA

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Abstract Groundwater abstraction has resulted in spring flow and groundwater base-flow declines in the Hillsborough River system of central Florida, USA. These declines have resulted in reduction of inflows to the Tampa city reservoir as well as likely adverse environmental effects on riverine and estuarine biota. Causes evaluated for the declines include effects of groundwater development, reduced rainfall, and land alterations. The karstic, heterogeneic nature of the area renders groundwater flow modeling an ineffective method for overall evaluation. Therefore, the evaluation of these declines is accomplished through the systematic use of parametric and nonparametric statistical techniques. These techniques include contingency table analysis, linear regression, Kendall-Theil and Mann-Kendall trend analysis, locally weighted regression, Pearson correlation, Kendall-tau correlation, Spearman correlation, runs test, Student's *t* test, and the Kruskall-Wallis test. Data evaluated include groundwater withdrawals, rainfall, base flow, streamflow, stream stage, spring flow, and groundwater levels. Additional methods used include double mass analysis, base flow separation, a low-stage trend analysis, data visualization techniques, and water level change maps. The methodical application of these analyses and techniques to the hydrologic and climatic data yields the conclusion that the primary factor causing the spring flow and base-flow declines is lowered groundwater levels caused by over-abstraction.

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Résumé L'exploitation des eaux souterraines a induit la baisse du régime des sources et du débit d'étiage lié aux nappes, dans le système de la rivière de la Hillsborough, au centre de la Floride. Ces baisses ont eu pour résultats la réduction de l'afflux vers le réservoir de la ville de Tampa, ainsi que des effets environnementaux sur les biota des rives et de l'estuaire. Les causes de ces baisses - pompages, diminution des pluies, dégradation du sol – ont été estimées. La nature karstique et hétérogène de la zone rend la modélisation inapte à une évaluation globale. Dés lors, ces baisses sont évaluées grâce à l'application systématique de techniques statistiques paramétriques et non paramétriques. Ces techniques incluent des analyses par table de contingence, régression linéaire, tendances de Kendall-Theill et Mann-Khendall, Régression Polynômiale locale, corrélation de Pearson, corrélation de Kendall-tau, corrélation de Spearman, Runs test, test de Student, et test de Kruskall-Wallis. Les données évaluées sont les rabattements, les pluies, les débits d'étiage, autres débits, débits des sources et le niveau des nappes. D'autres méthodes utilisées incluent l'analyse par double masse, le découpage des hydrographes d'étiage, l'analyse des niveaux de base, différentes techniques de visualisation des données et enfin différentes cartes de niveau des eaux. L'application méthodologique de ces analyses et de ces techniques aux données climatiques et hydrologiques, conduit à la conclusion que le facteur primaire causant les baisses des débits et des niveaux, est la baisse des niveaux des nappes induit pas la sur-exploitation.

Resumen La extacción de agua subterránea ha ocasionado descensos en el flujo de base de agua subterránea y en el flujo de manantial en el sistema del Río Hillsborough en el centro de Florida. Estos descensos han ocasionado la reducción de la entrada de flujos en el reservorio de la ciudad de Tampa así como también efectos ambientales negativos en la biota de los estuarios y ríos. Las causas que se han evaluado para explicar los descensos incluye el desarrollo de aguas subterráneas, reducción en la cantidad de lluvia, y alteraciones en el terreno. La naturaleza kárstica y heterogénea del área hace que el modelizado de flujo de agua subterránea sea un método poco efectivo para la evaluación. Por lo tanto, la evaluación de los descensos se ha llevado a cabo mediante el uso sistemático de técnicas estadísticas paramétricas y no paramétricas. Estas técnicas incluye el análisis de tabla de

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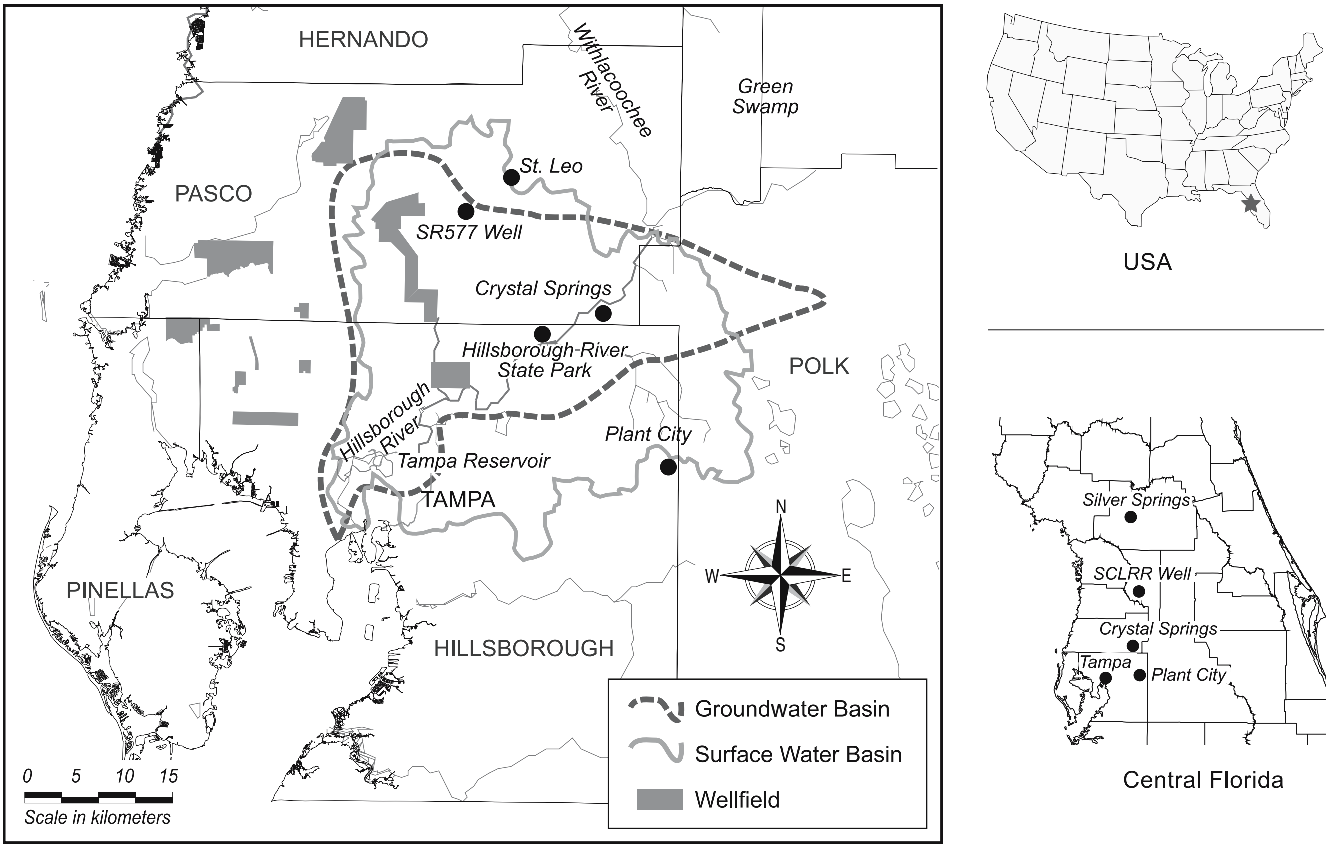

Fig. 1 Location map of Crystal Springs, Hillsborough River, Hillsborough River groundwater basin and surface water basin, public supply wellfields and major landmarks

contingencia, regresión lineal, análisis de tendencias Mann-Kendall y Theil-Kendall, regresión pesada localmente, correlación Pearson, correlación tau-Kendall, correlación Spearman, pruebas de corrida, prueba t-Student, y la prueba Kruskall-Wallis. Los datos evaluados incluye extracciones de agua subterránea, flujo de base, escorrentía, niveles de río, flujo de manantial, y niveles de agua subterránea. Los métodos adicionales utilizados incluye el análisis de doble masa, la separación de flujo base, análisis de tendencia de etapa baja, técnicas de visualización de datos, y mapas de cambio de niveles de agua. La aplicación metódica de estos analisis y técnicas a los datos climáticos e hidrológicos conduce a la conclusión de que el principal factor causante de la disminución del flujo base y del flujo del manantial es el descenso de niveles de agua subterránea ocasionados por sobreexplotación.

Keywords Groundwater development · Over-abstraction · Groundwater statistics · Karst

Introduction

Crystal Springs is a spring in west-central Florida, USA that discharges into the Hillsborough River. The Hillsborough River extends from the Green Swamp in central Florida to Hillsborough Bay near downtown Tampa (Fig. 1) on Florida's west coast. The river has a surface drainage basin area of about 1,789 km^2. The groundwater basin that contributes flow to the river was first delineated by Parker (1975), based on the May 1973 Floridan aquifer potentiometric surface. For this present study, the Hillsborough River groundwater basin (HRGWB) was determined based upon flowlines developed from the 10-year average Floridan aquifer potentiometric surface for the period 1988–1997, and encompasses about 1,400 km^2 (Fig. 2). The city of Tampa operates a dam and reservoir in the lower portion of the river (Fig. 1), which is a highly urbanized area. During low-flow periods such as the spring season or during droughts, nearly all of the flow of the river comes from groundwater base flow and spring flow. Therefore, the low flow regimen is very important to the city's water supply. The biological importance of the low-flow regime has yet to be evaluated, although studies of such regimes elsewhere have shown important biological aspects (Smith and Wood 2002; Petts et al. 1999). Upstream of the reservoir, surface development that would affect flow of the river is minimal. Flows to this portion are derived from surface runoff and groundwater base flow to the river and its numerous tributaries and springs, chiefly Crystal Springs. Significant groundwater withdrawals occur from public supply wellfields in the northwest portion of the HRGWB and the surrounding area (Fig. 1).

Evaluation of estimated base flow data for the Hillsborough River in west-central Florida, and Crystal Springs

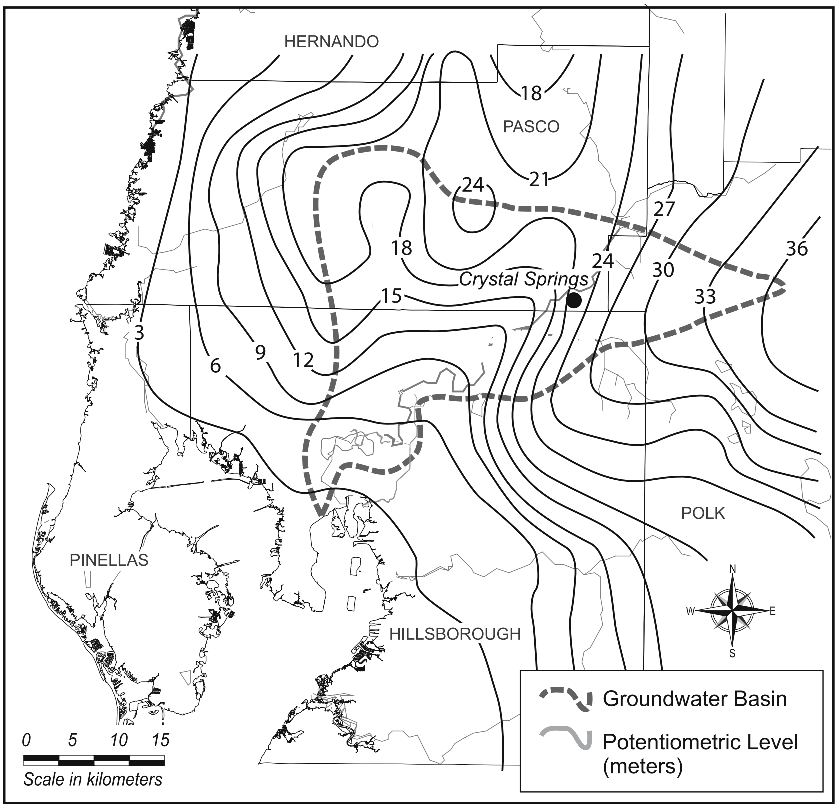

Fig. 2 Delineation of the Hillsborough River groundwater basin based on persistent flowlines using the 10-year average Floridan aquifer potentiometric surface for the period 1988–1997

which discharges into the river, reveals statistically significant declining trends over the last 30 years. It is important to discern the cause or causes for such declines so that strategies can be developed to check or reverse the trends if they are the result of anthropogenic changes. Possible causes for the declines include declining rainfall, groundwater abstraction, and physical changes in the watershed. Integrated ground and surface water models are being developed, but such models are particularly problematic in a karst region, and it will likely be many years before there are sufficient data available to use them with a high degree of confidence in this area. Similarly, there are inadequate data to construct a detailed water budget for the area. Use of multiple procedures that lead to the same general conclusion allows confidence in the results (Bales and Pope 2001). On this basis, a number of carefully chosen data analysis and statistical techniques were used to evaluate the hydrologic data and develop conclusions.

Previous studies

The contribution of groundwater to the Hillsborough River was first noted by Menke et al. (1961), who observed the considerable inflow of groundwater to the river from Crystal Springs. Wolansky and Thompson (1987) determined that during periods of low flow in the river, groundwater discharge, particularly from Crystal Springs, comprises the primary flow component of the river. Taylor (1997) evaluated stream flow and base flow at several stations along the Hillsborough River and its tributaries and found that all but one station were declining for both parameters. Champion and DeWitt (2000) found that water quality data suggest that the aquifer source area for spring flow is primarily toward the northwest of the spring.

Hydrogeologic setting

The principal hydrogeologic units in this karst region consist of, in descending order, a thin surficial aquifer, a discontinuous confining layer of highly variable thickness, and the upper Floridan aquifer system. The surficial aquifer is comprised of undifferentiated sands and minor clay deposits of Quaternary to Pliocene age. The confining units are predominately phosphatic clay with minor limestone of the Miocene-age Hawthorn Group. The upper Floridan aquifer consists of karstic limestone and dolomite of the Oligocene-Eocene age Suwannee, Ocala, and Avon Park formations. The Floridan is a productive and highly transmissive aquifer, with transmissivity ranging from 2,200–12,000 m^2/day, and is the primary source for groundwater withdrawals within the area. Because of the high transmissivity, the effects of groundwater pumpage can extend to great distances. The Hillsborough River Basin area is characterized by many karst

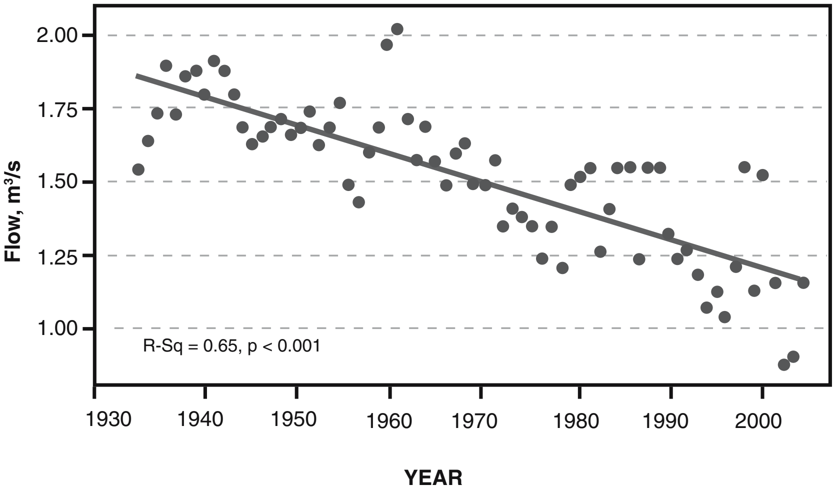

Fig. 3 Crystal Springs annual average flow and linear regression line indicating a sustained flow decline over the period of record

features. Numerous sinkholes, springs and vents open to the Floridan aquifer have been documented throughout the area, many of which are adjacent to or within the bed of the Hillsborough River. The spring vents themselves emanate from the Suwannee limestone.

Spring flow analyses

Flow of Crystal Springs is measured by the US Geological Survey, taking the difference between Hillsborough river discharge measurements made immediately upstream of the spring at USGS gauge No. 02301990 and immediately downstream of the spring at USGS gauge No. 02302010. The frequency of measurement is not uniform, as there are periods when the river is out of its banks and it is not possible to take an accurate measurement. To determine whether the spring-flow data are of acceptable quality to perform statistical analyses, it was necessary to test whether the sampling frequency is equally distributed through out the year. This was accomplished by performing contingency table analysis (Miller and Fruend 1985) on the sampling frequency of monthly spring-flow discharge measurement. The null hypothesis is that the sample proportions are evenly distributed (the data are independent and there is no relationship between the years and the months of sampling). The contingency table analysis shows that the declining flow trend is present in all months of the year, and that there is no significant difference in measurement frequency that would skew the data.

Average annual spring flow at Crystal Springs was analyzed using linear regression (Helsel and Hirsch 2002), which indicates that flow has declined approximately 30% over the period 1933–1999 (Fig. 3). A Kendall-Thiel trend line (Helsel and Hirsch 2002) was also developed from the flow data, which produces a declining slope that is significant at α=0.05 using the non-parametric Hamed-Rao modified Mann-Kendall test (Hamed and Rao 1998).

Visual inspection of the data indicates that the declining trend is not linear, but appears to fluctuate

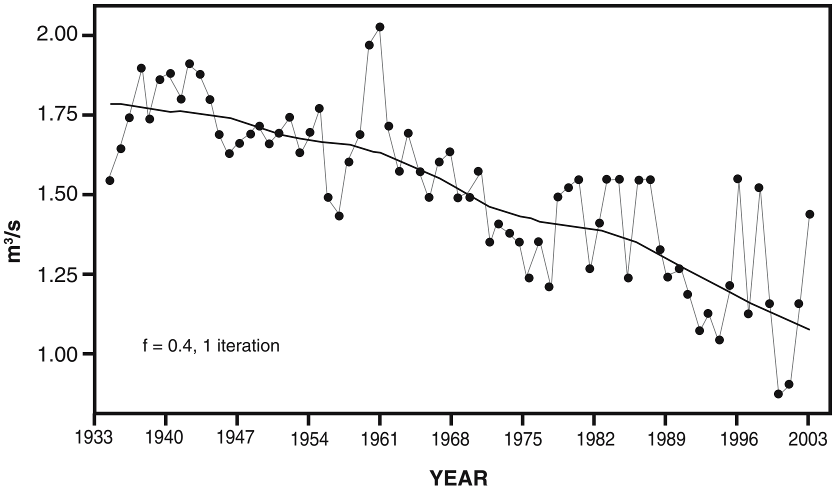

Fig. 4 Locally-weighted regression (LOWESS) of Crystal Springs annual average flow data indicating a varying degree of decline (slope changes) over the period of record. The variations are attributable to changes in the magnitude and distribution of groundwater withdrawals over time

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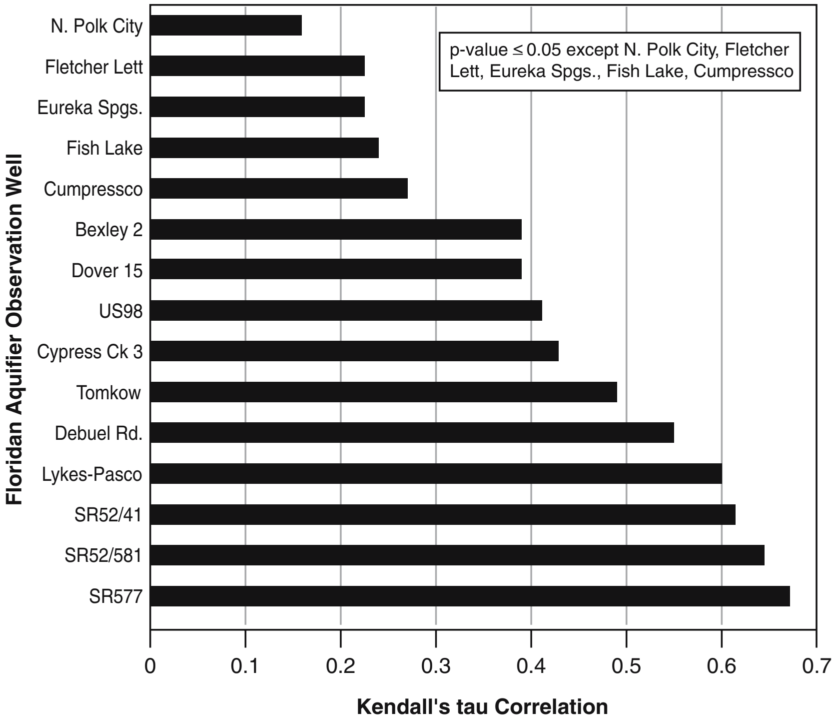

Fig. 5 Correlation of Crystal Springs discharge and area potentiometric levels, based on annual average data for 1978–2002

throughout the data record. To evaluate shorter time spans within the period of record, linear regression trend analysis was performed on decadal datasets starting with year 1933 (i.e., 1933–1942 followed by 1934–1943, and so on.). A statistically significant (α=0.05) increasing trend was observed for each decadal dataset until the dataset beginning in 1943 (i.e., 1943–1952). When discharges for the decadal datasets beginning in 1943 through to 1952 were progressively evaluated, the trends became statistically insignificant. The decadal datasets starting at 1953 show statistically significant negative trends from that point forward. This analysis indicates that the declining trend in spring flow began in the mid-1950s and has continued since, varying in degree.

This non-linear pattern was also visualized (Fig. 4) using a locally-weighted regression smoothing (LOWESS) trend analysis (Helsel and Hirsch 2002). The degree of smoothing *f*-factor was set at 0.4, with 1 iteration so that the data window for weighting remained relatively narrow to accentuate differences through the time period. The resulting graph shows that the slope changes throughout the period of decline, with sharper declines noted in the early 1960s and from the mid-1980s forward. Therefore, the processes affecting spring flow are dynamic and some factor or factors either moderate or overwhelm others at given times during the record producing a non-linear response.

To investigate the relationship between spring flow and potentiometric levels, the correlation of Crystal Springs discharge and potentiometric levels was evaluated for 15 Floridan aquifer wells in the area surrounding the HRGWB. The nonparametric Kendall's tau correlation coefficient (Helsel and Hirsch 2002) was determined for each dataset (Fig. 5). Ten of the wells show significant correlation at α<0.05. The strongest correlations (R^2>0.6) occur in the area northwest of the spring (Fig. 6), where large potentiometric level declines have occurred due to groundwater withdrawals. An exception is the Cypress Creek 3 well, which displays only moderate correlation (R^2=0.43) because it lies within a wellfield and more greatly influenced by immediately adjacent groundwater withdrawals. Moderate correlations (R^2=0.4–0.6) occur north of the spring, in a sand-ridge an area of relatively high agricultural groundwater withdrawals, with the exception of the Cumpressco Ranch well which is located in the hydrologically dissimilar Green Swamp. Moderate correlation also occurs at the Debuel Road well west of the spring in an area of concentrated withdrawals from public supply wellfields. Low (R^2<0.4) to non-significant (α>0.05) correlations occur outside the HRGWB and away from the spring and groundwater basin.

The potentiometric levels most highly correlated to spring flow are in the predominate direction of groundwater flow to the spring based on geochemical studies (Champion and DeWitt 2000) and are in the area where the largest groundwater withdrawals occur. The site with the strongest correlation is the SR577 Well (R^2=0.67) located approximately 24 km (15 miles) northwest of the spring. The strong correlation between historic potentiometric levels and spring flow is apparent when the 10-year moving average spring flow and SR577 Well groundwater levels are overlain (Fig. 7).

Flow data were compared between Crystal Springs and Silver Springs, a spring located about 110 km north of Crystal Springs, using double-mass analysis (Searcy and Hardison 1960). Comparison of Crystal Springs cumula-

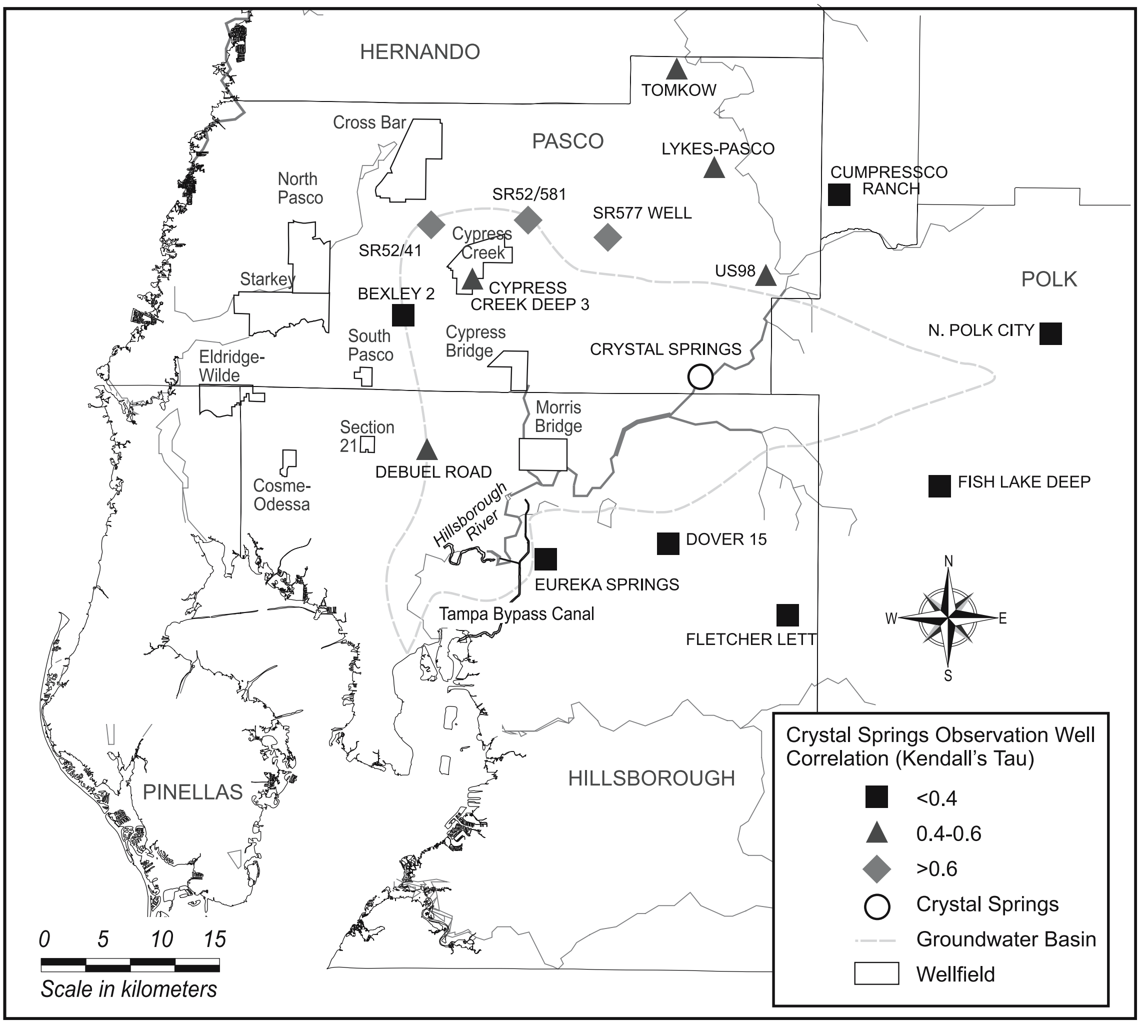

Fig. 6 Locations of wells used in correlation analysis and Crystal Springs. The strength of correlation is greatest in the groundwater basin northwest of the spring in the area of major groundwater withdrawals

tive discharge to Silver Springs cumulative discharge yields good correlation with a model based upon early data up to the 1950s, after which there is slight divergence until the late 1960s, whereupon a sustained divergence in discharge characteristics is seen (Fig. 8). Both spring discharges were then compared to rainfall at the St. Leo

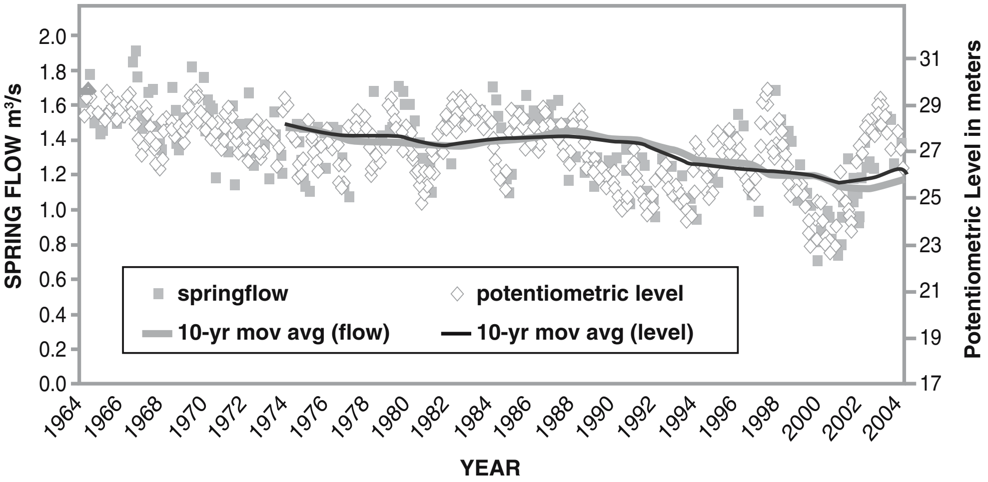

Fig. 7 Crystal Springs flow and SR577 well aquifer levels with 10-year average plotted, showing the high degree of correlation between aquifer levels northwest of the Spring and spring flow through time

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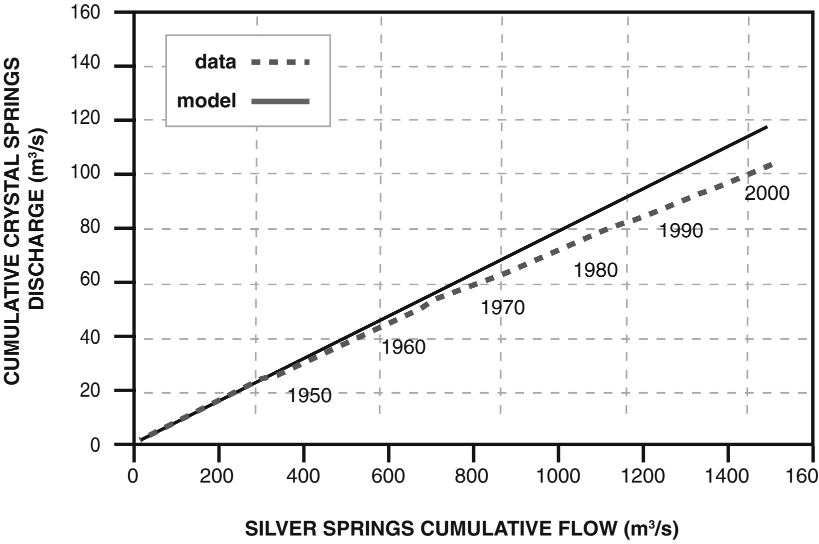

Fig. 8 Double mass analysis of Silver Springs and Crystal Springs cumulative flows, showing slight divergence in the 1950s and 1960s, and substantial divergence beginning in the late 1960s. The *solid line* is a model based on the early-time relationship

station, located about 16 km northwest of Crystal Springs, using double-mass analysis. These results indicated that Silver Springs and Crystal Springs cumulative discharges, and St. Leo rainfall correlate well with a model based upon early data until the late 1970s, at which point flow at Crystal Springs diverges (Fig. 9). This divergence indicates that some factor or factors operating on Crystal Springs flow has changed the flow relationship between Crystal Springs and Silver Springs flow, and St. Leo rainfall, after the mid-to-late 1960s.

Base flow and stage analyses

For the Hillsborough River State Park flow station (USGS gauge No. 02303000) data, estimated daily base flow was separated from the daily total discharge by an algorithm first described by Perry (1995) and used by Taylor (1997). This base flow separation algorithm consists of: (1) fixing a period for the analysis of 60 days, (2) determining and centrally plotting the daily moving minimum for the moving period from the daily data, and (3) determining and centrally plotting the daily moving average for the moving period from the moving minimums. The estimated base flow was smoothed by plotting the annual moving average, updated daily. From this moving annual average, a long-term LOWESS smoothed line was fit to these data. The smoothing factors chosen were *f*=0.85, 2 iterations, so that the data window for weighting is relatively wide to allow only relatively large changes to be discerned. The resulting LOWESS line displays a break in slope and declining trend starting in the mid-late 1960s, indicating that the decline in base flow begins about that time (Fig. 10).

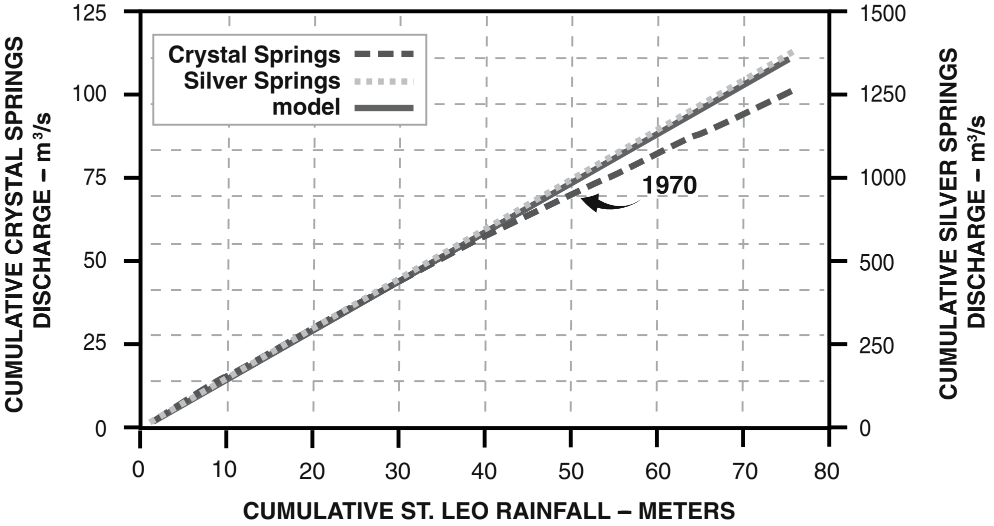

Fig. 9 Double mass, Crystal Springs flow, Silver Springs flow, and St. Leo rainfall, showing divergence of Crystal Springs flow to Silver Springs flow and a model based on the early-time relationship between rainfall and spring flow

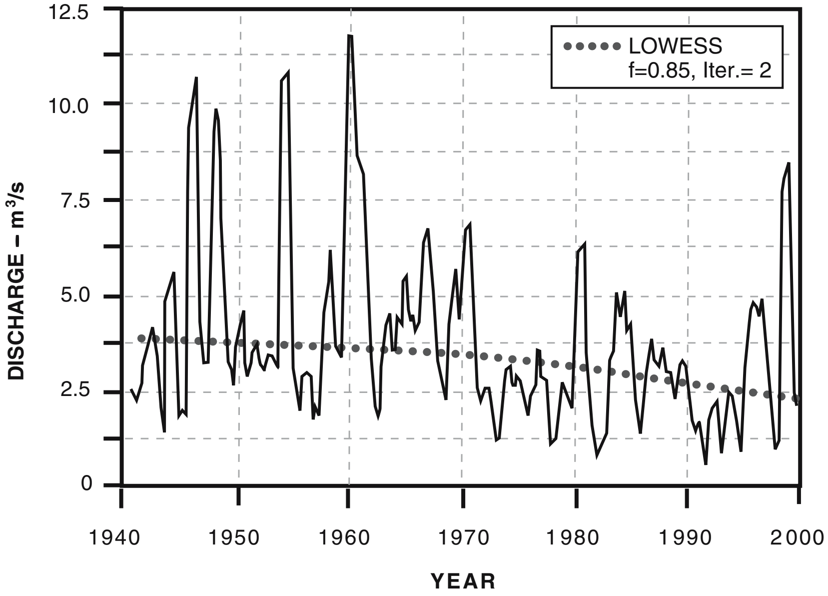

Fig. 10 Hillsborough River at State Park estimated annual average base flow vs. time and locally-weighted regression (LOWESS) showing a declining trend beginning in the 1960s

Low-stage trend analysis was performed on river stage data at the Hillsborough River State Park station. These data began in 1967, whereas the river flow data began in 1933. This analysis consisted of examining the daily river stage data for the base period 1967–1975, which corresponds to the onset of base-flow decline, for minimum values. During this period, river stage did not fall below 10.4 m (34 ft)—National Geodetic Vertical Datum of 1929 (NGVD). Since 1975, new lows have been periodically established through recent time. To determine whether a trend in reduced stage is evident, the number of days the stage fell to 10.4 m NGVD or lower was plotted and a regression line fitted through the data. The resulting trend line has a statistical significance of α=0.05. The number of days per year that stage was at or below 10.4 m NGVD has steadily increased over time, from zero days in 1967 to over 40 days in 2000.

Groundwater withdrawal estimation

Because the river and spring are groundwater fed, evaluation of groundwater withdrawals from the groundwater basin, or that affect the basin, is a necessary component of study. Previous modeling studies indicate that, for the northern Tampa Bay area including the HRGWB, approximately 33% of the groundwater discharge occurs through groundwater withdrawals (Yobbi 2000). Evaluation of estimated historical groundwater withdrawal in the HRGWB portion of the northern Tampa Bay area was accomplished for four

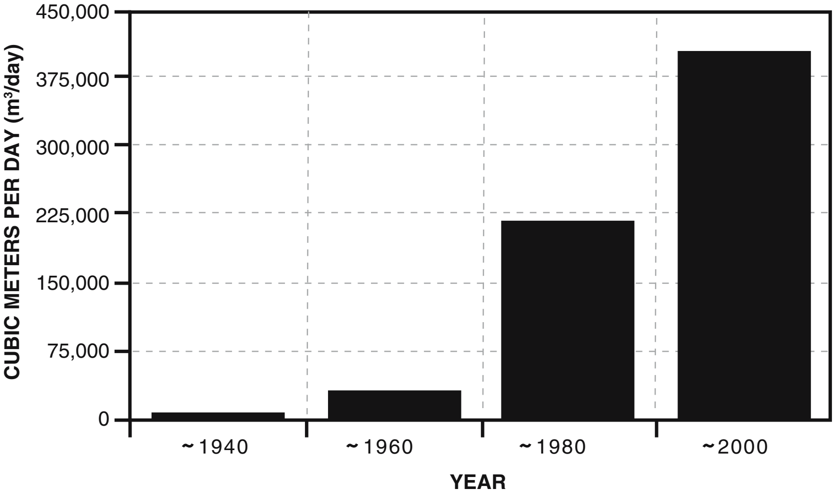

Fig. 11 Estimated groundwater withdrawals in the Hillsborough River groundwater basin at four approximate time periods, 1940, 1960, 1980, and 2000

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approximate points in time: 1940, 1960, 1980, and 2000 (Fig. 11). Utilizing US Bureau of Census data (2000) and assuming a standard per capita rate of 0.57 m^3/day (150 gallons/day), public supply withdrawals for these municipalities were estimated for 1940 and 1960. Pumpage data are available for the circa-1980 and 2000 public supply use from the Southwest Florida Water Management District database. Historical agricultural use and acreages in the area were determined using information from Koo (1963), Florida Board of Conservation (1966), Pride (1970), Harrison and Koo (1977), Smajstrla et al. (2000), and the National Agricultural Statistics Service database for Florida (NASS 2000) A modified Blaney-Criddle methodology (Cohen 1992) was utilized to develop estimates of agricultural withdrawals. Other uses in the area are relatively minor. The relative proportion of groundwater withdrawal by use category in the northern Tampa Bay area (Hancock and Smith 1996) is as follows: public supply 77%, mining 13%, recreational 8%, and all others 2%.

Evaluation of estimated groundwater withdrawals over time indicate that there has been greater than an order of magnitude increase in withdrawals since 1960 (Fig. 11). Total groundwater withdrawals from the basin are estimated to have increased by an order of magnitude from the 1960s to the late 1990s, from less than 38,000 to about 405,000 m^3/day. Currently, withdrawals from the basin are primarily from public supply wellfields (Fig. 1), and most of that pumpage is exported from the basin. To gain some perspective on the scale of pumpage losses from the water budget of the basin, it is important to consider the scale of groundwater withdrawals from this relatively small groundwater basin. The 405,000 m^3/day estimated withdrawal equates to nearly 151 million m^3 removed from the groundwater basin in 1 year, although some small portion of that quantity returns to the system as these withdrawals are not 100% consumptive. It is worth noting that, because of the widespread wetland and lake-level deterioration caused by wellfield withdrawals, the wellfields have recently been required to reduce pumpage. This reduction should begin to positively affect the spring flow and baseflow declines, if the reductions are not offset by other withdrawals.

Groundwater pumpage outside the basin that could impact groundwater levels within the basin was also evaluated. Withdrawals from wellfields to west of the basin undoubtedly affect levels within the basin as these withdrawals are large-scale and in close proximity to the basin. The first of these wellfields began production in 1931, with three additional wellfields constructed from the late 1950s through the early 1970s, withdrawing a total of 265,000 m^3/day by that time. Three additional wellfields have been constructed in this area since the mid-1970s, withdrawing on average an additional 130,000 m^3/day. Additionally, citrus production withdrawals north of the eastern portion of the basin would be expected to have some influence on basin levels. Both of these areas are further discussed in the potentiometric levels discussion that follows. Floridan aquifer potentiometric levels across the state have generally been declining since levels have been measured as a result of flowing artesian wells and groundwater withdrawals. However, there are no long-term (i.e., beginning circa 1930) wells in the area of the HRGWB or Crystal Springs, so this factor cannot be accurately assessed. The nearest well with long-term data, the SCL Railroad well located approximately 50 km north of the spring, declined approximately 1.5 m between 1935 and 1980, and continues to decline.

Significant regional withdrawals that might have affected the upper basin historically include those of the phosphate region to the southeast, and citrus processing and production north of the spring (Tibbals et al. 1980). Estimates of withdrawals from the phosphate region indicate that withdrawals dramatically increased from about 380,000 m^3/day in the mid-1950s to a peak of about 1,514,000 m^3/day in the mid-1970s (SWFWMD 2004). These withdrawals appear to have influenced potentiometric levels in the HRGWB, as discussed below in the section Potentiometric levels analysis. Since that time, withdrawals in this area have decreased to about 1,020,000 m^3/day and generally relocated further from the basin. The withdrawals north of the spring, primarily for citrus processing, approximated 115,000 m^3/day during the 1960s to early 1970s, diminishing substantially thereafter (Tibbals et al. 1980). Pumpage data for this area for the year 2004 from the water management district database indicate groundwater withdrawals of approximately 16,000 m^3/day. However, 2004 was an abnormally wet year that reduced irrigation needs, and only larger uses are required to report pumpage, so this value is likely an underestimate.

The displacement of the phosphate industry (and associated groundwater withdrawals) southward over time, together with the general reduction in withdrawals in that area and north of the spring, would tend to diminish associated pumpage effects on the HRGWB as time has progressed. Therefore, these outside influences most likely had the greatest effect on basin potentiometric levels (and spring flow, base flow) in the mid-1950s to mid 1970s, substantially decreasing thereafter. This impact to potentiometric levels, and that of the public supply wellfields west of the basin, corresponds to the period where spring levels were declining prior to development of the public supply wellfields within the HRGWB.

Rainfall analyses

Analysis of annualized rainfall data was performed for three individual long-term National Weather Service stations in the area of the Hillsborough River groundwater basin: St. Leo, Plant City, and Hillsborough River State Park. Additionally, analysis was performed on the water management district's Hillsborough Basin rainfall dataset, which is comprised of 38 stations of varying record length across the watershed. The dataset for the Hillsborough River State Park station is deficient in that there were ten missing values dispersed throughout the period of record. The missing values were estimated using a transfer function (McCuen 1989) that related the State Park station data to the data from the nearby St. Leo and Plant City stations, with an R^2 value of 0.99. Linear regression (Helsel and Hirsch 2002) of data for the St. Leo station (beginning 1933), the Hillsborough River State Park station (beginning 1948), Plant City (beginning 1901), and Hillsborough Basin (beginning 1915) indicates no statistically significant trends at α=0.1. The Hillsborough Basin data (1915–2003) were also evaluated using the modified non-parametric Mann-Kendall test, with no trend discerned at α=0.05. To evaluate more recent trends that might be masked when viewing the entire period of record, the data from these stations were then analyzed using linear regression only for the period since 1960, and the period since 1970, to correspond to the timeframe when the onset of base flow and spring-flow declines is most evident. No significant trend in mean annual rainfall was found for any of these time periods for any station.

Using the Hillsborough Basin data set, each consecutive 10 years of the rainfall record was tested using the parametric least squares method for a statistically significant time trend. It was found that only three of these periods display a statistically significant time trend at an α=0.05. These periods were (1) the 10-year period ending in 1960, which display a positive slope of 6.25 cm/year, (2) the 10-year period ending in 1991 that display a negative slope of –4.25 cm/year, and (3) the 10-year period ending in 1998 that display a positive slope of 5.0 cm/year.

To further investigate whether defined patterns in rainfall exist, the Hillsborough Basin rainfall data were analyzed by lagging the data and evaluating the correlation of lagged time periods. This analysis fails to find statistically significant correlation for any lagged period when tested using Pearson's parametric or Spearman's nonparametric tests for correlation (McCuen 2003). This indicates that while the process (data) may tend to lie to one side or the other of the mean for a random period before moving to the other side of the mean, it does this in a random, unpredictable fashion. During the time of changing from one side of the mean to the other side of the mean, a statistically significant trend may occur for some selected period, but does not necessarily occur on every event.

To test the hypothesis that rainfall patterns have changed over time, a nonparametric run test (Draper and Smith 1981) was conducted using monthly St. Leo rainfall data. This test was run on monthly data for 5 and 10 years, at 10-year increments up to 60 years, and for the entire period of record. In all cases, the results indicate that the monthly precipitation patterns have not significantly changed over time. Additionally, parametric Student's *t* tests were performed comparing the periods pre-and post-1960 and pre-and post-1970 on all four rainfall data sets. In all cases the tests indicate no significant difference (at α=0.05) in rainfall amounts for any of the periods.

The spring discharge and the rainfall data each were tested using the Kruskal-Wallis nonparametric test (Miller and Fruend 1985) for equivalence of population for the pre-1971 period to the post-1970 period. The spring discharge displays a statistically significant difference (α=0.05) between the two periods while the rainfall is not statistically different. Therefore, the discharge-rainfall relationship changed even though rainfall did not change.

Potentiometric levels analyses

In addition to the spring-flow/potentiometric levels correlation previously described, an earlier investigation of the water resources of the northern Tampa Bay area, which includes the HRGWB, provides useful insight (Hancock and Smith 1996). Their investigation included an evaluation of the effects of groundwater withdrawals using a regional calibrated groundwater flow model. This study indicates that groundwater withdrawals have created extensive areas of drawdown in the Floridan aquifer, including the northwest portion of the Hillsborough River groundwater basin. This drawdown affects the quantity of groundwater available for base flow to Crystal Springs, the Hillsborough River and its tributaries. The model results also indicate that the surficial aquifer drawdown resulting from the Floridan aquifer withdrawals extends into both the surface water basin and groundwater basin of the Hillsborough River and its tributaries. The reduction in surficial aquifer water levels affects the runoff and water-table base flow characteristics within the affected area of the surface water basin, and reduces available quantities of water to spring flow, river base flow, and river total flow.

Maps of changes in elevation of the potentiometric surface can provide a useful tool in measuring the local effects of groundwater discharge (Davis and DeWiest 1966). Mills and Laughlin (1976) produced potentiometric surface change maps for the Floridan aquifer in central Florida comparing the periods 1964–1969 and 1969–1975. Their maps indicate that the large aquifer drawdown associated with phosphate and citrus withdrawals to the southeast of the Hillsborough River and Crystal Springs extended into the HRGWB in the mid-1960s to mid-1970s. Potentiometric level comparisons of the period prior to production of major groundwater withdrawals from public supply wellfields within the basin to recent time were also made. Change-maps comparing May 1971 (USGS 1971) potentiometric levels with May 2001 (Duerr 2001) potentiometric levels show a large decline in the north-northwest portion of the basin related to regional wellfield pumpage, citrus irrigation, and municipal pumpage (Fig. 12). The areas of decline match very well with the spring flow to potentiometric level correlations discussed previously and displayed in Fig. 6. These analyses indicate that, from a temporal standpoint, the aquifer-level declines from groundwater withdrawals coincide with the spring flow and base-flow declines.

Watershed alterations

Although the extreme southern end of the Hillsborough River is highly developed (the river traverses the city of Tampa before discharging to Hillsborough Bay), the middle to northern portions of the watershed, which are

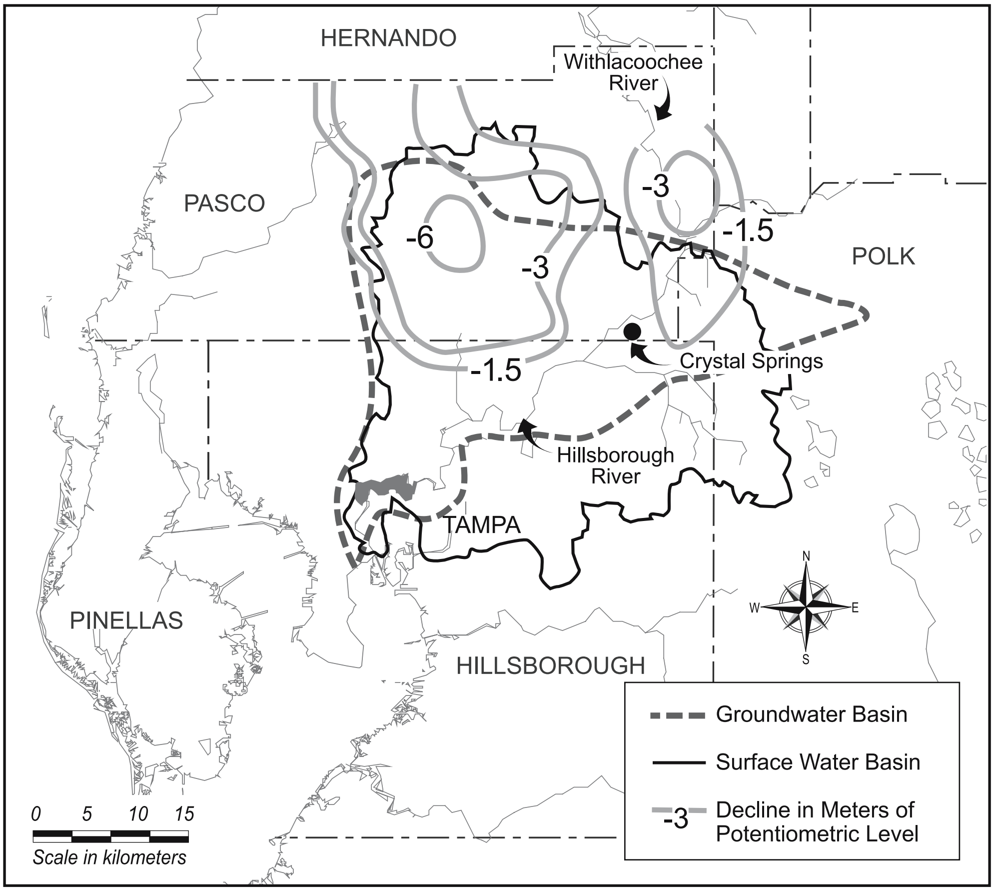

Fig. 12 Floridan aquifer potentiometric level change between May 1971 and May 2001, showing large areas of potentiometric surface change (decline) northwest and north of Crystal Springs

the source areas for groundwater discharge to the spring and river, have seen limited surface development that might affect recharge to the groundwater basin, and which therefore might affect spring flow or base flow. The land uses in the area were first described in detail in the early 1960s (Florida Board of Conservation 1966). The Board of Conservation report indicates that the majority of land uses in the upper watershed in the 1960s consisted of riverine swamps, upland forests, rangeland, and non-intensive farming. Recent evaluation of land usage in the area demonstrate that land use there has not significantly changed (SWFWMD 2000). Land development typically results in a greater amount of impervious surface, and increased drainage. Had significant land development

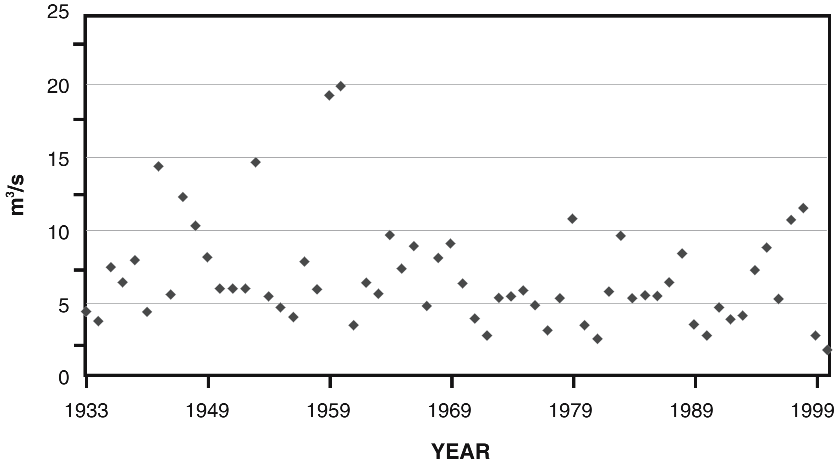

Fig. 13 Plot of Hillsborough River at State Park annual average total flow over the period of record, indicating the lack of increased flow (runoff) over time that would be expected if the area had experienced increased land development

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occurred, the result would be more runoff, a situation that is not supported by the stream-flow data (Fig. 13) Therefore, it is unlikely that land alterations within the watershed have significantly contributed to the flow declines.

Summary and conclusions

Multiple statistical and analytical techniques were systematically utilized to evaluate the causes of spring flow and base-flow declines of the Hillsborough River system in central Florida. The analyses indicate that spring flow began declining in the mid-1950s, and both spring flow and groundwater base flow have markedly declined since the late-1960s to early-1970s. Hillsborough River base flow correlates well with rainfall up to the late 1960s/early 1970s, after which the correlation significantly decreases. Rainfall amounts in the Hillsborough River area show no trends when viewed annually, seasonally, or at a monthly scale and whether reviewing the entire period of record or multi-decadal time periods. As statistically significant changes in rainfall amounts or patterns have not been found, spring flow and base flow declines cannot be attributed to rainfall. There is no evidence that land-use alterations have occurred that would diminish spring flows and base flows.

The flow declines that occurred in the mid-1950s through the 1970s coincide with groundwater withdrawals outside the basin that affected basin potentiometric levels during that time period. The overall spring and river-flow decline displayed since the 1970s coincides with the expansion of highly consumptive groundwater withdrawals from public supply wellfields, as well as other uses in the basin. Statistical methods and analytical methods indicate that since the 1970s, groundwater levels have declined in the northwest portion of the groundwater basin, which is the area geochemically determined to be the primary source of spring flow. These methods also substantiate the decline in groundwater base flow within the river and discharge at Crystal Springs. Via comparisons of Crystal Springs flow to another spring in an area of relatively minor groundwater development, and by the fact that the rainfall/spring flow relationship changes over time, the indication that the flow declines are related to groundwater development rather than rainfall is bolstered by the lack of correlation between rainfall and spring flow or base flow.

Prior to extensive development of the groundwater resources, the water resources and associated natural systems were in a state of approximate dynamic equilibrium. Short- term fluctuations in water levels and flows occurred because of rainfall variations, but viewed over the long-term the systems were in balance. The imposition of groundwater withdrawals upon this equilibrium creates a new source of discharge, and must be balanced by an increase in recharge, decrease in previous discharge, loss of storage in the aquifer, or a combination of these (Theis 1940). In the situation where no significant increase in recharge (e.g., rainfall) occurs, decreased discharge (e.g., spring flow or base flow) must result (Bredehoeft et al. 1982). Multiple analytical and statistical techniques were methodically employed to investigate the observed base flow and spring-flow declines. When accumulated, these techniques provide a confident basis for the assertion that the flow declines are caused by potentiometric level reductions that result from groundwater abstraction.

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References

Bales JD, Pope BF (2001) Identification of changes in streamflow characteristics. J Am Water Res Assoc 37(1):91–104

Bredehoeft JD, Papadopulus SS,Cooper HH Jr (1982) Groundwater: the water budget myth in scientific basis of water resource management. National Research Council Geophysics Study Committee, National Academy Press, Washington, DC, pp 51–57

Cohen R (1992) Agricultural water use model, AGMOD, Version 2.0. Southwest Florida Water Management District, Brooksville, FL, p 25

Davis SN, DeWiest RJM (1966) Hydrogeology. Wiley, New York, p 463

Champion KM, DeWitt DJ (2000) Origin of nitrate in ground water discharging from Crystal Springs, Pasco County, Florida. Southwest Florida Water Management District, Brooksville, FL, p 192

Draper NR, Smith H (1981) Applied regression analysis, 2nd edn. Wiley, New York, p 709

Duerr AD (2001) Potentiometric surface of the upper Floridan Aquifer, west-central Florida, May 2001. US Geol Surv Open File Report, OF 01-0310, USGS, Reston, VA, p1

Florida Board of Conservation (1966) Florida land and water resources, Southwest Florida. Florida Board of Conservation, Division of Water Resources, Tallahassee, FL, p 181

Hamed KH, Rao AR (1998) A modified Mann-Kendall trend test for autocorrelated data. J Hydrol 204:182–196

Hancock MC, Smith DA (1996) Northern Tampa Bay Water Resource Assessment Project, vol 1, Surface-water/groundwater interrelationships. Southwest Florida Water Management District, Brooksville, FL, p 341

Harrison DS, Koo RC (1977) Irrigation methods and equipment for production of citrus in Florida. Institute of Food and Agricultural Sciences Water Resources Council Publication No. 10, Institute of Food and Agricultural Sciences, Gainesville, FL, p 2

Helsel DR, Hirsch RM (2002) Statistical methods in water resources. Techniques of water resources investigations of the US Geol Surv, Book 4, USGS, Reston, VA, p 510

Koo RC (1963) Effects of frequency of irrigations on yield of orange and grapefruit. Proc Florida Horticultur Soc 76:1–5

National Agricultural Statistics Service (2000) Database for Florida, http://www.nass.usda.gov/fl/, Accessed 10 June 2000

McCuen RH (1989) Hydrologic analysis and design. Prentice-Hall, Englewood Cliffs, NJ, p 867

McCuen RH (2003) Modeling hydrologic change. Lewis, New York, p 433

Menke CG, Meredith EW, Wetterhall WS (1961) Water resources of Hillsborough County, Florida. Florida Geological Survey Report of Investigations No. 25. Florida Geol Surv, Tallahassee, FL, p 100

Miller I, Fruend JE (1985) Probability and statistics for engineers. Prentice-Hall, Englewood Cliffs, NJ, p 432

Mills LR, Laughlin CP (1976) Potentiometric surface of the Floridan Aquifer May 1975, and change of potentiometric surface 1969 to 1975, Southwest Florida Water Management District and adjacent areas. US Geol Surv Water Res Inves No. 76–80, USGS, Reston, VA, p 1

DOI 10.1007/s10040-006-0040-5

Parker GG (1975) Water and water problems in the Southwest Florida Water Management District and some possible solutions. Water Res Bull 11(1):1–20

Perry RG (1995) Regional assessment of land use nitrogen loading of unconfined aquifers, PhD Thesis, Department of Civil and Environmental Engineering, University of South Florida, Tampa, FL, p 229

Petts GE, Bickerton MA, Crawford C, Learner DN, Evans D (1999) Flow management to sustain groundwater: dominated stream ecosystems. Hydrol Proc 13:497–513

Pride RW (1970) Estimated water use in Florida, 1965. Florida Bureau of Geology Map Series No. 36, Florida Bureau of Geology, Tallahassee, FL, p 1

Searcy JK, Hardison CH (1960) Double-mass curves. Manual of hydrology: Part I, General surface water techniques. US Geol Surv Water Supply Paper 1541-B, USGS, Reston, VA, p 66

Smajstrla AG, Haman DZ, Zazueta FS (2000) Irrigated acreage in Florida. Institute of Food and Agricultural Sciences Publication AE083, Institute of Food and Agricultural, Gainesville, FL, p 8

Smith H, Wood PJ (2002) Flow permanence and macroinvertebrate community variability in limestone spring systems. Hydrobiologia 487(1):45–58

SWFWMD (2000) Hillsborough river comprehensive watershed atlas. Southwest Florida Water Management District, Brooksville FL, p 21

SWFWMD (2004) Southern water use caution area recovery strategy. Southwest Florida Water Management District, Brooksville FL, p 120

Taylor M (1997) Investigation of stream/aquifer response in two Florida watersheds. University of South Florida, Tampa, FL, p 7

Theis CV (1940) The source of water derived from wells: essential factors controlling the response of aquifer development. Civil Eng 10(5):277–280

Tibbals CH, Andersen W, Laughlin CP (1980) Ground-water hydrology of the Dade city area, Pasco County, Florida, with emphasis on the hydrologic effects of pumping from the Floridan Aquifer. US Geol Surv Water Res Inv No. 80–33, USGS, Reston, VA, p 64

US Bureau of Census (2000) United States Census http://www.census.gov. Accessed 20 June 2000

US Geological Survey (1971) Potentiometric surface of Floridan Aquifer, Southwest Florida Water Management District, May 1971. USGS, Reston, VA, p 1

Wolansky RM, Thompson TH (1987) Relation between ground water and surface water in the Hillsborough River Basin, west-central Florida. US Geol SurvWater Res Inv Report 87-4010, USGS, Reston, VA, p 58

Yobbi DK (2000) Application of Least-Squares Regression to Ground-Water Flow Modeling, West-Central Florida. US Geol Surv Water Res Inv Report 00-4094, USGS, Reston, VA, p 58

DOI 10.1007/s10040-006-0040-5