

Prepared in cooperation with the Southwest Florida Water Management District

Creating a Monthly Time Series of the Potentiometric Surface in the Upper Floridan Aquifer, Northern Tampa Bay Area, Florida, January 2000–December 2009



Scientific Investigations Report 2014–5038

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

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By Terrie M. Lee and Geoffrey G. Fouad

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Conversion Factors

Inch/Pound to SI

Multiply	Ву	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi ²)	2.590	square kilometer (km ²)
	Flow rate	
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m ³ /s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

GIS	geographic information system
Lidar	light detection and ranging
ME	mean error
NTB	Northern Tampa Bay
RMSE	root-mean-square error
USGS	U.S. Geological Survey

Creating a Monthly Time Series of the Potentiometric Surface in the Upper Floridan Aquifer, Northern Tampa Bay Area, Florida, January 2000–December 2009

By Terrie M. Lee and Geoffrey G. Fouad

Abstract

In Florida's karst terrain, where groundwater and surface waters interact, a mapping time series of the potentiometric surface in the Upper Floridan aquifer offers a versatile metric for assessing the hydrologic condition of both the aquifer and overlying streams and wetlands. Long-term groundwater monitoring data were used to generate a monthly time series of potentiometric surfaces in the Upper Floridan aquifer over a 573-square-mile area of west-central Florida between January 2000 and December 2009. Recorded groundwater elevations were collated for 260 groundwater monitoring wells in the Northern Tampa Bay area, and a continuous time series of daily observations was created for 197 of the wells by estimating missing daily values through regression relations with other monitoring wells. Kriging was used to interpolate the monthly average potentiometric-surface elevation in the Upper Floridan aquifer over a decade. The mapping time series gives spatial and temporal coherence to groundwater monitoring data collected continuously over the decade by three different organizations, but at various frequencies. Further, the mapping time series describes the potentiometric surface beneath parts of six regionally important stream watersheds and 11 municipal well fields that collectively withdraw about 90 million gallons per day from the Upper Floridan aquifer.

Monthly semivariogram models were developed using monthly average groundwater levels at wells. Kriging was used to interpolate the monthly average potentiometric-surface elevations and to quantify the uncertainty in the interpolated elevations. Drawdown of the potentiometric surface within well fields was likely the cause of a characteristic decrease and then increase in the observed semivariance with increasing lag distance. This characteristic made use of the hole effect model appropriate for describing the monthly semivariograms and the interpolated surfaces. Spatial variance reflected in the monthly semivariograms decreased markedly between 2002 and 2003, timing that coincided with decreases in well-field pumping. Cross-validation results suggest that the kriging interpolation may smooth over the drawdown of the potentiometric surface near production wells.

The groundwater monitoring network of 197 wells yielded an average kriging error in the potentiometric-surface elevations of 2 feet or less over approximately 70 percent of the map area. Additional data collection within the existing monitoring network of 260 wells and near selected well fields could reduce the error in individual months. Reducing the kriging error in other areas would require adding new monitoring wells. Potentiometric-surface elevations fluctuated by as much as 30 feet over the study period, and the spatially averaged elevation for the entire surface rose by about 2 feet over the decade. Monthly potentiometric-surface elevations describe the lateral groundwater flow patterns in the aquifer and are usable at a variety of spatial scales to describe vertical groundwater recharge and discharge conditions for overlying surface-water features.

Introduction

The Upper Floridan aquifer is one of the Nation's most prolific groundwater sources and is the principal source of potable water in Florida (Bush and Johnston, 1988; Marella, 2009), yet there is a growing recognition of the need to limit groundwater withdrawals in some areas to assure sustainable hydrologic regimes in overlying surface waters (Winter and others, 1998; Barnett, 2007). This need is especially true in the Northern Tampa Bay area of west-central Florida, where groundwater pumping for municipal supply is spatially concentrated, and the attendant lowering of groundwater levels has contributed to wetland desiccation and reduction of streamflows (Southwest Florida Water Management District, 1996; Rochow, 1998; Lee and others, 2009; Southwest Florida

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Water Management District, 2010). The regionally extensive and transmissive limestone formations of the Upper Floridan aquifer are overlain by lower-permeability clays that confine the aquifer to different degrees (Miller, 1986; Bellino, 2011). Wetlands, lakes, and streams are located in the sandy surficial deposits above the semi-confining clays and these water bodies interact with groundwater in the shallow surficial aquifer. The intervening confining unit impedes vertical flow between the Upper Floridan aquifer and the overlying surficial aquifer, and can leave the groundwater in the deeper limestone aquifer with the potential to rise above the top of its geologic layer. For this reason, the elevation to which groundwater rises in a tightly cased well penetrating a confined aquifer reflects the potentiometric (or piezometric) head at that location, and interpolating point values of groundwater elevations across a regionally extensive confined aquifer creates a potentiometric surface (Bear, 1979, p. 62).

In response to the seasonal recharge and discharge of groundwater, the undulating potentiometric surface of the Upper Floridan aquifer can approach, or rise above, the elevation of the water table in the surficial aquifer or it can be at a vertical distance far below the water table. Whether the potentiometric-surface elevation is above or below the watertable elevation determines whether the vertical groundwater flow direction between the two aquifers is upward or downward (fig. 1). The rate of the vertical groundwater flow, in turn, is governed by the elevation difference and the permeability of the intervening confining unit. The water table in the surficial aquifer is not mapped in central Florida, but the water-table elevation approaches land surface in wetland-dominated landscapes (Haag and Lee, 2010). For this reason, the vertical height of the potentiometric surface above or below the land surface can provide a comparable measure of the hydrologic condition of the imbedded surface-water features (Lee and others, 2009). Areas where groundwater flows upward toward the surficial aquifer have been mapped beneath streams and wetlands in west-central Florida by comparing light detection and ranging (LiDAR)-based land-surface elevations to one or two static views of the potentiometric-surface elevation in the Upper Floridan aquifer (Lee and others, 2010; Metz, 2011). By extension, a long-running monthly time series of potentiometric surfaces could be used in a geographic information system (GIS) framework to generate time-dependent and spatially-distributed variables quantifying the extent of upward and downward groundwater flow around wetlands and streams through time (Fouad and Lee, 2011). At present, few if any such time series exist for aquifers in the United States.



Figure 1. Conceptual drawing showing relative positions of the water table in the surficial aquifer system and the potentiometric surface in the Upper Floridan aquifer and the associated vertical flow direction (modified from and used courtesy of the St. Johns River Water Management District, Palatka, Florida).

In practice, constructing a time series of maps displaying the potentiometric-surface elevation in an aquifer is challenging because it requires a groundwater monitoring network capable of providing a continuous time series of the groundwater elevation at each well. Continuous and synchronized measurements must be made at enough wells, and water-level measurements from wells must be sufficiently correlated to one another, to allow accurate estimation of missing data. In addition, the spatial density of monitoring wells must be sufficient to reduce the uncertainty in the interpolated elevations to an acceptable level (Olea, 1984; Olea and Davis, 1999; Yang and others, 2008). Kriging, the geostatistical approach pioneered by Daniel Krige, is an exact interpolator at points where data are given, and uses a least-square-error approach to minimize the error of the predicted values between known data points (Krige, 1951). The statistical basis of kriging is preferable to deterministic interpolation schemes because it allows the uncertainty in the interpolated values to be quantified. The associated uncertainty directly improves the meaningfulness of the results and can be used further to optimize the location of wells in groundwater monitoring networks (Olea, 1984; Olea and Davis, 1999; Fisher, 2013; Varouchakis and Hristopulos, 2013). In the United States, kriging techniques have been used to map the water-table elevation in the Ogallala Formation in western Kansas (Dunlap and Spinazola, 1984), to improve mapping of the High Plains aquifer in the south-central United States (Olea and Davis, 1999), and to map water levels in regional aquifers in Idaho (Fisher, 2013), Kansas, Arkansas, Oklahoma, and Missouri (Gillip and others, 2008).

Purpose and Scope

The purpose of this report is to create two mapping time series: one that describes potentiometric surfaces in the Upper Floridan aquifer in the Northern Tampa Bay area of Florida for the decade January 2000 through December 2009 and a second that describes the associated estimation errors. The specific objectives of the report are to (1) describe an approach for creating continuous daily values of the potentiometricsurface elevation at numerous well locations in the Upper Floridan aquifer and (2) to describe the kriging approaches that were used to interpolate the potentiometric surface elevations between monitoring wells and to quantify the estimation error in the surface elevations. The report also describes the spatial and temporal characteristics of the groundwater monitoring network in the region.

Thousands of observations of the groundwater level in the Upper Floridan aquifer are available in the Northern Tampa Bay area of Florida as a result of groundwater monitoring networks operated by the U.S. Geological Survey (USGS), the Southwest Florida Water Management District, and Tampa Bay Water, a municipal water supplier (Southwest Florida Water Management District, 2013; Tampa Bay Water, 2013; and U.S. Geological Survey, 2013a). The three organizations work cooperatively to monitor the potentiometric-surface elevation, especially near the region's municipal well fields (Yobbi and Barr, 1982; Ortiz, 2008). The study included the examination of groundwater elevations at 260 monitoring wells distributed across a 573-square-mile region. After assessing the spatial and temporal characteristics of the monitoring data and estimating missing observations at monitoring wells, kriging interpolation was used to generate a time series of 120 gridded-value surfaces describing the monthly average potentiometric-surface elevation of the Upper Floridan aquifer between January 2000 and December 2009. An additional 120 gridded-value surfaces provided the kriging standard deviation values that quantified uncertainty in the interpolated potentiometric surfaces. The spatial and temporal characteristics of the kriged potentiometric surfaces are briefly described and discussed.

Description of the Study Area

The study area in west-central Florida is a low-lying coastal region that extends about 30 miles (mi) inland from the Gulf of Mexico and 30 mi northward of Tampa, Florida (fig. 2). The study area includes parts of four counties-Hillsborough, Pinellas, Pasco, and Hernando-within the Gulf Coastal Lowlands and the Western Valley physiographic regions described by White (1970). Both physiographic regions are characterized by flat terrain and a water table that approaches land surface. Although land-surface elevations exceed 200 feet (ft) National Geodetic Vertical Datum of 1929 (NGVD 29) on sandhills bordering the northeast corner of the study area, most of the area is below 100 ft NGVD 29 and slopes gradually and uniformly toward the coastline (fig. 2). Thousands of seasonally inundated freshwater wetlands and dozens of lakes are located in the study area. Headwater wetlands contribute seasonal runoff to streams and rivers that flow westward toward the Gulf of Mexico or southward toward Tampa Bay (Haag and Lee, 2010). The drainage basins of the Pithlachascotee and Anclote Rivers are largely within the study area, as well as Cypress Creek, a tributary to the Hillsborough River. The study area includes much of the middle drainage basin of the Hillsborough River that flows through metropolitan Tampa and into Tampa Bay, and two smaller streams that flow into the bay farther west (fig. 2).

The study area is in the Northern Tampa Bay (NTB) area (fig. 2), a region with large cumulative groundwater withdrawals where water resources are intensively managed (Southwest Florida Water Management District, 1993, 1996, 1999; Geurink and Basso, 2013). Tampa Bay Water operates 11 municipal well fields in the study area. Most of the groundwater pumping from the Upper Floridan aquifer is concentrated inside eight well-field properties that range in size from about 1 to 13 square miles (mi²). Groundwater pumping is also concentrated at three other locations where production wells lie outside of defined well-field properties in areas referred to as dispersed well fields (fig. 3). Collectively, about 200 production wells are currently permitted to withdraw groundwater at an average rate of 90 million gallons per day (Mgal/d) (Tampa Bay Water, 2013).





Figure 2. Digital elevation model of the study region in the Northern Tampa Bay area of west-central Florida showing streams, U.S. Geological Survey drainage-basin boundaries, and Tampa Bay Water well-field property boundaries.



Figure 3. Study area showing the spatial density of groundwater withdrawals in and around well-field properties in the Northern Tampa Bay area of west-central Florida (modified from Geurink and Basso, 2013).

Artesian flow conditions in the Upper Floridan aquifer and the slow, upward discharge of groundwater into the overlying surficial aquifer likely were widespread phenomena within the Cypress Creek and Hillsborough River drainage basins before the development of large groundwater withdrawals from the Upper Floridan aquifer (Johnston and others, 1980; Ryder, 1985). Groundwater from the Upper Floridan aquifer discharges upward at numerous springs along the coastline and onshore at spring vents in area streams (Guerink and Basso, 2013). The regional hydrogeology of west-central Florida and the local hydrogeology in well fields of the NTB area are described in previous studies (Ryder, 1985; Tihansky and Knochenmus, 2001; Lee and others, 2009; Metz, 2011; Geurink and Basso, 2013).

Groundwater withdrawals and subsequent drawdown of the potentiometric surface are concentrated inside municipal well fields where about one-third of the land surface is covered by wetlands (Yobbi and Barr, 1982; Haag and Lee, 2010; Geurink and Basso, 2013). To reduce the impact of withdrawals on wetlands and streams, Tampa Bay Water reduced groundwater withdrawals in the 11 regional well fields to about 90 Mgal/d from a historic annual average of about 158 Mgal/d (Southwest Florida Water Management District, 1999; Tampa Bay Water, 2000; Metz, 2011). The mandated reduction in groundwater pumping began in late 2002 and early 2003, and coincided with a period of above-average rainfall (fig. 4) (U.S. Geological Survey, 2005; Verdi and others, 2006). Monthly and annual groundwater pumping rates from the well fields increase and decrease in response to water demands during dry and wet climate periods, respectively, and both factors affect the potentiometric-surface elevation in the study area. The regional climate is humid subtropical, and the average annual rainfall in the study area is about 50 inches per year (in/yr). Most of the annual rainfall occurs from June through September, and October through May is relatively dry (Chen and Gerber, 1990) (fig. 4).

Methods Used to Create Monthly Potentiometric Surfaces

A database analysis and kriging methods were combined to create a time series of maps describing the monthly average potentiometric-surface elevation of the Upper Floridan aquifer in the Northern Tampa Bay area. The overall groundwater monitoring network was characterized by defining the spatial distribution of the monitoring wells and the number of observations made at each well over the decade of interest. Missing daily observations were estimated by generating predictive equations from an analysis of the correlation between groundwater levels in wells. Observed and estimated daily values were used to calculate monthly average groundwater levels at each well. The kriging approach was then applied to interpolate monthly average potentiometric surfaces.



Figure 4. Bar charts showing (*A*) annual average groundwater withdrawal rate from regional well fields, and (*B*) annual total rainfall for 2000 through 2009, Northern Tampa Bay area.

Monitoring Well Network

The temporal and spatial characteristics of the groundwater monitoring data were analyzed to determine how these characteristics affect the accuracy of the kriged potentiometric surface. The groundwater monitoring network consists of 260 monitoring wells drilled into the Upper Floridan aquifer. The wells were constructed and monitored by the USGS, Tampa Bay Water, or the Southwest Florida Water Management District, and water-level observations were obtained for each well for the entire period of record (fig. 5; app. 1). The period of record, the measurement frequency, and the periods of missing data varied for each well. The number of daily observations made each month was quantified for each well, and the temporal density of daily observations was mapped. The spatial characteristics of the well network were evaluated in ArcMap 10.0 (Esri, 2011). The distances between all of the wells were calculated using a point-distance calculation (Geospatial Modelling Environment, 2013).

The water levels in wells within and immediately around individual well fields were assumed to be better correlated to one another than to wells located farther away, and were assumed to be more sensitive to pumping from the nearest well field than more distant well fields. Therefore, wells were grouped into subregions that were defined by a buffer distance around each well field, and the statistical dependence in groundwater levels was analyzed between wells within each subregion and not across the entire population of wells. The buffer distance, selected by trial and error, was increased outward from the well-field boundary by 0.5-mi increments until the number of wells inside the buffer either exceeded 20 or stopped increasing in proportion to the area. For the eight well-field properties, subregions extended 3 mi out from the property boundaries (fig. 5). For the three dispersed well fields, subregions were delineated by coalescing the 3-mi buffers around individual production wells. All of the wells within each well-field subregion were identified and mapped (app. 1; fig. 6).

Estimation of Missing Daily Groundwater Levels

A subset of 197 wells was selected from the entire network of 260 groundwater monitoring wells to interpolate the potentiometric surface. Wells were excluded if they had observations for less than 3 percent of the 10-year time period, were missing consecutive years of record, or were a deep well co-located with a shallower well that was used in the interpolation (app. 1). Missing daily water levels for this subset of wells were estimated using the methods described in Conrads and Petkewich (2009). For each of the 11 subregions, correlation between 1990–2009. Monitoring wells with observations highly correlated to a given well were used to generate simple linear regression models fitted by a least-squares approach.

The five wells most correlated to the given well were considered predictor wells and were used to generate five linear regression models capable of predicting water levels for the subject well. The number of predictive equations was set to five to limit the uncertainty in the approach while gaining the maximum ability to estimate missing values over the entire time period. The slope and y-intercept of the linear predictor equations are listed in appendix 2. To estimate missing daily values at a given well, the predictor equation for the most highly correlated well was applied first. If the most highly correlated well had no observations during the dates of the missing data, then other predictor equations were applied in order of descending correlation coefficient (R). If none of the five predictor wells had observations during the data gap, missing values at a given well remained missing (Conrads and Petkewich, 2009). The procedure is made practicable by the relatively large number of daily monitoring wells in the network and the decades-long period of observations. Predictor wells with daily observations could be used to estimate missing daily values at wells with weekly or bi-monthly

measurements. These estimates were far more descriptive than straight-line interpolation, especially in areas affected by well-field pumping. After filling in as much missing record as possible, the daily data were used to create monthly average estimates of the groundwater level at each monitoring well. These monthly average point values were interpolated to create the monthly average potentiometric surfaces.

Geostatistical Methods for Mapping Potentiometric Surfaces

The mathematical interpolation was applied to a rectangular area delineated by the location of the farthest north, south, east, and west of the subset of 197 wells (fig. 5). Potentiometric-surface elevations were interpolated throughout this rectangular area using the Geostatistical Analyst extension available in ArcGIS 10.0 software (Esri, 2011). The potentiometric surface was expected to be most accurately interpolated where the number of monitoring wells is greatest; therefore, the final map area was defined by the extent of the 11 coalesced buffers (fig. 5). The resulting regional map area is lobed along its western, northern, and eastern edges. Along its southern boundary, a straight line was used to connect the buffer areas where they were not touching. Enclosing the southern edge of the potentiometric map in this manner adds a narrow band of land between the well-field subregions to the east and west, and only six monitoring wells were located in this area (fig. 5; app. 1). Wells in this "gap" area were included with wells in the nearest well-field subregion to create the regression equations needed to estimate missing daily values of groundwater levels (fig. 6).

Kriging

Monthly average potentiometric surfaces were spatially interpolated using kriging, a geostatistical technique widely applied for groundwater mapping (Dunlap and Spinazola, 1984; Kay and others, 2006; Gillip and others, 2008; Varouchakis and others, 2012; Fisher, 2013). Geostatistical techniques such as kriging treat spatially distributed observations as random variables in which distance affects the relation between observations, a characteristic called spatial dependence. Interpolated surfaces are fitted to the geographic dataset by stochastic models of spatial dependence between observation points within a specified distance (Oliver and Webster, 1990). The fit is accomplished through two phases: (1) constructing statistical models that represent the spatial dependence of the observation points and (2) applying the models of spatial dependence to interpolate surfaces. The twophase procedure offers notable advantages over other spatial interpolation methods. A key advantage to using geostatistical techniques is the ability to quantify the error associated with estimated values (Virdee and Kottegoda, 1984). Estimation error can be quantified as the kriging standard deviation associated with the interpolated values. Additionally, geostatistical



Figure 5. Study area showing the subregions delineated for each well field, the extent of the overall interpolation, and the extent of the final potentiometric maps.



B. Cypress Creek



Figure 6. Location of groundwater monitoring wells inside each of the 11 subregions delineated around well fields in the study area.



Figure 6. Location of groundwater monitoring wells inside each of the 11 subregions delineated around well fields in the study area. —Continued



Figure 6. Location of groundwater monitoring wells inside each of the 11 subregions delineated around well fields in the study area. —Continued

techniques allow interpolation of surfaces that reflect the spatial variability in the data, while other interpolation methods apply mathematical functions to represent trends in the data without considering the spatial variability of those trends (for example, spline) (Oliver and Webster, 1990). In this kriging analysis, groundwater levels in the well network each month were treated as an independent spatial distribution, and temporal dependence between monthly surfaces was not considered (Rouhani and Myers, 1990).

Kriging applies the two-phase procedure of geostatistical techniques to predict unknown values on the basis of spatial dependence in the observed values. Kriging provides estimates at given locations by weighting surrounding observations according to their spatial autocorrelation (Oliver and Webster, 1990). For instance, observations more correlated to a given location receive the greatest weight in estimating that location's value. Conversely, less correlated observations are assigned less weight. The emphasis on spatial autocorrelation makes kriging particularly suitable for observations known to be spatially correlated within a certain distance, such as groundwater levels in an aquifer, and where the degree of spatial variation in the attribute is relatively similar across the scale of interest.

Drawdown due to well-field pumping could cause localized areas to have greater than the regional spatial variance in the potentiometric-surface elevations. While movingwindow kriging techniques have been developed to analyze the potential effect of differing degrees of spatial variation on the interpolated surface (Haas, 1990), assigning windows to areas with similar levels of spatial variation requires arbitrary decisions that can obscure regional trends across designated windows (Guttorp and Sampson, 1992). An analysis of the data in this study revealed that kriging and moving-window kriging produced similar potentiometric surfaces within the ranges of uncertainty (S. Reader, University of South Florida, written commun., May 2011). For this analysis, kriging is used and the potentiometric surface is treated as a coherent whole.

Semivariograms for Kriging Potentiometric-Surface Elevations

The statistical model of spatial autocorrelation was defined using the semivariogram. A semivariogram displays the empirical semivariance $\hat{\gamma}$ of the difference of measured variables on the y axis:

$$\hat{\gamma}(h) = \frac{1}{2} \cdot \frac{1}{n(h)} \sum_{i=1}^{n(h)} (z(x_i + h) - z(x_i))^2$$

where

h	is the distance between ordered data,
Ζ	is the measured value at a particular

n(h) is the number of paired data separated by a distance of h. The semivariance can be viewed as the whole variance of z values at a given separation distance h; or more specifically, the variance of measured values at the given separation vector h (Bachmaier and Backes, 2011). The x-axis displays the linear separation distance between pairs of points or the "lag distance" (Virdee and Kottegoda, 1984). When all observation pairs are plotted, the resulting graph reveals a variable's spatial autocorrelation pattern by displaying how much variability to expect between the groundwater levels in wells separated by a given distance (fig. 7). Observation pairs with the least semivariance typically plot near the graph's origin where the lag distance between the observations is small, indicating a common pattern of spatial autocorrelation, namely that observations closer to each other are more similar than those farther apart (Oliver and Webster, 1990).

The pattern of spatial autocorrelation was modeled mathematically by fitting a least-squares best-fit curve called a theoretical semivariogram through the empirical data of each monthly semivariogram. Semivariogram modeling and all other geostatistical tasks were carried out using ArcGIS 10.0 Geostatistical Analyst (Esri, 2011). Variables controlling the shape of theoretical semivariogram curves are shown in figure 7. Lag distances were divided into intervals, and the average semivariance was displayed for all well pairs within that interval (or bin) to summarize the spatial autocorrelation pattern. The distance intervals for bins and number of bins are important for properly calculating and presenting the average semivariance and were set by parameters called "lag size" and "number of lags," respectively. Lag size was set to 1 kilometer (km), or about the median distance between the nearest monitoring wells (0.68 mi (1.1 km)) and for 12 lags (fig. 7). Each lag contained at least 69 observation pairs for calculating the average semivariance. The number and size of lags were constant across months; therefore, monthly semivariogram models were fitted using average semivariance in the same groups of monitoring wells. The lag distance at which modeled semivariance no longer increases is the "major range." Modeled semivariance at the major range is the "sill." The intercept of the best-fit curve on the y-axis is the "nugget." A non-zero nugget was a regular characteristic of the best-fit curves implying some small but finite semivariance exists between two observations with no lag distance. The "partial sill" is the sill minus the nugget (fig. 7).

Prior to modeling the semivariogram, an exploratory data analysis was performed to characterize and remove any regional trends in the monthly average groundwater levels. Overall, the observed groundwater levels in wells declined from the northeastern region of the study area, where the land-surface elevations were highest, toward the coastline, where the land-surface elevations were lowest (fig. 2). A disproportionate number of the monitoring wells are located at lower elevations in the southwestern part of the study area. Removing the geographic trend resolved the lack of normality by reducing the similarity among nearby sampling locations. Geographic trends existed every month and were modeled using three-dimensional plots of monthly average groundwater



Figure 7. Representative empirical semivariogram showing best-fit hole effect curve for May 2000.

levels oriented in longitudinal and latitudinal directions. A second-order polynomial fit the geographic trend in all months for all directions (isotropic). With the regional trend removed, the semivariogram reflects the remaining spatial autocorrelation patterns in the potentiometric surface, namely those imposed by groundwater pumping and local topographic effects. Kriging interpolation using detrended data is referred to as universal kriging (Fisher, 2013).

The semivariogram model was selected after evaluating three curve forms that fit the overall appearance of the data: J-Bessel, Gaussian, and hole effect. The hole effect curve was chosen to model monthly semivariograms because it best represented the characteristic cyclical pattern in the empirical semivariance. The hole effect curve is particularly suited for phenomena with periodic spatial patterns and gradients interrupted by structural features (that is, holes) (Pyrcz and Deutsch, 2003). Holes in the interpolated surface can occur where the potentiometric surface is drawn down by groundwater pumping. The hole effect model has been used to interpolate spatial phenomena with holes, or patchy distributions, such as precipitation over a mountainous landscape (Goovaerts, 2000), groundwater quality in an urban area (Nas and Berktay, 2010), and groundwater elevations affected by geologic features (Nikroo and others, 2010). Additionally, of the three curves evaluated for this study, the hole effect curve had the smallest monthly cross-validation error.

The equation parameters defining the hole effect semivariogram curves were initially assigned by the "optimize model" function in ArcGIS 10.0 Geostatistical Analyst (Esri, 2011). This function uses a least-square error analysis

to generate a best-fit equation through the data. Parameters for the monthly best-fit equation were then slightly adjusted if necessary to align the front end of the curve through the average semivariance values near the nugget, where the lag distances were shortest. These small adjustments were made "by eve" to improve the accuracy of the kriged elevations at these shorter lag distances. The major range values were retained from the optimize model function. Hole effect semivariogram curves used to interpolate monthly potentiometric surfaces can be reproduced by applying the final curve-fit parameters (app. 3). Theoretical semivariogram models have been optimized in other studies using visual adjustments (Walker and Loftis, 1997) and weighting schemes (Varouchakis and Hristopulos, 2013). Because the best-fit curve for each month was modeled individually, curve-fit parameters can be viewed as response variables over time.

Potentiometric surfaces of the Upper Floridan aquifer were kriged using the monthly hole effect semivariogram models, and interpolated elevations were saved in griddedsurface datasets. Gridded surfaces are composed of 100 x 100-meter (m) (328 x 328-ft) grid cells. Grid-cell size was chosen through a trial-and-error process constrained to horizontal resolutions compatible with the purpose of the potentiometric-surface map, spatial variation of the phenomenon, and the spatial distribution of the input data (Hengl, 2006). A horizontal resolution of 100 m was considered reasonable for capturing the spatial variability in the monthly potentiometric surfaces, given the available distribution of monitoring wells within the subregions around each well field (figs. 5 and 6).

Estimating Uncertainty in the Potentiometric Surfaces

Kriging standard deviation was used to quantify the error associated with the interpolated potentiometric-surface elevations. The spatially distributed kriging standard deviation varies monthly as a function of the variance in the monthly semivariogram and the distance between monitoring wells (Olea and Pawlowsky, 1996). The kriging standard deviation or square root of the variance can be used to define the confidence interval about each interpolated point if errors are assumed to be normally distributed (Dunlap and Spinazola, 1984). Gridded-value surfaces of the monthly kriging standard deviation were generated to show where the potential error of estimating the potentiometric surface is greatest and where additional monitoring wells may be needed.

Cross validation was used to assess how closely the kriging interpolation could estimate the observed groundwater level at a well when the observed value was not used in the interpolation. The implemented cross-validation analysis, also called jack-knife cross-validation or leave-one-out cross validation, was executed as follows: (1) exclude one monitoring well from the interpolation, (2) perform the interpolation without the excluded monitoring well, (3) calculate the difference between the observed value and the interpolated surface at the excluded monitoring well, (4) repeat this process for every monitoring well, and finally (5) summarize the crossvalidation differences at individual wells across all months, and summarize the cross-validation differences that exist at all wells for a given month. The average cross-validation difference at a given well over time was quantified by a mean error (ME) and is referred herein as cross-validation error. The cross-validation differences at all wells for a given month were summarized using a cross-validation root-mean-square error (RMSE).

Cross-validation results were used to infer smoothing effects of the kriging. Kriging interpolation gives elevations with the minimum error variance in a least-squares sense, but it contributes a smoothing effect whereby low values are overestimated and high values are underestimated (Olea and Pawlowsky, 1996). Smoothing can be advantageous because it prevents the interpolation of details not present in the input data. However, large cross-validation differences at wells can reveal attributes in the potentiometric surface that are documented in a limited number of wells and so become smoothed over when those observations are absent. One spatial feature that could be smoothed over is the drawdown of the potentiometric surface by pumping from groundwater production wells. This relatively small-scale spatial feature has the potential to become smoothed over by kriging in areas where a single or limited number of monitoring wells record the effect.

Interpolation of Potentiometric Surfaces in the Upper Floridan Aquifer

Characteristics of the Monitoring Well Network

About 75 percent of the 260 established monitoring wells in the Northern Tampa Bay area, or 197 wells, were usable for interpolating the potentiometric surface over the 573-mi² map area. The spatial density of usable monitoring wells was large compared to the approximately 600 wells that were used to map the potentiometric surface of the Upper Floridan aquifer across 9,700 mi² of west-central Florida (one well per 16.1 mi² of area) (Ortiz, 2008).

The number of total monitoring wells within the boundaries of each of the 11 subregions ranged from 15 to 60 (table 1). The number of usable monitoring wells ranged from 11 in the South Pasco subregion (fig. 6D) to 45 in the Eldridge Wilde subregion (fig. 6E), and usable wells could be clustered in areas and not distributed evenly over subregions. With 45 usable monitoring wells in 66.7 mi², the Eldridge Wilde subregion had the greatest concentration of wells on average-one monitoring well for every 1.5 mi2. Cypress Bridge had the smallest average well density of any subregion with one monitoring well for every 4.5 mi^2 (table 1). The gap area between the 11 well-field subregions had five usable monitoring wells in an area of 81.4 mi² or one well per 16.3 mi². Cross Bar Ranch subregion was comparable to the gap area in size (83.6 mi²) and had one well for every 3.2 mi². Some monitoring wells are within multiple subregions and are listed as such in appendix 1. Half of the 197 wells used for mapping had a neighboring well within a distance of 0.68 mi, and three-fourths of the wells had three neighboring wells within a radius of 2 mi (fig. 8). The farthest outlying well, 165, was in the gap area southwest of the Morris Bridge subregion and had the maximum point distances to its five closest neighboring wells (fig. 8) (app. 1).

Mapping subregions also yielded widely different numbers of daily water-level observations in wells each month. Although the Eldridge Wilde subregion had the highest spatial density of wells, its wells had the lowest frequency of observations of any subregion. On average during the decade (and also for January 2009, the month with the peak number of daily observations), Eldridge Wilde subregion had the most wells with less than five observations per month (fig. 9). Many wells had two observations per month (or about 6.6 percent of all days as listed in appendix 1). Cross Bar Ranch and Cypress Creek subregions had the greatest number of wells with more than 25 observations per month (fig. 9). At both of these subregions, however, wells with the fewest observations (less than five per month) were located close to the production wells where the elevation of the potentiometric surface can change rapidly and where more frequent water-level observations would likely improve the accuracy of monthly average values. Other monitoring wells with less than five observations Table 1. Characteristics of the groundwater monitoring network in the 11 well-field subregions and the gap area.

Map subregion (abbreviation used in appendix 1)	Well field associated with map subregion	Subregion area (mi²)	Total monitoring wells in subregion	Usable monitoring wells in subregion	Unused monitoring wells	Tampa Bay Water production wells in subregion	Spatial density of usable monitoring wells (mi ² per well)
CBRW	Cross Bar Ranch	83.6	32	26	6	17	3.2
CCW	Cypress Creek	74.7	43	34	9	13	2.2
COSME	Cosme-Odessa	43.8	21	19	2	21	2.3
СҮВ	Cypress Bridge	72.4	17	16	1	10	4.5
EWW	Eldridge Wilde	66.7	60	45	15	55	1.5
MBW	Morris Bridge	50.0	22	14	8	20	3.6
NOP	North Pasco	34.9	16	12	4	4	2.9
NWH	Northwest Hillsborough	50.5	23	20	3	6	2.5
SECT21	Section 21	40.7	30	16	14	7	2.5
SPW	South Pasco	41.8	15	11	4	8	3.8
STRKY	Starkey	92.6	32	26	6	14	3.6
Gap area	N/A	81.3	6	5	1	0	16.3

[mi², square miles; N/A, not applicable]

per month were located near the production wells for Morris Bridge and Starkey well fields.

Estimated Daily Groundwater Levels

The number of daily groundwater levels that needed to be estimated decreased moderately during the decade from about 40 percent of all daily values in January 2000 to below 30 percent in December 2009 (fig. 10). The decrease in estimated values, and increase in observed values, was roughly equivalent to changing about 20 wells from a monthly to daily observation frequency. Missing daily values at each of the 197 wells could be estimated by using up to five predictive equations; however, most estimates were made by using the first three predictive equations (app. 2). The top graph in figure 11 shows the frequency distribution of the regression correlation coefficients (R) used to generate all 985 predictive equations (fig. 11A). Cumulatively, 89 percent of the predictive equations had a correlation coefficient greater than or equal to 0.9, and over 95 percent had R values greater than 0.85. The lower graph shows the frequency distribution of the R values actually used to estimate missing values (fig. 11*B*; app. 2). About 71 percent of the missing values were predicted using equations with associated R values of 0.95 or greater, 87 percent had R values of 0.90 or greater, and 92 percent of missing values were predicted using equations with R values of 0.85 or greater.



Figure 8. Summary statistics describing the distances between each monitoring well in the network and its five closest neighboring wells.



A. Average number of observations per month,



Cross Cros

Ranch

Cypress

Bridge

Morris

Bridge

EXPLANATION Well-field property

B. Month with least observations, February 2003

Gulf

Bay



Figure 9. Number of daily water-level observations per month at each groundwater monitoring well (A) on average over the decade, (B) in the month with the fewest observations, and (C) in the month with the most observations.

A hydrograph for well 252 in the Starkey subregion shows the observed daily groundwater levels and gaps in the record for 2 years of the study decade (fig. 12; app. 2). The predicted daily groundwater levels for well 252 based on the predictor equations (P2 and P3) are also shown and can be used to fill gaps in the observed record. Well 252 has the short name STRKY REGIONAL FLDN in appendixes 1 and 2. Predicted values using P1 are not shown, because, although P1 was slightly better correlated with well 252 over the entire regression record, P1 had no observations during this 2-year period from which to base predictions (app. 2). Therefore, the second-best predictor well, P2, supplied most of the missing values (fig. 12). After as many missing values as possible were estimated for all 197 wells, 90 percent of all daily values for the 10-year study period were either observed or estimated -56 percent were observed and 34 percent were estimatedand 10 percent were missing.

Monthly Average Potentiometric Surfaces

A mapping time series consisting of 120 gridded surfaces describes the monthly average potentiometric-surface elevations in the Upper Floridan aquifer from January 2000 to December 2009. The best-fit parameters for the 120 monthly hole effect semivariograms used in the kriging are given in appendix 3. The highest (September 2004) and lowest (May 2000) monthly average potentiometric surfaces of the 10 years are shown with gridded values of the potentiometricsurface elevation color-shaded into 5-ft intervals (fig. 13). The highest elevation values on the potentiometric surface consistently occur where the topographic elevations are highest,



Figure 10. Percentage of all daily groundwater levels that were estimated each month.

on the eastern edge of the maps, and potentiometric surface elevations decrease toward the coastline (figs. 2 and 13). The overall slope in the potentiometric surface is interrupted by a trough of low potentiometric-surface elevations that follow the channel of Cypress Creek and reach their lowest values inside Cypress Creek well field, leaving a crescent-shaped mound in the surrounding surface. Ten other well fields encircle the roughly centralized mound in the potentiometric surface. Groundwater pumping lowers the potentiometric surface inside these well fields, causing lower-elevation contour lines to be farther upgradient at well fields compared to adjacent areas, with the possible exception of South Pasco, which appears to have little effect on the shape of the 5-ft contour lines (fig. 13).



Figure 11. Histograms comparing the frequency distribution of correlation coefficients for linear equations (*A*) available for predicting missing daily values, and (*B*) actually used for predicting missing daily values.



Figure 12. Observed and estimated daily groundwater levels at well 252 in the Starkey subregion between May 1, 2001, and May 1, 2003.

The highest monthly average potentiometric-surface elevations differed from the lowest by about 15 ft in most of the map area and by as much as 30 ft in some locations (fig. 13*A* and *B*). The potentiometric surface was highest in September 2004, a month that followed reductions in wellfield pumping and also had record high rainfall because of multiple hurricanes (U.S. Geological Survey, 2005; Metz, 2011). The potentiometric-surface elevation was about 90 ft above NGVD 29 at the eastern edge of the map, declined to 60–65 ft above NGVD 29 beneath Cypress Creek well field, and was 75–80 ft above NGVD 29 west of Cypress Creek well field (fig. 13*A*). Potentiometric-surface elevations were between 20–25 ft above NGVD 29 below much of Eldridge Wilde well field, the westernmost well field in the study area.

The lowest potentiometric surface of the study decade (based on lowest gridded elevation value) occurred in May 2000, during an extended drought and prior to mandated reductions in well field pumping (fig. 13B). The potentiometric-surface elevation was about 75 ft above NGVD 29 along the eastern map boundary, 35-40 ft above NGVD 29 beneath Cypress Creek well field, and 0-5 ft above NGVD 29 beneath Eldridge Wilde well field. When potentiometric surface elevations for all months were averaged for the decade, the average potentiometric-surface elevation was 80-85 ft above NGVD 29 at the eastern margin of the map, 50-55 ft above NGVD 29 beneath Cypress Creek well field, and 70–75 ft above NGVD 29 to the west of Cypress Creek well field. Potentiometric-surface elevations beneath much of Eldridge Wilde well field were between 15 ft and 20 ft above NGVD 29 (fig. 13C). When gridded elevations across the entire 573-mi² map area were averaged into a single value, the spatially averaged potentiometric surface was highest in September 2004 at 46.78 ft above NGVD 29 and lowest in May 2001 at 35.65 ft above NGVD 29 (fig. 14).

Uncertainty in the Monthly Average Potentiometric Surfaces

Cross-validation errors revealed the discrepancy between the observed groundwater level at a well and the interpolated value when the observation was left out of the interpolation (fig. 15). For the majority of well locations, kriging appeared to produce little systematic bias in the interpolated value. For 127 of the 197 wells, the monthly average cross-validation error was less than ± 2 ft (app. 1). For the remaining wells, cross-validation errors were $\pm 2-4$ ft at 45 wells and were greater than ± 4 ft at 25 wells. Cross-validation errors were relatively consistent across months, and the largest values consistently occurred at the same wells. Six monitoring wells had average monthly cross-validation errors that exceeded ± 10 ft: wells 7, 17, and 20 in the Cross Bar Ranch subregion, wells 75 and 78 in the Cosme-Odessa subregion, and well 165 near the Morris Bridge subregion (figs. 6 and 15).

Large cross-validation errors can reveal anomalous readings at individual wells, limitations of the monitoring network to sample small-scale characteristics of the potentiometric surface, and the effect of limited observations along the edge of the map. For instance, well 78 in the Cosme-Odessa well field had the largest monthly average cross-validation error (-21.13 ft) calculated as the interpolated value at the well minus the observed value (app. 1). If the observed value for well 78 were excluded from the kriging, its interpolated groundwater level based on neighboring wells would be 21.13 ft lower than its observed value. In fact, the large cross-validation error reveals the anomalously high groundwater levels in this well that are thought to be caused by the well being finished in the intermediate confining unit above the Upper Floridan aquifer (M. Hancock, Southwest Florida



EXPLANATION Potentiometric-surface elevation, monthly average, in feet above NGVD 29



20 Line of equal elevation of the potentiometric surface-In feet above NGVD 29. Contour interval 5 feet





C. Average, January 2000–December 2009



Figure 13. Months with the (*A*) highest and (*B*) lowest monthly average potentiometric-surface elevations, and the (*C*) average potentiometric-surface elevation between January 2000 and December 2009.



Figure 14. Spatially averaged potentiometric-surface elevation between January 2000 and December 2009.



Figure 15. Monthly average cross-validation values at the 197 monitoring wells.

Water Management District, written commun., July 2013). The adjacent well, 75, also had a large cross-validation error that was positive (13.54 ft) probably because when this well is censored, its interpolated value is raised by the anomalously high groundwater levels at well 78 (app. 1). Because the elevated groundwater levels observed in well 78 did not occur in any of the surrounding wells, the anomalous value at this well had little effect on the interpolated potentiometric surface; however, the large cross-validation error may lend support for dropping the well from the monitoring network. Wells 17 and 20 also had large cross-validation errors (-13.03 ft and 11.31 ft, respectively). Their proximity to production wells suggest their values could be affected by anomalously low elevations in the potentiometric surface around a cone of depression (fig. 15).

Large cross-validation errors also occurred at wells that were far from nearest neighbor wells or were located near the edge of the map with no surrounding wells. For instance, well 165 is in the gap area between well-field subregions (-12.98 ft), and wells 196 and 160 are on or near the edge of subregions (7.84 ft and -6.91 ft, respectively). Border effects also could explain the large cross-validation error at well 7 in the Cross Bar subregion (15.02 ft). Cross-validation results indicate the importance of having measurements in wells around the map border.

The monthly root-mean-square (RMSE) cross-validation error for all 197 wells varied by month and was positively correlated to the monthly well-field pumping (fig. 16; linear R^2 =0.70). This correlation supports the theory that monthly cross-validation errors are associated with drawdown in the potentiometric surface and that smoothing effects are increased during higher pumping months when drawdown effects are greater. The monthly cross-validation errors declined following the reductions in well-field pumping in late 2002, and the highest values occurred around the seasonally driest months (April, May, June), when monthly pumping from well fields peaked (fig. 16).

The monthly kriging error reflects, in part, the spatial variance in the observed groundwater levels each month. Monthly hole effect semivariogram models indicate that, overall, the spatial variance in groundwater levels was greater in dry months prior to well field cutbacks than in subsequent dry months, as evidenced by the monthly partial sill and nugget values (fig. 17). Partial sill values and nugget values declined in late 2002 and, in subsequent years, showed peaks in April, May, or June when the regional potentiometric surface was low and well field groundwater pumping rates were greatest.

A second mapping time series with 120 gridded surfaces describes the kriging error associated with the monthly average potentiometric-surface elevations. Monthly kriging errors depend on the variance described in the monthly semivariogram and the spatial distribution of monitoring wells. Inside well fields, where monitoring wells typically were concentrated, the kriging error in the monthly average potentiometric-surface elevations averaged 2 ft or less and, in selected months, was less than 1 ft (fig. 18*A* and *C*). The magnitude of



Figure 16. Correspondence between monthly total well-field pumping and monthly root-mean-square cross-validation error for all wells.

kriging error tended to be similar across some well-field properties, such as Eldridge Wilde, Cosme-Odessa, South Pasco, and Section 21, but inside other properties it increased where well density decreased. For instance, potentiometric-surface elevations in the southwestern corner of Starkey well field were prone to slightly greater kriging error than the central Starkey well field (fig. 18*C*).

Kriging errors immediately outside of well-field properties also varied. The greatest error was in the Morris Bridge subregion where errors exceeded 6 ft in May 2000, the month with the largest kriging errors (fig. 18). When the kriging error was evaluated for each well-field subregion, the largest range and averages of the gridded values were for Morris Bridge and Cypress Bridge subregions. The Cosme-Odessa subregion had the lowest average kriging error (table 2). Kriging error was greatest in the gap area and averaged more than 4 ft in the map's southeast corner (fig. 18). When evaluated inside stream drainage basins, the kriging errors were greatest in the upper and middle areas of the Hillsborough River Basin (table 2).

Overall, the existing monitoring network allows monthly average potentiometric-surface elevations to be estimated over much of the map with an average kriging error of less than 2 ft. When averaged over all months during the study decade, the kriging error for about 70 percent of the mapped area was less than 2 ft. Kriging error was greater than 4 ft across less than 6 percent of the map area (fig. 18). Potentiometricsurface elevations for the wettest conditions had less kriging error than the driest conditions. In September 2004, the month when the potentiometric surface was highest, smoothest,



Figure 17. Partial sill and nugget values for monthly semivariograms from January 2000 to December 2009.

and least affected by pumping, the uncertainty was less than 2 ft for 87 percent of the map area. Only 2 percent of the map area in September 2004 had uncertainties that exceeded 4 ft. In contrast, in May 2000, the month with the lowest potentiometric-surface elevation and the largest kriging errors, only 30 percent of the mapped area had a kriging error that was under 2 ft. The majority of the mapped area (56 percent) had kriging errors between 2 and 4 ft, and 14 percent of the area had errors greater than 4 ft.

The statistical methods described in this report amount to a modeling approach for creating a representation of the monthly average potentiometric surface. The results are constrained by the assumptions in the approach as well as the limitations of the data. These assumptions add an additional uncertainty to the elevations in the interpolated potentiometric surface, and for this reason monthly average potentiometric surfaces were estimated instead of a weekly average or daily average surface. For instance, interpolated elevations are sensitive to how well the functional form (mathematical model) of the theoretical semivariogram fits the experimental semivariogram. The theoretical semivariogram curve was adjusted "by eye" in this study to improve its fit to data at the shortest lag distances. Future studies can determine whether or not this additional effort is justified and whether other ways of modeling the semivariogram could improve the kriged surfaces. Monthly average groundwater elevations at a well were also subjected to the standard error in the regression equations used to estimate missing daily values and the number of values estimated for each month. The standard error of regression for predicting daily water levels was less than 1 ft for 75 percent of the equations, and for half of the equations the standard errors were less than 0.7 ft (app. 2). For this reason, the uncertainty contributed by estimating missing daily values is expected to be smaller than the kriging error.





EXPLANATION

<1

>6

5

1 to 2 >2 to 4 >4 to 6

Kriging error, in feet

Line of equal kriging error-In feet.

Contour interval 1 and 2 feet

10 KILOMETERS

10 MILES



C. Monthly average, January 2000–December 2009





Table 2. Kriging error by mapping subregion and stream drainage basin.

[Subregion names are defined in table 1; HUC, hydrologic unit code; Drainage basin outlines are shown in figure 2]

Subregion or drainage basin	Summary statistics for gridded values of the monthly kriging standard deviation, in feet				
Subregion	Average	Minimum	Maximum	Range	
Cross Bar Ranch (CBRW)	1.77	0.93	4.29	3.36	
Cypress Creek (CCW)	1.57	0.77	3.84	3.07	
Cosme-Odessa (COSME)	1.30	0.96	2.51	1.55	
Cypress Bridge (CYB)	2.09	0.89	6.84	5.94	
Eldridge Wilde (EWW)	1.42	0.74	3.10	2.37	
Morris Bridge (MBW)	2.25	0.83	6.27	5.44	
North Pasco (NOP)	1.74	0.89	4.73	3.84	
Northwest Hillsborough (NWH)	1.67	0.95	4.99	4.04	
Section 21 (SECT 21)	1.42	0.94	2.32	1.38	
South Pasco (SPW)	1.55	1.05	2.36	1.31	
Starkey (STRKY)	1.81	0.89	5.73	4.84	
Gap area	3.07	1.44	6.01	4.56	
Drainage basin (HUC Number) ¹	Average	Minimum	Maximum	Range	
Anclote River (310020705)	1.62	0.74	3.10	2.37	
Pithlachascotee River (310020704)	1.75	0.91	4.29	3.37	
Cypress Creek-Hillsborough River (310020504)	1.79	0.77	5.42	4.65	
Upper Hillsborough River (310020503)	3.59	1.28	6.84	5.56	
Middle Hillsborough River (310020505)	2.86	0.83	6.01	5.18	
Moccasin Creek-Double Branch (310020601)	1.45	0.80	4.99	4.19	
Rocky Creek-Sweetwater Creek (310020602)	1.51	0.94	4.79	3.85	
Weeki Wachee River - Double Hammock Creek (310020703)	2.59	0.99	5.73	4.74	

¹HUC source: Watershed Boundary Dataset (WBD) in the National Hydrography Dataset http://nhd.usgs.gov/index.html.

The groundwater monitoring network used in this study was developed to address the regulatory requirements of monitoring Upper Floridan aquifer potentiometric-surface elevations in and around 11 municipal well fields. The kriged potentiometric surfaces and the spatially distributed kriging error offer new ways to improve the groundwater monitoring network. For instance, in some well fields, such as Eldridge Wilde, the potentiometric surface perhaps could be interpolated with similar error using fewer wells if the well locations were optimized (Olea and Davis, 1999; Fisher, 2013), and mapping could be improved by collecting more daily groundwater observations. The 573 mi² mapped area also encompasses parts of six stream drainage basins in the Northern Tampa Bay area: Anclote River, Pithlachascotee River, Cypress Creek-Hillsborough River, Middle Hillsborough River, Rocky Creek-Sweetwater Creek, and Mocassin Creek-Double Branch (fig. 2) (U.S. Geological Survey, 2013b). Understanding time-varying potentiometric-surface elevations at the scale of the drainage basin could supply new evidence to improve water-management decisions affecting streams and their interconnected wetlands.

Summary and Conclusions

Kriging of long-term groundwater monitoring data was used to create a monthly time series of the potentiometric surface in the Upper Floridan aquifer over a 573-mi² area of west-central Florida for the period January 2000 to December 2009. Groundwater levels were collated for 260 monitoring wells in the Northern Tampa Bay area, and a continuous time series of daily groundwater levels was created for 197 of these wells by using regression relations with other monitoring wells to estimate missing daily values. During the 10-year study period, 56 percent of the daily values were measured, 34 percent were estimated, and 10 percent were missing. Monthly average elevations at monitoring wells were interpolated into a monthly time series of the potentiometric surface in the Upper Floridan aquifer over the decade. The resulting potentiometric-surface maps give spatial and temporal coherence to groundwater measurements that were collected routinely in wells over the decade, but at various time intervals, and by three different organizations. The potentiometric surface of the Upper Floridan aquifer is described across parts of six regionally important stream watersheds as well as 11 municipal well fields that withdraw a total of approximately 90 million gallons per day from the Upper Floridan aquifer.

The monthly average groundwater levels at wells were viewed as independent spatial distributions, and 120 best-fit semivariograms were constructed for kriging interpolation. Localized drawdown in the potentiometric surface across the map area was likely responsible for the characteristic decrease and then increase in semivariance at greater lag distances in the monthly semivariograms. The hole effect model was selected as the functional form to describe the semivariograms because it could represent the periodic behavior and because it had the lowest cross-validation error of the compared models. Curve-fit parameters for the hole effect model were first optimized in ArcMap 10.0 and then slightly altered "by eye" if needed to improve the fit of the curve at its front end or for the shortest lag distances. Semivariograms were used to krige the 120 monthly average potentiometric surfaces and to map the monthly kriging standard deviation or kriging error.

Decreasing spatial variance in the monthly semivariogram decreased the kriging error in the potentiometric surfaces between 2000 and 2003, and was coincident with decreases in well-field pumping and wetter climate conditions. Partial sill and nugget values decreased while the major range stayed roughly constant. The location of wells with the largest cross-validation errors, and the temporal correlation between monthly cross-validation errors and monthly wellfield pumping, suggest that kriging interpolation may smooth over the drawdown of the potentiometric surface near production wells.

Potentiometric-surface elevations within the mapped area fluctuated by as much as 30 ft, and the spatially averaged elevation for the entire map rose by about 2 ft over the decade. The groundwater monitoring network of 197 wells yielded a kriging error in the monthly average potentiometric-surface elevations that averaged 2 ft or less for about 70 percent of the map area. Maps of the kriging error can be used to guide the addition of new monitoring wells to the existing network. The hole effect semivariogram model was used for this analysis. The sensitivity of the interpolation results to other semivariogram models or curve-fitting strategies was not examined.

Surface-water and groundwater resources are interconnected in the karst terrain of Florida. The kriged potentiometric surfaces quantify monthly average groundwater conditions in the Upper Floridan aquifer for the Northern Tampa Bay area. In addition, the time series of potentiometric surfaces offers a versatile metric for assessing the hydrologic conditions of overlying streams and wetlands at spatial scales ranging from a single wetland to a stream drainage basin.

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