Extending the Monthly Time Series of the Potentiometric Surface in the Upper Floridan Aquifer, Northern Tampa Bay area, Florida, January 1990-December 2015

By Terrie M. Lee and Geoffrey G. Fouad

March 2017

Prepared for Tampa Bay Water

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Suggested citation:

Lee, T.M. and Fouad, G.G., 2017, Extending the monthly time series of the potentiometric surface in the Upper Floridan aquifer, Northern Tampa Bay area, Florida, January 1990-December 2015: Data products and technical report prepared for Tampa Bay Water (Clearwater, FL) by HSW Engineering, Inc. (Tampa, FL), March 2017, 30 p.

Report and data products available at: *www.swfwmd.state.fl.us/data/hydrologic/index.php#other-hydro-data*

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Prepared by HSW Engineering, Inc.

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Introduction

For nearly three decades, groundwater levels in the Upper Floridan aquifer have been routinely monitored in hundreds of wells in the Northern Tampa Bay area of Florida (Figure 1). The wells are maintained and data are collected by the local municipal water supplier, Tampa Bay Water, and two governmental agencies: Southwest Florida Water Management District and the US Geological Survey. The missions of all three agencies require unbiased and long-term physical evidence to describe hydrologic conditions in the Upper Floridan aquifer in the Northern Tampa Bay area.

For this reason, a method was developed by the USGS in cooperation with Southwest Florida Water Management District to create a highly spatially-resolved, monthly time series of potentiometric surface maps for the Upper Floridan aquifer using the monitoring data from the groundwater network (Lee and Fouad, 2014). The potentiometric maps describe a 573-mi^2 area covering portions of six regional stream watersheds and the entirety of 11 municipal wellfields. The analysis by Lee and Fouad (2014) created a 10-year time series from 2000 to 2009. However, a longer time series was needed to analyze the effect of climate and wellfield operations on the region's hydrology, one spanning multiple decades. For this reason, Tampa Bay Water funded a study to extend the length of the mapping time series to 26 years, from 1990 to 2015, using the same methods. Because surface and groundwater interact in the karst geology of the Northern Tampa Bay area, the highly spatially-resolved potentiometric-surface maps not only describe changes in the groundwater level of the Upper Floridan aquifer, they chronicle changes in the hydrologic setting of the overlying wetlands, lakes, and streams (Lee and Fouad, 2014; Guerink and Basso, 2013; Haag and Lee, 2010; Southwest Florida Water Management District, 2005; Lee and others, 2009; Metz, 2011). As such, the extended mapping time series provides a versatile line of hydrologic evidence to use in evaluating historic reductions in groundwater pumping from municipal wellfields in the Northern Tampa Bay area.

Objectives

The objective of the study is to create an extended time series of digital maps describing the monthly-average potentiometric surface of the Upper Floridan in the Northern Tampa Bay area for the 26-year period from 1990 to 2015. Specific objectives include: (1.) describing and characterizing all monitoring data used for the analysis; (2.) describing minor modifications made to the approach of Lee and Fouad (2014); and (3.) describing the on-line data products that were produced for the 26-year timeframe.

The 26-years of potentiometric-surface maps for the Northern Tampa Bay area is packaged in a sequence of 312 gridded (raster) data layers. Each layer describes a monthly average potentiometric-surface from January 1990 to December 2015 (312 layers reflects 26 years times 12 months per year). An associated 312 gridded data layers covers the same time period and displays the spatially-distributed error of estimating the mapped potentiometric-surface elevations each month. The complete list of data products for the extended time series is given below. The products with an asterisk** next to them are publicly available for download from the SWFWMD website at *www.swfwmd.state.fl.us/data/hydrologic/index.php#other-hydro-data*. The other products are available upon request from Tampa Bay Water. Daily gap-filled water levels at 195 monitor wells are also available from Southwest Florida Water Management District.

Products

A **water-level database** containing all of the retrievable daily observations of the potentiometric surface elevation in the Upper Floridan aquifer between 1990 and 2015 at the 197 monitor wells used in this study was provided to Tampa Bay Water. An appendix table (**Appendix 1****) describes the characteristics of each well and its frequency of daily observations.

Continuous daily water levels that include the observed and estimated (gap-filled) values for each well were provided to Tampa Bay Water. The regression models that were used to estimate missing values are provided in an appendix table (**Appendix 2****) and includes statistics describing the strength of the models and how often they were used.

Monthly average water levels** at each well were calculated from the daily water levels. The monthly average values are available for download in as an excel table in **Appendix 3**.

Monthly-average potentiometric surface maps** interpolated using kriging and based on the monthly-average water levels. The surfaces are provided as raster grids with x and y cell dimension of 100 meters, and saved as GeoTIFF files for use in a variety of geographic information systems.

Kriging error surfaces** generated for the monthly-average potentiometric surfaces. The error surfaces describe the standard deviation around the kriged surface, and provide confidence intervals for the estimated water levels. Kriging error surfaces are in the same gridded format as the potentiometric surfaces.

Metadata** describing the gridded data products are provided in a single Readme.txt text file. The text file includes a description of each file name and data associated with the file.

Cross-validation errors are tabled for each month for each well. The last 2 columns in Appendix 1 summarize the mean monthly cross-validation error at each monitor well**.

Summary report** describing the study methodology and results.

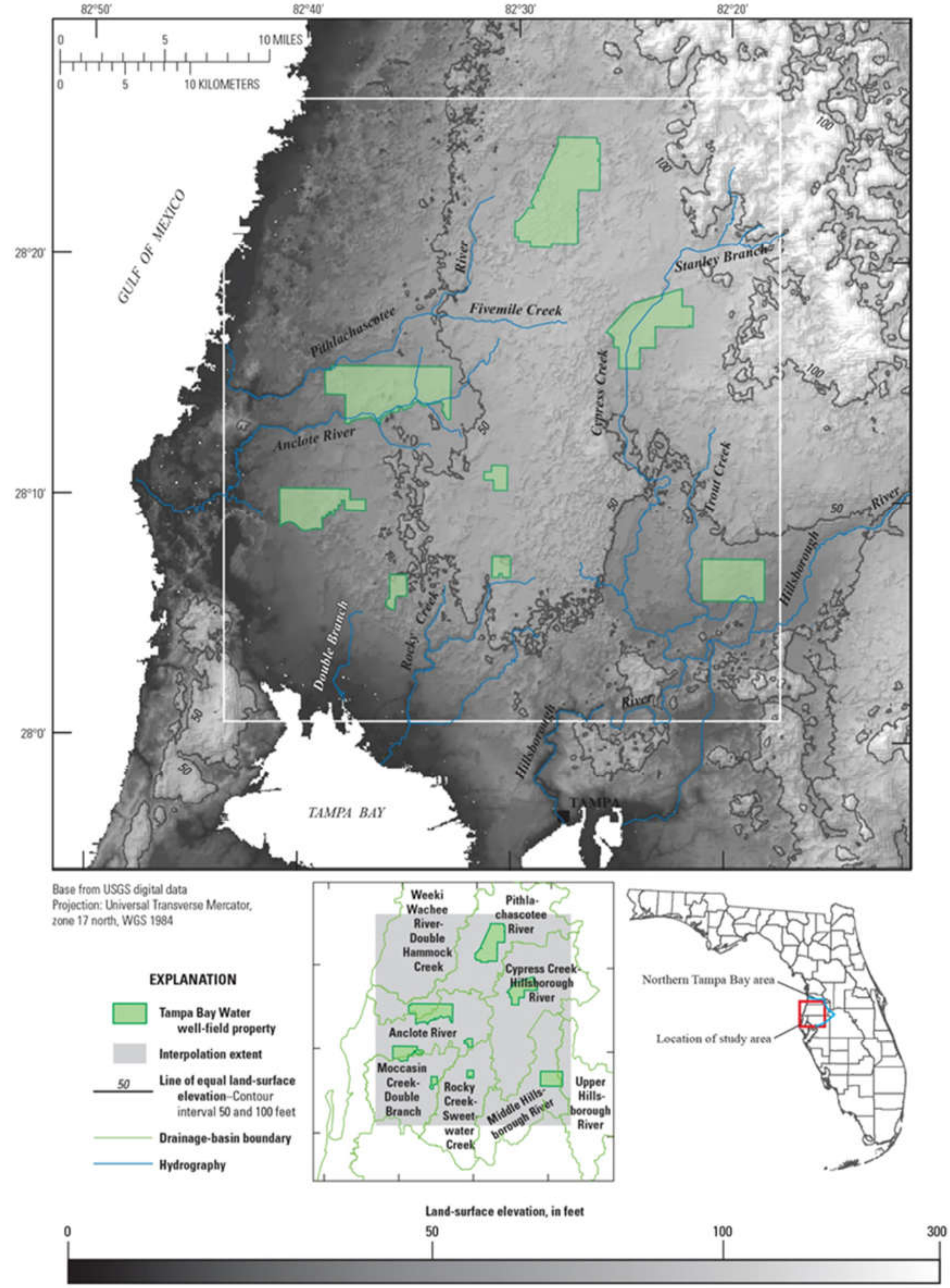


Figure 1. Digital elevation model of the study region in the Northern Tampa Bay area showing streams, USGS stream drainage basin divides, and Tampa Bay Water wellfield properties. The white rectangle shows the total extent of the interpolated potentiometric-surface elevations. Figure credit Lee and Fouad (2014).

Background

The US Geological Survey (USGS) in cooperation with the Southwest Florida Water Management District (SWFWMD) published a monthly time series of the UFA potentiometric surface from 2000-2009 (see the project page at http://pubs.usgs.gov/sir/2014/5038/). The time series maps the potentiometric surface over a 573-mi^2 area in the Northern Tampa Bay area, and describes portions of six regional watersheds and all 11 municipal wellfields that collectively pumped 90 million gallons per day (Figure 1). Potentiometric surface elevations are used by Tampa Bay Water to optimally manage their groundwater withdrawals and to minimize the induced downward leakage from the overlying surficial aquifer and surface-water features. The Southwest Florida Water Management District monitors potentiometric surface elevations in the Upper Floridan aquifer as part of their regulatory oversight of groundwater use in the region. The reader is referred to Lee and Fouad (2014) for additional background on water-resource management issues in the Northern Tampa Bay (NTB) area and a description of the physical setting.

The current project maps the potentiometric surface at the same scale as the earlier study. The potentiometric surfaces were mapped using the methods initially developed in Fouad and Lee (2011a) and later established in Lee and Fouad (2014). Extending the analysis of the potentiometric surface to cover the period 1990 to 2015 captures conditions before and after large groundwater pumping cutbacks in NTB area wellfields (Figure 2).

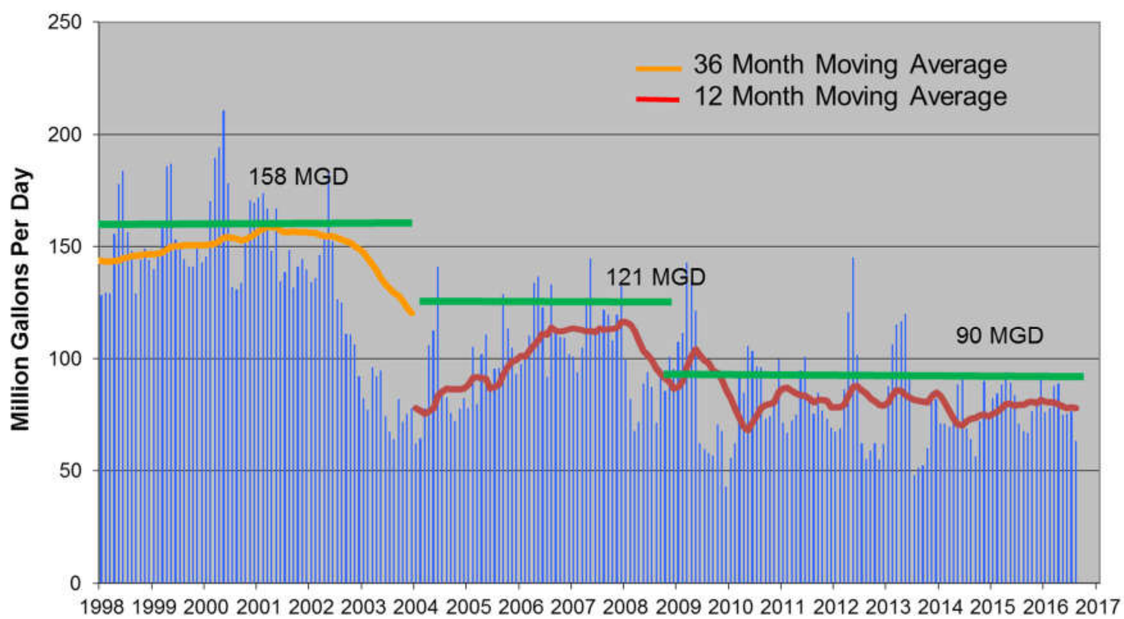


Figure 2. Cumulative monthly groundwater pumping at 11 wellfields operated by Tampa Bay Water in the Northern Tampa Bay wellfields from 1998 to 2016, and moving average pumping rates. Figure source: M. Hancock, Southwest Florida Water Management District, Dec. 2016.

The kriging approach used in this and the earlier study by Lee and Fouad (2014) generates a rectangular interpolated surface the extent of which is defined by the location of the most northern, southern, eastern, and western monitoring wells in the network (Figure 3). The published maps are clipped from this larger surface to be closer to the well fields and the greatest concentration of the monitoring wells. The greater spatial density of monitoring wells in the final map area reduces the kriging standard error associated with estimated potentiometric-surface elevations.

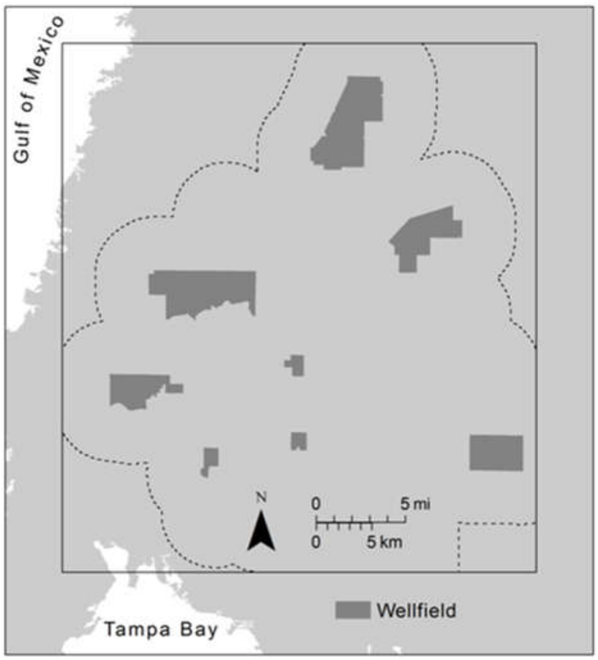


Figure 3. Geographic extent of the study area used by Lee and Fouad (2014) showing the rectangular interpolated area (solid line) and the 573-square mile mapped area of the potentiometric surface in the Upper Floridan aquifer (dashed line).

Methods

Methods used for the analysis are described briefly in this section, with the emphasis placed on describing minor modifications made to the kriging interpolation approach. The approach applied for this study has been described previously by Lee and Fouad (2014) and the reader is referred there for an expanded description.

Monitoring-Well Characteristics

Groundwater elevation data from monitoring wells were gathered from TBW, SWFWMD, and USGS databases. At our request, each agency supplied all available measurements of potentiometric elevations of the Upper Floridan aquifer in feet above the National Geodetic Vertical Datum of 1929 (NGVD29). Period-of-record data were requested for the same 197 monitoring wells previously used to map the potentiometric surface from 2000-2009 (Lee and Fouad, 2014). The interpolated elevations for the potentiometric surface covers a rectangular area that extends to the farthest monitoring well in each cardinal direction. The rectangular area includes all of the area identified for the recovery assessment (Tampa Bay Water, 2013).

Groundwater levels are collected at differing frequencies in each well ranging from monthly to hourly. Observations describe potentiometric-surface elevations in the Upper Floridan aquifer at that location.

Groundwater levels at 197 monitoring wells were compiled into a table of daily observations from 06/08/1951-08/17/2016 (see NGVD29_ft_Water_Levels_Full_Time_Series.xlsx in the Water_Level_Database folder). The maximum value was used for days with multiple observations from different agencies or field and continuous measurements. Monitoring wells have daily observations at different frequencies. An additional table characterizes the frequency of daily observations at each well using values such as the percent of days with observations for a given time period (see Well_Information_Table.xlsx in the Water_Level_Database folder). This table also describes the physical characteristics of the wells (e.g. location, altitude, and depth) and the agencies that collected data at each well. A key provides a list of definitions for all of all the well characteristics in the table (see ColumnKey sheet in Well_Information_Table.xlsx). The name of the well is its unique identifier for all the deliverables of this project.

The number of daily groundwater-level observations at each well was tallied and compared to the number of daily observations retrieved and published in the previous project (Lee and Fouad, 2014, Appendix 1). For the majority of the wells, the number of observations retrieved for the two studies was identical. However, data supplied for our first request included 24 wells that had fewer daily observations than were previously published for the same time period by Lee and Fouad (2014). Data for these 24 wells were requested again from the respective agencies. This reduced to 13 the number of wells with fewer daily observations than the previous study. All 13 wells can be identified using a table accompanying the groundwater level database produced for this project (see Well_Information_Table.xlsx in the Water_Level_Database folder).

Personnel were contacted at each agency regarding these wells, but additional daily observations were not retrieved. Most of the missing daily observations were collected for research projects that used given wells. For instance, 2 of the 13 wells were missing daily values previously-published by USGS in Lee and others (2009). One of these two wells, Cypress Ck W29 FLRD Well Near Drexel FL was missing the most daily observations (826). The other, Cypress Ck W19 FLRD Well Near Drexel FL was missing the second-most (473). These data were in the USGS NWIS database, but were flagged as unavailable for public retrieval at the time of this request (written comm. USGS, Sandra Kinneman, Oct. 5, 2016). Two project wells operated by Southwest Florida Water Management District also retrieved fewer daily observations between 2000-2009: STWF 1A West 95ft FLDN Well NR New Port Richey FL (435 fewer) and STWF 1A Central 100ft FLDN Near New Port Richey FL (383 fewer). The discrepancy in the remaining 9 wells was less, ranging from 1 to 69 daily observations.

Estimating Missing Daily Groundwater Levels (Gap Filling)

Missing daily groundwater levels were estimated (i.e. gap-filled) in order to create a time series for calculating monthly average groundwater levels at the monitoring wells. The gap filling and all subsequent steps of the methods did not use two wells because Keystone Park FLDN Well was completed in a confining unit above the UFA (Michael Hancock, SWFWMD, written communication, July 2013) and CBR-B-14 Well Near Masaryktown FL has an unknown datum shift (this well is listed in the Tampa Bay Water database as CRB-B-1-4 Well Near Masaryktown FL) (Warren Hogg, TBW, written communication, June 2016).

The remaining 195 monitoring wells were assigned to one or more of eleven smaller regions for the gap filling. These subregions were delineated by 3-mi buffers around each of the 11 wellfields (Figure 4). Gap filling was accomplished by correlating the groundwater levels of wells inside each respective subregion. Wells around the same wellfield tend to share the effects of the same set of pumping wells and have groundwater levels that are more correlated to each other than to wells from different wellfields. Wells outside of a 3-mi buffer were assigned to the nearest subregion.

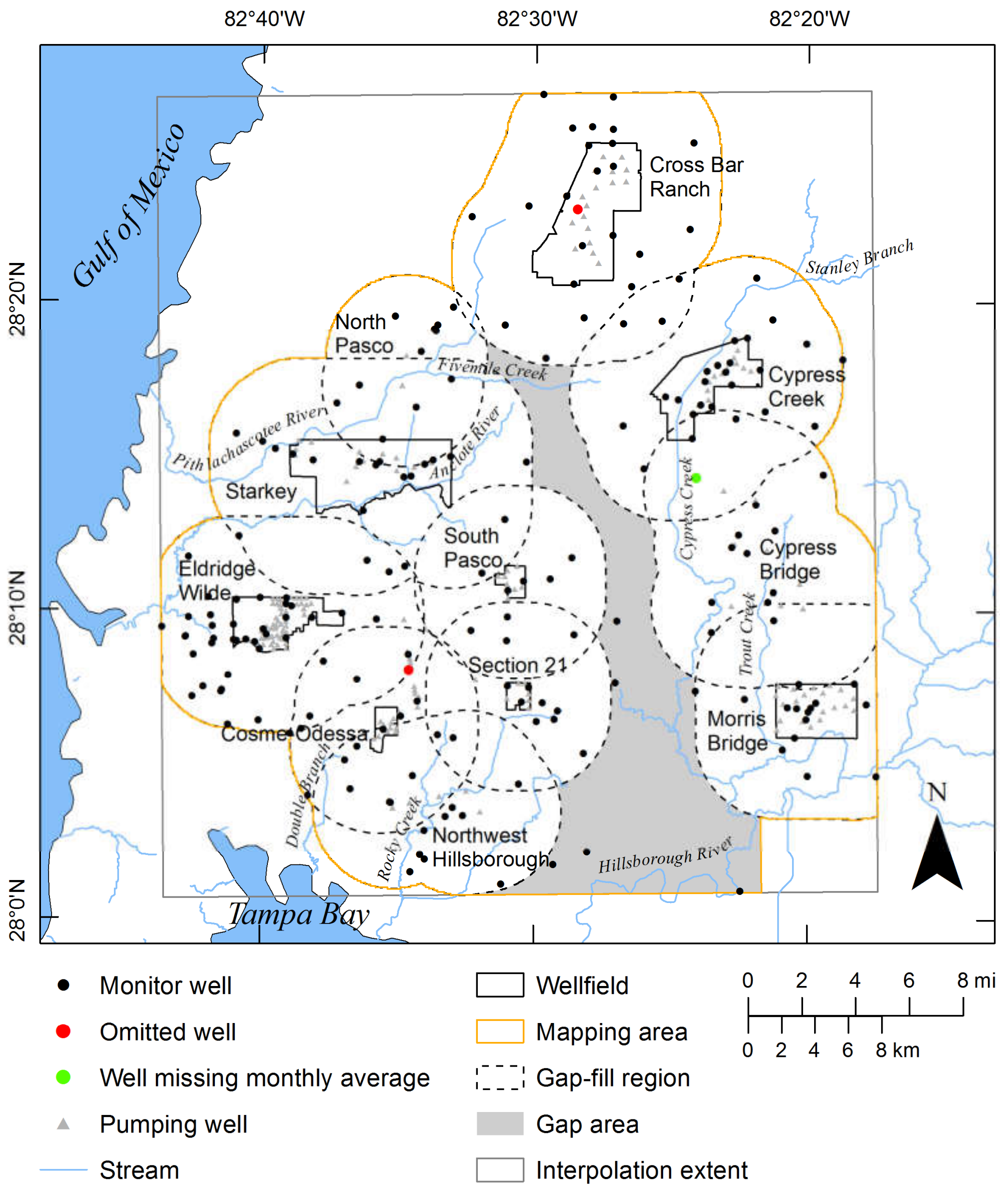


Figure 4. Location of all 197 wells used in Lee and Fouad (2014) analysis, the two wells removed (red points) leaving the 195 wells used for this analysis, regions around each wellfield (dashed lines) used to group wells for the gap-fill analysis, and the overall mapping area (gold line). Two wells that could not be gap-filled for the entire 312-month period are shown in green (CYB-CYX-1-AP and CYB-CYX-1-SUW Well Near Land O' Lakes FL).

Daily groundwater level observations were used to develop linear regression models by correlating pairs of monitoring wells in each subregion. The regression models for each well pair were ranked according to the Pearson correlation coefficient (r) of their daily observations. Wells with larger r values were ranked higher. The number of regression models used to gap-fill a given well was limited by standard error (i.e. standard deviation of model errors). Regression models with a standard error greater than 3 ft were not used for the gap-fill. Missing daily groundwater levels were gap-filled using:

$$M_{td} = \left(\beta_0 + \beta_1 O_{pd}\right)_{md} \tag{1}$$

where M is the missing groundwater level for target well t on day d, the equation to the right of the equals sign is the highest ranked regression model m with an observed groundwater level on day d, β_0 and β_1 are respectively the y-intercept and slope of the best-fit line estimated using the ordinary least squares method, and O is the observed groundwater level for predictor well p on day d. The gap-filled daily groundwater levels were converted into monthly averages at each well to map the potentiometric surface.

Geostatistical Analysis and Kriging

A geostatistical analysis was used to map the monthly average potentiometric surface. The Geostatistical Analyst extension of ArcGIS 10.4 (Esri, 2016) was used for the geostatistical analysis. Kriging was applied because it models the spatial autocorrelation (i.e. stronger relation between closer points) common in groundwater levels. The spatial autocorrelation of monthly average groundwater levels was examined without the effect of a regional trend in the potentiometric surface. The UFA drains from the Brooksville Ridge in the northeastern part of the study area towards the coast. A second-order polynomial in all directions (i.e. isotropic) fit the regional trend in a previous study of the same area (Lee and Fouad, 2014), and was used here to remove the regional trend for subsequent modeling of the spatial autocorrelation between groundwater levels. Removing the regional trend also served to increase the normality of the groundwater levels, which is necessary to calculate the standard error of the kriging.

Spatial autocorrelation was modeled using a semivariogram for each set of monthly average groundwater levels. A semivariogram was used to plot the difference of groundwater levels on the y axis as semivariance (S):

$$S(H) = \frac{1}{2}\frac{1}{N(H)}\sum_{i=1}^{N(H)}\left(Z(X_i + H) - Z(X_i)\right)^2 \tag{2}$$

where H is the distance between ordered groundwater levels in meters, $N(H)$ is the number of paired groundwater levels separated by a distance of H, and Z is the groundwater level at a particular location X for groundwater level pair i. The x axis of the semivariogram was the distance between paired groundwater levels.

The observed semivariogram was modeled using a hole effect curve. The hole effect curve fit the observed pattern of semivariance characterized by a peak and decline at larger distances. The periodicity of observed semivariance was associated with physical features, such as river valleys and wellfield draw down areas, in which groundwater levels were more similar at opposite sides of the feature. The hole effect curve served as the semivariogram model for interpolating the monthly average potentiometric surface. The standard error of the potentiometric surface was mapped using the standard deviation of semivariogram model errors.

A best-fit curve was used to model, or describe the behavior of, the semivariogram data for each month of the time series (Figure 5). A set of parameters define the best-fit curve; and thus, the semivariogram model. The parameter-optimization method of Geostatistical Analyst was used to identify parameters that minimized the cross-validation error of the model. The curve-fit parameters for each monthly semivariogram were recorded, and the resulting semivariogram models were used to generate potentiometric and standard-error surfaces from 1990-2015. All digital surfaces (raster grids) have 100-m grid cells. The minimum grid dimension is constrained by the density of the monitoring wells. Working with this constraint, spatial resolution was increased as much as possible to allow grid dimensions to approach the smaller scale of overlying surface-water features (Lee and Fouad, 2014).

The semivariogram models of this study were fit differently than the previous study to map the potentiometric surface (Lee and Fouad, 2014). The previous study initially fit the semivariogram model using the parameter-optimization method and then manually adjusted the model based on visual fit. The two methods for fitting the semivariogram model were evaluated by comparing their respective effects on the potentiometric surface. The method used in this project was also applied to the monthly-average groundwater levels published for the previous study. Using the new method, the potentiometric and standard error surfaces were generated for the 2000-2009 period and compared to the surfaces published in Lee and Fouad (2014). The difference between the monthly surfaces was evaluated by subtracting the previously published surface from the newly created surface and calculating descriptive statistics, such as the mean, of the difference between the surfaces.

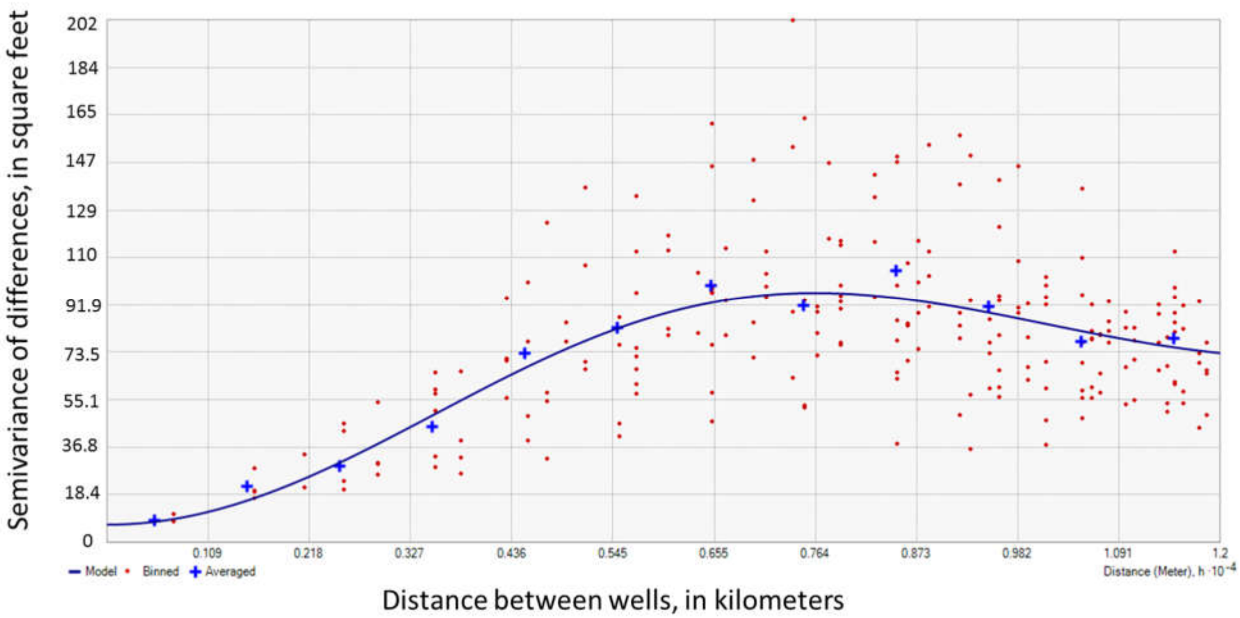


Figure 5. Empirical semivariogram showing the best-fit hole-effect curve for May 2000. (May 2000 had the poorest curve fit of the 312 months, yet still displays the characteristic periodic shape. Other months show a closer distribution of points around the best-fit curve.)

Cross-Validation Analysis

A cross validation analysis was performed to indicate the potential for the kriging to over-smooth the interpolated potentiometric-surface elevations between the monitoring-well locations. In a cross-validation analysis the inference of over-smoothing is arrived at by omitting the elevation value at a monitor well from the kriging, interpolating the potentiometric-surface elevation at that location using surrounding wells, and calculating the difference between the interpolated value and the actual value. This process was repeated for each monitoring-well for each of the 312 monthly surfaces. Summary statistics, such as the monthly mean absolute difference, were calculated to describe the difference between the interpolated values and groundwater levels during cross validation. Differences are calculated as the interpolated value minus the observed value. These differences, which may be positive or negative in value, are typically referred to as cross-validation errors.

Results

Monitoring-Well Data

The physical characteristics of the original 197 wells are summarized in Appendix 1 along with the length of the available monitoring record and the percent of daily data that are available for the period 1990-2015. The well index numbers and names in Appendix 1 are those used in Lee and Fouad (2014) (see SIR 2014-5038 Appendix 1), and so are directly referenceable to all of the maps and tables provided in the earlier report.

Two wells used in the previous analysis by Lee and Fouad (2014) were dropped from the current analysis by request from staff at the monitoring agencies (Appendix 1). Keystone Park FLDN Well (index #78) was concluded to have been completed in a confining unit above the UFA

(Michael Hancock, SWFWMD, written communication, July 2013). CBR-B-14 Well Near Masaryktown FL (index #17) was recommended to be dropped due to uncertainty in elevation datum correction (Warren Hogg, TBW, written communication, June 2016).

The number of daily water-level observations collected per month at individual monitoring wells, also called the temporal data density, varied widely across the monitoring network (Figure 6). For instance, one or several daily water-level observations could be made each month by hand in a given monitoring well (eg., monthly or biweekly). If no measurements were made in a month, because, for instance, the well did not yet exist or because of instrument failure, the number of observations could be zero. Monitoring wells with 25 to 31 daily water-level observations per month typically reflect automated, continuous daily observations. Daily water-level observations that number between these two end members (eg., 15 to 20 observations per month) likely reflect continuous daily monitoring interrupted by mechanical problems or power interruptions. Temporal data density at a given well could change over the course of the 26-year record, varying from biweekly or weekly, to daily water-level observations.

Within the monitoring network, February 1991 had the fewest daily water-level observations of any month during the 26-year period (Figure 6). Alternatively, August 2008 had the greatest number of daily water-level observations. The average number of daily observations per month at each well, for the entire 26-year period, is shown for comparison. In each case, the wells with the fewest observations were concentrated in the southwest area of the map.

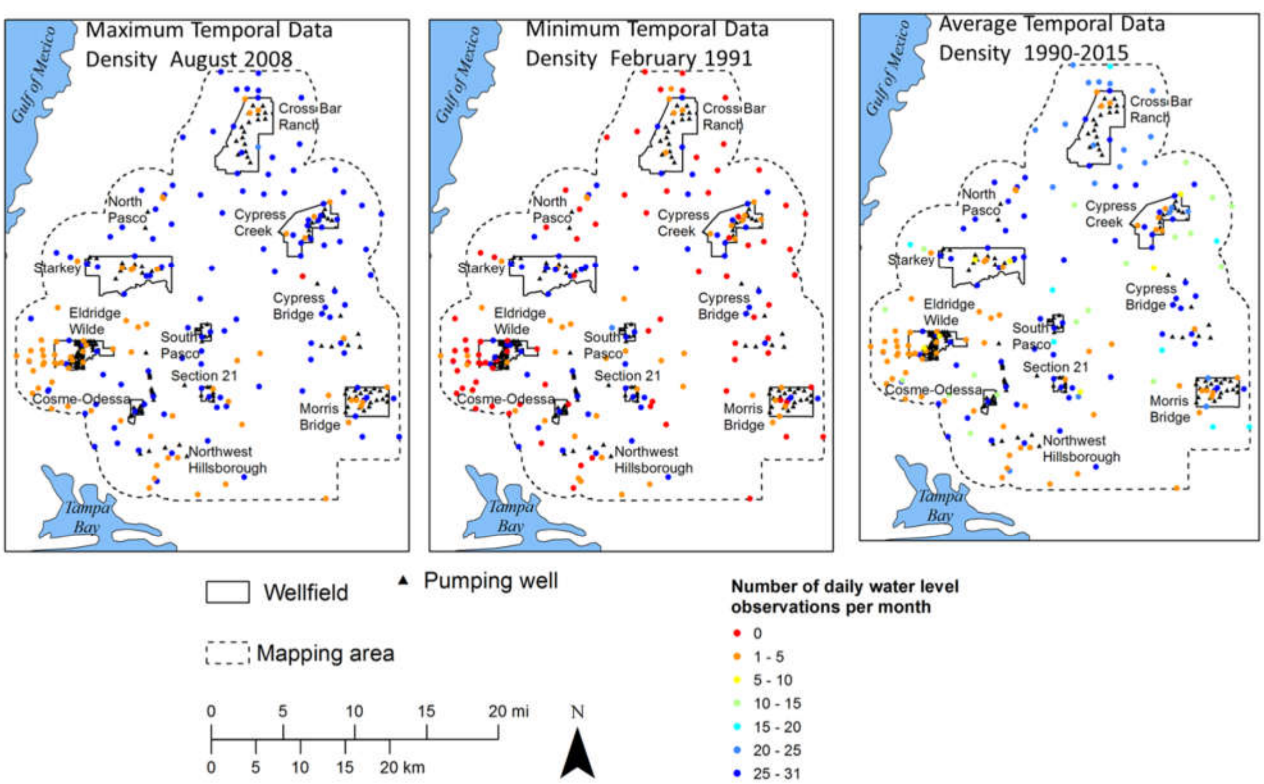
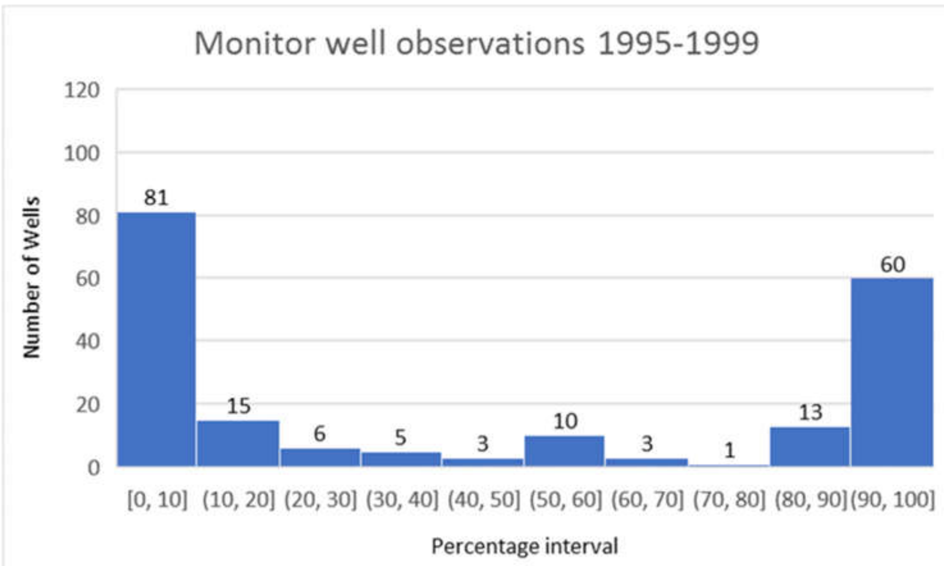


Figure 6. Number of daily water-level observations per month at groundwater monitoring wells.

Comparing the frequency of daily water-level observations during two time periods shows the marked increase in the efficiency of collecting daily values in network wells (Figure 7). Appendix 1 lists the overall percentage of daily readings available at each well for the entire mapping period (1990-2015). In addition, it shows the percent of daily observations for two 5-year periods: an early period 1995-1999, and later period 2010-2015. If water-levels are measured once to several times per month, the frequency of data collection was between 3% or 6% of the total number of days, respectively. The highest collection frequency in monitoring wells was continuous daily data (100%) (Figure 7).



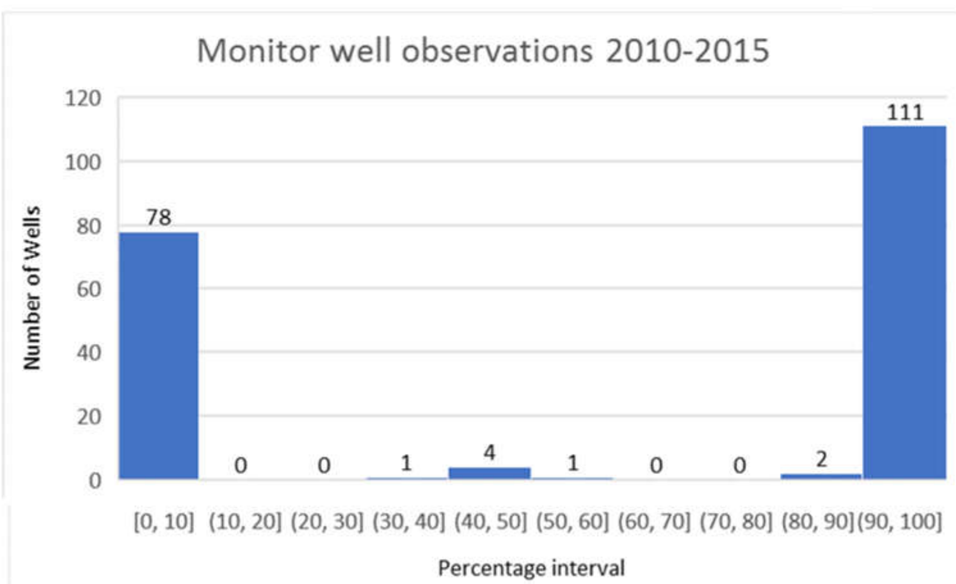


Figure 7. Histograms showing the number of monitoring wells making various frequencies of daily observations per month during two 5-year time periods: 1995-1999 and 2010-2015.

The number of monitoring wells with continuous daily observations increased markedly over the 26 years. In the early time period, (1995-1999) measurement were being made for 10 percent or less of all days (0-10% bin) at 81 monitoring wells. Only 60 wells had continuous daily data (90-100% of possible daily values per month) (Figure 7, top histogram). In contrast, 111 out of the 195 wells in the network had continuous daily measurements between 2010 and 2015 (Figure 7, bottom histogram). The number of wells with the lowest frequency of readings (0-10% bin) remained fairly steady in both periods (78 wells compared to 81).

The increasing number of daily observations through time had the effect of decreasing the percentage of daily observations in the well network that needed to be estimated (Figure 8). Nearly 65% of all daily values were estimated during 1990 and 1991, with the remaining values being measured. By 2008, less than 35% of the daily values in the network had to be estimated and roughly two-thirds of the required daily values were measured. The percentage of daily values that had to be estimated increased slightly between 2008 and 2015, but remained below 40%.

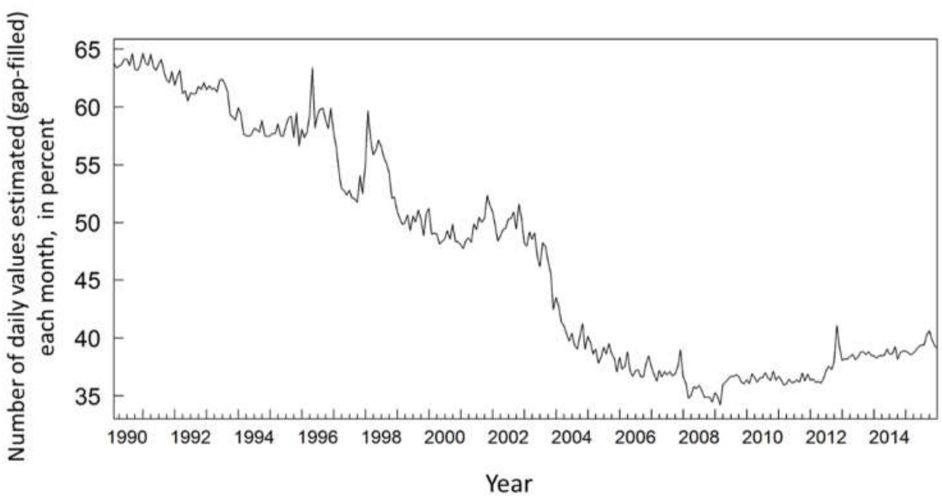


Figure 8. Percentage of all daily groundwater levels that were estimated each month.

Missing daily observations were estimated or gap-filled using linear equations derived by correlating observed groundwater levels in the subject well to observed levels in surrounding wells. The predictor wells that correlated highly with a given subject well, and the corresponding equations used to predict missing values for each subject well, are shown in Appendix 2, along with R values and standard errors of estimate.

About 94% of estimated daily values were predicted using linear equations with correlation R values of 0.85 or greater (Figure 9) and a standard error of estimate, SE, of 1.6 ft or less (Figure 10). Ninety-nine percent of the equations had R values of 0.75 or greater. The R values of the predictive equations are comparable to those reported by Lee and Fouad (2014).

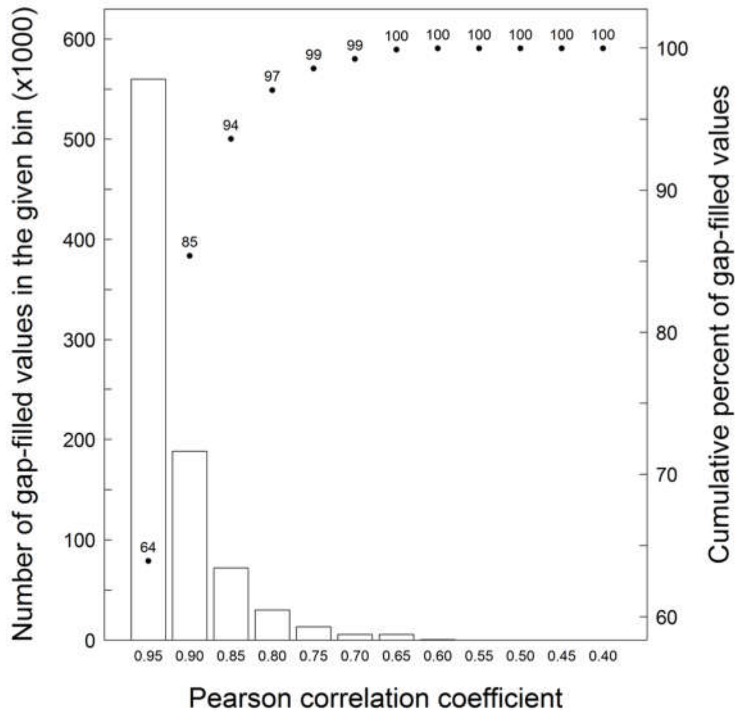


Figure 9. Histogram showing the frequency distribution of the correlation coefficients of linear equation models used to estimate missing daily values.

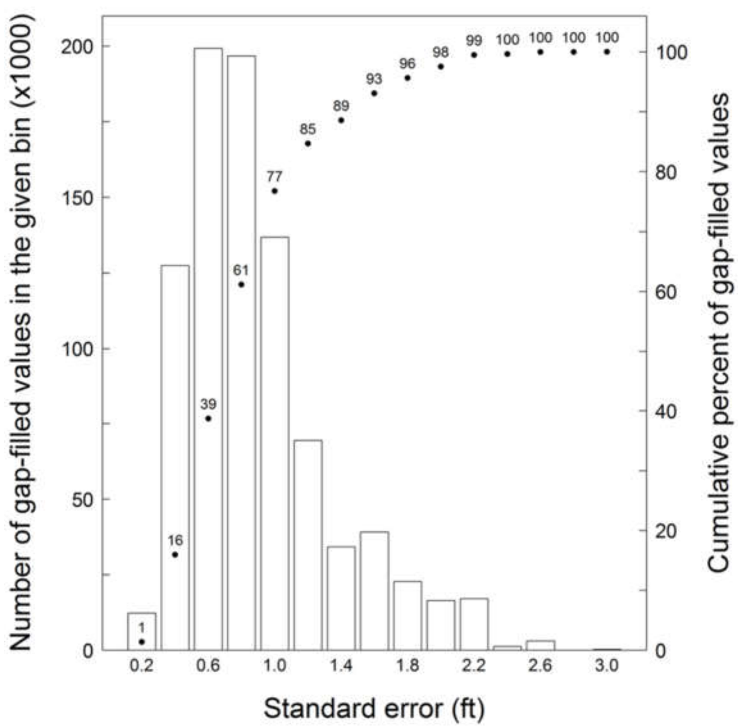


Figure 10. Histogram showing the frequency distribution of standard errors of linear equation models used to estimated missing daily values.

Estimated Daily and Monthly-Average Groundwater Levels

Gap-filling missing daily values with estimated daily values generated a continuous 26-year long daily time series for nearly all of the wells in the network. Daily values were used to generate monthly-average groundwater levels at each well for the kriging interpolation. The resulting monthly time series data allows groundwater levels to be compared across all 195 wells in the monitoring network over the 26-year long time period (Figure 11). For instance, an increasing trend in monthly groundwater elevations can be seen in selected wells in the Eldridge-Wilde and Cypress Creek wellfields. The monthly-average values at each monitoring well were used for the kriging interpolation and these data are provided in Appendix 3.

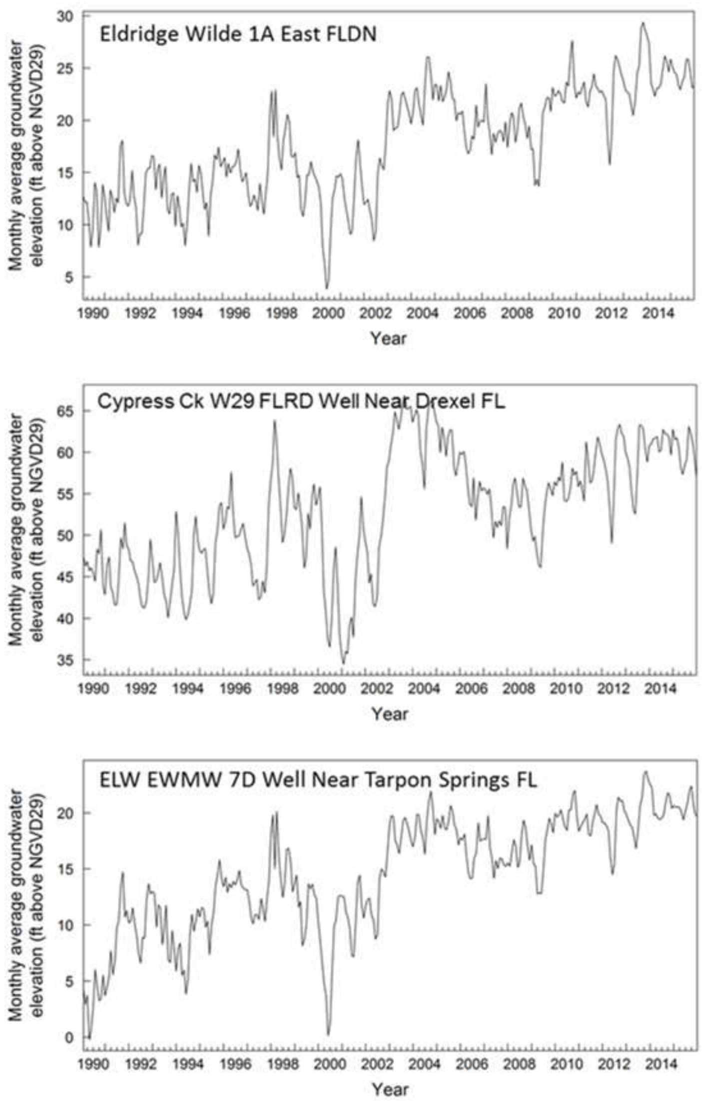


Figure 11. Hydrographs showing monthly-average groundwater levels in selected wells in the Northern Tampa Bay area between 1990 and 2015.

Only two monitoring wells in the 195-well network had missing monthly values after the gap filling. Both wells (#68 and #69) are located between Cypress Creek and Cypress Bridge wellfields: CYB-CYX-1-AP and CYB-CYX-1-SUW Well Near Land O' Lakes FL. The wells are important to the understanding of the potentiometric surface near Cypress Creek. The wells are located between the stream channel of Cypress Creek and a production well. Both wells were missing the same months and about a quarter of the total record: 71 months of the 312-month period (Appendix 3). No other wells are located nearby or as equally close to Cypress Creek.

Cross-Validation Error

Cross-validation differences or errors indicated the relative importance of various monitoring wells for accurately describing the potentiometric surface. The last column in Appendix 1 lists the mean cross-validation error at each well for the entire 312-month period. Cross-validation differences can be positive or negative. An error with a negative sign indicates the interpolated elevation at the well was below the observed elevation by the error amount. Positive errors indicate the interpolated elevation was above the monitor well's value. Appendix 1 also lists the mean of the absolute value of the monthly cross-validation errors. The identical or nearly identical *magnitude* of the mean value and mean absolute value for most wells indicates the smoothing bias at a well was consistently either positive or negative over all 312 months.

Of the 195 monitoring wells in the network, the majority of wells (108 wells) had monthly mean cross-validation errors for the 26-year period that were less than ± 2.0 ft. Of these, 17 wells had cross validation errors that were less than 0.5 ft, suggesting that the data collected at some of these wells may be redundant. Fifteen wells had cross-validation errors that were greater than ± 6 ft. These larger cross-validation errors can indicate a well with anomalous readings, or the absence of neighboring wells experiencing the same local phenomenon. The absence of neighboring wells experiencing similar groundwater elevations can reflect insufficient neighboring wells within a large area, or too few wells in a small area where water-levels differ greatly on a smaller scale, such as near cones of depression around pumping wells.

Most of the wells with cross-validation errors greater than 6 feet are located near the edge of the map where pumping stresses are low, wells are more spread out, and the wells lack surrounding wells (wells 1, 3, 5, 7, 14, 160, 165, 180, and 182) (Appendix 1, Figure 12; and see Figure 6 in Lee and Fouad (2014)). Alternatively, wells 20, 73, 82, 85, and 110 are more centrally located to well fields and close to production wells, suggesting groundwater levels in these wells document pumping effects their surrounding wells do not.

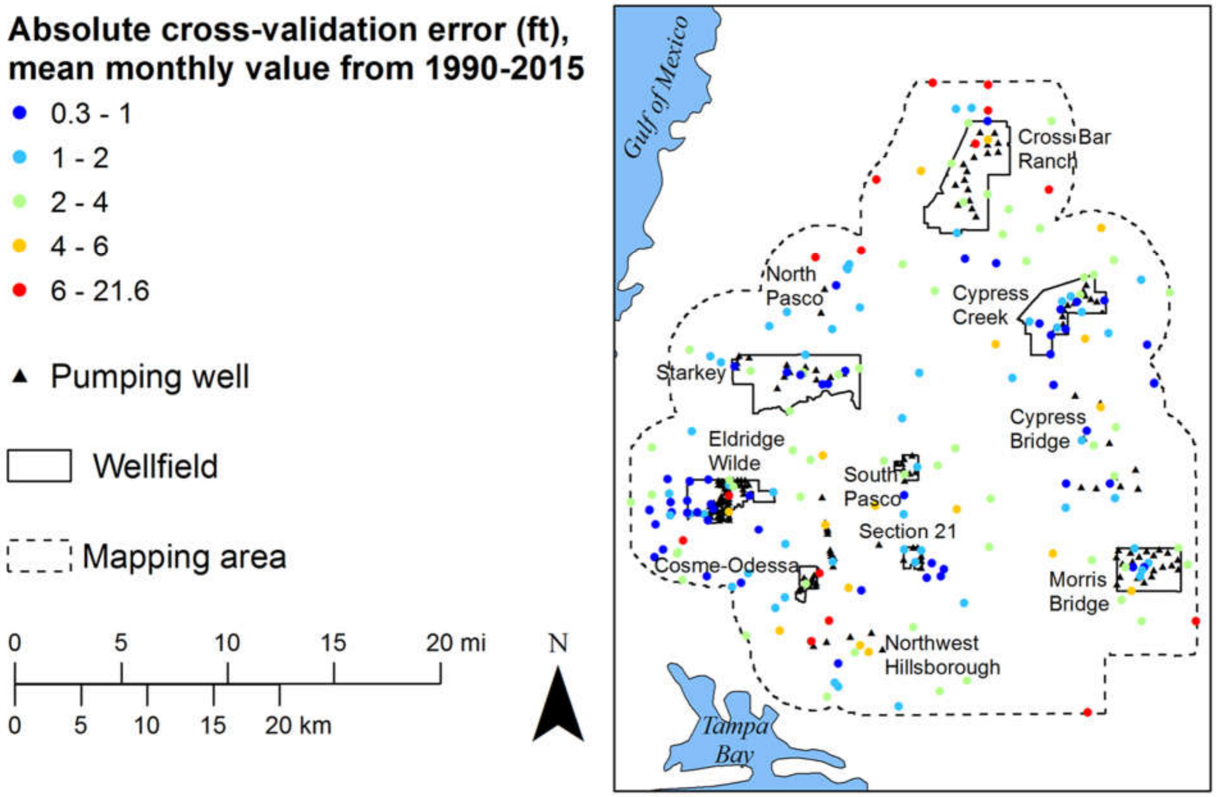


Figure 12. Monthly average cross-validation errors at the 195 monitoring wells for the period 1990-2015. (Monitoring wells ID numbers are labeled in Figure 6 in Lee and Fouad (2014) and are referenceable to Appendix 1.)

The 26-year average cross-validation errors at each well shown in Figure 12 are higher than the cross-validation errors for recent months. The 26-year average errors are also higher at some wells than the 10-year average for 2000-2009 shown in Figure 15 in Lee and Fouad (2014). This result reflects averaging errors for the longer period extending backward in time to 1990. Mean cross-validation errors in all 195 wells decreased substantially over the 26-year period (Figure 13). Mean cross-validation errors were consistently higher in the decade between 1990 and 1999 than in the years following 2003. Mean cross-validation errors decreased during 2002 and 2003, and remained consistently lower thereafter. The decrease in cross-validation error coincides with large decreases in total groundwater pumping from wellfields (Figure 13). Lee and Fouad (2014) noted a similar decline during 2002-2003 and discuss explanations for the decline.

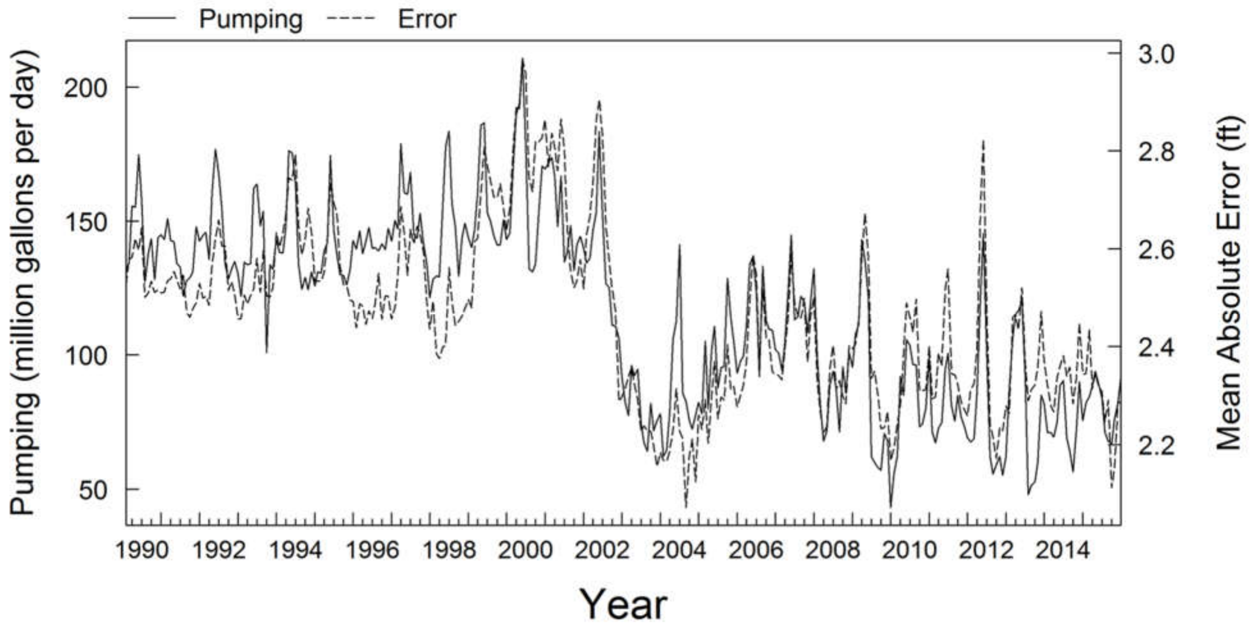


Figure 13. Correspondence between the monthly mean absolute cross-validation error and the monthly cumulative groundwater pumping from Tampa Bay Water wellfields.

Monthly-Average Potentiometric Surfaces

A mapping time series consisting of 312 gridded surfaces describes the monthly-average potentiometric surface in the Upper Floridan aquifer from January 1990 to December 2015. The mapping time series is derived by kriging interpolation of monthly average groundwater elevations at wells. Curve-fit parameters for the monthly hole-effect semivariograms used in the kriging interpolations are summarized in Appendix 4. The magnitude of the curve-fit parameters through time is shown in Figure 14. As discussed by Lee and Fouad (2014), the magnitude of the monthly partial sill and nugget declined between 2002 and 2003 (Figure 14), coincident with the timing of a large decrease in cumulative groundwater withdrawals from Tampa Bay Water wellfields (Figure 2). Following this decline, the optimized curve-fit parameters were lower and fluctuated monthly in response to wetter and drier seasonal climate and pumping conditions.

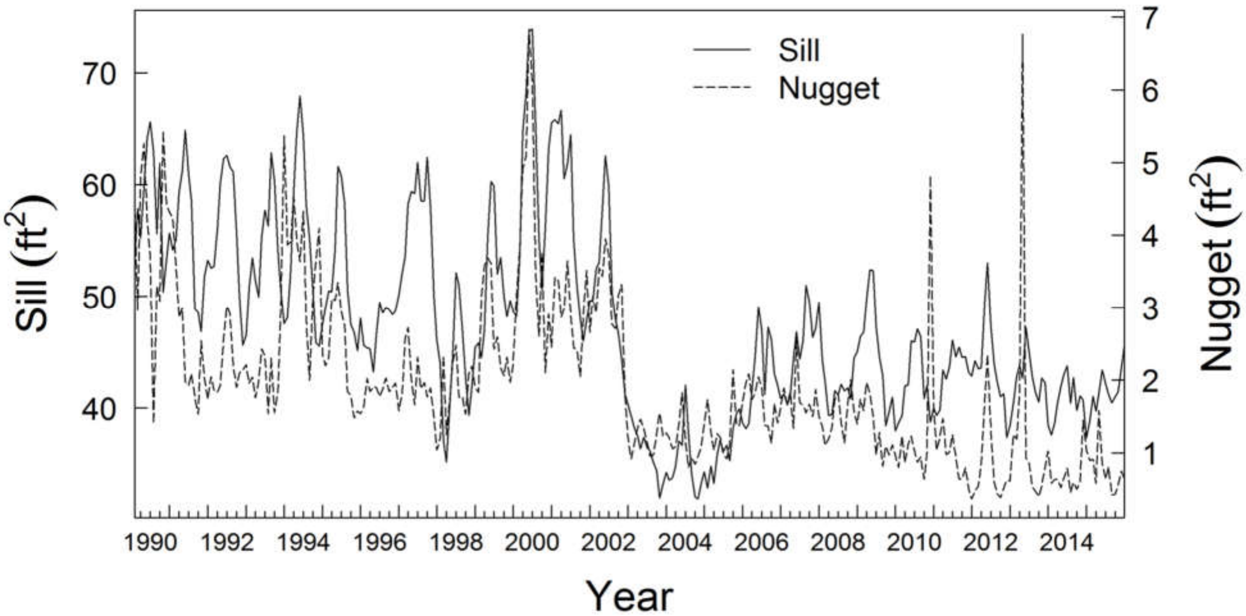


Figure 14. Partial sill and nugget values for the monthly semivariograms from January 1990 to December 2015.

The months with the minimum and maximum potentiometric-surface elevations during the 26-year mapping period are shown in Figure 15 with a 5-foot contour interval. The temporal average potentiometric-surface is shown for comparison. The highest pixel elevation to occur in the gridded potentiometric surfaces was 91.7 ft and the lowest was 0.6 ft.

When all pixel elevations in the 573 mi^2 map area are averaged, the spatially-averaged potentiometric-surface elevation was highest in September 2004 and lowest in June 2001 (Figure 16). This finding is fundamentally the same as in Lee and Fouad (2014), where September 2004 was found to have the highest spatially-averaged potentiometric surface during 2000-2009, and May 2000 to have the lowest. The historically high potentiometric surface elevation in September 2004 was the result of record-setting rainfall from hurricanes and concomitantly low wellfield pumping (USGS, 2005; Figure 2). Potentiometric-surface elevations have increased steadily since 2006 and the average surface elevation in 2015 was comparable to that in September 2004 (Figure 16). In the extended analysis, the lowest average elevation of the 26 years occurred in June 2001 compared with May 2000 in the earlier study. Both minima occur within the same drought period (Verdi and others, 2006). The potentiometric-surface elevations in these two months are similar to one another in both studies (compare Figure 16 to Figure 14 in Lee and Fouad (2014)).

The average potentiometric-surface elevation of the mapped area has increased overall since 1990 and steadily since 2006 (Figure 16). The average potentiometric-surface elevation of the collective area inside wellfield properties (50.4 mi^2) was computed separately and has increased at a rate faster than the average for the entire map area. In the 1990's the potentiometric surface elevation inside wellfield properties was around 5 feet lower than the overall map area, with some fluctuations for wet and dry seasons. Since 2010, the elevation inside wellfield properties is closer to that of the greater map area during the wet season peaks. During the dry-seasons, the seasonally-lowest elevations inside the wellfields remain lower than those of the entire mapped area, but have moved closer to in the last 3-5 years.

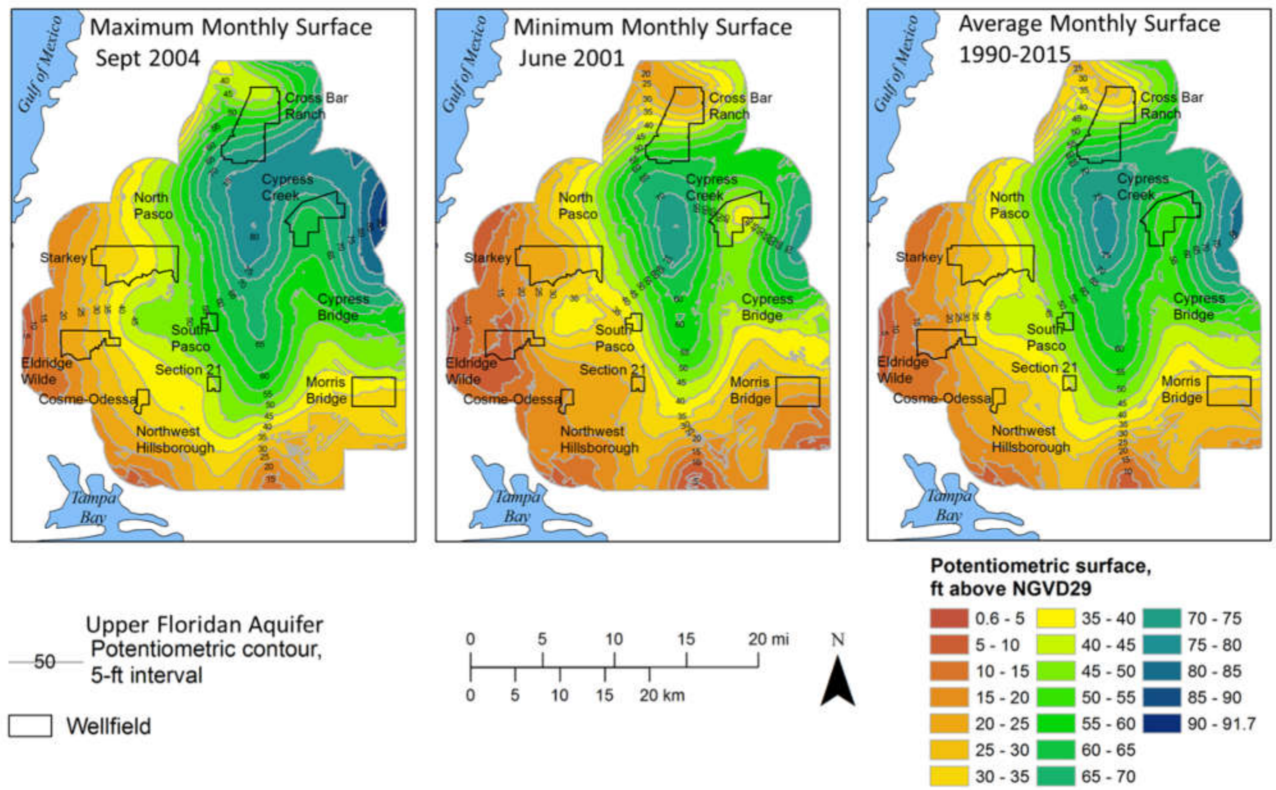


Figure 15. Monthly maximum, minimum, and average potentiometric surfaces for the period January 1990 to December 2015.

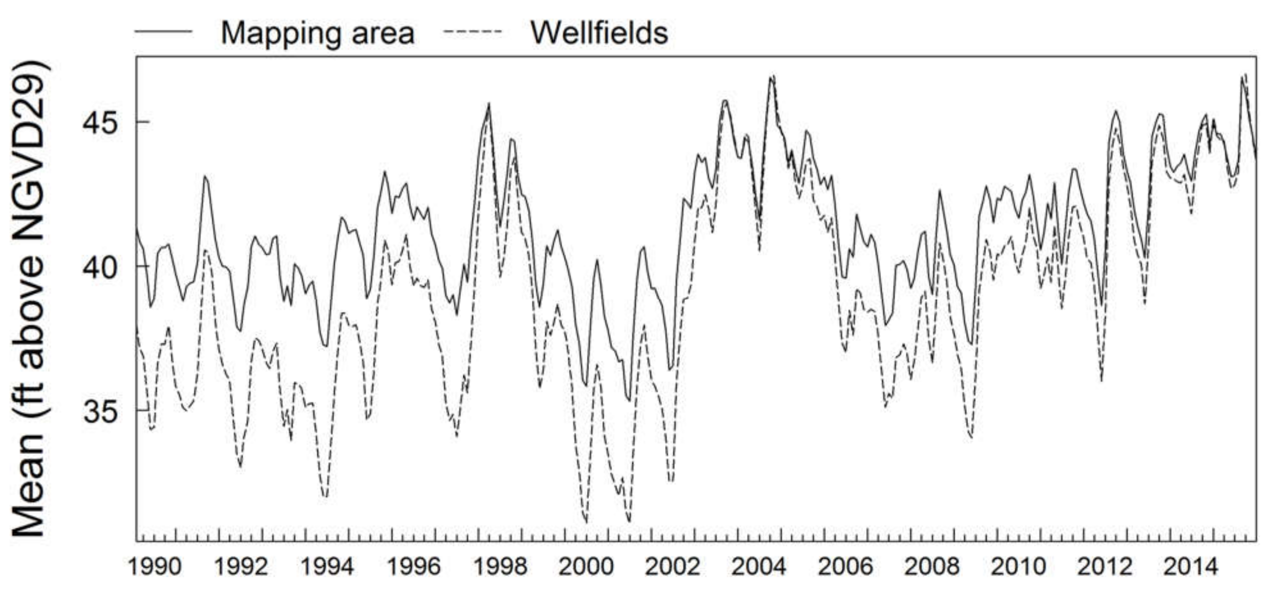


Figure 16. Spatially-averaged monthly potentiometric-surface elevations for the 573-square mile mapping area, and for the 50.4-square mile area inside wellfield property boundaries, January 1990 to December 2015.

Uncertainty in the Monthly-Average Potentiometric Surfaces

The spatial distribution of kriging standard errors provides an estimate of uncertainty in the monthly potentiometric-surface elevations. The spatially-distributed standard error varied monthly with pixel values ranging from a minimum of 0.2 ft to a maximum of 10.6 ft (Figure 17). Kriging standard errors reflects the degree of spatial variance in the monthly-average groundwater levels. In general, the greater the degree of "unevenness" in the potentiometric surface, the greater the spatial variance, and the larger the standard errors. Thus, standard errors tend to be greater for drier months with more groundwater pumping. In months when the potentiometric surface is higher and smoother, such as wetter months with less groundwater pumping, spatial variance and standard errors tend to be less.

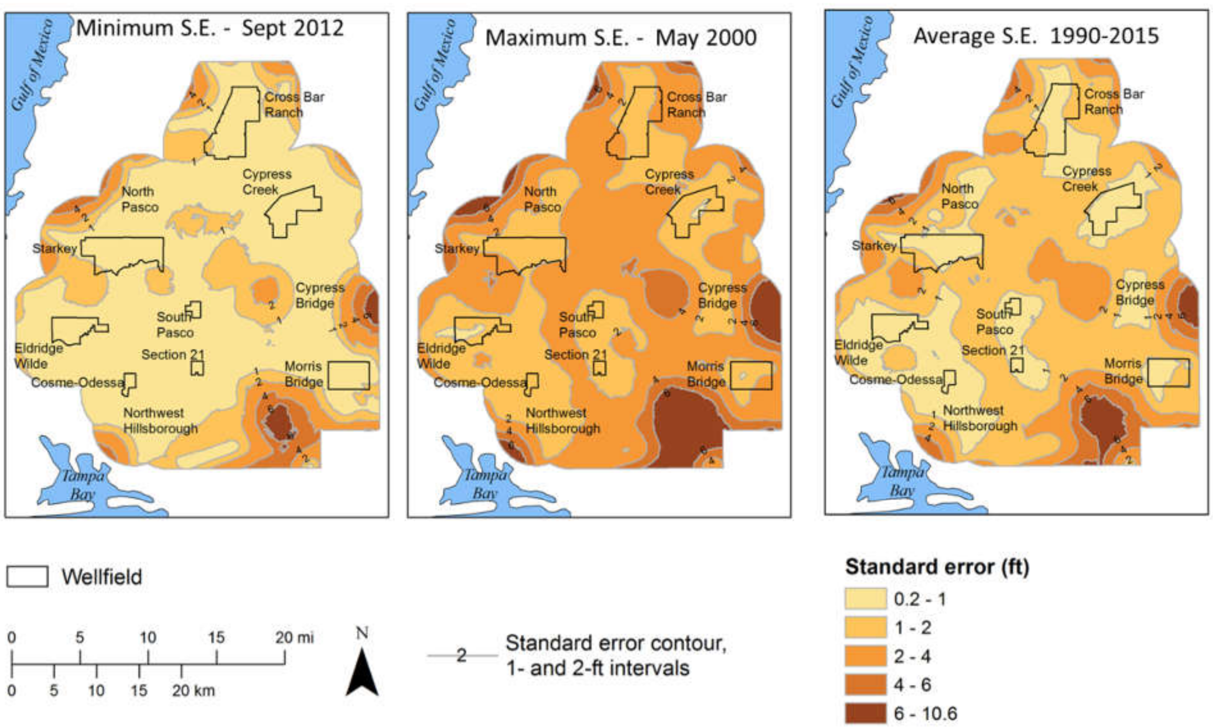


Figure 17. Monthly maximum, minimum, and average kriging standard error in the potentiometric surfaces.

The month with the maximum standard error in the potentiometric surface was May 2000, during a severe drought (Figure 17). This finding is the same as in Lee and Fouad (2014). However, the earlier study found September 2004 to have the least error in the potentiometric surface. September 2004 had exceptionally high rainfall and flooding due to an active hurricane season influenced by a strong El Nino climate condition. In the extended study, minimum errors occur in September of 2012, eight years later and under more typical climate conditions. Average kriging standard error for the map area was noticeably higher between 1990-2002 than in the period from 2003 onward (Figure 18). The average error also appears to be noticeably lower following the latest cutbacks in 2009-2010 especially during the months of the wet seasons (Figure 18).

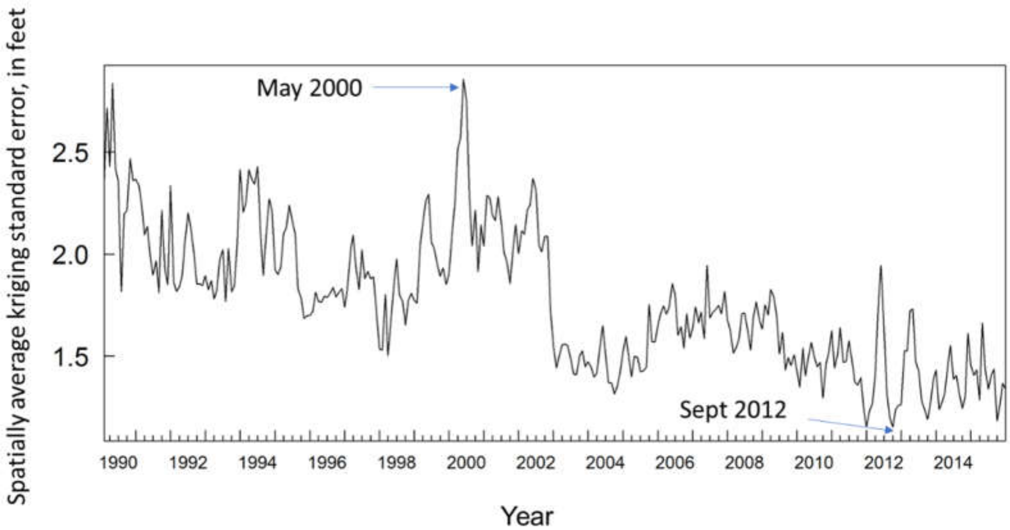


Figure 18. Spatially-averaged monthly kriging standard error for the map area, January 1990 to December 2015.

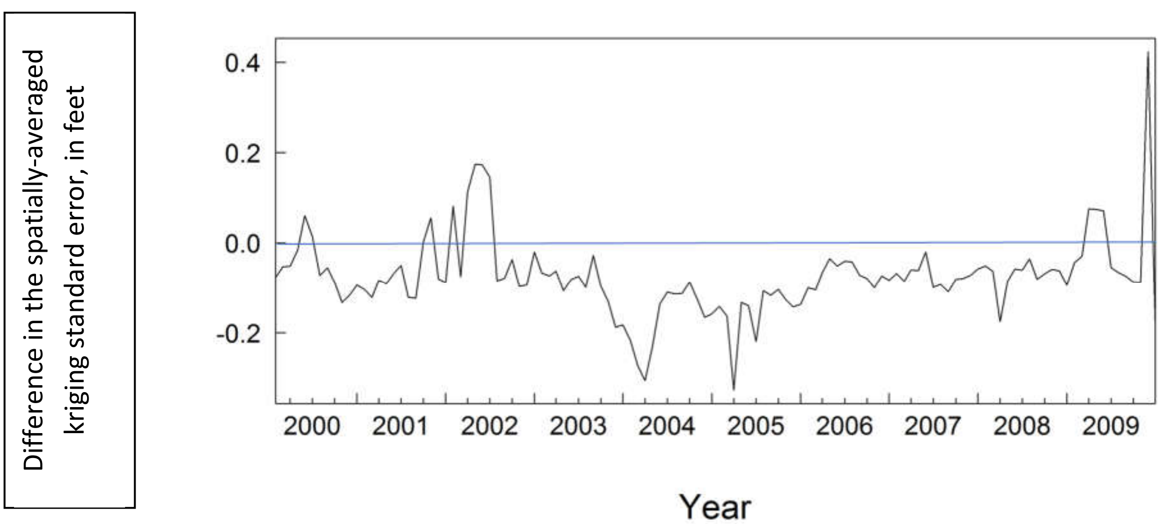


Figure 19. Difference in the spatially-averaged monthly kriging standard error in this study versus Lee and Fouad (2014) for January 2000 to December 2009.

Overall, kriging standard errors appeared to be lower using the automated optimization routine to curve-fit the semivariograms in this extended analysis compared to the manual curve-fitting used in the original analysis of Lee and Fouad (2014). Gridded standard error layers derived from the original 10-year analysis and those derived from the extended 26-year analyses for January 2000 to December 2009 were subtracted. Figure 19 shows the spatial average of this difference through time. Standard errors from the earlier method were subtracted from the new method. Thus, the mostly negative values indicate the mean standard error of estimating the potentiometric surface elevation was typically greater by 0.1-0.2 ft in the original method than for the same time period in the extended analysis. The improvement was relatively small, and in selected months a manual curve fit method may be better. However, the improvement in standard error afforded by the automated method was fairly consistent. If the results for this 10-year period are generally indicative, then the methodology used in the extended analysis is preferable to the earlier approach that relied on minor curve-fitting adjustments by eye. The process used here is consistently applied through an all automated process and optimization routine, and the values of kriging standard error are lower overall based on the 10-year comparison.

Reclipping the Mapping Time Series

The kriging analysis interpolates the potentiometric surface within a rectangular region of the Northern Tampa area. The published time series of the potentiometric surface in the Upper Floridan aquifer is a lobed-shaped area clipped from the rectangular raster grids (Figure 4). This map area was selected because it centers on the 11 wellfield properties, where the concentration of monitoring wells is densest and the kriging standard areas were smallest. The 573 mi^2 map area encompasses numerous surface-water features in the Northern Tampa Bay area, including lakes and wetlands, and parts of six stream drainage basins: Anclote River, Pithlachascotee River, Cypress Creek-Hillsborough River, Middle Hillsborough River, Rocky Creek-Sweetwater Creek, and Moccasin Creek-Double Branch. To increase the versatility of the mapping layers, the boundaries of the mapped area could be expanded to encompass selected surface-water features if the uncertainty in the added data were acceptable.

For example, Tampa Bay Water and the Southwest Florida Water Management District each have a regulatory responsibility to assess the hydrologic recovery occurring at 684 unmonitored wetlands following legally-mandated decreases in wellfield pumping (Figure 2 and Figure 20). The vast majority of the wetlands fall within the map area of the final time series. Yet, some wetlands fall just outside the northeast border of the map. Clipping the raster grids slightly beyond the current map boundary allows all 684 unmonitored wetlands to fall within the mapping time series (Figure 21). Reclipping the map area would require contacting Tampa Bay Water for the complete rectangular potentiometric surfaces at http://www.tampabaywater.org/contact-us.aspx. Areas outside of the extent provided here should be used with caution and with close attention to the standard error in the potentiometric-surface elevations.

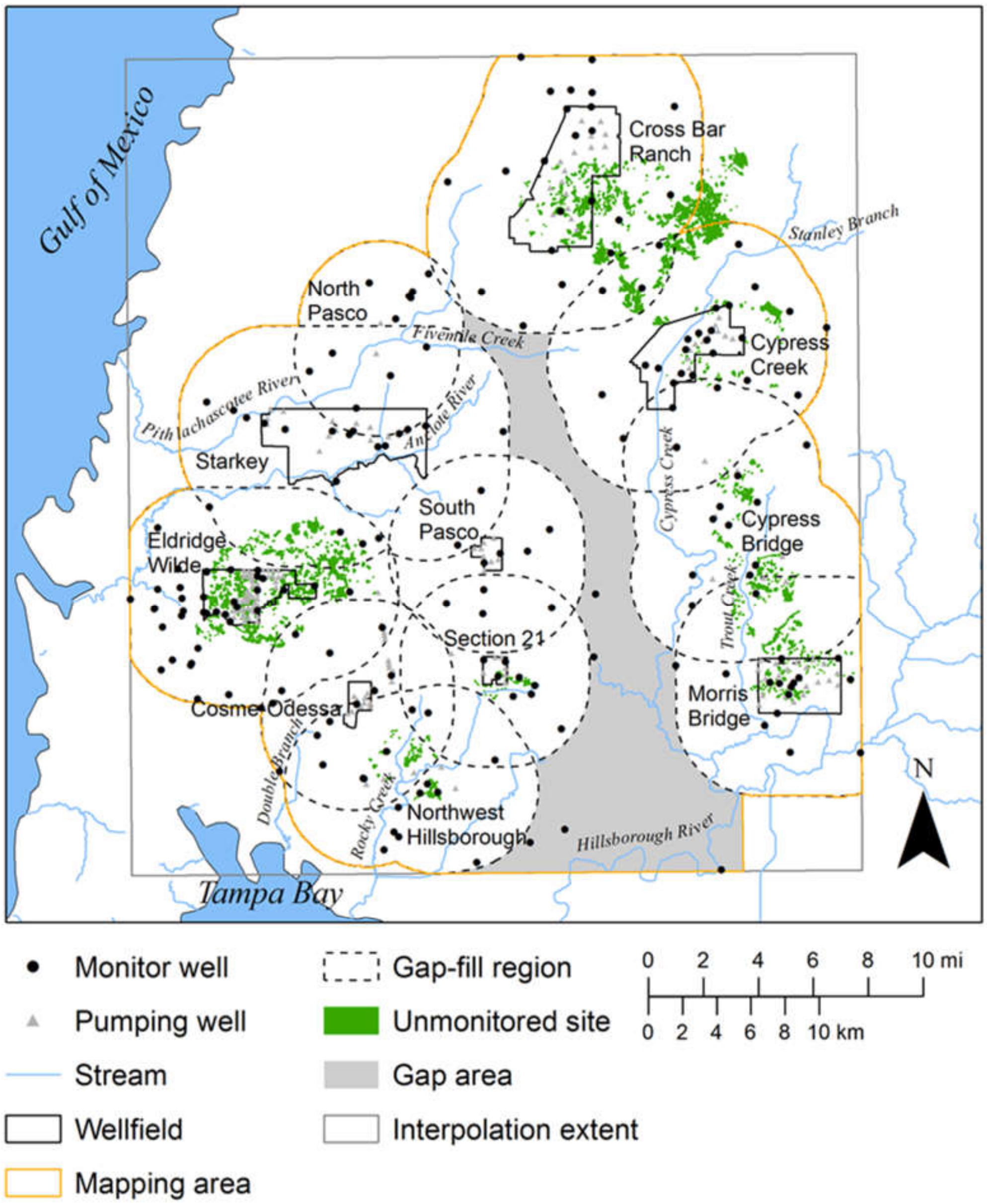


Figure 20. Location of 684 unmonitored wetlands (polygons shown in green) on the potentiometric-surface map area.

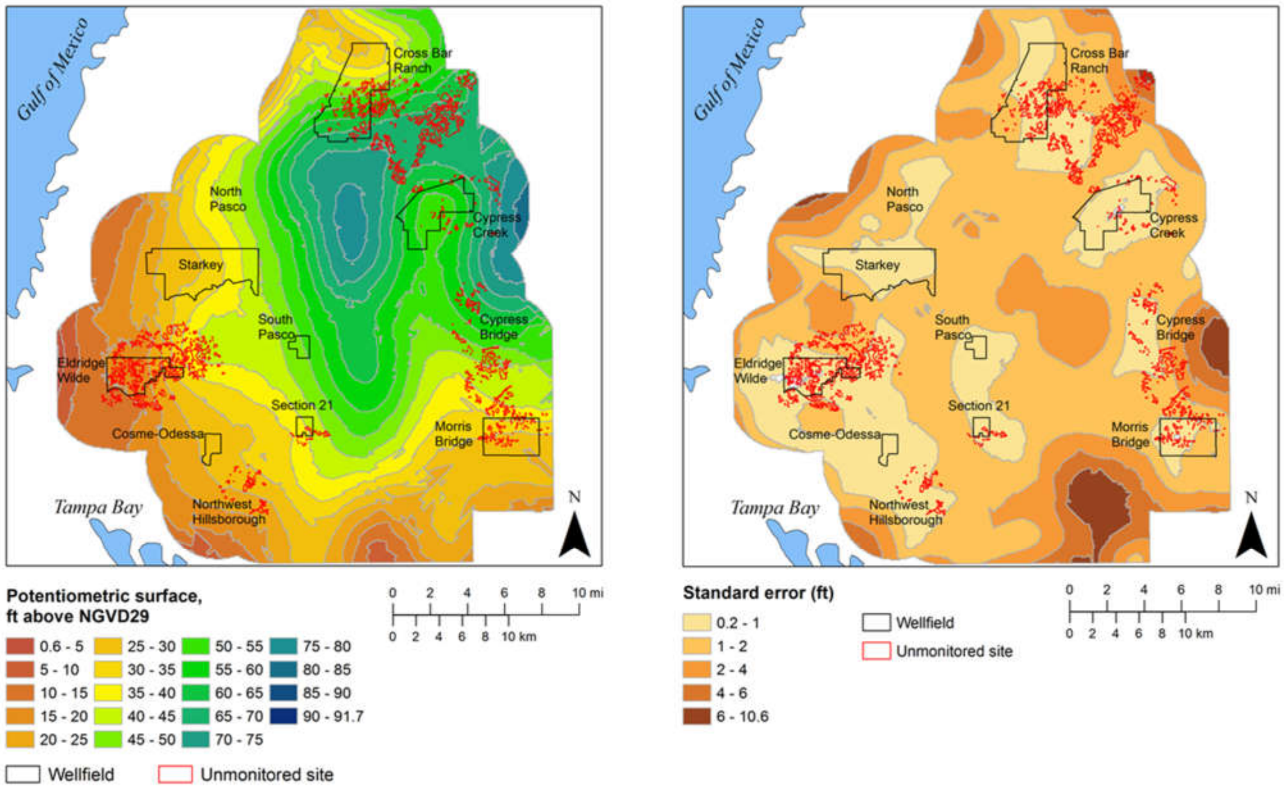


Figure 21. Unmonitored wetland polygons (in red) shown on re-clipped maps of the 26-year average potentiometric-surface and kriging standard error.

Summary

This study generated digital data layers describing the monthly potentiometric-surface elevations in the Upper Floridan aquifer in the Northern Tampa Bay area of Florida over 26-years, from 1990 to 2015. An additional time series of digital data layers quantifies the kriging standard error, or uncertainty, associated with the elevations. Because the mapping time series spans multiple decades, it can be used to analyze the effect of changing climate and wellfield operations on the region's hydrology. The highly spatially-resolved potentiometric-surface maps quantify changes in the groundwater levels of the Upper Floridan aquifer through time, and reciprocal changes in the hydrologic setting of overlying wetlands, lakes, and streams.

Study results include a summary of the available raw data for 195 monitoring wells used in this analysis, and gap-filled time series of both the monthly-average and daily potentiometric-surface elevations in each well. The interpolation methods used in this report are those of Lee and Fouad (2014) with slight modifications that are described herein. This study uses an overall similar approach to extend the available mapping time series to 26 years, from the original 10-year time series described in Lee and Fouad (2014).

This analysis and brief summary document are the work of the same two authors. Although the new analysis is completely redone, we use the conceptual groundwork provided by our earlier study. We intentionally strived to make it easy for the reader to use the results from the original

USGS report and from this new analysis in concert. For that reason, this report uses the same naming and numbering conventions to identify wells as in Lee and Fouad (2014). This allows all of the site maps and tables in the first report to extend to the current report, and makes it easy for the reader to access the in-depth discussions in Lee and Fouad (2014) on many of the topics touched upon in this extended analysis.

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