Changes in Wetland Groundwater Conditions in the Northern Tampa Bay Area from 1990 to 2015

By Terrie M. Lee[1] and Geoffrey G. Fouad[2]

Prepared for Tampa Bay Water

Suggested citation:

Lee, T.M., and Fouad, G.G., 2018, Changes in wetland groundwater conditions in the Northern Tampa Bay area from 1990 to 2015. Data products and technical report prepared for Tampa Bay Water (Clearwater, Florida) by HSW Engineering, Inc. (Tampa, Florida), 50 p.

Report and data products available at
https://www.swfwmd.state.fl.us/resources/data-maps/hydrologic-data#WGC

[1]Department of Natural Sciences, St Petersburg College, St Petersburg, Florida, *lee.terrie@spcollege.edu*
[2]Geographic Information Systems Program, Monmouth University, West Long Branch, New Jersey, *gfouad@monmouth.edu*

Prepared by HSW Engineering, Inc.

Contents

Figures

Tables

Changes in Wetland Groundwater Conditions in the Northern Tampa Bay Area from 1990 to 2015

By Terrie M. Lee and Geoffrey G. Fouad

INTRODUCTION

In Florida, protecting the ecology and hydrology of wetlands is a priority of water managers, and hundreds of freshwater wetlands are directly monitored in cooperation with federal, state, and local governmental agencies. Yet the large number of monitored wetlands is small compared to the overall wetland population, making it difficult to understand changes affecting wetlands at the landscape scale. Approximately a hundred thousand geographically isolated palustrine wetlands occur in the mid-peninsula of Florida alone. Most of these wetlands are small yet combined their area is comparable in size to the Everglades of South Florida (Haag and Lee, 2010). Their scattered geographic distribution is key to another aspect of their importance: palustrine wetlands are the headwaters to all major streams in central Florida (Ewel and Odum, 1984). The practical limits to monitoring a population of this magnitude requires that spatially-distributed hydrologic data, based on empirical measurements attributable to monitored and unmonitored wetlands alike, be used to assess the effects of groundwater withdrawals, climate, and land use on wetlands and streams in a region.

One empirical measurement that has been directly related to the hydrological and ecological status of wetlands in central Florida is the vertical hydraulic head difference driving saturated groundwater flow between the flooded wetland, shallow surficial aquifer, and deeper confined Upper Floridan aquifer (Lee et al., 2009; Metz, 2011; Lee and Fouad, 2014). In a detailed study of wetland water budgets, wetland leakage losses were directly proportional to the downward head difference, which equals the elevation difference between the wetland water surface and the potentiometric surface in the deeper Upper Floridan aquifer (Lee et al., 2009).

This vertical hydraulic head difference, which has units of length and can have an upward or downward direction, provided the basis for a surrogate metric: the elevation difference between the land-surface elevation inside the wetland and the potentiometric surface elevation in the Upper Floridan aquifer. This distance was also shown to be proportional to wetland leakage. By eliminating the requirement for standing water elevation in the wetland, and relying on the wetland land-surface elevation, a comparable time series of elevation differences can be computed for any wetland with known land-surface elevations and a nearby well recording the potentiometric elevation in the Upper Floridan aquifer, regardless of whether the wetland is monitored or unmonitored, wet or dry, cypress or marsh, augmented or impacted (Lee et al., 2009). The method has been previously applied to selected wetlands and streams in the mantled karst terrain of central Florida to provide lines of evidence of pumping impacts on wetland hydrology and vegetation, and on stream-groundwater interactions (Lee and Hughes, 2010; Metz, 2011). The following study extends the concept by developing a spatial time series of monthly groundwater conditions for a regional wetland population of 10,516 wetlands over 26 years. The results are used to quantify hydrologic changes in monitored and unmonitored wetlands before and after historic cutbacks in groundwater pumping from well fields.

Purpose and Scope

The purpose of this report is to describe changes in the groundwater conditions of a regional population of wetlands in the Northern Tampa Bay area over a 26-year period, specifically changes in their potential to generate runoff to area streams and to leak water to groundwater. The regional water supplier, Tampa Bay Water, operates 11 well fields in the study area. Approximately half-way through the 26-year period of interest, groundwater pumping from the Upper Florida aquifer by Tampa Bay Water was reduced from approximately 150 million gallons per day (mgd) to less than 90 mgd. The associated hydrologic response of wetlands in the region is interpreted by using the time series of groundwater conditions calculated in two principal populations of wetlands. The first population is 10,516 freshwater palustrine wetlands mapped in the study area as part of the National Wetlands Inventory. The second population is 1,092 wetlands that are of specific concern to Tampa Bay Water, and to the Southwest Florida Water Management District, the State environmental regulatory agency that permits water use.

This report defines a variable called wetland groundwater condition and applies it to quantify two aspects of the hydrologic condition of individual wetlands. The first result is binary. Wetland groundwater conditions are divided into one of two types, either a discharging groundwater condition or a recharging groundwater condition. The second result breaks recharging groundwater conditions into categories and ranks them for their potential to cause wetland leakage. These two results conveying wetland groundwater condition – groundwater discharge or recharge and ranked recharge – are calculated for 26 years (1990 to 2015) in more than 10,000 individual wetlands in the Northern Tampa Bay area. The values provide standardized, census data of groundwater conditions for two large wetland populations over time. Groundwater conditions are also color-coded and mapped to describe spatial changes.

Population statistics for the groundwater conditions in the National Wetlands Inventory wetlands are compared to those for the Tampa Bay Water wetlands. Then the conditions in various subpopulations within these two populations are compared, for instance the groundwater conditions of wetlands inside well fields are compared to groundwater conditions in wetlands outside of well fields. Statistics describing groundwater conditions are examined throughout the 26-year period, focusing on changes in the annual average conditions, and the seasonal conditions in May and September. Population statistics are also compared for the 13 years (1990-2002) prior to large cutbacks in groundwater pumping from municipal well fields and the 13 years after cutbacks (2003-2015). Pre- and post-cutback results are then contrasted with "predevelopment" groundwater conditions, i.e. average wetland groundwater conditions estimated to occur in the complete absence of groundwater pumping. Finally, temporal trends in wetland groundwater conditions are analyzed before and after cutbacks after first detrending the data for correlation to rainfall. Before the analysis of wetland groundwater conditions begins, an analysis is made of the uncertainty associated with using LiDAR data to describe land-surface elevations in wetlands.

Background

The Northern Tampa Bay area extends about 30 miles north of metropolitan Tampa and about 20 miles onshore of the Gulf of Mexico (Figure 1). In this low-lying terrain comprised mostly of the Western Valley and Gulf Coastal Lowlands physiographic regions (White, 1970), palustrine wetlands make up over 25 percent of the land area. In the mantled karst geologic setting, the transmissive carbonate formations of the Upper Floridan aquifer are overlain by a thin, semi-confining clay layer and topped by permeable sands and clayey sands (Sinclair et al., 1985). Groundwater from the Upper Floridan aquifer discharges upward along the coastline into spring fed rivers that flow into the Gulf of Mexico in Pasco and Hernando Counties. Farther inland springs such as Crystal Springs and Sulphur Springs discharge groundwater from the Upper Floridan aquifer into the Hillsborough River which flows into Tampa Bay.

Groundwater flows upward between the Upper Floridan aquifer and the surficial aquifer wherever the potentiometric-surface elevation in the semi-confined Upper Floridan aquifer is above the elevation of the water table in the surficial aquifer, or more conservatively, where it is above the land-surface elevation (Figure 2). While the rate of upward discharge into the surficial aquifer may be slow where the clays of the semi-confining unit are intact, the upward flow direction prevents water in wetlands and streams from leaking downward. The combined effect is to increase the potential for streams and other surface water features to gain groundwater, and to increase the potential for shallow palustrine wetlands to store runoff and overflow to streams (Lee and Hughes, 2010). Like capillaries in the human circulatory system, small palustrine wetlands, and the network of channels that connect them together, bring runoff from the outermost extent of the drainage basin back to the major arteries of rivers and streams.

Alternately, recharging groundwater conditions occur when the potentiometric surface in the Upper Floridan aquifer is below the water table in the surficial aquifer and the stage of wetlands, lakes, and streams. With recharging conditions, groundwater in the surficial aquifer, and water in surface-water features, flows vertically downward toward the Upper Floridan aquifer. Lowering the potentiometric-surface elevation in the Upper Floridan aquifer by pumping groundwater increases the downward head difference and speeds the downward flow rate, increasing leakage losses from wetlands and reducing inundation. Thus, in the permeable karst terrain of central Florida, palustrine wetlands persist where they achieve a balance between the extent and duration of discharging and recharging groundwater conditions seasonally, annually, and over the long-term.

Recharging and discharging groundwater conditions are described for two wetland populations (Figures 3 and 4). The first population is the 10,516 freshwater palustrine wetlands from the National Wetlands Inventory (US Fish and Wildlife Service, 2017) that fall inside the mapping area shown in Figure 1. They are largely unmonitored and include forested and marsh type wetlands, not riverine wetlands or lakes. The second wetland population is the 1,092 freshwater wetlands of regulatory interest to Tampa Bay Water. Of these wetlands, 410 have monitoring data describing vegetation, water levels, or both, and 305 of the wetlands have had ground-level surveys to obtain a land-surface elevation inside the wetland (Figure 4). To comply with their regulatory permits, Tampa Bay Water requires empirically-based evidence to argue the degree of hydrologic recovery that has occurred at unmonitored wetlands in and around its well fields following cutbacks in groundwater pumping. The large unmonitored population is represented in this study by the National Wetlands Inventory wetland population.

Prior to legally mandated cutbacks in well field pumping that started in 2003 (Interlocal Agreement, 1998, p. 75), the cumulative groundwater withdrawal rate from the 11 well fields in the Northern Tampa Bay area averaged about 150 mgd between 1990 and 2002 (Figure 5). After the cutbacks, the average withdrawal rate decreased to below 90 mgd. The effects of the regional pumping and climate on potentiometric-surface elevations in the Upper Floridan aquifer

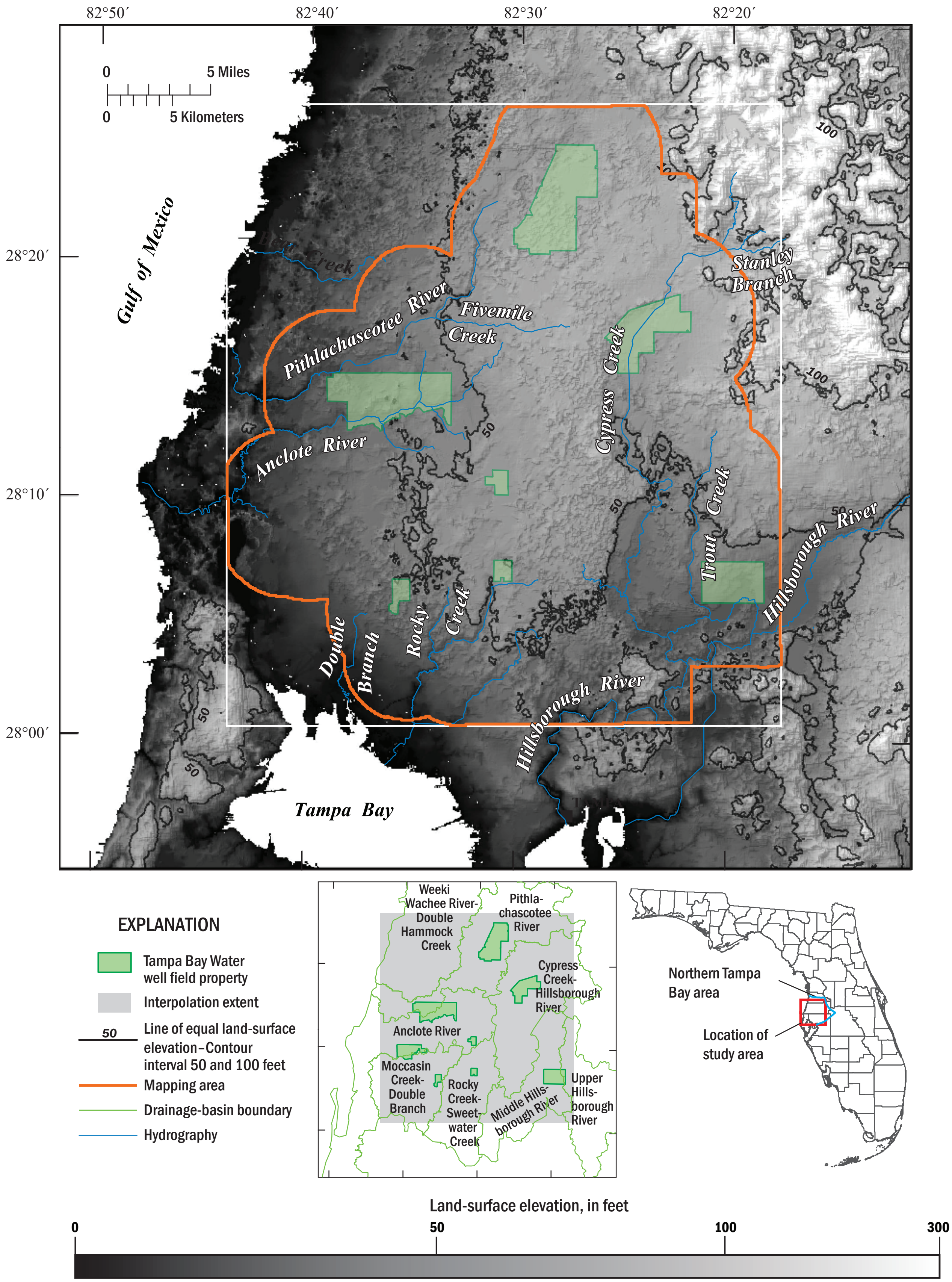


Figure 1. Terrain in the Northern Tampa Bay area showing the study area, streams, US Geological Survey stream drainage-basin boundaries, and Tampa Bay Water well field properties.

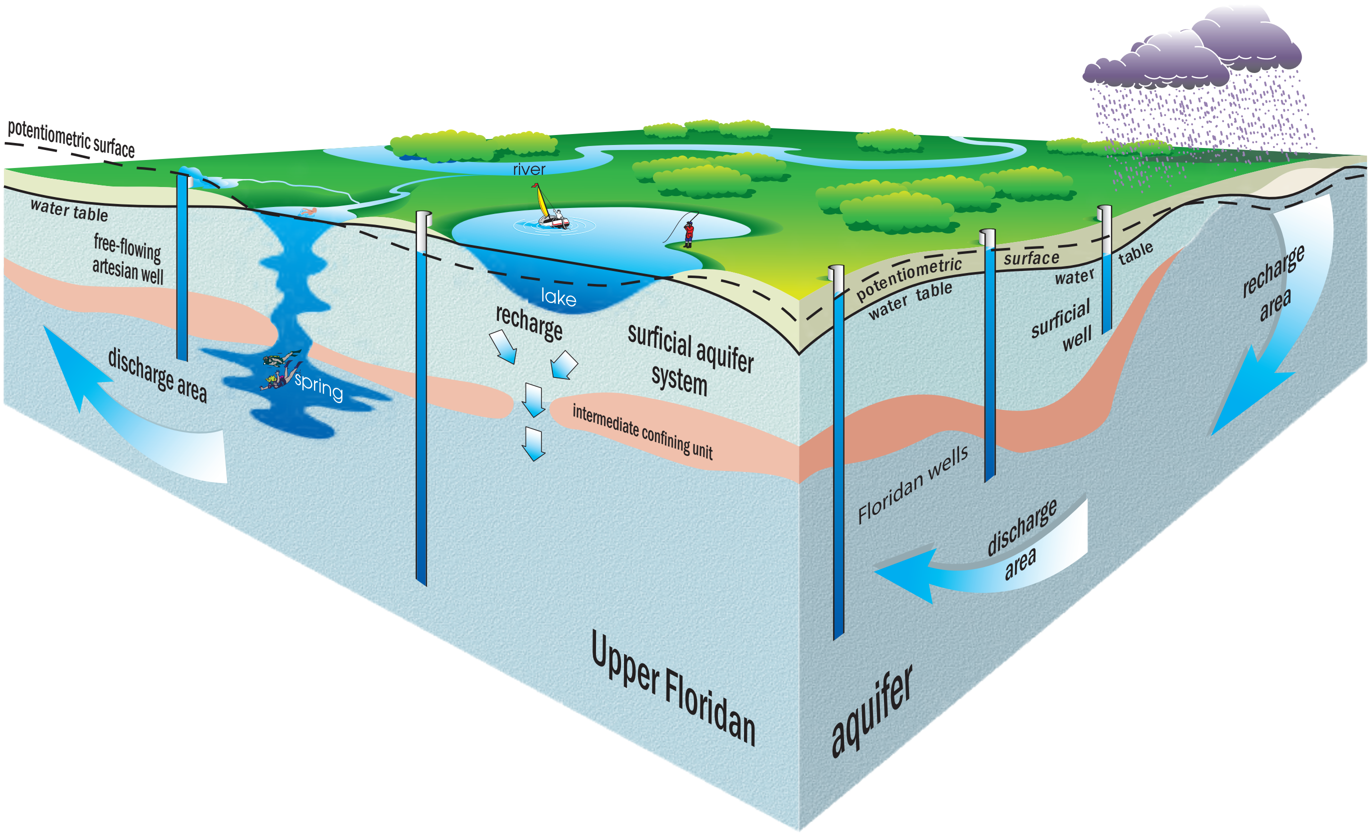


Figure 2. Conceptual drawing showing relative positions of the water table in the surficial aquifer and the potentiometric surface in the Upper Floridan aquifer and the associated vertical flow direction (modified from and used courtesy of the St Johns River Water Management District, Palatka, Florida).

is recorded by Tampa Bay Water and regulatory agency, Southwest Florida Water Management District, using more than 260 monitoring wells. This study relies on previously published mapping products based on the groundwater levels in these wells to describe the monthly average elevation of the potentiometric surface of the Upper Floridan aquifer in the area (Lee and Fouad, 2014; Lee and Fouad, 2017).

Changes in rainfall, combined with changes in pumping, influence wetland groundwater conditions. Rainfall in the mapping area was tracked using 1-km Daymet grids (Thornton et al., 2018) with monthly totals weighted based on area (Figure 6). The plot of 12-month moving rainfall totals (green line) illustrates large departures from average annual rainfall over the study time period (dashed line) and a possible upward trend since 2009. The major departures from the average may be attributed to large-scale climate patterns associated with the El Niño-Southern Oscillation (ENSO). ENSO can result in El Niño (wet) and La Niña (dry) conditions in Florida (Schmidt et al., 2001). These conditions may have an interannual influence on rainfall as in the El Niño (wet) conditions of 1998, followed sharply by the La Niña (dry) conditions of 1999 and 2000 (Wolter and Timlin, 2011).

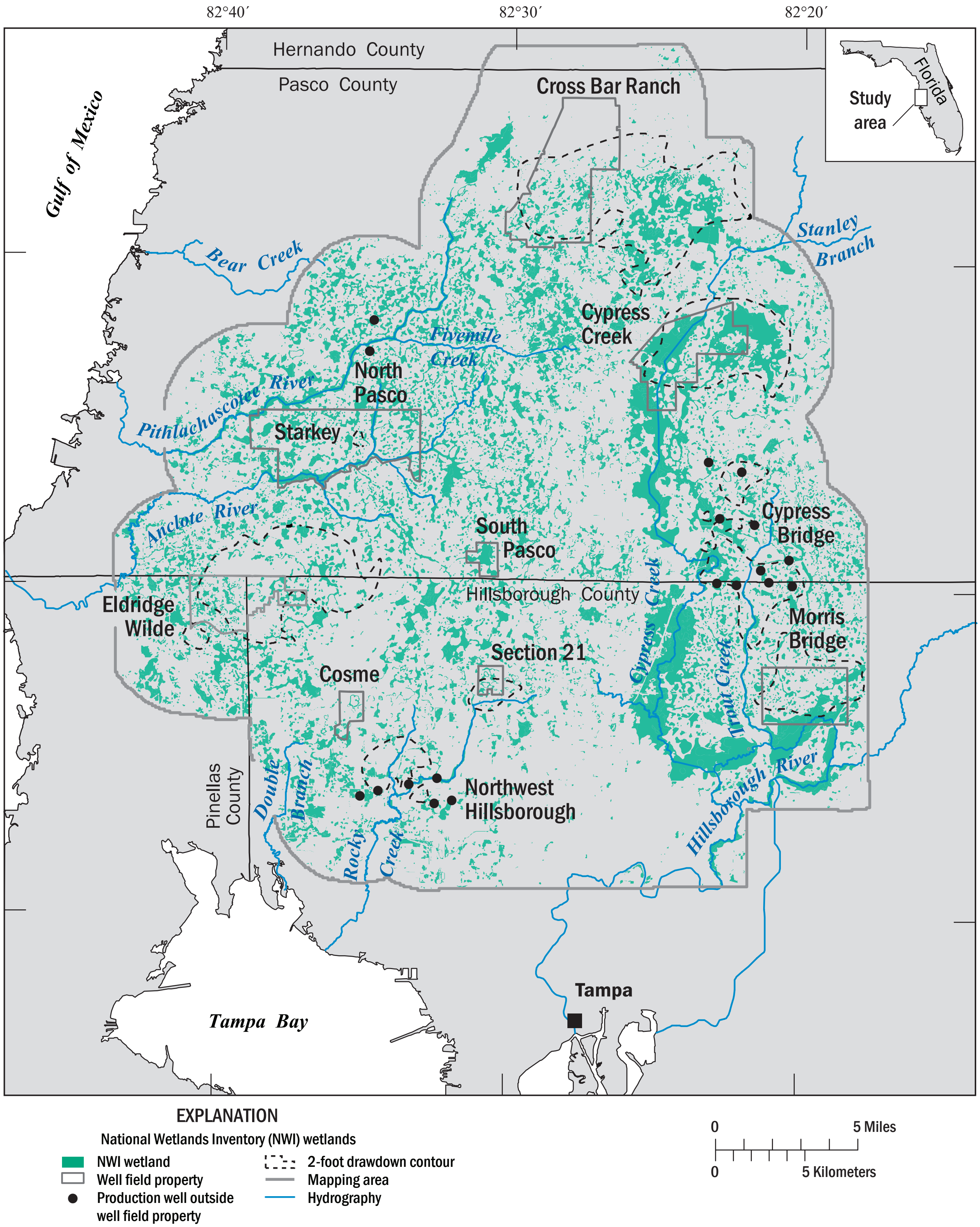


Figure 3. Study area showing the location of 10,516 freshwater palustrine wetlands from the National Wetlands Inventory.

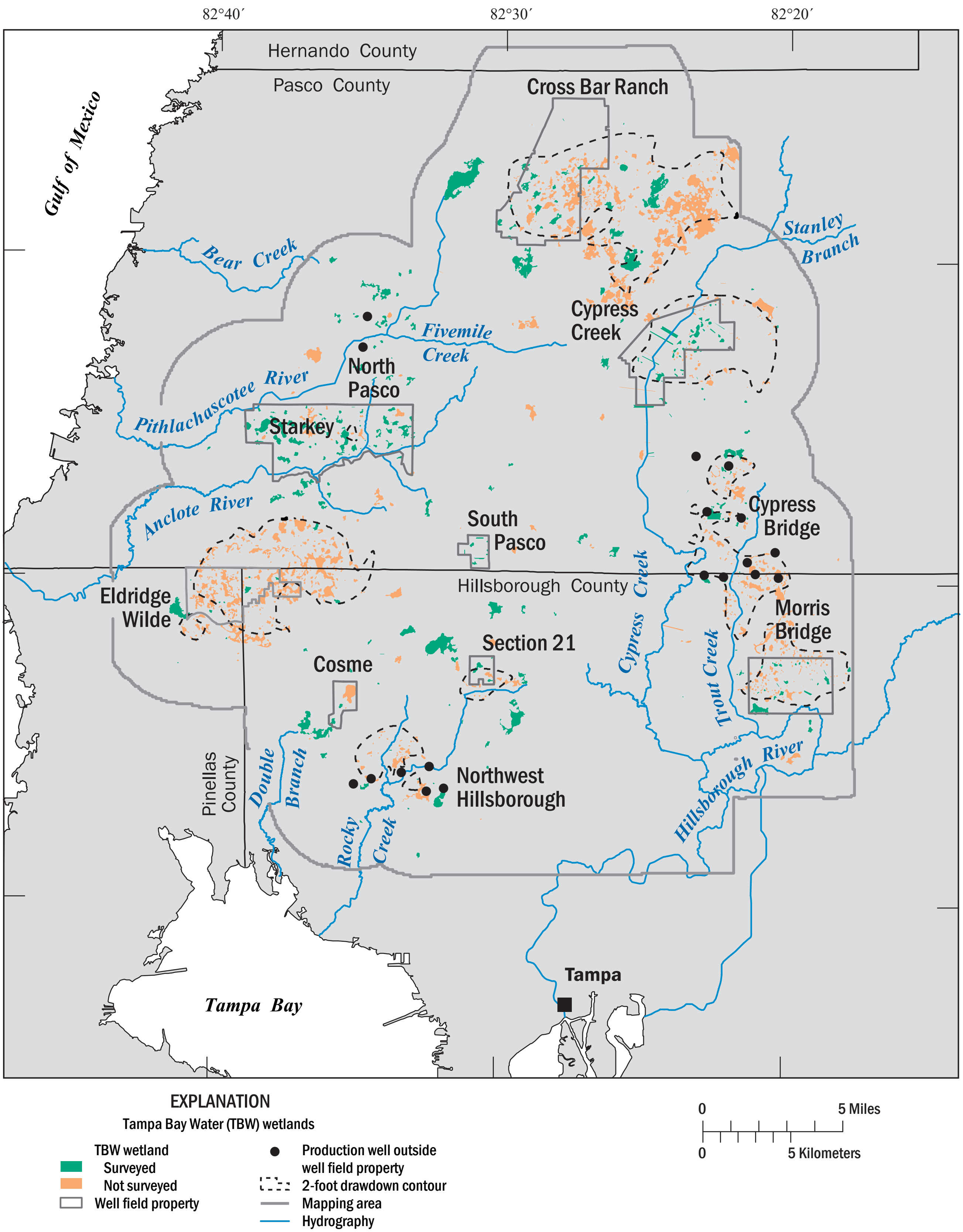


Figure 4. Study area showing the location of 1,092 freshwater wetlands and lakes in a Tampa Bay Water database. Land-surface elevations are surveyed inside 305 of the wetlands.

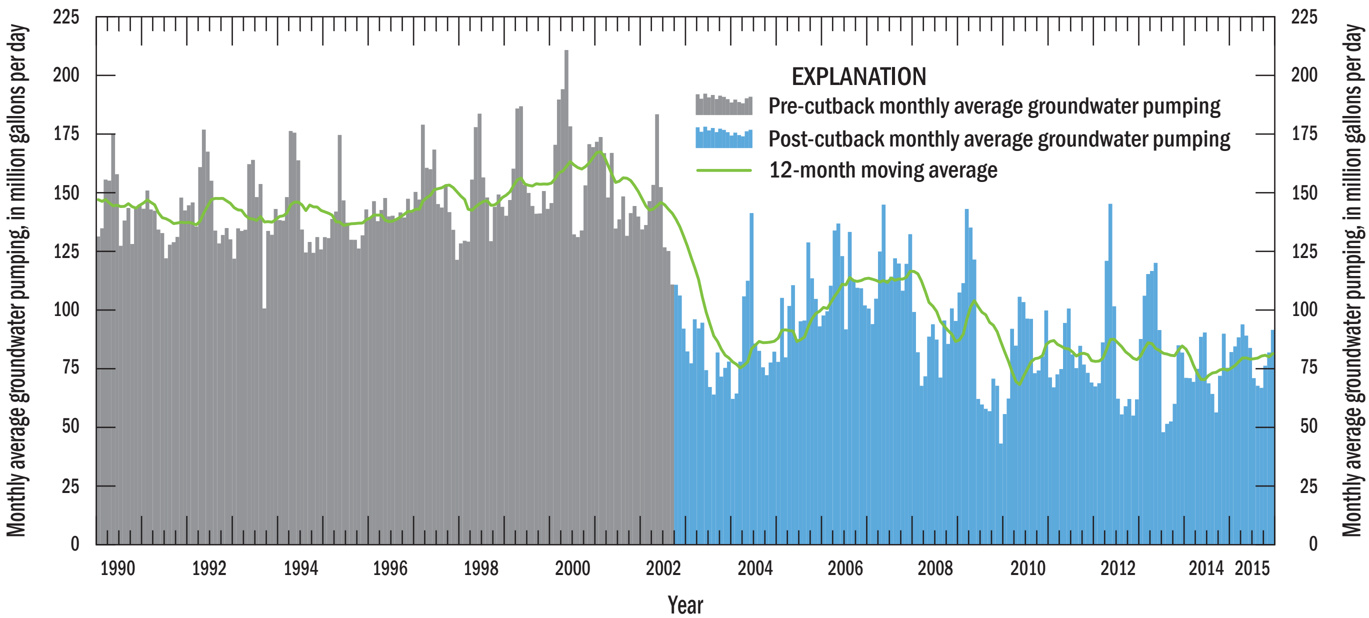


Figure 5. Cumulative monthly groundwater pumping rate at 11 Tampa Bay Water well fields in the Northern Tampa Bay area between 1990 and 2015.

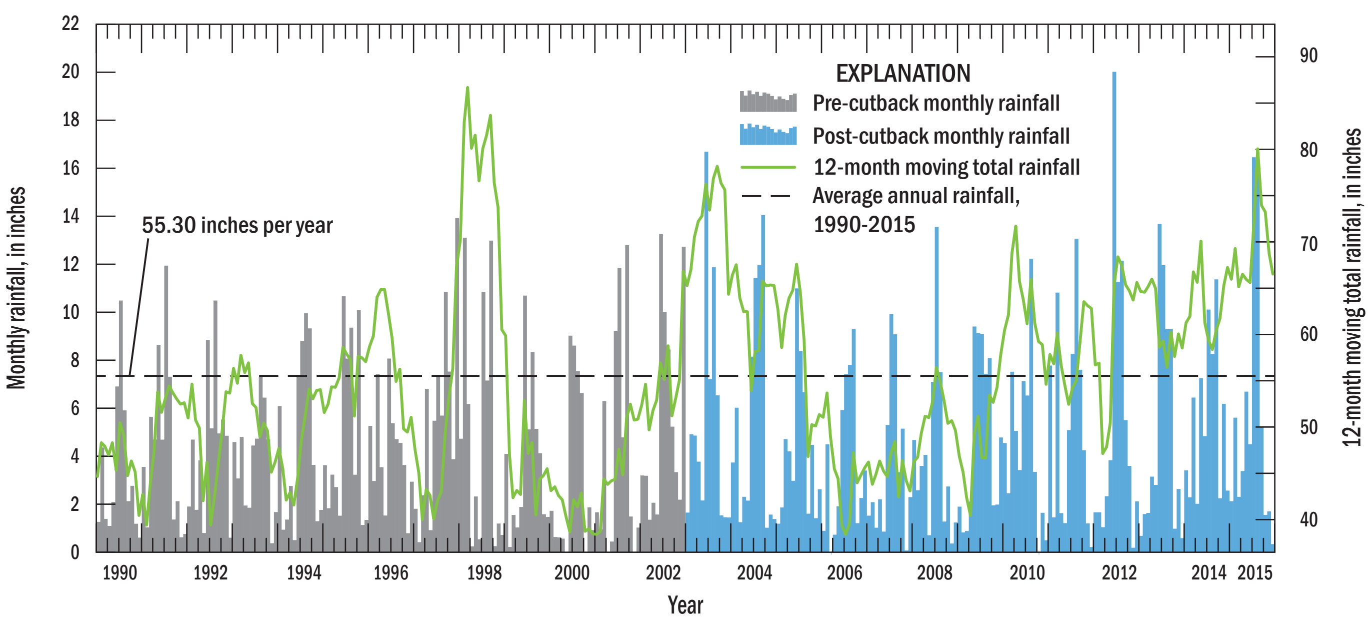


Figure 6. Monthly rainfall over the mapped area based on area-weighted totals from gridded Daymet climatological data.

METHODS

Assessing Regional Groundwater Conditions

Regional groundwater conditions were mapped as a preliminary step to assess groundwater conditions at individual wetlands. A 26-year time series of the Upper Floridan aquifer potentiometric surface (Lee and Fouad, 2017) was used to map monthly groundwater conditions for a 581-mi^2 area covering 11 well fields and parts of six regionally important stream drainage basins (Figure 1). Monthly groundwater conditions were mapped as follows:

$$G_m = P_m - L \qquad (1)$$

where P is the potentiometric surface in month m and L is the land surface based on LiDAR elevation data acquired from the Southwest Florida Water Management District. The resulting difference surface equaled groundwater conditions G in units of feet above or below land surface.

The LiDAR land-surface elevation data were provided in feet above (or below) the North American Vertical Datum of 1988 (NAVD 88). Potentiometric-surface elevations referenced the National Geodetic Vertical Datum of 1929 (NGVD 29). Land-surface elevations were converted to NGVD 29 using the National Geodetic Survey's VERTCON v2.1 grid (*https://www.ngs.noaa.gov/PC_PROD/VERTCON/*) as follows: NAVD 88 LiDAR – VERTCON = NGVD 29 LiDAR. The conversion grid had a root-mean-square error of 2 cm at 381,833 ground control points (Milbert, 1999). The converted LiDAR elevations were assessed for accuracy in wetlands (see Assessing the Accuracy of LiDAR Elevation Data in Wetlands section) and compared to monthly potentiometric surfaces (Equation 1).

Groundwater conditions G in Equation 1 were mapped using the same resolution (i.e. 5-ft grid cells) as the LiDAR land-surface data. Monthly potentiometric surfaces used a 328-ft (or 100-m) grid. To compare the LiDAR and potentiometric surfaces, the grids were resampled using a nearest neighbor technique. LiDAR and potentiometric elevations were assigned to cells in the groundwater conditions grid based on the shortest Euclidean distance between grid cell centers. This way no LiDAR or potentiometric elevations were changed. Then, the difference between LiDAR and potentiometric elevations at each grid cell was calculated as in Equation 1.

A predevelopment potentiometric surface for the Upper Floridan aquifer was used to map hypothetical groundwater conditions in the absence of pumping. The steady-state elevation of the potentiometric surface without groundwater pumping was modeled by Bush and Johnston (1988) and later digitized by Bellino (2011) using 820-ft (or 250-m) grid cells. The predevelopment potentiometric surface was used the same way as monthly potentiometric surfaces to map groundwater conditions in the study area.

Groundwater conditions were classified as discharging or into different categories of recharging condition (Table 1). The single discharging category describes areas where the potentiometric surface is at or above land surface. Recharging categories divide the distance of the potentiometric surface below land surface into 5-ft intervals. The same classification was applied on wetland groundwater conditions (described in the next section), with one less recharge category (i.e. > 20 ft below land surface removed). Regional groundwater conditions were classified on a monthly basis and converted into a 26-year animation available at *https://www.swfwmd.state.fl.us/resources/data-maps/hydrologic-data#WGC*.

Assessing Wetland Groundwater Conditions

Wetland groundwater conditions were derived from regional groundwater conditions described in the previous section. Grid cells intersecting a wetland were used to calculate the average distance of the potentiometric surface above or below land surface on a wetland-by-wetland basis. This calculation is illustrated in Figure 7. Regional groundwater conditions were mapped as the difference between the potentiometric surface (dashed line) and LiDAR land surface (solid line). The average difference was then calculated in the wetland. The potentiometric surface changed less than the LiDAR land surface because it had larger (328-ft) grid cells. The calculation illustrated in Figure 7 was used to generate a 312-month time series of groundwater conditions at individual wetlands. The same calculation was performed using a predevelopment potentiometric surface (Bellino, 2011) to depict wetland groundwater conditions in the absence of groundwater pumping.

Table 1. Categories of discharging and recharging groundwater conditions based on the distance of the Upper Floridan aquifer potentiometric surface above or below land surface.

[*, Potentiometric surface at or above land surface;
**, Categories end at >15 for wetland groundwater conditions]

Category	Type	Map Color	Distance of the Potentiometric Surface Below Land Surface, in Feet
1	Discharging	Dark blue	*
2	Recharging	Light blue	>0 to 5
3	Recharging	Yellow	>5 to 10
4	Recharging	Orange	>10 to 15
5	Recharging	Red	>15 to 20; >15**
6	Recharging	Green	>20

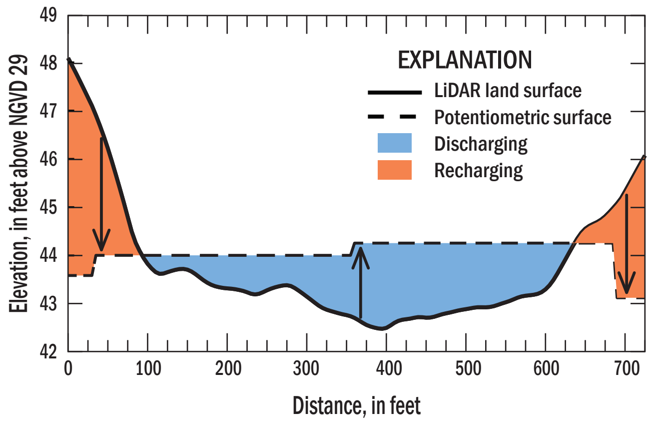


Figure 7. Discharging and recharging groundwater conditions defined by the relative positions of the land surface and the potentiometric surface of the Upper Floridan aquifer. Gridded values of the potentiometric-surface elevation for September 2005 and LiDAR land-surface elevations are shown for a cross section through wetland NP-05.

Wetland Populations and Data Products

Wetlands used to create data products for the Tampa Bay Water Wetland Groundwater Conditions project were based on two main populations: 10,516 National Wetlands Inventory (US Fish and Wildlife Service, 2017) wetlands (Figure 3) and 1,092 Tampa Bay Water wetlands identified for a recovery analysis (Figure 4). The two main populations were divided into 21 subpopulations based on geographic areas, such as inside or outside well field properties. Tampa Bay Water wetlands have four additional subpopulations based on attributes identifying monitored, unmonitored, cypress, and marsh wetlands. The total number of wetland populations equaled 48 (i.e. 2 main populations + 21 National Wetlands Inventory subpopulations + 25 Tampa Bay Water subpopulations).

Wetland populations examined in this report include the two main populations, wetlands in and out of areas with more groundwater pumping effects (i.e. well fields and a 2-foot drawdown contour in the surficial aquifer as delineated by Tampa Bay Water (2013)) and monitored versus unmonitored Tampa Bay Water wetlands. The two main populations were examined to evaluate if the Tampa Bay Water wetlands selected for a recovery analysis had similar changes in groundwater conditions as the larger National Wetlands Inventory sample. The same idea was behind comparing groundwater conditions in monitored and unmonitored wetlands. Wetlands were divided in and out of areas, such as well fields, to evaluate how wetland groundwater conditions have responded locally and regionally to pumping cutbacks.

The same set of data products were generated for each wetland population. The data products are organized by file type and wetland population as shown in Figure 8 and include

(1) Regional groundwater conditions covering the wetland populations for 312 months
(2) LiDAR land surface used to create the above deliver-able and assessed for accuracy in wetlands (see the next section)
(3) Monthly maps of regional groundwater conditions classified into discharge and recharge categories as in Table 1 and data on the area of each category
(4) Monthly and annual time series of groundwater conditions in each wetland of a population and population statistics, such as the mean, for each month and year
(5) A geodatabase mapping the wetlands and time series from the above deliverable
(6) A trend analysis of monthly and seasonal groundwater conditions for each wetland population
(7) Box and whisker plots of annual groundwater condi-tions for each wetland population and data used in the plots
(8) Annual percentage of wetlands in groundwater condi-tion categories (Table 1) and pie charts illustrating this data
(9) Annual percentage of wetlands above and below a wetland groundwater index value and bar plots illustrating this data

Time series in the deliverables span a 26-year period (1990-2015), including time periods before and after groundwater pumping cutbacks starting in 2003 (Interlocal Agreement, 1998, p. 75). Before that time, groundwater pumping from 11 well fields in the study area averaged 145 mgd from 1990-2002. After pumping cutbacks, the average decreased to 89 mgd from 2003-2015 (Figure 5). These two time periods are labeled “pre-cutback” (1990-2002) and “post-cutback” (2003-2015) in this report. However, pumping cutbacks occurred at different times for individual well fields (Erin Hayes, Tampa Bay Water, written communication, May 8, 2018). For this reason, well fields had different cutback time periods for a trend analysis (deliverable 6).

Annual groundwater conditions in deliverables 7-9 were investigated using annual averages, dry season (i.e. April-June) averages, wet season (i.e. July-September) averages, and months historically used (e.g. Ortiz, 2011) to track changes in the dry and wet seasons (i.e. May and September, respectively). May and September (rather than dry and wet season averages) are used in this report for comparable results to historical potentiometric surfaces.

The groundwater condition time series for the 10,516 National Wetlands Inventory wetlands are available for download as a geodatabase and as tabular data at *https://www.swfwmd.state.fl.us/resources/data-maps/hydrologic-data#WGC* .

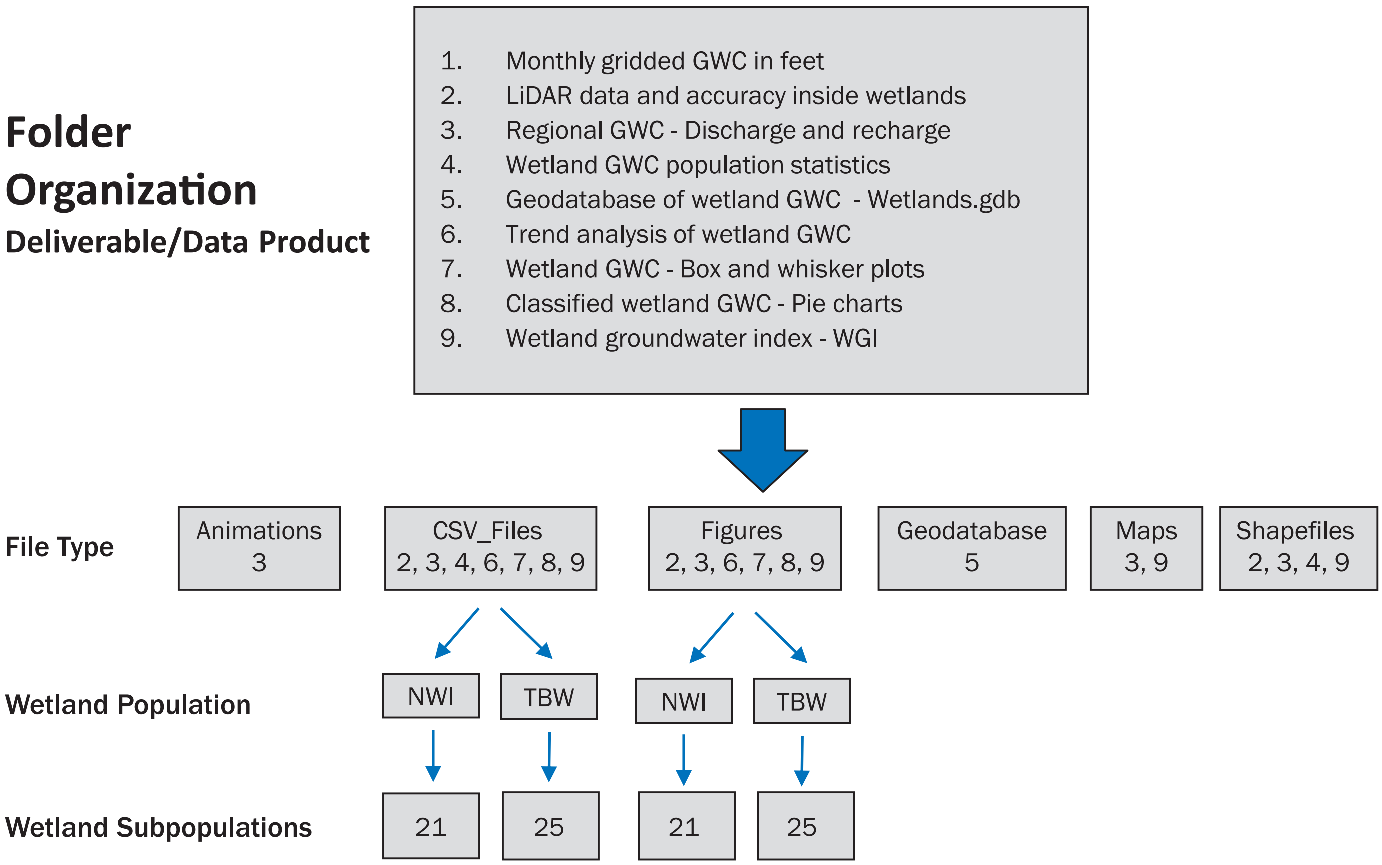


Figure 8. Folder organization of the data products generated in the study. GWC is groundwater conditions.

Assessing the Accuracy of LiDAR Elevation Data in Wetlands

Accuracy of LiDAR land-surface elevations in wetlands was critical to calculate wetland groundwater conditions. Therefore, LiDAR elevations in wetlands were compared to ground-surveyed elevations. The ground-surveyed elevations were retrieved from a Tampa Bay Water database and included surveys conducted over a 30-year time period (Hayes et al., 2018). The database had ground-surveyed elevations in 305 wetlands in the study area (Figure 4). Surveyed points in 222 wetlands were near staff gages used to measure water levels (i.e. areas where water normally pools in the wetland). This is important because the LiDAR used here does not penetrate water and surveyed points were likely in error-prone areas for LiDAR measurements. In addition, 13 surveyed points were in wetlands classified as lakes by Tampa Bay Water, which may mean these points are covered in water year round.

The number of ground-surveyed wetlands (305) was far smaller than the 10,516 National Wetlands Inventory wetlands analyzed in this study (Figure 3). To assess if the smaller sample was representative of the National Wetlands Inventory wetlands, the two samples were compared using histograms to illustrate the distribution of wetland surface areas. Wetland surface area was used because it generally relates to the topography (e.g. depth) of depressional wetlands in Florida (Lane and D'Amico, 2010).

The elevation at the ground-surveyed point was compared to the elevation in the overlying 5 × 5-ft LiDAR grid cell. The two sets of elevation data were compared using histograms and a linear regression, which described the correlation (R^2), dispersion (standard error), and vertical offset (y-intercept) between LiDAR and ground-surveyed elevations in wetlands.

Population Statistics

Population statistics, such as the median, were used to characterize annual wetland groundwater conditions. Monthly groundwater conditions were averaged for calendar years from 1990-2015 at each wetland in a population. Annual averages across the wetlands were used to create box and whisker plots as in Tukey (1977, p. 39-43), with whiskers extending to the farthest non-outlier value (i.e. last data point within 1.5 × (75^{th} percentile – 25^{th} percentile) from the box), box drawn to the 25^{th} and 75^{th} percentiles, and bar in the box indicating the median value. Annual box and whisker plots were compared to one calculated using a predevelopment potentiometric surface (Bellino, 2011), indicating wetland groundwater conditions without groundwater pumping. Box and whisker plots were also generated using seasonal data (i.e. May, September, dry season (April-June) average, and wet season (July-September) average). Annual average and seasonal box and whisker plots were produced for 48 wetland populations (Table 2), and associated population statistics were saved in data tables (see deliverable 7). Results presented here are limited to annual average versus predevelopment groundwater conditions and seasonal (i.e. May and September) groundwater conditions in the two main wetland populations (i.e. National Wetlands Inventory and Tampa Bay Water wetlands).

A special comparison was conducted using monitored and unmonitored Tampa Bay Water wetlands to assess if the two populations had similar groundwater conditions. The number of monitored and unmonitored wetlands was equal to 410 and 682, respectively. Annual groundwater conditions, including annual averages and seasonal data (i.e. May and September), at these wetlands were averaged over the complete 26-year record and pre- (1990-2002) and post-cutback (2003-2015) time periods. Although groundwater pumping cutbacks occurred at different times for individual well fields, monitored and unmonitored wetlands cover multiple well fields across the study area, which had a large pumping decline (56 mgd) between the pre- and post-cutback time periods. In addition, predevelopment groundwater conditions were compared for the monitored and unmonitored wetlands. Comparisons in the various time periods (i.e. predevelopment, pre-cutback, post-cutback, and complete period of record) were conducted descriptively using the population averages and statistically using the Student's *t*-test of the difference between the averages. The Student's *t*-test assumes the two datasets have equal variances and normal distributions. The latter assumption can be ignored for sufficiently large samples with more than 80 observations (Ratcliffe, 1968). The variances of monitored and unmonitored wetlands were compared using an F-test for normally distributed data (i.e. Anderson-Darling normality test p-value > 0.05) or Levene's test for non-normally distributed data (i.e. Anderson-Darling normality test p-value ≤ 0.05). If the variances were not equal based on either the F-test or Levene's test (i.e. p-value ≤ 0.05), then estimates of the variance in monitored and unmonitored wetlands were used in a Welch's t-test for unequal variances (Welch, 1951).

Classified Groundwater Conditions

Wetland groundwater conditions were classified as discharging or recharging, including four different recharge categories (Table 1). The categories served to summarize the percentage of wetlands with different groundwater conditions. The percentage of wetlands in each groundwater condition category was calculated using annual average and seasonal (i.e. May, September, dry season (April-June) average, and wet season (July-September) average) data. Results were then displayed using annual and seasonal pie charts from 1990-2015. The groundwater condition categories were applied on 48 wetland populations (Table 2) to generate data tables and pie charts of the percentage of wetlands in each category (see deliverable 8). Data tables and pie charts are presented in this report for the two main populations (i.e. National Wetlands Inventory and Tampa Bay Water wetlands) classified using annual average, May (dry season), and September (wet season) data.

The percentage of wetlands in each groundwater condition category was analyzed for changes in pre- (1990-2002) and post-cutback (2003-2015) time periods marked by a 56 mgd decrease in groundwater pumping from 11 well fields in the study area. Changes were analyzed using the average percentage of wetlands in each groundwater condition category before and after pumping cutbacks. Pre- and post-cutback averages were assessed for statistically significant changes using the Student's *t*-test as specified in the previous section. Statistical testing of pre- and post-cutback changes was repeated using annual average and seasonal (i.e. May and September) data for the two main wetland populations (i.e. National Wetlands Inventory and Tampa Bay Water wetlands) and subpopulations in and out of well fields or a 2-foot drawdown contour in the surficial aquifer (Tampa Bay Water, 2013). The subpopulations were evaluated to assess changes in groundwater condition categories for wetlands in and out of areas potentially influenced by groundwater pumping effects.

Wetland groundwater condition categories were mapped for the pre- (1990-2002) and post-cutback (2003-2015) time periods. Annual groundwater condition data, including averages, May (dry season), and September (wet season), were averaged for each wetland before and after groundwater pumping cutbacks. Pre- and post-cutback averages were then classified using the wetland groundwater condition categories (Table 1). Wetlands were mapped using the color associated with their groundwater condition category. The same color-coding was applied on the wetlands using a predevelopment potentiometric surface (Bellino, 2011) to assess groundwater condition categories for a hypothetical scenario without groundwater pumping. The predevelopment categories were compared to annual average categories before and after pumping cutbacks. Maps of wetland groundwater condition categories were generated for the two main populations (i.e. National Wetlands Inventory and Tampa Bay Water wetlands).

Wetland Groundwater Index

Wetland groundwater conditions were compared through time against an index value. The wetland groundwater index was calculated using the median of annual wetland groundwater conditions before pumping cutbacks from 1990-2002. Annual wetland groundwater conditions were compared to the index as follows:

$$D_{wy} = G_{wy} - I_w \qquad (2)$$

where D is the difference between groundwater conditions G and the index value I at wetland w in year y. The result

Table 2a. Characteristics of the National Wetlands Inventory wetland population and subpopulations.

[Wetland polygons are treated as complete features and wetland areas that extend beyond the mapped area are included in the value of wetland area. *, Wetland area at Cypress Creek well field (CYC) includes several large wetland polygons that extend beyond the mapped area. References - Florida Department of Environmental Protection (FDEP), 2004, Intermediate aquifer system thickness. FDEP Geospatial Open Data; Tampa Bay Water (TBW), 2013, Defining areas of investigation for recovery analysis. Tampa Bay Water Report, 22 p.; Tampa Bay Water (TBW), 2016, Kriging methodology: Analyzing surficial aquifer drawdown from historical groundwater pumping, 2013-2016; Tampa Bay Water Report, 19 p.]

	Wetland Population Name	Description	Mapped Area (mi^2)	Number of Wetland Polygons	Wetland Area (mi^2)
1	NWI	All freshwater palustrine wetland polygons of the National Wetlands Inventory (NWI) contained within the study area	581.03	10,516	127.45
2	Wellfield	NWI wetlands inside 8 well field properties and 3-mile buffered areas around Cypress Bridge, North Pasco, and Northwest Hillsborough dispersed well fields	200.65	4,584	61.03
3	Not_In_Wellfield	NWI wetlands located outside 8 well field properties and 3 buffered areas	380.38	5,932	66.42
4	Two_Foot_Drawdown_New	NWI wetlands inside 2-foot drawdown contour of TBW (2016)	65.75	1,342	28.73
5	Not_In_Two_Foot_Drawdown_New	NWI wetlands outside 2-foot drawdown contour of TBW (2016)	515.28	9,174	98.72
6	Two_Foot_Drawdown_Original	NWI wetlands inside 2-foot drawdown contour of TBW (2013)	68.28	1,381	29.04
7	Not_In_Two_Foot_Drawdown_Original	NWI wetlands outside 2-foot drawdown contour of TBW (2013)	512.75	9,135	98.41
8	Intermediate_Confining_Unit	NWI wetlands in intermediate confining unit of FDEP (2004)	108.68	1,029	17.84
9	Not_In_Intermediate_Confining_Unit	NWI wetlands in area outside intermediate confining unit of FDEP (2004)	472.34	9,487	109.60
10	Consolidated_Wellfield	NWI wetlands inside 8 well field properties	47.39	1,004	25.12
11	Not_In_Consolidated_Wellfield	NWI wetlands outside 8 well field properties	533.63	9,512	102.33
12	CBR	NWI wetlands inside Cross Bar Ranch well field property	12.87	216	2.24
13	COS	NWI wetlands inside Cosme well field property	1.10	32	0.30
14	CYB	NWI wetlands inside Cypress Bridge well field 3-mile buffered area	72.37	1,930	26.70
15	CYC*	NWI wetlands inside Cypress Creek well field property	7.63	89	9.53
16	ELW	NWI wetlands inside Eldridge Wilde well field property	5.54	206	2.00
17	MBR	NWI wetlands inside Morris Bridge well field property	6.02	149	3.81
18	NOP	NWI wetlands inside North Pasco well field 3-mile buffered area	34.87	726	11.17
19	NWH	NWI wetlands inside Northwest Hillsborough well field 3-mile buffered area	50.41	1,061	7.64
20	S21	NWI wetlands inside Section 21 well field property	0.86	17	0.19
21	SOP	NWI wetlands inside South Pasco well field property	0.98	14	0.60
22	STK	NWI wetlands inside Starkey well field property	12.39	281	6.45

Table 2b. Characteristics of the Tampa Bay Water wetland population and subpopulations.

[**, subpopulation that occurs only within the TBW_Wetland population: (1) monitored, (2) unmonitored, (3) cypress, and (4) marsh wetlands; References - Florida Department of Environmental Protection (FDEP), 2004, Intermediate aquifer system thickness. FDEP Geospatial Open Data.; Tampa Bay Water (TBW), 2013, Defining areas of investigation for recovery analysis. Tampa Bay Water Report, 22 p.; Tampa Bay Water (TBW), 2016, Kriging methodology: Analyzing surficial aquifer drawdown from historical groundwater pumping, 2013-2016. Tampa Bay Water Report, 19 p.]

	Wetland Population Name	Description	Mapped Area (mi^2)	Number of Wetland Polygons	Wetland Area (mi^2)
1	TBW_Wetland	TBW wetlands identified as monitored and unmonitored	581.03	1,092	23.70
2	Wellfield	TBW wetlands inside 8 well field properties and 3-mile buffered areas around Cypress Bridge, North Pasco, and Northwest Hillsborough dispersed well fields	200.65	697	11.45
3	Not_In_Wellfield	TBW wetlands located outside 8 well field properties and the 3 buffered areas	380.38	395	12.25
4	Two_Foot_Drawdown_New	TBW wetlands inside 2-foot drawdown contour of TBW (2016)	65.75	737	13.78
5	Not_In_Two_Foot_Drawdown_New	TBW wetlands outside 2-foot drawdown contour of TBW (2016)	515.28	355	9.91
6	Two_Foot_Drawdown_Original	TBW wetlands inside 2-foot drawdown contour of TBW (2013)	68.28	814	15.53
7	Not_In_Two_Foot_Drawdown_Original	TBW wetlands outside 2-foot drawdown contour of TBW (2013)	512.75	278	8.16
8	Monitored_Wetland**	TBW wetlands that are monitored	11.55	410	11.55
9	Unmonitored_Wetland**	TBW wetlands that are unmonitored	12.15	682	12.15
10	Cypress**	TBW cypress wetlands	4.06	194	4.06
11	Marsh**	TBW marsh wetlands	1.25	52	1.25
12	Intermediate_Confining_Unit	TBW wetlands in intermediate confining unit of FDEP (2004)	108.68	172	6.45
13	Not_In_Intermediate_Confining_Unit	TBW wetlands in area outside intermediate confining unit of FDEP (2004)	472.34	920	17.24
14	Consolidated_Wellfield	TBW wetlands inside 8 well field properties	47.39	417	7.19
15	Not_In_Consolidated_Wellfield	TBW wetlands outside 8 well field properties	533.63	675	16.51
16	CBR	TBW wetlands inside Cross Bar Ranch well field property	12.87	80	1.99
17	COS	TBW wetlands inside Cosme well field property	1.10	4	0.24
18	CYB	TBW wetlands inside Cypress Bridge well field 3-mile buffered area	72.37	208	2.32
19	CYC	TBW wetlands inside Cypress Creek well field property	7.63	64	0.64
20	ELW	TBW wetlands inside Eldridge Wilde well field property	5.54	78	1.81
21	MBR	TBW wetlands inside Morris Bridge well field property	6.02	98	0.67
22	NOP	TBW wetlands inside North Pasco well field 3-mile buffered area	34.87	59	1.35
23	NWH	TBW wetlands inside Northwest Hillsborough well field 3-mile buffered area	50.41	57	1.55
24	S21	TBW wetlands inside Section 21 well field property	0.86	8	0.11
25	SOP	TBW wetlands inside South Pasco well field property	0.98	8	0.07
26	STK	TBW wetlands inside Starkey well field property	12.39	77	1.64

was classified as either above the index ($Dwy \geq 0$) or below the index ($Dwy < 0$). The percentage of wetlands in each class was calculated annually from 1990-2015. Annual groundwater conditions were analyzed using annual average, May (dry season), and September (wet season) data for the National Wetlands Inventory wetland population. Further analysis was conducted using 48 wetland populations (Table 2) and five time intervals (i.e. annual average, May, September, dry season (April-June) average, and wet season (July-September) average) for deliverable 9 of the Tampa Bay Water Wetland Groundwater Conditions project.

Trends in Wetland Groundwater Conditions

A trend analysis was conducted to assess upward or downward changes in groundwater conditions for the 48 wetland populations in Table 2. Trends were analyzed using a wetland population's monthly median value for the height of the potentiometric surface above or below land surface between January 1990 and December 2015. Median groundwater conditions were adjusted for the effects of rainfall using 1-km Daymet grids (Thornton et al., 2018). Monthly grids were converted to rainfall totals for different wetland populations using an area-weighted approach as follows:

$$R_m = \frac{\sum_{i=1}^{n} F_i \times D_i}{\sum_{i=1}^{n} F_i} \quad (3)$$

where R is the rainfall total of month m in inches per grid cell, F is the fraction of grid cell i covered in wetlands, D is the rainfall depth at grid cell i in inches, and n is the total number of grid cells.

Trend tests were applied to assess if upward or downward changes in wetland groundwater conditions were statistically significant. Trend tests have a null hypothesis that there is no trend and estimate the probability that the null hypothesis is true (p-value). At a given probability, such as a p-value ≤ 0.05, the null hypothesis is rejected, and an upward or downward trend is statistically significant.

A p-value may not be correct if some assumptions are not met. Assumptions vary depending on the trend test. Trend tests based on linear regression (i.e. fitting a line through a time series) assume a linear trend and variation around the trend is normally distributed and has constant variance (i.e. homoscedasticity). These assumptions are problematic in this study because trend tests are applied on 48 different wetland populations before and after pumping cutbacks and for the complete period of record (i.e. 144 total tests). If the data departs from the assumptions of regression, then a nonparametric test that does not assume the general form of the trend is a better alternative (Hirsch et al., 1991).

Mann-Kendall is a nonparametric trend test adaptable to a range of trends at different wetland populations. The test is equivalent to Kendall's test for correlation in which one of the variables is time (Mann, 1945). The correlation indicates an upward or downward trend over time. The only assumption is that the time series is not autocorrelated (e.g. time $\boldsymbol{t}$ is not correlated to time $\boldsymbol{t}$ - 1). Autocorrelation was monitored using a lag-1 autoregressive model (i.e. AR(1) model) of the previous month versus the present month. An AR(1) model coefficient > 0.1 indicates that the Mann-Kendall test may falsely detect a trend that does not exist (von Storch, 1995). Due to the large degree of autocorrelation in monthly wetland groundwater conditions, a modified Mann-Kendall test was used to accommodate autocorrelation up to an AR(1) model coefficient ≤ 0.6 (Hirsch and Slack, 1984).

The modified Mann-Kendall test is for seasonal hydrologic data with a cyclical dry season (e.g. May groundwater conditions) and wet season (e.g. September groundwater conditions). The test was applied month by month as will be shown and is less sensitive to autocorrelation because it estimates the covariance between months. Before applying the test, wetland groundwater conditions were adjusted for the effects of rainfall using a LOWESS (locally weighted scatterplot smooth) curve of monthly median groundwater conditions versus rainfall totals (Equation 3). A LOWESS curve does not assume a linear relation between two variables. Local polynomial curves are fit to a fraction of the data around each point (Cleveland, 1979). In this case, the curve was fit using ⅔ of the data surrounding each point (e.g. 17 values around each year of a 26-year annual time series) in order to neither overfit (i.e. extend the curve to local minima or maxima) or oversmooth (i.e. remove changes in slope). The curve was subtracted from wetland groundwater conditions to derive residuals with the effects of rainfall removed. The residuals were used for the trend tests.

The seasonal Mann-Kendall test modified for autocorrelation was applied on monthly residuals (E). The month (1,…,n) was adjusted for short-term changes in rainfall, such as extended dry or wet periods, based on the residuals from a regression model of time versus rainfall (Alley, 1988). The new units of time T were used to calculate the test statistic S as follows:

$$S = \sum_{i<j} sign\ (E_h - E_g) \times sign\ (T_h - T_g) \quad (4)$$

where $sign$ converts the result x of subtracting month g from month h to

$$sign\,(x) = \begin{cases} 1 \text{ if } x > 0 \\ 0 \text{ if } x = 0 \\ -1 \text{ if } x < 0 \end{cases} \quad (5)$$

The above was applied separately on m months to derive the seasonal test statistic S' as follows:

$$S' = \sum_{g=1}^{m} S_g \tag{6}$$

The significance of the test statistic S' was evaluated against the distribution Z with mean 0 and variance calculated using the covariance between months g and h to account for temporal autocorrelation. The variance of Z was calculated as

$$var\ (Z) = \left(K_{gh} + 4 \text{ x} \sum_{i=1}^{n} R_{ig} \text{ x } R_{ih} - n \text{ x } (n+1)^2\right)/3 \tag{7}$$

where K is the test statistic evaluated between years p and q as $\sum_{p<q} sign\ (E_{qg} - E_{pg})$ x $(E_{qh} - E_{ph})$, n is the number of years in the time series, and R is the rank of E for year i in the given month. The resulting variance was used to calculate the Z score (i.e. number of standard deviations from mean 0) for the test statistic S' and its associated p-value without assuming no monthly autocorrelation.

Table 3. Trend tests applied on median groundwater conditions (G) in 48 wetland populations for deliverable 6 of the Tampa Bay Water project (adapted from Helsel and Hirsch, 2002).

[*, Tests presented in this report]

Type of Trend Test	Not Adjusted for Rainfall	Adjusted for Rainfall (R)
Non-seasonal		
Nonparametric	Mann-Kendall test on G	*Mann-Kendall test on residuals E from LOWESS of G versus R
Mixed	–	Mann-Kendall test on residuals E from regression of G versus R
Parametric	Regression of G versus time, then test significance of coefficient for time	Regression of G versus R and time, then test significance of coefficient for time
Seasonal		
Nonparametric	Seasonal Mann-Kendall test on G	*Seasonal Mann-Kendall test on residuals E from LOWESS of G versus R
Mixed	Regression of deseasonalized G (G – seasonal median) versus time, then test significance of coefficient for time	Seasonal Mann-Kendall test on residuals E from regression of G versus R
Parametric	Regression of G versus time and periodic functions (sine and cosine), then test significance of coefficient for time	Regression of G versus R, time, and periodic functions (sine and cosine), then test significance of coefficient for time

The slope of the trend through monthly residuals E was estimated based on Sen's slope (Sen, 1968), which is the median of all slopes between each pair of values. Seasonal Sen's slope (Hirsch et al., 1982) was calculated for each month m on all pairs of years $p < q$ as follows:

$$B_{mpq} = \frac{(E_{mq} - E_{mp})}{(q - p)} \tag{8}$$

The seasonal slope B is the median of B_{mpq}. The seasonal Mann-Kendall test is related to B because the test statistic S' is equal to $\sum sign\ (B_{mpq})$. As a result, both S' and B indicate the same trend direction (unless B is zero).

Deliverable 6 of the current project has a broader trend analysis of wetland groundwater conditions than is described here and includes multiple trend tests with and without rainfall (Table 3). Methods and results presented here are the strongest (i.e. least sensitive to assumptions) for evaluating trends across wetland populations. The larger trend analysis includes non-seasonal and seasonal tests. Trends were evaluated at different time intervals. In addition to monthly groundwater conditions, other time intervals were used to (1) reduce autocorrelation (i.e. quarterly and May and September time series), (2) examine changes in the dry and wet seasons (i.e. May, September, dry season (April-June) average, and wet season (July-September) average time series), and (3) account for a lag in the effects of rainfall (i.e. 1-, 2-, and 3-month moving totals). Time periods were evaluated before pumping cutbacks, after pumping cutbacks, and for the complete period of record.

RESULTS

Wetland Population Characteristics

The physical characteristics of the main wetland populations and their respective subpopulations are described in Table 2. Both populations are exclusively freshwater wetlands. The Tampa Bay Water wetlands are not an exact subset of the National Wetlands Inventory population. Some of the Tampa Bay Water wetlands are wetlands originally from the National Wetlands Inventory but with updated polygons outlining their perimeters as a result of wetland delineation surveys. Other wetland features are narrow strips that represent cross-sectional survey transects through several wetland polygons in a floodplain area, and some wetlands are identical to the National Wetlands Inventory polygons.

The first entry describes the main wetland population, either the National Wetlands Inventory population (Table 2a) or the Tampa Bay Water wetland population (Table 2b). Subsequent entries describe various subpopulations taken from the main population. Wetland subpopulations are grouped by shared geographic areas or traits, for instance, only wetlands inside the Cross Bar Ranch well field property, or only monitored wetlands.

Subpopulation characteristics show that while more wetlands lie outside of well field properties (5,932) than inside them (4,584), wetlands cover a greater percentage of the area inside well field properties than outside them (compare Wellfield to Not_In_Wellfield in Table 2a). Wetlands cover about 30 percent (61 mi^2 out of 201 mi^2) of the area inside well fields, whereas outside well fields they cover about 17 percent of the area (66 mi^2 out of 380 mi^2). Note that "inside well fields" refers to the area inside eight well field properties (shown on Figure 3) and three buffer areas encompassing Cypress Bridge, North Pasco, and Northwest Hillsborough dispersed well fields, as described by Lee and Fouad (2014, 2017).

The smaller Tampa Bay Water population of 1,092 wetlands reflects about 10 percent of the number of wetlands in the National Wetlands Inventory population, but about 19 percent of the total wetland area, due to greater regulatory interest in large wetlands. Nearly two-thirds of the entire Tampa Bay Water population, 697 wetlands, are found inside well fields, where they may experience a larger influence from groundwater pumping than wetlands outside well fields (Table 2b). Forested wetlands (Cypress) outnumber marshes (Marsh) by 3.7 to 1, close to the ratio of about 3:1 described for central Florida in Dahl (2005, p. 53).

The size distributions of wetlands in the two main wetland populations are similar overall, with most wetlands smaller than 5 acres in size (Figures 9a and b). However, the size distribution of the Tampa Bay Water wetland population is biased larger than the regional population, with a smaller percentage of all wetlands in the less than 5-acre category

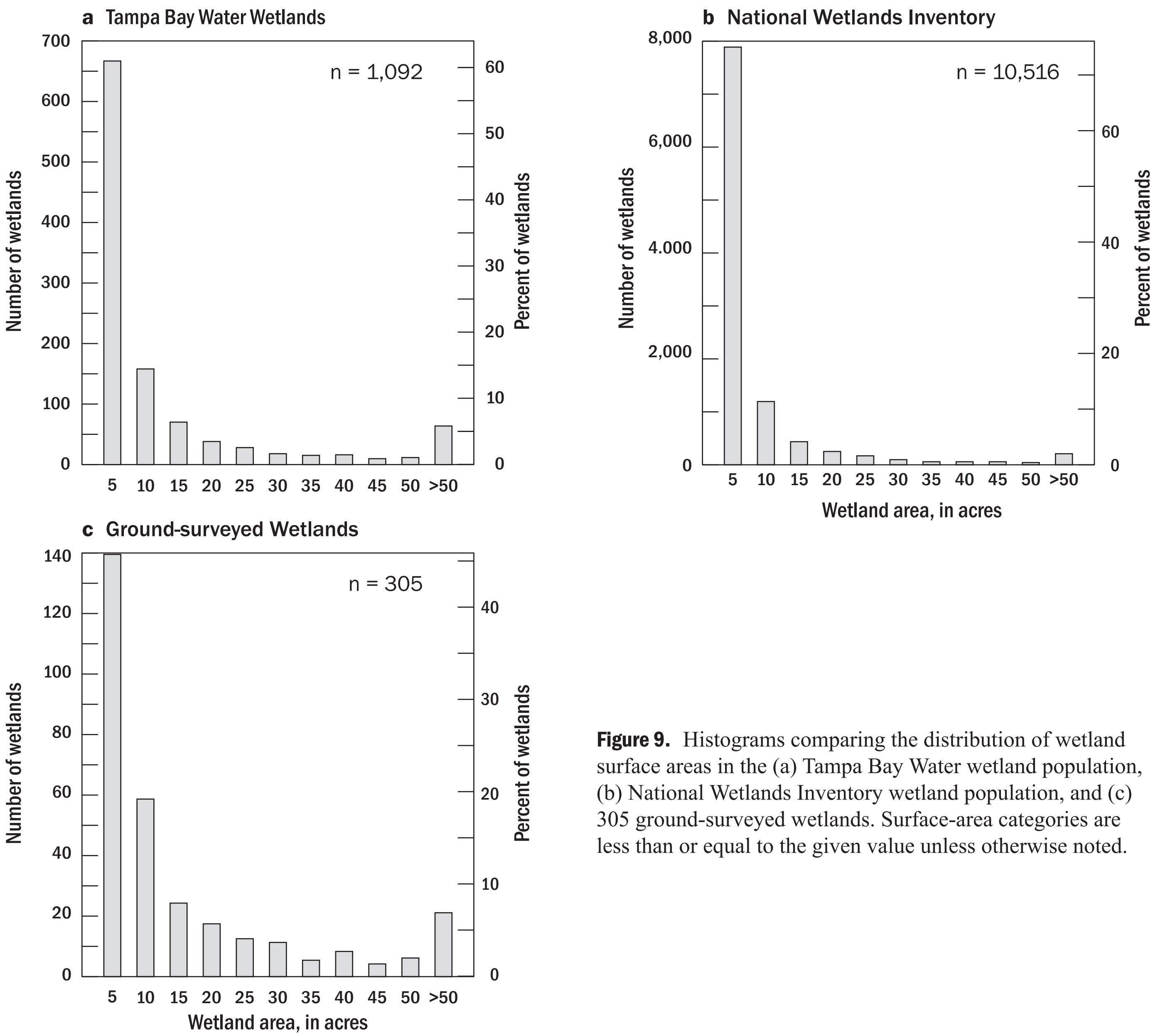


Figure 9. Histograms comparing the distribution of wetland surface areas in the (a) Tampa Bay Water wetland population, (b) National Wetlands Inventory wetland population, and (c) 305 ground-surveyed wetlands. Surface-area categories are less than or equal to the given value unless otherwise noted.

compared to the National Wetlands Inventory. About 61 percent of all wetlands in the Tampa Bay Water population are less than 5 acres in size, whereas about 75 percent of the National Wetlands Inventory wetlands are in this size category. The Tampa Bay Water population has slightly higher percentages of wetlands between 5 and 10 acres in size and greater than 50 acres in size when compared to the National Wetlands Inventory population.

Accuracy of LiDAR Elevations in 305 Wetlands

The accuracy of LiDAR land-surface elevations in wetlands was assessed using ground-surveyed elevations from 305 wetlands. Since the sample of ground-surveyed wetlands was far smaller than the 10,516 National Wetlands Inventory wetlands in the study area, wetland surface area was assessed to evaluate if the ground-surveyed wetlands were representative of the larger sample based on a readily measurable characteristic associated with wetland topography (Lane and D'Amico, 2010). The distribution of wetland surface areas in the regional population (Figure 9b) was compared to that of ground-surveyed wetlands (Figure 9c). The two wetland populations had similar distributions overall. Most wetlands were smaller than 5 acres in both populations, and both distributions had a right tail generally consisting of fewer wetlands in larger surface-area categories. The key difference between the two populations was that the ground-surveyed wetlands had more wetlands in larger surface-area categories, such as about 8 percent more ground-surveyed wetlands from 5 to 10 acres in size and about 5 percent more ground-surveyed wetlands larger than 50 acres.

The analysis of 305 surveyed wetlands found that land-surface elevations inside wetlands based on LiDAR data were highly correlated (R^2 = 0.99) with the ground-surveyed elevations at the same locations, and the standard error of the regression was 1.81 ft (Figure 10). The slope of the linear relationship was 1.00 ft/ft. However, the intercept of 1.53 ft indicates that the LiDAR-based land-surface elevations inside wetlands were consistently higher than the ground-surveyed elevations.

The bias (i.e. LiDAR elevations higher than ground-surveyed elevations) is evident in the distribution of wetland land-surface elevations based on the two datasets (Figure 11). Both distributions are bimodal and similar in shape, with small tails at each end. However, the distributions are not a perfect match as the standard error and bias in the LiDAR-based data shift some wetlands into higher categories (Figure 11). For instance, the largest percentage of ground-surveyed elevations occurs from 40 to 45 feet above NGVD 29, whereas 45 to 50 feet above NGVD 29 has the largest percentage of LiDAR elevations.

From this analysis, the uncertainty associated with LiDAR estimates of land-surface elevations inside wetlands in the study area was concluded to be 1.53 ft (i.e. the y-intercept in Figure 10) plus or minus the standard error of 1.81 ft. The linear correlation between the two types of wetland land-surface elevations improved when 13 wetlands classified as lakes were excluded from the surveyed population. For the remaining population of 292 wetlands, the slope remained 1.00 ft/ft, but the intercept, or positive bias, decreased to 1.38 ft. The coefficient of determination (R^2) remained 0.99, but the standard error decreased to 1.55 ft.

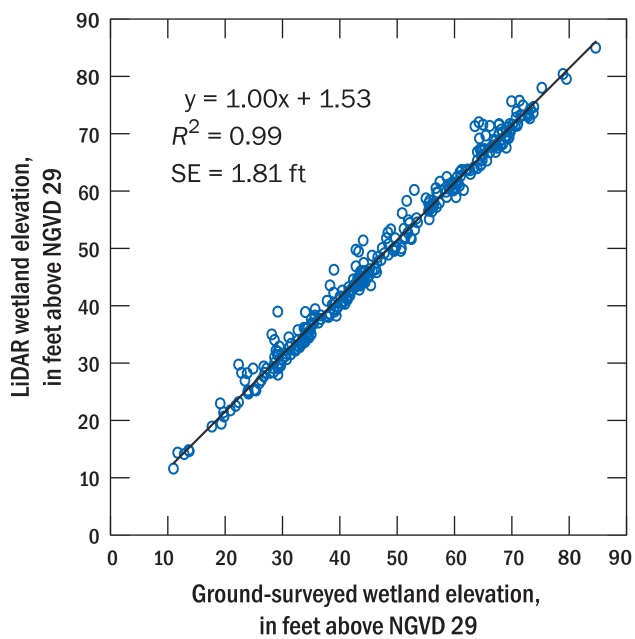


Figure 10. Linear relationship between ground-surveyed and LiDAR-based land-surface elevations in 305 Tampa Bay Water wetlands.

Several physical factors have been described that could contribute to uncertainty and bias in LiDAR-based elevations inside wetlands (Hayes et al., 2018; Jones Edmunds & Associates, 2011). LiDAR-based elevations could be biased higher if standing water was in the wetlands. Elevation differences may be because LiDAR elevations were estimated over 25-ft^2 grid cell areas, as opposed to point elevations measured in a ground survey. Marsh wetlands may contribute relatively more uncertainty than forested wetlands. LiDAR-based elevations in marshes had a larger range of uncertainty (standard error = 1.58 ft) than forested wetlands (standard error = 1.29 ft) when compared to ground-surveyed elevations. Uncertainty may be greater in marshes due to thick vegetation that can prevent the LiDAR signal from reaching the ground.

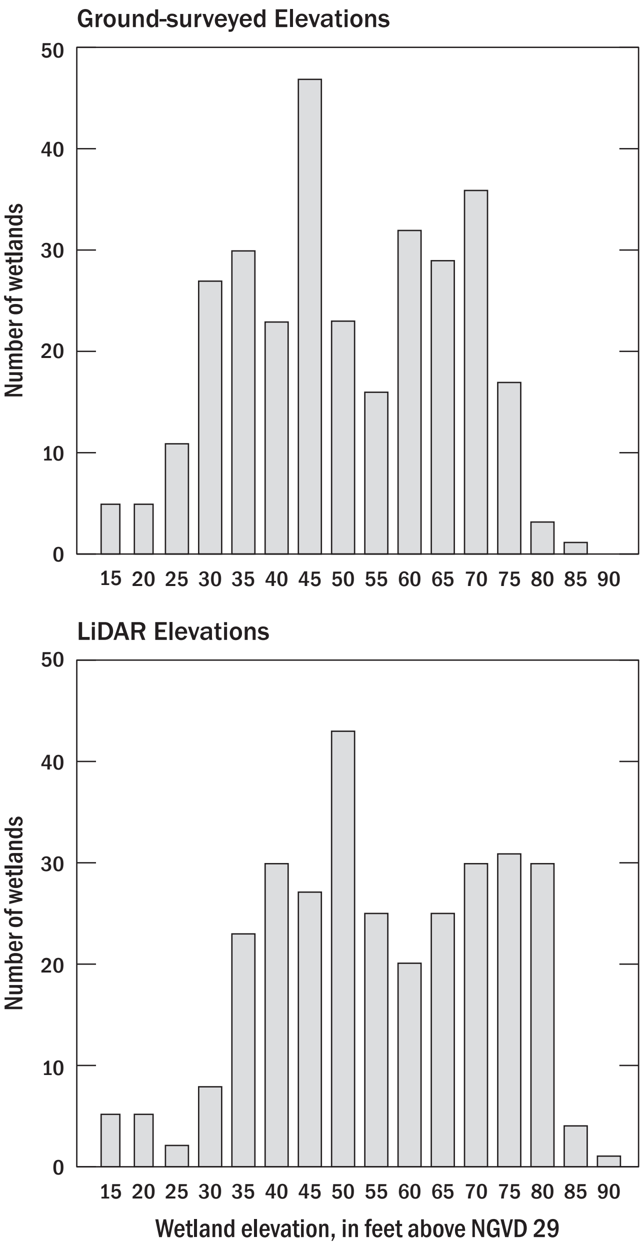


Figure 11. Distribution of land-surface elevations in 305 Tampa Bay Water wetlands based on ground surveying methods and LiDAR data.

Regional Groundwater Conditions

Regional maps were created in an animated time series to display areas where groundwater was discharging and recharging across a 581-mi^2 area in the Northern Tampa Bay area from January 1990 to December 2015. The animations show areas of discharging groundwater conditions expanding and contracting with the seasons, and the reciprocal changes in areas of recharging groundwater conditions.

Discharging groundwater conditions across the region are shown for one month, September 2015, selected from the 312-month time series (Figure 12). September 2015 was near the end of the wet season and had one of the highest potentiometric-surface elevations in the Upper Floridan aquifer after cutbacks in well field pumping (Lee and Fouad, 2017). As a result, discharging groundwater conditions, shown as dark blue areas, are widespread, occurring in wetland-dominated areas that act as the headwaters to tributary streams, below more geographically isolated wetlands, and along the stream channels of the Anclote River, Pithlachascotee River, Fivemile Creek, Hillsborough River, Cypress Creek, Trout Creek, Double Branch, and Rocky Creek. Smaller areas of wetlands with discharging groundwater conditions appear near the upstream ends of smaller tributaries such as Thirteenmile Creek in Hillsborough County which flows from the west into Cypress Creek, and Brushy Creek which flows from the Section 21 well field into Rocky Creek.

Discharging groundwater conditions likely increase the size of the contributing area in the six stream drainage basins that are partially represented within the mapping area (Figure 1; Fouad and Lee, 2011; Lee and Hughes, 2010). Areas that lacked discharging groundwater conditions in September 2015 included the northern extent of the Cross Bar Ranch well field, where the Upper Floridan aquifer is unconfined (Florida Department of Environmental Protection, 2004), and a region of northwestern Hillsborough County roughly bounded by five well fields: (moving clockwise from the north) South Pasco, Section 21, Northwest Hillsborough, Cosme, and Eldridge Wilde.

Areas without groundwater discharge in September 2015 are areas of groundwater recharge where the potentiometric surface lies below the land surface (Figure 13). September 2015 has one of the lowest groundwater recharge conditions in the mapping time series. The vertical distance of the Upper Floridan aquifer potentiometric surface below land surface partly dictates the recharge potential of the surficial aquifer and surface water features. For this reason, the recharging groundwater conditions are classified into five additional color categories in Figure 13. If we assume a static water table elevation that mirrors land surface, then light blue areas, where the potentiometric surface is within 5 ft of land surface, have the least potential for downward recharge. Red and green areas, where the potentiometric surface is 15 to 20 ft below land surface, or greater than 20 ft, respectively, have the greatest potential for downward recharge and wetland leakage.

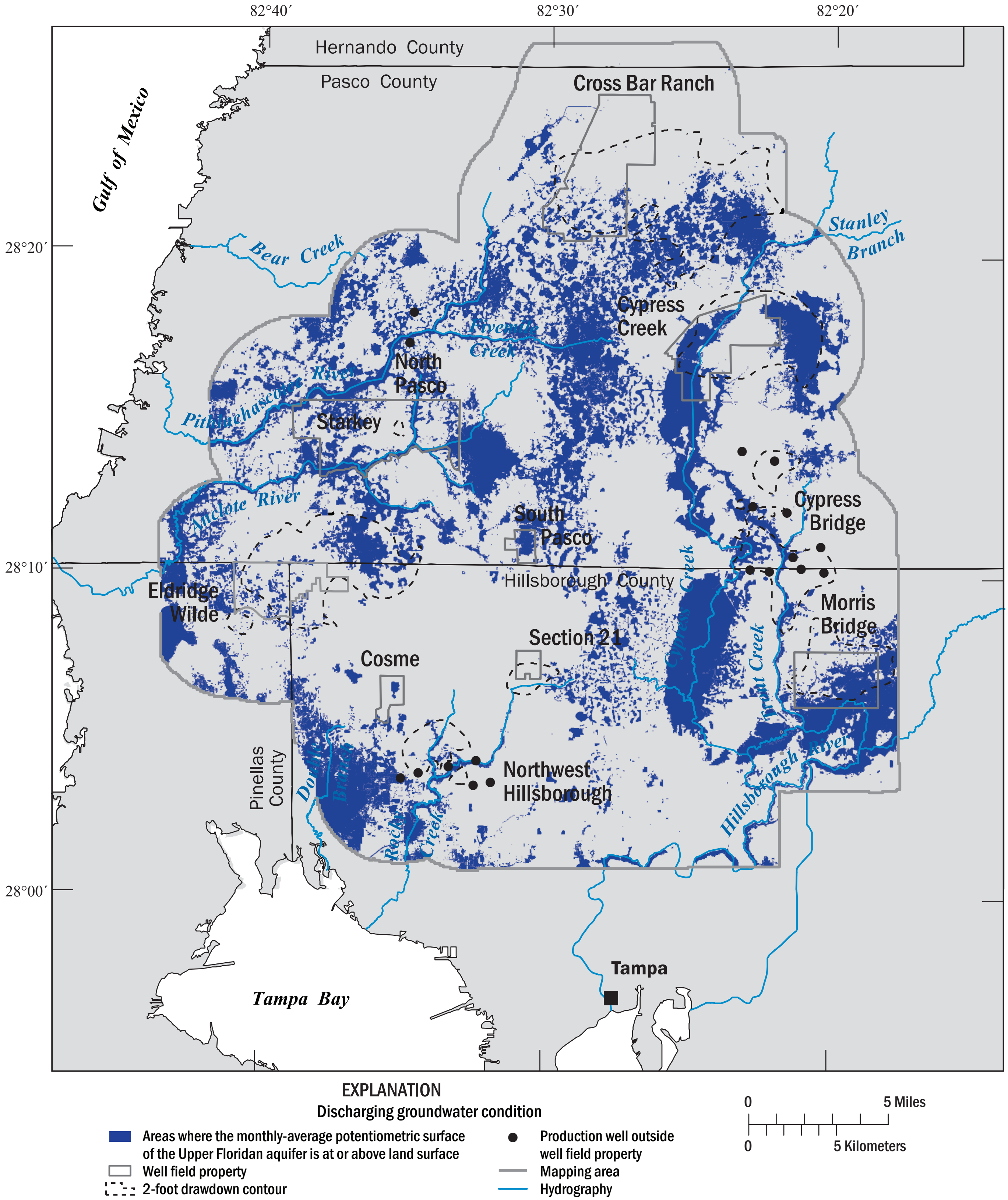


Figure 12. Discharging groundwater conditions in the Northern Tampa Bay area in September 2015.

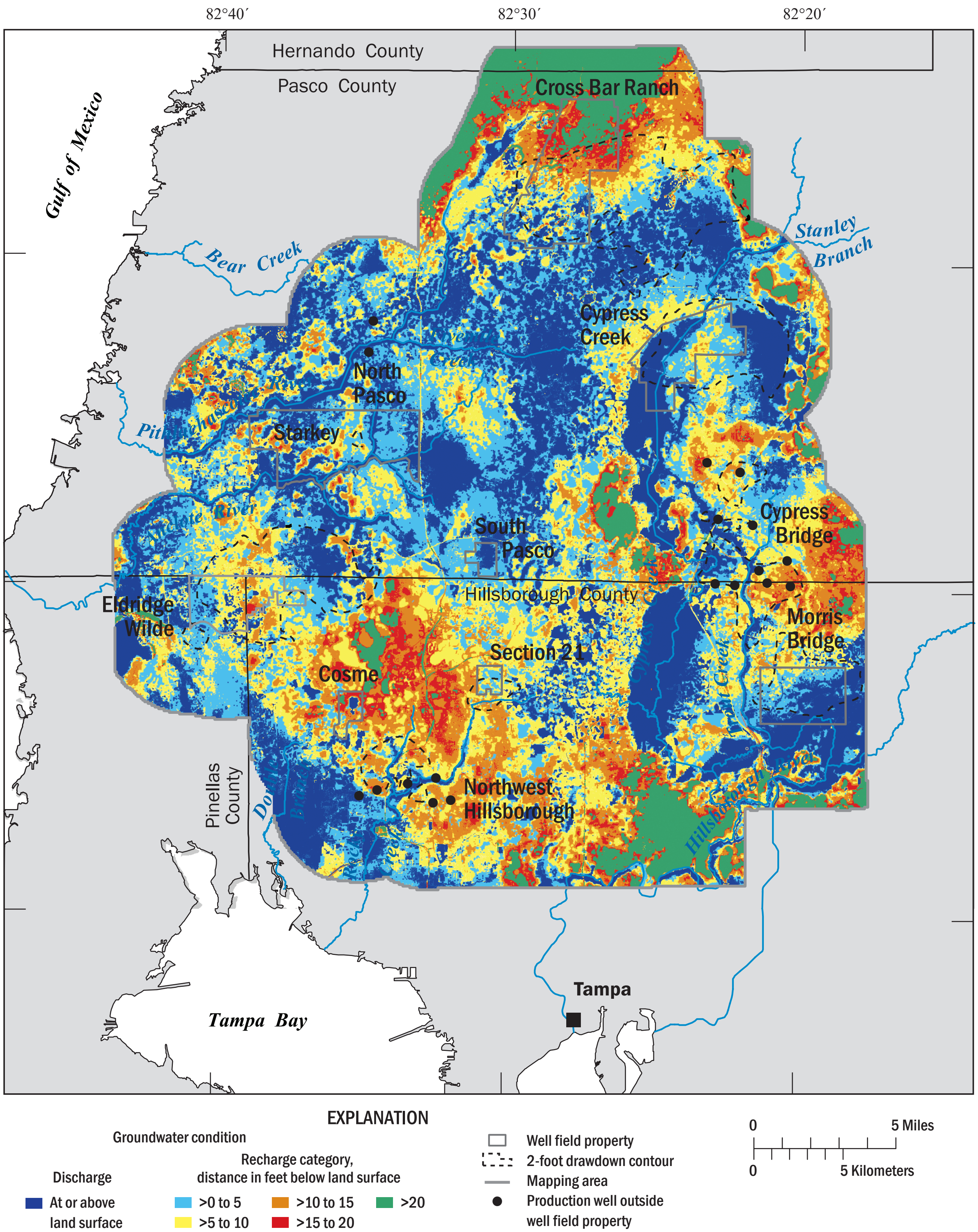


Figure 13. Discharging and recharging groundwater conditions in the Northern Tampa Bay area in September 2015.

Most of the highest recharge areas in Figure 13 are located where there is a combination of drawdown of the potentiometric surface by groundwater pumping plus locally higher land-surface elevations. For instance, the conspicuous green area of high recharge in the southeast corner of the map is associated with both locally higher land-surface elevations (Figure 1) and concentrated groundwater pumping of 3 to 5 mgd per mi^2 by users other than Tampa Bay Water (see Geurink and Basso (2013), Figure 2.70 and Lee and Fouad (2014), Figure 3). Perhaps not surprisingly, few wetlands occur in this area (Figure 3). Two other green (high) recharge areas are characterized by slightly higher land-surface elevations, drawdown due to well field pumping, and fewer wetlands: the northern half of Cross Bar Ranch well field and the area northeast of Cosme well field (Figure 13). A green area in the center-right region of the map just north of the Hillsborough County line is likely due to higher land surface elevations, although some drawdown from surrounding well fields may contribute to the higher recharge category. Another green recharge area occurs east of Cypress Bridge dispersed well field in an area with numerous wetlands and locally higher land surface elevations.

Wetland Groundwater Conditions-Population Statistics

Regional groundwater conditions lay the foundation for describing wetland groundwater conditions. This section describes the statistical distribution of wetland groundwater conditions in different wetland populations in May and September, and on an annual average basis. Annual average conditions (i.e. the average of 12 monthly values) are used to compare year-to-year variability in the wetland population, and to compare annual average conditions with predevelopment conditions. Statistically significant changes in wetland groundwater conditions are summarized for different wetland populations.

Predevelopment Groundwater Conditions

Predevelopment wetland groundwater conditions give an indication of the historical annual average groundwater conditions that were sufficient to evolve and sustain the regional wetland population. Thus, predevelopment population statistics become benchmarks that can be compared to contemporary wetland groundwater conditions and used as targets for recovering impaired wetlands.

Predevelopment groundwater conditions in the 10,516 National Wetlands Inventory wetlands follow a roughly normal frequency distribution that has a distinct central tendency and a longer tail to the left (Figure 14). The most frequently occurring groundwater condition in the wetland population is a recharge category with the potentiometric surface 0 to 5 ft below the land surface. Wetlands with the potentiometric surface 5 to 10 feet below land surface is the next most frequent category. The mean groundwater condition for the National Wetlands Inventory population is -4.71 ft and median is -4.65 ft, where negative indicates distance below land surface. Thus, in half of the wetland population, the predevelopment potentiometric surface of the Upper Floridan aquifer is either above land surface or within a distance of 4.65 ft below land surface. For 75 percent of the wetlands, the predevelopment potentiometric surface is within 8.10 ft of land surface. The number of wetlands decreases as the distance of the predevelopment potentiometric surface below land surface increases (see the tail to the left in Figure 14).

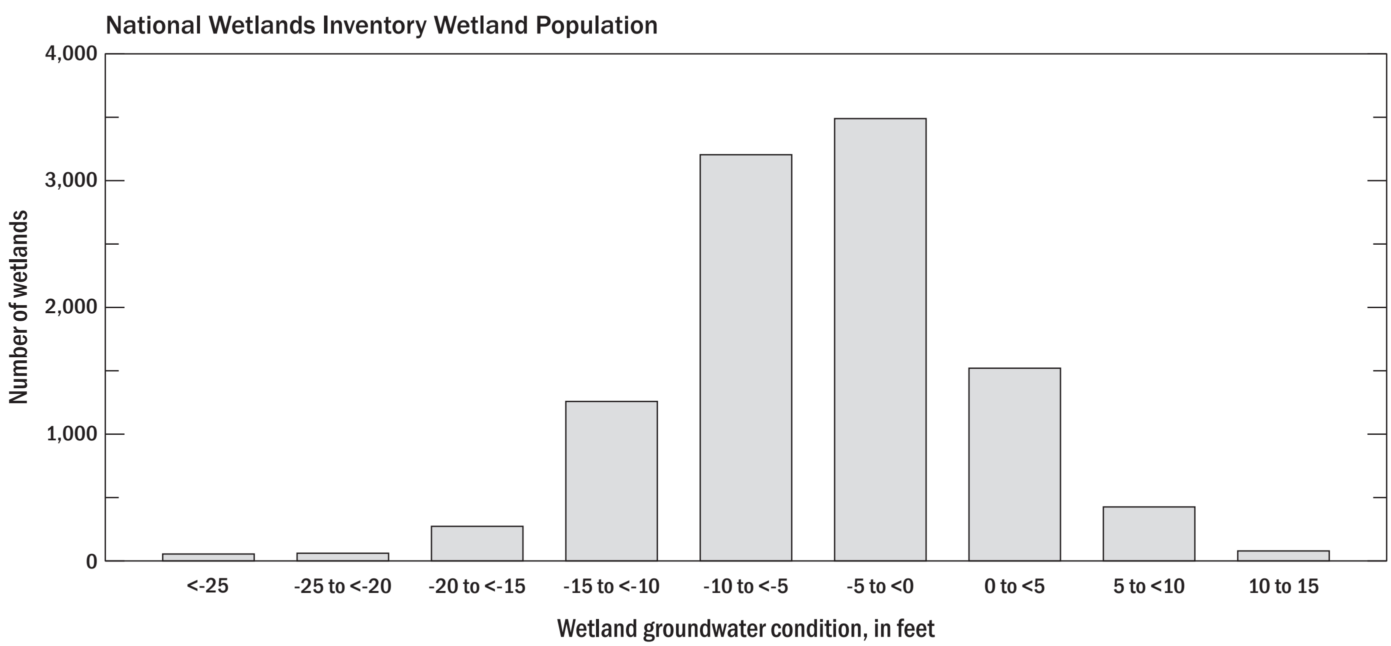


Figure 14. Distribution of predevelopment groundwater conditions in the National Wetlands Inventory wetland population.

The predevelopment median groundwater condition observed for the entire National Wetlands Inventory population changed for various (sub)populations. The Tampa Bay Water wetland population had a median predevelopment groundwater condition of -4.10 ft, or slightly closer to land surface than the median for the National Wetlands Inventory population (-4.65 ft). For the subpopulation of Tampa Bay Water wetlands inside well fields, the predevelopment median groundwater condition was -2.47 ft. Similarly, the subpopulation of National Wetlands Inventory wetlands inside well fields had a median predevelopment groundwater condition of -3.39 ft, indicating a potentiometric surface about a foot closer to land surface than for the entire National Wetlands Inventory population. This result could possibly reflect lower topographic elevation of wetlands inside well fields than outside, as well as higher potentiometric-surface elevations. Both characteristics would be consistent with the higher percentage of wetland area inside well fields than outside well fields (Table 2a).

Annual Average Groundwater Conditions

After pumping cutbacks, wetlands in the National Wetlands Inventory population experienced annual average groundwater conditions that more closely resembled predevelopment conditions than before cutbacks (Figure 15). Prior to cutbacks (1990-2002), median groundwater conditions were typically 5 to 10 ft below land surface (12 of 13 years) and minimum non-outlier values were typically 20 to 25 ft below land surface (9 of 13 years). After cutbacks (2003-2015), median groundwater conditions were typically 0 to 5 feet below land surface (9 of 13 years), closer to the predevelopment median of -4.65 ft, and non-outlier minima were typically 10 to 18 ft below land surface (9 of 13 years) and close to the non-outlier minimum predevelopment condition.

Contrary to this trend, the maximum (discharging) groundwater conditions were closer to the predevelopment maximum prior to cutbacks. The maximum non-outlier value of the potentiometric surface above wetland land surface became several feet lower in the post-cutback period (Figure 15). The interquartile range between the 25th and 75th percentile values decreased markedly after cutbacks. In several years after cutbacks, when rainfall was well above the long-term average (2003-2005 and 2012-2015 in Figure 6), groundwater conditions in the National Wetlands Inventory population displayed a higher median and smaller interquartile range than their predevelopment condition.

Annual average groundwater conditions in the Tampa Bay Water wetland population showed patterns similar to the National Wetlands Inventory population but conditions were comparatively lower both before and after cutbacks (Figure 16). Prior to cutbacks, non-outlier minima in the Tampa Bay Water wetland population were typically 25 to 30 ft below land surface (9 of 13 years), and the entire interquartile range (25th to 75th percentile values) of groundwater conditions was often below the predevelopment median (10 of 13 years). After cutbacks, median groundwater conditions were closer to land surface, the interquartile range is somewhat smaller, and non-outlier minimum annual average conditions are about 8 ft higher (from an average of -26.46 ft before cutbacks to -18.07 ft after cutbacks). The population

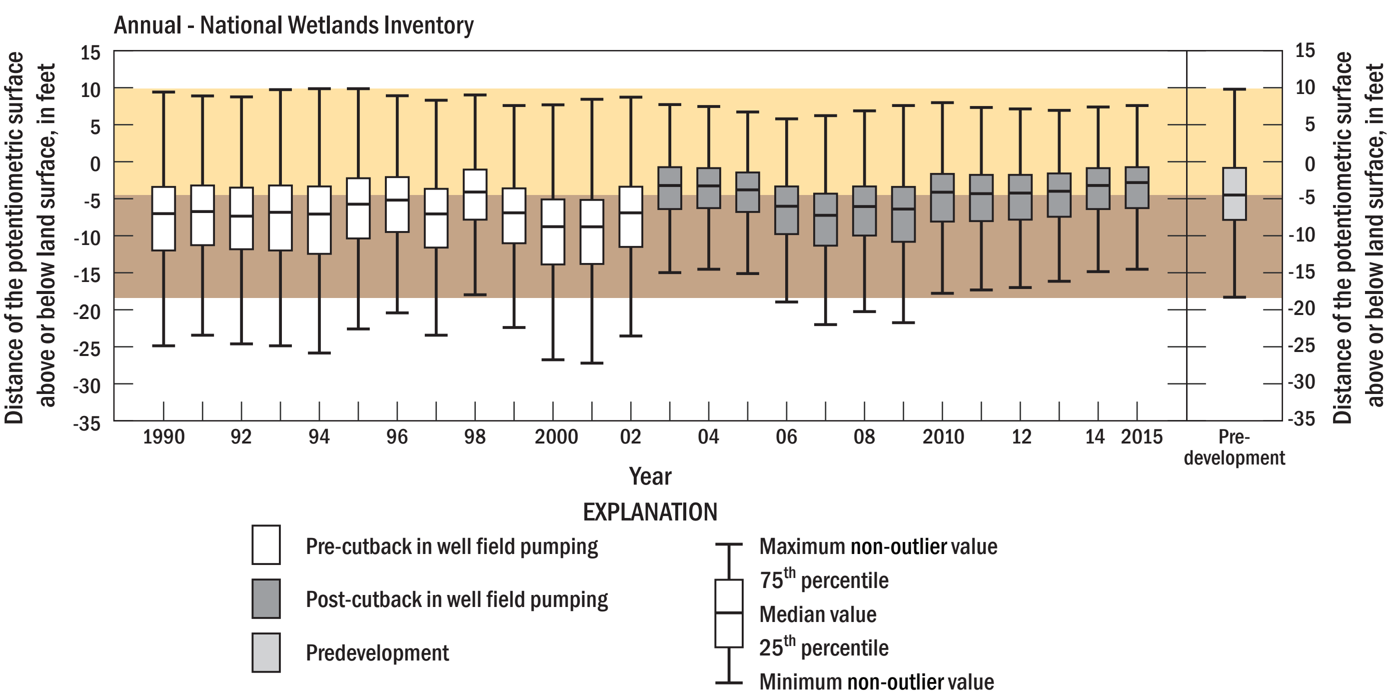


Figure 15. Annual average groundwater conditions in the National Wetlands Inventory wetland population from 1990 to 2015. Groundwater conditions in this population are also shown based on the simulated steady-state predevelopment potentiometric surface of Bush and Johnston (1988).

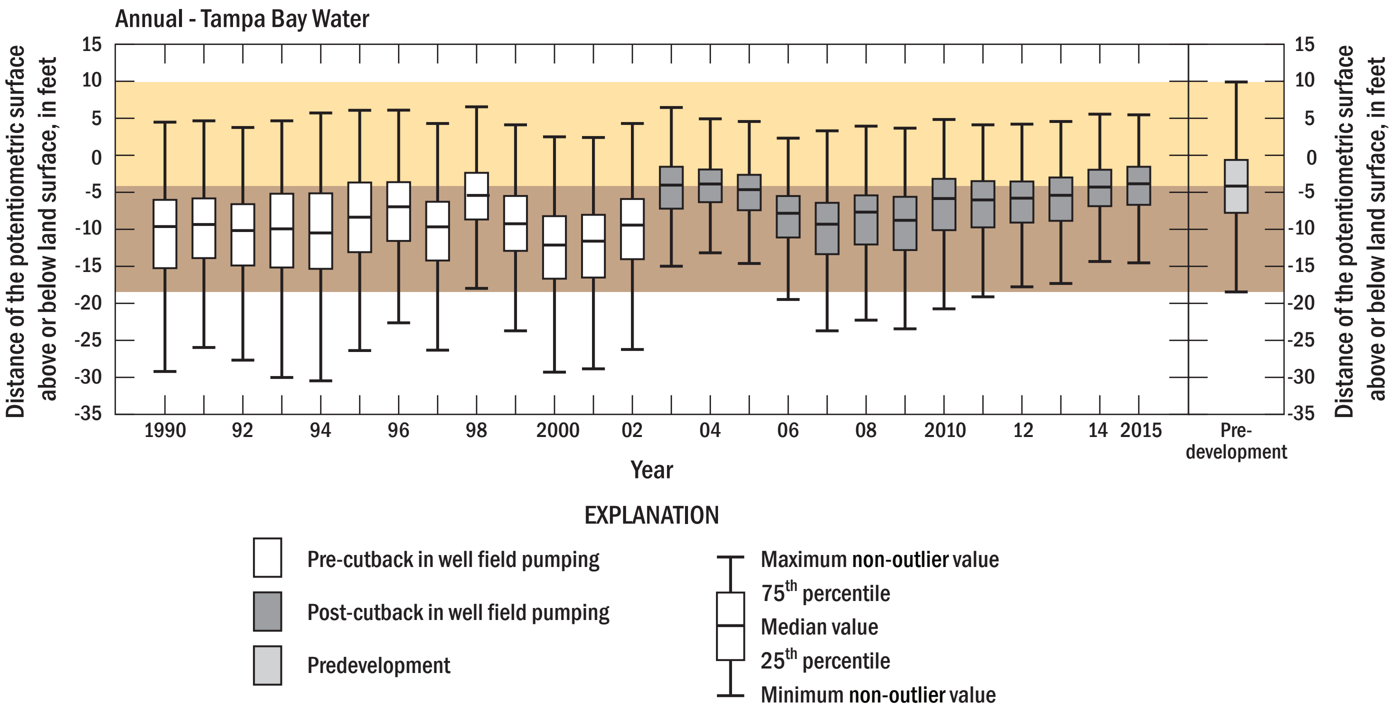


Figure 16. Annual average groundwater conditions in the Tampa Bay Water wetland population from 1990 to 2015. Groundwater conditions in this population are also shown based on the simulated steady-state predevelopment potentiometric surface of Bush and Johnston (1988).

median approached the predevelopment median during the wettest years after cutbacks (2003-2005 and 2014-2015 in Figure 6). In drier years from 2006 to 2009, when annual rainfall was below the long-term average, the interquartile range fell below the predevelopment median, resembling pre-cutback conditions, except that non-outlier minimum groundwater conditions were higher. Maximum groundwater (discharge) conditions were several feet lower in the Tampa Bay Water wetland population than in the National Wetlands Inventory population in years prior to cutbacks and did not increase after cutbacks.

May and September Groundwater Conditions

Wetland groundwater conditions in both May and September were higher in the National Wetlands Inventory population after cutbacks compared with before cutbacks, but conditions varied year to year (Figure 17). On the graphs, the interval from 0 to 5 ft below land surface is shaded gold to help visually compare the yearly variation.

Prior to cutbacks, median May groundwater conditions in Figure 17a were typically 5 to 10 ft below land surface (10 of 13 years), reaching 10 to 15 ft below land surface in the 2000 to 2002 drought years (Figure 6). Non-outlier minima groundwater conditions were typically 25 to 30 ft below land surface (9 of 13 years). In two exceptionally wet years, 1996 and 1998, non-outlier minima and median values were notably higher.

After cutbacks, May median values were in the gold interval from 0 to 5 ft below land surface for 6 of 13 years, and between 5 and 10 ft below land surface for 7 years. Non-outlier minima rose and were 15 to 20 ft below land surface for 7 of 13 years, and between 20 and 25 ft below land surface for another 3 years. A drought in 2007 and extreme dry seasons in 2009 and 2012 were associated with non-outlier minima greater than 25 ft below land surface. The wettest years (2003-2005 and 2014-2015) had non-outlier minima close to 15 ft below land surface. Both before and after cutbacks some wetlands in the population had discharging groundwater conditions in May, but May maxima appeared to undergo a steady decline across the 26-year period, similar to the decrease seen in the annual average maxima (Figure 15).

Wetland groundwater conditions in September changed markedly in the National Wetlands Inventory population after pumping cutbacks (Figure 17b). Prior to cutbacks, the median wetland groundwater condition was 5 to 10 ft below land surface in 9 of 13 years, and non-outlier minima were typically 20 to 28 ft below land surface (10 of 13 years). After pumping cutbacks, median groundwater conditions were in the gold band of 0 to 5 ft below land surface for 12 of 13 years, and non-outlier minima were typically 10 to 18 ft below land surface (10 of 13 years). The interquartile range from the 25th to 75th percentile values was noticeably smaller post-cutback, and in 6 years the interquartile range falls almost entirely inside the interval from 0 to 5 ft below land surface,

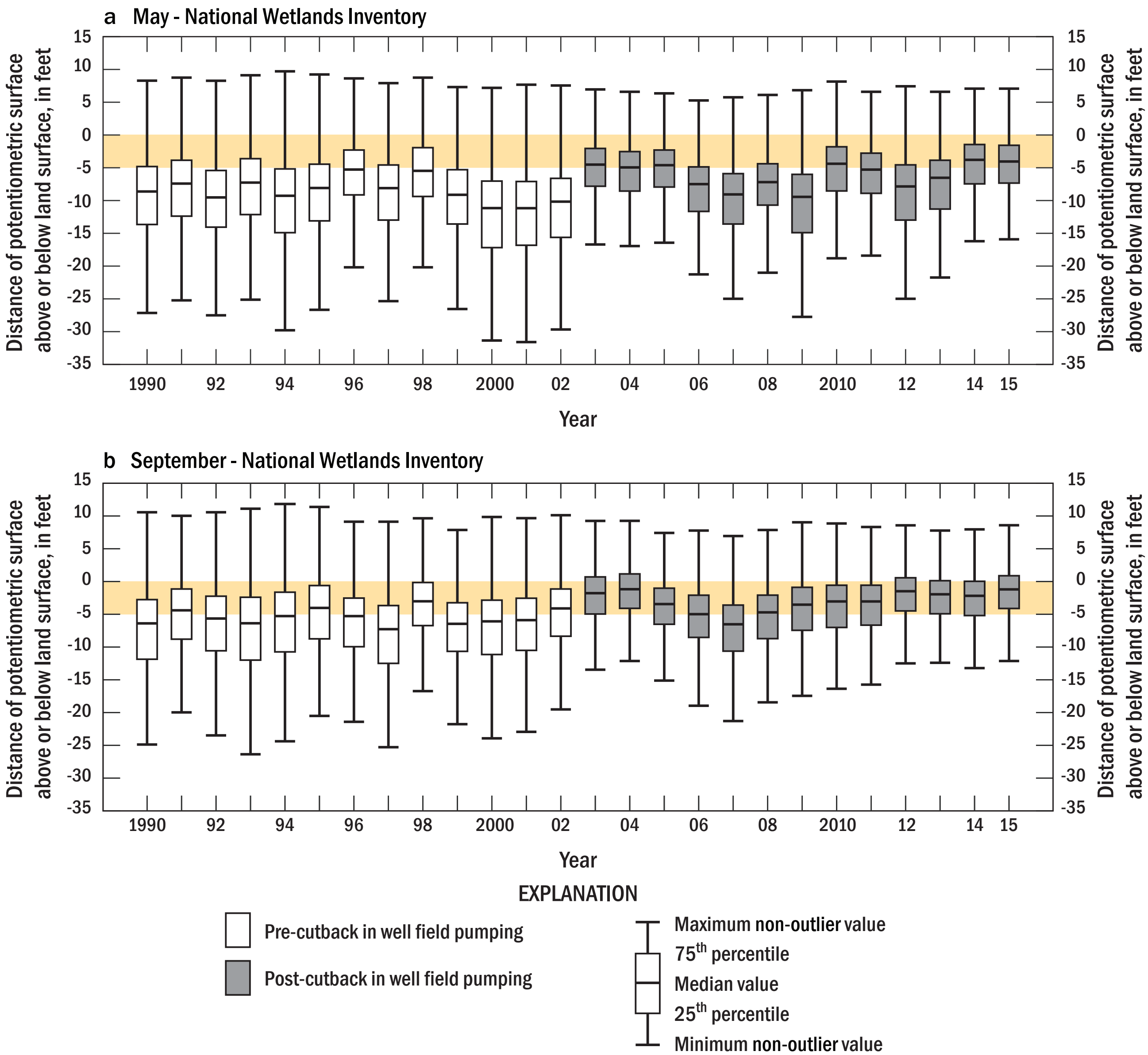


Figure 17. Monthly average groundwater conditions in the National Wetlands Inventory wetland population in (a) May and (b) September from 1990 to 2015.

indicating that three-quarters of the National Wetlands Inventory wetlands experienced either the lowest recharge condition category or discharging groundwater conditions in September of those years (2003-2004 and 2012-2015).

Groundwater conditions in the Tampa Bay Water wetland population in May also were higher after pumping cutbacks (Figure 18a). Prior to cutbacks, the median groundwater condition for the Tampa Bay Water wetland population in May was 10 to 16 ft below land surface in all but the two wettest years (1996 and 1998 in Figure 6). Non-outlier minima were close to or greater than 30 ft below land surface in 9 of 13 years. After cutbacks, median May groundwater conditions were mostly 5 to 10 ft below land surface, except for the drought in 2007 and extreme dry seasons in 2009 and 2012 when they were 10 to 15 ft below land surface. May median groundwater conditions in the Tampa Bay Water wetland population did not recover to within 0 to 5 ft below land surface after pumping cutbacks, as they did for the National Wetlands Inventory population. After cutbacks, May minima excluding outliers were generally higher but were variable: within 20 to 30 ft below land surface in 7 years and between 15 and 20 ft in 6 years. The 25^{th} to 75^{th} interquartile range became smaller after pumping cutbacks, most notably in the wettest years from 2003 to 2005 and 2014 to 2015. Maximum non-outlier values for the population commonly were above land surface (discharging) in years both before and after cutbacks. However, in some years discharging groundwater conditions were virtually absent in May in the Tampa Bay Water wetlands,

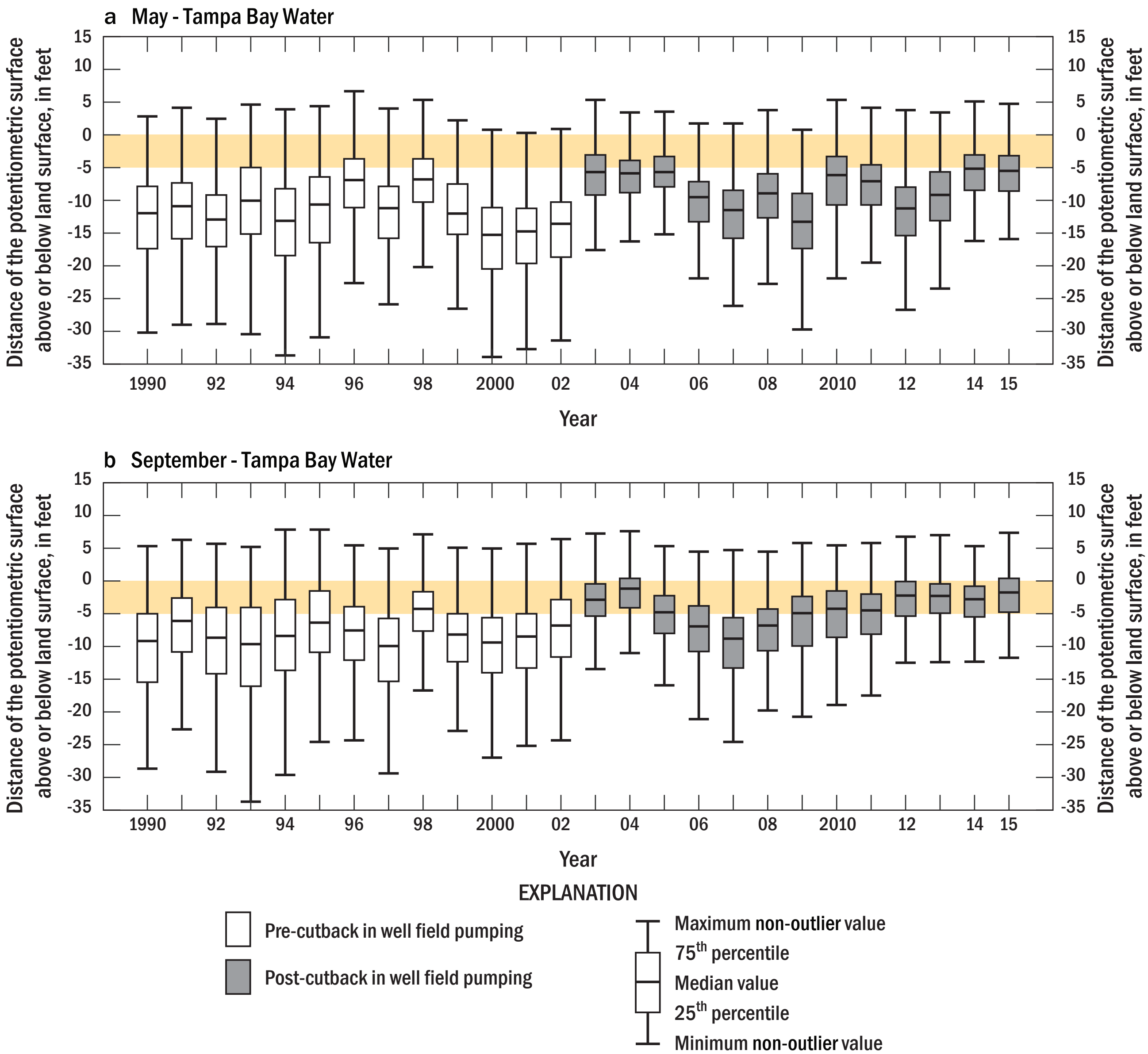


Figure 18. Monthly average groundwater conditions in the Tampa Bay Water wetland population in (a) May and (b) September from 1990 to 2015.

for instance, during drought years from 2000 to 2002 and the extreme dry season of 2009.

September groundwater conditions show a greater increase than May conditions in the Tampa Bay Water wetland population (Figure 18b). Prior to cutbacks in pumping, the median groundwater condition in September was typically 5 to 10 ft below land surface (12 of 13 years) and the non-outlier minima ranged from 23 to 35 ft below land surface in 11 of 13 years. After cutbacks, the median groundwater condition in September was typically 0 to 5 ft below land surface (10 of 13 years), and non-outlier minima were at or within 20 ft below land surface in 10 of 13 years, and no greater than 15 ft below land surface in the last 4 years. The interquartile range and range of non-outlier values were reduced after cutbacks, indicating less variable groundwater conditions across the wetland population in September.

Monitored Versus Unmonitored Wetlands

Groundwater conditions in two subpopulations within the Tampa Bay Water population, monitored wetlands (n = 410) and unmonitored wetlands (n = 682), were significantly different from one another before and after cutbacks, for each of the time intervals evaluated (Table 4). These two subpopulations were compared to evaluate whether the average

Table 4. Comparison of the wetland groundwater conditions in monitored and unmonitored subpopulations of the Tampa Bay Water population before and after cutbacks in well field pumping.

[Values are the average of wetland potentiometric surface minus land surface in feet; Negative values are below land surface; Averages and statistical tests based on 410 monitored wetlands and 682 unmonitored wetlands; Significant difference between the averages of the two subpopulations evaluated using a Student's t-test; Result of Student's t-test indicates a significant difference (Yes) if p-value ≤ 0.05]

Time Interval of the Population Average	Wetland Subpopulation and Statistical Difference	Temporal Averages Including Predevelopment, Pre- and Post-cutback, and All Years			
		Predevelopment	Pre-	Post-	All
Annual	Monitored	-2.1	-8.5	-5.3	-6.9
	Unmonitored	-5.8	-11.2	-7.8	-9.5
	Significant difference?	Yes	Yes	Yes	Yes
	p-value	0.00	0.00	0.00	0.00
May	Monitored	-	-10.6	-7.2	-8.9
	Unmonitored	-	-13.3	-9.8	-11.5
	Significant difference?	-	Yes	Yes	Yes
	p-value	-	0.00	0.00	0.00
September	Monitored	-	-7.2	-3.8	-5.5
	Unmonitored	-	-10.0	-6.0	-8.0
	Significant difference?	-	Yes	Yes	Yes
	p-value	-	0.00	0.00	0.00

groundwater conditions they experienced en masse were similar before and after cutbacks. If they were similar, it would imply that monitored wetlands, as a group, with their associated hydrology and ecology data, could serve as a proxy of conditions in the unmonitored wetlands. But the average groundwater conditions in the two subpopulations appear to be significantly different, and the significant differences were maintained when the groundwater conditions were compared for different time periods. Different average groundwater conditions suggest that wetlands in each population may need to be further grouped by shared physical factors, such as the wetland land surface elevation or proximity to pumping wells, to isolate monitored and unmonitored wetlands with comparable groundwater conditions.

Classified Groundwater Conditions

Temporal Characteristics

Differences in the groundwater conditions of the National Wetlands Inventory and Tampa Bay Water wetland populations, and changes in their yearly conditions, become increasingly evident when the percentage of wetlands that fall into five categories are compared. The resulting pie charts use the same color categories as color-classified maps (Figures 19 and 20). For the National Wetlands Inventory wetlands, the most noticeable change in groundwater condition is the reduction in the percentage of wetlands in the two highest recharge categories, orange and red, and the increase in the two blue categories after cutbacks (Figure 19). Recharging conditions diminish after cutbacks for all three time intervals although they are temporarily reversed by drier years from 2006 to 2009 (Figure 6). Other than these years, May pie charts show a major reduction in the percentage of wetlands in the orange and red categories after cutbacks in pumping. September pie charts are notable for the striking increase of wetlands in the discharging (dark blue) category and reduction in the red recharge category after pumping cutbacks. Yearly percentages in each groundwater condition category, and each of the time intervals (i.e. annual average, May, and September), are listed for the entire National Wetlands Inventory population (Table 5) and the subpopulation within well fields (Table 6).

Compared to the National Wetlands Inventory population, the Tampa Bay Water population had a larger percentage of wetlands in the two highest recharge categories prior to cutbacks, especially in the red category, and minimal discharging groundwater conditions on an annual average basis and in May (Figure 20). After cutbacks, the red recharge category was noticeably reduced for annual averages and in September, and less so in May. The percentage of wetlands experiencing discharging groundwater conditions increased markedly in September (Table 7).

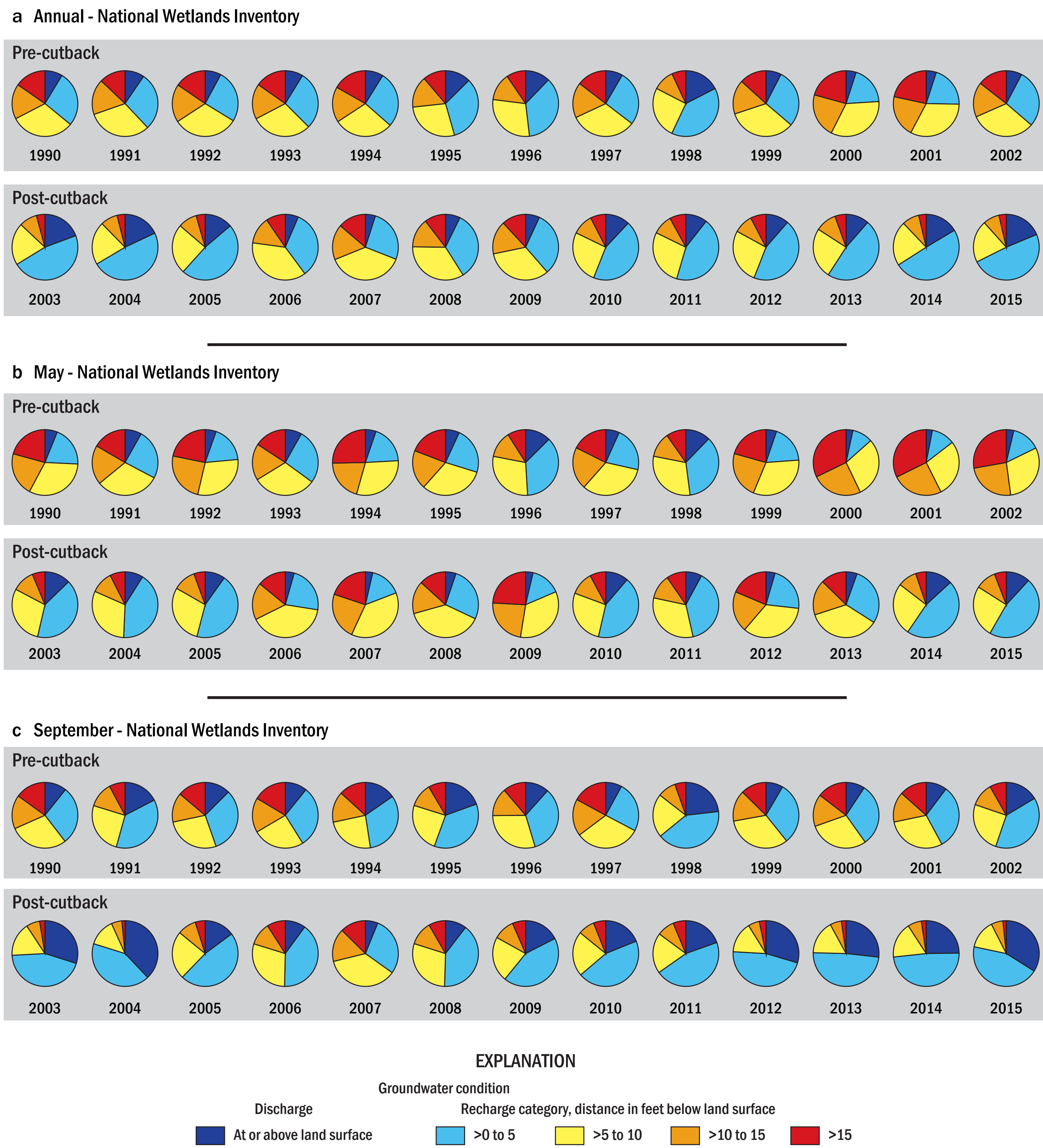


Figure 19. Percentage of the National Wetlands Inventory population in each wetland groundwater condition category (a) on annual average, and in (b) May and (c) September from 1990 to 2015.

Table 5. Percentage of the National Wetlands Inventory population in each wetland groundwater condition category from 1990 to 2015.

[Values are the percentage of wetlands in each groundwater condition category; National Wetlands Inventory population has 10,516 wetlands]

Year	Annual Groundwater Condition					May Groundwater Condition					September Groundwater Condition				
	At or Above Land Surface	Recharge Category				At or Above Land Surface	Recharge Category				At or Above Land Surface	Recharge Category			
		>0 to 5 ft	>5 to 10 ft	>10 to 15 ft	>15 ft		>0 to 5 ft	>5 to 10 ft	>10 to 15 ft	>15 ft		>0 to 5 ft	>5 to 10 ft	>10 to 15 ft	>15 ft
1990	8.7	27.3	31.5	17.3	15.3	6.1	19.6	32.1	21.5	20.7	10.7	28.8	28.8	16.6	15.0
1991	9.5	28.5	31.7	17.4	12.9	8.1	24.6	31.4	19.3	16.6	17.4	37.0	25.4	12.4	7.8
1992	7.9	25.9	32.1	18.7	15.5	5.4	18.1	30.1	24.5	21.8	12.5	32.1	27.1	14.5	13.8
1993	8.8	28.7	29.9	17.4	15.3	8.1	26.9	31.2	18.0	15.8	10.8	30.3	25.4	17.0	16.4
1994	8.8	27.7	29.3	17.4	16.8	5.2	18.9	30.2	20.3	25.3	15.4	32.2	24.1	15.1	13.2
1995	12.6	33.0	27.7	15.4	11.3	6.8	22.9	31.8	19.3	19.2	19.5	36.1	24.3	11.7	8.5
1996	12.2	35.9	28.9	13.5	9.5	12.5	36.5	29.0	13.0	9.0	11.6	33.7	29.5	13.9	11.2
1997	8.3	27.1	32.6	17.3	14.6	6.7	21.8	33.0	20.9	17.6	7.9	24.8	32.0	18.2	17.1
1998	17.4	39.6	25.6	10.5	6.9	12.2	35.7	30.1	12.2	9.7	23.2	40.9	21.4	9.1	5.4
1999	7.6	28.7	33.7	16.9	13.2	5.2	18.6	32.4	23.1	20.6	8.4	30.8	32.9	15.2	12.6
2000	5.0	19.1	33.4	21.8	20.7	3.3	10.1	29.5	24.9	32.2	9.3	30.9	29.4	15.8	14.6
2001	5.0	20.3	32.5	20.6	21.6	3.0	11.5	28.1	25.1	32.3	10.3	31.9	29.6	14.9	13.4
2002	7.7	28.6	32.1	17.1	14.5	3.7	14.1	30.1	24.4	27.8	16.4	38.8	25.0	11.5	8.2
2003	19.3	46.9	20.7	8.8	4.2	12.8	40.9	29.1	11.1	6.2	29.9	44.3	16.6	6.6	2.6
2004	18.0	48.5	21.2	8.4	3.9	9.0	41.7	30.9	10.9	7.5	38.0	41.9	13.4	5.2	1.6
2005	13.8	47.9	24.6	9.3	4.4	9.9	44.2	29.2	11.2	5.5	14.9	47.4	23.7	9.2	4.9
2006	6.5	33.4	37.2	13.3	9.5	4.4	23.1	40.1	18.3	14.1	10.1	40.3	29.4	11.2	9.1
2007	4.9	26.1	37.9	17.4	13.7	3.6	15.5	37.7	23.2	19.9	6.1	28.7	36.3	16.2	12.6
2008	7.2	33.8	34.1	14.4	10.4	5.2	26.8	38.6	16.1	13.3	10.4	40.0	29.4	11.8	8.3
2009	6.9	31.7	33.1	16.4	11.9	3.7	14.9	34.0	23.3	24.2	17.5	43.4	22.2	10.4	6.5
2010	12.0	44.0	26.2	10.3	7.5	11.3	42.3	27.1	11.5	7.8	18.9	44.9	22.1	8.1	6.0
2011	10.6	43.9	27.7	9.8	8.0	7.9	38.6	31.9	12.0	9.6	19.6	45.7	19.9	8.6	6.3
2012	11.4	44.5	27.1	9.4	7.6	4.5	22.3	34.5	20.1	18.6	29.6	46.3	15.3	5.6	3.3
2013	11.4	47.7	25.0	10.4	5.5	5.4	28.6	36.0	17.3	12.7	26.8	48.6	16.7	5.6	2.3
2014	16.4	49.6	21.9	8.4	3.7	13.2	46.3	26.0	9.4	5.2	24.8	48.5	17.5	6.8	2.4
2015	18.7	48.9	20.7	8.0	3.6	11.8	46.4	25.7	10.1	5.9	34.0	44.3	14.2	5.8	1.7

Table 6. Percentage of the National Wetlands Inventory subpopulation inside well fields in each wetland groundwater condition category from 1990 to 2015.

[Values are the percentage of wetlands in each groundwater condition category; Inside well field population has 4,584 wetlands inside 8 well field properties and 3-mile buffered areas around Cypress Bridge, North Pasco, and Northwest Hillsborough dispersed well fields]

Year	Annual Groundwater Condition					May Groundwater Condition					September Groundwater Condition				
	At or Above Land Surface	Recharge Category				At or Above Land Surface	Recharge Category				At or Above Land Surface	Recharge Category			
		>0 to 5 ft	>5 to 10 ft	>10 to 15 ft	>15 ft		>0 to 5 ft	>5 to 10 ft	>10 to 15 ft	>15 ft		>0 to 5 ft	>5 to 10 ft	>10 to 15 ft	>15 ft
1990	8.9	28.3	30.4	17.1	15.3	6.1	21.7	29.1	23.1	20.0	10.1	31.4	27.5	16.3	14.8
1991	10.0	28.2	30.2	18.7	12.8	8.0	25.4	29.1	21.3	16.1	18.2	34.6	24.9	13.3	9.0
1992	8.0	26.9	30.7	20.4	14.1	5.4	20.4	25.7	27.1	21.4	14.1	33.9	25.9	14.9	11.2
1993	9.1	31.2	28.1	17.9	13.6	8.0	29.9	28.7	18.8	14.6	11.7	33.1	22.9	16.9	15.3
1994	10.9	30.5	27.6	17.8	13.3	5.8	21.6	28.5	21.5	22.6	19.2	35.6	21.2	15.1	8.9
1995	15.3	35.2	24.6	15.9	9.1	7.2	25.1	30.8	19.5	17.3	24.3	37.3	20.5	11.7	6.2
1996	12.8	35.9	27.4	15.3	8.6	12.3	36.3	28.8	14.7	7.9	11.3	33.3	28.1	15.6	11.7
1997	8.6	27.4	31.9	17.8	14.4	7.0	22.8	30.6	21.6	18.0	8.0	26.7	30.9	18.2	16.3
1998	17.4	36.3	25.8	13.6	7.0	10.9	31.1	31.2	15.5	11.3	23.6	38.4	21.2	11.3	5.4
1999	7.0	26.5	32.8	19.0	14.6	4.2	17.4	28.2	25.6	24.6	8.0	29.5	31.5	17.5	13.5
2000	4.8	18.8	30.4	23.7	22.3	3.2	8.2	26.3	25.9	36.4	10.3	31.0	28.4	16.6	13.7
2001	5.0	20.8	30.2	22.4	21.5	3.3	11.0	24.5	27.6	33.7	12.4	32.2	28.4	15.0	12.1
2002	9.2	29.4	30.4	17.3	13.6	3.9	14.7	27.8	25.8	27.7	19.9	37.3	22.7	12.5	7.6
2003	21.0	41.9	21.9	11.1	4.1	14.6	36.0	29.8	13.4	6.2	27.3	42.6	18.9	8.6	2.7
2004	18.3	43.2	23.3	11.2	4.0	9.9	33.9	33.7	14.2	8.4	34.8	41.7	15.6	6.4	1.4
2005	14.2	41.6	27.1	12.0	5.1	10.1	37.3	32.4	13.6	6.6	14.6	42.1	26.8	11.6	4.9
2006	6.6	28.6	37.6	16.2	11.0	4.6	18.8	36.4	22.8	17.4	9.8	37.3	29.5	12.2	11.2
2007	5.4	23.1	38.1	19.2	14.1	4.1	13.3	33.4	26.9	22.3	5.9	26.3	37.7	17.7	12.3
2008	6.5	32.6	34.4	15.4	11.1	5.3	26.5	37.6	17.1	13.6	8.7	38.4	29.8	13.8	9.3
2009	6.0	29.6	33.1	17.7	13.6	3.4	13.2	30.7	25.1	27.5	18.2	42.3	22.4	10.7	6.4
2010	11.6	40.2	26.9	12.0	9.3	10.4	39.5	27.9	12.6	9.7	19.5	40.0	22.6	10.5	7.4
2011	9.3	40.0	28.7	12.2	9.9	7.4	35.0	31.8	13.8	12.0	17.3	41.5	22.1	11.7	7.4
2012	10.4	39.4	27.4	11.9	10.8	4.8	19.0	28.7	24.2	23.4	25.7	43.9	16.5	8.9	5.0
2013	10.6	39.6	28.7	13.4	7.7	5.6	23.1	32.4	22.2	16.9	23.4	45.6	19.5	8.6	3.0
2014	14.3	44.2	25.5	11.1	4.9	11.1	40.0	30.3	12.0	6.6	21.7	44.8	21.3	9.3	2.9
2015	15.2	44.1	25.1	11.4	4.1	9.7	39.6	29.6	14.1	7.0	28.6	43.8	17.7	8.1	1.8

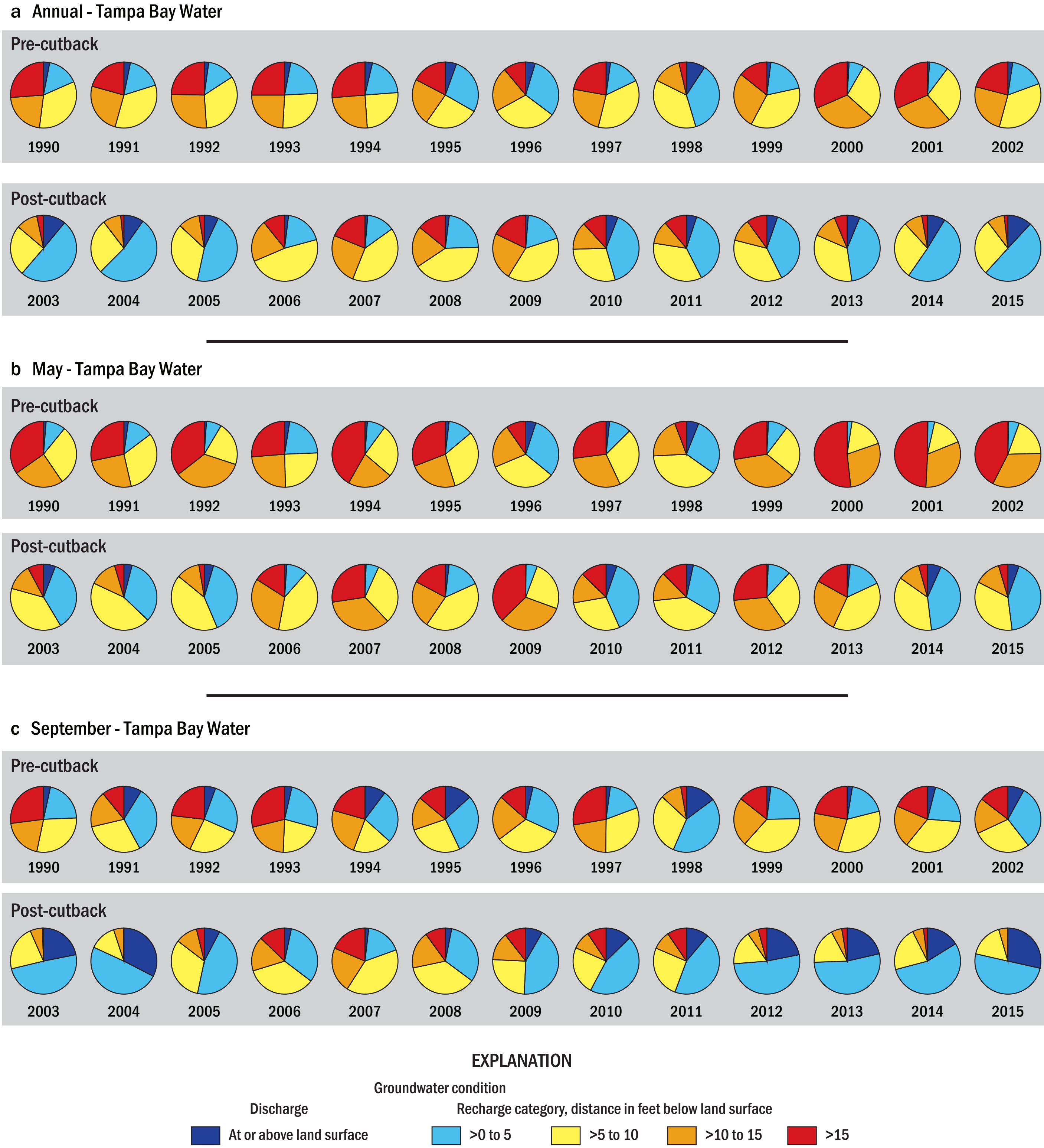


Figure 20. Percentage of the Tampa Bay Water population in each wetland groundwater condition category (a) on annual average, and in (b) May and (c) September from 1990 to 2015.

Table 7. Percentage of the Tampa Bay Water population in each wetland groundwater condition category from 1990 to 2015.

[Values are the percentage of wetlands in each groundwater condition category; Tampa Bay Water population has 1,092 wetlands]

Year	Annual Groundwater Condition					May Groundwater Condition					September Groundwater Condition				
	At or Above Land Surface	Recharge Category				At or Above Land Surface	Recharge Category				At or Above Land Surface	Recharge Category			
		>0 to 5 ft	>5 to 10 ft	>10 to 15 ft	>15 ft		>0 to 5 ft	>5 to 10 ft	>10 to 15 ft	>15 ft		>0 to 5 ft	>5 to 10 ft	>10 to 15 ft	>15 ft
1990	3.0	15.4	33.6	21.8	26.2	1.3	9.6	29.6	24.8	34.7	3.4	21.0	28.9	19.7	27.0
1991	3.2	16.9	34.2	25.0	20.7	2.2	12.5	31.7	25.3	28.3	8.8	33.2	29.3	17.8	10.9
1992	2.2	13.6	33.1	26.4	24.7	1.1	7.4	21.5	34.4	35.5	5.6	26.0	25.5	19.7	23.2
1993	3.0	21.2	26.7	24.1	25.0	2.5	21.9	25.3	24.1	26.3	3.6	25.6	21.5	20.4	28.8
1994	3.7	20.1	25.1	24.8	26.3	1.2	8.9	26.2	22.0	41.8	10.3	26.4	19.0	23.7	20.6
1995	5.5	27.7	26.5	23.0	17.3	1.8	12.1	31.3	23.9	30.9	13.3	29.6	26.9	16.3	13.9
1996	4.7	30.6	31.8	21.9	11.1	5.0	30.9	32.8	21.6	9.7	3.6	28.3	32.8	22.0	13.4
1997	2.2	15.7	36.0	24.0	22.2	1.7	10.8	30.5	29.9	27.0	2.1	17.2	30.9	22.1	27.7
1998	9.2	36.2	36.9	14.0	3.7	6.0	28.8	39.4	20.1	5.8	14.8	41.7	30.4	10.3	2.7
1999	2.0	19.6	36.2	27.9	14.3	0.8	9.5	25.5	36.5	27.6	2.0	22.7	36.9	24.0	14.4
2000	0.9	7.4	28.3	31.9	31.5	0.2	2.2	17.3	28.6	51.7	2.6	18.5	33.6	23.3	22.1
2001	0.9	9.3	28.3	29.9	31.6	0.2	3.3	15.4	32.0	49.2	3.9	22.3	34.7	20.6	18.5
2002	2.4	17.0	34.8	24.8	21.0	0.4	5.2	19.0	32.9	42.5	8.1	31.4	28.6	17.4	14.6
2003	11.0	50.3	24.9	10.5	3.3	5.9	35.5	37.9	12.9	7.8	21.9	49.4	22.2	6.0	0.5
2004	9.8	52.7	27.1	8.9	1.6	4.0	33.2	44.8	13.5	4.6	32.6	49.3	13.1	4.8	0.3
2005	7.0	46.4	33.5	10.5	2.6	4.6	39.0	42.3	11.4	2.7	7.7	45.6	32.1	10.8	3.8
2006	1.9	18.9	47.8	20.6	10.8	1.1	10.4	41.4	31.1	15.9	3.3	32.1	34.9	16.9	12.8
2007	1.4	13.7	40.9	25.2	18.8	0.5	6.2	31.1	34.7	27.4	1.8	17.7	39.6	22.3	18.6
2008	1.9	22.6	41.1	20.2	14.1	1.8	16.4	41.3	23.3	17.2	3.1	32.1	36.5	18.3	10.0
2009	1.3	18.8	38.7	23.4	17.9	0.2	5.5	24.9	32.1	37.3	8.3	42.4	25.0	13.7	10.5
2010	5.9	39.7	29.0	13.6	11.8	5.3	38.0	28.9	15.0	12.7	12.6	45.1	23.8	9.1	9.3
2011	5.0	37.5	35.0	11.4	11.2	3.4	30.1	39.8	14.3	12.4	11.2	44.5	25.7	9.1	9.5
2012	5.3	37.3	36.4	11.1	10.0	0.7	11.2	28.4	33.2	26.5	21.9	51.8	16.7	5.3	4.3
2013	6.2	41.5	33.8	12.2	6.3	1.5	16.6	38.8	26.2	16.9	21.4	53.0	17.7	5.2	2.7
2014	8.7	50.9	28.6	9.0	2.8	6.7	41.4	36.7	10.8	4.4	16.2	54.7	21.7	5.4	2.0
2015	11.9	49.8	27.9	8.5	1.8	5.5	42.5	34.5	12.9	4.6	28.5	50.1	16.9	4.3	0.2

Pre- Versus Post-Cutback Statistical Comparison

Wetland groundwater condition categories (see Tables 5-7) were used to statistically compare pre- (1990-2002) and post-cutback (2003-2015) time periods. Pre- and post-cutback changes in the National Wetlands Inventory groundwater condition categories are summarized in Table 8. When annual average wetland groundwater conditions are considered, cutbacks in pumping did not significantly increase the percentage of the wetland population in the discharging groundwater condition category. The number of wetlands in this category did increase after cutbacks from 9.2 percent (of 10,516 wetlands) to 12.1 percent but the change was not statistically significant. The percentage of all wetlands classified as discharging for the predevelopment condition, 19.7 percent, is shown for comparison.

A significant increase did occur in the percentage of wetlands in the 0-5 ft recharge category after cutbacks: from 28.5 to 42.1 percent of the population (Table 8). The increase in the percentage of wetlands in this category comes from statistically significant decreases in wetlands populating the two highest recharge categories. Wetlands in the orange recharge category, >10-15 ft, decreased from 17.0 to 11.1 percent of the population. Wetlands in the red category, >15 ft, decreased from 14.5 to 7.2 percent, and became much closer to the predevelopment estimate of 4.2 percent of the population in this category. The percentage of wetlands in the >5-10 ft category (yellow) remained relatively unchanged, and similar to the predevelopment percentage. Many wetlands that had discharging groundwater conditions under predevelopment conditions appear to now occupy the lowest recharge category of >0-5 ft. For the predevelopment condition, 53 percent of the National Wetlands Inventory wetland population had groundwater conditions in the discharging plus lowest recharge (>0-5 ft) categories combined. After cutbacks in pumping, 54 percent of all wetlands fell within these two categories, but with more of the wetlands in the lowest recharge category, >0-5ft, and fewer in the discharging category.

In May, groundwater conditions after cutbacks showed significant decreases in the percentage of the National Wetlands Inventory wetland population in the two highest recharge categories (>10-15 ft and >15 ft; Table 8). Results also indicate a significant increase of wetlands in the >0-5 ft recharge category. No significant change occurred in the percentage of wetlands experiencing discharging groundwater conditions.

Pumping cutbacks were associated with significant changes in every groundwater condition category in September. Significant decreases occurred in the three highest recharge categories (>5-10 ft, >10-15 ft, and >15 ft), while significant increases occurred in the percentage of wetlands with discharging groundwater conditions and the lowest recharge condition (>0-5 ft).

Table 8. Changes in groundwater conditions of the National Wetlands Inventory wetland population after pumping cutbacks.

[Values are the percentage of wetlands in each groundwater condition category; National Wetlands Inventory population has 10,516 wetlands; Significant change between pre- and post-cutback averages evaluated using a Student's *t*-test; Result of Student's *t*-test indicates a significant upward (Yes (up)) or downward (Yes (down)) change if p-value ≤ 0.05]

Time Interval of the Population Average	Pre- and Post-cutback Temporal Averages and Statistical Change	Percentage of Wetlands in Each Groundwater Condition Category				
		Discharging	Recharging (distance below land surface)			
		At or Above Land Surface	>0-5 ft	>5-10 ft	>10-15 ft	>15 ft
Annual	Predevelopment	19.7	33.3	30.7	12.1	4.2
	Pre	9.2	28.5	30.8	17.0	14.5
	Post	12.1	42.1	27.5	11.1	7.2
	Significant change?	No	Yes (up)	No	Yes (down)	Yes (down)
	p-value	0.09	0.00	0.09	0.00	0.00
May	Pre	6.7	21.5	30.7	20.5	20.7
	Post	7.9	33.2	32.4	15.0	11.6
	Significant change?	No	Yes (up)	No	Yes (down)	Yes (down)
	p-value	0.36	0.01	0.25	0.01	0.00
September	Pre	13.3	33.0	27.3	14.3	12.1
	Post	21.6	43.4	21.3	8.5	5.2
	Significant change?	Yes (up)	Yes (up)	Yes (down)	Yes (down)	Yes (down)
	p-value	0.01	0.00	0.01	0.00	0.00

The Tampa Bay Water wetlands exhibited similar changes overall to the National Wetlands Inventory population (Table 9). After cutbacks, the highest recharge categories (>10-15 ft and >15 ft) significantly decreased in both wetland populations and significantly increased in the lowest recharge category (>0-5 ft). For the Tampa Bay Water wetlands after cutbacks, the percentage of wetlands in the lowest recharge category on an annual average basis was similar to predevelopment conditions. The percentage of Tampa Bay Water wetlands with discharging groundwater conditions on an annual average basis significantly increased after cutbacks, whereas the increase was not significant in the National Wetlands Inventory population. In spite of the increase, the percentage gap between predevelopment conditions and observed conditions for Tampa Bay Water wetlands remained larger than for the National Wetlands Inventory population. Both wetland populations had similar changes in seasonal (May and September) discharging groundwater conditions.

Pre- and post-cutback changes differed for the subpopulations of the National Wetlands Inventory wetlands that were inside well fields and outside well fields (Table 10). Inside well fields, wetlands in the two highest recharge categories (>10-15 ft and >15 ft) significantly decreased after cutbacks. But inside well fields wetlands lost from these two categories stayed in a relatively higher recharge category than outside well fields. For instance, on an annual average basis, the percentage of wetlands outside well fields that had discharging groundwater conditions or were in the >0-5 ft recharge category significantly increased after cutbacks. Inside well fields, there was only a significant increase in the >0-5 ft recharge category and no significant increase in discharging groundwater conditions.

Wet and dry seasons emphasize the different response to cutbacks of wetland groundwater conditions inside and outside well fields. For May, the percentage of wetlands outside well fields in the lowest recharge category, >0-5 ft, significantly increased (Table 10). Inside well fields, a significant increase occurred in the percentage of wetlands in the next higher recharge category, >5-10 ft. The results indicate that, after cutbacks, more wetlands outside well fields shifted to lower recharge conditions than inside well fields.

Similarly, September groundwater conditions responded differently to cutbacks inside and outside well fields (Table 10). The percentage of wetlands significantly decreased for the three highest recharge categories (>5-10 ft, >10-15 ft, and >15 ft) outside well fields, but only the two highest recharge categories (>10-15 ft and >15 ft) significantly decreased inside well fields. As a result of a greater decrease in recharge conditions outside well fields, discharging groundwater conditions and the lowest recharge category (>0-5 ft) significantly increased. Only the lowest recharge category significantly increased inside well fields.

Changes in the groundwater condition categories after cutbacks were evaluated for the National Wetlands Inventory wetlands inside and outside a simulated 2-foot drawdown contour (Tampa Bay Water, 2013; Table 11). The change in groundwater condition categories on an annual average basis was generally larger inside the drawdown contour than inside well fields (Table 10). The highest recharge categories (>10-15 ft and >15 ft) decreased after cutbacks for wetlands inside

Table 9. Changes in groundwater conditions of the Tampa Bay Water wetland population after pumping cutbacks.

[Values are the percentage of wetlands in each groundwater condition category; Tampa Bay Water population has 1,092 wetlands; Significant change between pre- and post-cutback averages evaluated using a Student's t-test; Result of Student's t-test indicates a significant upward (Yes (up)) or downward (Yes (down)) change if p-value ≤ 0.05]

Time Interval of the Population Average	Pre- and Post-cutback Temporal Averages and Statistical Change	Percentage of Wetlands in Each Groundwater Condition Category				
		Discharging	Recharging (distance below land surface)			
		At or Above Land Surface	>0-5 ft	>5-10 ft	>10-15 ft	>15 ft
Annual	Predevelopment	21.4	34.1	30.1	8.0	6.4
	Pre	3.3	19.3	31.6	24.6	21.2
	Post	5.9	36.9	34.2	14.2	8.7
	Significant change?	Yes (up)	Yes (up)	No	Yes (down)	Yes (down)
	p-value	0.04	0.00	0.25	0.00	0.00
May	Pre	1.9	12.5	26.6	27.4	31.6
	Post	3.2	25.1	36.2	20.9	14.6
	Significant change?	No	Yes (up)	Yes (up)	Yes (down)	Yes (down)
	p-value	0.12	0.01	0.00	0.04	0.00
September	Pre	6.3	26.5	29.2	19.8	18.3
	Post	14.7	43.7	25.1	10.1	6.5
	Significant change?	Yes (up)	Yes (up)	No	Yes (down)	Yes (down)
	p-value	0.01	0.00	0.14	0.00	0.00

Table 10. Changes in groundwater conditions of the National Wetlands Inventory wetlands inside and outside well fields after pumping cutbacks.

[Values are the percentage of wetlands in each groundwater condition category; Inside well field population has 4,584 wetlands inside 8 well field properties and 3-mile buffered areas around Cypress Bridge, North Pasco, and Northwest Hillsborough dispersed well fields; Outside well field population has 5,932 wetlands; Significant change between pre- and post-cutback averages evaluated using a Student's *t*-test; Result of Student's *t*-test indicates a significant upward (Yes (up)) or downward (Yes (down)) change if *p*-value ≤ 0.05]

Time Interval of the Population Average	Wetland Subpopulation	Pre- and Post-cutback Temporal Averages and Statistical Change	Percentage of Wetlands in Each Groundwater Condition Category				
			Discharging	Recharging (distance below land surface)			
			At or Above Land Surface	>0-5 ft	>5-10 ft	>10-15 ft	>15 ft
Annual	Inside well field	Predevelopment	29.9	30.9	25.5	10.5	3.2
		Pre	9.8	28.9	29.3	18.2	13.9
		Post	11.5	37.5	29.1	13.5	8.4
		Significant change?	No	Yes (up)	No	Yes (down)	Yes (down)
		p-value	0.32	0.00	0.90	0.00	0.00
	Outside well field	Predevelopment	11.9	35.1	34.8	13.3	5.0
		Pre	8.7	28.2	32.0	16.1	14.9
		Post	12.5	45.6	26.3	9.3	6.3
		Significant change?	Yes (up)	Yes (up)	Yes (down)	Yes (down)	Yes (down)
		p-value	0.03	0.00	0.01	0.00	0.00
May	Inside well field	Pre	6.6	22.0	28.4	22.2	20.9
		Post	7.7	28.9	31.9	17.8	13.7
		Significant change?	No	No	Yes (up)	Yes (down)	Yes (down)
		p-value	0.35	0.07	0.00	0.03	0.03
	Outside well field	Pre	6.7	21.1	32.4	19.2	20.5
		Post	8.0	36.6	32.7	12.7	9.9
		Significant change?	No	Yes (up)	No	Yes (down)	Yes (down)
		p-value	0.39	0.00	0.89	0.00	0.00
September	Inside well field	Pre	14.7	33.4	25.7	15.0	11.2
		Post	19.7	40.8	23.1	10.6	5.8
		Significant change?	No	Yes (up)	No	Yes (down)	Yes (down)
		p-value	0.09	0.00	0.21	0.00	0.00
	Outside well field	Pre	12.3	32.6	28.5	13.8	12.8
		Post	23.0	45.4	19.9	6.9	4.7
		Significant change?	Yes (up)	Yes (up)	Yes (down)	Yes (down)	Yes (down)
		p-value	0.00	0.00	0.00	0.00	0.00

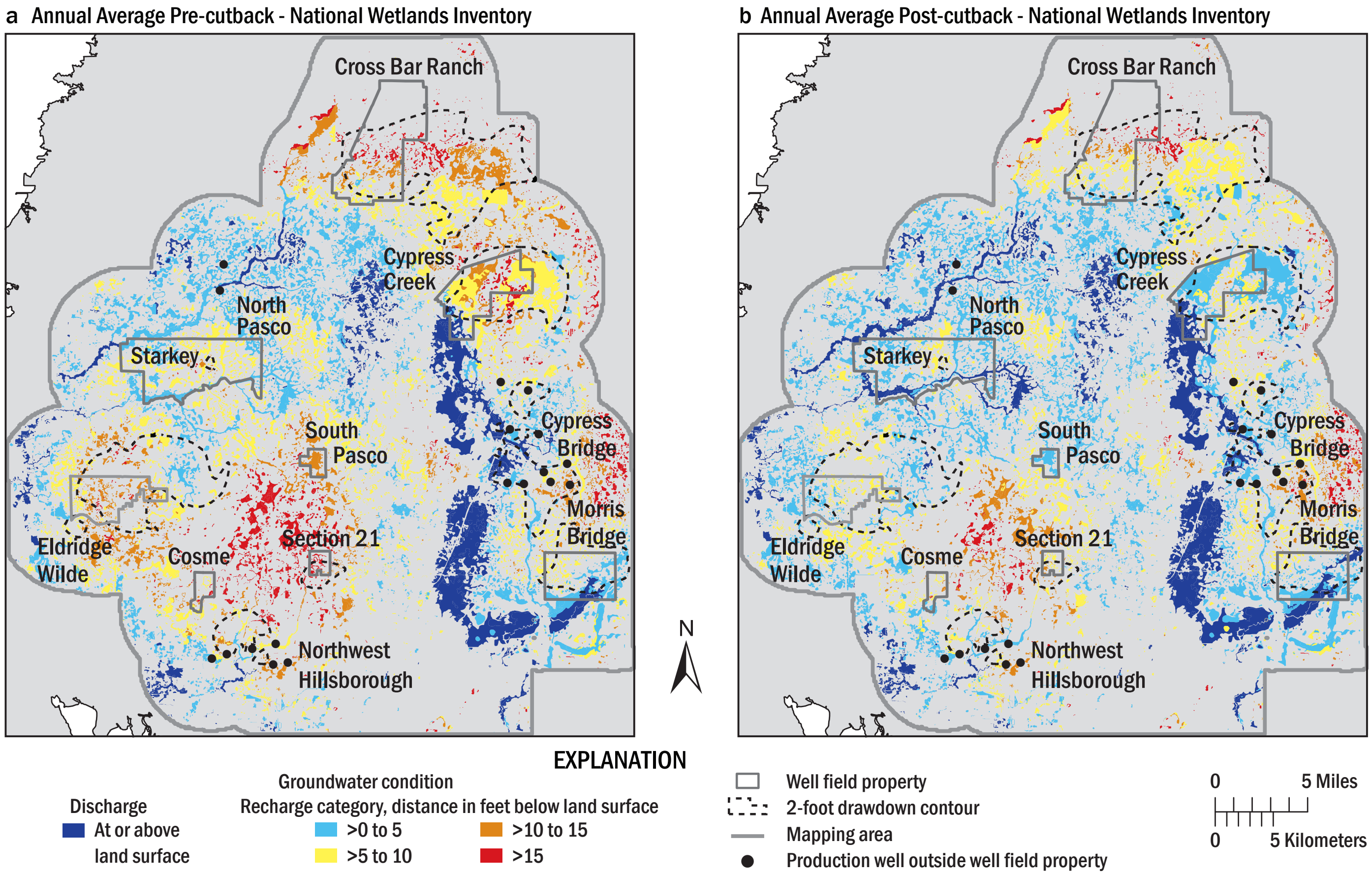
and outside the drawdown contour. Wetlands lost from these categories shifted to recharging categories closer to land surface (see significant increases in >0-5 ft and >5-10 ft recharge categories) or, to a lesser degree, the discharging category. Changes in annual average groundwater condition categories inside versus outside the drawdown contour differed because larger decreases in the two highest recharge categories (>10-15 ft and >15 ft) inside the drawdown contour generated significant increases in the >0-5 ft and >5-10 ft recharge categories. Smaller decreases in recharge categories outside the drawdown contour resulted in a significant increase in the >0-5 ft recharge category, which became larger than predevelopment conditions. If annual average groundwater conditions in more of these wetlands shift above land surface, discharging groundwater conditions outside the drawdown contour may resemble that of predevelopment conditions.

Table 11. Changes in groundwater conditions of the National Wetlands Inventory wetlands inside and outside of a 2-foot drawdown contour (Tampa Bay Water, 2013) after pumping cutbacks.

[Values are the percentage of wetlands in each groundwater condition category; Inside drawdown population has 1,381 wetlands inside a simulated 2-foot drawdown contour delineated by Tampa Bay Water (2013); Outside drawdown population has 9,135 wetlands; Significant change between pre- and post-cutback averages evaluated using a Student's *t*-test; Result of Student's *t*-test indicates a significant upward (Yes (up)) or downward (Yes (down)) change if *p*-value ≤ 0.05; Reference - Tampa Bay Water (TBW), 2013, Defining areas of investigation for recovery analysis. Tampa Bay Water Report, 22 p.]

Time Interval of the Population Average	Wetland Subpopulation	Pre- and Post-cutback Temporal Averages and Statistical Change	Percentage of Wetlands in Each Groundwater Condition Category				
			Discharging	Recharging (distance below land surface)			
			At or Above Land Surface	>0-5 ft	>5-10 ft	>10-15 ft	>15 ft
Annual	Inside drawdown	Predevelopment	18.4	30.1	35.9	8.7	6.9
		Pre	4.3	15.4	29.3	28.3	22.6
		Post	5.1	31.6	35.5	17.3	10.4
		Significant change?	No	Yes (up)	Yes (up)	Yes (down)	Yes (down)
		p-value	0.57	0.00	0.02	0.00	0.00
	Outside drawdown	Predevelopment	19.9	33.7	30.0	12.6	3.8
		Pre	10.1	30.4	30.9	15.3	13.2
		Post	12.8	42.5	26.7	10.6	7.3
		Significant change?	No	Yes (up)	Yes (down)	Yes (down)	Yes (down)
		p-value	0.13	0.00	0.04	0.00	0.00
May	Inside drawdown	Pre	2.7	10.9	24.6	28.8	33.0
		Post	2.3	20.6	34.8	24.5	17.9
		Significant change?	No	No	Yes (up)	No	Yes (down)
		p-value	0.67	0.06	0.01	0.21	0.02
	Outside drawdown	Pre	7.6	23.8	31.7	18.9	18.1
		Post	8.4	33.6	31.8	14.3	11.9
		Significant change?	No	Yes (up)	No	Yes (down)	Yes (down)
		p-value	0.56	0.02	0.92	0.02	0.02
September	Inside drawdown	Pre	7.4	19.4	29.6	23.9	19.6
		Post	13.6	38.9	27.8	11.8	7.9
		Significant change?	No	Yes (up)	No	Yes (down)	Yes (down)
		p-value	0.07	0.00	0.57	0.00	0.00
	Outside drawdown	Pre	13.9	34.4	27.2	13.1	11.3
		Post	22.3	43.7	20.6	8.3	5.0
		Significant change?	Yes (up)	Yes (up)	Yes (down)	Yes (down)	Yes (down)
		p-value	0.01	0.00	0.00	0.00	0.00

Wet and dry season changes inside and outside the drawdown contour (Table 11) were similar to those inside and outside the well fields (Table 10). Inside the drawdown contour, groundwater condition categories that showed a significant increase were in relatively higher recharge categories than outside the drawdown contour. May groundwater conditions followed this pattern with a significant increase occurring in a higher recharge category (>5-10 ft) inside the drawdown contour than outside the drawdown contour (>0-5 ft). In September, groundwater conditions inside the drawdown contour significantly increased in the lowest recharge category (>0-5 ft), but outside the drawdown contour, discharging groundwater conditions significantly increased.



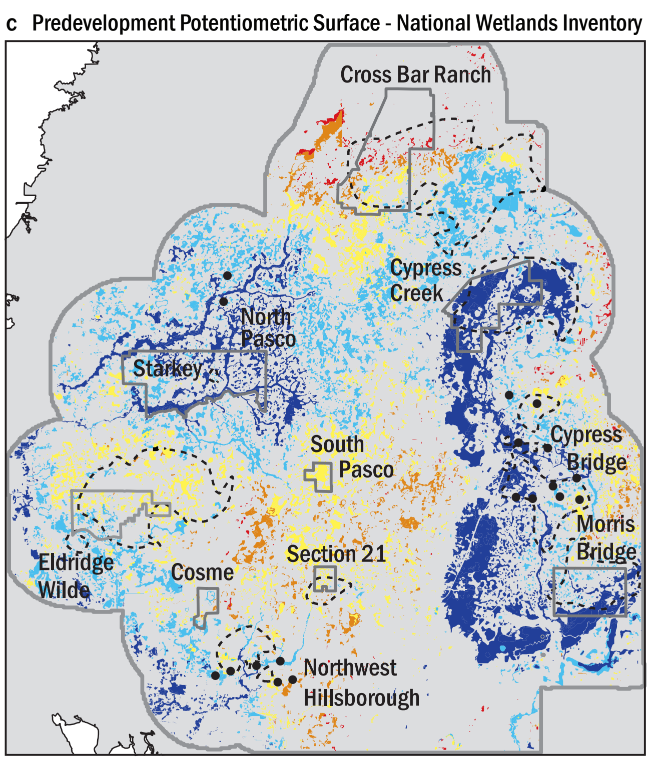


Figure 21. Classified wetland groundwater conditions in the National Wetlands Inventory population (a) before and (b) after cutbacks in well field pumping, and (c) prior to any pumping in the Upper Floridan aquifer.

Spatial Characteristics

Maps show the spatial changes in wetland groundwater conditions that occurred across the Northern Tampa Bay area over 26 years. The first series of maps illustrates groundwater conditions for the 10,516 National Wetlands Inventory wetlands, the second for 1,092 Tampa Bay Water wetlands. There is a lot of information displayed in both map series, and it is not possible to elaborate on all of the changes that are displayed. For that reason, the reader is encouraged to spend time studying the different areas of the maps where the wetlands are of particular interest to them. In this section, we present an overview of the changes in wetland groundwater conditions occurring in different regions of the Northern Tampa Bay area, on an annual average basis, which averages the seasonal extremes, and in May and September, which exemplify dry and wet seasonal extremes.

Annual average wetland groundwater conditions inside well fields and within stream drainage basins show a marked hydrologic recovery in the 13 years (2003-2015) after pumping cutbacks compared to the 13 years (1990-2002) before cutbacks (Figure 21). Groundwater recharge categories decreased to light blue – the lowest recharge category – in wetlands in and around Cypress Creek, Morris Bridge, South Pasco, and Starkey well fields. Discharging groundwater conditions (dark blue), which had been absent in wetlands along a stretch of about 10-15 miles of the Pithlachascotee River before cutbacks, extend along the entire length of the river and into some smaller tributaries along the main stream channel after cutbacks.

Discharging groundwater conditions also occur along much of the Anclote River after cutbacks, whereas they were nearly absent before cutbacks (Figures 21a and b). Notably, discharging groundwater conditions returned at some geographically isolated headwater wetlands of the Anclote River and at wetlands that bracket the main stream channel, traits that are estimated to occur under predevelopment conditions (Figure 21c). Discharging wetland conditions also appear for several miles along a tributary that flows into the Anclote from the south. Low recharge conditions on annual average still characterize most wetlands in Starkey well field and the wetlands for several miles along the Anclote River where it borders Starkey well field.

Wetlands east of Double Branch, between Cosme and Northwest Hillsborough well fields, as well as along Double Branch, went from yellow (higher recharge) to light blue (lower recharge) on annual average after cutbacks (Figures 21a and b). In a similar fashion, lower recharging conditions (light blue) replaced higher recharging conditions (yellow) at wetlands along Trout Creek in the western half of Morris Bridge well field after cutbacks. Discharging wetland conditions do not typify this western half of Morris Bridge well field but do occur at the eastern end of the property and beyond the eastern boundary. The predevelopment map suggests discharging groundwater conditions were once prevalent for wetlands in Morris Bridge well field around parts of Trout Creek and the middle Hillsborough River (Figure 21c). Groundwater conditions in wetlands in South Pasco well field rose by about 10 feet – from orange to light blue – after cutbacks and showed less recharge potential than the estimated predevelopment conditions.

Hydrologic recovery inside four other well field properties, Cross Bar Ranch, Cosme, Eldridge Wilde, and Section 21, mostly took the form of reducing the recharge potential on annual average of wetlands from red and orange categories into the yellow and light blue categories (Figures 21a and b). Eldridge Wilde and Section 21 showed the most change. Changes were less obvious at Cosme well field. Wetlands in Cross Bar Ranch well field, and east of the well field, had less recharge potential after cutbacks, and wetlands along the southern well field boundary shifted to the lowest recharge category (light blue). Wetlands inside Cross Bar Ranch generally had a higher recharge potential, both before and after cutbacks, than wetlands in other well fields. After cutbacks, the wetland conditions inside Cross Bar Ranch were fairly similar to predevelopment conditions (Figure 21c). However, wetlands east of Cross Bar Ranch – and inside a simulated 2-foot drawdown contour – were not similar to predevelopment conditions. After cutbacks, these wetlands were in lower recharge categories – changing from red and orange to yellow. Yet, most wetlands in this area remained at a higher recharge potential than their estimated predevelopment condition (Figures 21b and c).

Of the three dispersed well fields, Cypress Bridge, North Pasco, and Northwest Hillsborough, Cypress Bridge well field appears to have undergone the least discernible change between pre- and post-cutback time periods based on annual average conditions (Figures 21a and b). This result is consistent with the fact that groundwater pumping was not cutback at Cypress Bridge well field as much as other wellfields and remained at similar levels during both periods. After cutbacks the number of wetlands with dark and light blue conditions increases around North Pasco well field, but not around Cypress Bridge well field where recharge categories remain yellow, orange, and red. For the predevelopment condition, wetlands in the vicinity of Cypress Bridge and North Pasco well fields display discharging and low recharge (dark and light blue) groundwater conditions (Figure 21c), a result that indicates the potential importance of these wetlands for generating runoff in their respective drainage basins. Wetland groundwater conditions in the vicinity of Northwest Hillsborough well field have less recharge potential after cutbacks, especially notable along the channel of Rocky Creek, and appear similar to predevelopment conditions.

In May, wetland groundwater conditions inside several well fields changed markedly between pre- and post-cutback time periods (Figure 22). Before pumping cutbacks, discharging groundwater conditions were absent in National Wetlands Inventory wetlands on all well fields. After cutbacks, discharging groundwater conditions appear in wetlands along lower Trout Creek in Morris Bridge well field. Discharging groundwater conditions also appear in selected wetlands next to Cypress Creek in the southwest corner of Cypress Creek well field, and numerous wetlands south of the well field where they create a wide buffer of discharging conditions along Cypress Creek. Other wetlands inside Cypress Creek well field changed from red and orange recharge categories to yellow and light blue. Some wetlands with an orange recharge category persisted in the center of the well field. Groundwater conditions in a large area of wetlands east of Cypress Creek well field rose by about 10 feet, shifting from an orange to light blue recharge category.

Average May groundwater conditions prior to cutbacks consisted of orange and yellow recharge categories for wetlands inside Starkey well field and the entire region between the Anclote and Pithlachascotee Rivers (Figure 22a). Wetlands south of the Anclote River between Starkey and Eldridge Wilde well fields experienced similar recharge conditions. After cutbacks, recharging conditions in these same wetlands in May were reduced, with virtually no wetlands in the orange recharge category (Figure 22b). Wetlands between Starkey and Eldridge Wilde well fields shifted from the orange to the yellow recharge category, and yellow to light blue in some areas, for overall lower recharge conditions. Wetlands inside Starkey well field were mostly in the lowest (light blue) recharge category after cutbacks, except for a pocket of higher recharge (yellow) wetlands in the center and north of the well field.

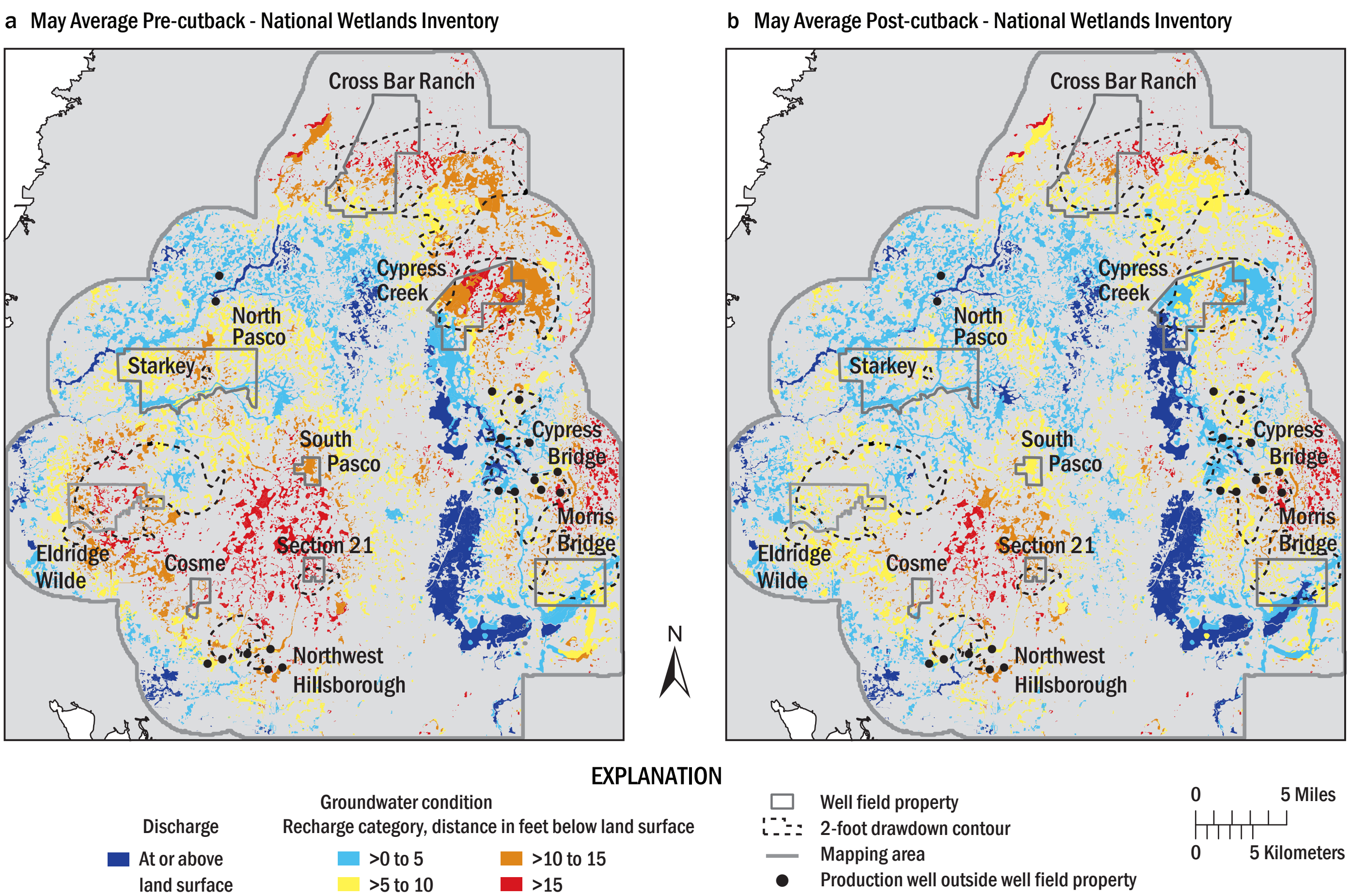


Figure 22. Classified wetland groundwater conditions in May for the National Wetlands Inventory population (a) before and (b) after cutbacks in well field pumping.

Average wetland groundwater conditions in May in Cosme, Eldridge Wilde, and South Pasco well fields recovered 5 to 10 feet, changing from high recharge categories of red and orange before cutbacks, to mostly yellow after cutbacks (Figure 22). Wetlands in Section 21 well field changed from a red (higher) to orange (lower) recharge category.

Wetlands around Cypress Bridge dispersed well field had average groundwater conditions in May that remained largely unchanged from the pre-cutback to the post-cutback time period, again likely reflecting the fact that groundwater pumping remained similar at this well field (Figure 22). Minor exceptions to this were wetlands along Trout Creek and another stream running diagonally across Cypress Bridge production wells. These wetlands changed from discharging to recharging, or from lower to higher recharge categories after cutbacks, perhaps because these wetlands were in the 2-foot drawdown contour or near production wells. Recharge conditions diminished somewhat in May for wetlands in Cross Bar Ranch well field, but in Cross Bar Ranch, Cypress Bridge, and Section 21 well fields, wetlands still displayed the highest recharge categories in May after pumping cutbacks.

Changes in the average September groundwater condition of National Wetlands Inventory wetlands after cutbacks point to a recovery of the hydrologic connection between geographically isolated headwater wetlands and main channels of streams (Figure 23). Discharging groundwater conditions follow wetlands along the main channels of the Anclote and Pithlachascotee Rivers and extend up tributaries into headwater wetlands that also have discharging groundwater conditions. After cutbacks, discharging groundwater conditions also extend upstream along Fivemile Creek and into an area of headwater wetlands.

In September, both before and after pumping cutbacks, discharging groundwater conditions (dark blue) occur at wetlands along much of Cypress Creek where it flows outside of Cypress Creek well field. Before pumping cutbacks, the groundwater condition of wetlands bracketing the stream had an abrupt change inside the well field (Figure 23). Here, prior to cutbacks, wetlands buffering the creek were in recharge categories ranging from red to yellow, and wetlands to the east of the stream in the eastern well field were mostly in the yellow recharge category. After cutbacks, the September

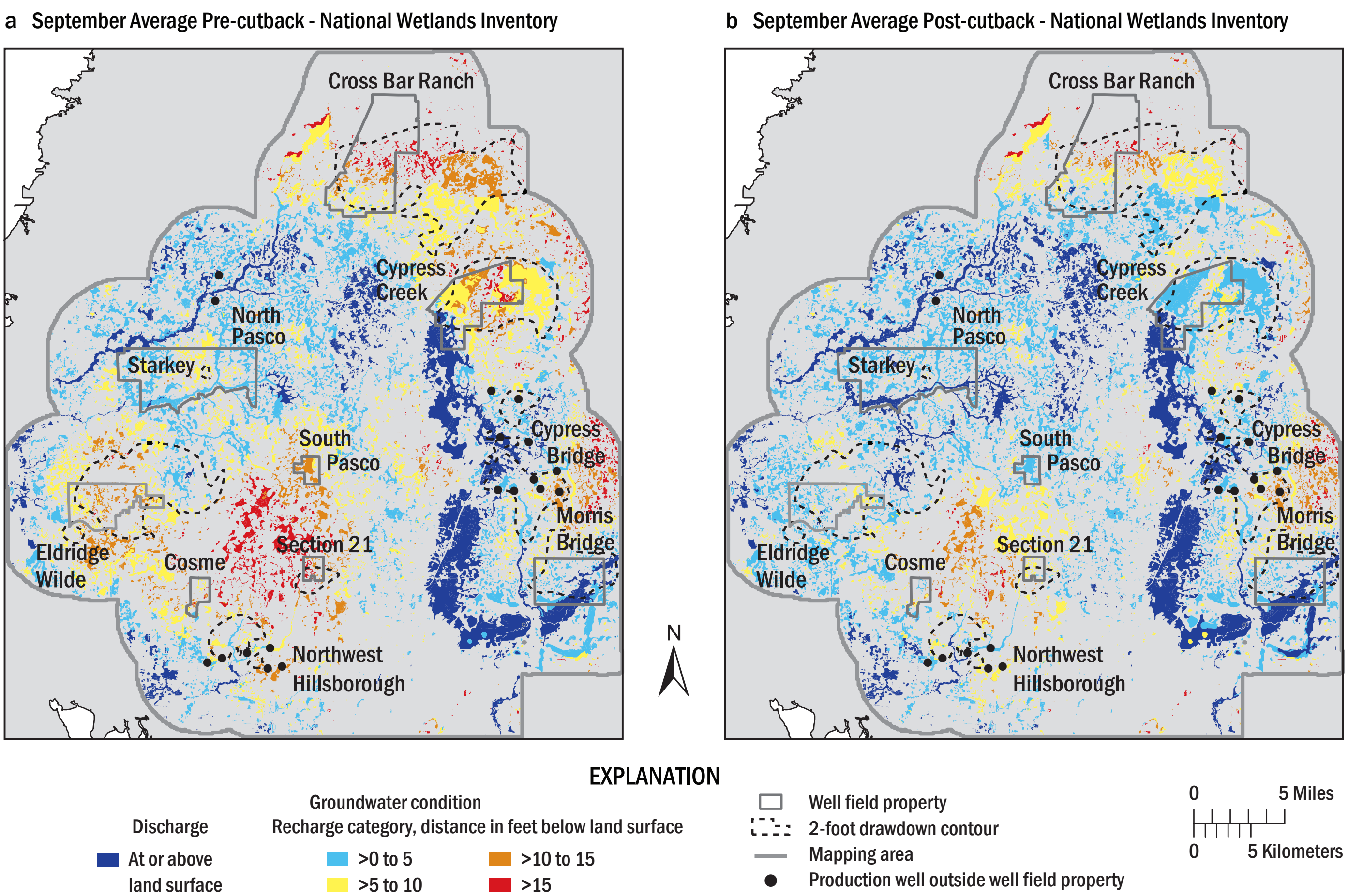


Figure 23. Classified wetland groundwater conditions in September for the National Wetlands Inventory population (a) before and (b) after cutbacks in well field pumping.

condition for most of the wetlands inside the well field was the lowest recharge category (light blue). The decrease in recharge potential of these wetlands in September suggests a commensurate increase in their potential to generate runoff to Cypress Creek.

After cutbacks, the wetland recharge potential in September also declined in Cosme, Eldridge Wilde, Section 21, and South Pasco well fields (Figure 23). In contrast, wetlands around Cypress Bridge dispersed well field had no obvious change in groundwater conditions after pumping cutbacks, and high recharge conditions in the orange and red categories remained to the east of the production wells. Wetlands in Morris Bridge well field experienced little change in September groundwater conditions before and after cutbacks, and the wetlands continued to have discharging groundwater conditions (dark blue) or the lowest recharge condition (light blue). At Cross Bar Ranch well field, September groundwater conditions after pumping cutbacks created a horizontal band of light blue wetlands with the lowest recharge conditions, the band clips the southern end of the well field and extends into the wetland-dominated area east and south of the well field. Although wetlands north of this band have a comparatively higher recharge potential, the September post-cutback conditions were closer than any other period to resembling predevelopment groundwater conditions for wetlands in this area (compare Figures 21c and 23b).

Classified groundwater conditions mapped in the 1,092 Tampa Bay Water wetlands (Figures 24, 25, and 26) have similar conditions as wetlands at the same location in the larger National Wetlands Inventory population (Figures 21, 22, and 23). Wetland water levels and vegetation surveys at the 410 monitored wetlands in the Tampa Bay Water population can be related to the groundwater condition time series developed here. Relationships between wetland water levels and groundwater conditions, and potentially vegetation, can be extrapolated to unmonitored wetlands experiencing similar groundwater conditions. In this way groundwater conditions for the Tampa Bay Water wetlands dovetail with the National Wetlands Inventory population to describe the regional wetlands from a drainage-basin perspective.

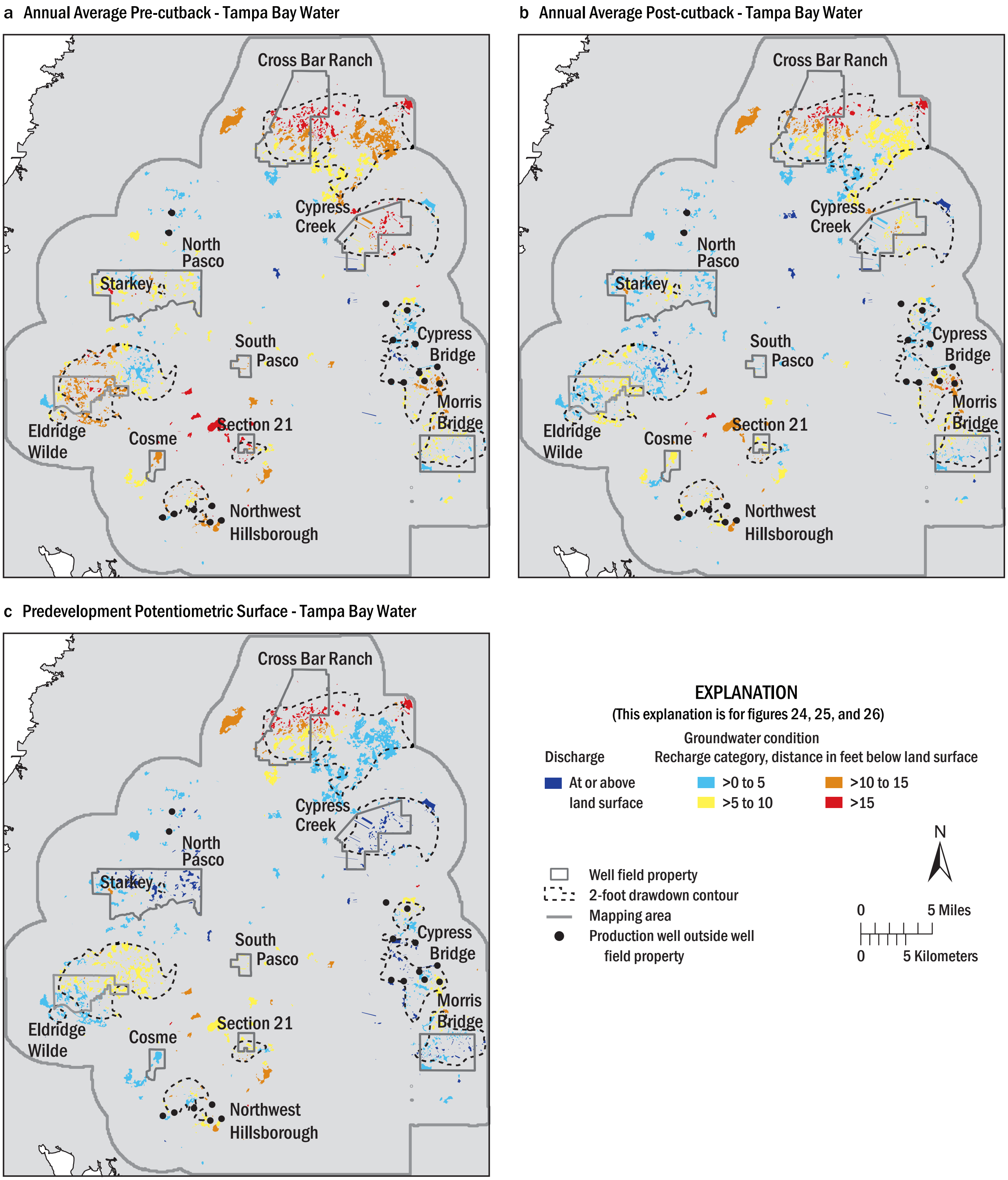


Figure 24. Classified wetland groundwater conditions in the Tampa Bay Water population (a) before and (b) after cutbacks in well field pumping, and (c) prior to any pumping in the Upper Floridan aquifer.

a May Average Pre-cutback - Tampa Bay Water

b May Average Post-cutback - Tampa Bay Water

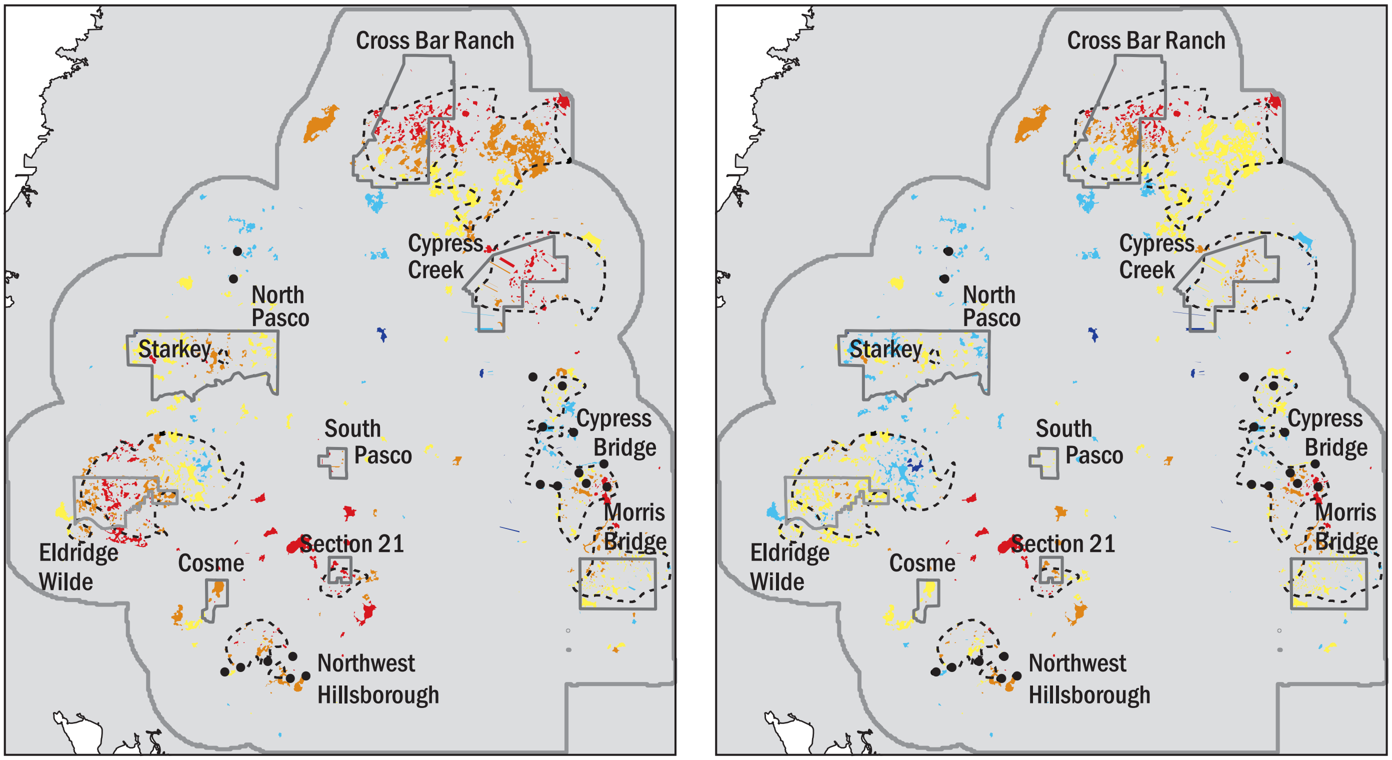


Figure 25. Classified wetland groundwater conditions in May for the Tampa Bay Water population (a) before and (b) after cutbacks in well field pumping.

a September Average Pre-cutback - Tampa Bay Water

b September Average Post-cutback - Tampa Bay Water

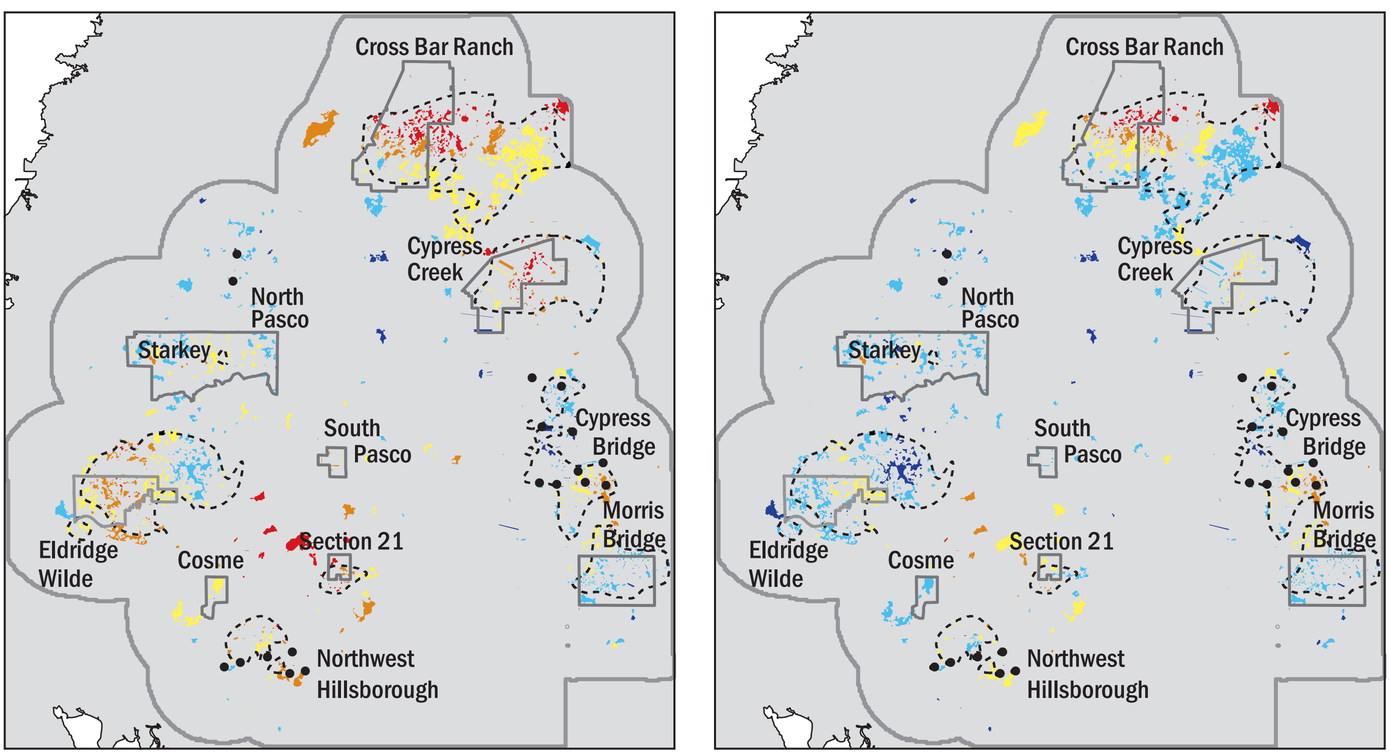


Figure 26. Classified wetland groundwater conditions in September for the Tampa Bay Water wetland population (a) before and (b) after cutbacks in well field pumping.

Wetland Groundwater Index

The percentage of National Wetlands Inventory wetlands above and below a wetland groundwater index (i.e. median groundwater conditions before pumping cutbacks) was tracked using annual average, May, and September groundwater conditions (Figure 27). On average, about half of the wetlands were above the index before pumping cutbacks from 1990-2002. After pumping cutbacks, the average percentage of wetlands above the index increased to 76.5 percent, 74.6 percent, and 79.5 percent for annual average, May, and September groundwater conditions, respectively.

Annual variations in Figure 27 can be attributed to changes in rainfall (Figure 6). For example, nearly all wetlands were above the index in 1998 due to large rainfall totals. The opposite happened two years later in an unusually dry year in which few wetlands had annual average and May groundwater conditions above the index (Figures 27a and b). These changes were associated with El Niño and La Niña climatic phases. Large rainfall totals in 1998 coincided with a strong El Niño (Wolter and Timlin, 2011). The dry year that followed two years later was marked by a La Niña (Wolter and Timlin, 2011). Both phases have been linked to large rainfall totals (El Niño) and dry periods (La Niña) in Florida (Schmidt et al., 2001). In September, the dry period in 2000 had wetlands above the index (Figure 27c) because convective summer storms persist despite La Niña conditions (Schmidt et al., 2001). The effects of rainfall were evident in other years, such as the dry (La Niña) year in 2001 and wet (El Niño) year in 2003. For this reason, wetland groundwater conditions were adjusted for the effects of rainfall to identify trends in the following section.

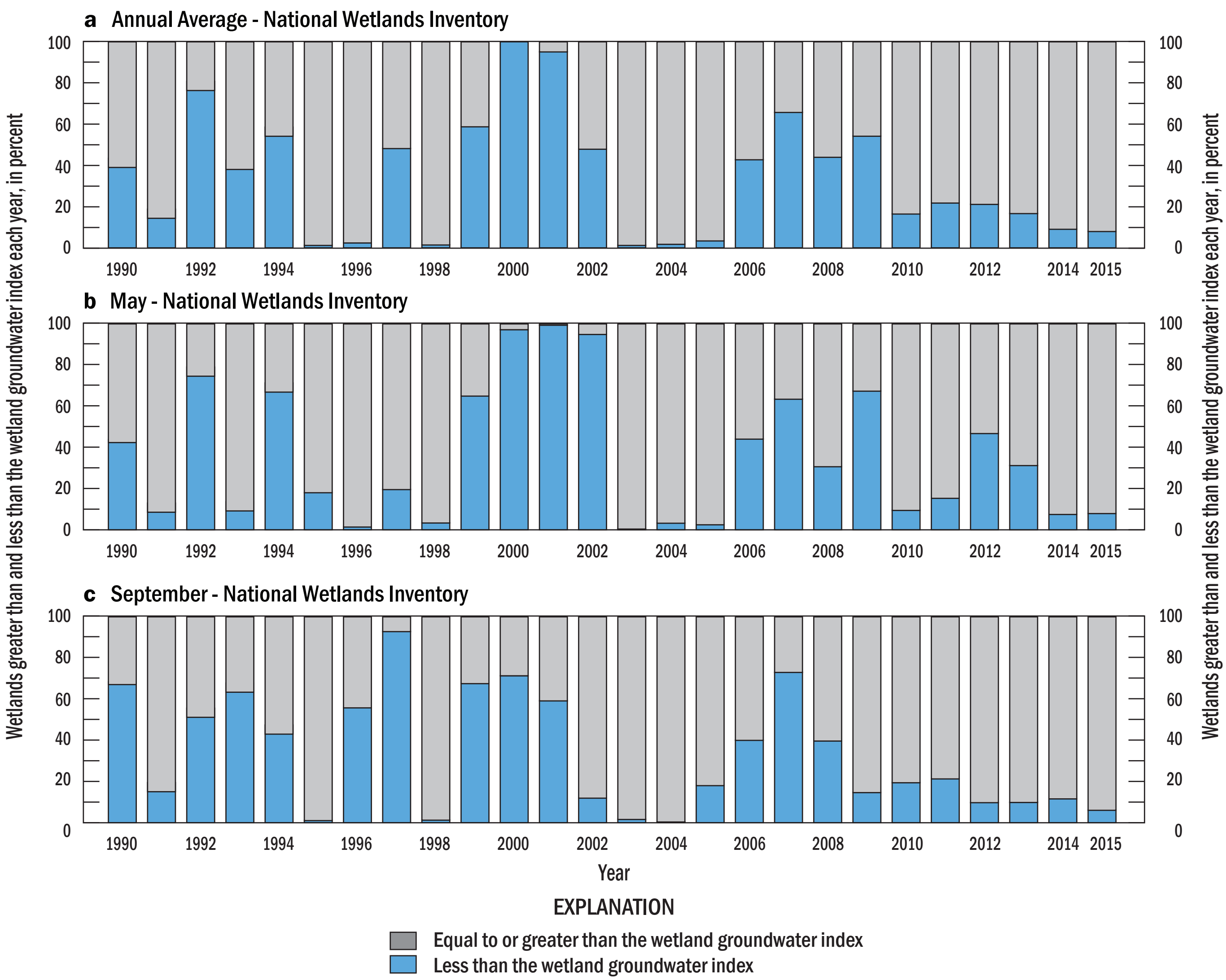


Figure 27. Percentage of the National Wetlands Inventory wetland population with groundwater condition values above and below the wetland groundwater index value (a) on annual average, and in (b) May and (c) September from 1990 to 2015.

Trends in Wetland Groundwater Conditions

Trends in monthly median groundwater conditions adjusted for the effects of rainfall were analyzed for various wetland populations based on the National Wetlands Inventory (Table 12). A seasonal Mann-Kendall test was applied to produce reliable *p*-values for autocorrelated data with an AR (1) coefficient ≤ 0.6. A *p*-value ≤ 0.05 was used to identify a statistically significant trend (i.e. Yes (up) or Yes (down)). Trends were characterized before pumping cutbacks (pre), after pumping cutbacks (post), and for the complete period of record (all). Few trends were statistically significant for the time periods before and after pumping cutbacks. However, the trends during these time periods were as expected, with mostly negative slopes (i.e. 11 of 16 wetland populations) before cutbacks and positive slopes (i.e. 13 of 16 wetland populations) after cutbacks. If considering regional wetland populations not subject to a particular pumping regime (i.e. first five populations in Table 12), then all slopes were negative before cutbacks and positive after cutbacks.

The complete period of record had statistically significant upward trends for 13 of 16 wetland populations (Table 12). Regional wetland populations (i.e. the first five in Table 12) all had statistically significant upward trends. Trends were measured using a seasonal slope estimator in units of feet/year. The slope estimator indicates that groundwater conditions in the National Wetlands Inventory (NWI) wetland population increased at a rate of 0.127 feet/year, or 3.30 feet (0.127 feet × 26 years), over the complete period of record. Wetland groundwater conditions recovered more outside well fields (0.158 feet/year) than inside well fields (0.079 feet/year). The opposite occurred in a 2-foot drawdown contour delineated for a Tampa Bay Water wetland recovery analysis (Tampa Bay Water, 2013). Wetlands inside the drawdown contour had a larger increase in groundwater condition values (0.235 feet/year) than those outside the drawdown contour (0.117 feet/year). This indicates that wetlands in the 2-foot drawdown contour responded more to pumping cutbacks than wetlands in well field properties, similar to previous results comparing wetland groundwater condition categories in which larger changes after cutbacks occurred in the drawdown contour than the well fields (Tables 10 and 11).

Tampa Bay Water wetland populations had similar monthly median groundwater condition trends as National Wetlands Inventory populations (Table 13). Like the National Wetlands Inventory, few Tampa Bay Water wetland populations had statistically significant trends before (pre) and after (post) pumping cutbacks, but many (i.e. 16 of 20 wetland populations) had statistically significant upward trends in groundwater conditions for the complete period of record (all). Monitored and unmonitored wetland populations, critical for Tampa Bay Water's wetland recovery analysis, both had statistically significant upward trends, with groundwater condition values increasing at a faster rate for unmonitored wetlands (slope = 0.226 feet/year) than monitored wetlands (slope = 0.161 feet/year).

Monthly median groundwater conditions, after adjusting for rainfall, are plotted in Figure 28 for the National Wetlands Inventory wetland population. Sen's slope was used to estimate the slope of trend lines through monthly median groundwater conditions in feet/month before and after pumping cutbacks. The resulting trends indicate a total decrease in median groundwater conditions of 0.765 feet

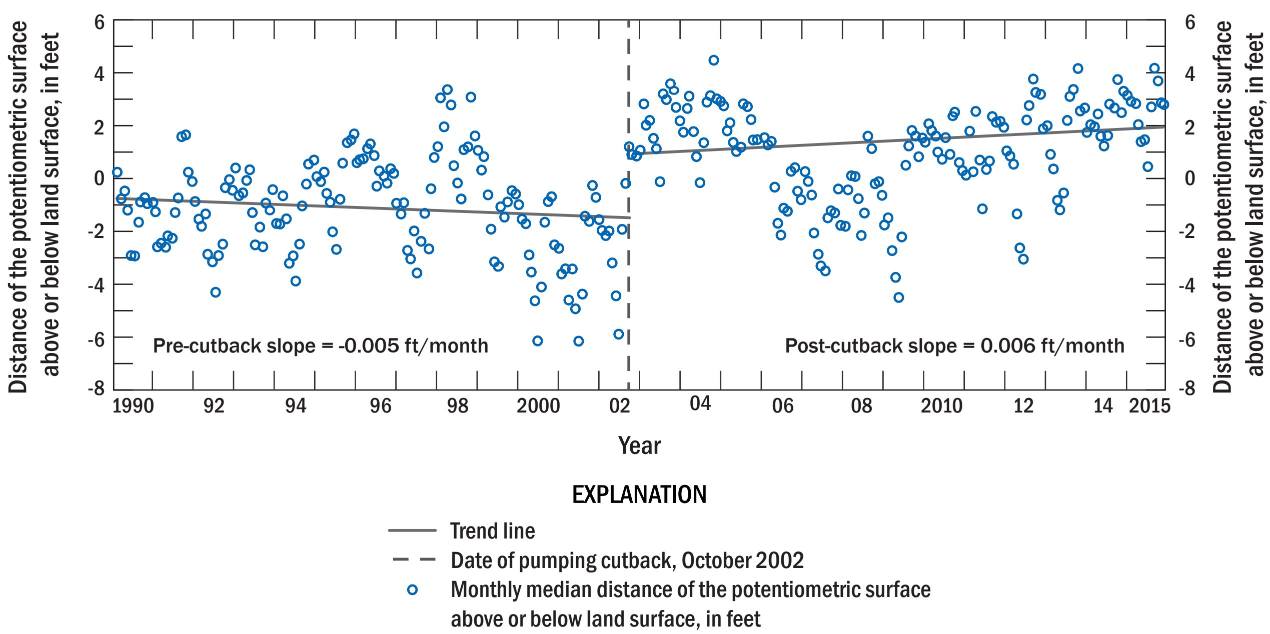


Figure 28. Trends in the monthly median groundwater condition, after adjusting for rainfall, of wetlands in the National Wetlands Inventory population before and after cutbacks in well field pumping.

Table 12. Upward and downward trends in wetland groundwater condition for the National Wetlands Inventory population and selected subpopulations, after adjusting for rainfall, for pre- and post-cutback periods, and for all years.

[Wetland populations are defined in Table 2; Monthly well field pumping rates are shown in Figure 5; Individuai well fields can have different pre- and post-cutback time periods; Upward (Yes (up)) or downward (Yes (down)) trend if p-value ≤ 0.05; Trend p-value may not be reliable if AR(1) coefficient (autocorrelation) ≥ 0.6; Slope measured seasonally in feet/year]

Wetland Population	Period	Dates of Pre- and Post-cutback Periods and Period of Record	Trend	Trend p-value	Slope	AR(1) Coefficient
NWI	Pre	Jan 1990 - Sep 2002	No	0.48	-0.051	0.41
	Post	Oct 2002 - Dec 2015	No	0.43	0.069	0.68
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.127	0.67
Wellfield	Pre	Jan 1990 - Sep 2002	No	0.39	-0.084	0.49
	Post	Oct 2002 - Dec 2015	No	0.76	0.021	0.63
	All	Jan 1990 - Dec 2015	Yes (up)	0.03	0.079	0.54
Not_In_Wellfield	Pre	Jan 1990 - Sep 2002	No	0.70	-0.032	0.39
	Post	Oct 2002 - Dec 2015	No	0.29	0.096	0.69
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.158	0.74
Two_Foot_ Drawdown_Original	Pre	Jan 1990 - Sep 2002	No	0.91	-0.019	0.41
	Post	Oct 2002 - Dec 2015	No	0.52	0.098	0.71
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.235	0.69
Not_In_Two_Foot_ Drawdown_Original	Pre	Jan 1990 - Sep 2002	No	0.48	-0.052	0.42
	Post	Oct 2002 - Dec 2015	No	0.39	0.061	0.69
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.117	0.67
CBR	Pre	Jan 1990 - Sep 2002	No	0.93	-0.027	0.49
	Post	Oct 2002 - Dec 2015	No	0.38	0.258	0.74
	All	Jan 1990 - Dec 2015	Yes (up)	0.04	0.235	0.63
COS	Pre	Jan 1990 - Sep 2002	No	0.30	-0.100	0.43
	Post	Oct 2002 - Dec 2015	No	0.08	0.206	0.67
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.230	0.77
CYB	Pre	Jan 1990 - Sep 2002	No	0.23	-0.161	0.67
	Post	Oct 2002 - Dec 2015	No	0.16	-0.159	0.59
	All	Jan 1990 - Dec 2015	No	0.53	-0.026	0.48
CYC	Pre	Jan 1990 - Sep 2002	No	0.52	0.130	0.31
	Post	Oct 2002 - Dec 2015	No	0.97	-0.019	0.75
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.449	0.69
ELW	Pre	Jan 1990 - Sep 2002	No	0.10	0.246	0.58
	Post	Oct 2002 - Dec 2015	Yes (up)	0.04	0.217	0.69
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.422	0.93
MBR	Pre	Jan 1990 - Sep 2002	No	0.21	-0.203	0.51
	Post	Oct 2002 - Dec 2015	No	0.50	-0.069	0.44
	All	Jan 1990 - Dec 2015	No	0.99	0.003	0.47
NOP	Pre	Jan 1990 - Dec 2007	No	0.74	-0.019	0.52
	Post	Jan 2008 - Dec 2015	Yes (up)	0.02	0.263	0.69
	All	Jan 1990 - Dec 2015	No	0.09	0.046	0.54
NWH	Pre	Jan 1990 - Sep 2011	Yes (up)	0.02	0.075	0.54
	Post	Oct 2011 - Dec 2015	No	0.37	0.104	0.47
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.114	0.80
S21	Pre	Jan 1990 - Sep 2004	No	0.80	0.063	0.51
	Post	Oct 2004 - Dec 2015	Yes (up)	0.02	0.477	0.71
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.418	0.85
SOP	Pre	Jan 1990 - Sep 2002	Yes (down)	0.01	-0.369	0.72
	Post	Oct 2002 - Dec 2015	No	0.30	0.131	0.63
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.389	0.82
STK	Pre	Jan 1990 - Dec 2007	No	0.15	0.093	0.49
	Post	Jan 2008 - Dec 2015	Yes (up)	0.02	0.412	0.74
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.2010	0.78

Table 13. Upward and downward trends in wetland groundwater condition for the Tampa Bay Water population and selected subpopulations, after adjusting for rainfall, for pre- and post-cutback periods, and for all years.

[Wetland populations are defined in Table 2; Monthly well field pumping rates are shown in Figure 5; Individual well fields can have different pre- and post-cutback time periods; Upward (Yes (up)) or downward (Yes (down)) trend if *p*-value ≤ 0.05; Trend *p*-value may not be reliable if AR(1) coefficient (autocorrelation) ≥ 0.6; Slope measured seasonally in feet/year]

Wetland Population	Period	Dates of Pre- and Post-cutback Periods and Period of Record	Trend	Trend *p*-value	Slope	AR(1) Coefficient
TBW_Wetland	Pre	Jan 1990 - Sep 2002	No	0.79	-0.036	0.39
	Post	Oct 2002 - Dec 2015	No	0.54	0.075	0.67
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.204	0.70
Wellfield	Pre	Jan 1990 - Sep 2002	No	0.38	-0.088	0.49
	Post	Oct 2002 - Dec 2015	No	0.72	0.030	0.61
	All	Jan 1990 - Dec 2015	Yes (up)	0.01	0.135	0.58
Not_In_Wellfield	Pre	Jan 1990 - Sep 2002	No	0.73	0.067	0.44
	Post	Oct 2002 - Dec 2015	No	0.26	0.185	0.77
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.303	0.79
Two_Foot_Drawdown_Original	Pre	Jan 1990 - Sep 2002	No	1.00	0.000	0.41
	Post	Oct 2002 - Dec 2015	No	0.64	0.059	0.66
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.230	0.71
Not_In_Two_Foot_Drawdown_Original	Pre	Jan 1990 - Sep 2002	No	0.79	-0.022	0.32
	Post	Oct 2002 - Dec 2015	No	0.21	0.107	0.65
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.157	0.67
Monitored_Wetland	Pre	Jan 1990 - Sep 2002	No	0.67	-0.050	0.37
	Post	Oct 2002 - Dec 2015	No	0.41	0.087	0.63
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.161	0.63
Unmonitored_Wetland	Pre	Jan 1990 - Sep 2002	No	0.99	-0.004	0.41
	Post	Oct 2002 - Dec 2015	No	0.54	0.070	0.67
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.226	0.73
Cypress	Pre	Jan 1990 - Sep 2002	No	0.67	-0.050	0.38
	Post	Oct 2002 - Dec 2015	No	0.19	0.121	0.66
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.170	0.68
Marsh	Pre	Jan 1990 - Sep 2002	No	0.29	-0.135	0.44
	Post	Oct 2002 - Dec 2015	No	0.90	0.025	0.71
	All	Jan 1990 - Dec 2015	No	0.13	0.091	0.53
CBR	Pre	Jan 1990 - Sep 2002	No	0.65	-0.156	0.51
	Post	Oct 2002 - Dec 2015	No	0.54	0.217	0.82
	All	Jan 1990 - Dec 2015	No	0.09	0.239	0.61
COS	Pre	Jan 1990 - Sep 2002	No	0.30	-0.104	0.41
	Post	Oct 2002 - Dec 2015	No	0.10	0.218	0.63
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.254	0.76
CYB	Pre	Jan 1990 - Sep 2002	No	0.13	-0.235	0.66
	Post	Oct 2002 - Dec 2015	No	0.14	-0.170	0.56
	All	Jan 1990 - Dec 2015	No	0.24	-0.055	0.47
CYC	Pre	Jan 1990 - Sep 2002	No	0.31	0.241	0.32
	Post	Oct 2002 - Dec 2015	No	0.92	0.030	0.76
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.519	0.73
ELW	Pre	Jan 1990 - Sep 2002	No	0.11	0.230	0.54
	Post	Oct 2002 - Dec 2015	Yes (up)	0.04	0.226	0.68
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.436	0.93

Table 13. Upward and downward trends in wetland groundwater condition for the Tampa Bay Water population and selected subpopulations, after adjusting for rainfall, for pre- and post-cutback periods, and for all years. —Continued

[Wetland populations are defined in Table 2; Monthly well field pumping rates are shown in Figure 5; Individual well fields can have different pre- and post-cutback time periods; Upward (Yes (up)) or downward (Yes (down)) trend if p-value ≤ 0.05; Trend p-value may not be reliable if AR(1) coefficient (autocorrelation) ≥ 0.6; Slope measured seasonally in feet/year]

Wetland Population	Period	Dates of Pre- and Post-cutback Periods and Period of Record	Trend	Trend p-value	Slope	AR(1) Coefficient
MBR	Pre	Jan 1990 - Sep 2002	No	0.25	-0.182	0.53
	Post	Oct 2002 - Dec 2015	No	0.46	-0.072	0.46
	All	Jan 1990 - Dec 2015	No	1.00	0.002	0.45
NOP	Pre	Jan 1990 - Dec 2007	No	0.43	0.044	0.56
	Post	Jan 2008 - Dec 2015	Yes (up)	0.02	0.297	0.62
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.119	0.69
NWH	Pre	Jan 1990 - Sep 2011	Yes (up)	0.01	0.125	0.63
	Post	Oct 2011 - Dec 2015	No	0.93	0.016	0.45
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.178	0.80
S21	Pre	Jan 1990 - Sep 2004	No	0.82	0.049	0.51
	Post	Oct 2004 - Dec 2015	Yes (up)	0.02	0.454	0.72
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.420	0.85
SOP	Pre	Jan 1990 - Sep 2002	Yes (down)	0.01	-0.361	0.72
	Post	Oct 2002 - Dec 2015	No	0.27	0.130	0.62
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.383	0.82
STK	Pre	Jan 1990 - Dec 2007	No	0.14	0.092	0.52
	Post	Jan 2008 - Dec 2015	Yes (up)	0.02	0.408	0.69
	All	Jan 1990 - Dec 2015	Yes (up)	0.00	0.2015	0.81

(-0.005 feet × 153 months) before cutbacks and increase of 0.954 feet (0.006 feet × 159 months) after cutbacks. The time series plot shows why trends before and after cutbacks may not be statistically significant (Table 12). Large point clouds are above and below the trend lines, corresponding to prolonged wet periods, such as 1998, and dry periods, such as 2007 (Figure 6). Despite accounting for month-to-month changes in rainfall, longer-term patterns related to El Niño (wet) and La Niña (dry) phases may have influenced wetland groundwater conditions in years like 1998 and 2007 (Wolter and Timlin, 2011). Rainfall patterns on a similar time scale as El Niño and La Niña phases were evaluated using 1-, 2-, and 3-month moving rainfall totals (see results in deliverable 6). Trends adjusted for 1-month (pre-cutback slope = -0.005 feet/month; post-cutback slope = 0.005 feet/month), 2-month (pre-cutback slope = -0.006 feet/month; post-cutback slope = 0.004 feet/month), and 3-month (pre-cutback slope = -0.006 feet/month; post-cutback slope = 0.003 feet/month) moving rainfall totals were similar to trends adjusted for monthly rainfall (Figure 28). Since rainfall totals did not fully account for the influence of El Niño and La Niña phases, wetland groundwater conditions could be adjusted using an index that measures the strength of El Niño and La Niña phases, like the multivariate ENSO (El Niño-Southern Oscillation) index (Wolter and Timlin, 2011).

Trends in May (dry season) and September (wet season) groundwater conditions after adjusting for rainfall were analyzed in various National Wetlands Inventory wetland populations during the complete 26-year period of record (Table 14). The seasons were not split into before and after pumping cutback time periods due to small sample sizes ($n \leq 13$). Over the 26 years, September had stronger trends than May, with 14 of 16 wetland populations registering statistically significant upward trends in September versus only 5 of 16 in May. However, trends in September were aided by larger autocorrelation (AR(1) coefficients) than in May. Wetland populations with upward trends in May were all in well fields. Groundwater conditions in these wetlands may have increased due to pumping cutbacks in the dry season. The two wetland populations that did not have upward trends in September were both in well fields. Upward trends may have been suppressed due to pumping regimes specific to Cypress Bridge (CYB) and Morris Bridge (MBR) well fields.

Positive slopes in Table 14 indicate that May and September groundwater condition values over the 26-year time period increased in wetland populations. The only exception was Cypress Bridge (CYB) wetland groundwater conditions in May (slope = -0.047 feet/year). Like earlier monthly results (Table 12), slopes in May and September were larger outside well fields than inside well fields. The difference may be due

Table 14. Upward and downward trends in May (dry season) and September (wet season) wetland groundwater conditions for the National Wetlands Inventory population and selected subpopulations after adjusting for rainfall during the complete period of record.

[Wetland populations are defined in Table 2; Monthly well field pumping rates are shown in Figure 5; Upward (Yes (up)) or downward (Yes (down)) trend if p-value ≤ 0.05; Trend p-value may not be reliable if AR(1) coefficient (autocorrelation) ≥ 0.6; Slope measured seasonally in feet/year]

Wetland Population	Season	Trend	Trend p-value	Slope	AR(1) Coeffi-cient
NWI	May	No	0.16	0.063	-0.05
	Sep	Yes (up)	0.00	0.157	0.58
Wellfield	May	No	0.43	0.033	-0.04
	Sep	Yes (up)	0.01	0.103	0.47
Not_In_Wellfield	May	No	0.06	0.090	-0.01
	Sep	Yes (up)	0.00	0.190	0.63
Two_Foot_Draw-down_Original	May	No	0.10	0.098	0.06
	Sep	Yes (up)	0.00	0.295	0.66
Not_In_Two_Foot_Drawdown_Original	May	No	0.22	0.070	-0.05
	Sep	Yes (up)	0.00	0.148	0.57
CBR	May	No	0.51	0.080	0.26
	Sep	Yes (up)	0.00	0.292	0.51
COS	May	No	0.06	0.104	0.10
	Sep	Yes (up)	0.00	0.272	0.62
CYB	May	No	0.45	-0.047	0.14
	Sep	No	0.57	0.020	0.32
CYC	May	Yes (up)	0.01	0.315	0.22
	Sep	Yes (up)	0.00	0.495	0.62
ELW	May	Yes (up)	0.00	0.339	0.48
	Sep	Yes (up)	0.00	0.435	0.72
MBR	May	No	0.86	0.021	-0.11
	Sep	No	0.66	0.023	0.49
NOP	May	No	0.66	0.008	-0.07
	Sep	Yes (up)	0.03	0.063	0.30
NWH	May	No	0.22	0.035	0.08
	Sep	Yes (up)	0.00	0.147	0.60
S21	May	Yes (up)	0.01	0.222	0.24
	Sep	Yes (up)	0.00	0.536	0.84
SOP	May	Yes (up)	0.02	0.222	0.16
	Sep	Yes (up)	0.00	0.489	0.74
STK	May	Yes (up)	0.01	0.121	0.20
	Sep	Yes (up)	0.00	0.206	0.53

to local effects of pumping in well field properties. Previous monthly results (Table 12) were again similar to May and September groundwater conditions for a 2-foot drawdown contour in the surficial aquifer system (Tampa Bay Water, 2013). Wetlands in the drawdown contour had larger slopes in May and September than wetlands out of the drawdown contour. This may be because wetlands in the drawdown contour have responded more to cutbacks in groundwater pumping. The Tampa Bay Water wetlands (not shown here), subject to a wetland recovery analysis, had larger slopes in May (0.103 feet/year) and September (0.256 feet/year) than the National Wetlands Inventory (NWI) population. The faster recovery rates may be because many Tampa Bay Water wetlands are in the 2-foot drawdown contour, which has responded more to pumping cutbacks.

CONCLUSIONS

The monthly groundwater conditions of thousands of wetlands in the Northern Tampa Bay area have shown a significant upward trend from 1990 to 2015 based on statistics for two wetland populations in the region: National Wetlands Inventory wetlands and Tampa Bay Water wetlands. Climate was wetter after pumping cutbacks in 2003 than before. However, upward trends in wetland groundwater conditions are evident in both wetland populations after groundwater conditions are adjusted for rainfall. The rainfall adjusted statistics suggest that the upward trends in groundwater condition are attributable to decreased groundwater pumping from Tampa Bay Water well fields.

The upward trend in wetland groundwater conditions is due to an increase in the potentiometric-surface elevations in the Upper Floridan aquifer over the period. In most regions of the Northern Tampa Bay area, and for most time intervals evaluated, wetland groundwater conditions after pumping cutbacks show decreased potential for downward recharge and wetland leakage. In some areas, typically in headwater wetlands and wetlands buffering stream channels, recharging groundwater conditions have been replaced with discharging groundwater conditions for certain times of the year. Discharging groundwater conditions make wetlands more likely to flood and more likely to generate overland flow to nearby tributaries and streams.

Groundwater pumping cutbacks in well fields had a regional effect on wetland conditions. After cutbacks, the percentage of wetlands that ranked in the highest recharge categories decreased significantly outside of well fields, as well as inside. The monthly groundwater conditions of wetlands inside well fields also had an upward trend. However, all well fields did not contribute equally to the trend. Two well fields, Cypress Bridge and Morris Bridge, are notable for having no statistically significant trend upward or downward in monthly wetland groundwater conditions over the 26-year period, or in May and September. In contrast, five well fields (Cypress Creek, Eldridge Wilde, Section 21, South Pasco, and Starkey) showed upward trends in monthly wetland groundwater conditions for the 26-year period, and in May and September. Overall, the recovery (increasing slope) of monthly wetland groundwater conditions was larger for September than May. As a result, groundwater conditions in September could contribute a relatively greater effect on the upward trend in annual average conditions.

The altered wetland groundwater conditions in September after pumping cutbacks influenced the hydrology in the Northern Tampa Bay area at a landscape scale. Discharging groundwater conditions were intact along entire river corridors and extended upstream toward headwater wetlands, particularly the Pithlachascotee and Anclote Rivers and their tributaries. Prior to pumping cutbacks, streams and small tributaries were more likely to flow through wetlands and uplands with recharging groundwater conditions.

Accounting for month-to-month changes in rainfall made long-term trends in groundwater conditions evident over 26 years. Climate extremes from El Niño (wet) and La Niña (dry) phases were related to wetland groundwater conditions, despite controlling for rainfall. In future studies, wetland groundwater conditions could be adjusted using an index that measures the strength of El Niño and La Niña phases, like the multivariate ENSO (El Niño-Southern Oscillation) index, or other longer-term climate patterns, like the Atlantic Multidecadal Oscillation, known to influence hydrologic conditions in the Northern Tampa Bay area (Southwest Florida Water Management District, 2004).

Wetland groundwater condition values are subject to uncertainty in their absolute magnitude due to errors in wetland land surface elevations estimated from LiDAR data and the mapped kriging error in the potentiometric surface (see Lee and Fouad, 2017). At its largest the uncertainty could be on the order of several feet, offsetting a wetland's groundwater condition by a category. The uncertainty in absolute magnitudes, however, would not affect the time trend in groundwater conditions at an individual wetland or the trends in the groundwater condition of populations of wetlands over the 26-year study period.

REFERENCES CITED

Alley, W.M., 1988, Using exogenous variables in testing for monotonic trends in hydrologic time series. Water Resources Research v. 24, p. 1955-1961. *https://doi.org/10.1029/WR024i011p01955*

Bellino, J.C., 2011, Digital surfaces and hydrogeologic data for the Floridan aquifer system in Florida and in parts of Georgia, Alabama, and South Carolina. US Geological Survey Data Series 584. *https://pubs.usgs.gov/ds/584*

Bush, P.W., and Johnston, R.H., 1988, Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama. US Geological Survey Professional Paper 1403-C, 80 p. *https://pubs.usgs.gov/pp/1403c*

Cleveland, W.S., 1979, Robust locally weighted regression and smoothing scatterplots. Journal of the American Statistical Association v. 74, p. 829-836. *https://doi.org/10.1080/01621459.1979.10481038*

Dahl, T.E., 2005, Florida's wetlands: An update on status and trends 1985 to 1996. US Fish and Wildlife Service report, 80 p. *https://www.fws.gov/wetlands/documents/Floridas-Wetlands-An-Update-on-Status-and-Trends-1985-to-1996.pdf*

Ewel, K.C., and Odum, H.T., eds., 1984, Cypress Swamps: Gainesville, University Presses of Florida.

Florida Department of Environmental Protection (FDEP), 2004, Intermediate aquifer system thickness. FDEP Geospatial Open Data. *geodata.dep.state.fl.us/datasets/intermediate-aquifer-system-thickness*

Fouad, G., and Lee, T.M., 2011, Using monthly average potentiometric surfaces and light detection and ranging (LiDAR) data to investigate surface and groundwater relations in west-central Florida. Association of American Geographers Annual Meeting, April 12-16, 2011, Seattle, Washington, USA. *http://www.aag.org/galleries/conference-files/AAG2011_Printed_Program.pdf*

Geurink, J.S., and Basso, R., 2013, Development, calibration, and evaluation of the integrated Northern Tampa Bay hydrologic model. Prepared for Tampa Bay Water and the Southwest Florida Water Management District. *https://integratedhydrologicmodel.org/Portals/0/xPlugin/uploads/2017/7/6/INTB_ModelReport.pdf*

Haag, K.H., and Lee, T.M., 2010, Hydrology and ecology of freshwater wetlands in central Florida--A primer. US Geological Survey Circular 1342. 138 p. https://pubs.usgs.gov/circ/1342

Hayes, E., Fouad, G., and Lee, T.M., 2018, LiDAR accuracy assessment in 305 wetlands. American Water Resources Association Spring Specialty Conference, April 22-25, 2018, Orlando, Florida, USA. https://www.awra.org/meetings/Orlando2018/docs/FinalProgram.pdf

Helsel, D.R., and Hirsch, R.M., 2002, Trend analysis. In: Statistical methods in water resources. US Geological Survey Techniques of Water-Resources Investigations Book 4, Chapter A3, p. 323-356. https://pubs.usgs.gov/twri/twri4a3

Hirsch, R.M., Alexander, R.B., and Smith, R.A., 1991, Selection of methods for the detection and estimation of trends in water quality. Water Resources Research v. 27, p. 803-813. https://doi.org/10.1029/91WR00259

Hirsch, R.M., and Slack, J.R., 1984, A nonparametric trend test for seasonal data with serial dependence. Water Resources Research v. 20, p. 727-732. https://doi.org/10.1029/WR020i006p00727

Hirsch, R.M., Slack, J.R., and Smith, R.A., 1982, Techniques of trend analysis for monthly water quality data. Water Resources Research v. 18, p. 107-121. https://doi.org/10.1029/WR018i001p00107

Interlocal Agreement, 1998, Amended and restated interlocal agreement reorganizing the West Coast Regional Water Supply Authority. State of Florida legal document, 116 p., available at https://www.tampabaywater.org/agency/reports-and-documents

Jones Edmunds & Associates, 2011, Wetland hydrologic analysis: Wetland classification and basin character study. Southwest Florida Water Management District Report Certificate of Authorization #1841, 59 p.

Lane, C.R., and D'Amico, E., 2010, Calculating the ecosystem service of water storage in isolated wetlands using LiDAR in north central Florida, USA. Wetlands v. 30, p. 967-977. https://doi.org/10.1007/s13157-010-0085-z

Lee, T.M., and Fouad, G.G., 2014, Creating a monthly time series of the potentiometric surface in the Upper Floridan aquifer, Northern Tampa Bay area, Florida, January 2000-December 2009. US Geological Survey Scientific Investigations Report 2014–5038, 26 p. https://pubs.er.usgs.gov/publication/sir20145038

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. Tampa Bay Water Report, 30 p., available under Other Hydrologic Data Sources at https://www.swfwmd.state.fl.us/resources/data-maps/hydrologic-data

Lee, T.M., Haag, K.M., Metz, P.A., and Sacks, L.A., 2009, The comparative hydrology, water quality, and ecology of selected natural and augmented freshwater wetlands in west-central Florida. US Geological Survey Professional Paper 1758, 152 p. https://pubs.er.usgs.gov/publication/pp1758

Lee, T.M., and Hughes, J.D., 2010, Effect of groundwater levels and headwater wetlands on streamflow in the Charlie Creek basin, Peace River watershed, west-central Florida. US Geological Survey Scientific Investigations Report 2010-5189, 77 p. https://pubs.er.usgs.gov/publication/sir20105189

Mann, H.B., 1945, Nonparametric tests against trend. Econometrica v. 13, p. 245-259.

Metz, P.A., 2011, Factors that influence the hydrologic recovery of wetlands in the Northern Tampa Bay area, Florida. US Geological Survey Scientific Investigations Report 2011-5127, 58 p. https://pubs.er.usgs.gov/publication/sir20115127

Milbert, D.G., 1999, National Geodetic Survey (NGS) height conversion methodology. National Geodetic Survey, Silver Spring, Maryland, USA. https://www.ngs.noaa.gov/TOOLS/Vertcon/vert_method.html

Ortiz, A.G., 2011, Potentiometric surface of the upper Floridan aquifer, west-central Florida, May 2011. US Geological Survey Scientific Investigations Map 3183. https://pubs.usgs.gov/sim/3183

Ratcliffe, J.F., 1968, The effect on the t distribution of non-normality in the sampled population. Journal of the Royal Statistical Society, Series C (Applied Statistics) v. 17, p. 42-48. https://doi.org/10.2307/2985264

Schmidt, N., Lipp, E.K., Rose, J.B., and Luther, M.E., 2001, ENSO influences on seasonal rainfall and river discharge in Florida. Journal of Climate v. 14, p. 615-628. https://doi.org/10.1175/1520-0442(2001)014<0615:EIOSRA>2.0.CO;2

Sen, P.K., 1968, Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association v. 63, p. 1379-1389. https://doi.org/10.1080/01621459.1968.10480934

Sinclair, W.C., Knutilla, R.L., Gilboy, A.E., and Miller, R.L., 1985, Types, features, and occurrence of sinkholes in the karst of west-central Florida. US Geological Survey Water-Resources Investigations Report 85-4126, 81 p.

Southwest Florida Water Management District (SWFWMD), 2004, Florida river flow patterns and the Atlantic Multidecadal Oscillation. Southwest Florida Water Management District Report, 80 p. *https://www.swfwmd.state.fl.us/sites/default/files/medias/documents/riverflow_patterns.pdf*

Tampa Bay Water (TBW), 2013, Defining areas of investigation for recovery analysis. Tampa Bay Water Report, 22 p.

Tampa Bay Water (TBW), 2016, Kriging methodology: Analyzing surficial aquifer drawdown from historical groundwater pumping, 2013-2016. Tampa Bay Water Report, 19 p.

Thornton, M.M., Thornton, P.E., Wei, Y., Mayer, B.W., Cook, R.B., and Vose, R.S., 2018, Daymet: Monthly climate summaries on a 1-km grid for North America, version 3. Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. *https://doi.org/10.3334/ORNLDAAC/1345*

Tukey, J.W., 1977, Exploratory data analysis. Reading, Massachusetts, USA, Addison-Wesley, 688 p.

US Fish and Wildlife Service, 2017, National Wetlands Inventory. US Department of the Interior, Fish and Wildlife Service. *https://www.fws.gov/wetlands*

von Storch, H., 1995, Misuses of statistical analysis in climate research. In: von Storch, H., and Navarra, A. (Eds.), Analysis of climate variability. Springer, Berlin, Germany, pp. 11-26. *https://doi.org/10.1007/978-3-662-03744-7_2*

Welch, B.L., 1951, On the comparison of several mean values: An alternative approach. Biometrika v. 38, p. 330-336. *https://doi.org/10.2307/2332579*

White, W.A., 1970, The Gulf Coastal Lowlands. In: The geomorphology of the Florida peninsula. Florida Bureau of Geology Geological Bulletin No. 51, pp. 142-155. *ufdc.ufl.edu/UF00000149/00001*

Wolter, K., and Timlin, M.S., 2011, El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). International Journal of Climatology v. 31, p. 1074-1087. *https://doi.org/10.1002/joc.2336*