Data Reduction and Analysis of Hydrologic Data for Selected Tree Islands (3AN1, 3AS3, and 3BS1) Volume 2—Water-Level Data Analysis

SFWMD Purchase Order 4500026695

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1 INTRODUCTION

Tree islands are topographically elevated, typically tear-shaped features with their long axis oriented parallel to surface-water flow. The islands consist of tall trees, shrubs, and saw grass, and "provide habitat for a wide variety of terrestrial plants and animals" (Bevier and Krupa, 2001). Tree islands, which are very sensitive to changes in hydrologic conditions and extreme wet and dry periods, are considered indicators of the overall ecological health of the Everglades system. Hence, information collected from tree islands will be crucial to better understanding the hydrologic conditions in the Everglades.

In 2000, South Florida Water Management District began monitoring meteorological data and groundwater and surface-water levels at selected tree islands as part of a 5-year, multidisciplinary study conducted in cooperation with the Florida Fish and Wildlife Conservation Commission, the Florida Center for Environmental Studies, the U.S. Geological Survey, and several universities. The three selected tree islands—3AN1, 3AS3, and 3BS1—are all located in Water Conservation Area 3 (fig. 1). Previous reports have documented the construction of wells and stilling wells at the tree islands (Bevier and Krupa, 2001) and summarized the results of a preliminary assessment of groundwater-surface-water interactions (Krupa and Gefvert, 2006; Steve Krupa, SFWMD, written commun., 2008). However, a compilation report is needed to assess the quality of the data collected, and to analyze factors affecting groundwater levels and flow. This two-volume report summarizes the results of a quality-assurance and data-analysis project conducted on site information and time-series data collected from May 2000 through June 2008.

1.1 Objectives

The objective of this contract (Purchase Order 4500026695) is to obtain professional consulting services for quality assurance and analysis of hydrometeorological data at three tree island sites (3AN1, 3AS3, and 3BS1) in the Everglades (fig. 1). The objectives of the project are as follows:

1. Generate sets of high-quality site information and time-series data collected from monitoring stations at 3AN1, 3AS3, and 3BS1
2. Analyze seasonal, meteorological, and other factors that affect groundwater and surface-water levels at the three tree islands
3. Determine horizontal and vertical groundwater flow at the three tree islands

Volume 1 of this report contains the summary of the quality-assurance review and revisions of the data (objective 1). Volume 2 contains an analysis of the factors affecting surface-water and ground-water levels at the three tree islands (objectives 2 and 3).

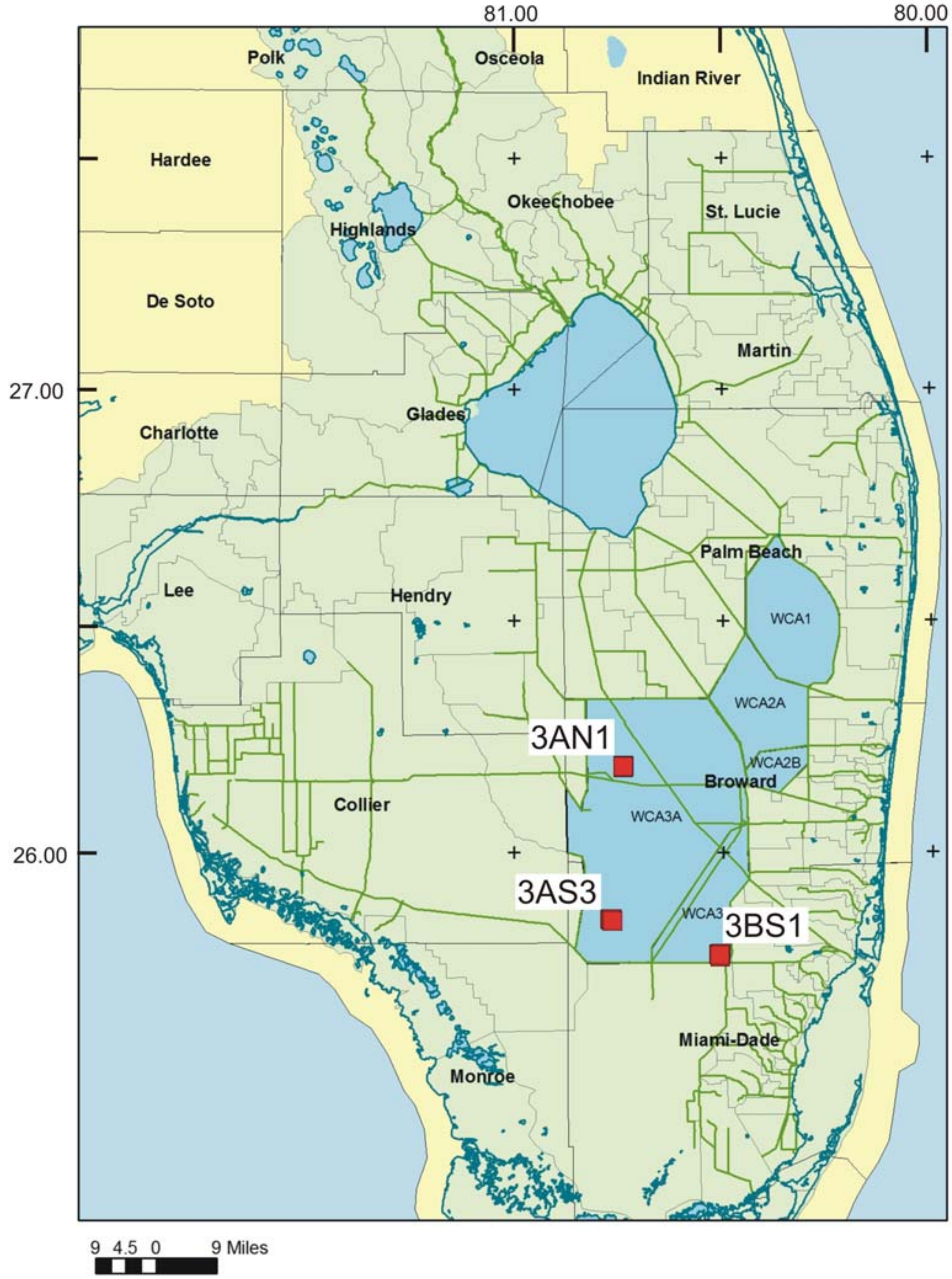


Figure 1 Location of the three tree islands

1.2 Scope of Work

The overall scope of work for the project is to conduct quality assurance/quality control assessment of site information and time-series data for 23 wells, 3 stilling wells, and 1 weather station used to monitor ground-water levels, surface-water stage, and various meteorological data. The hydrologic conditions, seasonal fluctuations, and factors affecting ground- and surface-water levels also were analyzed. The work was conducted off-site by staff at Adamski Geological Consulting, LLC (AGC). The project includes the following components:

Component 1 Quality-assurance and quality-control analyses were conducted on site information and time-series data collected at the three tree islands. The site location, construction information, and time-series data through December 31, 2006, were previously reviewed as part of a 2-year project for Taiye Sangoyomi, PE (SFWMD). However, a new survey of the stations was conducted in September 2007, which resulted in slight adjustments to the reference and land-surface elevations at most of the stations. Time-series data collected at the stations were adjusted using correction factors to account for the new reference elevations. In addition, data from the three stilling wells and meteorological station had not been previously reviewed, but were extensively analyzed as part of this project. All QA/QC analysis closely followed methods outlined in standard operating procedures (SOPs) of the SFWMD (Sangoyomi and others, 2005; Sangoyomi and others, 2006; Sangoyomi and Lambright, 2006).

Component 2 The seasonal fluctuations in ground-water level and surface-water stage at the three islands were identified. The dates on which maximum and minimum water levels occurred were documented for analysis in component 3. Data were analyzed for the effects of weather and operation of structures on fluctuations of ground-water levels and stage.

Component 3 The vertical and horizontal movement of water at the three tree islands was mapped and analyzed. The maps and analysis were done using extreme data (periods of water level minimums and maximums) and average data. The results were documented in this report.

The purpose of this report is to summarize work conducted by AGC on the project and document the results. During this period, site information and time-series data from 23 monitoring wells, 3 surface-water stations, and 1 meteorological station (henceforth, known as target stations) were reviewed and revised for quality assurance and quality control. The revised data are submitted with volume 1 of this report for approval and uploading into DBHYDRO. The purpose of this report also is to summarize results of statistical and other analyses conducted on the time-series data to determine groundwater flow and factors affecting groundwater and surface water levels.

1.3 Data Sources

The site information and time-series data for all 27 stations were collected by SFWMD and stored in the DBHYDRO database. The data from the target stations used for analysis during this project were downloaded directly from DBHYDRO (Table 1).

Station number from SOW	*Station name*	*Source DBKEY*	*Agency*	*Strata (feet)*	*MOD1 DBKEY*
1	3AN1W1_GP	OH532	WMD	14.5	UD202
2	3AN1W1_GW	OH531	WMD	32.9	UD201
3	3AN1W1_H	OH538	WMD	0	
4	3AN1W2_GP	OH534	WMD	15	UD200
5	3AN1W2_GW	OH533	WMD	49.6	UD199
6	3AN1W3_GP	OH536	WMD	14.5	UD204
7	3AN1W3_GW	OH535	WMD	31.7	UD205
8	3AN1W4_GP	OH537	WMD	4.1	UD203
9	3AS3W1_GP	PT035	WMD	8.7	UD311
10	3AS3W1_GW	M6884	WMD	26.4	UD300
11	3AS3W1_H	M6883	WMD	0	
12	3AS3W2_GP	PT036	WMD	8.5	UD361
13	3AS3W2_GW	M6885	WMD	25	UD360
14	3AS3W3_GP	PT037	WMD	8.5	UD312
15	3AS3W3_GW	M6887	WMD	28.6	UD301
16	3AS3W4_GP	PT038	WMD	10.7	UD313
17	3AS3W4_GW	M6886	WMD	30	UD299
18	3BS1W1_GP	PT039	WMD	15	UD307
19	3BS1W1_GW	M6890	WMD	34	UD295
20	3BS1W1_H	M6889	WMD	0	
21	3BS1W2_GP	PT040	WMD	13.5	UD308
22	3BS1W2_GW	M6891	WMD	30	UD296
23	3BS1W3_GP	PT041	WMD	15	UD309
24	3BS1W3_GW	M6892	WMD	28.5	UD298
25	3BS1W4_GP	PT042	WMD	14	UD310
26	3BS1W4_GW	M6893	WMD	34	UD297
27	3AS3W3_R	M6888	WMD		
28	3AS3WX	LA373	WMD		
29	3AS3WX	LA374	WMD		
30	3AS3WX	LA372	WMD		
31	3AS3WX	LA364	WMD		

Table 1 Site information for target wells, stilling wells, and weather station. [WMD, South Florida Water Management District]

2 METHODS

In late 1999, SFWMD began drilling and installing monitor wells at selected tree islands. Four sets of dual-zone monitor wells were installed at each of the tree islands for continual monitoring of groundwater levels. Dual-zone wells were installed northwest, northeast, and south of each tree island, with a final set of wells located within the tree island. The resulting four sets of wells at each island are identified as W1, W2, W3, and W4, respectively (figs. 2 through 4). With one exception (3AN1W4), each dual-zone site contains a shallow (depths range from 4.1 to 15 ft) ¾-inch diameter piezometer and a deeper (depths range from 26.4 to 49.6 ft) 2-inch diameter well installed in the same borehole. A detailed description of well construction and data-collection activities is provided in Bevier and Krupa (2001).

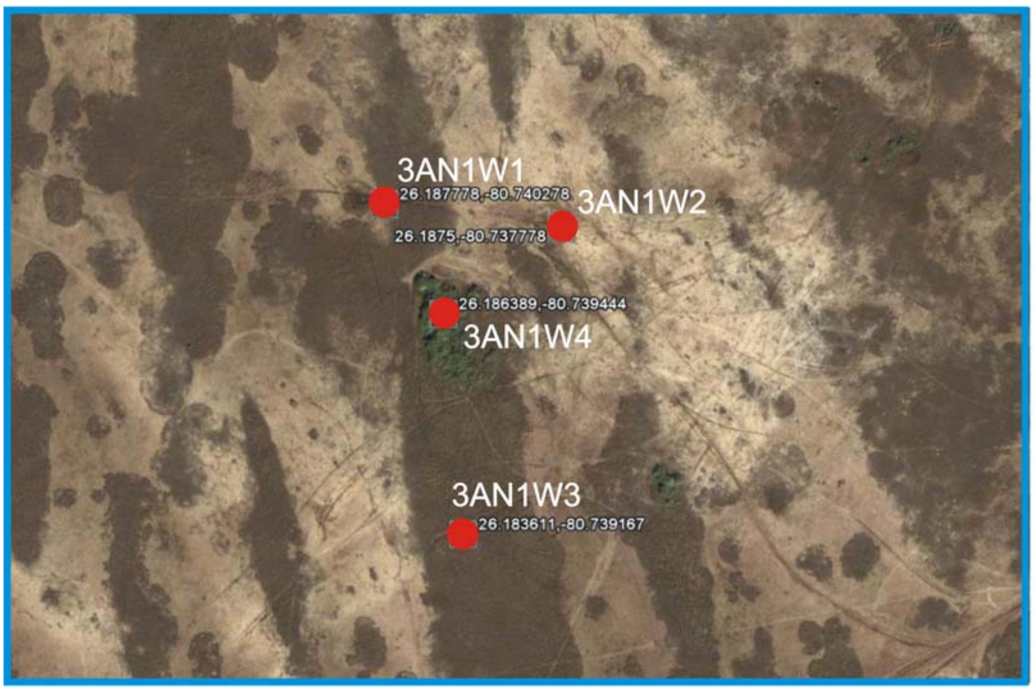


Figure 2 Location of target stations at Tree Island Site 3AN1.

Figure 3 Location of target stations at Tree Island 3AS3.

Figure 4 Location of target stations at Tree Island 3BS1.

In addition, W1 sites at each tree island also have an adjacent stilling well to monitor surface-water stage. Finally, a weather station for monitoring air temperature, barometric pressure, evapotranspiration, humidity, solar radiation, and wind speed was installed at 3AS3. A preliminary assessment of water-level and water-quality data from the tree islands is discussed in Krupa and Gefvert (2006). An in-depth quality-assurance assessment of the site and time-series data is discussed in volume 1 of this report.

Time-series (water level) data were collected continually (15-min increments) at all wells and stilling wells using pressure transducers and data loggers. The data analyzed as part of this project were daily averages of the incremental data. All of the stations were recently surveyed to accurately determine the elevation of the land surface, top of rock, and top of well casing at each site (Keith and Schnars, PA, 2007). Correction factors were applied to the daily-average data to account for elevation changes from the 2007 surveys.

Location coordinates, well depth, and time-series data for the 27 stations were downloaded from DBHYDRO. Other site information, such as reference and land-surface elevations and well depths, were previously obtained and (or) verified from survey reports and recorder registration worksheets.

The site information and time-series data were analyzed for quality assurance according to SFWMD protocols (Sangoyomi and others, 2005; Sangoyomi and others, 2006; Sangoyomi and Lambright, 2006). Volume 1 of this report contains a description of the methods as well as the results of that analysis.

Statistical methods, such as descriptive statistics and correlations, were used to describe the distribution of the time-series data, and determine relations among the variables. The non-parametric Wilcoxon rank-sum also was used to statistically analyze for differences between median values of two groups. An existing regression model (Cindy Bevier, SFWMD, written commun., 2008) was used to analyze the direction and flow of groundwater at the three tree islands. The model was run with and without data from the wells on the islands (W4 sites), but results from both analyses were similar. In general, the results discussed in this report are from the model run without the W4 wells. Results of the analyses were illustrated using hydrographs, scatter plots, and box plots. An example box plot is shown in figure 2.

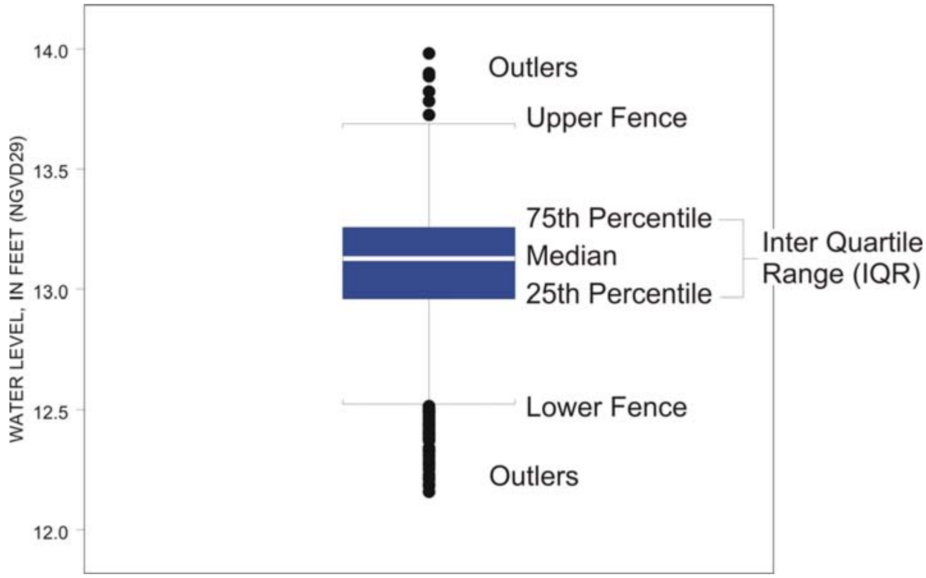


Figure 5 Sample box plot showing lower (Q1) and upper (Q3) quartiles, inter quartile range, and outliers.

Horizontal and vertical groundwater flow was analyzed using a series of maps and cross sections for each tree island. Six water-level maps were generated for each of the three tree islands (appendix) to illustrate horizontal groundwater flow during two dry periods, two wet periods, and two periods with average conditions. Average conditions for analysis were determined by selecting dates on which the water level in the deep well at the W1 site (for example, 3AS3W1_GW) was equal to the median value for that well. Cross sections were generated to show vertical and horizontal groundwater flow during one dry season and one wet season for each well. Vertical groundwater flow over time also was determined by subtracting the value of water level in the deep well from the water level in the adjacent piezometer or stilling well on the same date. A positive value indicates downward migration or recharge of groundwater, whereas a negative value indicates upward migration or discharge of groundwater.

Well depths (Strata variable in DBHYDRO) are listed as feet below land surface (bls), unless otherwise noted. Water-level data, and reference and land-surface elevations are listed as feet above mean sea level, and are based on the National Geodetic Vertical Datum of 1929 (NGVD29). Horizontal locations are based on North American Datum of 1983 (NAD83) and Florida State Plane coordinates.

3 ENVIRONMENTAL AND HYDROGEOLOGIC SETTING

Southern Florida is a topographically flat region, with land-surface elevations ranging from near sea level to a few tens of feet above sea level. Land-surface elevations at the three island sites range from 5.4 ft above NGVD29 at 3BS1W1 to 11.8 ft above NGVD29 at 3AN1W4 (table 2). The islands themselves are only slightly elevated above the surrounding land. Topographic relief—the difference between maximum and minimum elevations—at each island ranges from 1.7 ft at 3AN1 to 4.7 ft at 3BS1.

As noted earlier, tree islands are topographically elevated, typically tear-shaped features located within wetland systems of southern Florida (figs. 1 through 4). The tree islands generally are oriented their long axis parallel to surface-water flow (Bevier and Krupa, 2001). Tree islands, which are very sensitive to changes in hydrologic conditions and extreme wet and dry periods, are considered indicators of the overall ecological health of the Everglades system.

The islands coincide with, and possibly result from, structural highs in the underlying limestone. Table 2 shows the elevation of the top of the limestone at the four well sites at each of the three tree islands. A layer of organic matter (muck, soil, and leaf litter), ranging from 0.3 to 5.6 ft thick (table 2), overlies the limestone.

Well Site	Land-surface elevation (top of muck; ft above NGVD29)	Elevation of top of limestone rock (ft above NGVD29)	Thickness of organic matter (ft)
3AN1W1	10.2	9.9	0.3
3AN1W2	10.1	9.4	0.8
3AN1W3	10.5	9.3	1.2
3AN1W4	11.8	10.8	1.0
3AS3W1	8.4	4.6	3.8
3AS3W2	8.1	4.8	3.3
3AS3W3	8.9	3.3	5.6
3AS3W4	10.3	6.2	4.1
3BS1W1	5.4	2.8	2.6
3BS1W2	5.5	3.1	2.4
3BS1W3	6.2	2.2	4.0
3BS1W4	10.1	8.9	1.2

Table 2 Land-surface and top of rock elevations at the 12 well sites (based on survey data from Keith and Schnars, PA, 2007). Well sites on each island are highlighted in yellow.

Climate in southern Florida is subtropical with hot, humid summers and mild winters. Meteorological data from 3AS3 indicate that air temperatures ranged from 7.3 to 30.0 degrees Celsius (^{o} C) during the period of record, with a median value of 24.6 ^{o} C. Rainfall accumulations in the wet season (June – September) can be up to 36 inches, and as much as 3.7 inches was recorded in a single day. As a result of the intense rainfall, humidity values recorded at 3AS3 ranged from 48.8 to 95 percent, with a median value of 76.4 percent.

The high rates of rainfall have resulted in abundant surface-water and wetland resources surrounding the numerous tree islands (figs. 2 – 4). Photographs indicate that natural stream channels generally are absent, and most surface-water flow is overland sheet flow. The wetlands and surface water also interact with the underlying carbonate aquifer. Even during much of the dry season (October – May), the wetland surrounding the islands remains inundated, possibly as a result of groundwater discharge. Table 3 shows the percentage of time the water level in each well was higher than land-surface elevation, indicating the site is inundated with water. Tree islands 3AN1 and 3AS3 also are periodically inundated during the wet season.

Well	Land-surface elevation (in feet above NGVD29)	Percentage of time water level exceeded land-surface elevation
3AN1W1_GP	10.2	92.6
3AN1W1_GW	10.2	92.8
3AN1W1_H	10.2	95.4
3AN1W2_GP	10.1	93.3
3AN1W2_GW	10.1	94
3AN1W3_GP	10.5	74.7
3AN1W3_GW	10.5	76.8
3AN1W4_GP	11.8	17.9
3AS3W1_GP	8.4	99.7
3AS3W1_GW	8.4	99.2
3AS3W1_H	8.4	98.5
3AS3W2_GP	8.1	100
3AS3W2_GW	8.1	100
3AS3W3_GP	8.9	85.9
3AS3W3_GW	8.9	84.9
3AS3W4_GP	10.3	23.4
3AS3W4_GW	10.3	20.0
3BS1W1_GP	5.4	89.7
3BS1W1_GW	5.4	89.4
3BS1W1_H	5.4	88.8
3BS1W2_GP	5.5	85.4
3BS1W2_GW	5.5	84.7
3BS1W3_GP	6.2	65.8
3BS1W3_GW	6.2	69.9
3BS1W4_GP	10.1	0
3BS1W4_GW	10.1	0

Table 3 Percentage of time water levels in each well were higher than land-surface elevations. Wells on each island are highlighted in yellow.

Beginning in the 1910s, canals and associated structures (gates, culverts, and pump stations) have been constructed in southern Florida for the purpose of water management (Bevier and Krupa, 2001). The installation and operation of these structures has significantly modified the hydrology of southern Florida, and likely affects the water levels and flow of groundwater in and around the tree islands. An analysis of potential effects is part of this project, and discussed in section 5.2.

4 SEASONAL FLUCTUATIONS

4.1 Meteorological Data

Most of the meteorological data show seasonal fluctuations. Air temperature recorded at 3AS3WX generally decreases during the winter, and increases during the spring and summer months (Volume 1 Appendix). Potential evapotranspiration, which is related to solar and photosynthetic radiation, is least around the time of the winter solstice and greatest around the start of summer (fig. 6). Evapotranspiration (ET) can be a large component of an area's water balance. ET rates from nine sites in the Everglades ranged from 42.4 to 57.4 inches per year (German, 2000). High rates of solar radiation and evapotranspiration likely contribute to groundwater and surface-water level declines during periods of low rainfall. Barometric pressure and humidity (Volume 1 Appendix) also have cyclic patterns related to seasons as well as storm systems that affect the area.

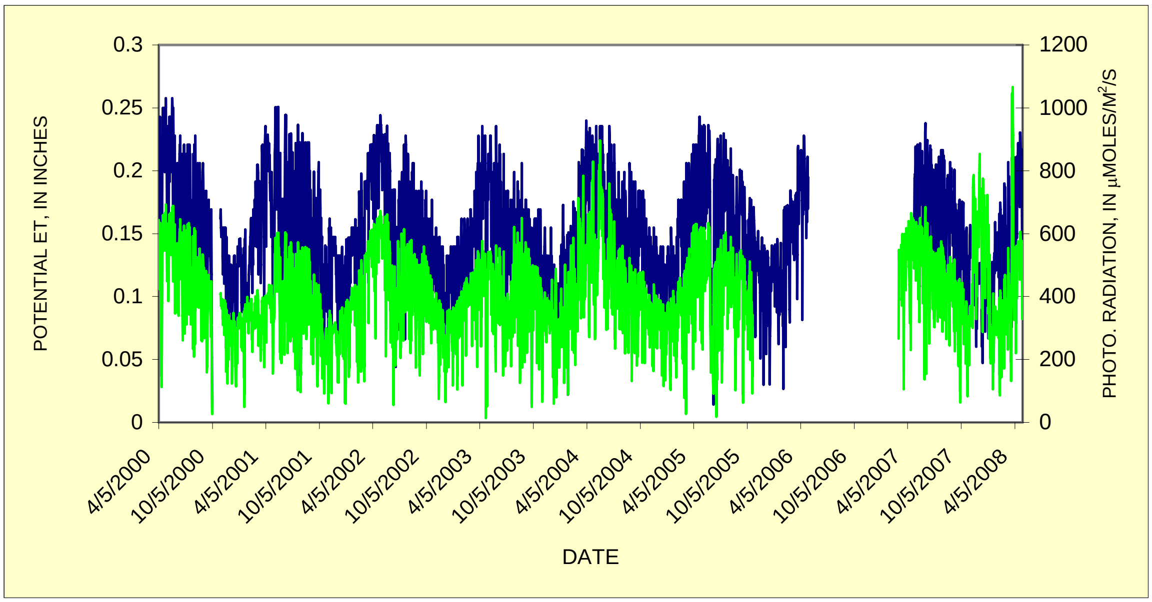


Figure 6 Seasonal fluctuations in potential evapotranspiration (blue) and photosynthetic radiation (green) recorded at station 3AS3WX.

Along with ET, the seasonal fluctuations of rainfall have a large impact on groundwater and surface-water levels at the tree islands. In general, southern Florida has two seasons with respect to rainfall—a wet season that extends from June through September of each year, followed by a dry season from October through May. Data collected from June 1, 2000 through May 31, 2008 at station 3AS3W3_R indicate that the cumulative rainfall during the 4-month wet season ranged from 17.0 (2002) to 36.2 inches (2005) with a media of 30.4 inches. In contrast, rainfall during the dry season was significantly less during the same period of record, ranging from 10.2 (2007) to 25.2 inches (2003) with a median of 16.1 inches. The dry season that ended in May 2007 is missing 49 values, so the actual rainfall during that season could be greater than 10.2

inches. Figure 7 shows the cumulative rainfall during each wet and dry season at 3AS3W3_R.

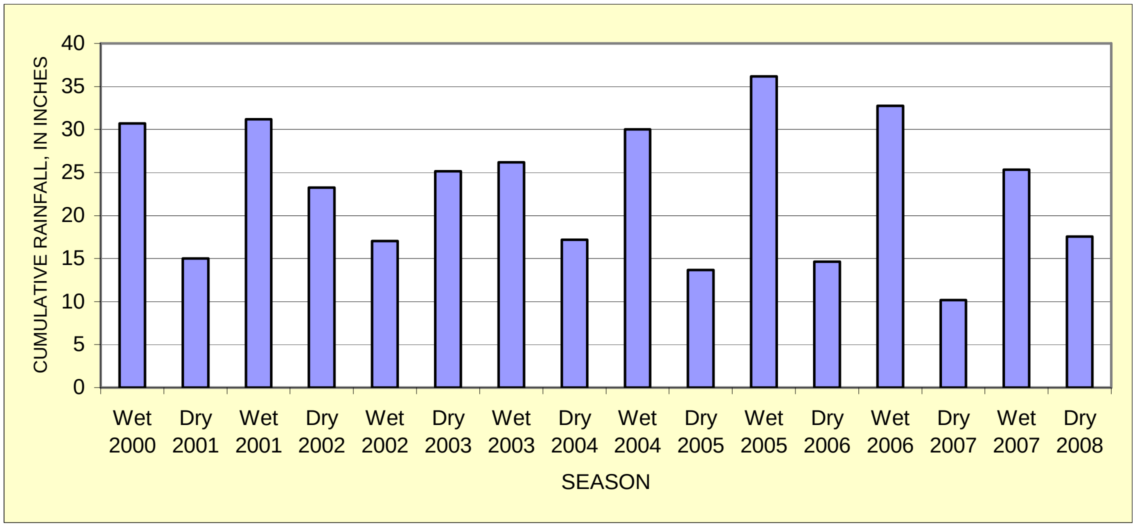


Figure 7 Cumulative rainfalls during each annual wet and dry season at station 3AS3W3_R.

The source of rainfall often differs between the wet and dry seasons. Dry season rainfall usually is associated with weather fronts as air masses with different temperatures and pressures interact. Wet season rainfall results primarily from isolated summer storms together with less frequent tropical storms and periodic hurricanes. The isolated storms generally result in large variations in rainfall between different rain stations across the region.

4.2 Water-Level Data

Surface-water stage and groundwater levels also show significant seasonal fluctuations. Water levels generally increase during the wet season, and decline during the dry season, which imparts a sinusoidal pattern to the hydrograph over periods greater than one year (see hydrographs in Volume 1 Appendix). A preliminary analysis of these seasonal fluctuations was conducted by Krupa and Gefvert (2006). The fluctuations, along with the occurrence of minimum and maximum water levels, at each tree island are also discussed below.

For brevity, the discussion below focuses primarily on the sites with stilling wells in order to assess surface water and ground water fluctuations, but the fluctuations in water levels in other wells are similar due to the strong correlation among all the wells at each tree island. For example, the water level in well 3AN1W1_GP (depth = 14.5 ft) is strongly correlated to the water level in well 3AN1W2_GW (depth = 49.6 ft) (fig. 8; R^2=0.99).

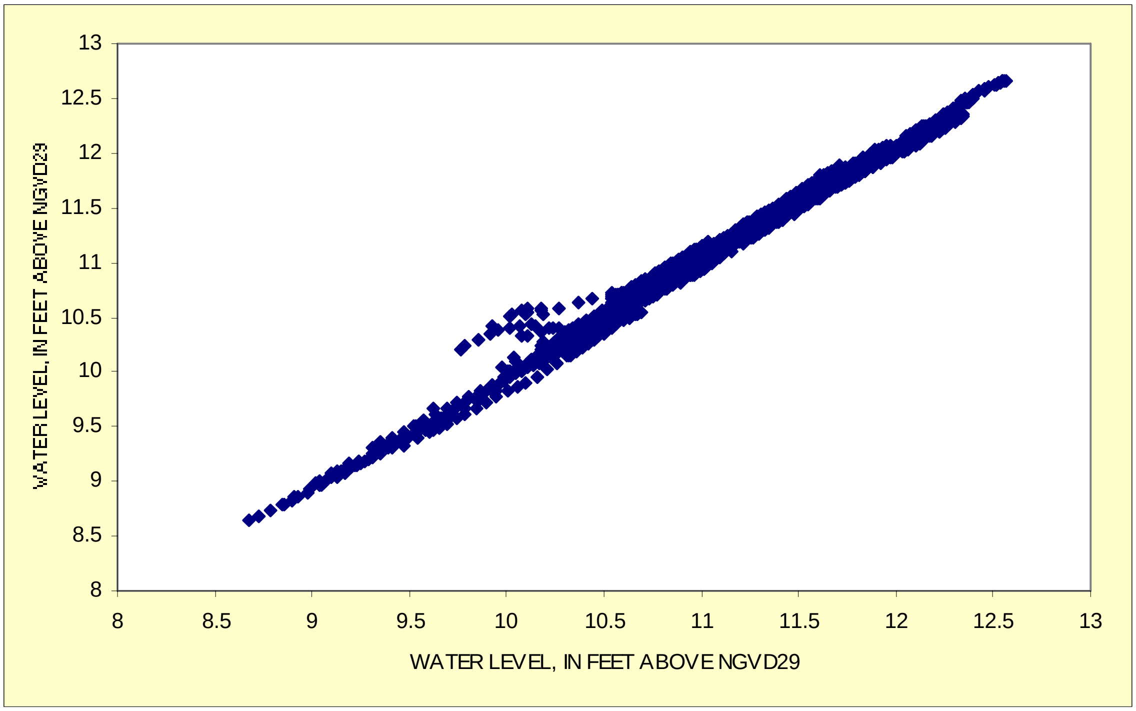


Figure 8 Water level in well piezometer 3AN1W2_GW (Y axis) is plotted against water level in piezometer 3AN1W1_GP (R^2=0.99).

4.2.1 3AN1

Surface-water stage and groundwater levels in the stations at 3AN1 generally decline through the dry season and increase during the wet season. Water levels in the wells and the stilling well generally are at their lowest level (annual minimum) in mid to late May, although in 2005, the annual minimum water levels occurred on March 2 and 3 (Appendix A). Water levels in the wells and stilling wells peak each year (annual maximum) in late September to early October. In 2005, the annual maximum water levels occurred on July 11, and were consistently elevated through mid November.

The minimum water levels during the entire period of record occurred on May 31, 2007 (fig. 9; Appendix A), which coincides with the low rainfall during the 2007 dry season. In March and May 2007, water level in the stilling well declined below the pressure transducer, and possibly below the bottom of the well, which resulted in anomalous data (see Volume 1 Sect. 4.3 Station 3: 3AN1W1_H).

Figure 9 Water levels in wells 3AN1W1_GP (blue) and 3AN1W1_GW (green) and stilling well 3AN1W1_H (red) from October 1, 2006 through September 30, 2007. The horizontal brown line represents land-surface elevation at the station.

The maximum water levels for the entire period of record occurred on July 11, 2005 (fig. 10; Appendix A), which coincides with the excessive rainfall during the wet season of 2005. The maximum water level on that date was 12.648 ft above mean sea level in well 3AN1W1_GW. Water levels in the associated piezometer and stilling well were slightly lower at 12.565 and 12.632 ft above mean sea level, respectively. These water levels indicate that vertical flow on this date was extremely complex. The water level in the stilling well was higher than the level in the piezometer, indicating downward flow as might be expected toward the end of the wet season. However, the water level in the deep well is higher than the levels in either the piezometer or the stilling well, which indicates an overall upward flow of groundwater. The water levels in all three stations were continually higher than 12 ft above mean sea level through November 15.

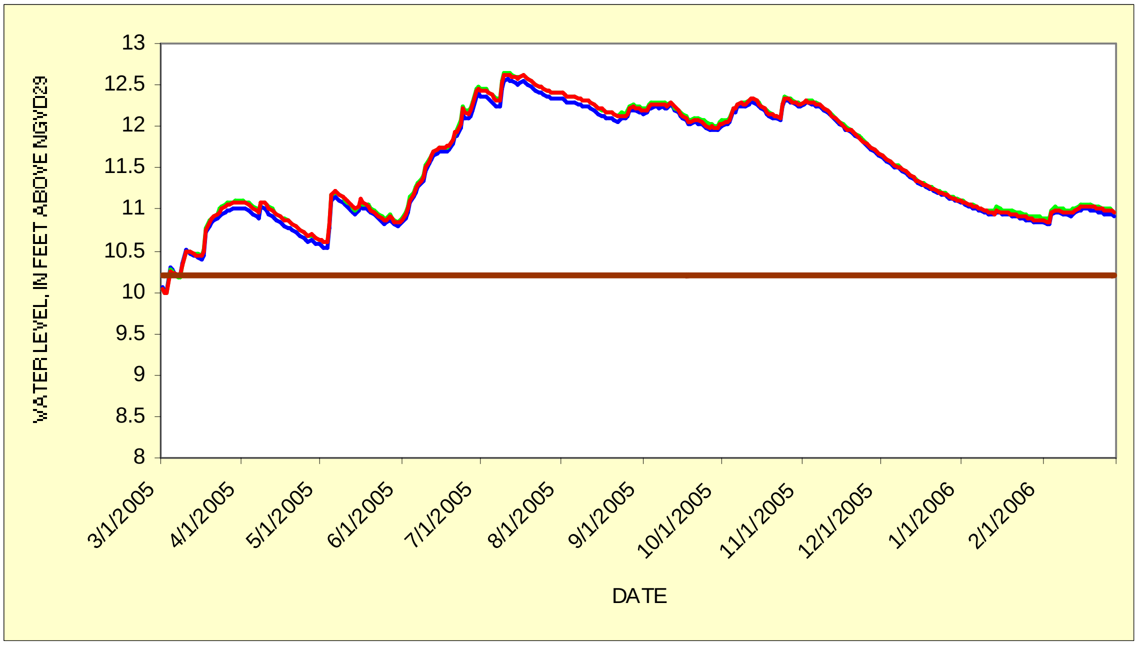


Figure 10 Water levels in wells 3AN1W1_GP (blue) and 3AN1W1_GW (green) and stilling well 3AN1W1_H (red) from March 1, 2005 through February 28, 2006. The horizontal brown line represents land-surface elevation at the station.

4.2.2 3AS3

As with 3AN1, surface-water stage and groundwater levels in the stations at 3AS3 generally decline throughout the dry season and increase during the wet season. Water levels in the wells and the stilling well generally are at their lowest in mid to late May, although annual minimum water levels occurred as early as April 25 in 2003, and as late as June 14 in 2004 (Appendix A). Water levels in the wells and stilling well peak each year in late September to early October. In 2005, the annual maximum water level occurred on September 2, and in 2001 and 2007, the annual maximum water levels occurred in early November.

The minimum water levels (entire period) in three of the wells and the stilling well at 3AS3 occurred on May 22, 2001 (fig. 11). The minimum water level in 3AS3W2_GW occurred on May 31, 2007. Minimum water levels in the piezometers also occurred on May 31, 2007; however, data-collection activities did not begin for those stations until July 2003.

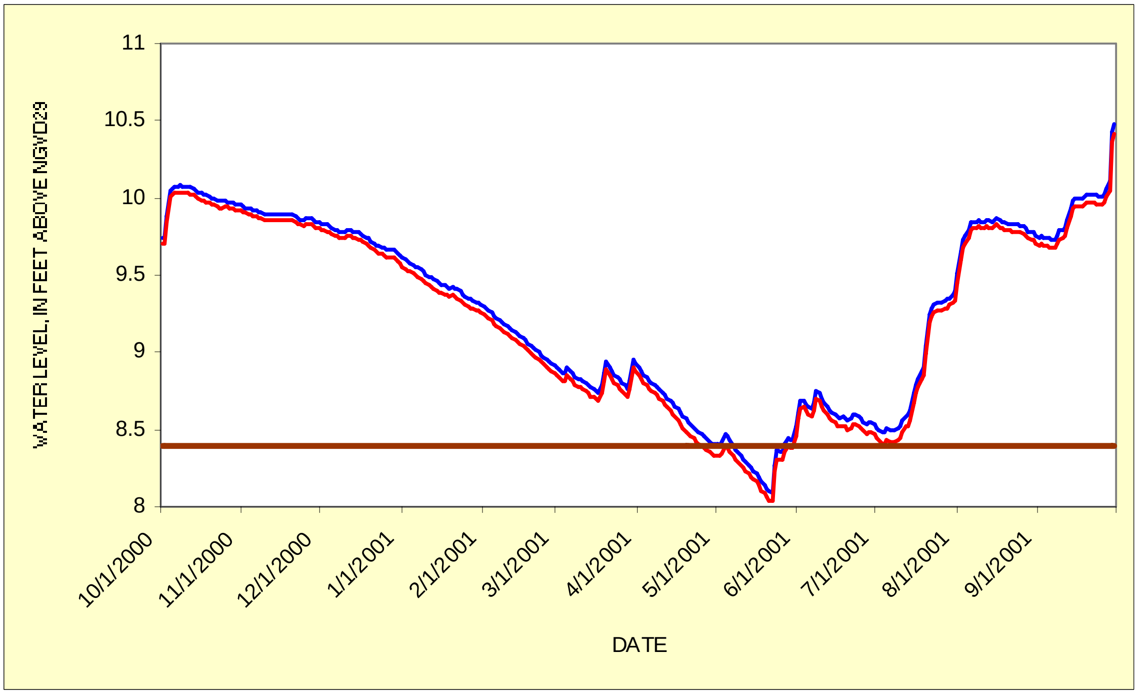


Figure 11 Water levels in well 3AS3W1_GW (blue) and stilling well 3AS3W1_H (red) from October 1, 2000 through September 30, 2001. The horizontal brown line represents land-surface elevation at the site.

The maximum water levels in the stilling well and all but one of the deep wells occurred on September 2, 2005 (fig. 12; Appendix A). The maximum water level in piezometer 3AS3W2_GP occurred on September 30, 2003. The water level in 3AS3W1_GW on September 2, 2005 was 11.273 ft above mean sea level. Water levels in the associated piezometer and stilling well on that same date were slightly lower at 11.232 and 11.216 ft above mean sea level, respectively. Water levels at the end of the wet season in 2005 were continually higher in the deep well than levels in either the piezometer or stilling well; therefore, vertical groundwater flow appears to be upward, even at the end of the wet season

Figure 12 Water levels in wells 3AS3W1_GP (blue) and 3AS3W1_GW (green) and stilling well 3AS3W1_H (red) from June 1, 2005 through May 31, 2006. The horizontal brown line represents land-surface elevation at the site.

4.2.3 3BS1

As with 3AN1 and 3AS3, surface-water stage and groundwater levels in the stations at 3BS1 generally decline through the dry season and increase during the wet season. Water levels in the wells and the stilling well generally are at their lowest in mid to late May, although annual minimum water levels occurred as early as March 3 in 2005, and as late as July 2 in 2004 (Appendix A). Water levels in the wells and stilling well reach their annual maximum each year in late September to early October, although peak water levels occurred on November 12, 2006 in piezometer 3BS1W3_GP.

The minimum water levels (entire period) in the four deep wells and the stilling well occurred on May 21 and 22, 2001 (fig. 13), which coincides with the minimum water levels in the deep wells and stilling well at 3AS3. The minimum water levels in the piezometers occurred on May 31, 2007 (Appendix A); however, data-collection activities did not begin until July 2003.

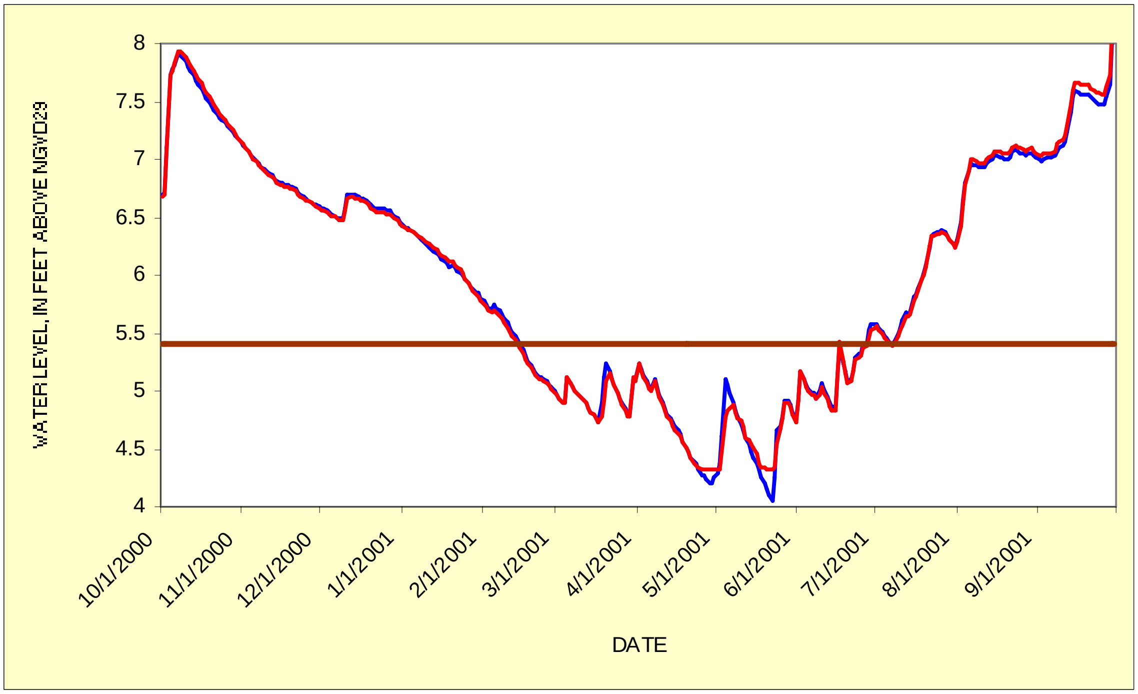


Figure 13 Water levels in well 3BS1W1_GW (blue) and stilling well 3BS1W1_H (red) from October 1, 2000 through September 30, 2001. The horizontal brown line represents land-surface elevation at the site.

The maximum water levels in the four deep wells and stilling well occurred on October 25, 2001 (fig. 14; Appendix A). The water level in the stilling well (8.525 ft above NGVD29) was higher than the water level in the adjacent deep well (8.384 ft), indicating subsurface water flow was downward. The maximum water level in three of the four piezometers occurred on September 12, 2005. On that date, the water level in the stilling well (8.457 ft above NGVD29) was higher than the levels in either the adjacent piezometer (8.407 ft above NGVD29) or deep well (8.35 ft). Hence, vertical flow of water appears to have been downward.

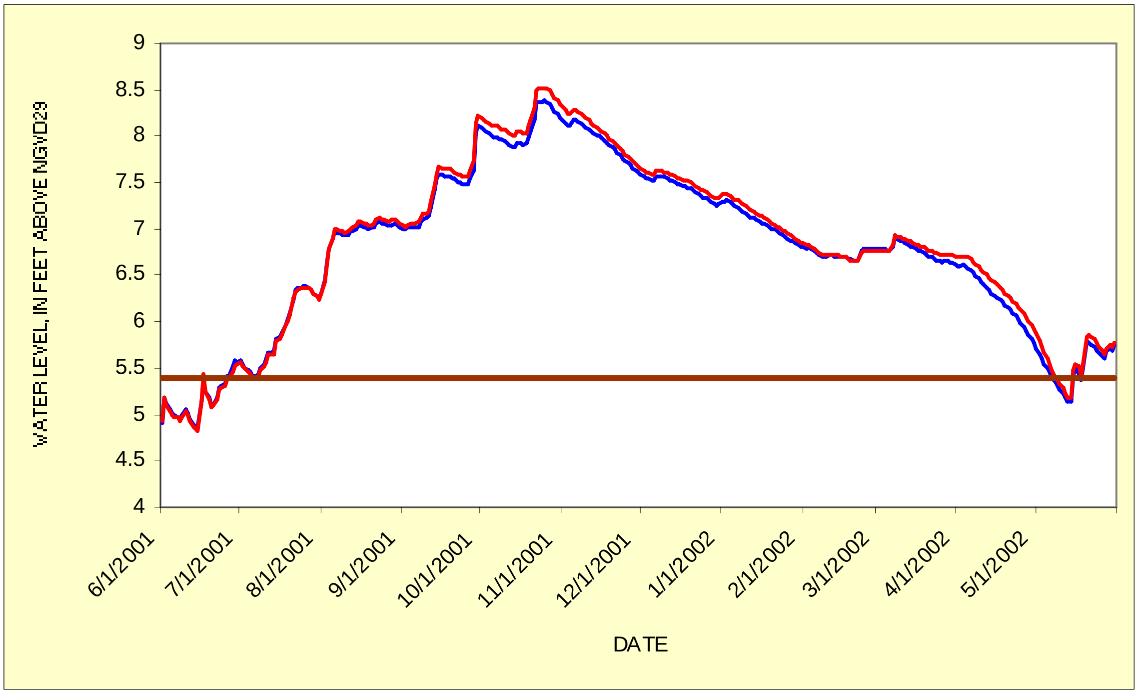


Figure 14 Water levels in wells 3BS1W1_GW (blue) and stilling well 3BS1W1_H (red) from June 1, 2001 through May 31, 2002. The horizontal brown line represents land-surface elevation at the site.

5 FACTORS AFFECTING WATER LEVELS

5.1 Meteorological Conditions

Groundwater and surface-water levels at the three tree islands appear to be strongly related to rainfall at the sites. Water levels in the wells and stilling wells increase during the wet season and decline during the dry season (fig. 15). This relation occurs regardless of the well depth.

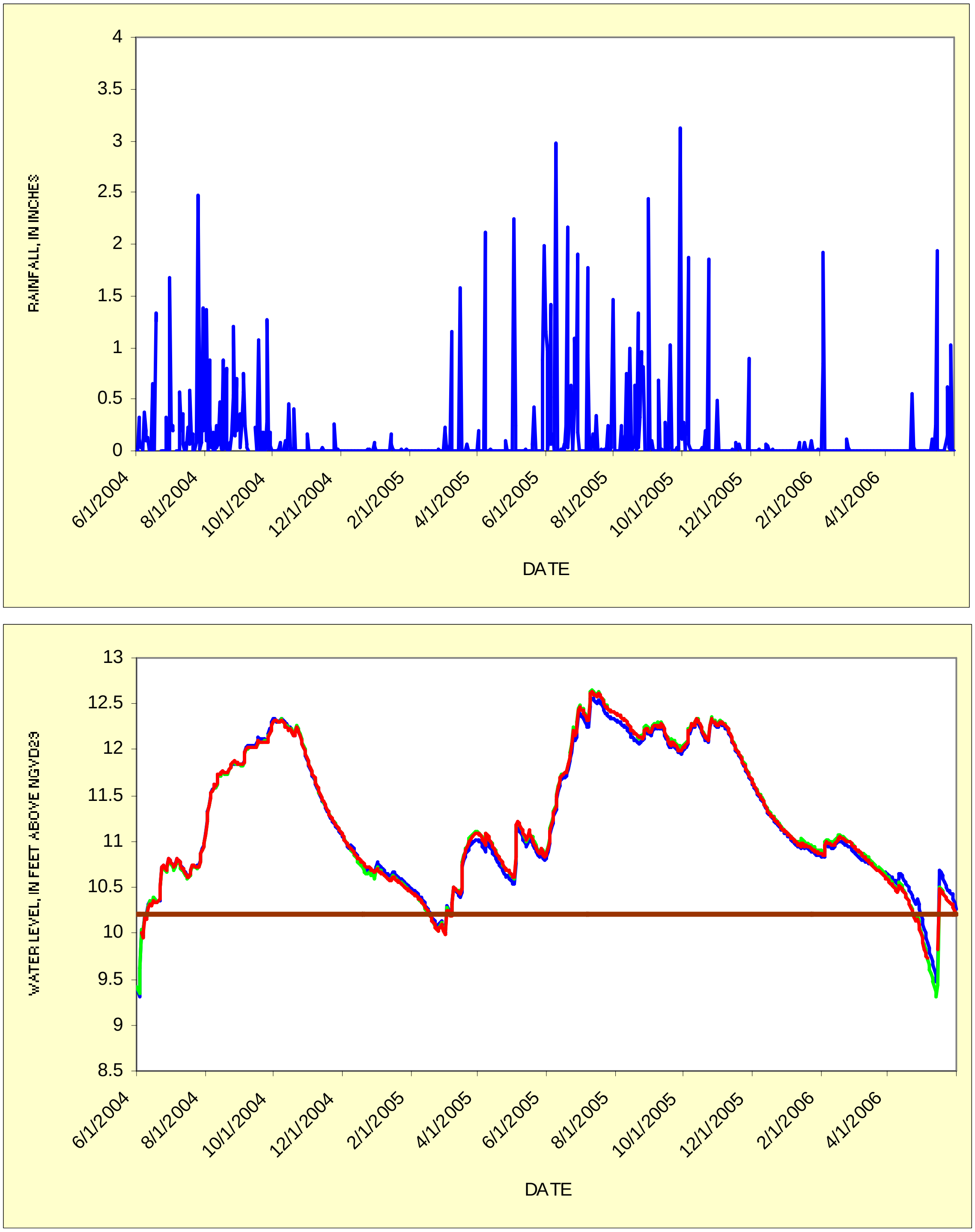


Figure 15 Response of water levels in stations 3AN1W1_H (red), 3AN1W1_GP (blue) and 3AN1W1_GW (green) to rainfall during 2004 and 2005 wet seasons. The horizontal brown line in the bottom graph represents land-surface elevation at the site.

Results from the Wilcoxon rank-sum test indicate that groundwater and surface-water levels were statistically higher at the end of each wet season compared to water levels at the end of each dry season (fig. 16; $p<0.01$). In addition, groundwater and surface-water levels were positively correlated ($R^2=0.78$) to cumulative rainfall at the end of each wet and dry season (fig. 17). In other words, higher accumulated rainfalls during the season resulted in higher water levels in each station.

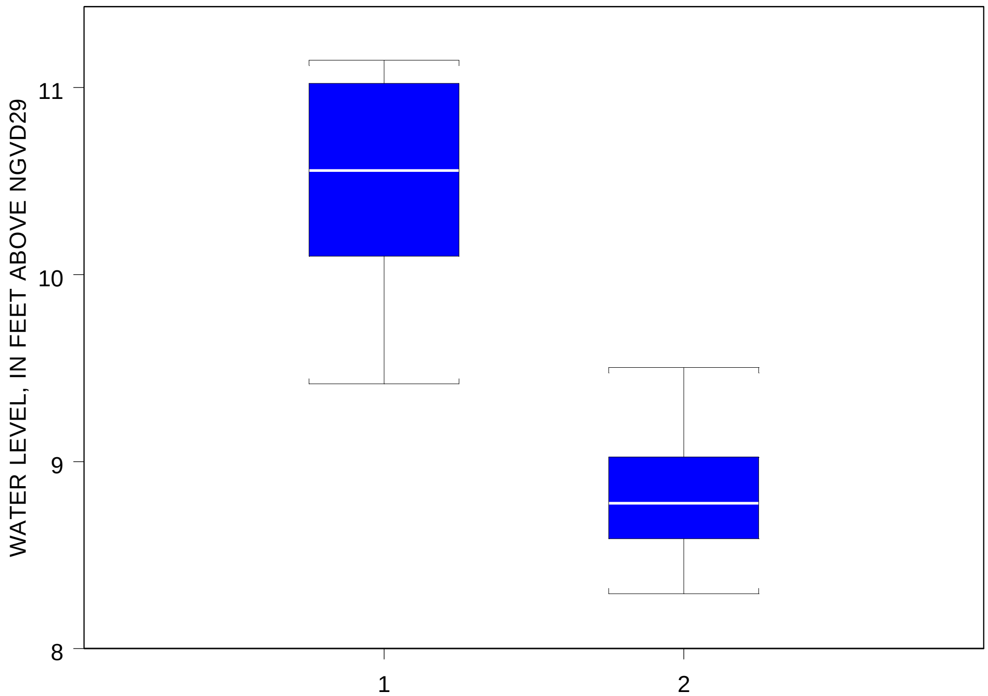
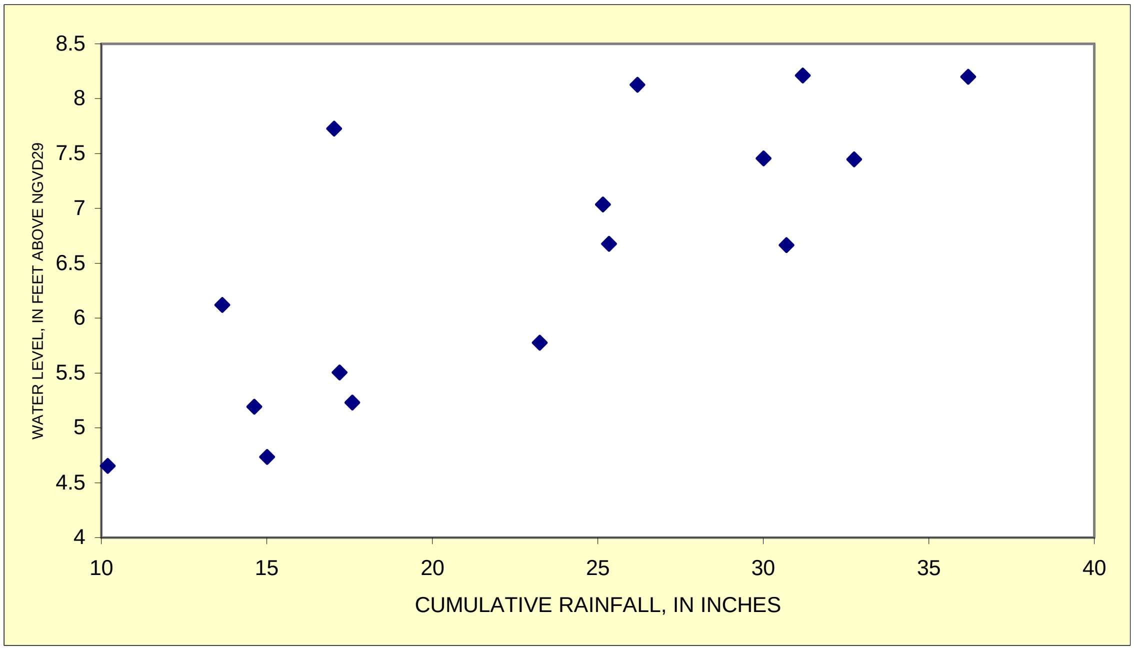


Figure 16 Groundwater levels in well 3AS3W1_GW are significantly higher ($p<0.01$) at the end of each wet season (1) compared to groundwater levels in the same well at the end of each dry season (2).



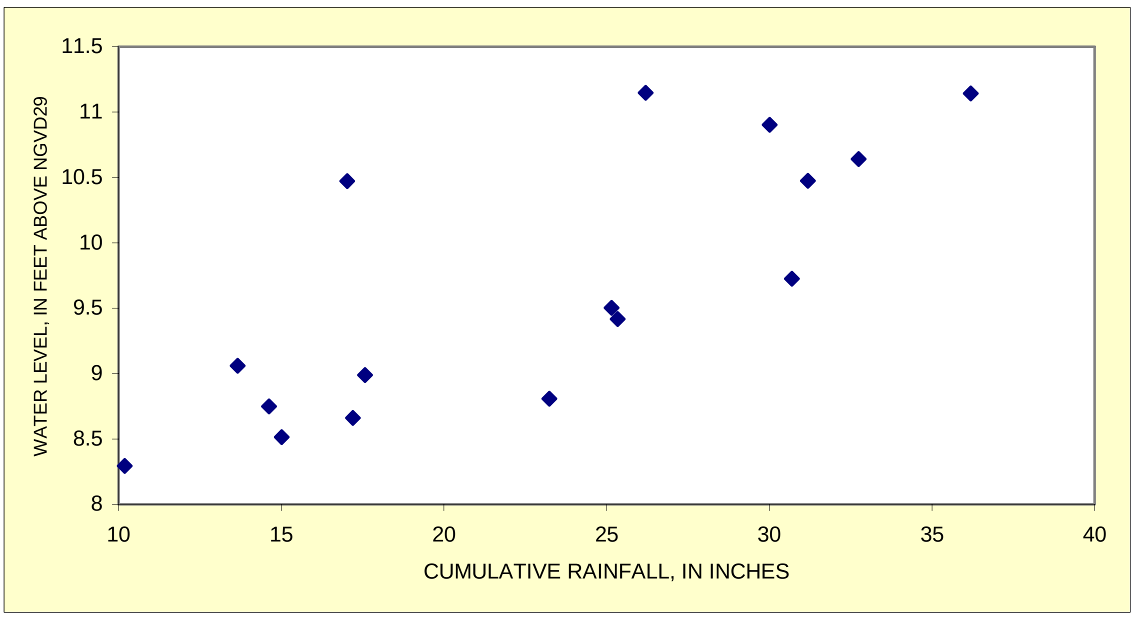


Figure 17 Water level in stations 3BS1W1_H (top) and 3AS3W1_GW plotted against cumulative rainfall (3AS3W3_R) after each wet season and each dry season.

Groundwater and surface-water levels also increased sharply after each individual storm or rainfall. Figure 18 shows that groundwater and surface-water levels at 3AS3W1 increased about 0.4 ft after the 3.7-in rainfall recorded at 3AS3W3_R on February 13, 2008. Groundwater and surface-water levels also increased after smaller rainfalls occurred on March 8 and 22, 2008.

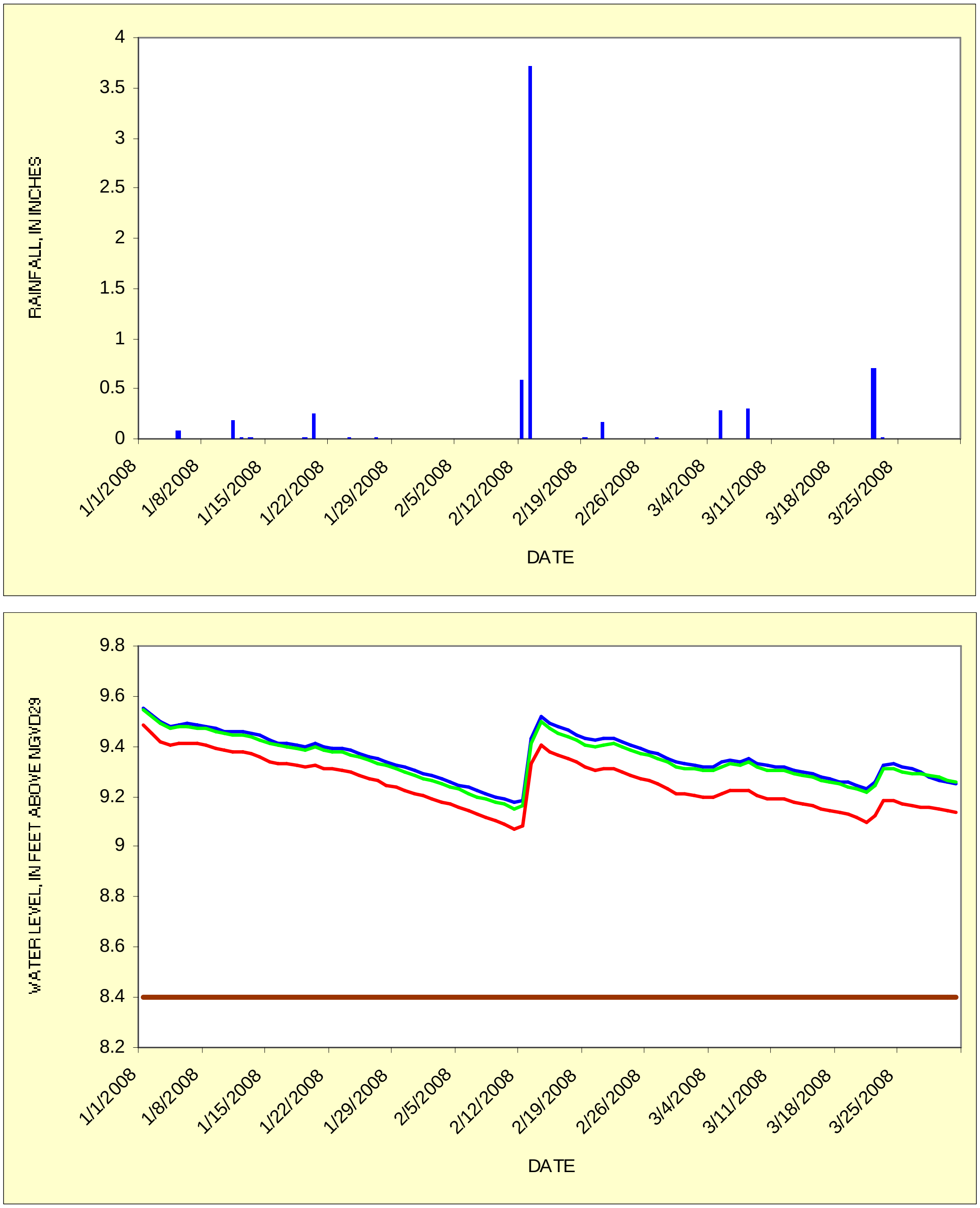


Figure 18 Response of water levels in stations 3AS3W1_GP (blue), 3AS3W1_GW (green), and 3AS3W1_H (red) to rainfalls recorded at 3AS3W3_R (top). The horizontal brown line represents land-surface elevation at the site.

The increase in groundwater and surface-water levels for each well at 3AS3 also is significantly correlated to the amount of each individual rainfall recorded at 3AS3W3_R (fig. 19; table 4). The correlation between water levels and rainfall was weaker for stations at 3AN1 and 3BS1, possibly because many of the storms recorded at 3AS3W3_R were localized, and data from that station are not necessarily accurate for rainfalls at the other two tree islands.

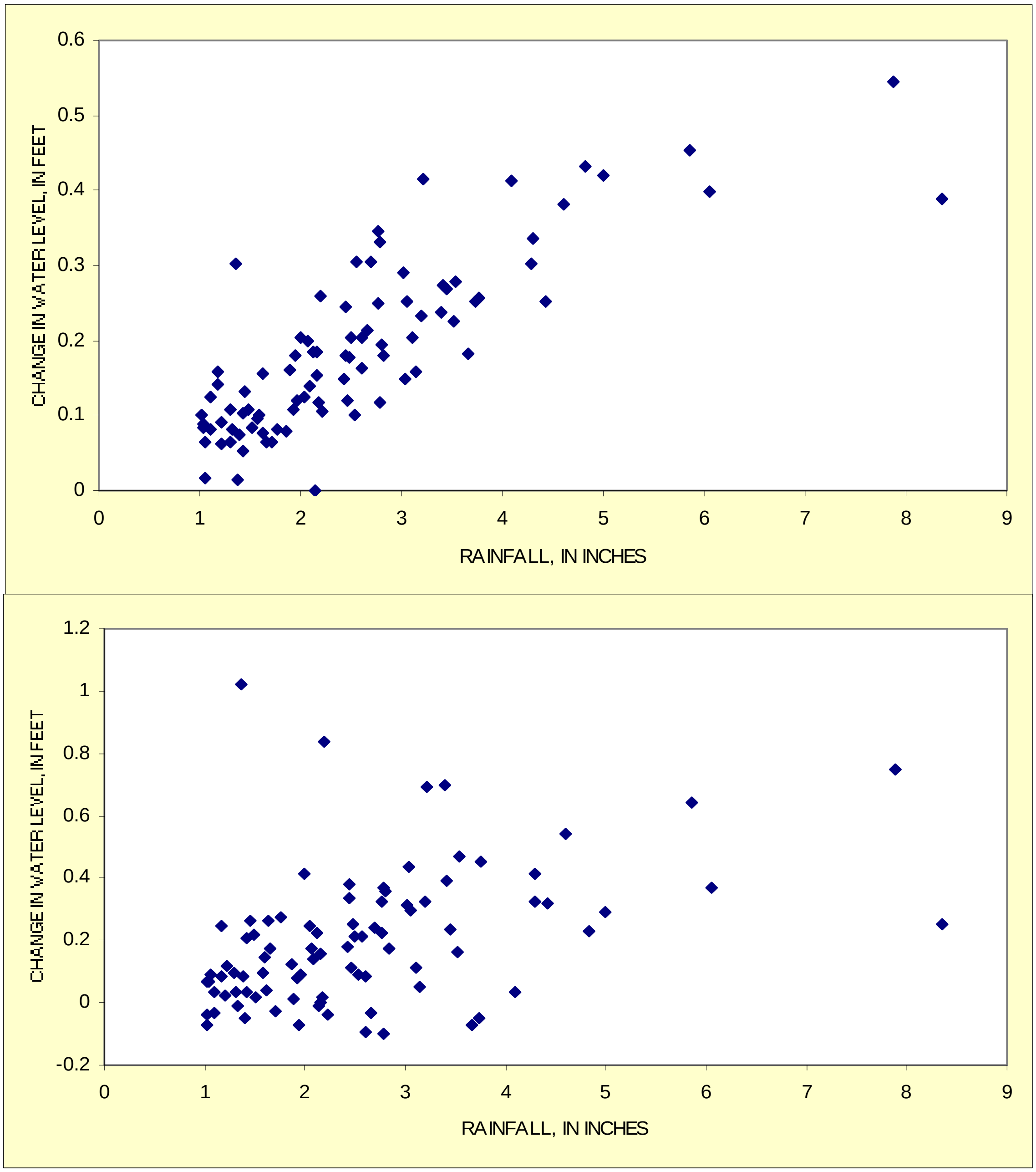
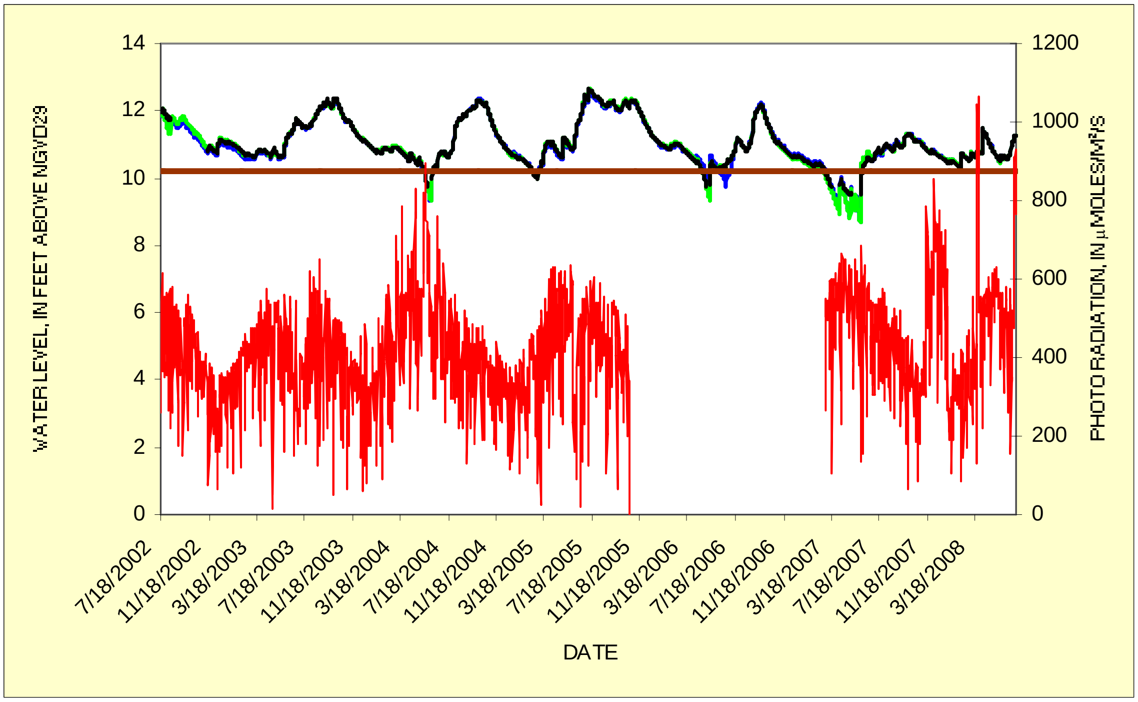


Figure 19 The change in water level in stations 3AS3W3_GW (top; R^2=0.87) and 3BS1W1_H (R^2=0.52) plotted against rainfall from individual storms recorded at 3AS3W3_R.

Station	Number of Samples	Correlation Factor (R^2)
3AN1W1_GP	62	0.30
3AN1W1_GW	62	0.29
3AN1W1_H	62	0.12
3AS3W3_GP	55	0.86
3AS3W3_GW	89	0.87
3AS3W1_H	89	0.87
3BS1W1_GP	55	0.54
3BS1W1_GW	89	0.53
3BS1W1_H	89	0.52

Table 4 Results of correlation analyses between increases in water level and amount of rainfall from individual storms recorded at 3AS3W3_R.

Surface- and groundwater levels generally are inversely related to photosynthetic radiation and potential evapotranspiration (ETP). Groundwater and surface-water levels decline as photosynthetic radiation and evapotranspiration increase (fig. 20). Evapotranspiration is related to solar radiation (itself a function of cloud cover and length of daylight), air temperature, humidity, precipitation, and wind speed. As a result, potential evapotranspiration shows not only large seasonal variations, but also daily and other short-term variations from storms and other factors. Hence, although the general relation between water levels and ETP is apparent, statistical correlation is difficult due to these large short-term fluctuations (fig. 21).



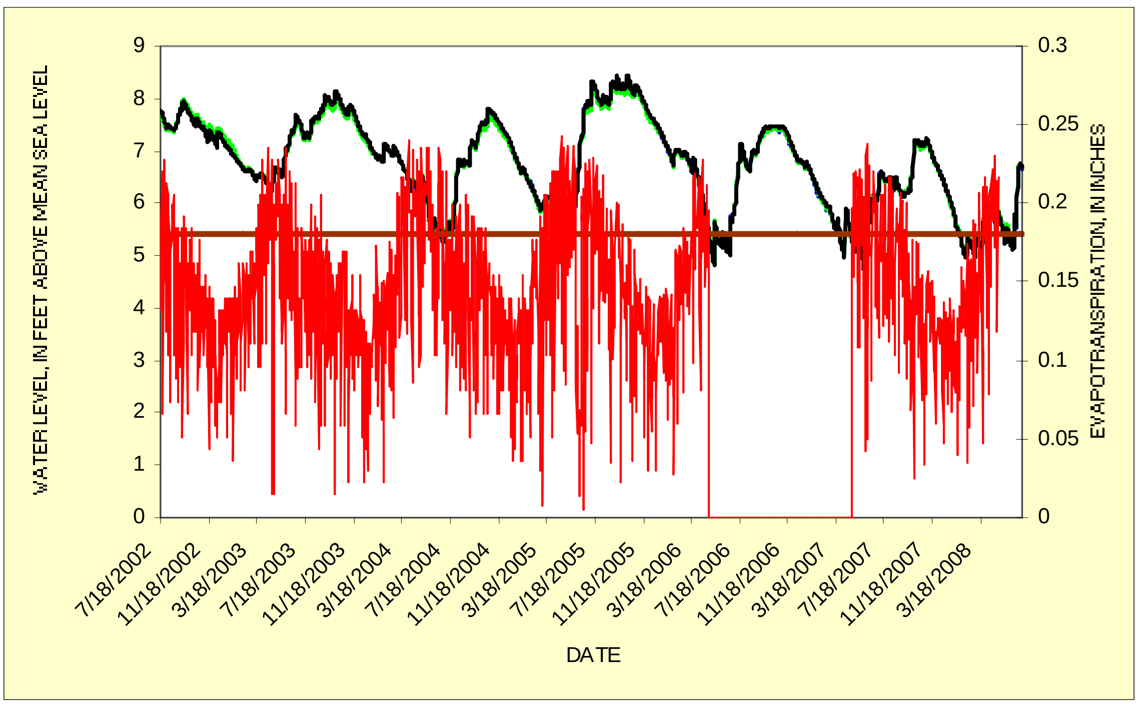
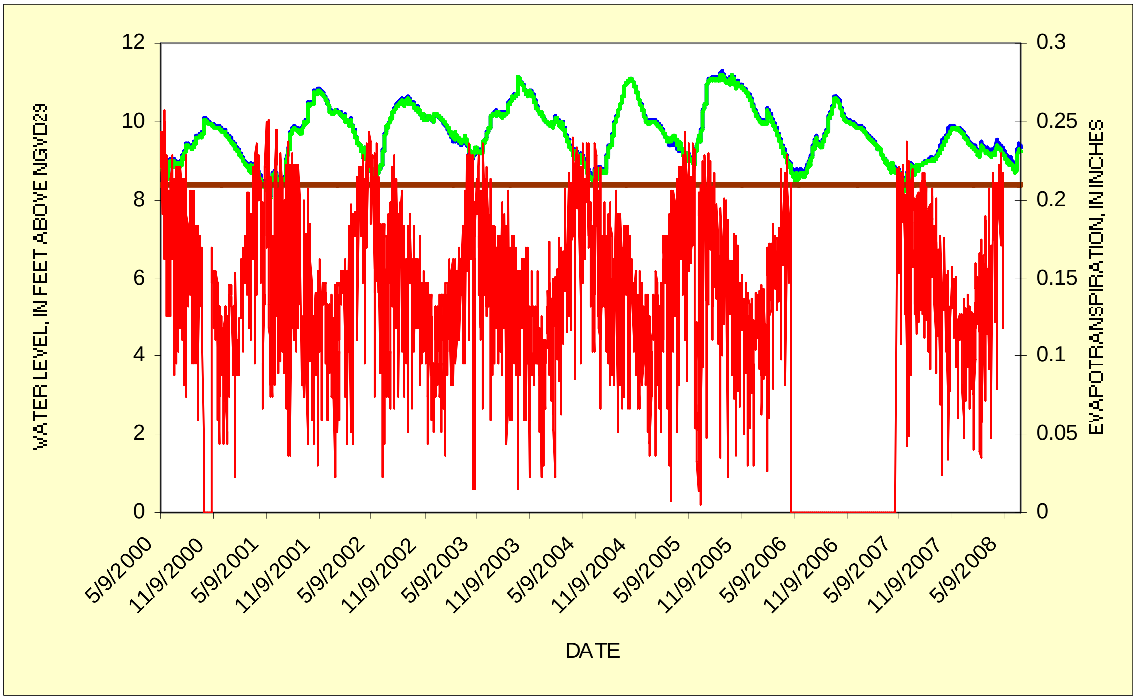


Figure 20 Water levels in the shallow piezometers (blue), deep wells (green) and stilling wells (black) at sites 3AN1W1 (top) and 3BS1W1 (bottom) plotted with photosynthetic radiation (top, red) and potential evapotranspiration (bottom, red) recorded at 3AS3WX. The horizontal brown line on each graph represents land-surface elevation at the sites.



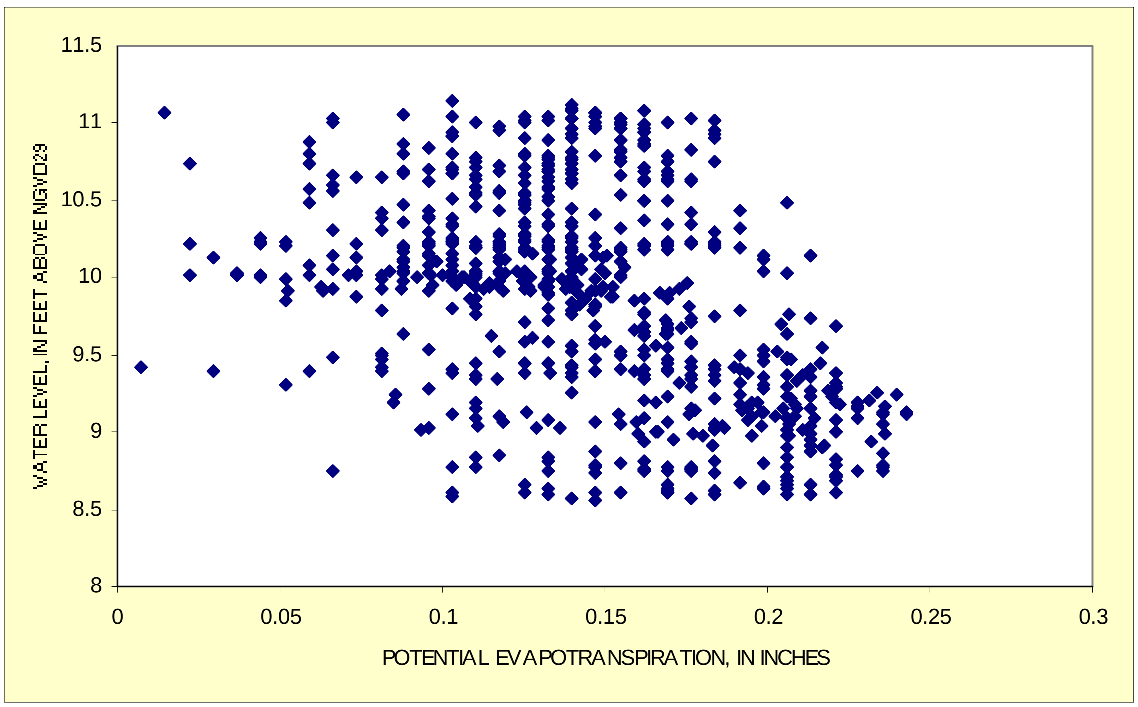
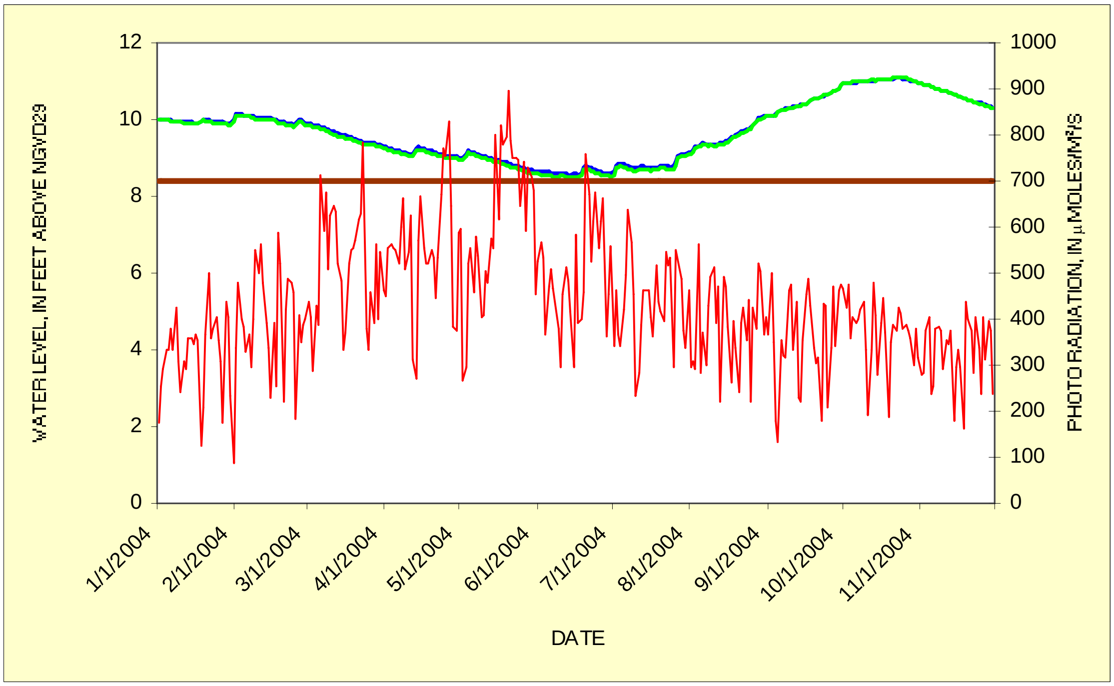


Figure 21 Water levels in stations 3AS3W1_GW (blue) and 3AS3W1_H (green) are plotted with potential evapotranspiration (red) over time (top). Water levels in well 3AS3W3_GW are plotted against potential evapotranspiration (correlation coefficient = -0.43).

The effects of photosynthetic radiation and evapotranspiration on water levels are even more apparent on plots of shorter duration (figs. 22 and 23). In particular, the peak in photosynthetic radiation that occurs each mid day coincides with a slight (0.01 ft) daily decline in groundwater and surface-water levels at 3AS3W1 (fig. 23). This trend continues even after the water levels decline below land-surface elevation, probably as a result of water uptake by plant roots. Water levels in wells show a similar daily decline when plotted with sap flow in plants, which, like photosynthetic radiation, peaks during the middle of each day (Steve Krupa, SFWMD, written commun., 2008).



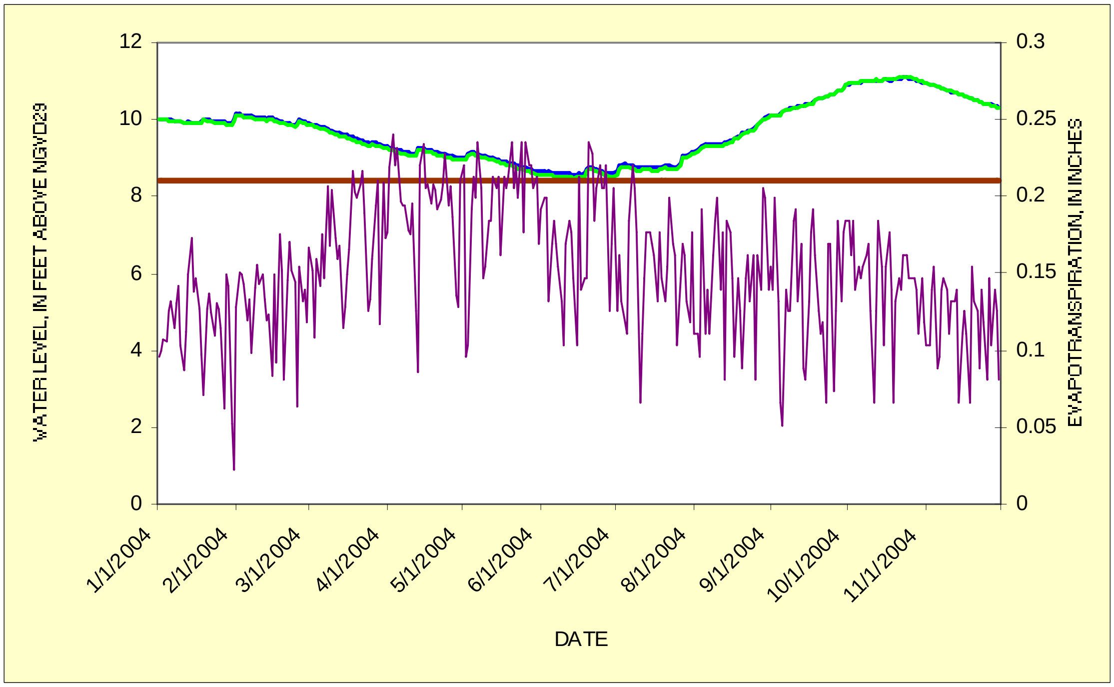


Figure 22 Water levels in stilling well 3AS3W1_H (green) and deep well 3AS3W1_GW (blue) decline as photosynthetic radiation (top, red) and evapotranspiration (bottom, dark blue) increase. The horizontal brown line represents the land-surface elevation at 3AS3W1.

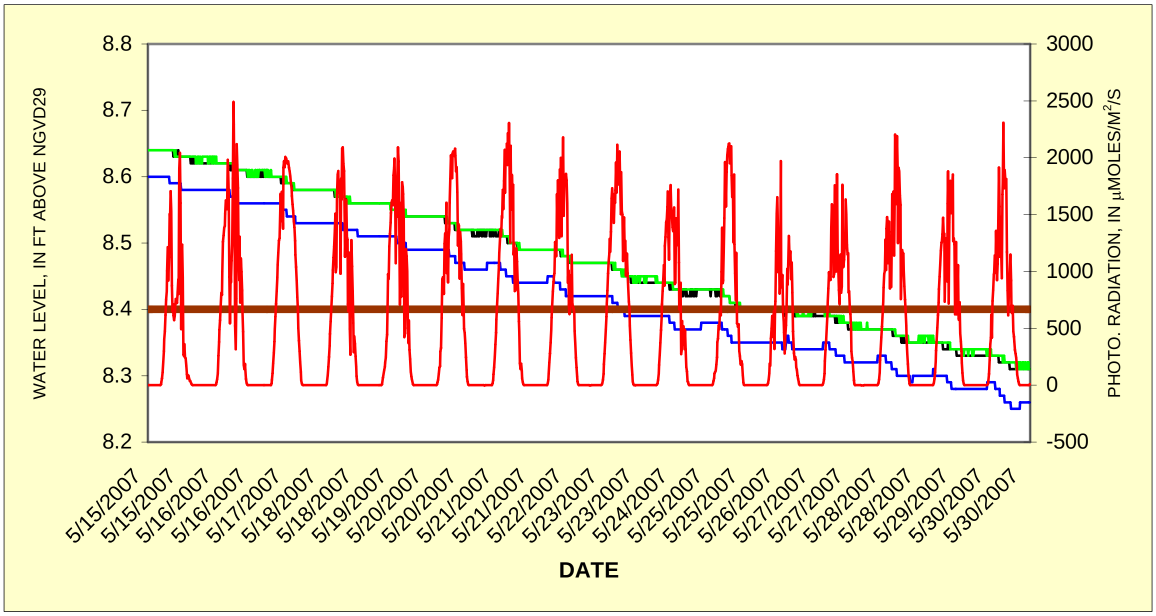


Figure 23 Water levels in wells 3AS3W1_GP (black) and 3AS3W1_GW (green) and stilling well 3AS3W1_H (blue) decline in response to maximum daily peaks in photosynthetic radiation (red). The horizontal brown line represents land-surface elevation at site 3AS3W1.

Other meteorological factors, such as barometric pressure and humidity, have cyclic patterns, but do not appear to affect groundwater or surface-water levels at the tree islands. Air temperature exhibits seasonal patterns, which weakly mimic groundwater and surface-water levels (fig. 24). However, this relation is rather indirect, as wet-season storms, which increase water levels, are a product of warm temperatures in the summer months.

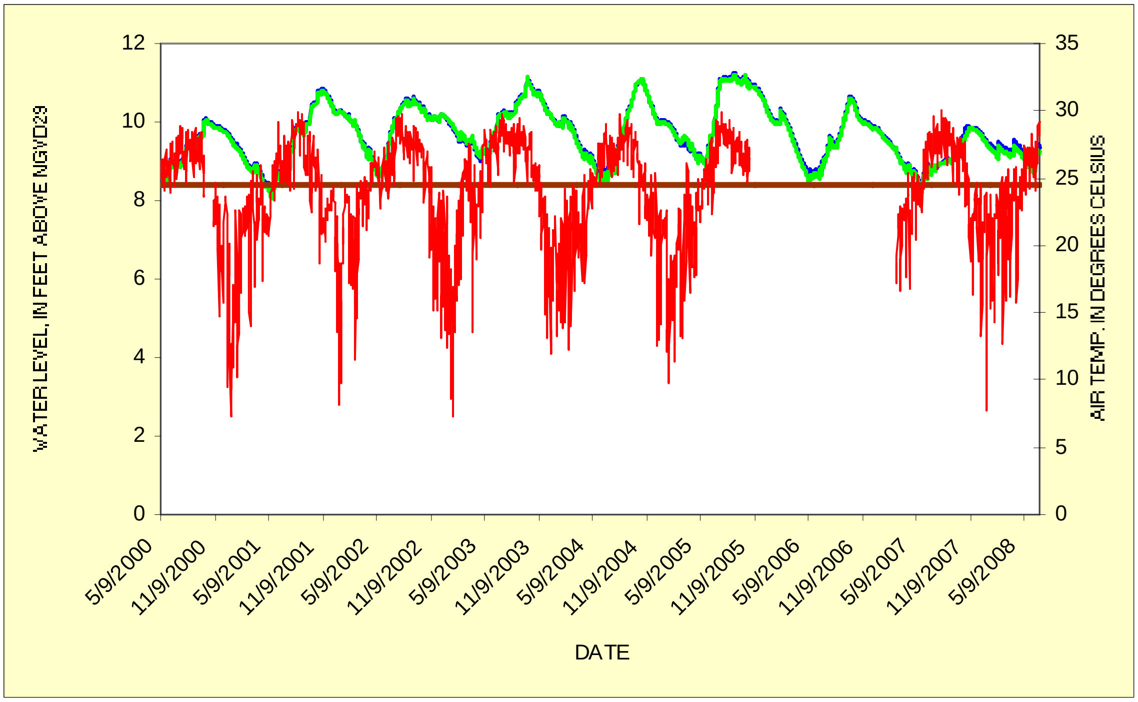


Figure 24 Water levels in stations 3AS3W1_GW (blue) and 3AS3W1_H (green) are plotted with air temperature (red) recorded at 3AS3WX. Water levels are in feet above mean sea level; air temperatures are in degrees Celsius. The horizontal brown line represents land-surface elevation at 3AS3W1.

5.2 Operation of Structures

Groundwater and surface-water levels at the three tree islands appear to fluctuate according to natural processes. Water levels increase as a result of precipitation, and decline smoothly during dry periods as a result of evapotranspiration. However, a number of structures that control flow are present in canals near the three tree islands. The relation of stage at these structures was compared to surface-water and groundwater levels to determine if operation of the structures affects the hydrology of the tree islands.

5.2.1 3AN1

Groundwater and surface-water levels were compared to stage data from structure S339 to determine the effects on island hydrology. Structure S339 is a spillway on the C-123 Canal just east-northeast of Tree Island 3AN1 (fig. 25). The canal trends northwest to southeast. Daily mean stage is monitored on both the headwater (upstream) and tailwater (downstream) sides of the spillway. Water levels in stations 3AN1W1_GW and 3AN1W1_H closely coincide with stage on the tailwater side of S339, but are less correlated to stage on the headwater side (figs. 26 and 27). Stage data from the headwater side contains sharp peaks, which probably result from excessive rainfalls. The magnitude of these peaks is diminished on the tailwater side of S339 (fig. 26). The strong correlation between water levels at 3AN1 and stage on the tailwater side of S339 indicates that operation of this structure or other nearby structures could be affecting the hydrology at the tree island. The correlation appears to weaken when water levels in 3AN1W1_H decline below land-surface elevation at the site (fig. 27).

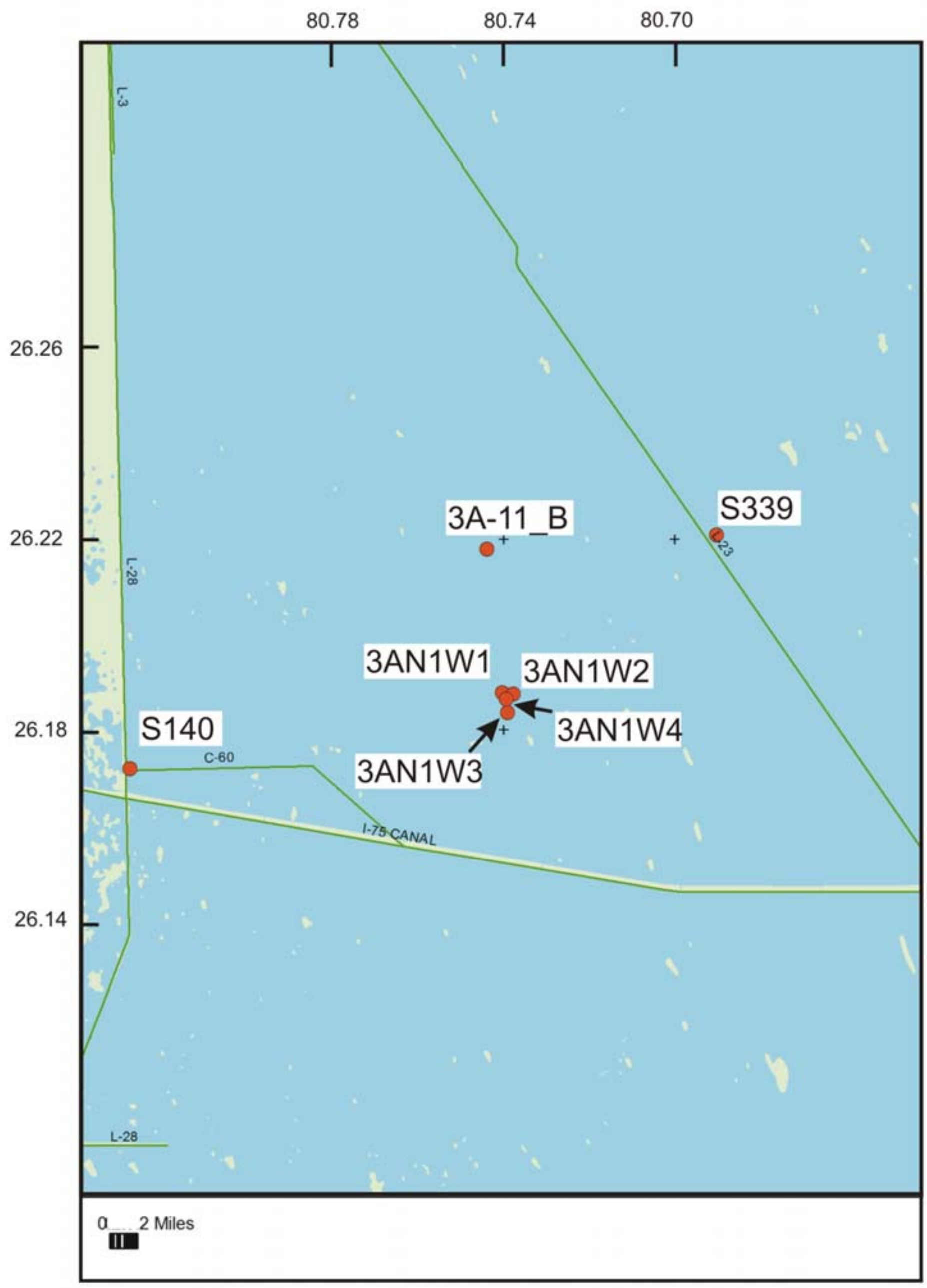


Figure 25 Location of selected surface-water stations in relation to sites at tree island 3AN1.

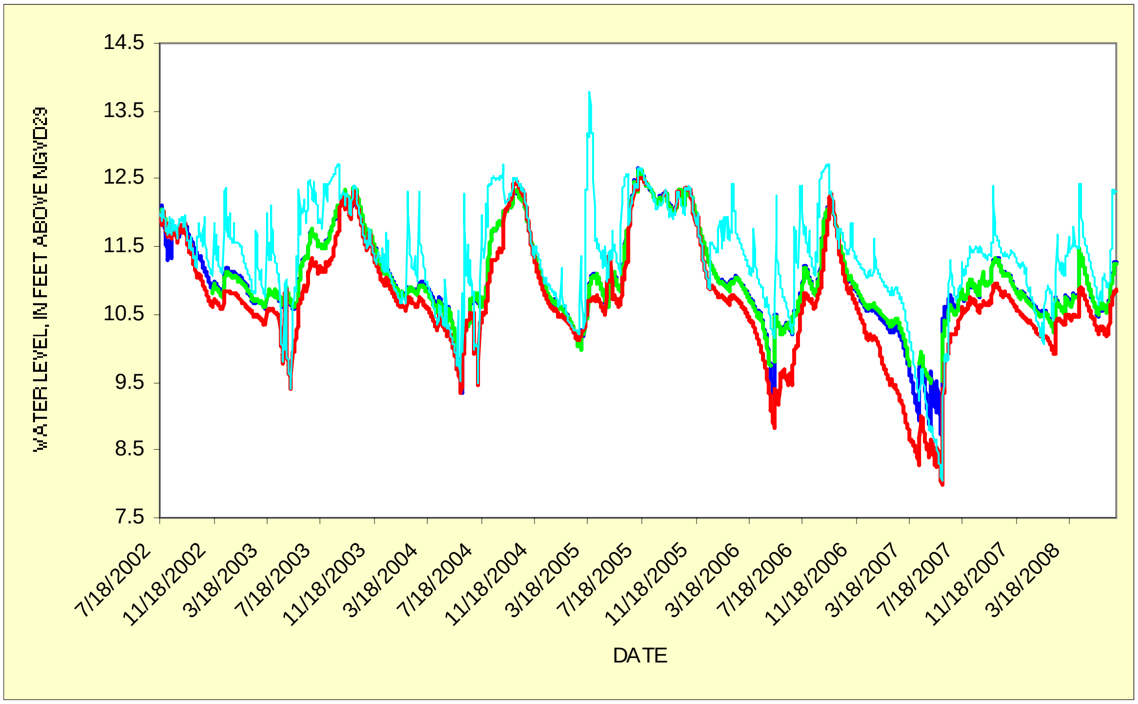
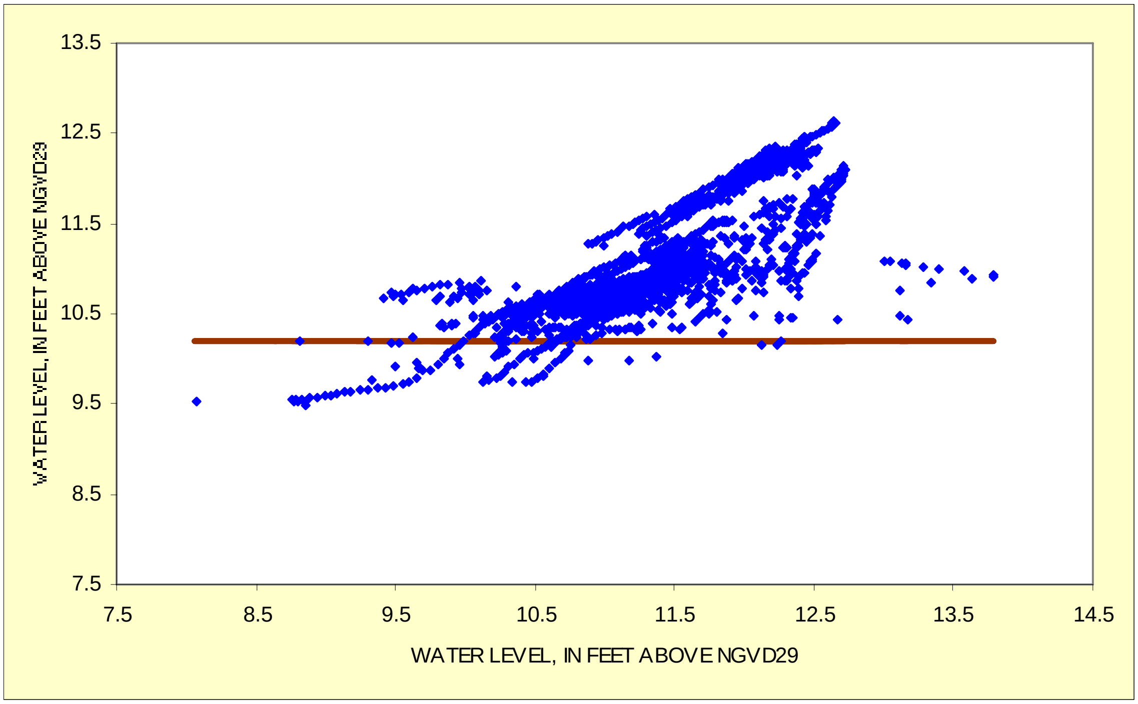


Figure 26 Water levels in stations 3AN1W1_H (green) and 3AN1W1_GW (blue) are plotted with stage from the headwater (cyan) and tailwater (red) side of structure S339 on the C-123 Canal.



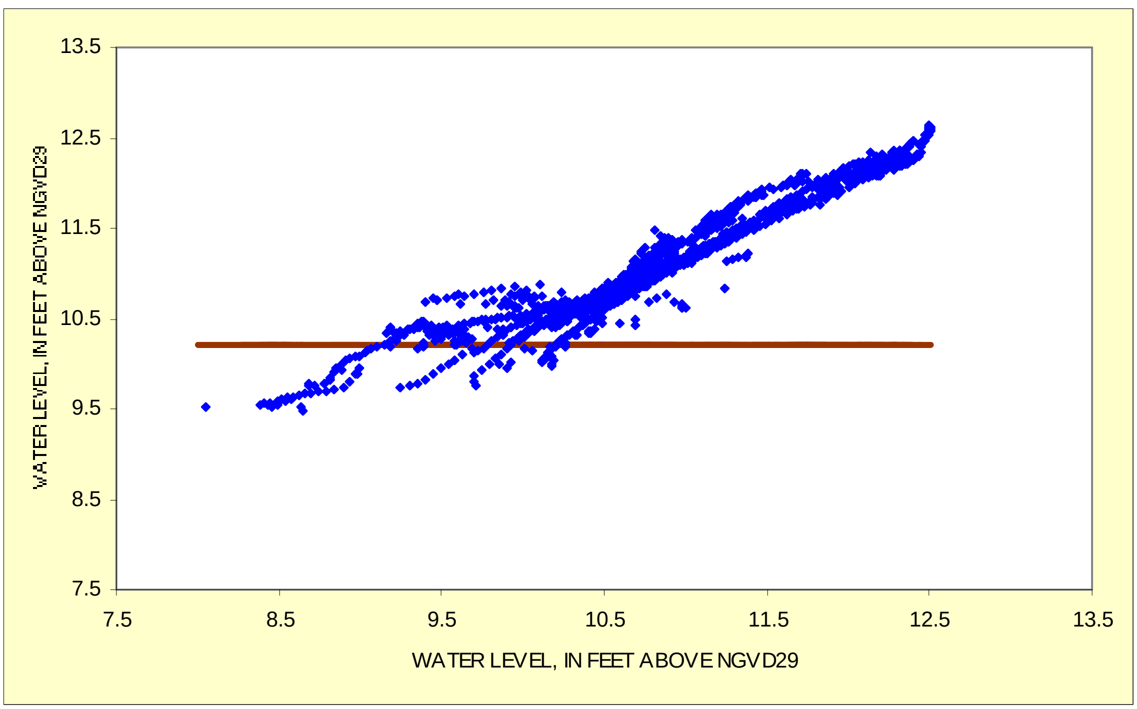


Figure 27 Water level in stilling well 3AN1W1_H (Y axis) is plotted against stage at the headwater (top; correlation coefficient = 0.79) and tailwater (bottom; correlation coefficient = 0.96) side of structure S339 on the C-123 Canal. The horizontal brown line represents land-surface elevation at well 3AN1W1_H.

5.2.2 3AS3

A number of structures are present near tree island 3AS3 (fig. 28), of which culvert S-343A south-southwest of the tree island at the junction of levees L-28 and L-29, and spillways S12A and S12B on L-29, south of the tree island, were selected. The groundwater and surface-water levels at 3AS3 closely coincide with stage on the headwater side of each structure, but are less correlated with stage of the tailwater sides of the structures (figs. 29 and 30).

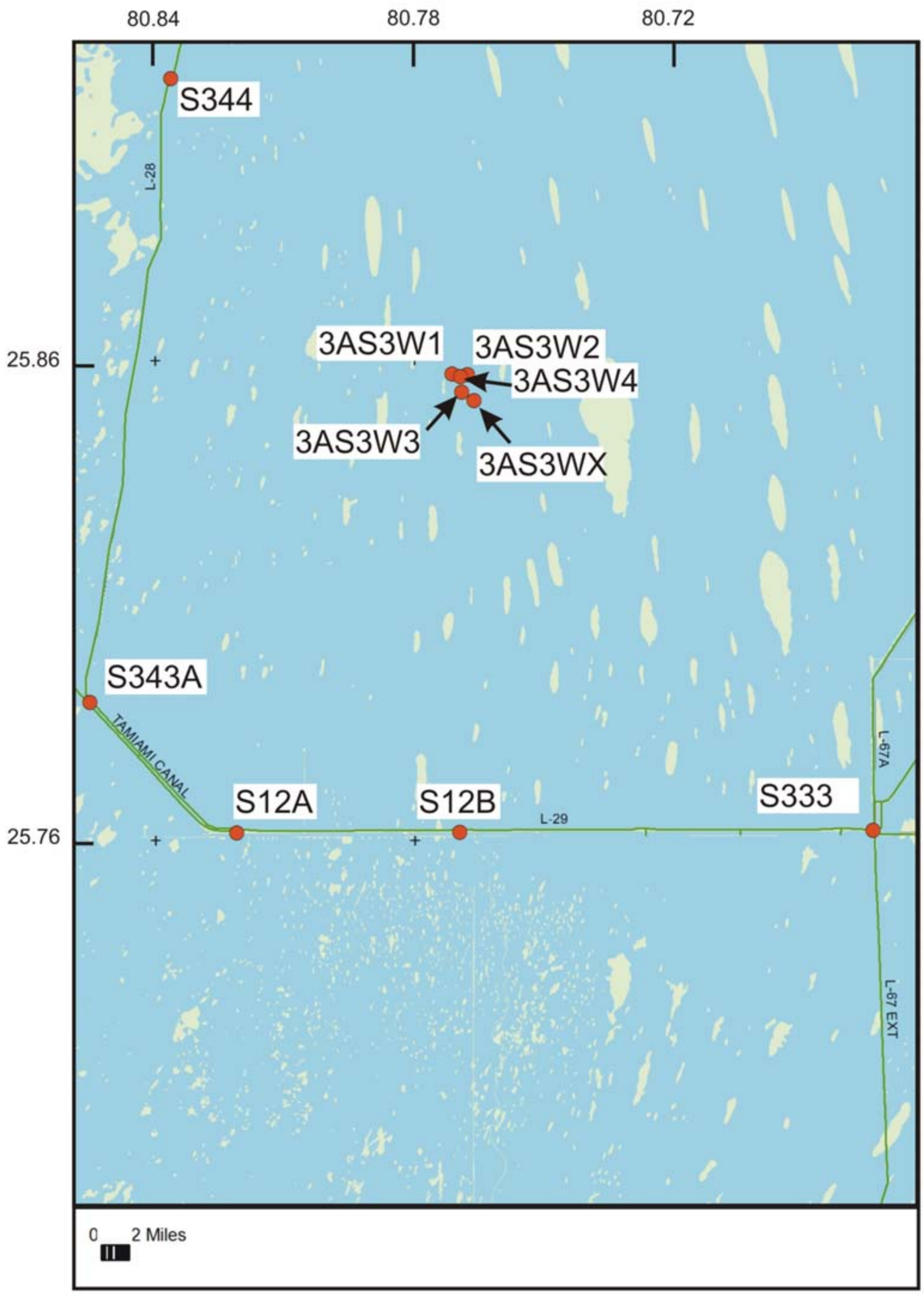
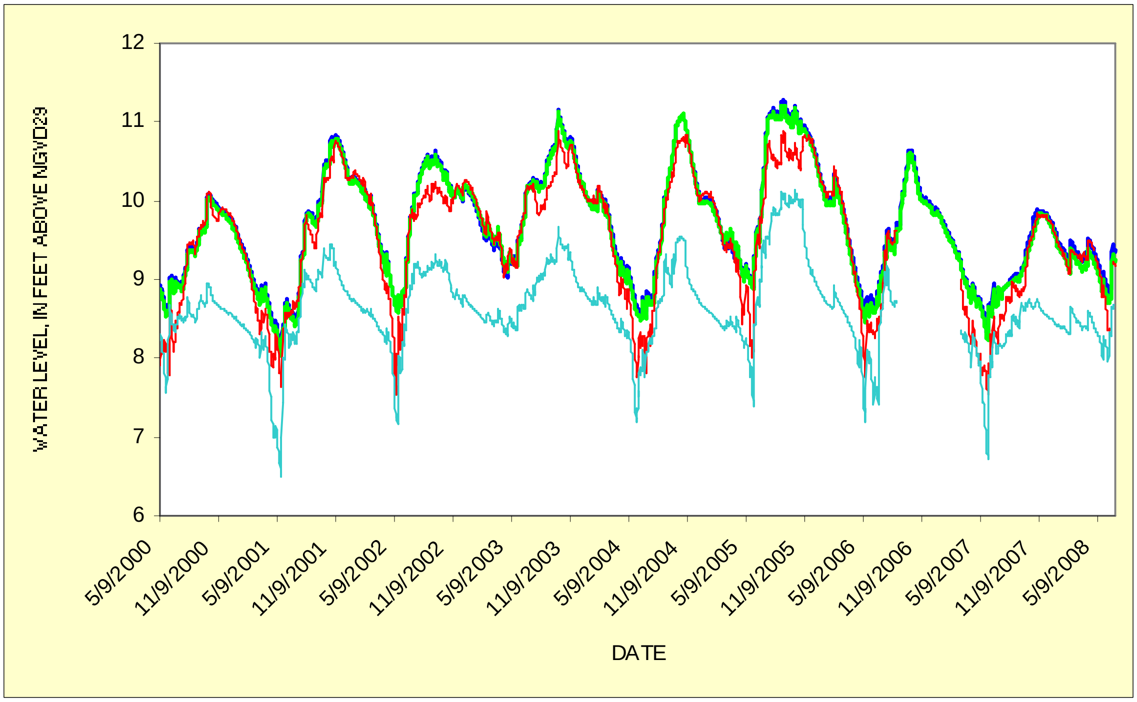


Figure 28 Location of selected surface-water stations in relation to sites at tree island 3AS3.



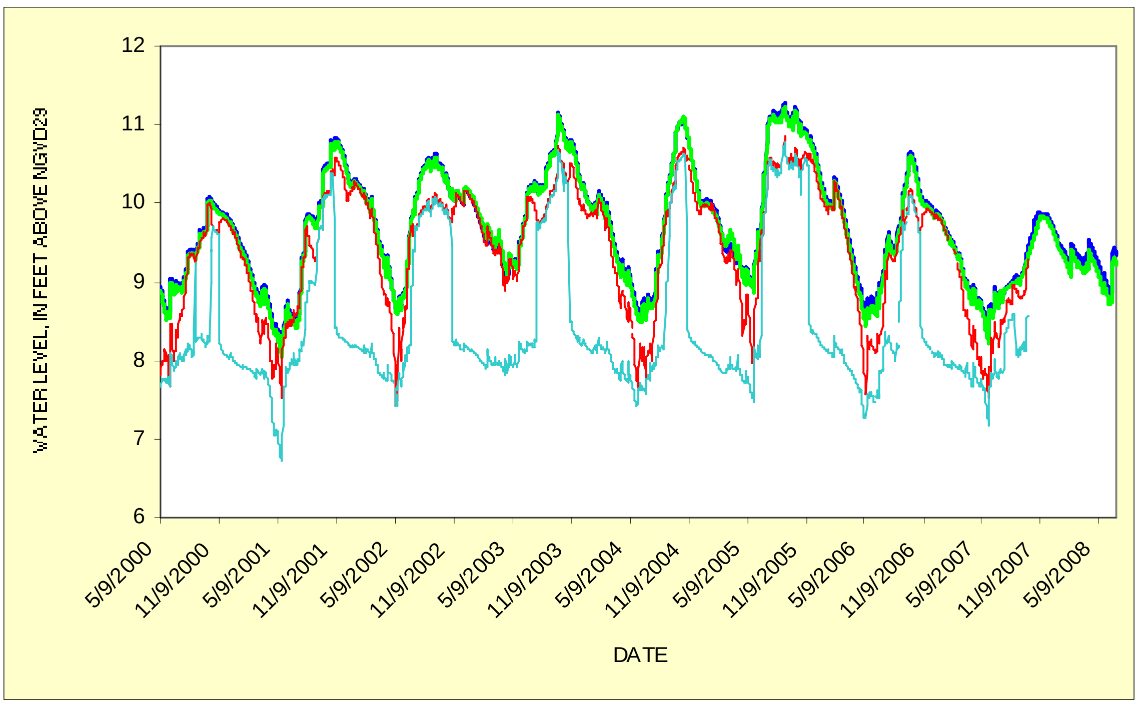
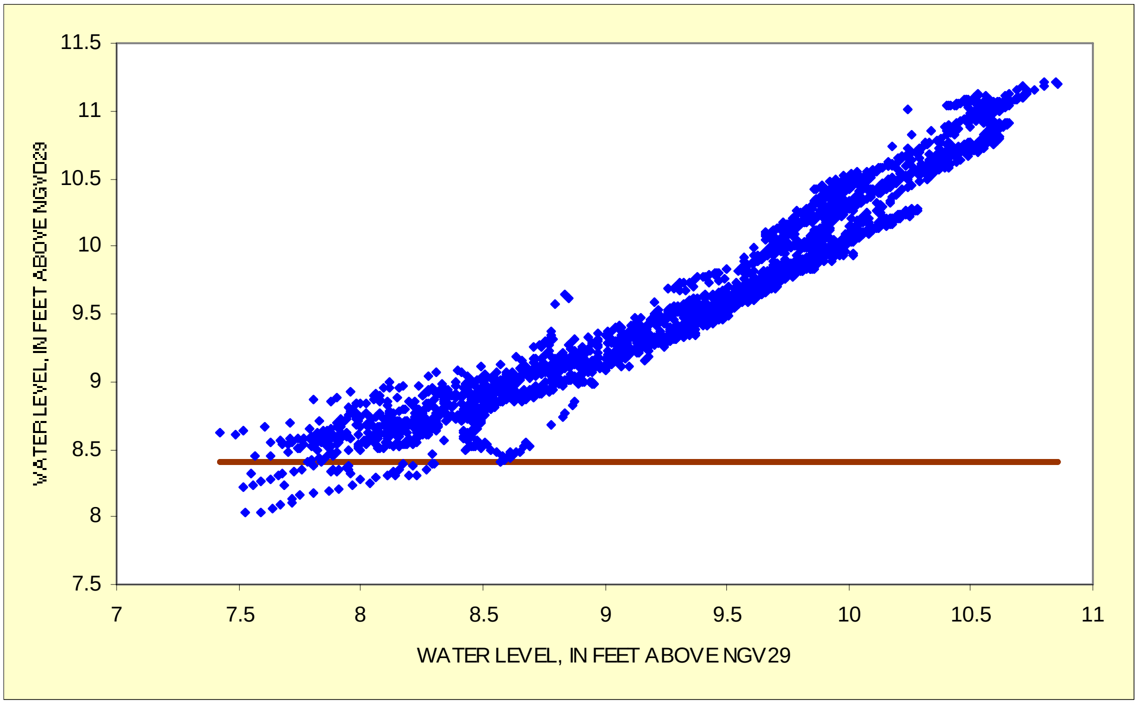


Figure 29 Water levels in station 3AS3W1_GW (green) and 3AS3W1_H (blue) plotted with stage at the headwater (red) and tailwater (cyan) sides of structures S-343A (top) and S12 (bottom).



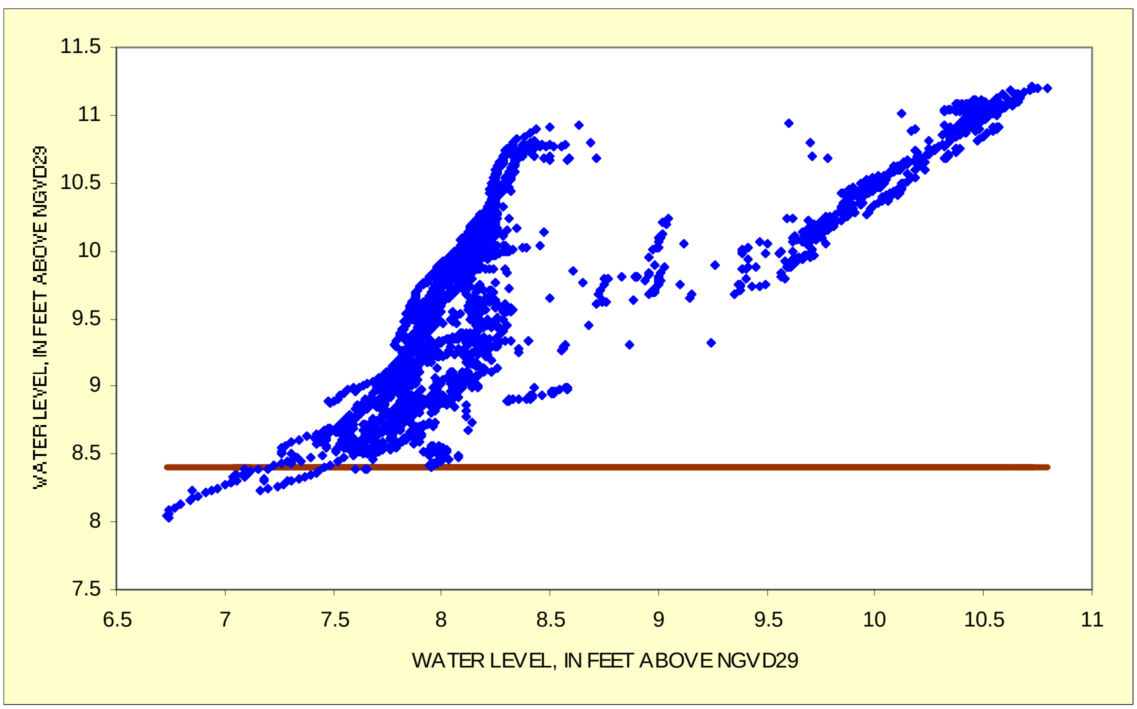


Figure 30 Water level in stilling well 3AS3W1_H (Y axis) is plotted against stage at the headwater side of spillway S12B (top; correlation coefficient = 0.96) and tailwater side of spillway S12A (bottom; correlation coefficient = 0.77). The horizontal brown lines represent land-surface elevation at 3AS3W1_H.

The stage data from the tailwater side of spillway S12A has a bimodal distribution, with one set of data representing relatively low stage levels and a second set of data representing relatively high levels. Changes from low-level to high-level stage are abrupt, and generally coincide with peaks in stage at 3AS3W1_H (fig. 29). These abrupt peaks in tailwater stage probably result from water being released from WCA3 into the canal. Declines from high-level to low-level stage are equally abrupt, and could result from the closing of gates and preventing water from entering the canal. As a result, the hydrology at 3AS3 is affected by the operation of structures, which maintain groundwater and surface-water levels within a certain range of values.

5.2.3 3BS1

Surface-water stage and groundwater levels in the stations at 3BS1 coincide with stage data at nearby spillway S334 (fig. 31), which is located just southeast of the tree island on the Tamiami Canal; however, water levels at 3BS1 correlate less well to tailwater stage at the same spillway (figs. 32 and 33). In general, the stage in the tailwater side of the spillway stays relatively constant except during very dry periods, at which time the gate on the spillway is probably closed and presumably not affecting the water levels at the tree island. Occasional peaks in the tailwater stage are abrupt, and could result from releasing water from WCA3 into the canal. Overall, the effect of the spillway on the hydrology of 3BS1 is difficult to assess; however, the close proximity of the structure indicates that the hydrology of 3BS1 probably is greatly affected by their operation.

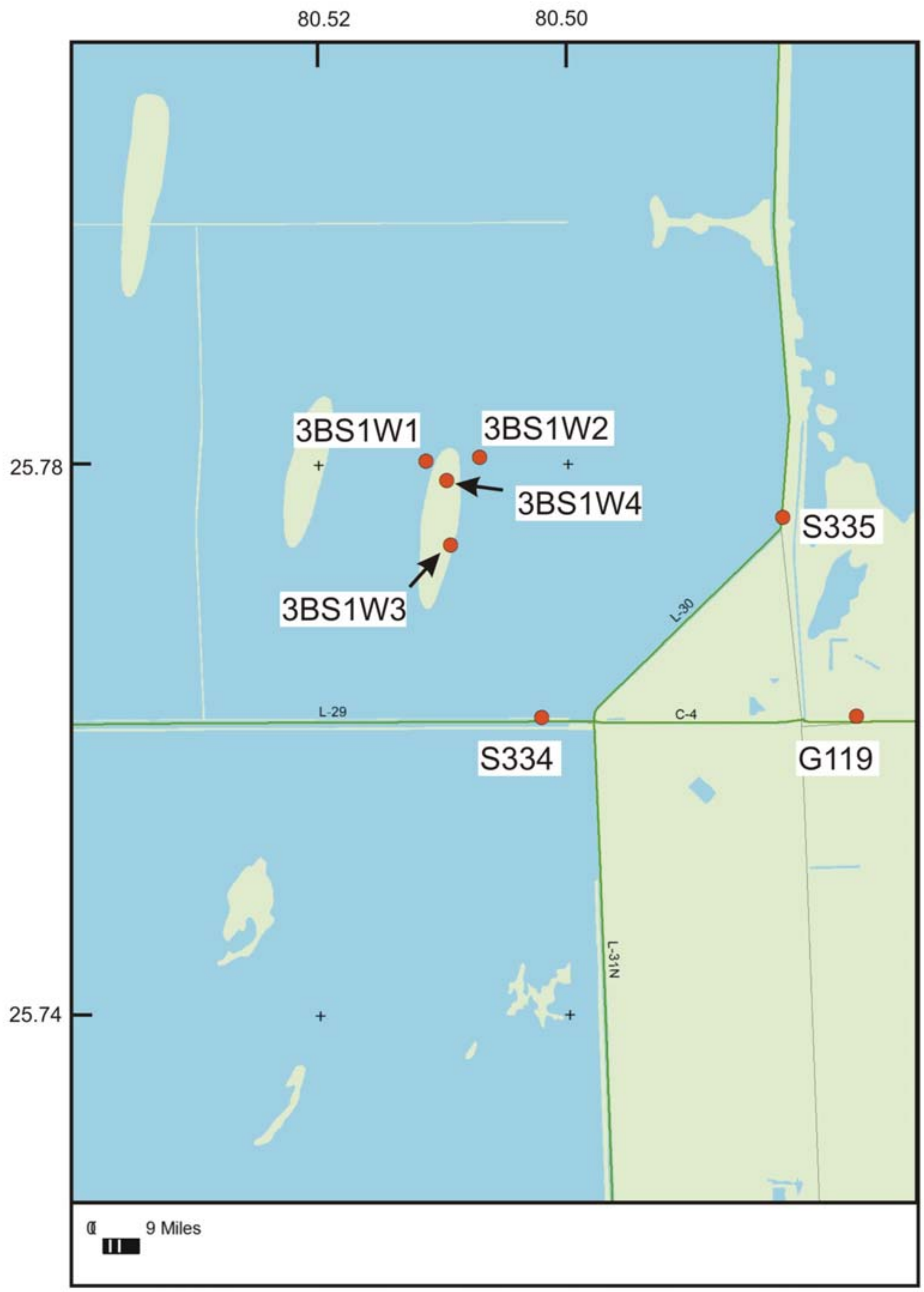


Figure 31 Location of selected surface-water stations in relation to sites at tree island 3BS1.

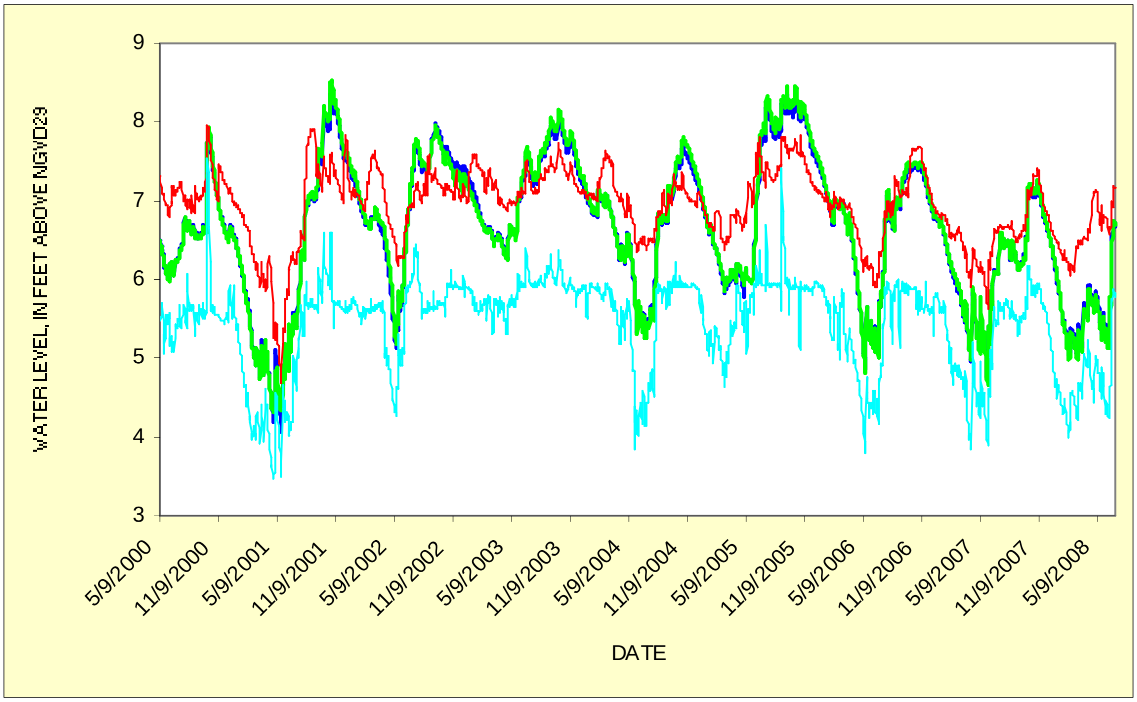
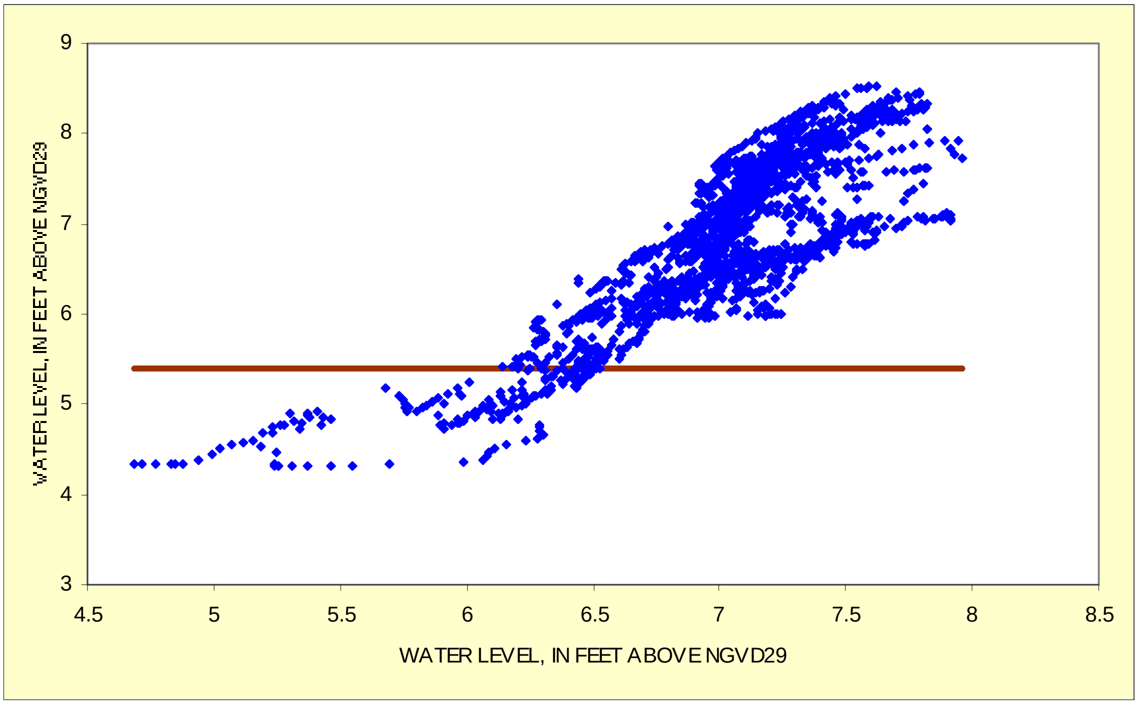


Figure 32 Water levels in station 3BS1W1_GW (green) and 3BS1W1_H (blue) plotted with stage at the headwater (red) and tailwater (cyan) sides of spillway S334 on the Tamiami Canal.



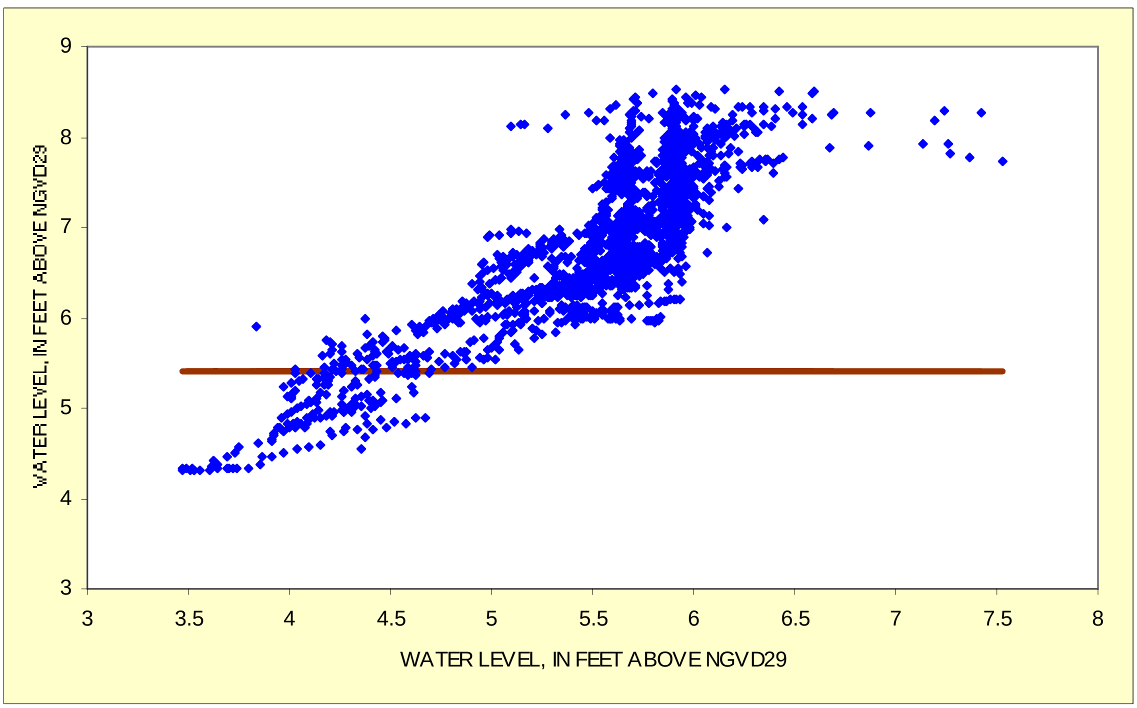


Figure 33 Water level in stilling well 3BS1W1_H (Y axis) is plotted against stage at the headwater side (top; correlation coefficient = 0.85) and tailwater side of spillway S334 (bottom; correlation coefficient = 0.88). The horizontal brown lines represent land-surface elevation at station 3BS1W1_H.

6 GROUNDWATER FLOW

The vertical and horizontal flow of groundwater at each of the tree islands was analyzed using the daily-values data. Maps and cross sections were constructed to show the potentiometric surfaces during extreme conditions and during average conditions. These results indicate that groundwater flow at the islands is complex, with groundwater flow at each island varying temporally and spatially. In general, water levels in the wells and piezometers at each tree island differ only a few hundreds or a few tenths of a foot on the same date. These small differences indicate rather flat a water table and potentiometric surface, which probably result from the flat topography and high hydraulic conductivities. Bevier and Krupa (2001) reported hydraulic conductivities at 3AS3 ranged from 0.58 to 103.6 feet per day (ft/d) in the piezometers and 1.5 to 16.08 ft/d in the deep wells. Hydraulic conductivities at 3BS1 ranged from 30.82 to 184 ft/d in the deep wells (Bevier and Krupa, 2001). Similarly, the small differences between water levels in piezometers and adjacent deep wells indicate good hydraulic connection between the vertical zones in the aquifer.

6.1 3AN1

The regression model results show that groundwater flow at 3AN1 varies from 0.009 to 1.855 ft/d, with a median of 0.184 ft/d (table 5). The direction of flow ranges from 0.2 to 180 degrees from north, with a median of 48 degrees. However, the direction provided by the model is actually the orientation or trend of the flow, without regard to true direction. In other words, a value of 90 degrees from north can indicate flow either from west to east or east to west.

Statistics	Flow (feet per day)	Direction (degrees from true north)
Minimum	0.009	0.2
Mean	0.233	64
Median	0.184	48
Maximum	1.855	180
Standard Deviation	0.181	54.3
Variance	0.033	2,945

Table 5 Summary statistics for groundwater flow and direction at tree island 3AN1

Groundwater flow at 3AN1 generally increases as water levels decline, possibly as a result of increasing gradients (figs. 34). However, groundwater flow fluctuated erratically at the beginning of the period of record for unknown reasons.

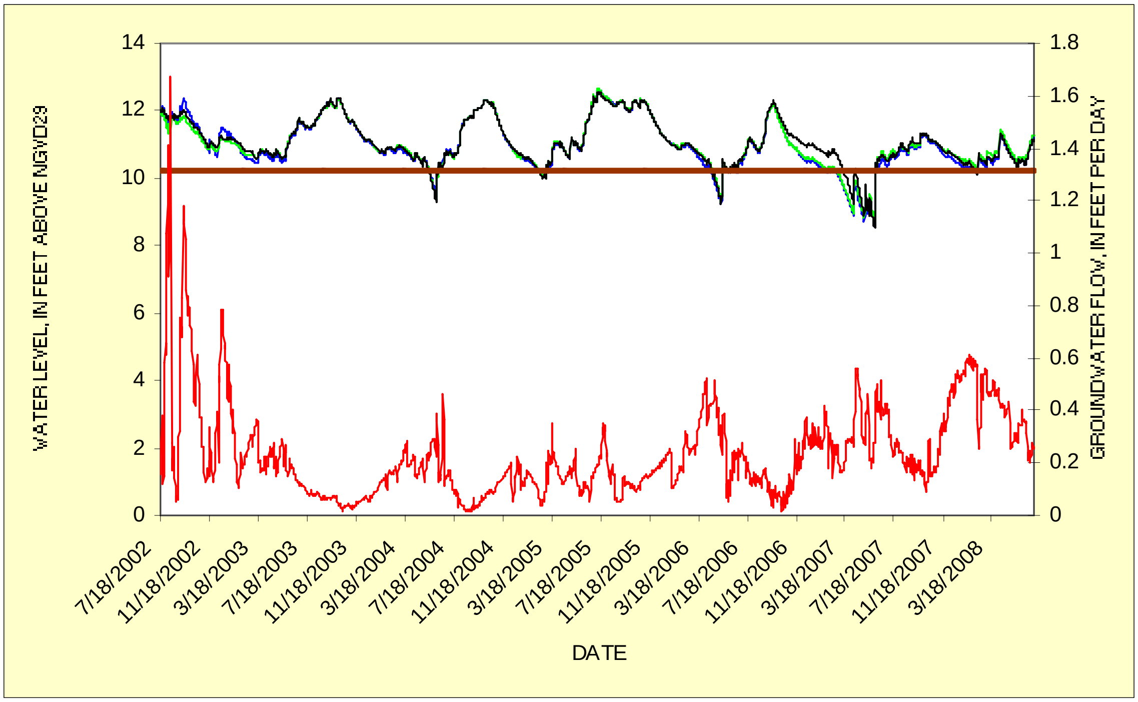


Figure 34 Groundwater flow (red) is plotted with water-level data from wells 3AN1W1_GW (green), 3AN1W3_GW (blue) and 3AN1W4_GP (black). The horizontal brown line represents land-surface elevation at site 3AN1W1.

The direction of vertical groundwater flow was qualitatively determined at three well sites by subtracting the water level in the deep well from the water level in the stilling well (3AN1W1) or the piezometer at each site. A positive value indicates downward migration or recharge, and a negative value indicates upward migration or discharge. A small (1 – 2) percent of the time the value was 0, indicating minimal vertical flow. Table 6 shows the percentage of time during the period of record that groundwater at each well pair is either flowing downward or upward. The results indicate that 60 – 70 percent of the time, groundwater is discharging at sites 3AN1W1, 3AN1W2, and 3AN1W3. Site 3AN1W4, which only has a shallow piezometer, could not be analyzed. The direction of groundwater flow does not fluctuate seasonally or appear to be related to water levels (fig. 35).

Well Site	Percentage of time vertical flow is upward	Percentage of time vertical flow is downward
3AN1W1	61	37
3AN1W2	72	27
3AN1W3	73	26

Table 6 Vertical groundwater flow at tree island 3AN1

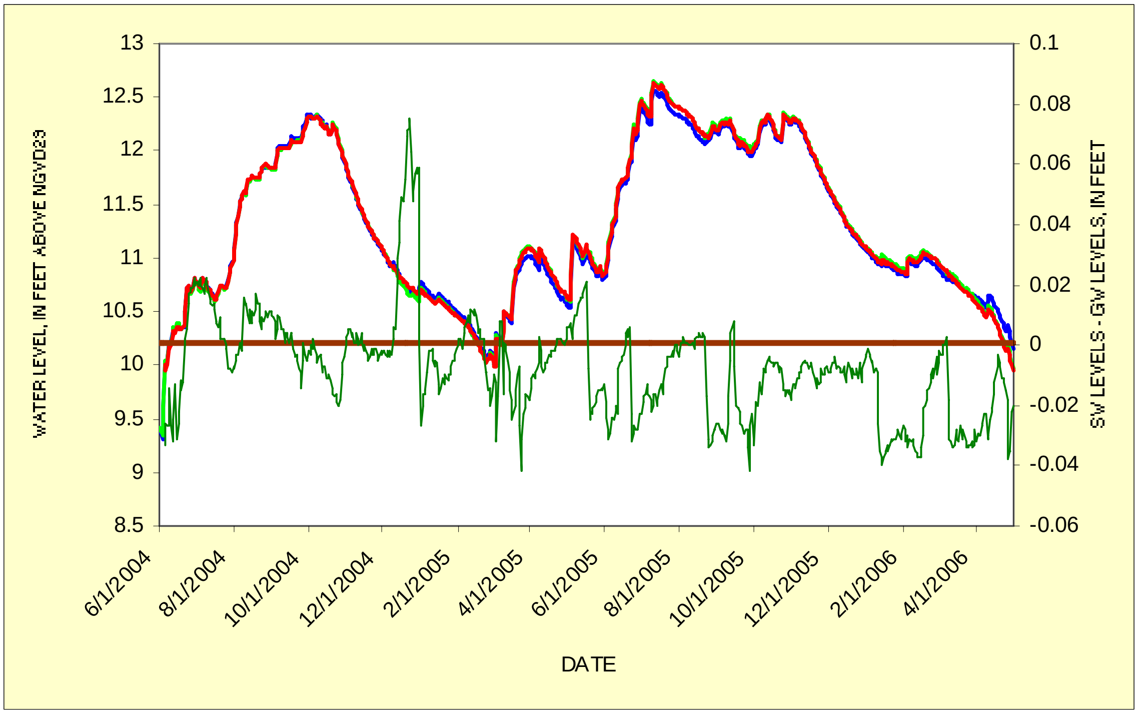


Figure 35 The difference between surface-water and groundwater levels (dark green) is plotted with water levels in stations 3AN1W1_GP (blue), 3AN1W1_GW (green), and 3AN1W1_H (red). The horizontal brown line represents land-surface elevation at 3AN1W1.

The configuration of the water table in the aquifer changes over time with seasonal fluctuations in water levels in the wells. For example, levels in the wells in October 2004 (annual maximum) show mounding of ground water under the tree island (fig. 36). Cross sections indicate that water levels were relatively high and even the tree island was inundated (fig. 37, top). Water levels in the piezometers indicate the water table slopes to the south. Furthermore, the water level in the shallow piezometer was higher than the level in the deep well at 3AN1W1, indicating vertical flow was downward. However, flow conditions were reversed at 3AN1W3, south of the tree island, where water level in the deep well was higher than the level in the shallow piezometer. In other words, groundwater appears to be recharging north of the tree island at 3AN1W1, flowing south of the island, and then discharging at 3ANW3.

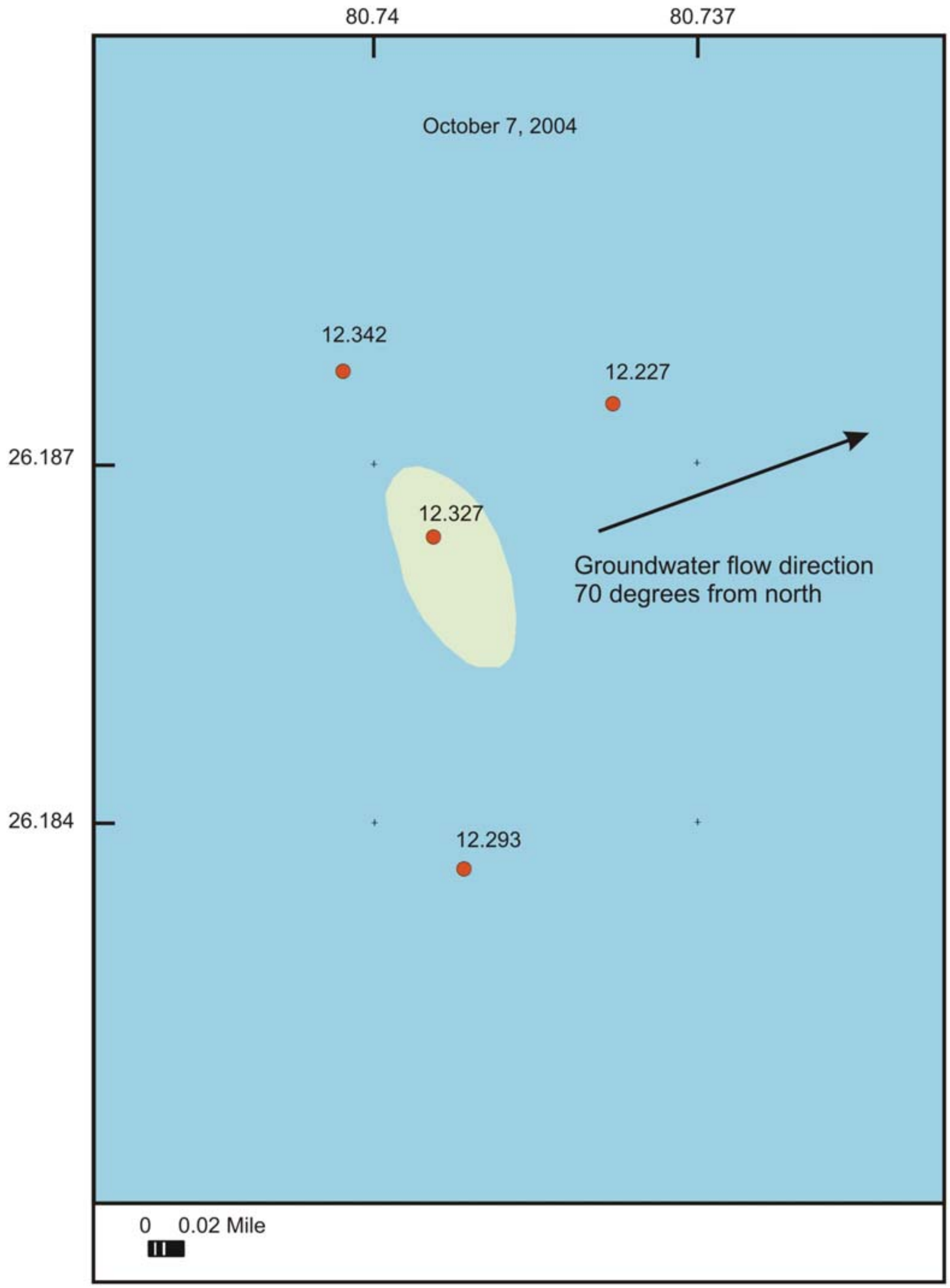


Figure 36 Water levels in shallow piezometers in and around 3AN1 on October 7, 2004. Direction of flow is based on regression model.

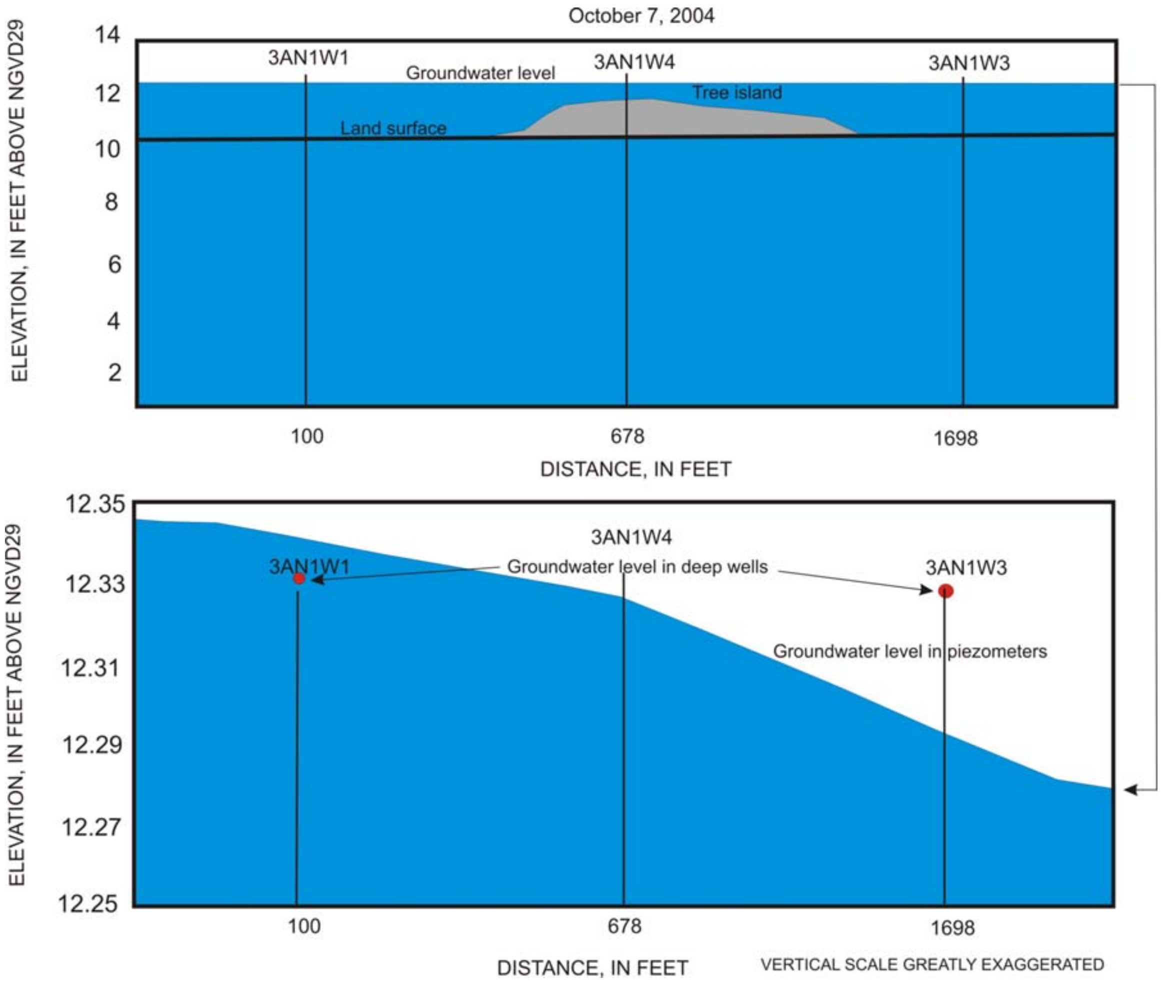


Figure 37 Cross sections showing the configuration of the water table and water levels in deep wells at 3AN1 on October 7, 2004. Water levels beyond the wells were estimated using extrapolation.

Water levels in the wells during May 2007 (annual minimum) indicate a depression of ground water under the tree island (fig. 38). During this time, water levels in the wells were nearly 2 ft below land surface (fig. 39, top). Water levels in the piezometers indicate a depression in the water table beneath the tree island (fig. 39, bottom). The deeper roots from the trees could be causing higher evapotranspiration rates at the island, and subsequently a more rapid lowering of the groundwater. As a result, local groundwater flow appears to be toward the island, with overall groundwater flow to the southeast.

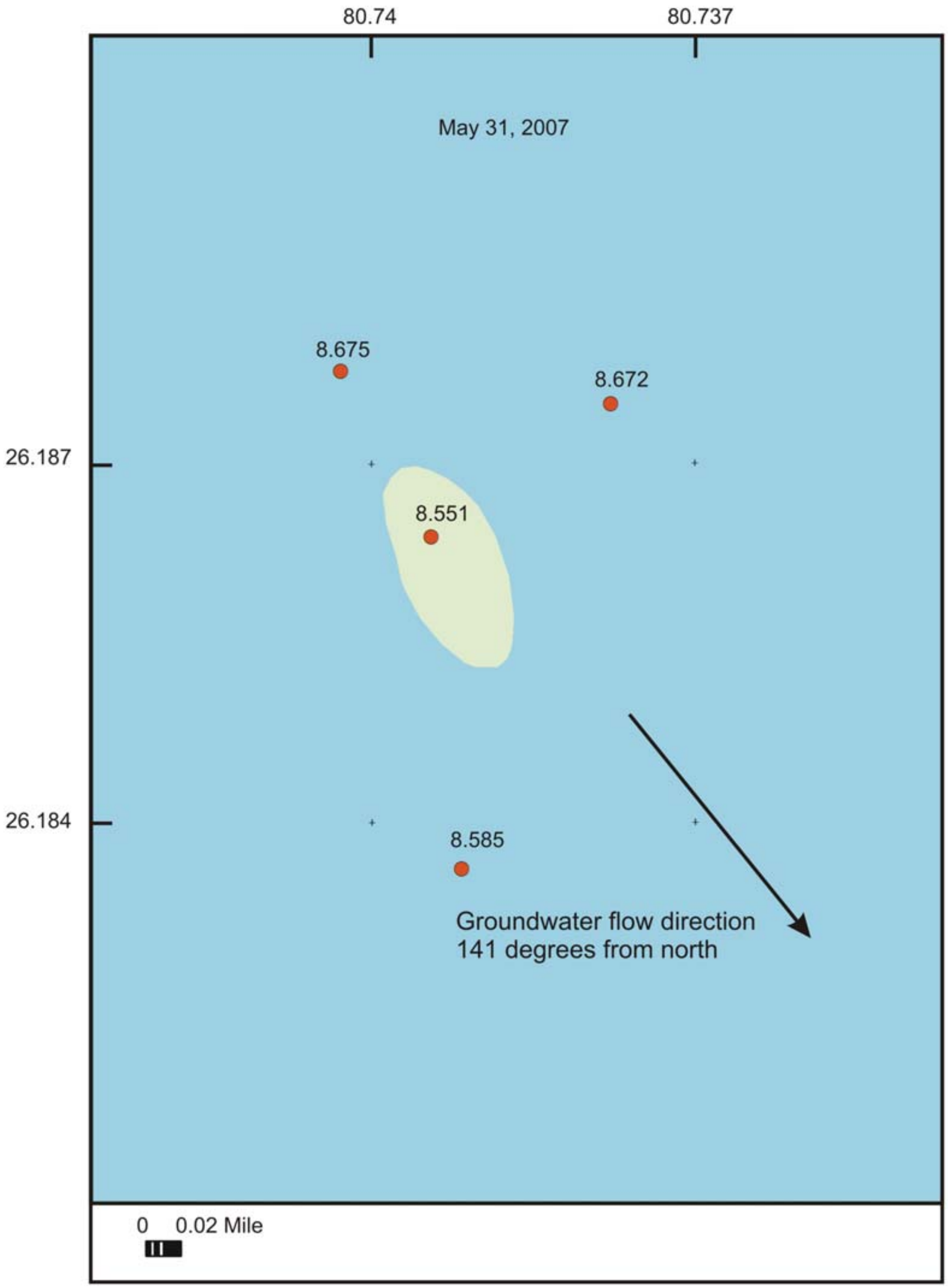


Figure 38 Water levels in shallow piezometers in and around 3AN1 on May 31, 2007. Direction of flow is based on regression model.

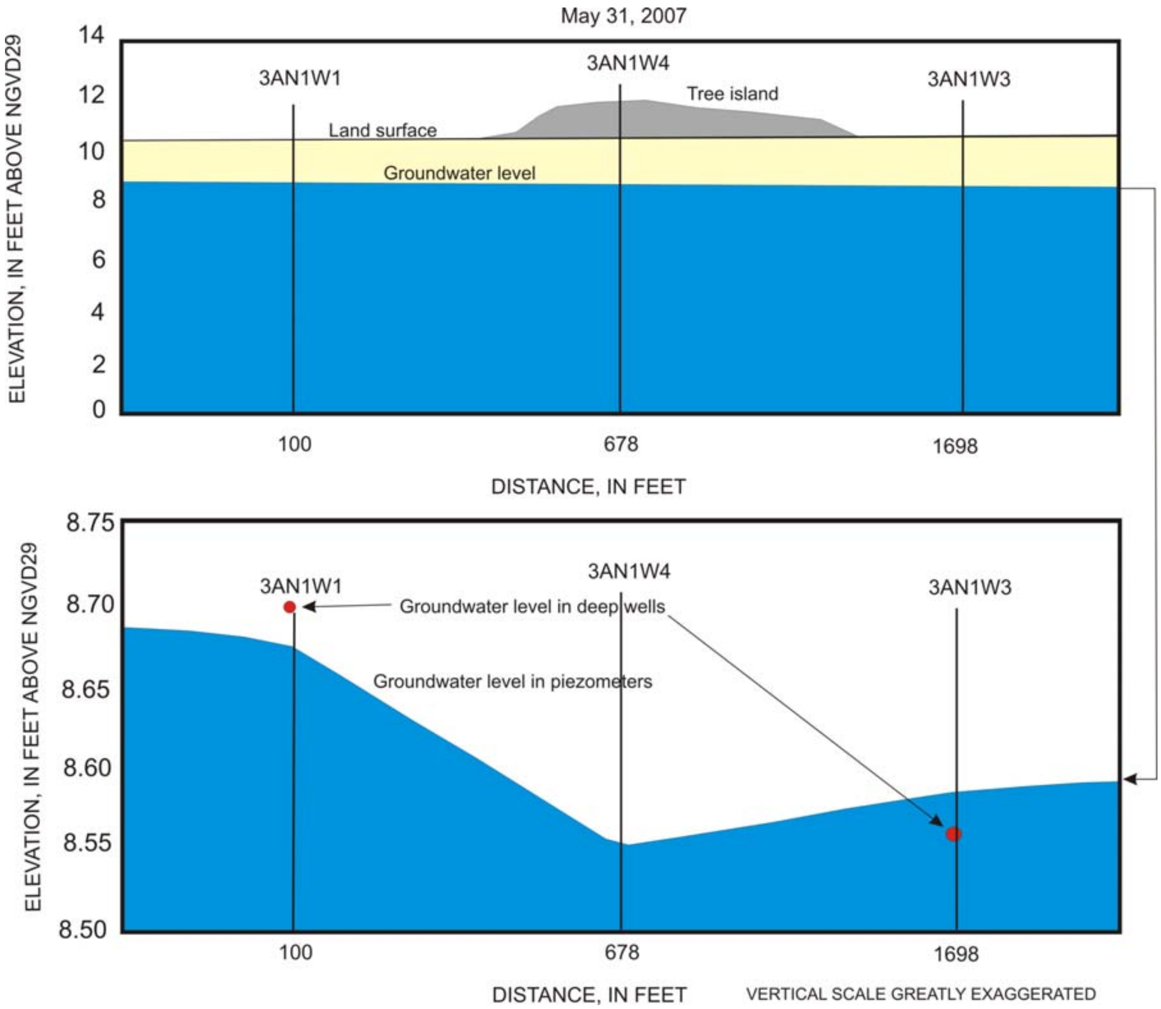


Figure 39 Cross sections showing the configuration of the water table and water levels in deep wells at 3AN1 on May 31, 2007. Water levels beyond the wells were estimated using extrapolation.

The groundwater depression under the tree island in May 2007 could be a unique situation caused by the low rainfall and extreme dry conditions that existed in early 2007. A map of water levels in June 2004 indicates mounding of groundwater under the island, similar to October 2004 (Appendix B). In general, the water level in the piezometer at 3AN1W4 is consistently higher than the water levels in 2 to 3 of the other piezometers around the tree island (Appendix B). The higher groundwater levels under the island indicate that water is flowing horizontally away from the island to the surrounding areas. Vertical movement of groundwater appears to fluctuate over time, with areas surrounding the tree island alternately serving both as places of groundwater recharge and groundwater discharge. Overall, the groundwater hydrology is complex, with numerous flow paths and changing directions.

6.2 3AS3

The regression model results show that groundwater flow at 3AS3 varies from 0.002 to 0.777 ft/d, with a median of 0.082 ft/d (table 7). These flow values are significantly less than the flow at 3AN1, which had a median value of 0.184 ft/d. The direction of flow ranges from 0.1 to 180 degrees from north, with a median of 94 degrees (east-west).

Statistics	Flow (feet per day)	Direction (degrees from true north)
Minimum	0.002	0.1
Mean	0.106	94
Median	0.082	94
Maximum	0.777	180
Standard Deviation	0.084	44.6
Variance	0.007	1,997

Table 7 Summary statistics for groundwater flow and direction at tree island 3AS3

Groundwater flow at 3AS3 fluctuates over time, but does not appear to be related to seasons or changes in water levels in the wells (figs. 40). The maximum flow occurred on February 16, 2007, shortly after a gap in the data that lasted from January 1 – February 10, 2007. The high flow rates do not coincide with extremes in rainfall or other environmental factors. The high flow rates, which extend from February 11 to about mid March, could be anomalies, but the water-level data upon which the flow is based appear valid.

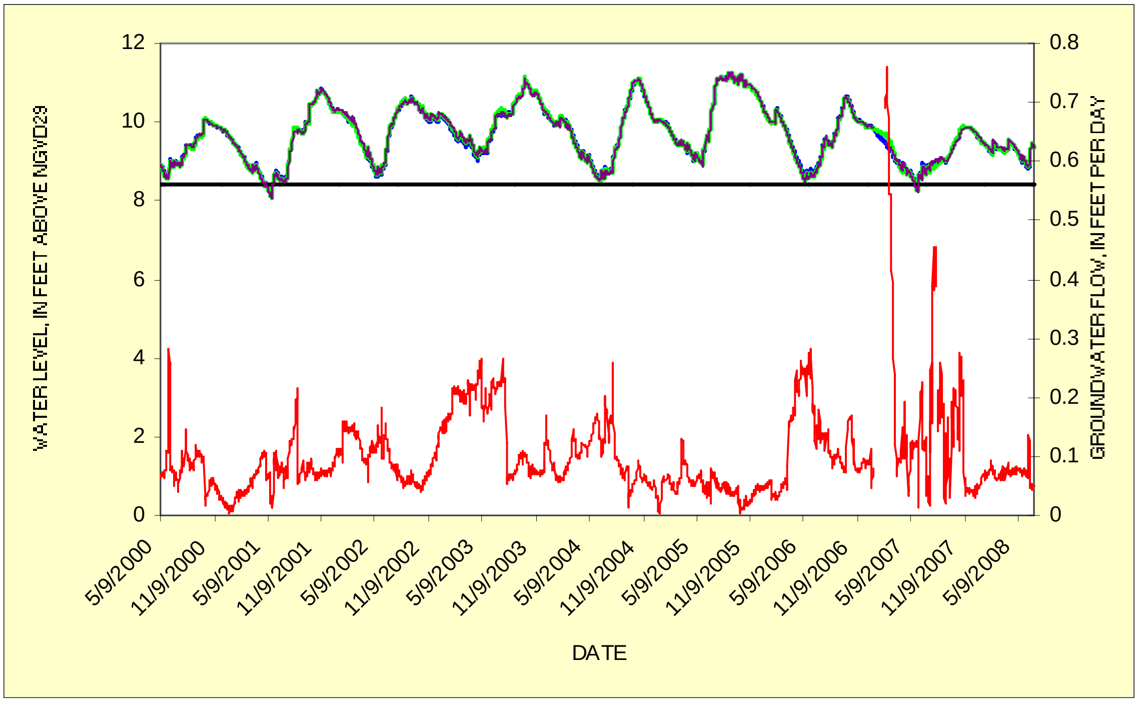


Figure 40 Groundwater flow (red) is plotted with water-level data from wells 3AS3W1_GW (blue), 3AS3W2_GW (green) and 3AS3W3_GW (black). The horizontal brown line represents land-surface elevation at site 3AS3W1.

The direction of vertical groundwater flow was determined at all four well sites by subtracting the water level in the deep well from the water level in the stilling well (3AS3W1) or the piezometer at each site. A positive value indicates downward migration or groundwater recharge, and a negative value indicates upward migration or groundwater discharge. A small (1 – 3) percent of the time the value was 0, indicating no vertical flow. Table 8 shows the percentage of time during the period of record that groundwater at each well pair is either flowing downward or upward. About 80 - 90 percent of the time, groundwater is discharging at sites north of the tree island (3AS3W1 and 3AS3W2). Groundwater underlying the tree island (site 3AS3W4) and south of the island (3AS3W3) alternates between flowing upward (discharging) and flowing downward (recharging). The direction of groundwater flow does not fluctuate seasonally or appear to be related to water levels in the wells (fig. 41). The difference between surface-water and groundwater levels at 3AS3W1 is consistently negative, indicating groundwater discharge. The maximum value of 0.172 occurred on March 22, 2005, and could be related to a rainfall of 1.58 inches that occurred on March 17. Additional analysis of the data is needed to determine the factors affecting the vertical movement of groundwater.

Well Site	Percentage of time vertical flow is upward	Percentage of time vertical flow is downward
3AS3W1	90	10
3AS3W2	84	15
3AS3W3	50	47
3AS3W4	42	56

Table 8 Vertical groundwater flow at tree island 3AS3

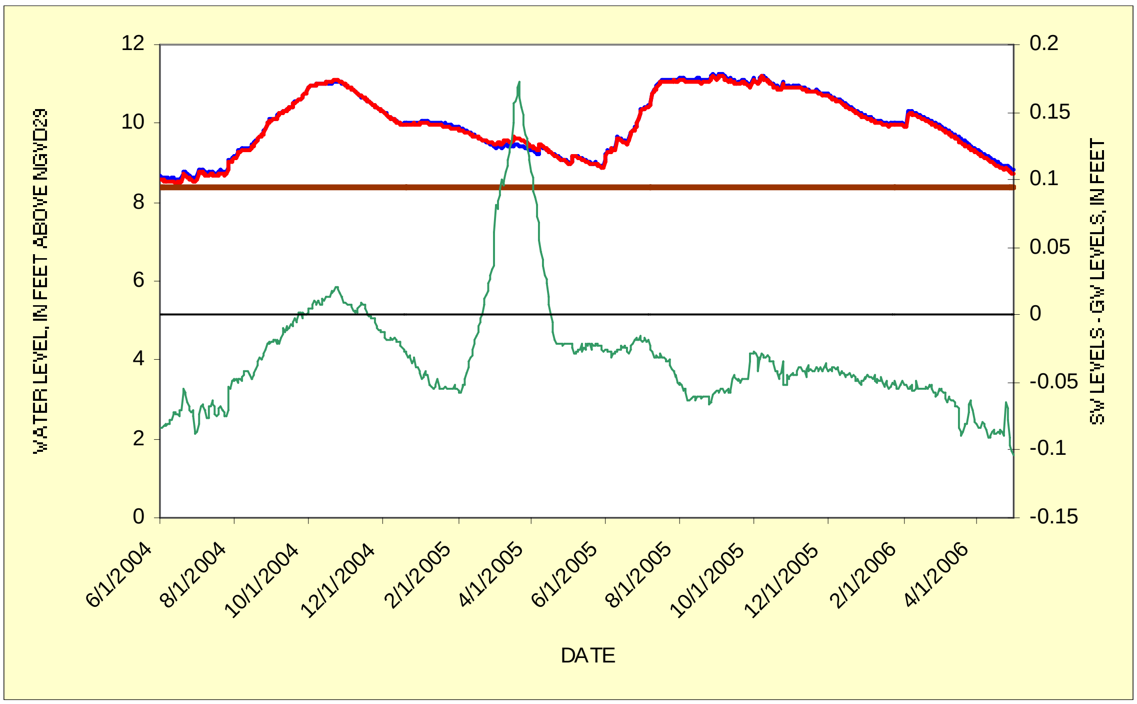


Figure 41 The difference between surface-water and groundwater levels (dark green) is plotted with water levels in stations 3AS3W1_GW (blue) and 3AS3W1_H (red). The thick horizontal brown line represents land-surface elevation at 3AS3W1.

As with 3AN1, the configuration of the water table at 3AS3 changes over time with seasonal fluctuations in water levels in the wells. Water levels in the wells in October 2004 (annual maximum) indicate a similar mounding of groundwater under the tree island (fig. 42). Cross sections indicate that water levels were relatively high and even the tree island was inundated (fig. 43, top). Water levels in the piezometers indicate the water table has an overall slope to the north. Unlike 3AN1, water levels in the four piezometers at 3AS3 are higher than water levels in their adjacent deep wells on this date, indicating vertical flow was downward and groundwater was recharging throughout the entire area.

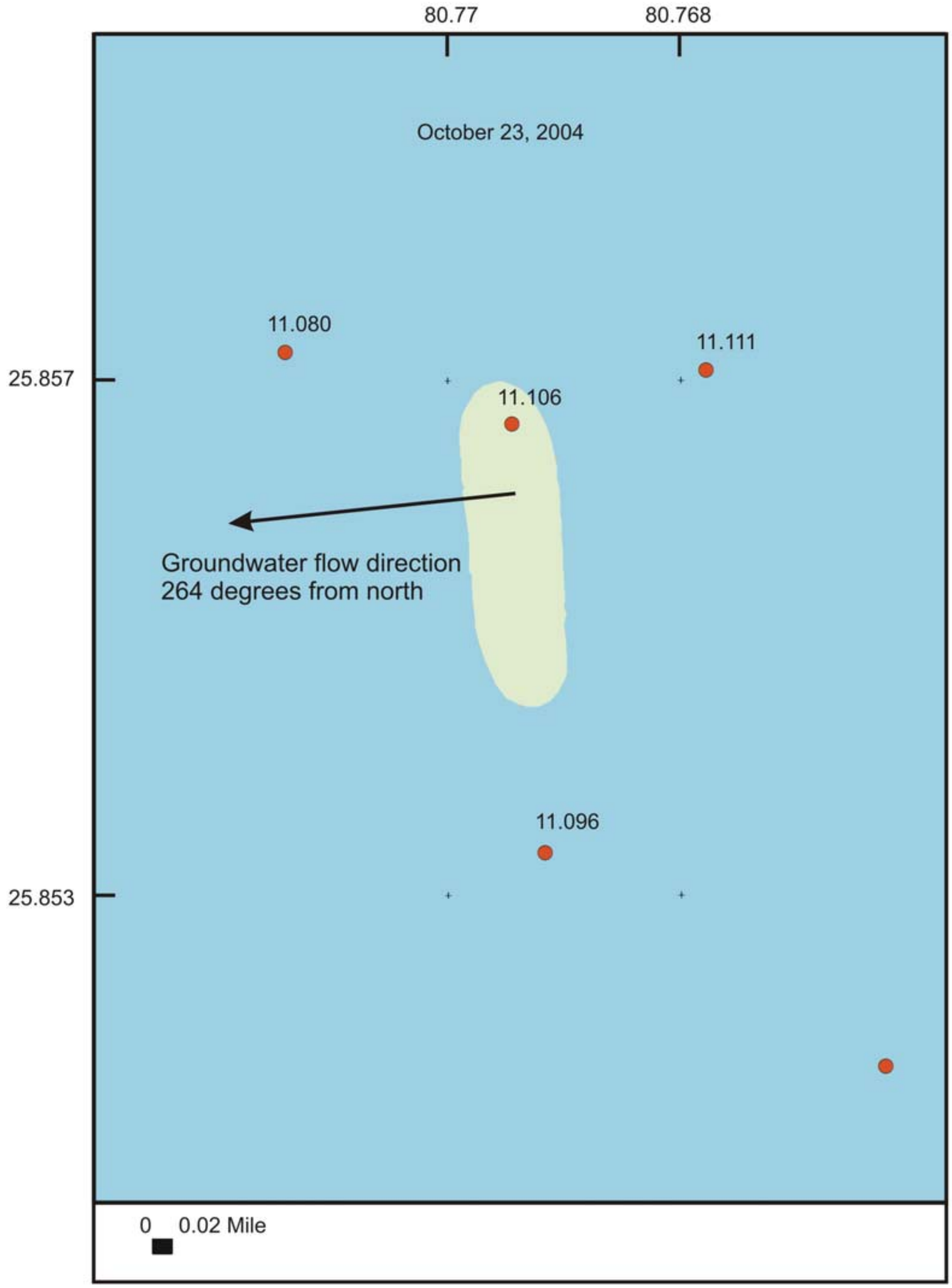


Figure 42 Water levels in deep wells in and around 3AS3 on October 23, 2004. Direction of flow is based on regression model.

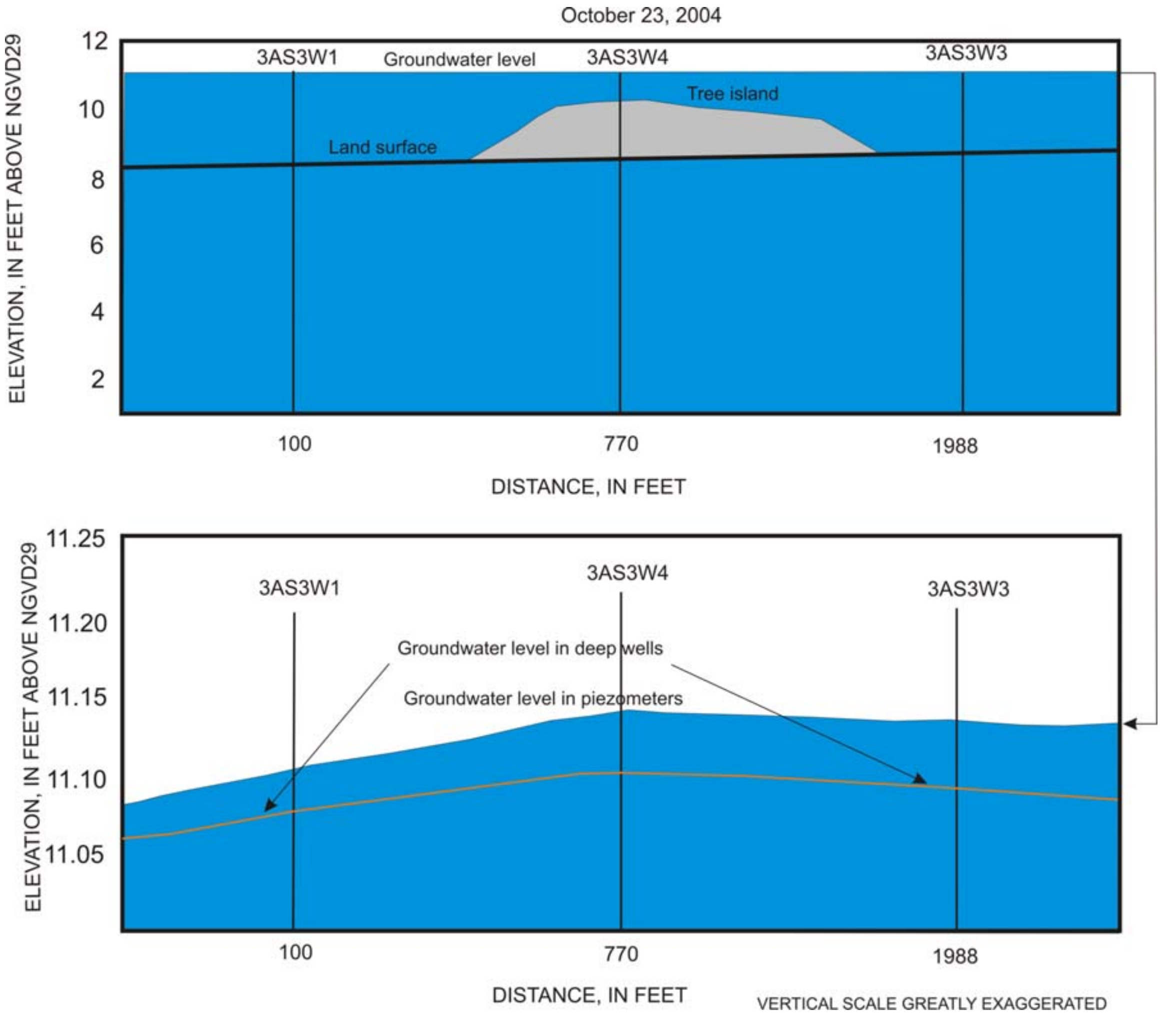


Figure 43 Cross sections showing the configuration of the water table and water levels in deep wells at 3AS3 on October 23, 2004.

Water levels in the deep wells during May 2007 (annual minimum) show a slope in the potentiometric surface to the south-southeast (fig. 44). Water levels in the wells at all four locations were below land surface, ranging from 0.2 ft below land surface at 3AS3W1 to 0.7 ft below land surface at 3AS3W3 (fig. 45, top). Unlike 3AN1, water levels in the piezometers do not indicate a depression in the water table beneath the tree island; however, the gradient in the water table is steeper north of the tree island compared to the gradient south of the tree island (fig. 45, bottom). The deep roots from the trees at the island, and subsequent high rates of evapotranspiration, or other hydrogeologic factors could be causing the change in gradient under the tree island. In addition, water levels are higher in the piezometer compared to the water level in the adjacent deep well at 3AS3W1, indicating downward migration of groundwater. In contrast, water level in the deep well at 3AS3W3 is higher than the level in the adjacent piezometer, indicating groundwater is upwelling into more shallow zones. In summary, the water levels in the wells and piezometers around 3AS3 indicate a localized groundwater flow system, with groundwater migrating downward north of the tree island, then flowing south, and ultimately migrating upward to shallow zones near 3AS3W3. Additional analysis is needed to determine the factors affecting these small spatial changes in the water table.

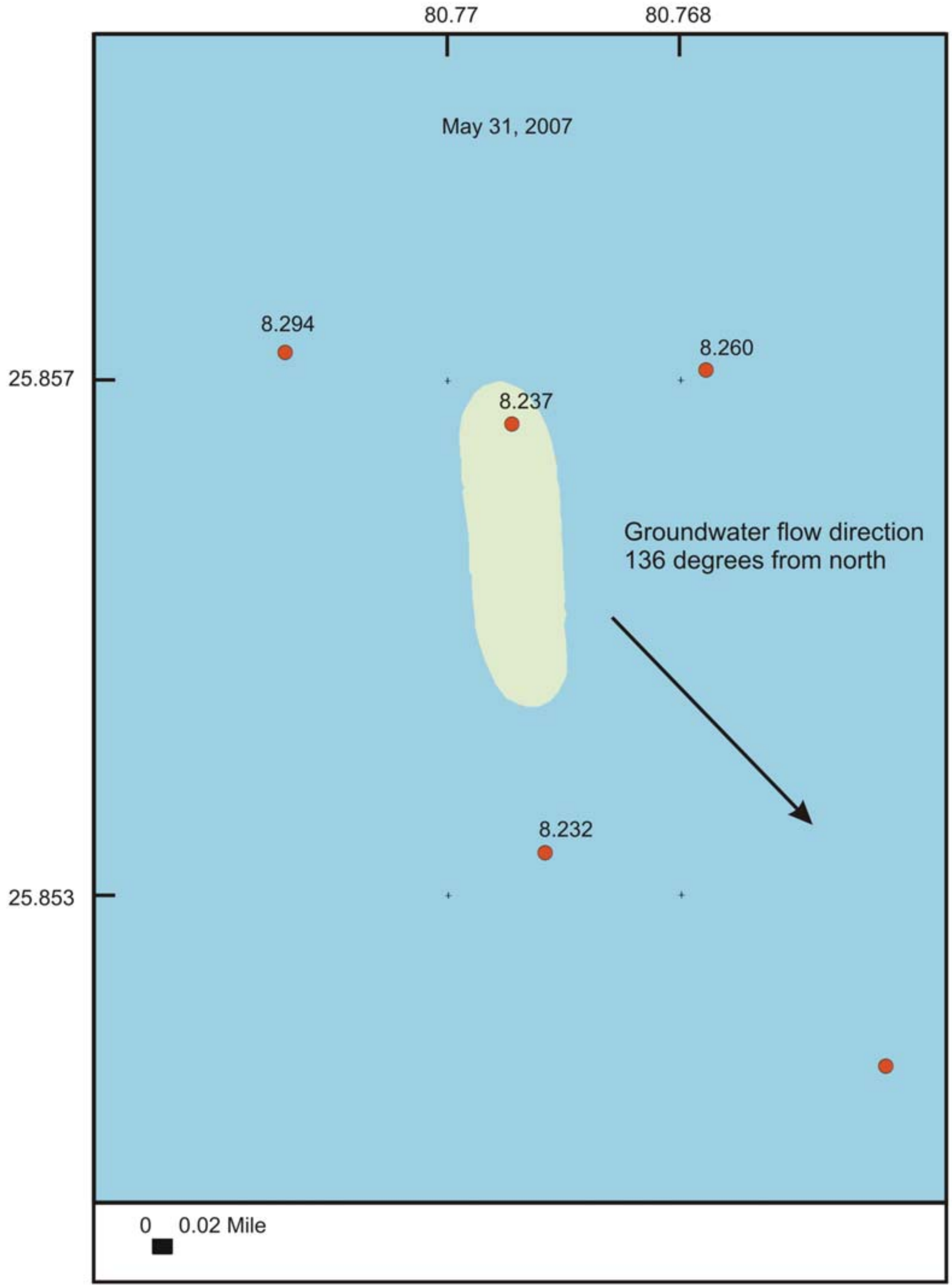


Figure 44 Water levels in deep wells in and around 3AS3 on May 31, 2007. Direction of flow is based on regression model.

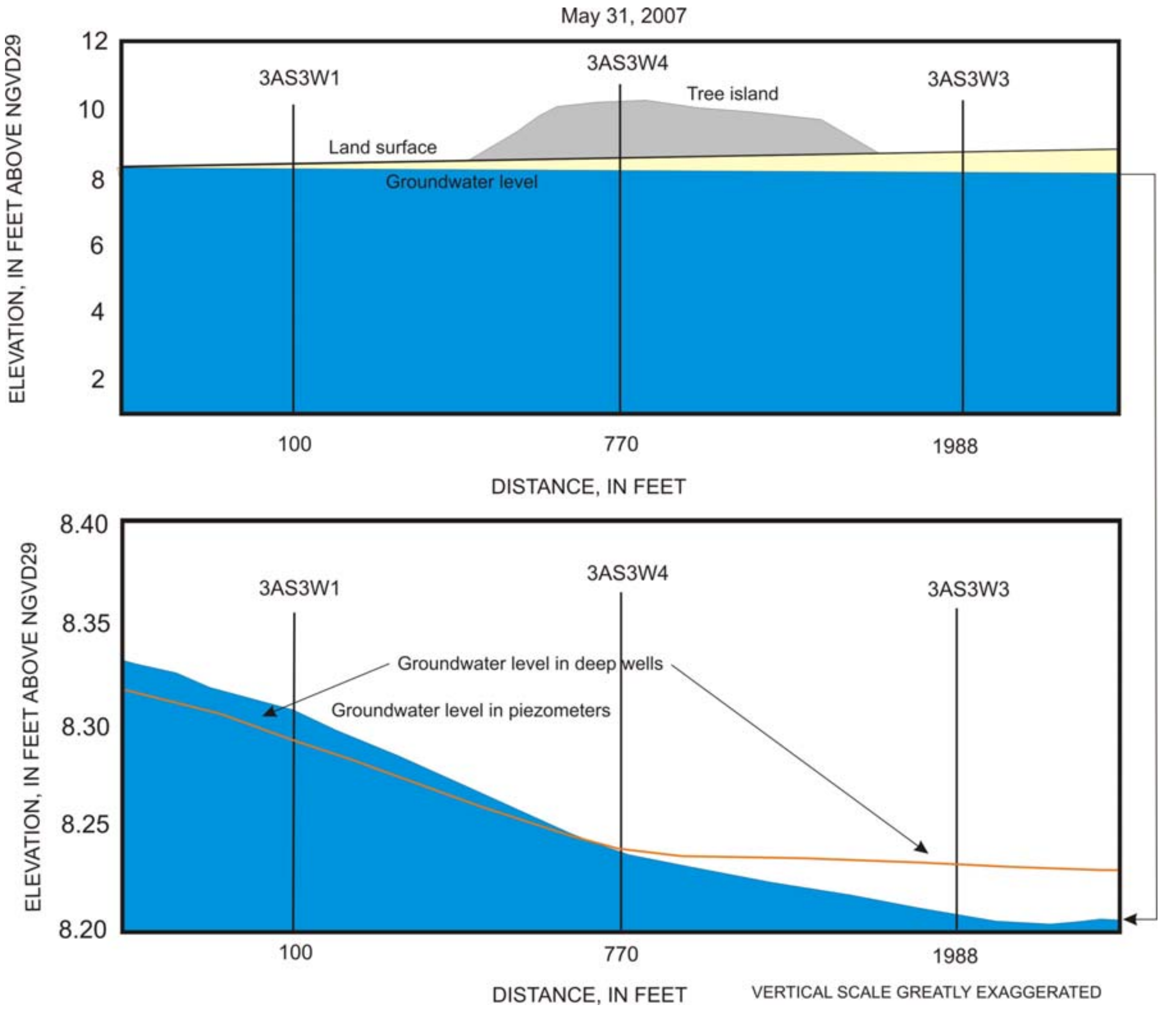


Figure 45 Cross sections showing the configuration of the water table and water levels in deep wells at 3AS3 on May 31, 2007. Water levels beyond the wells were estimated using extrapolation.

With the exception of May 31, 2007, water levels in the piezometer and deep well at 3AS3W4 generally are higher than the water levels in most of the other piezometers and wells around the tree island (Appendix B). The higher groundwater levels under the island indicate that water is flowing horizontally away from the island to the surrounding areas. Vertical movement of groundwater appears to fluctuate over time, with areas north of the tree island serving primarily as places of groundwater recharge, and areas south of the island serving both as places of groundwater recharge and groundwater discharge. As with 3AN1, the groundwater hydrology at 3AS3 is complex, with numerous flow paths and changing directions.

6.3 3BS1

The regression model results show that groundwater flow at 3BS1 varies from less than 0.001 to 1.684 ft/d, with a median of 0.096 ft/d (table 9). The range of flow values is comparable to the flow at 3AN1. However, the median value at 3BS1 is closer to the median value of flow at 3AS3, which was 0.082 ft/d. The direction of flow ranges from 79 to 109 degrees from north, with a median of 90 degrees (east-west). In other words, most of the flow is oriented in an east-west direction. The results for flow direction were similar regardless of whether the water levels at the island (well site 3BS1W4) were included in the model or not.

Statistics	Flow (feet per day)	Direction (degrees from true north)
Minimum	<0.001	79
Mean	0.132	90
Median	0.096	90
Maximum	1.684	109
Standard Deviation	0.154	1.748
Variance	0.024	3.055

Table 9 Summary statistics for groundwater flow and direction at tree island 3BS1

Groundwater flow at 3BS1 fluctuates over time, but only roughly corresponds to seasons or changes in water levels in the wells (figs. 46). Higher flow rates generally occur during declines in groundwater levels, possibly as a result of increases in gradients. As with 3AS3, the maximum flow occurred in February 2007, shortly after a gap in the data that lasted from January 1 – February 10, 2007. The high flow rates do not coincide with extremes in rainfall or other environmental factors. The high flow rates, which extend from February 11 to about mid March, could be anomalies, but the water-level data upon which the flow is based appear valid. The similarity with the peak in flow rate at 3AS3 (see fig. 40) could indicate these data are valid. More analysis, perhaps using incremental data over shorter time periods, is needed to determine the factors affecting temporal variations in flow rates.

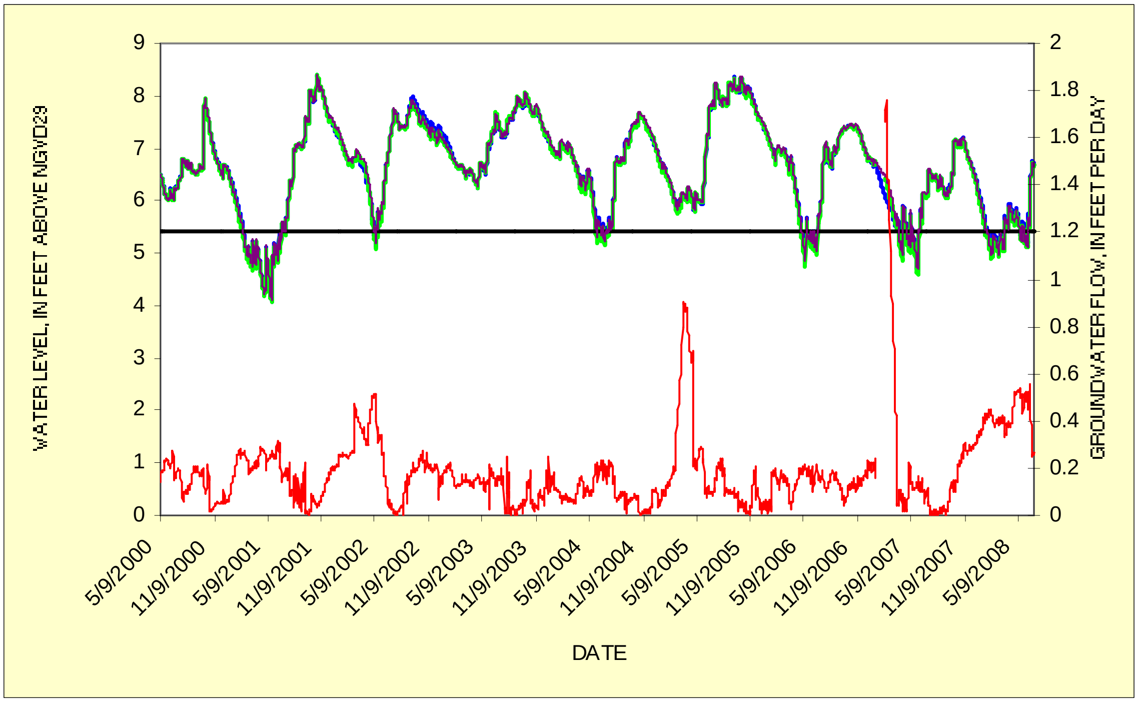


Figure 46 Groundwater flow (red) is plotted with water-level data from wells 3BS1W1_GW (blue), 3BS1W3_GW (green) and 3BS1W4_GW (black). The horizontal brown line represents land-surface elevation at site 3BS1W1.

The direction of vertical groundwater flow was determined at all four well sites by subtracting the water level in the deep well from the water level in the stilling well (3BS1W1) or the piezometer at each site. A positive value indicates downward migration or groundwater recharge, and a negative value indicates upward migration or groundwater discharge. As with the other two tree islands, a small (1 – 2) percent of the time the value was 0, indicating no vertical flow. The results indicate that most of the time (56 – 76 percent), groundwater is flowing downward at all four well sites at 3BS1 (table 10). The downward flow of groundwater occurs throughout the year, but the difference between surface-water (or shallow groundwater) levels and water levels in the deep wells increases as the water levels in the wells increase (fig. 47). Upward movement of groundwater only seems to occur at the end of the dry season, during periods of annual water-level minima.

Well Site	Percentage of time vertical flow is upward	Percentage of time vertical flow is downward
3BS1W1	37	62
3BS1W2	22	76
3BS1W3	42	56
3BS1W4	36	63

Table 10 Vertical groundwater flow at tree island 3BS1

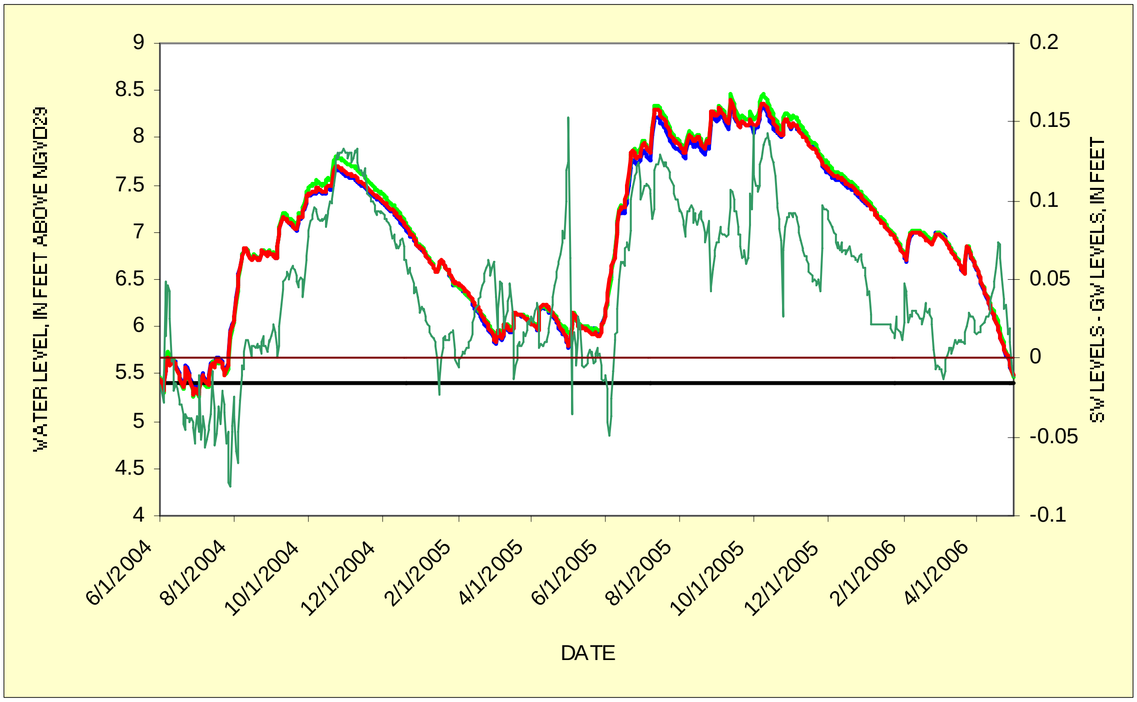


Figure 47 The difference between surface-water and groundwater levels (dark green) is plotted with water levels in stations 3BS1W1_GP (red), 3BS1W1_GW (blue) and 3BS1W1_H (green). The thick horizontal brown line represents land-surface elevation at 3BS1W1.

As with the other two tree islands, the configuration of the water table at 3BS1 changes over time with seasonal fluctuations in water levels in the wells. Water levels in the wells in October 2004 (annual maximum) indicate mounding of groundwater under the tree island (fig. 48), with the water level in the well at the island (3BS1W4) being higher than the water levels in any of the other three deep wells. Cross sections indicate that water levels were relatively high, inundating most of the land around the island. However, unlike the other two islands on this date, the tree island at 3BS1 was not inundated (fig. 49, top). The topographic relief is higher at 3BS1 than at either of 3AN1 or 3AS3 (table 2), which could explain the lack of inundation. In addition, 3BS1 is in close proximity to the urban areas of Miami-Dade County (fig. 1). Groundwater withdrawals by the cities could result in the overall downward migration of groundwater (table 10) and a decline in groundwater levels. Water levels in the piezometers indicate the water table has an overall slope to the north. Similar to 3AS3, water levels in the four piezometers at 3BS1 are higher than water levels in their adjacent deep wells on this date, indicating vertical flow was downward and groundwater was recharging throughout the entire area.

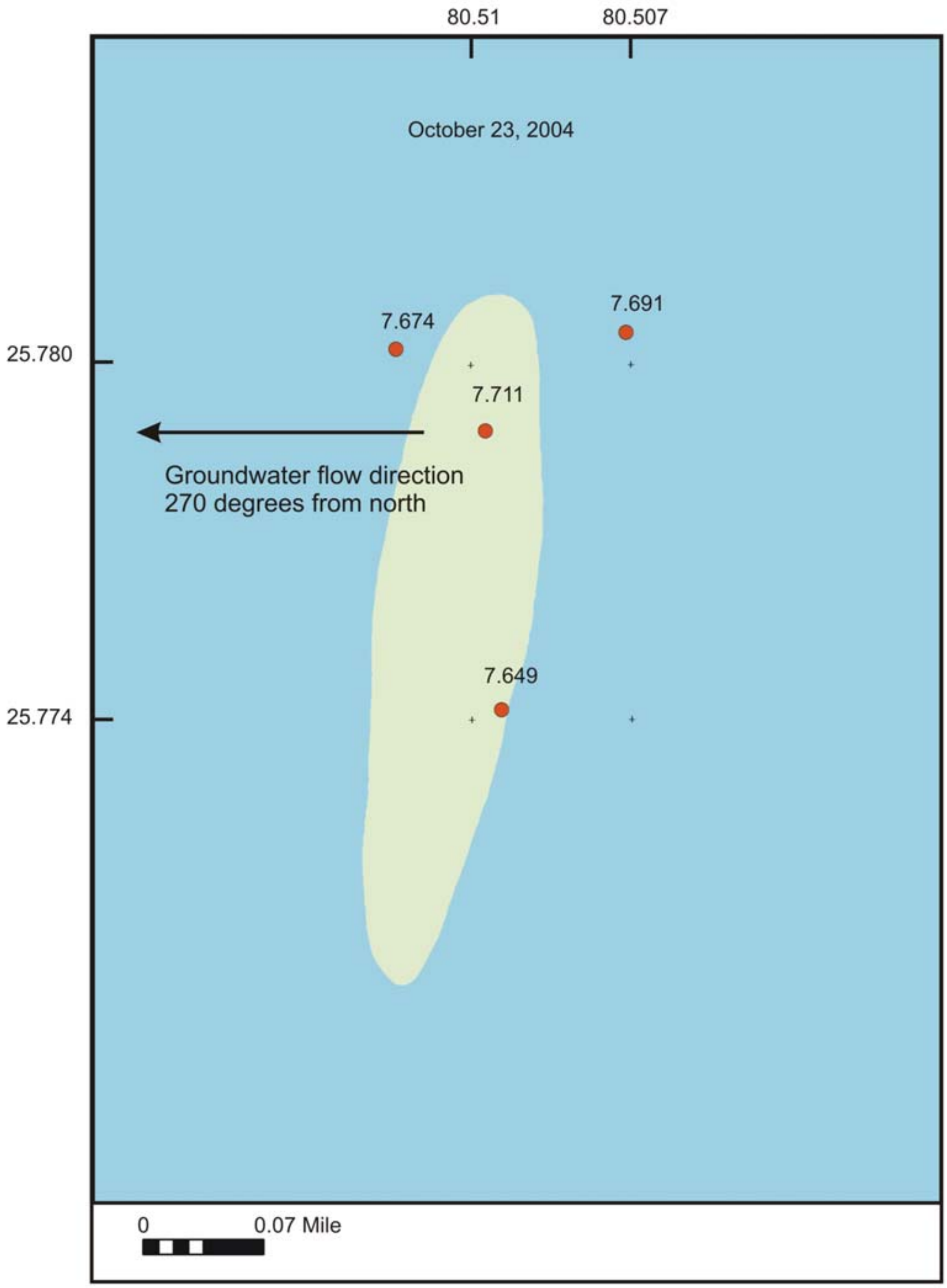


Figure 48 Water levels in deep wells in and around 3BS1 on October 23, 2004. Orientation of flow from the regression model was 90 degrees from north, but the direction of flow was estimated to be from east-west (270 degrees).

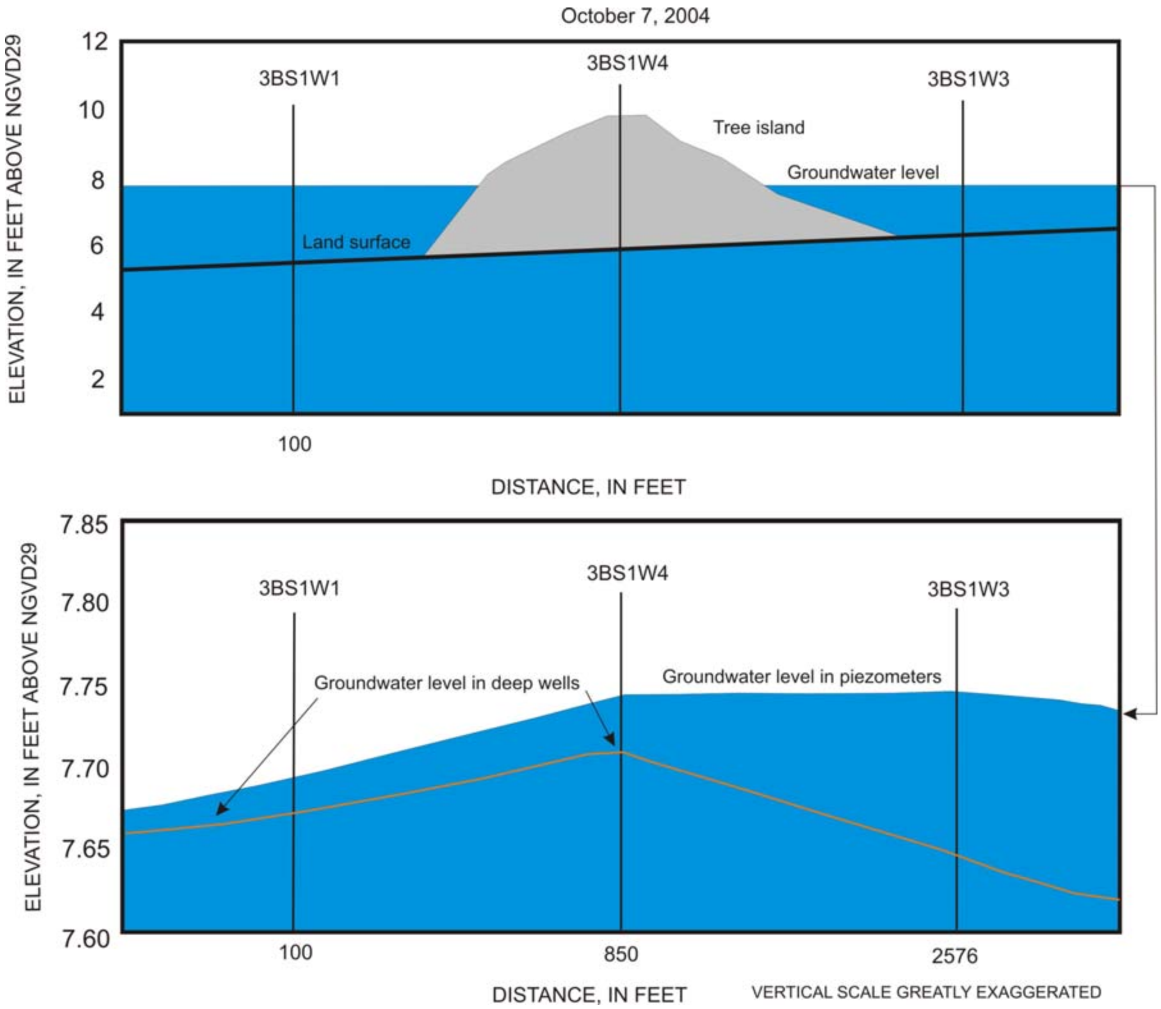


Figure 49 Cross sections showing the configuration of the water table and water levels in deep wells at 3BS1 on October 23, 2004.

Water levels in the deep wells during May 2007 (annual minimum) also show a mound in the potentiometric surface under the tree island (fig. 50). Water levels in the wells at all four locations were below land surface, ranging from 0.7 ft below land surface at 3BS1W1 to 1.6 ft below land surface at 3BS1W3 (fig. 51, top). The water level at 3BS1W4 was 5.41 ft below land surface. Water levels in both the piezometers and deep wells indicate a mounding of groundwater under the tree island (fig. 51, bottom), which is in contrast to the depression in the water table under 3AN1 on the same date. The water levels in the piezometers and deep wells also indicate that vertical groundwater flow is downward at sites 3BS1W1 and 3BS1W4, but is upward at 3BS1W3.

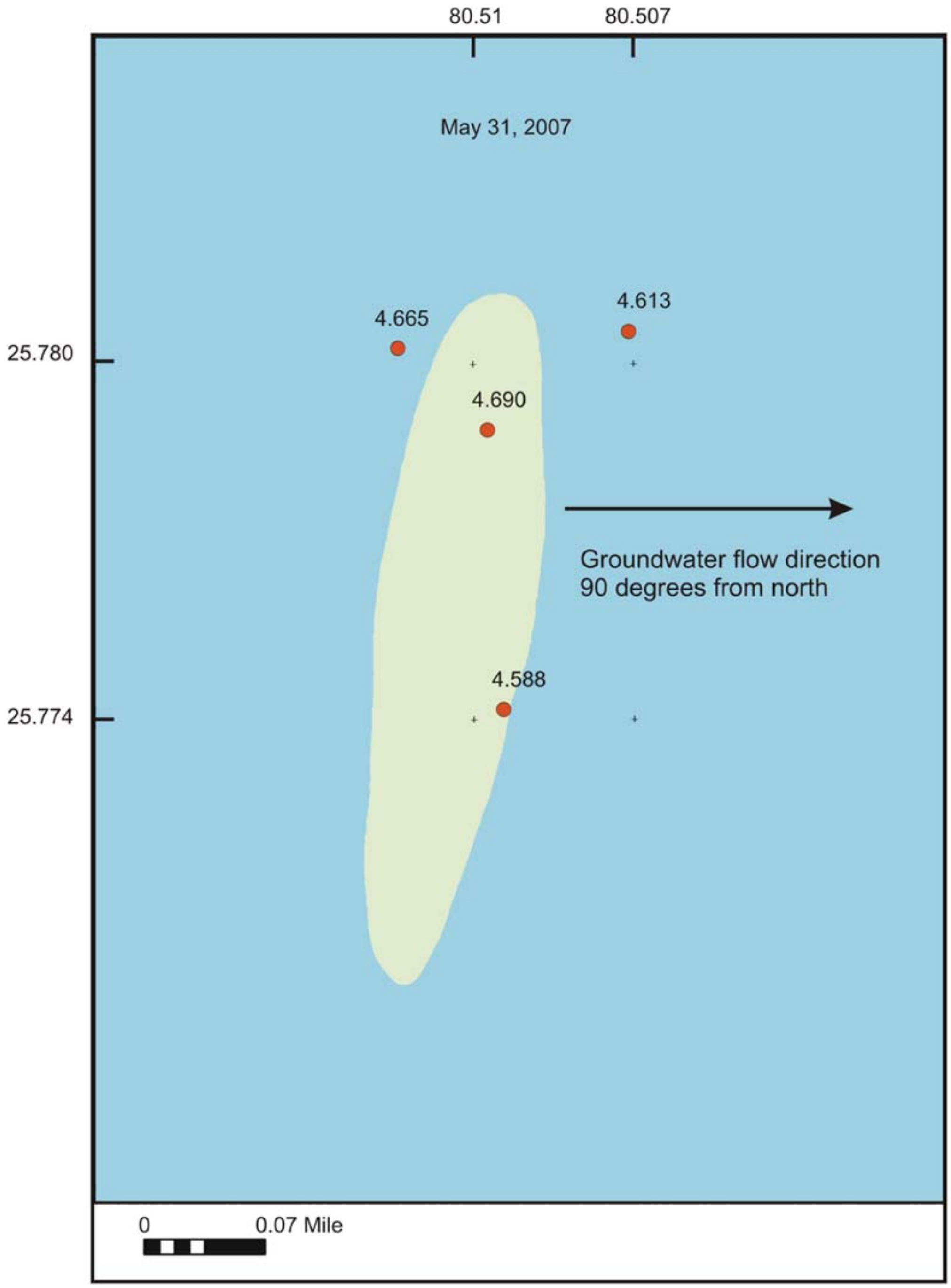


Figure 50 Water levels in deep wells in and around 3BS1 on May 31, 2007. Direction of flow is based on regression model.

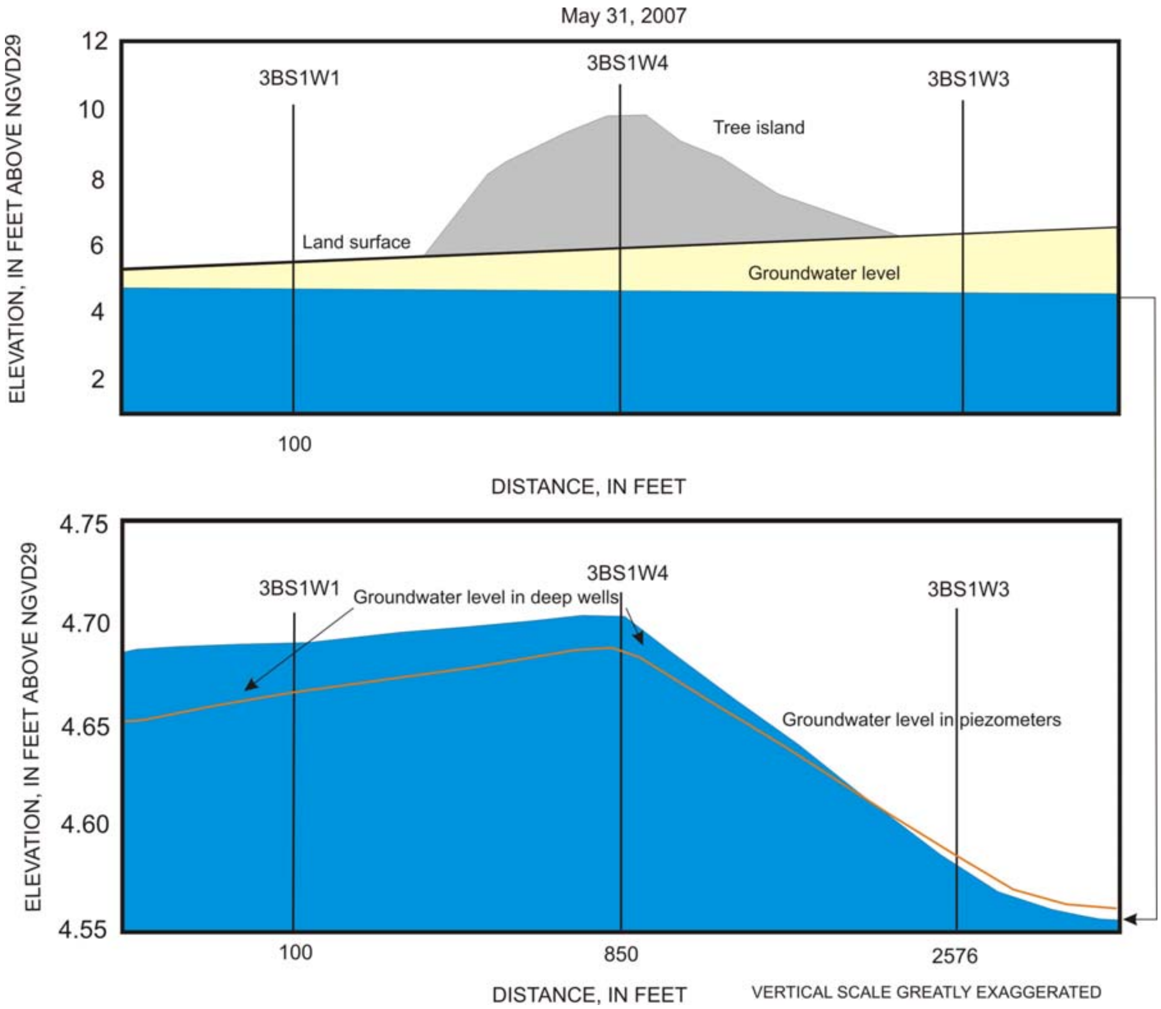


Figure 51 Cross sections showing the configuration of the water table and water levels in deep wells at 3BS1 on May 31, 2007. Water levels beyond the wells were estimated using extrapolation.

In summary, water levels in the piezometers and deep wells at and around 3BS1 indicate a persistent mounding of groundwater underneath the tree island itself (Appendix B). This mounding is inconsistent with the constant 90 degree direction of flow determined by the regression model. Even when the water levels at 3BS1W4 are disregarded, the groundwater flow at 3BS1 appears to range from southeast to southwest (figs. 48 and 50; Appendix B). Vertical groundwater movement is primarily downward, possibly a result of groundwater withdrawals from nearby urban areas in Miami-Dade County. Additional study is needed to verify actual groundwater flow directions and correlations between groundwater levels and withdrawals.

7 RECOMMENDATIONS

The results of this project, which was limited in scope to the daily-value data, provided an overview of the hydrology of the tree islands. However, additional analyses could be conducted on the extensive incremental and daily-value data to obtain an even more detailed understanding of the factors affecting the complex flow systems underlying the tree islands. Recommended analyses could include, but are not limited to, the following:

- Modify the regression model code to provide true direction of flow
- Determine the frequency of flow direction changes, and environmental or anthropogenic factors that affect flow direction
- Run the regression model with water-level data from nearby surface-water stations or monitor wells to determine direction and quantity of flow for larger areas
- Use incremental water-level and meteorological data to better quantify the effects of rainfall, evapotranspiration, and photosynthetic radiation on water levels
- Use incremental data to better understand factors and conditions affecting the vertical movement of groundwater
- Investigate the effect of groundwater withdrawals on the hydrology of 3BS1
- Couple the water-level and water-quality data from the stations to provide insight into the local flow systems underlying the islands

Geochemical modeling also could be used to help determine sources of inorganic constituents and chemical reactions along flow paths. These proposed investigations could be conducted as a single large project or as multiple smaller projects over time, to best satisfy SFWMD needs.

8 SUMMARY

Tree islands are tear-shaped topographic features in the relatively flat, low-lying landscape of southern Florida. Tree islands are only slightly (a few feet) elevated above the surrounding wetland, but are an important habitat for plants and animals. Tree islands are sensitive to changes in their hydrologic conditions; hence, a better understanding of the factors affecting the hydrology of tree islands is needed in the efforts to protect and restore the Everglades.

In 2000, the South Florida Water Management (SFWMD) began monitoring groundwater and surface-water levels, respectively, at three tree islands (designated 3AN1, 3AS3, and 3BS1) in Water Conservation Area 3 to better understand the unique hydrologic and ecologic conditions of the sites. A series of dual-zone monitor wells were installed at each of the three tree islands. Well pairs, which consisted of a shallow piezometer (depths from 4.1 to 15 ft below land surface) and a deep groundwater well (depths from 25 – 49.6 ft below land surface), were installed just northwest (W1), northeast (W2), and south of each island (W3). A well pair (W4) also was installed within each island. A stilling well was installed adjacent to the W1 well pair at each of the three islands to monitor surface-water stage. Water-level data were collected at 15-minute increments from the wells and stilling wells using pressure transducers and data loggers. A meteorological station also was established at 3AS3.

The water-level and meteorological data from the tree islands were analyzed for seasonal fluctuations and factors affecting water levels. Water-level data from the monitor wells also were analyzed to assess horizontal and vertical flow of groundwater. These analyses were primarily conducted using daily averages of the incremental data.

Meteorological data varied according to season, as was expected. Maximum air temperatures occurred in late August and September, and minimum air temperatures occurred in January and early February. Photosynthetic radiation and evapotranspiration peaked in May and June, and reached minimum values in late November and December.

Southern Florida generally has two seasons with respect to rainfall—a wet season that occurs from June through September and a dry season that lasts from October through May. During the period of record, data collected from the meteorological station at 3AS3 indicated cumulative rainfall during the wet season ranged from 17 to 36 inches, whereas cumulative rainfall during the dry season ranged from 10 to 25 inches.

Groundwater and surface-water levels also exhibit seasonal and temporal fluctuations related to meteorological conditions. Water levels in the wells and stilling wells generally reached minimum values toward the end of the dry season, around May of each year, and peaked in late September or October at the end of the wet season. Groundwater and surface-water levels were statistically higher at the end of the wet season compared to water levels at the end of the dry season. Furthermore, the amount of increase in groundwater and surface-water levels after a rain storm was positively correlated to the amount of rainfall during the storm.

The abundant rainfall in southern Florida results in the areas around the islands, and even the islands themselves, to be periodically or frequently inundated. For example, water-level data indicate the areas surrounding 3AS3 were inundated 85 to 100 percent of time during the period of record, while the island itself was inundated up to 24 percent of the time. The island at 3AN1 was inundated nearly 18 percent of the time, but the island at 3BS1 was never inundated, possibly from the higher topographic relief at that island.

Evapotranspiration and photosynthetic radiation also affected groundwater and surface-water levels at the tree islands. In general, water levels in wells and stilling wells declined as evapotranspiration and photosynthetic radiation increased. Analysis of incremental data indicated daily declines in water levels in wells at 3AS3 coincided with peaks in photosynthetic radiation that occurred during the middle of each day.

At any one time, the difference in water levels between well pairs installed at the same island was small, usually less than a tenth of a foot. The difference in water levels between the shallow piezometer and deep well in the same well pair was equally small. Small differences in water levels indicate a flat water table with low gradients, and result from the high hydraulic conductivity of the aquifer.

Results of regression analysis indicate groundwater flow at each island varied over time, and generally was higher at 3AN1 than at the other two islands. Groundwater flow at 3AN1 ranged from 0.009 to 1.855 feet per day (ft/d), with a median of 0.184 ft/d, whereas groundwater flow at 3AS3 ranged from 0.002 to 0.777 ft/d, with a median of 0.082 ft/d. Groundwater flow at 3BS1 ranged from less than 0.001 to 1.684 ft/d, with a median of 0.096 ft/d.

The direction of horizontal groundwater flow varied widely during the period of record, possibly from changing gradients with seasonal fluctuations in water levels. However, water levels indicated mounding of groundwater under all three islands. Mounding indicates that groundwater is flowing laterally away from each island to the areas underlying the surrounding wetland.

In contrast, water levels during May 2007 indicate a depression formed in the groundwater underlying the island 3AN1. This depression appears to be a unique situation caused in part by the low rainfall and excessive dry conditions in early 2007. Evapotranspiration by deep-rooted trees on the island could have contributed to the formation of the groundwater depression. Horizontal groundwater movement would have been toward the depression during this time. Additional study is needed to determine if the depression occurred at other times or if similar depressions ever formed under the other two islands.

Differences between water levels in the deep wells and water levels in the adjacent piezometers or stilling wells indicated the direction of vertical groundwater flow. Vertical groundwater flow was upward 60 to 70 percent of the time in the areas surrounding 3AN1. Groundwater flow also was upward 84 to 90 percent of the time in areas north of 3AS3; however, vertical groundwater was downward 47 and 56 percent of the time underlying the island and areas just south at 3AS3. Vertical groundwater flow was downward at 56 to 76 percent of the time in and around 3BS1. Groundwater withdrawal from nearby urban areas in Miami-Dade County could be affecting vertical groundwater flow at 3BS1.

Nearby canals also could be affecting the hydrology of the tree islands. Surface-water levels at the three tree islands strongly correlated with water levels at several of the structures on nearby canals. Water levels in the stilling wells at 3AN1, 3AS3, and 3BS1 correlate to stage at S339_T (tailwater), 12B_H (headwater), and S334_T (tailwater), respectively. Further study is needed to document this effect.

In summary, the hydrology of the tree islands is complex, with considerable interaction between groundwater and surface. Mounding of groundwater indicates local lateral flow is away from the islands to areas underlying the surrounding wetlands, with direction of regional flow varying over time and with seasonal conditions. At 3AN1 and 3AS3, groundwater generally flows downward at the island and discharges in areas underlying the wetlands. Groundwater flow is primarily downward underlying areas in and around 3BS1. The downward movement of groundwater at 3BS1 could be related to groundwater withdrawals at nearby urban areas.

Additional analysis of the water-level data is recommended to further quantify meteorological and other factors affecting vertical and horizontal groundwater flow. These analyses can be coupled with existing water-quality data collected from the wells to better understand flow paths in the groundwater underlying the three tree islands.

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