Seasonal Variability of Near Surface Soil Water and Groundwater Tables in Florida: Phase II

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Disclaimer

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	poundforce per square inch	6.89	kilopascals	kPa

NOTE: Volumes greater than 1000 l shall be shown in m^3.

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	psi

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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16. Abstract

The seasonal high groundwater table (SHGWT) is a critical measure for design projects requiring surface water permits including roadway design and detention or retention pond design. Accurately measuring and, more importantly, predicting water table elevations is a complex process controlled by numerous factors including soil composition, rainfall, adjacent surface water levels, tidal influences, topography, connection between underlying aquifers, and perched water table conditions. The objective of this research effort is to provide a tool for estimating probable high water table elevations. The resulting SHGWT estimates can then be incorporated into a risk-based analysis for design and management decisions. The application presented in this report is based upon expansion of a methodology presented by the USGS (Frimpter, 1981 and Socolow et al., 1994) which estimates water table levels at a site of interest based upon historic period of record data from a reference well. The primary distinction between previous studies and the work presented here is that previously only one reference well was selected to estimate the high water level at a site of interest. The reference well database application developed for this project considers all reference wells that are similar to a site of interest and provides a range of probable high water levels.

17. Key Word Seasonal high groundwater table, high water level, soil, regression, tidal, exceedance probability	18. Distribution Statement		
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Executive Summary

The seasonal high groundwater table (SHGWT) is a critical measure for design projects requiring surface water permits including roadway design and detention or retention pond design. In addition to constructability issues, the long-term maintenance of roadways and retention ponds is impacted by these cited levels. In regions characterized by poorly drained soils and high seasonal water tables the functional designs are highly sensitive to the SHGWT. However, accurately measuring, and more importantly, predicting water table elevations is a complex process controlled by numerous factors including soil composition, rainfall, adjacent surface water levels, tidal influences, topography, connection between underlying aquifers, and perched water table conditions. Being able to reliably predict water table elevations, particularly maximum or high water levels, with some indication of the probability and risk associated with these estimates would be advantageous to the design process.

This report presents the results of research conducted for the Florida Department of Transportation (FDOT) regarding development of a tool which provides estimates of probable seasonal high groundwater table (SHGWT) elevations. The resulting SHGWT estimates can then be incorporated into a risk-based analysis for design and management decisions. The general concept is based upon a methodology developed by the United States Geological Survey (USGS) for application in Massachusetts (Frimpter, 1981) and Rhode Island (Socolow et al., 1994). The primary distinction between previous studies (Frimpter (1981) and Socolow et al., 1994) and the work presented for this project is that previously only one reference well was selected and used to manually estimate the high water level at a site of interest. The reference well database application developed for this project considers all reference wells that are similar to a site of interest and provides a range of probable high water levels for the site.

Visual Basic for Applications (VBA) and Excel were used to develop the tools required for creating a reference well database for estimating probable SHGWT levels. A pilot-scale application was created using 322 surficial observation wells (192 active; and 130 inactive) operated and maintained by the South Florida Water Management District (SFWMD). Over 23,000 well pair correlations were generated resulting in the selection of seventy-six reference wells that demonstrate at least moderate positive correlation ($R^2 \geq 0.50$), while having sufficient period of record of water table observations to be representative of long term trends in water table fluctuations. The inherent assumption in the methodology applied is that reference wells that demonstrate at least moderate correlation to one another (based upon similar hydrogeologic characteristics) will demonstrate similar linear relationships to sites of interest having the same site characteristics.

Upon completion of the correlation analysis it was found that the wells with moderate to strong correlations were distributed within four distinct natural drainage basins: Kissimmee, Lower East Coast (LEC), Lower West Coast (LWC), and Upper East Coast (UEC). Based upon this outcome, the wells were sorted into five zones that were defined by the natural drainage basins with the fifth zone being the product of dividing the LEC into two zones (northern – Broward and Palm Beach Counties, and southern – Miami-Dade County). A reference well database was created for each zone storing the well's observation records, summary data, exceedance probability distributions, and hydrographs.

Application of the USGS methodology within a reference well database framework has proven to be reliable for the study area (south Florida) when the reference well and site of interest share similar characteristics (particularly similar maximum annual water level ranges, and hydrograph trends—which most likely correspond to similar precipitation patterns). The most important thing to note is that estimated water levels at a site of interest can be under- or over-estimated based upon the relative water levels within the wells at the time of observation. The largest errors are present when comparing wells with inconsistent hydrograph trends (i.e. a reference well was in a region with dry conditions and the site of interest was in a region experiencing wetter conditions), and with dissimilar observed historical maximum annual water level ranges.

The uncertainty associated with predicted water levels is often times greater when based upon one single reference well. For this reason, the program developed for this project does not simply identify one "most similar" reference well, but instead provides a set of wells with corresponding ranges of probable high water levels which are presented so that the user can review all relevant information. This allows any subsequent design decisions to be based upon either worse case scenario, best case scenario, or a probable range depending upon the available data and design criteria.

The strength of the reference well database application is that it was designed to be flexible in its development and maintenance, so that as the number of potential reference wells increases continual analysis can be conducted to better understand the relationship between various characteristics and water level variations. Site characteristics such as soil type, drainage properties, vegetation, land use, can be considered to refine the reference well selection process. Additionally, as the number of potential reference wells increases, the boundaries that define reference well zones can also be refined. Finally, the program can be adapted so that the reference well selection process becomes more automated based on predefined criteria. This would involve establishing selection thresholds based upon specific design parameters and regulatory guidelines.

The last section of this report discusses a similar methodology and application for estimating tidally influenced groundwater levels. Similar to the inland reference well database, this method uses exceedance probabilities of observed historic data from tide gages throughout the state of Florida to estimate the probable magnitude and inland extent of tidally influenced groundwater elevations.

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1. Introduction

1.1. Purpose and Scope.

The water table represents a relatively simple concept—the level at which water exists below ground surface; however, accurately measuring and, more importantly, predicting water table elevations is a complex process controlled by numerous factors. The groundwater level and its range of fluctuation are required design factors for most projects that involve altering the landscape (such as development within uplands and wetlands, installation of septic systems, dredging and filling activities, roadway construction, and agricultural alterations that impede or divert the flow of surface waters). Therefore being able to reliably predict water table elevations, particularly maximum or high water levels, with some indication of the probability and risk associated with these estimates would be advantageous to the design process.

This report presents the results of research conducted for the Florida Department of Transportation (FDOT) regarding development of a tool which provides estimates of probable seasonal high groundwater table (SHGWT) elevations. The resulting SHGWT estimates can then be incorporated into a risk-based analysis for design and management decisions. The general concept is based upon a methodology developed by the United States Geological Survey (USGS) for application in Massachusetts (Frimpter, 1981) and Rhode Island (Socolow et al., 1994). This method estimates water table levels at a site of interest based upon historic period of record data from an observation well (or reference well). The transfer of information from the reference well to the site of interest is based upon linear regression and four fundamental assumptions which will be discussed in the following section.

1.2. USGS Technique for Estimating Groundwater Levels.

A relationship between the groundwater levels at an observation well (or reference well) and a site of interest was presented by Frimpter (1981) in an effort to predict future high, low, and median groundwater levels in Massachusetts (Frimpter, 1981). The relationship between the wells is expressed as a proportion where the ratio between the potential water level change and annual water level range at a site of interest is equal to the ratio of the potential water level change and the maximum annual water level range at a reference well (Frimpter, 1981 and Socolow et al., 1994). This relationship is defined in the following equation and is illustrated in Figure 1 (Frimpter, 1981 and Socolow et al., 1994).

$$\frac{S_c - S_h}{W_c - W_h} = \frac{S_r}{W_r} \qquad \textbf{(1)}$$

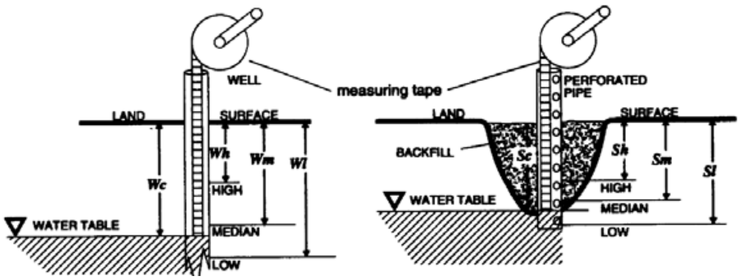


Figure 1. Relationship between the reference well on the left and the site of interest on the right (Adapted from Socolow et al., 1994).

Rearranging Equation 1 results in the final development of the following equations used in estimating high, low, and median groundwater levels expressed in depth below ground surface.

$$S_h = S_c + \frac{S_r}{W_r}(W_h - W_c) \qquad \textbf{(2)}$$

$$S_m = S_c + \frac{S_r}{W_r}(W_m - W_c) \qquad \textbf{(3)}$$

$$S_l = S_c + \frac{S_r}{W_r}(W_l - W_c) \qquad \textbf{(4)}$$

Where:
S_c = measured depth to water at site of interest
S_h = estimated depth to probable high water level at site of interest
S_l = estimated depth to probable low water level at site of interest
S_m = estimated depth to probable median water level at site of interest
S_r = range of water level depths at site of interest (based upon exceedance probability)
W_c = measured depth to water for the reference well
W_h = depth to recorded high water level for reference well
W_l = depth to recorded low water level for reference well
W_m = depth to recorded median water level for reference well
W_r = recorded maximum annual water level range for reference well

The fundamental assumptions asserted by Frimpter (1981) and Socolow in this technique are: (1) Water levels will fluctuate in the future as they have in the past, (2) Water levels will fluctuate seasonally, (3) Groundwater fluctuations depend on site geology, and (4) Water levels throughout the State are affected by similar precipitation and climate (Socolow et al., 1994). When selecting a reference well for estimating groundwater levels, the well should have similar lithology and depth to groundwater as the site of interest. Also, the wells should be of similar topography, especially if the aquifers are sand and gravel (Socolow et al., 1994).

When comparing the Massachusetts and Rhode Island conditions to those present in Florida a few distinctions should be noted. First is that when considering Florida, the assumption that water levels are affected by similar precipitation throughout the State may not be reasonable due to regional storm activities that occur, particularly in the summer. Second, is that the Massachusetts and Rhode Island studies only incorporate two soil types (sand and gravel; and till) when classifying the reference wells. Further distinction within the soil types was made based upon the topography in which sand and gravel aquifers were present. Comparatively, Florida exhibits minimal topographic variation and has soils composed predominantly of sand and karst materials with layers or lenses of clay and organics. Water levels are highly influenced by precipitation as Florida receives an average of 54 inches of rain each year. Water table levels are also influenced by the underlying Floridan Aquifer and its complex interconnections with the surficial aquifer system. Other factors that affect water table elevation are the varied vegetation throughout the state and the impact of urbanization (man-made alteration) which is particularly relevant in south Florida.

Due to the complex nature of the hydrological systems throughout Florida, it was concluded that the first step for selection of potential reference wells was to perform a blind correlation analysis using all surficial aquifer observation wells in SFWMD that had an adequate historic period of record. The intent was to analyze a large number of wells without applying preconceived assumptions regarding which wells should be similar. The result of the correlation analysis would be to indicate which reference wells are most similar (based upon strength of correlation). It was also believed that innate trends in the data would emerge providing sufficient evidence to indicate what variables or characteristic result in strong correlation between a reference well and a site of interest.

Correlation analyses were conducted using data collected from the SFWMD groundwater observation well network. A total of 322 surficial wells (≤32 ft bgs) were used: with 192 currently active; and 130 that are now inactive. The inactive wells were included in the analysis to provide additional data for testing and validation purposes.

Visual Basic for Applications (VBA) and Excel were used to develop the tools required for analyzing the large amount of data collected. Over 23,000 well pair correlations were analyzed. The VBA programs provide considerable flexibility for developing and maintaining the SHGWT reference well database and application. Additionally, the application was developed so that it can be readily modified to include parameters that would further categorize or classify a reference well in order to improve the accuracy of the methodology. For example, precipitation data, soil type, watersheds and sub-watersheds, vegetation, land use, and topography all could be included in the analysis to provide more detailed classification of reference wells. This allows for the reference well application can be continuously improved upon as more data becomes available and is incorporated.

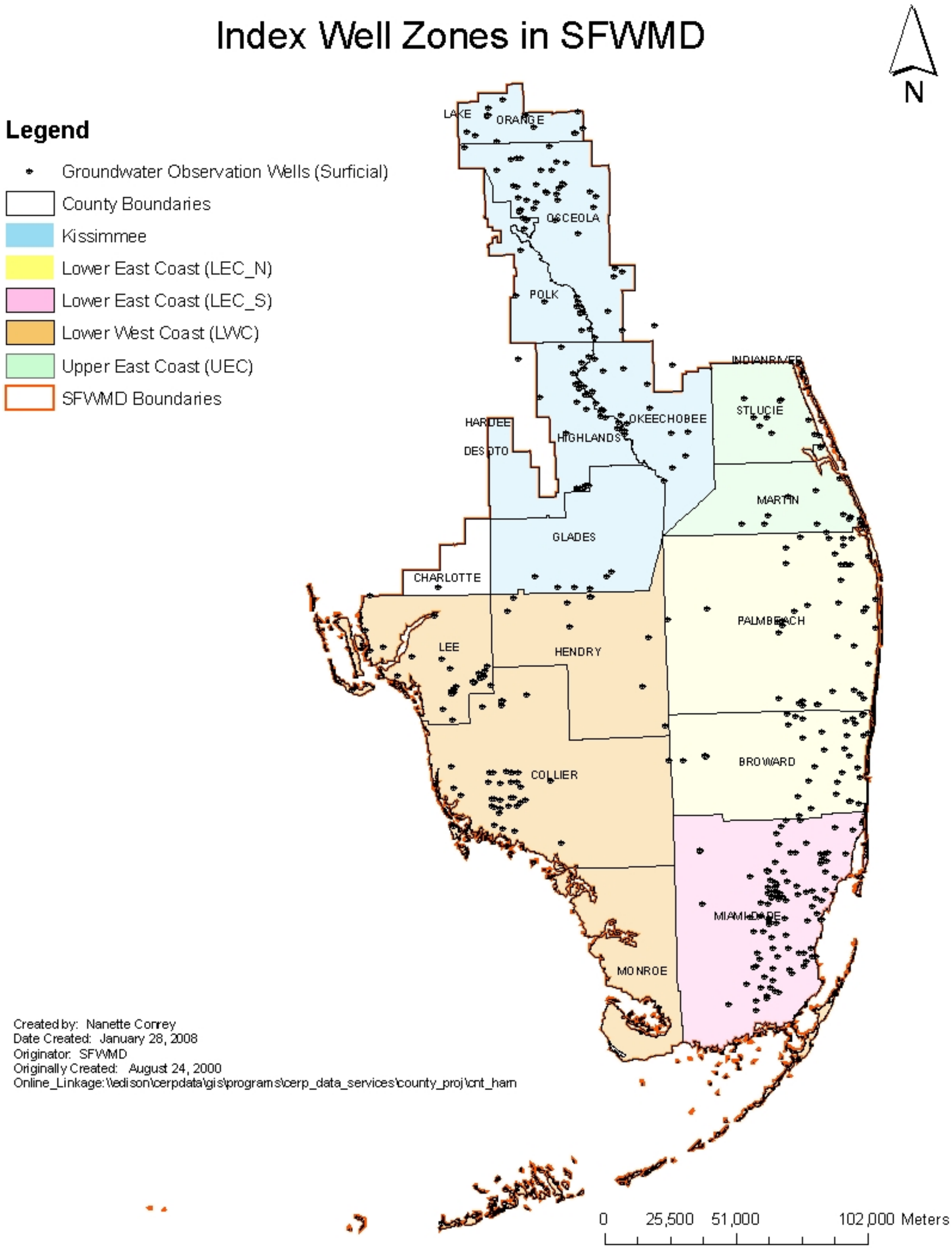


Figure 2. Reference well zones in SFWMD.

2. Hydrogeologic Setting of South Florida.

Florida's topography is generally flat with a very low slope. The elevations are highest on the east coast and decrease westward. The soil material is predominantly sand to fine sand mixed with layers of clay throughout the strata. These strata formed less than 6 million years ago when the sea level was approximately 25 feet higher (SFWMD 1, 2006). The features were formed in a depositional environment. The groundwater table can range from permanently ponding to over 150 feet below ground surface (bgs). There are numerous lowlands, wetlands, marshes and swamps throughout the state where organic materials (peat & muck) are located (SFWMD 1, 2006).

SFWMD includes the Kissimmee, Lake Okeechobee, and the Everglades ecosystem (see Figure 2) that covers an area of approximately 9,000 square miles (SFWMD 1, 2006). This system used to be one hydrological system that extended from what is now Orlando to the Florida Bay (250 miles). SFWMD is now made up of 4 sub-regions that are defined by natural watersheds (SFWMD 1, 2006).

The Kissimmee Basin is the northernmost region in SFWMD. It consists of the Kissimmee Chain of Lakes, and Kissimmee River that terminates at Lake Okeechobee. The water table in all but 2 of the counties (Highlands & Glades) in the southern area of the basin is greater than 20 feet bgs with a maximum depth of approximately 150 feet bgs (SFWMD 2, 2006). The deeper wells were not be used in this analysis as FDOT generally does not work in depths greater than 25 feet bgs.

The Upper East Coast (UEC) consist of 2 counties, St. Lucie and Martin that is immediately east of Lake Okeechobee. The area along the coastline is primarily developed; however, the land west of the urban regions is farmland with isolated wetlands that are more frequent near Lake Okeechobee. The inland wells are all located near the canals that traverse across the UEC from Lake Okeechobee to the Atlantic (SFWMD 5, 2006).

The Lower East Coast (LEC) consists of 4 distinct areas: the urban area that extends from Palm Beach south to an area just north of the keys, the Everglades Agricultural Area (EAA) that lies immediately south of Lake Okeechobee and is primarily irrigated farmland, three water conservation areas (WCA) that are located east and south of the EAA made up of isolated wetlands and undeveloped evergreens and pasture, and the everglades located at the southernmost tip of the Florida peninsula (SFWMD 3, 2006). Most of the groundwater observation wells are distributed throughout the urban areas; however there are some clusters of wells in the WCA's. In addition, there are a handful of wells in the EAA and everglades (Figure 2).

The Lower West Coast (LWC) consists of the Caloosahatchee River basin, which has a mix of farmlands and isolated wetlands. There is an urban area that traverses along the west coast from Fort Meyers to Naples. South of Fort Meyers and east of the urban areas there is a mix of farm land, undeveloped pastures and isolated wetlands. The Big

Cypress National Preserve is at the southernmost area of the LWC. This area is primarily cypress forests with small pine hammocks and marshes (SFWMD 4, 2006).

Within southern Florida is a series of canals and levees that have altered the natural conditions of Lake Okeechobee and the everglades, as well as the estuaries where the canals discharge. These alterations have been amplified by environmental impacts due to increased agricultural and urban activities.

There are 2 major aquifers in the SFWMD: the Floridan and Biscayne. The Floridan aquifer is a confined aquifer composed of limestone and is overlain by the Hawthorne confining unit at depths from approximately 50 to 80 feet bgs (SFWMD 1, 2006). The Biscayne aquifer is at the southernmost tip of the Florida peninsula. It is an unconfined shallow aquifer that extends from the water table a few feet deep to as deep as 150 feet bgs and is one of the most productive aquifers in the world (SFWMD 1, 2006).

The surficial aquifer in SFWMD overlays the Hawthorne confining unit, which is generally as deep as 50 feet bgs and can be as deep as 400 feet bgs in the St. Lucie County. The surficial aquifer consists primarily of unconsolidated sand, shelly sand and sand with some layers of clays and silts intermittently dispersed in the aquifer media.

There is an intermediate aquifer in the Southwestern portions of SFWMD in Hillsborough, Polk and Lee counties. This aquifer lies between the surficial and Floridan aquifers and is confined between two clay layers (SFWMD 1, 2006). The aquifer consists primarily of sand, shell and limestone. The lateral flow in this aquifer is generally from Polk County down to the low lining features in the Gulf of Mexico (SFWMD 1, 2006).

3. Observation Well Network

The SFWMD was established in 1972 by the Florida Legislature to manage the state's water resources. SFWMD is one of 5 similar districts in Florida and includes parts or all of 16 counties in the southern most region of the State (SFWMD 1, 2006). The district is divided into 4 planning regions (Figure 2) based on natural watershed boundaries: Kissimmee Basin (KB), Upper East Coast (UEC), Lower East Coast (LEC), and Lower West Coast (LWC).

The SFWMD has operated several hundred groundwater observation wells throughout the district since its conception, and by 2003 most of the wells were instrumented with data loggers that consistently record daily water level measurements. The water level data that was applied in this study was obtained from SFWMD's website using the DBHYDRO application. The water level data is measured in feet and decimal fractions of feet observed at specific times each day at each well. The accuracy of the measurement is 0.01 feet and is based on a measurement below a point referenced to land-surface datum. The measurement point of the land-surface datum is at the top of the well casing measured to the depth of the groundwater table.

Wells within the KB watershed are dispersed throughout the region with wells distributed along the Kissimmee River basin as it travels north to south into Lake Okeechobee. There are also wells distributed amongst the various isolated wetlands within the watershed. As mentioned previously, groundwater levels within Orange, Osceola, Polk and Okeechobee counties typically are from 20 to 150 feet bgs. The deeper levels were not used in this analysis as they would have minimal affect on the seasonal high water table with respect to design and construction at land surface. The wells that were used in the correlation analysis were primarily clustered in the area identified as the Buck Island Ranch which straddles the Harney Pond Canal. This area is primarily irrigated farmland in Highlands County. There are 22 wells in that area with water levels ranging from 21 feet bgs to 29 feet bgs.

The UEC is sparsely populated with observation wells primarily located along the west coast region which is mostly urban. These wells were not used if they showed any impact from pumping or production. There were also wells distributed along the C-44 Channel that travels northeast from Lake Okeechobee and discharges into the South Fork St. Lucie River. These wells are inland and are not influenced by tidal effects and were used in the analysis

The LEC has a series of wells that are distributed along the Caloosahatchee River as it travels from Lake Okeechobee to Lake Hicpochee and then into San Carlos Bay. There are also a series of wells in the isolated wetlands regions southeast of Fort Meyers and a series of wells that are located in Big Cypress National Preserve south of Alligator Alley.

The LWC has wells along the urban regions from Palm Beach all the way to the northern tip of the Florida Keys. There are also well clusters located throughout the Water Conservation Areas (WCA) that are south of the Okeechobee River and are part of the Everglades Restoration project. Clusters of wells are present on the eastern border of the Everglades Agricultural Area (EAA) (SFWMD 4, 2006).

4. Methodology

4.1. SFWMD Observation Well Analysis.

This study included data from 190 active and 132 inactive surficial aquifer observation wells maintained by SFWMD. Selected wells had typical water level depths ranging from 0 to 32 feet below ground surface (bgs). The range of observation periods for the wells was from 1978 to June 2006. VBA computer programs were developed for the analysis to more efficiently sort, collate, analyze and store the enormous amount of data used in this research. The summary and historic water level data for each observation well were obtained online from SFWMD using the DBHYDRO application. The VBA programs were used to sort and organize the relevant information for each well based upon the county in which a well was located and pre-determined ranges of water table depths: 0-6 ft bgs, 6-12 ft bgs, 12-18 ft bgs, 18-23 ft bgs, 23-28 ft bgs, and 28-32 ft bgs. These files (included on the project CD) were used for all additional analysis conducted during the project. The data for each well were sorted in Excel workbooks based upon the following criteria.

Table 1. Data fields used for well classification within reference well database.

Summary Item:	Description
Start Date	First date a groundwater observation is recorded
End Date	Last date a groundwater observation is recorded
# Days in Service	Number of days that the well was operating
# Total Observations	Number of days that an observation was recorded
Min Obs Value	Minimum or highest water level measured at well
Max Obs Value	Maximum or lowest water level measured at well
# Actual Obs (>0)	Number of observations that were recorded to be below ground surface elevation
# Actual Obs (<0)	Number of observations that were recorded to be above the ground surface elevation (ponding conditions)
# Actual Obs (=0)	Number of observation that were recorded to be at ground surface. These observations were discarded.
Frequency (%)	Ratio between the number of days an observation was recorded and the number of days the well was in service (expressed in a percentile)
Latitude	Latitudinal position of the observation well
Longitude	Longitudinal position of the observation well
Actual County	County that the observation well resides within
Soil Data:	***Data observed within a 200 foot buffer around observation well***
Layer Depth Min/Max	Depth of the layer observed in SSURGO data base. Up to 3 layers were documented for each well.
AASHTO	AASHTO classification of soil
Hydro Grp	Hydro Group classification of soil
Hydric	Hydric soil – Yes/No
Drainage	Drainage characteristics of soil
Order	Order classification of soil
Subgroup	Subgroup classification of soil
Texture	Soil texture
Comp %	Percent of the soil that is classified as the soil type defined in the layer being described.

The sorted files also include hydrograph plots for each well so that water level trends can be compared, and the continuity of each time series can be considered. Figure 4 illustrates a sample hydrograph for Observation Well OH537 located in Broward County. The soil data documented in the summary table is based on a 200 foot buffer centered on each well. The buffer that was created using Soil Survey Geographic (SSURGO) database within a GIS (Geographic Information System). Compilation and sorting of the soil data as well as the formatting of the reference well database files is automated by the VBA programs generated for this project. At the time of this study, not all counties had soil survey data sets that were available as GIS files. The Natural Resources Conservation Service (NRCS) was in the process of posting the data files, when the soil databases are available the data can be readily incorporated to the well summary files and utilized in future analyses.

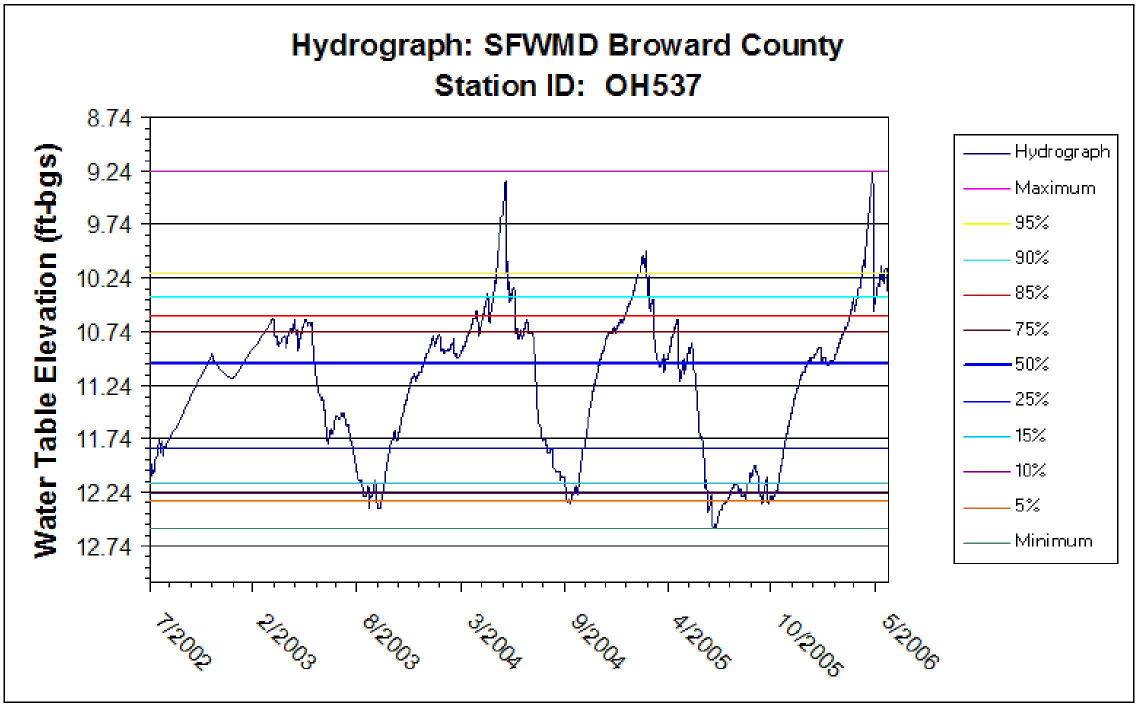


Figure 3. Hydrograph of historical groundwater levels at Station OH537 in Broward County.

4.2. Exceedance Probability Analysis

Exceedance probabilities were calculated for each well to determine the high, median and low water table levels from the historic period of record. The exceedance probability is a sample statistic that is calculated by sorting the observation data in ascending order (in this case the calculation is based upon water level depth below ground surface). The sorted values are then ranked and the probability of exceedance is calculated using the following equation:

$$\text{exceedance probability} = \left(\frac{\text{rank } i}{n+1}\right) \times 100\% \qquad \textbf{(5)}$$

Where:
Rank i = rank of the i^{th} observation from 1 to n
n = total number of observations

Using the same criteria as outlined by Frimpter (1981) and Socolow et al. (1994), the high water level (Wh) was selected as the water level with a 5% probability of being exceeded or equaled which also means that there is a 95% probability that the water level will not be exceeded. And similarly, the median (Wm) and low (Wl) water levels are selected as the 50% and 95% exceedance probability values, respectively. It should be noted that selection of the high, mean, and low water levels based upon the exceedance probability values of 5%, 50%, and 95% was done in an effort to remain consistent with the values that were used in the Frimpter (1981) and Socolow et al. (1994) studies.

Once established, the Wh, Wm, and Wl values are used with Equations 2 through 4 to estimate the high, median, and low water levels at a site of interest. Figure 4 provides an example of how the high, median and low water levels were determined at Station OH537 in Broward County. A primary difference between previous studies (Frimpter (1981) and Socolow et al., 1994) and this work is that previously only one reference (or observation) well was selected to manually estimate the water levels at a site of interest. The reference well application developed for this project considers all similar wells and provides a range of probable high water levels for a site of interest. VBA programs were developed which automate the reference well analysis. The process includes the creation of summary files for each reference well which includes the data fields outlined in Table 1 as well as the observed maximum and average annual water level range for each reference well. The summary sheet includes exceedance probability curves as illustrated in Figure 4, and a period of record data summary which outlines the available water level data for each of the wells that are similar to the site of interest (Table 2 provides an example of the period of record data summary).

Table 2. Period of record data summary.

				Water Table Elevation Range (feet)			Measured Water Table Elevation (feet bgs)	
Station ID	Period of Record	Latitude	Longitude	Max Range	Year	Avg Range	Lowest Observation	Highest Observation
P0804	1978 to 2003	25.4836	-80.1536	14.94	1985	8.99	6.75	-14.01
P0803	1978 to 2003	25.3234	-80.3009	8.63	1981	4.51	9.80	0.46
P0789	1978 to 2003	25.2736	-80.2212	5.12	1981	3.24	6.23	0.17
P0922	1984 to 2003	25.2621	-80.3424	3.98	2001	2.84	6.15	1.59
15929	1994 to 2006	25.2621	-80.3424	3.98	2001	3.08	6.20	1.78
P0921	1978 to 2003	25.4760	-80.1124	6.48	2000	3.61	8.00	1.10
P0919	1978 to 2003	25.4200	-80.1536	6.68	2000	2.71	8.62	1.30
P0788	1978 to 2003	25.4312	-80.1348	6.63	2000	3.35	8.16	1.07
7103	1985 to 2006	25.3721	-80.3230	4.40	2001	3.12	8.20	2.04
5508	1984 to 1992	25.3721	-80.3230	4.51	1990	-6.30	7.43	0.00

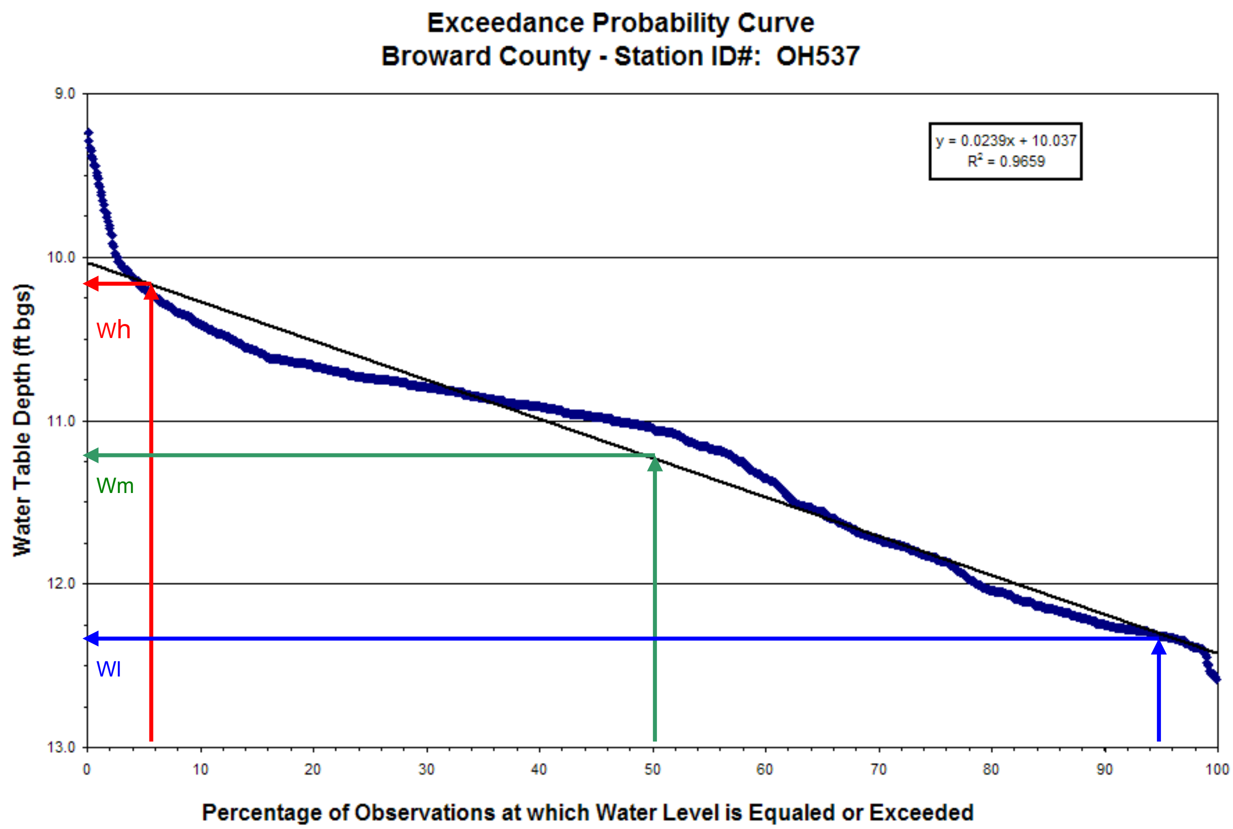


Figure 4. Exceedance probability curve illustrating the high, median, and low water levels for station OH537 in Broward County.

4.3. Well Pair Correlations.

Correlation is a statistical method that is used to evaluate the relationship between to variables x and y, more specifically correlation measures the strength and direction linear relationship between x and y (Ott and Longnecker, 2004). In this study, the water levels at two observation wells were correlated where $\bar{x}$ and $\bar{y}$ are the sample means of the observation values for each of the wells and it is assumed that a linear relationship exists between water levels within the wells (Figure 5). VBA programs within Excel were used to calculate the correlation coefficient (R) for each possible well pair using Equation 6.

$$R = Correl(X,Y) = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}} \qquad \textbf{(6)}$$

The correlation coefficients (R) were then used to calculate the coefficient of determination (R^2) using Equation 7 which provides an indication of the goodness of fit of a linear trend line to the data. The closer the R^2 value is to 1, the more accurately the liner regression model will predict variable Y based upon observed values of X. In this case, the intent was to evaluate the strength of linear correlation between wells, and determine how accurately observed water levels from one well can be used to predict levels in another. As noted by Frimpter (1981), it was typically found that wells in similar soils had higher correlations than those in dissimilar soils. The Reference Well database was created by selecting all well pairs exhibiting at least a moderate correlation ($R^2 \geq 0.50$) (Ott et al. 2004). For testing and validation purposes, the well pairs were designated as being either moderately ($0.8 > R^2 > 0.5$) or strongly ($R^2 > 0.8$) correlated.

$$R^2 = \left[Correl(X,Y)\right]^2 \quad \textbf{(7)}$$

Well pair correlations were first conducted for all wells within the same water level ranges (i.e. all wells with water levels in the 0-6 feet bgs were compared first). Then, wells of sequential water level ranges were compared, for example, all wells with water levels within the 6-12 feet bgs were compared to wells with water levels within the 0-6 feet bgs and 12-18 feet bgs. It should be noted that only water level observations that occurred on the same day were used in the well pair correlation analysis, which is a distinction from Frimpter's and Socolow's studies where observations occurring up to 15 days apart were used to represent values occurring approximately at the same time.

Once selection of reference well was complete, the maximum annual range of water level fluctuation for each of the selected wells was used in the development of an exceedance probability curve to estimate the quantites of the distribution of the maximum annual ranges for each group of wells showing at least moderate correlation. The exceedance probability curves provide the data required to generate *Sr* values which are applied in Equations 1 through 4. This technique provides the user with the ability to choose a desired probability of occurrence or 'risk' that the maximum water level range would be equaled or exceeded based on the scope and intent of the project. In this study, to be consistent with the methods of Frimpter (1981) and Socolow et al. (1994), the Sr value is assigned based upon the median of the maximum annual water level range (the procedure is outlined on page 26 of Appendix A).

Once the correlation analysis had been completed for all wells, the wells were grouped based upon well pair correlation strength. As one might expect, there were visible spatial patterns (grouping) based upon the strength of correlation between reference wells. It was determined that there were five distinct regions or zones exhibiting moderate to strong correlation and these zones were consistent with the four natural watersheds within the SFWMD drainage basin. The LEC basin was further divided into two zones (northern – LEC_N, southern – LEC_S). Although, it is one drainage basin, the northern portion of the basin has lower water table elevations (in general), and the southern zone is consistent with the Biscayne surficial aquifer. Next, an exceedance probability curve was generated for each of the zones, which can be used to determine the *Sr* value and then used to estimate high water levels at sites of interest within the zone. This is based on the assumption that all wells residing within a particular zone will have similar ground water responses, or more specifically, the ground water levels will be linearly related (The procedure is outlined in Appendix A).

VBA programs were developed to automate the correlation analysis, and the results are organized in Excel workbooks (included in Project CD) that contain a worksheet for each well pair along with a correlation matrix that provides a tabulated summary of all of the correlation coefficients (R) and R^2 values. Observations from each well that were recorded on the same date are listed in chronological order and the data summary includes the period of record start and end dates, the number of shared observations, number of years observed, and the minimum and maximum observations for each well. The data also include the high, median and low observed water level depths along with the *Sr* value determined by using the corresponding exceedance probability curve related to the appropriate zone that the site of interest resides in. The annual maximum range for each well is calculated and tabulated in the summary data. If a well pair showed at least a moderate correlation ($R^2 \geq 0.50$), a scatter plot (Figure 5) including the best-fit linear regression line was created which provides the equation of the regression line and the corresponding R^2 value.

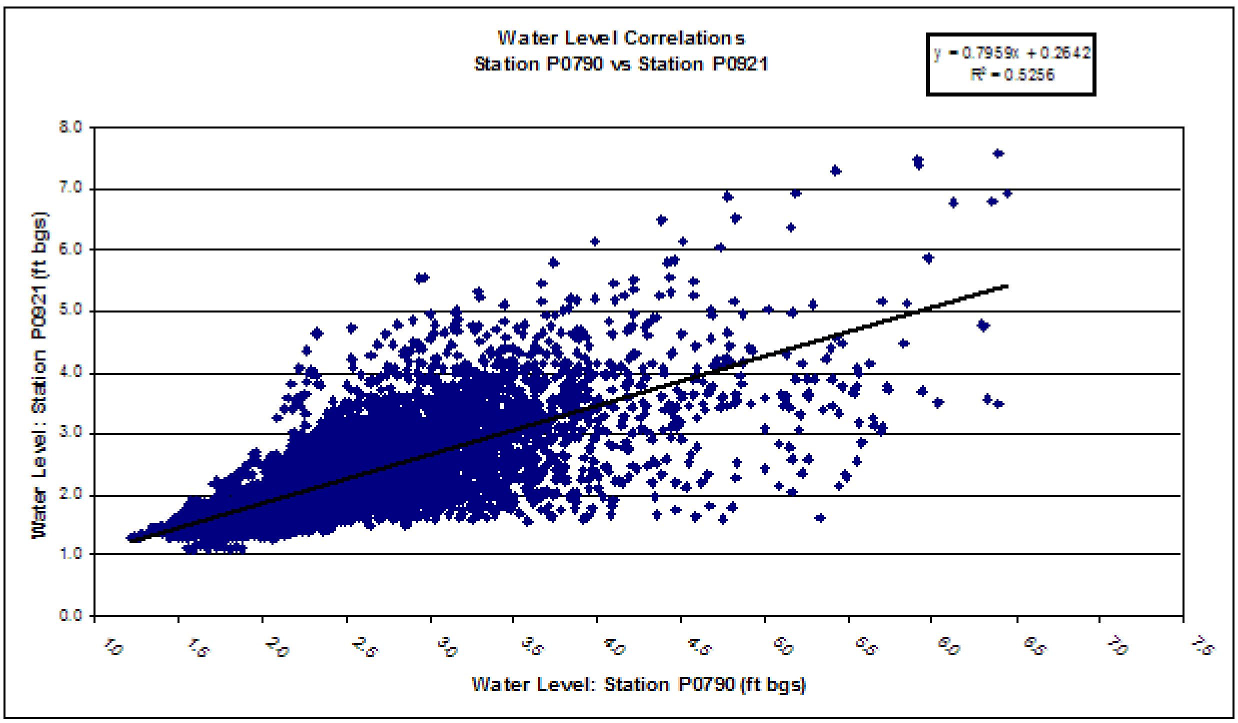


Figure 5. Scatter plot of water levels from stations P0790 and P0921 including a linear regression line and the corresponding equation for the line.

5. Results

The application discussed in this report was developed by first selecting reference wells that demonstrate at least moderate positive correlations ($R^2 \geq 0.50$). Second, the reference wells and all related data regarding those wells were transferred to data files created for each of the five zones defined within the SFWMD region. Finally, a VBA program was developed that uses the data in the reference well files to predict water levels at a site of interest based on the zone the SOI resides in, distance between the reference well and SOI, and the similarity of the water table depths.

5.1. Reference Well Selection.

There were 322 observation wells maintained by SFWMD that were analyzed in this study and considered for selection based upon their data consistency and dependability as well as the length of observation history (must exceed two consecutive years for new wells and five years for wells that are now inactive). Only active wells were selected for the reference well database; however, inactive wells with sufficient historical data were used in the correlation analysis in order to provide additional data to test the accuracy of the SHGWT application. It should be noted that reference well selection was an extremely time consuming process, as 23,149 well pair correlations were analyzed using the 322 wells. The correlations were derived using only observations from each well that occurred on the same day and only between wells with similar water table elevation ranges. For example, wells with water table levels within 0 to 6 feet bgs were not correlated to wells with water table depths greater than 12 feet bgs. Table 3 illustrates which groups of wells were correlated to one another.

Table 3. Well pair correlation depths.

Depths of Wells Being Correlated	Well Pair Depth	Well Pair Depth	Well Pair Depth
0 to 6 ft bgs	0 to 6 ft bgs	6 to 12 ft bgs	
6 to 12 ft bgs	6 to 12 ft bgs	0 to 6 ft bgs	12 to 18 ft bgs
12 to 18 ft bgs	12 to 18 ft bgs	6 to 12 ft bgs	18 to 23 ft bgs
18 to 23 ft bgs	18 to 23 ft bgs	12 to 18 ft bgs	23 to 28 ft bgs
23 to 28 ft bgs	23 to 28 ft bgs	18 to 23 ft bgs	28 to 32 ft bgs
28 to 32 ft bgs	28 to 32 ft bgs	23 to 28 ft bgs	

Of the over 23,000 correlated well pairs approximately 25 percent of the pairs did not share common dates of observations, so there was no correlated relationship that could be determined between those wells. This occurred when inactive wells were paired with more recently installed wells.

From the 322 wells analyzed, 116 wells were chosen for additional analysis to determine if they could be used as reference wells for estimating water table levels at other sites. All of the selected wells demonstrated a moderate correlation to at least one other reference well. These wells were selected based upon the assumption that wells that demonstrate positive correlations or linear relationships between other observation wells with similar characteristics will also demonstrate positive correlations with a site of interest that has similar characteristics (Frimpter, 1981 and Socolow et al., 1994)

The Frimpter (1981) and Socolow et al. (1994) studies selected their reference wells by first categorizing all wells based on soil and topographic characteristics. For the work presented in this report, there were no predefined characteristics used to sort or categorize the wells prior to correlation. Instead, a blind correlation was applied to all candidate wells without any preconceived assumptions regarding which wells should be most similar. This allows for the most similar wells to be identified based upon linear regression, and then the factors contributing to their similarity can be considered.

5.2. Reference Well Database.

This study revealed that there were clusters of wells with positive correlations and each of these clusters lied within one of the four natural sub-drainage basins of the SFWMD region. Considering the spatial distribution of the well clusters, five zones were identified as regions that shared similar characteristics which would result in a linear relationship between the water table levels of all the wells residing within those zones. The zones consist of the four sub-watersheds of the SFWMD region (LEC, UEC, LWC, and Kissimmee basins) with the LEC sub-basin being divided into two zones, northern and southern. Individual reference database files were generated for each zone using a VBA program. Each of the database files contains the exceedance probability worksheets for the selected reference wells per zone along with seven additional worksheets which includes the following information:

- summary data for each well;
- a list of all of the well pairs associated with the selected reference wells;
- a histogram illustrating the frequency of the annual high and low water levels by month;
- each zones water level range exceedance probability curve that is used to derive the S_r value for that particular zone;
- the frequency distribution of groundwater levels for each reference well; and
- a summary of the mean and median water level values for each well.

Zone LEC-North has 22 reference wells with 7 pairs of wells residing at the same spatial location but installed at a different strata, leaving 15 unique well locations. All of the wells reside in either Broward or Palm Beach counties. The lowest water levels occur most frequently in October and the highest in May, June and March. Water table depths range from 8.01 feet bgs (Wells F9552/F9553) to 16.21 bgs (Well FF848) and the average maximum annual water level range or fluctuation is 4.05 feet with a minimum range of 2.04 feet at Well S8546 and a maximum range of 6.43 feet at Well F9553. Well J8199 has been active since 1981 with all of the other selected wells installed after 1997.

Figure 6 illustrates the water level range exceedance probability curve for zone LEC-N. This figure graphically demonstrates how the Sr value is selected based upon a desired level of risk. For example, figure 6 demonstrates that a *Sr* value of 4.01 feet represents the maximum annual water level range (or annual fluctuation) that is equaled or exceeded only 50% of the time in zone LEC-N. In more general terms, the smaller the percentage of probability selected (corresponding to a larger maximum annual range), the smaller the probability of exceeding the resulting estimated water level at the site of interest (Socolow et al., 1994). Consequently, using a 5% exceedance probability value would result in a higher estimate (or a greater range of predicted water level fluctuations). This provides a more conservative estimate—resulting in a higher estimated water level—but, there is less chance of the estimated water level being exceeded.

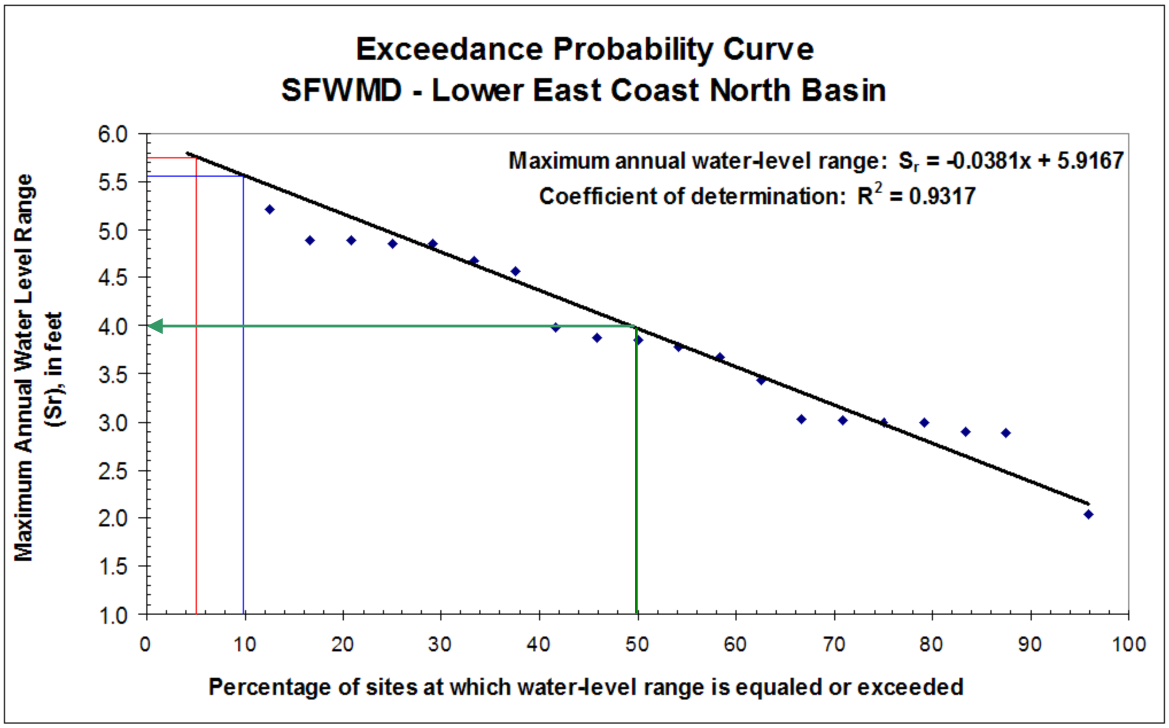


Figure 6. Water level range exceedance probability curve for zone LEC-N.

Zone LEC-South has 29 reference wells with 8 pairs of those wells residing at the same spatial location but installed at a different strata, leaving 17 unique well locations all in Miami-Dade county. The lowest water levels occur most frequently in September and October in this zone while the highest water levels most frequently occur in May. The range of water table depths are from 4.94 feet bgs (Well OU427) to 11.28 feet bgs (Well M6884) and the average maximum annual water level range or fluctuation is 3.34 feet with a minimum range of 1.57 feet at Well TA916 and a maximum range of 13.69 feet at Well OU427. Wells 7103, 15929, 15930, and 15933 were all installed in the mid 1980's while all of the remaining selected wells in the zone were installed after 1996 with most of those wells installed after 2000. The maximum annual water level range exceedance probability curve for reference wells in zone LEC-S is illustrated in Figure 7. As discussed previously (see discussion of figure 6), the *Sr* value of 2.97 feet represents the maximum annual water level range that has been observed to be equaled or exceeded 50% of the time in zone LEC-S.

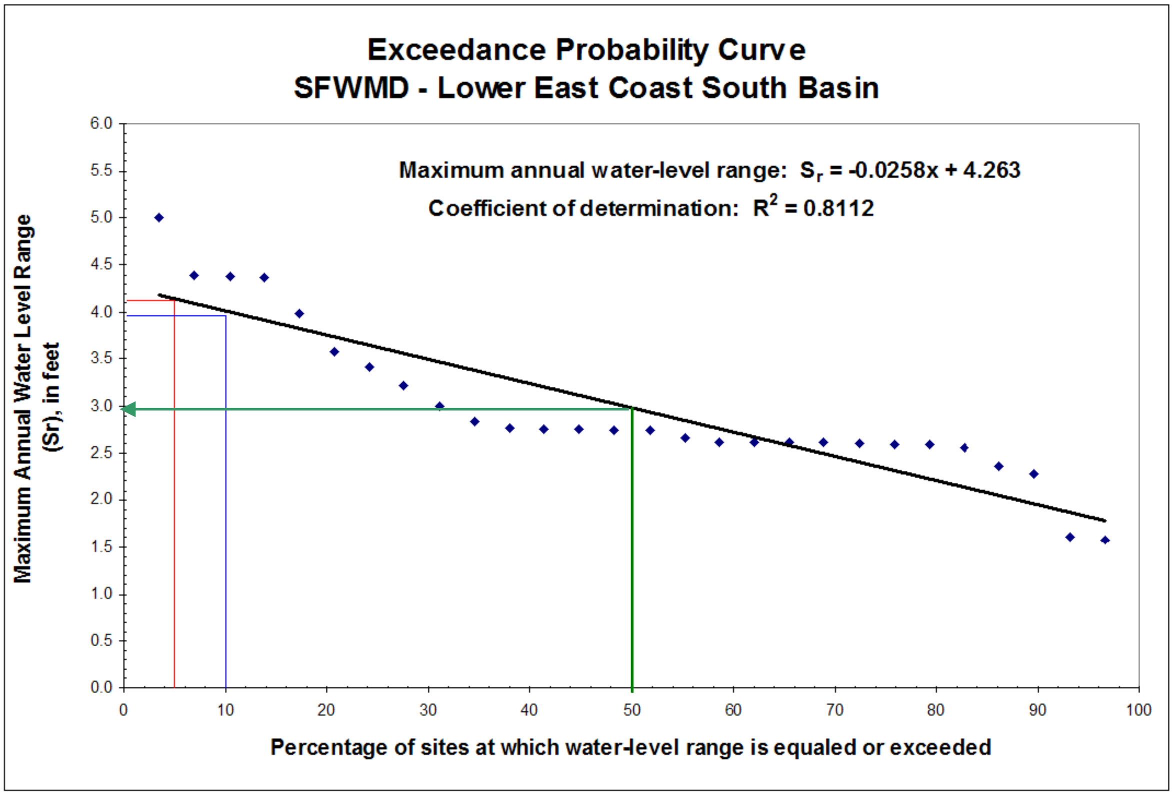


Figure 7. Water level range exceedance probability curve for zone LEC-S.

Zone UEC has 7 reference wells all at unique locations residing within either Martin or St. Lucie counties. The lowest water levels occur most frequently in October and the highest water levels most frequently occur in May. The water table depths of the reference wells in this zone range from 5.00 feet bgs (Well FF824) to 16.38 feet bgs (Well F1263). The average maximum annual water level range is 5.96 feet with a minimum range of 4.70 feet at Well HA462 and a maximum range of 8.02 feet at Well F1275. All of the wells were installed in 1987. The corresponding maximum annual water level range exceedance probability curve for this zone is illustrated in Figure 8. As discussed previously (see discussion of figure 6), the *Sr* value of 5.79 feet represents the water level range or fluctuation that is equaled or exceeded 50% of the time.

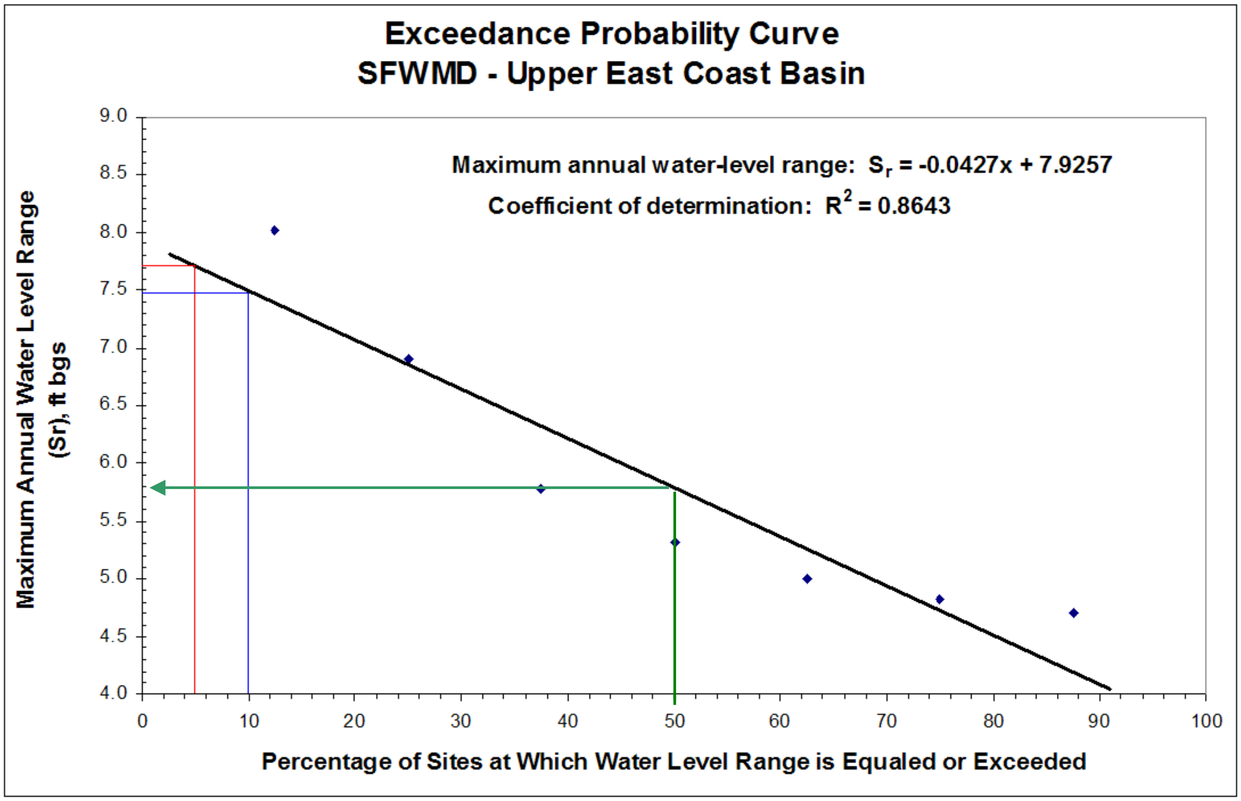


Figure 8. Water level range exceedance probability curve for zone UEC.

Zone LWC has 34 reference wells with 1 pair residing at the same spatial location but installed at a different strata, which leaves 33 unique well locations. Wells in zone UEC all reside in either Collier, Lee, Hendry or Glades counties. The lowest water levels in this zone occur most frequently in September and the highest water levels occur most frequently in May and June. Water table depths range from 0.75 feet bgs (Wells L7551) to 31.16 feet bgs (Well L7525) and the average water level range or fluctuation is 6.56 feet. A minimum water level annual range of 2.97 feet occurred at Well L7446 and a maximum range of 20.83 feet at Well L7551. All of the reference wells in this zone were installed after 1997 with most of the wells installed before 2000. The annual water level exceedance probability curve (Figure 9) for zone LWC indicates that a *Sr* value of 6.13 feet represents the maximum annual water level range that is equaled or exceeded 50% of the time.

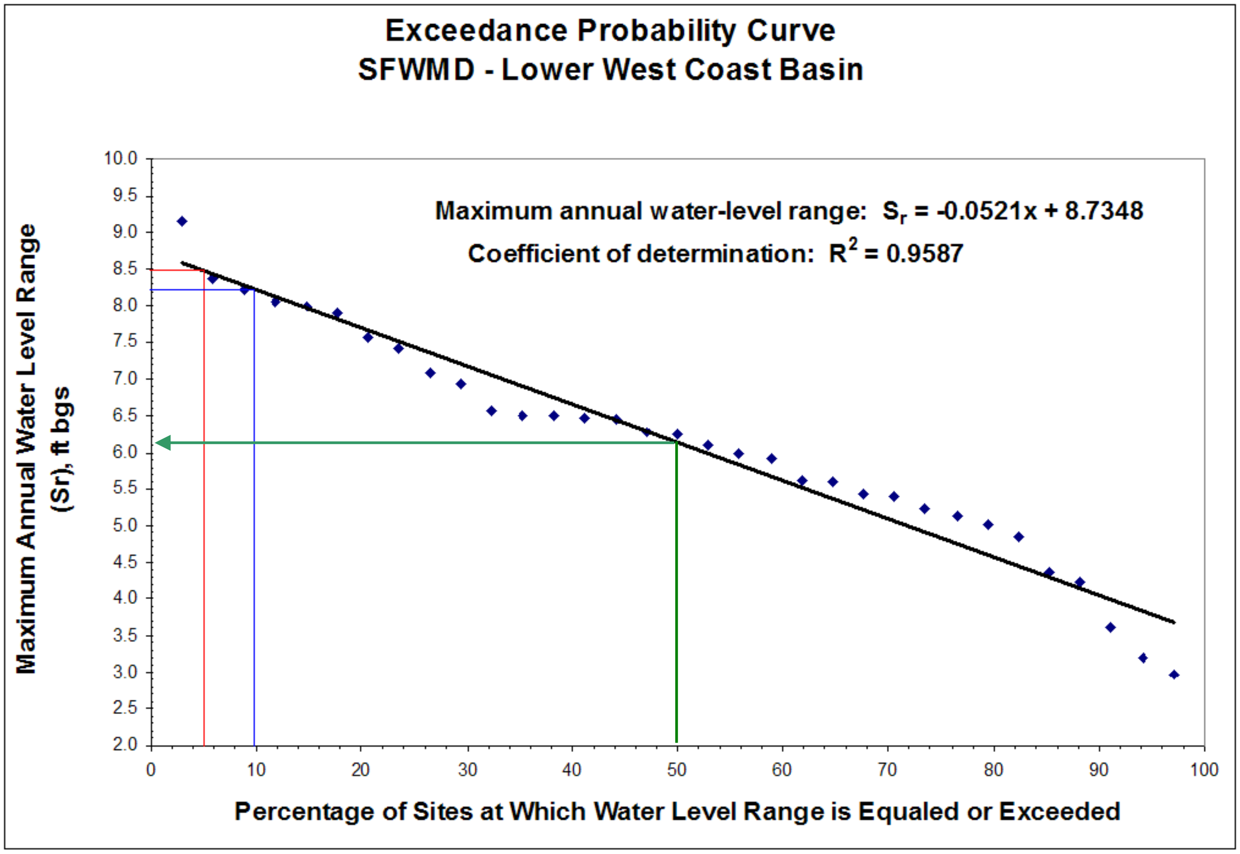


Figure 9. Water level range exceedance probability curve for zone LWC.

Zone Kissimmee has 23 reference wells all located at unique locations with 22 wells in Highland County and 1 well in Okeechobee County. The lowest water levels occur most frequently in September and the highest in May. Water table depths range from 20.12 feet bgs (Well 15581) to 28.80 bgs (Well M6518) and the average maximum annual water level range or fluctuation is 5.50 feet with a minimum range of 4.35 feet at Well M6536 and a maximum range of 6.91 feet at Well M6516. Well 15581 has been active since 1992; however all of the other reference wells in the Kissimmee zone were installed in 2000. Figure 10 illustrates the water level range exceedance probability curve for the Kissimmee zone with a *Sr* value of 5.47 feet representing the maximum annual water level range that is equaled or exceeded 50% of the time.

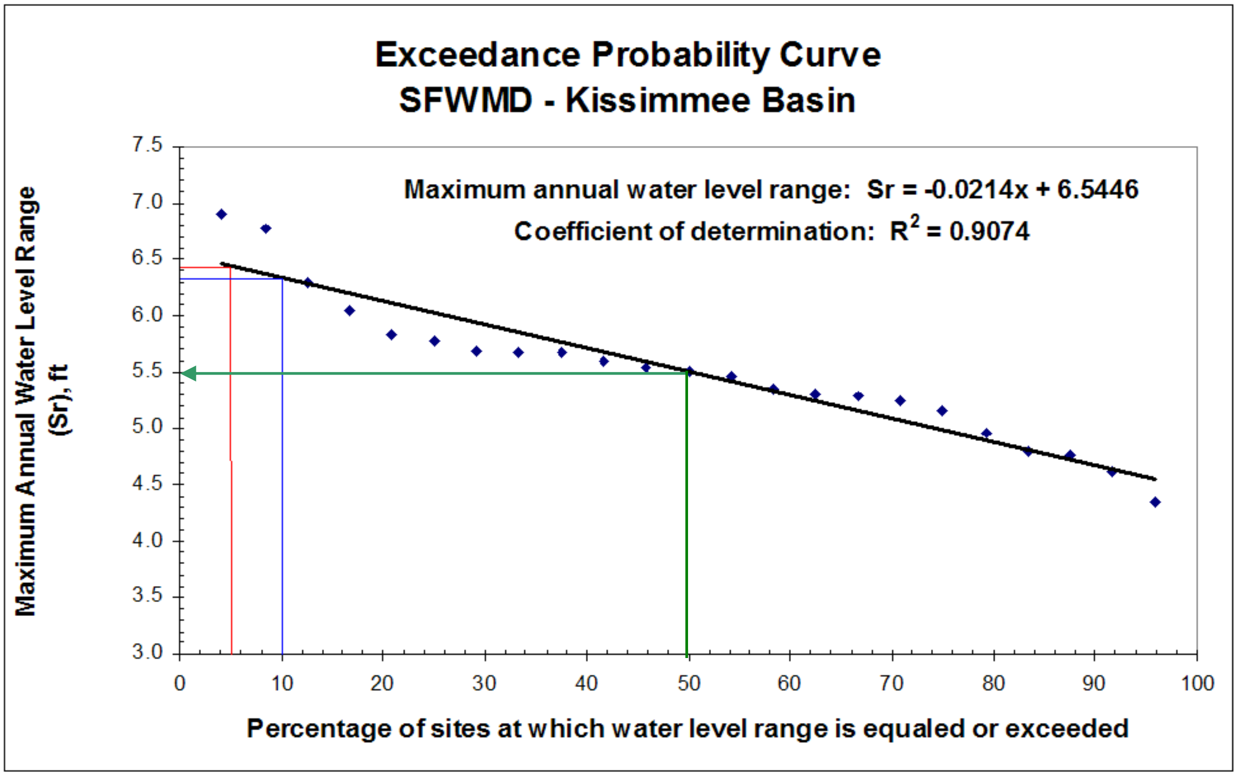


Figure 10. Water level range exceedance probability curve for zone Kissimmee.

5.3. Water Table Depth Application.

To use the water table depth estimating tool developed in this study, the user only needs Microsoft Excel, the Excel program file that contains the VBA macro used to run the program, and the five reference well database files that were discussed in the previous section. The user has the flexibility to dictate where the program file, database files and the output files are stored on their personal computers by defining the corresponding path for these files in the 'Reference Data' worksheet which is one of five worksheets that make up the program file (Figure 11, and Appendix A).

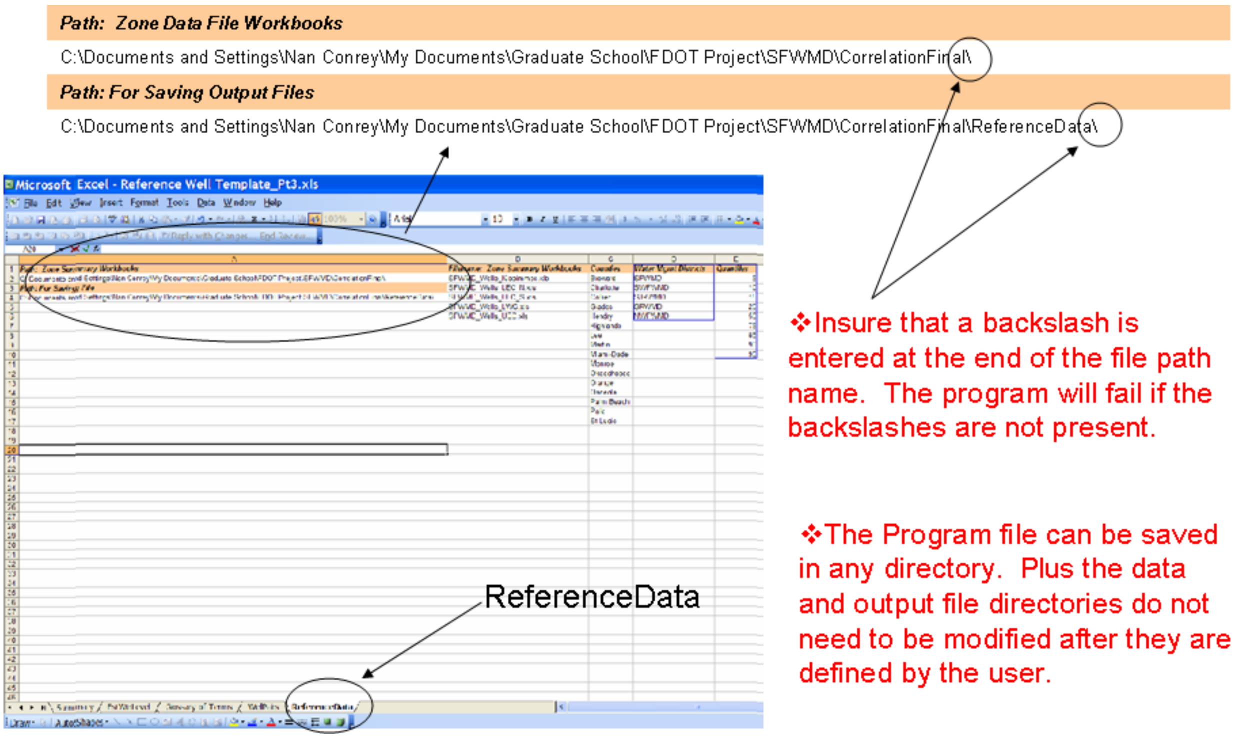


Figure 11. Instruction in defining pathways to store and retrieve Excel files required to run VBA application.

The input data is entered in the 'Summary' worksheet. The required input data includes the following:

- site of Interest ID or Name;
- latitude and longitude of the site of interest;
- water management district and county in which the site of interest is located;
- measured water table depth (in feet bgs) at the site of interest as well as the date the observation was recorded;
- output file name (defined by user);
- exceedance probability value (expressed as a percentage) used to define the corresponding Sr value – remember that the lower the exceedance probability value the greater the range of estimated values;
- a specified maximum number of days that can occur between the date in which the water level was measured at the site of interest and the observation at the reference well; and
- the number of wells to be included in the output graphs.

The program first determines which zone the site of interest is located within and then accesses the corresponding reference well database file to perform analysis. The summary data for each reference well in the zone is copied to the 'Summary' worksheet and sorted by the well name. Each of the reference well exceedance probability worksheets is also copied to the output file along with the well pair data that is copied to the 'WellPairs' worksheet. Next the program estimates the high, low and median water levels for the site of interest using each of the reference wells that have observations on the same day that the observation was taken at the site of interest. This data is tabulated in the 'EstWtrLevel' worksheet and sorted in ascending order based on the distance between the reference wells and the site of interest. An exceedance probability distribution curve of the estimated water levels is created using each of the reference wells to calculate the corresponding water table depths, see Figure 12 and Appendix A.

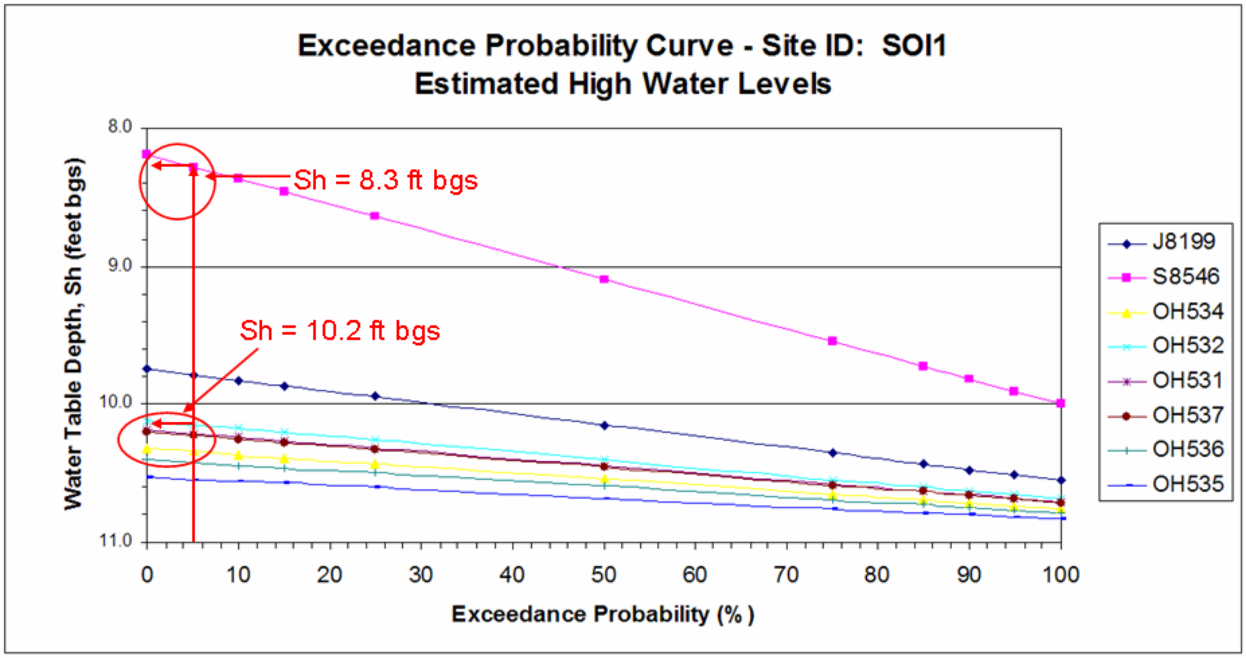


Figure 12. Exceedance probability distribution curve providing output data for test site SOI1.

The data is then used with an 'Observation Comparison' chart that graphs the high, low, and median water levels for each of the reference wells along with the water levels measured at both the reference well and the site of interest. This chart is used to illustrate the relationship between the water levels at the reference wells and the site of interest. For example, Figure 13 is the 'Observation Comparison' chart for the same site of interest and observation value used to create Figure 12 above. It is clear that wells OH534, OH532, OH531, OH537, OH536, and OH535 are more closely related based on water table depths than wells J8199 and S8546. In this example, using well J8199 as the reference well would result in an estimated high water table level that is over 2.0 feet greater than if wells that had more similar water table depths were used even though well J8199 is closer to the site of interest. It is reasonable to conclude that the reference wells with more similar water table depths would provide a more accurate estimate. The chart in Figure 13 can also be used to predict if the reference well water levels reflect a dry or wet period by comparing the observation value to the mean observation value of each reference well. To provide the most accurate prediction of estimated SHGWT levels, the reference well used to predict those levels should have similar conditions. More specifically, if the SOI is in a region that is in a wet period, then the reference well observation should be above its median water level indicating it too is in a wet period.

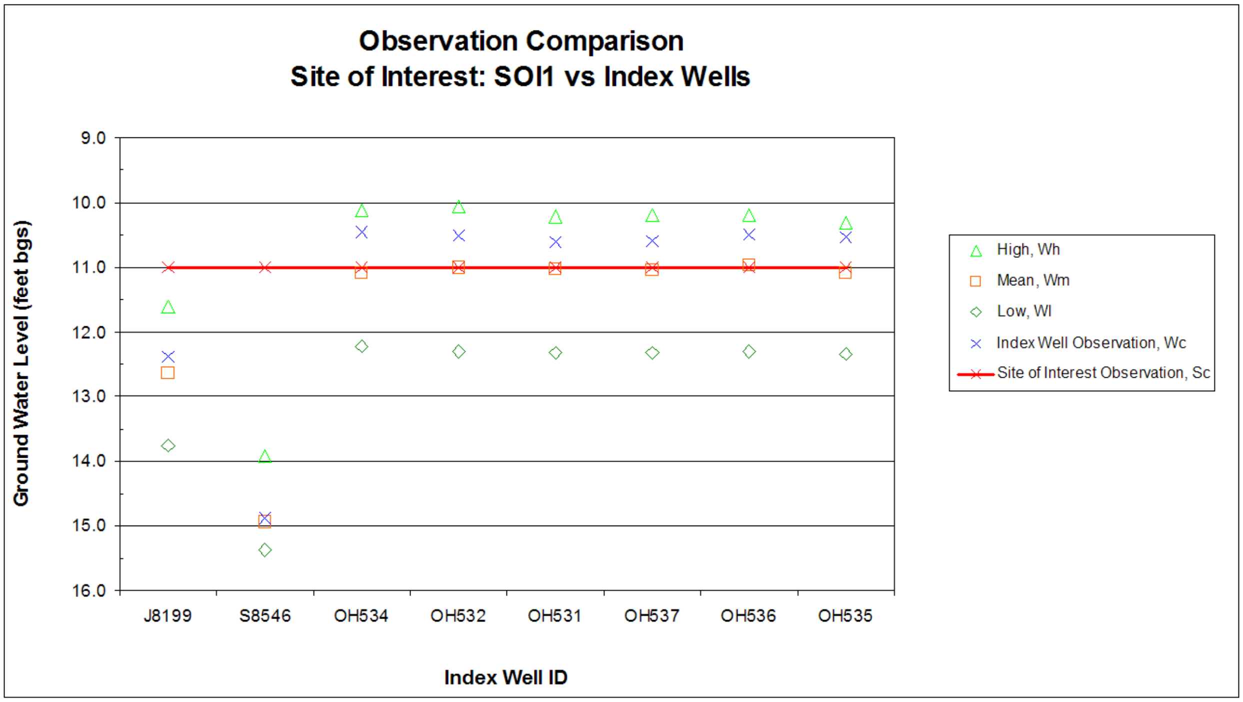


Figure 13. Observation comparison data – site of interest vs. reference wells – output data for test site SOI1.

This program provides the end user with the flexibility to compare the characteristics of all of the reference wells within a particular zone to the characteristics of the site of interest. The user can then determine which reference well or wells would provide the most accurate prediction based on the needs of the particular project. Currently, the factors being examined are the characteristics of the drainage basin or zone, distance between the reference well and site of interest, and the relationship between water table depths of the different wells. Additional characteristics, such as soil type or site vegetation, can also be considered to evaluate the similarities in water levels between reference wells and a site of interest.

5.4. Application Testing and Validation.

To test the methodology applied in the application, well pairs were selected based on the following factors: at least one of the wells was included in the reference well database, which means that there is at least a moderate correlation ($R^2 \geq 0.50$), and at least 2 years of daily observation data (wells with longer periods of record were included in the reference well database, but 2 years of daily data was sufficient for testing and validation purposes). For testing and validation 120 well pairs in the LEC basin were considered, these included active as well as inactive wells. Hydrographs representing the water table elevations for the reference well, the Test Well, and the estimated elevation values were created to illustrate the results. The estimated value hydrographs were developed as a time series of multiple runs using the SHGWT application. (In other words the application was used to generate estimates over a time frame matching the period of record of the reference well).

In examining the results, there were some trends that emerged and were worth noting. For example, Figure 14 below illustrates the hydrographs of two strongly correlated wells ($R^2 = 0.989$) and the resulting estimated high water table elevation determined using the USGS method. In this case the wells are less than ¼ mile apart and therefore most likely experience similar weather patterns and may likely have the similar soil types. The chart demonstrates that a fairly consistent high water (SHGWT) estimate is provided no matter when the observations are recorded at the test well (simulated site of interest) resulting in a reliable estimate of the SHGWT level (within 0.5 ft) over the five-year period of record.

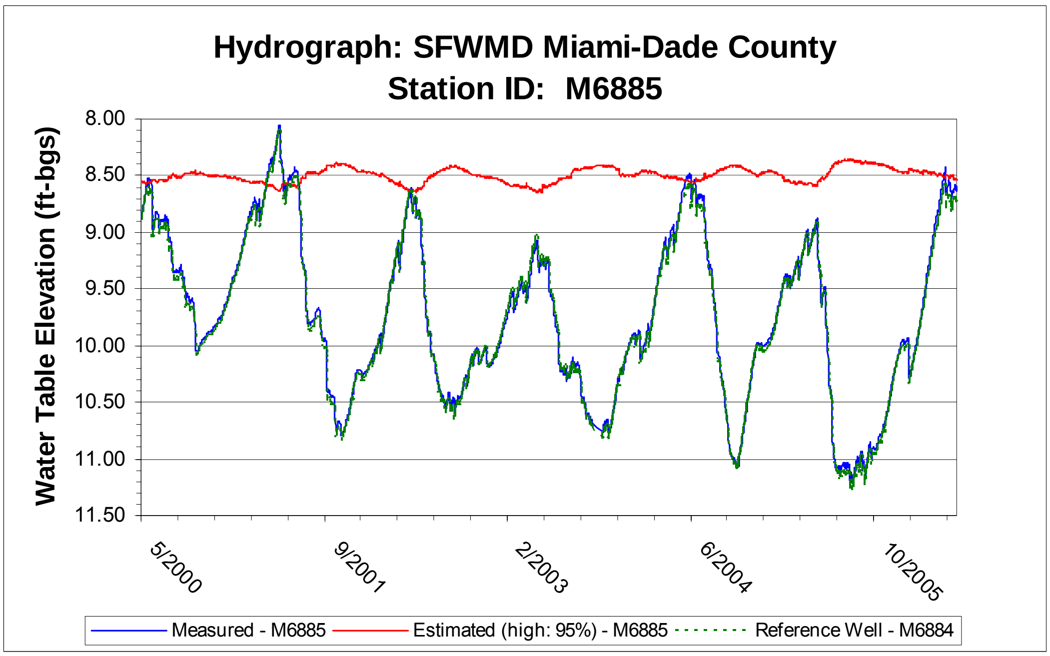


Figure 14. Results using reference well M6884 to estimate water table levels at Well M6885. Demonstrates ability of SHGWT application to predict high water levels between wells that are strongly correlated and close in proximity (quarter mile apart).

Figures 15 and 16 illustrate wells that are strongly correlated ($R^2 = 0.96$), however there is some variation in the high water estimate due to the difference in elevations and the regions where the reference well and sit of interest hydrograph patterns diverge. These wells are approximately 1.5 miles apart; however, the hydrograph patterns are very similar. The wells are most likely affected by similar weather patterns and most likely have similar soil types. Even though the wells are strongly correlated, the high groundwater estimates range from ~11.6 feet bgs to ~10.8 feet bgs depending on the date the observations are measured. But, these wells still provide fairly good estimates of the high groundwater tables (within 0.8 ft for both cases).

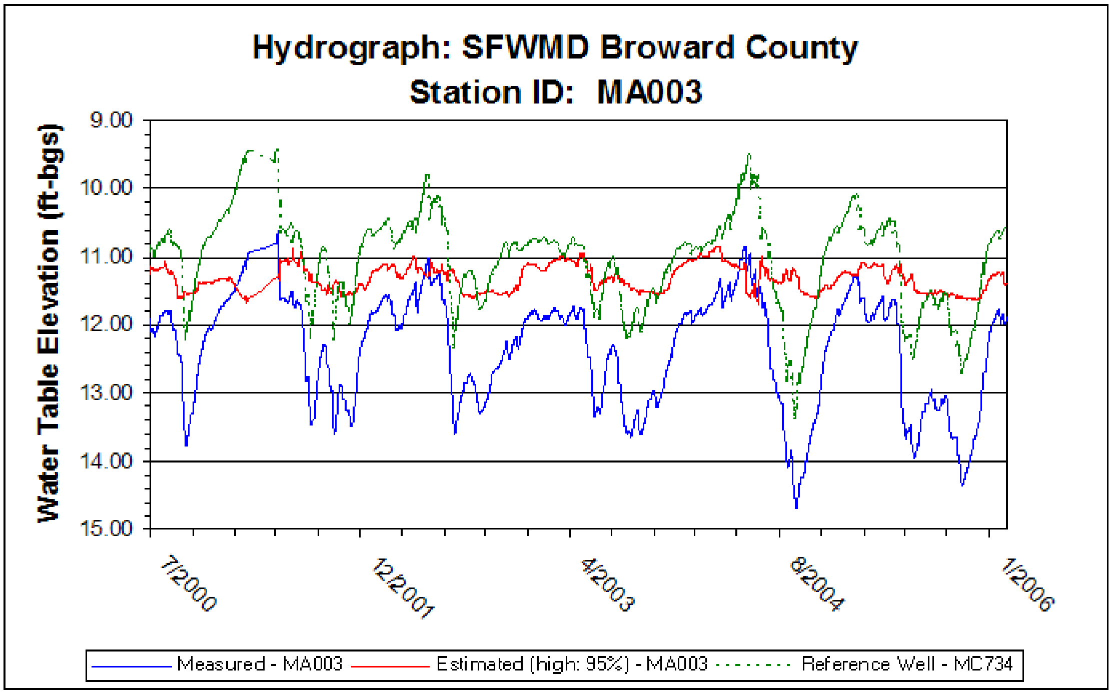


Figure 15. Results using reference well MA003 to estimate water table levels at Well MC734. Demonstrates wells that are strongly correlated within proximity of 1.5 miles.

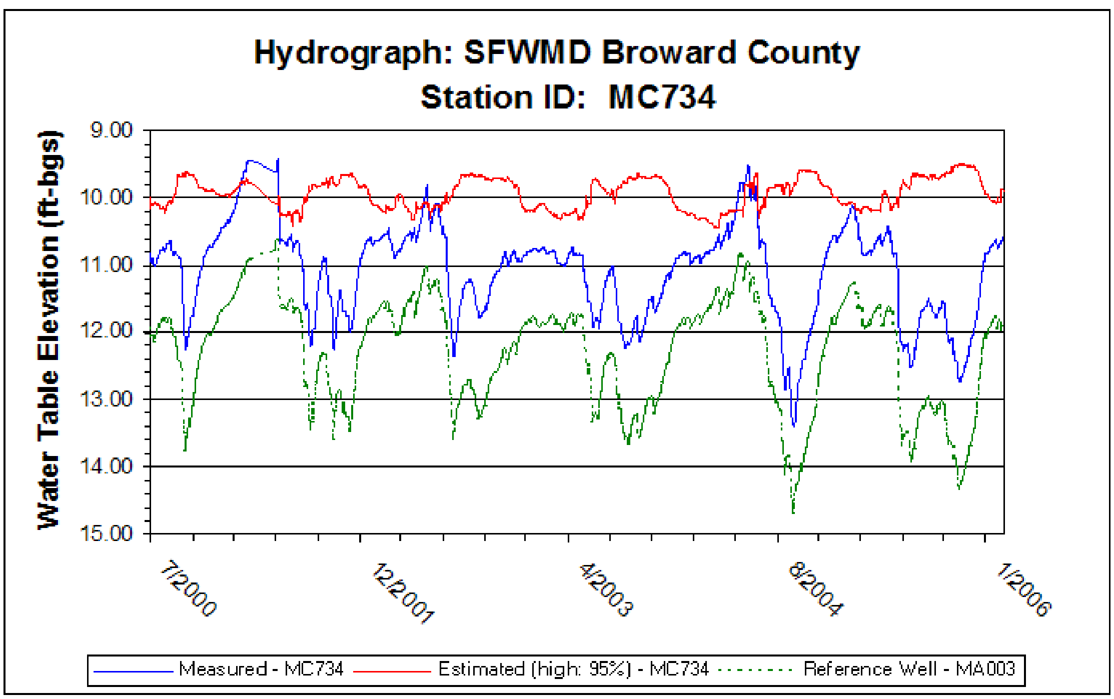


Figure 16. Results using reference well MC734 to estimate water table levels at Well MA003. Demonstrates wells that are strongly correlated within proximity of 1.5 miles.

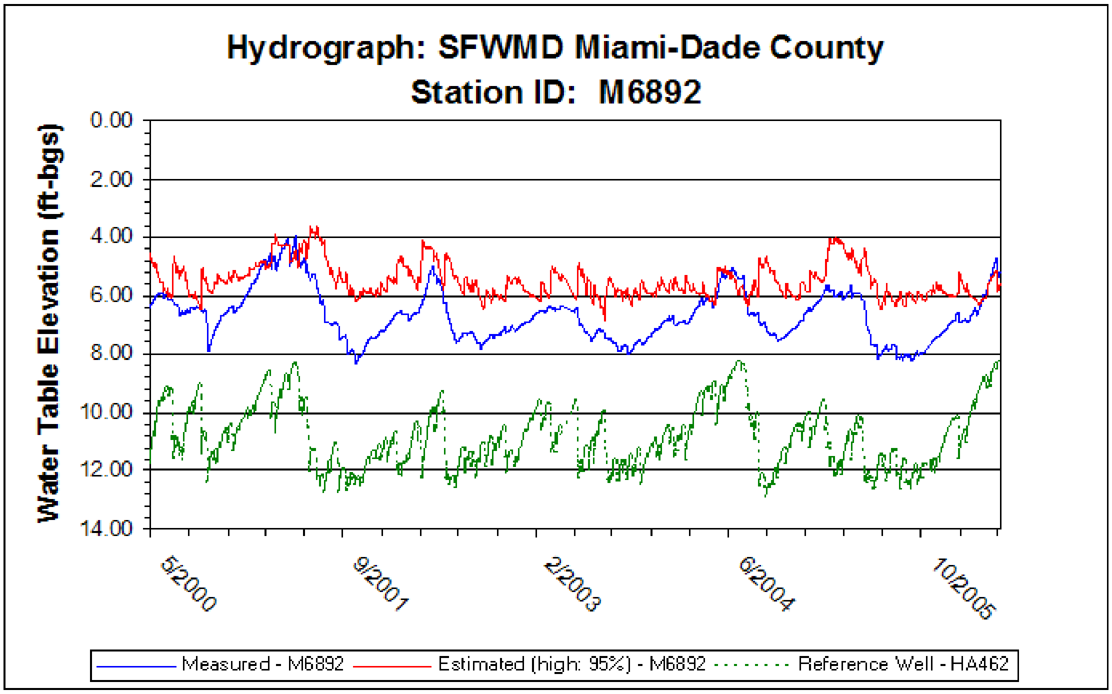


Figure 17. Results using reference well HA462 to estimate water table levels at Well M6892. Demonstrates wells that are moderately correlated, but 100 miles apart.

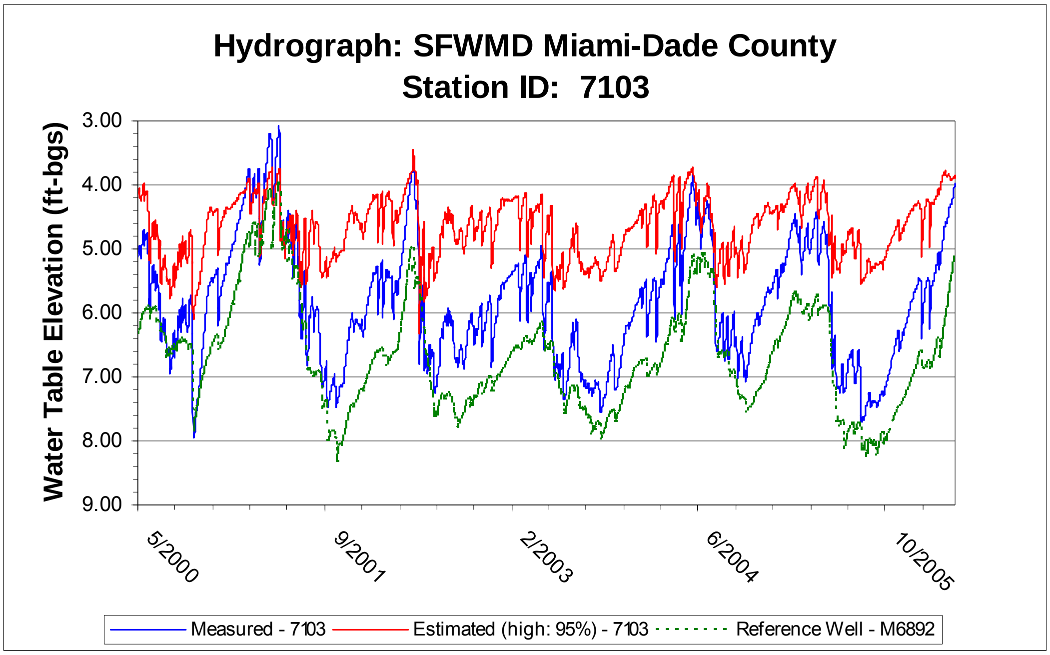


Figure 18. Results using reference well M6892 to estimate water table levels at Well 7103. Wells that are strongly correlated, 6 miles apart. Demonstrates impact of time of observation.

Figure 17 illustrates that the estimated values are strongly influenced by the trends within the reference well hydrograph. These wells have similar maximum annual water level ranges (M6892 = 4.36 feet; HA462 = 4.70 feet) and even though they are more than 100 miles apart, the hydrographs demonstrate moderate correlation (R^2 = 0.573). The estimated high water values do not match the actual measured time series values at Well M6892 (because they are shifted based upon the difference in mean water levels between the two wells), but the mean predicted peak value is within 2.0 ft of the actual observed value (with the worse case being 3 feet). It is important to note that the purpose of this application is not to accurately match the entire time series (we are not trying to reproduce the hydrograph); the intent is to simply generate an accurate prediction of the peak water level with a confidence interval (or an expected range of expected peak water levels). Which, at least for these two wells, is possible to within 2 to 3 feet even though they are approximately 100 miles apart?

The wells charted in Figure 18 are strongly correlated (R^2 = 0.84) even though they are over 6 miles apart. They most likely experience similar weather patterns, and even have similar annual maximum ranges; however, the hydrograph patterns are significantly different resulting in underestimating the high water level by approximately 3 feet when the reference well observation is measured during dry periods or low water table levels.

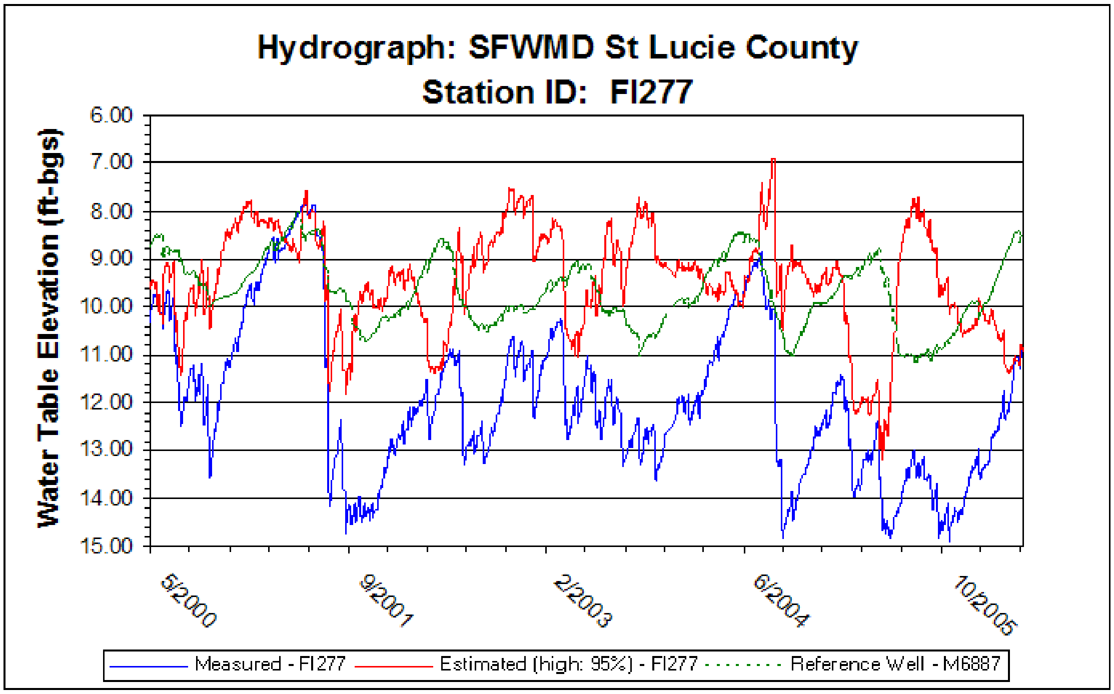


Figure 19. Results using reference well M6887 to estimate water table levels at well F1277. Demonstrates wells that are moderately correlated with dissimilar hydrograph trends.

Figures 19 and 20 demonstrate the impacts on the estimated SHGWT levels when using reference wells with maximum water level ranges that are dissimilar to the site of interest. In Figure 19, the reference well and test well were moderately correlated (R^2 =

0.578). However, the hydrograph show considerable separation (the SOI maximum water level range is greater (6.91 feet) than the reference well (2.77 feet)). This hydrograph separation is expected as the wells are more than 100 miles apart. As such, the difference in the maximum annual water level range resulted in the underestimation of the SHGWT levels. The mean estimate is within 2.5 ft, while the worse case is an under-estimation of 5 feet. However, it should be noted that the underestimation errors can be improved upon by establishing criteria for the best time of year to take observations at the site of interest (i.e. do not make observations during dry season).

Figure 20 provides an example of using a reference well with a larger maximum annual water level range than the site of interest. In this case, the wells are approximately 65 miles apart and are moderately correlated ($R^2 = 0.601$). The high water table is over estimated during dry periods by up to 1.5 feet, but during the remaining periods, the estimated high water levels are more consistent with the actual value. In 2004, the reference well was experiencing some of its wettest periods, while the test site was relatively dry. The result was an under estimation of the high water table by approximately 0.7 feet. That section of the curve is an excellent example how dissimilar weather impacts or precipitation lead to the largest error between the actual and estimated SHGWT.

Figures 21 and 22 illustrate how differing water table depths can impact the estimated high water level. These wells are approximately 50 miles apart and are moderately correlated ($R^2 = 0.608$). Even though the water level depths differ as much as 4 feet, there is no indication that the estimated SHGWT levels were impacted by using reference wells with water table depths either higher or lower than the site of interest

5.5. Program Limitations.

The reliability for estimating the SHGWT levels using this method is limited by the basic assumption of the methodology (linear correlation of water levels) as well as limited knowledge of the characteristics of the site of interest. However, the primary limitation of the program is the limited number of reference wells that were used in the analysis. Although all surficial wells being operated by the SFWMD were tested, the result was a limited number of well clusters (zones) being selected as reference wells to represent large drainage areas with complex and varied characteristics including anthropogenically altered systems (i.e. drainage canals, pump stations, and levees) that affect water table levels. Because, the accuracy of the method relies on similarities between the reference wells and a site of interest, it is clear that more reference wells are required in order to have a database that is representative of as many distinct regions with different hydrologic characteristics as possible.

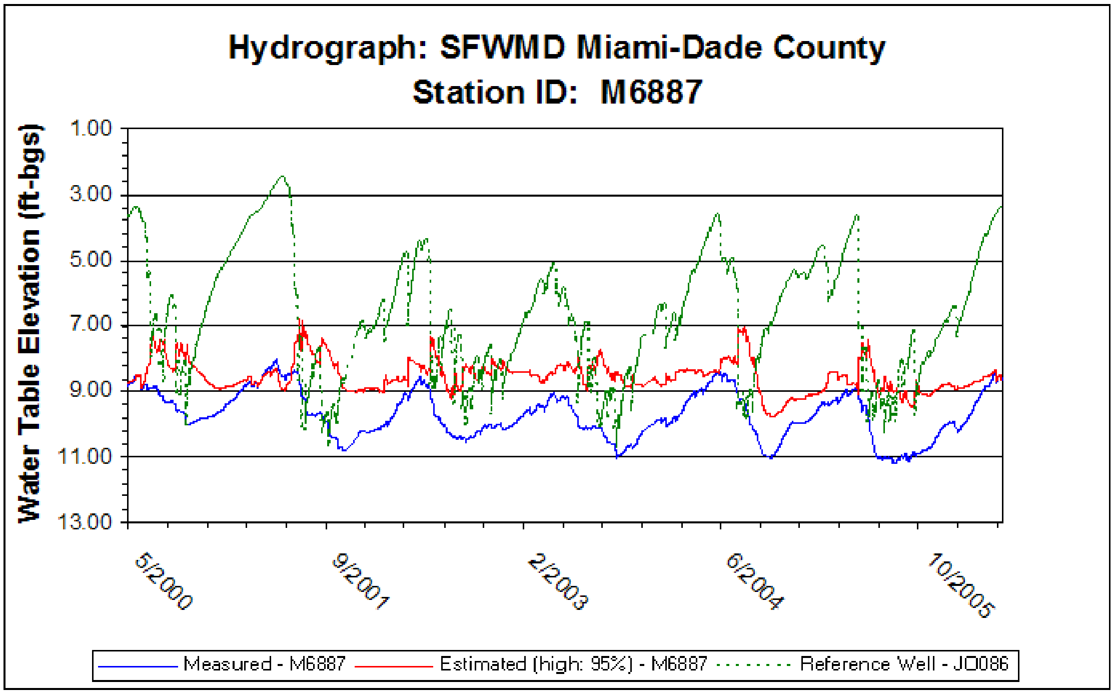


Figure 20. Results using reference well JO086 to estimate water table levels at Well M6887. Demonstrates wells that are moderately correlated with dissimilar maximum annual water level ranges and hydrograph trends.

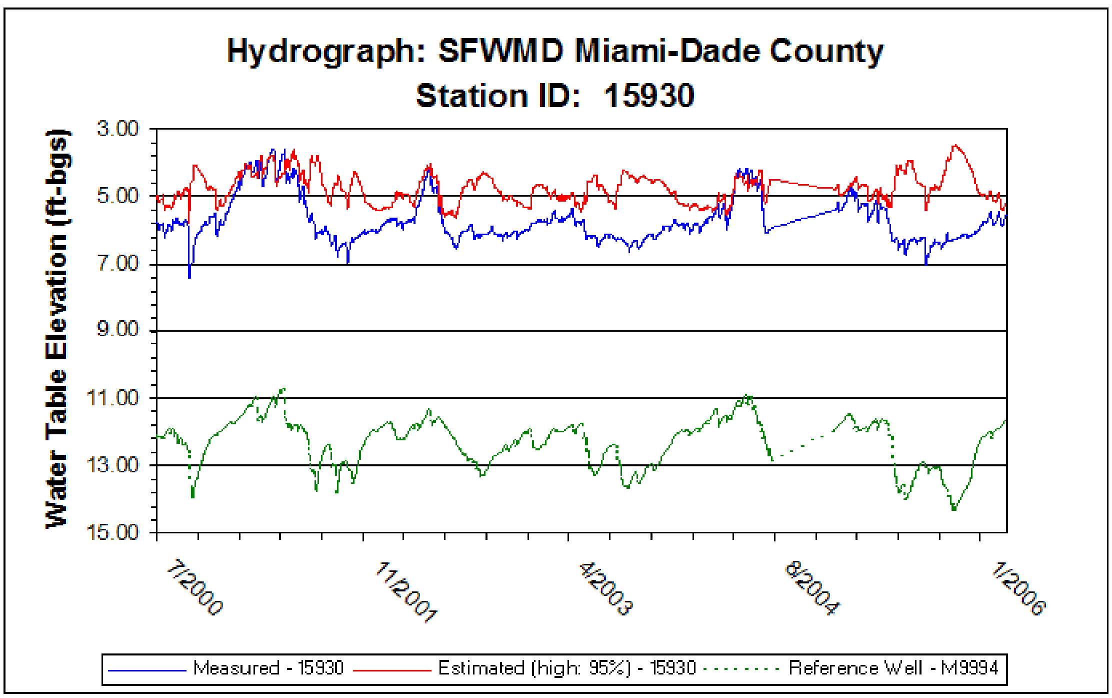


Figure 21. Results using reference well M9994 to estimate water table levels at Well 15930. Demonstrates wells that are moderately correlated with dissimilar water levels, but similar hydrograph trends**.**

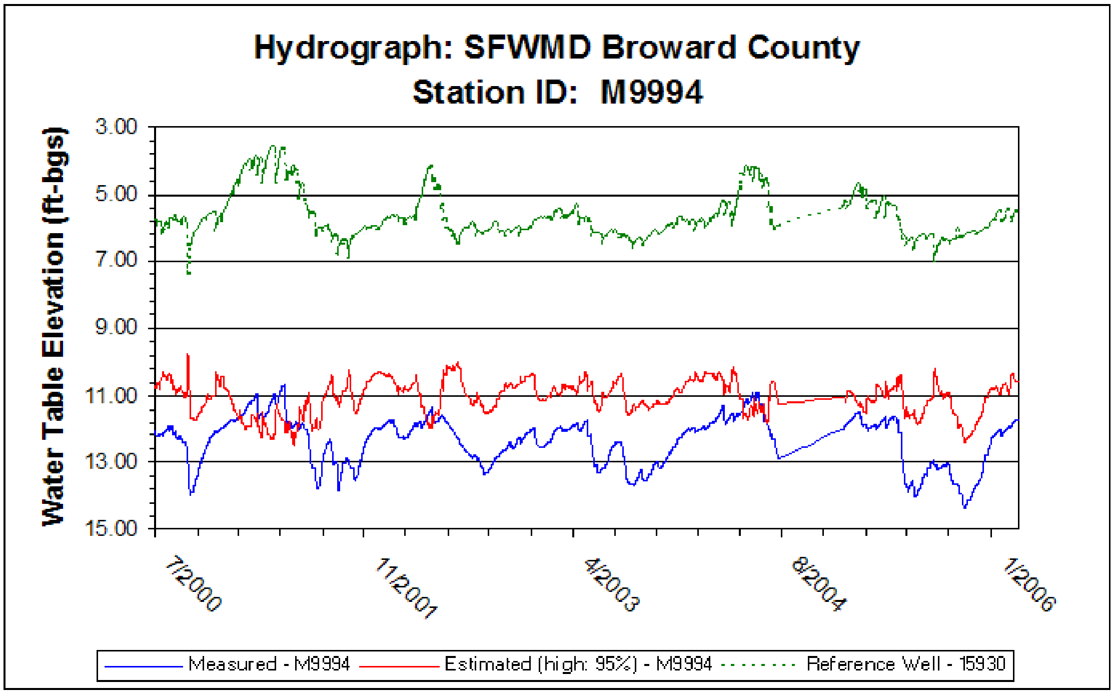


Figure 22. Results using reference well 15930 to estimate water table levels at Well M9994. Demonstrates wells that are moderately correlated with dissimilar elevations but similar hydrograph trends.

6. Summary and Conclusions

The purpose of this study was to develop a tool for estimating the seasonal high groundwater level at a site of interest where there may be minimal record of water level observations. The results demonstrate that it is possible for a single water level measurement at a site of interest to be related to long-term observed water levels from a reference well database in order to predict a range of probable high water levels at the site of interest. However, the accuracy of the method is improved with longer periods of observation at the site of interest. An ideal application scenario would be to obtain daily water levels from a site of interest for several weeks to months during the wet season.

The tool presented in this report was developed by expanding upon a method developed by the USGS for application in Massachusetts (Frimpter, 1981) and Rhode Island (Socolow et al., 1994). Application of the USGS methodology within a reference well database framework has proven to be reliable for the study area (south Florida) when the reference well and site of interest share similar characteristics (particularly similar maximum annual water level ranges, and hydrograph trends—which most likely correspond to similar precipitation patterns). The most important thing to note is that estimated water levels at a site of interest can be under- or over-estimated based upon the relative water levels within the wells at the time of observation. The largest errors are present when comparing wells with inconsistent hydrograph trends (i.e. using a reference well in a region with dry conditions and when the site of interest is in a region experiencing wetter conditions), and with dissimilar observed historical maximum annual water level ranges.

The selection of reference wells is based upon the proximity of the site of interest to reference well zones (or watersheds) of similar hydrologic and hydrogeologic characteristics. Only wells within the same zone as the site of interest are used to predict seasonal high water levels. The application summarizes relevant information such as the water table depth, reference well hydrographs, maximum annual water level range, distance from site of interest, and whether the well is in a dry or wet period for the user to review and possibly refine the well selection process. Once all viable reference wells are identified, then the user can use the corresponding exceedance probability distribution curves to define a range of probable high water levels based upon the acceptable risk that the estimated water level may be exceeded.

The best result often occurred with reference wells closest to the site of interest, but simply selecting reference wells based upon the minimum distance between sites can produce inaccurate predictions. Likely reasons for this are dissimilar soil characteristics which often may be related to the impact of altered systems. For example, a reference well may be very close to a site of interest but if it is influenced by a canal or levee then the water levels may not be strongly correlated. Consequently, suitable reference wells should be selected based on all of the data provided rather than just one criterion.

The uncertainty associated with predicted water levels is often times greater when based upon one single reference well. For this reason, the program developed for this project does not simply identify one "most similar" reference well, but instead provides a set of wells with corresponding ranges of probable high water levels which are presented so that the user can review all relevant information. This allows any subsequent design decisions to be based upon either worse case scenario, best case scenario, or a probable range depending upon the available data and design criteria.

The strength of the program is that it was designed to be flexible in its development and maintenance so that as the number of potential reference wells increases continual analysis can be conducted to better understand the relationship between various characteristics and water level variations. Site characteristics such as soil type, drainage properties, vegetation, land use, can be considered to refine the reference well selection process. Additionally, as the number of potential reference wells increases, the boundaries that define reference well zones can also be refined. Finally, the program can be adapted so that the reference well selection process becomes more automated based on predefined criteria. This would involve establishing selection thresholds based upon specific design parameters and regulatory guidelines.

As mentioned previously, it should be noted that selection of the high, mean, and low water levels based upon the exceedance probability values of 5%, 50%, and 95% was done simply in an effort to remain consistent with the values that were used in the Frimpter (1981) and Socolow et al. (1994) studies. For risk-based design and analysis, these values (particularly the high water level) can be assigned based upon the level of risk that would be acceptable if the predicted water level were to be exceeded. For example, in terms of a typical design problem, what would be the resulting cost if the estimated high water level were exceeded? Then the next question to consider becomes, "Is this cost acceptable?"

7. SHGWT application for tidally Influenced groundwater levels

7.1. Review of project objectives.

One of the objectives of phase I of this project was to consider the relationship between water table elevations and known boundary conditions. Where the term "known boundary" refers to cases in which there is one known boundary condition that predominantly affects the water table (Newman, et al., 2006). The primary focus of the known boundary condition investigation was to consider the affect of tidal variations on groundwater elevations.

As discussed in the final report for phase I of this project (Newman, et al., 2006), analytical solutions exist which relate tidal levels to water table elevations. For sites where water fluctuations are predominantly tidal (minimal wave activity) these analytical solutions can be used to estimate the inland extent of tidal variations based upon period of record tidal information. One possibility would be to use measures such as the MSL, MHW, and MHHW as predictors for the peak groundwater levels (Newman et al., 2006). Another possibility, investigated here, is to use the tidal exceedance probability from period of record observations to estimate peak groundwater levels. The data from the

Stuart, Florida site (Newman et al., 2006) were used to evaluate the relationship of tidal exceedance probabilities to peak groundwater elevations.

7.2. Relationship between tidal elevation and groundwater elevation

Figure 23 shows the exceedance probabilities for peak tide and groundwater levels at the Stuart, Florida site which was instrumented for phase I of this project. It is evident from the plot that the exceedance probability distributions for peak groundwater (well) levels and tide elevations are closely related. It can be seen that the peak tidal elevation is typically 0.5 feet greater than the groundwater elevation. It should be noted however, that figure 23 does include or imply any temporal relationship. The exceedance probability is a sample statistic which is generated by ranking all observed values, but does not take into account the time of observation. Based upon period of record observation at the site, it is estimated that the typical lag between tide and groundwater level response is approximately 4.5 hours. One must keep in mind however that this is an average value over the period of record and does not mean that the water levels will consistently lag the tide by 4.5 hours. But, the intent of this method is not to predict when a peak will occur, but rather to estimate what the probable peak value will be. What is indicated by figure 23 is that regardless of when it occurs, the peak groundwater level at this site should not exceed the peak tidal elevation, and as such, the tide should be a consistent predictor of peak groundwater elevations.

7.3. Using tidal exceedance probability to predict high groundwater

In order to determine how well tidal elevations could predict groundwater elevations, a series of tidal exceedance probabilities were compared to period of record groundwater levels at the Stuart, Florida site (figures 24 and 25). Figure 24 shows a 6-month period demonstrating the shift from low (July) to high (October) water levels, while figure 25 focuses on the peak water level conditions. The 1%, 5%, and 10% tidal exceedance probabilities are compared to the observed groundwater levels and the long-term mean sea level (MSL), mean high water (MHW), and Mean Higher High Water (MHHW) for the site. It should be noted that the exceedance probabilities were generated based upon the period of observation for this study, while the MSL, MHW, and MHHW are based upon long-term period of record data for the site. It can be seen that the 1% exceedance probability (1% EP) overestimates the peak groundwater level by 0.2 feet, while the 5% and 10% exceedance probabilities (5% EP and 10% EP) underestimate the peak groundwater level by 0.2 feet and 0.4 feet respectively. Further analysis of long-term exceedance probabilities (based upon period of record tidal data) could provide a reliable tool for estimating tidally influenced seasonal high groundwater tables for sites similar to the Stuart, Florida site.

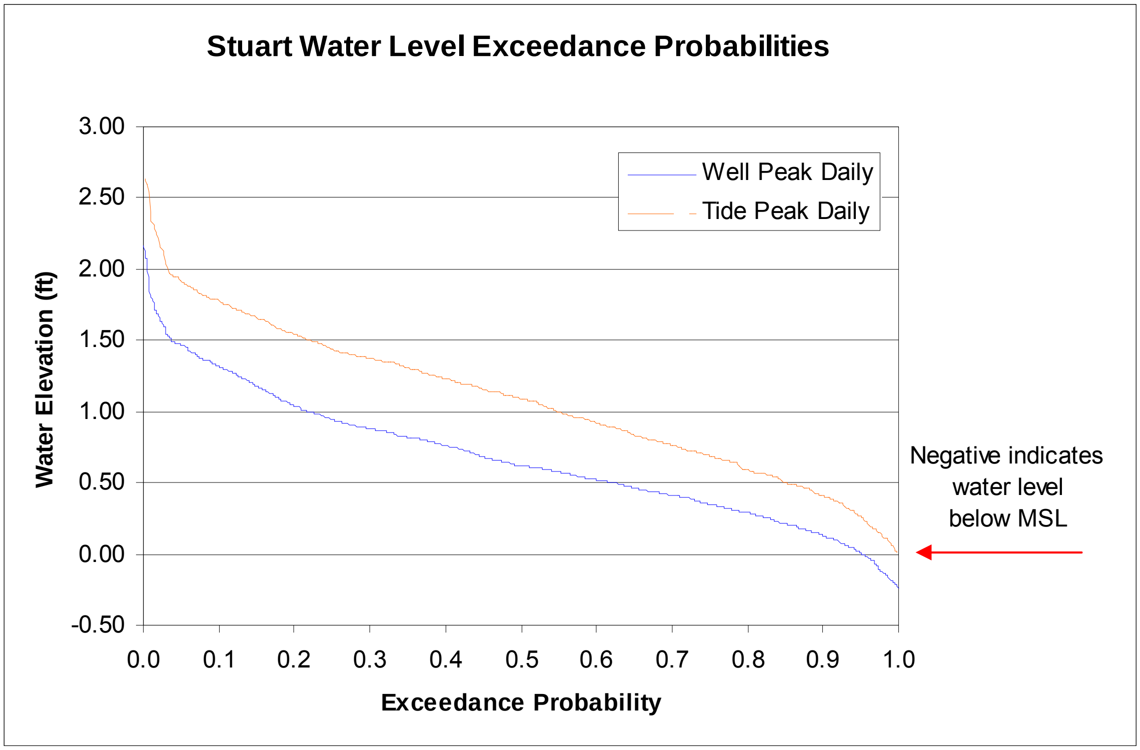


Figure 23. Exceedance probabilities for peak tide and groundwater levels at Stuart, Florida site. The figure demonstrates similarity in trends between tide and groundwater levels.

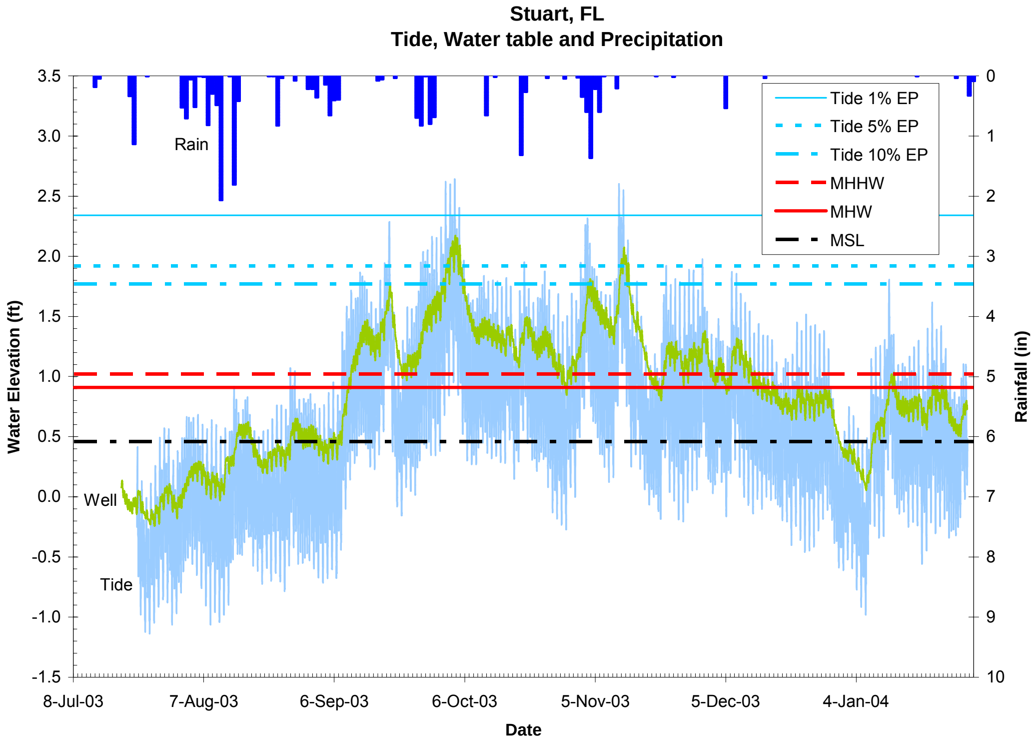


Figure 24. Transition from low to peak water levels observed in 2003 at Stuart, Florida.

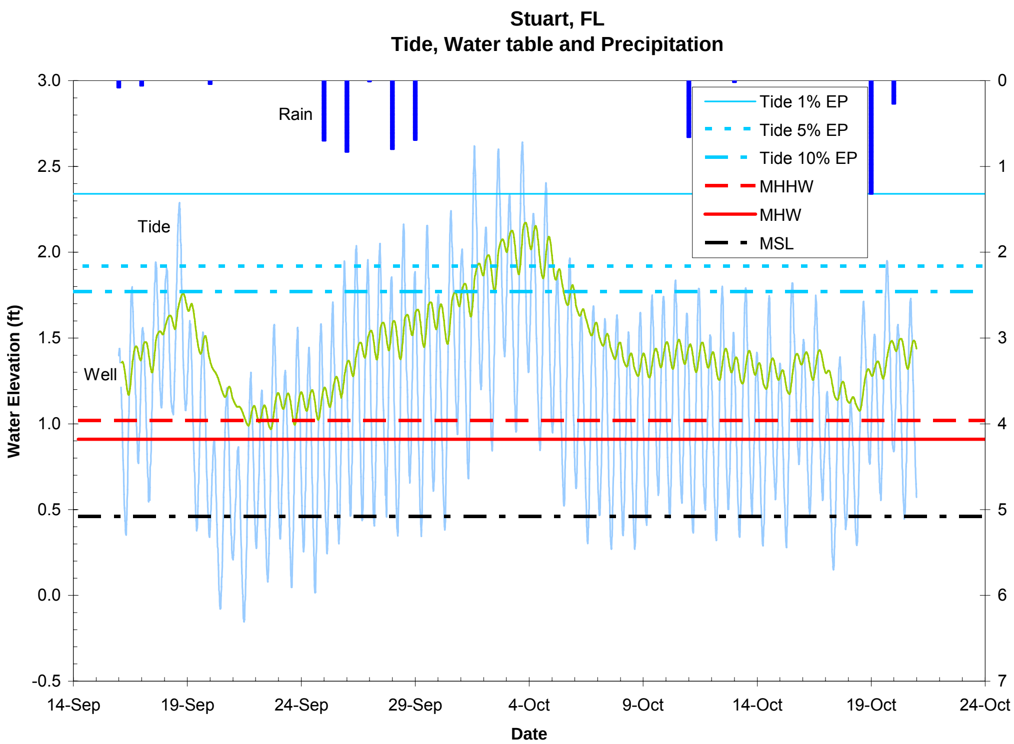


Figure 25. Comparison of tidal exceedance probabilities (EP) to peak groundwater levels observed for 2003 at Stuart, Florida site.

7.4. Tidal application for SHGWT

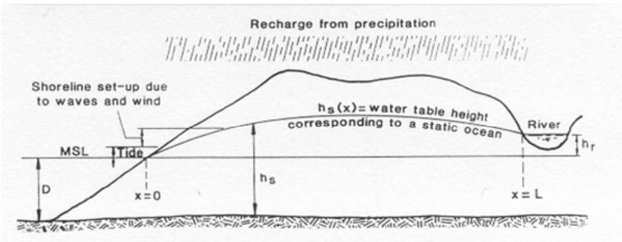
Using the analytical solutions discussed in phase I of this project (Newman et al., 2006), an Excel application was developed for estimating SHGWT elevations based upon observed tidal elevations. The Excel application in its current form is based upon application of the analytic solutions covered in phase I (Figures 26 and 27). However, for sites similar to the Stuart site (where groundwater levels are primarily influenced by tidal variations) the application could be applied in a manner similar to the inland reference well database presented in the earlier sections of this report. By utilizing the tide gage station data summarized in the Excel application (Tables 4 and 5), a tidal reference well database could be generated to predict groundwater levels based upon observed tidal exceedance probabilities.

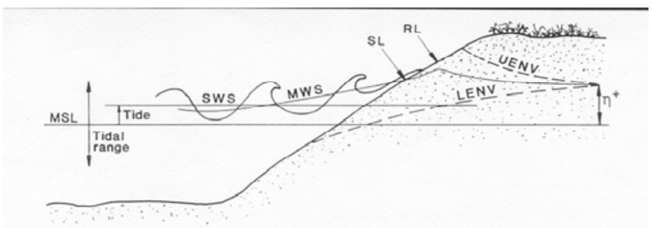
7.5. Tidal application limitations and recommendations

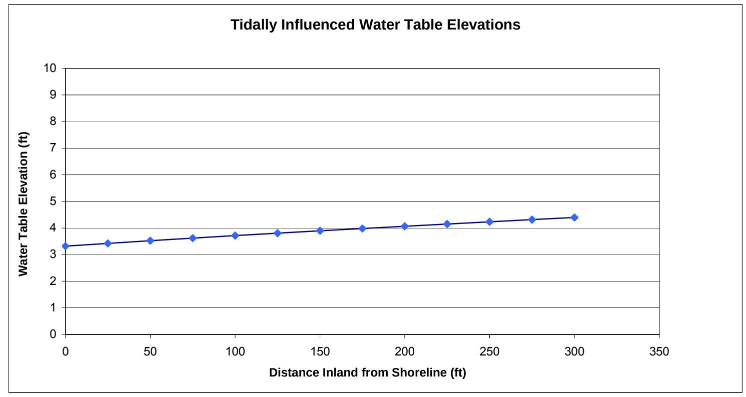
Limitations: For sites at which there is significant wave activity and sloping beach faces, estimating the induced variation in the water table is a far more complex problem due to water table over-height or super-elevation conditions (Newman et al., 2006). In order to accurately estimate the magnitude of over-height, multiple contributing factors must be considered: the shape of the beach face contributing to over-height, wave generated over-height, and wind setup over-height. Each of these factors is variable and site-specific. As such, site specific observations are necessary in order to consider water table over height conditions.

Recommendations: For sites with conditions similar to the Stuart, FL site (minimal wave activity) historic tidal information along with the methods discussed in this report can be applied to estimate the magnitude and inland extent of tidal variations in the water table at a site of interest based upon a reference database of tidal exceedance probabilities. However, for sites similar to the Cape Canaveral, AFS site presented in phase I (considerable wave activity with a sloping beach face) the presence of water table over height conditions make estimating water table elevations more difficult. Site specific observations would be required in order to evaluate water table over height conditions.

Tidally Influenced Water Table Estimates





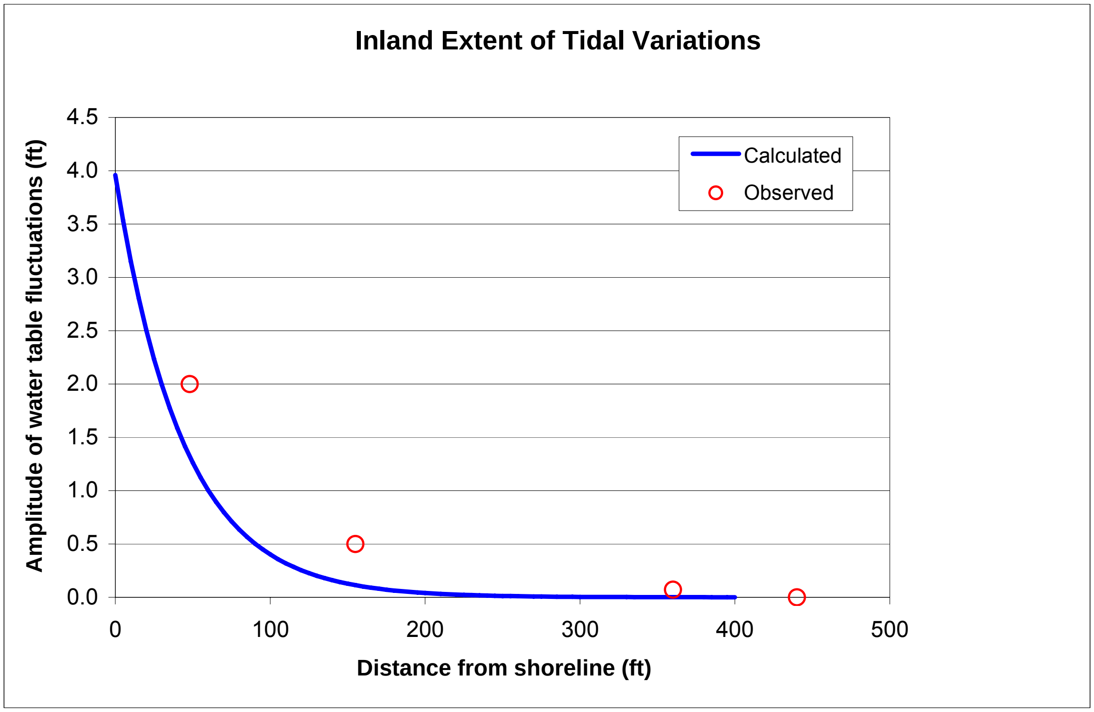


Depth of MSL above base of aquifer	D =	4 ft	
Inland location of observed water table elevations	L =	440 ft	
Water table elevation at reference location a distance L from shoreline	h_r =	2 ft	
Recharge rate (precipitation)	i =	0.01 ft/day	48 in/yr
Hydraulic conductivity	K =	80.2 ft/day	
Distance inland at which water table is to be estimated	x =	200 ft	

Figure 26. Tidally influenced water table estimates. Output from tidal application tool.

Inland extent of tidal variations

Tidal amplitude	h_o =	3.96 ft	3.96		
Specific yield	S_y =	0.2			
Tidal period	t_o =	1 day		K	60 ft/day
Transmissivity	T = Kb =	1200 ft^2/day		b	20 ft



Distance from shore to site of interest

x = 100 ft

Estimated amplitude of tidal fluctuation
A_x = 0.40 ft

Figure 27. Estimated inland extent of tidal variations. Output from tidal application tool.

Table 4. Example of tide gage station information summarized in the tidal application worksheet.

Station	DCP	Station Name	Latitude	Latitude	Latitude	dec_latitude	Longitude	Longitude	Longitude	dec_longitude	Install Date	Removal Date	Pub. Date	Tidal Epoch
8720001	0	ST. MARYS RIVER HEADWATERS	30	47.2	N	30.7866667	81	50.4	W	81.84	11/14/1977	6/21/1978	2/5/2004	1983-2001
8720004	0	CRANDALL, ST. MARYS RIVER	30	43.3	N	30.7216667	81	37.3	W	81.62166667	11/22/1977	6/6/1978	2/5/2004	1983-2001
8720006	0	LITTLE ST. MARYS RIVER	30	43.9	N	30.7316667	81	43.6	W	81.72666667	12/6/1977	6/21/1978	5/16/2003	1983-2001
8720007	0	ROSES BLUFF	30	42.2	N	30.7033333	81	34.6	W	81.57666667	12/14/1977	6/9/1978	2/5/2004	1983-2001
8720023	0	CHESTER, BELLS RIVER	30	41	N	30.6833333	81	32	W	81.53333333	1/12/1978	8/15/1978	5/15/2003	1983-2001
8720030	0	FERNANDINA BEACH, AMELIA RIVER	30	40.3	N	30.6716667	81	27.9	W	81.465	05/18/1898	12/31/1918	4/21/2003	1983-2001
8720051	0	LANCEFORD CREEK, LOFTON	30	38.6	N	30.6433333	81	31.4	W	81.52333333	1/10/1978	1/15/1979	2/5/2004	1983-2001
8720058	0	KINGSLEY CREEK, SEABOARD R.R.	30	37.9	N	30.6316667	81	28.6	W	81.47666667	1/6/1978	7/11/1978	2/5/2004	1983-2001
8720084	0	BOGGY CREEK, UPPER NASSAU RIVER	30	35.3	N	30.5883333	81	39.8	W	81.66333333	2/3/1978	8/15/1978	2/5/2004	1983-2001
8720086	0	AMELIA CITY, SOUTH AMELIA RIVER	30	35.2	N	30.5866667	81	27.8	W	81.46333333	10/31/1973	4/17/1979	7/2/2003	1983-2001
8720093	0	HALFMOON ISLAND	30	34.6	N	30.5766667	81	36.5	W	81.60833333	1/18/1978	9/1/1978	2/5/2004	1983-2001
8720097	0	CUNO, LOFTON CREEK	30	34.6	N	30.5766667	81	34.3	W	81.57166667	2/17/1978	8/15/1978	2/5/2004	1983-2001
8720098	0	NASSAUVILLE, NASSAU RIVER EAST	30	34.1	N	30.5683333	81	30.9	W	81.515	12/17/1977	3/21/1979	7/2/2003	1983-2001
8720119	0	MINK CREEK ENT., NASSAU RIVER	30	32.2	N	30.5366667	81	34.9	W	81.58166667	2/21/1978	4/17/1979	10/30/2003	1983-2001
8720135	0	NASSAU RIVER ENTRANCE	30	31.1	N	30.5183333	81	27.2	W	81.45333333	3/15/1978	11/9/1978	2/5/2004	1983-2001
8720137	0	SAWPIT CREEK ENTRANCE	30	30.8	N	30.5133333	81	27.4	W	81.45666667	3/15/1978	9/18/1978	8/14/2003	1983-2001
8720143	0	SAWPIT CREEK	30	30.2	N	30.5033333	81	28.3	W	81.47166667	2/6/1978	8/18/1978	2/5/2004	1983-2001
8720148	0	TIGER POINT, PUMPKIN HILLS CREEK	30	30.1	N	30.5016667	81	29.7	W	81.495	3/17/1978	4/10/1979	2/5/2004	1983-2001
8720168	0	SIMPSON CREEK	30	27.9	N	30.465	81	25.9	W	81.43166667	3/14/1978	9/6/1978	2/5/2004	1983-2001
8720186	0	FORT GEORGE ISLAND	30	26.4	N	30.44	81	26.3	W	81.43833333	3/29/1978	10/4/1978	2/5/2004	1983-2001
8720189	0	CEDAR HEIGHTS	30	26.2	N	30.4366667	81	38.5	W	81.64166667	8/9/1977	2/13/1978	2/5/2004	1983-2001
8720194	0	LITTLE TALBOT ISLAND	30	25.8	N	30.43	81	24.3	W	81.405	8/30/1977	12/28/1977	5/28/2004	1983-2001
8720203	0	BLOUNT ISLAND BRIDGE	30	24.8	N	30.4133333	81	32.7	W	81.545	8/15/1977	1/23/1978	2/5/2004	1983-2001
8720213	0	TROUT R., SHERWOOD FOREST	30	25.2	N	30.42	81	43.7	W	81.72833333	3/21/1978	1/4/1979	2/26/2004	1983-2001
8720214	1	DEGAUSSING STRUCTURE, MAYPORT NAVAL STA.	30	23.8	N	30.3966667	81	23.7	W	81.395	4/23/1995	6/10/1996	9/15/2004	1983-2001
8720215	0	JACKSONVILLE, NAVY FUEL DEPOT	30	24	N	30.4	81	37.6	W	81.62666667	8/26/1977	3/28/1978	1/23/2004	1983-2001
8720216	0	RIBAULT RIVER, LAKE FOREST	30	23.9	N	30.3983333	81	41.9	W	81.69833333	3/22/1978	10/4/1978	1/23/2004	1983-2001
8720217	0	MONCRIEF CREEK ENTRANCE	30	23.5	N	30.3916667	81	39.7	W	81.66166667	8/26/1977	2/7/1978	5/15/2003	1983-2001
8720218	1	BAR PILOTS DOCK, ST JOHNS RIVER	30	23.8	N	30.3966667	81	25.8	W	81.43	6/29/1995	6/10/1996	2/10/2005	1983-2001
8720220	0	MAYPORT	30	23.6	N	30.3933333	81	25.9	W	81.43166667	4/26/1928	5/10/1983	4/21/2003	1983-2001
8720221	0	FULTON, ST. JOHNS RIVER	30	23.4	N	30.39	81	30.4	W	81.50666667	8/31/1977	3/6/1978	1/23/2004	1983-2001
8720224	1	MAYPORT (FERRY DEPOT), ST JOHNS RIVER	30	23.7	N	30.395	81	25.9	W	81.43166667	3/20/1997	3/11/1998	5/16/2005	1983-2001
8720225	0	PHOENIX PARK	30	23	N	30.3833333	81	38.2	W	81.63666667	8/17/1977	2/23/1978	1/23/2004	1983-2001
8720232	0	PABLO CREEK ENTRANCE	30	22.6	N	30.3766667	81	26.9	W	81.44833333	8/30/1977	3/6/1978	2/26/2004	1983-2001
8720242	0	LONGBRANCH (USE-DDP), ST JOHNS RIVER	30	21.6	N	30.36	81	37.2	W	81.62	4/28/1928	5/1/1968	2/10/2005	1983-2001
8720267	0	PABLO CREEK	30	19.4	N	30.3233333	81	26.3	W	81.43833333	8/19/1977	1/23/1978	1/23/2004	1983-2001
8720274	0	LITTLE POTTSBURG CREEK	30	18.6	N	30.31	81	36.6	W	81.61	6/14/1978	1/29/1979	2/5/2004	1983-2001
8720291	0	JACKSONVILLE BEACH	30	17	N	30.2833333	81	23.2	W	81.38666667	5/1/1974	4/30/1975	8/14/2003	1983-2001
8720296	0	ORTEGA RIVER ENTRANCE	30	16.7	N	30.2783333	81	42.3	W	81.705	8/9/1978	2/13/1979	2/26/2004	1983-2001
8720305	0	OAK LANDING	30	15.2	N	30.2533333	81	25.8	W	81.43	7/18/1978	1/25/1979	2/26/2004	1983-2001
8720333	0	PINEY POINT, ST. JOHNS RIVER	30	13.7	N	30.2283333	81	39.8	W	81.66333333	3/10/1978	2/22/1979	2/5/2004	1983-2001
8720357	1	I-295 BRIDGE, WEST END, ST JOHNS RIVER	30	11.5	N	30.1916667	81	41.5	W	81.69166667	4/25/1995	7/10/1997	12/10/2004	1983-2001
8720374	0	ORANGE PARK, ST. JOHNS RIVER	30	10.1	N	30.1683333	81	41.7	W	81.695	5/18/1978	11/22/1978	5/16/2005	1983-2001
8720398	0	PALM VALLEY, ICWW	30	8	N	30.1333333	81	23.2	W	81.38666667	6/13/1978	2/1/1979	5/31/2005	1983-2001

Table 5. Example of tide gage data summarized in the tidal application worksheet.

Station	MHHW	MHW	DTL	MTL	MSL	MLW	MLLW	GT	MN	DHQ	DLQ	HWI	LWI
8720001	6.58	6.43	4.99	5.02	5.32	3.61	3.39	3.2	2.83	0.15	0.22	5.45	11.4
8720004	7.16	6.89	4.51	4.48	4.68	2.05	1.86	5.29	4.84	0.26	0.19	2.46	8.68
8720006	7.86	7.67	5.56	5.54	5.85	3.4	3.25	4.61	4.27	0.19	0.15	4.18	9.87
8720007	8.92	8.57	5.56	5.48	5.66	2.39	2.2	6.72	6.18	0.34	0.19	1.95	7.85
8720023	8.86	8.51	5.45	5.38	5.55	2.24	2.03	6.82	6.27	0.35	0.21	1.81	7.58
8720030	8.26	7.91	4.98	4.9	4.99	1.89	1.7	6.56	6.02	0.35	0.19	1.36	7.26
8720051	7.06	6.69	3.62	3.53	3.64	0.36	0.17	6.9	6.33	0.37	0.2	1.66	7.25
8720058	8.09	7.74	4.83	4.75	4.84	1.76	1.57	6.51	5.97	0.35	0.19	1.81	7.67
8720084	7.17	7.03	5.56	5.58	5.85	4.13	3.96	3.2	2.9	0.13	0.17	4.85	11.1
8720086	7.45	7.11	4.5	4.41	4.44	1.72	1.55	5.9	5.39	0.34	0.16	1.71	7.97
8720093	8.78	8.6	6.51	6.52	6.79	4.43	4.23	4.54	4.16	0.18	0.2	3.37	9.9
8720097	8.1	7.92	6.17	6.16	6.43	4.41	4.24	3.86	3.51	0.18	0.17	3.58	10.06
8720098	8.22	7.92	5.6	5.54	5.64	3.17	2.98	5.24	4.75	0.3	0.19	1.77	8.4
8720119	6.59	6.35	4.24	4.22	4.45	2.09	1.89	4.7	4.26	0.24	0.2	2.58	9.35
8720135	8.92	8.58	6.08	6	5.93	3.42	3.23	5.69	5.16	0.34	0.19	1.07	7.95
8720137	10.04	9.69	7.24	7.16	7.15	4.64	4.45	5.58	5.05	0.35	0.19	1.14	7.62
8720143	9.36	9.02	6.58	6.48	6.51	3.94	3.8	5.57	5.08	0.34	0.14	1.45	7.79
8720148	8.79	8.5	6.11	6.06	6.25	3.61	3.43	5.36	4.89	0.29	0.18	2.74	9.04
8720168	8.08	7.74	5.31	5.2	5.25	2.66	2.53	5.55	5.08	0.34	0.12	1.44	7.55
8720186	8.46	8.16	5.85	5.77	5.86	3.38	3.24	5.22	4.78	0.3	0.14	1.54	7.82
8720189	6.33	6.18	4.72	4.69	4.73	3.19	3.11	3.22	2.99	0.15	0.08	2.26	8.86
8720194	8.83	8.42	5.8	5.69	5.61	2.96	2.78	6.05	5.45	0.41	0.19	0.77	7.05
8720196	7.76	7.52	5.43	5.37	5.48	3.23	3.1	4.66	4.29	0.25	0.12	1.7	7.85
8720198	7.59	7.39	5.64	5.59	5.59	3.8	3.69	3.9	3.59	0.2	0.1	1.69	7.92
8720203	5.75	5.55	3.87	3.82	3.94	2.08	1.99	3.76	3.47	0.19	0.09	1.86	8.08
8720211	2.09	1.79	-0.49	-0.56	-0.54	-2.92	-3.07	5.16	4.71	0.3	0.15	0.94	6.89
8720213	6.91	6.77	5.48	5.46	5.44	4.15	4.06	2.85	2.61	0.14	0.09	2.85	9.21
8720214	2.18	1.85	-0.47	-0.55	-0.55	-2.95	-3.11	5.3	4.81	0.33	0.16	0.81	6.93
8720215	7.94	7.81	6.54	6.51	6.51	5.21	5.13	2.81	2.6	0.13	0.08	2.36	8.78
8720216	7.85	7.75	6.45	6.44	6.41	5.14	5.06	2.79	2.6	0.1	0.08	1.37	8.16
8720217	7.65	7.52	6.29	6.27	6.25	5.01	4.93	2.72	2.51	0.13	0.08	2.32	8.87
8720218	14.04	13.77	11.55	11.49	11.51	9.2	9.05	5	4.57	0.27	0.15	1.13	6.98
8720219	7.48	7.34	5.62	5.61	5.64	3.88	3.76	3.71	3.46	0.13	0.12	1.83	8.12
8720220	6.67	6.4	4.23	4.17	4.22	1.95	1.8	4.87	4.45	0.27	0.15	1.15	7.08

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Demonstration of a VBA Script for Estimating Probable Water Table Elevations

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Introduction

Seasonal High Groundwater Table

- The water table and its range of fluctuation are required design factors for most projects that involve altering the landscape (Environmental Resource Permit—ERP)
- Typically, it is the maximum or high water level that is a required design criterion
- Most common terms: Seasonal High Groundwater Table (SHGWT) or Seasonal High Water Level (SHWL)

Seasonal High Groundwater Table

- None of the existing methods for estimating SHGWT provide an indication of the probability or “risk” associated with the actual estimates
- In order to address issues of risk the Duration and Frequency of inundation must be considered.

    Specifically, how often and for how long is water at a given depth?

Project Intent

- The purpose of this research is to develop a tool that provides estimates for probable SHGWT which can then be incorporated into a "risk-based" analysis
- Develop a Reference Well database that contains historic water table elevations for Florida
- Apply historic data with linear regression in order to estimate water levels at a site of interest
- Concept is based upon a methodology developed by the United States Geological Survey (USGS) for application in Massachusetts and Rhode Island (Frimpter, 1981 and Socolow et al., 1994)

USGS Procedure

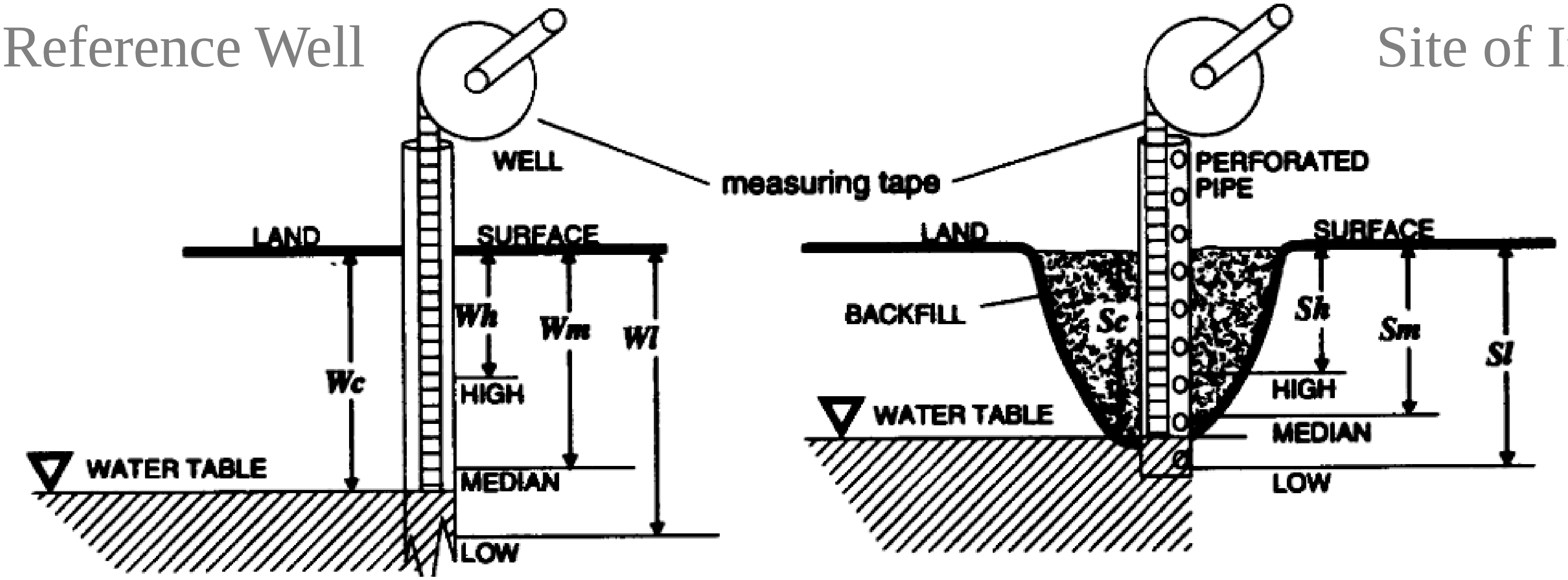
Concept

Based upon the equivalent relation between:

$$\frac{\text{The ratio of potential water level change to maximum annual water level range at a site of interest}}{\text{The ratio of potential water level change to annual water level range at a reference well}}$$

Reference Well

Site of Interest



Where:

W_c = measured depth to water for reference well on a given date

W_h = depth to recorded high water level for reference well (historic)

W_m = depth to recorded mean water level for reference well (historic)

W_l = depth to recorded low water level for reference well (historic)

S_c = observed depth to water at site of interest

S_h = estimated depth to probable high water level at site of interest

S_m = estimated depth to probable mean water level at site of interest

S_l = estimated depth to probable low water level at site of interest

Relationship

$$\frac{W_h - W_c}{W_r} = \frac{S_h - S_c}{S_r} \qquad \text{Eqn. 1}$$

$$S_h = S_c + \frac{S_r}{W_r}(W_h - W_c) \qquad \text{Eqn. 2}$$

Where:

S_c = observed depth to water at site of interest

S_h = estimated depth to probable high water level at site of interest

S_r = expected range of water level depth at site of interest (selected based upon exceedance probability)

W_r = recorded maximum annual water level range for reference well

Methods

Assumptions Used in USGS Method

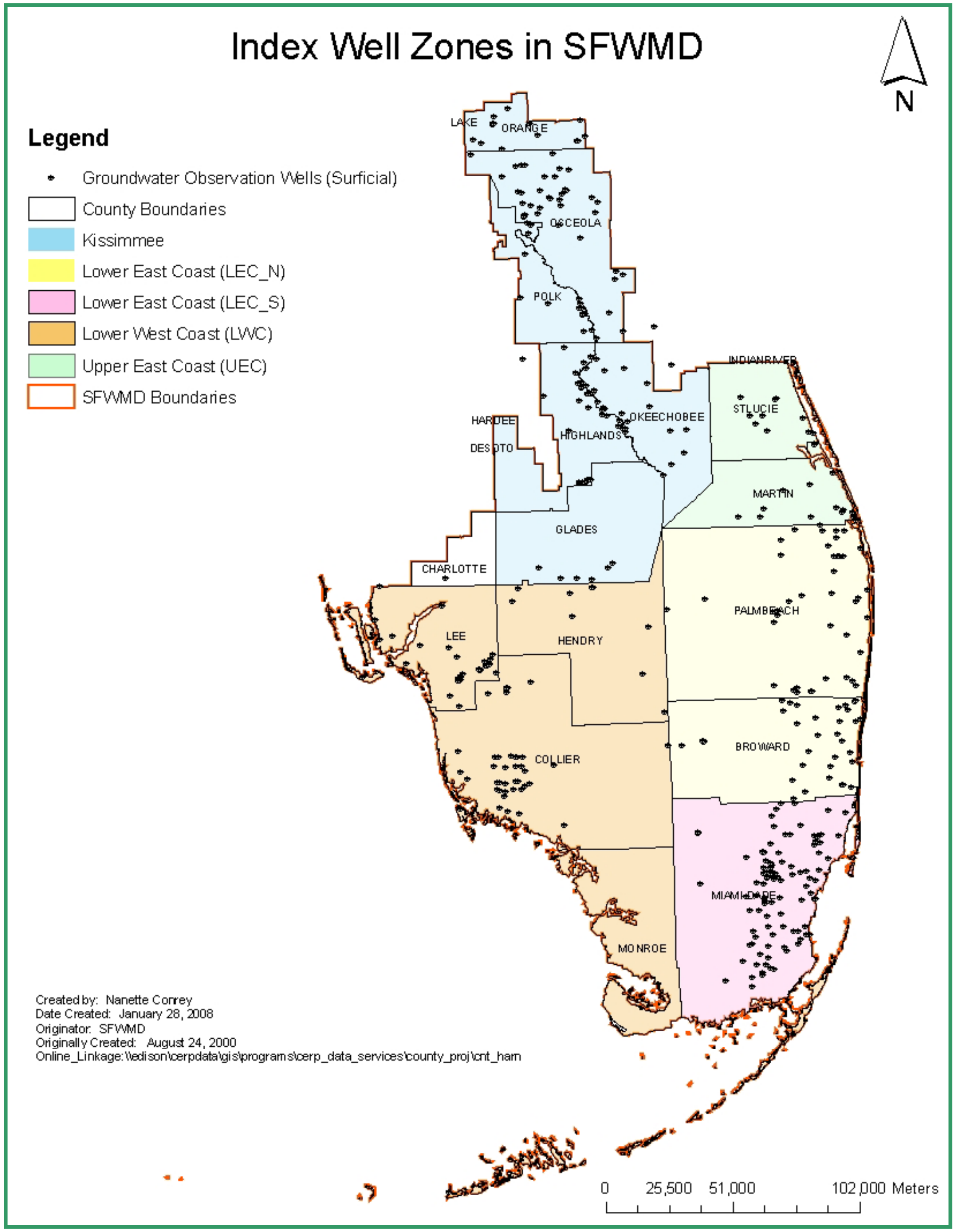
(*Socolow and Frimpter, 1994)*

- Water levels will fluctuate in the future as they have in the past
- Water levels fluctuate seasonally
- Ground water fluctuations depend on site geology
- Region of interest is affected similarly by precipitation and climate

Step 1. Correlation Analysis

- 322 surficial observation wells in SFWMD
  - 190 Active Wells
  - 132 Inactive Well

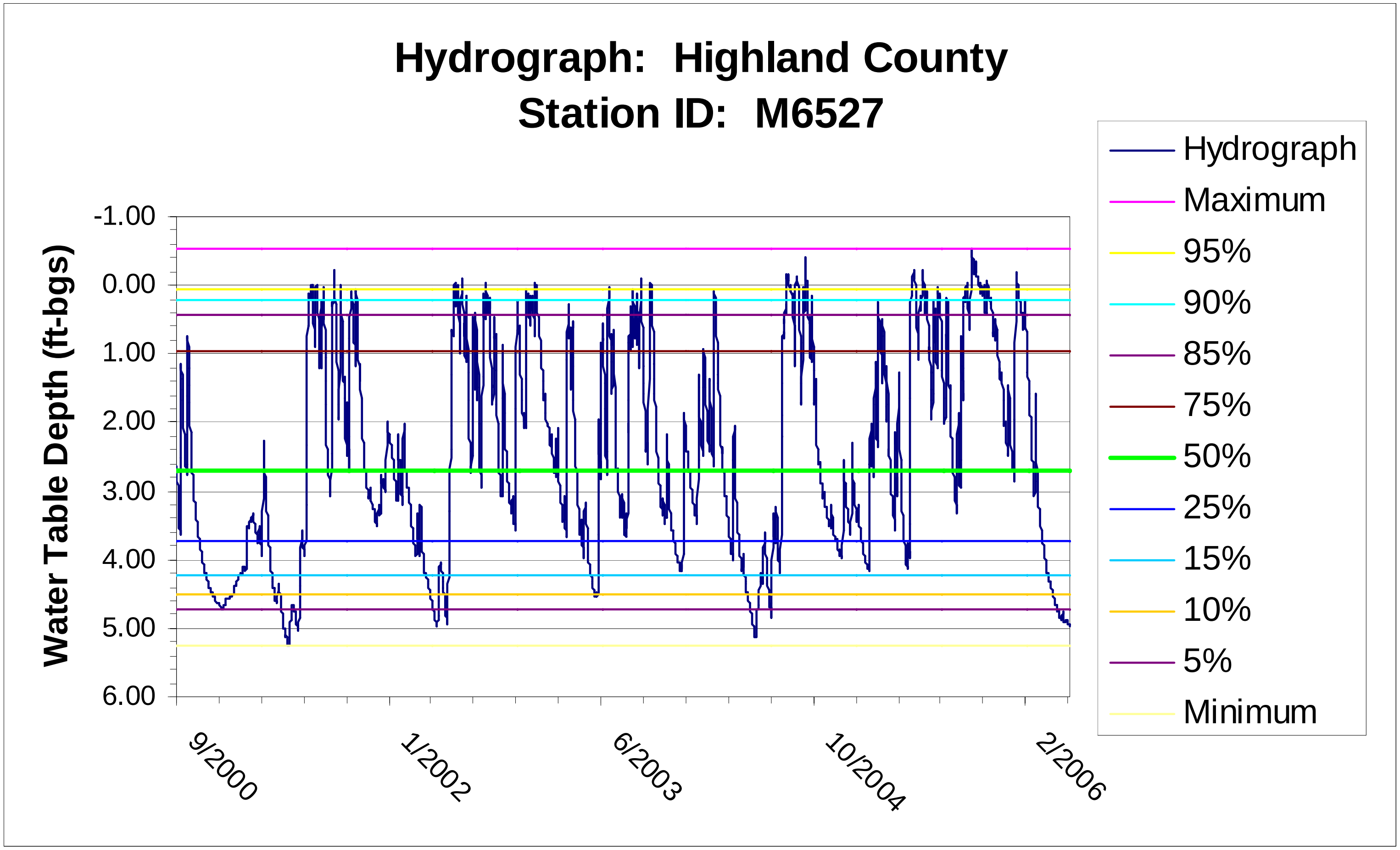
~190 Active → Reference Well Candidates



Step 2. Analyze Data

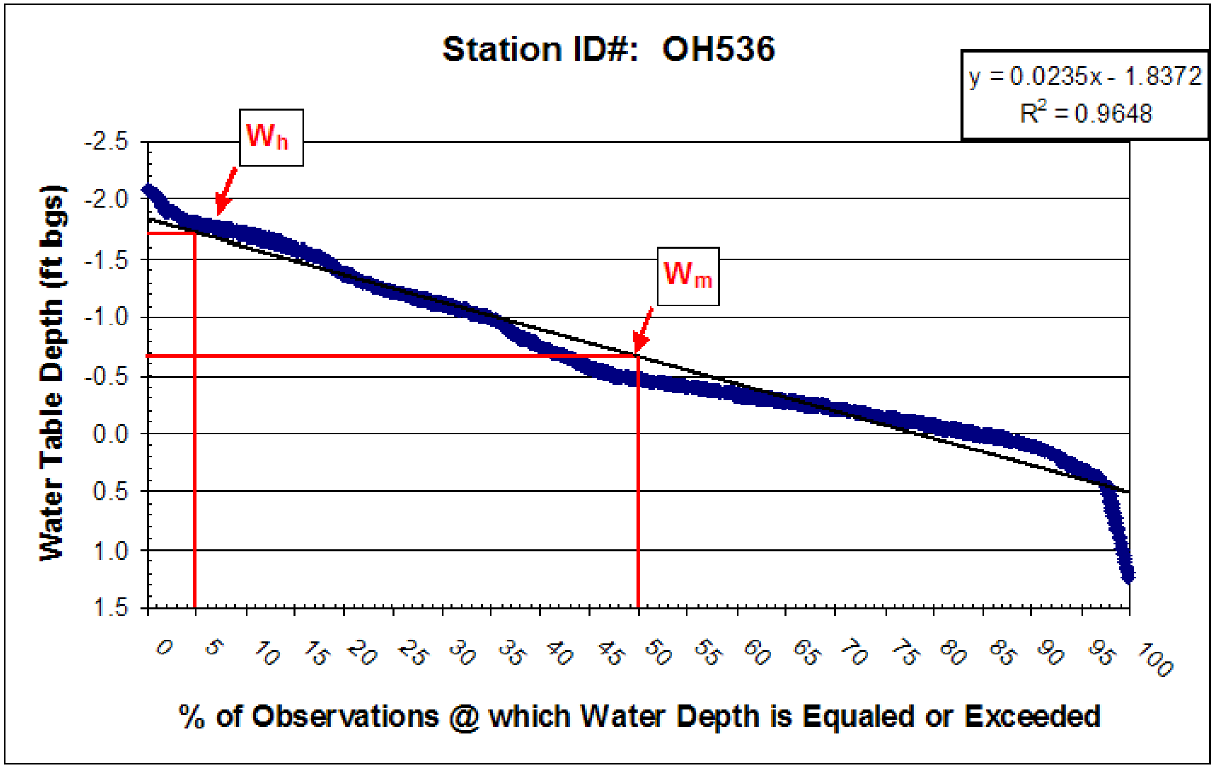
- Hydrographs
  - Illustrated precipitation patterns and data continuity
- Exceedance probability analysis
  - Used to determine W_h, W_m, and W_l values for each well

Step 2. Analyze Data: Hydrographs



•Illustrates the probability distribution of the historical water table levels

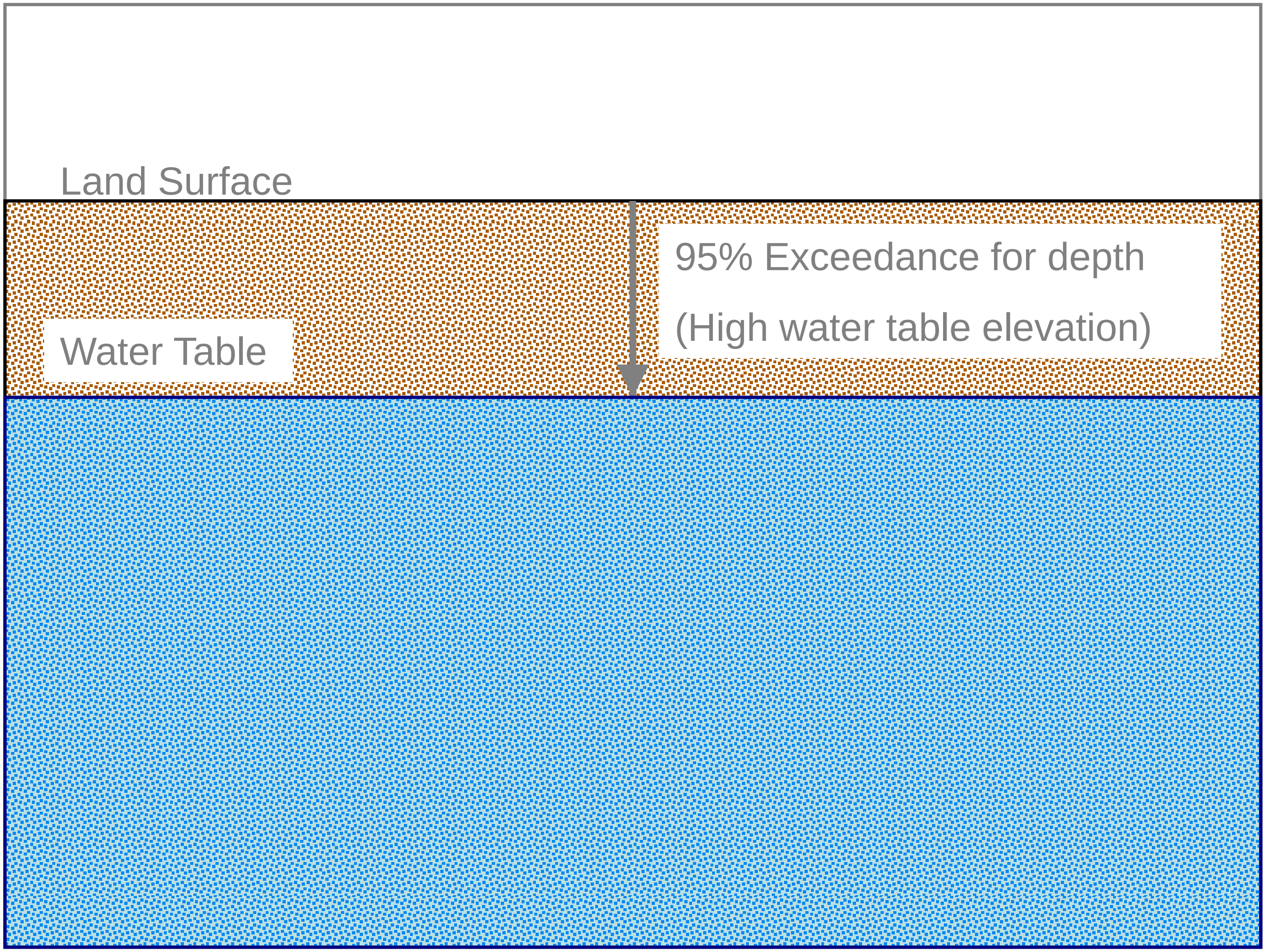
Step 2. Analyze Data: Exceedance Probability Curves



•Probability distribution of the water table levels

• Used to determine W_h, W_m, and W_l values using 5%, 50%, and 95% probability, respectively, that the water table depth will be less than or equaled (Example: there is a 5% probability that the water table depth will be less than 10.2 feet bgs (W_h) - this also means that there is a 95% probability that the water depth will exceed 10.2 feet bgs)

•5%, 50%, and 95% probabilities were used to be consistent with intervals used in the Frimpter (1981) and Socolow et al. (1994) studies



Land Surface
95% Exceedance for depth
(High water table elevation)
Water Table

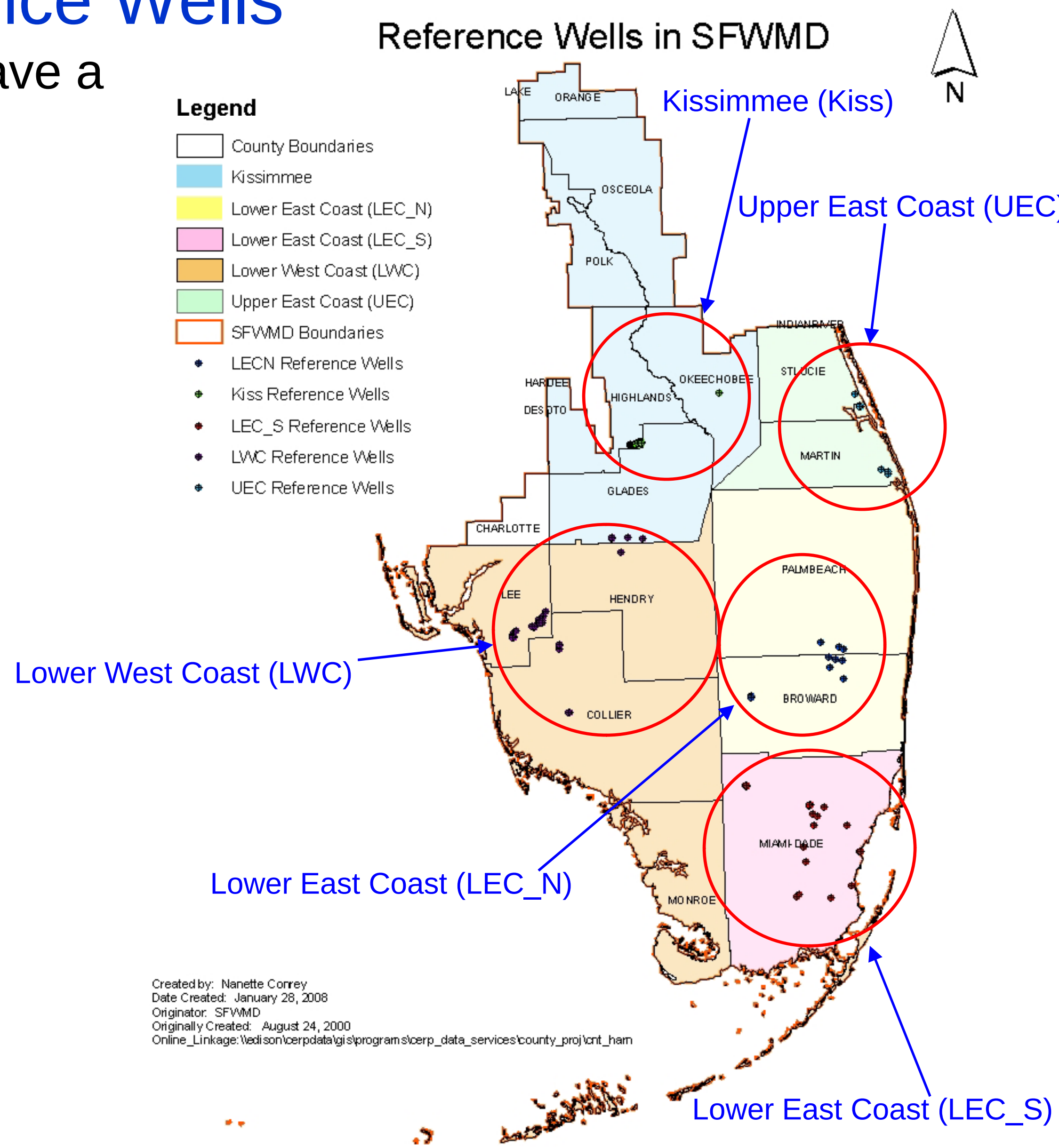
Step 3. Select Reference Wells

- ***Based on the assumption that if the water level at a well (Reference Well) demonstrated a positive correlation or linear relationship to other wells with similar characteristics (such as soil type and precipitation) then that well would also demonstrate a similar relationship at other sites with the same characteristics***
- The reference wells were selected based upon the strength of the linear correlation between each well pair
  - Strong Correlation (Socolow et al., 1994): Correlation Coefficient>0.85
  - Moderate Correlation (Socolow et al., 1994): Correlation Coefficient>0.70
- Wells with periods of record of more than 4 years
- 5 zones were identified to have wells that were positively correlated to one another
  - These zones corresponded to natural drainage basins

Step 3. Select Reference Wells

- Selected all well pairs that have a correlation coefficient > 0.70
  - 146 wells with positive correlations
    - 76 active wells
      - ❖ Reference Wells

- Five zones of positively correlated wells emerged – boundaries established using natural drainage basins



Step 4. Create Reference Well Data Files

Step 4. Create Reference Well Data Files

- Created data files for each zone
  - Contains data for each reference well
    - Summary Data
    - Observations
    - Annual minimum, maximum, and range values
    - Hydrographs
    - Exceedance Probability Curve
  - Contains summary data for each zone
    - Exceedance Probability Curve – used to determine S_r value used in Equations 1 and 2
    - Minimum & maximum observation histogram
    - Well pair correlation summary
    - Mean, Median, and Maximum Water Level Analysis

Application Procedure

Application Procedure

Step 1. Application setup

Step 2. Input data

Step 3. Run macro

Step 4. Interpret Output

❖Program Limitations

Step 1. Application Setup

- What do you need to run the program?
  - Microsoft Excel
  - Program File
  - Five Reference Well Data Files (1 for each zone)
- Program is run via an Excel Workbook using a VBA macro
- User has flexibility to dictate where the program file, data files, and output files are stored

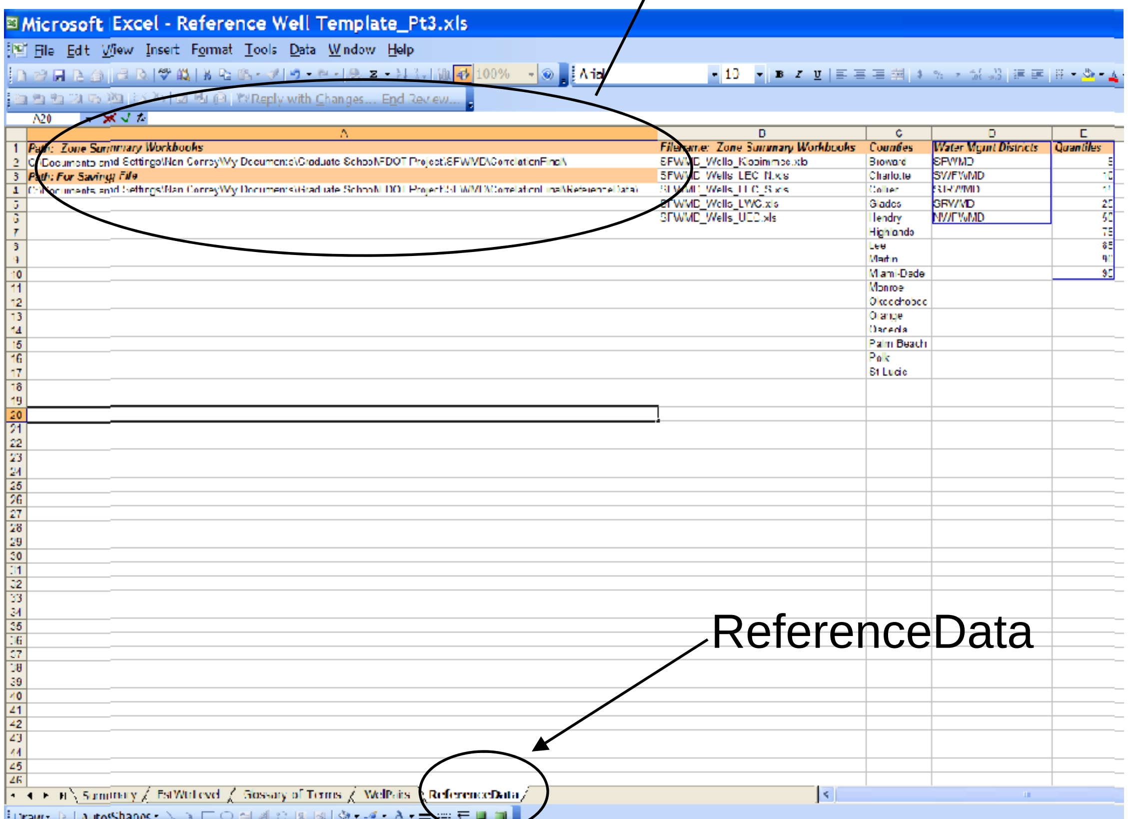
Step 1. Program File Overview

- Consists of 5 worksheets within the Excel workbook
  - Summary
    - Input Data
    - Output Data
  - Estimated Water Level ‘EstWtrLevel’
    - output data
  - Glossary of Terms
  - Well Pair Summary Data
    - Output Data
  - ReferenceData
    - User defined Data and Output file directory path are provided in this worksheet

Step 1. Storing Data & Output Files

✓User defines where data files and output files are stored by entering paths to directories in the 'ReferenceData' worksheet in the Program File

Path: Zone Data File Workbooks
C:\Documents and Settings\Nan Conrey\My Documents\Graduate School\FDOT Project\SFWMD\CorrelationFinal\
Path: For Saving Output Files
C:\Documents and Settings\Nan Conrey\My Documents\Graduate School\FDOT Project\SFWMD\CorrelationFinal\ReferenceData\



❖Insure that a backslash is entered at the end of the file path name. The program will fail if the backslashes are not present.

❖The Program file can be saved in any directory. Plus the data and output file directories do not need to be modified after they are defined by the user.

Step 2. Input Data

- Required input data for the Site of Interest
  - Entered in the ‘Summary’ worksheet only

✓ Site of Interest ID
✓ Latitude & Longitude
✓ Water Management District
✓ County
✓ Observation Date
✓ Observation Value (feet bgs)
✓ Output File Name
✓ No. Wells to be Graphed

✓ Exceedance Probability (%)
✓ Specified Observation Range (days)

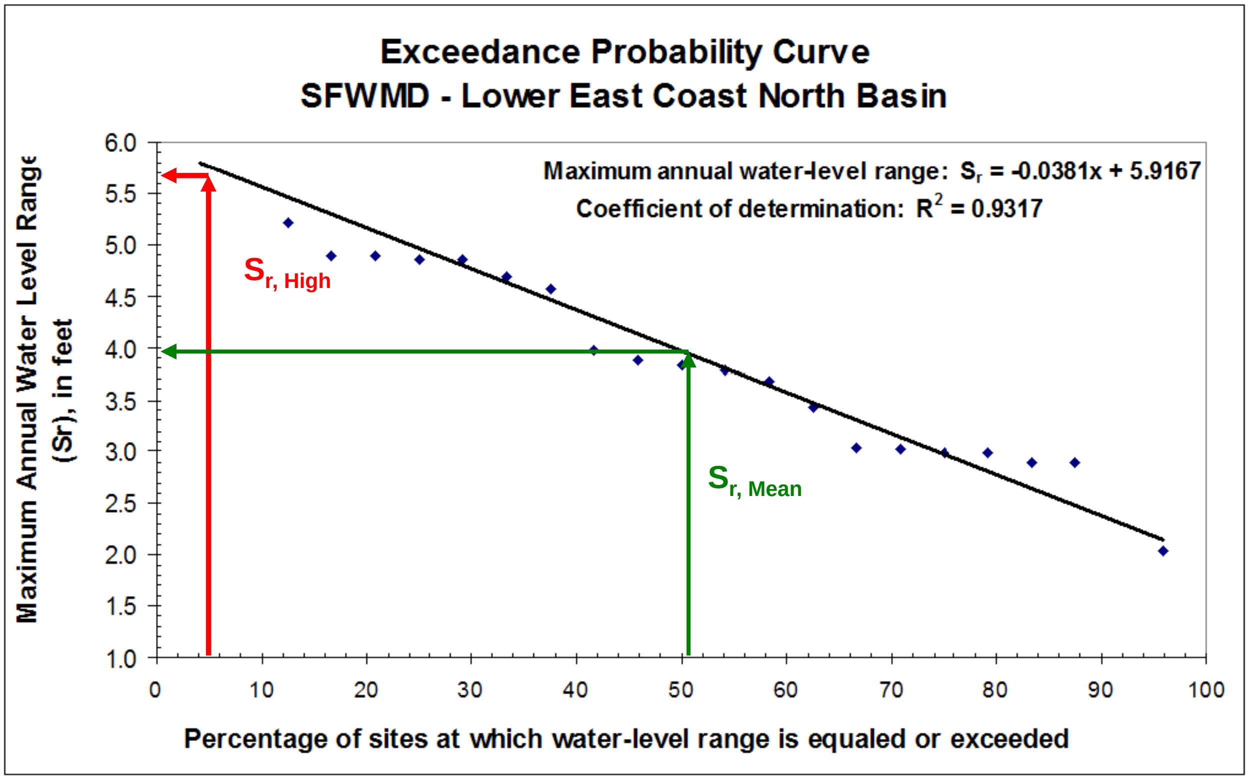
Water Table Estimation Worksheet

Site of Interest ID:	SOI1							Zone:
Latitude: (decimal xx.xxxx):		26.2200	WMD:	SFWMD	Section:			# Wells in Zone:
Longitude: (decimal xx.xxxx):		-80.2600	County:	Broward	Township:			# Selected Wells:
					Range:			S_r, High (feet):
**Latitudes and longitudes must be in decimal radians*								S_r, Median (feet):
								S_r, Low (feet):
Site of Interest Observation Data:								
Observation Date:		3/31/2006	File Name:		Test3	# Wells to be Graphed:		10
Observation Water Table Depth (feet bgs):		11.00	Exceedance Probability (%)		5			
Max Range of Depth bgs (± feet):		10.0	Specified Observation Range (days)		15			

Step 2. Input Data

✓ Exceedance Probability (%)

USGS Equation: $$Sh = Sc + [(Sr/Wr)(Wh - Wc)]$$



Site of Interest Parameters:

Sh= estimated depth to high water level at site of interest

Sc = measured depth to water level at site of interest

Sr = range of water level at the site of interest

Reference Well Parameters:

Wr = maximum annual water level range at reference well

Wh = depth to high water level (95th percentile) at reference well

Wc = Measured depth to water level at reference well (observed on the same day as the observation at the Site of Interest)

***Sr is based upon a linear fit to the maximum annual range of all wells in a given zone (Socolow established Sr based on soil types)

Step 2. Input Data (cont)

✓ Specified Observation Range (days)

Example:

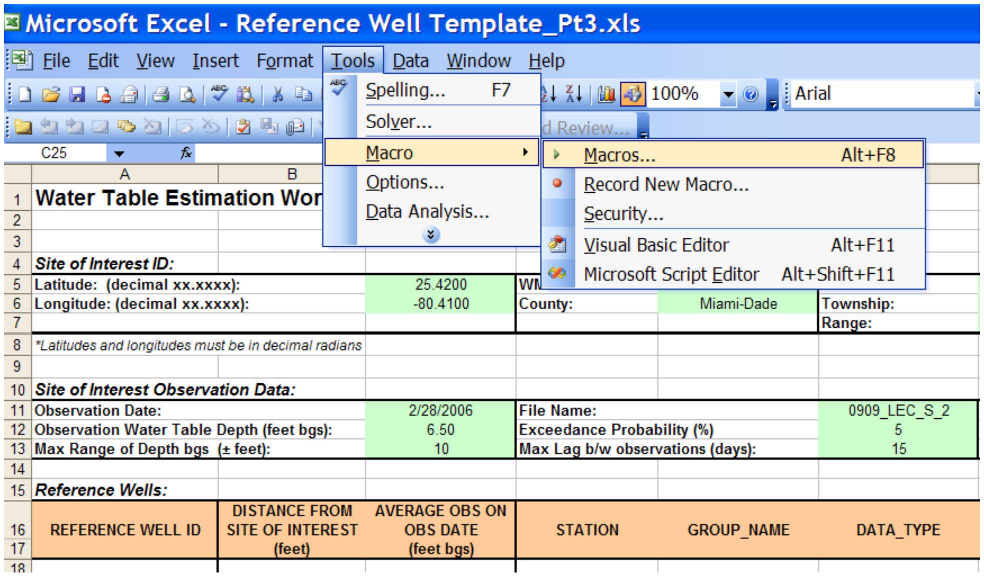
Observation Date 5/15/06 at Site of Interest

If no observation exists on the specified date at reference well, then…

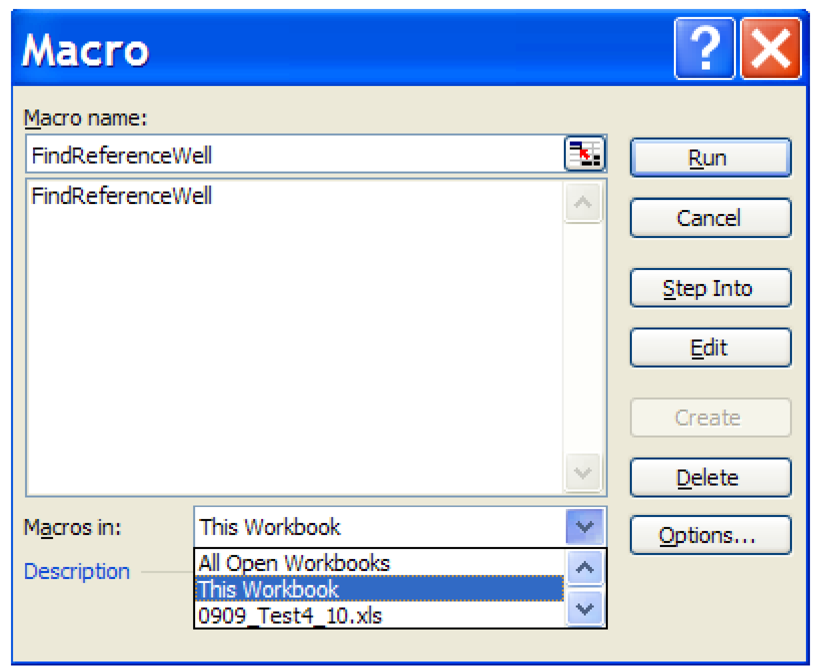
- Program will search for a Reference Well observation within a specified period defined by user
  - Steps one day at a time both forward and backward up to the specified number of days
- Recommended not to exceed 15 days (Socolow and Frimpter, 1994)
  - This represents a 30 day span

Step 3. Run VBA Script

- Macro can be run from any location within Program file



- From Tools menu bar:
  - Click on '*Macro*'
  - Click on '*Macros'*
  - Macro dialogue box will appear.



- In Macro Dialogue Box:
  - Select the 'Macros in:' box – '*This Workbook*'
    - This will eliminate any macros from the list that are not related to the Program file
  - Highlight *'FindReferenceWell*' Macro
  - Click on *Run* tab
  - Program will immediately begin
  - When it is complete, the Output File will be open
  - Examine output data

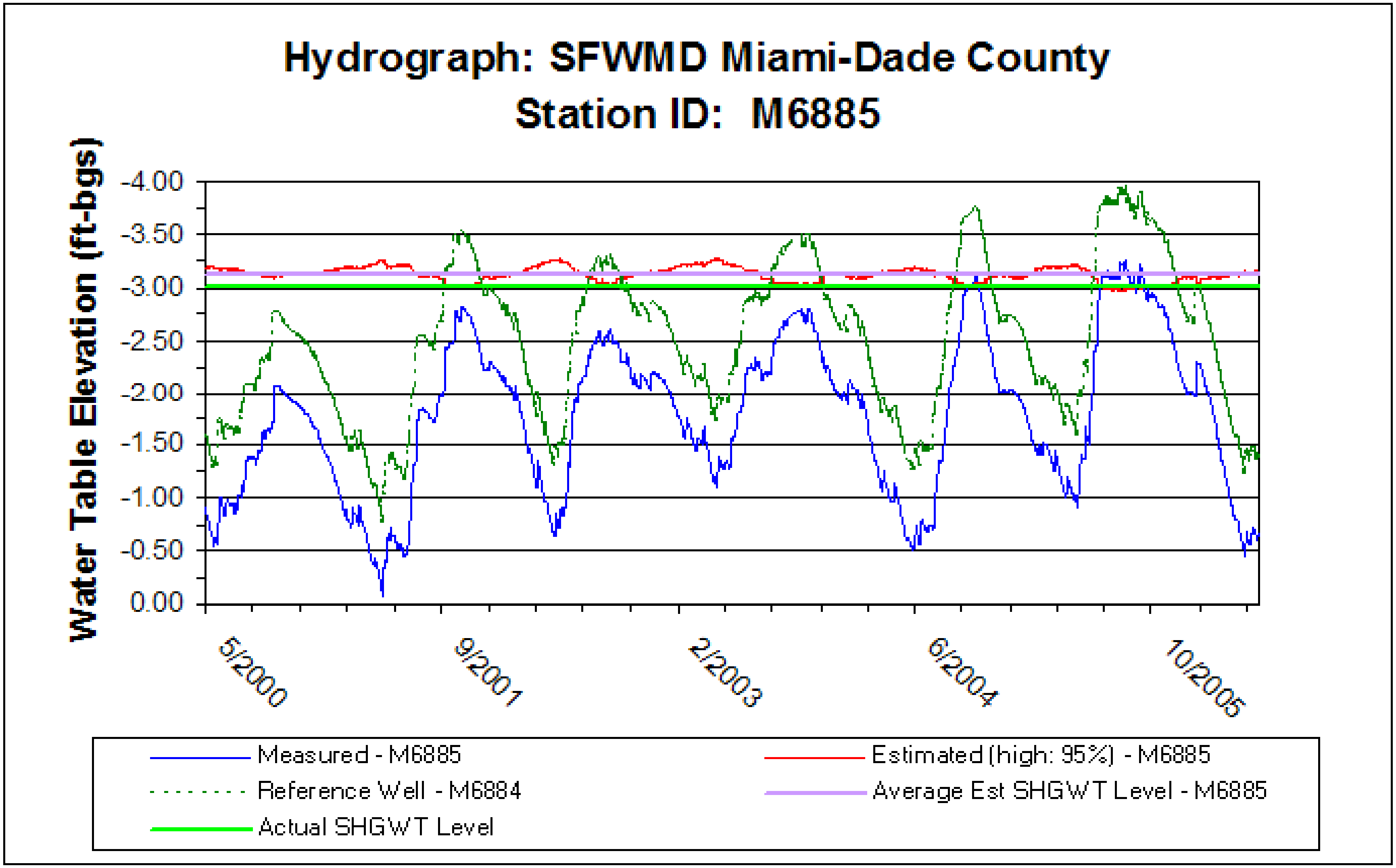
Step 4. Interpret Output: USGS Reference Well Selection Criteria

- Select Reference Wells that are nearest the site of interest
  - Use topographic setting and depth to water as primary guides.
- The Reference Well should have approximately the same measured depth to the water table as the site of interest
- The Reference Well should have similar antecedent rainfall conditions as the site of interests
- Reference Wells should have similar expected water level ranges based on known conditions at site of interest
- The Reference Well should be completed at sites with similar soil characteristics

Application Testing and Validation

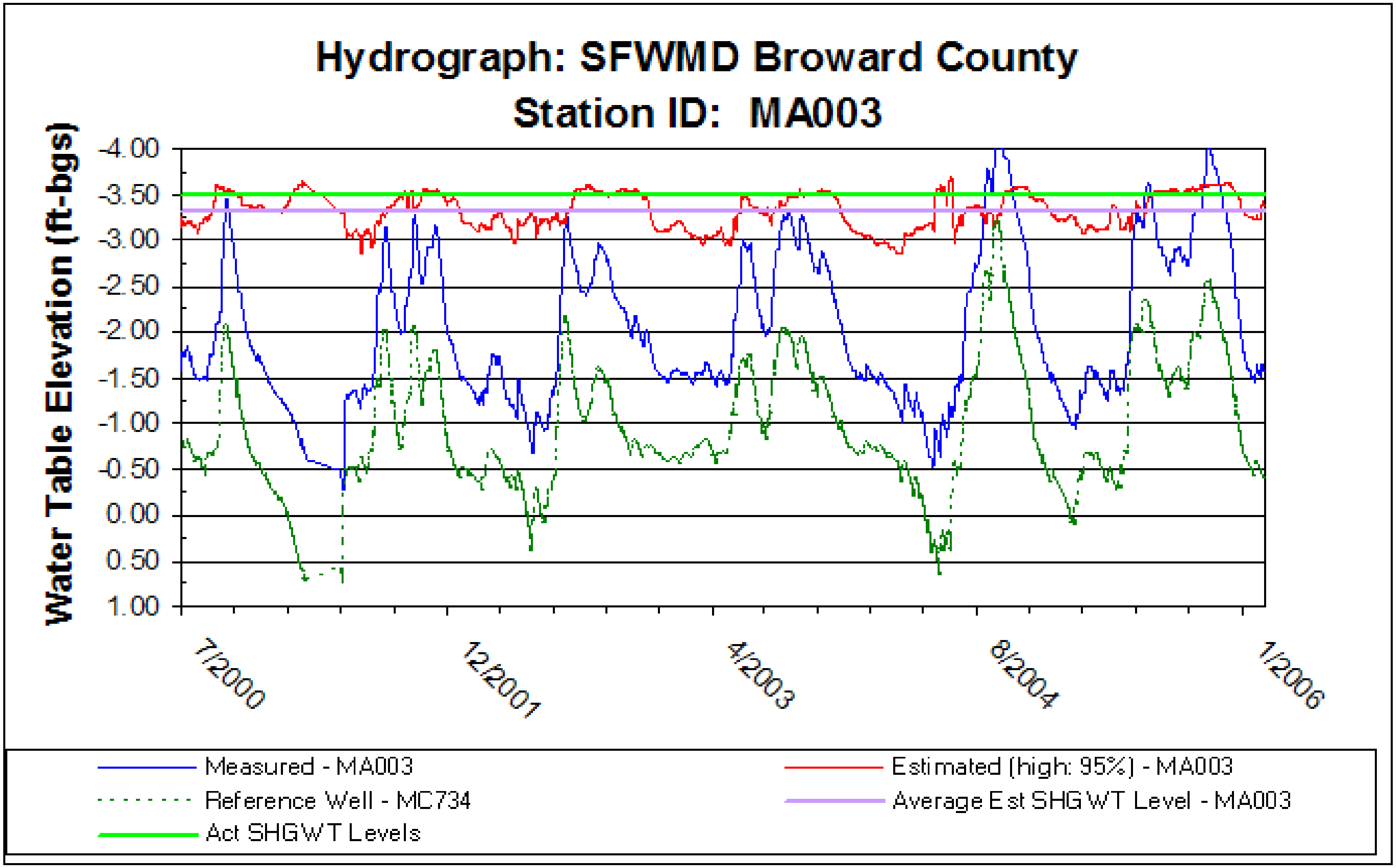
Predicted High Water Level

- Wells ~ 0.25 miles apart
  - (Actual SHGWT – Average Estimated SHGWT)< 0.25 ft



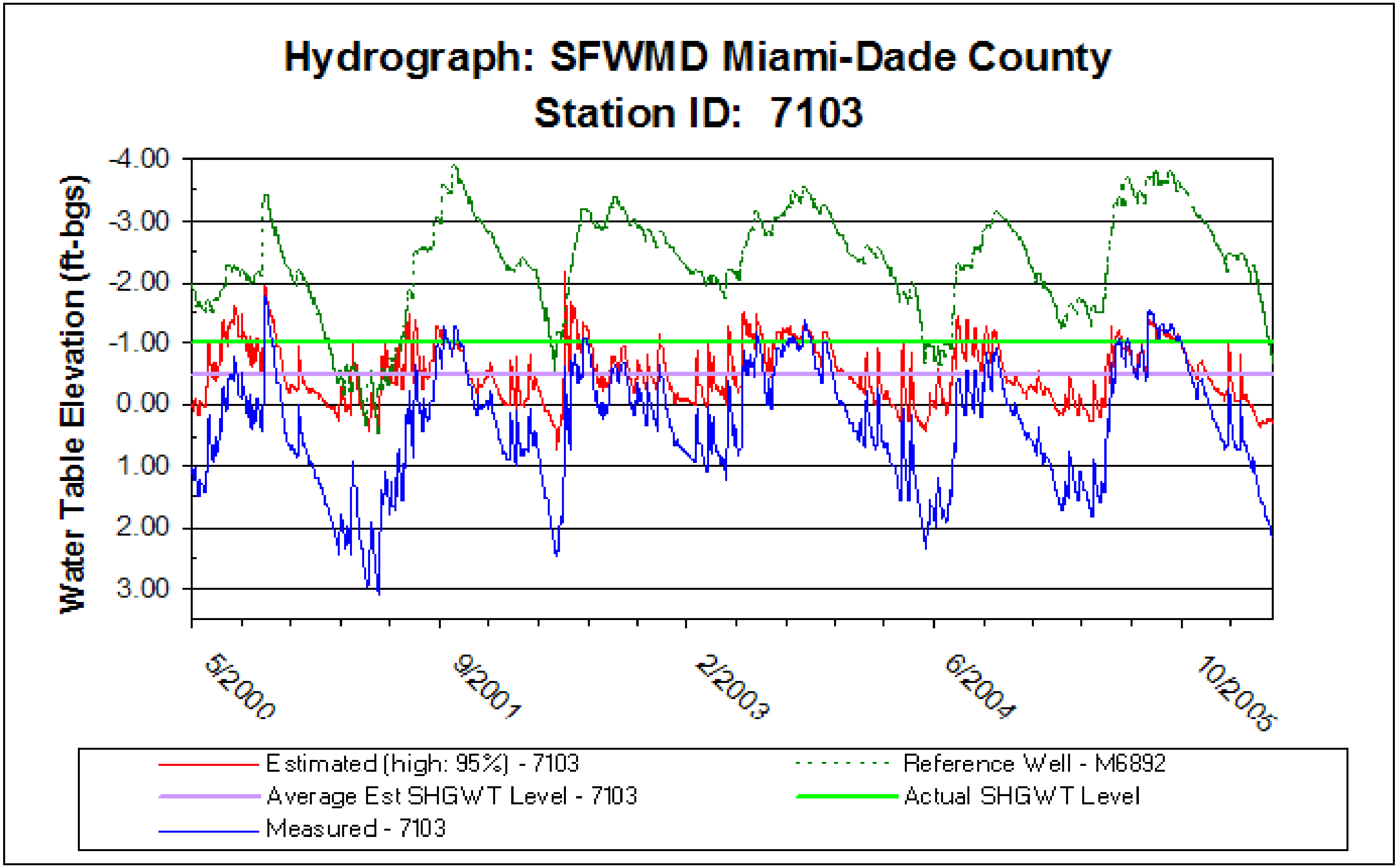
Predicted High Water Level

- Wells ~ 1.5 miles apart
  - (Actual SHGWT – Average Estimated SHGWT)< 0.5 ft



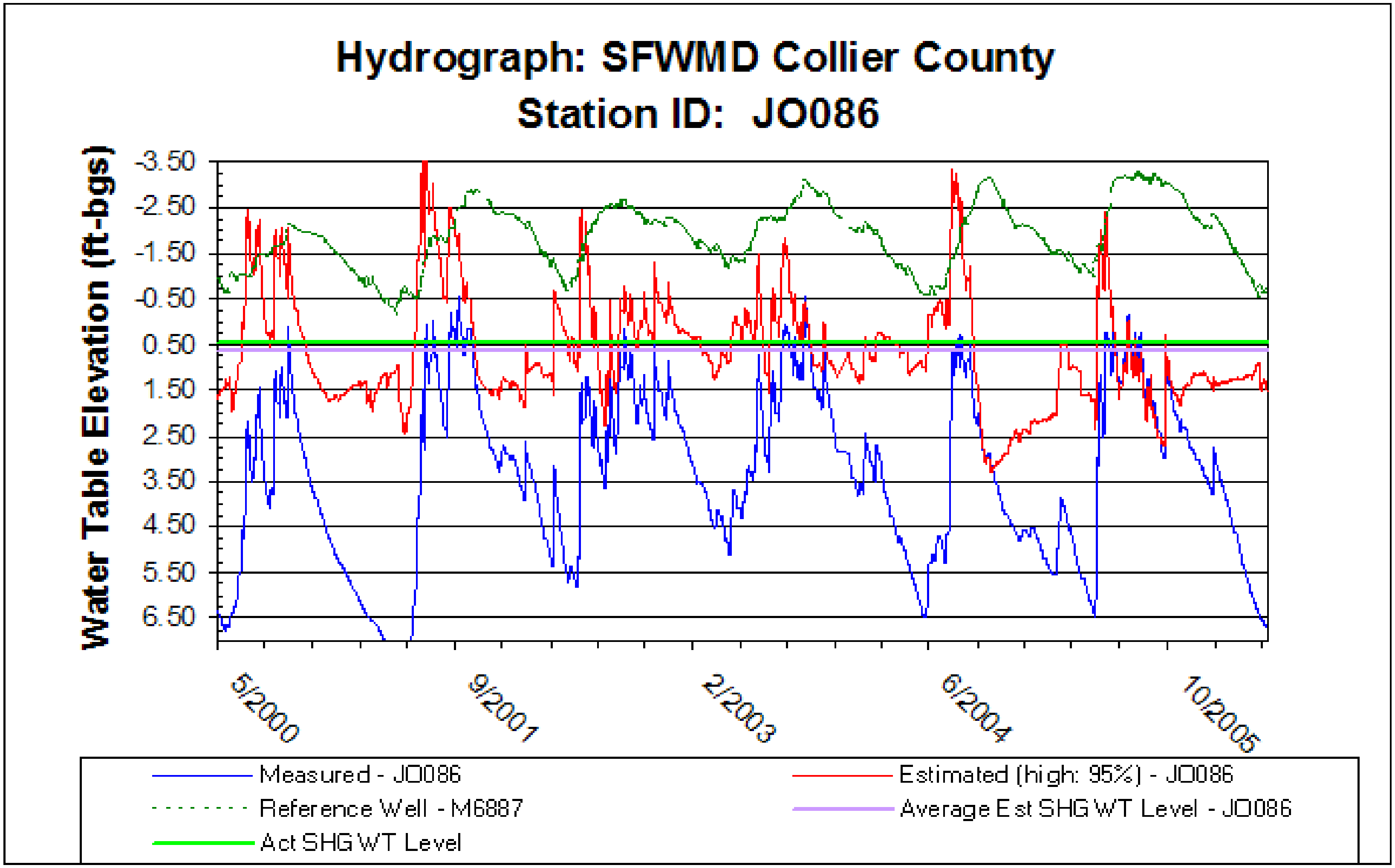
Predicted High Water Level

- Wells ~ 6.0 miles apart
  - (Actual SHGWT – Average Estimated SHGWT)~ 0.5 ft



Predicted High Water Level

- Wells >100 miles apart
  - (Actual SHGWT – Average Estimated SHGWT)< 0.5 ft



Program Limitations

- Limited number of Reference Wells representing a large geographic area with varying characteristics and climatic occurrences

Continued Validation

- Examine what length of time required to predict a reasonable average SHGWT level.
  - Is this dependent upon any other aquifer characteristic
    - soil type, vegetation, relationship between water table depths and distance between wells
- Determine impact ponding conditions have on results
  - Are there circumstances where method is invalid?
- Include more wells in analysis to achieve more complete coverage of each zone.

Referenced Literature

- Soccolow, R.S., M.H. Frimpter, M. Turtora, and R.W. Bell. 1994. A Technique for estimating groundwater levels at sites in Rhode Island from observation-well data. U.S. Geological Survey, Water-Resources Investigations Report 94-4138.
- Frimpter, M.H. 1981. Probable high groundwater levels in Massachusetts: U.S. Geological Survey Water Resources Investigations Open File report 80-1008, 20 p.

Glossary of Terms

Term	Definition
# Selected Wells	The number of index wells selected for the current analysis.
# Wells in Zone	This is the total number of index wells that are in the defined zone where the site of interest is located.
# Wells to be Graphed:	This is the number of Sh vs Exceedance Probability graphs to be created by the program. The graphs illustrate the estimated probability that a ground water depth will be equaled or exceeded using the closest Index Wells to the site of interest.
***Max Range of Depth bgs (± feet):**	This value will be added and subtracted (+/-) from the site of interest's water table depth value and the results define a range of values that is used to select the Index Wells. This is accomplished by first calculating the average water table depth observed at the index well on the date that the observation was taken at the site of interest. An Index Well is selected if the average depth to ground water on the observation date falls within the range of ground water depth values defined by the 'Max Range of Depth' value. This function is used only to provide flexibility in the selection of the Index Wells.
AASHTO	American Association of State Highway and Transportation Officials developed soil terminology or classifications to be used specifically for geotechnical engineering purposes. It is based on particle-size distribution and Atterberg limits, such as liquid limit and plasticity index. This classification system is covered in AASHTO Standard No. M 145-91 (1995) and consists of a symbol and a group index. The classification is based on that portion of the soil that is smaller than 3 inches in diameter.
AGENCY	Defines the water management district or regulating agency that is operating the observation well.
BASIN	Defines the basin and sub-basin that the observation well resides in.
bgs	below ground surface
County	The County that the site of interest is located within
COUNTY	Defines the County that the well resides in.
DATA_TYPE	The type of data that is represented by the observation (i.e. water level (NGVD29), sulfide, water temperature).
END_DATE	The last date that an observation is recorded.
EstWtrLevel	Estimated Water Level Worksheet that contains output data, including: distance between the Index Well and the Site of Interest, average water table elevation at the Index Well occurring on the date that the observation at the site of interest was taken (this is for the entire period of record for the Index Well); estimated high, low and median values for the site of interest based on data from each Index Well; and comments that would indicate the relationship between the Index Well and Site of Interest observations.
Exceedance Probability (%)	This is the user defined exceedance probability (level of risk) that is used in calculating the high and low Sr values. The smaller the exceedance probability the larger the range of high, low and median estimated water levels.
File Name	User defined file name that will be used when the document is saved.

FREQUENCY	The frequency at which the summary data, or raw data, is stored on the database. DA, for daily data, means there is one value per day on the database. It does not mean this particular data set changes, or is appended to, every day.
GROUP_NAME	Represents a logical grouping of the time series associated with a common name.
Kiss	Refers to the Kissimmee Water Basin that is the northernmost sub-basin within the SFWMD boundaries consisting of parts or all of Orange, Osceola, Polk, Okeechobee, Highlands, and Glades counties.
LAT	Latitude in DDMMSS.
Latitude	The latitude of the site of interest - must be in decimal format (XX.XXXX).
LEC_N	Refers to northern section of the Lower East Coast Water Basin that is a sub-basin within the SFWMD boundaries consisting of parts or all of Palm Beach, Broward, Hendry, and Collier Counties.
LEC_S	Refers to the southern section of the Lower East Coast Water Basin that is a sub-basin within the SFWMD boundaries consisting of parts or all of Miami-Dade and Monroe Counties.
LON	Longitude in DDMMSS.
Longitude	The longitude of the site of interest - must be in decimal format (XX.XXXX).
LWC	Refers to the Lower West Coast Water Basin that is a sub-basin within SFWMD boundaries consisting of parts or all of Glades, Charlotte, Lee, Hendry, Collier, and Monroe Counties.
Max Lag b/w Observations (days)	This is used to define the Wc value (measured depth to ground water at the Index Well on the Observation date) in the Frimpter Equation. This is used in case there is no observation taken at the Index Well on the observation date. The user defined value is used to define the maximum number of days prior to or after the observation date that a ground water depth measurement at the Index Well can be used for estimating ground water depths at the site of interest.
MAX OBS	References the maximum observation observed over the entire historical period of record - recorded in feet below ground surface.
MIN OBS	References the minimum observation observed over the entire historical period of record - recorded in feet below ground surface.
Observation Date	The day that a measurement of depth to the water table was taken. This can be entered in any format and the program will read as data mm/dd/yyyy.
RANGE	Sections of land in Florida are referenced according to the Township, Range, and Section System (otherwise known as the Congressional Land Survey System). The District assigns a township, range and section to each location for which data is received. Each Congressional township is divided into 36 sections of land with each section approximately one square mile. Each township is described as a number of rows or tiers north or south of a baseline. A range is referenced according to a number east or west of a principal meridian. There are some areas, however, where the Congressional Land Survey System was not completed. An example of this is in the middle of Lake Okeechobee. In such areas the township and range are null or zero.
RECORDER	Defines the type of recording device or method being used at each observation well.

REFERENCE WELL ID	An identifier unique to each observation well (time-series observations) referenced as the DBKEY value. DBKEY's are programmatically assigned in a sequential manner.
SECTION	Sections of land in Florida are referenced according to the Township, Range, and Section System (otherwise known as the Congressional Land Survey System). The District assigns a township, range and section to each location for which data is received. Each Congressional township is divided into 36 sections of land with each section approximately one square mile. Each township is described as a number of rows or tiers north or south of a baseline. A range is referenced according to a number east or west of a principal meridian. There are some areas, however, where the Congressional Land Survey System was not completed. An example of this is in the middle of Lake Okeechobee. In such areas the township and range are null or zero.
Sh	Estimated depth to high water level at the site of interest (feet - bgs)
Sl	Estimated depth to low water level at the site of interest (feet - bgs)
Sm	Estimated depth to median water level at the site of interest (feet - bgs)
Sr, High/Low (feet)	The high/low range of water level within a zone (feet). This value is calculated using the linear regression equation determined by the exceedance probability curve developed based on the maximum water level ranges of each of the index wells in the corresponding zone. The equation is y = mx + b, where, y is the maximum range, x is the exceedance probability value (%), and m and b are the slope and intercept, respectively, defined by the linear regression trend line. In this case, X = user defined exceedance probability value.
Sr, Median (feet)	The median range of water level within a zone (feet). This value is calculated using the linear regression equation determined by the exceedance probability curve developed based on the maximum water level ranges of each of the index wells in the corresponding zone. The equation is y = mx + b, where, y is the maximum range, x is the exceedance probability value (%), and m and b are the slope and intercept, respectively, defined by the linear regression trend line. In this case, X = 50 representing the 59% exceedance probability.
START_DATE	The first date that an observation is recorded.
STATION	The location at which the time series was recorded. A station has a specific latitude and longitude with which it is associated.
STATISTIC_	Defines how and when an observations are made at each well (i.e. morning reading, mean value for interval, maximum value for interval, lowest tide)
STRATA	A z-coordinate relative to the local ground elevation for most cases. For groundwater wells, strata are equal to the distance (feet) from land surface to the bottom of the monitored interval (i.e. bottom of screen depth or open hole) and are a positive number.

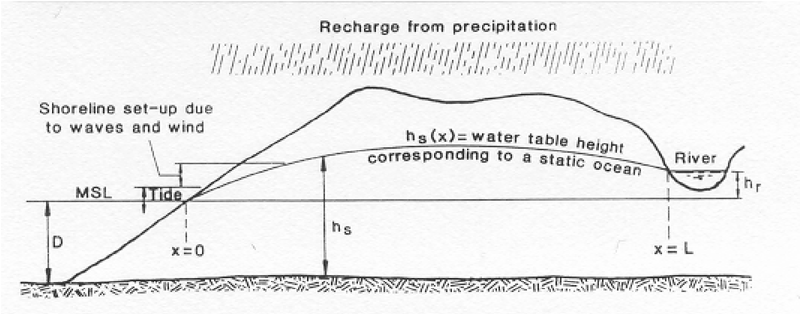
TOWNSHIP	Sections of land in Florida are referenced according to the Township, Range, and Section System (otherwise known as the Congressional Land Survey System). The District assigns a township, range and section to each location for which data is received. Each Congressional township is divided into 36 sections of land with each section approximately one square mile. Each township is described as a number of rows or tiers north or south of a baseline. A range is referenced according to a number east or west of a principal meridian. There are some areas, however, where the Congressional Land Survey System was not completed. An example of this is in the middle of Lake Okeechobee. In such areas the township and range are null or zero.
UEC	Refers to the Upper East Coast Water Basin that is a sub-basin within SFWMD boundaries consisting of parts or all of Okeechobee, St. Lucie, and Martin counties.
Water Management District	The water management district that the site of interest is located within.
Water Table Depth (feet bgs)	The measured depth of the water table below ground surface at the site of interest taken on the observation date.
Wc	Measured depth to water level at the Index Well (feet - bgs)
WellPairs	Well pair summary worksheet - contains summary data regarding all well pairs related to the selected Index Wells.
Wh	Depth to high water level (95th percentile) at the Index Well (feet - bgs)
Wl	Depth to low water level (5th percentile) at the Index Well (feet - bgs)
Wm	Depth to median water level (50th percentile) at the Index Well (feet - bgs)
Wr	Maximum annual water level range recorded for the Index Well (feet - bgs)
Zone	The zone is defined by the program and is selected based on the County in which the site of interest is in. There are 5 zones which represent the 4 sub-basins that make up the SFWMD. The zones are Kissimmee (Kiss), Lower East Coast North (LEC_N), Lower East Coast South (LEC_S), Lower West Coast (LWC), and Upper East Coast (UEC).

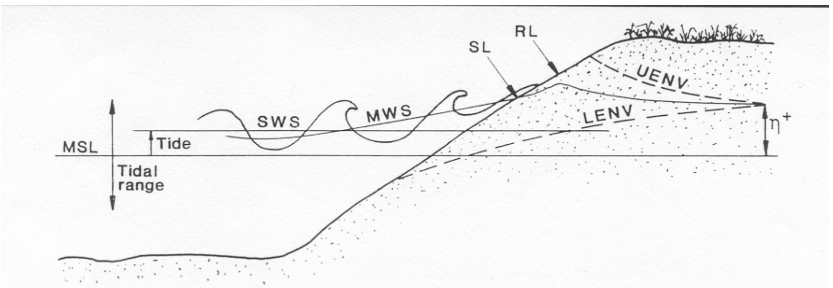
Appendix C. Tidal Application Excel Worksheet

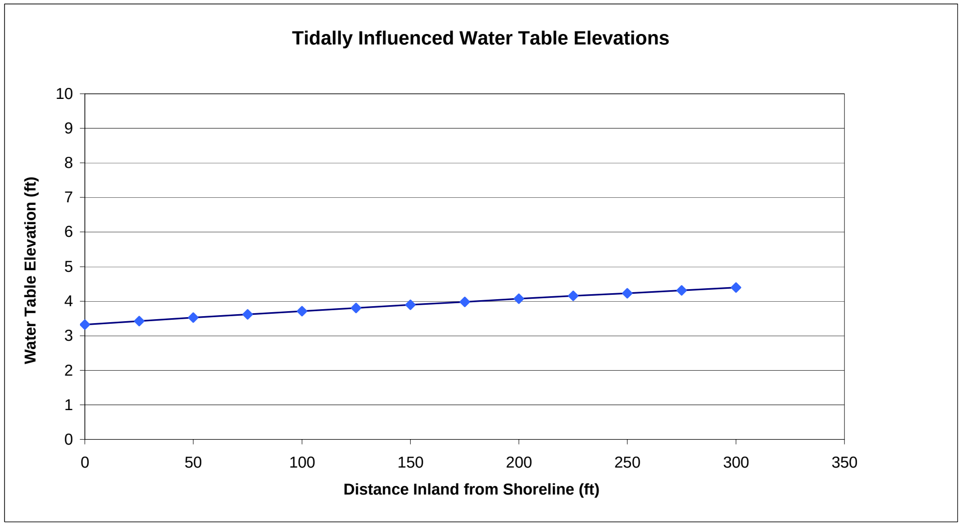
This appendix contains selected output and screen captures from SHGWT tidal application.

The SHGWT tidal application Excel Worksheet is included in the project electronic appendix (CD).

Tidally Influenced Water Table Estimates



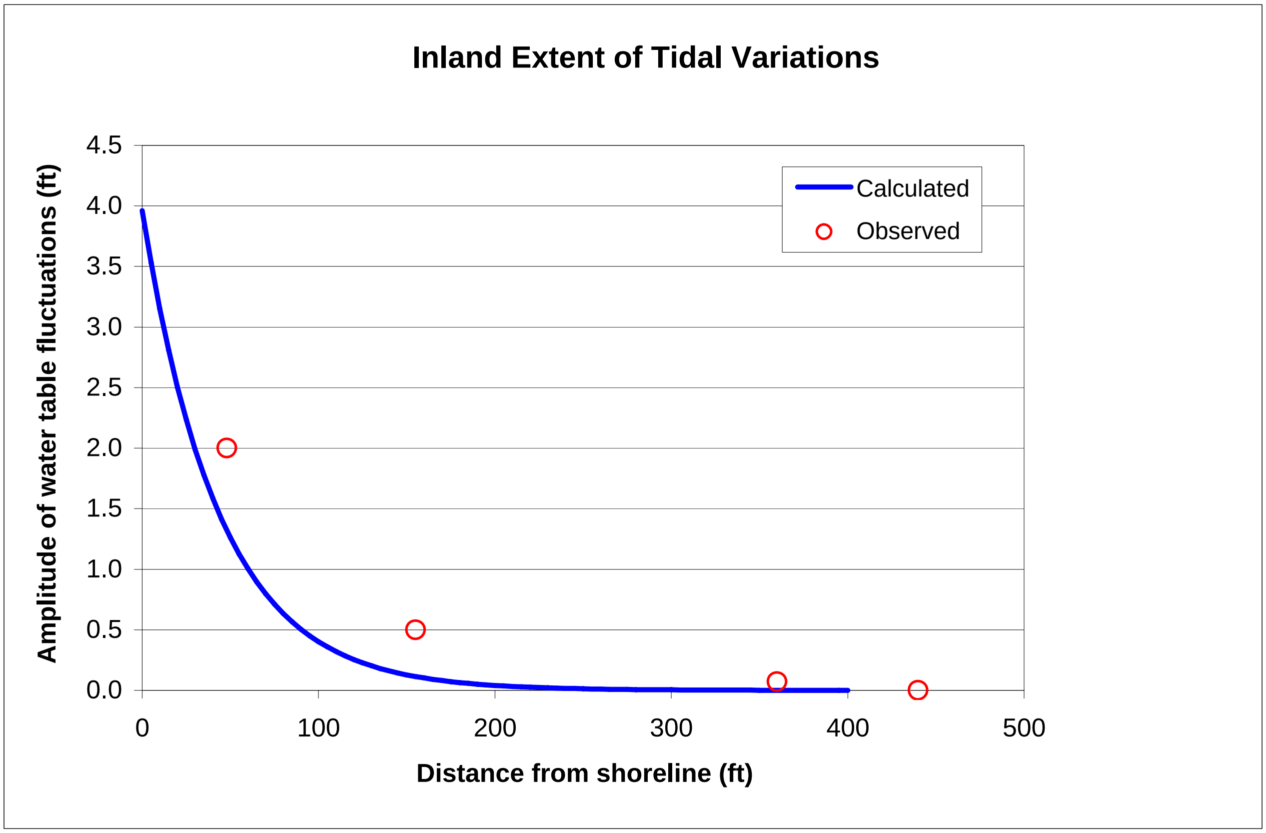




Depth of MSL above base of aquifer	D =	4	ft	
Inland location of observed water table elevations	L =	440	ft	
Water table elevation at reference location a distance L from shoreline	h_r =	2	ft	
Recharge rate (precipitation)	i =	0.01	ft/day	48 in/yr
Hydraulic conductivity	K =	80.2	ft/day	
Distance inland at which water table is to be estimated	x =	200	ft	

Inland extent of tidal variations

Tidal amplitude	h_o =	3.96 ft	3.96		
Specific yield	S_y =	0.2			
Tidal period	t_o =	1 day		K	60 ft/day
Transmissivity	T = Kb =	1200 ft^2/day		b	20 ft



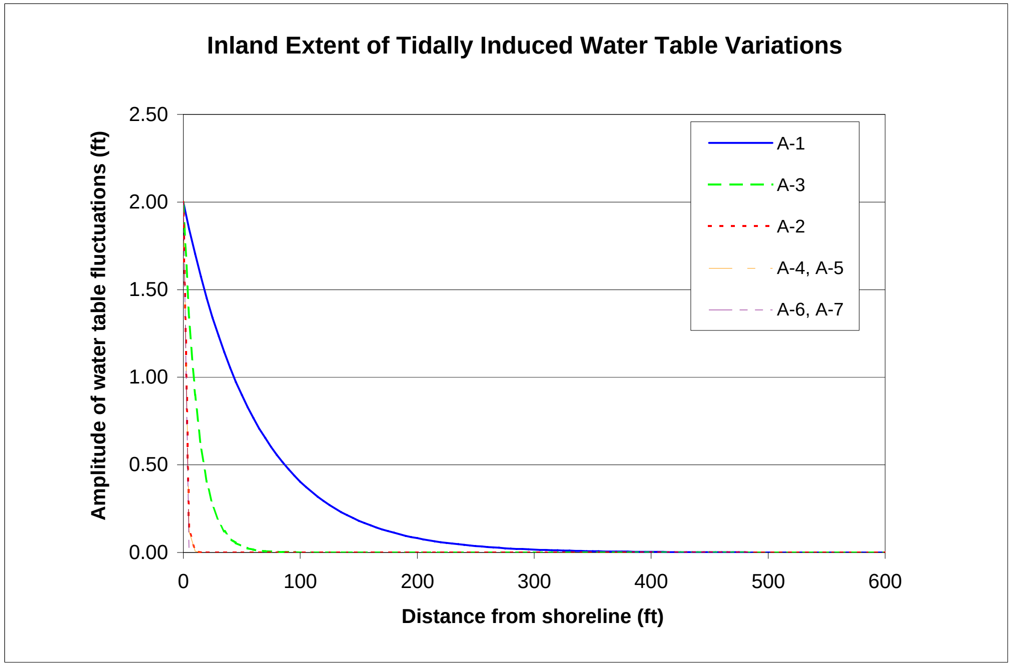
Distance from shore to site of interest

x = 100 ft

Estimated amplitude of tidal fluctuation	
A_{x} =	0.40 ft

Inland extent of tidal variations

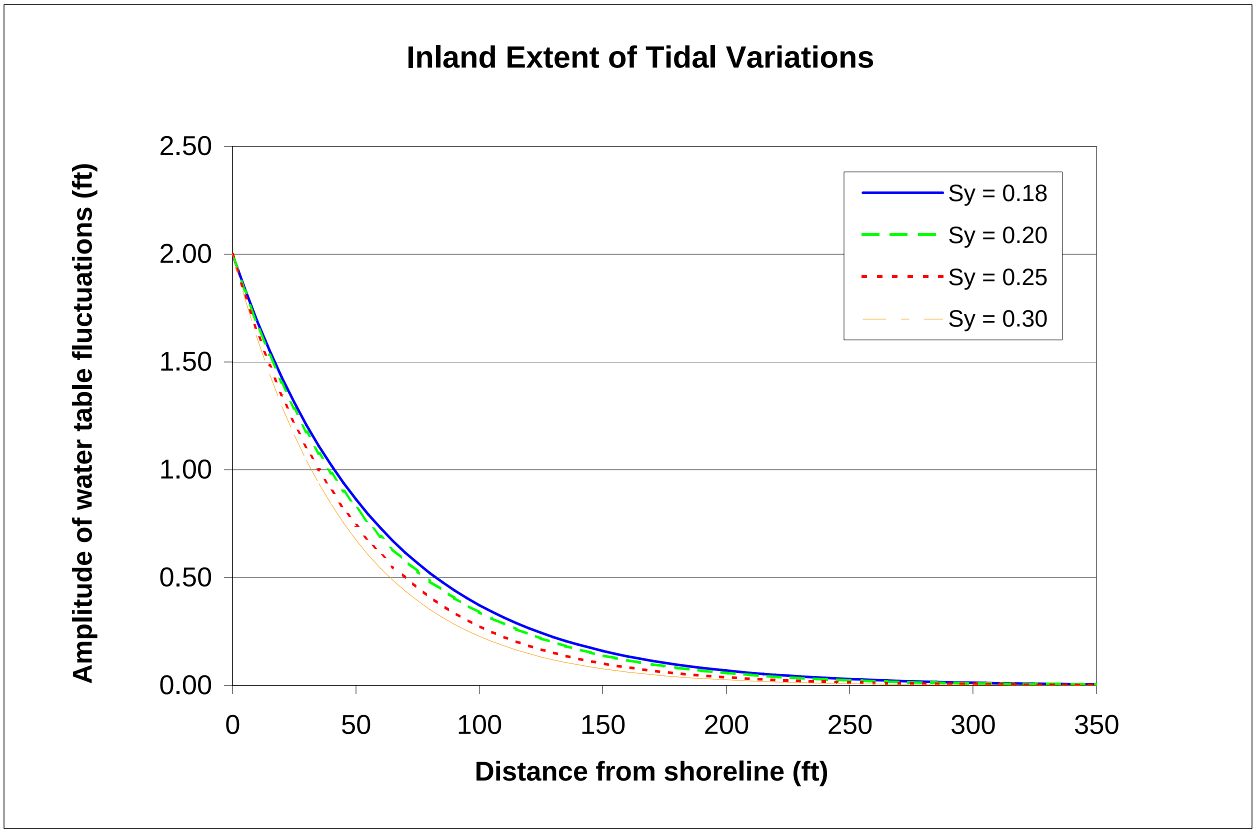
		A-1	A-3	A-2	A-4, A-5	A-6, A-7	
Tidal amplitude	h_o =	2	2	2	2	2	ft
Specific yield	S_y =	0.3	0.33	0.07	0.2	0.06	
Tidal period	t_o =	1	1	1	1	1	day
Hydraulic Conductivity	K =	147.4	6.46	0.03	0.08	0.0003	ft/day
Aquifer depth	b =	25	25	25	25	25	ft
Transmissivity	T =	3685	161.5	0.75	2	0.0075	ft^2/day



AASHTO Classification	Inland Extent (ft)	
	Lower Bound	Upper Bound
A-1	400	--
A-3	70	400
A-2	10	70
A-4, A-5	5	10
A-6, A-7	0	5

Inland extent of tidal variations

Tidal amplitude	h_o =	2	2	2	2	ft
Specific yield	S_y =	0.18	0.2	0.25	0.3	
Tidal period	t_o =	1	1	1	1	day
Transmissivity	T = Kb =	2000	2000	2000	2000	ft^2/day



Material	AASHTO Classification	Specific Yield (%)		
		Maximum	Minimum	Average
coarse gravel	A-1	26	12	22
medium gravel	A-1	26	13	23
fine gravel	A-1	35	21	25
gravelly sand	A-1	35	20	25
coarse sand	A-1	35	20	27
medium sand	A-1	32	15	26
fine sand	A-3	28	10	21
silt	A-4, A-5	19	3	18
sandy clay	A-2	12	3	7
clay	A-6, A-7	5	0	2

A-1
A-1
A-1
A-1
A-1
A-1
A-3
A-4, A-5
A-2
A-6, A-7

(Johnson 1967 as quoted by C.W. Fetter 1994)
Johnson, A.I., 1967, Specific yield--compilation of specfic yields for various materials. U.S. Geological Survey Water Supply Paper 1662-D, 74 p.
Fetter, C. W. (1994). *Applied Hydrogeology*, 3rd ed. Upper Saddle River, NJ: Prentice Hall, Inc.

From website:
http://www.co.portage.wi.us/Groundwater/undrstnd/soil.htm#Specific%20Yield

another resource:
http://www.aquifertest.com/forum/properties.htm

Material	AASHTO Classification	Hydraulic Conductivity (cm/s)			Specific Yield (%)		
		Maximum	Minimum	Average	Maximum	Minimum	Average
Gravel	A-1	3.12E+00	03.00E-02	4.03E-01	13	25	21
Coarse Sand	A-1	6.61E-01	9.00E-05	5.20E-02	18	43	30
Medium Sand	A-1	5.67E-02	9.00E-05	1.65E-02	16	46	32
Fine Sand	A-3	1.89E-02	2.00E-05	2.28E-03	1	46	33
Silt	A-4, A-5	7.09E-04	9.00E-09	2.83E-05	1	39	20
Silty/Clayey Sand	A-2-4	1.00E-03	1.00E-08	1.00E-05	3	12	7
Clay	A-6, A-7	4.70E-07	1.00E-09	9.00E-08	1	18	6

Hydraulic Conductivity (ft/day)		
Maximum	Minimum	Average
8844.09	85.0394	1142.36
1873.70	0.2551	147.40
160.72	0.2551	46.77
53.57	0.0567	6.46
2.01	2.55E-05	8.02E-02
2.83	2.83E-05	2.83E-02
1.33E-03	2.83E-06	2.55E-04

Source: Batu, 1998, Dawson and Istok, 1991

Material	AASHTO Classification	Particle Size (mm)			Porosity (dimensionless)			Specific Yield (%)			Hydraulic Conductivity (m/day)		
		Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
Very coarse gravel		32	64										
Coarse gravel		16	32		0.24	0.4		0.1	0.26		860	8600	
Medium gravel		8	16		0.24	0.44		0.13	0.45		20	1000	
Fine gravel		4	8		0.25	0.4		0.15	0.4				
Very fine gravel		2	4										
Very coarse sand		1	2										
Coarse sand		0.5	1		0.2	0.5		0.15	0.45		0.08	860	
Medium sand		0.25	0.5		0.29	0.49		0.15	0.46		0.08	50	
Fine sand		0.1	0.25		0.25	0.55		0.01	0.46		0.01	40	
Very fine sand		0.05	0.125										
Silt		0.002	0.05		0.34	0.7		0.01	0.4		1.00E-04	2	
Clay		< .002			0.33	0.7		0	0.2		< 10e-2		

Source: Chin, Water Resources Engineering Text, Pg. 612

Tidal Station Metadata

These data were obtained from the website:

http://140.90.121.76/data_retrieve.shtml?input_code=100301000acc

The information was pulled individually from the listing for each site using the units of FEET

Datum information is available under: reports-National Geodetic Survey

Accepted Datums (W7) - National Tidal Datum Epoch (1983-2001)

Station -- Unique seven character identifier for the station
MHHW -- Mean Higher-High Water
MHW -- Mean High Water
DTL -- Mean of MHHW and MLLW
MTL -- Mean of MHW and MLW
MSL -- Mean Sea Level
MLW -- Mear
MLLW -- Mean Lower-Low Water
GT -- Difference between MHHW and MLLW
MN -- Difference between MHW and MLW
DHQ -- Difference between MHHW and MHW
DLQ -- Difference between MLW and MLLW
HWI -- Greenwich Mean High Water Interval in Hours
LWI -- Greenwich Mean Low Water Interval in Hours

Elevations are in Feet - referenced to station datum

NGVD29: Reference surface established by the US Coast and Geodetic Survey in 1929
as the datum to which elevation data were referenced.
It is based on the mean sea level in the conterminous United States.

NAVD88:

http://www.ngs.noaa.gov/PUBS_LIB/NAVD88/navd88report.htm