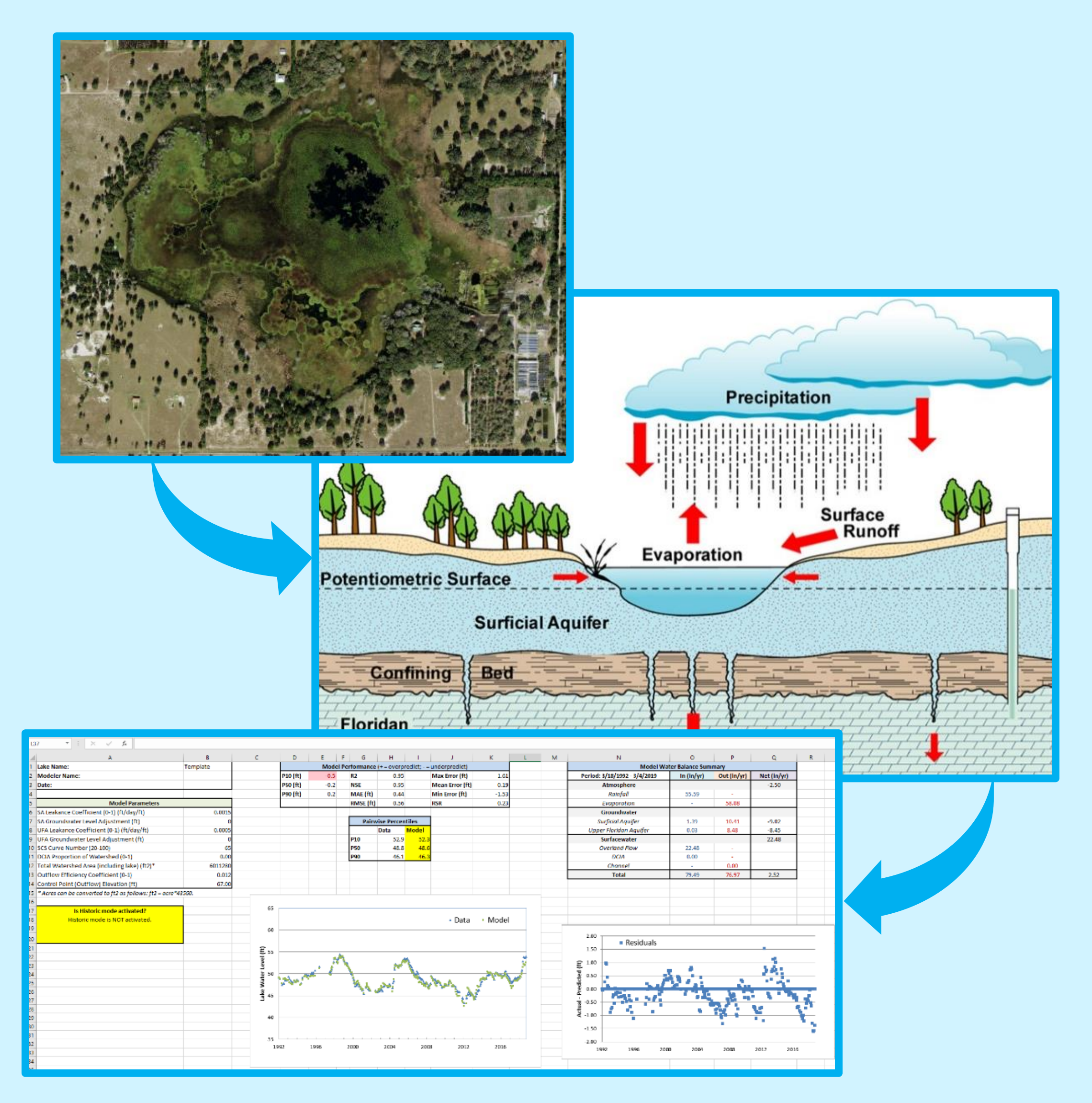
Lake Water Budget Models: Construction and Application to Support the Development of Lake Minimum Levels



	A	B
1	**Lake Name:**	Template
2	**Modeler Name:**	
3	**Date:**	
5	**Model Parameters**	
6	SA Leakance Coefficient (0-1) (ft/day/ft)	0.0015
7	SA Groundwater Level Adjustment (ft)	0
8	UFA Leakance Coefficient (0-1) (ft/day/ft)	0.0005
9	UFA Groundwater Level Adjustment (ft)	0
10	SCS Curve Number (20-100)	65
11	DCIA Proportion of Watershed (0-1)	0.00
12	Total Watershed Area (including lake) (ft2)*	6011280
13	Outflow Efficiency Coefficient (0-1)	0.012
14	Control Point (Outflow) Elevation (ft)	67.00
15	*Acres can be converted to ft2 as follows: ft2 = acre*43560.	

Is Historic mode activated?
Historic mode is NOT activated.

Model Performance (+ = overpredict; - = underpredict)					
P10 (ft)	0.5	R2	0.95	Max Error (ft)	1.61
P50 (ft)	-0.2	NSE	0.95	Mean Error (ft)	0.19
P90 (ft)	0.2	MAE (ft)	0.44	Min Error (ft)	-1.53
		RMSE (ft)	0.56	RSR	0.23

Pairwise Percentiles	Data	Model
P10	52.9	52.3
P50	48.8	48.6
P90	46.1	46.3

Model Water Balance Summary			
Period: 3/18/1992 - 3/4/2019	In (in/yr)	Out (in/yr)	Net (in/yr)
Atmosphere			-2.50
Rainfall	55.59	-	
Evaporation	-	58.08	
Groundwater			
Surficial Aquifer	1.39	10.41	-9.02
Upper Floridan Aquifer	0.03	8.48	-8.45
Surfacewater			22.48
Overland Flow	22.48	-	
DCIA	0.00	-	
Channel	-	0.00	
Total	79.49	76.97	2.52

July 1, 2022

Southwest Florida
Water Management District

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Table of Contents

Introduction and Background

This report describes the conceptualization of a water budget model and processes used for lake minimum levels development, with reference to a template model spreadsheet, *Lake Water Budget Model Template.xlsx*. For definitions of the terms “minimum level”, “P10”, “P50”, “P90,” and “Historic” used throughout this report, see Rules 40D-8.021 and 8.624, Florida Administrative Code.

Water budgets (also called water balances) are widely used to represent hydrologic fluxes for lakes and other waterbodies (e.g., Healey et al., 2007; Mitchell & Jawitz, 2013). Using this approach, change in lake stage or volume can be calculated as the difference between its summed inflows and summed outflows over a specified time period.

Examples of studies using water budgets for specific Florida lakes include Fellows & Brezonik (1980), Deevey (1988), Sacks et al. (1992), Belanger & Kirkner (1994), Grubbs (1995), Lee & Swancar (1997), Motz (1998), Sacks et al. (1998), Swancar et al. (2000), Motz et al. (2001), Watson (2001), Metz & Sacks (2002), McBride et al. (2010), Viridi & Sacks (2012), Swancar (2015), and McBride et al. (2017). Schiffer (1998) provides a generalized overview of the hydrology and water budgets of central Florida lakes, and Healy et al. (2007) explore the use of water budgets for water resource management, including an example from Florida. Water budgets have also been used by the Southwest Florida Water Management District for the development of minimum levels for numerous lakes.

Among these studies, inflows universally include precipitation directly on the lake, while outflows include evaporation from the lake and leakage to the groundwater system. Depending on the lake and study, inflows can also include groundwater fluxes, overland flow, augmentation to the lake, and contributions from other surface waterbodies (such as streams), while outflows can include direct surface withdrawals and losses through structures or channels.

The water budget model implemented by the District for the development of minimum lake levels is a calibrated spreadsheet model that tracks lake water inputs and outputs on a daily timestep to calculate an estimated lake water level. The default model includes precipitation, evaporation, surficial aquifer fluxes, Upper Floridan aquifer fluxes, overland flow, directly connected impervious area (DCIA) runoff, and surface outflow from a single fixed-elevation structure. A conceptual diagram of the water budget is shown in Figure 1.

This conceptualization is generally adequate to describe the water balance for many District lakes. On an as-needed basis, channel inflows, additional surface outflows, augmentation, direct surface withdrawals, or other terms can be added. However, no model can perfectly represent the complex physical reality, and professional scientific judgement is essential when developing the models, interpreting their results, and applying them in decision-making processes. The following section describes the terms and equations used in the default water budget model, with reference to a template file, *Lake Water Budget Model Template.xlsx*.

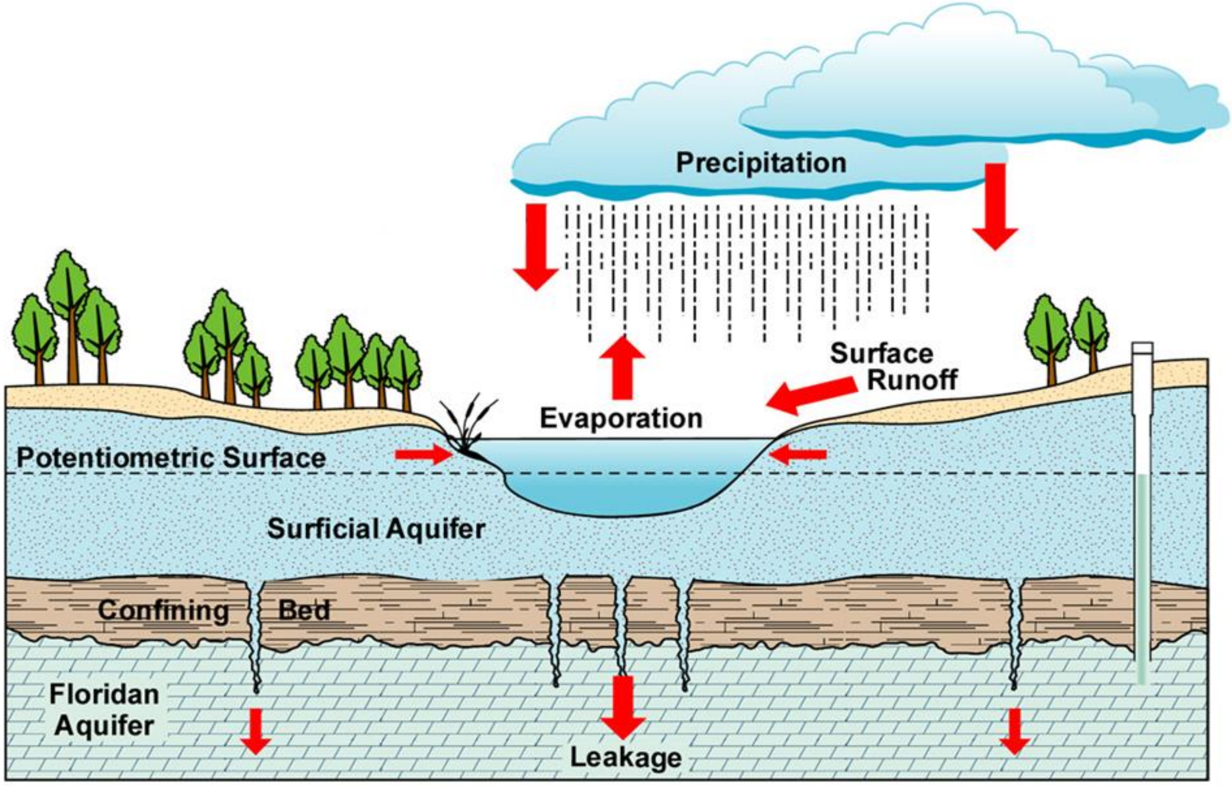

Figure 1. Major components of a lake water budget (surface outflow and DCIA not shown).

Water Budget Model Terms and Equations

Overview

In a lake with a single outflow from a single fixed-elevation structure, no augmentation, no direct surface withdrawals, and no channelized inflow, the water budget model can be simplified as Equations 1 and 2, where `LAKE` is the lake stage, $\Delta \texttt{S}$ is the change in storage, `RAIN` is rainfall directly onto the lake, `EVAP` is evaporation directly from the lake, `NET_UFA` is net exchange between the lake and Upper Floridan aquifer (positive or negative), `NET_SA` is net exchange between the lake and surficial aquifer (positive or negative), `OVERLAND` is overland flow into the lake from its watershed, `DCIA` is runoff from impervious surfaces directly connected to the lake, and `CHAN_OUT` is surface outflow from a fixed-elevation structure from the lake, all in linear units (ft).

$$(1)\quad \texttt{LAKE}_n = \texttt{LAKE}_{n-1} + \Delta \texttt{S}_n$$

$$(2)\quad \Delta \texttt{S}_n = \texttt{RAIN}_n - \texttt{EVAP}_n + \texttt{NET\_UFA}_n + \texttt{NET\_SAS}_n + \texttt{DCIA}_n + \texttt{OVERLAND}_n - \texttt{CHAN\_OUT}_n$$

The change in storage can be added to the prior day's lake stage to calculate an estimated lake stage for the current day. In the template water budget model spreadsheet, Equations 1 and 2 are implemented in the *WB Calculations* worksheet in Column U. Required inputs and parameters for the model are summarized in Table 1.

LAKE

For the first day of a model simulation, $\texttt{LAKE}_n$ is initialized using an observed lake water level elevation. Starting with the second day of the simulation, $\texttt{LAKE}_n$ is calculated using Equations 1 and 2. Lake water level data are available from the District's Environmental Data Portal (EDP)[1].

In the template water budget model spreadsheet, observed lake data are input into the *Input*| *Hydrologic Data* worksheet in *Column B*, where the first reading will be used to initialize the lake stage in the water budget model. Therefore, *Cell B2* is required, but additional lake values are optional and are used to calculate residuals, by comparing pairwise model predictions to observed lake data, to assess model performance. On the *WB Calculations* worksheet, *Column U* has the predicted daily lake stages as calculated by the model. On the *Input*| *Parameters & Performance* worksheet, figures are shown of modeled and observed lake water levels.

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[1] https://internaledp/applications/logininternal.html?publicuser=internal

Table 1. Summary of required inputs and parameters for the default water budget model, with location in the template spreadsheet. Calibrated parameters are shown in *italics*.

Term	Description	Worksheet, Column/Cell
LAKE$_n$	Lake stage elevation (ft)	Input| Hydrologic Data, B (observed) WB Calculations, U (modeled)
RAIN$_n$	Rainfall (ft*)	Input| Hydrologic Data, E*
L_UFA	Upper Floridan leakance coefficient (0-1) (ft/d/ft)	Input| Parameters & Performance, B8
UFA$_n$	Upper Floridan groundwater level elevation (ft)	Input| Hydrologic Data, D (water levels) Input| Parameters & Performance, B9 (adjustment
SA$_n$	Surficial aquifer groundwater level elevation (ft)	Input| Hydrologic Data, C (water levels) Input| Parameters & Performance, B7 (adjustment)
L_SA	Surficial aquifer leakance coefficient (0-1) (ft/d/ft)	Input| Parameters & Performance, B6
CN_{II}	Curve number, AMCII (20-100) (dimensionless)	Input| Parameters & Performance, B10
AREA_WS	Area of lake's watershed, inclusive of the lake (ft^2)	Input| Parameters & Performance, B12
AREA_LAKE$_n$	Area of the lake, based on current lake stage and stage-area curve (ft^2)	Input| Stage-Area, A (stage) and B (area)
P_DCIA	Directly connected impervious area (0-1) (dimensionless)	Input| Parameters & Performance, B11
K_O	Structure efficiency coefficient (0-1) (ft/day/ft)	Input| Parameters & Performance, B13
CTRL_PT	Elevation of structure or feature (natural or manmade) controlling surface outflow from the lake (ft)	Input| Parameters & Performance, B14

** This value is entered in units of in, and the model handles conversion to units of ft.*

RAIN

$\texttt{RAIN}_n$ is used to calculate rainfall falling directly onto the lake and is also used in runoff calculations ($\texttt{DCIA}_n$ and $\texttt{OVERLAND}_n$). Rainfall is compiled using the best available data, typically using radar rainfall[2] or the nearest rain gage with quality data. Daily data are required for the entire model period. To achieve this, the data source can vary throughout the model as needed.

Rainfall data are available from the District's EDP. The Climate Data Online[3] service of the National Oceanic and Atmospheric Administration may include sites not available in EDP, and in some cases, local and regional agencies (such as water utilities) may have additional rainfall data.

In the template water budget model spreadsheet, rainfall data (in units of inches; the model handles conversion) are input into the *Input| Hydrologic Data* worksheet in *Column E*. On the *Input| Parameters & Performance* worksheet, under the "Model Water Balance Summary" table, *Cell O4* shows the average annual flux for rainfall for the entire model period. Additionally, the *Diagnostic Graphs* worksheet displays the rainfall time series.

EVAP

Swancar (2015) found that seasonal evaporation rates are generally similar for lakes in central Florida that have similar depths. Using an energy budget method, the study evaluated data from Lake Starr in Polk County and Lake Calm in Hillsborough County and found that, despite 60 miles of (mostly east-west) distance between the lakes, their evaporation rates were nearly identical.

Therefore, the template water budget uses Lake Starr evaporation data available from work associated with Swancar et al. (2000) and Swancar (2015). For any period in the model that falls within August 1996 to July 2011 (the period for which Lake Starr evaporation data are available), Lake Starr monthly total evaporation data are disaggregated into daily total evaporation time series (assuming a uniform distribution) and used in the model. For months that occur before August 1996 or after July 2011, period-of-record means for the month of the year from the Lake Starr evaporation data are used (i.e., a repeating time series), disaggregated into daily values.

Therefore, no input is required on the modeler's part for $\texttt{EVAP}_n$, unless a change to evaporation data is needed. For example, for lakes located at the extreme northern or

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[2] http://shnyprod01.ad.swfwmd.net:3838/dcb/NexradDataRetrieval/

[3] https://www.ncdc.noaa.gov/cdo-web/

southern ends of the District, Lake Starr evaporation data may not be representative, necessitating small adjustments to evaporation (e.g., Cameron & Ellison, 2020).

In the template water budget model spreadsheet, default evaporation data are built into the *Evap Lookup* worksheet, which is referenced in the *WB Calculations* worksheet in *Column P*. On the *Input| Parameters & Performance* worksheet, under the “Model Water Balance Summary” table, *Cell P5* shows the average annual flux for evaporation for the entire model period. Additionally, the *Diagnostic Graphs* worksheet displays the evaporation time series.

NET_UFA

Fluxes between the lake and Upper Floridan aquifer ($\texttt{NET\_UFA}_n$, ft) can be estimated using a Darcian approach that multiplies the vertical head difference between the Upper Floridan ($\texttt{UFA}_n$, ft) and (modeled) lake ($\texttt{LAKE}_n$, ft) water level elevations by a leakance coefficient ($\mathtt{\mathit{L\_UFA}}$, ft/d/ft) as shown in Equation 3.

$$(3)\quad \texttt{NET\_UFA}_n = \mathit{L\_UFA} * (\texttt{UFA}_n - \texttt{LAKE}_n)$$

Upper Floridan aquifer (UFA) water levels are obtained from the nearest representative Upper Floridan well with quality data. UFA water level data are available from the District’s EDP. Daily data are required for the entire model period (i.e., monthly data must be interpolated into daily data for use in the model). Depending on typical UFA water levels at the well versus the lake, UFA water level values may be adjusted to better reflect potentiometric conditions at the lake. The adjustment value, if any is needed, can be determined through review of UFA well data from multiple sites in the area (if possible) and potentiometric surface maps (empirical or modeled), which can be used to compare UFA water levels in the area of the lake versus the well, and other relevant data. Semi-annual potentiometric surface maps are available in the District’s Geographic Information System (GIS) layers[4]. The farther the well is located from the lake, the more likely an adjustment will be appropriate. Adjustments may also be needed if either the well or lake is located near a center of heavy withdrawals that would cause localized water level changes or is located in an area of relatively steep hydraulic gradients.

Water has the potential to move downward from the lake into the UFA when its stage is higher than the UFA groundwater level, and vice versa. While $\texttt{NET\_UFA}_n$ can be positive or negative, it is usually negative at lakes, because $\texttt{LAKE}_n$ exceeds $\texttt{UFA}_n$.

Physically, leakance is equal to the average vertical hydraulic conductivity of the confining unit separating the lake and aquifer, divided by the thickness of the confining unit. Since

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[4] \\ad.swfwmd.net\swfShare\PDrive\LayerFiles

this is not precisely known at lakes, `L_UFA` is a calibration parameter (i.e., it can be changed in the lake budget model to better match simulated lake stage with observed values). It represents the ease with which water can move vertically between the lake and UFA, with higher values increasing the hydraulic connection between the lake and UFA (“leakiness”).

Given Florida’s karst hydrogeology, the leakance coefficient and associated fluxes can vary widely (e.g., Fellows & Brezonik, 1980; Deevey, 1988; Belanger & Kirkner, 1994; Grubbs, 1995; Katz et al., 1995; Lee & Swancar, 1997; Motz, 1998, Sacks et al., 1998; Swancar et al., 2000; Motz et al., 2001; Watson, 2001; Lee, 2002; Metz & Sacks, 2002; Sacks, 2002; Swancar, 2015; McBride et al., 2017). In west-central Florida, the `L_UFA` typically varies between 10^{-2} ft/d/ft (very leaky) to 10^{-6} ft/d/ft (tightly confined), with inferred lake leakiness values informed by long-term vertical head differences between the lake and UFA (larger head differences suggest tighter conditions, and smaller head differences suggest more leaky conditions). For most isolated lakes in Florida, flux varies between less than 1 to as high as 50 in/yr, with 10 to 30 in/yr typical.

To increase confidence in assessing lake-UFA hydraulic connection and reasonableness of the `L_UFA` value selected for the model, other information should be reviewed, such as lithology (review of nearby well logs), aquifer performance tests, presence of sinkholes in or near the lake, thickness of the intermediate confining unit, and the hydrogeologic province where the lake is located.

These hydrogeologic provinces are generally defined by their degree of hydraulic connection between the surficial aquifer (SA) and UFA as regionally unconfined, semi-confined, well-confined, and perched conditions (Table 2; Basso, 2019). Appendix 1 contains Basso’s (2019) report describing west-central Florida’s hydrogeologic provinces.

Additionally, the reasonableness of `L_UFA` can be assessed by converting a long-term value for `NET_UFA` into units of in/yr, as shown in Equation 4 and **Error! Reference source not found.**. This is achieved by multiplying `L_UFA` and the average vertical head difference between the lake and UFA (`LAKE-UFA`, ft) with a conversion factor, which provides the flux to the UFA from the lake (`UFA_FLUX`, in/yr). `UFA_FLUX` can be compared to the expected flux as determined by a referenced or reasonable source, such as those provided above.

`(4) UFA_FLUX = L_UFA*(LAKE-UFA)*365*12`

It would be highly unusual for flux to exceed annual precipitation values, unless an additional source, such as from augmentation or a connected stream, supplies water to the lake. Therefore, if `L_UFA` results in high values (e.g., >50 in/yr) of `UFA_FLUX` at an isolated lake, the parameter value is suspect and should be reconsidered. For example, given a leakance of 0.003 ft/d/ft and a long-term vertical head difference of 10 ft between

Table 2. Descriptive indicators for hydrogeologic province definitions (modified from Basso, 2019).

Province	Physiographic Region	SA-UFA Hydraulic Head Difference (ft)	Soil Infiltration Index (SURGO)	Slope from Nested SA-UFA Well Regression	Intermediate Confining Unit (ICU) Thickness (ft)	Typical Leakance Coefficient (ft/d/ft)
Confined	*	>20	*	<0.5	>50	1 x 10^{-4} to 1 x 10^{-6}
Semi-Confined	Yes	1 – 20	*	0.5 - 1	1 - 50	5 x 10^{-3} to 5 x 10^{-5}
Regionally Unconfined	*	<1	*	0.9 – 1.0	0 - 20	N/A
Perched	Yes	>20	C-D	<0.5	>20	N/A**

** Not used. ** = No significant hydraulic connection to the UFA. In addition to the criterion listed above, more qualitative factors such as land use/cover, depth to water table, sinkhole density, dendritic stream hydrography (or lack thereof), and aquifer permeability (karst enhanced) were also reviewed to help determine the extent of each hydrogeologic province. The combination of all information helped provide the basis for delineation of each province.*

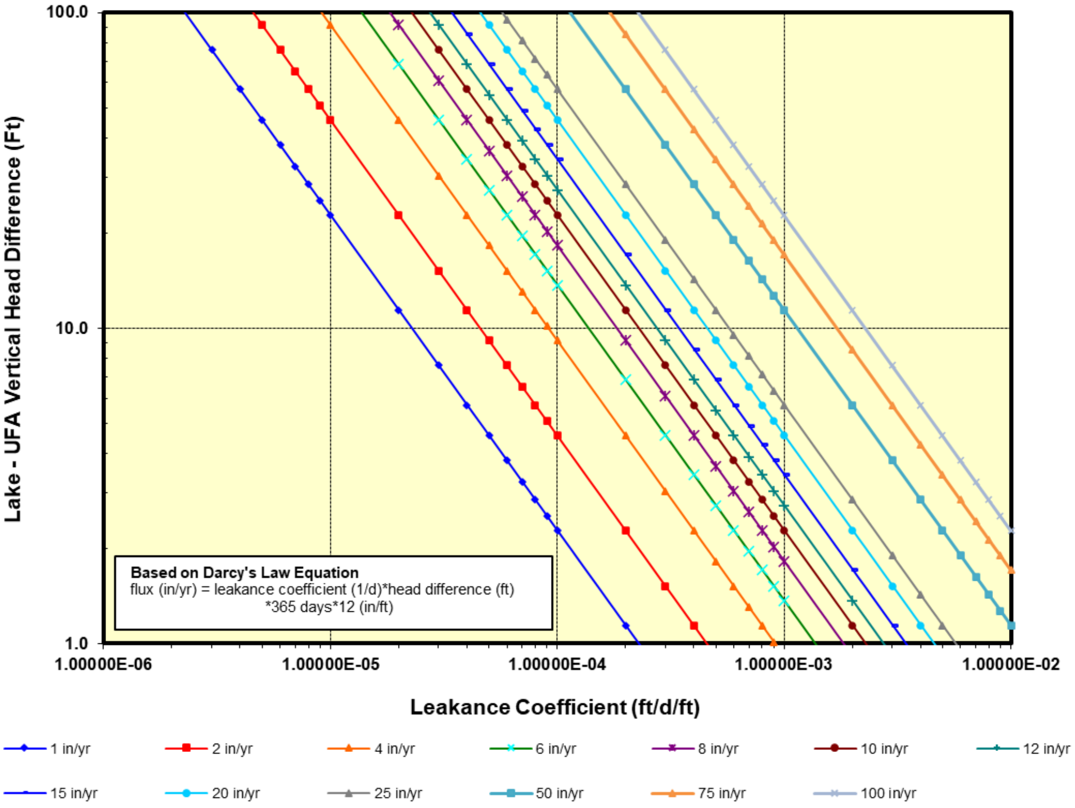

Figure 2. Graphical representation using Darcy's Law to calculate flux (diagonal lines) from the lake to the UFA given a leakance coefficient (x-axis) and long-term lake-UFA vertical head differences (y-axis).

the lake and UFA, the resulting flux would exceed 100 in/yr, a clearly unreasonable rate for an isolated lake in west-central Florida. In this case, the lake modeler would have good reason to reduce the leakance coefficient parameter to bring the flux into a more realistic range. If the water budget model calibrated well with this high leakance, and lowering the leakance caused poor model calibration, then some other parameter is likely contributing to excess inflow in the model, usually runoff or surficial aquifer seepage. In such case, adjustments to these parameters might be necessary to facilitate a smaller leakance coefficient and maintain overall model calibration. The water budget model is sensitive to L_UFA, as will be discussed later.

In the template water budget model spreadsheet, UFA water level data are input into the *Input| Hydrologic Data* worksheet in *Column D*. The leakance coefficient is entered into the *Input| Parameters and Performance* in *Cell B8*, and an optional constant groundwater level adjustment can be entered in *Cell B9*. Daily groundwater level data are required for the entire model period (i.e., monthly data must be interpolated into daily data for use in the model). In the *WB Calculations* worksheet, fluxes appear in *Column L.* On the *Input| Parameters & Performance* worksheet, under the "Model Water Balance Summary" table, *Cells O8 to Q8* show the average annual flux for the entire model period. Additionally, the *Diagnostic Graphs* worksheet displays time series of UFA water levels and fluxes.

NET_SA

Fluxes between the lake and surficial aquifer (NET_SA_n, ft) can be estimated using the difference between the surficial aquifer (SA_n, ft) and (modeled) lake ($LAKE_n$, ft) water level elevations multiplied by a leakance coefficient (L_SA, ft/d/ft), as shown in Equation 5.

$$(5)\quad NET\_SA_n = L\_SA * (SA_n - LAKE_n)$$

The leakance coefficient, L_SA, is a calibrated constant parameter, with consideration given to soils and sediments in and around the lake, the hydraulic conductivity of the surficial aquifer (SA) around the lake, and hydraulic gradient between the lake and SA. L_SA represents the ease with which water can move between the lake and SA, with higher values increasing volume of flux. Therefore, this parameter controls the amount of SA seepage into the lake.

Conceptually, L_SA should be larger than L_UFA, since the intermediate confining unit (ICU) that exists between the lake and the deeper UFA always provides some hydraulic resistance to lake-UFA interaction, whereas no distinct hydrogeologic unit separates the lake and SA. A typical value used in previous water budget models for Northern Tampa

Bay area lakes has been 0.002 ft/d/ft, which indicates a very leaky, almost direct, connection between the SA and lake. A high number such as this appears reasonable, since it seems likely that the SA would have a direct connection with the lake, with just thin and discontinuous lakebed sediments potentially separating the two. Relatively few studies on lakebed sediment thickness and hydraulic conductivity exist for Florida lakes, but reported thickness values typically range between 0 to 13 ft, while estimates of hydraulic conductivity are typically on the order of 10^{-2} ft/d, although both parameters vary within and between lakes (Sacks et al., 1992; Katz et al., 1995; Lee & Swancar, 1997; Swancar et al. 2000; Lee, 2002; Metz & Sacks, 2002; Kenney et al., 2016; Summerfield et al., 2018). Heath (1983) reports hydraulic conductivity for silts, a typical lakebed sediment, as between 10^{-3} to 10^{1} ft/d. Collectively, these suggest a central estimate of L_SA on the order of 10^{-3} ft/d/ft, but with wide variability possible. Overall, as noted in the “Future Improvements” section of this document, L_SA is poorly understood for lakes, and additional work is needed to better understand lake-SA relationships, especially since the water budget model is sensitive to L_SA, as discussed in a later section on sensitivity testing.

Water moves into the lake when the SA water level is higher than the lake stage, and vice versa, moderated by L_SA. A lake’s relationship with the SA can vary between gaining, losing, and flow-through conditions (e.g., Schiffer, 1996; Metz and Sacks, 2002; Virdi et al., 2013). Although one of these conditions may occur more commonly than the others at a given lake, a single lake can experience each of these three conditions over time, in response to changes in climate and withdrawals. Therefore, seepage can occur from the lake to the SA, but typically, the long-term net SA flux is into the lake (e.g., Lee et al., 2014), as the SA water level elevation usually exceeds the lake stage.

Using isotopic data for 81 lakes in west-central Florida, Sacks (2002) found large variability in groundwater inflow rates, ranging from 0 to >100 in/yr (representing approximately 0 to 80% of inflows), with a median of approximately 30 in/yr (representing approximately 40% of inflows). Other studies on individual lakes in Florida also vary widely in estimated groundwater inflows, typically reporting between 10 to 50 in/yr (e.g., Fellows & Brezonik, 1980; Lee & Swancar, 1997; Swancar, 2000; Motz et al., 2001; Watson et al., 2001; Virdi et al., 2013).

For the purposes of the water budget model, SA water levels are obtained from the nearest representative SA well with quality data. These data are available from the District’s EDP. Daily data are required for the entire model period (i.e., monthly data must be interpolated into daily data for use in the model). Depending on the typical SA water level at the well versus the lake, SA water level values may be adjusted to better reflect conditions at the lake. In many areas of the District, the SA locally varies with topography. The adjustment value, if any is needed, can be determined through review of topographic differences between the lake and well, as well as review of SA well data from multiple sites in the area (if possible) and review of water level surface maps (empirical or modeled), which can be used to compare SA water levels in the area of the lake versus the well. Adjustments may also be needed if either the well or lake is located near a center of heavy withdrawals that would cause localized effects or land surface elevation changes abruptly such as the Lake Wales Ridge.

As noted above, at some lakes, SA inflow occurs along some portions of the lake, with SA outflow occurring along other portions of the same lake, such as along the Lake Wales Ridge and in Northern Tampa Bay area (e.g., Sacks et al., 1998; Metz and Sacks, 2002; Virdi et al., 2013). At these flow-through lakes, SA water levels would be higher than the lake water level on one side of the lake and lower on the other. As the default water budget model template only includes one term for SA fluxes, to use this model for such lakes, SA water levels should be adjusted to represent the *average* surficial aquifer water level, in order to represent the *net* SA flux.[5] As discussed later in the "Future Improvements" section, more research is needed to better understand SA fluxes at lakes.

As a check of the reasonableness of modeled SA fluxes, Darcian flow fluxes can be calculated for the perimeter of the lake. Dividing the lakeshore into x number of line segments, net flux from the SA (SA_FLUX, in/yr) can be calculated as the sum of flow from each segment as shown in Equation 6, where K is the hydraulic conductivity of the SA (ft/d), ΔH is the difference in water level elevation between the SA and lake (ft), D is the distance between the well and lakeshore (ft), Y is the length of the lakeshore segment (ft), and Z is the thickness of the seepage front (which occurs along the SA-lake interface and can be estimated using the nearshore lake depth or bathymetry; ft). Note that Fellows & Brezonik (1980) and Lee (2002) found that most groundwater exchange with the SA occurs within approximately 25 to 100 ft of the lakeshore.

$$(6)\quad SA\_FLUX = 365*12*\sum_{j=1}^{x} K*\frac{\Delta H_j}{D_j}*Y_j*Z_j$$

To help determine K, estimates of the hydraulic conductivity for different materials can be found in Heath (1983), with sand anywhere between 10^{-1} to 10^{3} ft/d (larger grain sizes and cleaner sands have higher values). Typical values for west-central Florida range from 10 to 20 ft/d but can reach as high as 30 to 50 ft/d along sand ridges. Estimates of hydraulic conductivity can be obtained from nearby aquifer performance test (APT) data for the SA (available in the District's GIS layers), soil survey information (available in the District's GIS layers), or values of hydraulic conductivity from regional groundwater flow

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[5] A template is available implementing a flow-through SA option for lakes, *Lake Water Budget Model Flow-through Template.xlsx*, which explicitly separates inputs and calculations for SA inflow and SA outflow.

models such as ECFTX, INTB, PRIM, or NDM5[6]. Values for $\texttt{SA\_FLUX}$ derived using Equation 6 can be compared to average annual estimates from water budget model; large discrepancies may suggest that one or both of L_SA and the SA water level adjustment should be reconsidered.

In the template water budget model spreadsheet, SA water level data are input into the *Input| Hydrologic Data* worksheet in *Column D*. The leakance coefficient is entered into the *Input| Parameters and Performance* in *Cell B6*, and an optional constant groundwater level adjustment can be entered in *Cell B7*. Daily groundwater level data are required for the entire model period (i.e., monthly data must be interpolated into daily data for use in the model). In the *WB Calculations* worksheet, fluxes appear in *Column I.* On the *Input| Parameters & Performance* worksheet, under the "Model Water Balance Summary" table, *Cells O7 to Q7* show the average annual flux for the entire model period. Additionally, the *Diagnostic Graphs* worksheet displays time series of SA water levels and fluxes.

DCIA

Rainfall falling onto impervious areas directly connected to the lake, such as roads and drainage systems, has no opportunity to infiltrate and therefore flows directly to the lake within a short amount of time. This inflow to the lake is called "directly connected impervious area" (DCIA) inflow.

DCIA inflow to the lake ($\texttt{DCIA}_n$, ft) can be calculated by multiplying rainfall ($\texttt{RAIN}_n$, ft) by the relevant proportion (P_DCIA, dimensionless) of the lake watershed area ($\texttt{AREA\_WS}$, ft^2) divided by the current lake area ($\texttt{AREA\_LAKE}_n$, ft^2), as shown in Equation 7.

$$(7)\quad \texttt{DCIA}_n = \texttt{RAIN}_n * P\_DCIA * \texttt{AREA\_WS}/\texttt{AREA\_LAKE}_n$$

P_DCIA is a calibrated constant parameter that represents the proportion of the lake's watershed (inclusive of the lake) that is directly connected to the lake via impervious surfaces. The value is between 0 and 1, but for most lakes, it is near-zero, rarely above 10 percent of the contributing area (0.10). Reasonable values for P_DCIA can be determined through review of land use geospatial data and aerial imagery (available in the District's GIS layers), site visits, and site reports. Additionally, the U.S. Geological Survey's National Land Cover Dataset provides satellite-derived geospatial data on impervious surfaces for the continental United States at a resolution of 30 meters.[7]

The lake's watershed area ($\texttt{AREA\_WS}$) can be determined by applying watershed delineation techniques to digital elevation data (available in the District's GIS layers) and

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[6] \\ad.swfwmd.net\swfShare\GWModels

[7] https://www.mrlc.gov/data?f%5B0%5D=category%3Aurban%20imperviousness

reviewing any available lake-specific or engineering watershed[8] data and reports. Staff from the Engineering and Watershed Management Section can provide assistance with locating available watershed delineations or providing review of new delineations.

The lake area, $\texttt{AREA\_LAKE}_n$, varies by day according to the lake stage and is determined using the lake's stage-area curve. The stage-area curve is typically created by District staff using an in-house Python script that combines and interpolates LiDAR data and professionally-surveyed bathymetric and topographic data. The current day's lake area is estimated using the stage-area curve given the previous day's lake stage. The water budget model uses the previous day's stage to estimate $\texttt{AREA\_LAKE}_n$ in order to avoid circular formulae references, because the current day's stage is the output.

Lake watershed area and lake area are often reported in units of acres, but the template water budget model requires units of ft^2. To convert acres to ft^2, multiply acres by a conversion factor of 43,560 ft^2/ac.

In the template water budget model spreadsheet, *`P_DCIA`* is entered in the *Input| Parameters and Performance* worksheet in *Cell B11* and `AREA_WS` in Cell B12. DCIA fluxes are calculated in the *WB Calculations* worksheet in *Column R*. On the *Input| Parameters & Performance* worksheet, under the "Model Water Balance Summary" table, *Cell O11* shows the average annual DCIA inflow for the entire model period. Additionally, the *Diagnostic Graphs* worksheet displays a time series of DCIA inflows.

OVERLAND

Overland flow is calculated via the SCS curve number methodology (NRCS, 1986), an empirically-derived approach that is widely used in stormwater studies, but with a modification by CH2MHill (2003) to better account for conditions in Florida.

Curve numbers are dimensionless empirical parameters that can vary between 0 (low runoff) and 100 (highest runoff). Sandy soils, deep water table conditions, and low development are associated with lower curve numbers. Clayey soils, shallow water table conditions, and higher development are associated with greater curve numbers. NRCS (1986) contains a table of suggested curve numbers for various soil and land use combinations.

Additionally, higher antecedent moisture conditions (AMC) result in more saturated soils and therefore higher runoff, necessitating higher curve numbers. The SCS methodology incorporates three antecedent moisture conditions: AMCI (dry), AMCII (average), and AMCIII (wet). To better reflect runoff responses in Florida, CH2MHill (2003) adds a fourth

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[8] \\ad.swfwmd.net\swfShare\EngProj

condition, AMCIV (moderately dry). The curve numbers for the different AMC are related as shown in Equations 8 through 10 (CH2MHill, 2003). Note that the average condition curve number, CN_{II}, is the basis for the others.

$$(8)\ CN_{I} = CN_{II} - [20*(100 - CN_{II})]/[100 - CN_{II} + EXP(2.533 - 0.0636*[100 - CN_{II}])]$$

$$(9)\ CN_{III} = CN_{II} * EXP[0.00673*(100-CN_{II})]$$

$$(10)\ CN_{IV} = 0.5*(CN_{I} + CN_{II})$$

As described in CH2MHill (2003), CNI is used when total rainfall is 0.00 inches for the previous six days, CNIV when total rainfall is 0.00 inches for the previous five days, CNII when total rainfall is 0.00 to 0.25 inches for the previous three days, and CNIII when total rainfall exceeds 0.25 inches for the previous three days.

The water budget model is initialized with the AMCII curve number, CN_{II}. CN_{II} is a calibrated parameter, with consideration given to soils and land uses in the lake watershed (exclusive of the lake). Regionally, CN_{II} values in the Northern Tampa Bay area typically range between 60 and 80, while in the well-drained, deep-water table northern areas and southern ridge portions of the District, curve numbers typically range between 30 and 60. Due to the calculations for CN_{I} and CN_{III}, CN_{II} cannot be less than 20 or greater than 100. Using geospatial data for soil hydrologic groups and land use, available from the District's GIS layers, an average weighting procedure can be used to calculate an average curve number specific to the lake's watershed (exclusive of the lake), which can be used as a starting point and guide for calibration of CN_{II}. CN_{II} is used for the first six days of the model, after which the model begins assessing antecedent moisture conditions and Equations 8 through 10 to determine CN_{n}.

The daily curve number CN_{n} is used with $RAIN_{n}$ in Equation 11 to calculate the depth of "excess" rainfall (rainfall available for overland flow), $EXCESS\_RAIN_{n}$ (in) for the watershed (NCRS, 1986).

$$(11)\ EXCESS\_RAIN_{n} = [12*RAIN_{n} - 0.2*(1000/CN_{n} - 10)]^{2} / [RAIN_{n} - 0.8*(1000/CN_{n} - 10)]$$

Since the size of the watershed also determines how much overland flow the lake receives, $EXCESS\_RAIN_{n}$ (in) must be converted to feet and then multiplied by the watershed area ($AREA\_WS$, ft^{2}), exclusive of the lake and the portion of the watershed that has already been addressed by $DCIA_{n}$. To convert the resulting volume (ft^{3}) into linear units (ft), the product is divided by the lake area, $AREA\_LAKE_{n}$ (ft^{2}). The lake is excluded from overland flow calculations because the lake itself does not generate runoff, and the $RAIN_{n}$ term captures rainfall that falls directly on the lake. The final value, $OVERLAND_{n}$ (ft), represents the increase in lake stage due to overland flow. This is shown in Equation 12.

$$(12)\ OVERLAND_{n} = EXCESS\_RAIN_{n}/12*[AREA\_WS*(1-P\_DCIA) - AREA\_LAKE_{n}]/AREA\_LAKE_{n}$$

Discussions with staff from the Engineering and Watershed Management and ERP Evaluation sections suggest that the SCS curve number method for calculating overland flow tends to overestimate overland flow in areas with well-drained soils, which dominate the northern areas with xeric, deep-water table conditions and southern ridge portions of the District (SWFWMD, 2008). If `OVERLAND` exceeds actual overland flow received by the lake, the excess water will typically be compensated for by increasing *`L_UFA`* (i.e., removing it from the lake via fluxes to the upper Floridan aquifer through vertical leakage), which will ultimately result in *`L_UFA`* and Historic percentiles that are too high (the Historic scenario is discussed in a later section).

Many studies for central Florida lakes assume negligible contribution by overland flow (e.g., Lee & Swancar, 1997; Metz, 2002; Swancar, 2000; Sacks, 2002). Swancar (2015) found that overland flow contributed to stage increases at Lake Calm in Hillsborough County (Northern Tampa Bay area) but not at Lake Starr in Polk County (southern District), which was attributed to poorly-drained soils occurring around the former and well-drained soils at the latter. Motz et al. (2001) and Watson et al. (2001) used the SCS curve number method in developing water budgets for north-central Florida lakes in well-drained settings, respectively Lakes Magnolia and Lowry (Sand Hill), both studies setting CN_{I} (dry) at 19, $\mathrm{CN}_{\mathrm{II}}$ (average) at 36, and $\mathrm{CN}_{\mathrm{III}}$ (wet) at 56. Motz et al. (2001) estimated annual runoff at 27.2 in/yr, while Watson et al. (2001) found near-zero runoff. As discussed in the “Future Improvements” section later, more accurate methods for estimating overland flow exist and should be considered for implementation in the future. In the meantime, the modeler should be aware of the limitations of SCS curve number method and scrutinize its results, in particular for lakes located within well-drained soils and deep-water table conditions (i.e., depth greater than 10 ft).

In the template water budget model spreadsheet, CN_{II} is entered on the *Input| Parameters and Performance* worksheet in *Cell B10* and lake stage-area relationships are entered on the *Input| Stage-Area* worksheet in *Column A* (stage) and *Column B* (area). Overland flow calculations are implemented in the *Runoff Calculations* worksheet and referenced in the *WB Calculations* worksheet in *Column Q*. On the *Input| Parameters & Performance* worksheet, under the “Model Water Balance Summary” table, *Cell O10* shows the average annual overland flow for the entire model period. Additionally, the *Diagnostic Graphs* worksheet displays a time series of overland flows.

CHAN_OUT

For a lake with surface outflow from a single fixed-elevation structure (such as a stable ditch or inoperable weir; e.g., channelized outflow), outflow ($\mathrm{CHAN\_OUT}_{n}$, ft), from the lake can be estimated using the difference between the structure elevation or control point (`CTRL_PT`, ft) and (modeled) lake (LAKE_{n}, ft) water level elevations, then multiplied by a dimensionless structure efficiency coefficient (`K_O`, dimensionless), as shown in Equation 13. Outflow only occurs when $\texttt{LAKE}_n$ exceeds `CTRL_PT`; otherwise, $\texttt{CHAN\_OUT}_n$ is zero.

$$(13)\ \texttt{CHAN\_OUT}_n = \text{min}\{0,\ K\_O*(\texttt{CTRL\_PT} - \texttt{LAKE}_n)\}$$

The control point is the elevation of the highest stable point along the outlet profile of a surface water conveyance system that principally controls lake water level fluctuations. The control point can be a manmade feature, such as a structure including weirs or culverts, or it can be a natural feature, such as a natural channel from the lake. In determining the control point, staff review of existing lake reports, assess digital elevation data (available in the District's GIS layers), conduct site visits, collaborate with staff from the Survey Section, and evaluate the most recent survey data. Geospatial data of structure locations and elevations may also be available from work developed by the Engineering and Watershed Management Section. The final elevation value of `CTRL_PT` is typically obtained through professional surveying of relevant features, whether manmade or natural. If the lake never experiences surface outflow (i.e., the lake is a closed basin lake), `CTRL_PT` can be set at some high elevation; for such lakes, a theoretical outflow elevation can be determined by review of digital elevation data (LiDAR offering the best resolution), even if lake water levels will never achieve that elevation.

The efficiency coefficient, `K_O`, is a calibrated constant parameter (dimensionless). Although the coefficient can vary between 0 and 1, where higher values increase outflow, it is typically on the order of a few hundredths (e.g., 0.01 to 0.05) but has been as high as the low tenths (e.g., 0.10 to 0.20). All else being equal, a larger structure would be more efficient. Natural channels tend to have lower efficiencies compared to manmade structures and channels. At most lakes, the control point elevation is usually positioned relatively high compared to typical lake stages, making this parameter most important in determining higher lake stage percentiles such as the P10 (10 percent exceedance value).

An option to implement the weir equation to estimate channel outflow was considered, but after discussions with Professional Engineers from the Engineering and Watershed Management Section, the efficiency coefficient approach was determined to be reasonable for a long-term simulation focused on specific exceedance percentiles (i.e., the P10 and P50), and preferable due its minimization of required parameters.

In the template water budget model spreadsheet, on the *Input*| *Parameters and Performance* worksheet, `K_O` is entered in *Cell B13* and `CTRL_PT` is entered in *Cell B14*. Surface outflow calculations are implemented in the *WB Calculations* worksheet in *Column S* and *Column T*. On the *Input*| *Parameters & Performance* worksheet, under the "Model Water Balance Summary" table, *Cell P12* shows the average annual surface outflow for the entire model period. Additionally, the *Diagnostic Graphs* worksheet displays a time series of surface outflows.

Additional Considerations

Model Time Period

Selecting the appropriate time period to use for the model requires balancing the availability of required data, the timing of any significant changes to land use in the watershed and structural conditions at the lake (since `DCIA`$_n$, `OVERLAND`$_n$, and `CHAN_OUT`$_n$ reflect current conditions at the lake), and the need to capture a period that is long enough to reasonably characterize lake hydrology. Very short model periods reduce the ability to adequately characterize lake hydrology and assess model performance. Very long model periods increase the likelihood of including land use or structural changes that would require different model parameterizations relative to current conditions (current structural conditions must be used for Historic percentiles) as well as encountering issues with the availability of quality data representative of the lake. In consideration of these factors, a model time period of approximately ten years is generally sufficient, although appropriate modeling for some lakes may require a longer time period.

Although it does not affect calibration, an understanding of how rainfall conditions during the model period compare to rainfall conditions over a longer-term period can provide context for later assessments and decision-making using model-based results.

The template water budget spreadsheet is only set up to handle a period of no more than approximately 10,000 days (27 years). For a model exceeding this length, all formulae must be extended appropriately.

Modifying the Model Structure

In the template water budget model spreadsheet, in the *WB Calculations* worksheet, *Column U* (which implements Equations 1 and 2) can be modified to remove terms or to incorporate additional terms. Existing terms can also be modified through the relevant columns, identified in previous sections. Examples of conditions that necessitate model modification include the following.

- For lakes located in the unconfined portion of the northern District, it may be appropriate to remove the term for surficial aquifer fluxes, as the Upper Floridan aquifer is also the water table.
- If the lake has channel inflows, more than one surface outflow, augmentation, direct surface withdrawals, or other fluxes not captured in the default water budget model template, additional terms will need to be added to the model.
- If the lake's surface outflow is controlled by an operable structure, the model will need to be modified to allow `CTRL_PT` to vary.

- If the water level modeled for a day falls below the range of stages available in the stage-area curve (either due to poor calibration or due to a scenario run), the model may stop outputting water levels past that point. Lake areas will also be very small at extremely low stages, and since calculations for DCIA runoff and overland flow involve dividing by lake area, this can result in extremely large values of runoff that can cause sudden, massive increases in modeled water levels. For these situations, the model structure may need to be modified to handle extreme low water levels and areas, perhaps by hard-coding a lower limit or expanding the stage-area curve.
- The default water budget model, *Lake Water Budget Model Template.xlsx*, only supports input of a single SA groundwater level series, used to represent the average SA through the lake to calculate *net* SA fluxes. At flow-through lakes, to better characterize SA fluxes, the SA term can be expanded to explicitly separate SA inflows and outflows. A flow-through modification of the default model template is available, *Lake Water Budget Model Flow-through Template.xlsx*, which supports input of two SA groundwater level series, one for SA inflow and one for SA outflow, and implements the corresponding calculations.

When adding terms, remember that volumetric terms, such as reported augmentation volumes, must be converted into linear units (ft) before inclusion in *Column U*. This conversion can be done by dividing a daily volume (ft^3) by the daily lake area (ft^2), which is available in the *WB Calculations* worksheet in *Column D*.

Model Review and Performance Guidelines

Overarching Principles

Errors occur due to the model's inability to completely represent the physical system, as well as due to errors and uncertainties associated with inputs and parameters used in the models. Winter (1981) provides a summary of uncertainties and errors associated with lake water budgets, while Moriasi et al. (2007; 2015) provide widely-accepted performance criteria for hydrologic modelling efforts.

During calibration of the water budget model, the modeler seeks to minimize residuals between pairwise model and observation data by modifying calibration parameters, while constraining parameters and outputs to reasonable values based on a physical understanding of the system. General guidelines for parameterization and associated fluxes were discussed earlier as each model term was introduced. At its simplest, the reasonableness of model outputs can be assessed through comparing observed to simulated lake water levels; however, all model calibration is non-unique, meaning that there are numerous combinations of parameter values that can produce acceptable calibrations (i.e., match of simulated and observed lake stages).

The key in any modeling effort is testing the reasonableness of any calibrated parameter with independent data or analysis and limiting parameter changes to physically realistic values or ranges of values given the hydrogeologic system. This practice provides more certainty to model predictions. Calibrated models can potentially produce acceptable modeled water levels but contain unrealistic parameterizations given the physical system. The modeler should also consider the magnitude of specific terms and their relative contribution to the overall water balance, and how this compares to expected fluxes at the lake as informed by previous work and other relevant information.

Calibration Criteria

Based on review of performance criteria for the District's regional groundwater models (Appendix 2), guidelines from Moriasi et al. (2007; 2015), and professional judgement considering the intended application of the water budget models, staff developed the following guidelines quantifying acceptable lake water budget model performance.

- P10 ≤ ±0.3 ft
- P50 ≤ ±0.1 ft
- P90 ≤ ±0.5 ft
- Mean Error ≤ ±0.3 ft
- MAE ≤ 0.75 ft
- RMSE ≤ 1.0 ft
- NSE ≥ 0.70
- Max Residual ≤ 2.0 ft
- Min Residual ≥ -2.0 ft

As the P10 and P50 most influence minimum levels development, minimizing the difference between these modeled and observed percentiles is emphasized. For most water budget models, the P50 is matched within a tenth of a ft and the P10 within a few tenths of a ft, and the Nash-Sutcliffe efficiency is very high (>0.80). Performance indices for each water budget model should be documented in the model report.

As previously noted, for every model, multiple calibration solutions exist that provide acceptable calibration. The parameterization that results in the best calibration (as judged by the above criteria) may not always best represent the physical system. Unrealistic parameterizations and fluxes should not be accepted, even if they result in ostensible improvements in calibration criteria relative to a more realistic parameterization. Ultimately, professional judgement must be applied in selecting which model parameterization best balances acceptable calibration with accurate representation of the physical system.

In the template water budget model spreadsheet, performance indices are calculated and shown on the *Input*| *Parameters & Performance* worksheet in the table labeled “Model Performance.” The figures on this worksheet show time series of modeled versus observed lake water levels and residuals, which can be used to identify specific time periods of poor model performance. This worksheet also contains a summary of lake inflows and outflows in the table labeled “Model Water Balance Summary,” which should be reviewed to determine if the calibration resulted in reasonable values. The *Diagnostic Graphs* worksheet has time series of model inputs, fluxes, and outputs, which can be used to identify potential issues with inputs and calculations (e.g., missing data, outliers, fluxes exceeding reasonable values).

Verification Testing

A verification test assesses the final calibrated model’s ability to predict water levels using a time period for which it was not calibrated. This confirms the model’s predictive ability outside of the calibration period and helps to exclude overfitting as a reason for acceptable model calibration. Performance metrics for the verification test are the same as those defined for calibration in the previous section.

A verification period of at least one year is desirable, but the appropriate length of the verification period requires balancing the length of time for which data are available against the length of time needed for adequate model calibration. Land use and structural conditions must be consistent between the verification period and the model period, since the model’s parameterization is specific to current land use and structural conditions. Therefore, while in some cases, considerable data may be available for the time period preceding the calibrated model, these earlier time periods may not be representative of the modern lake hydrology on which the model is constructed.

The simplest approach for verification is to withhold the last year of available data for verification testing (for example, if data to support modelling are available for 2010-2021, model calibration would use 2010-2020, and verification testing would use 2021). Alternatively, one or more years preceding the model period could be used, if land use and structural conditions are consistent between the two periods. To complete verification testing using this approach, a copy can be made of the final calibrated model spreadsheet file. Since the parametrization will remain the same between the final model and the verification test, only data on the *Input*| *Hydrologic Data* worksheet should be changed. All hydrologic input data on that worksheet should be removed and replaced with time series data for a period that was not used in calibration. After doing this, the performance indices will reflect performance of the verification period.

If model performance is poor for the verification period, first ensure that the parameterization is identical between the calibration and verification periods. Additionally, confirm that land use and structural conditions are consistent between the calibration and verification periods. If hydrologic data sources are different between the two (for example, one uses a different rain gage), consider how this could affect relative performance. If a short-term verification period reflects unusual climatic conditions (such as an extreme drought), poor performance may suggest that the calibrated model performs well for average conditions but is not adequate for extreme conditions, which could reflect inadequate parameterization or conceptualization. If clear and correctable reasons for poor verification performance cannot be identified, the default water budget model may not be appropriate for the lake, and the modeling approach for that lake may need to be reconceptualized.

Sensitivity Testing

In addition to evaluation of model calibration, an understanding of the model's sensitivity to specific terms, in consideration of uncertainty associated with those terms, can guide the appropriate level of confidence to place in model outputs. This helps to inform decision-making processes for the development and assessment of lake minimum levels.

Although the water budget models can typically achieve excellent calibration, sensitivity testing conducted for water budget models for three representative lakes, each located in a different hydrogeologic province (Northern District, Northern Tampa Bay, and Southern District), indicate that the aquifer leakance coefficients (particularly for the UFA), SA and UFA water levels, and the curve number are sensitive terms. Additionally, multiple calibration solutions exist that provide acceptable calibration (non-uniqueness). Appendix 2 contains a detailed description of the methods and results of the sensitivity testing applied to the three lakes.

The specific degree of sensitivity of the model results will vary by lake based on lake-specific factors and final parameterization. For example, at a lake with near-zero drawdown, the Historic percentiles will closely match the calibration percentiles, irrespective of parameterization. At a lake with a very small L_UFA, the model may be insensitive to even large changes in the UFA drawdown adjustment. Intuitively, lakes located where the UFA is semi-confined will exhibit the highest sensitivity to L_UFA, which can significantly affect estimates of lake impacts and Historic percentiles (discussed in the next section).

Although sensitivity and non-uniqueness do not impact the performance indices (i.e., residual-based metrics) of the final calibration, they have critical implications for model predictive scenarios. For example, the leakance coefficients determine the lake's response to changes in groundwater levels, which are increased as part of the Historic scenario (discussed in the next section). If a leakance coefficient is too high, the Historic scenario will produce percentiles that are too high, and vice versa. If the curve number is too high, excess water will be added to the lake, which will typically be compensated for by increasing the UFA leakance coefficient, ultimately resulting in Historic percentiles that are too high.

Sensitivity tests for each water budget model should be conducted and documented in the model report. Generally, multipliers and divisors of 2, 5, and 10 are appropriate for the leakance coefficients, and additions and subtractions of 1, 2, and 5 are appropriate for the curve number. Sensitivity to the drawdown adjustments should also be assessed. During sensitivity tests, all parameters but the test parameter should be held the same as the final calibration parameterization. Since Historic scenario outputs become the basis for minimum levels development, sensitivity test results should be reported with respect to the Historic scenario. That is, relative to the final calibration parameterization, how much would changing a parameter change the Historic P10 and Historic P50?

Summary

During model development and documentation, calibration performance metrics should be evaluated along with other aspects of the lake water budget models. Care should be given to ensure lake parameters and associated fluxes fall within a reasonable range and comply with regional hydrogeology. In interpreting model results, the sensitivity and uncertainty of model parameters and inputs should be considered.

Historic Scenario

Introduction

Development of lake minimum levels requires assessment of Historic water level percentiles, where Historic means no measurable impacts due to withdrawals but with current land use and structural alterations (and no augmentation) in place.

After a water budget model is calibrated, Historic lake water level percentiles can be estimated by increasing groundwater levels to remove the effects of withdrawals.

The water budget model does not estimate drawdown, so estimates of drawdown must be obtained using another source. The appropriate sources to use vary by lake and region but can include review of regional groundwater model data, empirical groundwater level changes, withdrawal data, lake stage data, local hydrogeologic information, and professional judgement. Drawdown estimates are required for both the SA and UFA. Professional Geologists in the Environmental Flows and Levels Section can provide assistance with developing appropriate drawdown estimates.

UFA Drawdown

UFA drawdown can be obtained using results from regional flow models, such as the East-Central Florida Transient Expanded model (ECFTX), Integrated Northern Tampa Bay model (INTB), Peace River Integrated Model (PRIM), or Northern District Model (NDM, which will be superseded by the Central Springs Model [CSM], an update and extension of the NDM that is currently in development). Based on each model’s domain and regional focus, NDM/CSM will typically be the best model to use for lakes in the Northern District, INTB for lakes in the Northern Tampa Bay area, and ECFTX and PRIM for lakes in the Southern District.

For a given scenario, these regional groundwater models predict groundwater level elevations for each model grid cell, which are geospatially referenced into shapefiles. For a given layer, drawdown is estimated by subtracting “pumps-on” scenario water levels from “pumps-off” scenario water levels. Each model scenario is associated with a specific time period with specific recharge (including rainfall) and withdrawal conditions. Therefore, careful consideration should be given to the time periods and groundwater withdrawal quantities underlying regional model pumps-on scenario results compared to the time periods and groundwater withdrawal quantities used for the lake water budget model calibration period. That is, are the magnitudes and locations of withdrawals incorporated in the regional model pumps-on scenario reasonably representative of withdrawals occurring during the period of the lake water budget model? Additionally, the model calibration in the area of the lake should be reviewed.

In the Northern Tampa Bay and Southern District regions, simulations using post-2010 groundwater withdrawal conditions provide the greatest confidence regarding existing impacts, as the post-2010 period represents the most current groundwater withdrawal conditions included in water budget model period. It is often desirable to compare or perhaps average the results of several models, if they overlap the lake and area of interest.

Additionally, a 5-year average of recent UFA potentiometric surface elevation subtracted from the predevelopment UFA potentiometric surface estimated by the U.S. Geological Survey[9] should be generated to calculate a historic head change from observed data. This value is useful to compare with model drawdown predictions to increase the level of confidence in historic drawdown estimates for the UFA.

In rare instances, when a nearby observation well has a sufficient period-of-record, empirical data can be used to estimate UFA drawdown by comparing water levels from the current period to water levels from an early period when withdrawals were not significant. When possible, to reduce the influences of rainfall on water level differences between the periods, this evaluation should compare longer-term (multiple years) averages calculated for each period. Rainfall should also be compared between the two periods to understand if it represents near-average conditions.

SA Drawdown

As for the UFA, estimates of SA drawdown can be obtained from regional flow models such as ECFTX, INTB, PRIM, or NDM/CSM. Once again, differences in time periods and groundwater withdrawals between regional model scenarios and the water budget model must be considered. However, relative to the UFA, additional uncertainties exist in estimating SA drawdown, and it is therefore especially critical to evaluate multiple lines of evidence and apply professional judgement. Specifically, SA drawdown is highly localized and, compared to the UFA, more difficult to determine. Uncertainty with predicted SA drawdown from regional models is also increased by the inherent difficulties in adequately representing SA-UFA connection at the local scale.

In addition to reviewing regional model results, one method for estimating SA drawdown is to calculate it as a fraction of UFA drawdown. Based on work conducted for the Northern Tampa Bay area (**Error! Reference source not found.**; Hancock & Basso, 1999Figure 1), given L_UFA, the ratio of SA to UFA drawdown ($\mathrm{DRAWDOWN\_SA/DRAWDOWN\_UFA}$, ft/ft or dimensionless) can be calculated using Equation 14. This fraction can be multiplied with UFA drawdown to estimate SA drawdown. However, this ratio is an approximation developed using results from a

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[9] https://pubs.usgs.gov/ds/584/

regional groundwater flow model by accumulating model cells grouped by equal drawdown intervals. Therefore, SA drawdown estimates derived this way should also be compared with other estimates, such as from regional groundwater models.

$$\text{(14)}\quad \mathrm{DRAWDOWN\_SA}/\mathrm{DRAWDOWN\_UFA} = \mathit{L\_UFA}/(8.3*10^{-4} + 0.98*\mathit{L\_UFA})$$

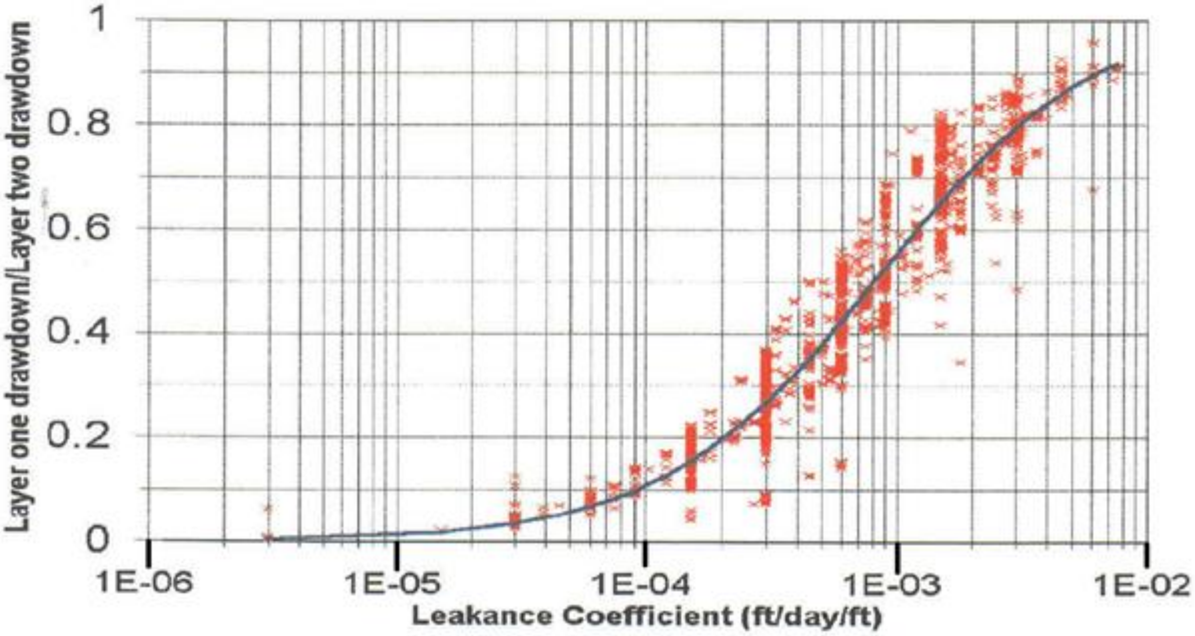

Figure 3. Relationship between surficial and Upper Floridan drawdown to Upper Floridan leakance coefficient (from Hancock and Basso, 1999).

In addition to uncertainty associated with the estimate of SA drawdown, uncertainty exists with its specific application in the lake water budget model. Since the SA-lake connection is high in most water budget models, drawdown in the SA is almost always reflected in lake water levels. In the physical world, this high degree of interaction (nearly a one-to-one relationship between the change in SA and lake water levels) may be somewhat attenuated by the immense storage difference between lakes (open water) and the SA (which typically has a specific yield of 10 to 20%). In fact, the ratio of drawdown shown in Equation 14 and **Error! Reference source not found.** is predicated on the typically low specific yield values of a fine-grained sand aquifer. Additionally, the water budget model assumes an average SA drawdown that is uniform around the lake but, in reality, SA drawdown is highly localized and would be variable around the lake due to local variations in hydrogeology and distances to pumping centers.

All of these factors create a higher level of uncertainty with determining drawdown in the SA versus the more regional UFA. To account for the great uncertainty associated with SA drawdown, sensitivity testing should be applied to the lake water budget model using varying degrees of SA drawdown. A range of SA drawdowns can be tested, including no adjustment, an adjustment value derived using Equation 14, and an adjustment value using regional flow model predictions. Ultimately, the modeler must exercise professional judgement in trying to find the most likely value through consideration of a variety of data, while recognizing the large degree of uncertainty with this adjustment.

Evaluating the Historic Scenario

In the template water budget model spreadsheet, the *InputOptional*| *Historic Mode* worksheet can be used to create a Historic scenario using a calibrated water budget model. For each date in the water budget model, daily drawdown estimates (as positive values) should be entered for the SA in *Column B* and for the UFA in *Column C*. A constant drawdown value can be used by simply repeating the value as needed. After this, *Cell B1* on this worksheet should be set to “yes”. The drawdown values are used by the *WB_Calculations* worksheet to increase groundwater level inputs. Model output will now reflect Historic conditions.

The change in water levels between calibrated modeled water levels and Historic scenario modeled water levels represents the predicted impacts to the lake. Although daily differences can be calculated, the model is not appropriate for short-term applications. The model’s focus is on estimating long-term percentiles, particularly the P50. However, as previously discussed, professional judgement should be applied in interpreting the results of the Historic scenario, with consideration given to uncertainty and sensitivity of model parameters, inputs, and drawdown adjustments.

For comparison with water budget model results, other estimates of lake impacts may be found using regional groundwater model results, review of empirical lake stage data, review of lake ecologic and health data, analytical methods, and other appropriate sources.

One method to check the reasonableness of impacts predicted by the water budget model is to use a hydrograph overlay procedure that compares the empirical water level data between the subject lake and hydrogeologically similar lakes that are relatively unimpacted. In this procedure, lake water levels for the modeled lake and a background (unimpacted) lake are plotted on the figure using a shared x-axis but separate y-axes, with the range of each y-axis having the same total span, and absolute elevations that are appropriate for each lake and which may differ between the lakes). The ranges of the y-axes should be configured so that water level maxima generally visually match between the lakes, as higher waters are less impacted by withdrawals than are lower water levels and therefore serve as more appropriate reference points. In this manner, water levels from the two lakes are overlain to note any differences in lake stage behavior. When the data encompass many years, monthly lake stages can be converted to mean annual values for easier interpretation of long-term behavior. The goal of this procedure is to test if lake stage behavior differs between a lake predicted to have substantial withdrawal-related impacts versus one or more lakes with no or minimal impacts. Relative to a background lake, a heavily impacted lake would typically show more extreme ranges (i.e., increased separation between minima and maxima) and consistently depressed (lower) water levels. If the Historic scenario predicts significant water levels increases for the target lake (indicating that the model and drawdown estimates together predict significant impacts to the lake), but the target lake’s empirical data already closely track a background lake (indicating the lake is minimally impacted), then the Historic scenario could be overpredicting impacts to the lake. This overprediction can occur due to inappropriate high drawdown or leakance coefficients.

Summary of Model Development Process

Overview

Development and application of the lake water budget model for minimum levels development involves three major components: model construction and calibration, model performance assessment, and Historic scenario development.

Professional scientific judgement is essential when developing the model, interpreting its results, and applying results in decision-making processes. No model can perfectly represent the complex physical reality, and all models include errors and uncertainty. However, properly applied, the lake water budget model can provide useful information about lake hydrology that can underly the development of defensible minimum levels.

An important, final step of the process is to document and archive the model. The model report documents model development and results, including inputs, parameters, performance, assumptions, and decision-making processes. Use the latest approved lake water budget model report template as a guide regarding the required information and appropriate format. To ensure quality, the model and its report should be reviewed by at least one other staff member, after which a meeting should be held with Section staff to present the modelling approach and findings. If staff review identifies concerns with the model, the modeler may need to revisit the model construction and calibration. At the end of the process, after the Governing Board approves any minimum levels associated with the model, the final model is archived in the Model Management system[10].

Model Construction and Calibration

1. Select an appropriate model time period.
2. Compile required input data for the entire model time period (see Table 1).
    a. Lake stage data
    b. SA water level data (daily)
    c. UFA water level data (daily)
    d. Rainfall data (daily)
3. Establish initial parameters (see Table 1).
    a. Calibrated parameters
        i. Runoff
            1. SCS curve number for the lake watershed
            2. Proportion of the lake watershed that is DCIA
        ii. SA Flux
            1. SA leakance coefficient

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[10] \\ad.swfwmd.net\swfShare\MFLModels

            2. SA water level adjustment
        iii. UFA Flux
            1. UFA leakance coefficient
            2. UFA water level adjustment
        iv. Surface outflow
            1. Outflow efficiency coefficient
    b. Non-calibrated parameters
        i. Area of the lake watershed
        ii. Control point (outflow) elevation
        iii. Stage-area curve for the lake
4. As needed, modify the model structure to add, adjust, or remove terms.
5. As needed, troubleshoot and address issues with input data and model function.
6. Achieve acceptable model calibration by adjusting calibration parameters.

Model Performance Assessment

7. Review performance indices for the final calibrated model.
8. Complete verification testing for the final calibrated model.
9. Complete sensitivity testing for the final calibrated model.

Historic Scenario Development

10. Determine drawdown for the UFA and SA.
11. Run the Historic scenario.

Model Reporting, Review, and Wrap-up

12. Document model development and results using the latest approved lake water budget model report template.
13. The model and report undergo detailed technical review by one or more technical staff. The modeler revisits the report and model as needed in response to review findings, and the model may go through several phases of redevelopment and review until a final draft is ready.
14. A meeting is held with section staff, the section manager, and the bureau chief to present on final draft model development and results.
15. After the minimum levels rulemaking process is complete for the lake that the model supports, the final approved model and associated files and report are stored in the Model Management system.

Future Improvements

Further research is needed to provide better constraints on L_SA. At sample lakes, to determine hydraulic gradients around the lake, SA monitor wells could be installed within a few hundred feet of the lakeshore at different positions around the lake. Slug tests could be conducted at these wells to estimate SA hydraulic conductivity. These wells would not only help determine the hydraulic gradient between the lake and SA but would also provide information about SA flow direction along all segments of the lake shore. At some lakes along the Lake Wales Ridge, SA inflow occurs on one side of the lake and SA outflow occurs on the opposite side, further complicating the modeling approach (e.g., Sacks et al., 1998). Flow-through conditions have also been observed at Northern Tampa Bay lakes (e.g., Metz and Sacks, 2002).

As part of a series of meetings hosted by Environmental Flows and Levels staff in 2021, Professional Engineers from the Engineering and Watershed Management and ERP Evaluation Sections reviewed the water budget model structure to develop recommendations for improving the model conceptualization and process. Foremost, Engineering staff noted that the SCS curve number method for calculating overland flow, which is empirically derived, tends to overestimate overland flow in areas with well-drained soils, which dominate the northern and southern portions of the District (SWFWMD, 2008). A physically-based and more accurate method for estimating overland flow, the Green-Ampt method, requires more parameterization and complex numerical modeling than is currently available in the water budget spreadsheet model. However, properly employed, the Green-Ampt method would substantially increase the accuracy of overland flow calculations. If the SCS curve number method is retained, engineering staff recommended applying the approach described in Harper & Baker (2007), which uses the standard number of three AMC conditions but with one set of criteria for the growing season and another for the dormant season. Staff plan to explore these options in the future, and in the meantime, should consider the potential for the water budget model to overpredict overland flow in well-drained soils.

Additionally, engineering staff recommended replacing the Lake Starr evaporation dataset with satellite-derived reference evapotranspiration available from the U.S. Geological Survey[11], multiplied by a crop coefficient for open water (1.05). Previously, staff working on lake minimum levels opted against using this data due to its provision on 2 km by 2 km grid cells, which is larger than most lakes with minimum levels. Therefore, the evapotranspiration estimate for grid cells for most lakes includes a mix of land covers. Additionally, these data are typically released with a lag of several years. Finally, sensitivity testing conducted by staff suggest that evaporation is not among the most

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[11] https://www.usgs.gov/centers/cfwsc/science/reference-and-potential-evapotranspiration

sensitive inputs, particularly since (relative to rainfall) evaporation does not vary as substantially from year to year. Therefore, staff have continued using the Lake Starr evaporation dataset in the lake water budget model. However, staff plan to explore the option to use the satellite-derived evapotranspiration data more in the future. Overall, however, the review found that the water budget modelling approach was reasonable.

Finally, the default water budget model template requires daily inputs and produces outputs; however, many data, including water level data, are available at a monthly timestep (and must be interpolated into monthly values). The default water budget model template could be converted from a daily to monthly as follows. First, on the *Input| Hydrologic Data* worksheet, water levels would be entered as monthly averages and rainfall as monthly sums. Second, evaporation would need to be converted to monthly sums, which could be achieved by modifying the lookup and calculations on the *WB Calculations* worksheet in *Column P*. Third, overland flow values would need to be converted to monthly sums; this could be achieved by completing the daily overland flow calculations and then aggregating the results into monthly sums, followed by referencing the latter in the *WB Calculations* worksheet in *Column R*. The risks and benefits of using a daily versus monthly model have not been thoroughly explored and may be worth visiting in the future.

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Appendix 1

Hydrogeologic Provinces within West-Central Florida

By Ron Basso, P.G.

1.0. Introduction

The elements of a conceptual model include defining the extent and characteristics of the aquifer system and developing an understanding of groundwater flow directions, sources, and sinks (US Army Corp of Engineers, 2005). Understanding the hydrogeologic system is absolutely crucial to the successful development of any numerical modeling effort. Every piece of available information on geology, physiographic regions, aquifer properties, water level response, water budgets, soil permeability, depth to water table, land cover, hydraulic head differences between aquifers, sinkhole density, thickness of confining units, and the regional configuration of the potentiometric surface is important toward building a good conceptual understanding of the groundwater system. This process is the first step in constructing and calibrating numerical groundwater flow models. If the conceptual model is poor or mischaracterized, simulation results from even a “well-calibrated” numerical model may render erroneous conclusions regarding groundwater system response.

This paper provides an assessment of the hydrogeology over central Florida, specifically the jurisdictional area of the Southwest Florida Water Management District (SWFWMD) and portions of east-central Florida. The description of the hydrostratigraphic units generally follows the naming convention of regional hydrogeologic units by the “Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definitions” (SEGS, 1986). This regional assessment has been divided into three broad regions: the south, central, and northern portions of the SWFWMD.

Within each geographic region, smaller hydrogeologic provinces have been defined based on available information. Hydrogeologic provinces are generalized areas where hydrology and/or geology have similar characteristics. Within west-central Florida, hydrogeologic provinces are largely based on the degree of confinement overlying the Floridan aquifer.

1.1 Regional Hydrogeologic Units over the Florida Peninsula

Four main hydrostratigraphic units describe the regional hydrogeologic framework of Florida (Hickey, personal communication). From the uppermost to the lowermost units, they are: (1) the surficial aquifer (SA), composed mainly of sand; (2) intermediate confining unit (ICU) composed mainly of fine grained clastic sediments, or if this rock sequence has water supply potential, intermediate aquifer system (IAS) composed mainly of carbonate rocks that are layers within the ICU; (3) Floridan aquifer system (FAS) composed mainly of limestone and dolostone with some carbonate rock intervals containing evaporites; and (4) sub-Floridan confining unit (SFCU) composed mainly of Paleocene Series evaporite beds (Hickey and Wilson, 1982). The concept of a “hydrogeologic system” was used by SEGS (1986) as a means of recognizing that each of the essential units could be further subdivided depending upon the purpose of a particular investigation. Miller (1986) subdivided the Floridan aquifer system (FAS) into an Upper Floridan aquifer (UFA), several carbonate rock middle confining units (MCUs) of varying lateral extents with one containing evaporites, and a Lower Floridan aquifer (LFA).

2.0 Hydrogeologic Province Definition

There are no strict quantitative criteria for defining a hydrogeologic province. As an author and groundwater professional, I recognize the diversity in opinion within the scientific community in defining these regions. I have attempted to use the best available information to assign the hydrogeologic characteristics of regions with the knowledge that as more data from drilling and testing becomes available, some of the province boundaries will almost certainly be refined. In fact, it is essential that data collection activities continue to be expanded in the future as there is a need to decrease the level of uncertainty with these descriptions which will lead to better numerical models of the region.

In this approach, hydrogeologic provinces were defined as regionally confined, semi-confined, regionally unconfined, or perched systems. Table 1 identifies some of the criteria used to define each province. A brief description of each province is provided below:

Table 1. Descriptive indicators for hydrogeologic province definition.

Province	Physiographic Region	Hydraulic Head Difference (ft)	Soil Infiltration Index	Slope from Nested Well Regression	ICU Thickness (ft)
Confined	*	>20	*	<0.5	>50
Semi-Confined	Yes	1 – 20	*	0.5 - 1	1 - 50
Regionally Unconfined	*	<1	*	0.9 – 1.0	0 - 20
Perched	Yes	>20	C-D	<0.5	>20

Note: * = not used.

In addition to the criterion listed in Table 1, more qualitative factors such as land use/cover, depth to water table, sinkhole density, dendritic stream hydrography (or lack thereof), and aquifer permeability were also reviewed to help determine the extent of each hydrogeologic province. The combination of all information helped provide the basis for delineation of each province.

2.1 Regionally Confined

This province contains a relatively thick and consistent confining layer or combination of confining layers which separate the surficial sand aquifer from the underlying Upper Floridan aquifer. Total confining unit thickness (ICU) is greater than 50 feet (ft) and the hydraulic head difference is generally greater than 20 ft except in coastal areas where the Floridan aquifer transitions from a recharge to discharge zone. Karst activity is limited to non-existent. Slope and r-squared values generated from linear regressions of water levels from surficial and Floridan aquifer nested monitor wells are generally less than 0.5. This hydrogeologic province is characterized by low recharge to the Floridan aquifer, seasonal water level changes of up to 20 ft in the Floridan aquifer, and large hydraulic head differences of greater than 20 ft between paired surficial and Floridan aquifer monitor wells (except in coastal regions). Typical effective leakance coefficient values range from 1×10^{-7} to less than 1×10^{-4} ft/d/ft.

2.2 Semi-Confined

This setting contains a saturated sand aquifer overlying a semi-confined Upper Floridan aquifer which is separated by a confining unit of variable thickness (usually less than 20 ft thick). Water levels in both the surficial and Upper Floridan aquifers fluctuate in a similar manner with hydraulic head differences greater than one but less than 20 ft. Karst activity is present due to variable confinement. Slope and r-squared values generated from linear regressions of water levels from surficial and Floridan aquifer nested monitor wells vary between 0.5 and 1. This hydrogeologic province is characterized by low to high recharge to the Floridan aquifer, highly correlated water level changes between the surficial and Upper Floridan aquifers, and hydraulic head differences of greater than one but less than 20 ft between paired surficial and Floridan aquifer monitor wells (except in coastal regions). Typical effective leakance coefficient values range from 1×10^{-4} to less than 1×10^{-2} ft/d/ft.

2.3 Regionally Unconfined

If the surficial sands are saturated, the water levels in both the shallow (sand) and deep (limestone) wells are essentially the same (less than one ft of difference) or the sands may be unsaturated. A clay semi-confining unit is usually present but may occasionally be absent. Water levels within the sands are typically deep, usually more than 10 ft below land surface except near coastal swamps, lakes, and within riverine floodplains. In some circumstances, the base of the sand unit becomes saturated only during extremely wet periods and remains dry most of the year. When the sands are perennially saturated, slope and r-squared values generated from linear regressions of water levels from shallow sand and Floridan aquifer nested monitor wells vary between 0.9 and 1.

Where the UFA is unconfined is a highly karst-dominated region. Dissolution of limestone is an active process via infiltration of rainwater because the limestone units of the Upper Floridan aquifer are close to land surface and the ICU is thin and discontinuous. The carbonate rocks of this region have been extensively and repeatedly subjected to chemical dissolution and deposition processes in response to sea-level fluctuations. Numerous sinkholes, internal drainage, and undulating topography that are typical of karst geology dominate the landscape. These active karst processes lead to enhanced permeabilities within the Upper Floridan aquifer. First-magnitude springs (> 100 cfs discharge) are found within this region. In addition, the highest recharge rates to the Upper Floridan aquifer occur here with values ranging between 10 and 30 inches per year.

The elevation of the Floridan aquifer water level in reference to the top of limestone is sometimes used to determine whether the UFA is exhibiting confined or unconfined conditions. While this criteria is generally recognized as a reliable indicator of artesian or non-artesian conditions, some caution must be used when it is employed in an active karst terrain. The top of the limestone is an erosional surface that has been highly modified due to active karst processes. It is not uncommon to see differences in the limestone elevation of 20 ft or more within a few hundred feet of distance. Therefore, in the unconfined region, the top of limestone elevation in reference to the groundwater level was not deemed sufficiently accurate to merit its use in the evaluation process. Comparison of measured water level elevation in each unit (sand and limestone) from paired nested wells provides the best measure of hydrostratigraphic conditions.

2.4 Perched Systems

This region generally corresponds to clay-rich surface soils within a defined physiographic region such as the Brooksville Ridge or Fairfield Hills. Where the clay-rich soils are sufficiently thick, they have limited dissolution of the underlying limestone leading to an undulating ridge and valley system with

land surface elevations often exceeding 150 ft NGVD. Numerous, localized, hydraulically "perched" lakes and water tables exist because of the generally thick clay confinement between the surface and the underlying UFA with hydraulic head differences varying from 20 to more than 100 ft. Scattered within the hydrogeologic province are localized karst "windows" which provide a source of high recharge to the underlying UFA. Lithologic information in this region generally shows a relatively thin layer of sand overlying rather thick clays. A distinct water table can exist within the surficial sand but it may only be present during extremely wet periods.

3.0 Hydrogeology of the SWFWMD

The hydrogeology of the SWFWMD (District) can generally be divided into three broad regions that correspond to major groundwater basins within the Upper Floridan aquifer (Figure 1). Within the District, from north to south, are the Northern West-Central Florida Groundwater Basin (NWCFGWB), the Central West-Central Florida Groundwater Basin (CWCFGWB), and the Southern West-Central

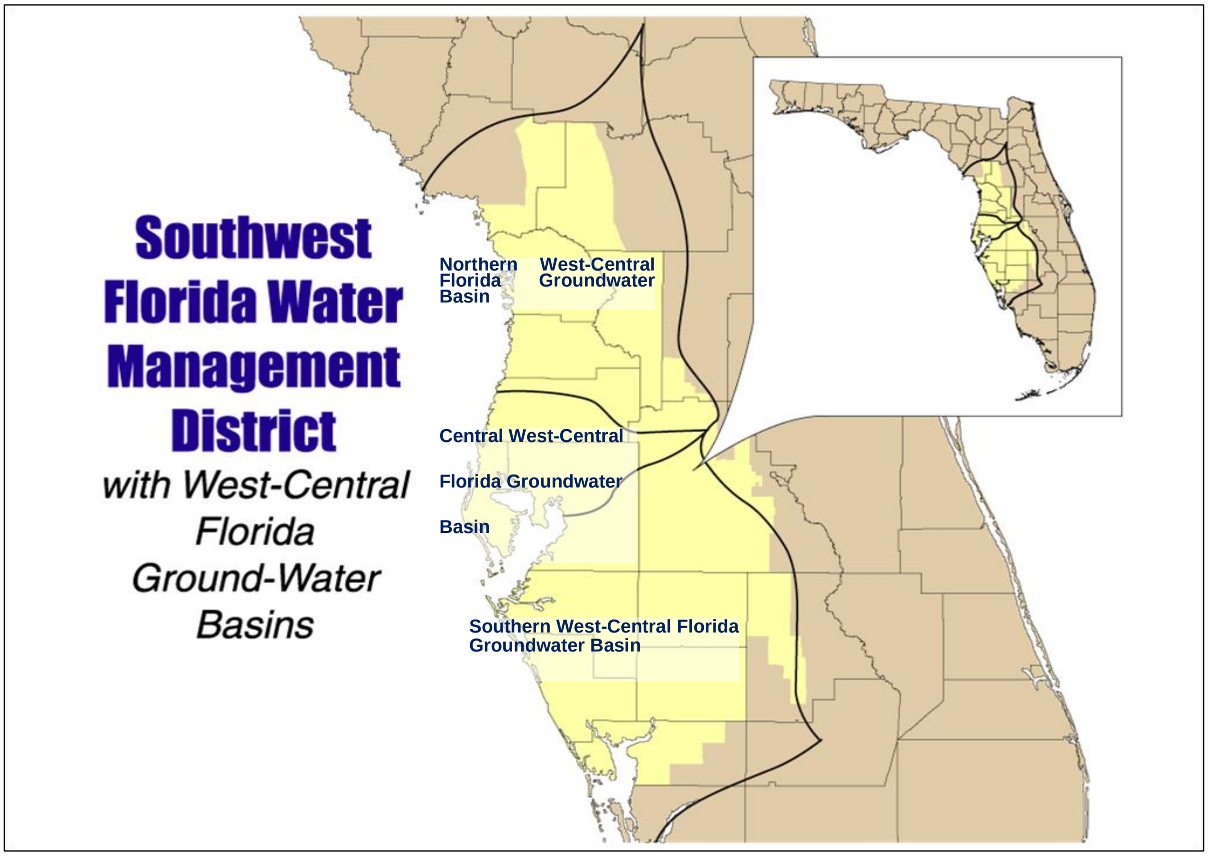

Figure 1. Location of the NWCFGWB, the CWCFGWB, and the SWCFGWB.

Florida Groundwater Basin (SWCFGWB). In general, the UFA is mostly unconfined in the NWCFGWB, semi-confined in the CWCFGWB, and well-confined in the SWCFGWB as the ICU thickens from north to south. There are, however, important sub-regional characteristics within each basin where the hydrogeologic system varies from this general pattern. These sub-regional areas or hydrogeologic provinces within each basin are the basis for this paper.

3.1 Southern West-Central Florida Groundwater Basin

While there are large physiographic regions such as the Southern Gulf Coastal Lowlands, De Soto Plain, and Polk Upland in the southern half of the District, unique hydrogeologic conditions occur along the Lakeland Ridge, the Lake Henry Ridge, the Winter Haven Ridge, and the Lake Wales Ridge (Figure 2). The Central Highlands Region of peninsular Florida consists of a series of near parallel north-south ridges that are remnants of beach and sand-dune systems associated with Miocene, Pliocene or Early Pleistocene shorelines (White, 1970). The region consists of xeric residual sand hills, beach ridges and dune fields which are interspersed with numerous sinkhole lakes and basins caused by erosion of the underlying limestone bedrock. The main axis of the Central Highlands is the Central Ridge, extending from southeastern Lake County in the north to southern Highlands County in the south **(**Wunderlin, 2010)**.** This comprises the Lake Wales Ridge, Winter Haven Ridge, Lake Henry Ridge and Bombing Range Ridge. An outlying ridge system to the west in Polk County comprises the Lakeland Ridge. In general, thick sandy soils promote low runoff, rapid infiltration, and high recharge rates along these ridges with the exception of the Lakeland Ridge and possibly the Lake Henry Ridge where poorly-drained soils are more prevalent and the ICU more competent.

In addition to the unique physiographic regions, the thickness of the ICU increases from north to south (Figure 3). The partitioning between the semi-confined to regionally confined UFA occurs along the extreme northern and eastern portions of the SWCFGWB. Within this broader context are

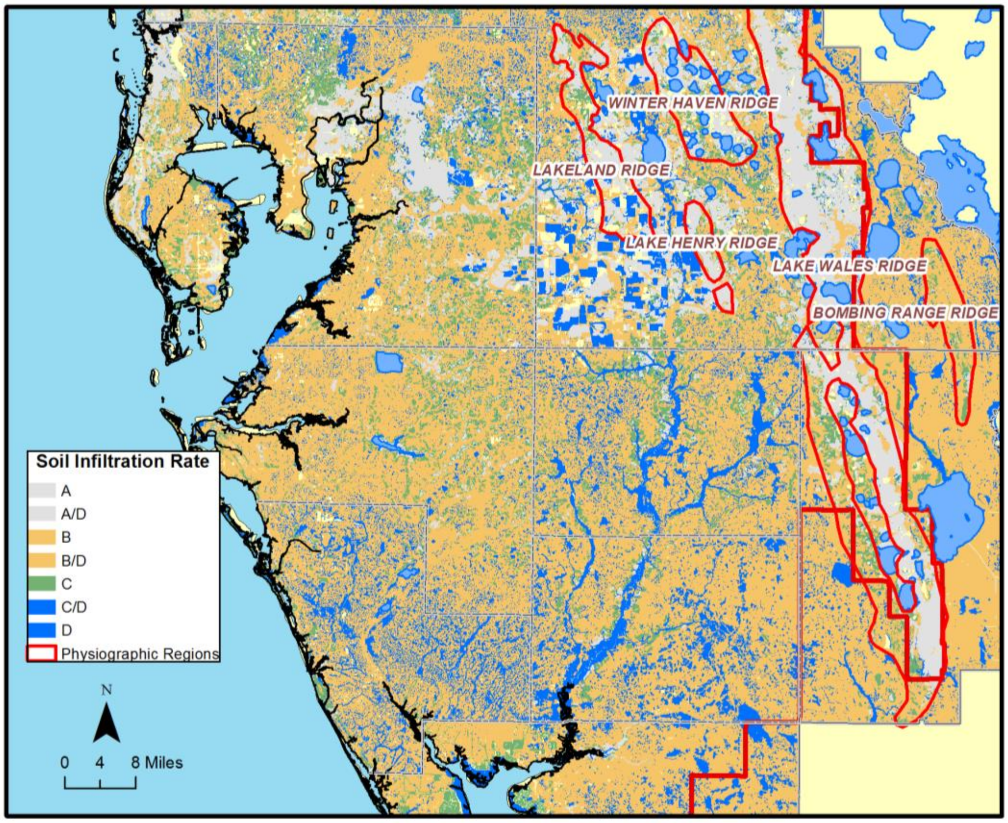

Figure 2. Location of ridges along with soil infiltration rate in the south half of the District.

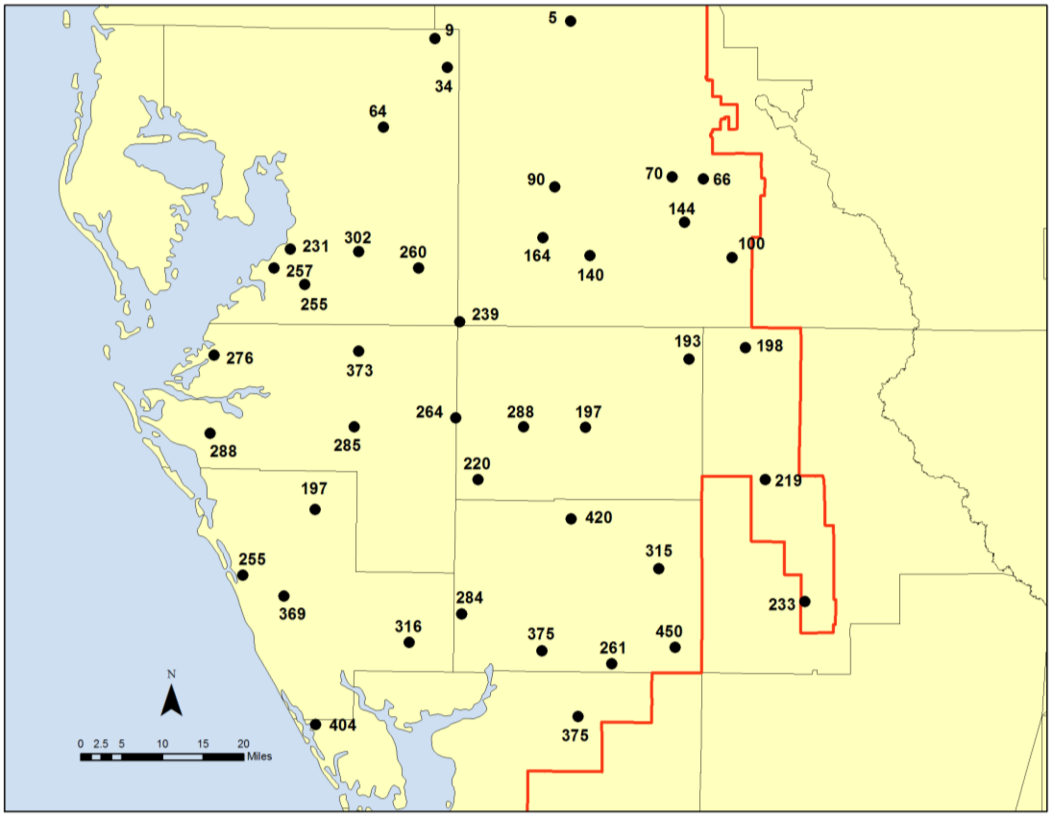

Figure 3. Intermediate confining unit thickness (ft). Data based on ICU thickness determined in each individual SWFWMD ROMP report.

other provinces such as the upper Peace River Karst Area and the Brandon Karst Terrain. A discussion of each hydrogeologic province located in the southern half of the District is included in the following sections.

3.1.1 Lakeland Ridge and Lake Henry Ridge

The Lakeland and Lake Henry ridges lie west of the central Florida ridge system. Both ridges are oriented north-northwest to south-southeast. Soil data generally indicates moderate to high infiltration sands covering both ridges (Figure 2). Along the Lakeland Ridge, sand thickness varies from zero to 53 ft (Figure 4). Average sand thickness is 21 ft based on data from eight sites. ICU thickness varies from 34 to 80 ft which forms a perched hydrogeologic province (Figure 5). Review of nested well hydrographs from three sites along the Lakeland Ridge indicates that hydraulic head differences vary from 77 to 130 ft between the surficial and Upper Floridan aquifers (Figure 6; Appendix A).

There are currently no nested wells located along the Lake Henry Ridge. Available data suggests, however, that a similar perched condition exists here. Land surface elevations generally vary from 150 to 250 Ft NGVD while the September 2009 UFA potentiometric surface ranged from 80 to 90 Ft NGVD within the ridge area (Figure 7). An ICU thickness of 140 ft was reported from the ROMP site closest to the Lake Henry Ridge.

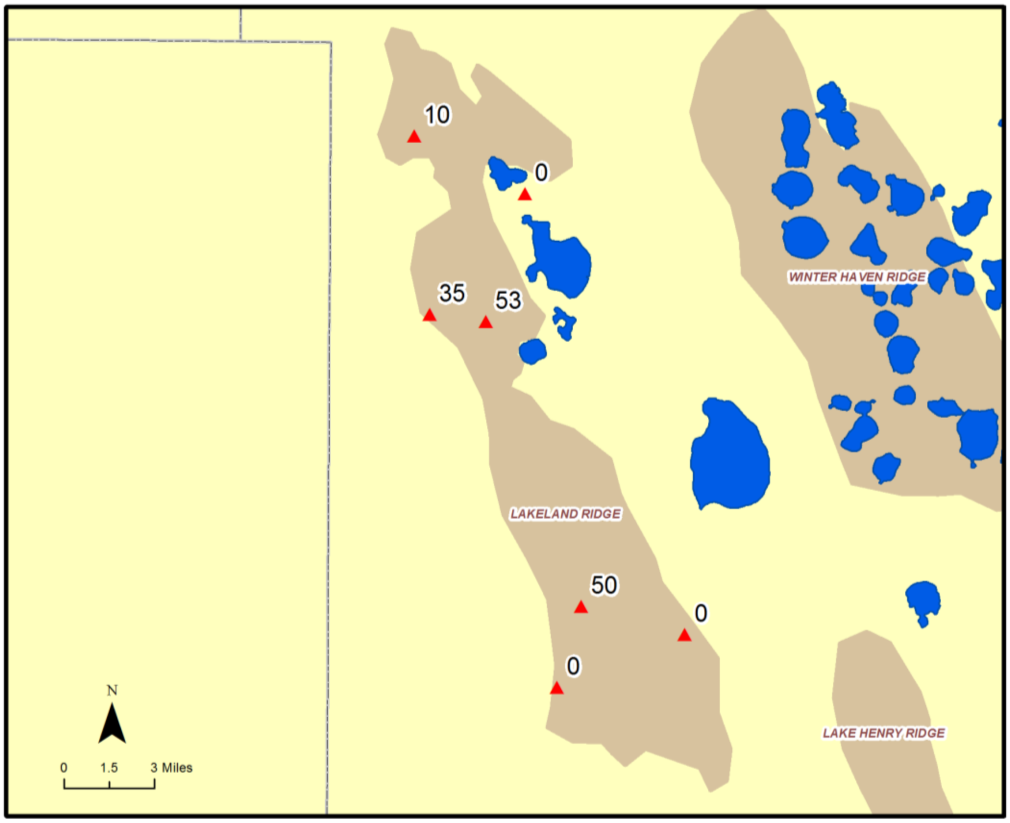

Figure 4. Sand thickness (ft) along the Lakeland Ridge (based on FGS lithologic logs).

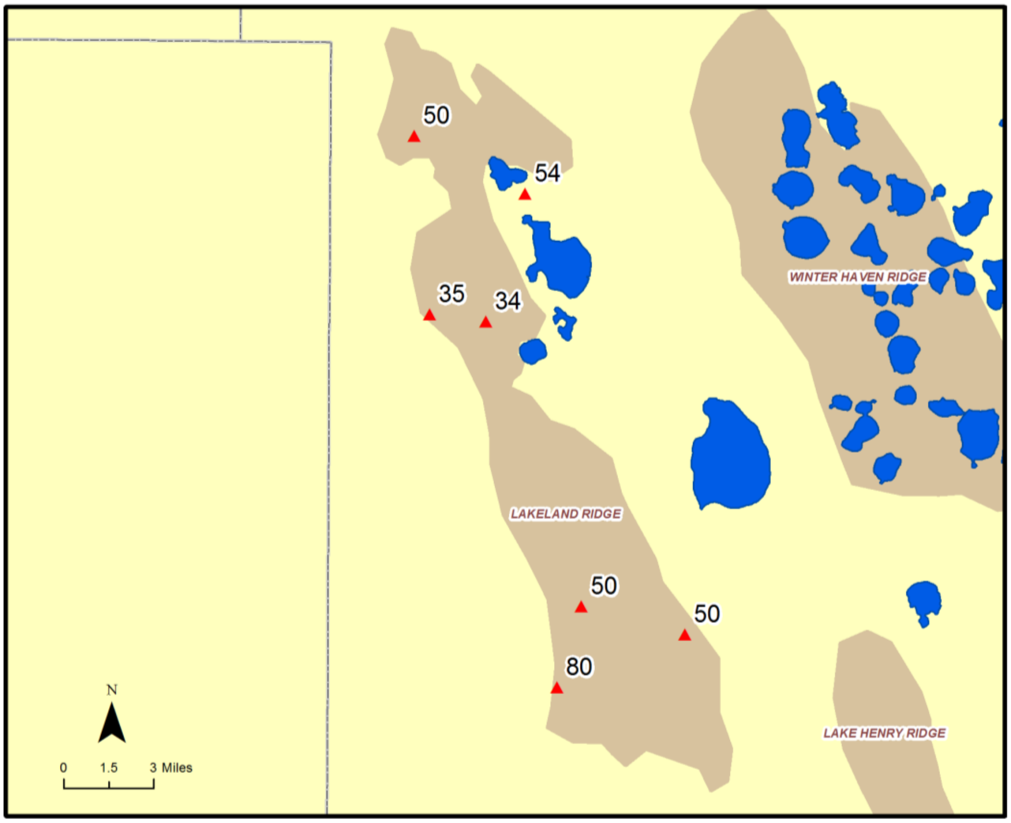

Figure 5. ICU Thickness (ft) along the Lakeland Ridge (based on FGS lithologic logs).

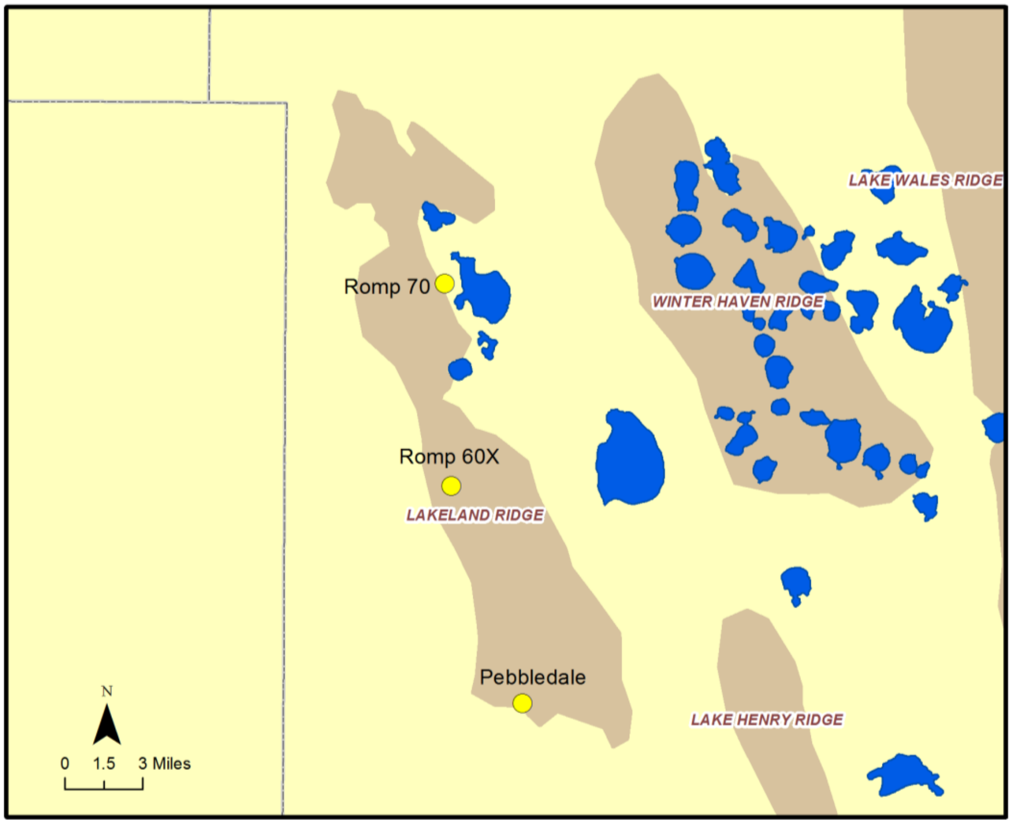

Figure 6. Location of nested monitor wells along the Lakeland Ridge.

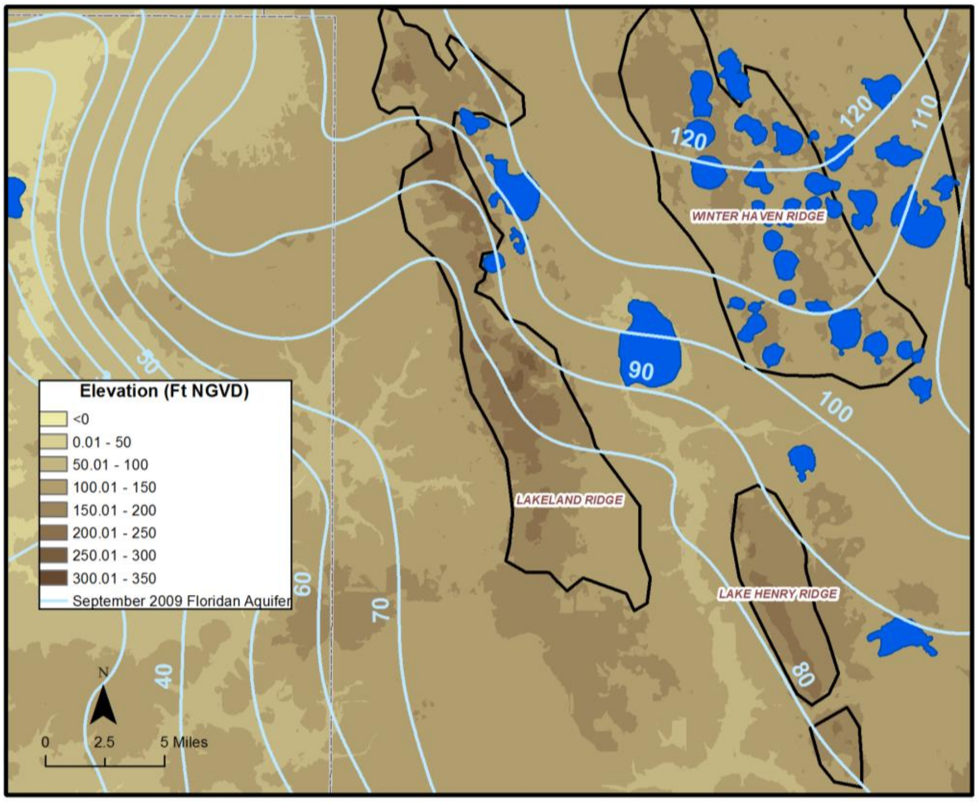

Figure 7. Land surface elevation with the September 2009 Upper Floridan aquifer potentiometric surface.

3.1.2 Winter Haven Ridge and Lake Wales Ridge

Both of these ridges contain closed basin lakes and sinkholes, deep water tables, and internal drainage. Surface drainage features are not well-developed. The Winter Haven Ridge consists mostly of small ridge remnants, reaching altitudes of about 200 Ft NGVD (Spechler and Kroening, 2007). The Lake Wales Ridge, located east of the Winter Haven Ridge, extends southward from Lake County, through Polk County and into Highlands County. The Lake Wales Ridge is the highest and longest of the ridges, with maximum altitudes of 305 Ft NGVD (Spechler and Kroening, 2007). The Lake Wales Ridge contains many sinkhole lakes and depressions, many of which do not have any surface-water outlets. In the southern part, the Lake Wales Ridge is divided into two secondary ridges by the Intra Ridge Valley (White, 1970). This valley was formed by the dissolution of the underlying limestone and contains numerous karst features.

Sand thickness along the Winter Haven Ridge varies from 30 to 100 ft based upon data from 10 sites (Figure 8). Average sand thickness along the Winter Haven Ridge was 71 ft. Review of ICU thickness along the ridge indicates discontinuous confinement with values ranging between 0 and 32 ft (Figure 9). Water table depth in this province varies from three to 51 ft below land surface (bls). Average water table depth is 25 ft bls (Figure 10). There is only one nested well site (Romp 76) along the extreme northern edge of the ridge. It indicates a long-term hydraulic head difference of five feet between the surficial and UFA. The discontinuous nature of the ICU and karst activity suggest that semi-confined conditions exist along the Winter Haven Ridge (Figure 11).

Sand thickness along the Lake Wales Ridge varies from 40 to 380 ft based upon data from 49 sites (Figure 12). Average sand thickness along the Lake Wales Ridge was nearly 200 ft. Review of clay thickness along the ridge indicates discontinuous confinement with values ranging between 0 and 233 ft (Figure 13). From nested wells, hydraulic head difference between the surficial and Upper Floridan aquifer varied from 0 to 90 ft with generally higher values toward the southern half of the ridge (Figure 14). Water table depth in this province varies from near land surface to 95 ft below land surface (bls). Average water table depth is 19 ft bls (Figure 15). Reported sinkholes are confined mostly to the northern half of the Lake Wales Ridge. All of this data suggests more competent confinement over the southern half of the ridge and its hydraulic connection may be locally derived from relict karst activity associated with lakes (Figure 16).

3.1.3 Upper Peace River Karst Area

The upper Peace River from Bartow to Fort Meade is a groundwater recharge area (Figure 17). The upper Peace River channel and floodplain are characterized by extensive karst development, with numerous fractures, crevasses, and sinks that have been eroded in the near-surface and underlying carbonate bedrock (Metz and Lewelling, 2010). This area reflects a reversal from historical groundwater discharge patterns that existed prior to the 1950s.

Historically, the floodplain along the upper Peace River contained artesian wells and a second magnitude spring (Kissengen Spring) that discharged an average of 20 million gallons per day (mgd) into the Peace River (Peek, 1951; Stewart, 1966). However, hydrologic conditions began to change as early as the 1930s, with an increase in groundwater use for mining and agriculture (Peek, 1951). Because of this increased water use, a 40-foot (ft) decline in groundwater levels over a 20-year period resulted in the cessation of flow of the artesian wells and Kissengen Spring (Peek, 1951).

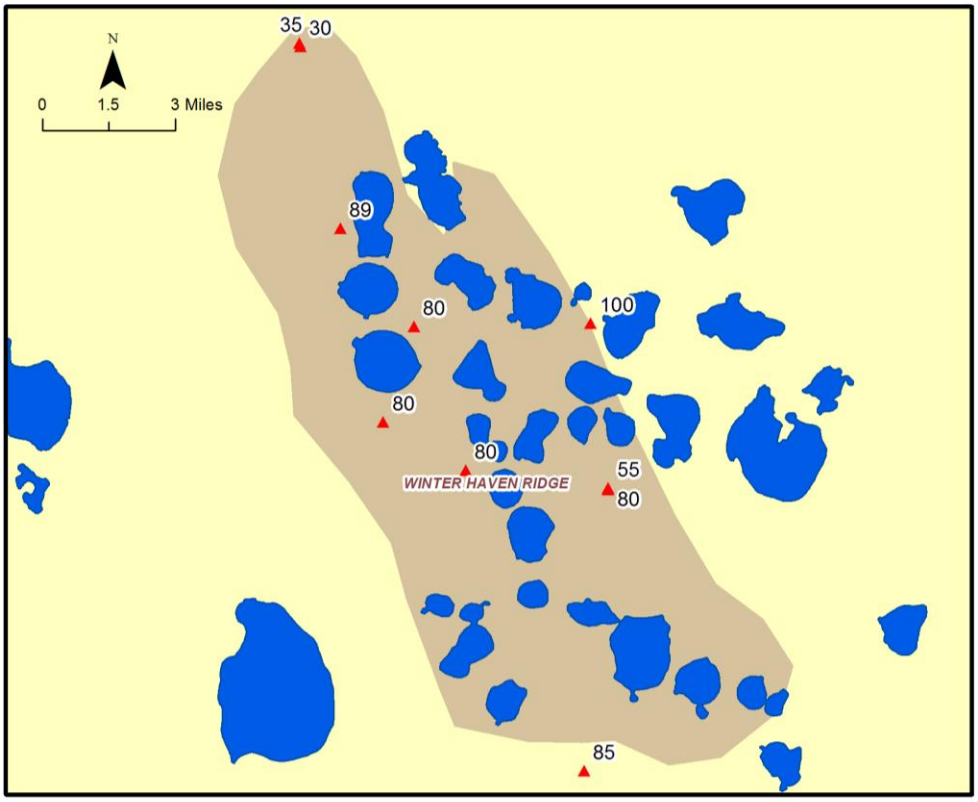

Figure 8. Sand thickness (ft) along the Winter Haven Ridge (based on FGS lithologic logs).

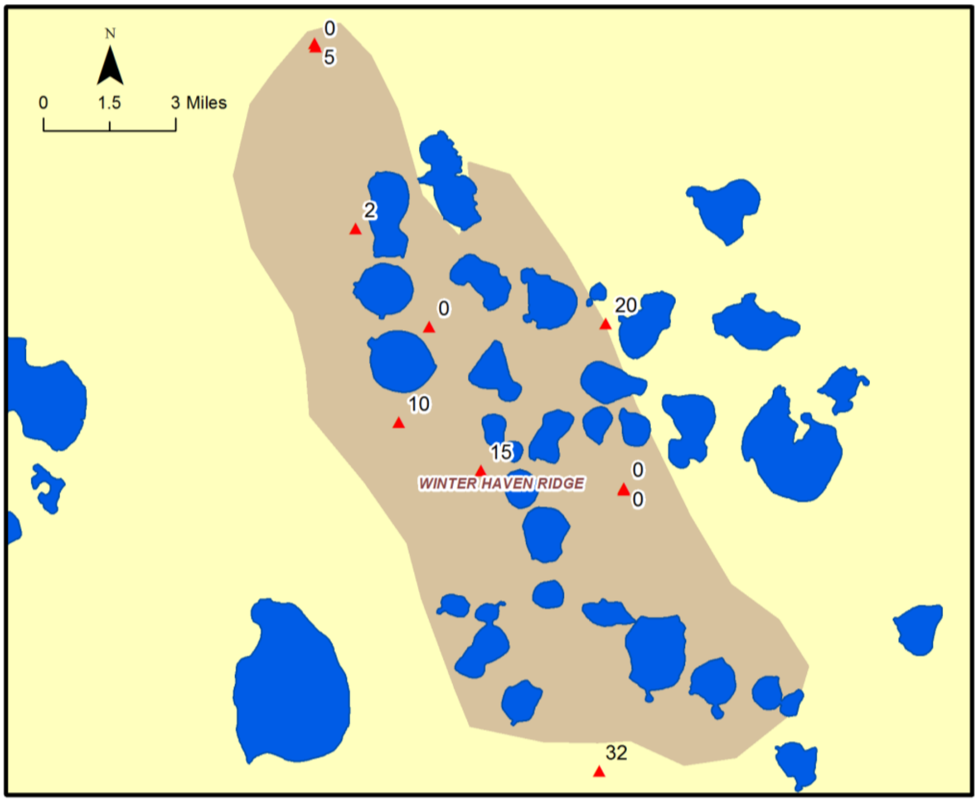

Figure 9. ICU thickness (ft) along the Winter Haven Ridge (based on FGS lithologic logs).

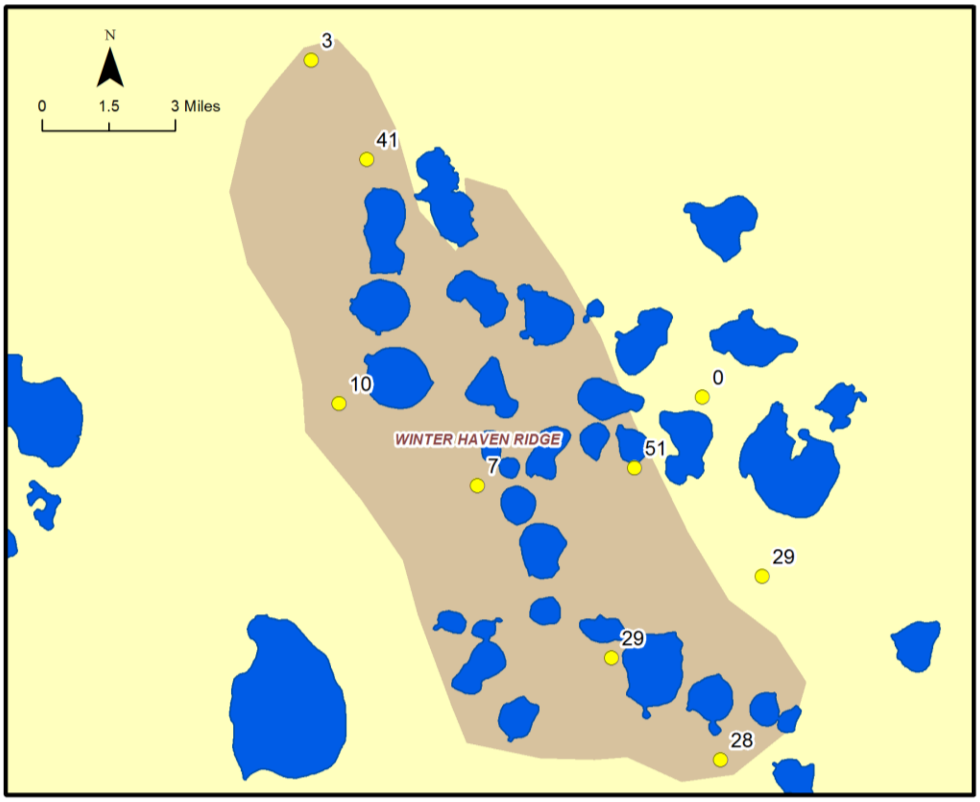

Figure 10. Water table depth (ft bls) within or near the Winter Haven Ridge.

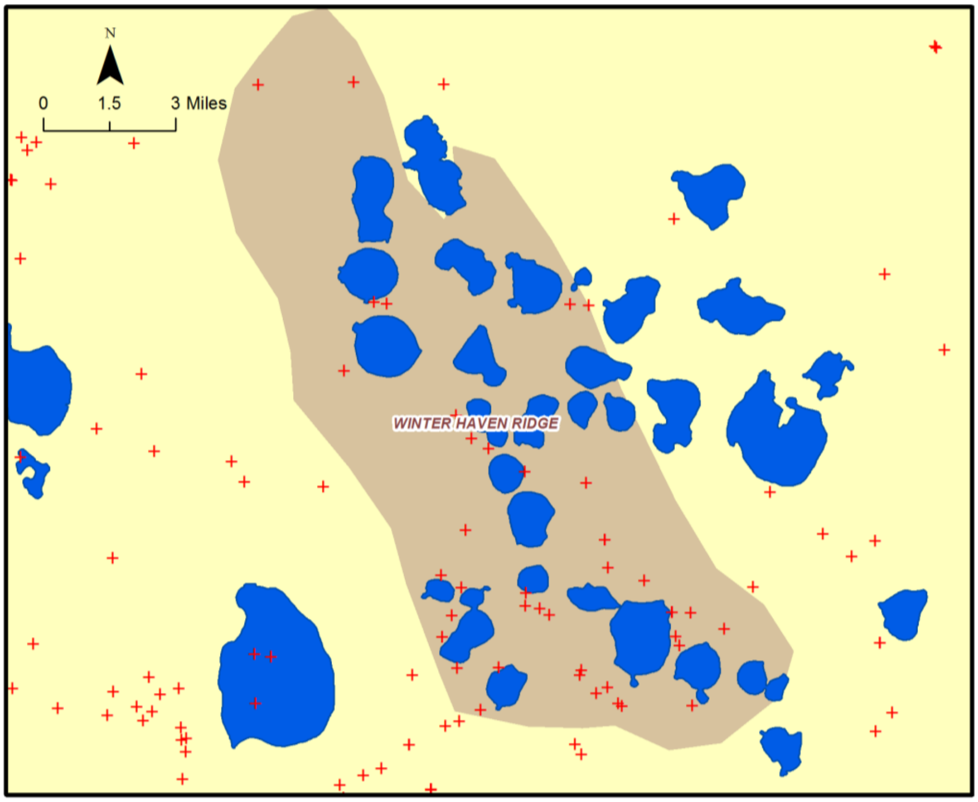

Figure 11. Location of sinkholes on or near the Winter Haven Ridge.

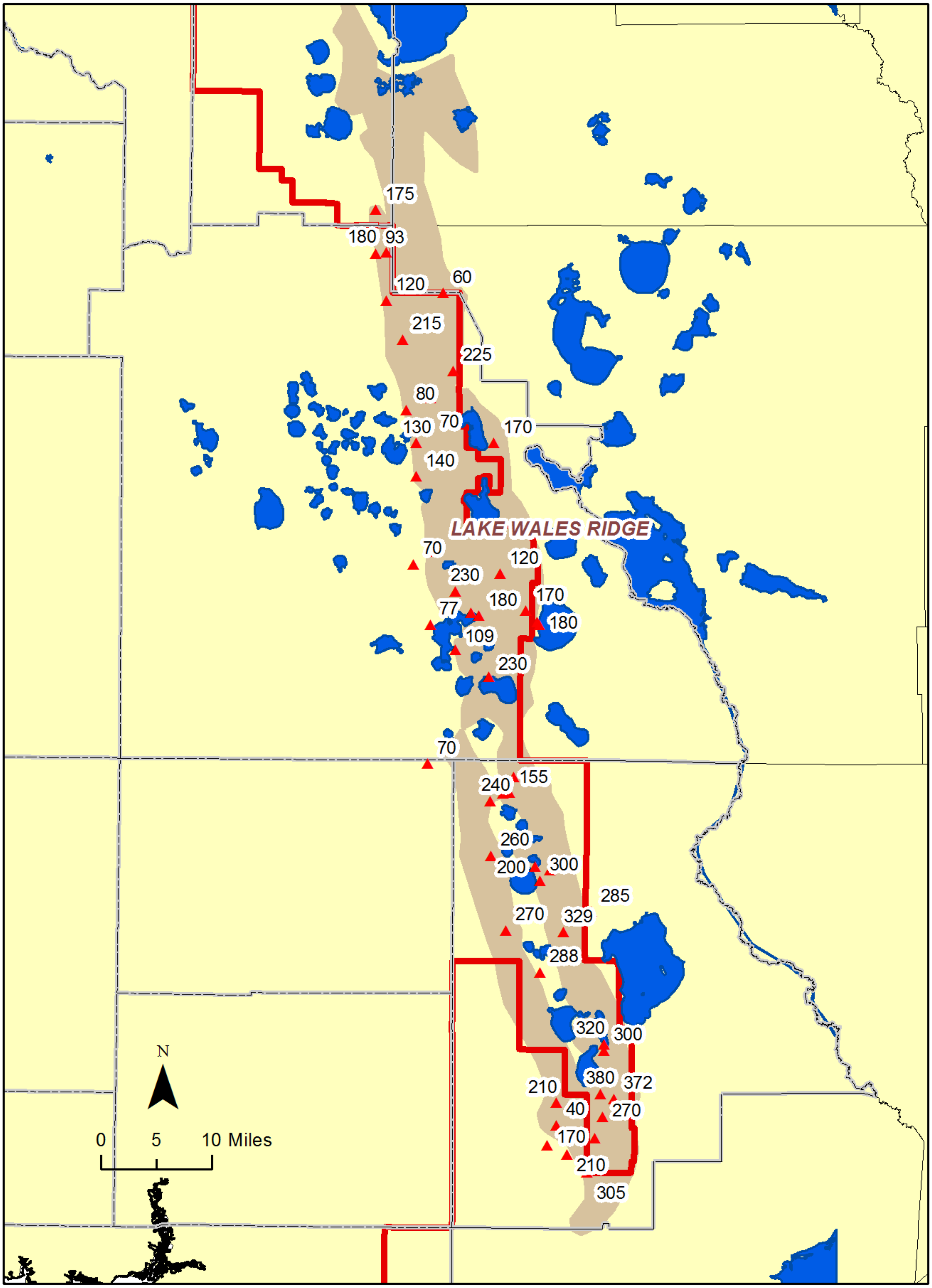

Figure 12. Sand thickness (ft) along the Lake Wales Ridge (based on FGS lithologic logs).

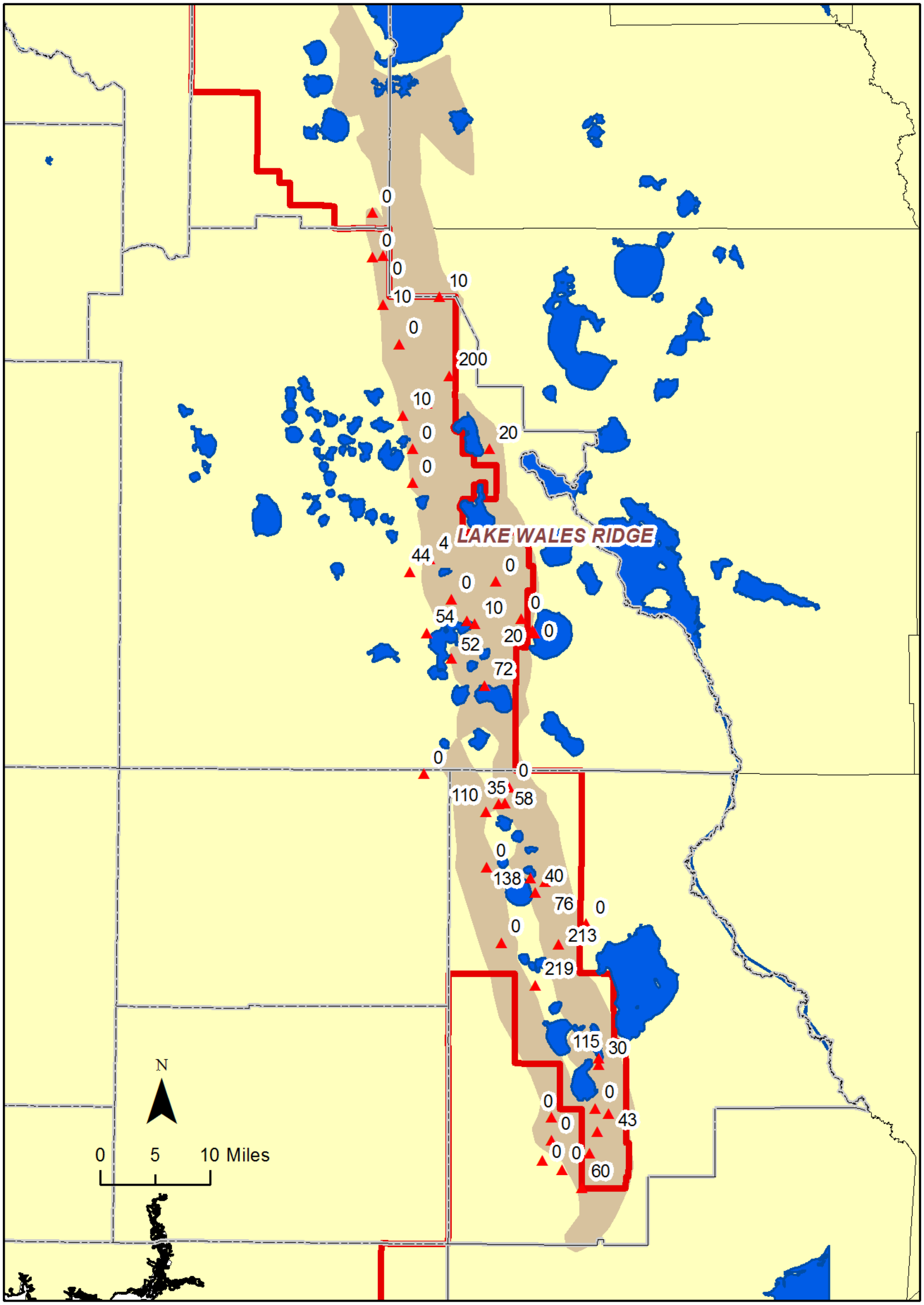

Figure 13. Clay thickness (ft) along the Lake Wales Ridge (based on FGS lithologic logs).

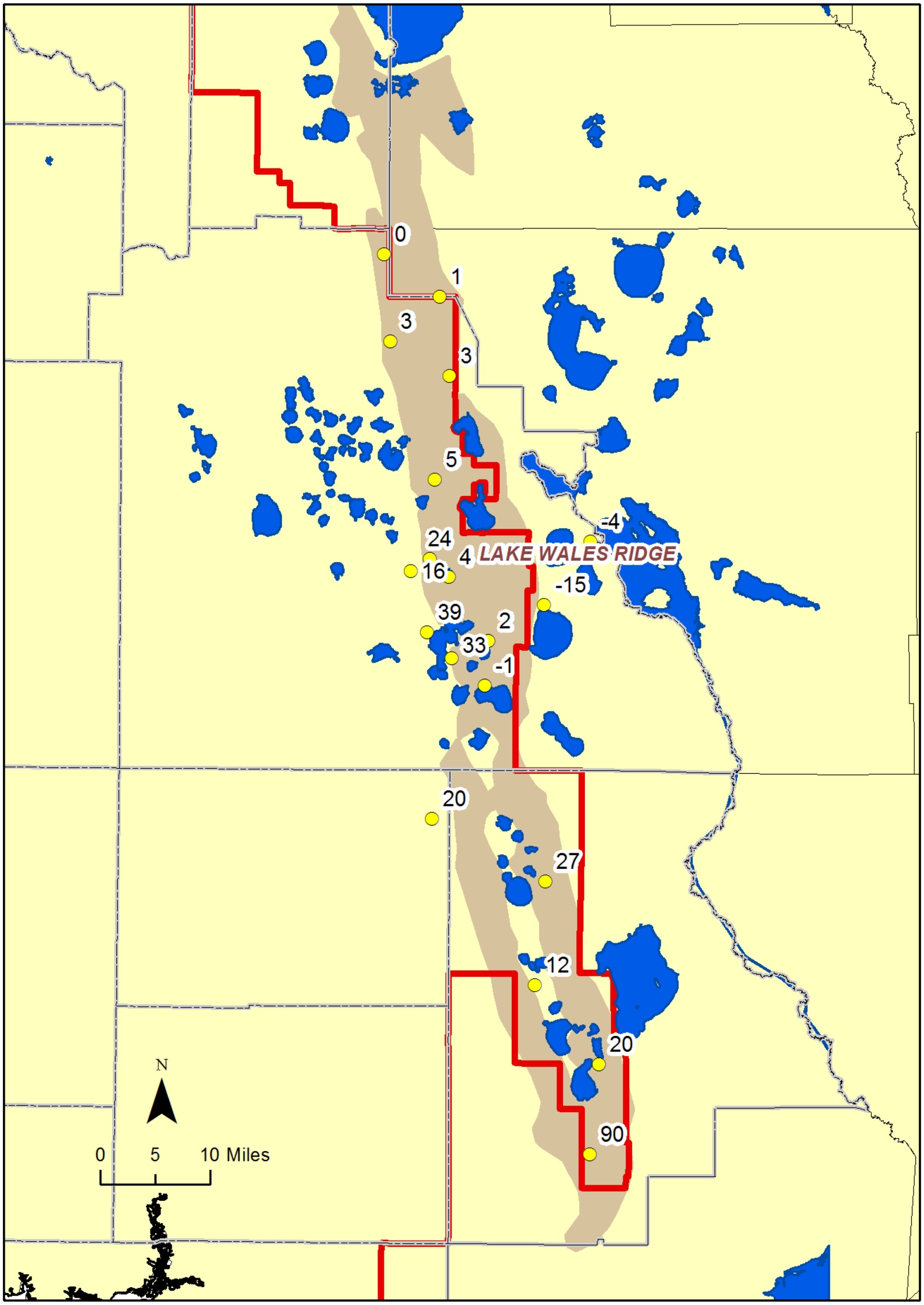

Figure 14. Average hydraulic head difference (ft) between surficial and Upper Floridan aquifer nested wells along the Lake Wales Ridge (Note: Period-of-Record, minimum 5-year length).

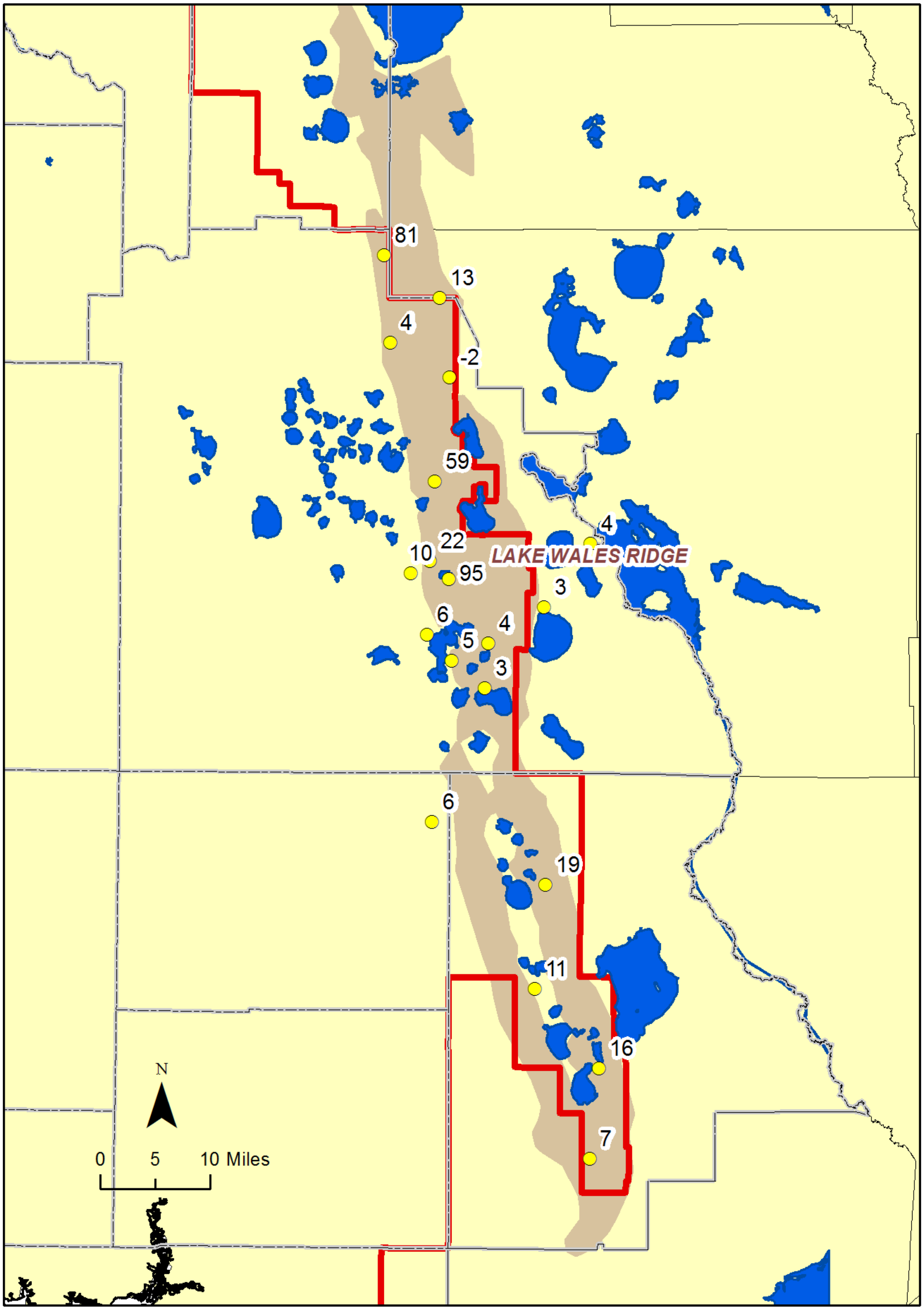

Figure 15. Average water table depth in feet below land surface from surficial aquifer wells along the Lake Wales Ridge (Note: Period-of-record, minimum 5 year length).

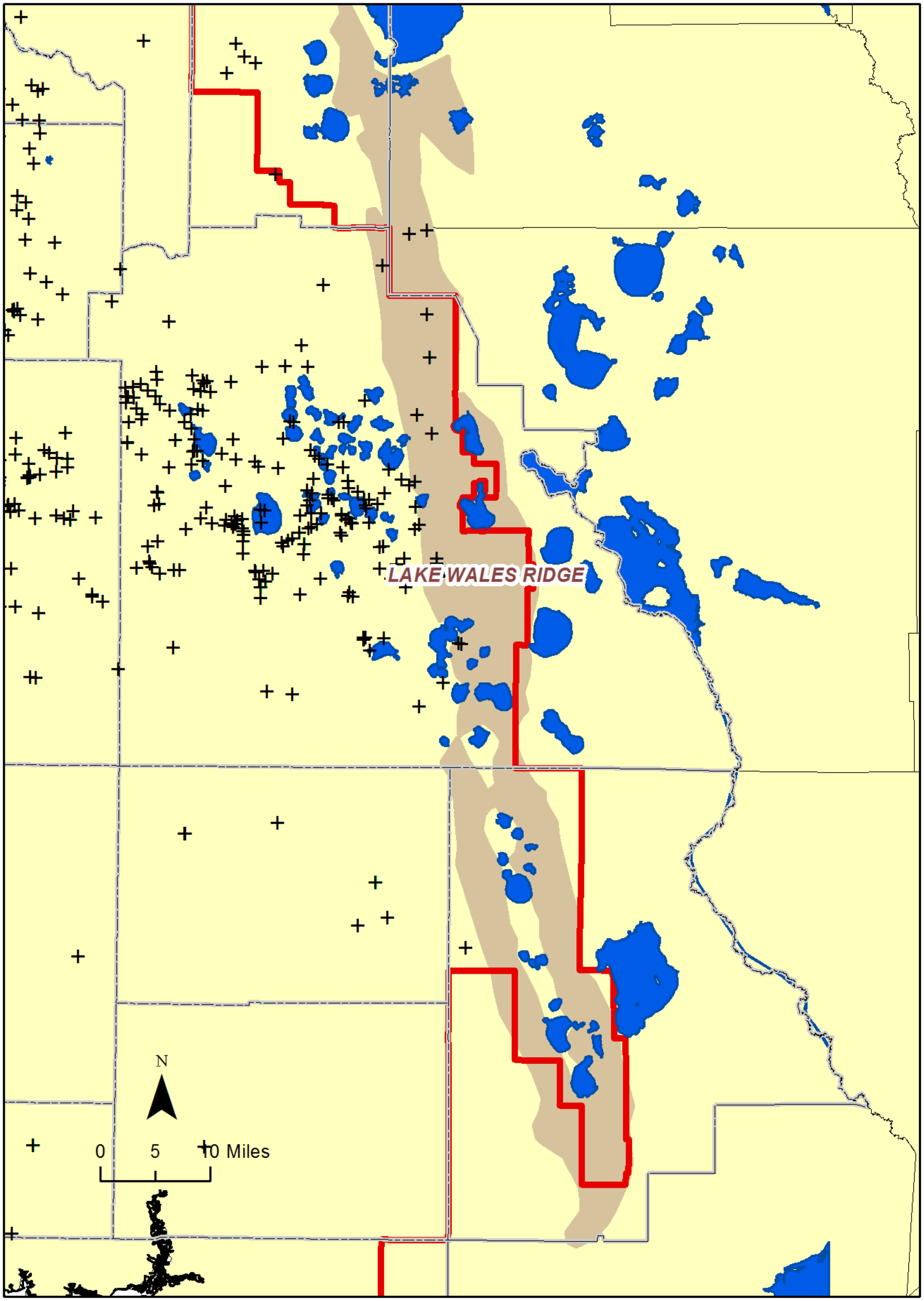

Figure 16. Location of sinkholes along or near the Lake Wales Ridge.

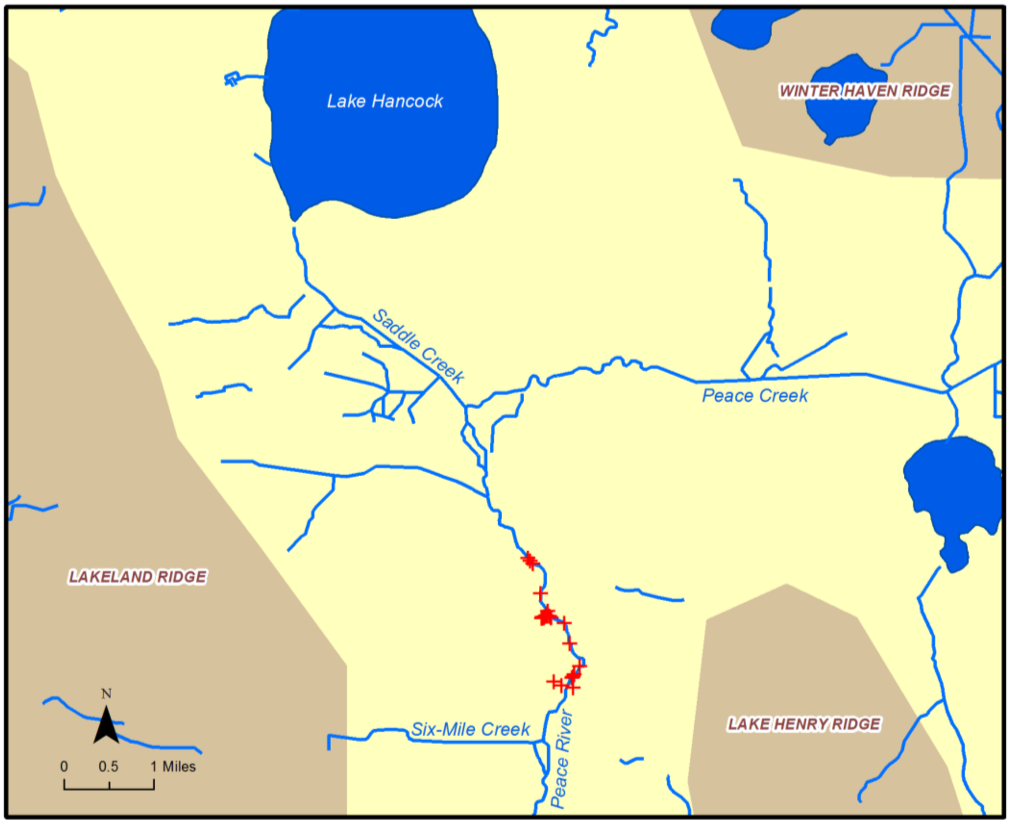

Figure 17. Location of major karst features along the upper Peace River (data from Metz and Lewelling (2010)).

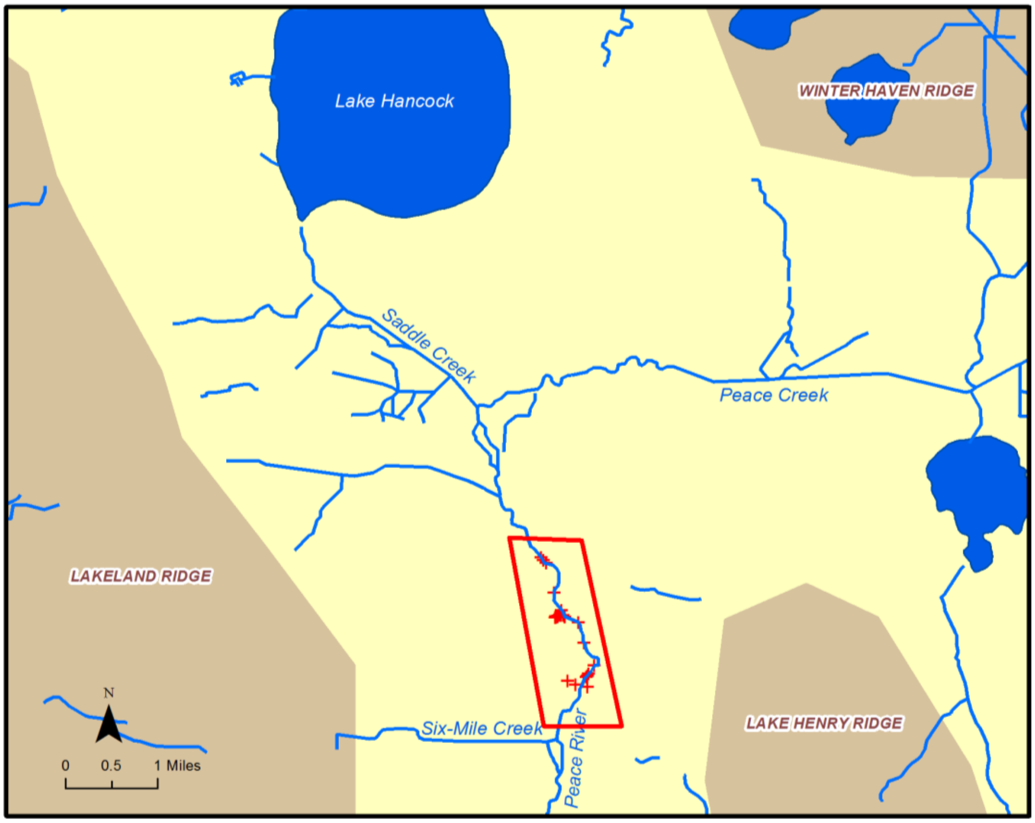

Figure 18. Semi-confined hydrogeologic province of the upper Peace River karst area.

An approximate 2-mi section of the upper Peace River, between Bartow and Homeland, is a highly karstified region where numerous features are located that are capable of draining the river water (Metz and Lewelling, 2010). Three main features, the Ledges, the Crevasses, and Dover Sink account for approximately 80 percent of stream flow seepage to the underlying intermediate and Upper Floridan aquifers during low flow conditions (Basso, 2009). Average dry season river flow losses were 17 cubic feet per second (cfs) based on a series of seepage measurements made by the USGS.

The section of the Peace River between Bartow and Homeland is considered a semi-confined hydrogeologic province with respect to the UFA (Figure 18). Information from Metz and Lewelling, (2010) indicates that a direct hydraulic connection between the riverbed and the UFA exists in the highly-karst section of the river. This condition extends to several large sinks in the adjacent floodplain. Therefore, a small karst “window” or semi-confined province has been defined for this section of the river.

3.1.4 Brandon Karst Terrain

The Brandon Karst Terrain (BKT) is an internally drained portion of the Polk Upland physiographic region that is characterized by sinkholes and hills formed by marine and coastal sands (USEPA, 2003). It is an area of approximately 40 square miles, located to the north of the Alafia River and west of Lithia Springs (SDI, 1998). Hydrogeology consists of a discontinuous and ephemeral surficial aquifer underlain by a leaky confining unit consisting of Hawthorn Group clays. The limestone in this area has been heavily weathered by chemical dissolution and the area is dominated by karst topography including a high density of ancient and modern sinkholes, internal drainage, springs, and significantly increased transmissivities in the UFA.

The BKT was first identified by Jones and Upchurch (1993) during an investigation into the source region for Buckhorn and Lithia Springs (Figure 19). SDI (1998) and SWFWMD (2005) also examined hydrogeologic conditions within the BKT. Based on 12 surficial aquifer well sites, depth to the water table in May 2001 varied from nine to 37 ft bls (SWFWMD, 2005). Average water table depth was 21 ft bls. Average hydraulic head differences between the surficial and Upper Floridan aquifers from five nested wells ranges from two to 28 ft indicating the variable nature of confinement across the BKT (Figure 20; Appendix B). Based upon the aforementioned information, the BKT is considered a semi-confined hydrogeologic province.

3.2 Southern West-Central Florida Groundwater Basin

The vast majority of the SWCFGWB lies within the confined hydrogeologic province as thick Hawthorn Group Clays generally provide tight confinement over the UFA except near the extreme northern and eastern sides (Figure 21). In this area, the Lake Wales Ridge, Winter Haven Ridge, and Brandon Karst Terrain, exhibit semi-confined conditions due to relict and active sinkhole activity. A small area along the Upper Peace River was also defined as semi-confined due to the high density of active karst features. Along the Lakeland and Lake Henry physiographic regions, a perched hydrologic system is present.

There is also a transition from confined to semi-confined conditions along the northern edge of the basin outside of the BKT and Winter Haven Ridge provinces as Hawthorn clays thin (Figure 21). In the areas of the basin outside of the individual provinces described previously, a combination of ICU thickness, hydraulic head difference, slope, and physiographic region boundaries were utilized to define the transition from confined to semi-confined conditions (Figures 22 and 23). This boundary was defined according to criteria listed in Table 1.

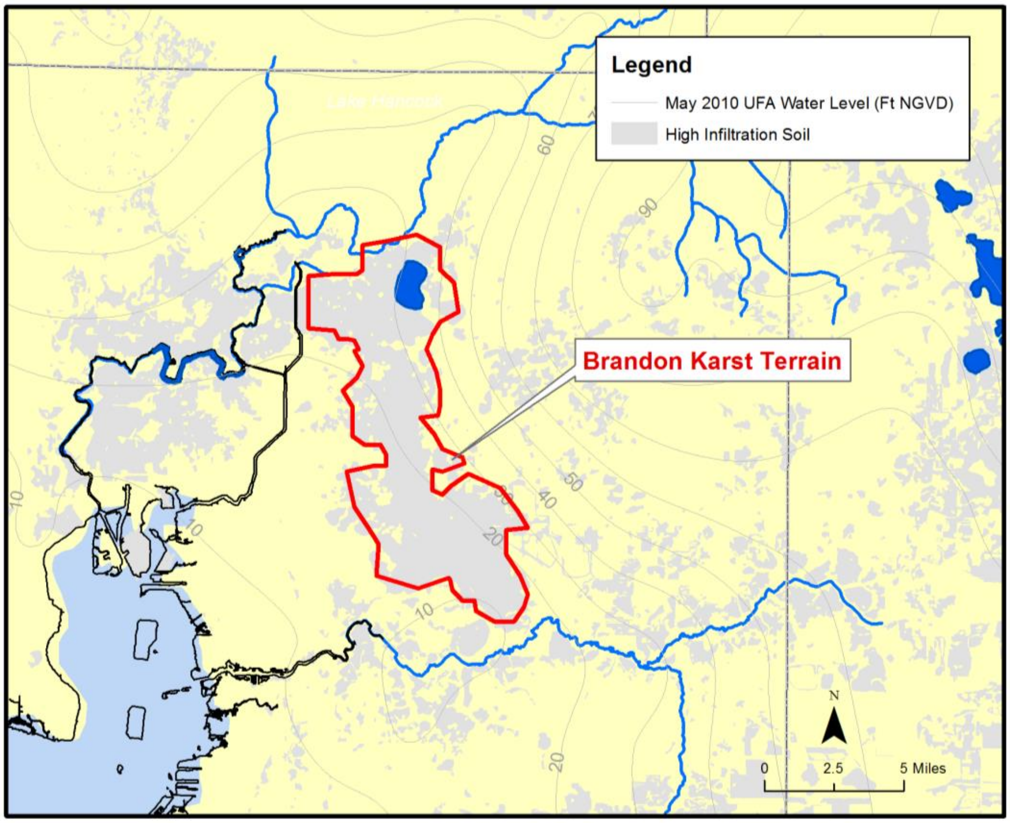

Figure 19. Location of the Brandon Karst Terrain.

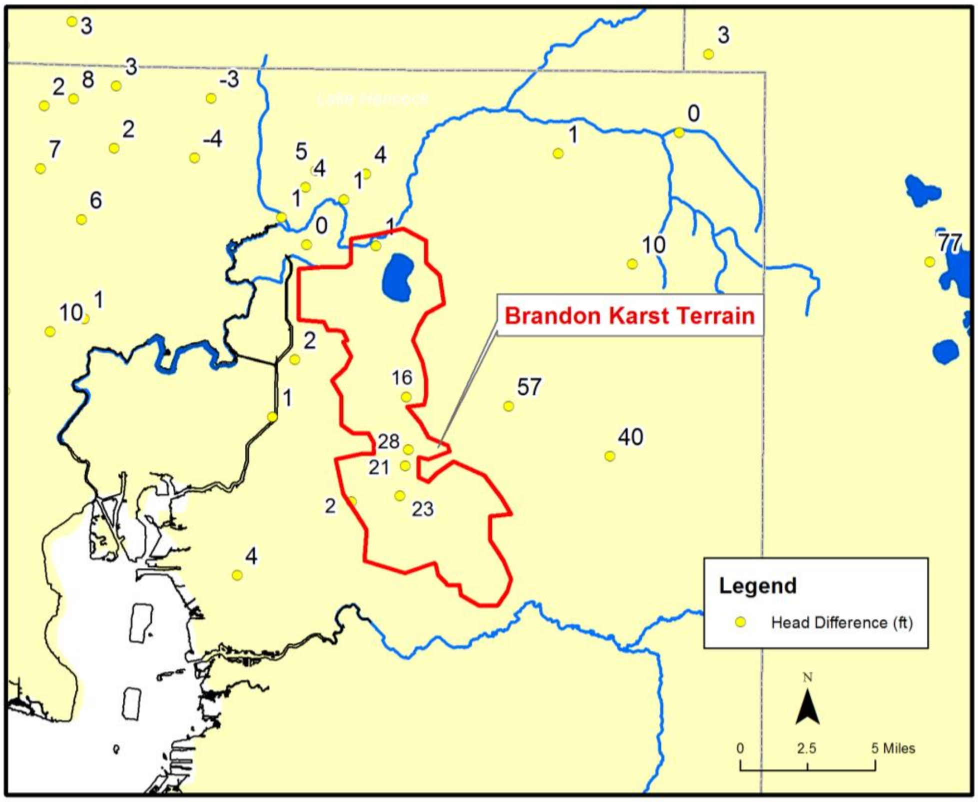

Figure 20. Average hydraulic head difference (ft) between the surficial and Upper Floridan aquifers within or near the Brandon Karst Terrain (Note: Period-of-Record, minimum 5-year length).

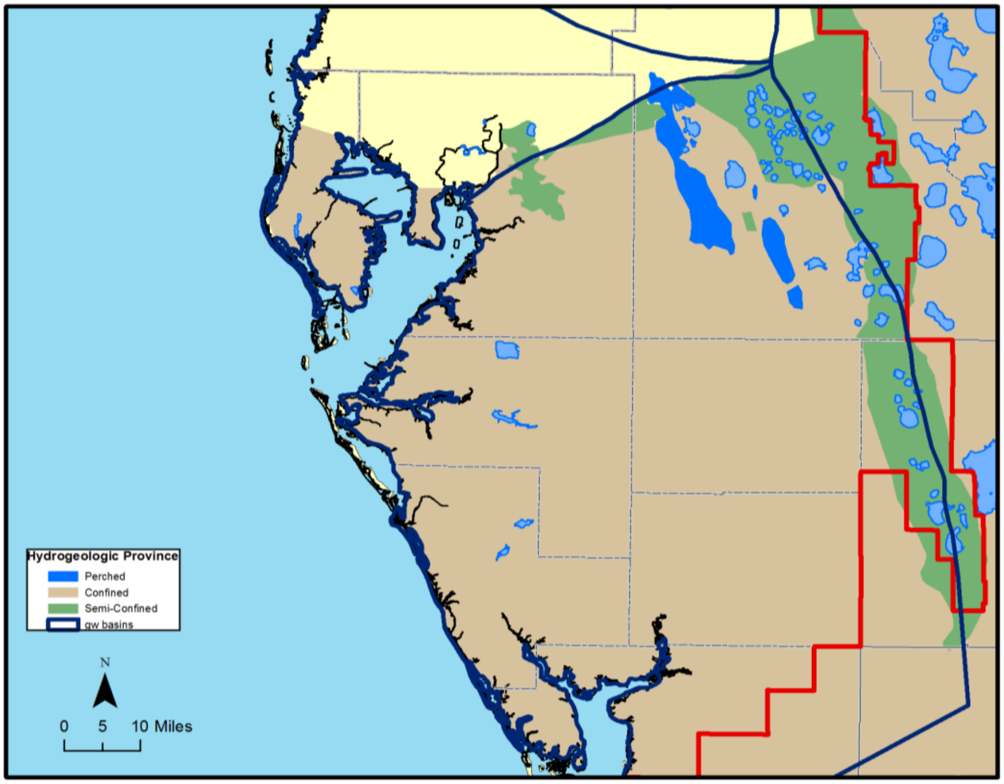

Figure 21. Location of hydrogeologic provinces in the Southern West-Central Florida Groundwater Basin.

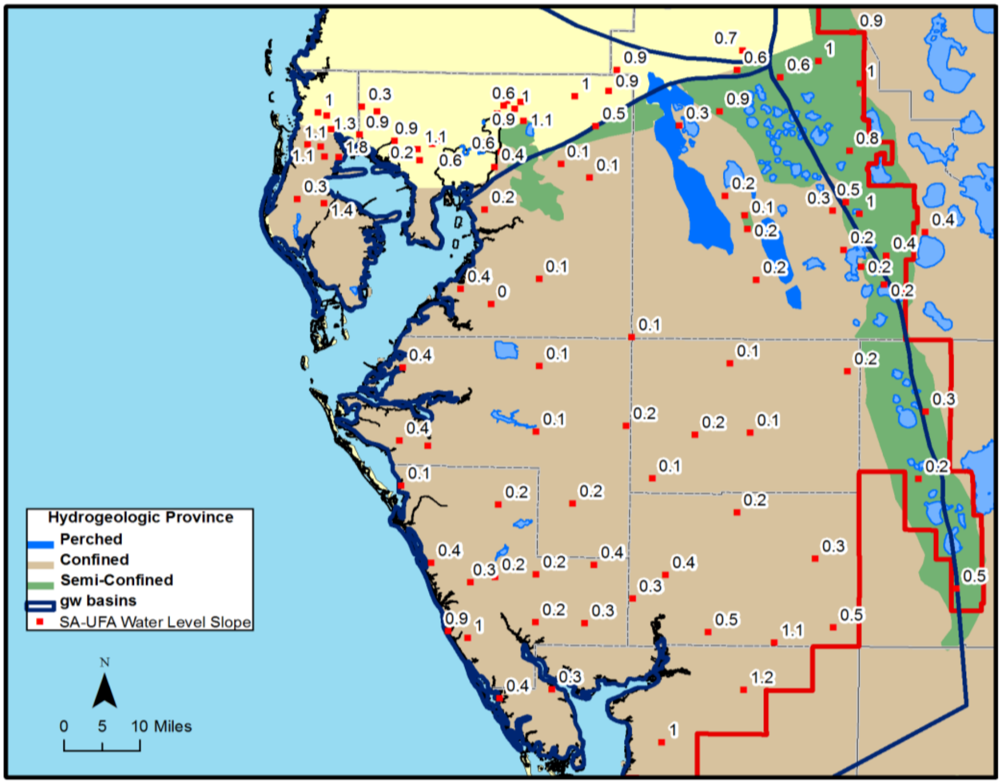

Figure 22. Daily slope values from linear regression of Surficial and Upper Floridan aquifer water levels at nested wells.

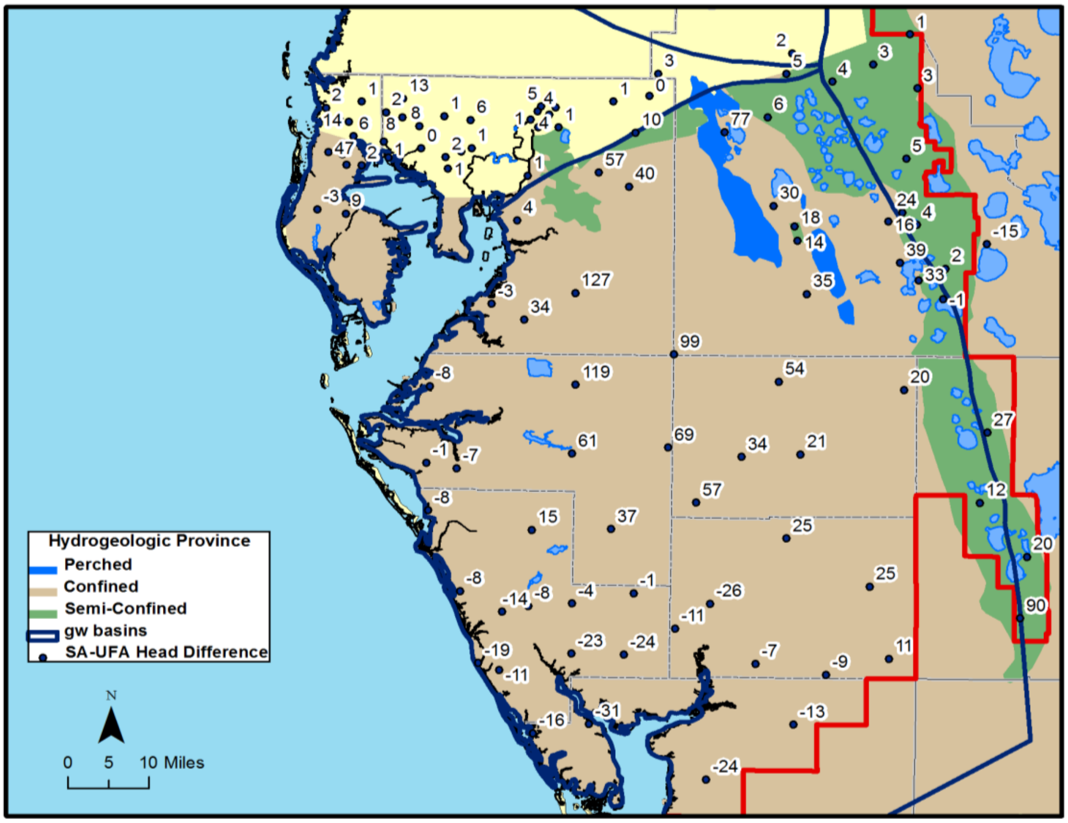

Figure 23. Average hydraulic head difference (ft) between Surficial and Upper Floridan aquifer water levels at nested wells (Note: period-of-record average, minimum 5 years of record).

This transition zone along the northern boundary of the SWCFGWB outside the individual defined provinces has the highest level of uncertainty in province definition. Available data along the northern boundary between the Winter Haven Ridge and Lake Wales Ridge and between the Lakeland Ridge and the Winter Haven Ridge is somewhat limited. Additional data collection in these two areas would improve the demarcation between confined and semi-confined conditions in this region.

The southern half of the Lake Wales Ridge province shows from several pairs of nested wells rather low slope values (0.2 to 0.4) and hydraulic head differences that range from 12 to 90 ft. This suggests that most of this area has good confinement away from the lakes. Regional groundwater flow models from Barcelo and Basso (1993) and Sepulveda (2002) have indicated high recharge to the UFA in this region yet the data suggests tighter confinement. Clay thickness is quite variable based on FGS lithilogic logs. It is likely that higher recharge flux to the UFA occurs as a result of relict karst features associated with the lakes in this region.

3.3 Central and Northern-West-Central Florida Groundwater Basins

Similar to the SWCFGWB, there are large physiographic regions within the northern half of the District such as the Northern Gulf Coastal Lowlands, the Tsala-Apopka plain, the Western Valley, the Sumter Upland, and the Lake Upland that do not strongly influence hydrogeologic province definition. There are, however, two physiographic regions, the Brooksville Ridge and Fairfield Hills areas, that directly influence province classification. In addition, the Green Swamp, although not defined as a physiographic region, also exhibits unique hydrologic characteristics that make it stand alone as a hydrogeologic province.

The southern half of the Brooksville Ridge and Fairfield Hills physiographic areas consist of numerous hills and depressions with relatively thick confinement. Where the clay-rich soils are thick, there is limited dissolution of the underlying limestone leading to an undulating ridge and valley system with land surface elevations often exceeding 150 ft NGVD. Numerous, localized, hydraulically "perched" lakes and shallow aquifers exist because of the generally thick clay confinement between the surface and the underlying UFA with hydraulic head differences varying from 20 to more than 100 feet.

In addition to these unique physiographic regions, the ICU thins considerably from the Tampa Bay area northward and eventually becomes discontinuous close to the boundary between the Central and Northern-West-Central Florida Groundwater Basins in northern Pasco County. The transition between the semi-confined to regionally confined UFA occurs in this area with the exception of the southern part of the Brooksville Ridge. Within this broader context is another province such as the Green Swamp.

A discussion of each hydrogeologic province located in the northern half of the District is included in the following sections.

3.3.1 Green Swamp

The Green Swamp is a largely undeveloped mosaic of cypress domes, hardwood forests, pine forests, prairies, and sand hills in central Florida (Figure 24). The Swamp occupies about 870 square miles in five Florida Counties - Polk, Sumter, Lake, Hernando, and Pasco. Land surface elevations vary between 75 and 200 feet. The Green Swamp is important to both surface and groundwater resources in central Florida and is a rich reservoir of biological diversity. The Swamp includes the headwaters of several important rivers including the Ocklawaha, Withlacoochee, Little Withlacoochee, Hillsborough, and Peace. Water levels with the Upper Floridan aquifer underlying the Swamp represent the highest potentiometric levels in peninsular Florida. Groundwater within the Floridan aquifer moves laterally from the Swamp to supply downgradient parts of the aquifer in other parts of central Florida.

The hydrogeologic framework in the Green Swamp area includes a surficial aquifer; a discontinuous intermediate confining unit (ICU), and a thick carbonate Floridan aquifer. At land surface and extending several tens of feet are generally fine-grained quartz sands that grade into clayey sand just above the contact with limestone. Sand thickness varies from two to 68 ft and averages 30 ft based upon 10 sites within the Green Swamp. In general, sand thickness is greatest along the eastern side of the Green Swamp that borders the Lake Wales Ridge (Figure 25). A thin, sometimes absent, sandy clay layer forms the ICU and overlies the limestone units of the UFA. ICU thickness varies from zero to 35 ft and averages 8 ft based on seven sites within the Green Swamp.

Based on the average period-of-record water levels for 13 surficial aquifer well sites, depth to the water table varied from three to seven ft bls. Average water table depth was four ft bls. Average hydraulic head difference between the surficial and Upper Floridan aquifers from 14 nested wells ranges from zero to five ft. The Upper Floridan aquifer is mostly semi-confined in the Green Swamp area.

The Green Swamp is an extensive area of wetlands and open water that forms a broad, flat plateau. While the limestone is generally shallow (close to land surface), it is relatively dense and impermeable which allows rainfall that infiltrates into the soil to mound or stack up at the surface. This creates a rather large reservoir of standing water, marshes, and cypress wetlands which forms the headwaters of five rivers. Due to the extensive area of open water and swamps, evaporation or evapotranspiration rates are high. This only provides enough water left over from rainfall to produce low to moderate recharge to the Upper Floridan aquifer (Basso, 2010). Because the Green Swamp sits at a

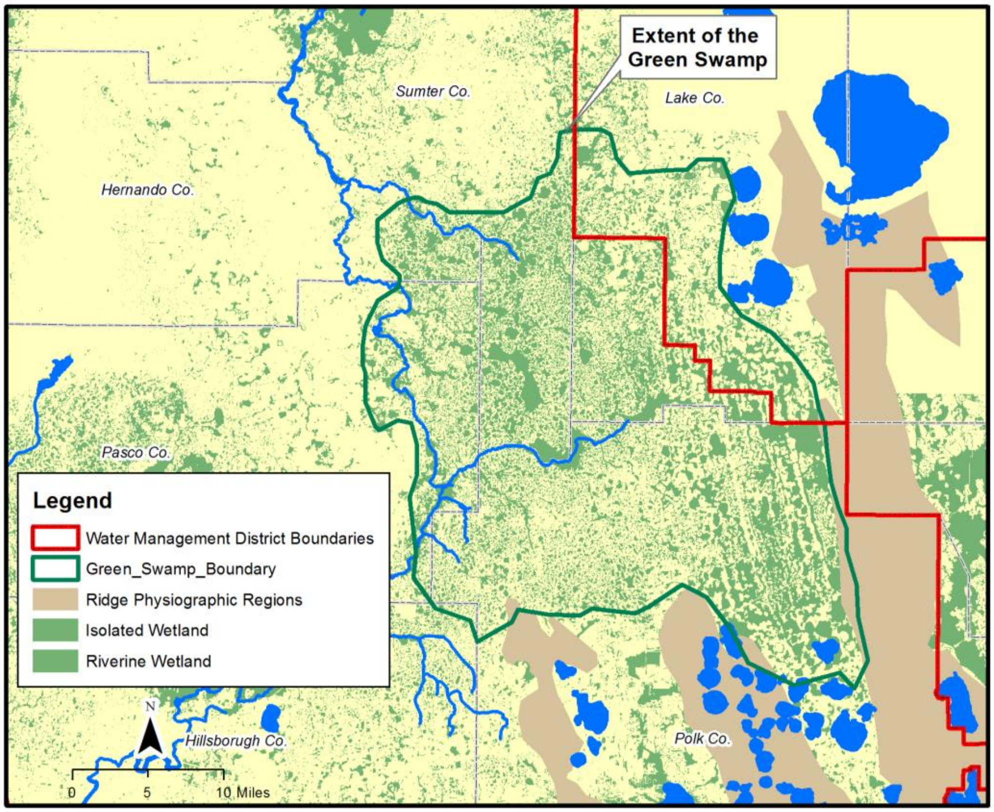

Figure 24. Location of the Green Swamp.

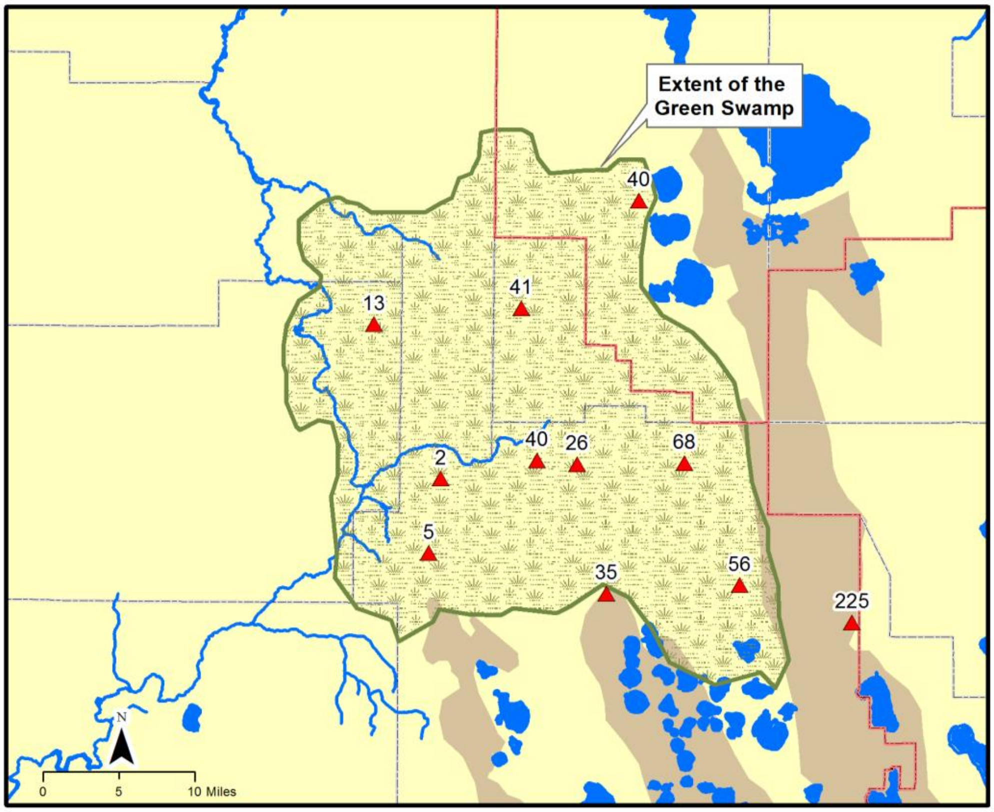

Figure 25. Sand thickness (ft) within or near the Green Swamp.

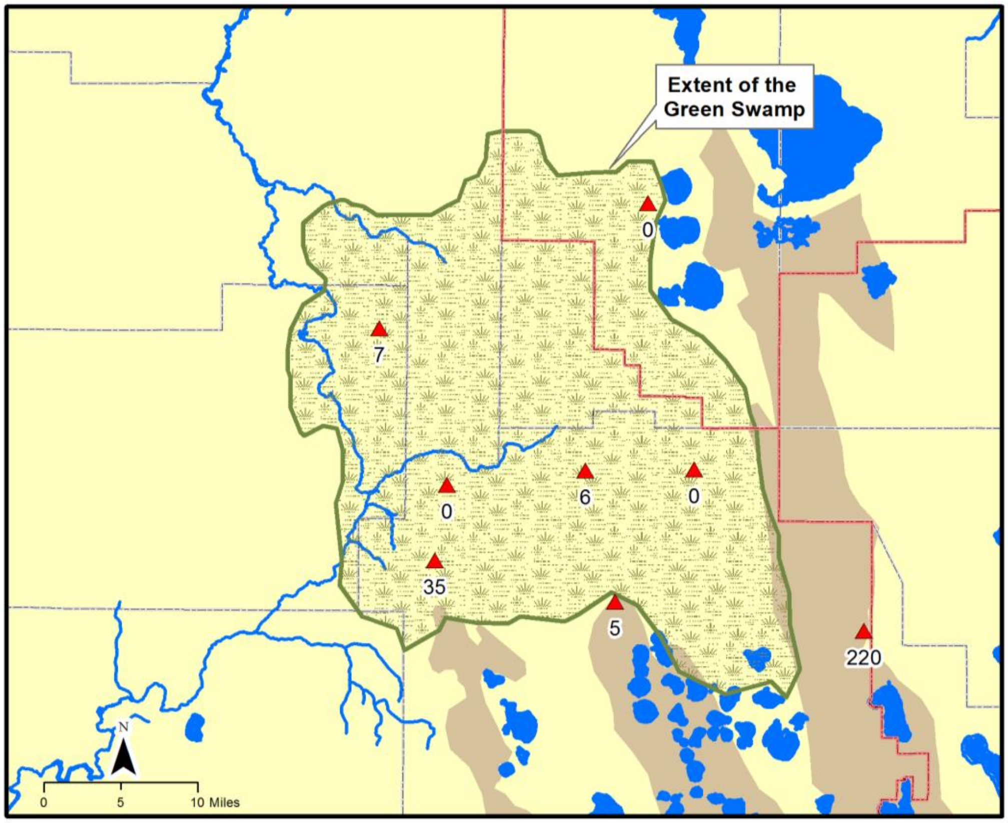

Figure 26. ICU thickness (ft) within or near the Green Swamp.

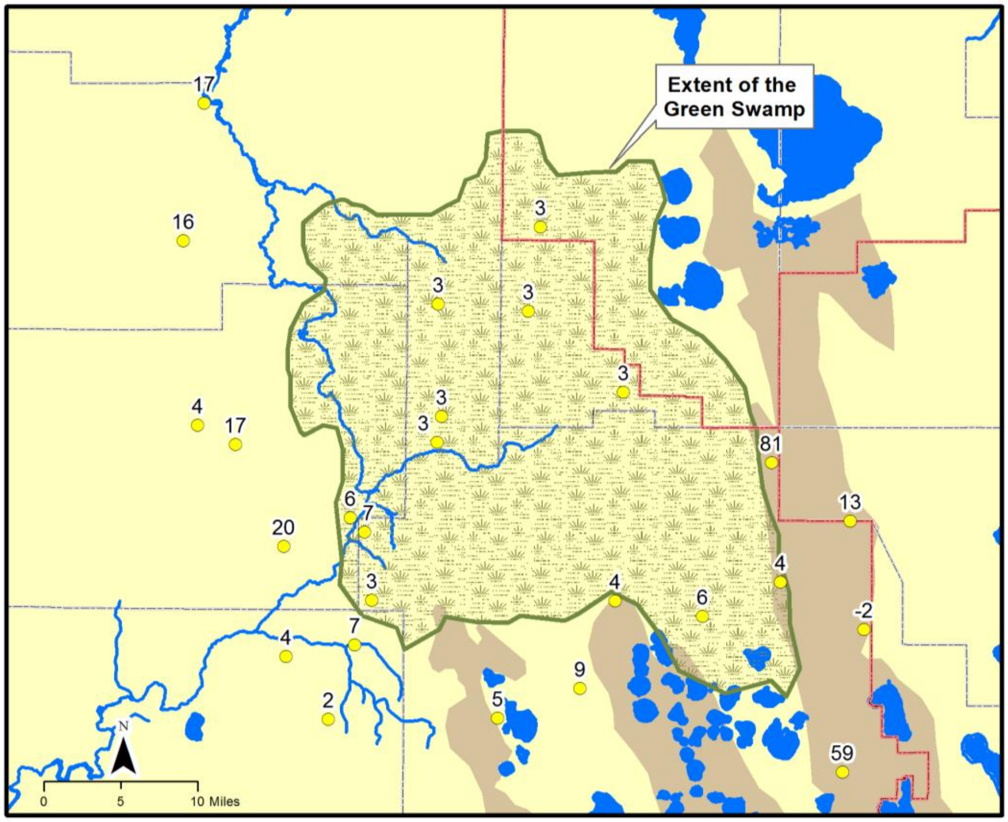

Figure 27. Average water table depth in feet below land surface from surficial aquifer wells within or near the Green Swamp (Note: Period-of-record, minimum 5 year length).

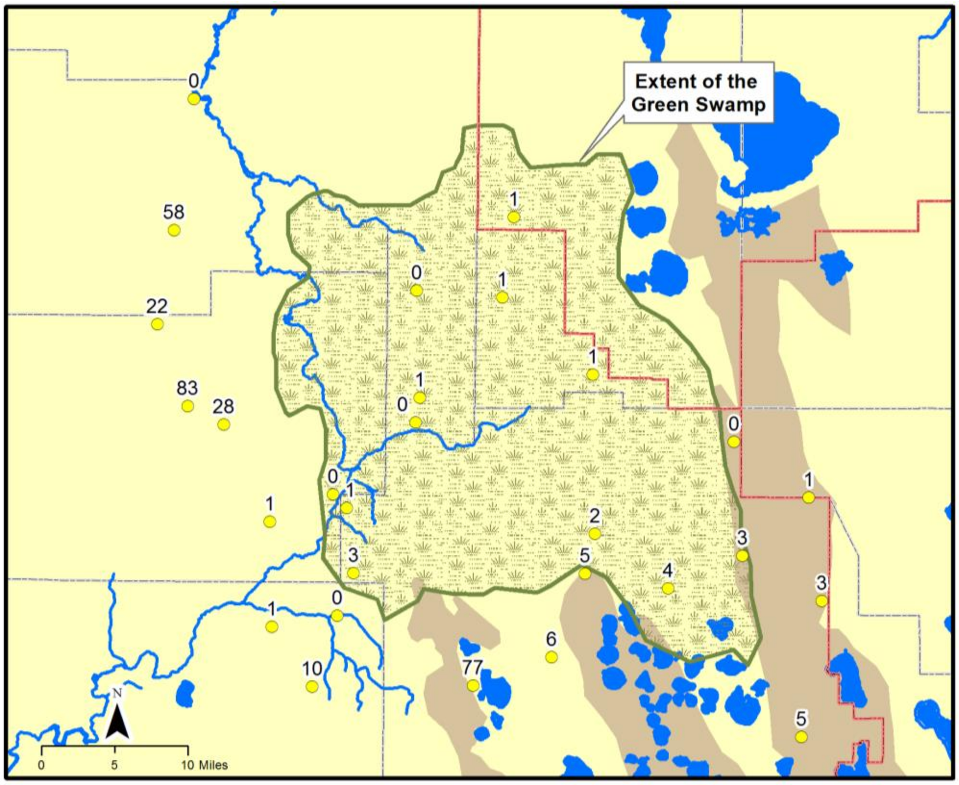

Figure 28. Average hydraulic head difference (ft) between Surficial and Upper Floridan aquifer water levels at nested wells (Note: period-of-record average, minimum 5 years of record).

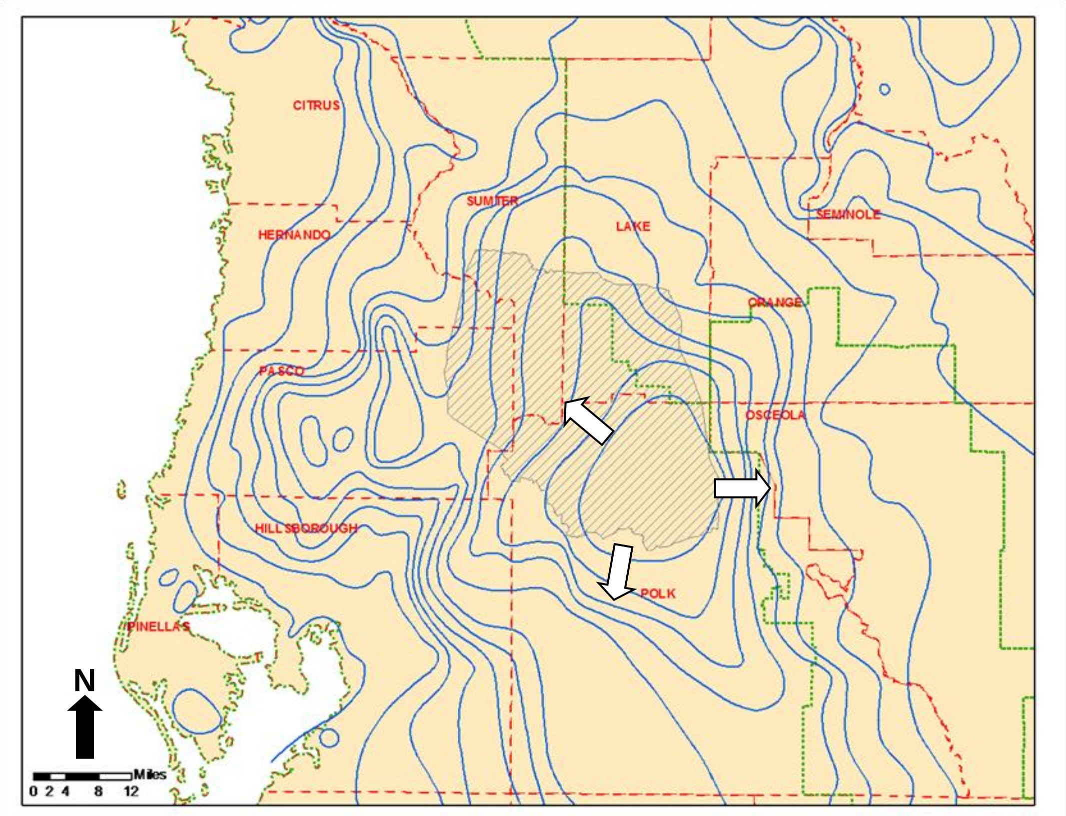

Figure 29. Groundwater flow direction and potentiometric surface of the Upper Floridan aquifer, September, 2002.

high land surface elevation and there are no significant groundwater withdrawals affecting aquifer levels, it is a regional high point in the Upper Floridan aquifer groundwater flow system (Figure 29). Located in

the southern part of the Green Swamp is the Polk City potentiometric high which reaches an elevation of 130 Ft NGVD. Groundwater moves laterally away from this high toward the northwest, southwest, and east.

Long-term water levels have been measured at several UFA monitor wells within or near the Green Swamp (Figure 30). Over the last 30 to 40 years, water levels in the UFA have remained stable although they have been affected by severe droughts from 1989-93, 1999-2001, and 2006-2008 (Figure 31). These water levels show no long term decreasing or increasing trend. The Upper Floridan aquifer is low-to-moderately productive and provides the primary source of groundwater in the area. Karst activity is generally absent in the Green Swamp due to a shallow water table and dense limestone of the UFA (Figure 32). Transmissivity values of the UFA within the Green Swamp averaged 20,000 ft^2/d based on three tests in eastern Pasco and southwest Lake County. This value is generally one to two orders of magnitude lower than transmissivity of the aquifer in the mostly unconfined, karst-dominated region northwest of the swamp.

3.3.2 Southern Brooksville Ridge

The southern half of the Brooksville Ridge physiographic area consists of numerous hills and depressions with relatively thick confinement. Where the clay-rich soils are thick, there is limited dissolution of the underlying limestone leading to an undulating ridge and valley system with land surface elevations often exceeding 150 ft NGVD. Numerous, localized, hydraulically "perched" lakes and shallow aquifers exist because of the generally thick clay confinement between the surface and the underlying UFA with hydraulic head differences varying from 20 to more than 100 feet (Basso, 2010). Sprinkled within the hydrogeologic province are localized karst "windows", such as Peck Sink, which provide a source of high recharge to the underlying UFA.

Lithologic information from District ROMP sites BR-1 and BR-2 along the Brooksville Ridge generally shows a relatively thin layer of sand (average 11 feet thick) overlying rather thick clays (varying from 34 to 72 feet in thickness). A distinct water table usually exists within the surficial sand but may only be present during the summer rainy season or extremely wet periods. The ROMP well nest BR-2 is representative of this hydrogeologic regime with an average hydraulic head difference between the surficial and Upper Floridan aquifers of nearly 71 feet (ft) (Figures 33 and 34). In general, the larger the hydraulic head difference, the greater confinement of the system. Hydrographs of several other nested well pairs along the Brooksville Ridge are contained in Appendix C.

The lakes that straddle the clay-rich soils of the southern Brooksville Ridge are generally hydraulically "perched" or separated from the underlying UFA. Thick clays beneath the lakes form a relatively impermeable barrier which support these perennial systems. If the lakes were in hydraulic connection with the UFA, their water levels would closely approximate the potentiometric surface elevation of the Upper Floridan aquifer. Based on an analysis of 16 lakes on the Brooksville Ridge, hydraulic head differences between lake stage and the elevation of the UFA during 2008 varied from +16 to +118 feet with the average head difference of +40 feet (Figure 35). In contrast, hydraulic head difference at Lakes Hunter, Weeki Wachee Prairie, and Big Fish, located west of the Brooksville Ridge, varied from +1 to +5 ft – where the clay confining unit is thin or discontinuous.

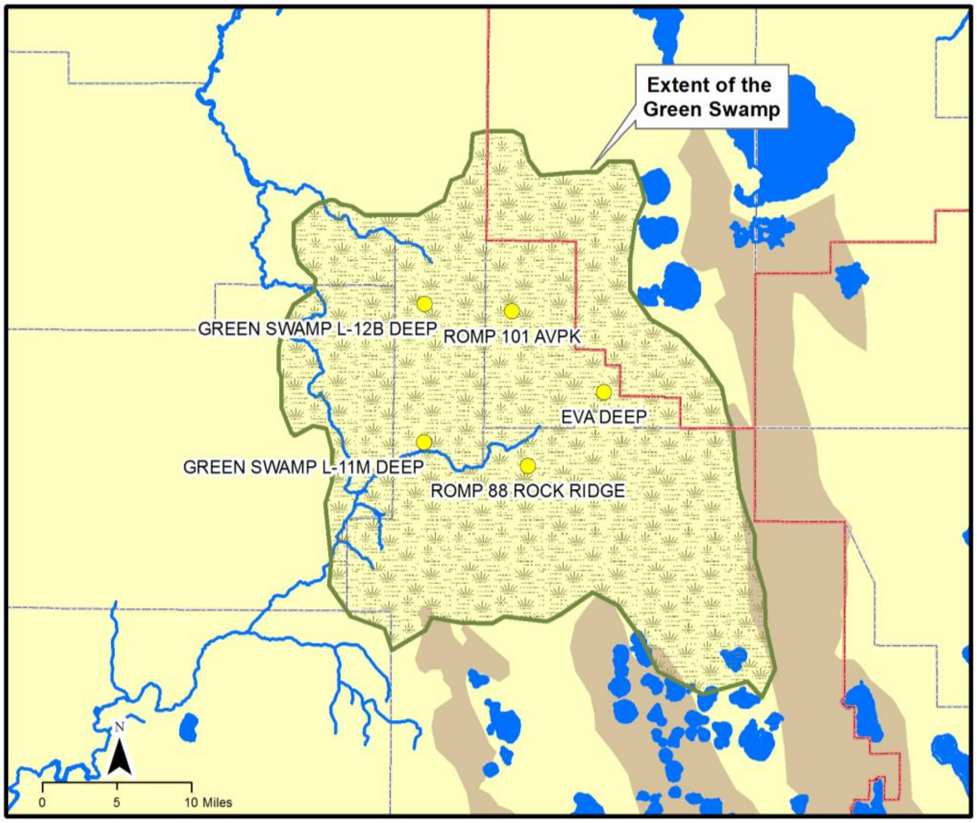

Figure 30. Location of Upper Floridan aquifer monitor wells within the Green Swamp.

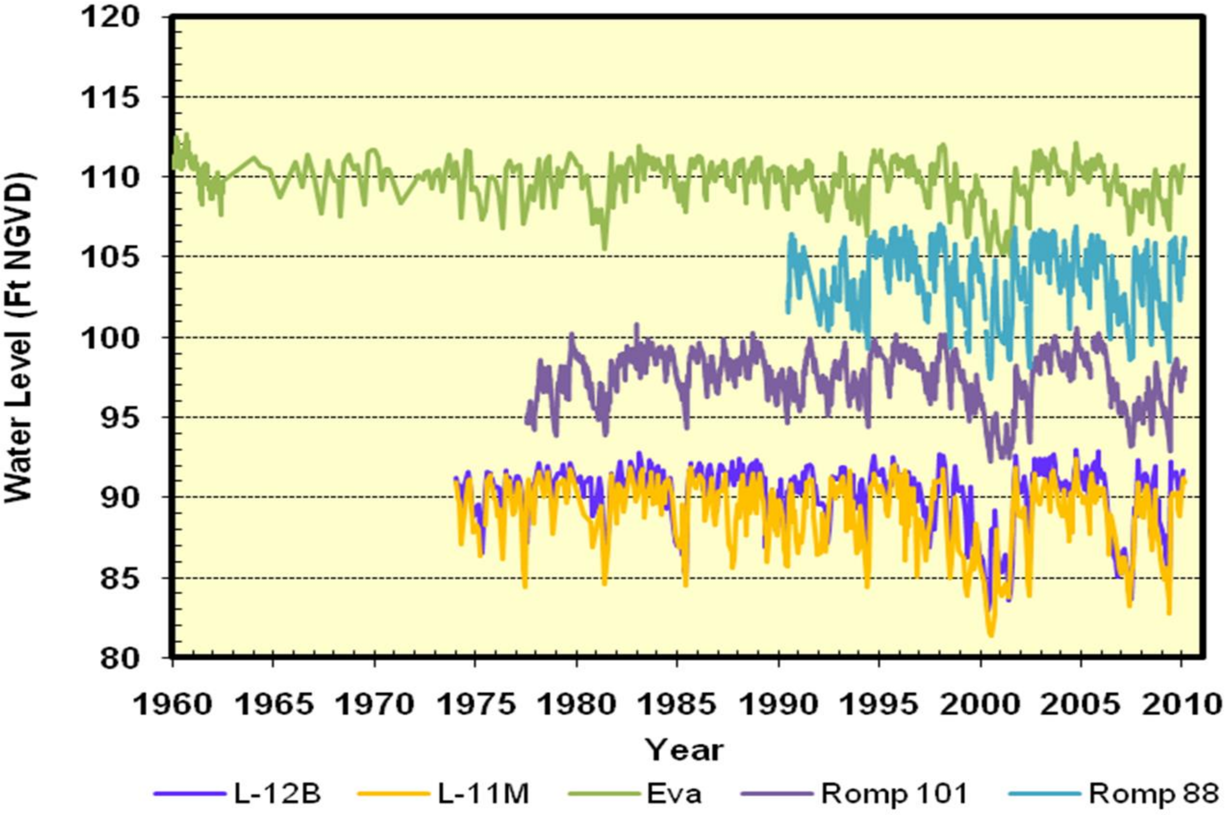

Figure 31. Water level history at Green Swamp monitor wells.

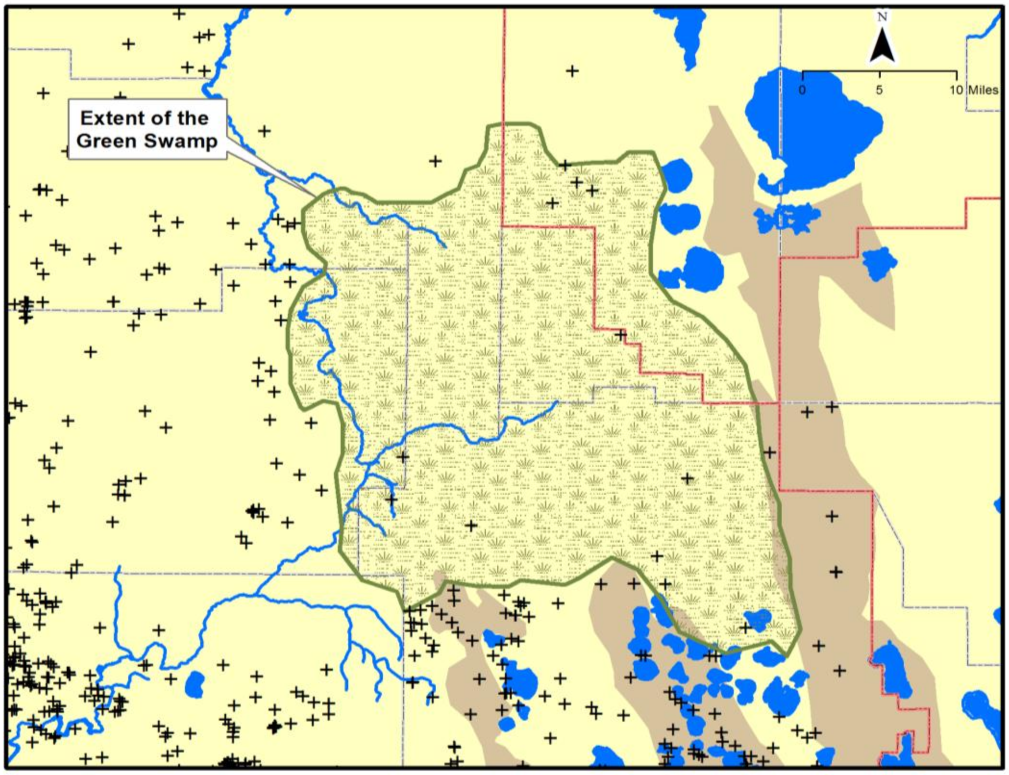

Figure 32. Location of reported sinkholes within or near the Green Swamp.

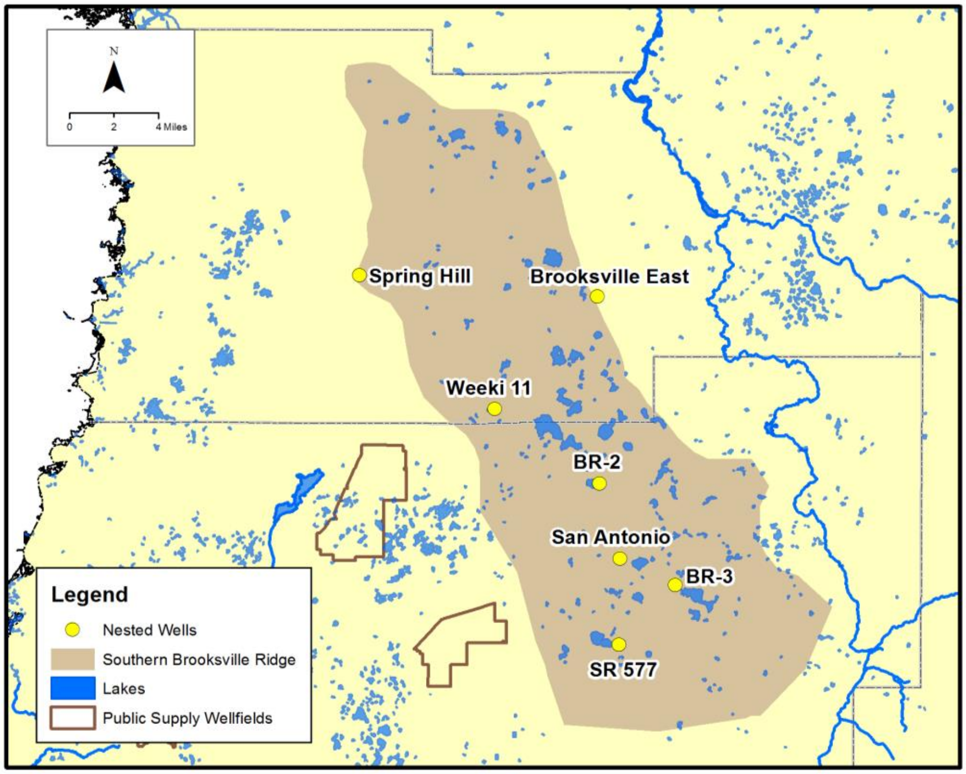

Figure 33. Located of nested surficial and Upper Floridan aquifer monitor wells in the southern Brooksville Ridge province.

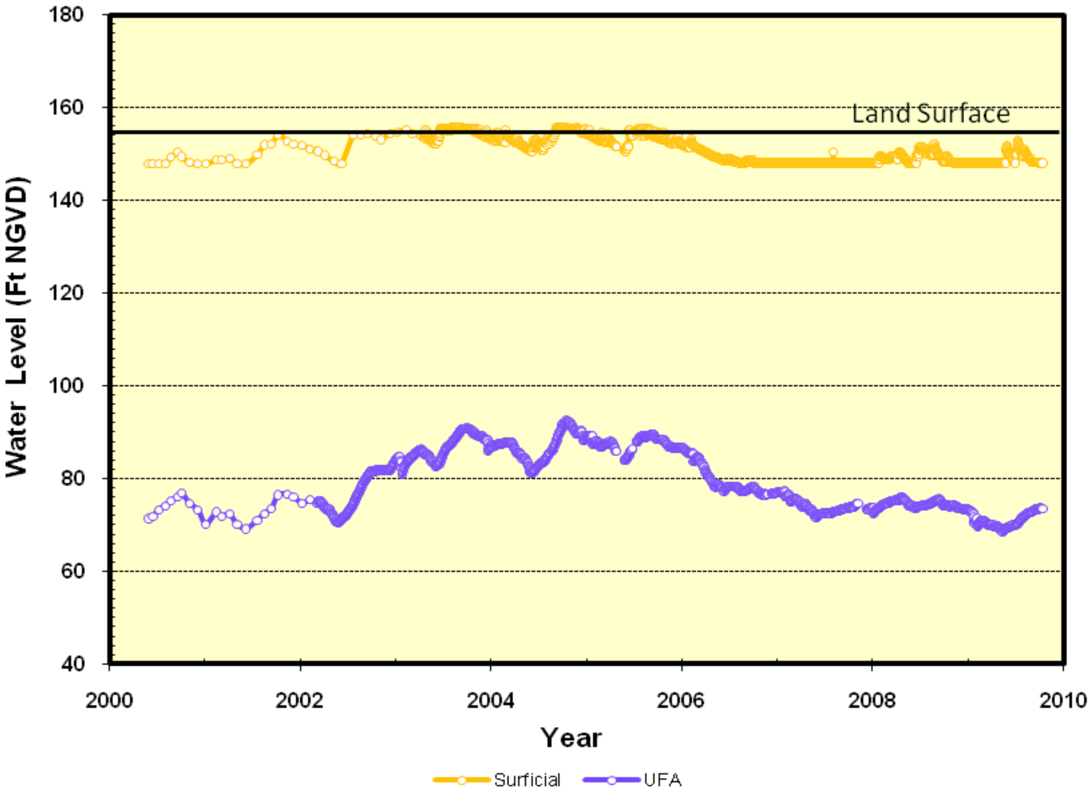

Figure 34. Water level history at the ROMP BR-2 well site.

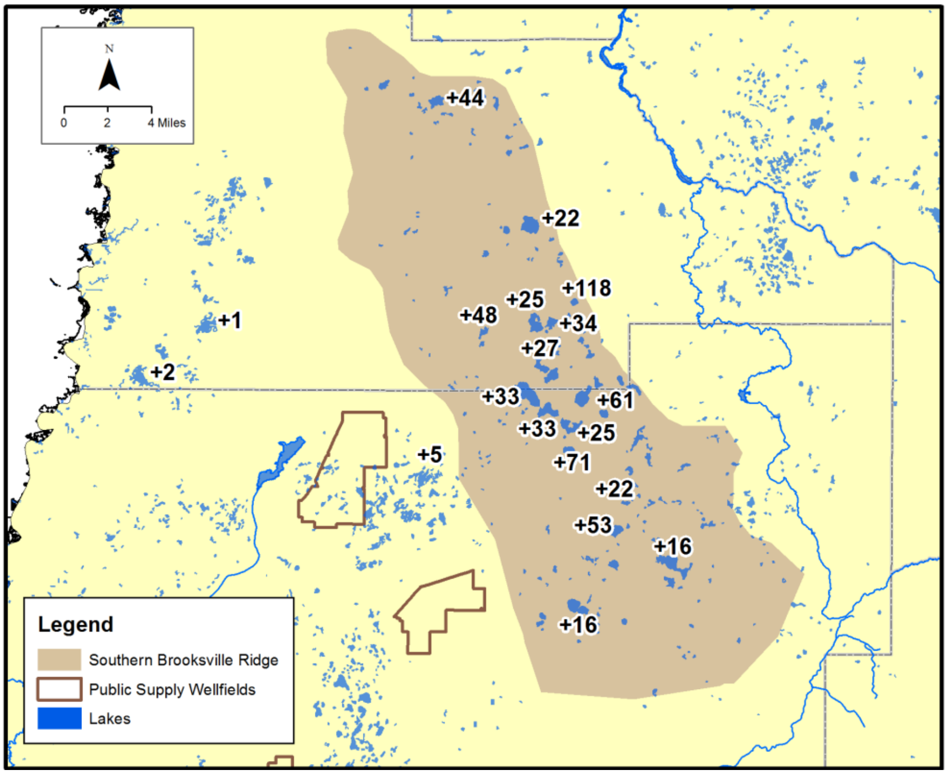

Figure 35. Hydraulic head difference (feet) between lake stage and the potentiometric surface of the Upper Floridan aquifer (average 2008 conditions except Big Fish which is 1997 due to recent augmentation).

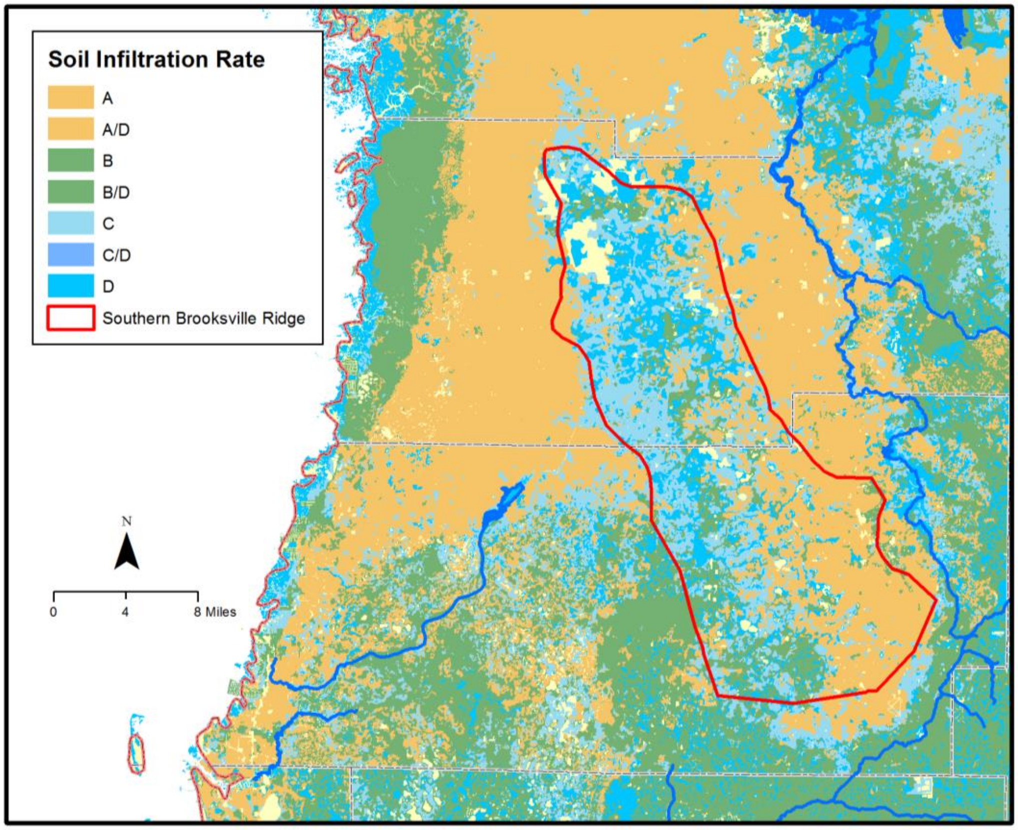

Figure 36. Soil infiltration rates within or near the southern Brooksville Ridge (Note: Highest Rate = A)

The delineation of the southern Brooksville Ridge province as a perched system is based on the hydraulic head difference between surficial and Upper Floridan aquifer monitor wells, soil infiltration rate information, and lake stage/UFA hydraulic head differences. The soil infiltration data largely provided the basis for the northern extent of this hydrogeologic province (Figure 36). This delineation is consistent with the conceptual model for the Integrated Northern Tampa Bay model.

3.4 Central West-Central Florida Groundwater Basin

The vast majority of the CWCFGWB lies within the semi-confined hydrogeologic province as Hawthorn Group clays generally thin and become discontinuous along northern Pasco County (Figure 37). Numerous consultant studies, USGS reports, and District information has documented this condition. The semi-confined nature of the Upper Floridan aquifer is well-defined in the District's Northern Tampa Bay Water Resource Assessment Project report (SWFWMD, 1996). An exception to this setting is the aforementioned Southern Brooksville Ridge province and the southern two-thirds of Pinellas County which reflects confined conditions.

There is also a transition from semi-confined to confined conditions along the southern edge of the basin outside of the BKT and Winter Haven Ridge provinces as Hawthorn clays thicken toward the south. In the areas of the basin outside of the individual provinces described previously, a combination of soil infiltration rates, hydraulic head difference, slope, and physiographic region boundaries were utilized to define semi-confined conditions (Figures 38 and 39). This boundary was defined according to criteria listed in Table 1.

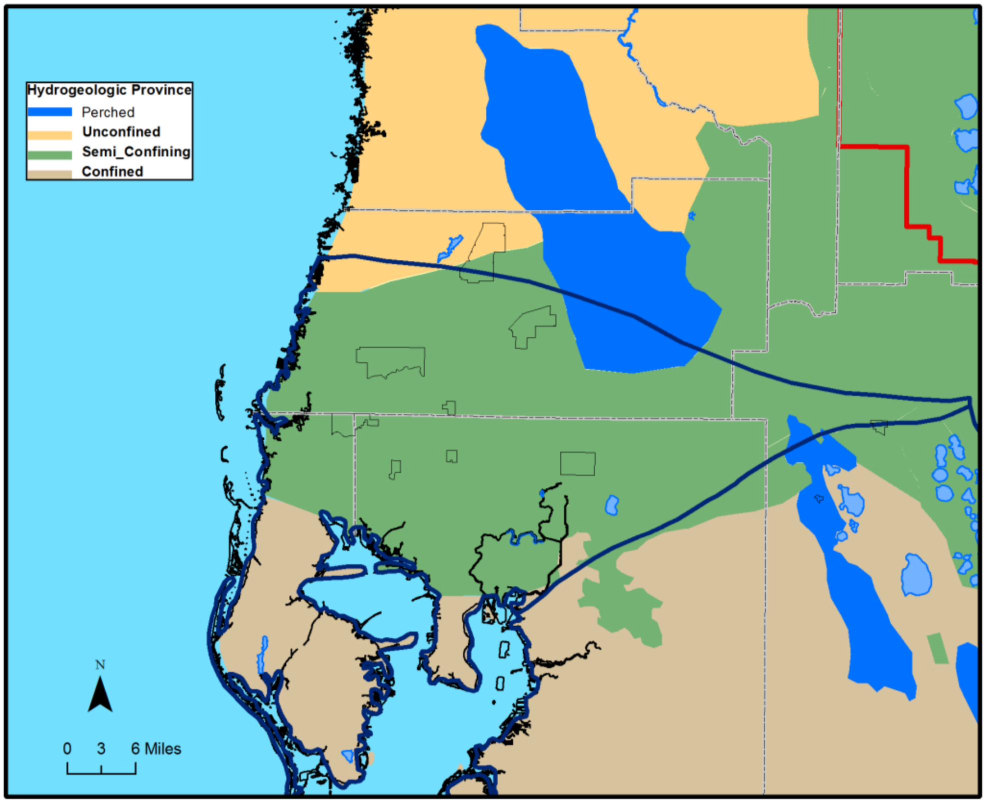

Figure 37. Location of hydrogeologic provinces within or near the Central West-Central Florida Groundwater Basin.

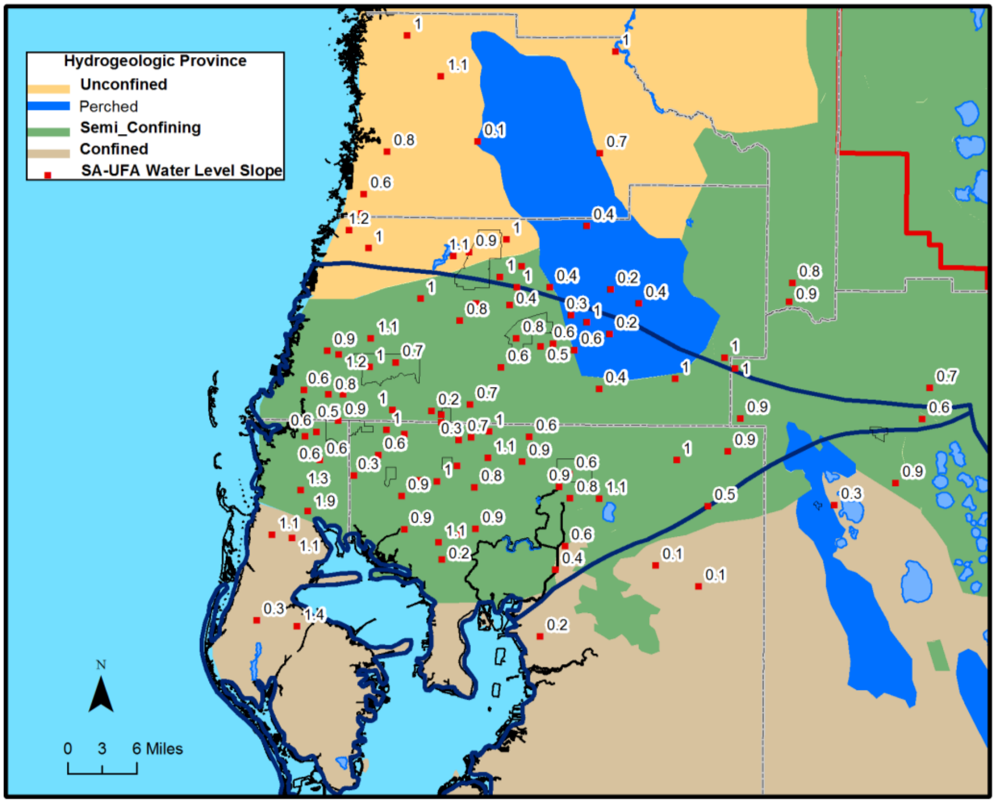

Figure 38. Daily slope values from linear regression of Surficial and Upper Floridan aquifer water levels at nested wells (Note: period of record).

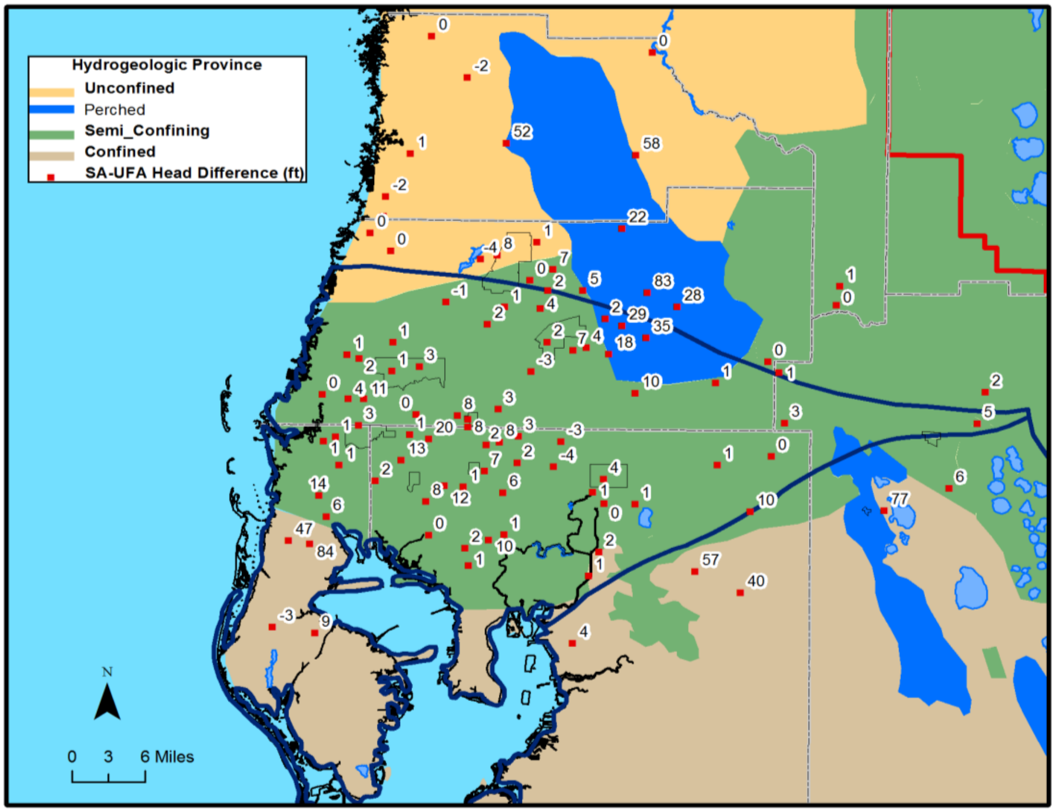

Figure 39. Average hydraulic head difference (ft) between Surficial and Upper Floridan aquifer water levels at nested wells (Note: period-of-record average, minimum 5 years of record).

A high soil infiltration zone along the eastern side of the Brooksville Ridge in the CWCFGWB has the highest level of uncertainty in province definition (see Figure 36). Soils data along the eastern side of the Brooksville Ridge indicates group A soils (high infiltration) in eastern Pasco County down to the City of Zephyrhills which may suggest unconfined conditions. Field data from nested wells is limited in this area. Additional data collection in this area would improve the demarcation between semi-confined and unconfined conditions in this region.

3.4.1 Fairfield Hills

The Fairfield Hills province occurs from southernmost Alachua County to northwestern Marion County (Figure 40). The extent of the province is the same as the Fairfield Hills physiographic region as delineated by White (1970). The Fairfield Hills has well-developed surface drainage, reflecting the relatively impermeable nature of the underlying Hawthorn Group sediments (Green and others, 2009). Like the southern Brooksville Ridge province, this area consists of numerous hills and depressions with relatively thick confinement. Where the clay-rich soils are thick, there is limited dissolution of the underlying limestone leading to an undulating hill and valley system with land surface elevations often exceeding 150 ft NGVD. Localized, hydraulically "perched" shallow aquifers may exist because of the generally thick clay confinement between the surface and the underlying UFA.

Information obtained from the District's ROMP 132 site located in the Fairfield Hills province indicates that surficial sands extend from land surface to three ft bls (Figure 40). Thick clays extend from three to 47 ft bls. Limestone is found from 47 to 1,637 ft bls which was the termination depth of drilling. This section is made up of permeable carbonates of the Ocala Limestone, the Avon Park Formation, and the

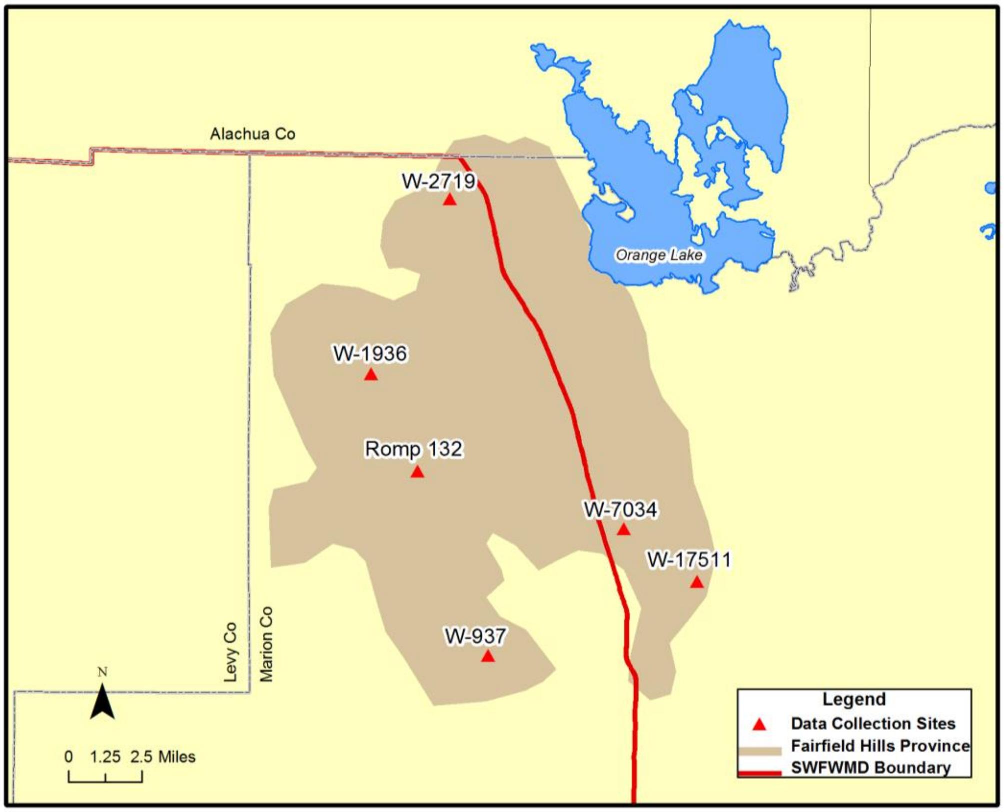

Figure 40. Location of the Fairfield Hills province and geologic data collection sites.

Oldsmar Formations. The measured water level of the Upper Floridan aquifer in March 2009 was 64 ft bls.Available information from the FGS and the District's Romp 132 site indicates that sand thickness ranges from being absent to 20 ft thick (Figure 41). Surficial sand thickness is generally thin averaging just seven ft from six sites across the province. Clay thickness varies from zero to 80 ft based on these same six sites (Figure 42). Average clay thickness is 31 ft.

3.5 Northern West-Central Florida Groundwater Basin

Most of the Northern West-Central Florida Groundwater Basin is characterized by regionally unconfined conditions except for the Fairfield Hills and Southern Brooksville Ridge perched provinces (Figure 43). Along the southern and eastern boundaries, a combination of nested well head difference, location of unsaturated (dry) sand wells, mapped extent of Hawthorn Group sediments, land cover, soil infiltration rates, and physiographic boundaries were utilized to define the transition from unconfined to semi-confined conditions (Figure 44). In addition, head difference and slope values between shallow sand and Upper Floridan aquifer well water levels along with site data from coring where the unconsolidated materials were unsaturated was also used to help define this large unconfined province (Figure 45). The conceptualization of the NWCFGWB is generally consistent with that defined by Hydrogeologic (2010) for the Northern District Groundwater Flow model.

Areas of uncertainty in the Northern Basin lie within the extreme northwest part along the Brooksville Ridge physiographic region in Levy County and within the transition from unconfined to semi-confined conditions along the eastern basin boundary in Sumter, Lake, and eastern Marion Counties. There is some evidence that near Lakes Marion, Bonable, and Tiger, a perched hydrogeologic setting exists. Along the Sumter-Lake County border, the boundary between unconfined and semi-confined conditions

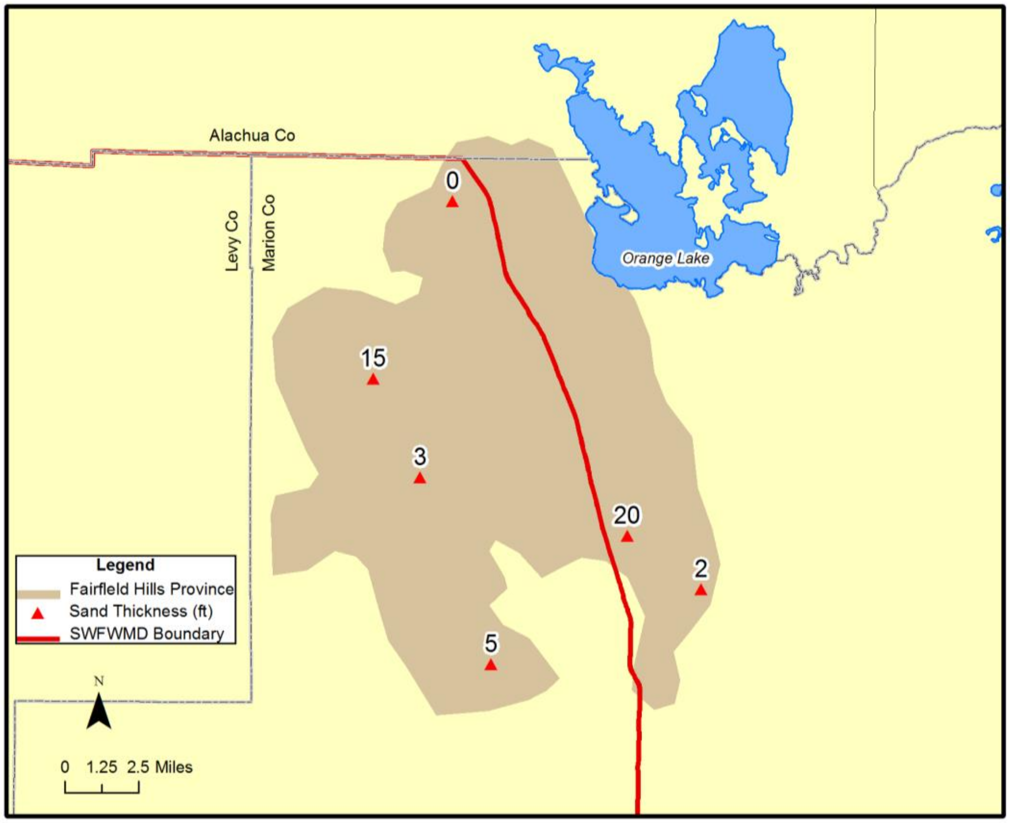

Figure 41. Sand thickness (ft) within or near the Fairfield Hills province.

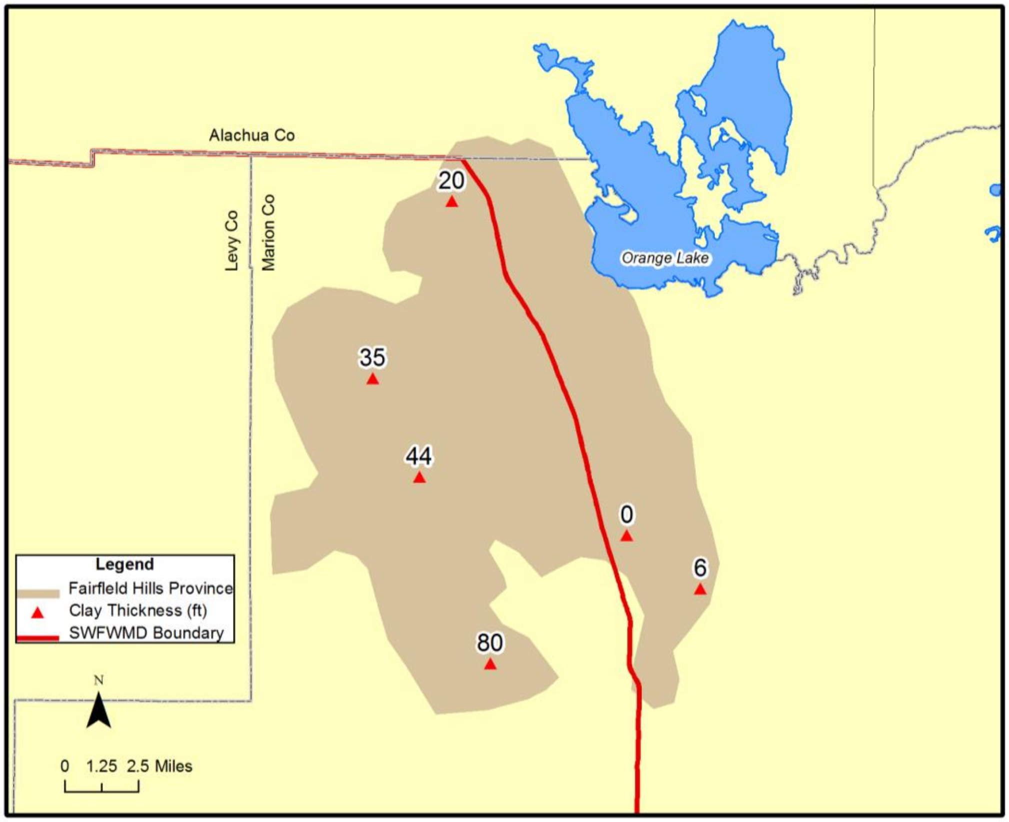

Figure 42. Clay thickness (ft) within or near the Fairfield Hills province.

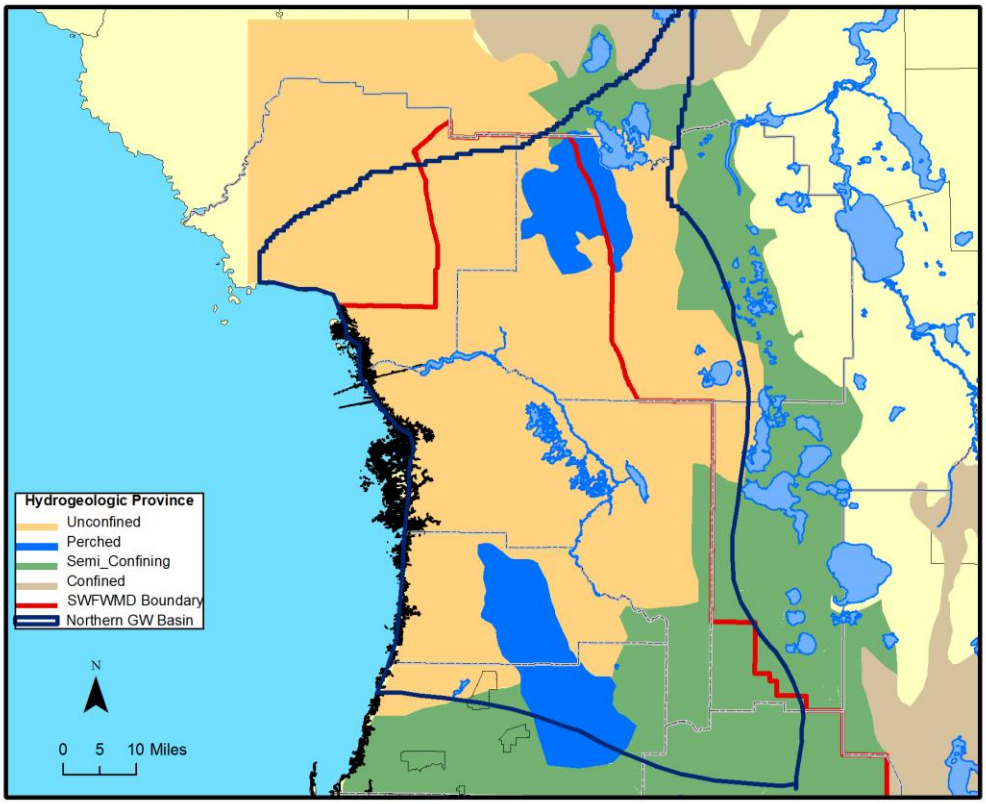

Figure 43. Hydrogeologic provinces within or near the Northern West-Central Florida Groundwater Basin.

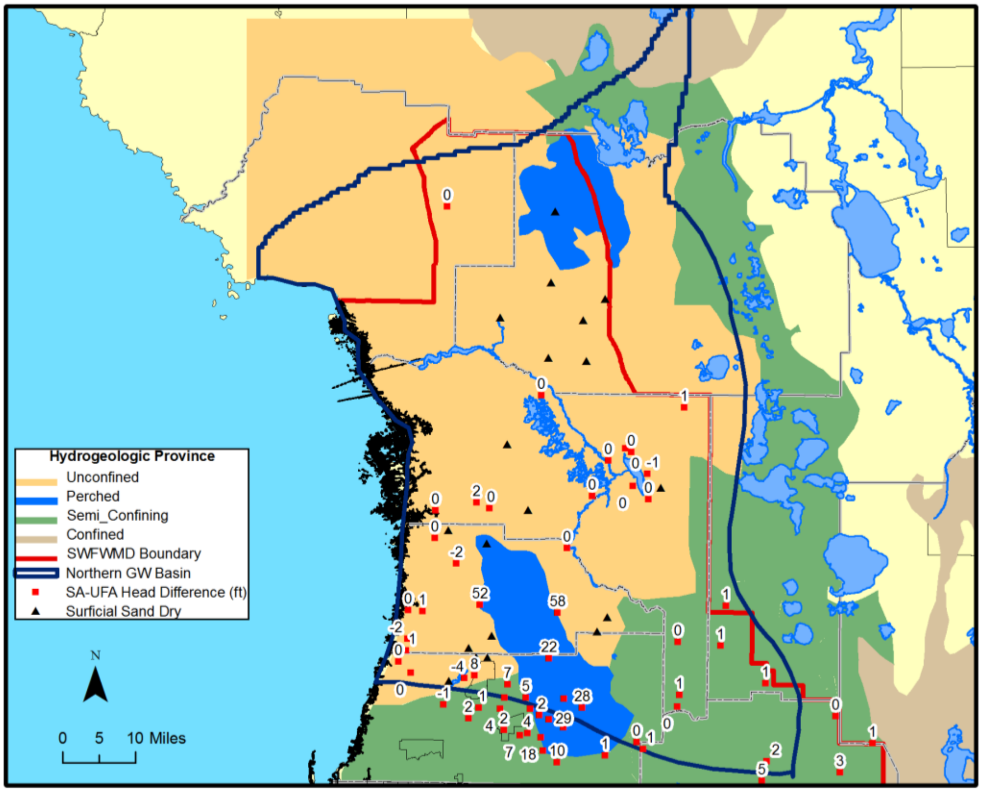

Figure 44. Average hydraulic head difference (ft) between shallow sand and Upper Floridan aquifer well water levels (Note: period-of-record average, minimum 5 years of record).

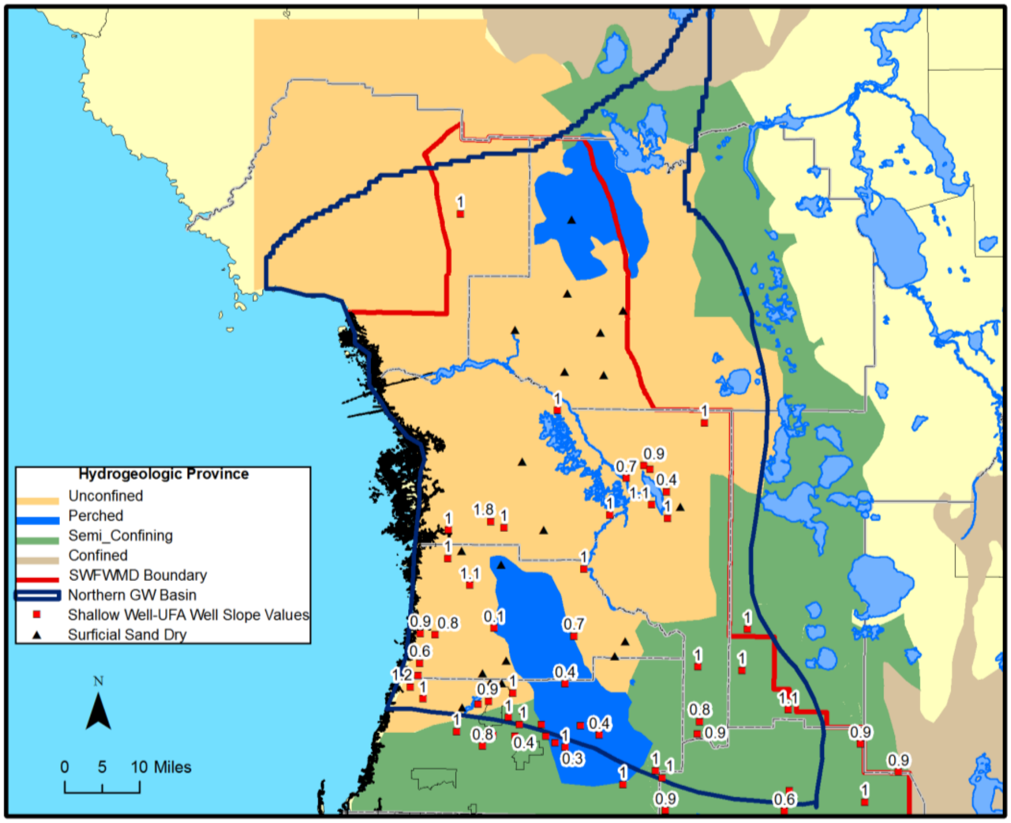

Figure 45. Daily slope values from linear regression of shallow sand and Upper Floridan aquifer well water levels (Note: period of record).

is not well-defined due to data limitations. Additional geologic exploration work and long-term monitoring in these areas will better refine the delineation of the regionally unconfined hydrogeologic province.

4.0 System Uncertainty and Recommendations for Future Work

Areas of uncertainty include the transition from confined to semi-confined conditions along the northern boundary of the Southern West-Central Florida Groundwater Basin between the Brandon Karst province and Lakeland Ridge and between the Lakeland Ridge and Winter Haven Ridge. Along the southern portion of the Lake Wales Ridge, the degree of hydraulic separation between the surficial and Upper Floridan aquifer suggests tighter confinement with perhaps the bulk of recharge entering through karst lake connections. In the Central West-Central Florida Groundwater Basin, the extent of the regionally unconfined province along the northeast side of the Southern Brooksville Ridge requires further evaluation as soils data suggests that it may extend further south into the Zephyrhills area. In the Northern West-Central Florida Groundwater Basin, a further examination is needed of whether perched hydrogeologic conditions occur along the northern Brooksville Ridge physiographic region in Levy County. Along the eastern basin boundary, a better demarcation is necessary between the regionally unconfined and semi-confined provinces. In all these areas, future exploratory drilling and testing by the District will greatly enhance our understanding of the physical system.

As more field data is collected a future version of this report will expand upon these province definitions. Transmissive properties of the UFA will be added to better define the permeability of this major aquifer. Once completed, this document will serve as a reference source for determining the expected range of hydraulic parameters for use in regional numerical models across the District. It will also provide a template for understanding the hydrogeologic framework in west-central Florida.

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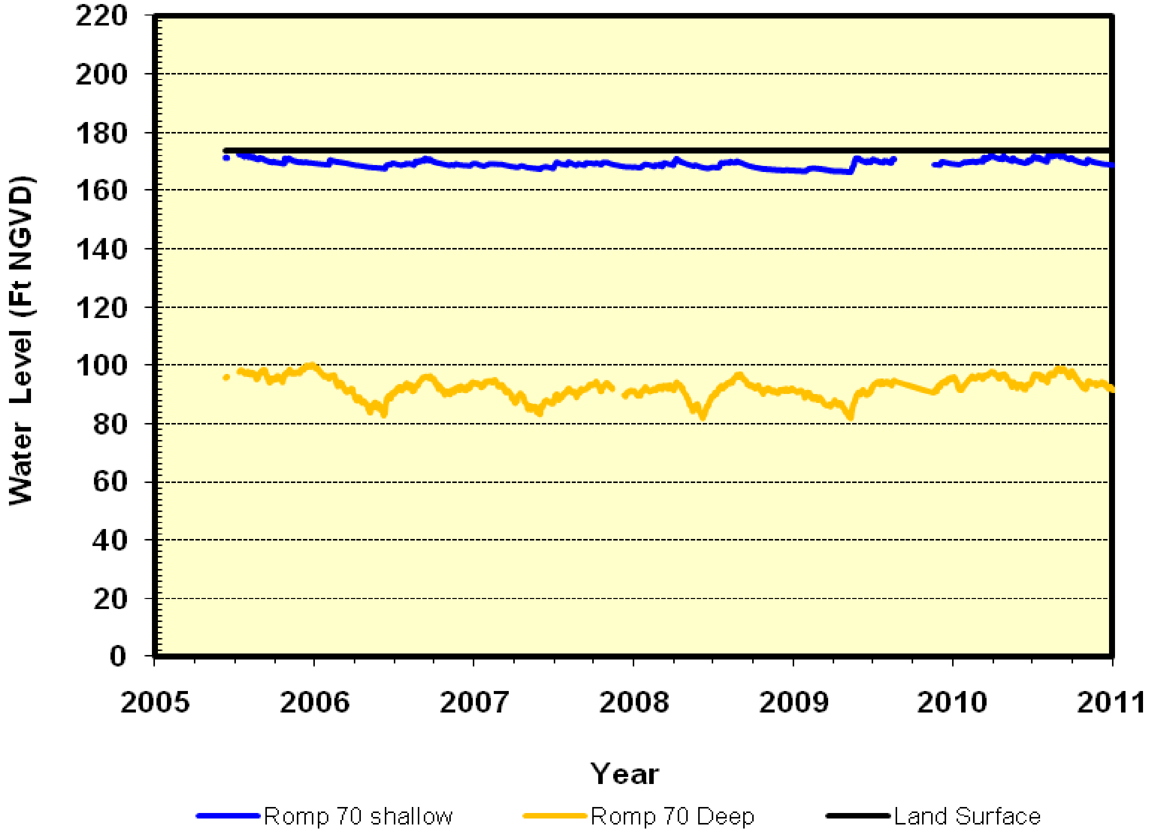
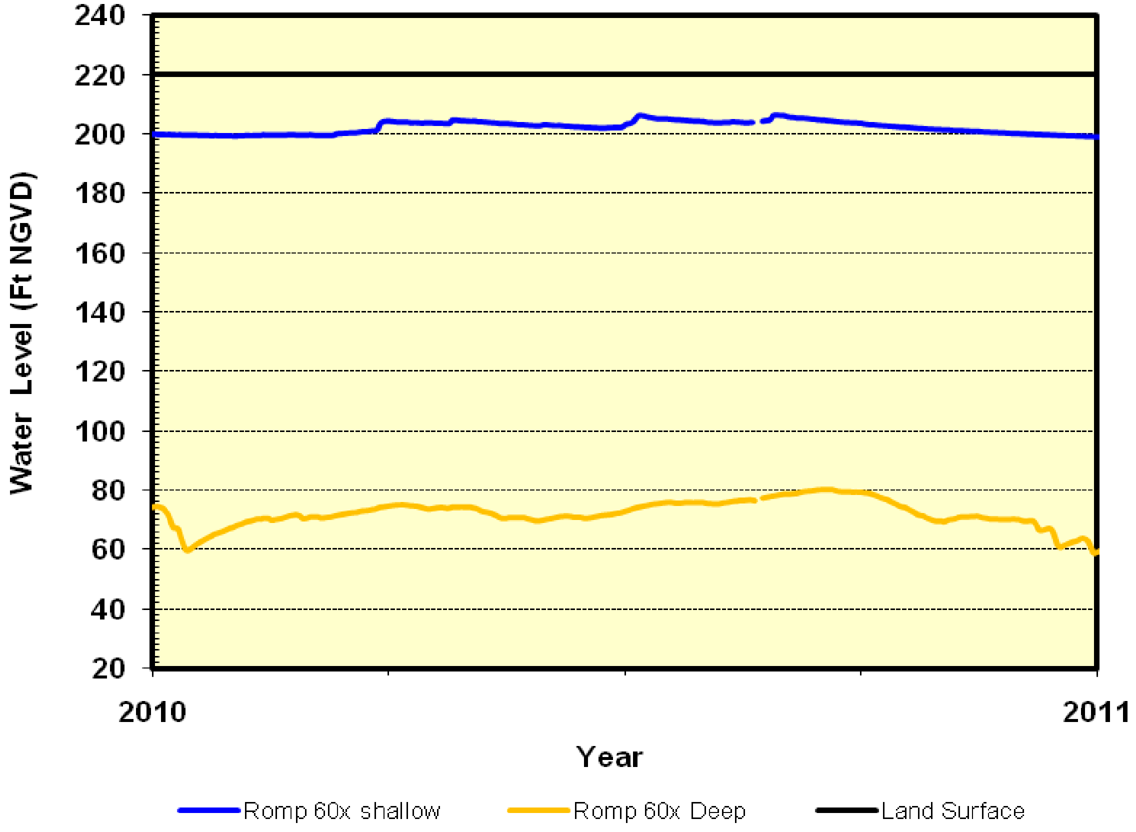
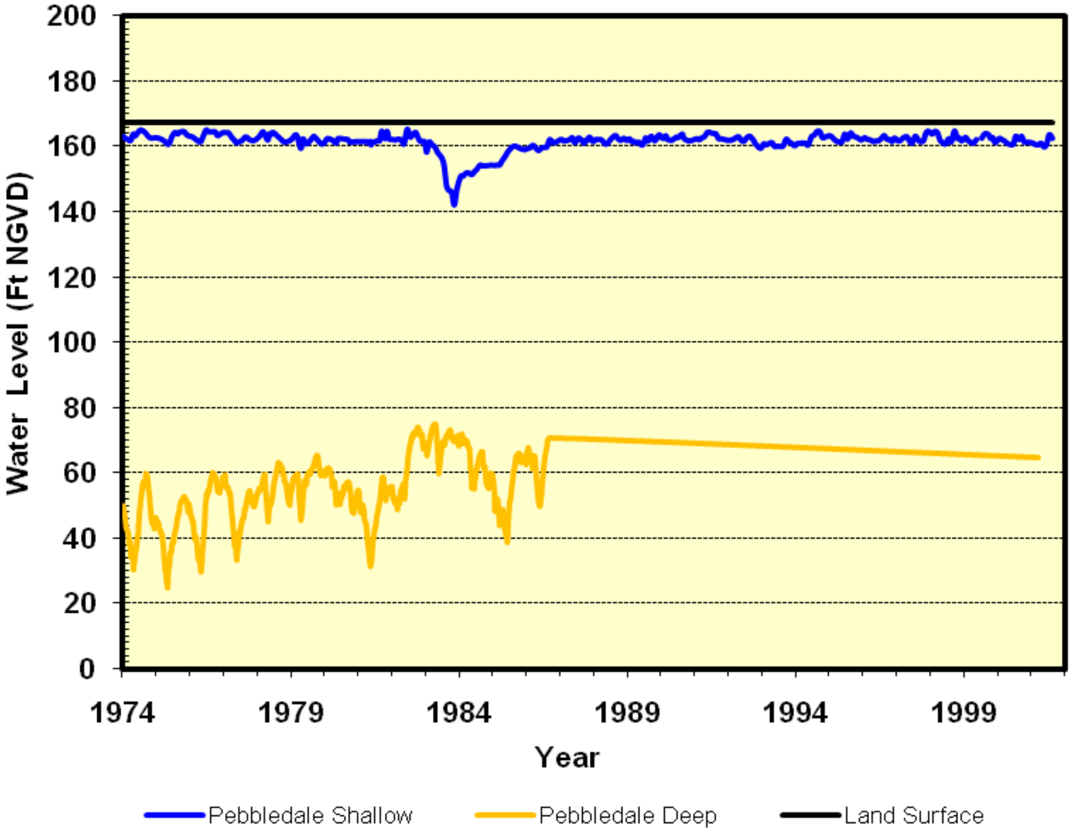
Appendix 1-A

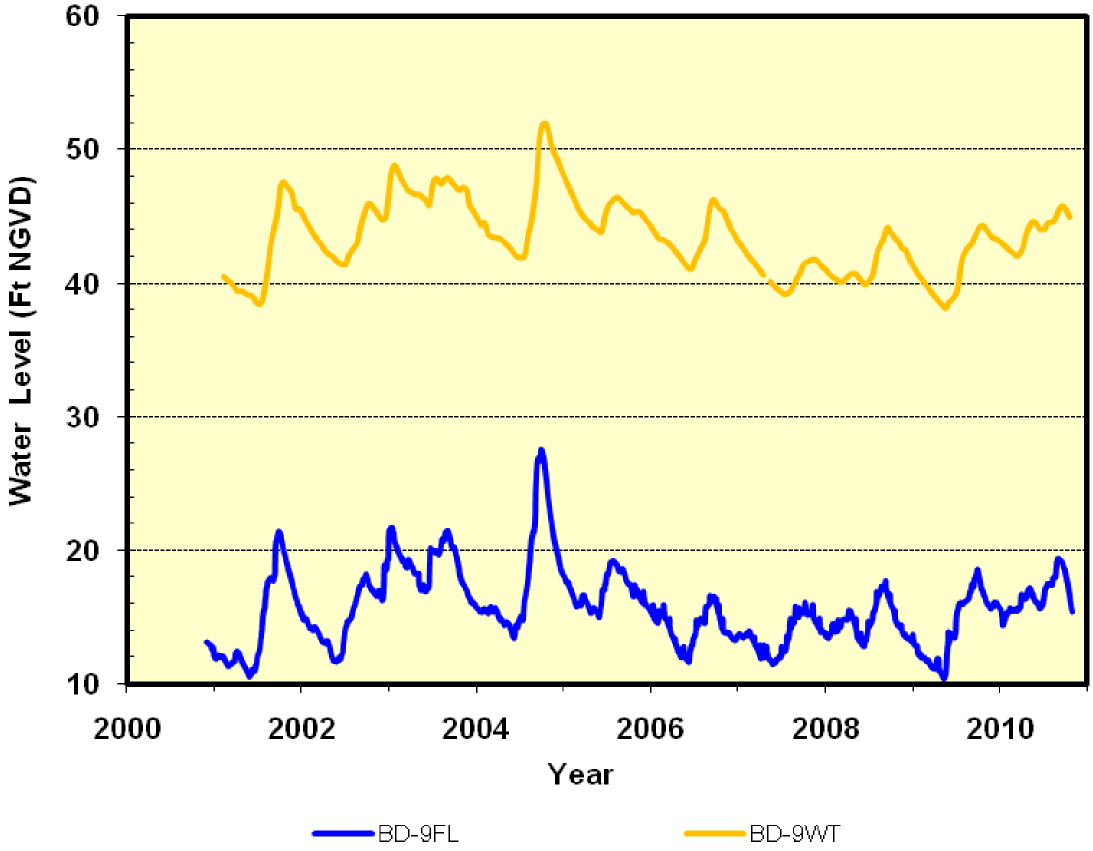

220
200
180
160
140
120
100
80
60
40
20
0
Water Level (Ft NGVD)
2005
2006
2007
2008
2009
2010
2011
Year
Romp 70 shallow
Romp 70 Deep
Land Surface

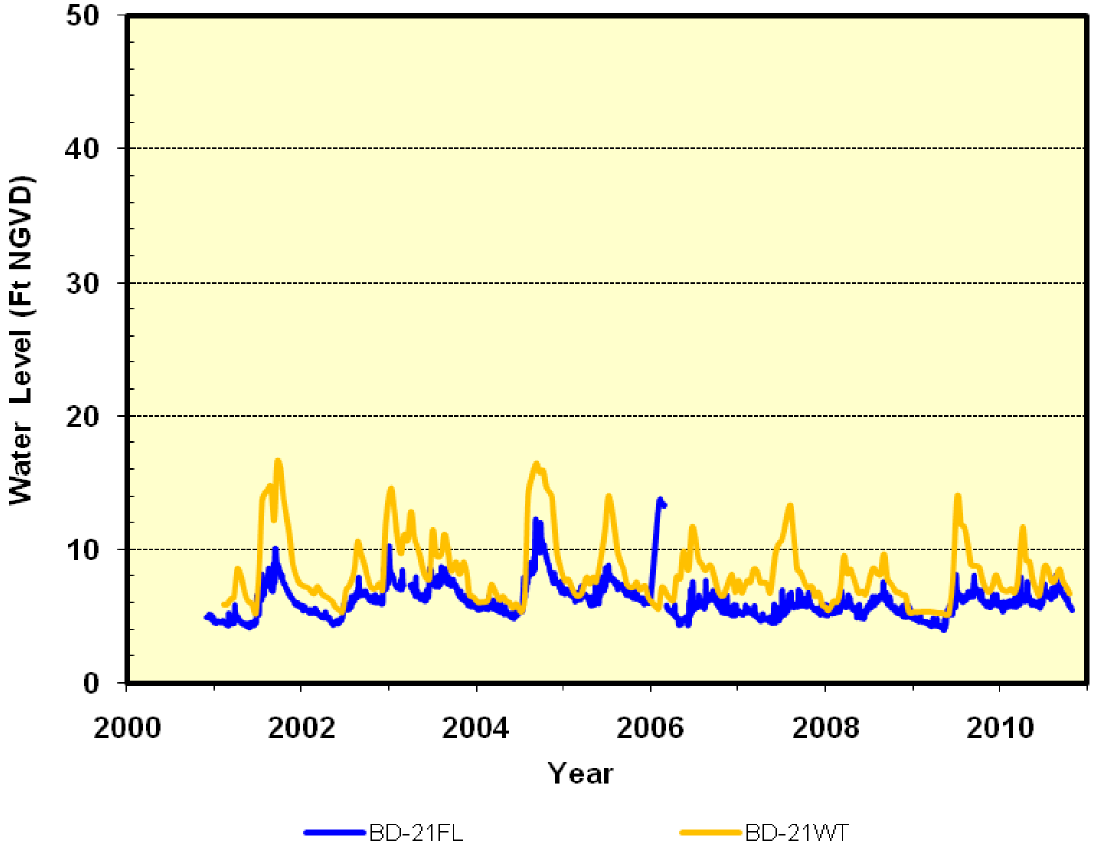

240
220
200
180
160
140
120
100
80
60
40
20
Water Level (Ft NGVD)
2010
2011
Year
Romp 60x shallow
Romp 60x Deep
Land Surface

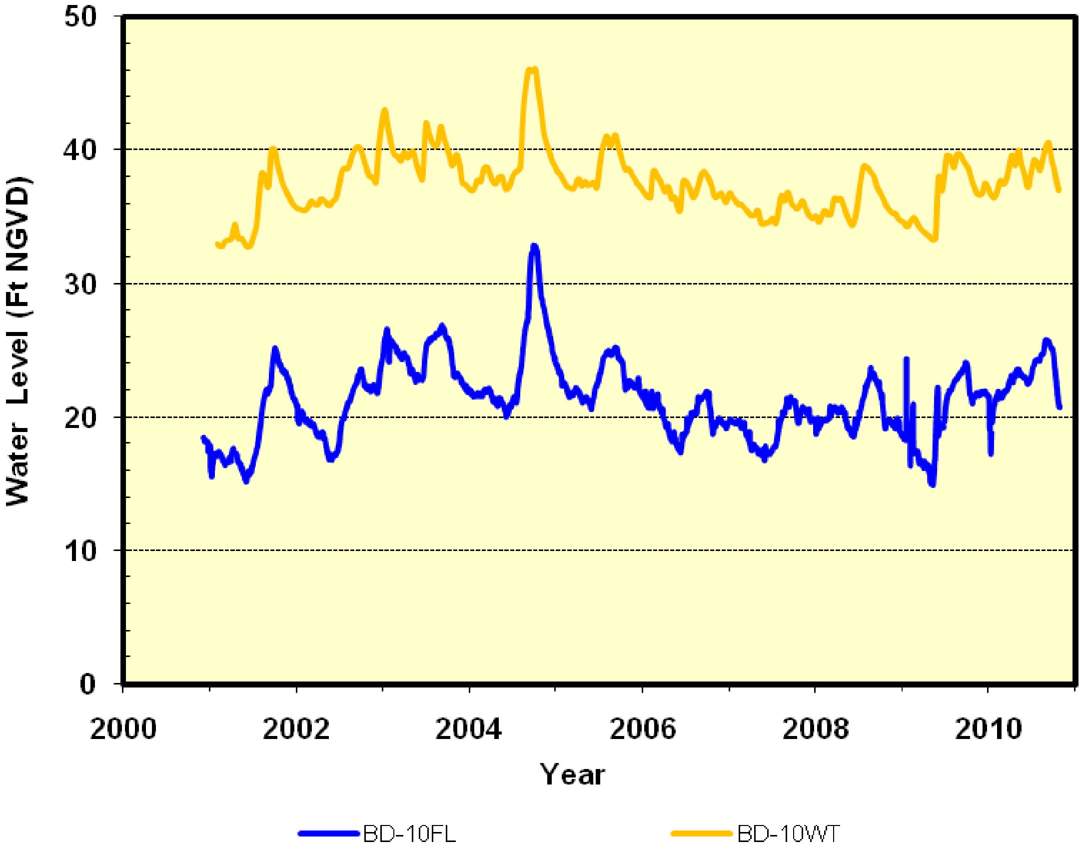


Water Level (Ft NGVD)
200
180
160
140
120
100
80
60
40
20
0
1974
1979
1984
1989
1994
1999
Year
Pebbledale Shallow
Pebbledale Deep
Land Surface

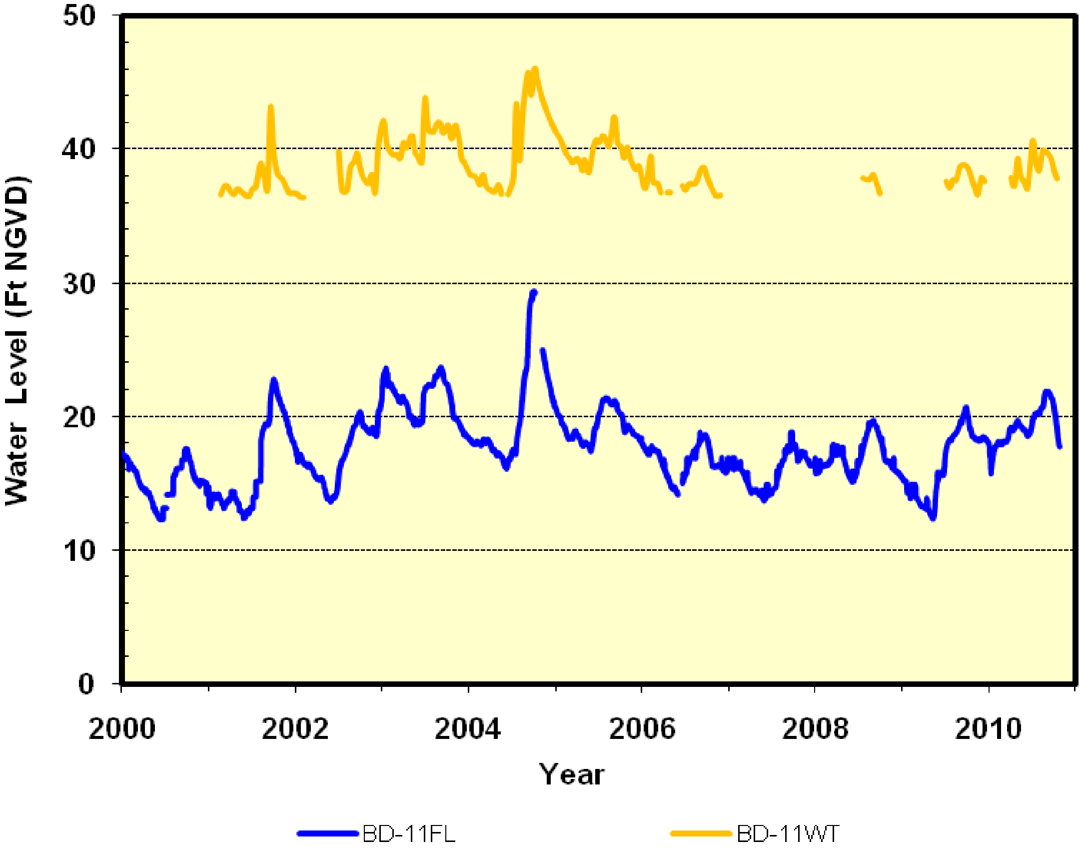
Appendix 1-B


60
50
40
30
20
10
Water Level (Ft NGVD)
2000
2002
2004
2006
2008
2010
Year
BD-9FL
BD-9WT

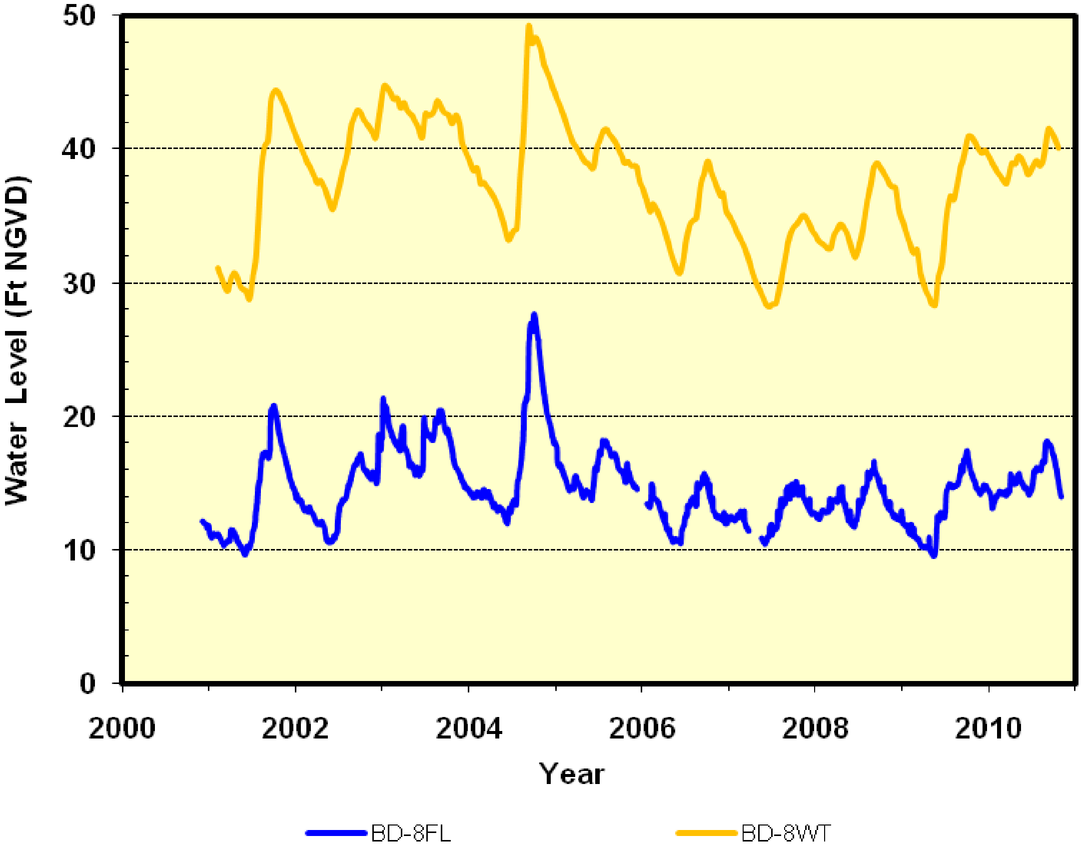

50
40
30
20
10
0
Water Level (Ft NGVD)
2000
2002
2004
2006
2008
2010
Year
BD-21FL
BD-21WT



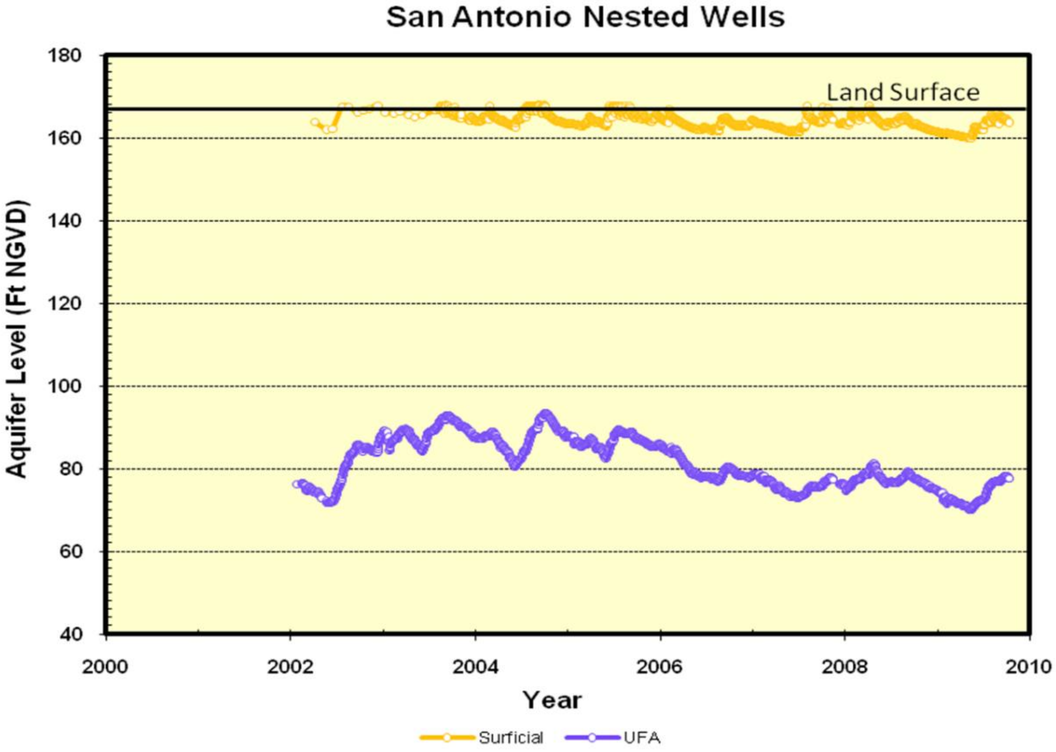
Water Level (Ft NGVD)
50
40
30
20
10
0
2000
2002
2004
2006
2008
2010
Year
BD-10FL
BD-10WT

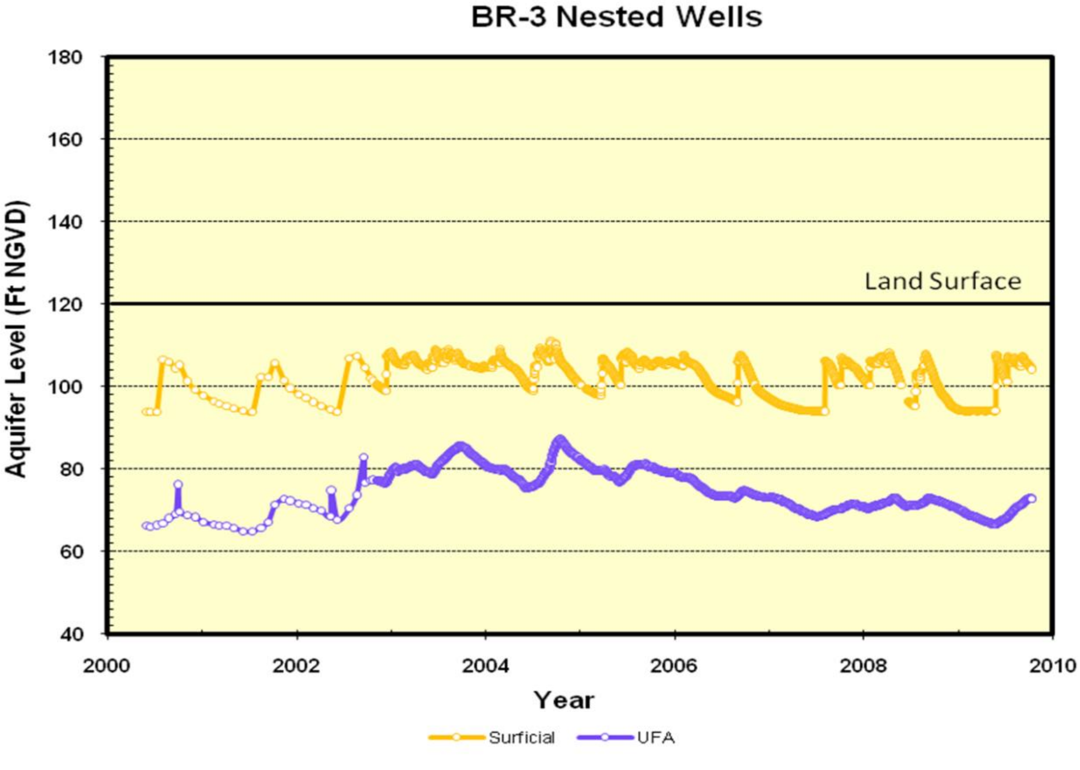


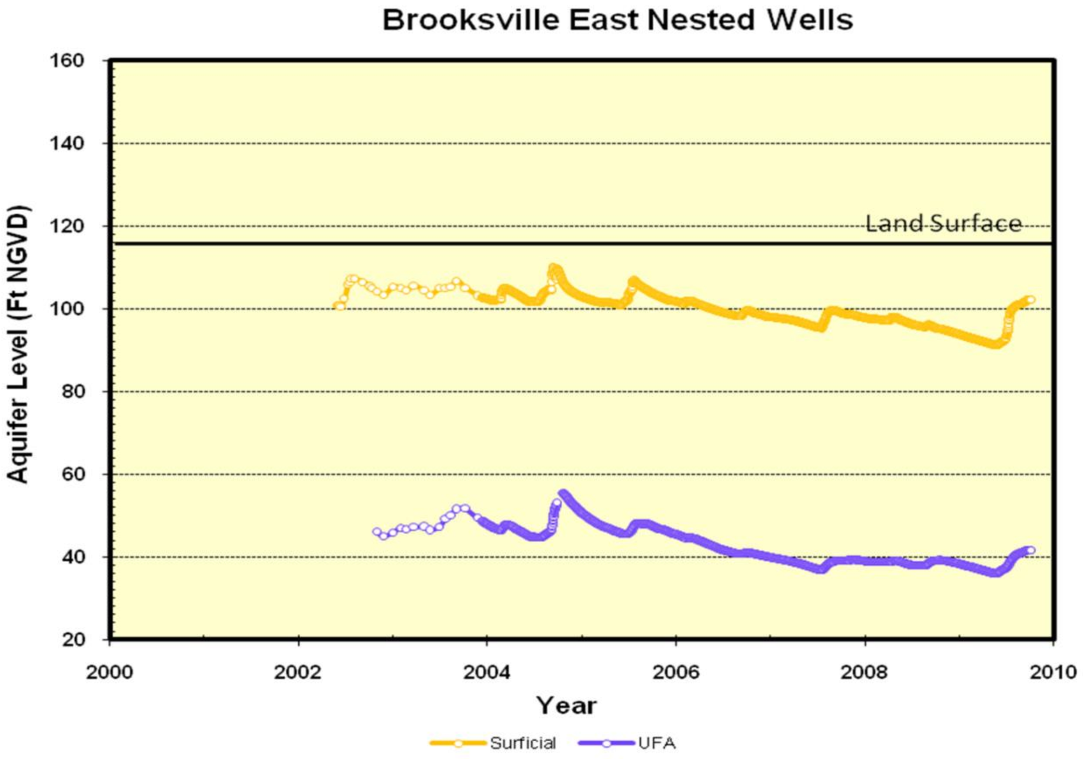
Water Level (Ft NGVD)
50
40
30
20
10
0
2000
2002
2004
2006
2008
2010
Year
BD-11FL
BD-11WT

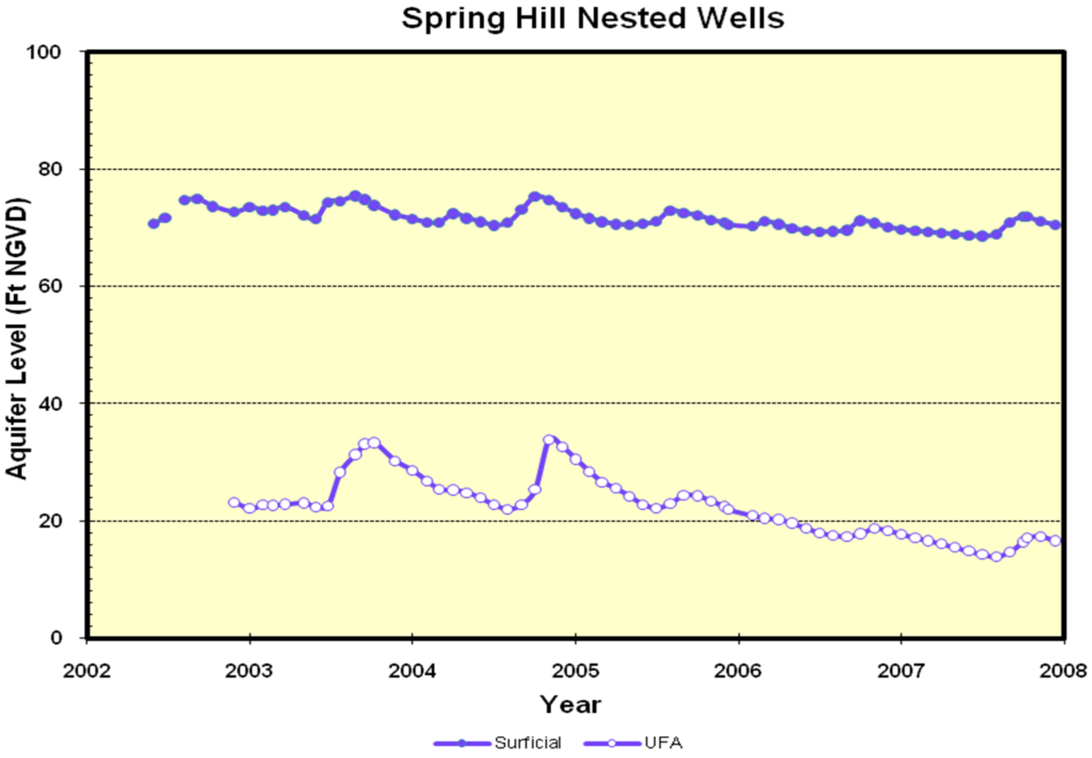

50
40
30
20
10
0
Water Level (Ft NGVD)
2000
2002
2004
2006
2008
2010
Year
BD-8FL
BD-8WT

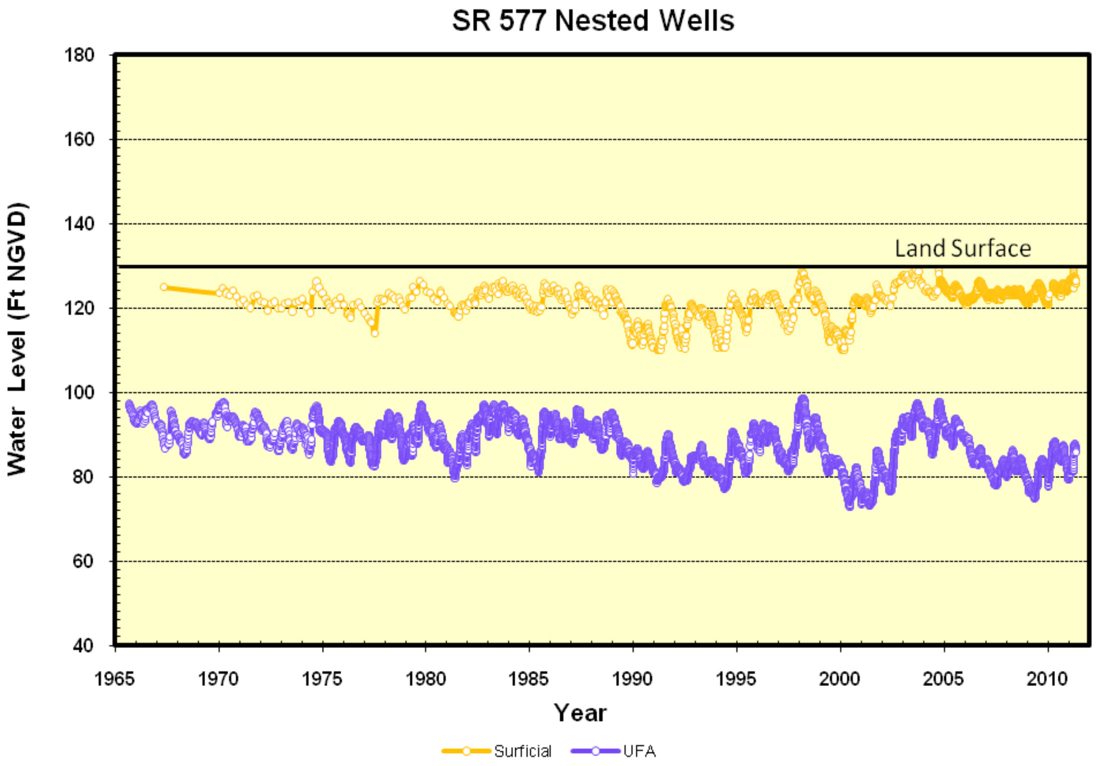
Appendix 1-C

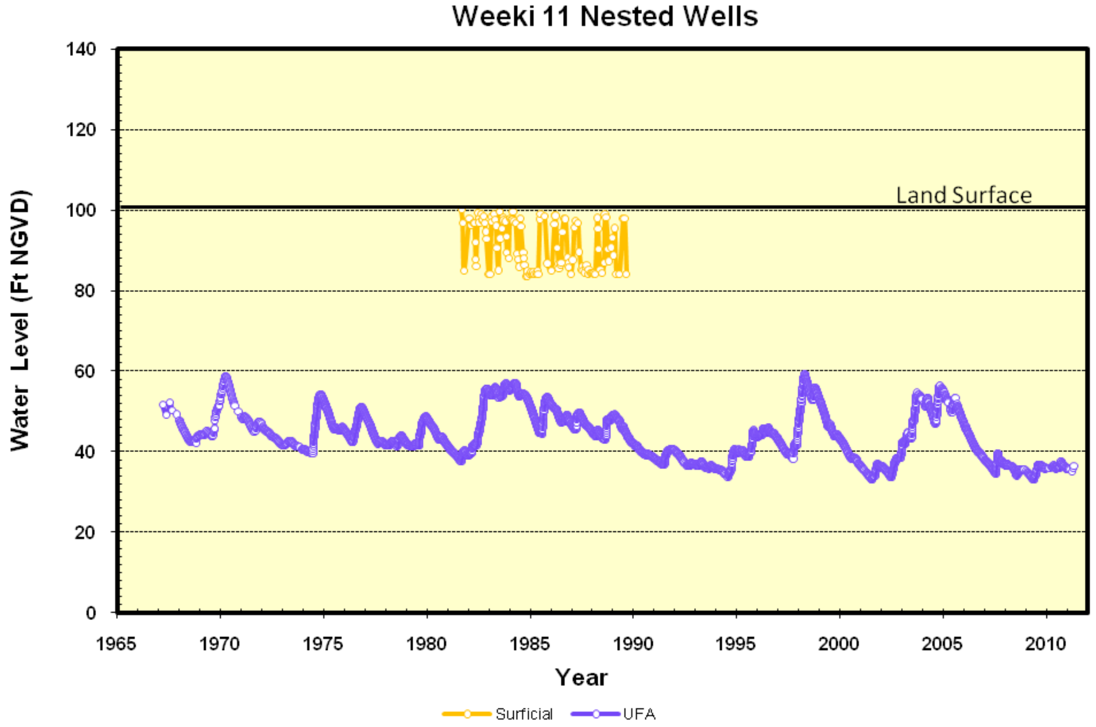

San Antonio Nested Wells
Land Surface
Aquifer Level (Ft NGVD)
180
160
140
120
100
80
60
40
2000
2002
2004
2006
2008
2010
Year
Surficial
UFA


BR-3 Nested Wells
Land Surface
Aquifer Level (Ft NGVD)
180
160
140
120
100
80
60
40
2000
2002
2004
2006
2008
2010
Year
Surficial
UFA


Brooksville East Nested Wells
Aquifer Level (Ft NGVD)
160
140
120
100
80
60
40
20
Land Surface
2000
2002
2004
2006
2008
2010
Year
Surficial
UFA


Spring Hill Nested Wells
Aquifer Level (Ft NGVD)
100
80
60
40
20
0
2002
2003
2004
2005
2006
2007
2008
Year
Surficial
UFA


SR 577 Nested Wells
Water Level (Ft NGVD)
180
160
140
120
100
80
60
40
Land Surface
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year
Surficial
UFA


Weeki 11 Nested Wells
Water Level (Ft NGVD)
140
120
100
80
60
40
20
0
Land Surface
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year
Surficial
UFA

Appendix 2

Parameter Sensitivity Testing of Lake Water Budget Models

By Jill Qi, Ph.D., Ron Basso, P.G., and Cortney Cameron, P.G.

1.0 Introduction

This appendix describes the methods and results of sensitivity testing applied to water budget models for three selected lakes. Lakes were selected from lakes with existing minimum levels with associated water budget models to represent different hydrogeologic provinces. Lake Alice (Hillsborough County) is located in a shallow water table, semi-confined setting in the Northern Tampa Bay region, Lake Easy (Polk County) is located in a high recharge, deep water table, semi-confined setting in the Southern Water Use Caution Area, and Lake Marion (Levy County) is located in a high recharge, karst-dominated, mostly unconfined setting in Northern part of the District (Basso, 2019). The sensitivity of a multitude of parameters was examined in the lake water budget model at each of the three lakes.

Model characteristics vary slightly between lakes. For example, the calibration period differs between lakes, and the drawdown correction methodology and results originally applied will vary in different regions of the District.

1.1 Lake Alice

Lake Alice is in northwest Hillsborough County, within the Brooker Creek watershed that forms part of the larger Tampa Bay watershed (Figure 1). Lake Alice has no significant inflow other than overland flow but discharges during high flow periods to Lake Taylor to the northeast via a reinforced concrete pipe. The topography is very flat, and flows are often negligible.

The hydrogeology of the area includes a sand surficial aquifer; a discontinuous, intermediate clay confining unit; and the thick carbonate Upper Floridan aquifer. In general, the surficial aquifer in the study area is in good hydraulic connection with the underlying Upper Floridan aquifer because the clay confining unit is generally thin, discontinuous, and breeched by numerous karst features. The surficial aquifer is generally ten to thirty feet thick and overlies the limestone of the Upper Floridan aquifer that averages nearly one thousand feet thick in the area (Miller, 1986). In between these two aquifers is the Hawthorn Group clay that varies between a few feet to as much as 25 feet thick. Because the clay unit is breached by buried karst features and has previously been exposed to erosional processes, preferential pathways locally connect the overlying surficial aquifer to the Upper Floridan aquifer resulting in moderate-to-high leakage to the Upper Floridan aquifer (Hancock and Basso, 1996).

1.2 Lake Easy

Lake Easy is located in east-central Polk County, on the Lake Wales Ridge, and is within the Kissimmee River watershed (Figure 2).

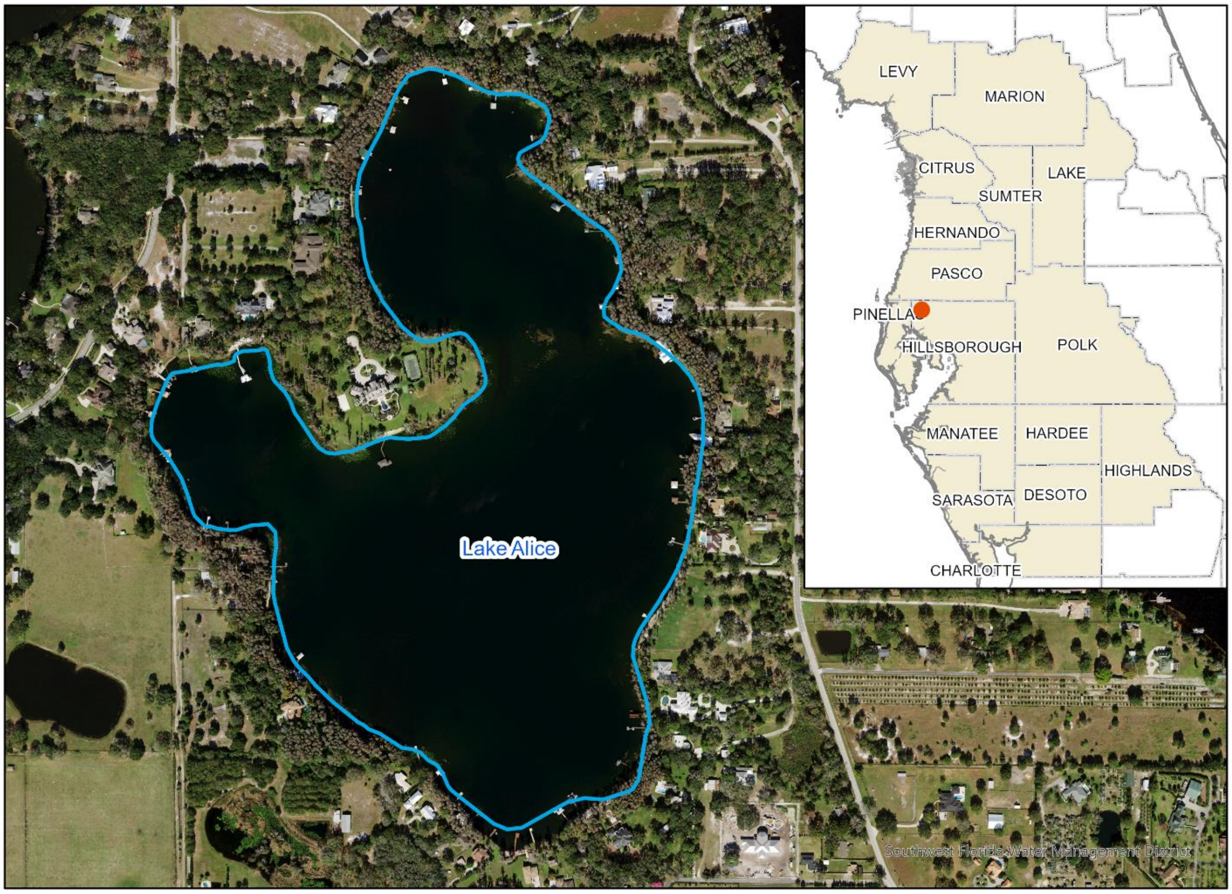


Figure 1. Location of Lake Alice in Hillsborough County, Florida.

The hydrogeology of the area includes a sand surficial aquifer; a clay confining unit perforated by karst features (sinkholes); and the thick carbonate Upper Floridan aquifer (Spechler and Kroening, 2007). Lake Easy is most likely a paleo-sinkhole lake that originated through the collapse of solution-enlarged features in the underlying Floridan aquifer (Barcelo and others, 1990). Sinkholes can provide more direct avenues for water from the surficial aquifer to recharge the underlying Upper Floridan aquifer. Most rainfall within the area of Lake Easy drains into the lake or is lost to evapotranspiration. The remaining rainfall recharges the surficial aquifer by percolating through unsaturated surficial deposits (Spechler and Kroening, 2007). The intermediate confining unit, or Hawthorn aquifer system, is present throughout much of Polk County and is locally absent or thin in the extreme northwestern part of Polk County (Spechler and Kroening, 2007). Below the Hawthorn aquifer system lies the limestone of the Upper Floridan aquifer system that ranges from approximately 300 feet thick in eastern Polk County to more than 1,200 feet thick in the southwestern part of the county (Spechler and Kroening, 2007). The top of the Floridan aquifer system ranged from 188 feet to 230 feet below the land surface according to the well completion reports. The Floridan aquifer system here consisted mainly of calcarenitic limestone with some dolomite lenses.

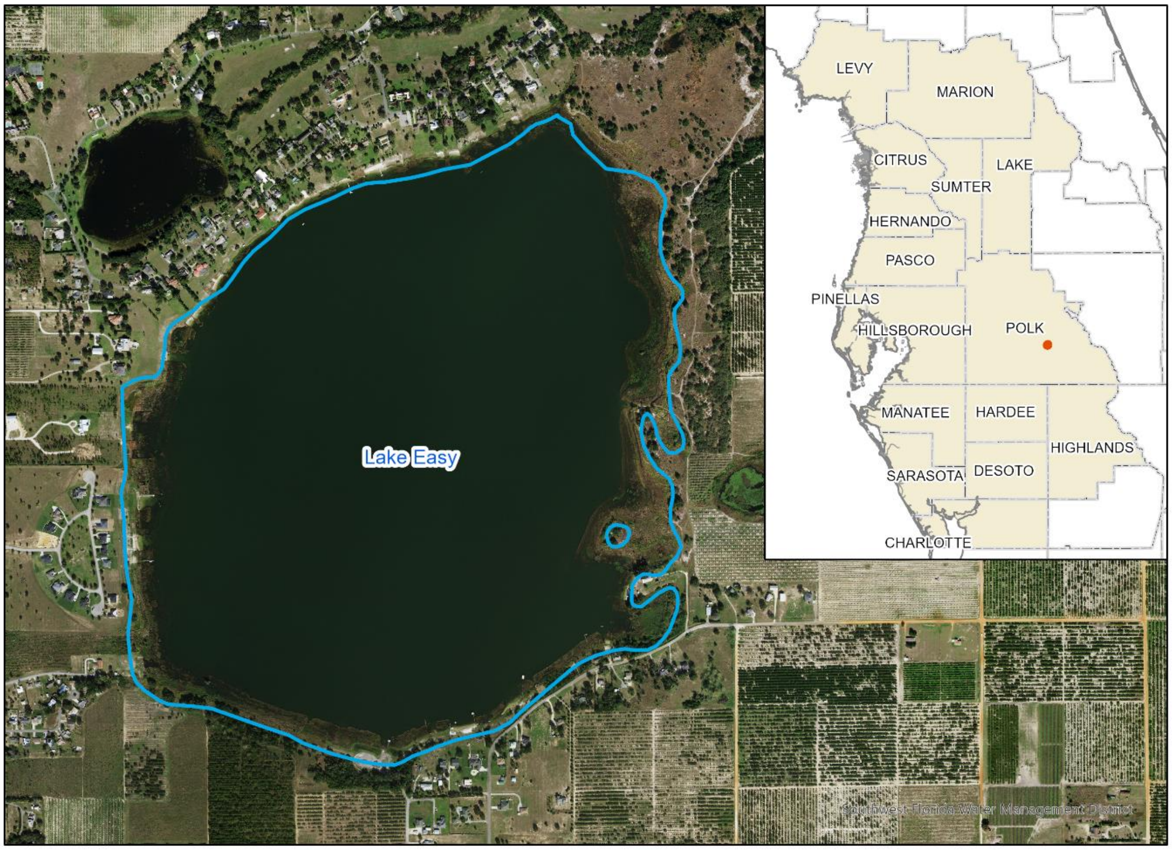


Figure 2. Location of Lake Easy in Polk County, Florida.

1.3 Lake Marion

Lake Marion is located in east-central Levy County, within the Waccasassa River watershed (Figure 3). Lake Marion is surrounded by hills with elevations as high as 110 feet (NGVD29). Lake Marion has no significant inflow other than overland flow. No outflow occurs from the basin currently. Lake Marion lies along the western edge of the northern half of the Brooksville Ridge, just one mile east of the Gulf Coastal Lowlands (White, 1970). The area is characterized by shallow sand deposits overlying clastic sediments of the Bone Valley and Alachua formations, with thicker sand layers occurring in the western portion of the Ridge.

The geologic units at Lake Marion include undifferentiated sand and clay sediments at the land surface, underlain by low-permeability clayey sediments of the Hawthorn Group, below which occurs the Ocala Limestone (Janosik, 2012). The undifferentiated sediments comprise the surficial aquifer and, based on the review of Janosik (2012) and driller's logs for several nearby wells, ranges from about 15 to 30 feet in thickness in the lake vicinity. The Ocala Limestone, an extremely weathered and loosely consolidated wackestone, represents the start of the upper Floridan aquifer, the top of which generally occurs in the area from between 20 to 60 feet below the land surface (Janosik, 2012; Table 1). The low-permeability clayey sediments of the Hawthorn Group, ranging from 5 to 30 feet in thickness near the lake, act locally as a confining unit between these two aquifers (Janosik, 2012). The permeability of the clayey sediments of the Hawthorn Group may slow vertical recharge of water to the Upper Floridan aquifer but overall appears insufficient to provide effective basal confinement of the surficial sands. According to Arthur and others (2008), the site is located at the boundary between the northern Brooksville Ridge and the surrounding region where the surficial aquifer is not delineated due to thin basal confinement that is "breached by sinkholes or fractures and precludes characterization as a laterally extensive or functional surficial aquifer by lack of hydraulic continuity." Therefore, this hydrogeologic setting is referred to as regionally unconfined (Basso, 2019).

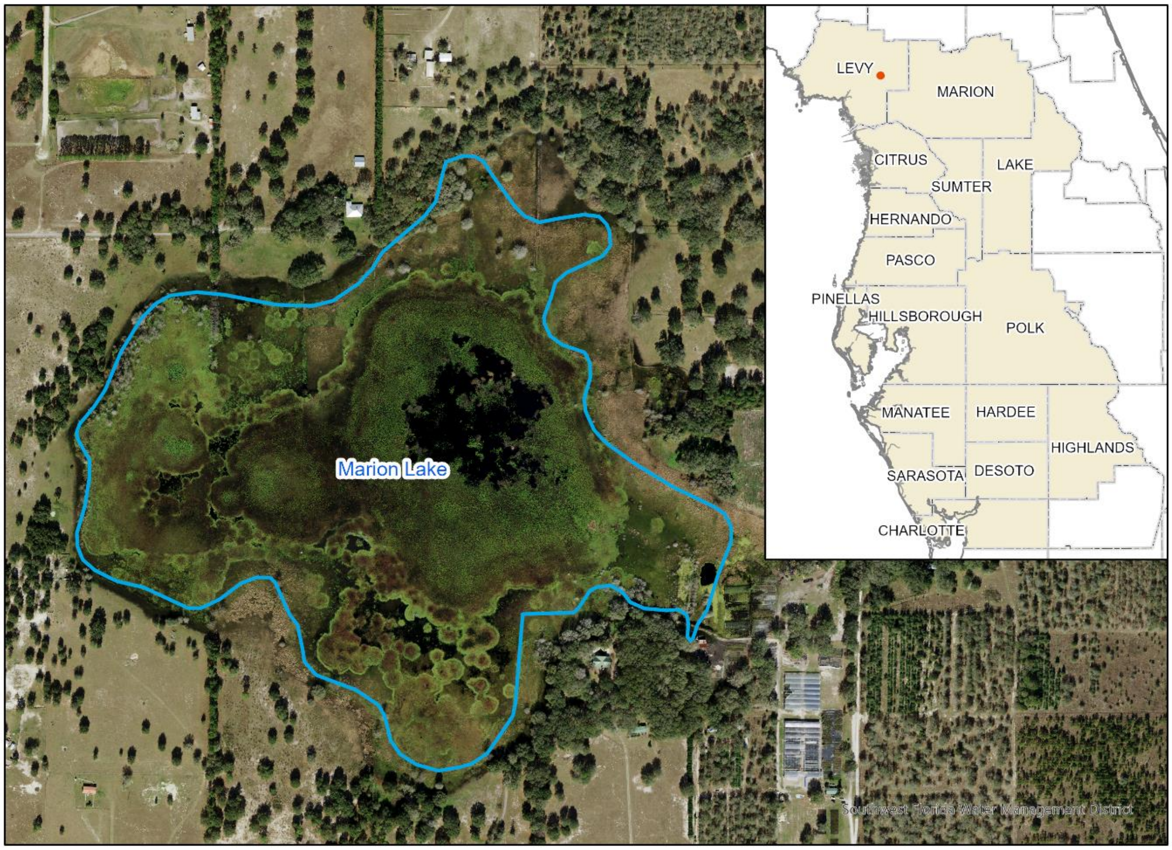


Figure 3. Location of Lake Marion in Levy County, Florida.

2.0 Sensitivity Testing Procedure

2.1 Sensitivity Tests

For each trial, starting with the original calibrated lake water budget model, one selected parameter or input was altered while all other parameters and factors of the model were kept constant. The performance of the trial model was evaluated against the performance metrics. Two diagnostic plots per trial were generated: 1) scatter plots of observed versus modeled trial water levels, and 2) time series of the trial and calibrated modeled water levels. Additionally, the resulting Historic percentiles from the trial model were compared with the Historic percentiles from the original model.

Parameters and inputs were selected based on a literature review from (Winter, 1981) Swancar et al. (2000), Sacks et al. (1994), Swancar et al. (2015), and Haag et al. (2005). The following parameters and inputs were tested at the indicated modification rates:

- Rainfall: ± 5%, 10%, and 25%
- Evaporation: ± 5% 10%, and 25%
- Overland flow
    - Watershed area: ± 5%, 10%, and 25%
    - CN: ± 1, 5, 10 and 20
    - DCIA: ± 5%, 10%, and 25%
        - If DCIA is originally 0, then 0.01, 0.05, and 0.10 values were used.
- Channel outflow coefficient: ± 50%, 100% (not applicable for some lakes)
- Leakance coefficients (individually and together): x 0.1, 0.2, 0.5, 2, 5 and 10
- Groundwater levels (individually and together)
    - Surficial aquifer (SA): ± 0.5 ft, 1 ft, and 2 ft
    - Upper Floridan aquifer (UFA): ± 1 ft, 2 ft, and 5 ft

These parameters and inputs were excluded from the sensitivity test:

- Lake bathymetry
- Lake stages
- Channelized inflow
- Outflow structure elevation

Lake bathymetry was excluded from the sensitivity test because it is highly dependent on sampling density, based on the literature review. Lake stage was excluded because it has been shown to be within 0.1’ based on survey accuracy. Channelized inflow was excluded because it does not apply to most lakes. Finally, outflow structure elevation was excluded because it has been shown to be within 0.1’ based on survey accuracy, but it is also subject to the unknown influence of unauthorized alterations.

2.2 Verification Tests

Retaining the original parameterization, the original lake water budget model was updated by adding a minimum of two years to the original calibration period. For the verification (added) years, model performance was reported comparing observed versus modeled lake levels.

2.3 Non-Uniqueness Tests

Multiple calibration solutions exist that provide acceptable calibration (non-uniqueness). However, other aspects of the model, including water budget components, should be evaluated to ensure the model is reasonably compliant with area hydrogeology.

To assess how non-uniqueness can influence water budget model results, at least three reasonable parameterizations were developed that provided a comparable fit to the original, calibrated parameterization. Special emphases were placed on changing the leakance coefficients and modifying other parameters while producing a similar fit. Performance metrics for each trial model were reported. Additionally, water budget Historic percentiles for each trial were calculated based on the drawdown correction as used in the original water budget model.

3.0 Performance Metrics

Water budget model performance metrics are shown in Table 1. Performance metrics were determined based on a review of the literature (Moriasi et al., 2007, 2015) and regional model calibration metrics, summarized in Table 2. Lake water level percentiles (Px) refer to exceedance percentiles and are used in minimum levels development. Metrics for mean absolute error (MAE), percent bias (PBIAS), Nash–Sutcliffe efficiency (NSE), coefficient of determination (R^2), and RMSE-observations standard deviation ratio (RSR) were developed following professional judgment and guidelines from Moriasi et al. (2007, 2015).

Table 1. Lake water budget model performance metrics and goals.

Metric	Unit	Goal
P10	feet	± 0.5
P50	feet	± 0.3
P90	feet	± 0.5
MAE	feet	≤ 1.5
RMSE	feet	≤ 2.5
RSR	-	≤ 0.7
PBIAS	-	≤ 15%
R^2	-	≥ 0.6
NSE	-	≥ 0.5

Table 2. Summary of regional models’ calibration metrics.

(1) Central Springs Model

Parameter	Metrics	Unit	Goal
UFA water level	PBIAS	-	<10%
	MAE (50% of wells)	feet	< 2.5
	MAE (80% of wells)	feet	< 5
	ME	feet	> ±0.5
	RSR	-	≤ 0.5
	R^2	-	> 0.85
	NSE	-	> 0.7
SA water level	PBIAS	-	<10%
	MAE (50% of wells	feet	< 2.5
	MAE (80% of wells)	feet	< 5
	ME	feet	> ±0.5
	RSR	-	≤ 0.7
	R^2	-	> 0.75
Springflow	MAE, first magnitude	cubic feet/second	< 5%

	MAE, second magnitude	cubic feet/second	< 10-20%
	R^2 (≥second magnitude)	-	> 0.6

* pending data availability

(2) Integrated Northern Tampa Bay Model

Parameter	Metrics	Unit	Goal
Water level, model-wide	ME	feet	= 0
	MEQ1	feet	= 0
	MEQ4	feet	= 0
	SA RMSE	feet	< 2
	UFA RMSE	feet	< 4
Water level, region-wide	ME	feet	< 2
	MEQ1	feet	< 2
	MEQ4	feet	< 2
	MAE	feet	< 3
Water level, individual well	ME	feet	< 4
	MEQ1	feet	< 4
	MEQ4	feet	< 4
	MAE	feet	< 5
Springflow	ME	cubic feet/second	< 10%

* ME = mean error; Q1 = upper quartile; Q4 = lower quartile

(3) East-Central Florida Transient Expanded Model

Parameter	Metrics	Unit	Goal
Water levels, CFWI	MAE (50% of targets)	feet	< 2.5
	MAE (80% of targets)	feet	< 5
Water levels, model-wide	Average RMSE	feet	< 5
	Average ME	feet	< 1
	Average MAE		< 5% of range
Springflow		cubic feet/second	Within ±10%

(4) District-Wide Regulatory Model

Parameter	Metrics	Unit	Goal
Water level	ME÷Range	feet	< 5%
	MAE÷Range	feet	< 10%

4.0 Test Results

4.1 Original Calibration

4.1.1 Lake Alice

The Lake Alice water budget model is described in Cameron and Hancock (2017). The Lake Alice water budget model [insert model link here], which covers the 1/1/1999 to 10/31/2016 period, was considered well-calibrated, as all performance metrics were met (Table 3 and Figure 4).

Table 3. Lake Alice water budget model summary (1/1/1999 to 10/31/2016).

(1) Lake Alice water budget model calibration performance

Metric	Performance
P10 (ft)	0.1
P50 (ft)	0.0
P90 (ft)	0.2
MAE (ft)	0.52
RMSE (ft)	0.66
NSE	0.92
PBIAS	0.001
RSR	0.29
R^2	0.92

(2) Lake Alice water budget model calibrated parameters

Parameter	Value
SA K (1/day)	0.002
UFA K (1/day)	0.00055
Outflow K (1/day)	0.022
Watershed Area (acre)	301.2
SCS CN	73
DCIA	0
SA Head Adjustment (ft)	0
UFA Head Adjustment (ft)	0

(3) Lake Alice water budget model fluxes (in/yr)

	In	Out	Net
UFA	0.0	28.1	-28.1
SA	12.3	0.7	11.6
Channel Flow	0.0	10.7	-10.7
Rain/ET	56.5	58.5	-2.0
Runoff	30.0	0.0	30.0

Total	98.8	98.0	0.80

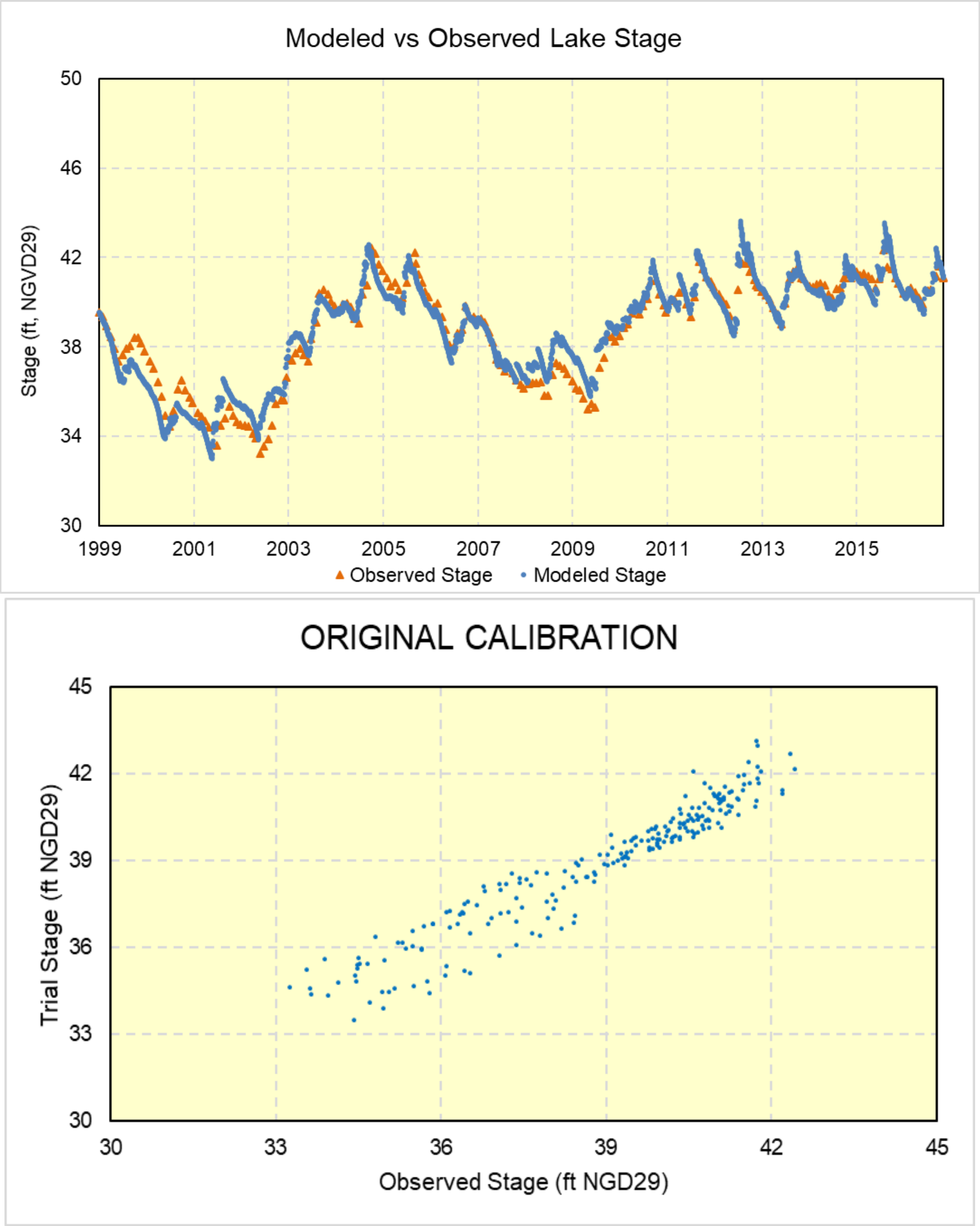


Figure 4. Time series (top) and scatter plot (bottom) showing modeled (“trial”) versus observed water levels for the original calibrated Lake Alice water budget model.

4.1.2 Lake Easy

The Lake Easy water budget model is described in Smith and Patterson (2019). The Lake Easy water budget model [insert model link here], which covers the 1/1/2004 to 12/31/2016 period, was considered well-calibrated, as all performance metrics were met (Table 4 and Figure 5).

Table 4. Lake Easy water budget model summary (1/1/2004 to 12/31/2016).

(1) Lake Easy water budget model calibration performance

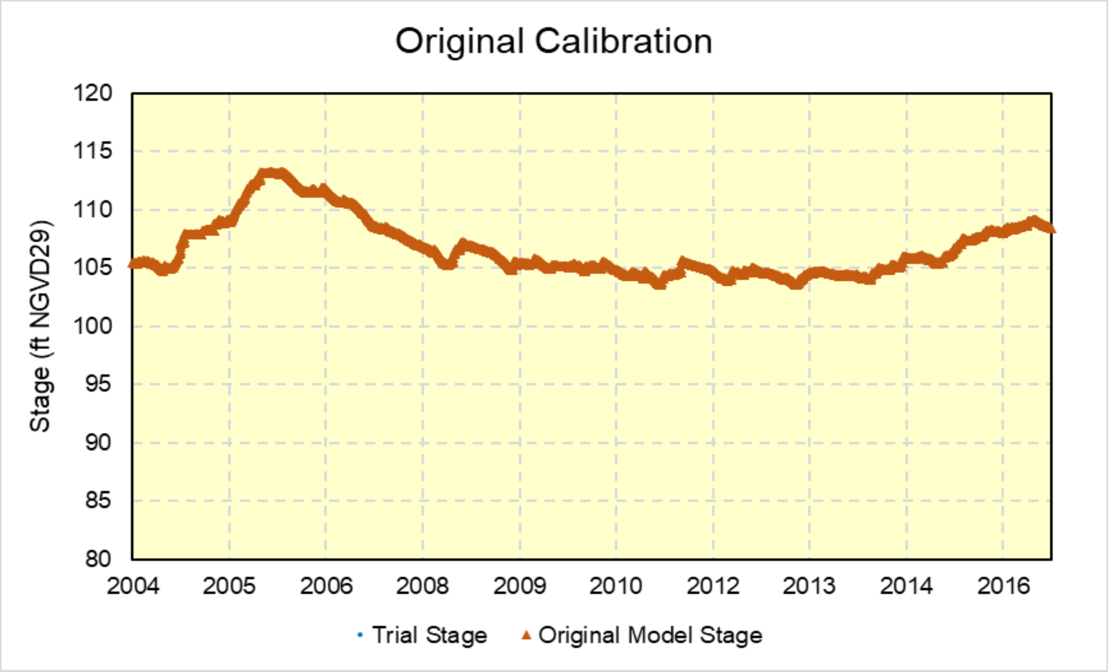
Metric	Performance
P10 (ft)	0.1
P50 (ft)	0.0
P90 (ft)	0.3
MAE (ft)	0.24
RMSE (ft)	0.34
NSE	0.95
PBIAS	0.00
RSR	0.22
R^2	0.95

(2) Lake Easy water budget model calibrated parameters

Parameter	Value
SA K (1/day)	0.0028
UFA K (1/day)	0.00055
Outflow K (1/day)	0
Watershed Area (acre)	1247
SCS CN	47
DCIA	0.05
SA Head Adjustment (ft)	3.4
UFA Head Adjustment (ft)	0

(3) Lake Easy water budget model fluxes (in/yr)

	In	Out	Net
UFA	0.0	24.8	-24.8
SA	21.9	0.0	21.9
Channel Flow	0.0	0.0	0.0
Rain/ET	54.2	59.0	-4.8
Runoff	10.4	0.0	10.4
Total	86.5	83.7	2.8



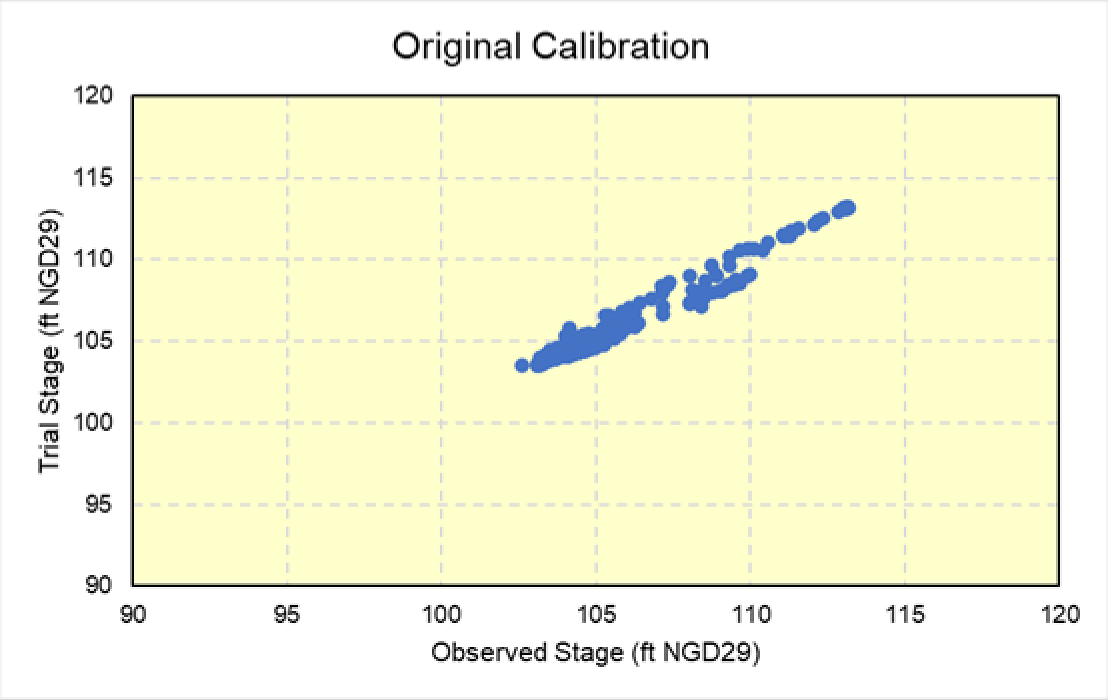


Figure 5. Time series (top) and scatter plot (bottom) showing modeled ("trial") versus observed water levels for the original calibrated Lake Easy water budget model.

4.1.3 Lake Marion

The Lake Marion water budget model is described in Cameron and Ellison (2020). The Lake Marion water budget model [insert model link here], which covers the 3/18/1992 to 3/28/2019 period, was considered well-calibrated, as all performance metrics were met (Table 5 and Figure 6).

Table 5. Lake Marion water budget model summary (3/18/1992 to 3/28/2019).

(1) Lake Marion calibration performance

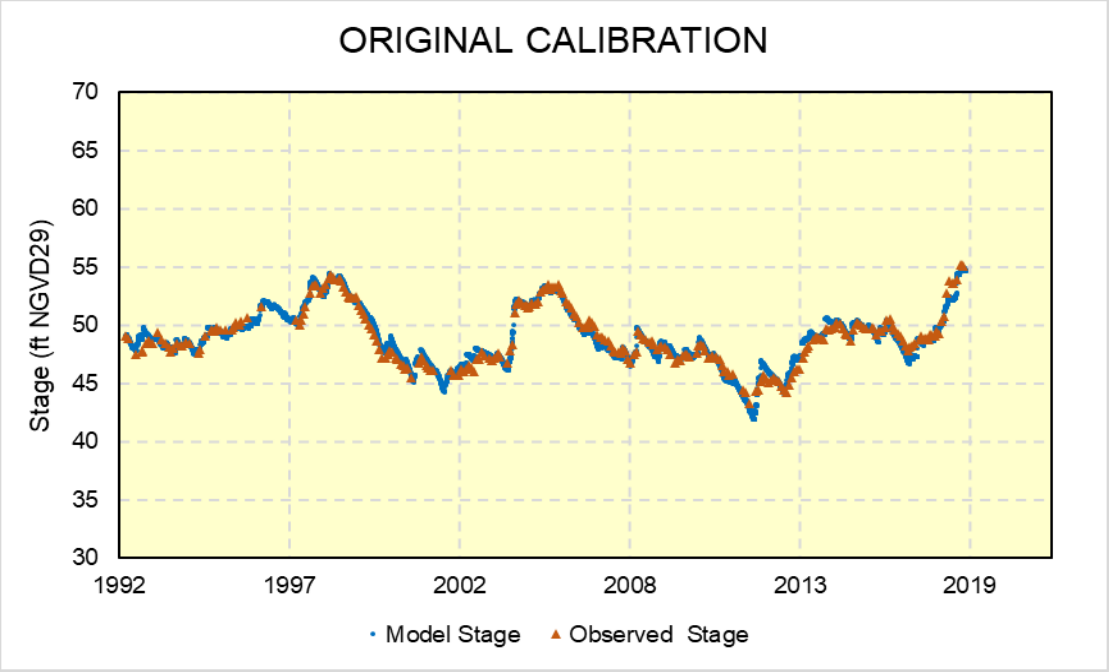
Metric	Performance
P10 (ft)	-0.4
P50 (ft)	0.0
P90 (ft)	0.4
MAE (ft)	0.40
RMSE (ft)	0.51
NSE	0.96
PBIAS	0.000
RSR	0.21
R^2	0.96

(2) Lake Marion calibration parameters

Parameter	Value
SA K (1/day)	0.0015
UFA K (1/day)	0.0005
Outflow K (1/day)	0.012
Watershed Area (acre)	138
SCS CN	65
DCIA	0
SA Head Adjustment (ft)	0
UFA Head Adjustment (ft)	0

(3) Lake Marion water budget model fluxes (in/yr)

	In	Out	Net
UFA	0.0	8.9	-8.9
SA	1.1	11.5	-10.4
Channel Flow	0.0	0.0	0.0
Rain/ET	55.5	55.2	0.3
Runoff	21.1	0.0	21.1
Total	77.7	75.6	2.10



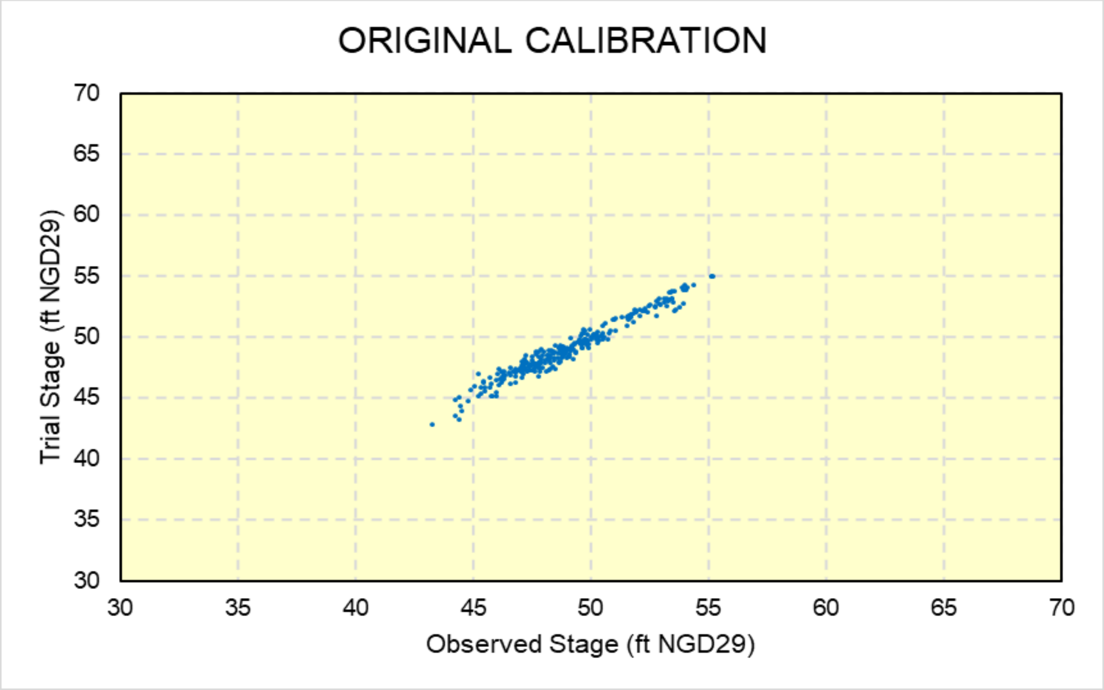


Figure 6. Time series (top) and scatter plot (bottom) showing modeled (“trial”) versus observed water levels for the original calibrated Lake Marion water budget model.

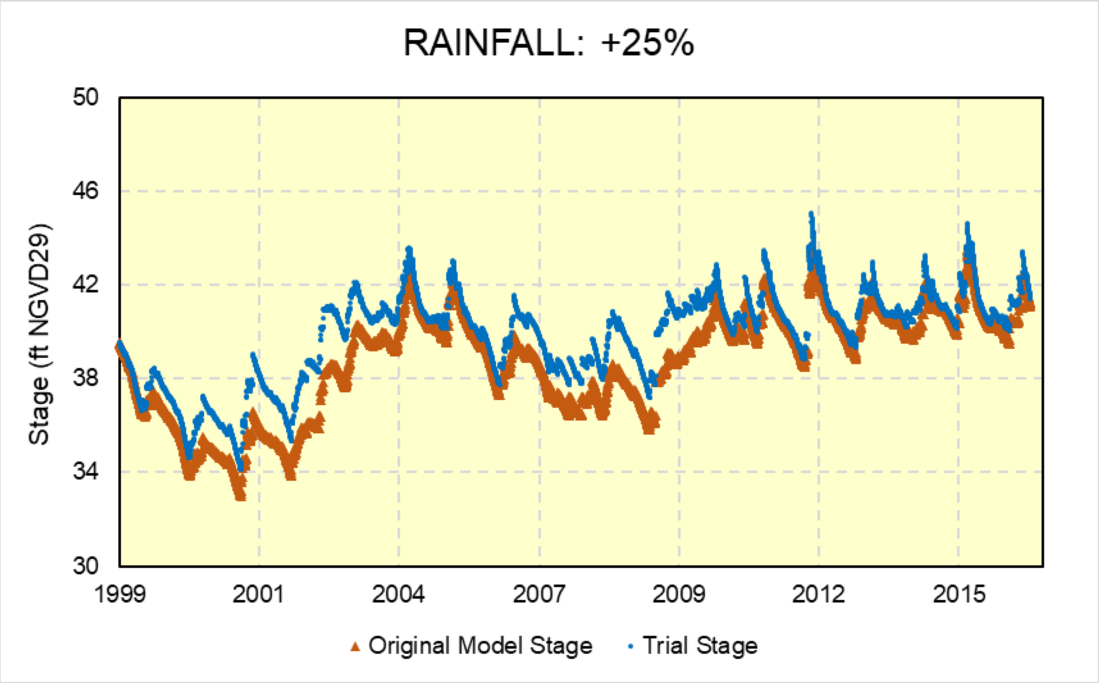
4.2 Sensitivity Tests

4.2.1 Rainfall

The daily rainfall input time series (`RAIN` in Cameron et al., 2022) was adjusted by ± 5%, 10%, and 25% for each lake. Water budget model performance was sensitive to rainfall changes. At just ±5% change in rainfall, no water budget model met all calibration criteria (Tables 6 to 8). Lake Marion's water budget model was the most sensitive to rainfall change: ±5% in rainfall corresponded to ±0.3 ft in the P50 (Table 8). Lake Alice's water budget model was the least sensitive to rainfall change: all performance metrics, other than percentiles (P10, P50, and P90) and RSR (at +25% rainfall), were met for all rainfall modifications. The difference in sensitivity between the lakes may be explained by the relative contribution of rainfall to the lake's water budget. Lake Marion's inflow is dominated by rainfall at 71%, while rainfall accounts for 57% of the inflow of Lake Alice. Additionally, rainfall input controls overland flow via a non-linear relationship that depends on the lake's curve number, so the lake's response to changes in rainfall also depends on the watershed curve number. Hydrographs and scatter plots of observed versus trial lake stages were generated for each trial [insert link to model files here]. For example, the result of the +25% rainfall trial for Lake Alice is shown in Figure 7.

Table 6. Lake Alice water budget model performance and Historic percentile changes with rainfall modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

Rainfall	-25%	-10%	-5%	±0%	+5%	+10%	+25%
P10 (ft)	-1.1	-0.3	-0.1	0.1	0.3	0.4	0.8
P50 (ft)	-1.8	-0.6	-0.2	0.0	0.2	0.5	1.0
P90 (ft)	-1.6	-0.5	-0.1	0.2	0.6	0.9	1.8
MAE (ft)	1.38	0.57	0.49	0.52	0.64	0.79	1.21
RMSE (ft)	1.52	0.71	0.63	0.66	0.83	1.02	1.63
NSE	0.57	0.91	0.93	0.92	0.87	0.81	0.51
PBIAS	-0.04	-0.01	0.00	0.00	0.01	0.01	0.03
RSR	0.65	0.31	0.27	0.29	0.36	0.44	0.70
R^2	0.93	0.94	0.93	0.92	0.89	0.86	0.73
ΔHP10	-0.7	-0.3	-0.1	0.0	0.2	0.3	0.6
ΔHP50	-1.3	-0.4	-0.2	0.0	0.2	0.3	0.6
ΔHP90	-1.8	-0.7	-0.3	0.0	0.3	0.5	1.2



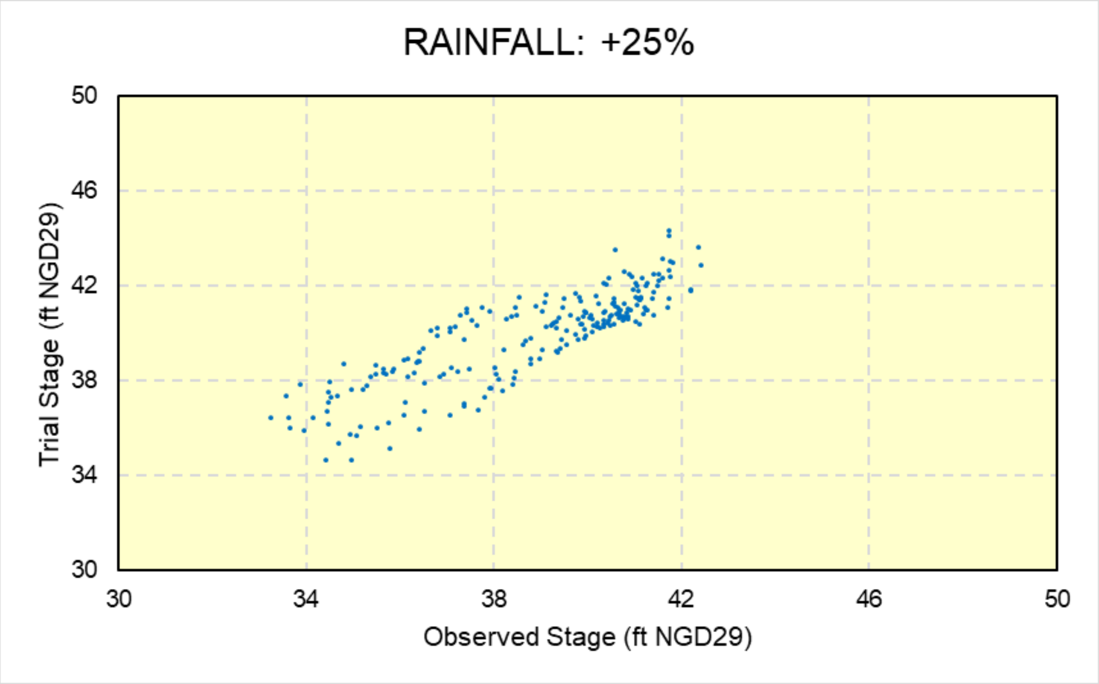


Figure 7. Time series (top) and scatter plot (bottom) showing modeled trial versus observed water levels for the +25% rainfall modification trial for the Lake Alice water budget model.

Table 7. Lake Easy water budget model performance and Historic percentile changes with rainfall modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

Rainfall	-25%	-10%	-5%	±0%	+5%	+10%	+25%
P10 (ft)	-0.6	-0.2	-0.1	0.1	0.4	0.7	1.5
P50 (ft)	-1.1	-0.4	-0.2	0.0	0.2	0.5	1.2
P90 (ft)	-0.7	-0.1	0.1	0.3	0.5	0.7	1.3
MAE (ft)	1.04	0.45	0.32	0.24	0.34	0.54	1.22
RMSE (ft)	1.12	0.53	0.39	0.34	0.45	0.62	1.27
NSE	0.51	0.89	0.94	0.95	0.92	0.85	0.36
PBIAS	-0.01	-0.004	-0.00	0.00	0.00	0.04	0.01
RSR	0.70	0.33	0.24	0.22	0.28	0.39	0.80
R^2	0.92	0.95	0.95	0.95	0.96	0.96	0.95
ΔHP10	-0.6	-0.3	-0.2	0.0	0.3	0.6	1.3
ΔHP50	-1.1	-0.4	-0.2	0.0	0.2	0.5	1.2
ΔHP90	-1.0	-0.3	-0.2	0.0	0.3	0.4	1.0

Table 8. Lake Marion water budget model performance and Historic percentile changes with rainfall modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

Rainfall	-25%	-10%	-5%	±0%	+5%	+10%	+25%
P10 (ft)	-2.5	-1.1	-0.7	-0.4	0.0	0.4	1.5
P50 (ft)	-1.8	-0.7	-0.3	0.0	0.3	0.6	1.5
P90 (ft)	-1.2	-0.2	0.1	0.4	0.7	1.0	1.9
MAE (ft)	1.88	0.75	0.50	0.40	0.51	0.75	1.65
RMSE (ft)	2.01	0.88	0.62	0.51	0.63	0.87	1.75
NSE	0.32	0.87	0.94	0.96	0.93	0.87	0.49
PBIAS	-0.04	-0.01	-0.01	0.00	0.01	0.01	0.03
RSR	0.82	0.36	0.25	0.21	0.26	0.36	0.72
R^2	0.89	0.95	0.96	0.96	0.96	0.96	0.94
ΔHP10	-2.1	-0.7	-0.4	0.0	0.4	0.7	1.8
ΔHP50	-1.9	-0.7	-0.3	0.0	0.3	0.6	1.5
ΔHP90	-1.8	-0.7	-0.3	0.0	0.3	0.6	1.5

4.2.2 Evaporation

Daily evaporation input (`EVAP` in Cameron et al., 2022) was adjusted by ± 5%, 10%, and 25% for each lake. Although evaporation was determined to be a sensitive parameter, overall water budget model performance was not as sensitive to evaporation modifications as rainfall modifications. At ±10% change in evaporation, no water budget model met all calibration criteria (Tables 9 to 11). The Lake Easy and Marion water budget models were more sensitive to evaporation changes than Lake Alice. At ±5%, Lake Easy and Marion water level percentiles diverged from calibration goals. The absolute water level change associated with each evaporation modification was relatively consistent for all three lakes. For example, at +25% evaporation, the P90 absolute change was -1.0 ft for Lake Alice (changed from 0.2 ft to -0.8 ft), -0.9 ft for Lake Easy, and -0.8 ft for Lake Marion. This could occur because all three tested lakes referenced an evaporation time series from Lake Starr, since seasonal evaporation rates are generally similar for lakes in central Florida that have similar depths (Swancar, 2015). However, because the initial calibration varied for each lake, the same changes in evaporation caused calibration goal failure at some lakes and not others. For example, at -5%, the P90 at all three lakes shifted up 0.2 ft. For example, Lake Alice's P90 residual shifted from 0.2 to 0.4 ft: still within the calibration goal of 0.5 ft. However, Lake Easy P90 shifted from 0.3 to 0.5 ft, failing the calibration goal. Similarly, Lake Marion shifted from 0.4 to 0.6 ft, failing the calibration goal. Hydrographs and scatter plots of observed versus trial lake stages were generated for each trial [insert link to model files here].

Table 9. Lake Alice water budget model performance and Historic percentile changes with evaporation modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

Evaporation	-25%	-10%	-5%	±0%	+5%	+10%	+25%
P10 (ft)	0.4	0.2	0.1	0.1	0.0	-0.1	-0.3
P50 (ft)	0.7	0.3	0.1	0.0	-0.1	-0.3	-0.7
P90 (ft)	1.3	0.6	0.4	0.2	0.0	-0.2	-0.8
MAE (ft)	0.85	0.61	0.55	0.52	0.51	0.52	0.73
RMSE (ft)	1.13	0.80	0.72	0.66	0.64	0.66	0.91
NSE	0.76	0.88	0.90	0.92	0.92	0.92	0.85
PBIAS	0.02	0.01	0.01	0.00	0.00	-0.01	-0.02
RSR	0.49	0.34	0.31	0.29	0.28	0.29	0.39
R^2	0.87	0.90	0.91	0.92	0.92	0.93	0.93
ΔHP10	0.2	0.1	0.1	0.0	0.0	-0.1	-0.3
ΔHP50	0.5	0.2	0.1	0.0	-0.2	-0.3	-0.6
ΔHP90	0.9	0.4	0.2	0.0	-0.2	-0.5	-1.1

Table 10. Lake Easy water budget model performance and Historic percentile changes with evaporation modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

Evaporation	-25%	-10%	-5%	±0%	+5%	+10%	+25%
P10 (ft)	1.1	0.5	0.3	0.1	0.0	-0.2	-0.5
P50 (ft)	1.0	0.4	0.2	0.0	-0.2	-0.4	-1.0
P90 (ft)	1.3	0.7	0.5	0.3	0.1	0.0	-0.6
MAE (ft)	1.04	0.48	0.31	0.24	0.30	0.40	0.92
RMSE (ft)	1.09	0.56	0.42	0.34	0.37	0.48	0.98
NSE	0.53	0.87	0.93	0.95	0.95	0.91	0.62
PBIAS	0.01	0.00	0.00	0.00	-0.00	-0.00	-0.01
RSR	0.69	0.35	0.27	0.22	0.23	0.30	0.62
R^2	0.95	0.95	0.95	0.95	0.95	0.95	0.95
ΔHP10	1.0	0.4	0.2	0.0	-0.1	-0.3	-0.6
ΔHP50	1.0	0.4	0.2	0.0	-0.2	-0.4	-1.0
ΔHP90	1.0	0.4	0.2	0.0	-0.1	-0.3	-0.9

Table 11. Lake Marion water budget model performance and Historic percentile changes with evaporation modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

Evaporation	-25%	-10%	-5%	±0%	+5%	+10%	+25%
P10 (ft)	0.7	0.1	-0.1	-0.4	-0.5	-0.7	-1.2
P50 (ft)	0.8	0.3	0.1	0.0	-0.1	-0.3	-0.7
P90 (ft)	1.2	0.7	0.6	0.4	0.2	0.1	-0.4
MAE (ft)	0.96	0.50	0.42	0.40	0.43	0.51	0.88
RMSE (ft)	1.06	0.62	0.54	0.51	0.55	0.64	1.02
NSE	0.81	0.94	0.95	0.96	0.95	0.93	0.83
PBIAS	0.02	0.01	0.00	0.00	0.00	-0.01	-0.02
RSR	0.43	0.25	0.22	0.21	0.23	0.26	0.42
R^2	0.96	0.96	0.96	0.96	0.95	0.95	0.93
ΔHP10	1.1	0.5	0.2	0.0	-0.2	-0.4	-0.9
ΔHP50	0.8	0.3	0.1	0.0	-0.1	-0.3	-0.7
ΔHP90	0.7	0.2	0.2	0.0	-0.2	-0.4	-0.8

4.2.3 Watershed area

The watershed area (`AREA_WS` in Cameron et al., 2022) was adjusted by ± 5%, 10%, and 25% for each lake. Compared to rainfall and evaporation, the water budget model was not as sensitive to watershed area modification. Other than water level percentiles (P10, P50, and P90), all performance metrics were met for all watershed area trials at all three lakes (Tables 12 to 14). Lake Marion's water budget model was the most sensitive to watershed area change: ±10% in the watershed corresponded to ±0.5 ft in the P10 or P90 (Table 14). Lake Easy's water budget model was the least sensitive to watershed area change: the only metric that didn't meet the calibration goal was the P90 for the +25% watershed area trial (Table 13). The difference in sensitivity can be explained by the relative contribution of runoff to the lake's water budget. The watershed area determines two lake inflows: overland flow (as a function of the watershed curve number) and DCIA flow (as a proportion of the watershed area). No other water budget flows incorporate the watershed area. Lake Marion's runoff comprised 27% of the lake's inflow (there was no DCIA flow for Lake Marion), while runoff (including DCIA flow) accounted for 14% of the inflow of Lake Easy. Hydrographs and scatter plots of observed versus trial lake stages were generated for each trial [insert link to model files here].

Table 12. Lake Alice water budget model performance and Historic percentile changes with watershed area modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

Watershed Area	-25%	-10%	-5%	±0%	+5%	+10%	+25%
P10 (ft)	-0.2	-0.1	0.0	0.1	0.1	0.2	0.4
P50 (ft)	-0.6	-0.1	-0.1	0.0	0.1	0.1	0.4
P90 (ft)	-0.5	-0.1	0.1	0.2	0.3	0.5	0.8
MAE (ft)	0.53	0.47	0.49	0.52	0.55	0.60	0.76
RMSE (ft)	0.67	0.61	0.63	0.66	0.71	0.77	0.98
NSE	0.92	0.93	0.93	0.92	0.91	0.89	0.82
PBIAS	-0.01	0.00	0.00	0.00	0.00	0.01	0.01
RSR	0.29	0.26	0.27	0.29	0.31	0.33	0.42
R^2	0.95	0.93	0.93	0.92	0.91	0.90	0.86
ΔHP10	-0.3	-0.1	0.0	0.0	0.1	0.1	0.3
ΔHP50	-0.4	-0.2	-0.1	0.0	0.0	0.1	0.3
ΔHP90	-0.6	-0.2	-0.1	0.0	0.1	0.2	0.4

Table 13. Lake Easy water budget model performance and Historic percentile changes with watershed area modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

Watershed Area	-25%	-10%	-5%	±0%	+5%	+10%	+25%
P10 (ft)	-0.1	0.1	0.1	0.1	0.2	0.2	0.4
P50 (ft)	-0.2	-0.1	-0.1	0.0	0.0	0.1	0.2
P90 (ft)	0.1	0.2	0.3	0.3	0.4	0.4	0.5
MAE (ft)	0.32	0.26	0.24	0.24	0.24	0.26	0.34
RMSE (ft)	0.39	0.35	0.34	0.34	0.36	0.37	0.44
NSE	0.94	0.95	0.95	0.95	0.95	0.95	0.92
PBIAS	-0.02	0.00	0.00	0.00	0.00	0.00	0.00
RSR	0.25	0.22	0.22	0.22	0.22	0.23	0.28
R^2	0.95	0.95	0.95	0.95	0.95	0.96	0.96
ΔHP10	-0.2	0.0	0.0	0.0	0.1	0.1	0.3
ΔHP50	-0.2	-0.1	-0.1	0.0	0.0	0.1	0.2
ΔHP90	-0.2	0.0	0.0	0.0	0.1	0.1	0.2

Table 14. Lake Marion water budget model performance and Historic percentile changes with watershed area modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

Watershed Area	-25%	-10%	-5%	±0%	+5%	+10%	+25%
P10 (ft)	-0.8	-0.5	-0.4	-0.4	-0.3	-0.2	0.0
P50 (ft)	-0.5	-0.2	-0.1	0.0	0.1	0.1	0.4
P90 (ft)	-0.1	0.3	0.3	0.4	0.5	0.5	0.7
MAE (ft)	0.56	0.42	0.40	0.40	0.41	0.43	0.56
RMSE (ft)	0.68	0.53	0.51	0.51	0.53	0.55	0.68
NSE	0.92	0.95	0.96	0.96	0.95	0.95	0.92
PBIAS	-0.01	0.00	0.00	0.00	0.00	0.00	0.01
RSR	0.28	0.22	0.21	0.21	0.22	0.23	0.28
R^2	0.96	0.96	0.96	0.96	0.96	0.96	0.95
ΔHP10	-0.4	-0.1	-0.1	0.0	0.1	0.2	0.4
ΔHP50	-0.5	-0.2	-0.1	0.0	0.1	0.1	0.4
ΔHP90	-0.5	-0.2	-0.1	0.0	0.1	0.1	0.3

4.2.4 Curve number

The watershed curve number, CN (CN_{II} in Cameron et al., 2022), was adjusted by ± 1, 5, 10, and 20 for each lake. The Lake Alice and Marion water budget models were more sensitive to CN modification compared to Lake Easy (Table 15-17). At ±1 CN, all performance metrics achieved the calibration goal. However, at ± 5 CN, percentiles for Lakes Alice and Marion were not within the acceptable calibration range (Tables 15 and 17). Lake Easy's performance metrics only failed at +10 and +20 CN (Table 16). The difference in sensitivity may be explained by the relative contribution of runoff to the lake's water budget. Overland flow accounts for 30% of inflow at Lake Alice and 27% at Lake Marion, versus just 7% at Lake Easy. Hydrographs and scatter plots of observed versus trial lake stages were generated for each trial [insert link to model files here].

Table 15. Lake Alice water budget model performance and Historic percentile changes with curve number (CN) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

CN	-20	-10	-5	-1	±0	+1	+5	+10	+20
P10 (ft)	-0.5	-0.2	-0.1	0.0	0.1	0.1	0.2	0.5	1.0
P50 (ft)	-1.2	-0.8	-0.3	-0.1	0.0	0.1	0.3	0.7	1.2
P90 (ft)	-1.4	-0.8	-0.3	0.1	0.2	0.3	0.7	1.4	2.8
MAE (ft)	0.93	0.59	0.49	0.50	0.52	0.54	0.69	0.93	1.59
RMSE (ft)	1.13	0.76	0.63	0.64	0.66	0.69	0.89	1.24	2.15
NSE	0.76	0.89	0.93	0.92	0.92	0.91	0.85	0.71	0.14
PBIAS	-0.02	-0.01	-0.01	0.00	0.00	0.00	0.01	0.02	0.04
RSR	0.49	0.33	0.27	0.28	0.29	0.30	0.38	0.54	0.93
R^2	0.93	0.94	0.94	0.92	0.92	0.91	0.88	0.82	0.59
ΔHP10	-0.5	-0.3	-0.1	0.0	0.0	0.0	0.2	0.4	0.8
ΔHP50	-1.0	-0.5	-0.2	-0.1	0.0	0.0	0.2	0.4	0.7
ΔHP90	-1.4	-0.8	-0.4	-0.1	0.0	0.1	0.4	0.8	1.9

Table 16. Lake Easy water budget model performance and Historic percentile changes with curve number (CN) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

CN	-20	-10	-5	-1	±0	+1	+5	+10	+20
P10 (ft)	0.0	0.0	0.1	0.1	0.1	0.2	0.3	0.4	1.0
P50 (ft)	-0.2	-0.2	-0.1	0.0	0.0	0.0	0.1	0.3	0.8
P90 (ft)	0.1	0.1	0.2	0.3	0.3	0.4	0.5	0.6	1.0
MAE (ft)	0.31	0.28	0.26	0.24	0.24	0.24	0.28	0.38	0.81
RMSE (ft)	0.39	0.36	0.34	0.34	0.34	0.35	0.39	0.49	0.88
NSE	0.94	0.95	0.95	0.95	0.95	0.95	0.94	0.90	0.69
PBIAS	-0.00	-0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
RSR	0.25	0.23	0.22	0.22	0.22	0.22	0.24	0.31	0.55
R^2	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
ΔHP10	-0.1	-0.1	0.0	0.0	0.0	0.1	0.2	0.3	0.9
ΔHP50	-0.2	-0.2	-0.1	0.0	0.0	0.0	0.1	0.3	0.7
ΔHP90	-0.2	-0.1	-0.1	0.0	0.0	0.1	0.2	0.3	0.7

Table 17. Lake Marion water budget model performance and Historic percentile changes with curve number (CN) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

CN	-20	-10	-5	-1	±0	+1	+5	+10	+20
P10 (ft)	-1.5	-1.0	-0.6	-0.4	-0.4	-0.3	0.0	0.3	1.2
P50 (ft)	-1.2	-1.0	-0.5	-0.1	0.0	0.1	0.4	0.9	1.9
P90 (ft)	-0.7	-0.6	-0.1	0.3	0.4	0.5	0.9	1.5	2.6
MAE (ft)	1.52	0.86	0.52	0.40	0.40	0.41	0.59	0.96	1.90
RMSE (ft)	1.70	0.97	0.64	0.51	0.51	0.53	0.74	1.14	2.09
NSE	0.52	0.84	0.93	0.96	0.96	0.95	0.91	0.78	0.26
PBIAS	-0.02	-0.02	-0.01	0.00	0.00	0.00	0.01	0.02	0.04
RSR	0.70	0.40	0.26	0.21	0.21	0.22	0.30	0.47	0.86
R^2	0.77	0.96	0.96	0.96	0.96	0.96	0.95	0.93	0.88
ΔHP10	-1.2	-0.6	-0.3	0.0	0.0	0.1	0.4	0.7	1.5
ΔHP50	-1.5	-1.0	-0.5	-0.1	0.0	0.1	0.4	0.9	1.9
ΔHP90	-1.3	-1.1	-0.5	-0.1	0.0	0.1	0.5	1.0	2.1

4.2.5 DCIA

DCIA (`P_DCIA` in Cameron et al., 2022) was adjusted at ± 5%, 10%, and 25% for each lake. If DCIA was originally 0, then 0.01, 0.05, and 0.10 values were used. DCIA of Lakes Alice and Marion were set at 0 originally, therefore 0.01, 0.05, and 0.10 values were tested. Water budget models were not as sensitive to DCIA modifications as rainfall, evaporation, or CN modifications. Lake Marion model was the most sensitive to DCIA change: at +1% DCIA, P90 did not meet the calibration goal (Table 20). Lake Easy model was the least sensitive to DCIA change: performance metrics met all calibration goals for all DCIA modifications (Table 19). There are two reasons for the difference in sensitivity. Firstly, the magnitudes of change for DCIA were different between Lake Easy and Lake Alice/Marion. DCIA of Lake Easy was set at 0.05 originally. With the maximum of ± 25% modification, the difference between trial DCIA and original DCIA of Lake Easy was at a maximum of 0.0125. While DCIA of Lakes Alice and Marion was changed from 0 to the maximum of 0.1, thus creating a maximum difference of 0.1. This difference was 8 times larger than the change of DCIA for Lake Easy. Secondly, the modification in DCIA resulted in a proportionally different DCIA flow within the water budget. With Lake Easy, the range of modification in DCIA generated 4 to 7% of inflow of the water budget, compared with 6% of inflow of the original calibration. With Lake Marion, at 0.1 DCIA, DCIA flow made up 19% of inflow at 16 in/yr. With Lake Alice, at 0.1 DCIA, DCIA flow made up 11% of inflow at 12 in/yr. Hydrographs and scatter plots of observed versus trial lake stages were generated for each trial [insert link to model files here].

Table 18. Lake Alice water budget model performance and Historic percentile changes with directly connected impervious area (DCIA) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

DCIA	±0%	+1%	+5%	+10%
P10 (ft)	0.1	0.1	0.2	0.3
P50 (ft)	0.0	0.1	0.2	0.4
P90 (ft)	0.2	0.3	0.6	0.9
MAE (ft)	0.52	0.53	0.59	0.70
RMSE (ft)	0.66	0.68	0.77	0.92
NSE	0.92	0.91	0.89	0.84
PBIAS	0.00	0.00	0.01	0.01
RSR	0.29	0.29	0.33	0.40
R^2	0.92	0.92	0.90	0.89
ΔHP10	0.0	0.0	0.1	0.2
ΔHP50	0.0	0.0	0.1	0.3
ΔHP90	0.0	0.1	0.3	0.5

Table 19. Lake Easy water budget model performance and Historic percentile changes with directly connected impervious area (DCIA)modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

DCIA	-25%	-10%	-5%	±0%	+5%	+10%	+25%
P10 (ft)	0.0	0.1	0.1	0.1	0.2	0.2	0.3
P50 (ft)	-0.1	-0.1	0.0	0.0	0.0	0.0	0.1
P90 (ft)	0.2	0.3	0.3	0.3	0.3	0.4	0.4
MAE (ft)	0.27	0.25	0.24	0.24	0.23	0.24	0.26
RMSE (ft)	0.35	0.34	0.34	0.34	0.35	0.35	0.37
NSE	0.95	0.95	0.95	0.95	0.95	0.95	0.95
PBIAS	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RSR	0.22	0.22	0.22	0.22	0.22	0.22	0.23
R^2	0.95	0.95	0.95	0.95	0.95	0.96	0.96
ΔHP10	-0.1	0.0	0.0	0.0	0.1	0.1	0.2
ΔHP50	-0.1	-0.1	0.0	0.0	0.0	0.0	0.1
ΔHP90	0.0	0.0	0.0	0.0	0.1	0.1	0.1

Table 20. Lake Marion water budget model performance and Historic percentile changes with directly connected impervious area (DCIA) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

DCIA	±0%	+1%	+5%	+10%
P10 (ft)	-0.36	-0.27	0.00	0.24
P50 (ft)	0.03	0.11	0.45	0.92
P90 (ft)	0.41	0.55	1.00	1.57
MAE (ft)	0.40	0.42	0.65	1.01
RMSE (ft)	0.51	0.54	0.79	1.18
NSE	0.96	0.95	0.89	0.77
PBIAS	0.00	0.00	0.01	0.02
RSR	0.21	0.22	0.33	0.48
R^2	0.96	0.96	0.95	0.94
ΔHP10	0.0	0.1	0.3	0.6
ΔHP50	0.0	0.1	0.5	0.9
ΔHP90	0.0	0.1	0.6	1.1

4.2.6 Channel outflow coefficient

The channel outflow coefficient (`K_O` in Cameron et al., 2022) was adjusted by ± 50%, and 100% for Lake Alice and Marion. Lake Easy had no outflow channel, so an adjustment was not applicable. Lake Marion's outflow channel had an elevation of 67 ft NGVD29; however, lake levels never exceeded this level in the water budget model period, so outflow never occurred (Table 22). For Lake Alice, the only performance metric not met occurred at -100% channel outflow coefficient (Table 21). In Lake Alice's original water budget model, channel outflow accounted for 12% of outflow. At +100% channel outflow, channel outflow comprised 13% of total outflow; at -100% channel outflow coefficient, channel outflow comprised 10% of the outflow. Since channel outflow only occurs at high water levels, the P10 was the only metric to show major changes in response to variations in the channel outflow coefficient. Therefore, the channel outflow coefficient was the least sensitive of all parameters tested. Hydrographs and scatter plots of observed versus trial lake stages were generated for each trial [insert link to model files here].

Table 21. Lake Alice water budget model performance and Historic percentile changes with channel outflow coefficient (K_O) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

K_O	-100%	-50%	±0%	+50%	+100%
P10 (ft)	1.8	0.4	0.1	-0.1	-0.2
P50 (ft)	0.3	0.1	0.0	0.0	-0.1
P90 (ft)	0.2	0.2	0.2	0.2	0.2
MAE (ft)	1.04	0.55	0.52	0.54	0.55
RMSE (ft)	1.31	0.70	0.66	0.67	0.68
NSE	0.68	0.91	0.92	0.92	0.91
PBIAS	0.02	0.01	0.00	0.00	0.00
RSR	0.56	0.30	0.29	0.29	0.29
R^2	0.89	0.92	0.92	0.92	0.92
ΔHP10	2.5	0.5	0.0	-0.2	-0.3
ΔHP50	0.8	0.1	0.0	-0.1	-0.1
ΔHP90	0.0	0.0	0.0	0.0	0.0

Table 22. Lake Marion water budget model performance and Historic percentile changes with channel outflow coefficient (K_O) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

K_O	-100%	-50%	±0%	+50%	+100%
P10 (ft)	-0.4	-0.4	-0.4	-0.4	-0.4
P50 (ft)	0.0	0.0	0.0	0.0	0.0
P90 (ft)	0.4	0.4	0.4	0.4	0.4
MAE (ft)	0.40	0.40	0.40	0.40	0.40
RMSE (ft)	0.51	0.51	0.51	0.51	0.51
NSE	0.96	0.96	0.96	0.96	0.96
PBIAS	0.00	0.00	0.00	0.00	0.00
RSR	0.21	0.21	0.21	0.21	0.21
R^2	0.96	0.96	0.96	0.96	0.96
ΔHP10	0.0	0.0	0.0	0.0	0.0
ΔHP50	0.0	0.0	0.0	0.0	0.0
ΔHP90	0.0	0.0	0.0	0.0	0.0

4.2.7 Leakance coefficients

Leakance coefficients (`L_SA` and `L_UFA` in Cameron et al., 2022) were adjusted by x 0.1, 0.2, 0.5, 2, 5, and 10, for the Surficial Aquifer (SA) and Upper Floridan Aquifer (UFA) individually and together. Water budget models were sensitive to leakance coefficient modifications (Table 23 to 25). For the SA leakance coefficient modification, Lake Easy's water budget model was the most sensitive and Lake Alice the least sensitive. For the UFA leakance coefficient modification, the Lake Easy water budget model was again the most sensitive, with Lake Marion the least sensitive (Table 26 to 28). For the combined SA and UFA leakance coefficient modification, Lake Marion's water budget model was the most sensitive and Lake Easy the least (Table 29 to 31). Hydrographs and scatter plots of observed versus trial lake stages were generated for each trial [insert link to model files here].

These differences in sensitivity can be explained by the different water budget components resulting from their unique hydrogeologic setting for each lake. For Lake Alice, during the model period, the SA water level was higher than the lake's water level, which was higher than the UFA water level. Therefore, water moved from the SA to the lake to the UFA. SA flow into the lake accounted for 13% of total inflow, and outflow into the UFA accounted for 29% of total outflow. For Lake Easy, the relative relationship between SA, lake, and UFA water levels mirrored Lake Alice; however, SA inflow into the lake accounted for 26% of total inflow, and outflow into UFA was 32% of total outflow. Therefore, Lake Easy's model was more sensitive to SA leakance changes. Both Lake Alice and Easy's models were sensitive to UFA leakance changes. For Lake Marion, the SA water level was not always higher than the lake's water level. This resulted in both inflow and outflow between SA and the lake. SA inflow into Lake Marion accounted for 3% of total inflow, and outflow into SA was 12% of total outflow. Outflow into UFA made up 13% of total outflow, explaining why Lake Marion's model was the least sensitive model to UFA leakance change.

When both SA and UFA leakance were modified for Lakes Alice and Easy, the modified flows from SA compensate for modified flows to the UFA (and vice versa) to a certain degree, lessening the impact on the lake water level. For example, when Lake Alice's SA and UFA leakance were both x0.1 of the original value, SA inflow was lowered to 0.8 in/yr (1% of total inflow), but UFA outflow also decreased to 3.2 in/yr (4% of total outflow). However, for Lake Marion, both SA and UFA net fluxes were dominated by outflow, so no compensating effects occurred when both SA and UFA leakance were modified; when SA and UFA leakance were both modified to x0.1 of the original value, SA inflow decreased to near-zero, SA outflow decreased to 2.7 in/yr (5% of total outflow), and UFA outflow decreased to 1.7 inch/year (2.8% of total outflow). The difference in SA inflow between the original model and trial model was 2.1 in/yr, while the difference for net groundwater (SA and UFA) was 14.7 in/yr. These results highlight the uniqueness of each lake.

Table 23. Lake Alice water budget model performance and Historic percentile changes with SA leakance (SA_K) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

SA_K	x 1/10	x 1/5	x 1/2	x 1	x 2	x 5	x 10
P10 (ft)	-0.3	-0.2	-0.1	0.1	0.2	0.5	0.8
P50 (ft)	-1.5	-1.2	-0.7	0.0	0.4	0.9	1.1
P90 (ft)	-0.7	-0.6	-0.2	0.2	0.7	1.2	1.4
MAE (ft)	0.97	0.81	0.53	0.52	0.71	0.98	1.16
RMSE (ft)	1.20	1.01	0.68	0.66	0.92	1.28	1.49
NSE	0.73	0.81	0.91	0.92	0.84	0.70	0.59
PBIAS	-0.02	-0.02	-0.01	0.00	0.01	0.02	0.03
RSR	0.52	0.43	0.30	0.29	0.40	0.55	0.64
R^2	0.90	0.92	0.93	0.92	0.88	0.82	0.78
ΔHP10	-0.3	-0.2	-0.1	0.0	0.2	0.4	0.7
ΔHP50	-0.7	-0.6	-0.3	0.0	0.3	0.6	0.7
ΔHP90	-0.7	-0.6	-0.2	0.0	0.1	0.3	0.4

Table 24. Lake Easy water budget model performance and Historic percentile changes with SA leakance (SA_K) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

SA_K	x 1/10	x 1/5	x 1/2	x 1	x 2	x 5	x 10
P10 (ft)	-3.0	-1.7	-0.5	0.1	1.1	1.6	1.9
P50 (ft)	-4.0	-2.9	-1.2	0.0	0.9	1.6	1.9
P90 (ft)	-3.9	-2.7	-0.9	0.3	1.1	1.6	1.7
MAE (ft)	3.92	2.83	1.13	0.24	0.91	1.56	1.81
RMSE (ft)	4.01	2.92	1.21	0.34	0.95	1.59	1.85
NSE	-5.34	-2.36	0.43	0.95	0.64	0.00	-0.35
PBIAS	-0.037	-0.027	-0.011	0.00	0.01	0.015	0.017
RSR	2.52	1.83	0.76	0.22	0.60	1.00	1.16
R^2	0.77	0.82	0.91	0.95	0.97	0.96	0.94
ΔHP10	-2.0	-1.3	-0.5	0.0	0.8	1.2	1.4
ΔHP50	-2.9	-2.1	-0.9	0.0	0.7	1.3	1.5
ΔHP90	-3.1	-2.2	-0.8	0.0	0.6	0.9	1.0

Table 25. Lake Marion water budget model performance and Historic percentile changes with SA leakance (SA_K) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

SA_K	x 1/10	x 1/5	x 1/2	x 1	x 2	x 5	x 10
P10 (ft)	0.5	0.4	0.0	-0.4	-0.5	-0.8	-0.9
P50 (ft)	1.1	0.8	0.4	0.0	-0.4	-0.6	-1.0
P90 (ft)	1.5	1.3	0.9	0.4	-0.2	-1.0	-1.2
MAE (ft)	1.16	0.96	0.57	0.40	0.63	1.12	1.50
RMSE (ft)	1.45	1.22	0.76	0.51	0.81	1.44	2.21
NSE	0.65	0.75	0.90	0.96	0.89	0.65	0.18
PBIAS	0.02	0.02	0.01	0.00	-0.01	-0.02	-0.02
RSR	0.59	0.50	0.31	0.21	0.33	0.59	0.91
R^2	0.86	0.89	0.94	0.96	0.92	0.82	0.55
ΔHP10	0.9	0.7	0.3	0.0	-0.1	-0.4	-0.5
ΔHP50	1.1	0.8	0.4	0.0	-0.4	-0.6	-0.9
ΔHP90	1.0	0.8	0.5	0.0	-0.6	-1.4	-1.8

Table 26. Lake Alice water budget model performance and Historic percentile changes with UFA leakance (UFA_K) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

UFA_K	x 1/10	x 1/5	x 1/2	x 1	x 2	x 5	x 10
P10 (ft)	0.5	0.5	0.4	0.1	-0.6	-3.2	-5.4
P50 (ft)	1.2	1.1	0.7	0.0	-1.4	-4.2	-6.5
P90 (ft)	2.5	2.2	1.4	0.2	-1.6	-4.7	-6.7
MAE (ft)	1.39	1.26	0.89	0.52	1.26	4.10	6.39
RMSE (ft)	1.81	1.65	1.18	0.66	1.44	4.27	6.57
NSE	0.39	0.49	0.74	0.92	0.61	-2.39	-7.02
PBIAS	0.03	0.03	0.02	0.00	-0.03	-0.11	-0.16
RSR	0.78	0.71	0.51	0.29	0.62	1.84	2.83
R^2	0.77	0.80	0.87	0.92	0.93	0.85	0.77
ΔHP10	0.3	0.2	0.2	0.0	-0.4	-1.5	-3.2
ΔHP50	0.6	0.5	0.4	0.0	-0.8	-2.6	-4.3
ΔHP90	1.1	1.0	0.7	0.0	-1.2	-3.3	-5.0

Table 27. Lake Easy water budget model performance and Historic percentile changes with UFA leakance (UFA_K) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

UFA_K	x 1/10	x 1/5	x 1/2	x 1	x 2	x 5	x 10
P10 (ft)	1.9	1.7	1.1	0.1	-0.9	-3.4	-5.5
P50 (ft)	1.7	1.5	0.9	0.0	-1.3	-3.7	-5.5
P90 (ft)	2.0	1.8	1.2	0.3	-1.1	-3.7	-5.8
MAE (ft)	1.74	1.53	0.93	0.24	1.30	3.75	5.66
RMSE (ft)	1.80	1.59	1.00	0.34	1.34	3.77	5.68
NSE	-0.27	0.01	0.60	0.95	0.29	-4.60	-11.71
PBIAS	0.017	0.015	0.009	0.00	-0.012	-0.036	-0.054
RSR	1.13	0.99	0.63	0.22	0.84	2.37	3.56
R^2	0.92	0.93	0.94	0.95	0.96	0.95	0.91
ΔHP10	1.3	1.2	0.7	0.0	-0.8	-2.6	-4.1
ΔHP50	1.2	1.0	0.6	0.0	-1.0	-2.8	-4.1
ΔHP90	1.3	1.1	0.7	0.0	-1.1	-3.0	-4.6

Table 28. Lake Marion water budget model performance and Historic percentile changes with UFA leakance (UFA_K) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

UFA_K	x 1/10	x 1/5	x 1/2	x 1	x 2	x 5	x 10
P10 (ft)	0.2	0.2	-0.1	-0.4	-0.8	-1.3	*
P50 (ft)	0.5	0.4	0.2	0.0	-0.4	-1.3	*
P90 (ft)	1.0	0.9	0.7	0.4	-0.1	-1.1	*
MAE (ft)	0.68	0.61	0.47	0.40	0.59	1.33	*
RMSE (ft)	0.83	0.76	0.61	0.51	0.74	1.55	*
NSE	0.89	0.90	0.94	0.96	0.91	0.59	*
PBIAS	0.01	0.01	0.01	0.00	-0.01	-0.03	*
RSR	0.34	0.31	0.25	0.21	0.30	0.64	*
R^2	0.95	0.95	0.96	0.96	0.94	0.88	*
ΔHP10	0.6	0.5	0.3	0.0	-0.4	-0.9	*
ΔHP50	0.5	0.4	0.2	0.0	-0.4	-1.3	*
ΔHP90	0.6	0.5	0.2	0.0	-0.5	-1.6	*

* The x10 trial resulted in errors because a modeled lake level dropped below the range of the available lake stage-area-volume curve.

Table 29. Lake Alice water budget model performance and Historic percentile changes with combinations of SA leakance (SA_K) and UFA leakance (UFA_K) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

SA_K	x 1/10	x 1/5	x 1/2	x 1	x 2	x 5	x 10
UFA_K	x 1/10	x 1/5	x 1/2	x 1	x 2	x 5	x 10
P10 (ft)	0.4	0.4	0.3	0.1	-0.2	-0.5	-0.6
P50 (ft)	1.3	1.1	0.5	0.0	-0.4	-0.9	-1.2
P90 (ft)	3.3	2.7	1.3	0.2	-0.6	-0.9	-1.2
MAE (ft)	1.64	1.40	0.79	0.52	0.68	1.10	1.35
RMSE (ft)	2.22	1.88	1.07	0.66	0.89	1.38	1.67
NSE	0.08	0.34	0.79	0.92	0.85	0.64	0.48
PBIAS	0.04	0.03	0.02	0.00	-0.01	-0.02	-0.03
RSR	0.96	0.81	0.46	0.29	0.38	0.60	0.72
R^2	0.61	0.73	0.89	0.92	0.90	0.84	0.78
ΔHP10	0.1	0.1	0.1	0.0	-0.1	-0.2	-0.1
ΔHP50	0.5	0.5	0.3	0.0	-0.3	-0.6	-0.7
ΔHP90	1.5	1.3	0.7	0.0	-0.6	-1.0	-1.3

Table 30. Lake Easy water budget model performance and Historic percentile changes with combinations of SA leakance (SA_K) and UFA leakance (UFA_K) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

SA_K UFA_K	x 1/10 x 1/10	x 1/5 x 1/5	x 1/2 x 1/2	x 1 x 1	x 2 x 2	x 5 x 5	x 10 x 10
P10 (ft)	2.1	1.6	0.8	0.1	0.2	0.2	0.2
P50 (ft)	2.5	1.4	0.3	0.0	0.1	0.2	0.3
P90 (ft)	2.6	1.5	0.6	0.3	0.2	0.0	-0.2
MAE (ft)	2.30	1.39	0.42	0.24	0.21	0.28	0.33
RMSE (ft)	2.41	1.50	0.61	0.34	0.26	0.35	0.42
NSE	-1.28	0.11	0.85	0.95	0.97	0.95	0.93
PBIAS	0.02	0.01	0.00	0.00	0.00	0.00	0.00
RSR	1.51	0.94	0.38	0.22	0.16	0.22	0.27
R^2	0.69	0.77	0.89	0.95	0.97	0.96	0.94
ΔHP10	1.7	1.3	0.6	0.0	0.0	0.1	0.1
ΔHP50	1.9	1.1	0.2	0.0	0.0	0.2	0.3
ΔHP90	1.8	1.0	0.2	0.0	-0.1	-0.3	-0.5

Table 31. Lake Marion water budget model performance and Historic percentile changes with combinations of SA leakance (SA_K) and UFA leakance (UFA_K) modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

SA_K UFA_K	x 1/10 x 1/10	x 1/5 x 1/5	x 1/2 x 1/2	x 1 x 1	x 2 x 2	x 5 x 5	x 10 x 10
P10 (ft)	2.3	1.5	0.5	-0.4	-0.7	-1.1	NA
P50 (ft)	3.5	2.2	0.9	0.0	-0.7	-1.1	NA
P90 (ft)	3.8	3.0	1.4	0.4	-0.5	-1.3	NA
MAE (ft)	3.39	2.33	1.00	0.40	0.86	1.65	NA
RMSE (ft)	3.83	2.68	1.21	0.51	1.06	2.54	NA
NSE	-1.47	-0.21	0.76	0.96	0.81	-0.08	NA
PBIAS	0.07	0.05	0.02	0.00	-0.01	-0.02	NA
RSR	1.57	1.10	0.49	0.21	0.44	1.04	NA
R^2	0.48	0.70	0.91	0.96	0.90	0.45	NA
ΔHP10	2.6	1.8	0.8	0.0	-0.3	-0.7	NA
ΔHP50	3.4	2.2	0.9	0.0	-0.6	-1.2	NA
ΔHP90	3.3	2.5	1.0	0.0	-1.0	-1.7	NA

4.2.8 Groundwater levels

Groundwater levels (`SA` and `UFA` in Cameron et al., 2022) were adjusted at ± 0.5, 1, and 2 feet for the SA, at ± 1, 2, and 5 feet for the SA and UFA, individually and together. Water budget models were sensitive to groundwater level modifications (Table 32 to 34). For SA water level modification, Lake Easy's water budget model was more sensitive, while less sensitive for the Lakes Alice and Marion models. Lake Easy's model showed lower sensitivity to UFA water level modifications than to SA water level modifications. Lake Alice and Marion's models were slightly less sensitive to UFA water level modifications than SA water level modifications (Table 35 to 37). For the combined SA and UFA water level modification, Lake Easy's water budget model was the most sensitive (Tables 38 to 40). Hydrographs and scatter plots of observed versus trial lake stages were generated for each trial [insert link to model files here].

The lakes' differing sensitivity to groundwater level modifications can be explained similarly to sensitivity to leakance coefficient modifications. SA inflow accounted for a much higher percentage of total inflow in the Lake Easy model than Lake Alice or Lake Marion. Therefore, higher sensitivity to SA water level change was expected for Lake Easy's model. For UFA water level change, Lake Alice's UFA leakance coefficient was within the same magnitude as SA leakance coefficient, while Lake Easy's UFA leakance coefficient is one magnitude smaller than SA leakance coefficient. When groundwater levels were changed, a higher model leakance resulted in larger changes in lake water levels. The situation is different for Lake Marion, as both inflow and outflow from SA and UFA occurred during the modeling period. When SA or UFA water levels were modified, the ratio of inflow to outflow changed. Although Lake Marion's UFA leakance coefficient was one magnitude smaller than SA leakance coefficient, the UFA water level modification was greater than for the SA. This combination of factors resulted in Lake Marion's model being slightly less sensitive to UFA than SA water level modifications.

Table 32. Lake Alice water budget model performance and Historic percentile changes with SA water level modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

SA Head	-2'	-1'	-0.5'	0'	+0.5'	+1'	+2'
P10 (ft)	-0.4	-0.1	0.0	0.1	0.2	0.3	0.4
P50 (ft)	-1.1	-0.4	-0.2	0.0	0.2	0.5	0.8
P90 (ft)	-1.0	-0.4	-0.1	0.2	0.5	0.8	1.4
MAE (ft)	0.88	0.57	0.51	0.52	0.58	0.68	0.95
RMSE (ft)	1.05	0.73	0.65	0.66	0.75	0.90	1.25
NSE	0.79	0.90	0.92	0.92	0.89	0.85	0.71
PBIAS	-0.02	-0.01	0.00	0.00	0.01	0.01	0.02
RSR	0.45	0.31	0.28	0.29	0.32	0.39	0.54
R^2	0.93	0.93	0.93	0.92	0.91	0.90	0.86
ΔHP10	-0.4	-0.2	0.0	0.0	0.1	0.2	0.3
ΔHP50	-0.8	-0.4	-0.2	0.0	0.2	0.3	0.5
ΔHP90	-1.3	-0.7	-0.3	0.0	0.3	0.6	1.2

Table 33. Lake Easy water budget model performance and Historic percentile changes with SA water level modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

SA Head	-2’	-1’	-0.5’	0’	+0.5’	+1’	+2’
P10 (ft)	1.8	0.9	0.6	0.1	-0.2	-0.4	-0.9
P50 (ft)	1.6	0.8	0.4	0.0	-0.4	-0.8	-1.6
P90 (ft)	2.0	1.1	0.7	0.3	-0.1	-0.5	-1.3
MAE (ft)	1.67	0.87	0.49	0.24	0.41	0.76	1.54
RMSE (ft)	1.71	0.93	0.58	0.34	0.48	0.82	1.59
NSE	-0.15	0.66	0.87	0.95	0.91	0.74	0.01
PBIAS	0.016	0.008	0.004	0.00	-0.003	-0.007	-0.015
RSR	1.07	0.59	0.36	0.22	0.30	0.51	1.00
R^2	0.95	0.95	0.95	0.95	0.95	0.95	0.95
ΔHP10	1.6	0.8	0.4	0.0	-0.4	-0.5	-1.1
ΔHP50	1.6	0.8	0.4	0.0	-0.5	-0.9	-1.7
ΔHP90	1.6	0.8	0.4	0.0	-0.4	-0.8	-1.6

Table 34. Lake Marion water budget model performance and Historic percentile changes with SA water level modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

SA Head	-2’	-1’	-0.5’	0’	+0.5’	+1’	+2’
P10 (ft)	-1.2	-0.8	-0.6	-0.4	-0.1	0.2	0.7
P50 (ft)	-0.7	-0.3	-0.1	0.0	0.2	0.3	0.7
P90 (ft)	-0.3	0.0	0.2	0.4	0.6	0.7	1.2
MAE (ft)	0.86	0.55	0.44	0.40	0.43	0.55	0.92
RMSE (ft)	0.99	0.68	0.56	0.51	0.55	0.66	1.02
NSE	0.83	0.92	0.95	0.96	0.95	0.93	0.82
PBIAS	-0.02	-0.01	0.00	0.00	0.00	0.01	0.02
RSR	0.41	0.28	0.23	0.21	0.22	0.27	0.42
R^2	0.94	0.95	0.95	0.96	0.96	0.96	0.96
ΔHP10	-0.9	-0.4	-0.2	0.0	0.3	0.5	1.1
ΔHP50	-0.7	-0.3	-0.1	0.0	0.2	0.3	0.7
ΔHP90	-0.8	-0.4	-0.3	0.0	0.2	0.3	0.7

Table 35. Lake Alice water budget model performance and Historic percentile changes with UFA water level modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

UFA Head	-5’	-2’	-1’	0’	+1’	+2’	+5’
P10 (ft)	-0.2	-0.1	0.0	0.1	0.1	0.2	0.3
P50 (ft)	-0.7	-0.2	-0.1	0.0	0.1	0.3	0.6
P90 (ft)	-0.6	-0.1	0.0	0.2	0.4	0.5	1.0
MAE (ft)	0.66	0.52	0.51	0.52	0.54	0.59	0.78
RMSE (ft)	0.83	0.66	0.65	0.66	0.70	0.76	1.02
NSE	0.87	0.92	0.92	0.92	0.91	0.89	0.80
PBIAS	-0.01	0.00	0.00	0.00	0.00	0.01	0.02
RSR	0.36	0.28	0.28	0.29	0.30	0.33	0.44
R^2	0.93	0.93	0.92	0.92	0.91	0.91	0.88
ΔHP10	-0.3	-0.1	0.0	0.0	0.0	0.1	0.2
ΔHP50	-0.6	-0.3	-0.1	0.0	0.1	0.2	0.4
ΔHP90	-0.9	-0.4	-0.2	0.0	0.2	0.4	0.8

Table 36. Lake Easy water budget model performance and Historic percentile changes with UFA water level modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

UFA Head	-5’	-2’	-1’	0’	+1’	+2’	+5’
P10 (ft)	1.0	0.5	0.3	0.1	0.0	-0.2	-0.4
P50 (ft)	0.8	0.3	0.2	0.0	-0.2	-0.3	-0.8
P90 (ft)	1.1	0.7	0.5	0.3	0.2	0.0	-0.5
MAE (ft)	0.87	0.41	0.29	0.24	0.28	0.36	0.76
RMSE (ft)	0.93	0.51	0.41	0.34	0.36	0.43	0.82
NSE	0.66	0.90	0.94	0.95	0.95	0.93	0.74
PBIAS	0.008	0.004	0.002	0.00	-0.001	-0.002	-0.007
RSR	0.59	0.32	0.25	0.22	0.22	0.27	0.51
R^2	0.95	0.95	0.95	0.95	0.95	0.95	0.95
ΔHP10	0.8	0.3	0.2	0.0	-0.2	-0.3	-0.5
ΔHP50	0.8	0.3	0.1	0.0	-0.2	-0.4	-0.9
ΔHP90	0.8	0.3	0.2	0.0	-0.2	-0.3	-0.8

Table 37. Lake Marion water budget model performance and Historic percentile changes with UFA water level modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

UFA Head	-5’	-2’	-1’	0’	+1’	+2’	+5’
P10 (ft)	-1.1	-0.7	-0.5	-0.4	-0.2	0.0	0.5
P50 (ft)	-0.6	-0.2	-0.1	0.0	0.1	0.2	0.6
P90 (ft)	-0.2	0.1	0.2	0.4	0.6	0.7	1.0
MAE (ft)	0.75	0.47	0.42	0.40	0.41	0.46	0.78
RMSE (ft)	0.88	0.60	0.54	0.51	0.53	0.58	0.89
NSE	0.87	0.94	0.95	0.96	0.95	0.94	0.87
PBIAS	-0.01	-0.01	0.00	0.00	0.00	0.01	0.02
RSR	0.36	0.25	0.22	0.21	0.22	0.24	0.37
R^2	0.94	0.95	0.95	0.96	0.96	0.96	0.96
ΔHP10	-0.7	-0.3	-0.1	0.0	0.2	0.4	0.9
ΔHP50	-0.6	-0.2	-0.1	0.0	0.1	0.2	0.6
ΔHP90	-0.6	-0.3	-0.2	0.0	0.1	0.2	0.6

Table 38. Lake Alice water budget model performance and Historic percentile changes with combinations of SA and UFA water level modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

SA Head	-2’	-1’	-0.5’	0’	+0.5’	+1’	+2’
UFA Head	-5’	-2	-1’	0’	+1’	+2’	+5’
P10 (ft)	-0.8	-0.3	-0.1	0.1	0.2	0.3	0.6
P50 (ft)	-1.9	-0.8	-0.3	0.0	0.3	0.7	1.2
P90 (ft)	-1.8	-0.7	-0.3	0.2	0.7	1.1	2.2
MAE (ft)	1.52	0.71	0.54	0.52	0.63	0.82	1.36
RMSE (ft)	1.67	0.89	0.69	0.66	0.83	1.09	1.76
NSE	0.48	0.85	0.91	0.92	0.87	0.78	0.43
PBIAS	-0.04	-0.02	-0.01	0.00	0.01	0.02	0.03
RSR	0.72	0.38	0.30	0.29	0.36	0.47	0.76
R^2	0.92	0.93	0.93	0.92	0.90	0.88	0.78
ΔHP10	-0.7	-0.3	-0.1	0.0	0.1	0.2	0.4
ΔHP50	-1.5	-0.6	-0.3	0.0	0.3	0.5	0.7
ΔHP90	-2.2	-1.0	-0.5	0.0	0.5	0.9	1.8

Table 39. Lake Easy water budget model performance and Historic percentile changes with combinations of SA and UFA water level modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

SA Head	-2’	-1’	-0.5’	0’	+0.5’	+1’	+2’
UFA Head	-5’	-2	-1’	0’	+1’	+2’	+5’
P10 (ft)	2.6	1.3	0.7	0.1	-0.3	-0.6	-1.6
P50 (ft)	2.4	1.1	0.6	0.0	-0.6	-1.1	-2.4
P90 (ft)	2.8	1.5	0.9	0.3	-0.2	-0.8	-2.1
MAE (ft)	2.47	1.19	0.64	0.24	0.54	1.07	2.34
RMSE (ft)	2.51	1.24	0.71	0.34	0.61	1.12	2.37
NSE	-1.47	0.40	0.80	0.95	0.85	0.51	-1.22
PBIAS	0.024	0.011	0.006	0.00	-0.005	-0.010	-0.02
RSR	1.57	0.78	0.45	0.22	0.38	0.70	1.49
R^2	0.94	0.95	0.95	0.95	0.95	0.95	0.94
ΔHP10	2.4	1.1	0.6	0.0	-0.4	-0.7	-1.8
ΔHP50	2.4	1.1	0.5	0.0	-0.6	-1.2	-2.5
ΔHP90	2.4	1.1	0.6	0.0	-0.6	-1.1	-2.5

Table 40. Lake Marion water budget model performance and Historic percentile changes with combinations of SA and UFA water level modification. The green shade indicates the original model calibration. The red shade indicates where model performance does not meet the calibration goal.

SA Head	-2’	-1’	-0.5’	0’	+0.5’	+1’	+2’
UFA Head	-5’	-2	-1’	0’	+1’	+2’	+5’
P10 (ft)	-1.8	-1.1	-0.7	-0.4	0.1	0.5	1.5
P50 (ft)	-1.3	-0.6	-0.2	0.0	0.3	0.6	1.5
P90 (ft)	-0.9	-0.2	0.1	0.4	0.7	1.0	2.1
MAE (ft)	1.42	0.75	0.51	0.40	0.50	0.78	1.70
RMSE (ft)	1.57	0.88	0.64	0.51	0.62	0.89	1.78
NSE	0.59	0.87	0.93	0.96	0.94	0.87	0.47
PBIAS	-0.03	-0.01	-0.01	0.00	0.01	0.02	0.03
RSR	0.64	0.36	0.26	0.21	0.25	0.37	0.73
R^2	0.91	0.94	0.95	0.96	0.96	0.96	0.95
ΔHP10	-1.4	-0.7	-0.4	0.0	0.5	0.9	1.9
ΔHP50	-1.3	-0.6	-0.2	0.0	0.3	0.6	1.5
ΔHP90	-1.3	-0.6	-0.4	0.0	0.2	0.6	1.6

4.3 Verification Tests

4.3.1 Lake Alice

Lake Alice’s water budget model was verified for the period of 7/20/2017 to 4/30/2021, with data obtained from the sources used for the original model (Cameron and Hancock, 2017). All performance metrics met the calibration goal, with several metrics (P10, P90, MAE, and PBIAS) performing better than the original calibration period (Table 41 and Figures 8).

Table 41. Lake Alice water budget model verification test performance.

Metric	Performance
P10 (ft)	0.2
P50 (ft)	-0.1
P90 (ft)	0.0
MAE (ft)	0.17
RMSE (ft)	0.24
NSE	0.84
PBIAS	0.001
RSR	0.41
R^2	0.88

4.3.2 Lake Easy

Lake Easy’s water budget model was verified for the period of 1/1/2017 to 4/30/2021, with data obtained from the sources used for the original model (Smith and Patterson, 2019). All performance metrics met the calibration goal, with several metrics (NSE, RSR, and R^2) performing better than the original calibration period (Table 42 and Figures 9).

Table 42. Lake Easy water budget model verification test performance.

Metric	Performance
P10 (ft)	-0.3
P50 (ft)	0.0
P90 (ft)	0.3
MAE (ft)	0.25
RMSE (ft)	0.36
NSE	0.96
PBIAS	0.00
RSR	0.20
R^2	0.96

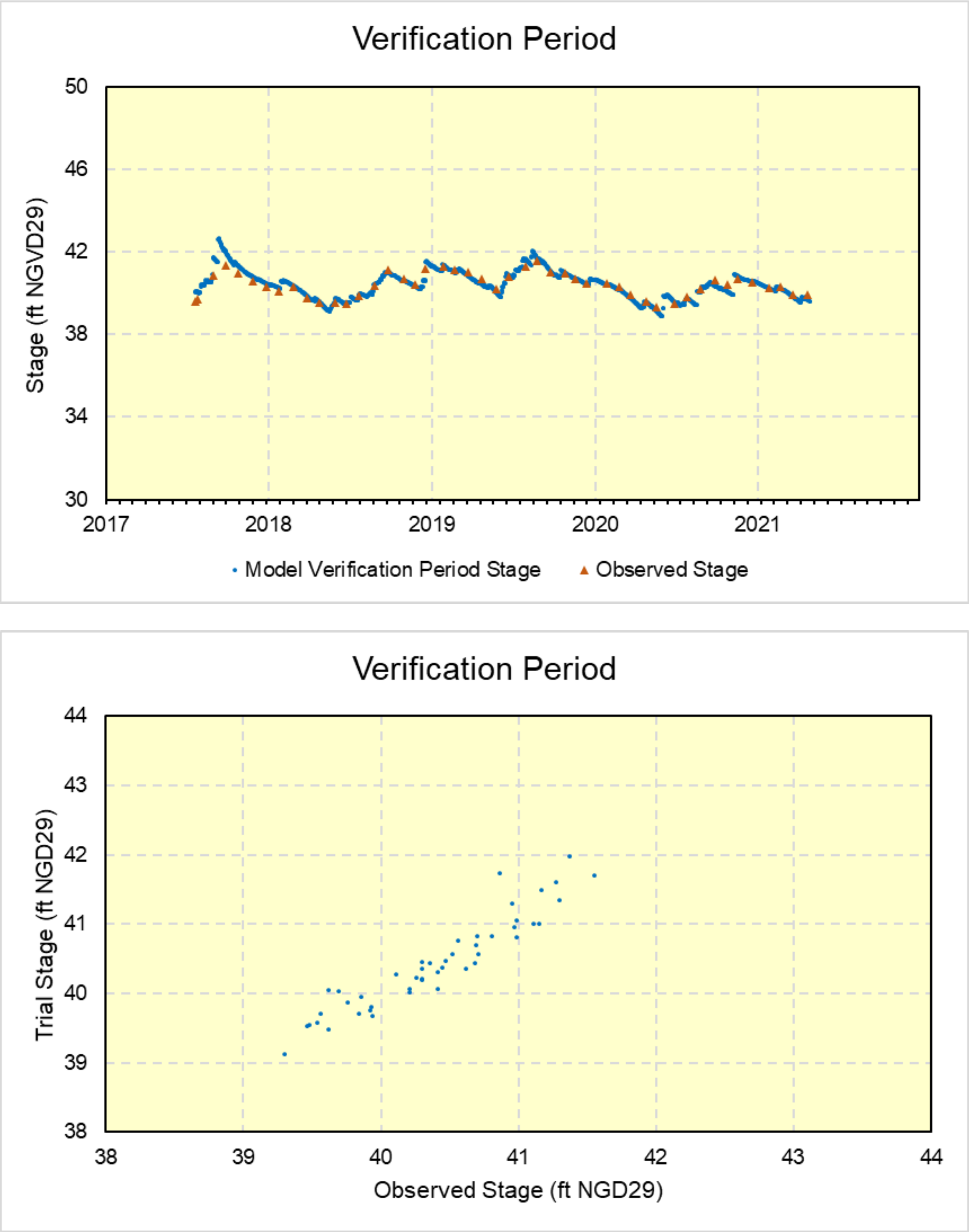


Figure 8. Time series (top) and scatter plot (bottom) showing modeled ("trial") versus observed water levels for the Lake Alice water budget model verification period.

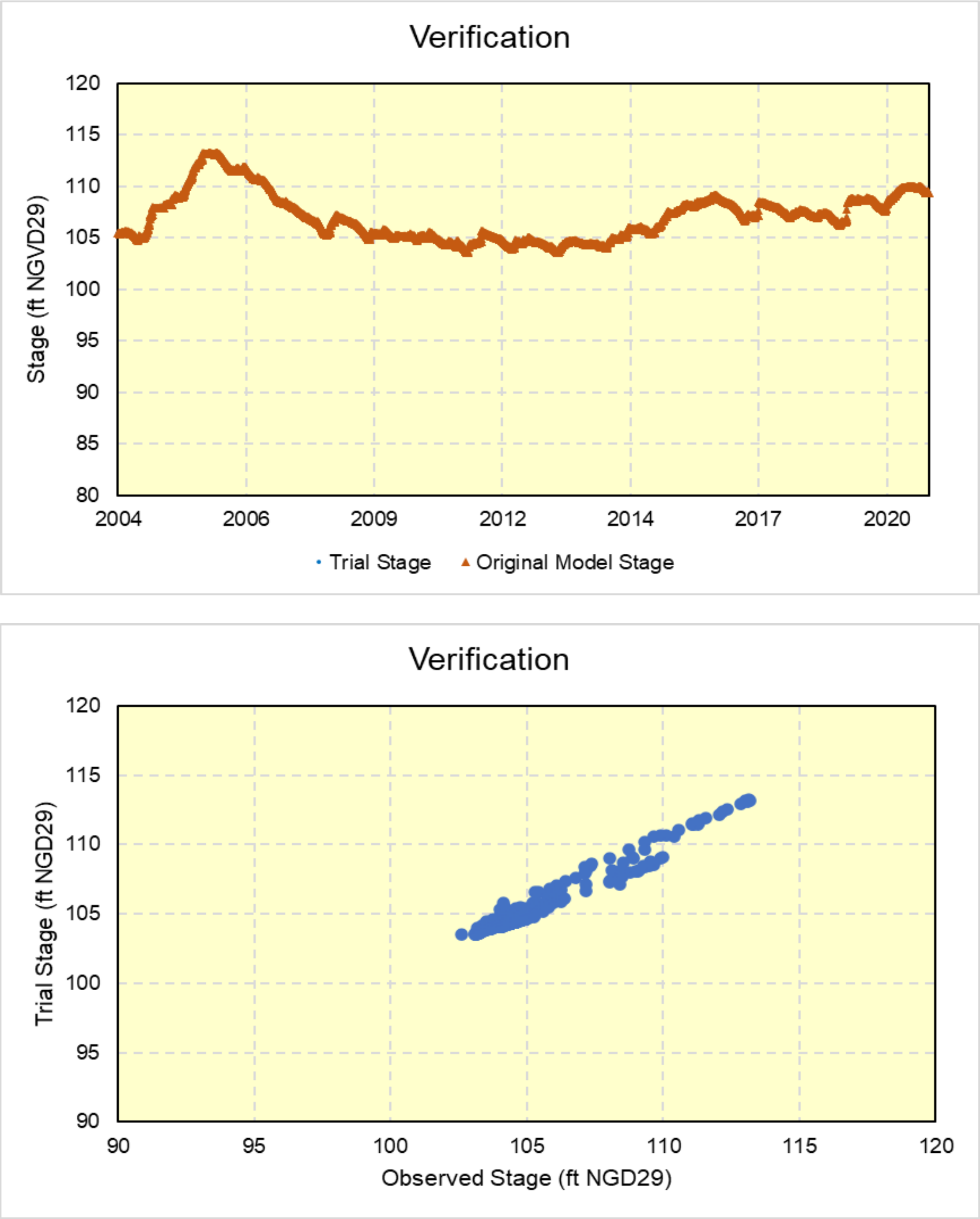


Figure 9. Lake Easy water budget model verification test hydrograph and scatter plot for trial stage vs observed stage.

4.3.3 Lake Marion

Lake Marion’s water budget model was verified for the period of 3/29/2019 to 4/30/2021, with data obtained from the sources used for the original model (Cameron and Ellison, 2020). All performance metrics met the calibration goal, with several metrics (P90, MAE, RMSE, RSR, and R^2) performing better than the original calibration period (Table 43 and Figures 10).

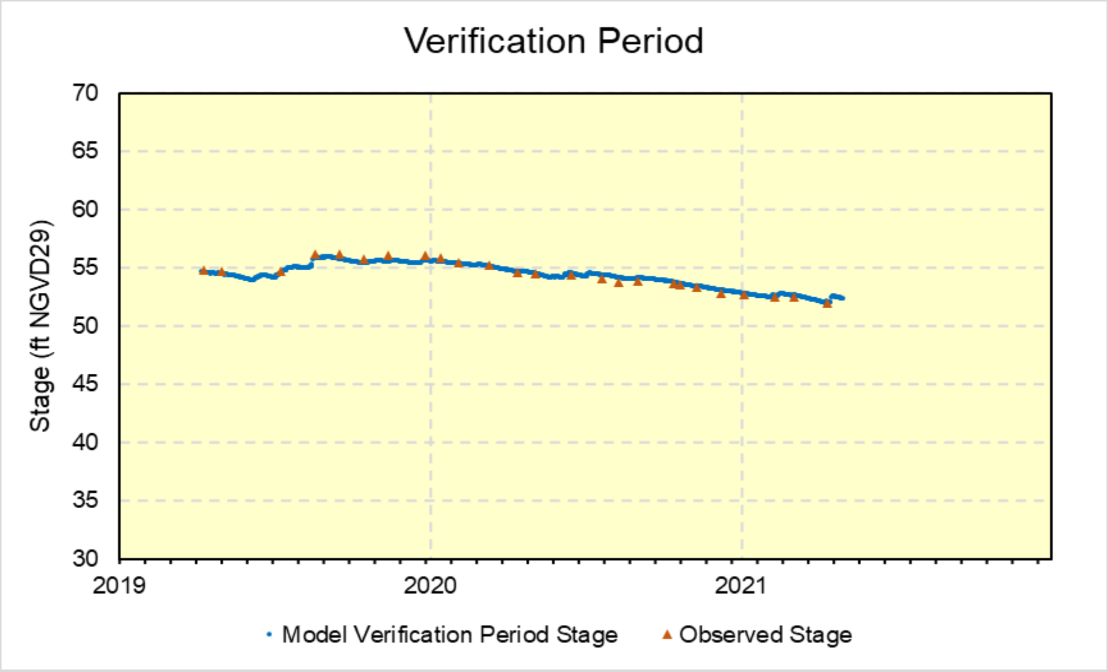
Table 43. Lake Marion water budget model verification test performance.

Metric	Performance
P10 (ft)	-0.4
P50 (ft)	0.0
P90 (ft)	0.1
MAE (ft)	0.22
RMSE (ft)	0.26
NSE	0.96
PBIAS	0.00
RSR	0.20
R^2	0.98

4.4 Non-Uniqueness Tests

4.4.1 Lake Alice

Five alternative parameterizations were developed that provide performance comparable to the original, calibrated parameterizations for the Lake Alice water budget model. SA and UFA leakance coefficients were modified slightly in alternate trials 1, 2, and 3, and were changed on the scale of magnitude in alternate trials 4 and 5 (Table 44). In alternate trial 1, SA leakance coefficient was lowered. To compensate for reduced SA inflow, UFA leakance coefficient was lowered. The outflow coefficient was increased to allow more outflow. CN was increased to allow more runoff. In alternate trial 2, SA leakance coefficient was increased. To compensate for increased SA inflow, UFA leakance coefficient was increased. CN was decreased to reduce runoff. In alternate trial 3, both SA and UFA leakance coefficients were decreased. CN was increased to allow more runoff. UFA water level was lowered 1 ft to allow more UFA outflow. In alternate trial 4, both SA and UFA leakance coefficients were increased at or over one magnitude. The outflow coefficient was increased by one magnitude to allow more outflow. SA and UFA water levels were adjusted to balance the water budget. Although the performance metrics were met for alternate trial 4, the hydrograph was much flashier than the original calibration and observed lake levels. Historic percentiles changed significantly. In alternate trial 5, SA water level was lowered by 3 ft. SA leakance was reduced to decrease SA inflow. The outflow coefficient was increased one magnitude to allow more outflow. Historic percentiles changed significantly.



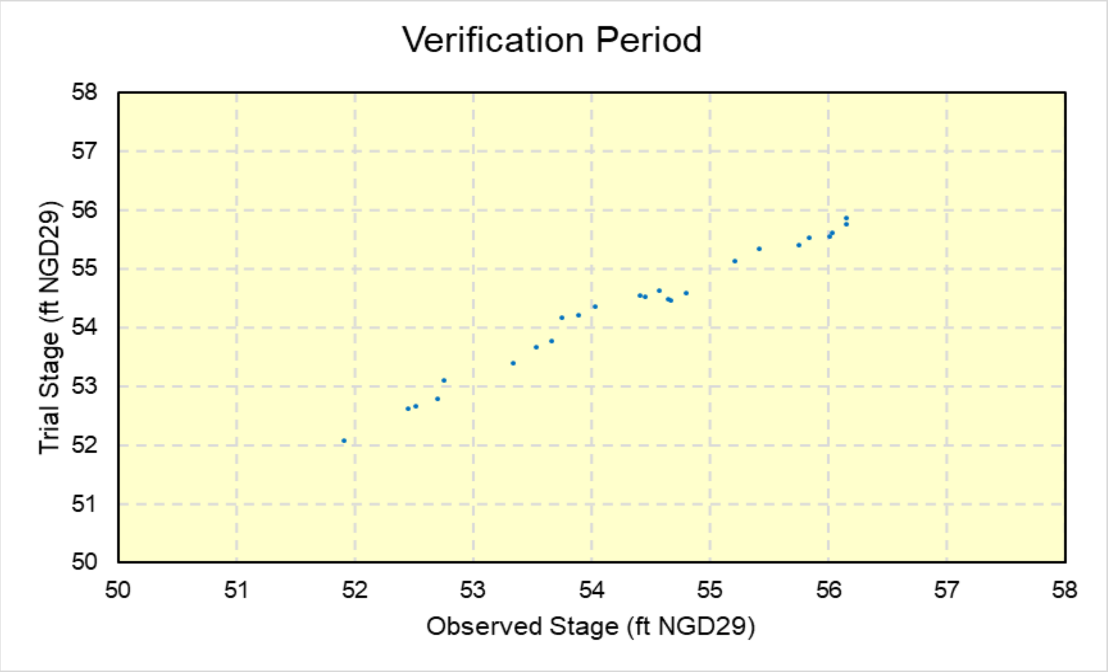


Figure 10. Time series (top) and scatter plot (bottom) showing modeled (“trial”) versus observed water levels for the Lake Marion water budget model verification period.

Table 44. Lake Alice water budget model alternate parameters and calibration performance.

(1) Alternate Parameters

Parameter	Original	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5
SA K (1/day)	0.0020	0.0015	0.0025	0.0015	0.02	0.0007
		0.0005		0.0005		0.0005
UFA K (1/day)	0.0005	0	0.00060	2	0.0015	5
Outflow K (1/day)	0.022	0.030	0.022	0.022	0.22	0.22
Watershed Area (area)	301.2	301.2	301.2	301.2	301.2	301.2
SCS CN	73	74	72	75	73	73
DCIA	0	0	0	0	0	0
SA Head Adjustment (ft)	0	0	0	0	1	-3
UFA Head Adjustment (ft)	0	0	0	-1	-1	0

(2) Performance

Metric	Original	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5
P10 (ft)	0.1	0.0	0.0	0.0	-0.1	0.1
P50 (ft)	0.0	0.0	0.0	-0.1	-0.1	0.0
P90 (ft)	0.2	0.3	0.1	0.2	0.0	0.4
MAE (ft)	0.52	0.52	0.53	0.51	0.9	0.50
RMSE (ft)	0.66	0.67	0.67	0.65	1.1	0.67
NSE	0.92	0.92	0.92	0.92	0.8	0.92
PBIAS	0.00	0.00	0.00	0.00	0.0	0.00
RSR	0.29	0.29	0.29	0.28	0.5	0.29
R^2	0.92	0.92	0.92	0.92	0.8	0.92
ΔHP10	0.0	-0.1	0.0	0.0	-0.4	-0.22
ΔHP50	0.0	-0.1	-0.1	-0.1	-0.9	-0.79
ΔHP90	0.0	0.1	-0.1	0.0	-2.1	-1.62

4.4.2 Lake Easy

Three alternative parameterizations were developed that provided performance comparable to the original, calibrated parameterizations for the Lake Easy water budget model (Table 45). In alternate trial 1, SA and UFA leakance coefficients were reduced at or over one magnitude. CN was increased to allow more runoff. DCIA was lowered to reduce DCIA flow. Although the model performance goal was met, the trial hydrograph did not capture the highs and lows of the observed lake levels. In alternate trial 2, SA leakance coefficient was lowered by about one magnitude and UFA leakance was reduced by 20 times. CN was increased to allow more runoff. This trial model performed better than alternate trial 1 on all performance metrics, except P10, however, still failed to capture the highs and lows of the observed lake levels. In alternate trial 3, SA and UFA leakance coefficients were both increased slightly. CN was increased to allow more runoff. Although the P10 and P90 did not perform as well as alternate trial1, this trial model was able to capture the observed hydrograph and there was no significant change to historic percentiles.

Table 45. Lake Easy water budget model alternate parameters and calibration performance.

(1) Alternate Parameters

Parameter	Original	Alternate 1	Alternate 2	Alternate 3
SA K (1/day)	0.002800	0.000200	0.000300	0.003200
UFA K (1/day)	0.000550	0.000055	0.000275	0.000720
Outflow K (1/day)	0	0	0	0
Watershed Area (area)	1247	1247	1247	1247
SCS CN	47	49	55	55
DCIA	0.05	0	0.05	0.05
SA Head Adjustment (ft)	3.4	3.4	3.4	3.4
UFA Head Adjustment (ft)	0	0	0	0

(2) Performance

Metric	Original	Alternate 1	Alternate 2	Alternate 3
P10 (ft)	0.1	0.0	0.4	0.2
P50 (ft)	0.0	0.0	0.0	0.0
P90 (ft)	0.3	0.0	0.0	0.3
MAE (ft)	0.24	0.68	0.58	0.22
RMSE (ft)	0.34	0.93	0.74	0.31
NSE	0.95	0.66	0.79	0.96
PBIAS	0.001	0.00	-0.001	0.00
RSR	0.22	0.59	0.46	0.19
R^2	0.95	0.68	0.79	0.96
ΔHP10	0.0	-0.2	0.6	0.1
ΔHP50	0.0	-0.2	0.4	0.0
ΔHP90	0.0	-0.4	0.1	0.0

4.4.3 Lake Marion

Three alternative parameterizations were developed that provided performance comparable to the original, calibrated parameterizations for the Lake Marion water budget model (Table 46). In alternate trial 1, SA leakance coefficient was lowered slightly and UFA leakance coefficient was increased slightly. CN was lowered to reduce runoff. SA water level was raised by 2 ft to allow more SA inflow. In alternate trial 2, SA leakance coefficient was lowered, the same value as in alternate trial 1. UFA leakance coefficient was increased higher than alternate trial 1. CN was lowered to the same value as alternate trial 1. SA water level was raised by 3 ft to allow more SA inflow. In alternate trial 3, SA leakance coefficient was unchanged, while UFA leakance coefficient was decreased by over one magnitude. To compensate for increased outflow to UFA, the watershed area was increased to allow more inflow. CN was increased to allow more runoff. And SA water level was increased to allow more SA flow. The scatter plot comparing this trial model to the original model stage was more spread out than alternate trials 1 and 2.

Table 46. Lake Marion water budget model alternate parameters and calibration performance.

(1) Alternate Parameters

Metric	Original	Alternate 1	Alternate 2	Alternate 3
SA K (1/day)	0.0015	0.001	0.001	0.0015
UFA K (1/day)	0.0005	0.00065	0.00089	0.0015
Outflow K (1/day)	0.012	0.012	0.012	0.012
Watershed Area (area)	138	138	138	145
SCS CN	65	58	58	71
DCIA	0	0	0	0
SA Head Adjustment (ft)	0	2	3	1
UFA Head Adjustment (ft)	0	0	0	0

(2) Performance

Performance	Original	Alternate 1	Alternate 2	Alternate 3
P10 (ft)	-0.1	0.1	0.0	-0.2
P50 (ft)	0.0	0.0	0.0	0.0
P90 (ft)	-0.2	0.3	0.3	0.3
MAE (ft)	0.52	0.40	0.38	0.54
RMSE (ft)	0.66	0.52	0.53	0.71
NSE	0.92	0.96	0.95	0.92
PBIAS	-0.001	0.00	0.00	0.00
RSR	0.29	0.21	0.22	0.29
R^2	0.92	0.96	0.96	0.92
ΔHP10	0.0	0.5	0.3	0.1
ΔHP50	0.0	0.0	0.0	0.0
ΔHP90	0.0	-0.1	-0.1	-0.1

5.0 Summary and Recommendations

Assessed lake water budget models met all calibration goals during original and verification model test periods. Generally, the models were sensitive to modifications in rainfall, evaporation, curve number, aquifer leakance coefficient, and groundwater levels. Lake water budget models were generally less sensitive to modifications in the watershed area, DCIA, and channel outflow coefficient. Of the sensitive parameters, aquifer leakance coefficients and curve numbers present the greatest challenges due to local variability and limited data available to fully characterize these parameters at each lake, leaving a range of plausible values. Variations in sensitivity among lake water budget models were expected and evident during sensitivity tests, due to the unique hydrogeologic setting of each lake.

Alternative parameter combinations that meet calibration goals exist. However, trial models with significant parameter modifications to the original, calibrated model parameters often resulted in unreasonable water budget components or failed to as closely match the lake's observed water levels as the original, calibrated parameter combination.

During model development and documentation, calibration performance metrics should be evaluated along with other aspects of the lake water budget models. Care should be given to ensure lake parameters and associated fluxes fall within a reasonable range and comply with regional hydrogeology. In interpreting model results, the sensitivity and uncertainty of model parameters and inputs should be considered.

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