APPENDIX B — HYDROLOGICAL ANALYSES

INTRODUCTION

In addition to extensive work conducted to understand the ecological structure and function, and most sensitive environmental values of priority waterbodies, assessing the status of minimum flows and levels (MFLs) requires substantial hydrological analysis. Several steps were involved in performing the hydrological analysis, including:

1. Review of available data for compiling long-term datasets;
2. Historical groundwater pumping impact assessment;
3. Development of lake level datasets representing no-pumping and current-pumping conditions; and
4. Estimating available water (freeboard or deficit).

Figure B - 1 shows the flowchart for the hydrological analysis. This document describes the first three steps and associated results. Appendix C includes the description of the last step and associated results.

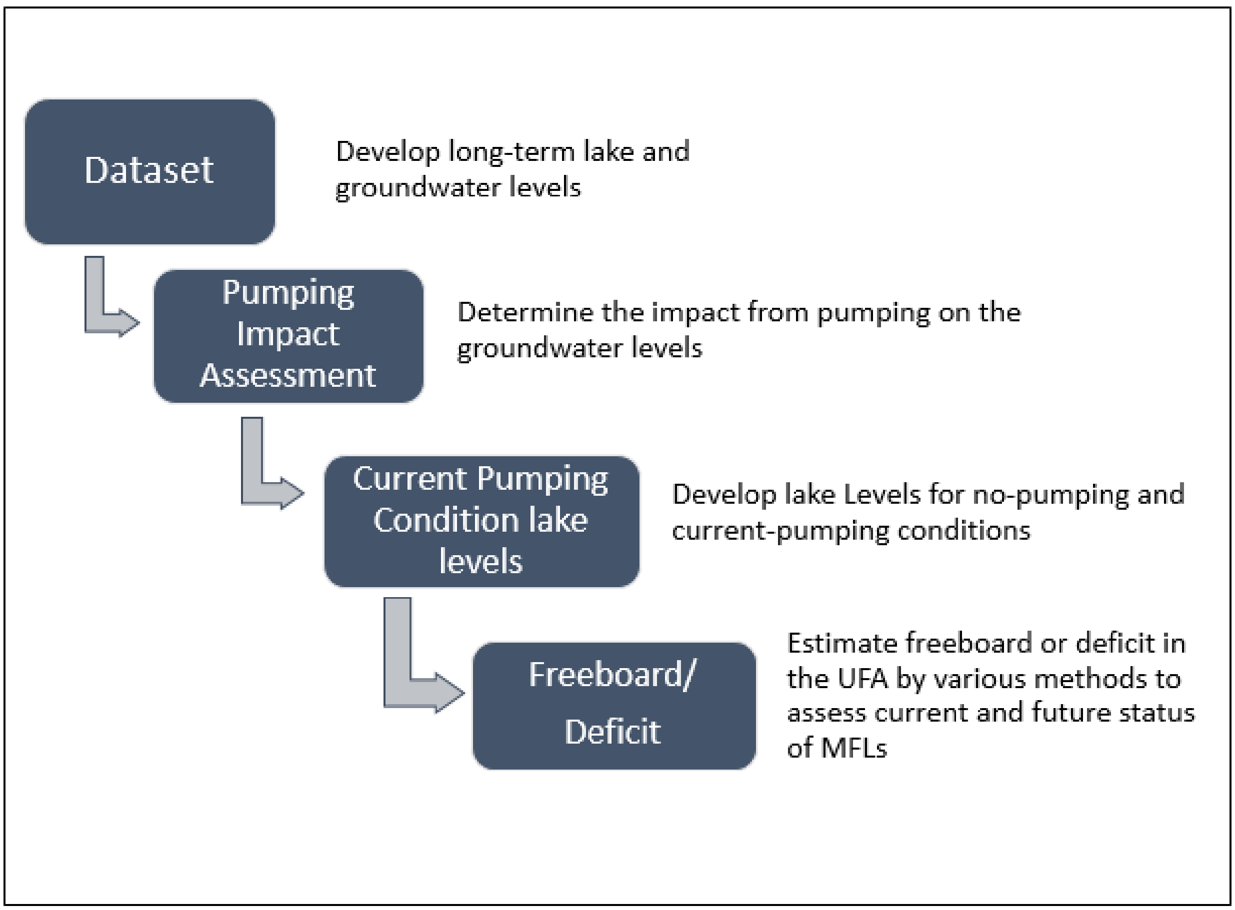

Figure B - 1. Flowchart for hydrological analysis process

BACKGROUND

The Lake Butler Chain (LBC) is located in the City of Deltona, west Volusia County, Florida. The lakes that make up the chain are northeast of the Lake Monroe (Figure B - 2). The LBC watershed boundary is made up of a number of different interconnected lakes that consist of lake Helen, Lake Macy, Lake Colby, Giddings Lake, Sand Lake, Three Island Lake, Angela Lake, Clara Lake, Theresa Lake, Louise Lake, Lake Butler Chain, Lake Doyle, and Savannah Lake (Figure B - 2). These lakes receive water from direct rainfall, surface runoff, baseflow, and inflow from upstream lakes. The lakes primarily lose water through evaporation and seepage into the Upper Floridan Aquifer (UFA), and infrequent outflow to the downstream lakes during high water level conditions (JEA, 2018).

The St. Johns River Water Management District (SJRWMD) contracted with the Jones Edmunds and Associates (JEA) to develop a hydrologic model using the EPA Storm Water Management Model (SWMM) (Rossman, 2015) for the LBC watershed (JEA, 2018). The simulation period for the model was from 1995 to 2016. The final model comprises lakes that are south of the Three Island Lake and consists of 30 sub-watersheds (Figure B - 3). The observed water levels of the Three Island Lake, Big Lake, and Lake Monroe were used as boundary conditions for the SWMM model (JEA, 2018). JEA calibrated the model for the period from 1995 to 2016. This model is hereafter referred as “the original SWMM model”. Subsequently, the SJRWMD updated and extended the original model to the period from 1948 to 2018 in order to estimate long-term lake water levels. The updated model was used to develop lake level datasets representing no-pumping and current-pumping conditions for MFLs status assessments.

Because minimum levels proposed for lake are based on an event-based approach associated with return periods (e.g., the recommended minimum frequent low level should be achieved once every five years, on average), MFLs assessment requires frequency analysis of lake levels. Due to the presence of short- and long-term climatic cycles and variabilities (e.g. El Nino Southern and Atlantic Multidecadal Oscillations), the frequencies of lake levels could be significantly different in wet periods such as in the 1960s than those in dry periods such as in the 2000s. Thus, it is important to perform frequency analysis using long-term lake levels so that the effect of short- and long-term climatic variations on lake levels can be captured.

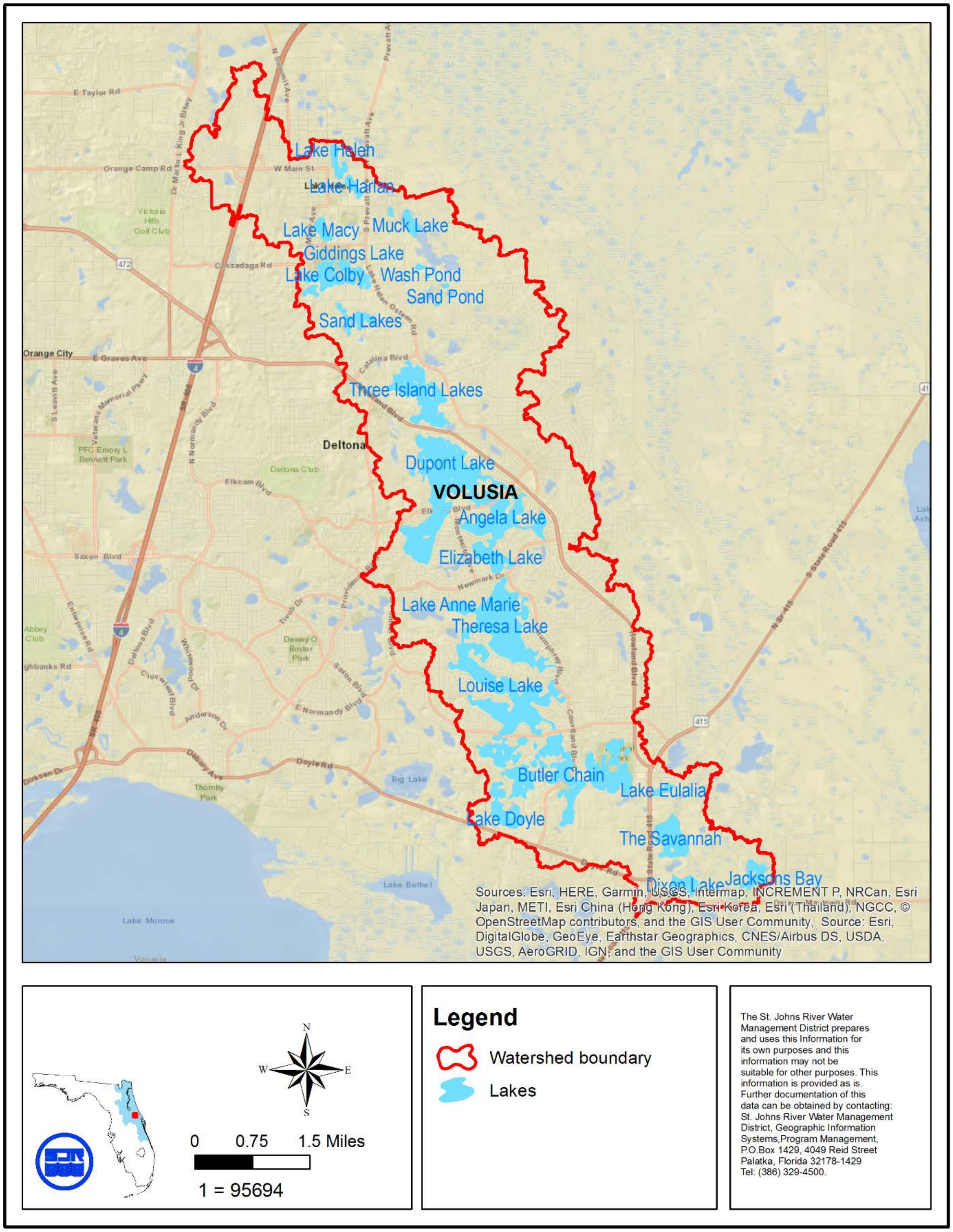

Figure B - 2. The Lake Butler Chain and its watershed boundary

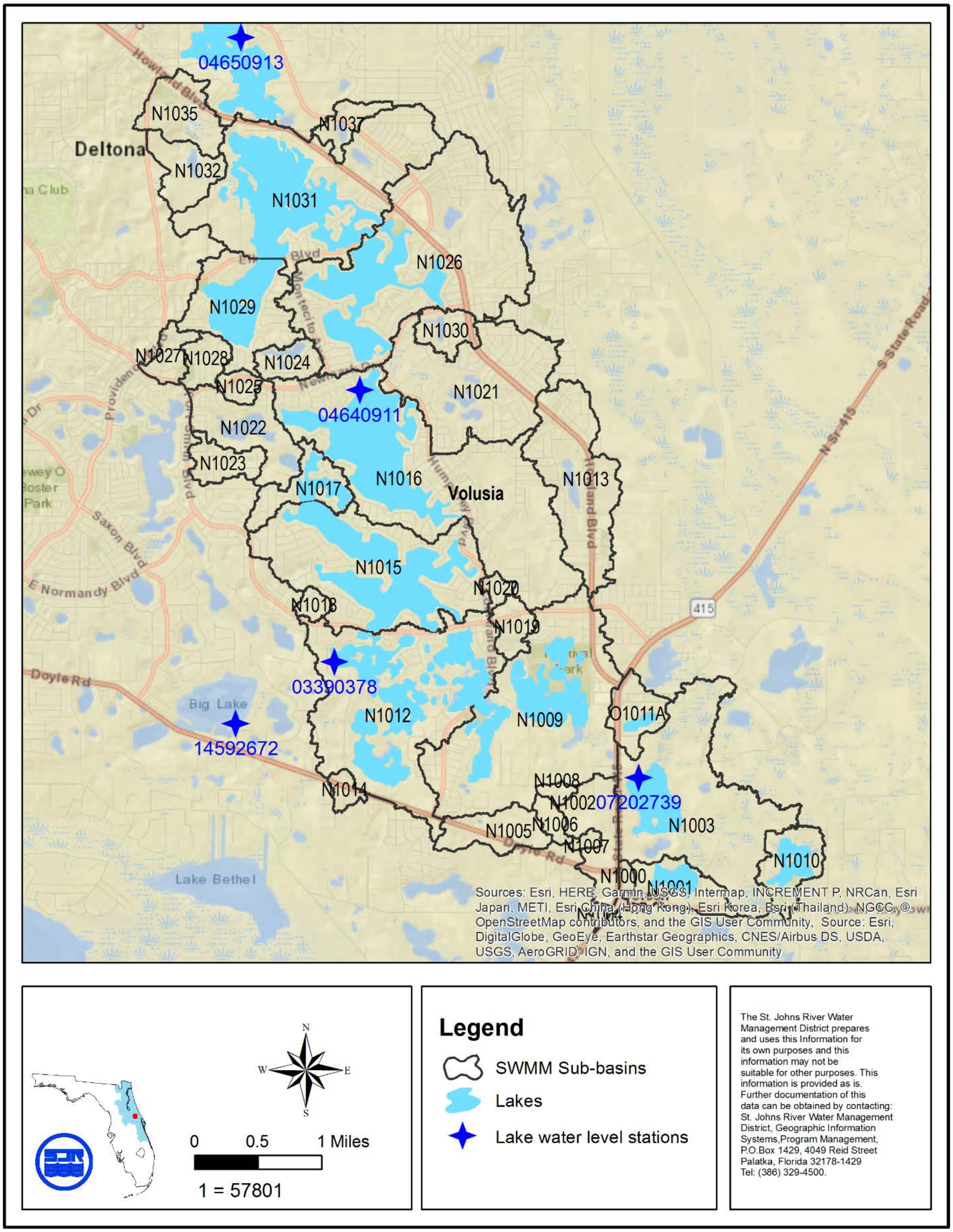

Figure B - 3. The SWMM model sub-basins with their nodes implemented in the model, and lake water level stations

REVIEW OF AVAILABLE DATA

Rainfall and Potential Evapotranspiration (PET)

Within the LBC watershed, there were seven SJRWMD daily rainfall stations (see Figure B - 4). In addition, NEXRAD rainfall data were available for the period from 1995 to the present from the SJRWMD databases. Rainfall data were compiled using the data from SJRWMD rain gauges and NEXRAD for each sub-watershed. Furthermore, two long-term NOAA rainfall stations at Deland and Sanford are in the vicinity of the watershed. Table B - 1 summarizes the rainfall data at all stations. The locations of the stations are shown in Figure B - 4.

Table B - 1: Summary of rainfall stations used in the Lake Butler Chain model

Station Number	Location	Source	Period of Record	Annual Rainfall (in)		
				Minimum	Mean	Maximum
3390379	Butler Lake	SJRWMD	1/06/1990 - 6/19/2002	16.12	51.36	69.35
3432319	Lake Colby	SJRWMD	1/06/1990 - 11/30/1996	38.48	57.01	75.58
3582316	Dupont Lake	SJRWMD	6/18/1992 - 9/30/1996	43.84	59.82	86.06
3800534	Lake Helen	SJRWMD	3/25/2000 - 6/29/2002	24.2	41.6	67.32
4030668	Lake Macy	SJRWMD	4/03/1994 - 6/29/2002	28.3	53.84	69.18
4640912	Theresa Lake	SJRWMD	1/05/1990 - 6/29/2002	26.36	52.17	70.87
4650914	Three Island Lake	SJRWMD	1/05/1990 - 6/29/2002	28.62	56.13	79.15
COOP:082229	DeLand	NOAA	1/01/1914 - 12/31/2018	38.48	55.54	84.03
GHCND:USC0087982	Sanford	NOAA	1/01/1914 - 12/31/2018	32.83	51.96	74.06

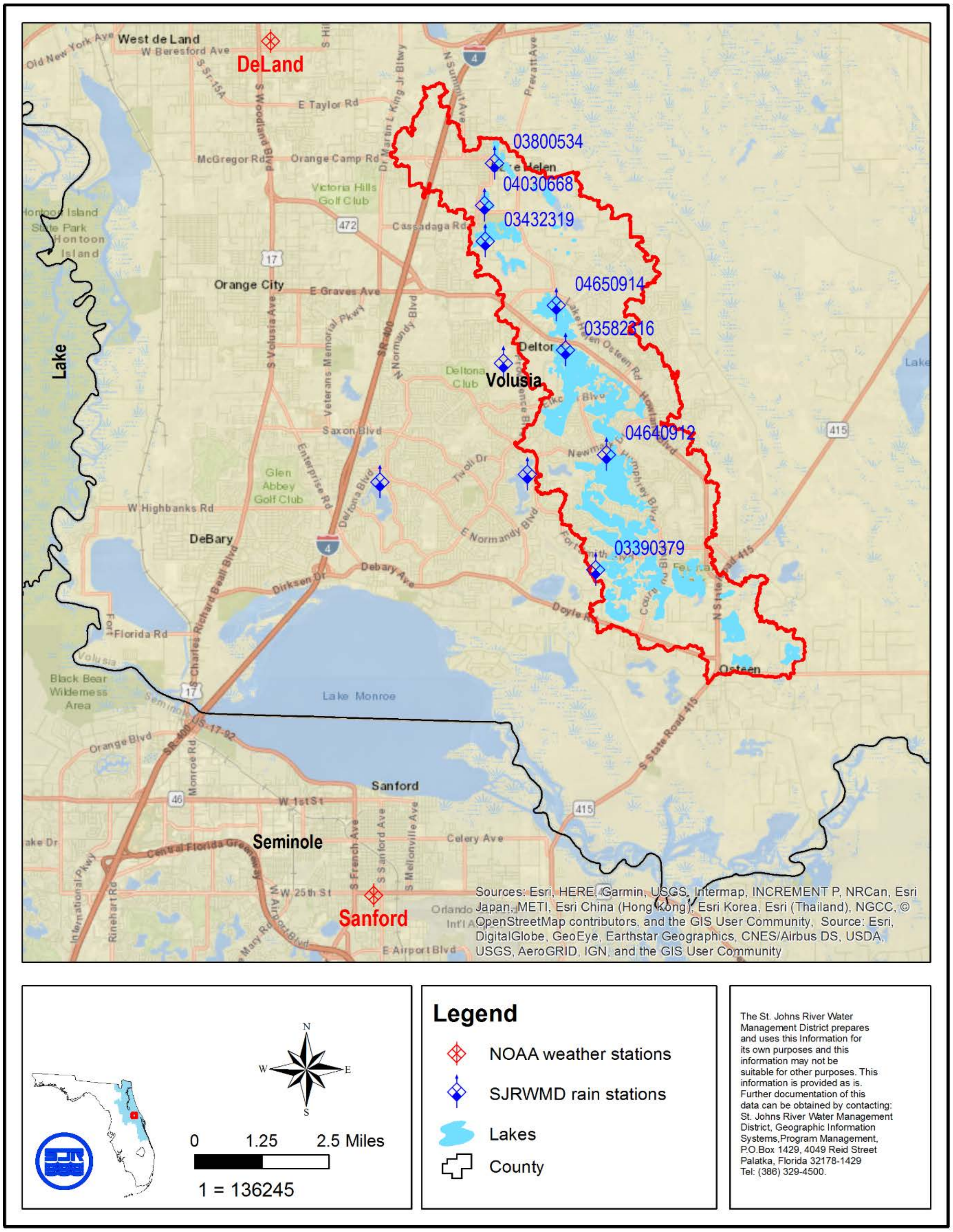

Figure B - 4. Meteorological stations

The original SWMM model used a combined rain gauge and NEXRAD rainfall data for the period from 1/1/1995 to 12/31/2016. The daily rainfall data of the seven SJRWMD rain stations (see Figure B - 4) from 1/1/1995 to 6/30/2002 (Table B - 1) were combined with the NEXRAD hourly rainfall data from 7/1/2002 to 12/31/2016 (JEA, 2018). The daily rain gauge values were disaggregated into hourly data using the Sanford NOAA hourly rainfall data as a reference. The Sanford NOAA station is the closest long-term station to the watershed. Therefore, for the long-term lake levels simulation, the Sanford hourly rainfall data from 1/1/1948 to 12/31/1994 and 1/1/2017 to 12/31/2018 were used to extend the rainfall data of the original SWMM model for each 30 sub-watersheds of the model. The result is a composite hourly rainfall data for the period from 1/1/1948 to 12/31/2018. Figure B - 5 shows the composite annual rainfall data of the LBC for this period.

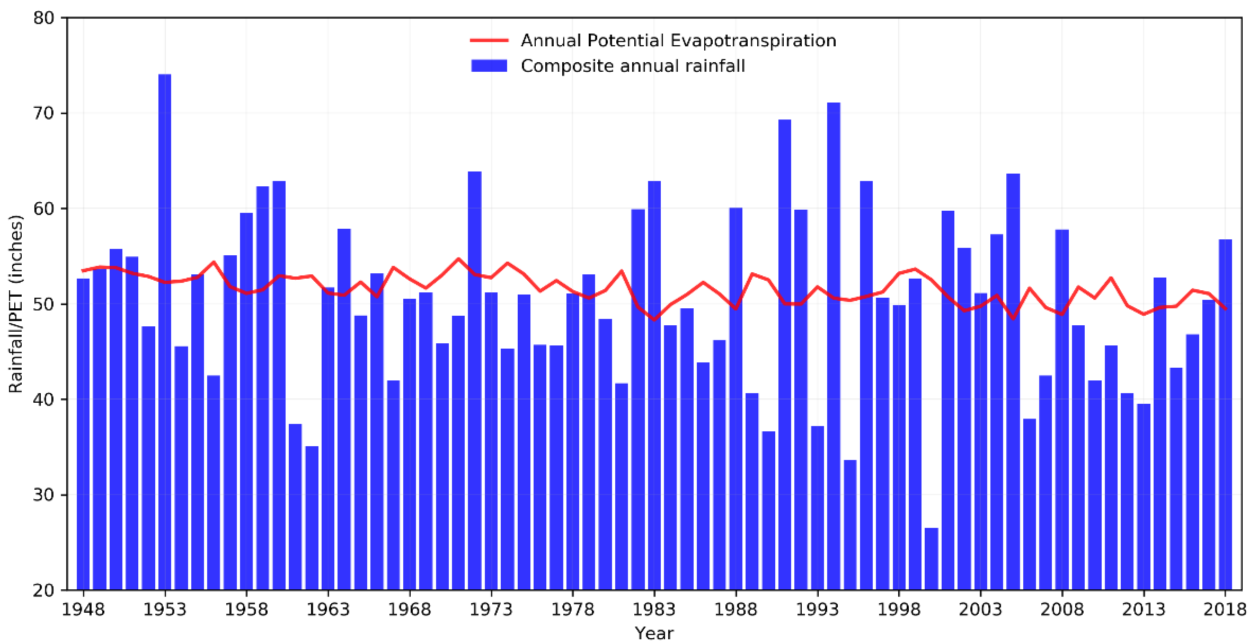

Figure B - 5. Composite annual rainfall and Potential Evapotranspiration (PET) of the Lake Butler Chain

PET data of the period from 1/1/1948 to 12/31/2018 were available from the SJRWMD databases at Deland and Sanford NOAA stations (Figure B - 4). The data was computed using Hargreaves and Samani (1985) method, but later scaled with correction factors to the U.S. Geological Survey (USGS) Geostationary Operational Environmental Satellites (GOES) Priestly-Taylor evaporation estimate (WSIS, 2012). The correction factors were obtained by regressing the Hargreaves-Samani PET data against the Priestly-Taylor PET data.

Since the original SWMM model was calibrated using the daily PET data at NOAA Sanford station, the same station data were also used for the long-term simulation. Figure B - 5 shows the annual PET values at Sanford station for the period from 1/1/1948 to 12/31/2018. Table B - 2 summarizes the PET values of this station.

Table B - 2. Summary of PET data at Sanford NOAA weather station

Station Number	Location	Source	Period of Record	Annual PET (in)		
				Minimum	Mean	Maximum
GHCND:USC0087982	Sanford	NOAA	1/1/1948 - 12/31/2018	48.31	51.57	54.71

Groundwater Levels

Groundwater level data were needed to simulate seepage rates beneath the lakes in the SWMM model. A number of Upper Floridan Aquifer (UFA) wells were reviewed during the analysis (Figure B - 6). Table B - 3 lists these wells with their period of records. Although well V-1149 is closer to Lake Butler Chain than well V-0772, the V-1149 station did not have long period of records (only from 2008). Thus, the original SWMM model used the data recorded at the station V-0772 to represent the UFA boundary condition in SWMM (JEA, 2018). The groundwater levels for the other stations were the offset values of the data at station V-0772 (JEA, 2018). Table B - 4 summarizes the UFA offset values at each modeled node of SWMM (see Figure B - 3). The SWMM model development and calibration report (JEA, 2018) includes more detail regarding these wells and offset values. Figure B - 7 shows the time series water levels of station V-0772 along with the two longest well record data of wells V-0101 and V-0510.

Table B - 3. Summary of groundwater wells within and around the watershed and the data period of record.

Station Name	Station #	Random Levels	Daily Average	Aquifer
USGS Well at Alamana (V-0101)	5681072	1936–2018	2006–2018	Upper Floridan
Helen Lake Cemetery (V-0777)	5701077	1998–2016	–	Upper Floridan
Galaxy Middle School (V-0837)	2590084	1999–2018	1999–2018	Inter-mediate Confining Unit
Galaxy Middle School (V-0772)	2591456	1936–2018	1995–2018	Upper Floridan
JC Mew FA Well (V-0510)	70881589	1936–2018	1989–2018	Upper Floridan

Table B - 4. UFA offset values at each SWMM lake node (see Figure B - 3 for the nodes locations)

Lake Node	UFA offset (ft)	Lake Node	UFA offset (ft)	Lake Node	UFA offset (ft)	Lake Node	UFA offset (ft)
N1001	0	N1016	1	N1030	4	N1041	5
N1003	1	N1017	4	N1031	2	N1043	5
N1009	2	N1021	4	N1032	0	N1046	11
N1010	-1	N1022	0	N1033	7	N1050	2
N1011	2	N1023	-1	N1035	0	N1052	10
N1012	2	N1024	1	N1036	3	N1054	8
N1013	4	N1026	4	N1037	6	N1059	5
N1015	1	N1029	0	N1040	1		

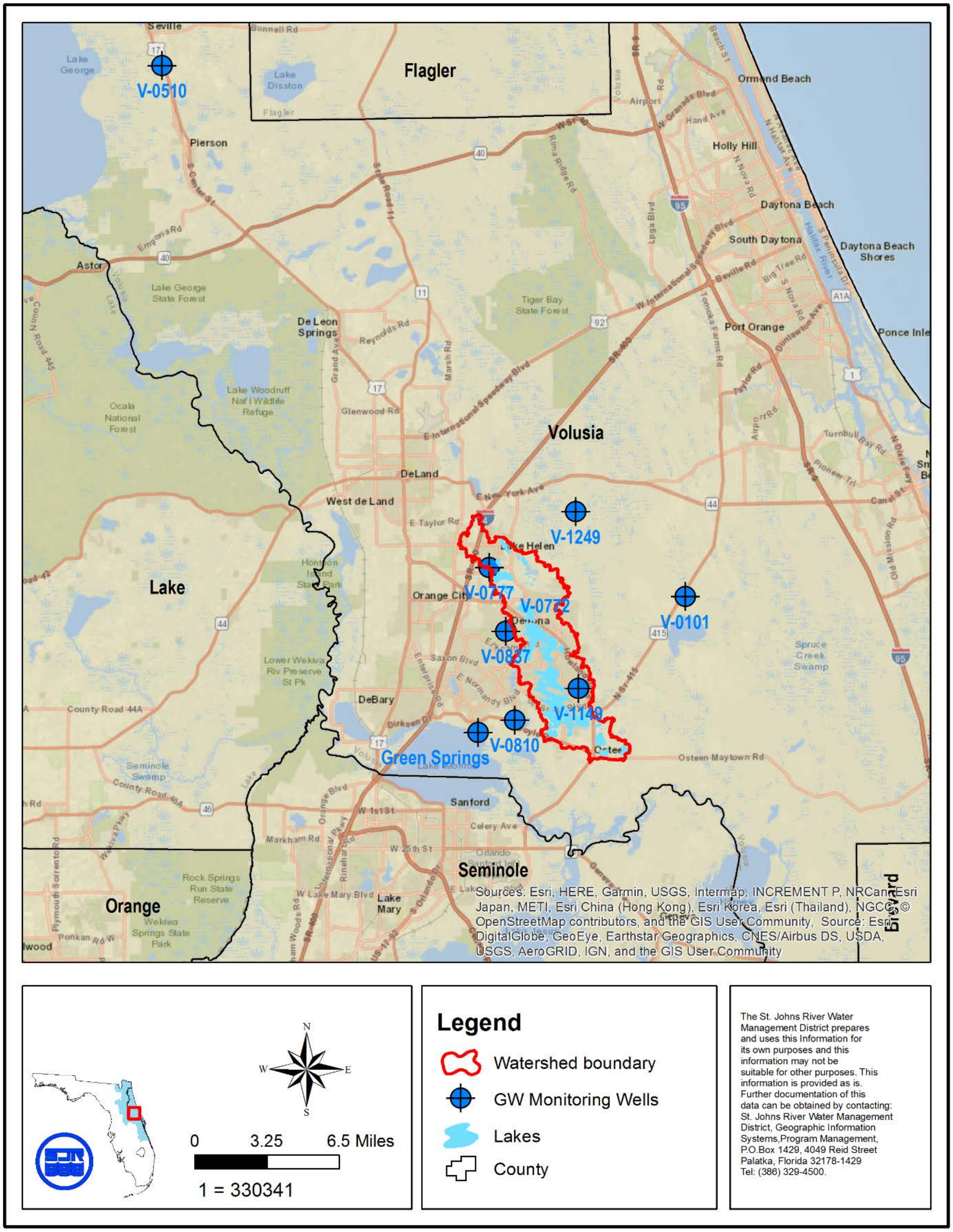

Figure B - 6. Upper Floridan aquifer wells in and around the watershed.

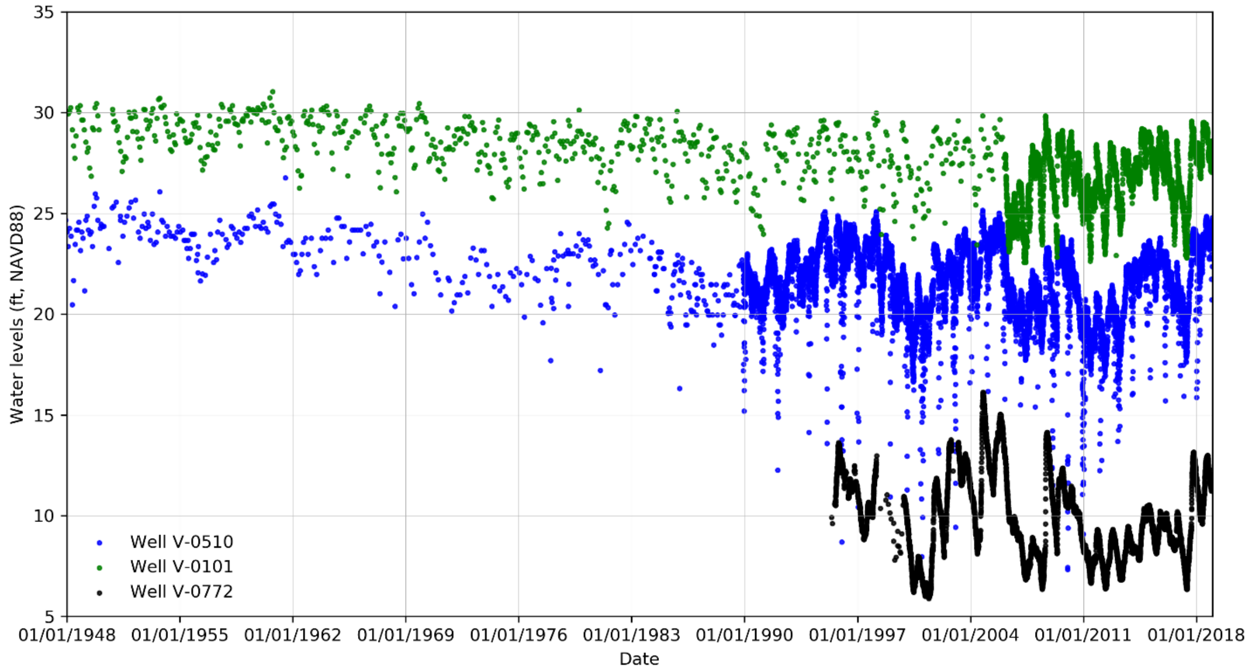

Figure B - 7. Groundwater levels

As mentioned earlier, groundwater level data from well V-0772 along with offset values (Table B - 4) were used to compute the exchange of flows between the UFA and the lakes. Thus, the groundwater levels of well V-0772 were extended back to 1948 for long-term lake levels simulations (from 1948 to 2018). The well data were extended based on the observed groundwater level data of wells V-0510 and V-0101. Wells V-0510, and V-0101 had the longest observed data starting from 1/10/1948 and 1/28/1948, respectively (Figure B - 7). All the three wells have similar hydrographs, indicating a strong correlation among themselves. Well V-0510 was selected to relate with well V-0772 for its data extension because well V-0510 shows more water level variabilities specially in the early period of the record. In addition, regression analysis shows an acceptable agreement between the two wells with a coefficient of determination, R^2, of 0.62 (Figure B - 8). However, well V-0510 also had a peculiar low water level spikes in the later period of the record (Figure B - 7). The low water spikes were most likely happened due to freeze protection irrigation. These low data were filtered by replacing with a unique value of 16.65 feet from the observed well data. The unique value was computed as mean minus three times of the standard deviation of the observed data to filter the low water level spikes.

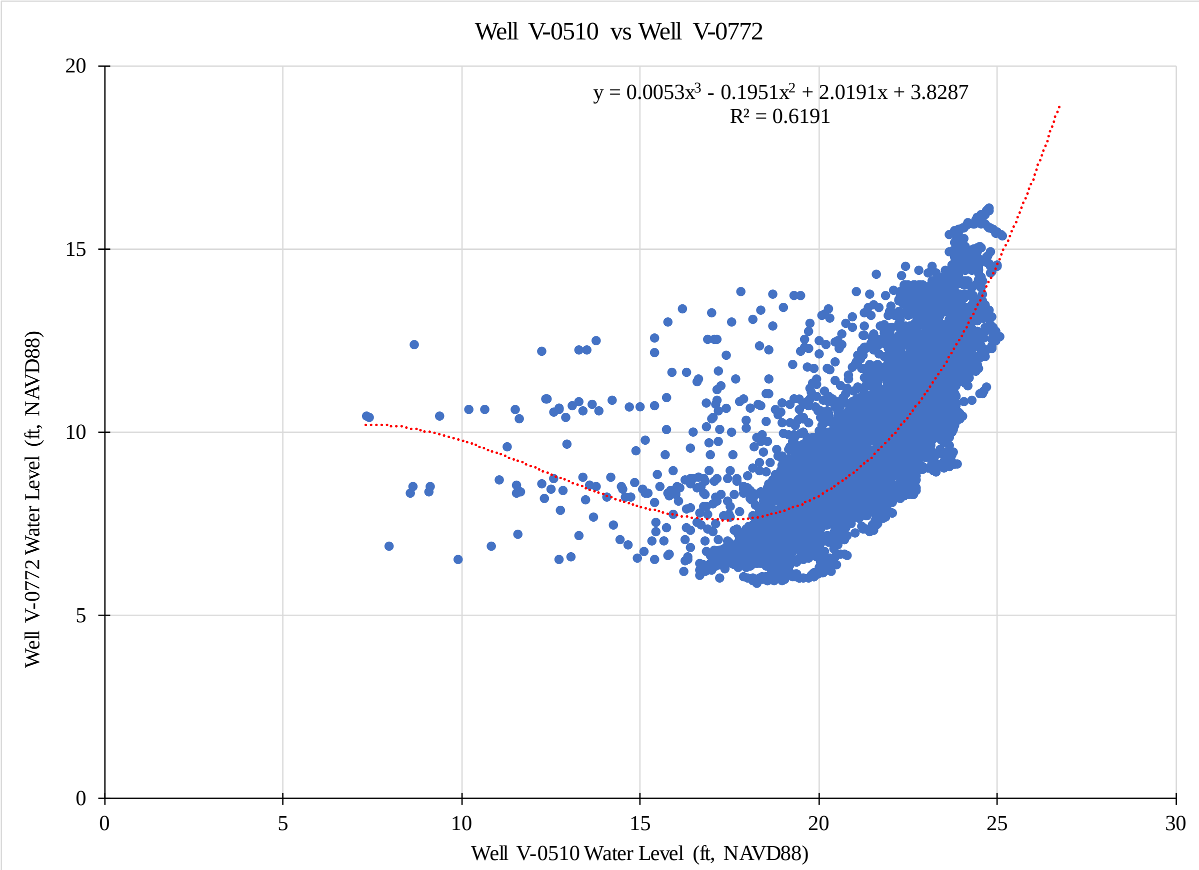

Figure B - 8 . Regression relationship between observed data at V-0510 and V-0772 wells.

Since the water levels at wells V-0772 and V-0510 exhibit similar pattern, water level offset approach was used to estimate water levels at well V-0772 from the observed water levels at well V-0510. The offset values were obtained from the concurrent water levels from the two wells. The overall mean monthly water level differences between the two wells was computed. Table B - 5 provides the computed mean monthly offset values.

Table B - 5. The overall monthly mean water level offset values between V-0510 and V-0772 wells

Month	**Offset values**
1	11.03
2	11.37
3	11.73
4	12
5	11.95
6	12.05
7	12.39
8	12.09
9	11.75
10	11.38
11	11.32
12	11.12

For every day of a month in which there was observed value only at well V-0510, its water level was offset by the mean monthly offset value to estimate the water level at well V-0772. After every observed well V-0510 data were used to fill gaps for well V-0772, based on the monthly offset values approach (Table B - 5), the still missing values of well V-0772 were linearly interpolated. Figure B - 9 shows the long-term extended groundwater levels at well V-0772 along with the filtered data of well V-0510 and observations.

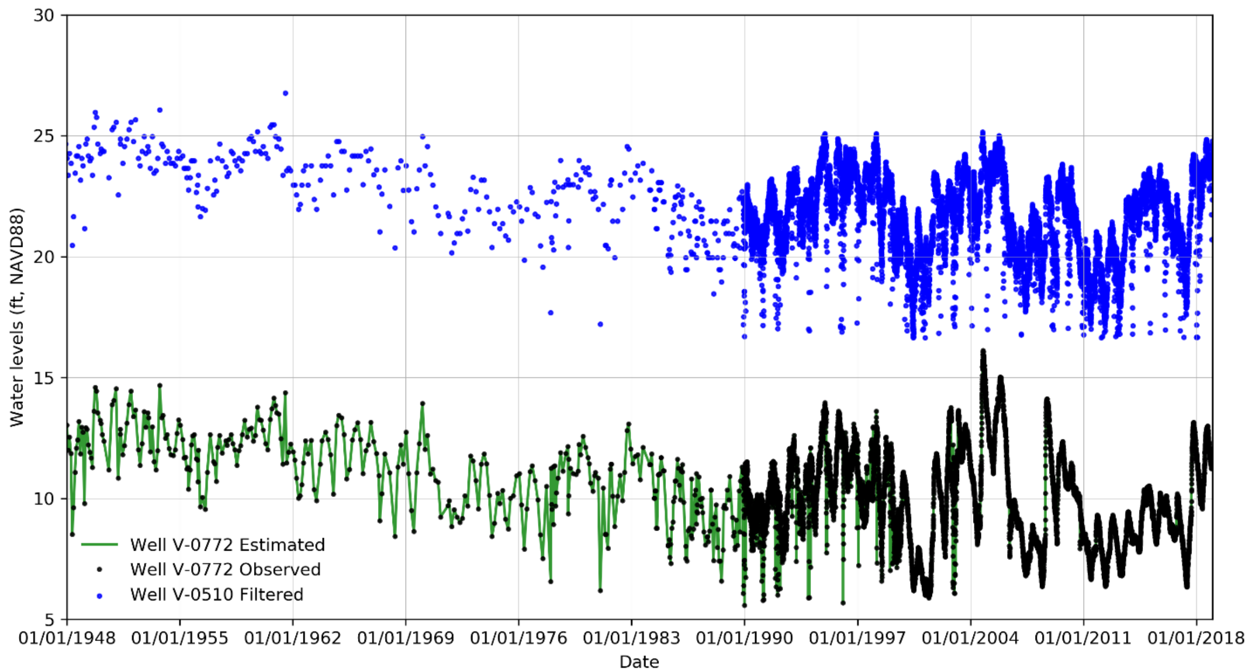

Figure B - 9. Observed and extended water levels at the V-0772 along with filtered water levels at V-0510 wells.

Finally, the completed long-term water level data of well V-0772 were used to compute UFA water levels at each node of the SWMM model (see Figure B - 3 for nodes detail). The UFA datasets were computed based on the offset values reported in Table B - 4.

Lake Levels

The water level data for all lakes within the LBC watershed were retrieved from the SJRWMD databases. The lakes had data with varying period of records as summarized in Table B - 6. Water levels data of most of the lakes were used in the model calibration. While Three Island Lake data was used for the northern boundary of the model, Big Lake and Lake Monroe data were assigned as the southern boundary of the model. The levels data of these three lakes were extended to provide long-term boundary conditions for the long-term simulations. Figure B - 10 presents observed water level hydrographs of the three lakes along with observed water level data of Lake Butler Chain and Savannah Lake.

Table B - 6. Summary of available lake water level data

Lake Name	Station Number	Hourly Continuous Data	Daily Average	Daily Non-Continuous
Big Lake	14592672	2014 - 2018	—	1999-2018
Lake Butler Chain	3390378	—	—	1990–2017
Dupont Lake	3580451	—	—	1965-2003
Lake Colby	3430386	—	—	1990–2018
Lake Helen	3800531	2005–2018	2005–2018	1990–2018
Lake Macy	4030667	—	—	1994–2018
Lake Monroe	USGS 02234500	—	1941-2018	—
The Savannah	7202739	2002–2018	2000–2018	—
Theresa Lake	4640911	2008–2018	2008–2018	1990–2018
Three Island Lakes	4650913	2002–2018	2000–2018	1990–2018

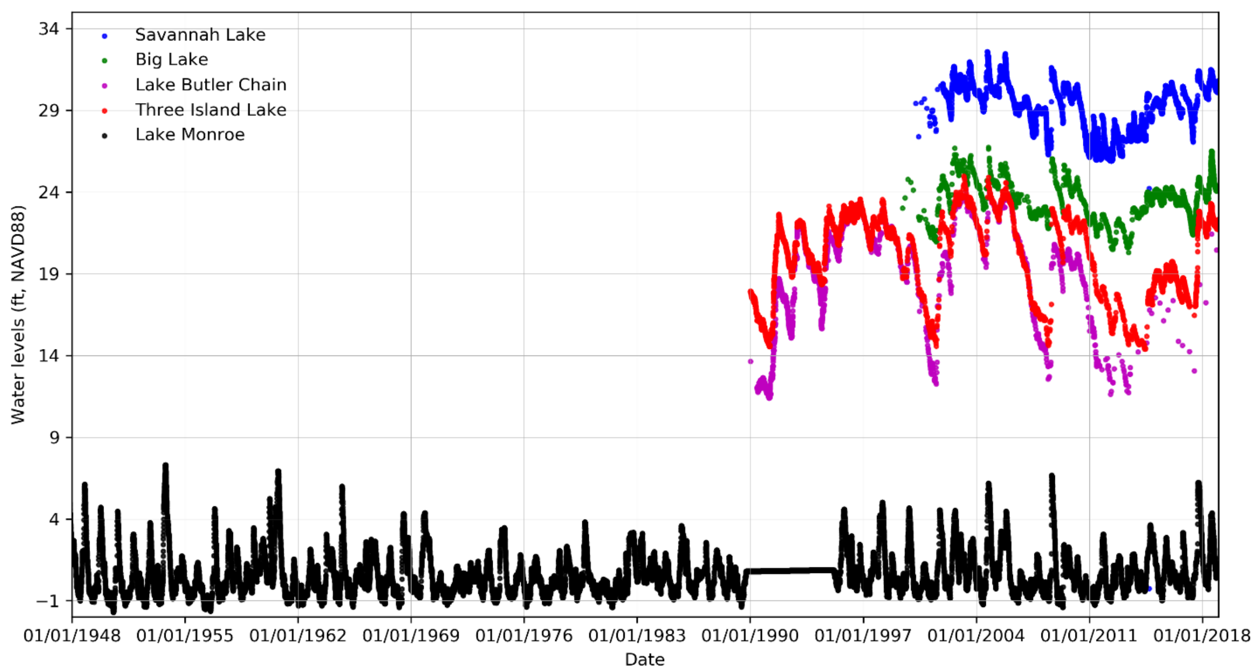

Figure B - 10. Observed lake level data within and around the Lake Butler Chain watershed.

Lake Butler Chain water levels show very similar pattern to Three Island Lake water levels but declines much more than the Three Island Lake during dry periods. This likely indicates that the Lake Butler Chain is strongly connected to the UFA system. Due to the presence of sinkholes at the Lake Butler Chain, the lake may experience more decline in water levels than the Three Island Lake during the extended dry periods. Big and Savannah Lakes have water levels that show similar pattern with the Lake Butler Chain but are higher by approximately 5 and 11 feet, on average, respectively. A summary of water level statistics for all lakes is provided in Table B - 7.

Table B - 7. Lake water levels summary statistics; elevations in feet, NAVD88

Statistics	Savannah Lake	Big Lake	Lake Butler Chain	Three Island Lake	Lake Monroe
Mean	29.2	23.6	18.7	20.0	0.7
Median	29.6	23.7	19.6	20.3	0.4
Standard Deviation	1.4	1.0	3.4	2.4	1.4
Range	6.7	6.4	13.0	10.6	9.0
Minimum	25.9	20.3	11.4	14.4	-1.7
Maximum	32.6	26.7	24.4	25.0	7.3

The observed water level data were complete for the Lake Monroe, and regressions were used to fill gaps for the Three Island and Big Lakes data. The line of organic correlation (LOC) regression was used to relate Three Island Lake levels with water levels of well V-0772. A polynomial regression equation was used to correlate the Big Lake levels with the water level data at well V-0772. Figure B - 11 and Figure B - 12 show the regression plots of the Three Island Lake and Big Lake against well V-0772, respectively. The regression equations were used to extend the water level data of the two lakes. Figure B - 13 and Figure B - 14 present the extended water level data for Three Island Lake and Big Lake, respectively.

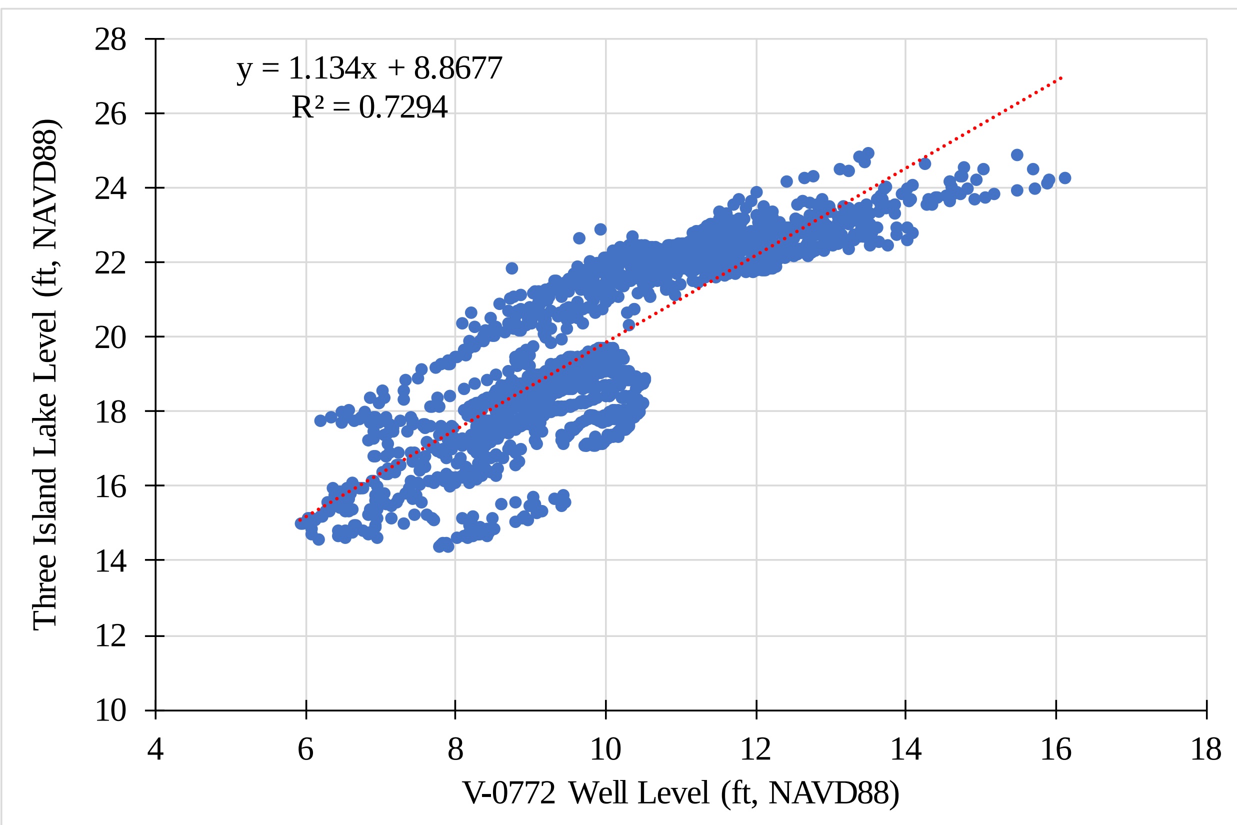

Figure B - 11. Line of organic correlation (LOC) between well V-0772 and Three Island Lake

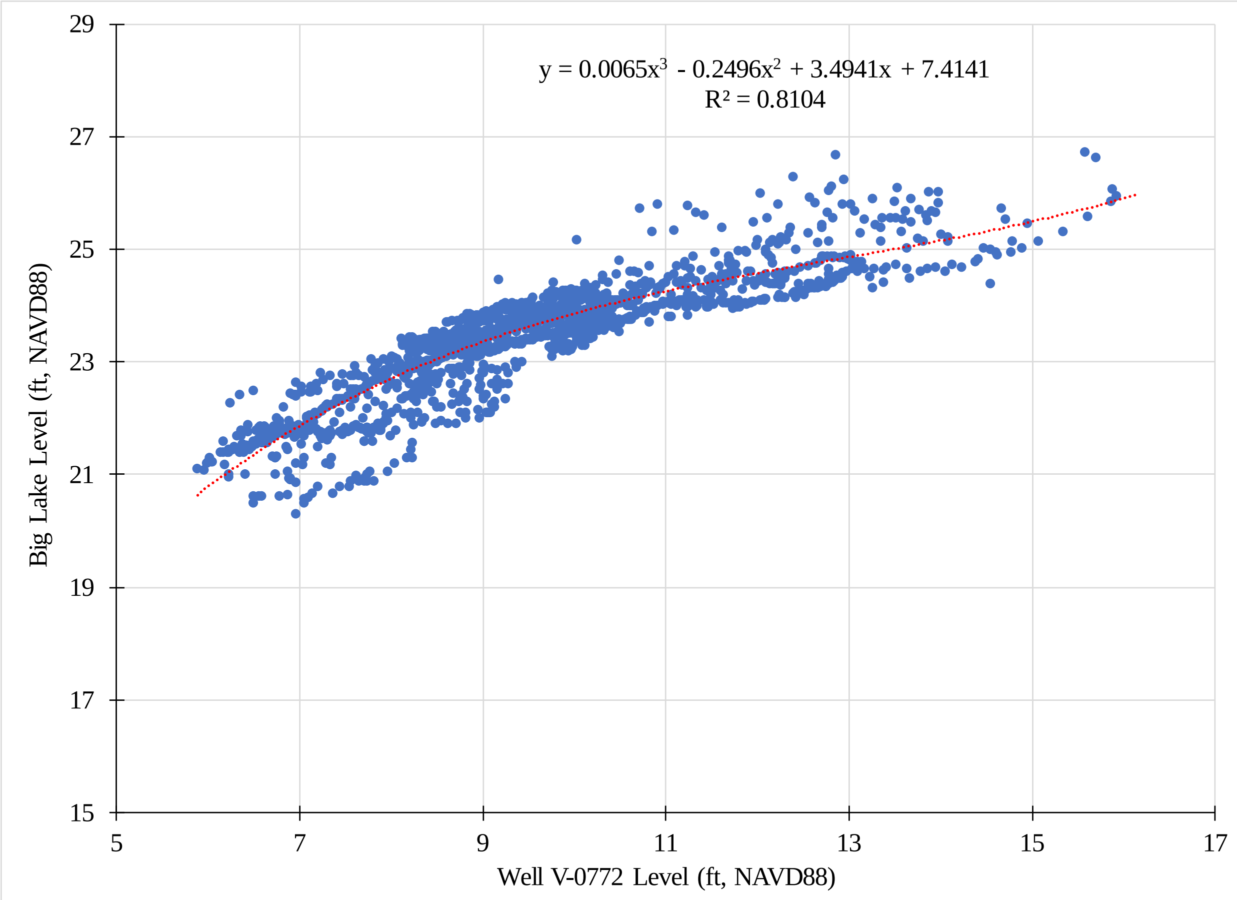

Figure B - 12. Regression relationship between well V-0772 and Big Lake

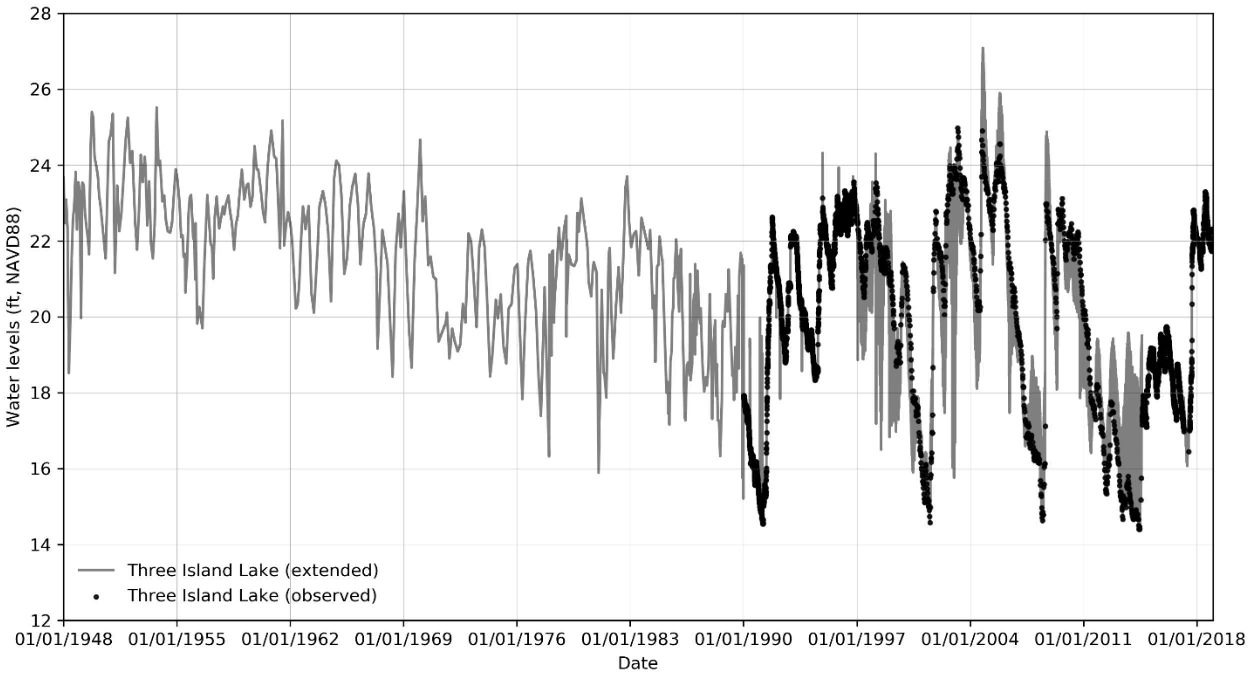

Figure B - 13. Three Island Lake observed and extended water levels

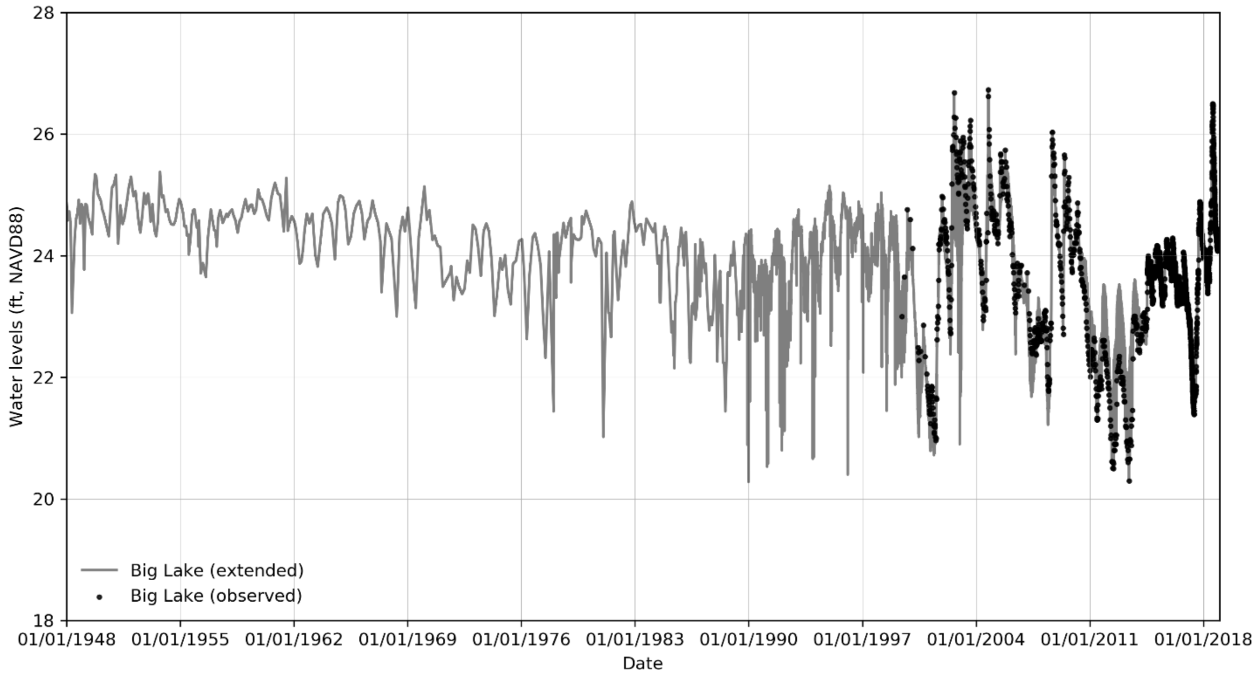

Figure B - 14. Big Lake observed and extended water levels

LONG-TERM SIMULATIONS

MFLs analysis requires long-term lake levels to capture the effect of short- and long-term climatic variations on lake levels. However, observed long-term lake levels were not available for the Lake Butler Chain before 1/4/1990 as shown in Figure B - 10. In addition, the available data were discontinuous and sparse especially for the late period (Figure B - 10). Thus, long-term lake levels simulation is needed for MFLs status assessments. The SWMM model of Lake Butler Chain (JEA, 2018) was used to estimate long-term lake levels using long-term rainfall, PET, boundary lake levels, and groundwater levels data (previously described).

Model Updates

In addition to extending hydro-meteorological and water levels data, the old bathymetry data of the Lake Butler was replaced with the recently collected high-resolution bathymetry data. The new bathymetry data was derived from two Digital Elevation Model (DEM) data sources. The first dataset was from the SJRWMD Lake Butler special purpose DEM data used for habitat analysis using the Hydroperiod Tool. The data was created based on geospatial modeling techniques combined with survey, Acoustic Doppler Profiler (ADP), field, and aerial photography-derived data. This data was particularly used to estimate lower elevations bathymetry (≤ 24.2 ft – NAVD88) of the lake. The second dataset was obtained from the 2006 Volusia County Light Detection And Ranging (LiDAR) data developed by Woolpert. The data was used to derive higher elevations bathymetry (> 24.2 ft – NAVD88) of the lake. The two datasets were eventually mosaiced to produce a combined new bathymetry data for the lake. The new bathymetry data were later converted to stage area curves using the SJRWMD Hydroperiod tool. Figure B - 15 compares the old and new stage area curves of the lake. The figure clearly indicates that the new bathymetry data generally produced larger areas for stages approximately ≤ 24 ft. As it was expected, the higher stages generate similar curves since stages > 24 ft were derived from the same LiDAR 2006 data that was used by the original SWMM model. Using the compiled long-term hydro-meteorological, water levels, and new bathymetry datasets, the original SWMM model was extended to the period from 1/1/1948 to 12/31/2018.

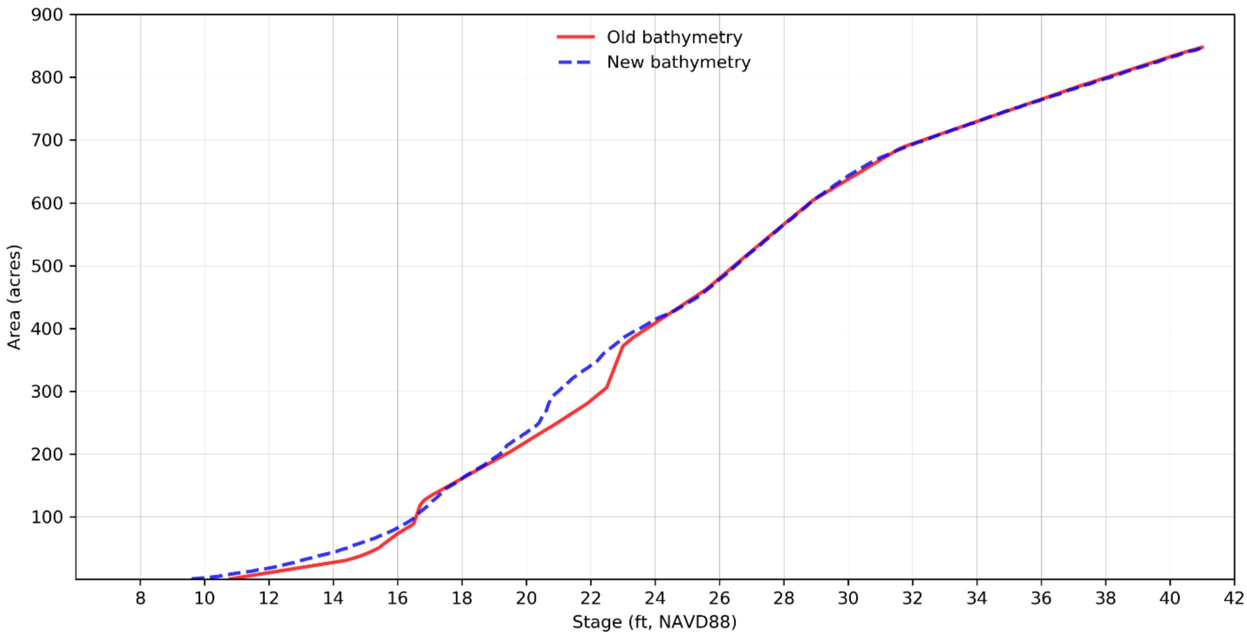

Figure B - 15. Stage area curves of the Lake Butler Chain

Model Improvements

The original SWMM model showed a continuity (mass balance) error of greater than 11% for the groundwater flow component (see Attachment A - 2). However, this value should be close to zero for reasonable groundwater flow simulations. After further investigation on groundwater parameter sets of the original SWMM model, it was found that the high continuity error could be caused by shallow surficial aquifers thickness. The bottom elevations of the original model were set to 1 to 6 ft below ground elevations as shown in Attachment A - 1. At the same time, the evaporation occurrence depth from the lower saturated zone was set to 5 ft. Since the thicknesses of some aquifers were even below 1 foot (see Attachment A - 1), this could potentially cause the continuity problem. In such settings, more evaporations from the lower saturated zone could dry out those aquifers that had thickness less than 5 ft. Additionally, high lower groundwater loss rate (LGLR), which controls amount of water seeps to the deep aquifer, was used in the original SWMM model. For example, some aquifers had LGLR of greater than 1 inch per hour whereas the remaining aquifers had lower values (see Attachment A - 1). However, from the annual average 2015 recharge map of the District, the LBC watershed receives annual average recharge rates of 5 to 10 inches per year (Boniol and Mouyard, 2016).

In order to resolve the groundwater balance error, the bottom elevations were reduced to at least 10 ft below the ground elevations. Since the error was negative and some aquifers with high LGLR values showed zero groundwater levels, the LGLR of those aquifers was also reduced to avoid drying out aquifers. For those aquifers, LGLR was modified to the average recharge rates of the area that is 7.5 inches per year (0.00086 inch per hour) (see Attachment A - 3). Lowering the bottom elevations significantly lowered the groundwater balance error from -11.51 to 0.56% for the same calibration period (1995 to 2016) of the original SWMM model (Attachment A - 2). It should be noted that reducing the LGLR alone did not improve the groundwater balance error but further reduced the error to 0.03 when used with the new bottom elevations (Attachment A - 2). In addition, the lowered LGLR considerably avoids the drying out of those aquifers that were dried out before (even after adjusting the bottom elevations) and produces reasonably well fluctuated groundwater levels (see Attachment A - 4 as example). While all these modifications fixed the groundwater balance error, the agreement between observed and simulated lake levels was reduced when the same calibrated parameter values of the original SWMM model were used (see Attachment A - 5). Therefore, the model was finally recalibrated to improve the representation of observed lake levels. As the modified model overestimated the observed lake levels, the groundwater flow coefficient (A1) was decreased from 0.001 to 0.0001 to reduce the baseflow values to the lake. In addition, the evaporation fraction from the upper unsaturated zone was increased from 0.35 to 0.45 for the same aquifers (see Attachment A - 3). It should be noted that SWMM parameters recalibration was performed only for those aquifers where the LGLR was set to 0.00086 in/hr.

Adjusting bottom elevations and LGLR not only fixed groundwater continuity error but also noticeably improved model performance for matching observed lake levels especially for the period from 1990 to 1994 (Figure B - 16). However, the observed lake levels during the dry period were still systematically overestimated. This was also noticed when the original SWMM model was used, indicating more water storage in the lake during the dry period (see Figure B - 16). On the other hand, accurately simulating the low levels is important as it critically affects the outcome of MFLs status assessment. A single leakance value was calibrated in the original SWMM model to 0.00055 to simulate seepage rates beneath the Lake Butler Chain to UFA. Findings suggested that a single leakance value would not provide adequate seepage rates to match between simulated and observed lake levels during the extended dry periods. Thus, dual leakance values were used to increase seepage rates during that periods. The two values were assigned based on UFA water levels, whereby the originally calibrated leakance value was used when UFA level > 9.5 ft – NAVD88. The second value was increased to 0.0055 for UFA level ≤ 9.5 ft – NAVD88. Such approach noticeably improved the model performance for matching observed low levels (Figure B - 16). Findings are consistent with previous studies at the District for Johns and Avalon Lakes (Robison, 2008a, and 2008b). A 1-year model spin-up period was also used to improve the initial conditions (e.g. soil moisture, lake levels) of the system (Figure B - 16).

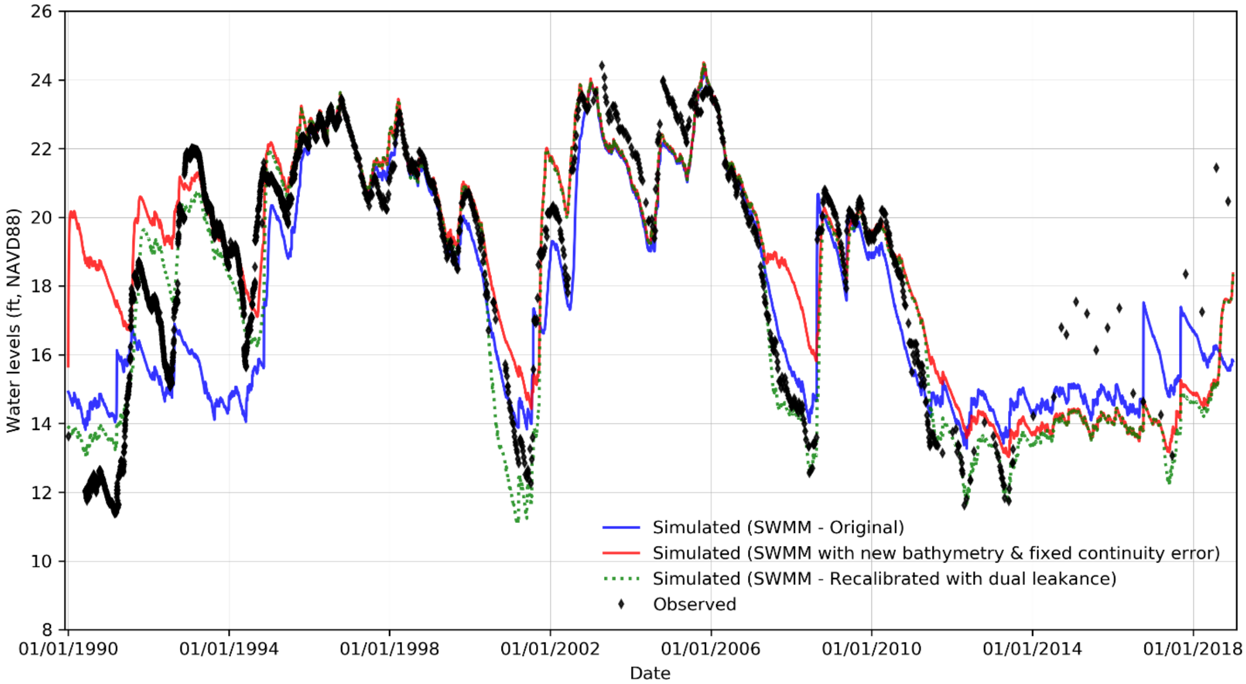

Figure B - 16. Comparison of observed and simulated water levels of Lake Butler Chain.

Overall, when compared to the original SWMM model, the updated and recalibrated SWMM model better simulates temporal evolution and variability of observed lake levels (Figure B - 16). This is also reflected by the high goodness-of-fit statistics (Table B - 8). For example, compared to the original daily results, the Nash-Sutcliffe efficiency (NSE) was significantly increased from 0.38 to 0.86 for the period 1990 to 2018. Similarly, the root mean squared error (RMSE) was reduced by more than 50% (Table B - 8). Other statistical evaluation criteria also showed improvement compared to the original SWMM results. Table B - 8 compares the goodness-of-fit statistics before and after fixing the groundwater continuity error, and recalibrating the model for different periods, including the calibration period of the original SWMM model (1995-2016) for easy comparison.

Table B - 8. Goodness-of-fit statistics of the original and recalibrated SWMM model

Statistics	**Daily (before mass balance error)** *			**Daily (after mass balance error)**		
	1990-2018	**1995-2016**	**1995-2018**	**1990-2018**	**1995-2016**	**1995-2018**
Nash-Sutcliffe efficiency (-)	0.38	0.92	0.92	0.86	0.94	0.93
Root mean squared error (ft)	2.70	0.90	0.90	1.29	0.83	0.86
Mean error (ft)	-1.49	-0.53	-0.52	0.11	0.08	0.06
Absolute mean error (ft)	1.98	0.64	0.65	0.98	0.56	0.57
Percent bias (%)	-7.98	-2.58	-2.57	0.59	0.37	0.31
Pearson correlation coefficient (-)	0.78	0.97	0.97	0.93	0.96	0.96

*Calculated after dual leakance values were used but before groundwater balance error was fixed

Historical Long-term Lake Levels

The updated and recalibrated SWMM model was used for long-term historical lake levels simulation. Figure B - 17 presents the long-term hydrographs of simulated lake levels along with observed data at station 03390378 (Figure B - 3) for the Lake Butler Chain. Observed lake level data were only available since 1/4/1990.

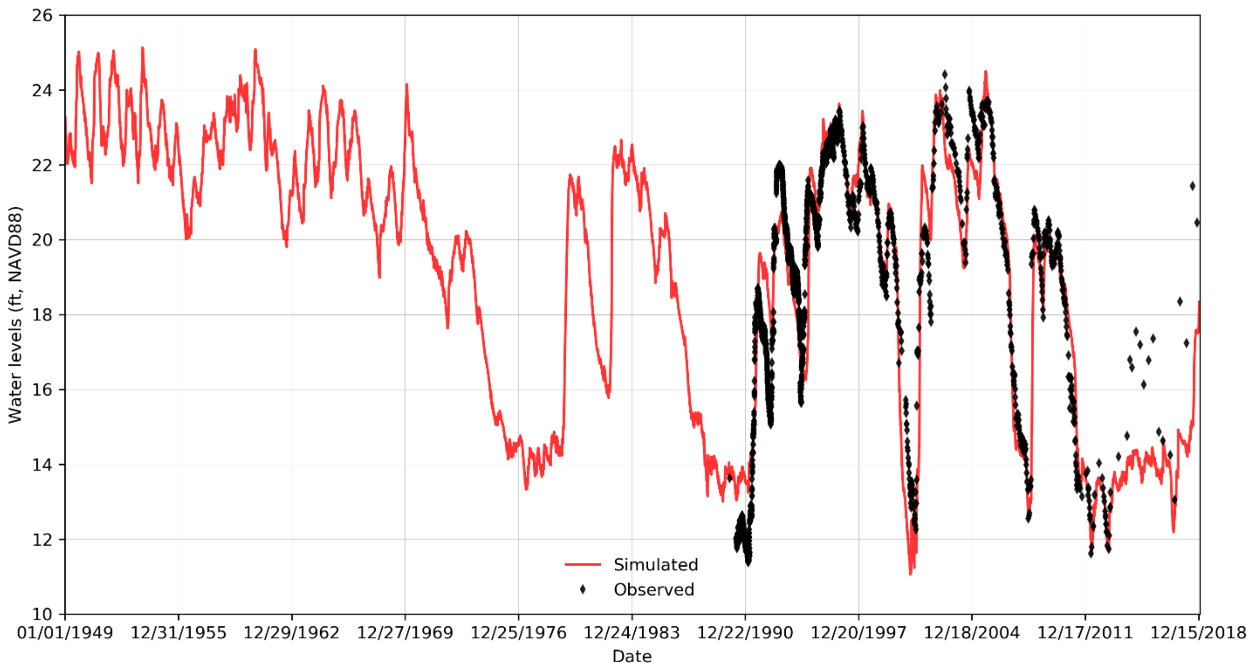

Figure B - 17. Comparison of long-term simulated and observed Lake Butler Chain Levels.

It should also be noted that the observed lake levels of LBC were recorded at the west side of the chain (see Figure B - 3). In SWMM, the LBC was represented as two lobes (nodes N1012 and N1009 as shown in Figure B - 3). The two lobes were hydraulically connected with conduits. Since the observed water levels data were only available at the west side of the chain, model calibration was only performed for this side (N1012). However, the calibrated parameter values of the west lobe were used for the east lobe (N1009). As it should be expected, such approach should simulate similar higher water levels (≥ 20 ft – NAVD88) for both lobes when they are assumed to be connected. However, this might not be the case when the two lobes are assumed to be disconnected especially during the dry periods. Therefore, the simulated low levels of the east lobe should be used with cautions due to lack of observed data to perform actual calibration process.

Development of No-Pumping and Current-Pumping Lake Levels

The current and future status of minimum levels developed for Lake Butler Chain need to be assessed. The objective of the current status assessment is to determine whether the Lake minimum levels are being achieved under the current pumping condition. Because of our limited understanding of possible future climatic conditions and difficulties in predicting future lake levels using global climate model forecasts, historical lake levels were considered to be the best available data and were adjusted for groundwater pumping impact to assess the current status of minimum levels.

The adjustment of historical lake levels requires considering the effect of current groundwater pumping on lake levels not only for the recent years but also for the entire period of record (from 1948 to 2018). Two sets of adjusted lake levels were developed: no-pumping condition and current-pumping condition lake levels. The no-pumping condition lake levels constitute a reference hydrologic condition in which lakes were not under the influence of any groundwater pumping for the period from 1948 to 2018. The current-pumping condition lake levels represent a reference hydrologic condition in which lakes were under the influence of current groundwater pumping constantly for the period from 1948 to 2018. Current groundwater pumping is defined as the average groundwater pumping from 2014 to 2018. An average of the past five years (from 2014 to 2018) of groundwater pumping was used to calculate the current-pumping condition so that it is more representative of the most recent average groundwater demand condition. Figure B - 18 shows the steps for developing lake levels for no-pumping and current-pumping conditions.

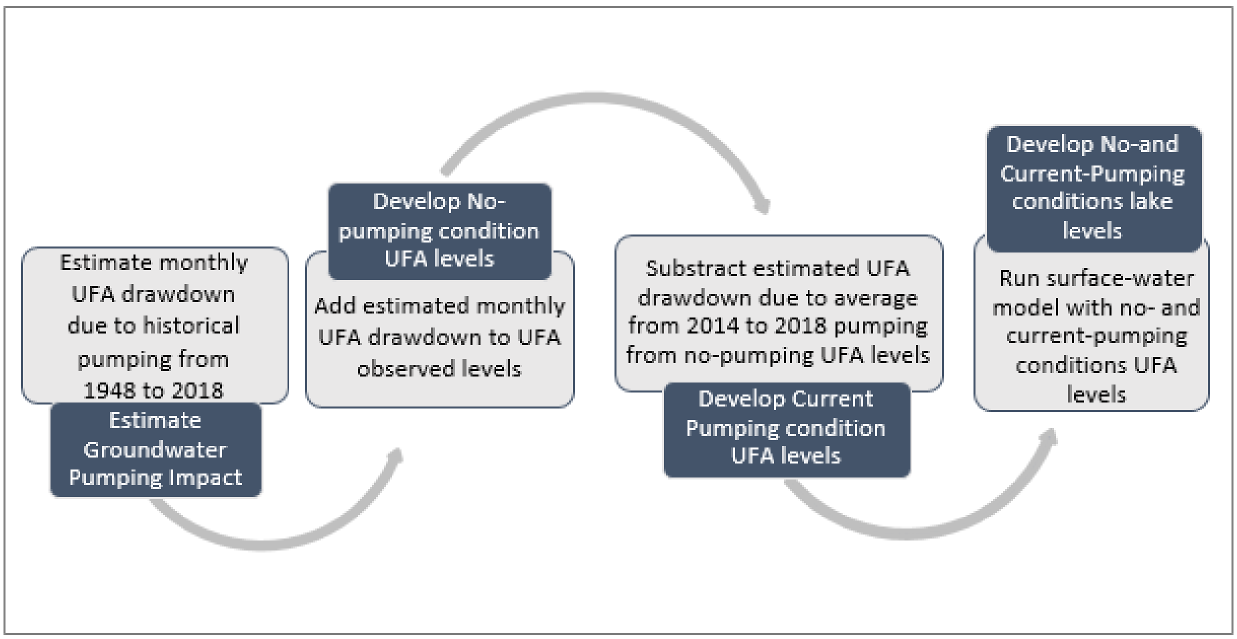

Figure B - 18. Steps for developing no-pumping and current-pumping condition lake levels

The updated SWMM model was used to develop no-pumping and current-pumping condition lake levels. To simulate the no-pumping and current-pumping condition lake levels, no-pumping and current-pumping groundwater levels near lake were required. As previously discussed, water level data from V-0772 well were used with some adjustments to compute the exchange of flows between the UFA and LBC in the model.

The first step in developing the current-pumping condition groundwater levels is to develop the no-pumping condition groundwater level dataset. This dataset was developed by adding an estimate of impact due to historical pumping (i.e., the UFA drawdown due to pumping) to the observed record. The current-pumping condition groundwater level dataset was developed by subtracting an estimate of impact due to current pumping (average groundwater pumping from 2014 to 2018) from the no-pumping groundwater levels. No-pumping and current-pumping condition groundwater levels were later input into the SWMM model to simulate no-pumping and current-pumping condition of lake levels.

Historical Groundwater Pumping Impact Assessment

Groundwater Use

It was assumed that most of the impact on LBC has been caused by groundwater pumping within a radius of 10-mile. Figure B - 19 shows the extent of 10-mile buffer zone but truncated in south to match with the Volusia groundwater model (Williams, 2006), which was used to estimate groundwater drawdowns at certain pumping rates. To estimate the impact on groundwater levels from pumping, monthly groundwater use data for the period 1948 to 2018 was compiled for the truncated 10-mile buffer zone (Figure B - 20).

The groundwater pumping data of 1948 to 2018 were estimated using the data available from different sources. The pumping data of the period 1995 to 2018 were from the SJRWMD historical water use databases with actual monthly use and station-level details. The data from 1965 to 1995 were based on the USGS published county-level water use (available every five years starting in 1965) and the annual SJRWMD county-level Annual Water Use Survey (AWUS), starting in 1978. Using these two sources, the water use data were aggregated to the county for every five years and some years in between from 1965. Any missing years for each county were estimated using an exponential growth assumption to create a complete aggregated table. If the USGS and AWUS estimates did not match, the published AWUS data were used. To estimate annual groundwater use data by county for the period before 1965, per capita groundwater use was estimated for each county. Multiplying the 1965 per capita water use by the historic county-level population from the U.S. Census, the annual groundwater uses by county were estimated for the period before 1965. The U.S. Census data were reported in 10-year intervals. An exponential growth was assumed to estimate the annual population between 10-year interval.

To disaggregate the annual data to monthly groundwater use, the average monthly proportions by county, which was estimated from the monthly SJRWMD database from 1995 to 2018, were applied to the annual data. Then, the monthly data were extracted within a 10-mile buffer zone of the lake. It should also be noted that the groundwater pumping within the 10-mile buffer zone was only used as a proxy to understand the variation of regional groundwater pumping from 1948 to 2018. The impact of groundwater pumping on lake levels was assessed based on all groundwater pumping within the Volusia groundwater model domain (described further below).

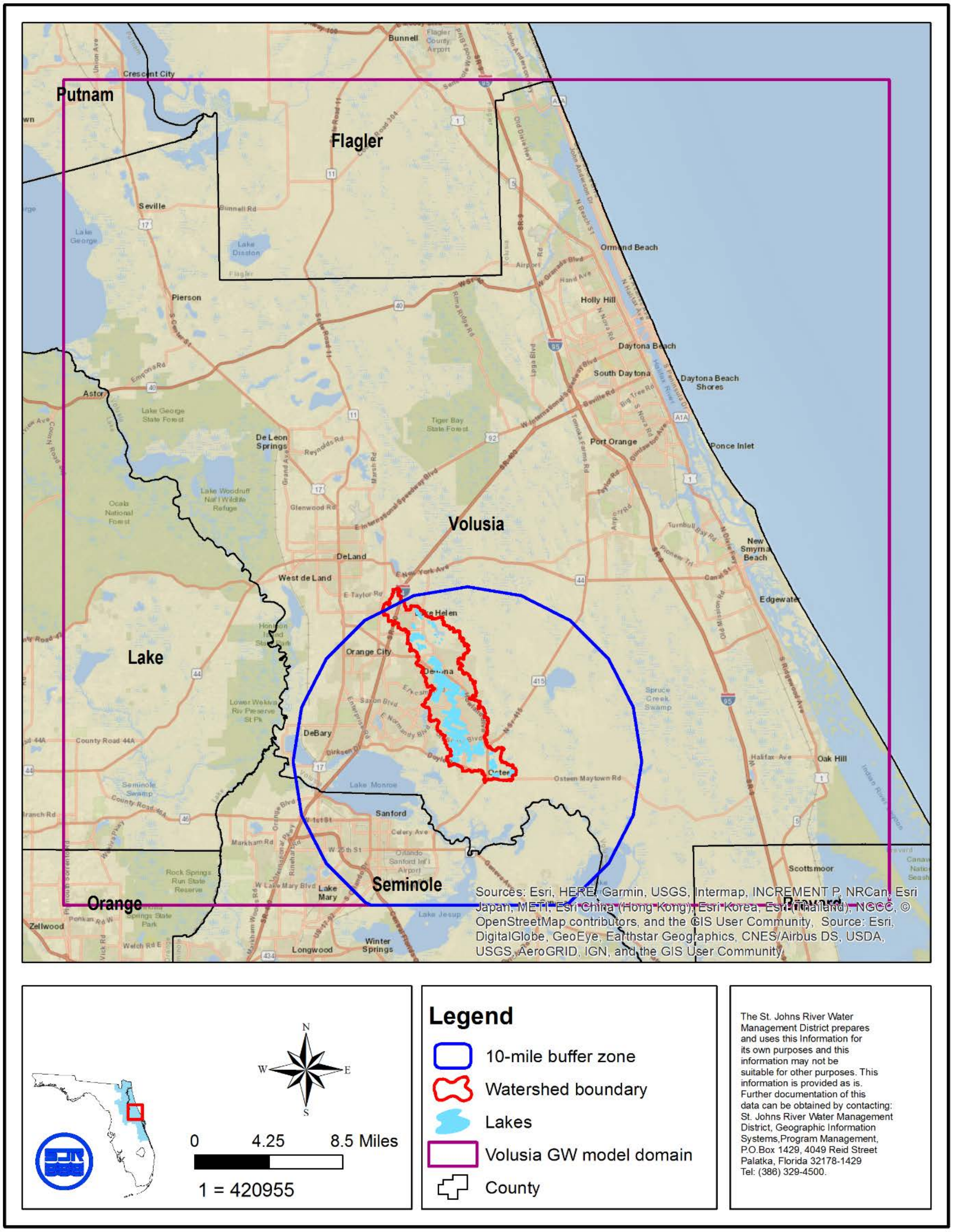

Figure B - 19. The 10-mile buffer zone of Lake Butler Chain and Volusia groundwater model boundaries. The 10-mile zone used to extract the groundwater drawdowns from Volusia groundwater model and monthly water use data.

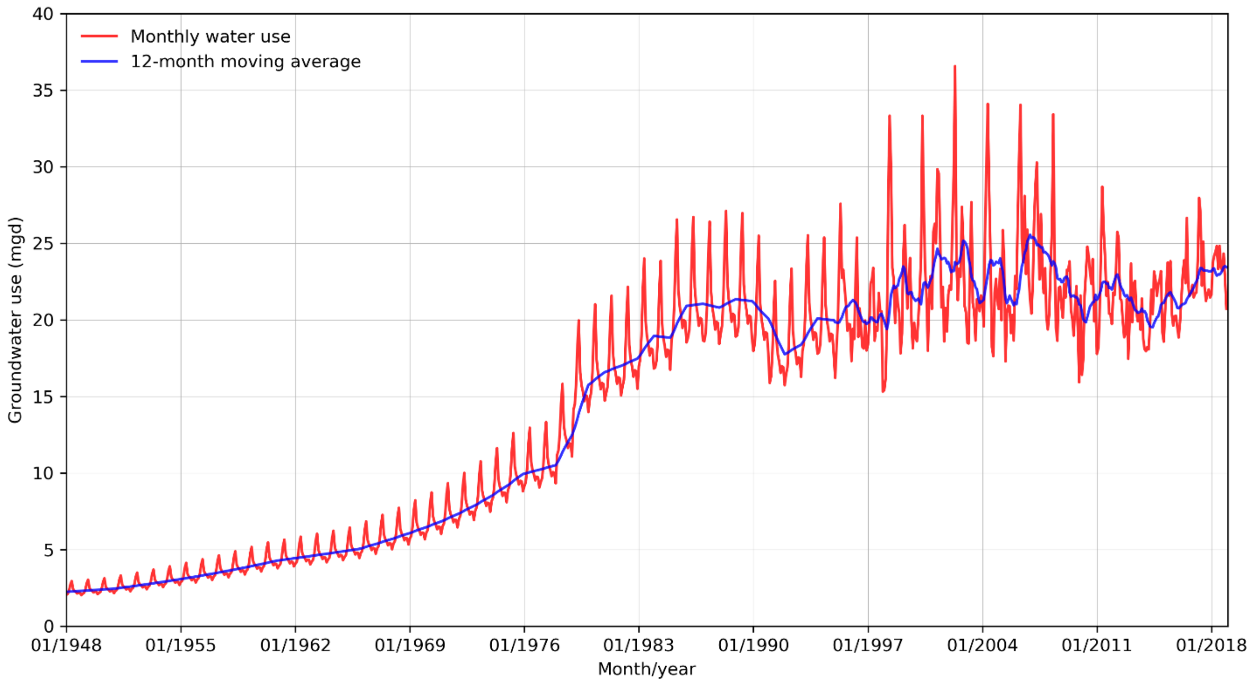

Figure B - 20. Estimated historical monthly groundwater uses and 12-month moving average within the 10-mile buffer zone

As shown in Figure B - 20, the monthly groundwater use data reached its highest in May 2002 (37 mgd) but had significantly declined (as much as 50%) after that. The average monthly groundwater use over the past five years (from 2014 to 2018) was approximately 22 mgd.

Groundwater Modeling

The SJRWMD Volusia groundwater model (Williams, 2006) was used for the groundwater pumping assessment. Originally calibrated to 1995 steady-state conditions, the Volusia groundwater model was later re-calibrated to include a second steady-state period representing hydrologic conditions for 2002. SJRWMD recently updated the steady-state model to 2010 and 2015 water use and boundary conditions. All simulations performed for this analysis utilized 2015 boundary conditions with various water use stresses. The boundary of the Volusia groundwater model is shown in Figure B - 19.

Estimated historical impact on groundwater levels

An estimate of drawdowns resulting from regional pumping from 1948 to 2018 on a monthly time step is needed for the no-pumping simulations. Because the Volusia groundwater model is a steady-state model, it was not designed to simulate monthly simulations over a long-time period (i.e from 1948 to 2018). To overcome the limitations of the model, a methodology was developed to estimate the impact of regional pumping on groundwater levels for every month of the period from 1948 to 2018. The methodology includes developing a relationship between groundwater pumping and the UFA drawdown beneath the lake using the Volusia groundwater model. To develop the relationship, the following model simulations were performed so that a wide range of pumping conditions can be included in the regression analysis.

- 1995 pumping
- 2002 pumping
- 2010 pumping
- 2015 pumping
- 2015 pumping decreased by 50%
- 2015 pumping decreased by 75%
- 2015 pumping decreased by 25%
- 2015 pumps-off
- 2040 pumping

The various pumping simulations were used to estimate the UFA drawdown beneath the Lake Butler Chain when compared to the 2015 pumps-off scenario. For example, the 2015 UFA drawdown beneath the lake was calculated by subtracting the simulated groundwater level under 2015 pumping condition from the simulated groundwater level under 2015 pumps-off condition. Figure B - 21 shows the regression plot of groundwater pumping rate and drawdown for the Lake Butler Chain.

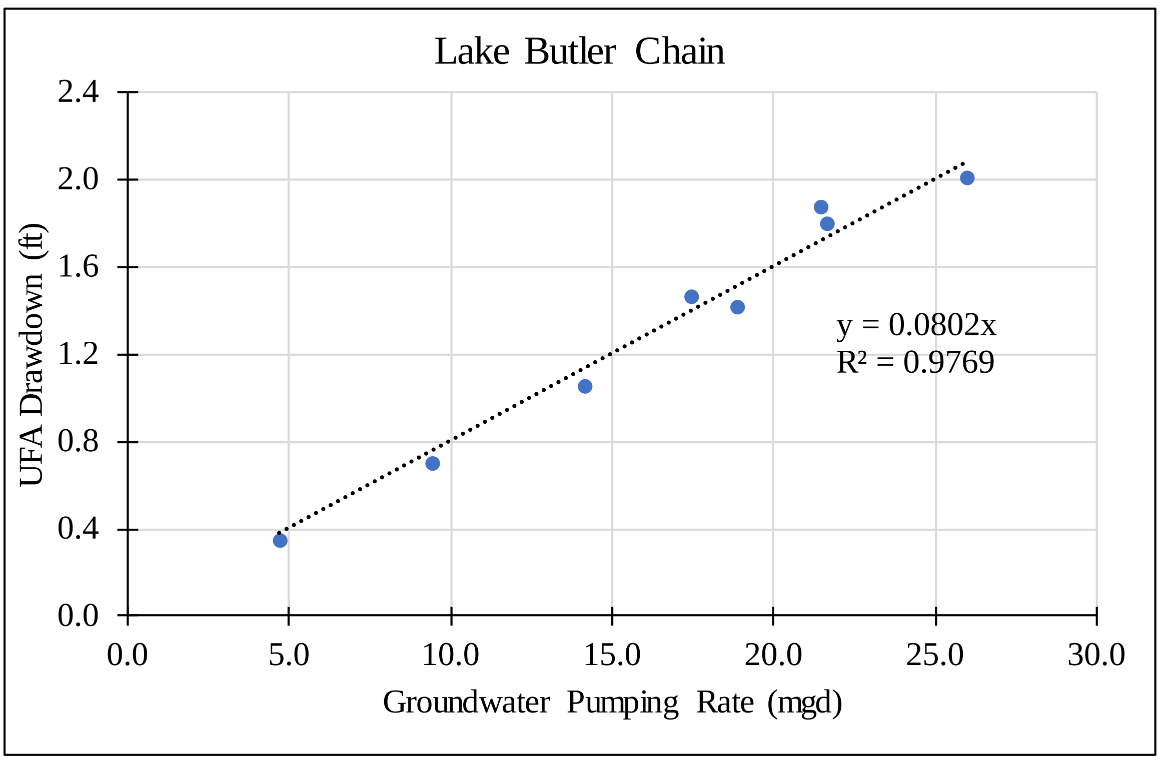

Figure B - 21. Relationship between UFA drawdown beneath Lake Butler Chain and groundwater pumping within the 10-mile buffer zone

A strong linear relationship exists between UFA drawdown within the 10-mile and groundwater pumping (Figure B - 21). Using the linear function shown in Figure B - 21 and the estimated 12-month moving average historical groundwater use data (Figure B - 20), monthly UFA drawdown beneath the lake due to historical groundwater pumping was estimated (Figure B - 22).

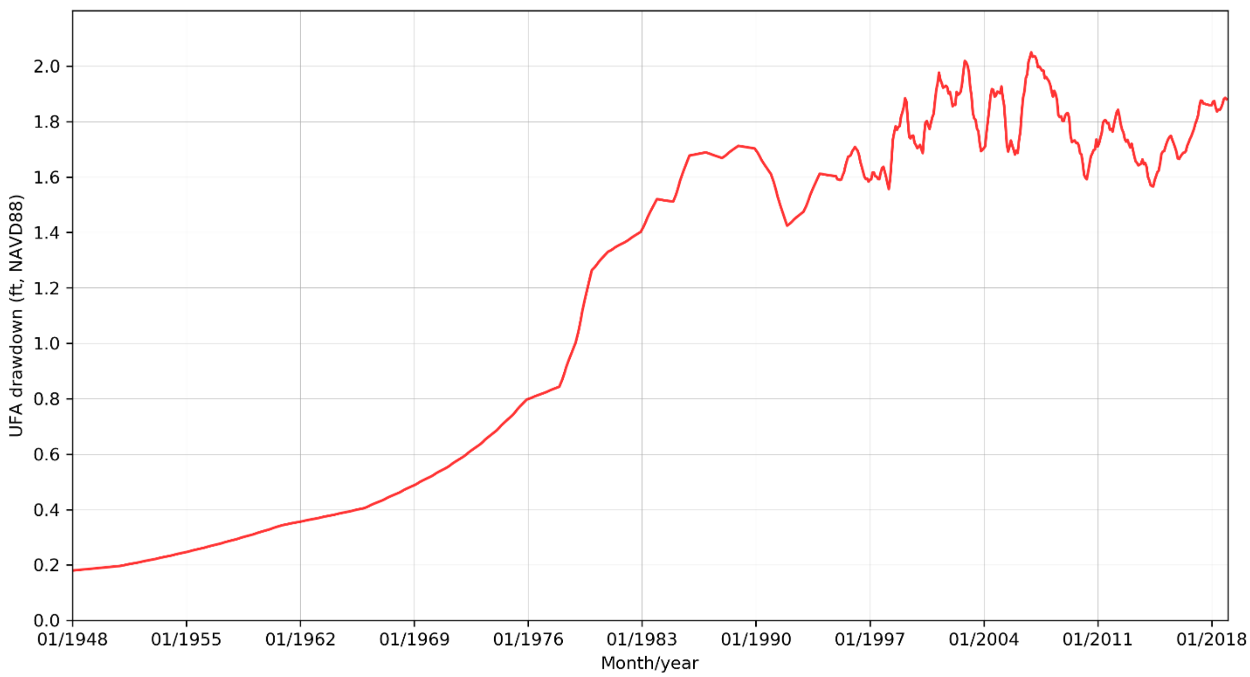

Figure B - 22. Estimated impact of groundwater pumping on UFA levels beneath Lake Butler Chain within the 10-mile buffer zone.

No-pumping condition groundwater levels

The monthly impacts from pumping as shown in Figure B - 22 were utilized to create no-pumping condition groundwater level datasets for the Lake Butler Chain. The monthly values were later disaggregated into daily impacts by using linear interpolation. The daily values were finally added to the daily observed groundwater level data to generate no-pumping condition groundwater level datasets for the lake.

Current-pumping condition groundwater levels

To generate current-pumping condition groundwater levels, the impacts from the average 2014 to 2018 pumping (Figure B - 22) were subtracted from the no-pumping condition groundwater levels. Figure B - 23 shows historical, no-pumping, and current-pumping conditions groundwater levels for the Lake Butler Chain.

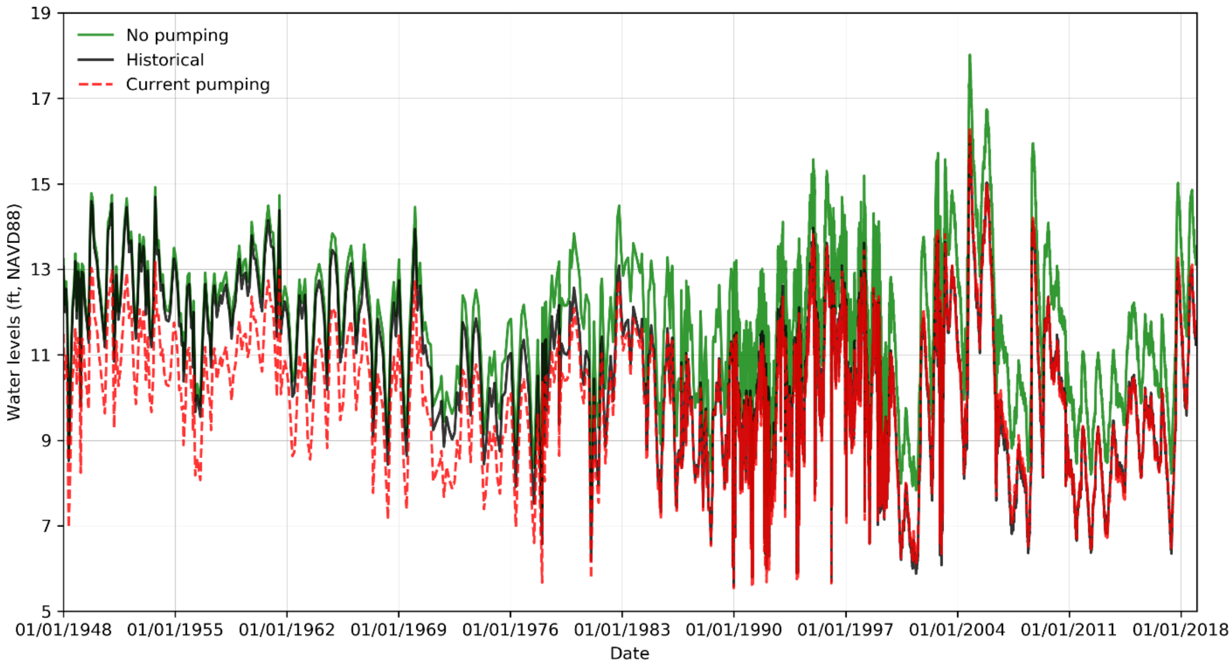

Figure B - 23. Estimated daily no-pumping and current-pumping UFA levels near Lake Butler Chain

Lake Level Datasets for MFLs Analysis

The no-pumping and current-pumping Lake Butler Chain levels were simulated by the long-term SWMM model using the no-pumping and current-pumping groundwater levels as boundary conditions (Figure B - 23).

Figure B - 24 shows historical, no-pumping, and current-pumping conditions lake levels. The figure indicates a more pronounced impact of no-pumping and current-pumping conditions on lake levels during the extended dry periods. Table B - 9 provides the descriptive statistics of historical (existing), no-pumping, and current-pumping condition lake levels.

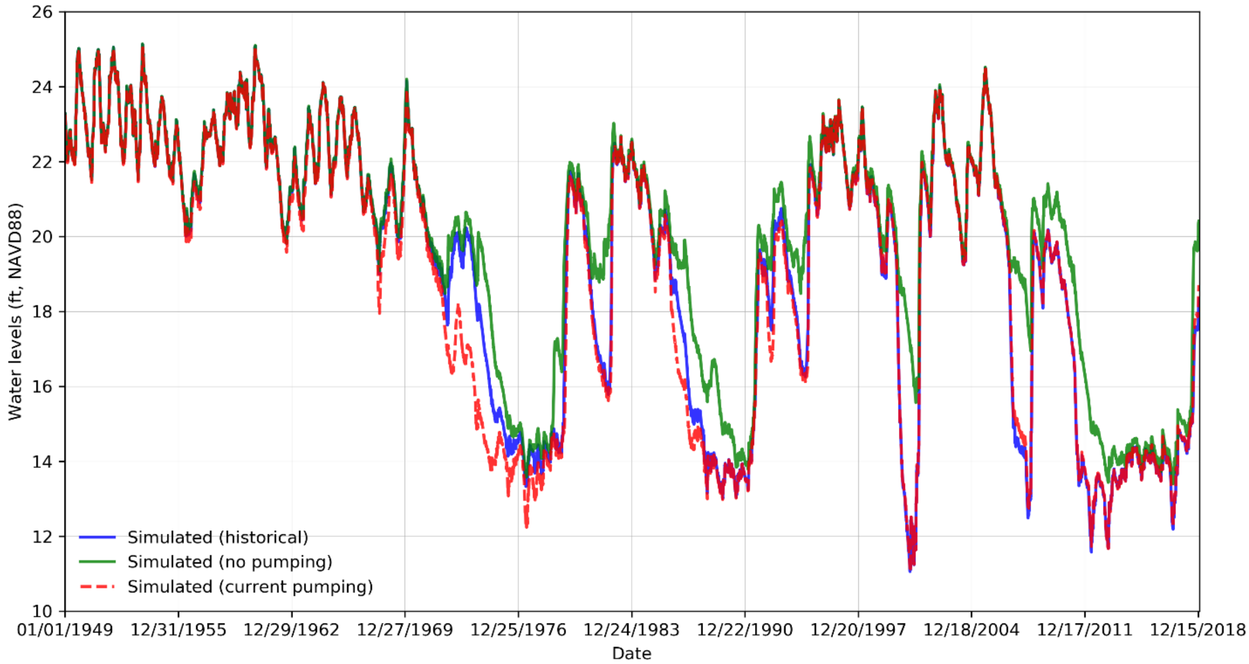

Figure B - 24. The estimated no-pumping, historical, and current-pumping condition levels for Lake Butler Chain.

Table B - 9. Descriptive statistics of simulated Lake Butler Chain stages for long term in feet

Statistics	No pumping	Historical	Current pumping
Mean	19.93	19.23	19.00
Median	20.69	20.24	20.07
Standard Deviation	3.05	3.60	3.69
Minimum	13.40	11.06	11.10
Maximum	25.14	25.13	25.08
Range	11.74	14.07	13.98

The current-pumping condition lake levels represent a reference hydrologic condition of the lake in which the total regional groundwater pumping impacting the lake is constant from 1948 to 2018 at a rate of averaged pumping from 2014 to 2018. Assuming the present climatic, rainfall, and other conditions of the period from 1948 to 2018 are representative of the conditions over the next 71 years, the current-pumping condition lake levels would reflect the future condition of the lake levels if the average regional groundwater pumping does not change from the period 2014 to 2018 condition. Because of our limited understanding of possible future climatic conditions and uncertainties in global climate model predictions, using historical conditions to generate current-pumping condition lake levels is reasonable. Therefore, the no-pumping and current-pumping condition lake level datasets shown in Figure B - 24 were used to assess the MFLs of the Lake Butler Chain.

SUMMARY AND CONCLUSIONS

For long-term lake level simulations and MFLs status assessments of the Lake Butler Chain, the original SWMM model was updated. The original model was calibrated for the period from 1995 to 2016. The SJRWMD subsequently extended the model to the period from 1948 to 2018. The model extension included reviewing, compiling, and creating long-term historical datasets, such as hydro-meteorological, lake levels, and groundwater levels data, which were used as model input and boundary conditions. The bathymetry data used in the original SWMM model was also updated with the recently collected high resolution bathymetry data.

The model was re-calibrated with additional parameters such as evaporation fraction from the upper unsaturated zone and groundwater flow coefficient, and the leakance values beneath the lake. Such modifications significantly improved the groundwater continuity error and the match between simulated and observed lake levels. Overall, goodness-of-fit values of Nash-Sutcliffe efficiency and Pearson correlation coefficient increased above 0.85.

For long-term lake level simulations, no-pumping and current-pumping conditions groundwater levels were created to assess pumping impacts. The no-pumping groundwater levels were created based on estimated UFA drawdowns beneath the lake and observed groundwater levels. The groundwater levels and UFA drawdowns beneath the lake under a wide-range of pumping conditions were simulated using the Volusia groundwater model. Because the groundwater model was developed for steady-state conditions, the model cannot simulate monthly UFA drawdowns due to pumping over the period 1948 to 2018. A linear relationship was developed between simulated groundwater pumping and UFA drawdowns beneath the lake for a steady-state condition. Based on the developed relationship and monthly water use data from the SJRWMD databases, monthly drawdowns were estimated. The monthly UFA drawdowns were later disaggregated to daily values and added to daily observed groundwater levels of the period 1948 to 2018 to create no-pumping condition groundwater levels. Then, the current-pumping condition groundwater level datasets were generated by subtracting the drawdown (impact) values of the past five years (from 2014 to 2018) average from the no-pumping groundwater levels.

Finally, the no-pumping and current-pumping condition groundwater levels were fed into the updated SWMM model as boundary conditions. The no-pumping lake levels represent hydrologic conditions in which the lake was assumed to be not under the influence of groundwater pumping, whereas the current pumping lake levels represent hydrologic conditions in which the lake was assumed to be under the impact of current groundwater pumping since 1948. The corresponding long-term lake levels were simulated by the updated SWMM model and used for MFLs status assessments.

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Attachment A

Attachment A - 1: Aquifers parameters used by the previously developed SWMM model.

Aquifers	Ksat (in/hr)	Etu (-)	Ets (ft)	LGLR (in/hr)	Esurf (ft)	Ebot (ft)	Egw (ft)	Thickness (ft)
A1000	14.25	0.35	5	14.25	41.471	35.471	35.471	6
A1001	7.328	0.5	5	0.023	26.63	25.73	25.93	0.9
A1002	10.509	0.35	5	0.05	30.458	24.458	25.606	6
A1003	7.008	0.5	5	0.023	28.464	27.564	27.764	0.9
A1004	11.198	0.35	5	11.198	41.042	35.042	35.249	6
A1009	7.854	0.5	5	0.023	9.813	8.913	9.113	0.9
A1010	4.884	0.5	5	0.023	36.252	35.352	35.552	0.9
A1012	6.379	0.5	5	0.023	9.688	8.788	8.988	0.9
A1013	12.038	0.35	5	12.038	23.395	17.395	18.672	6
A1014	11.179	0.35	5	0.01	29.385	23.385	24.424	6
A1015	6.829	0.5	5	0.023	10.499	9.599	9.799	0.9
A1016	7.315	0.5	5	0.023	14.76	13.86	14.06	0.9
A1017	6.591	0.35	5	6.591	14.76	8.76	9.225	6
A1021	11.152	0.35	5	11.152	14.76	8.76	9.834	6
A1022	6.901	0.5	5	0.023	14.76	13.86	14.06	0.9
A1023	10.867	0.5	5	0.023	14.76	13.86	14.06	0.9
A1024	11.45	0.35	5	11.45	14.76	8.76	9.207	6
A1026	8.229	0.35	5	8.229	14.76	8.76	9.731	6
A1027	10.122	0.35	5	10.122	18.692	12.692	12.901	6
A1028	9.805	0.35	5	9.805	17.14	11.14	11.495	6
A1029	6.818	0.5	5	0.023	17.44	16.54	16.74	0.9
A1030	12.984	0.35	5	12.984	15.78	9.78	10.74	6
A1031	6.9	0.35	5	6.9	22	16	17.411	6
A1032	8.934	0.5	5	0.023	17.44	16.54	16.74	0.9
A1035	9.689	0.5	5	0.023	17.921	17.021	17.221	0.9
A1037	8.848	0.35	5	8.848	28.84	22.84	23.62	6
A1064	7.315	0.5	5	0.023	14.76	13.86	14.06	0.9
A1019	11.743	0.35	5	11.743	23.261	17.261	17.558	6
A1020	14.25	0.35	5	14.25	19.408	13.408	13.408	6
A1025	9.569	0.35	5	9.569	17.748	11.748	12.087	6

Note: Ksat = Saturated hydraulic conductivity, Etu = Evaporation fraction from the upper unsaturated zone; Ets = Lower evaporation depth from the lower saturated zone; LGLR = Lower groundwater loss rate; Esurf = ground surface elevation; Ebot = Bottom elevation; Egw = Water table elevation. Blue values show LGLR greater than 0.1 inch per hour. Red values represent surficial aquifers thickness less than 1 foot.

Attachment A - 2: Continuity error summaries of the Lake Butler Chain SWMM model.

Module	SWMM original		10 ft reduced bottom elevation		10 ft reduced + LGLR = 0.00086	
Runoff Quantity Continuity	Volume acre-feet	Depth inches	Volume acre-feet	Depth inches	Volume acre-feet	Depth inches
Total Precipitation	762137.4	1182.4	762137.4	1182.4	762137.4	1182.4
Evaporation Loss	22217.4	34.5	21058.4	32.7	21074.2	32.7
Infiltration Loss	680590.9	1055.9	691044.2	1072.1	690976.4	1072.0
Surface Runoff	65548.4	101.7	55747.3	86.5	55806.3	86.6
Final Storage	0.0	0.0	0.0	0.0	0.0	0.0
Continuity Error (%)	**-0.82**		**-0.75**		**-0.75**	
Groundwater Continuity	Volume acre-feet	Depth inches	Volume acre-feet	Depth inches	Volume acre-feet	Depth inches
Initial Storage	3070.9	4.8	26249.9	40.7	26249.9	40.7
Infiltration	680590.9	1055.9	691044.2	1072.1	690976.4	1072.0
Upper Zone ET	228290.7	354.2	307425.8	476.9	304476.1	472.4
Lower Zone ET	171404.4	265.9	383.1	0.6	35379.9	54.9
Deep Percolation	359248.7	557.3	400918.9	622.0	266546.8	413.5
Groundwater Flow	2664.7	4.1	117.5	0.2	99798.6	154.8
Final Storage	771.7	1.2	4464.3	6.9	10814.3	16.8
Continuity Error (%)	**-11.51**		**0.56**		**0.03**	
Flow Routing Continuity	Volume acre-feet	Volume 10^6 gal	Volume acre-feet	Volume 10^6 gal	Volume acre-feet	Volume 10^6 gal
Dry Weather Inflow	0.0	0.0	0.0	0.0	0.0	0.0
Wet Weather Inflow	65545.3	21358.9	55744.4	18165.1	55802.5	18184.1
Groundwater Inflow	2664.7	868.3	117.5	38.3	99798.6	32520.9
RDII Inflow	0.0	0.0	0.0	0.0	0.0	0.0
External Inflow	738653.7	240701.3	738654.5	240701.6	738639.4	240696.7
External Outflow	56657.9	18462.8	48522.6	15811.8	112620.5	36699.1
Flooding Loss	572541.3	186571.1	579989.8	188998.3	546315.8	178025.2
Evaporation Loss	168948.7	55054.5	159660.0	52027.6	198804.1	64783.3
Exfiltration Loss	14823.1	4830.3	13105.3	4270.6	39727.1	12945.7
Initial Stored Volume	7569.4	2466.6	7569.4	2466.6	7569.4	2466.6
Final Stored Volume	1711.8	557.8	1117.1	364.0	4217.0	1374.2
Continuity Error (%)	**-0.03**		**-0.04**		**0.01**	

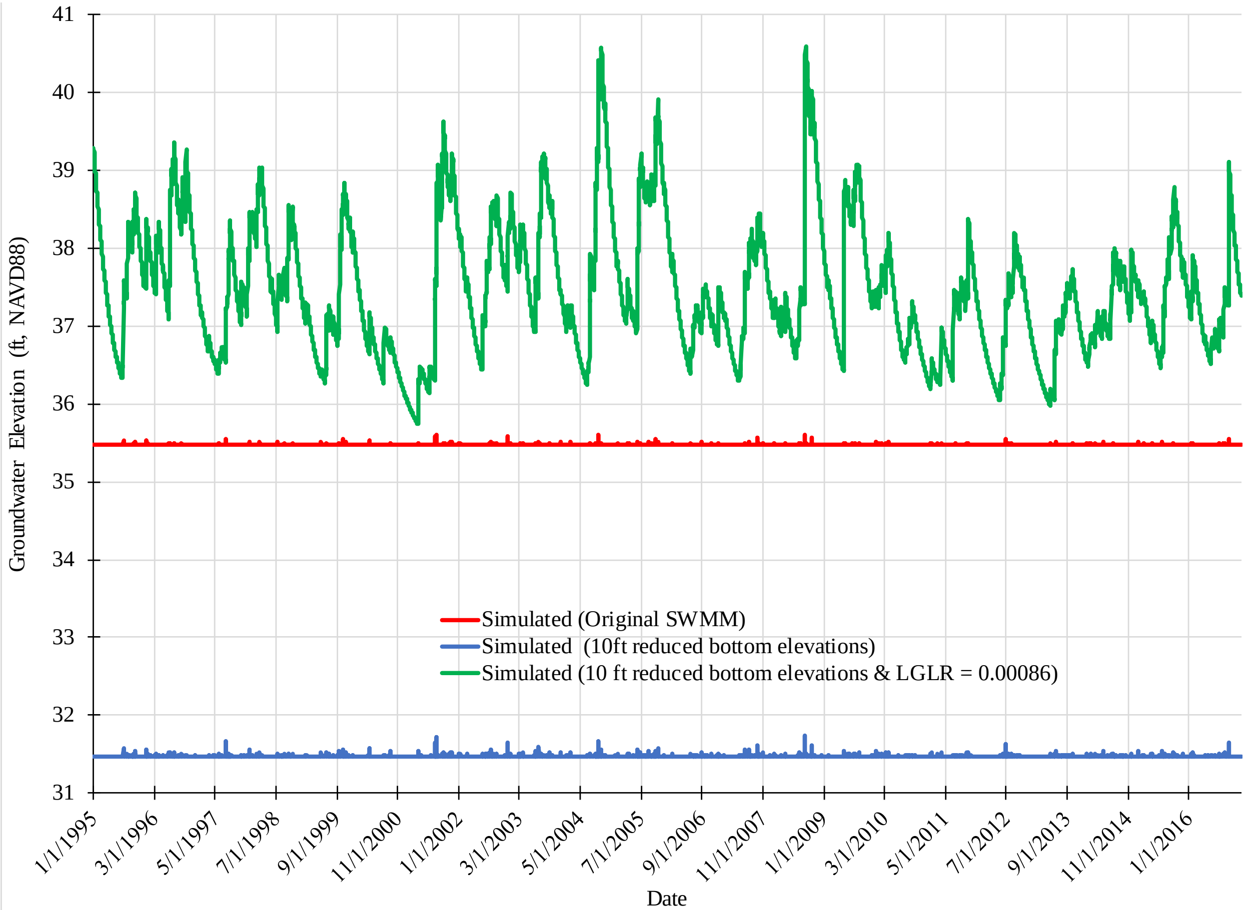
Note: LGLR = Lower Groundwater Loss Rate (inch per hour0

Attachment A - 3: Recalibrated groundwater parameter values of SWMM model. Bold refers re-calibrated values

Sub-basin	Aquifers	Node	Esurf-Org	Ebot-Org	Ebot_recalibrated	LGLR-Org	LGLR_recalibrated	Etu-Org	Etu - recalibrated	A1-Org	A1-recalibrated
B1000	A1000	N1000	41.471	35.471	**31.471**	14.25	**0.00086**	0.35	**0.45**	0.001	**0.0001**
B1001	A1001	N1001	26.63	25.73	**16.63**	0.023	0.023	0.5	0.5	0.001	0.001
B1002	A1002	N1002	30.458	24.458	**20.458**	0.05	0.05	0.35	0.35	0.001	0.001
B1003	A1003	N1003	28.464	27.564	**18.564**	0.023	0.023	0.5	0.5	0.001	0.001
B1004	A1004	N1004	41.042	35.042	**31.042**	11.198	**0.00086**	0.35	**0.45**	0.001	**0.0001**
B1009	A1009	N1009	9.813	8.913	**-0.187**	0.023	0.023	0.5	0.5	0.001	0.001
B1010	A1010	N1010	36.252	35.352	**26.252**	0.023	0.023	0.5	0.5	0.001	0.001
B1012	A1012	N1012	9.688	8.788	**-0.312**	0.023	0.023	0.5	0.5	0.001	0.001
B1013	A1013	N1013	23.395	17.395	**13.395**	12.038	**0.00086**	0.35	**0.45**	0.001	**0.0001**
B1014	A1014	N1014	29.385	23.385	**19.385**	0.01	0.01	0.35	0.35	0.001	0.001
B1015	A1015	N1015	10.499	9.599	**0.499**	0.023	0.023	0.5	0.5	0.001	0.001
B1016	A1016	N1016	14.76	13.86	**4.76**	0.023	0.023	0.5	0.5	0.001	0.001
B1017	A1017	N1017	14.76	8.76	**4.76**	6.591	**0.00086**	0.35	**0.45**	0.001	**0.0001**
B1021	A1021	N1021	14.76	8.76	**4.76**	11.152	**0.00086**	0.35	**0.45**	0.001	**0.0001**
B1022	A1022	N1022	14.76	13.86	**4.76**	0.023	0.023	0.5	0.5	0.001	0.001
B1023	A1023	N1023	14.76	13.86	**4.76**	0.023	0.023	0.5	0.5	0.001	0.001
B1024	A1024	N1024	14.76	8.76	**4.76**	11.45	**0.00086**	0.35	**0.45**	0.001	**0.0001**
B1026	A1026	N1026	14.76	8.76	**4.76**	8.229	**0.00086**	0.35	**0.45**	0.001	**0.0001**
B1027	A1027	N1027	18.692	12.692	**8.692**	10.122	**0.00086**	0.35	**0.45**	0.001	**0.0001**
B1028	A1028	N1028	17.14	11.14	**7.14**	9.805	**0.00086**	0.35	**0.45**	0.001	**0.0001**
B1029	A1029	N1029	17.44	16.54	**7.44**	0.023	0.023	0.5	0.5	0.001	0.001
B1030	A1030	N1030	15.78	9.78	**5.78**	12.984	**0.00086**	0.35	**0.45**	0.001	**0.0001**
B1031	A1031	N1031	22	16	**12**	6.9	**0.00086**	0.35	**0.45**	0.001	**0.0001**
B1032	A1032	N1032	17.44	16.54	**7.44**	0.023	0.023	0.5	0.5	0.001	0.001
B1035	A1035	N1035	17.921	17.021	**7.921**	0.023	0.023	0.5	0.5	0.001	0.001
B1037	A1037	N1037	28.84	22.84	**18.84**	8.848	**0.00086**	0.35	**0.45**	0.001	**0.0001**
B1064	A1064	N1064	14.76	13.86	**4.76**	0.023	0.023	0.5	0.5	0.001	0.001
B1019	A1019	N1019	23.261	17.261	**13.261**	11.743	**0.00086**	0.35	**0.45**	0.001	**0.0001**
B1020	A1020	N1020	19.408	13.408	**9.408**	14.25	**0.00086**	0.35	**0.45**	0.001	**0.0001**
B1025	A1025	N1025	17.748	11.748	**7.748**	9.569	**0.00086**	0.35	**0.45**	0.001	**0.0001**

Note: Org = Original; Esurf = Surface elevation in feet; Ebot = Bottom elevation in feet; LGLR = Lower groundwater loss rate (inch per hour); Etu = Evaporation fraction from the upper unsaturated zone; A1 = Groundwater flow coefficient (unitless).

Attachment A - 4: Impacts of bottom elevations and lower groundwater loss rate (LGLR) on simulated groundwater elevations of sub-basin 1000.



Attachment A - 5: Impacts of bottom elevation and lower groundwater loss rate on daily simulated levels of Lake Butler Chain. LGLR = Lower Groundwater Loss Rate.