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 water bodies, determining minimum flows and levels (MFLs) and assessing the status of waterbodies requires substantial hydrological analysis. The main purposes of the hydrological analysis to better understand the impact from groundwater pumping on lake levels and to develop a no- and current-pumping conditions long-term lake levels for MFL determination and assessment. Several steps were involved in performing the hydrologic analysis for the Lakes Brooklyn and Geneva MFLs determination and assessment, including:

1. Review of available data
2. Long-term rainfall analysis
3. Historical Groundwater pumping impact assessment
4. Development of lake level datasets representing no- and current-pumping conditions
5. Estimating available water (freeboard or deficit).

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

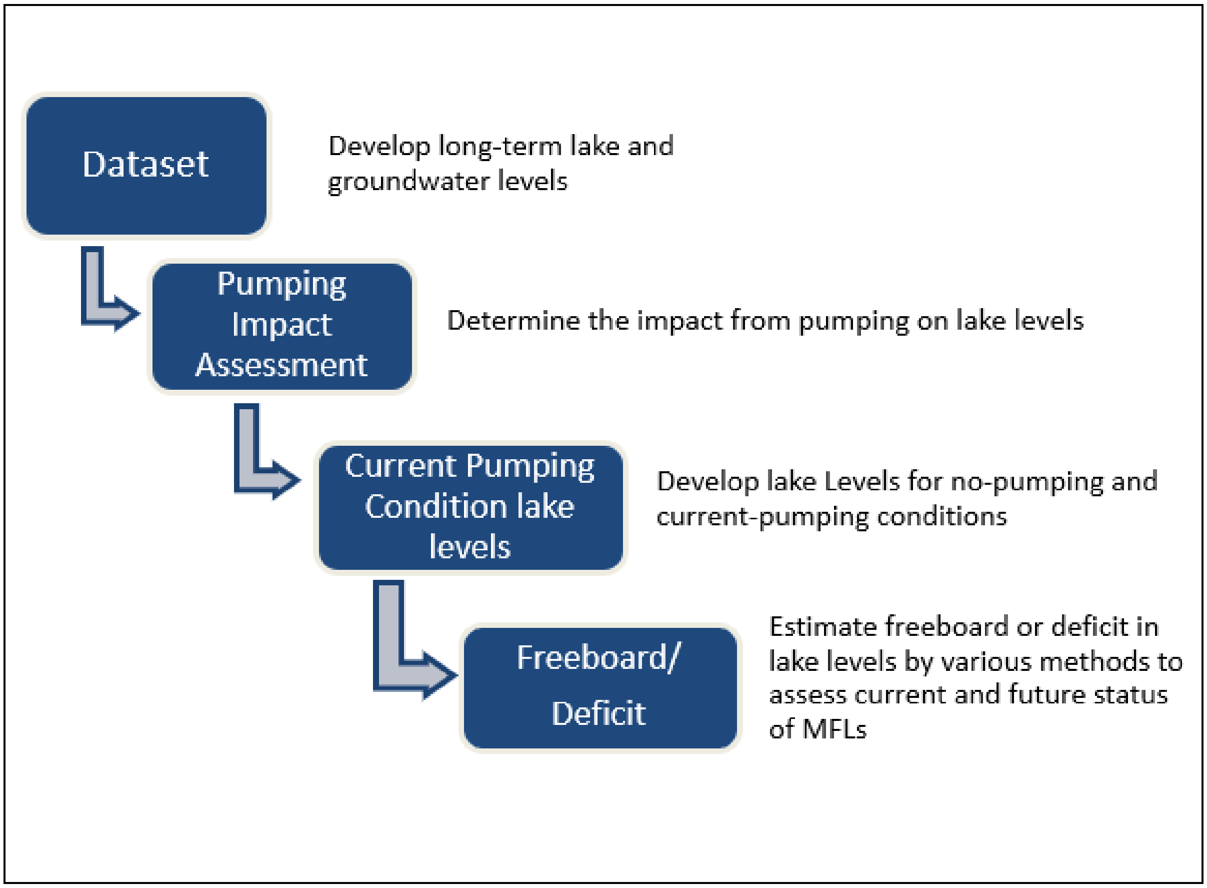

Figure B - 1. Flowchart for hydrological analysis process

SITE DESCRIPTION

Lakes Brooklyn and Geneva are sandhill/sinkhole lakes in southwestern Clay county, adjacent to the city of Keystone Heights, Florida (Figure B-1). They are among the most studied lakes in the District. Lakes Brooklyn and Geneva are part of a chain of lakes in the Upper Etonia Creek Basin (UECB). From highest to lowest elevation, these lakes include; Blue Pond, Lake Lowery, Magnolia Lake, Lake Brooklyn, Lake Keystone, Lake Geneva, and Oldfield Pond and Halfmoon Lake. Halfmoon lake is connected to Etonia Creek through Putnam and Goodson Prairies.

Alligator Creek is an intermittent stream that connects Blue pond, Lake Lowry, Lake Magnolia and Lake Brooklyn (Figure B-2). Alligator Creek provides inflows at the north shore of Lake Brooklyn and, during high water levels, outflow occurs on the southwestern shore of the lake. This outflow drains to Lake Keystone, which discharges to Lake Geneva, and ultimately to Etonia Creek and the St. Johns River (Motz et al 1991).

Surface water inflows are an important part of lake water budgets. The surface water inflow accounts for 81% of Magnolia Lake's inflow according to Motz (2001) and 71% of Brooklyn Lake's inflow according to Goodrich (1999). Lake Geneva has been an isolated lake since the 1970s. Inflow from Lake Brooklyn has ceased since then, except for a very brief period in 1998.

The Keystone Heights region sits at the southern end of the Trail Ridge, a formation of relatively high elevation sand hills traversing southern Georgia through northern Florida. The Trail Ridge is an extensive eolian transgressive (former coastal) dune that extends from Keystone Heights into southeastern Georgia (Force and Rich, 1989). Elevations along the Trail Ridge are amongst the highest in northeast Florida. The lakes in the UECB form a chain of decreasing elevation that fosters surface water inflow and sheet flow from the higher elevation lakes into the lower ones (Annable and Motz, 1996). Ground elevation near Keystone Heights declines southward and ranges from 205 ft NAVD88 to 100 ft NAVD88 (Gordu, 2014).

Lakes Geneva and Brooklyn are characterized by a large water level fluctuation range. Stability of lake levels in the UECB vary considerably. Of 121 Florida lakes, for which long term stage data are available, lakes within the UECB are among the most stable (e.g., Blue Pond) and among the most variable (e.g., Lake Brooklyn; Motz et al., 1991). Lake stage in the UECB correlates well with water table depth in the surficial aquifer system (SAS) (Annable 1996). The degree of connection to the aquifer is inconsistent between lakes (Clark, 1964). The connection between the UFA and lakes of the UECB results from sinkhole formation (Schiffer, 1998, Kindinger, 1999). Numerous collapse features lacking restrictive clay horizons have been identified within Lake Brooklyn (SDI 1992). Several field investigations were performed using seismic reflection surveys by Kindinger et al. (1994 and 1998) in the area, which revealed many sinkhole features in the lakes.

A thick, low-permeability confining layer exists throughout the basin, limiting vertical leakage to the UFA. Yobbi & Chappell (1979) studied the hydrology of the UECB by analyzing recharge and relationship between the rainfall and lake and groundwater levels. In this study, net average recharge to the UFA over the entire basin was estimated at 14 to 17 inches per year using water budget calculations. However, many lakes within this basin are sinkhole lakes and have significant connection to the UFA, allowing a significant amount of recharge to the UFA through vertical leakage. Consistent with this general pattern, Epting et al. (2008) classified Lakes Brooklyn and Geneva as isolated / intermittent sinkhole lakes with high leakage to the UFA. This high degree of connectivity between lakes and the UFA result in these lakes being an important recharge source to the UFA (Merritt, 2001, Bentley, 1977). Deevey (1988) estimated leakage from Lake Brooklyn to the UFA at a long-term average rate of approximately 36 inches per year from 1954 to 1986. The seepage from Lake Brooklyn can be very high during wet seasons. Hydraulic seepage meter tests were performed in Brooklyn Lake in a study by Hirsch & Randazzo (2000) to quantify the lake bottom seepage and analyze the factors influencing the lake seepage. The average recharge from Lake Brooklyn to the UFA was calculated in September through November 1997 at a high rate of approximately 100 inches/year. The recharge from Lake Geneva to the UFA, however, is estimated to be relatively modest. Deevey (1988) estimated leakage from Lake Geneva to the UFA at a long-term average rate of approximately 13 inches per year from 1954 to 1986. This indicates that Lake Brooklyn has much higher connection to the UFA than Lake Geneva does.

The UFA is confined and exhibits an elevated potentiometric surface (Annable et al., 1996) in this region. This confinement can restrict recharge from the SAS in areas surrounding the lakes while the lakes themselves act as conduits of infiltration. Thus, the UFA levels and Lakes Brooklyn and Geneva levels strongly influenced each other. Significant recharge to the UFA through these lakes in conjunction with relatively low transmissivity of the UFA has caused a doming of the potentiometric surface in this area.

The UFA horizontal flow direction is generally radially out to the north, west, and east in the study area. However, during dry years, it can be southeast due to impact of low lake levels on the UFA. The SAS horizontal flow direction is generally toward nearby lakes and overall is south in the study area. Vertically, the SAS flow direction is down.

Groundwater is pumped mostly from the UFA for public supply, agriculture, and mining near lakes. In addition to permitted users, a significant number of domestic self-supply water users are near the lakes.

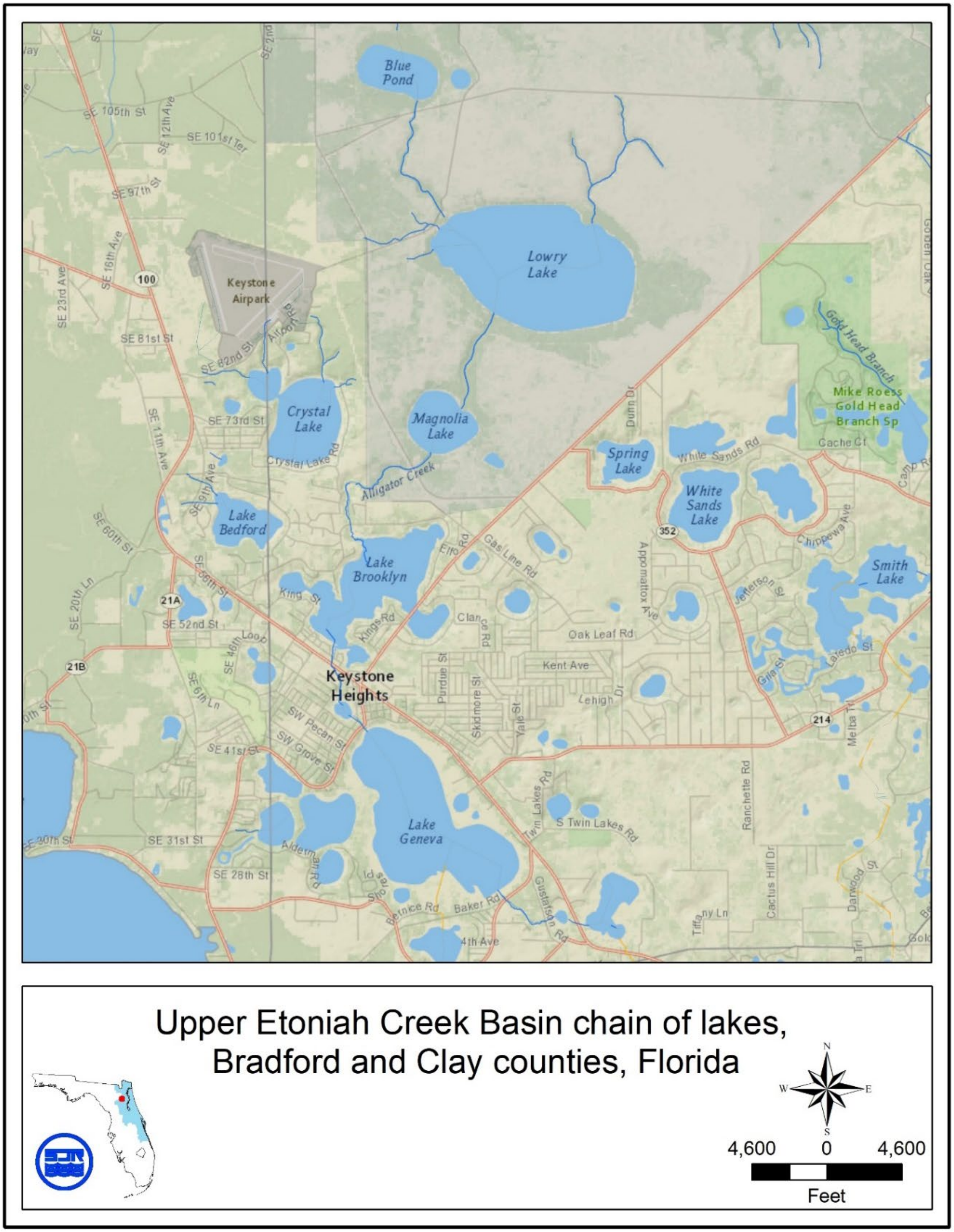

Figure B-2. Site Location Map

REVIEW OF AVAILABLE DATA

Rainfall

A composite rainfall dataset was compiled for Lakes Brooklyn and Geneva, because there is no rainfall gage near Keystone Heights with a long-term rainfall record (Figure B-3). The composite rainfall record was made from the following gauges: several Gainesville NOAA gauges from 1874 to 1989; Lake Brooklyn gauges from 1989 to 1991; Lake Geneva gauges with some additions from Lake Brooklyn from 1991 to 2001; Lake Lily gauges in 2002; and Gold head State Park gauges from 2002 to 2020. Over the long-term record, annual rainfall has ranged from 32.8 to 73.3 inches, and average annual rainfall over the POR is 50.8 inches, with a standard deviation of 8.8 inches.

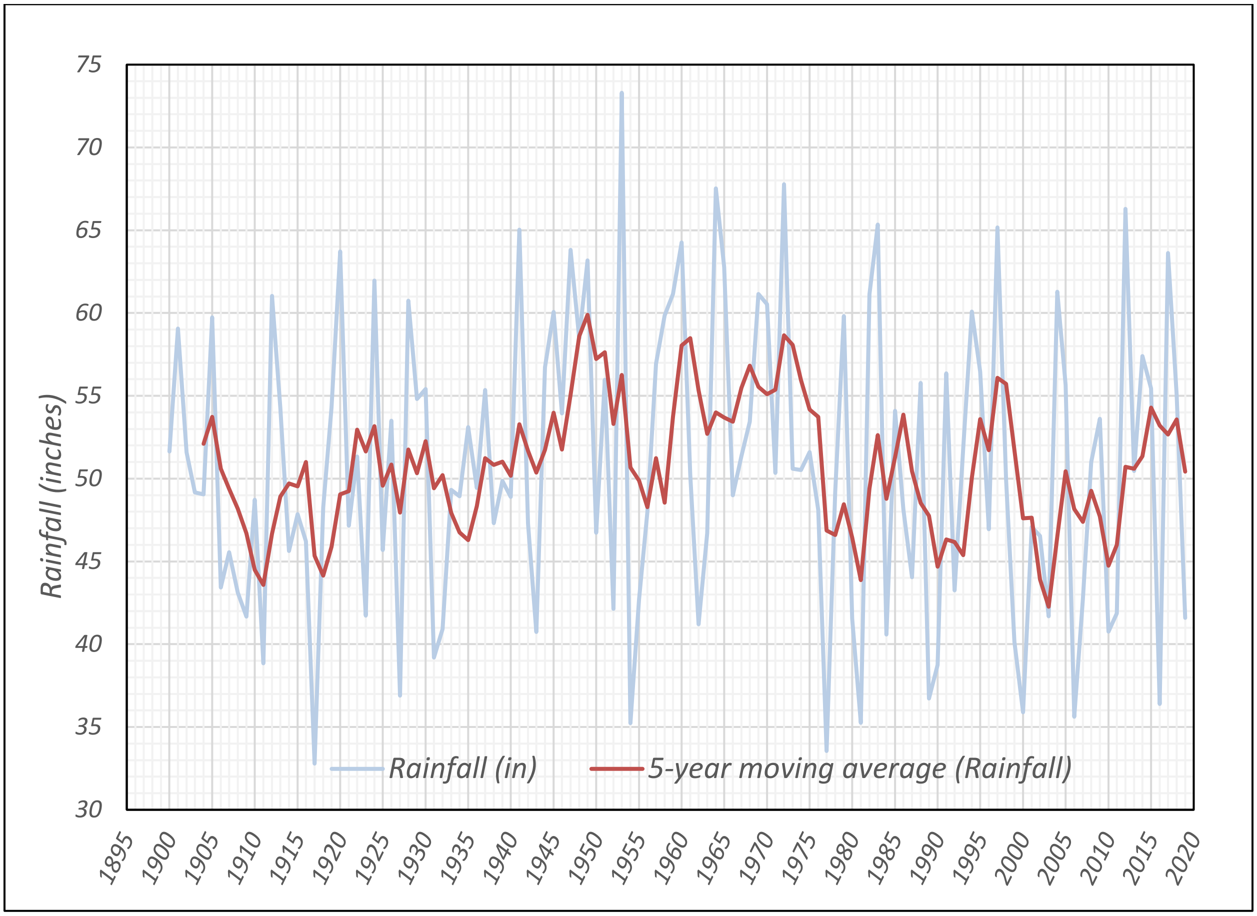

Figure B-3. Annual average rainfall

Water Level

The water level data for both lakes were retrieved from the SJRWMD database. Table B-1 summarizes the available dataset.

Figures B-4 and B-5 show the number of available water level records for Lakes Brooklyn and Geneva respectively. Figure B-6 shows observed water levels for Lakes Brooklyn and Geneva.

Table B-1. Summary of available water level data

Station Number	Station Name	Water Level Period of Record*
3360373	Lake Brooklyn at Keystone Heights	7/17/1957 - Current
11590497	Lake Geneva at Keystone Heights	7/1/1957 –Current

*Before 1957, there was only one measurement available which was in July 1948

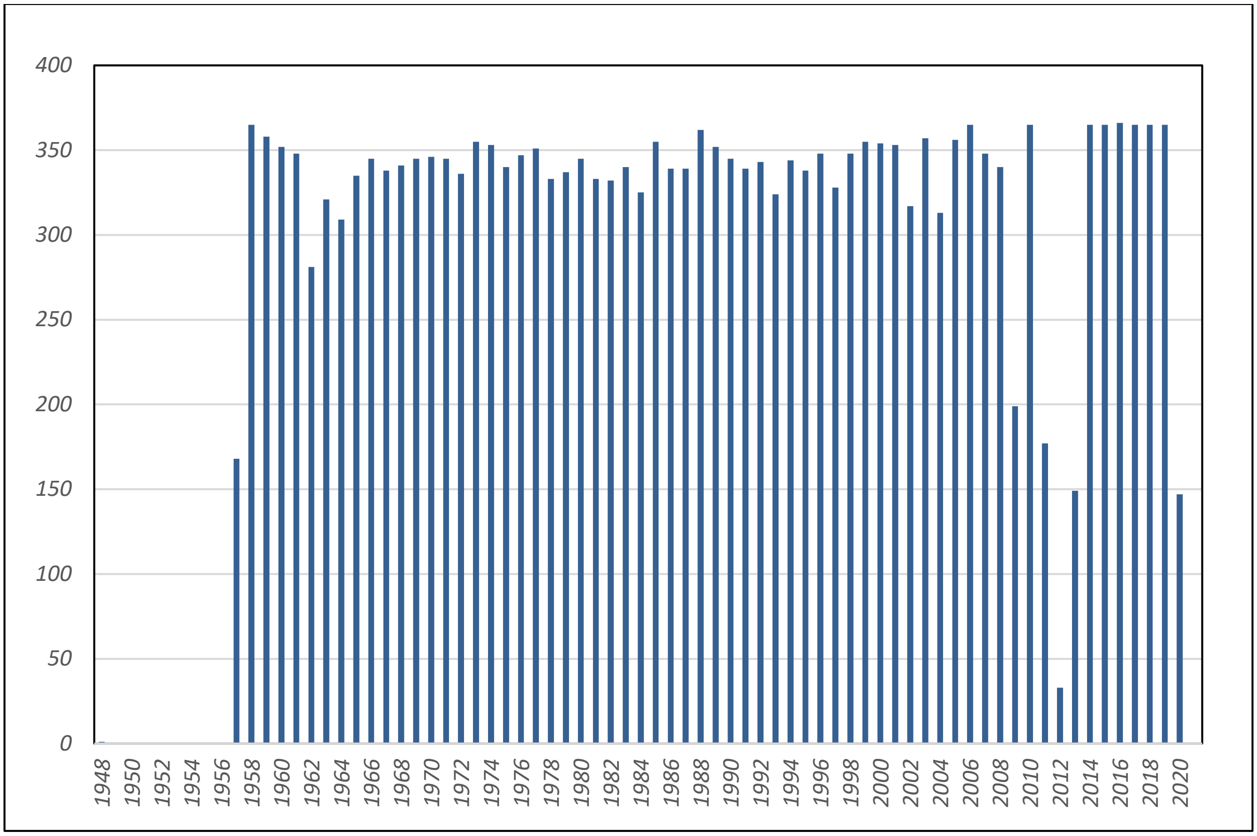

Figure B-4. Lake Brooklyn number of available water level records per year

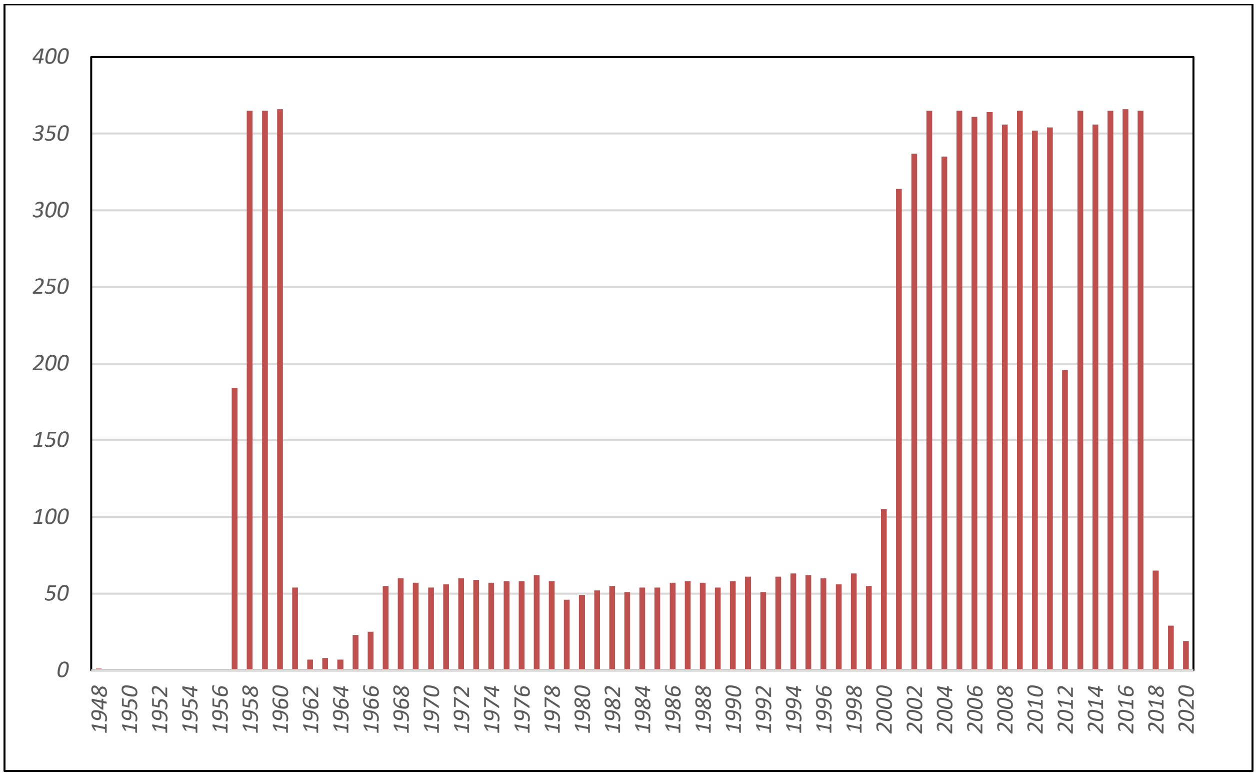

Figure B-5. Lake Geneva number of available water level records per year

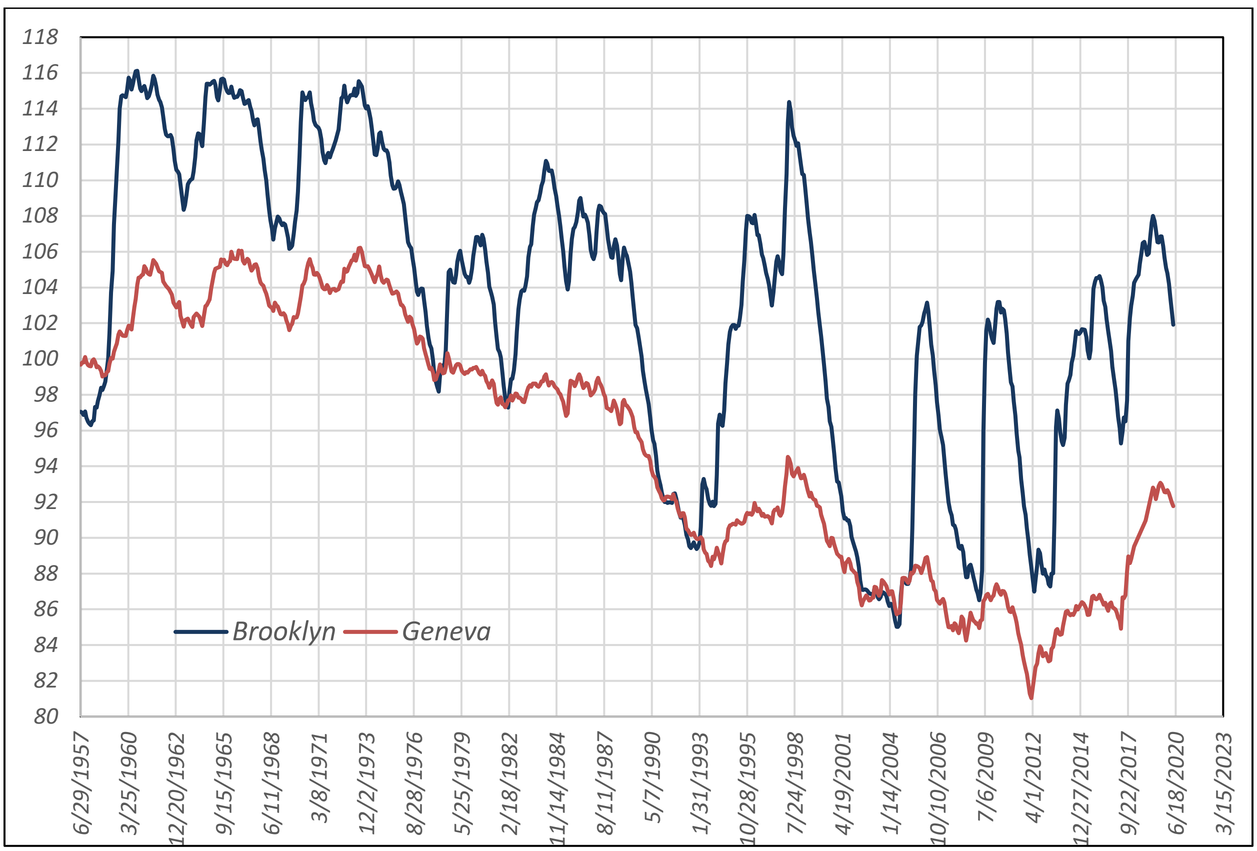

Figure B-6. Lakes Brooklyn and Geneva Water Levels

Lake Brooklyn's hydrograph reflects the influence of periodic surface water inflow and a high connectivity with the UFA. Lake Geneva has a markedly different hydrograph shape, relative to Lake Brooklyn. This is because Lake Geneva is less connected to the UFA and does not receive any surface flows from upstream waterbodies during long periods of low rainfall. The stage fluctuations for Lake Brooklyn (31.4 feet) and Lake Geneva (25.5 feet) are among the largest in Florida. Only 4 percent of 121 Florida lakes studied by Motz et al. (1991) exceeded a 20 feet range of fluctuation.

A summary of water level statistics for both lakes, from 1957 to 2019, is provided in Table B-2. The maximum observed water elevation (116.4 feet, NAVD88) for Lake Brooklyn was recorded in October 1960, weeks after Hurricane Donna passed over Florida. The minimum observed water elevation (85.0 feet, NAVD88) for Lake Brooklyn was recorded in July 2004. The maximum observed water elevation (106.4 feet, NAVD88) for Lake Geneva was recorded in July 1973. The minimum observed water elevation (80.9 feet NAVD88) for Lake Geneva was recorded in June 2012.

Table B-2. Water level (WL) summary statistics for Lakes Brooklyn and Geneva; elevations in NAVD88

Descriptive Statistics	Brooklyn WL	Geneva WL
Mean	103	95.2
Standard Error	0.1	0.0
Median	104.4	97.2
Standard Deviation	8.6	7.2
Range	31.4	25.5
Minimum	85.0	80.9
Maximum	116.4	106.4

The review of available data indicated that there was sufficient data available from 1957 to present to be used for the MFL analysis. However, because a complete set of regional groundwater pumping data was not available for 2019 and 2020 at the time of the analysis, only the data from 1957 to 2018 was included.

ANALYSIS OF WATER LEVEL DECLINES

Significant downward trends have been observed in Lakes Brooklyn and Geneva water levels over the past 40 to 50 years. The water levels of lakes Brooklyn and Geneva declined approximately 8 and 12 feet, respectively since 1960s. The magnitudes of average water level declines were estimated based on smoothed long-term average levels. Smoothing was required due to the presence of large fluctuations in water levels. Based on spectral analysis, the longest dominant periodic cycles in water levels were determined to be 12 and 15 years for Lakes Brooklyn and Geneva, respectively. Thus, water levels of the lakes were smoothed by loess smoothing technique using 12-year window for Lake Brooklyn and 15-year window for Lake Geneva to estimate the amount of water level decline occurred over the past 40 to 50 years. (Figure B-7 and B-8).

The primary reason why Lake Geneva declined more than lake Brooklyn is that Lake Brooklyn receives a significant amount of flows from the upstream lakes via Alligator Creek and discharges to Lake Geneva through Keystone Lake only during wet periods. However, Lake Geneva has not received any discharge from Brooklyn Lake since 1970s except for a brief period in 1998.

To help with establishing MFLs, the influences of climate (i.e. long-term rainfall variation) and regional groundwater pumping on lake levels were analyzed to understand the primary cause(s) of lake level declines.

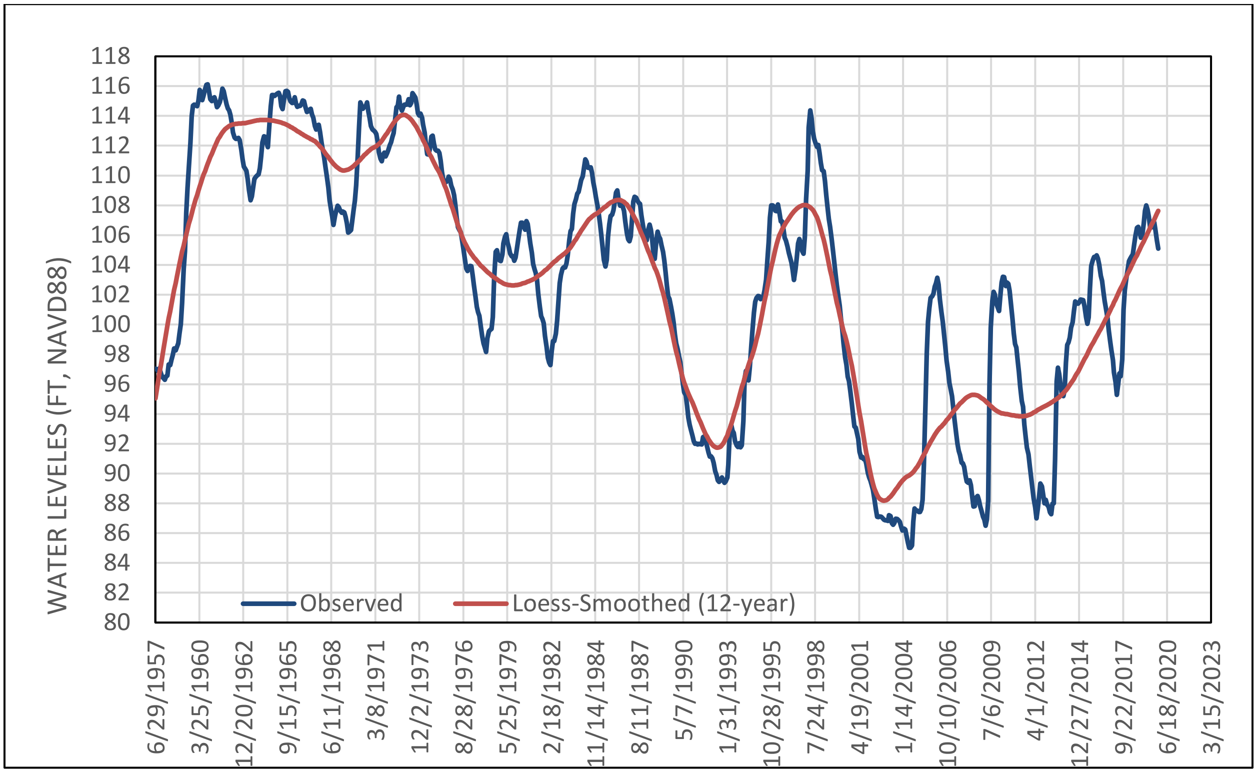

Figure B-7. Lake Brooklyn water levels

Figure B-8. Lake Geneva water levels

Long-term Rainfall Analysis

Analysis of declines in lake levels without understanding the influence of climate (i.e. climatic cycles) on lake system would be difficult. According to Florida Climate Institute, the climatic cycles such as El Nino Southern Oscillations (ENSO), Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO) have the strongest influence on Florida's climate variability (Kirtman et al., 2017).

ENSO cycles typically range from 2 to 7 years, PDO cycles typically range from 15 to 25 years and AMO cycles typically range 60 to 70 years (Schlesinger and Ramankutty 1994, Obeysekera et al. 2011 and Kuss and Gurdak 2014). Because of strong relationships of short and long-term climatic cycles such as ENSO and AMO to rainfall, river flows and groundwater levels in Florida (Enfield et al. 2001; Kelly 2004; Kuss and Gurdak 2014), the relationship of the climatic cycles and rainfall with lake level declines was investigated.

AMO is based on the sea surface temperature of the North Atlantic Ocean. The National Oceanic and Atmosphere Administration (NOAA) indicates that rainfall in central and south Florida becomes more plentiful when the Atlantic Ocean is in its warm phase, and droughts are more frequent in the cool phase. Figure B-9 shows the warm and cool phases of the AMO.

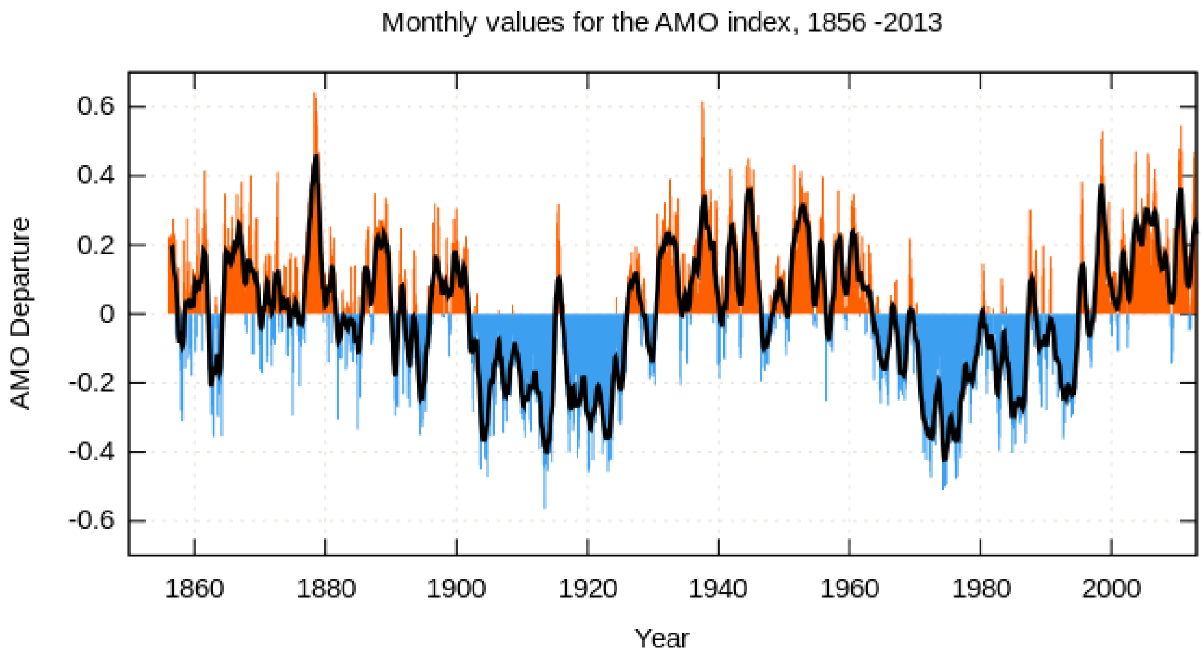

Figure B-9. Atlantic Multidecadal Oscillations

Figure B-10 shows annual rainfall compiled for Keystone Heights region and polynomial trendline. Polynomial trend was provided to better understand the changes in long-term average rainfall. The trend line shown in the figure indicates a potential long-term (about 70 to 80-year) rainfall cycle in which the period from 1945 to 1965 was generally very wet and the periods from 1910 to 1920 and from 1995 to 2005 were generally very dry. The wet and dry periods in long-term rainfall pattern seems to fairly coincide with the warm and cool phases of AMO shown in Figure B-8.

Long-term lake level trends were examined to determine if there is any relationship between the rainfall and climatic cycles and the lake levels. Figure B-10 and B-11 show the Lakes Brooklyn and Geneva monthly levels and polynomial trendlines.   Long term trends in Lakes Brooklyn and Geneva levels indicate a cyclic trend like rainfall and AMO cycle. Lake levels were high during the wet period (1945 to 1965) and were low during the dry period (1995 – 2005).

A close examination of the lake level trends showed that lake levels respond slowly to rainfall pattern. As shown in Figure B-9, there has been an increasing trend in rainfall in the region since 2002. A similar increasing trend can be observed in lake levels (Figures B-11 and B-12). However, the increasing trend in Lake Brooklyn levels seems to begin in 2004 - 2005 whereas the increasing trend in Lake Geneva levels seems to begin in 2013 – 2014. It appears that lakes respond to rainfall with a delay of 2 to 10 years. This could be attributed to the effect of storage in the regional aquifer and watershed and the delay in upstream flows reaching the lakes. It is not unexpected to see that Lake Brooklyn responds much quicker than Lake Geneva to recent increase in rainfall trend because Lake Brooklyn has been receiving a significant amount of surface flows from upstream lakes whereas Lake Geneva has been receiving none and mostly driven by groundwater levels.

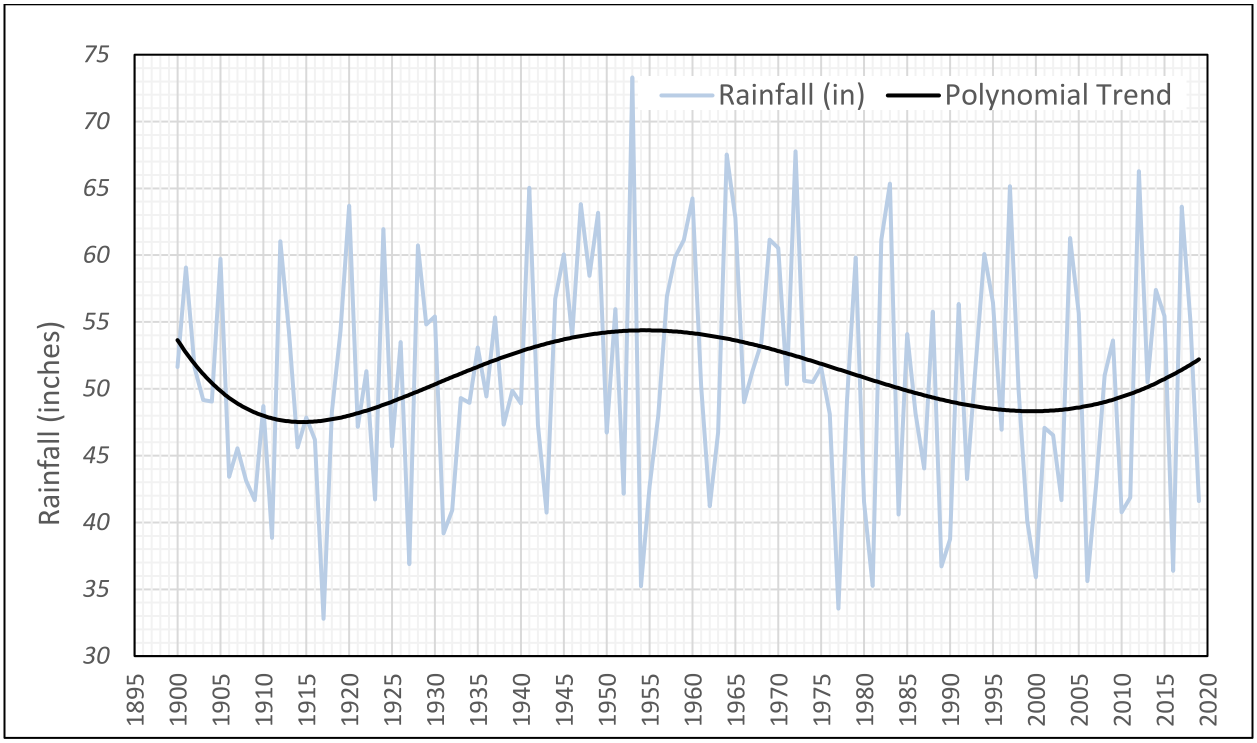

Figure B-10. Long-term rainfall pattern

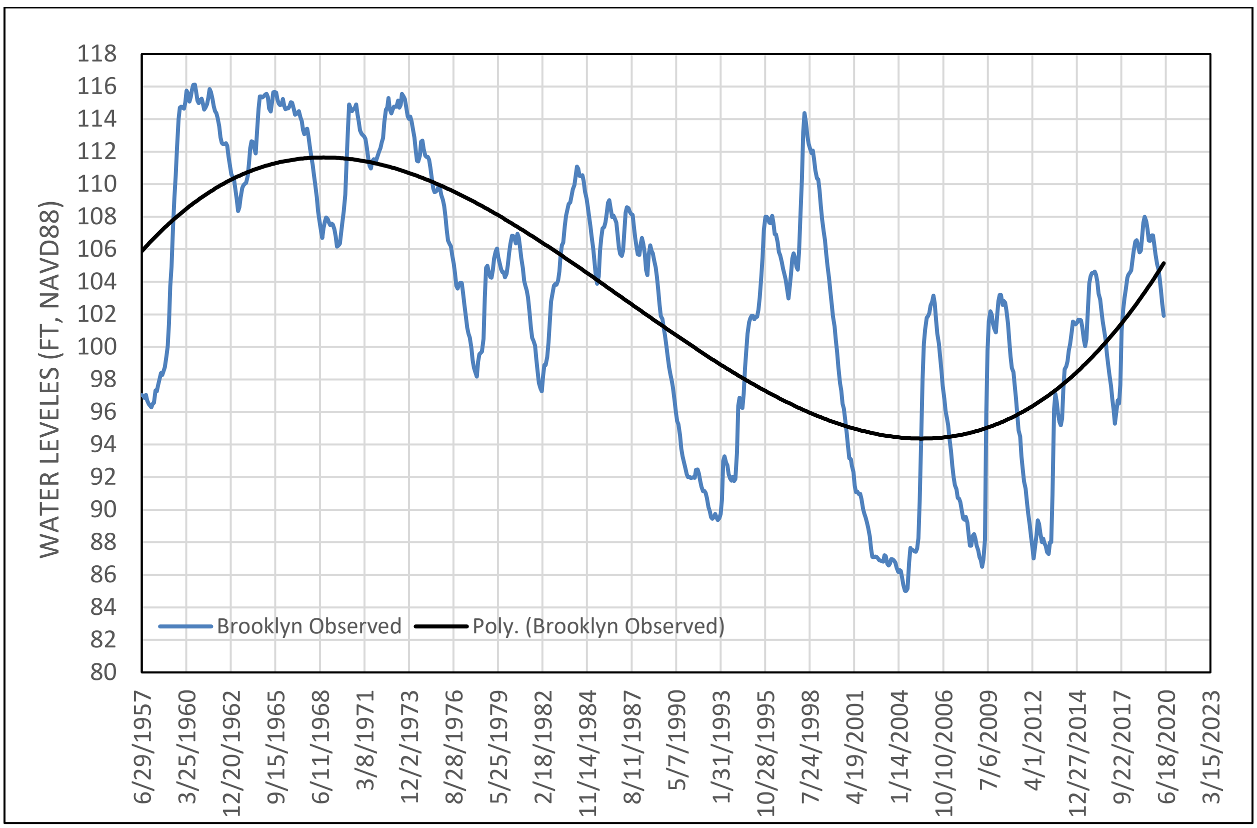

Figure B-11. Long-term trend in Lake Brooklyn levels

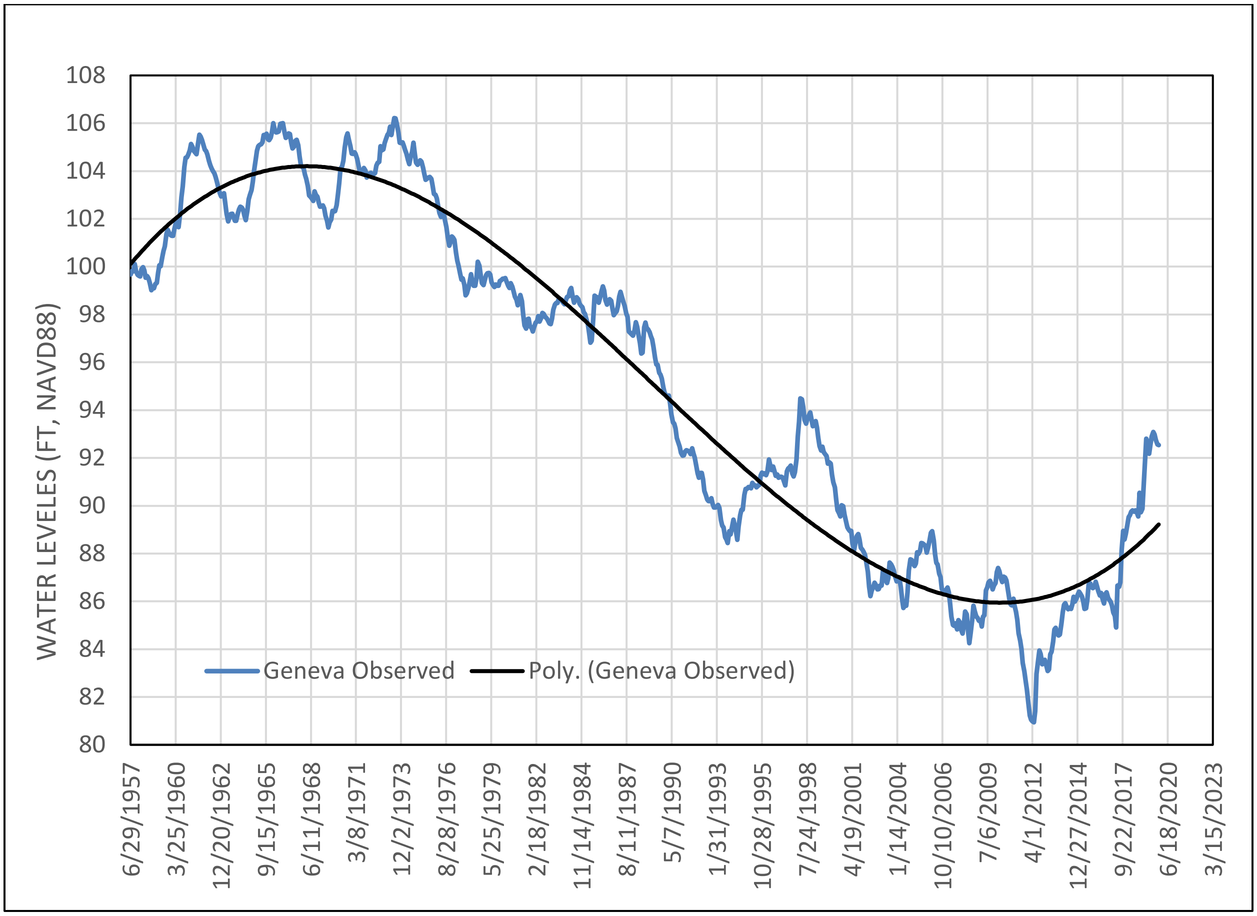

Figure B-12. Long-term trend in Lake Geneva levels

Located within an area of thick sand deposits and being highly connected to the UFA make Lakes Brooklyn and Geneva sensitive to prolonged periods of below average rainfall. Because of this physiographic setting, cumulative (i.e., back to back) years of below average rainfall makes the landscape very dry, contributing to reduction in surface water inflows and recharge to groundwater, causing declines in groundwater levels. This results in lower lake levels. From the 1930s to the early 1970s, there was a cumulative rainfall surplus of approximately 150 inches (Figure B-13). From the early 1970s to 2012, there was a rainfall deficit of approximately 105 inches. This period of reduced surface water inflows and recharge corresponds to a period of water level decline at Lakes Brooklyn and Geneva. This suggests that there is a close relationship between back-to-back years of below or above average rainfall and water levels at these lakes. This also suggests that it may take many years of above average rainfall to offset the effect of prolonged periods of drought on these lakes.

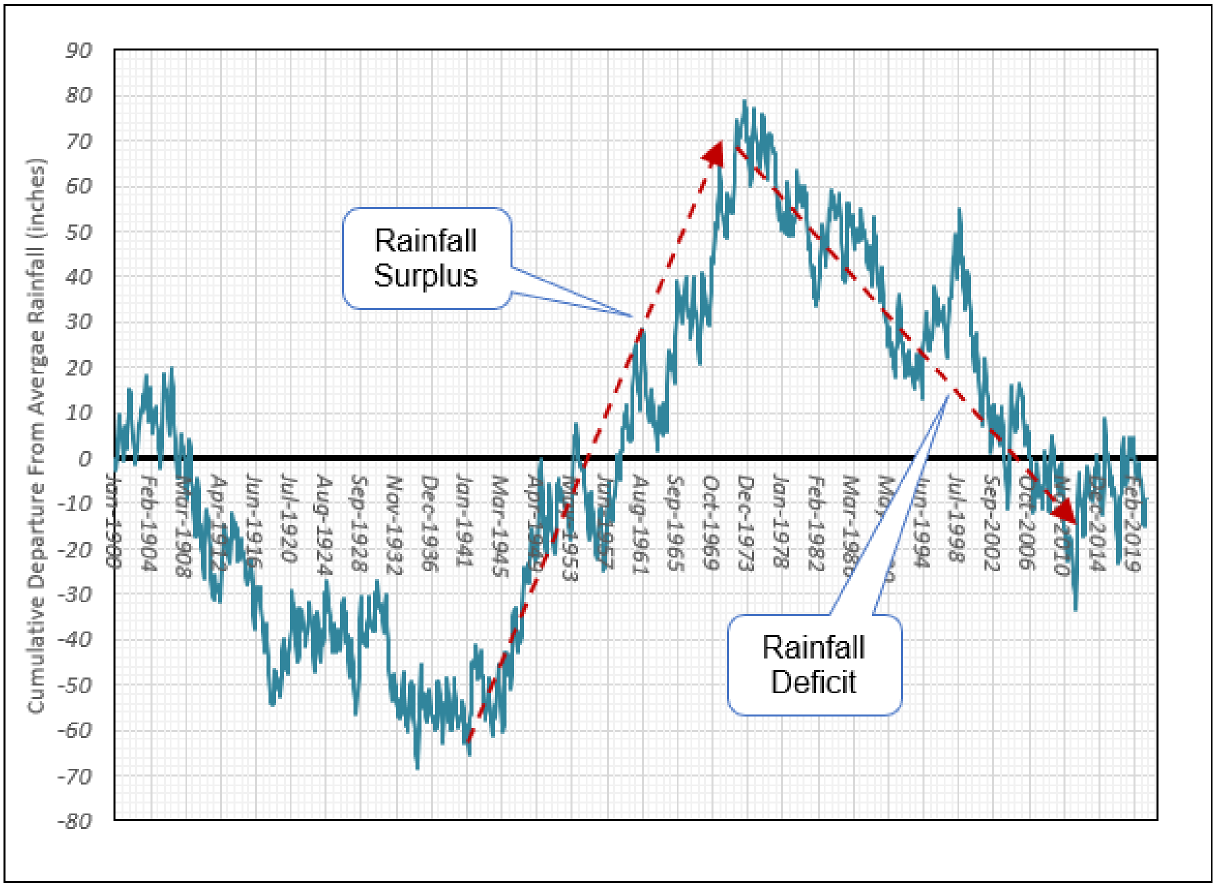

Figure B-13. Cumulative departure from average rainfall

Standardized Precipitation Index (SPI) results also support these findings. The SPI is a widely used index for characterizing meteorological drought on a range of timescales. On short timescales, the SPI is closely related to soil moisture, while at longer timescales, the SPI can be related to groundwater and reservoir storage (Keyantash, 2018). An SPI graph was developed using a composite of Gainesville and local Keystone Heights rainfall data (Figure B-14). As shown in the figure, a wet period (blue areas) was observed from the late 1940s to the late 1970s, followed by several severe dry periods (red areas) after the late 1970s. The latter is the same period when water levels at Lakes Brooklyn and Geneva declined significantly.

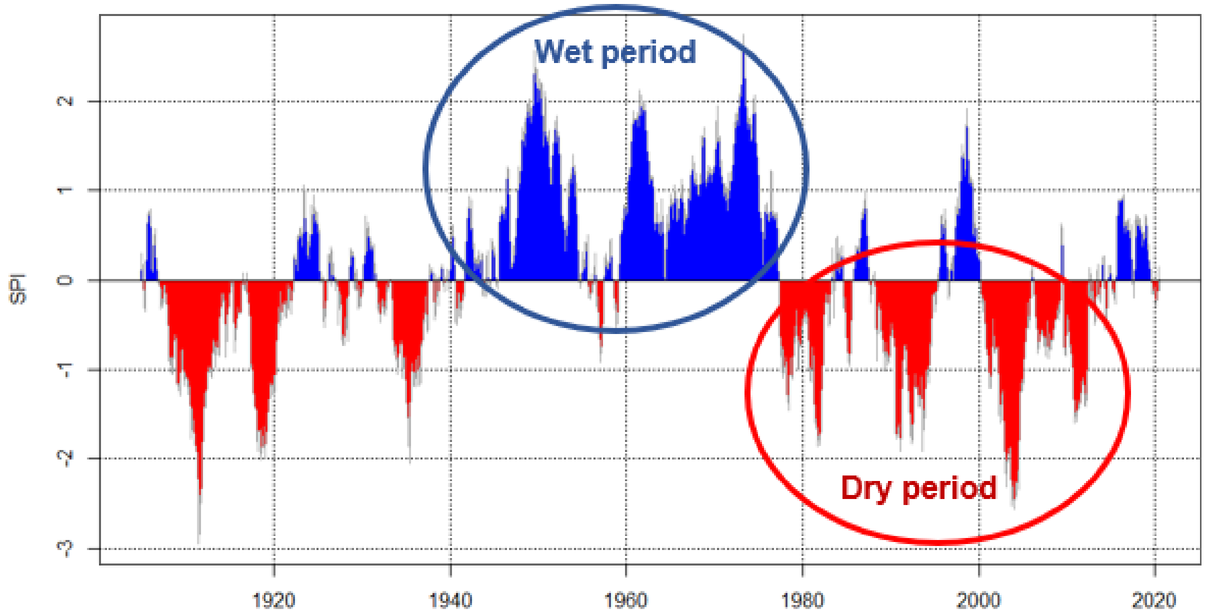

Figure B-14. Long-term 60-month Standard Precipitation Index

A comprehensive body of literature also corroborates that there is a strong correlation between lake levels and rainfall with increasing levels correlated with above average annual rainfall, and declining water levels correlated with below average annual rainfall (Yobbi and Chappell 1979, Motz et al. 1991, Robison 1992, Motz et al. 1994, Motz et al. 1995). Clark et al. (1963) conducted a study focusing on Brooklyn Lake in 1963 after the Brooklyn Lake water level declined approximately 20 feet in 3 years. The purpose of the study was to determine the reason for the steep decline in the lake levels. A water budget analysis was performed, and the study concluded that more than 3 years of drought in conjunction with high rates of leakage caused the 20 feet of declines in lake levels.

Historical Groundwater Pumping Impact Assessment

Lakes Brooklyn and Geneva have developed from collapse or subsidence sinkholes, creating a high degree of connection to the UFA. This makes them sensitive to any adverse changes in the groundwater system. In addition, because these lakes are located at the intersection of several groundwater basins in North Florida, they are also vulnerable to potential impact from regional groundwater pumping. Therefore, potential impact to Lakes Brooklyn and Geneva not only from local pumping but also from regional pumping were assessed.

Groundwater Use

To estimate the impact on lake levels from pumping, monthly groundwater use data was compiled for Alachua, Clay, Duval, Putnam and Bradford counties from 1957 to 2018 (see Figure B-15). The pumping in 2019 and 2020 was not included because complete datasets of 2019 and 2020 pumping were not available at the time of analysis. The five counties were selected because the groundwater use in these counties could potentially impact the groundwater levels near lakes Brooklyn and Geneva most based on regional groundwater modeling efforts such as Northeast Florida (NEF) and North Florida Southeast Georgia (NFSEG) regional groundwater models. It should also be noted that the groundwater pumping within five counties was only used as a proxy to understand the variation of regional groundwater pumping from 1957 to 2018. The impact of groundwater pumping on lake levels were assessed based the entire groundwater pumping within the NFSEG model domain.

The data included actual groundwater use reported by the consumptive use permit holders and estimated groundwater use for domestic self-supply and small agricultural use. As shown in Figure B-15, the total groundwater use in these counties reached its highest in 1988 (323 mgd) and declined until 1994. It increased again till 2006 (302 mgd) and has declined about 20% after 2006. The average groundwater use over the past five years (2014 – 2018) is approximately 238 mgd, which is similar to groundwater use in the early 1970s.

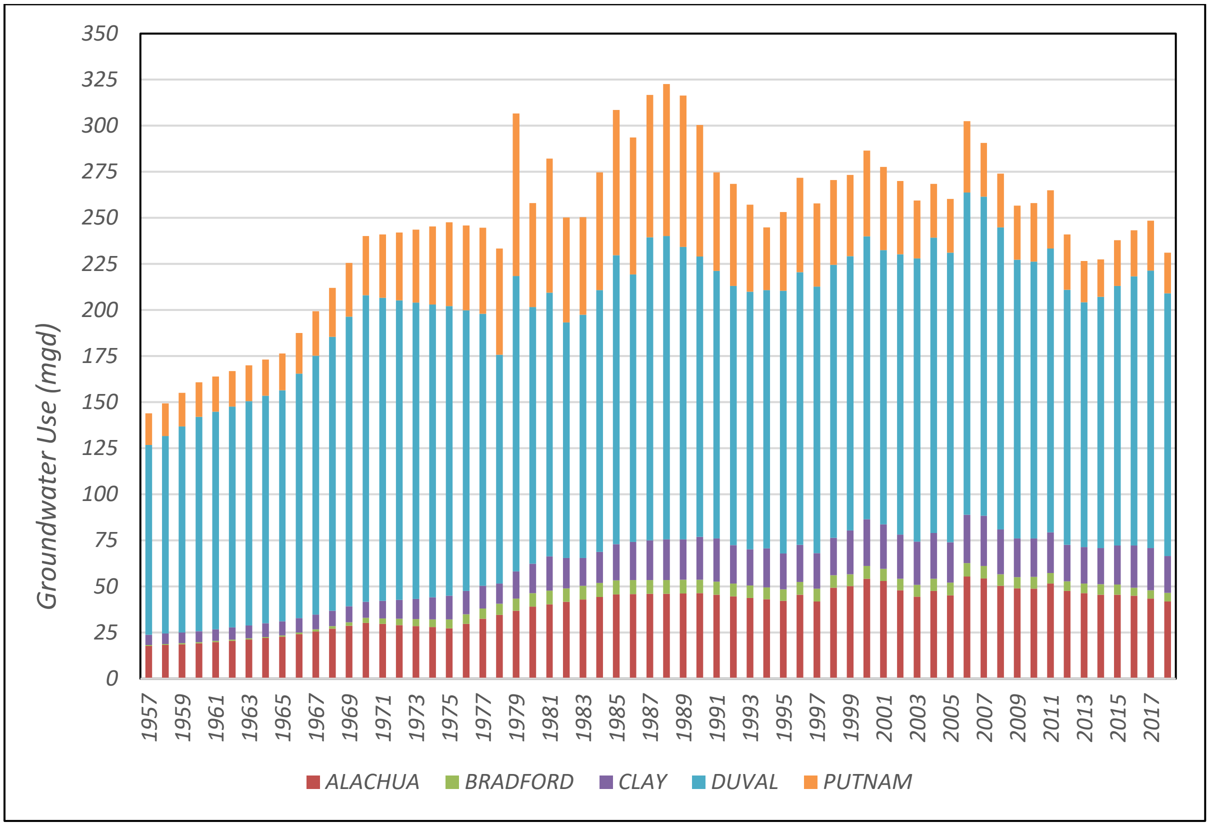

Figure B-15. Estimated historical groundwater uses in Alachua, Bradford, Clay, Duval and Putnam Counties

Groundwater Modeling

<u>Keystone Heights Subregional Transient Model</u>

The hydrologic system of Lakes Geneva and Brooklyn is very complex. Both lakes have strong interaction with the UFA and are heavily dependent on the flows from upstream lakes. Thus, a model simulating both groundwater and surface water system and their interaction was needed to better understand the relationship between the lakes and the groundwater system and the influence of climate and groundwater pumping. As a result, Keystone Heights subregional transient model (KHTM v1.0) was initially developed by Tetra Tech in 2017 and later updated and called KHTM v2.0 (SJRWMD, 2020). See attached for details regarding the updates to the KHTM. KHTM was developed using MODFLOW-NWT including lake and stream packages so that it can fully simulate the interaction between the groundwater and surface water features such as lakes and streams as well as change in lake levels and stream flows due to change in rainfall, ET and pumping. KHTM was calibrated to match monthly groundwater and lake levels as well as stream flows from 1995 to 2014. The model was later extended to simulate monthly water levels and flows up to 2018 and back to 1957.

North Florida Southeast Georgia Groundwater Model

Although KHTM v2.0 is fully capable of simulating local groundwater pumping near Lakes Brooklyn and Geneva, it cannot simulate the effect of regional groundwater pumping due to its limited model domain. It is common modeling practice to develop a refined local model such as KHTM v2.0 for a limited but critical area of concern and use a regional model to adjust lateral boundary conditions for simulation of regional groundwater pumping and recharge effects. Therefore, North Florida and South Georgia regional groundwater model (NFSEG) was used in conjunction with KHTM v2.0 for groundwater pumping impact assessment. SJRWMD and SRWMD have been jointly developing NFSEG model encompassing most of North Florida and South Georgia and some parts of South Carolina. The latest version of the model (NFSEG v1.1) has recently been completed (Durden et al. 2019). NFSEG v1.1 is a steady-state model which was calibrated to match average water levels and flows in 2001 and 2009.

Figure B-16 shows the boundaries of both NFSEG and KHTM models.

Estimated historical impact on lake levels

NFSEG v1.1 and KHTM v2.0 were used to estimate the impacts of groundwater pumping on lake levels. The KHTM v2.0 simulates monthly lake levels from 1957 to 2018. The NFSEG v1.1 was used to adjust the KHTM v2.0 lateral boundary conditions, which were set as general head boundaries (GHBs), to simulate the effects of regional pumping on lake levels.

Because the NFSEG v1.1 is a steady-state model, it does not produce drawdowns resulting from regional pumping on a monthly time step. To overcome this issue, a methodology was developed to estimate the impact of regional pumping on lake levels for every month from 1957 to 2018.

The first step was to adjust all monthly time steps of lateral boundaries of the KHTM using the same drawdown set obtained from the steady-state simulation of NFSEG model. This means that KHTM would simulate the same regional pumping condition for the entire simulation period which was from 1957 to 2018. Because the NFSEG model was calibrated under 2001 and 2009 hydrologic and pumping conditions only, by removing all the pumping and human-induced recharge wells in the model, two sets of drawdown estimates were obtained. The first set represented the total drawdown resulted from 2001 pumping condition and the second set represented the total drawdown resulted from 2009 pumping condition.

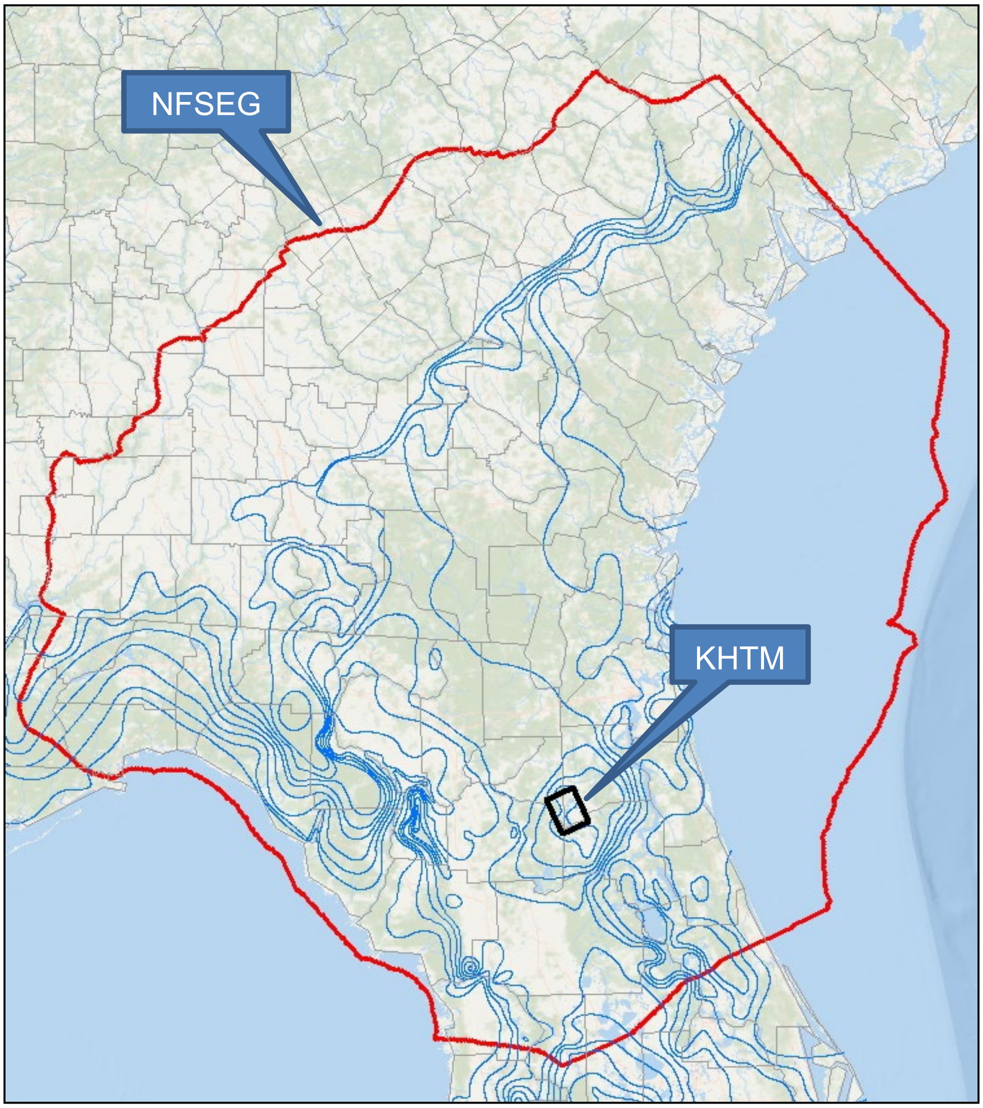

Figure B-16. NFSEG and KHTM model boundaries

Then, two KHTM simulations were performed. The first simulation was performed by adjusting all monthly lateral boundary elevations using the same 2001 drawdown dataset and the second simulation was performed by adjusting all monthly lateral boundary elevations using the same 2009 drawdown dataset. The adjustment was calculated for each GHB cell and applied to GHBs on cell-by-cell basis. The UFA elevations along GHBs were increased by from approximately 5 to 11 feet for 2001 pumps-off simulation and from approximately 4 to 9 feet for 2009 pumps-off simulation. Because regional pumping in 2001 was higher than that in 2009, the amount of adjustments applied to GHBs are higher for 2001 pumps-off simulation (Figure B-17).

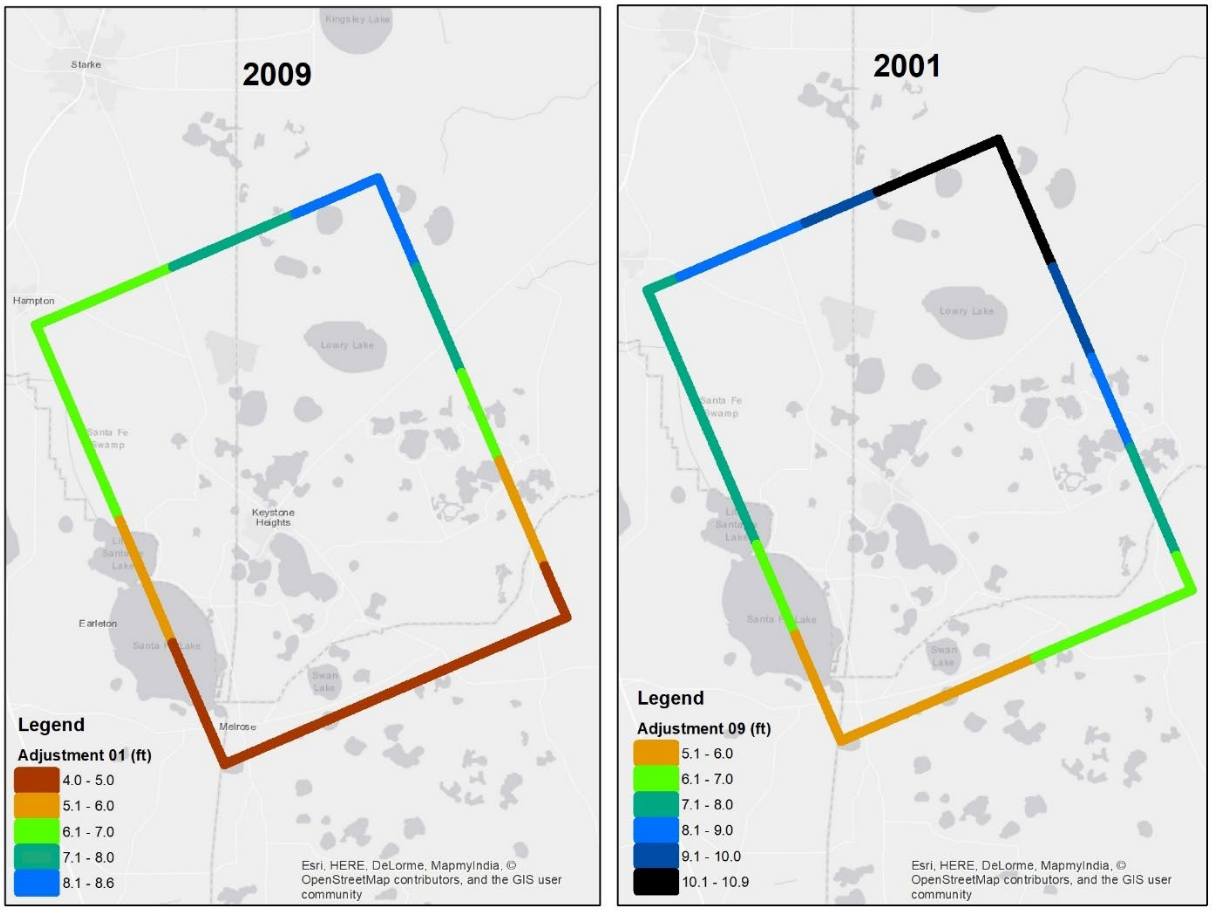

Figure B-17. KHTM GHB adjustment based on NFSEG 2001 and 2009 pumps-off simulations

It should be noted that the pumping in KHTM was not removed in these simulations to prevent any possible "double-count" since all pumping within NFSEG model domain including those near Keystone Heights were already removed in the NFSEG pumps-off simulations mentioned above. As a result, two lake level time series were generated for each lake. Figures B-18 and B-19 show the simulated levels of lakes Brooklyn and Geneva respectively. Because the regional pumping in 2001 was higher than the regional pumping in 2009, the simulated lake levels for 2001 pumps-off condition is higher than those for 2009 pumps-off condition.

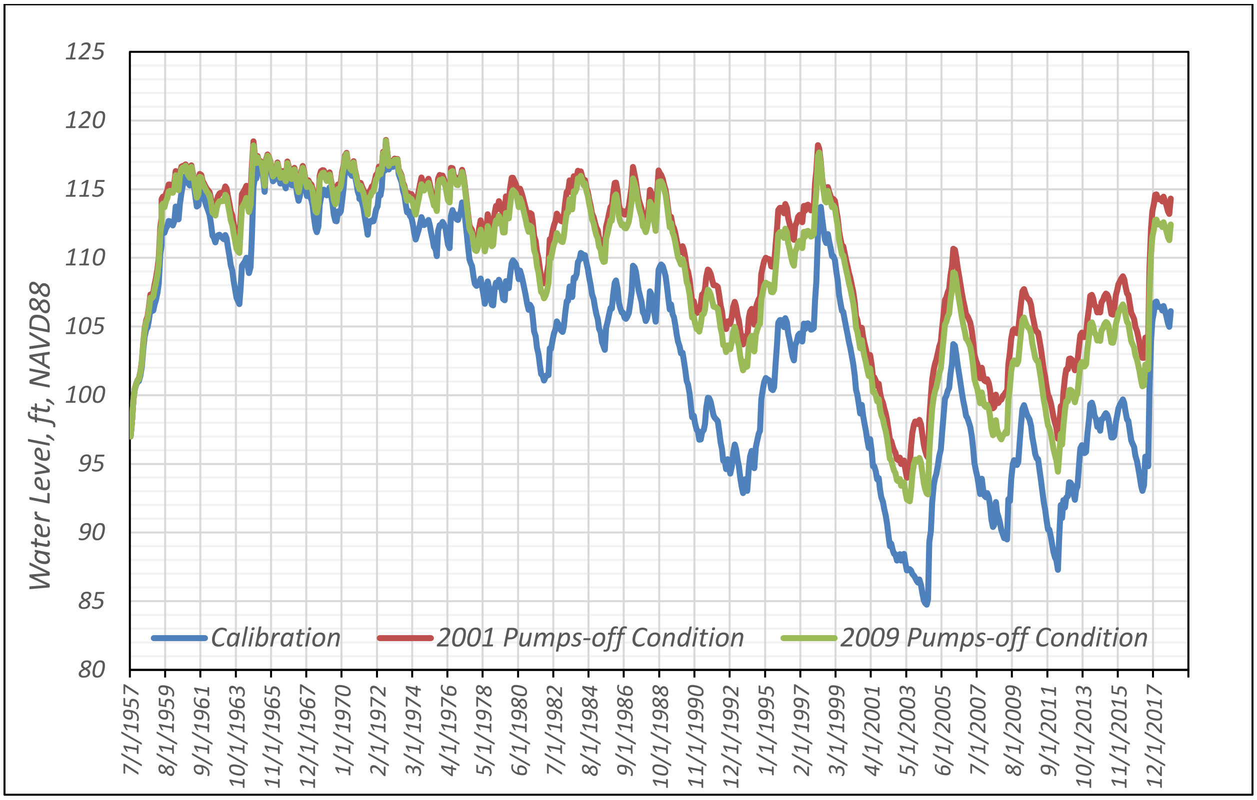

Figure B-18. Simulated Lake Brooklyn levels generated from KHTM

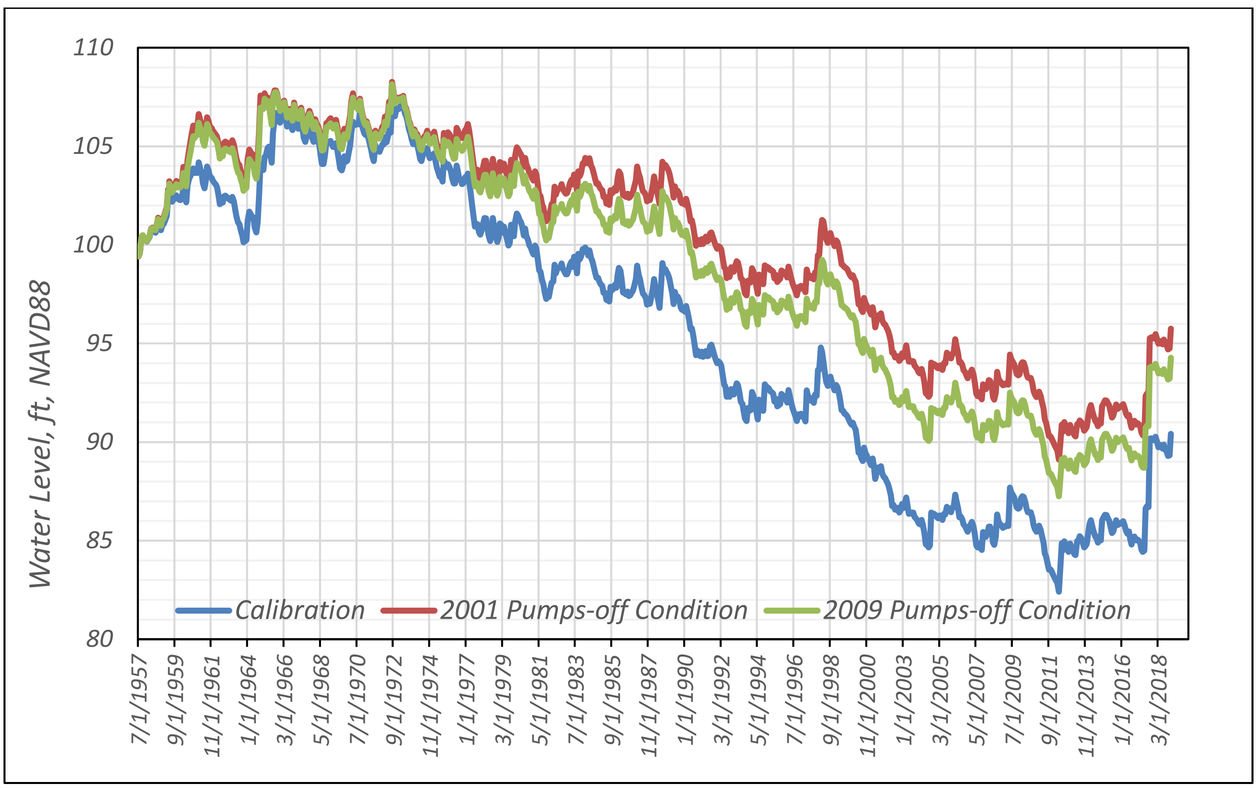

Figure B-19. Simulated Lake Geneva levels generated from KHTM

Because regional pumping has been changing over time as shown in Figure B-15, the next step was to develop a linear relationship between the regional groundwater pumping and change in simulated lake levels to accurately reflect the effect of change in pumping over time on lake levels.

To develop the relationship, the following NFSEG/KHTM simulations were performed so that a wide range of pumping conditions can be included in the regression analysis.

- 2001 pumping
- 2001 pumping decreased by 25%
- 2001 pumping decreased by 50%
- 2001 pumping decreased by 75%
- 2001 pumping increased by 25%
- 2001 pumps-off
- 2009 Pumping
- 2009 pumping decreased by 25%
- 2009 pumping decreased by 50%
- 2009 pumping decreased by 75%
- 2009 pumping increased by 25%
- 2009 pumps-off

Linear relationships were developed using the output of KHTM model for each month separately. KHTM is a transient model and simulated a variety of hydrologic conditions including dry, average and wet conditions. Because linear relationships were developed monthly, each relationship will be unique to the hydrological condition (dry, wet, or average) it was derived from. Since each linear relationship was used to make predictions only for the month which it was derived from, potential effect of non-linearity due to different hydrologic conditions was minimized. After review of the simple linear regression developed for each month, we noticed that adding Brooklyn lake levels as another predictor would greatly improve the fit between the model-simulated and the predicted lake level changes due to pumping. Therefore, we built a multiple linear regression using both pumping and lake Brooklyn levels as predictors for each month.

The following equation was used to develop a multiple linear regression for each month for each lake from 1957 to 2018.

$$LDD_k = A_k + B_k Q_k + C_k BrL_k$$

Where

LDD_k: Lake drawdown (feet) in month k

A_k = Intercept in month k

B_k and C_k: Regression coefficients

Q_k : 12-month moving average of total pumping (mgd) in month k for five counties listed in Figure B-14

BrL_k: Simulated Brooklyn Lake levels in month k

k : months from 7/1957 thru 12/2018

The relationship was developed for each month because the relationship between pumping and the resulting impact on lake levels could be different under different hydrologic conditions (e.g., during wet conditions, impact may be offset by surface water flows and surface runoff, etc.) and at different lake levels (e.g., change in lake storage and seepage to the UFA could be different).

The data shown in Figures B-18 and B-19 and total groundwater pumping simulated in NFSEG model for the five counties discussed in the previous section were used for development of linear monthly relationship. Using the monthly linear relationships, the monthly impact to lake levels resulted from pumping from 1957 to 2018 was estimated (see Figures B-20 and B-21). It should be noted that the groundwater pumping in five counties were considered only as proxy to develop the linear relationship and capture the variation of regional pumping over time. The NFSEG groundwater model simulations included pumping for the entire model domain.

The magnitude of groundwater impact to lakes is dependent on not only the magnitude of groundwater pumping but also the amount of surface water flows coming from the upstream lakes. The impact of pumping on lake levels during a dry period could be considerably higher than the impact of pumping on lake levels during a wet period for the same amount of pumping because of lack of surface water flows and runoff. Thus, although the amount of regional pumping in 1960s was not negligible, the impact of groundwater pumping on both lakes was relatively low. The groundwater impact had been largely offset by the amount of surface water flows coming from the upstream lakes during that period.

Lake Brooklyn has been continuously receiving surface water flows from the upstream lakes. However, after 1973, the amount of surface flows coming from the upstream lakes to Lake Brooklyn has declined and varied due largely to rainfall deficit. Because of this, the groundwater impact to lake Brooklyn has varied and become more pronounced after 1973.

Lake Geneva has not received any surface flow from Lake Brooklyn since 1973 except for a very brief period in 1998. As a result, the variation in groundwater impact on Lake Geneva has been less after 1973, compared to Lake Brooklyn. However, like Lake Brooklyn, the magnitude of groundwater impact on Lake Geneva levels has become more pronounced since then. In short, the groundwater pumping impact to both lakes has increased significantly after 1973 due to not only increase in regional groundwater pumping but also reduction in surface water flows and runoff, which have exacerbated the impact.

It should also be noted that the groundwater pumping impact on lakes has recently (since 2007) declined due to reduction in regional pumping as shown in Figures B-20 and B-21.

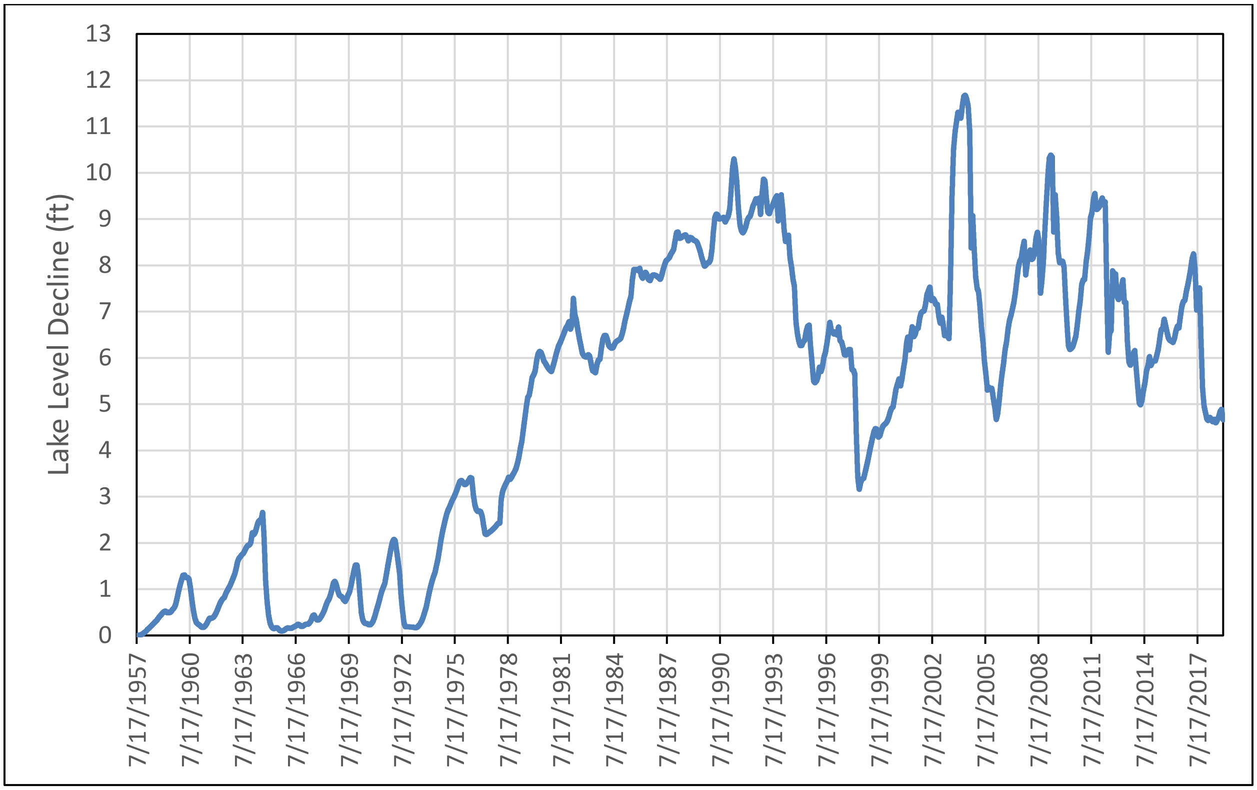

Figure B-20. The estimated impact of historical groundwater pumping on Lake Brooklyn levels

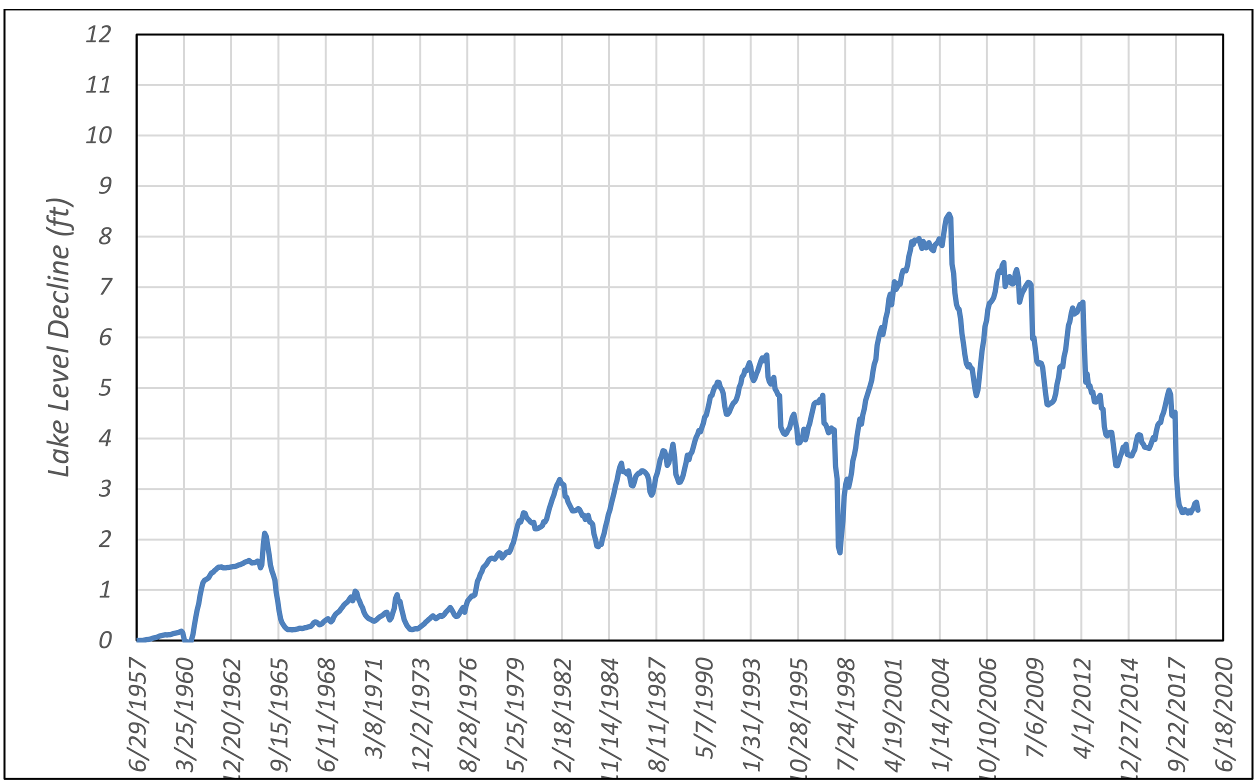

Figure B-21. The estimated impact of historical groundwater pumping on Lake Geneva levels

Discussion

Our analysis of long-term water level declines indicated that both long-term rainfall deficits and regional groundwater pumping have played critical roles in lowering lake levels over the past 40-50 years. The groundwater pumping impact to both lakes has increased considerably after 1973 due to not only increase in regional groundwater pumping but also reduction in surface water flows and runoff resulting from rainfall deficit which have exacerbated the impact. However, the groundwater pumping impact on lake levels has declined over the past five years due to approximately 20% reduction in regional pumping. Our analysis also suggests that it may take many years of above average rainfall to offset the effect of prolonged periods of drought on these lakes.

DEVELOPMENT OF LAKE LEVEL DATASETS FOR MFL ANALYSIS

The current and future status of minimum levels developed for Lake Brooklyn and Geneva 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.

Lake Brooklyn and Geneva MFL determinations and assessment are based on lake level datasets representative of current-pumping and no-pumping conditions (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 1957 to 2018. 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 1957 to 2018). Thus, 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 1957 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. The years 2019 and 2020 were not included because regional pumping data were not available at the time of this analysis.

The first step in developing the current-pumping condition lake levels, which in this case is the "average 2014-2018 pumping condition" lake levels, is to develop a "no-pumping condition" lake level dataset. The "no-pumping condition" lake level dataset was developed by adding an estimate of impact due to historical pumping (i.e., change in lake levels due to pumping) to each month in the observed record from 1957 to 2018. The "current-pumping condition" lake level dataset was developed by subtracting an estimate of impact due to current (average 2014-2018) pumping from the no-pumping lake levels in each month from 1957 to 2018.

"No-pumping condition" lake levels

The impacts from pumping as shown in Figures B-20 and B-21 were added to the monthly means of the observed lake level data to create a "no pumping condition" lake level dataset for Lakes Brooklyn and Geneva. These lake levels constitute a reference hydrologic condition of the lakes in which the impact from groundwater pumping is assumed to be minimal. The monthly datasets were later disaggregated into daily lake levels by linear interpolation.

"Current-pumping condition" lake levels

To develop the current-pumping-condition lake level dataset, the impact of current pumping on lake levels needs to be estimated. As previously discussed in Section 2.2, multiple linear regressions were developed to estimate the impact of pumping on lake levels for each month from 1957 to 2018. Using the linear monthly relationships and the average 2011-2018 pumping (about 238 mgd), a monthly time series of impact dataset was developed for each lake (Figures B-22 and B-23).

To generate current-pumping condition levels for each lake, the impacts from the average 2011-2018 pumping shown in Figures B-22 and B-23 were subtracted from the no-pumping condition lake levels. Figures B-24 and B-25 show both no-pumping and current-pumping conditions lake levels for Lakes Brooklyn and Geneva, respectively. The monthly datasets were later disaggregated into daily lake levels by linear interpolation.

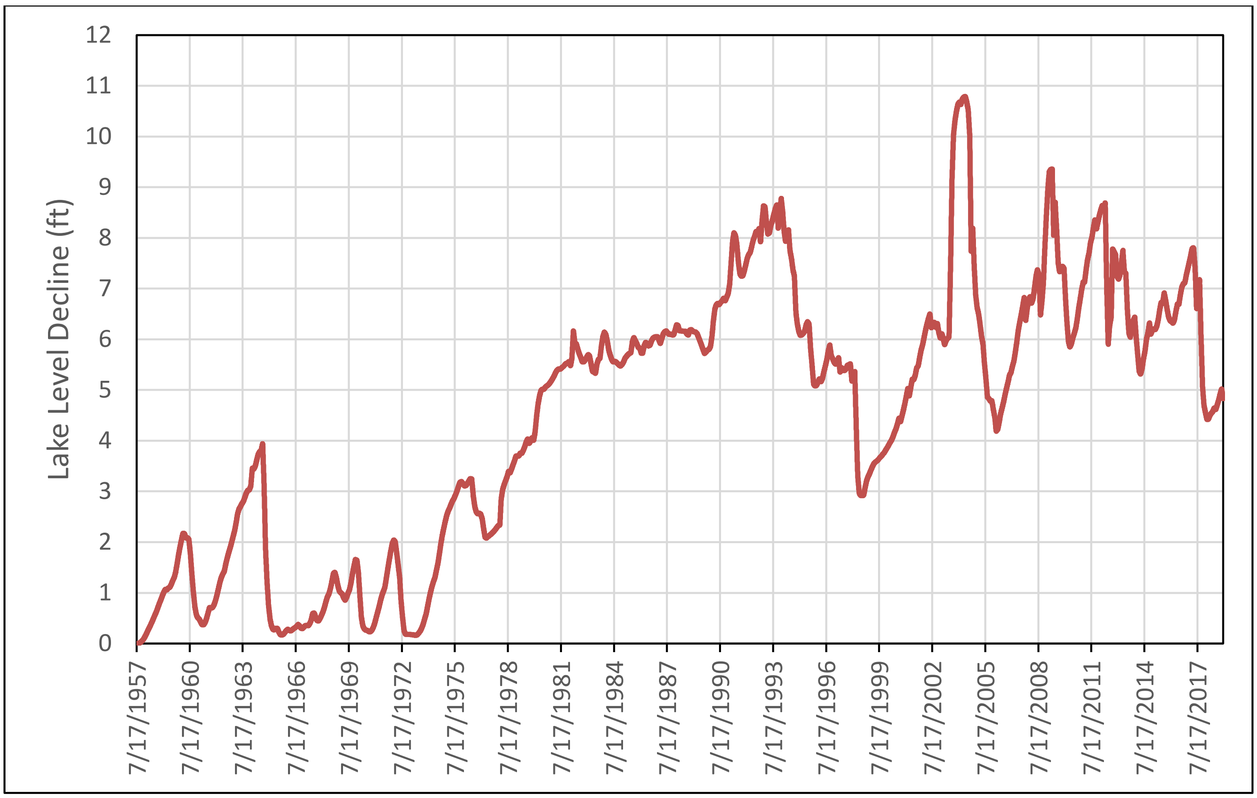

Figure B-22. The estimated impact of current groundwater pumping on Lake Brooklyn levels

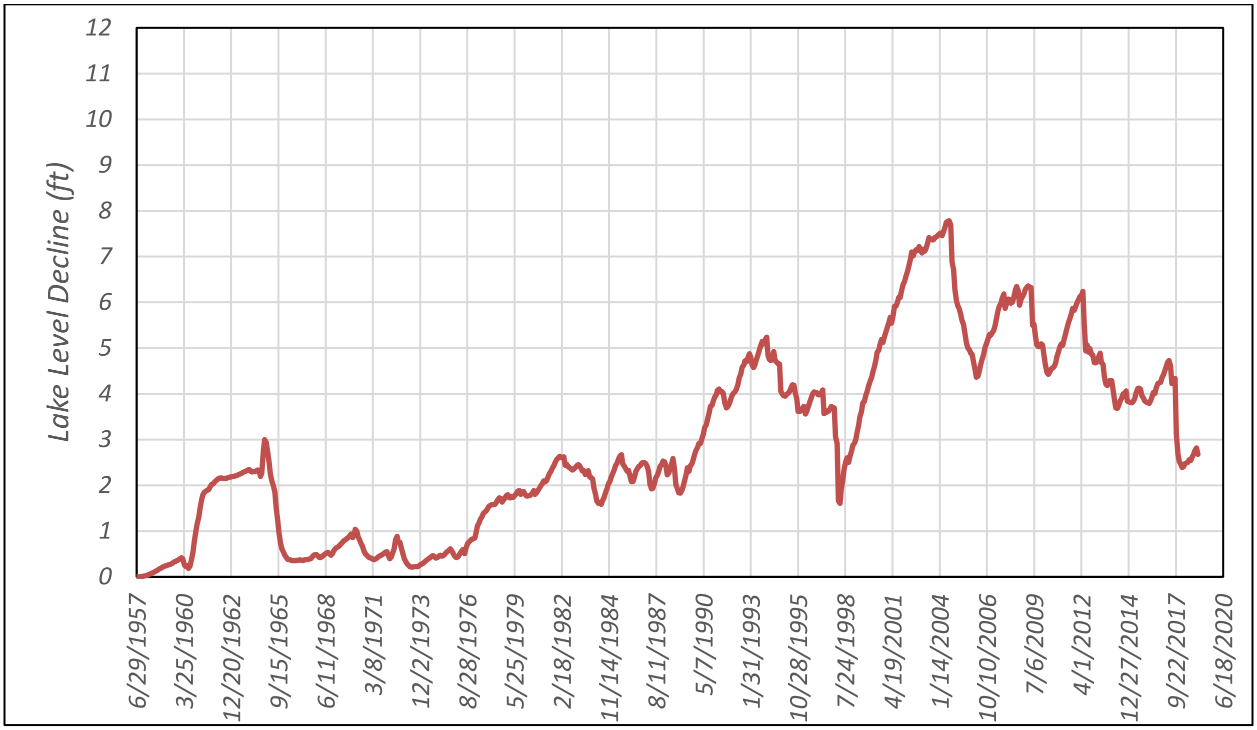

Figure B-23. The estimated impact of current groundwater pumping on Lake Geneva levels

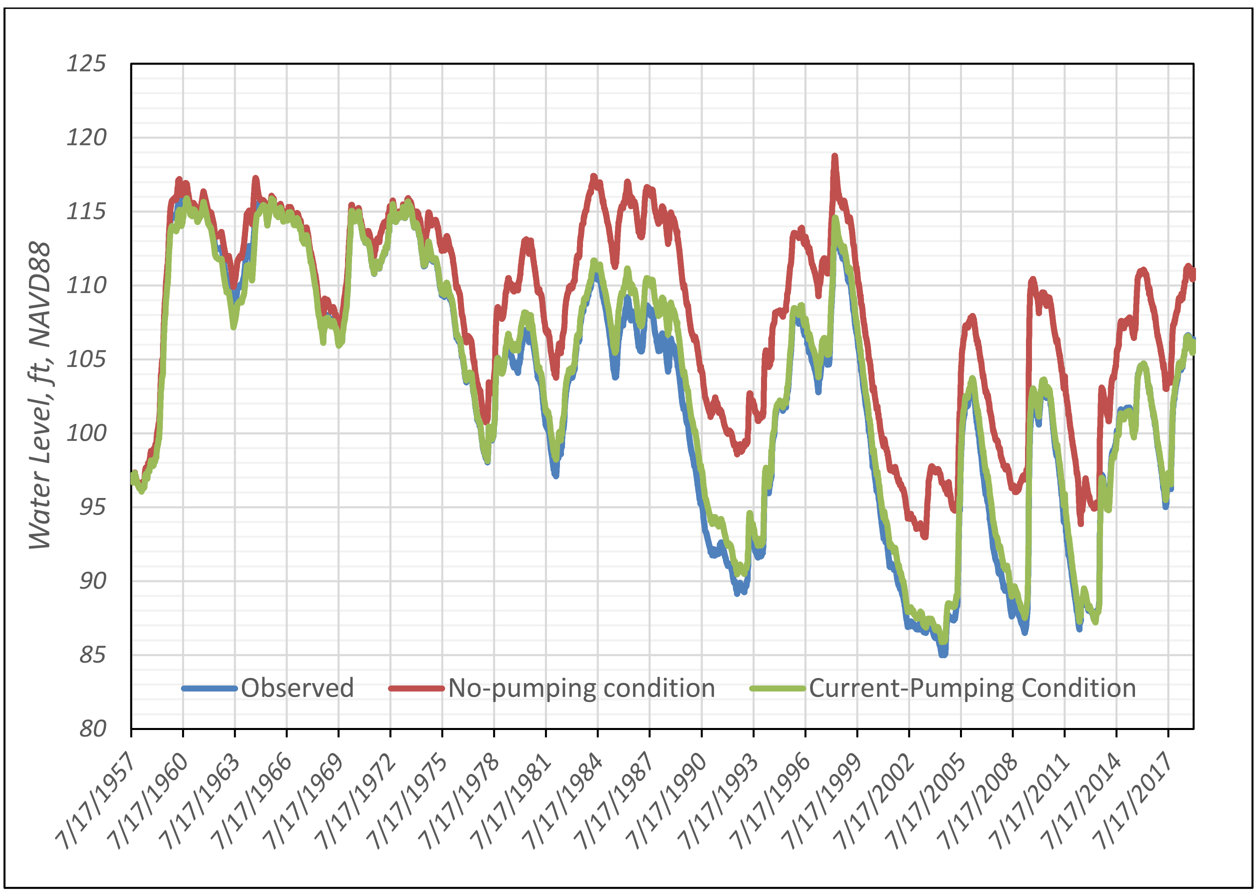

Figure B-24. The estimated no-pumping and current-pumping condition levels for Lake Brooklyn

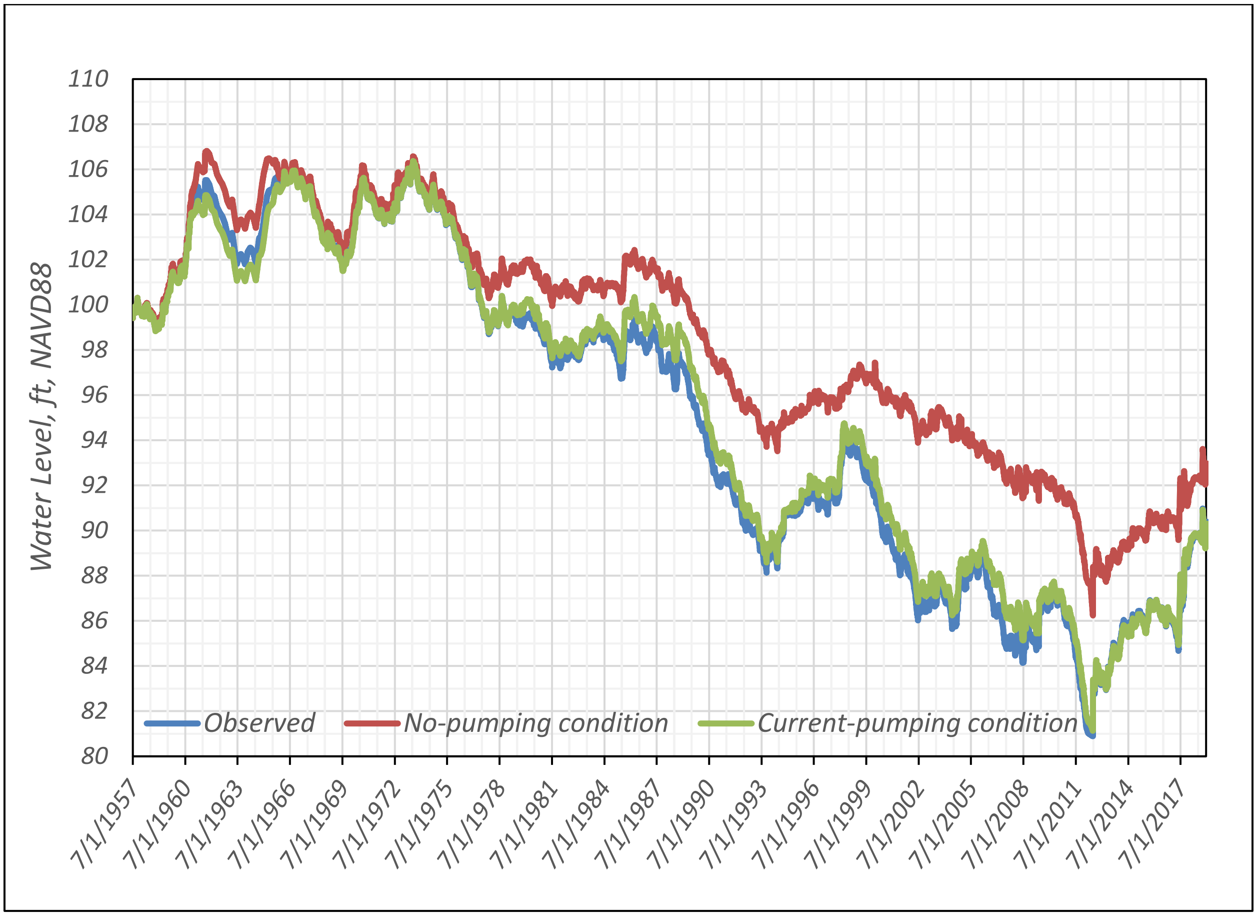

Figure B-25. The estimated no-pumping and current-pumping condition levels for Lake Geneva

The current-pumping condition lake levels represent a reference hydrologic condition of the lakes in which the total regional groundwater pumping impacting the lakes is constant from 1957 to 2018 at a rate of averaged pumping from 2014 to 2018. Assuming climatic, rainfall, and other conditions present from 1957 to 2018 are repeated over the next 58 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 2014-2018 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 Figures B-24 and B-25 were used to determine and evaluate the MFLs at Lakes Brooklyn and Geneva.

Several MFL criteria require lake levels being expressed as exceedance probabilities. Percent exceedance can be defined as the percent of the time a specified level will be equaled or exceeded over the period of record and be calculated as follows:

$$P = 100 * [m / (n + 1)]$$

Where P = Percent of time that a specified level will be equaled or exceeded

m = the rank of the specified level

n = the total number of level data over period of record

Figures B-26 and B-27 show exceedance probability curves of water levels for Lakes Brooklyn and Geneva, respectively.

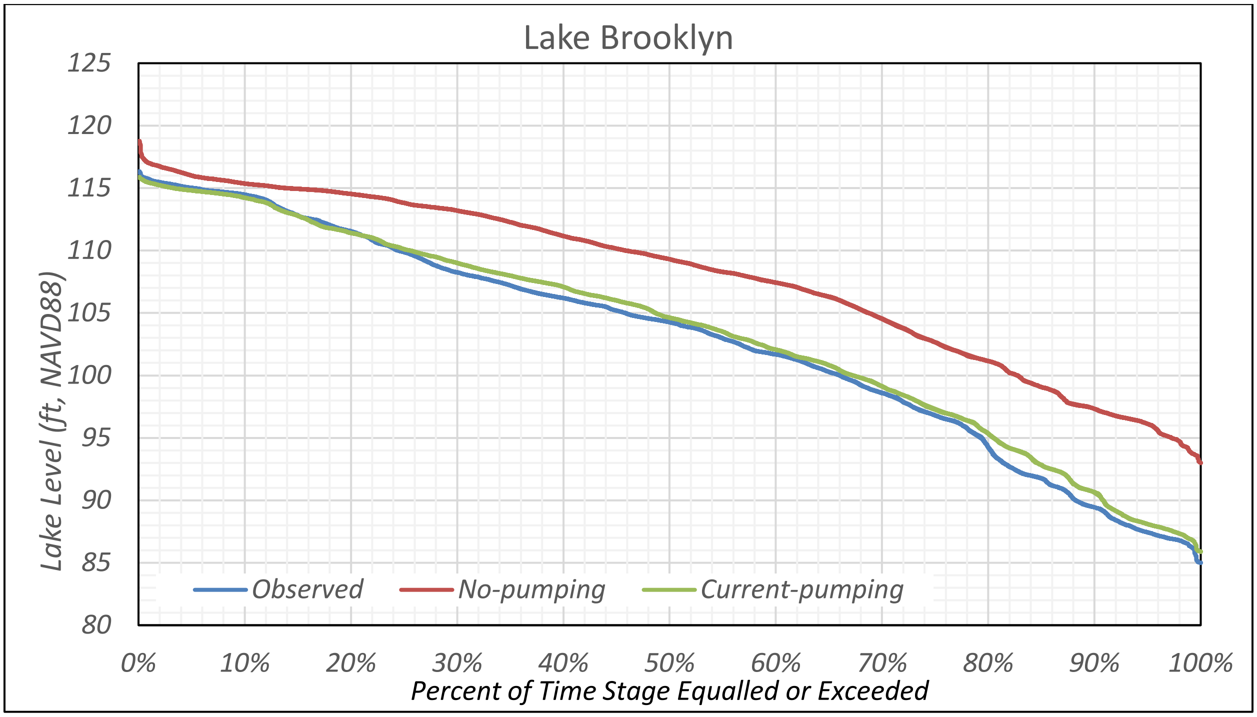

Figure B-24. Exceedance probability curve of Lake Brooklyn levels

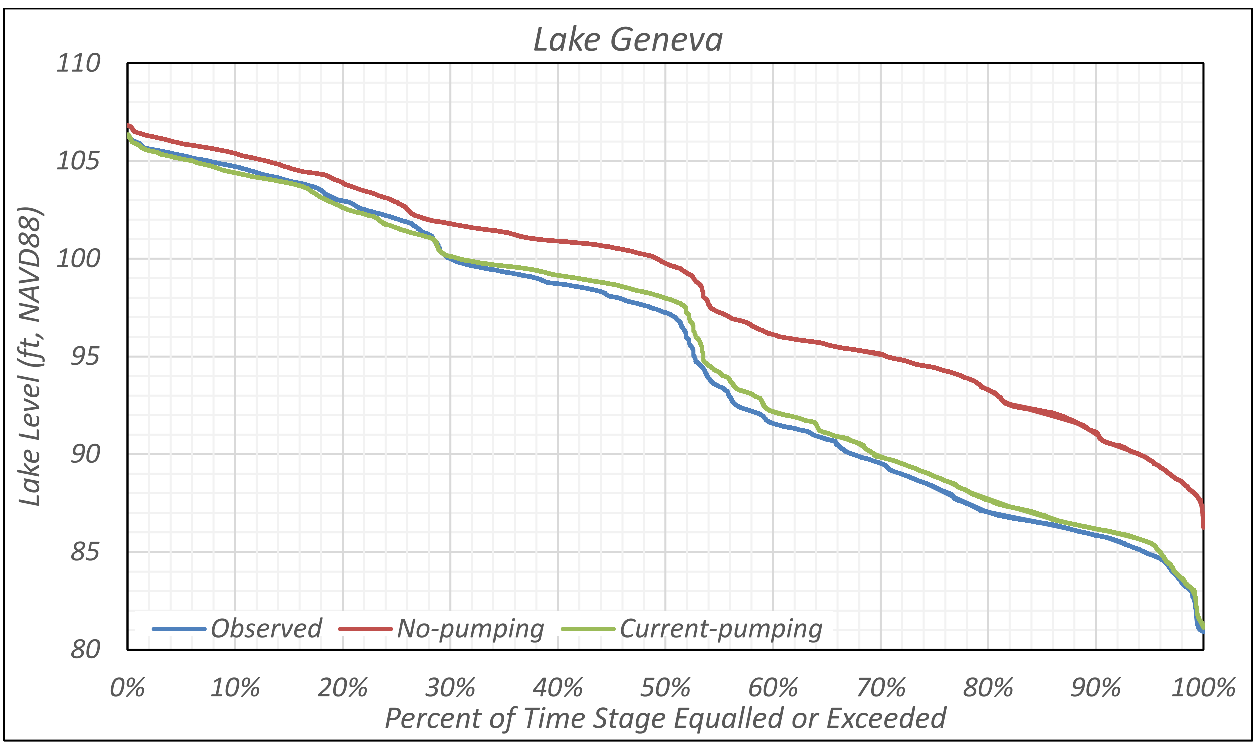

Figure B-25. Exceedance probability curve of Lake Geneva levels

REFERENCES

Clark, M., Musgrove, R., Menke, C., Cagel, J., 1963. Hydrology of Brooklyn Lake Near Keystone Heights, Florida. U.S. Geological Survey. State Board of Conservation Divisions of Geology. Florida Geological Society Report No. 33. Tallahassee.

Durden, D., Gordu F, Hearn D, Meridth L, Angel A, and Grubbs T. 2019. "North Florida Southeast Georgia Groundwater Model v1.1. Technical Publication SJ2019-01." St. Johns River Water Management District.

Enfield, D. B., Mestas-Nunez, A. M., Trimble, P. J., 2001. The Atlantic Multidecadal Oscillation and its relationship to rainfall and river flows in the continental U.S. Geophysical Research Letters. Vol 28. Pg. 2077–2080.

Kelly, M.H. ,2004. *Florida River Flow Patterns and the Atlantic Multidecadal Oscillation.* Draft report. Ecologic Evaluation Section. Southwest Florida Water Management District. Brooksville, FL. 80 pp. + appendix.

Keyantash, John & National Center for Atmospheric Research Staff (Eds). Last modified 08 Mar 2018. "The Climate Data Guide: Standardized Precipitation Index (SPI)." Retrieved from https://climatedataguide.ucar.edu/climate-data/standardized-precipitation-index-spi.

Kirtman, B. P., Misra, V., Burgman, R. J., Infanti, J., & Obeysekera, J. , 2017. Florida climate variability and prediction. In E. P. Chassignet, J. W. Jones, V. Misra, & J. Obeysekera (Eds.), Florida's climate: Changes, variations, & impacts (pp. 511–532). Gainesville, FL: Florida Climate Institute. https://doi.org/10.17125/fci2017.ch17

Kuss, A. J. M. and Gurdak, J. J., 2014. Groundwater level response in U.S. principal aquifers to ENSO, NAO, PDO, and AMO. J. Hydrol., 519, pp. 1939-1952

Merritt, M., 2001. Simulation of the Interaction of Karstic Lakes Magnolia and Brooklyn with the Upper Floridan Aquifer, Southwestern Clay County, Florida. U.S. Geological Survey Water-Resources Investigation Report 00-4204. Tallahassee, FL.

Motz, L. and Heaney, J., 1991. St. Johns River Water Management District Special Publication SJ 91-SP5 Upper Etonia Creek Hydrologic Study –Phase 1 Final Report. Palatka, FL.

National Oceanic and Atmosphere Administration (NOAA), 2018. Atlantic Multidecadal Timeseries. https://www.esrl.noaa.gov/psd/data/timeseries/AMO/.

National Oceanic and Atmosphere Administration (NOAA). Frequently Asked Questions about AMO. http://www.aoml.noaa.gov/phod/amo_faq.php#faq_5.

Obeysekera, J, et al. , 2011. Past and Projected Trends in Climate and Sea Level for South Florida. Interdepartmental Climate Change Group. South Florida Water Management District, West Palm Beach, Florida, Hydrologic and Environmental Systems Modeling Technical Report. July 5, 2011.

Schlesinger ME and Ramankutty N., 1994. An oscillation in the global climate system of period 65-70 years. Nature 367:723–726

SJRWMD, 2020. Keystone Heights Transient Model v2.0 (electronic files)