# HYDROLOGICAL MODELING OF THE CRYSTAL CHAIN OF LAKES, SEMINOLE COUNTIY, FLORIDA

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# Executive Summary

The St. Johns River Water Management District (SJRWMD) has been establishing Minimum Flows and Levels (MFLs) for the Crystal Chain of Lakes (CCL). The MFLs program designates the minimum hydrologic conditions that must be maintained for the lakes to avoid significant harm to water resources and ecosystem services, resulting from permitted water withdrawals. The CCL MFLs are scheduled for adoption in 2024. In support of the MFLs program, SJRWMD developed a continuous-simulation model for the CCL using a Hydrological Simulation Program – FORTRAN (HSPF) model to better understand the hydrologic processes and water budget components of the lakes and to develop lake level datasets necessary for MFLs evaluations.

Using the available hydro-meteorological and geospatial data, SJRWMD set up an HSPF model for the period from 1995 to 2019 and manually calibrated and validated the model for the period 2007 to 2019 and 1995 to 2006, respectively. Model performance was evaluated by simultaneously using graphical methods and several statistical evaluation metrics. The calibrated and validated model was subsequently extended to the period 1953 to 2019 for long-term simulations and MFLs modeling.

HSPF reasonably simulated the observed water levels temporal variations and magnitudes of the CCL for both the calibration and validation periods. We achieved better statistical values and ratings during the validation period, highlighting the capability of the model in simulating water levels outside the calibration period. More importantly, the model adequately replicated the observed low to medium levels of West and East Crystal Lakes, which are crucial for MFLs modeling and assessment processes. Overall, the HSPF model showed reasonable simulations of hydrologic and surface water-groundwater interaction processes of West and East Crystal Lakes. Therefore, it is concluded that the model can be used for MFLs modeling and scenarios analysis of the lakes.

This report summarizes the Crystal Chain of Lakes HSPF model development. Detailed information is contained in the appendices: existing data review (**Appendix A**), model development (**Appendix B**), model calibration and validation (**Appendix C**), long-term simulation (**Appendix D**), and sensitivity analysis (**Appendix E**).

# Existing Data Review

The Crystal Chain of Lakes (CCL) is located in the northwestern portion of Seminole County, Florida and includes Lake Como, Dawson Lake, West Crystal Lake, East Crystal Lake, Bel-Air Lake, Amory Lake, and Deforest Lake (Figure H - 1). West and East Crystal Lakes are the two major lakes of the chain. SJRWMD has been establishing MFLs for the CCL, which is scheduled for completion in 2024. To support the MFLs program, we developed a Hydrological Simulation Program – FORTRAN (HSPF) model (Bicknell et al., 2001) for the CCL.

We obtained and reviewed all available hydro-meteorological and geo-spatial data to set up an HSPF model for the CCL watershed. Data collection, review, and processes are detailed in **Appendix A**. We specifically collected, reviewed, and processed the following data:

- Lake levels
- Long-term groundwater levels
- Long-term rainfall and potential evapotranspiration (PET)
- Land use/land cover (LULC) map
- Soil map
- Topographic map

- Lake bathymetry and hydraulic structures.

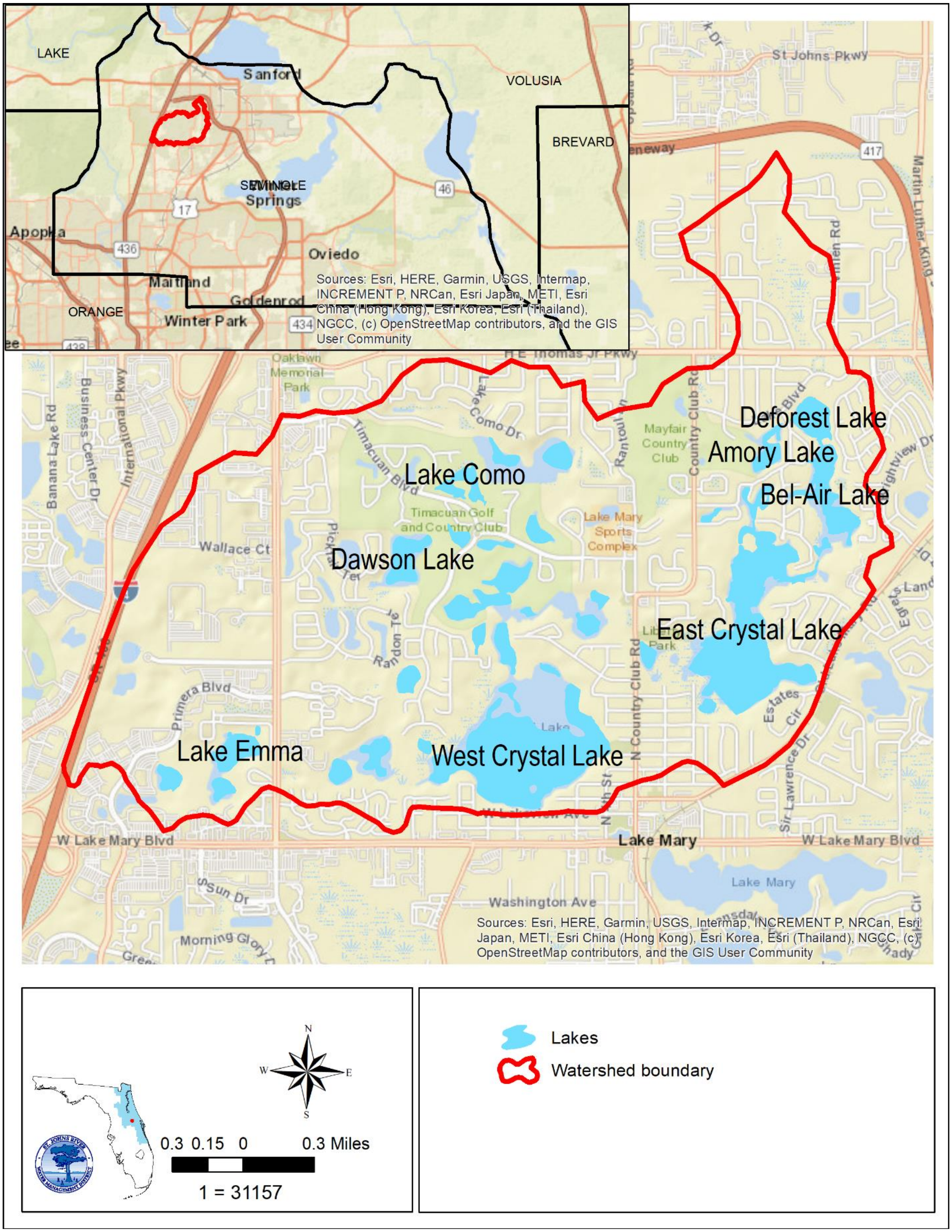


Figure H - 1. Location of Crystal Chain of Lakes watershed in Seminole County (top left corner) and the lakes (bottom).

# Well Record Gap Filling

The HSPF model used daily groundwater levels recorded at well S-0975 (see well location in Figure A-10 of **Appendix A**). The methodology used to fill gaps in groundwater levels is provided in detail in **Appendix A**. In general, the final time series for well S-0975 was created by using the observed data at well S-0975 when available and the estimated data from a regression model when no observed data was available at well S-0975. The regression model was developed using a Line of Organic Correlation (LOC) method to derive the relationship between the water levels at S-0975 and S-0125 wells. Figure H - 2 shows the extended long-term time series data at well S-0975 for the period from 1/1/1953 to 12/31/2019 along with the observed groundwater levels.

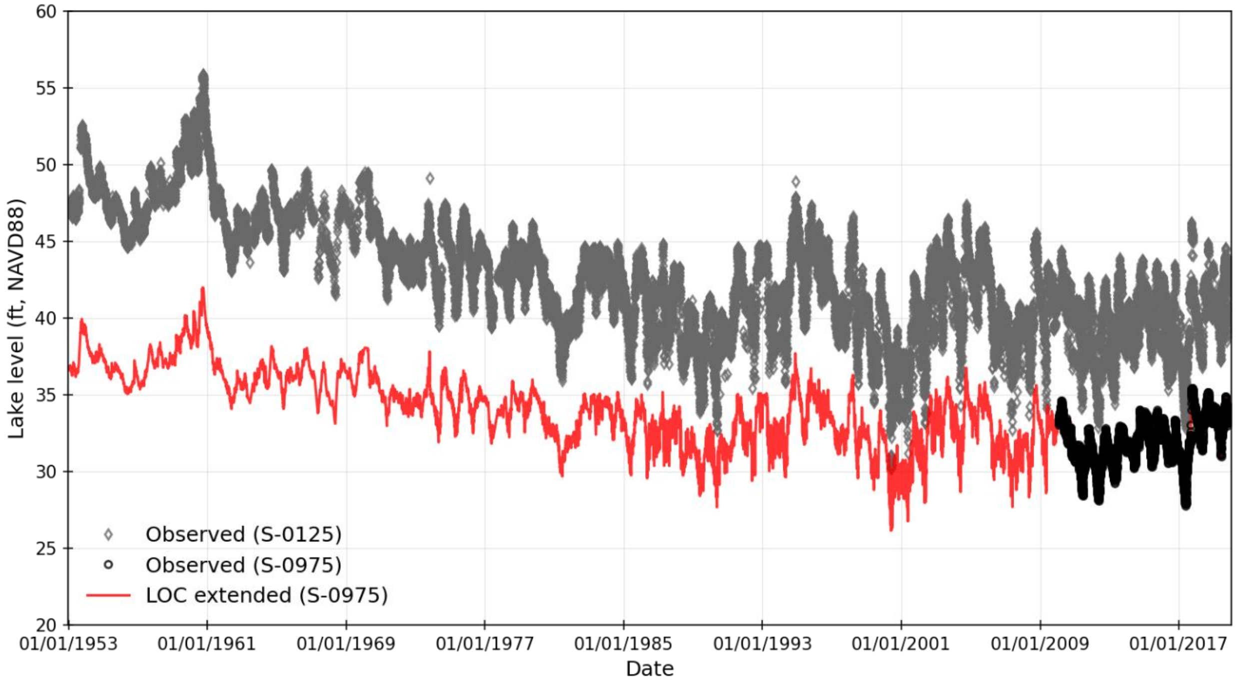


Figure H - 2. S-0975 observed and extended long-term time series levels.

# Bathymetry

Available bathymetry data for all lakes are detailed in **Appendix A**. However, after model calibration, validation, and long-term simulations were completed – a new bathymetry data with high resolution became available for West Crystal Lake. The new data was derived from a combination of USGS 2018 LiDAR-derived contours, field survey, and “heads up” digitized aerial photographs – all available in the SJRWMD’s GIS databases. While the field survey and digitized aerial photographs were used to represent the main part of the lake, the 2018 LiDAR data was used for the wetland portion around the lake and higher elevations. Also, the USGS 2018 LiDAR data that used for the wetland portion was adjusted using survey points whereas the higher elevation areas used unadjusted LiDAR data. We converted all the datasets to point elevations and used interpolation techniques to produce a composite raster map for a habitat analysis using the Hydroperiod Tool (HT) (Fox et al, 2012). We finally converted the raster data to stage-area curves using the HT. Figure H - 3 compares the old and new stage area curves of West Crystal Lake. The figure indicates noticeable differences between the two datasets, but the new bathymetric data generally produced smaller areas for stages approximately less than 33 and greater than 44 ft. We replaced the old stage-area curve in the HSPF model with the new curve.

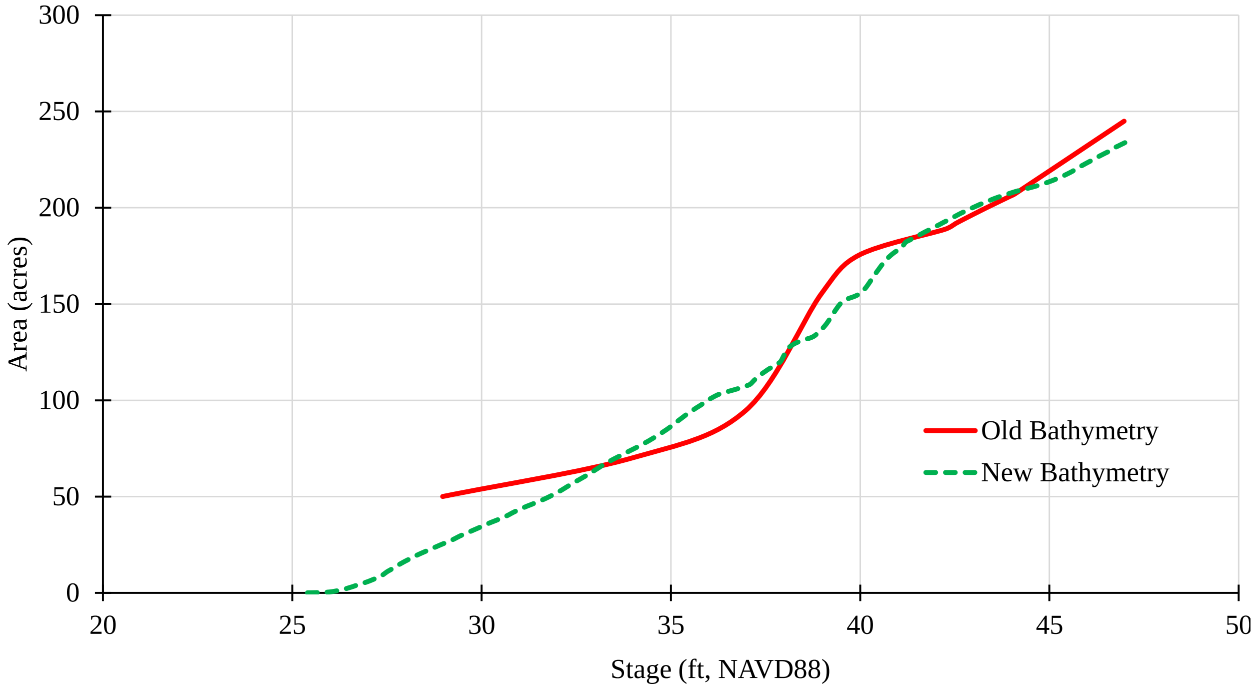


Figure H - 3. Old and new stage area curves of West Crystal Lake.

# Model Development

An HSPF model was developed to simulate the hydrologic conditions of the CCL watershed. Details on the model development process are provided in **Appendix B**. The model development specifically included:

- Delineating the watershed boundary and sub-dividing into sub-watersheds
- GIS intersections of LULC data with model's sub-watersheds
- User Control Input (UCI) development
- FTable development and incorporation into the model
- Incorporation of seepage flow between the lake and Upper Florida Aquifer (UFA)
- Rating curves development using an Interconnected Channel and Pond Routing (ICPR4) model (Streamline Technologies, 2018) and their incorporation into the HSPF model.

# Model Calibration and Validation

We manually calibrated the HSPF model of CCL for the period 2007 to 2019 and validated the model for the period 1995 to 2006. The model used a two-year warm-up period. The HSPF model simulated each lake and its associated contributing sub-watersheds and used the Special Actions module to simulate seepage to/from the UFA system and the hydraulic interactions between lakes. Detailed information on the HSPF model calibration and validation is provided in **Appendix C**.

Figure H - 4 compares simulated water levels (calibration period) for West Crystal Lake using the old and new bathymetry data, and Table H - 1 summarizes the goodness-of-fit statistics for the two bathymetries. As shown in Figure H - 4 and Table H - 1, replacing the old bathymetry data of the lake had insignificant impacts on simulated daily water levels and model performance. However, the updated model shows a tendency of further underestimating the low water levels as compared to the old model, especially since 2010. This is also reflected in lower statistical values (Table H - 1). We addressed this issue by slightly reducing the leakance value of West Crystal from 0.0023 to 0.0021 (Table H - 1). Although the overall results of old and updated models are similar, the higher resolution new bathymetry data along with a slight change in leakance value of West Crystal Lake improved the temporal dynamics of simulated lake levels and model performance. Therefore, the updated model is more reasonable in reproducing observed lake levels of West Crystal Lake and for further analysis.

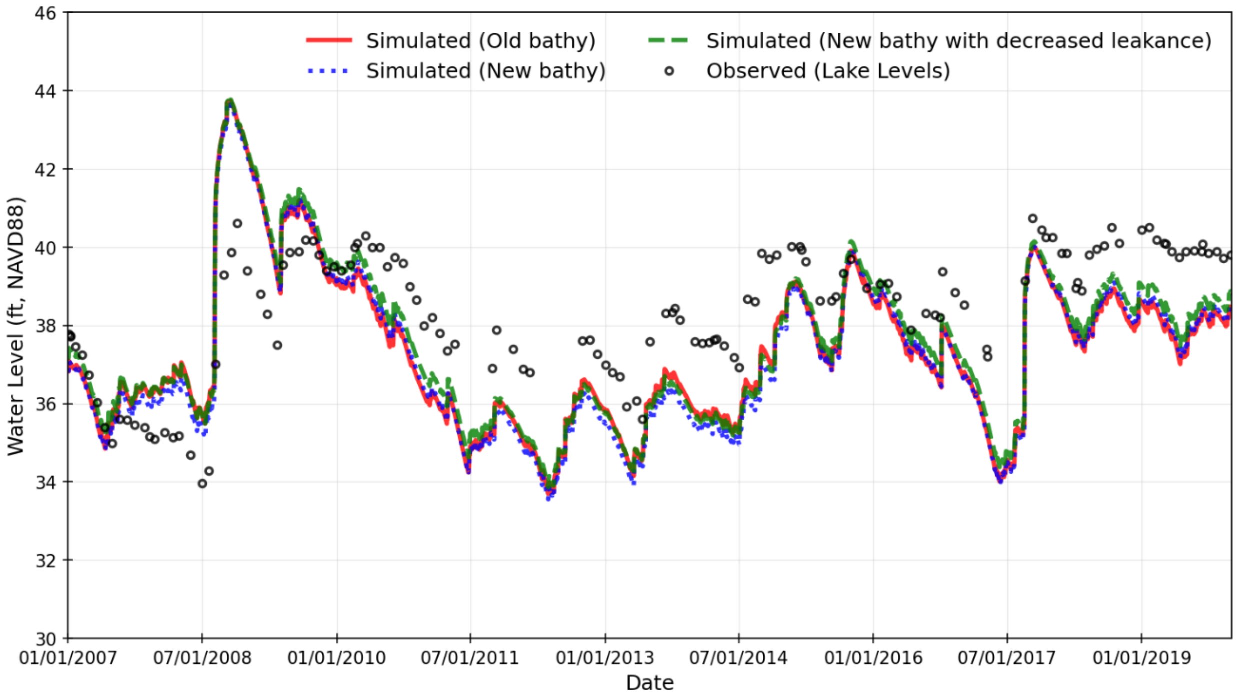


Figure H - 4. Observed and simulated water levels of West Crystal Lake using old and new bathymetry data.

Table H - 1. Goodness-of-fit statistics (calibration period) for old and updated results of West Crystal Lake.

| **Statistics** | **Description** | **Target** | **Old model** | **Updated model** | **Updated model (decreased leakance)** |
|---|---|---|---|---|---|
| NSE | Nash-Sutcliffe Efficiency | ≥ 0.80 | 0.01 | -0.02 | 0.14 |
| RMSE | Root Mean Squared Error | ≤ 1 ft | 1.62 | 1.65 | 1.51 |
| ME | Mean Error | ≤ │±1│ ft | -0.81 | -0.88 | -0.61 |
| ±1ft (%) | % of observations bracketed | ≥ 85 | 24.09 | 26.28 | 29.93 |

Figure H - 5 and Figure H - 6 present the daily observed and simulated water levels for West and East Crystal Lakes, respectively. The simulated water levels generally match the observed water levels in terms of temporal evolutions and variations for both the calibration and validation periods. However, we noticed that HSPF systematically underestimated the observed water levels of West Crystal Lake after 2009 even after updating the bathymetry data (Figure H - 5), while those periods were well simulated for East Crystal Lake as shown in Figure H - 6, and for the other lakes too.

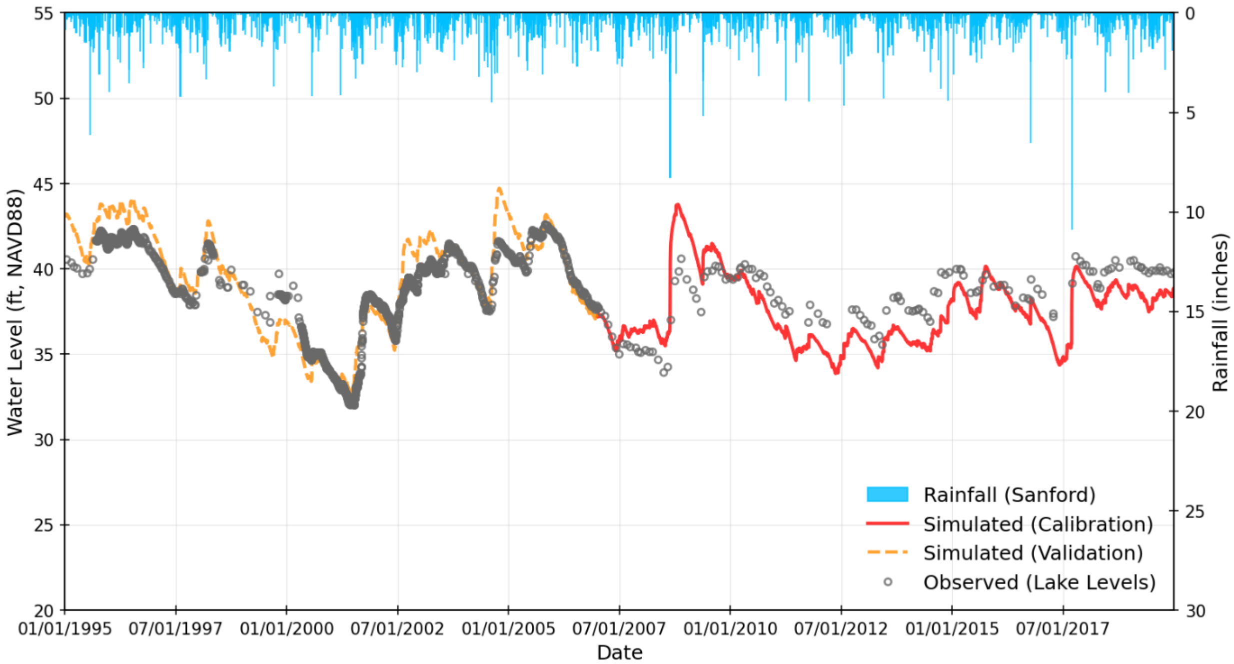


Figure H - 5. Observed and simulated stages for West Crystal Lake.

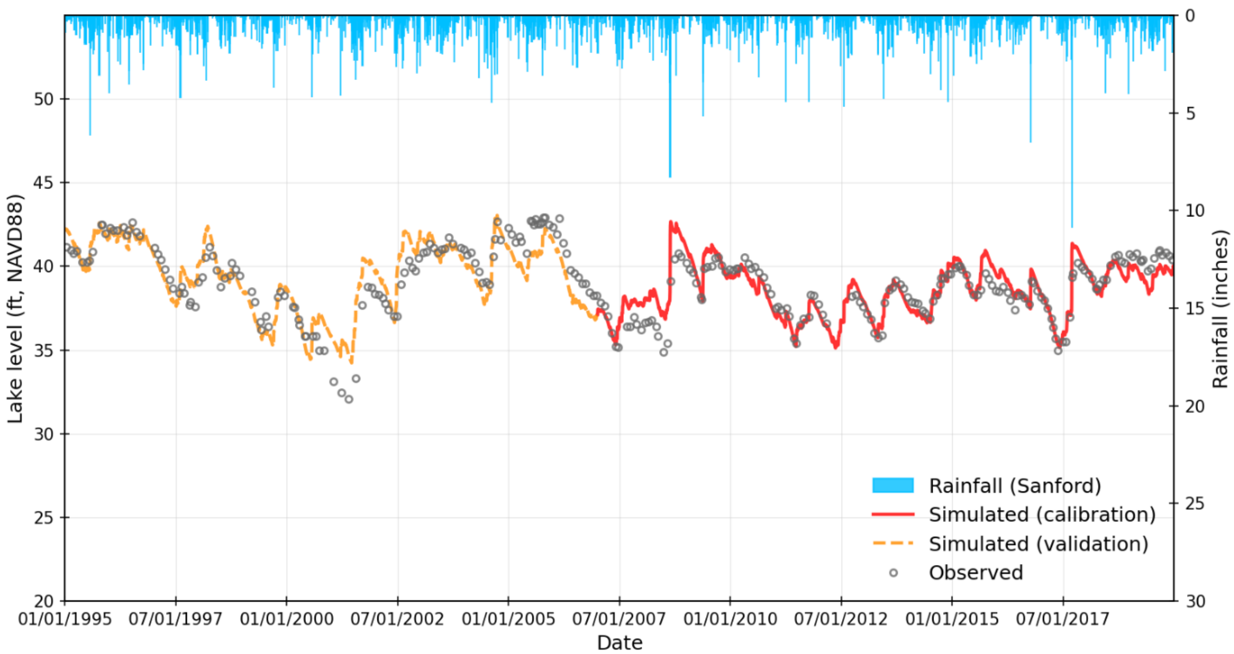


Figure H - 6. Observed and simulated levels for East Crystal Lake.

After 2006, observed water levels data at West Crystal Lake was not available from the SJRWMD hydrological databases. Consequently, we used observed water levels from Seminole County for the calibration period (2007 – 2019) and from SJRWMD for the validation period (1995 – 2006). During the calibration period of West Crystal Lake, targeted statistical values were not achieved particularly for NSE, RMSE, and percent of observations bracketed within ± 1ft, but significantly improved during the validation period (Table H - 2). Given the model performed well for East Crystal Lake and other lakes (see **Appendix C**), the reason for low performance of the model for West Crystal Lake's calibration period is not clear, but it could be due to observed water levels data quality as we used different data sources for the calibration and validation periods of West Crystal Lake.

Table H - 2. Daily goodness-of-fit statistics for calibration and validation periods.

| Period | Statistics | Target | West Crystal | East Crystal |
|---|---|---|---|---|
| Calibration (2007-2019) | NSE | ≥ 0.80 | 0.14 | 0.73 |
| | RMSE | ≤ 1 ft | 1.51 | 0.82 |
| | ME | ≤ \|±1\| ft | -0.61 | 0.17 |
| | ±1ft (%) | ≥ 85 | 29.93 | 81.01 |
| Validation (1995-2006) | NSE | ≥ 0.70 | 0.82 | 0.76 |
| | RMSE | ≤ 1 ft | 1.26 | 1.14 |
| | ME | ≤ \|±1\| ft | 0.57 | -0.06 |
| | ±1ft (%) | ≥ 75 | 51.18 | 58.96 |

Additionally, updating the bathymetric data for West Crystal Lake did not have any noticeable impacts on other lakes' simulated water levels and watersheds' water balance elements documented in **Appendix C**. Nevertheless, like simulated water levels of West Crystal Lake, the updated model along with the slightly lowered leakance value for West Crystal Lake had minor impacts on the lake's water balance components, as summarized in Table H – 3. The table indicates that evaporation and seepage to UFA dominate losses from the lake system during the calibration period. However, surface outflow dominates during the validation period due to the relatively wetter conditions and higher direct rainfall values as compared to the calibration period (Table H – 3), suggesting that seepage to UFA and evaporation processes are generally dominant components during the drier conditions.

Table H – 3. West Crystal annual average water balance elements (acre-feet) for updated model. Precent refers to the total inflow.

| Lake | Period | Direct Rainfall | Watershed Inflow | Evaporation | Seepage | Surface Outflow | Total Inflow | Total Outflow | Storage Change |
|---|---|---|---|---|---|---|---|---|---|
| West Crystal | Calibration | 512.5 | 762.1 | 489.1 | 523.9 | 245.5 | 1274.5 | 1258.5 | 16.0 |
| | Percent | 40.2 | 59.8 | 38.4 | 41.1 | 19.3 | | | 1.3 |
| | Validation | 670.6 | 2590.6 | 623.0 | 820.8 | 1897.2 | 3261.2 | 3340.9 | -79.8 |
| | Percent | 20.6 | 79.4 | 19.1 | 25.2 | 58.2 | | | -2.4 |

# Long-Term Simulations

The calibrated and validated model for the Crystal Chain of Lakes was used to simulate the lake level for an extended period from 1953 through 2019 using the best available rainfall, PET, and well level data. Like calibration and validation periods, the first two years were used for model warm-up. Figure H - 7 and Figure H - 8 compare the long-term simulated and observed lake levels of West and East Crystal Lakes, respectively. Due to lack of observed data before 1993, the figures also compare simulated water levels with the observed water levels from the closest lake, i.e, Sylvan Lake. The model adequately tracked the observed water levels of Sylvan Lake, indicating the long-term water levels of West and East Crystal Lakes produced by the HSPF model are reasonable.

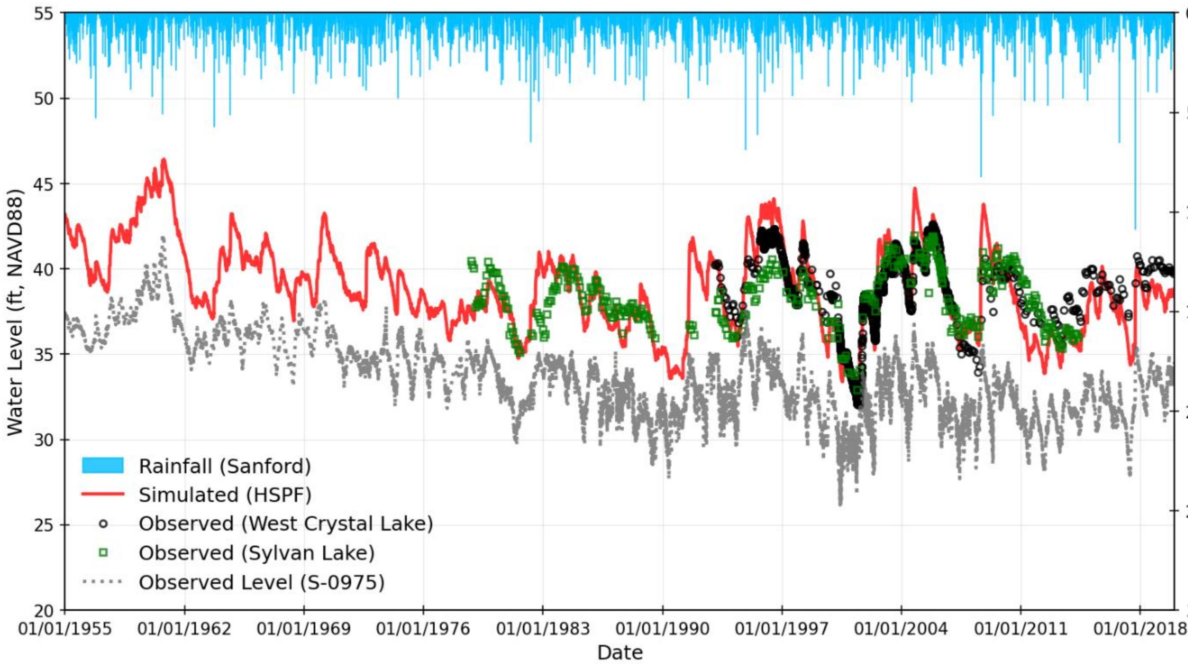


Figure H - 7. Long-term observed and simulated levels for West Crystal Lake.

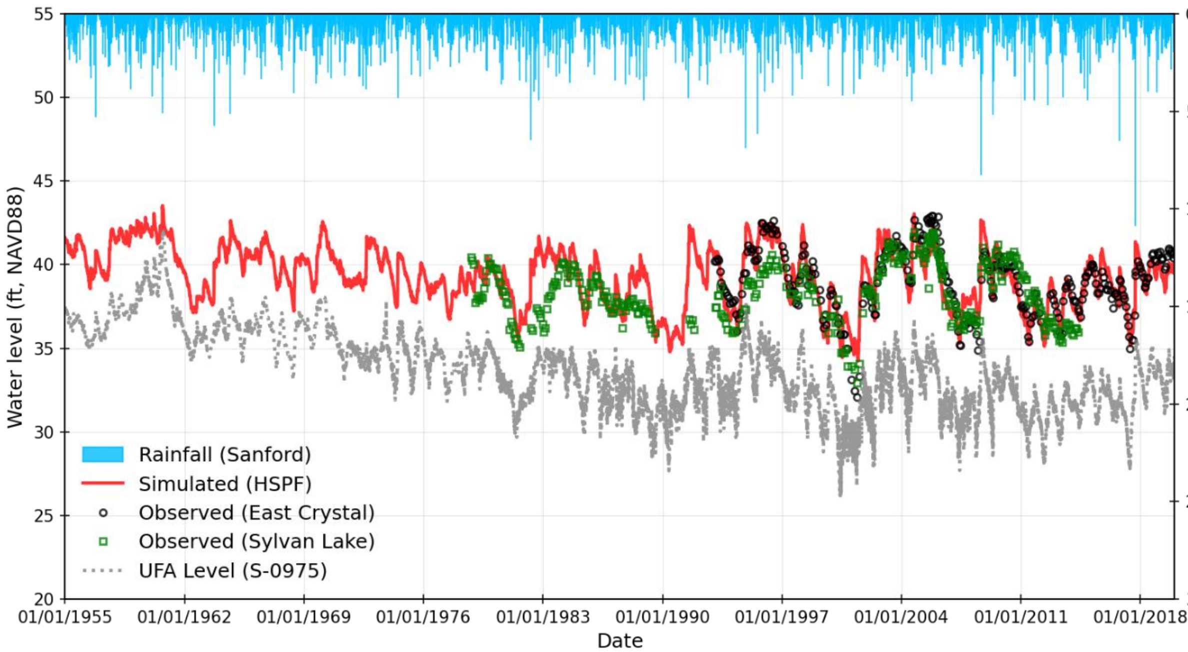


Figure H - 8. Long-term observed and simulated levels for East Crystal Lake.

Table H – 4 summarizes the model performance rating metrics for both West and East Crystal Lakes using the available period of record (POR). The calculated statistical values are generally reasonable for both lakes. Detailed information on the long-term simulation results is provided in **Appendix D**.

Table H – 4. Daily goodness-of-fit statistics for long-term period (1955-2019).

| Statistics | Description | West Crystal | East Crystal |
|---|---|---|---|
| NSE | Nash-Sutcliffe Efficiency | 0.81 | 0.76 |
| RMSE | Root Mean Squared Error | 1.26 | 0.97 |
| ME | Mean Error | 0.47 | 0.07 |
| ±1ft (%) | % of observations bracketed | 50.27 | 72.15 |

# Sensitivity Analysis

We performed the model sensitivity analysis for the calibration period (2007 – 2019) of the HSPF model and identified the most sensitive parameters affecting the hydrologic response of West and East Crystal Lakes. Detailed information on the sensitivity analysis is provided in **Appendix E**.

The five parameters analyzed during sensitivity analysis included: the fraction of groundwater inflow that goes to the inactive groundwater (DEEPFR), the leakance value used for the estimation of vertical seepage flows to the Upper Floridan Aquifer (k), an index of the infiltration capacity of the soil (INFILT), the lower zone evapotranspiration parameter (LZETP), and the lower zone nominal storage (LZSN).

Results of this analysis showed that the simulated lake levels were highly sensitive to changes in k, with simulated lake level time series considerably changing for each sensitivity run. The simulated lake levels showed moderate sensitivity towards DEEPFR and LZETP and low sensitivity towards INFILT and LZSN. In addition, the best model performance obtained during SA showed comparable results with the calibrated model performance, indicating the robustness of the model calibration process.

# Conclusions

In support of minimum flows and levels modeling of the Crystal Chain of Lakes (CCL), we developed an HSPF model to adequately simulate daily variations of long-term water levels for the CCL. Most of the daily statistical values met the targeted values during the calibration period except for the percent of observations bracketed within ± 1ft and Nash-Sutcliffe Efficiency, especially for West Crystal Lake. We achieved better statistical values and improved model performance ratings during the validation period, indicating the applicability of the model outside the calibration period. Overall, the HSPF model showed reasonable simulations of surface water-groundwater interaction and water levels of CCL, indicating the model can be used for minimum flows and levels modeling and scenario analysis.

# References

Bicknell B. R., Imhoff J. C., Kittle J. J., Jobes T. H., & Donigian, J. A. (2001). HYDROLOGICAL SIMULATION PROGRAM - FORTRAN, HSPF, Version 12, User's Manual. Athens, GA: U.S. Environmental Protection Agency - National Exposure Research Laboratory.

Fox S., Kinser P., Keenan L., Montague C., & Hydorn D. (2012). Appendix D. Hydroperiod Tool Analysis of St. Johns River Segment 7.

Streamline Technologies. (2018). ICPR4 Technical Reference.

# Appendix A – Existing Data Review

# TECHNICAL MEMORANDUM

**DATE:** September, 2021

**SUBJECT:** East Crystal Data Collection, Review, & Processing

## Introduction

The St. Johns River Water Management District (SJRWMD)'s Minimum Flows and Levels (MFLs) Program, mandated by the state water policy, is a District-wide effort to establish MFLs for priority lakes, streams and rivers, wetlands, springs, and groundwater aquifers. The program designates the minimum hydrologic conditions that must be maintained for these water resources to prevent significant harm resulting from permitted water withdrawals. Crystal Chain of Lakes (CCL) is a priority lake system listed on the District's MFLs priority list and scheduled for completion in 2024.

The CCL includes East and West Crystal Lakes, Bel-Air Lake, Deforest Lake, and Armory Lake, in Seminole County, Florida (Figure A - 1). The Chain of Lakes are located about four miles southwest of the City of Sanford. These lakes primarily receive water from direct precipitation, surface runoff, and base flow, and lose their water through evaporation and seepage into the Upper Floridan Aquifer (UFA).

We will set up, calibrate, and validate a continuous simulation hydrological model for the Crystal Chain of Lakes using a Hydrological Simulation Program – FORTRAN (HSPF) model (Bicknell et al., 1997). This technical memorandum focuses on the hydro-meteorological and geo-spatial data collection, review, analyses, and preparation/processing part of the model set up.

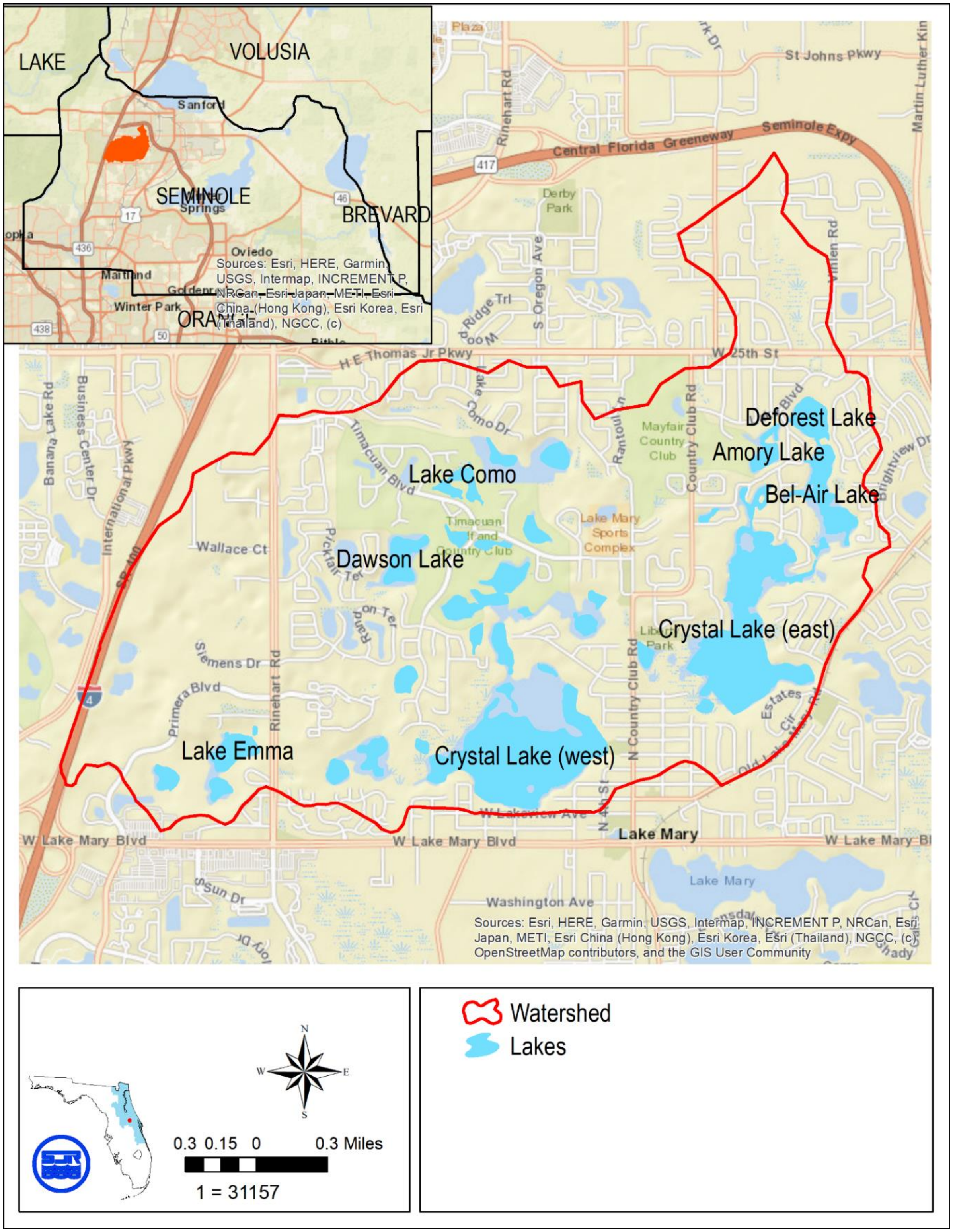


Figure A - 1. Location of Study area in Seminole County

# Data

## Digital Elevation Model

We obtained the Digital Elevation Model (DEM) data (10 m resolution) from the SJRWMD's GIS databases. For a few lakes (Amory, East Crystal, Bel-Air, and Deforest), we also obtained bathymetry data from the University of South Florida, USF (personal communication, 2020) and the East Crystal Chain-of-Lakes Hydrologic/Nutrient Budgets & Management Plans study (Environmental Research & Design (ERD), 2014). In addition, we will extract the old stage-area data used in the Interconnected Channel and Pond Routing (ICPR) model of the Monroe basin by Camp Dresser & McKee (CDM) (CDM, 2002) and utilize as a secondary data. Further, as the bathymetry data used in the CDM's model and reported in ERD (2014) were in NGVD29, we will convert the extracted data to NAVD88. Figure A - 2 presents the DEM and currently available bathymetry data from the USF. We will update the bathymetry if more site-specific data becomes available during this project work.

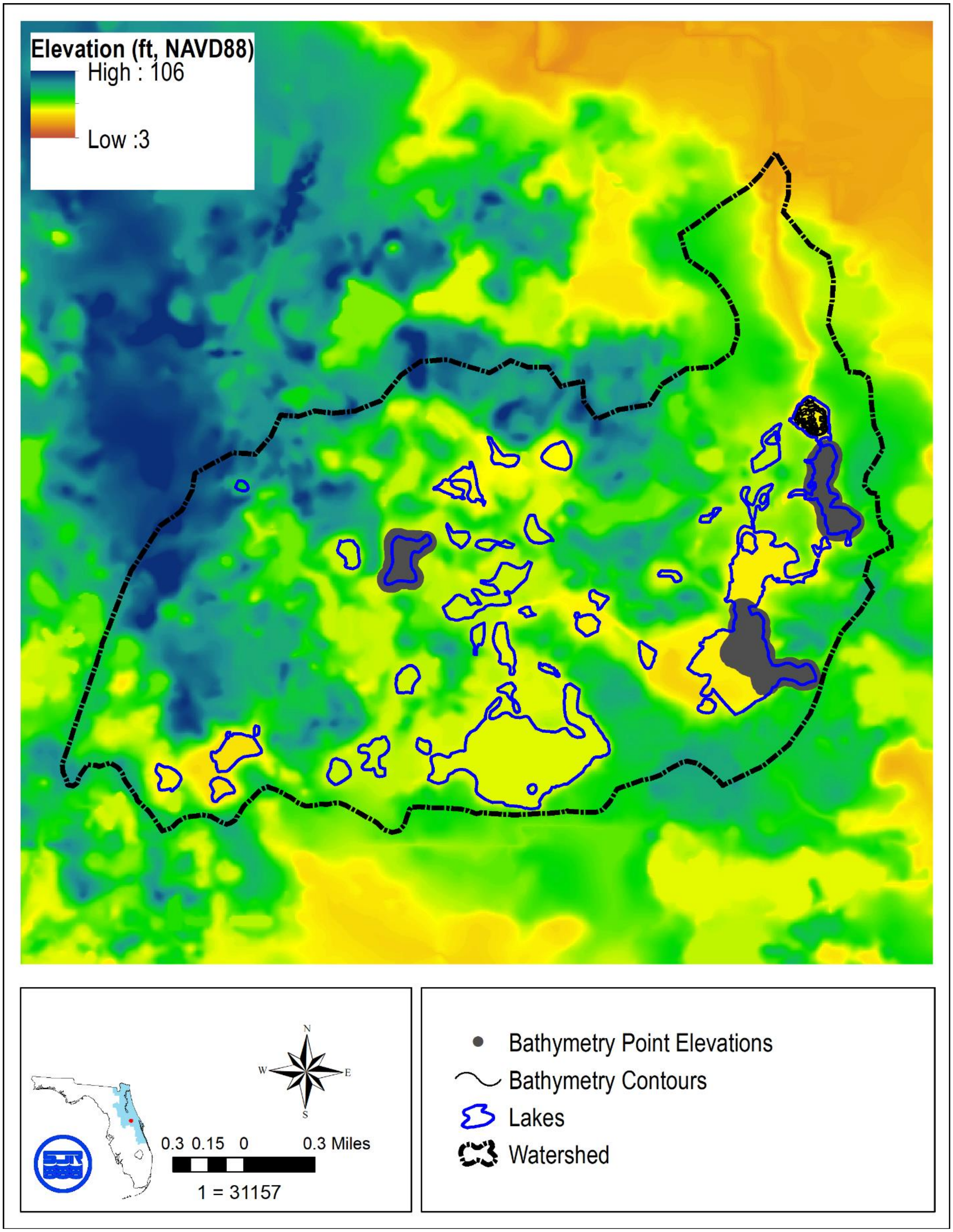


Figure A - 2. DEM and bathymetry data as obtained from the University of South Florida

## Watershed

The Crystal Chain of Lakes watershed (approximately 5.6 $mi^2$) discharges into the Lake Monroe at the downstream of Deforest Lake outlet (Figure A - 3). The watershed, which is characterized by a highly developed mixture of residential and commercial land uses (Figure A - 4 and Table A - 1), is part of the Middle St. Johns River (MSJR) basin (Figure A - 3). We will use the surface water basin boundary from the SJRWMD's GIS databases, but will verify this based on site visit and previous studies.

## Land use/Land cover

We obtained the Land Use/Land Cover (LULC) 2014 data from the SJRWMD's GIS databases. LULC data is shown in Figure A - 4. Table A - 1 summarizes the areal coverage of each LULC within the watershed whereby the developed (residential) and commercial/industrial areas account for more than 55% of the watershed. Lakes and surrounding areas represented as water and wetland in the LULC map (Figure A - 4) and account for about 25% of the watershed area (Table A - 1).

Table A - 1. Land use/land coverages of the Crystal Chain of Lakes Watershed

| Land use/land cover | Area (ac) | Area (%) |
|---|---|---|
| 1: Low density residential | 213.0 | 6.0 |
| 2: Medium density residential | 899.4 | 25.3 |
| 3: High density residential | 443.0 | 12.4 |
| 4: Commercial/Industrial | 432.8 | 12.2 |
| 6: Open | 55.6 | 1.6 |
| 7: Pasture | 2.6 | 0.1 |
| 8: General agriculture | 278.8 | 7.8 |
| 9: Groves | 6.6 | 0.2 |
| 10: Range/Shrub | 171.0 | 4.8 |
| 11: Forest | 186.5 | 5.2 |
| 12: Water | 255.8 | 7.2 |
| 13: Wetland | 616.3 | 17.3 |
| **Total** | **3561.4** | **100.0** |

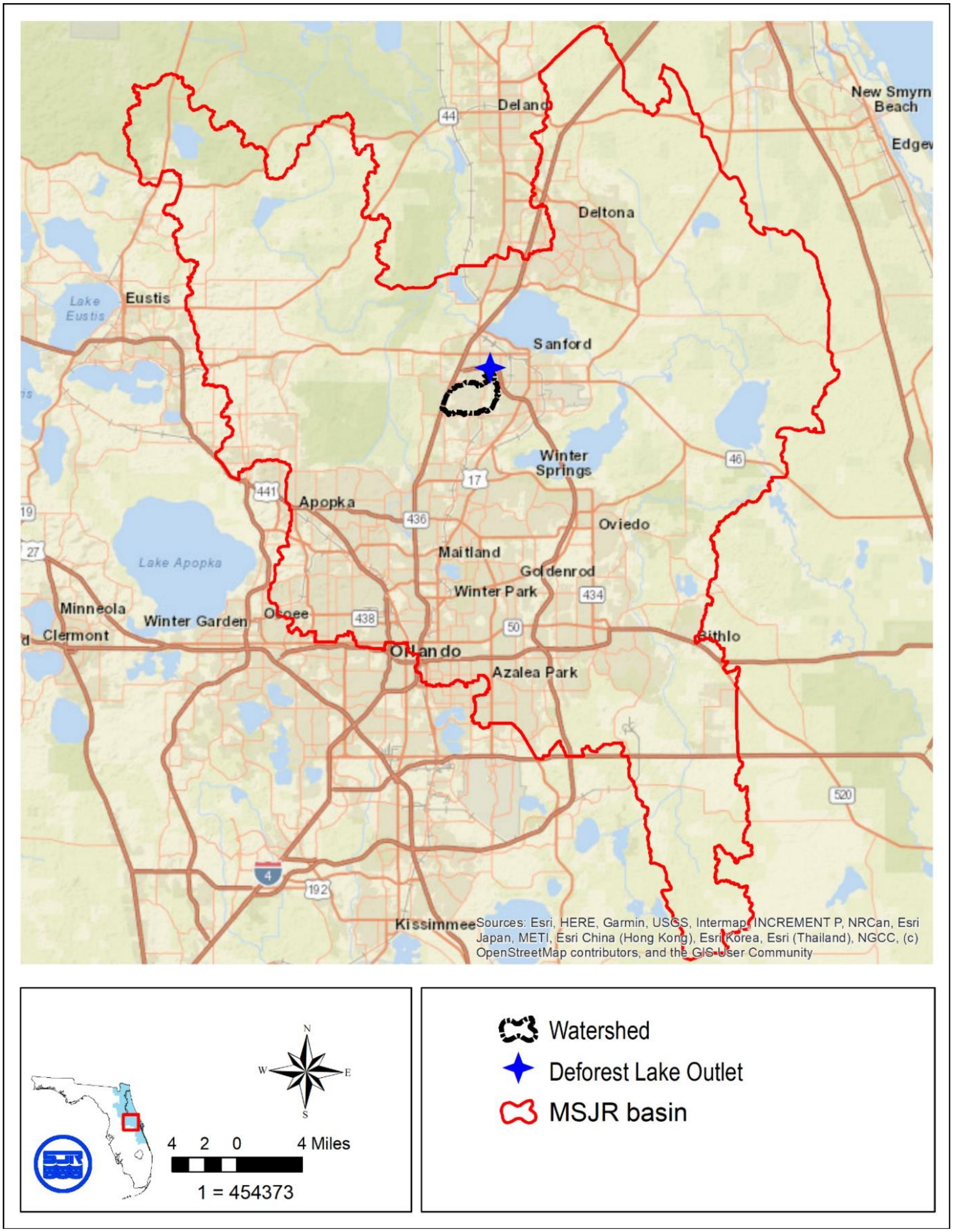


Figure A - 3. Location of Crystal Chain of Lakes Watershed in the Middle St. Johns River Basin

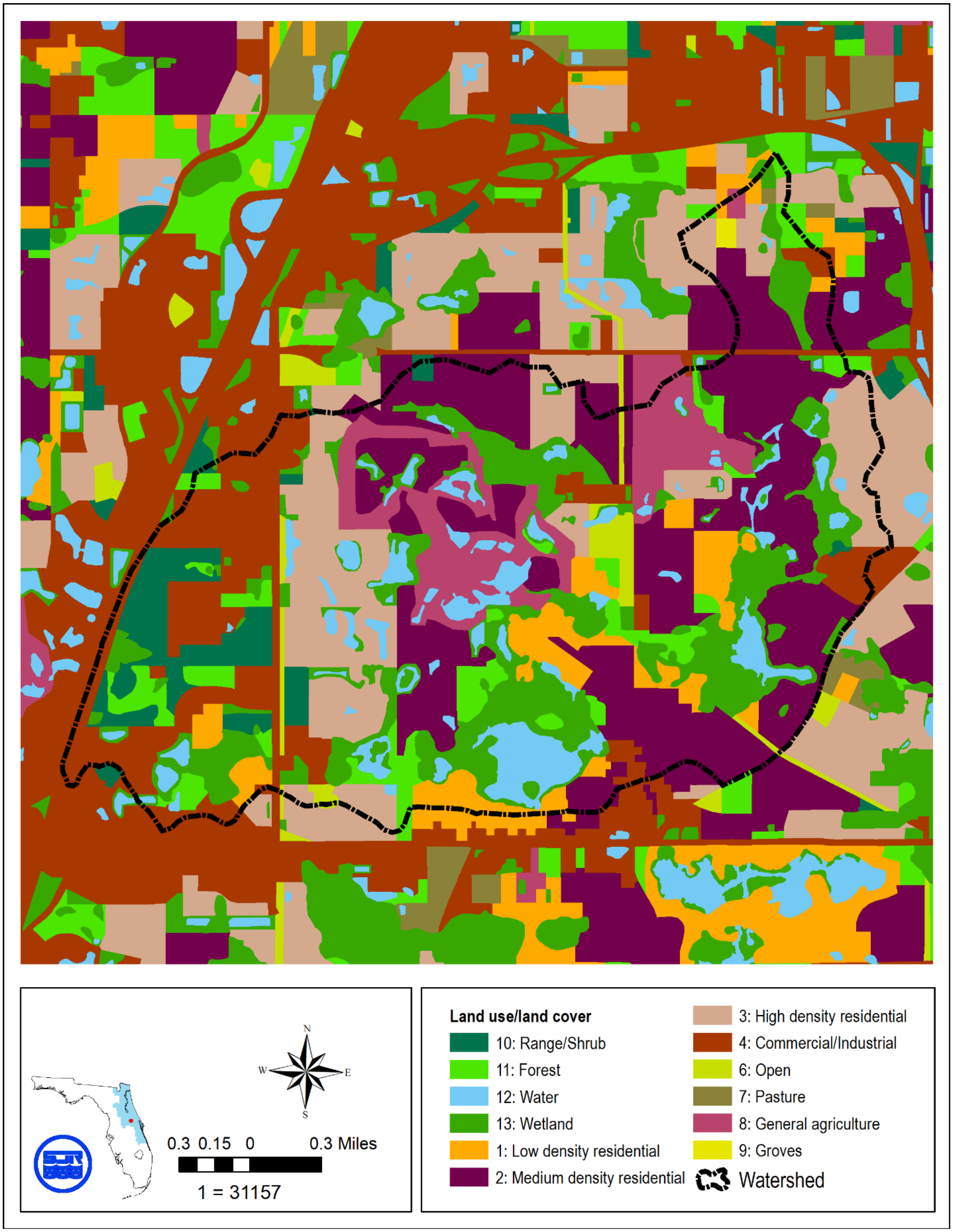


Figure A - 4. Land Use/Land Cover 2014. Numbers in legend represent District's land use/cover code

## Imperviousness Values

Based on the review of existing data, a site visit to survey and sample impervious fractions for the different LULC reported in Figure A - 4 are not available for the study area. Consequently, we will use the typical impervious fractions used for the HSPF models at the SJRWMD (Table A - 2). We will adjust the imperviousness values during the calibration step, if needed.

Table A - 2. Imperviousness fractions. Numbers in first column represent District's land use/land cover codes.

| Land use/land cover* | Imperviousness (%) |
|---|---|
| 1: Low density residential | 5 |
| 2: Medium density residential | 15 |
| 3: High density residential | 35 |
| 4: Commercial/Industrial | 50 |
| 5: Mining | 0 |
| 6: Open | 0 |
| 7: Pasture | 0 |
| 8: General agriculture | 0 |
| 9: Groves | 0 |
| 10: Range/Shrub | 0 |
| 11: Forest | 0 |
| 12: Water | 0 |
| 13: Wetland | 0 |

## Soils

We retrieved soil maps and corresponding properties for Seminole county from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) databases (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/office/ssr12/tr/?cid=nrcs142p2_010596). The soil maps delineate soils using soil hydrologic groups (SHG). While Table A - 3 summarizes the acreage of SHG within the study area, Figure A - 5 presents the spatial distribution of SHG. Type A soil, which is generally characterized with high infiltration rate and well drain condition, approximately covers two-third of the study area, and is followed by type A/D soil (Table A - 3). The latter soil experiences high infiltration rate and well drain during dry condition but become low infiltration rate and poorly drained condition when surface soil gets wet.

Table A - 3. Soil hydrologic group of the study area

| Soil Hydrologic Group | Acreage | Percentage |
|---|---|---|
| A | 2082.6 | 58.5 |
| A/D | 992.2 | 27.9 |
| Urban land | 147.3 | 4.1 |
| Water | 339.7 | 9.5 |
| **Total** | **3561.7** | **100.0** |

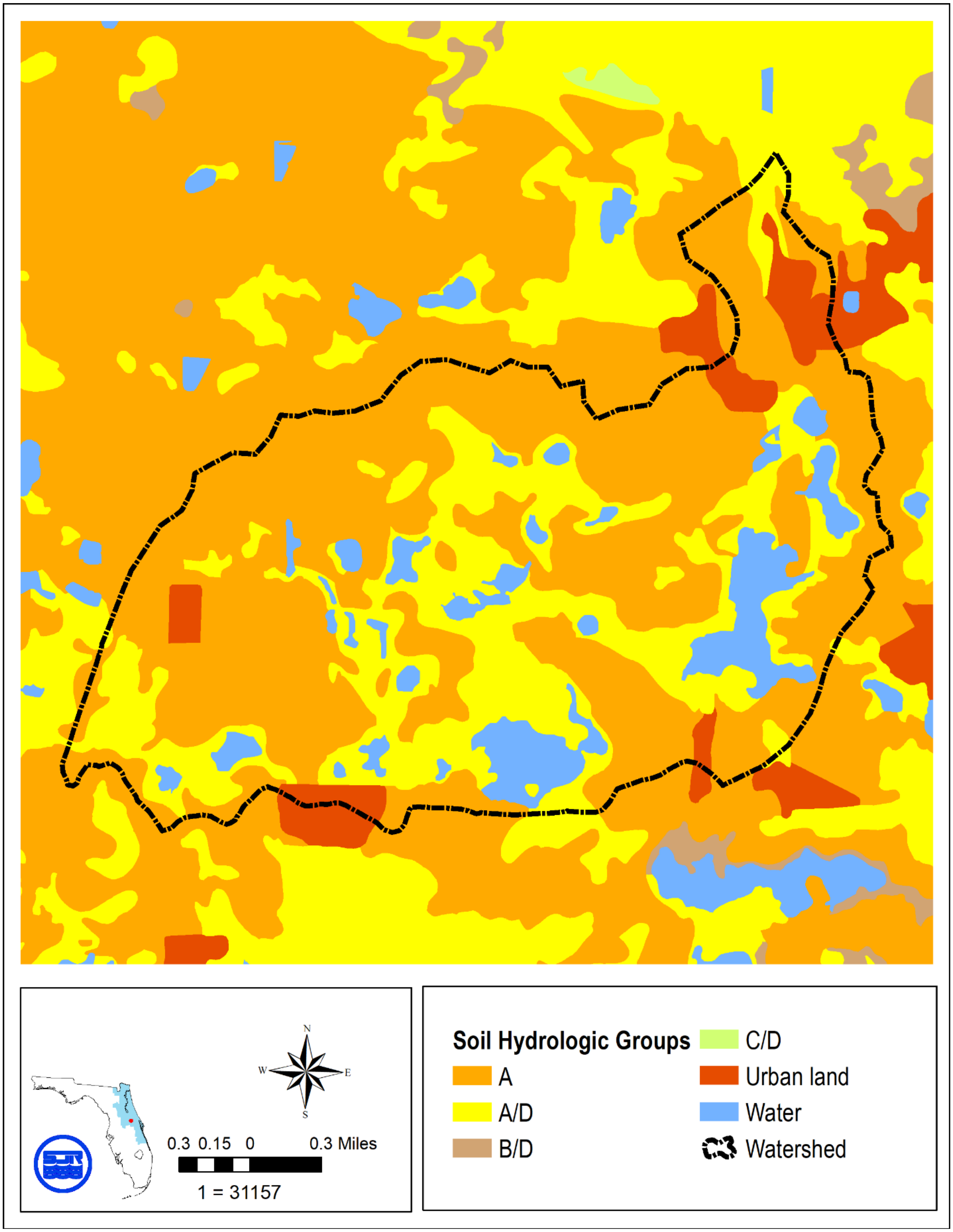


Figure A - 5. Soil hydrologic groups for the study area.

## Leakance

To model the leakage rates beneath the lakes, we will use the observed Upper Floridian Aquifer (UFA) stages along with leakance values. We will use the leakance values used in the East-Central Florida Transient (ECFTX) groundwater model of the SJRWMD (Central Florida Water Initiative (CFWI), 2020). Figure A - 6 shows the leakance values used in the ECFTX model for the study and surrounding area. However, we will average the gridded leakance values based on the lake polygons, which will be generated during the model set up, and using the zonal statistics tool of ArcGIS. Depending on the model performance, we will adjust the leakance values during model calibration process.

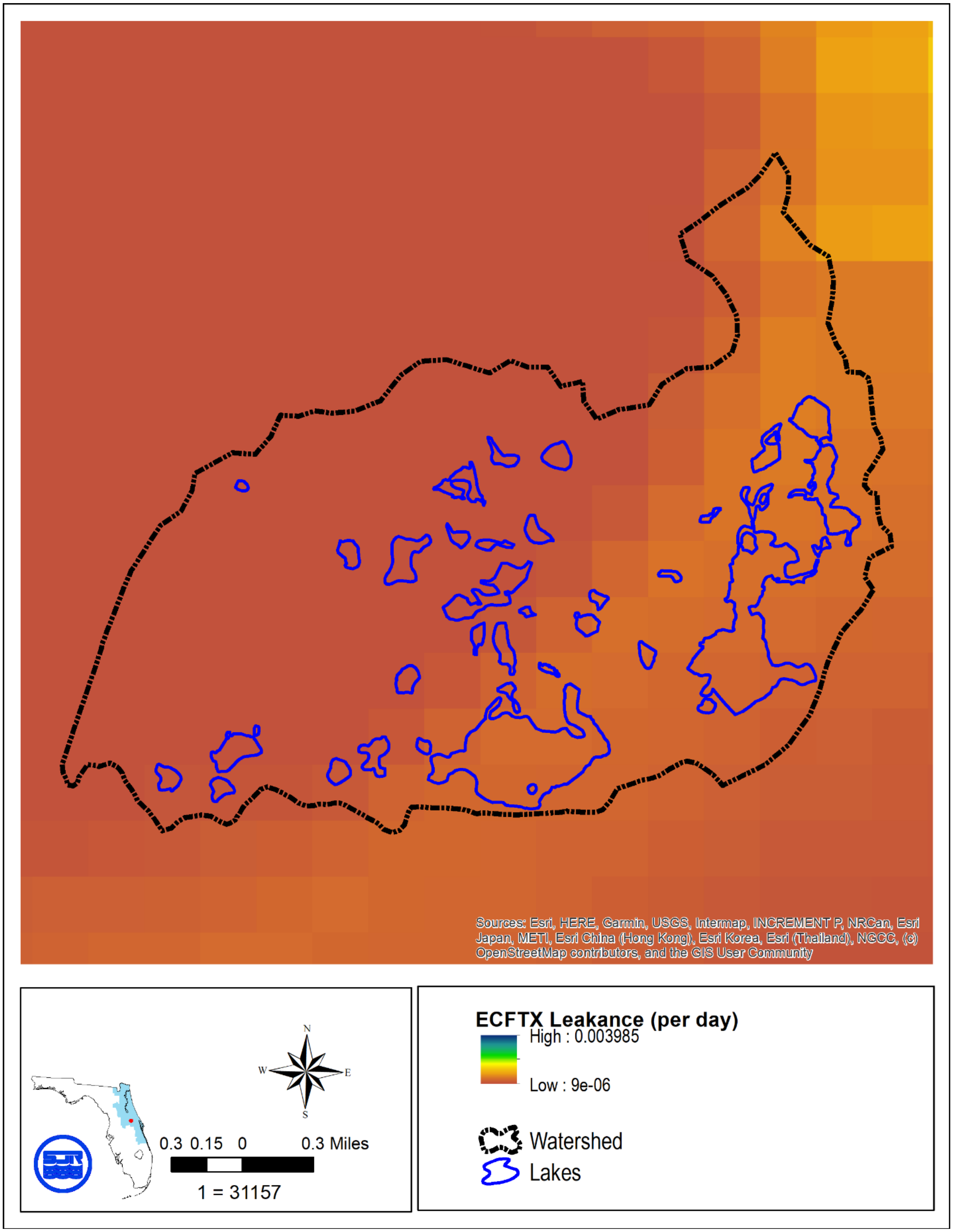


Figure A - 6. The ECFTX model leakance values

## Rainfall and Potential Evapotranspiration

Complete hourly NEXRAD rainfall data was available for the period from 1995 to 2019 from the SJRWMD's hydrometeorological databases. We selected 11 rainfall pixels (grids) within and around the Crystal Chain of Lakes watershed boundary (Figure A - 7). We downloaded the corresponding rain values for the period of record (POR). In addition to NEXRAD data, there are some daily rain gauge stations that are located within and around the watershed, and monitored by the SJRWMD and National Oceanic and Atmospheric Administration (NOAA) (Figure A - 7). Most of the stations monitored by the SJRWMD had discontinued records (Table A - 4). The NOAA's station at Sanford (GHCND:USC00087982) is the closet to the watershed and generally had a long-term POR as summarized in Table A - 4. Because the NEXRAD data were not available before 1995, we will first use the long-term recorded data at the Sanford station. We will also make the simulated results comparison with the NEXRAD data for the overlapping POR.

Table A - 4. Summary of available rain gauge stations

| Station Name | Station ID | Source | Available period |
|---|---|---|---|
| Lake Emma at Sanford | 3620463 | SJRWMD | 7/1/1995 to 9/22/1997 |
| Crystal Lake at Lake Mary | 3500415 | SJRWMD | 9/14/1995 to 6/29/2002 |
| Wekiva Park at Sanford | 4730928 | SJRWMD | 6/2/1993 to 1/15/2001 |
| Wekiva Marina | 4740929 | SJRWMD | 1/24/1992 to 10/30/1996 |
| OR0650 Rock Springs Wells at Sorrento | 11303088 | SJRWMD | 11/2/1994 to present |
| Charlotte St | 22752279 | SJRWMD | 8/11/1994 to 2/10/2009 |
| Wekiva Springs State Park | 30063053 | SJRWMD | 10/30/1992 to 7/9/2002 |
| Sanford | GHCND:USC00087982 | NOAA | 05/31/1956 to present |

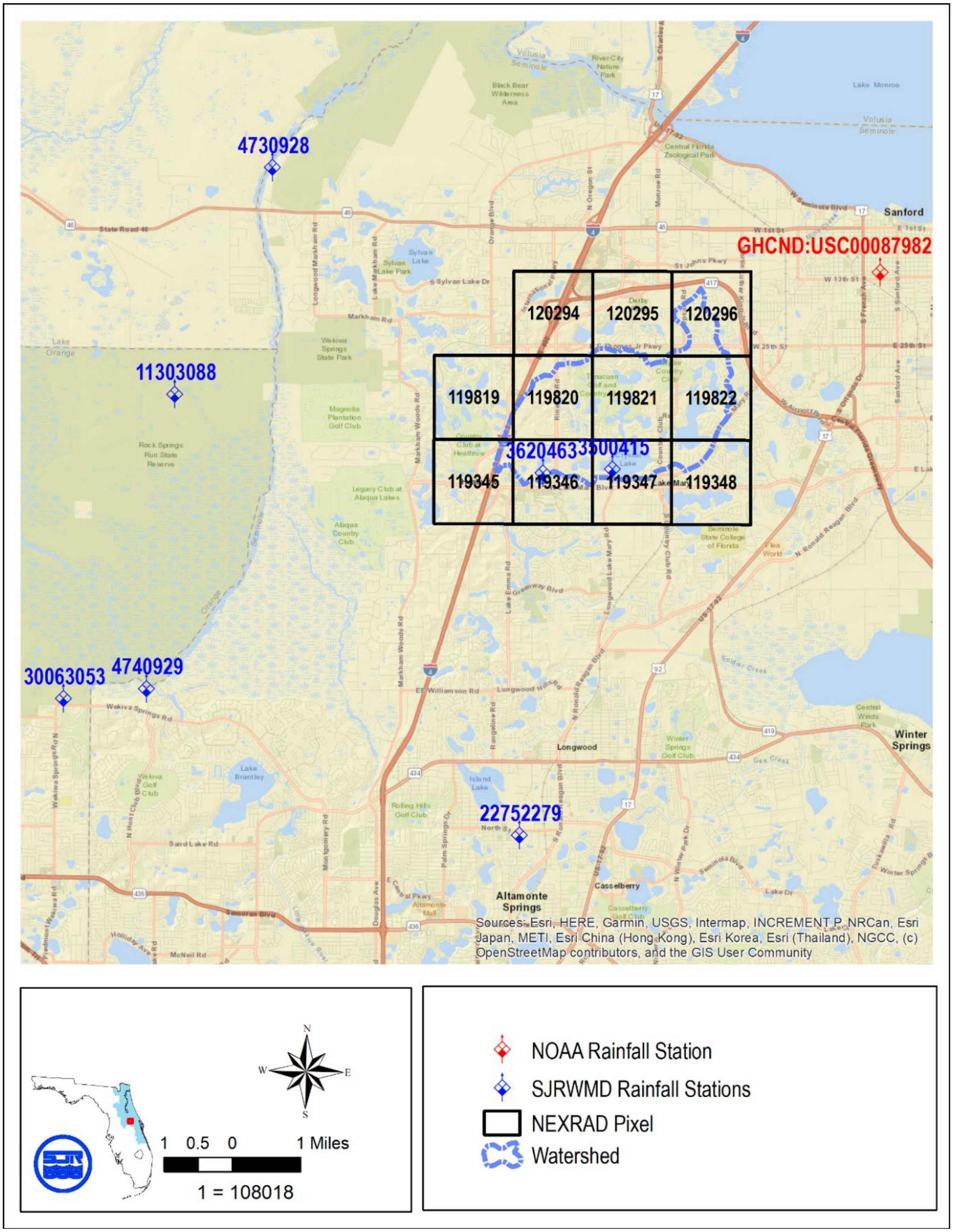


Figure A - 7. NEXRAD pixels and gauge stations for rainfall and potential evapotranspiration. Numbers represent pixels/stations IDs.

Figure A - 8 summarizes the annual rainfall values for two pixels located inside the CCL watershed and the NOAA station at Sanford. While the selected pixels show minor annual rainfall spatial variability, rain gauge values are generally higher than pixel values. For both NEXRAD and Sanford station, the lowest and highest rainfall values were recorded in 2000 and 2008, respectively, (Figure A – 7).

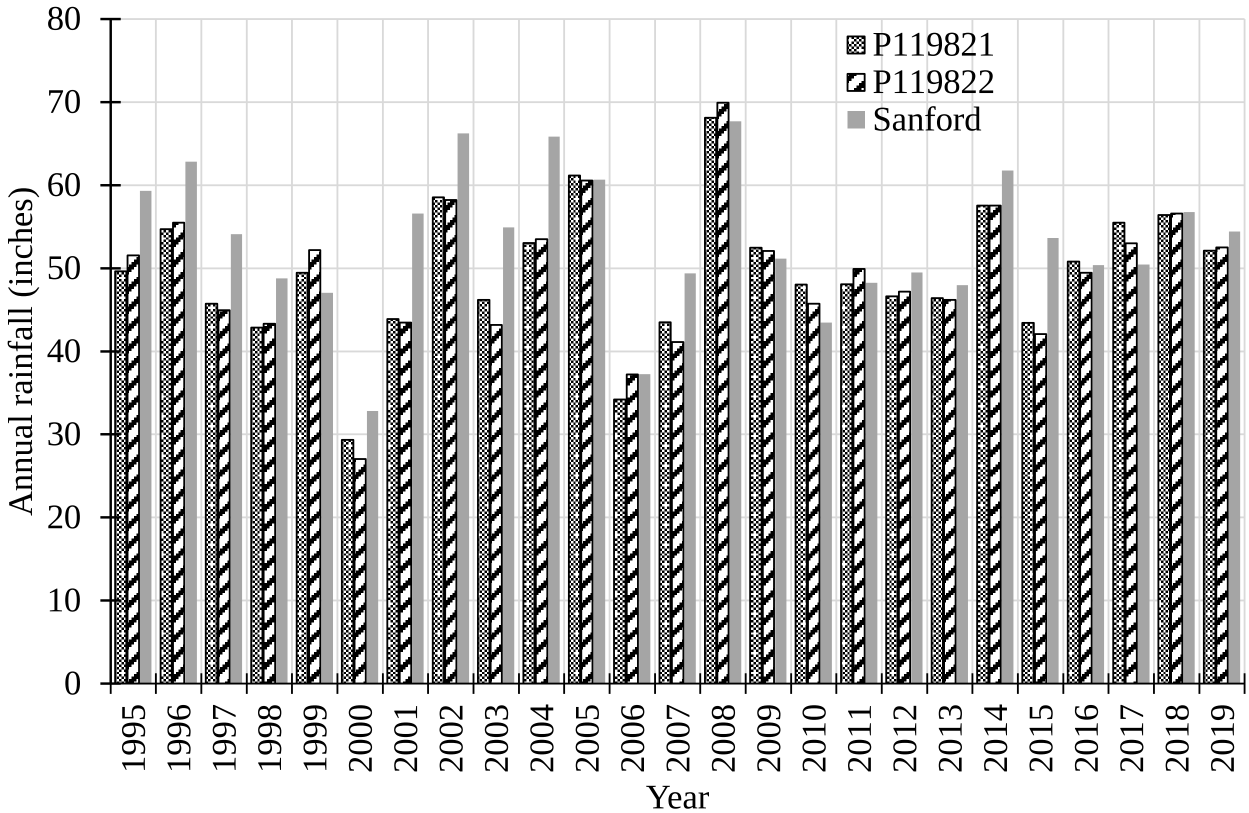


Figure A - 8. Annual rainfall values for pixels inside the East Crystal Lake watershed and Sanford station

Long-term estimated PET data using the Hargreaves's method (Hargreaves and Samani, 1985) and recorded daily maximum and minimum temperatures (since 1/1/1948) is available at the NOAA Sanford station. Figure A - 9 presents annual PET values for the period from 1995 to 2019. Unlike the annual rainfall values, the lowest PET was estimated in 2005 (Figure A - 9).

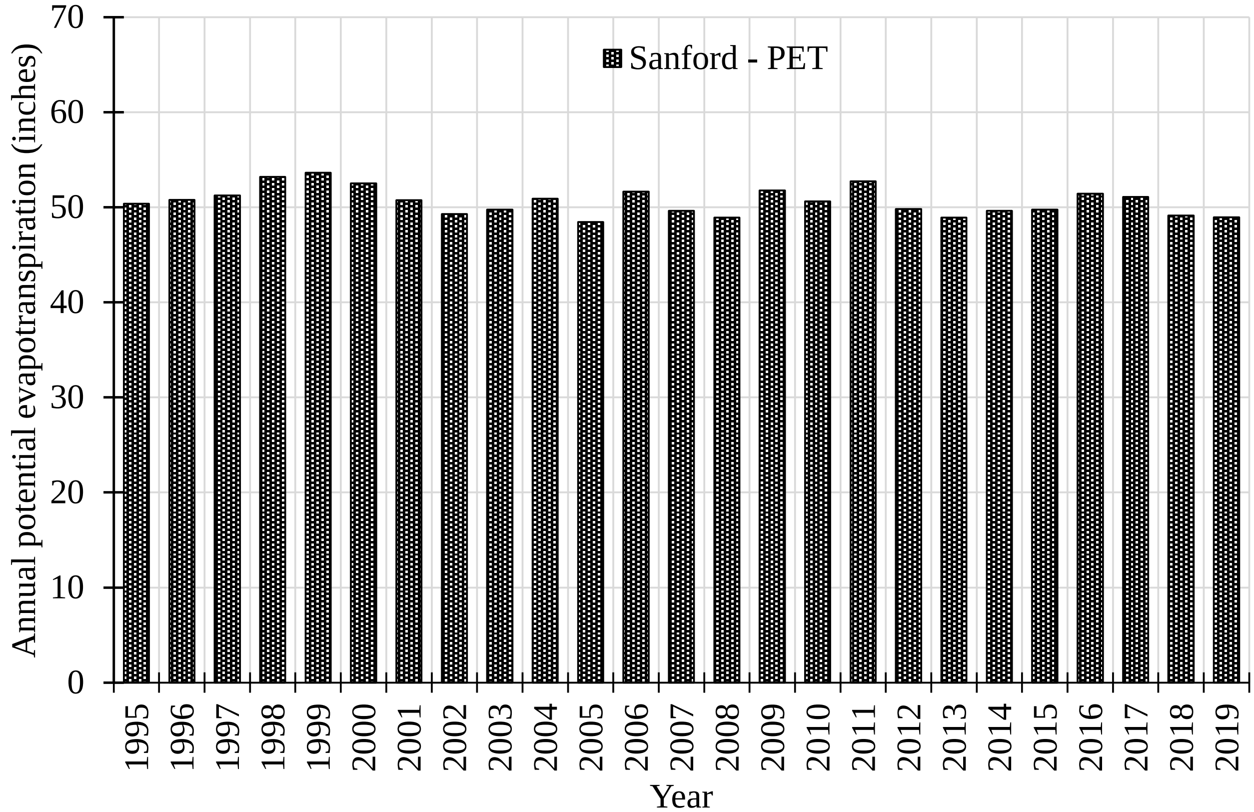


Figure A - 9. Annual potential evapotranspiration at NOAA Sanford

## Groundwater Levels

The Upper Floridan Aquifer (UFA) levels are needed for the HSPF model to simulate leakage rates beneath the lakes. We collected, reviewed, and analyzed a number of daily UFA wells data within and around the watershed for the period 1953 to 2019. Location of the wells are shown in Figure A - 10. S-0975 is located inside the watershed and therefore, selected to be used in the HSPF model. Figure A - 11 presents observed water levels for S-0975 and nearby wells. S-0206 and S-0123 had short-term POR but show similar water levels with S-0975 (Figure A - 11). S-0125 had long-term POR (since 10/25/1951) and generally shows similar temporal pattern and evolution with S-0975's data.

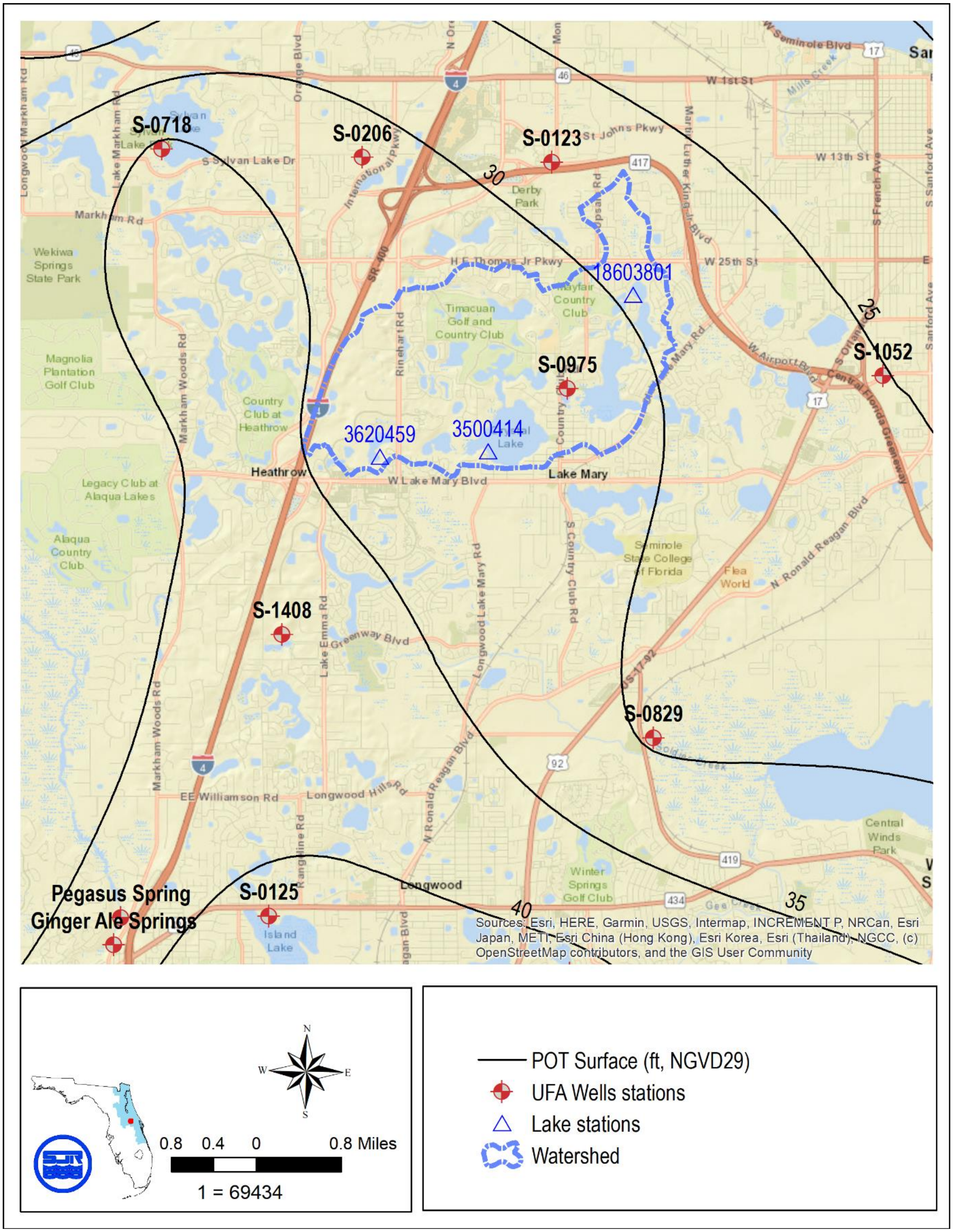


Figure A - 10. Location of UFA wells and lakes stations, and Potentiometric levels of September 2010 (NGVD29).

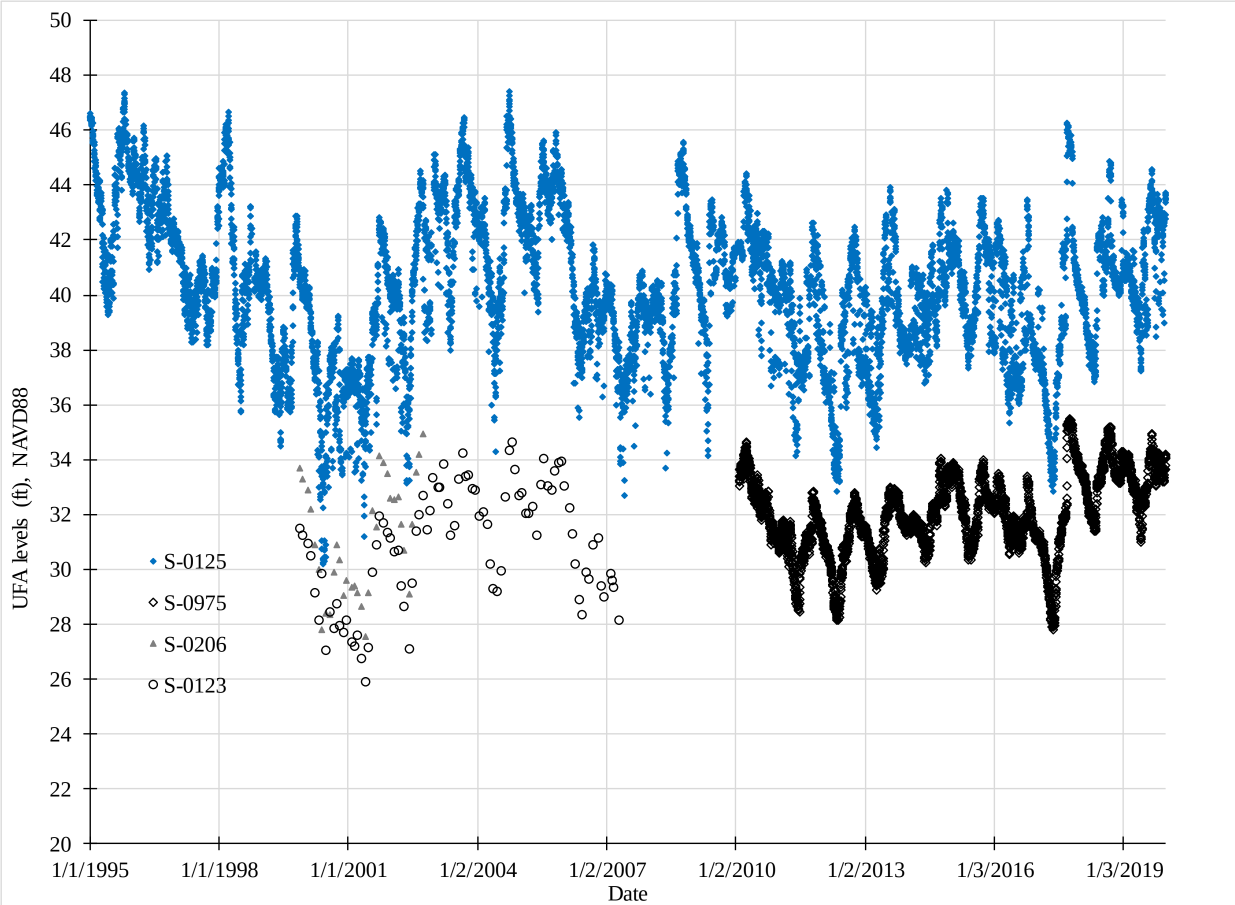


Figure A - 11. The daily observed UFA levels for wells within and around the watershed of East Crystal Lake

As S-0975 had irregularly recorded water levels since 1/29/2010 (Figure A - 11), we subsequently extended this well's data to the period from 1953 to 2019 based on the recorded values at well S-0125, which is located approximately 6 miles southwest of S-0975 and had a reasonable correlation with S-0975 ($R^2$ = 0.71). The scatter plot between observed water levels at S-0125 and S-0975 for the overlapping POR is shown in Figure A - 12. With similar temporal patterns between the two wells, water levels at S-0125 are averagely higher by approximately 8 ft (Figure A - 12). Due to long-term records at S-0125 and a reasonable correlation with S-0975, we used S-0125 to fill long-term missing values at S-0975. We filled the long-term missing values at S-0975 based on monthly offset values and line of organic correlation (LOC), including simple linear regression (SLR). We computed the monthly offsets and regression equations from the observed water levels at S-0975 and S-0125 for the overlapping POR.

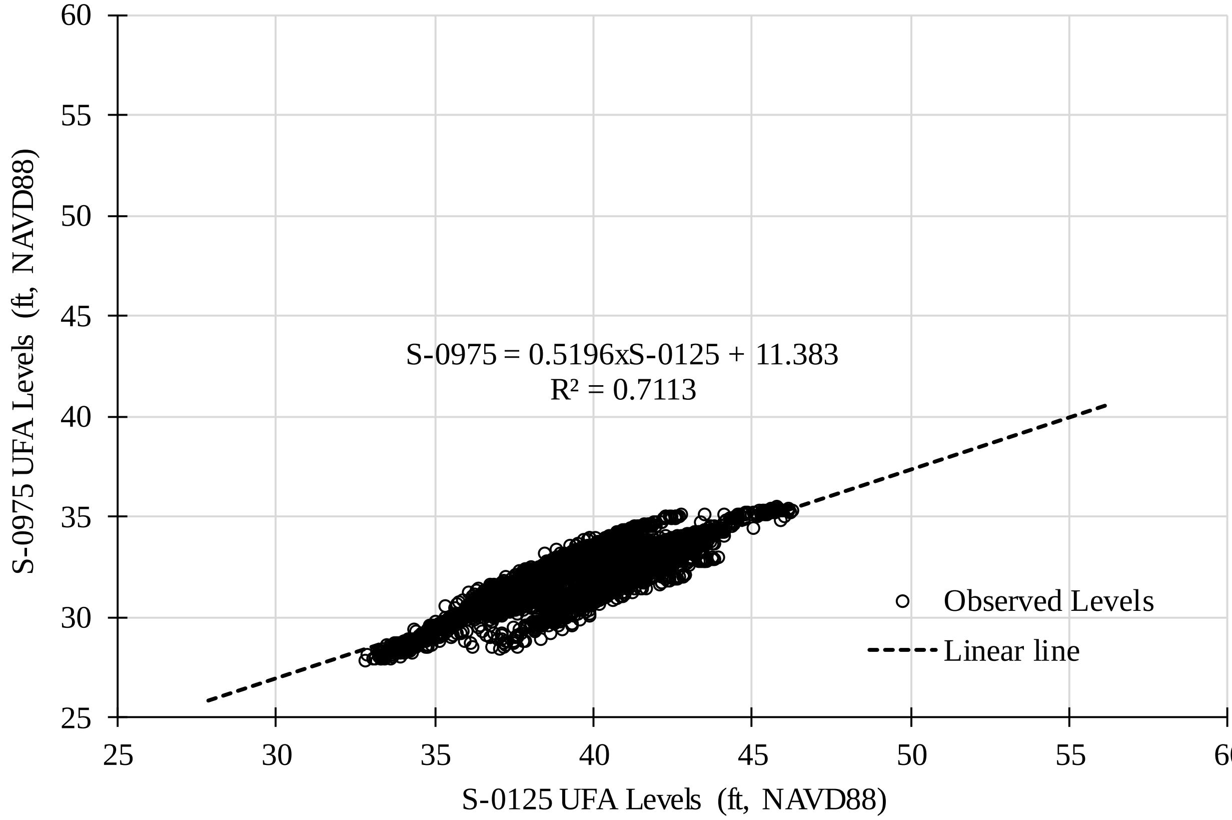


Figure A - 12. Observed UFA levels scatter plot between S-0125 and S-0975

Table A - 5 presents the monthly estimated offset values between the two wells. We estimated still missing values using linear interpolation technique. Figure A - 13 presents the gap-filled water levels at S-0975 along with the observed values.

Table A - 5. Summary of monthly offset values (S-0125 minus S-0975)

| Month | Offsets (ft) |
|---|---|
| 1 | 7.33 |
| 2 | 7.43 |
| 3 | 7.20 |
| 4 | 7.14 |
| 5 | 7.04 |
| 6 | 8.17 |
| 7 | 7.59 |
| 8 | 8.22 |
| 9 | 8.73 |
| 10 | 8.48 |
| 11 | 7.44 |
| 12 | 7.41 |

Figure A - 13 clearly indicates that the variance of the extended water levels using the monthly offset values is higher than that of observed data while the LOC and SLR methods provide reasonable values. Consequently, we will use the gap-filled data of S-0975 based on the LOC method, which is the commonly used method at the SJRWMD because it preserves the variance in the record.

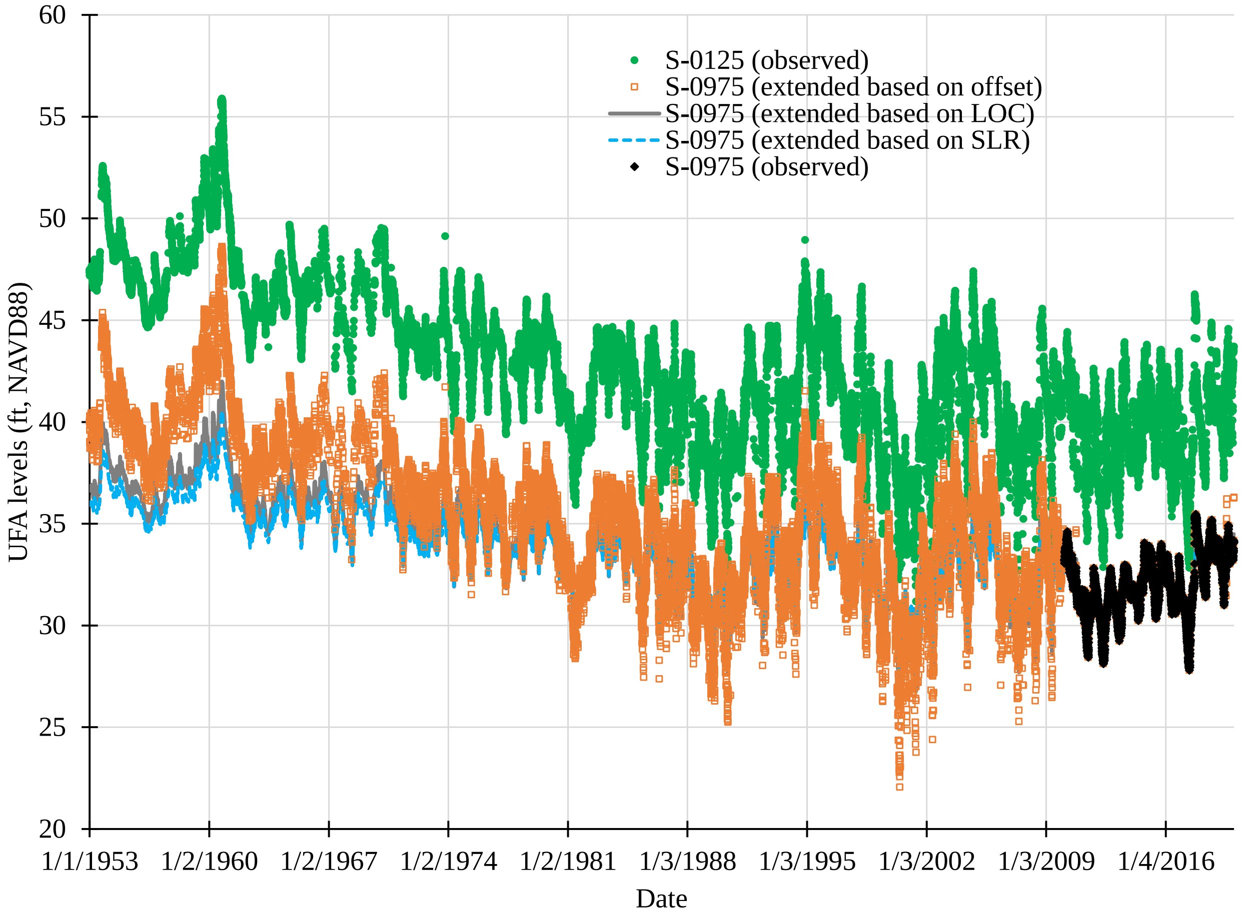


Figure A - 13. Observed and estimated UFA levels for Well S-0975

## Lake Levels

We retrieved water level data for Crystal Chain of Lakes within the watershed from the SJRWMD's and Seminole's county hydrologic databases. The lakes had irregularly POR data since 1993 as summarized in Table A - 6.

Table A - 6. Summary of lake water levels data. Values are in ft.

| Lake | Station ID | POR | Min | Max | Mean | Median | Standard deviation | Source |
|---|---|---|---|---|---|---|---|---|
| East Crystal | 7541 | 1/27/1993 to present | 32.10 | 42.95 | 39.02 | 39.10 | 1.99 | Seminole county |
| West Crystal | 3500414 | 9/13/1995 to 1/10/2007 | 32.03 | 42.62 | 38.22 | 38.57 | 3.00 | SJRWMD |
| DeForest | 18603801 | 10/22/2003 to present | 35.99 | 42.97 | 39.20 | 39.12 | 1.20 | SJRWMD |
| Emma | 3620459 | 5/11/1995 to 9/23/2007 | 37.02 | 42.44 | 40.89 | 41.41 | 1.25 | SJRWMD |

Historical water levels at all lakes show similar pattern and order of magnitudes (Figure A - 14). We will use the observed water levels of the lakes for model calibration and validation.

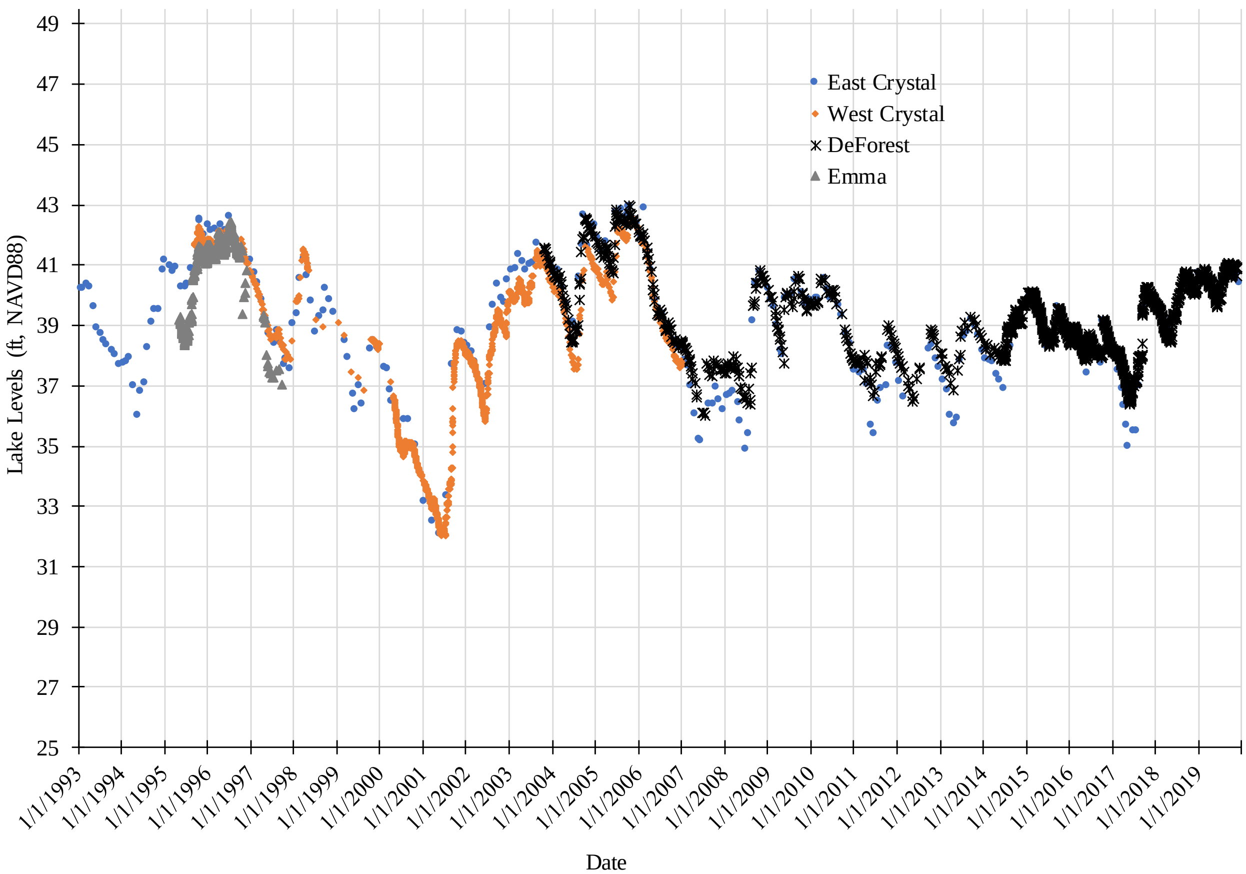


Figure A - 14. Observed water levels of Crystal Chain of Lakes

# Summary

For hydrological and MFLs modeling of Crystal Chain of Lakes, we collected, reviewed, analyzed, and processed the available hydro-meteorological and geo-spatial data of the watershed. In addition, we collected the ICPR model of the Monroe basin (CDM, 2002), including water control structures and their properties that we will re-process and use as inputs to the HSPF model of Crystal Chain of

Lakes. Based on the collected, reviewed, and analyzed data, model set up for the period from 1/1/1995 to 12/31/2019 can begin.

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# Appendix B – Model Development

# TECHNICAL MEMORANDUM

**DATE:** September, 2021

**SUBJECT:** Crystal Chain of Lakes HSPF Model Set up

## Introduction

The St. Johns River Water Management District (SJRWMD) has been establishing Minimum Flows and Levels (MFLs) for Crystal Chain of Lakes (CCL), located in Seminole County, Florida (Figure B - 1). The program designates the minimum hydrologic conditions that must be maintained for these lakes to avoid significant harm to water resources values, resulting from permitted water withdrawals. The program is scheduled for completion in 2024.

In support of the MFLs program, we have chosen a Hydrological Simulation Program – FORTRAN (HSPF) model (Bicknell et al., 1997) for hydrological and MFLs modeling of the CCL. The model simulates various hydrological processes, including surface water – groundwater interaction beneath the lakes. We have set up the HSPF model for the period from 1995 to 2019. This technical memorandum summarizes the HSPF model set-up. We will subsequently calibrate the model for the period from 2007 to 2019 and validate it for the period from 1995 to 2006.

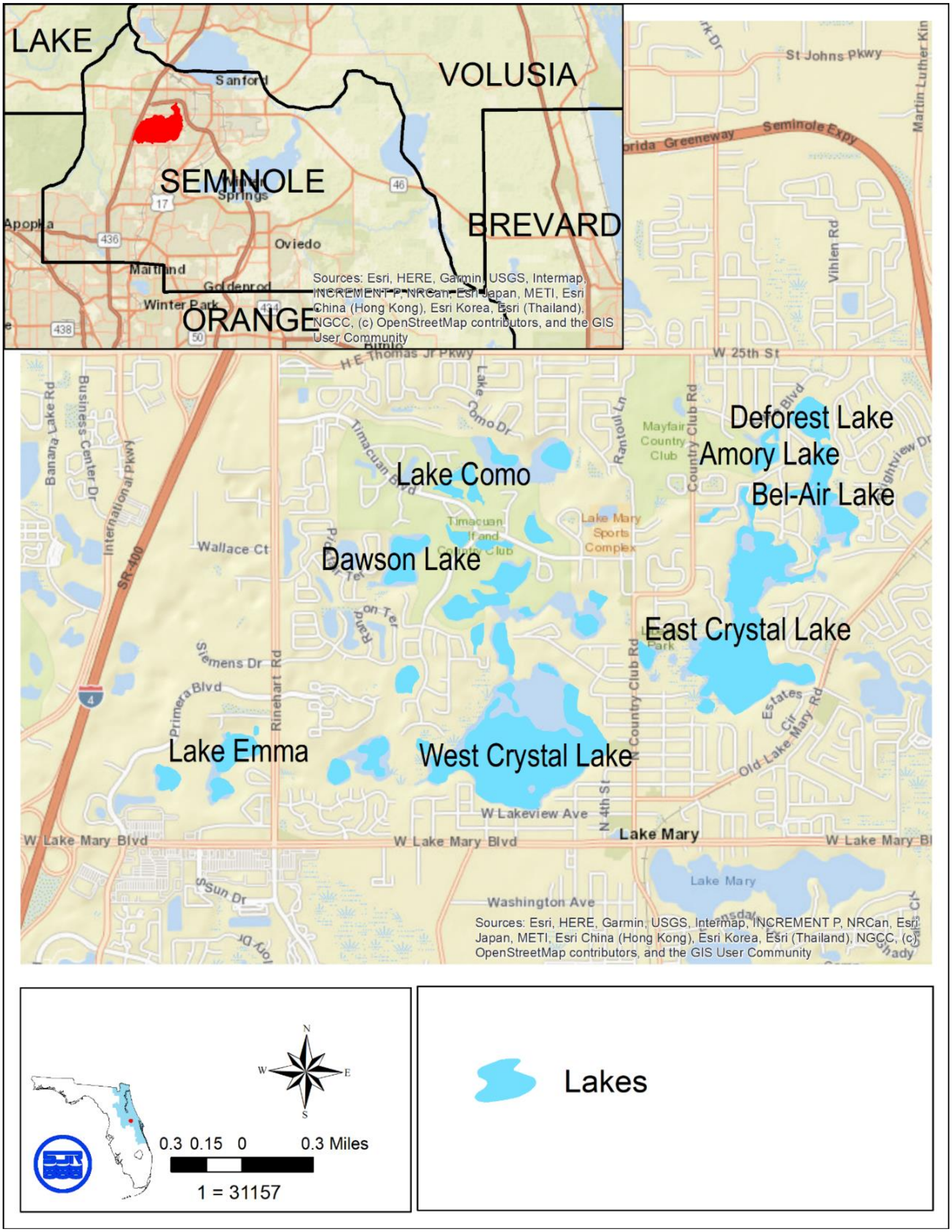


Figure B - 1. Location of Crystal Chain of Lakes (top left corner) in Seminole County

# Model set up

## Hydro-meteorological Data

We used the hydro-meteorological data processed and documented in Task A technical memorandum of this project. HSPF utilized the computed hourly rainfall data from daily rainfall records at the Sanford station of the National Oceanic Atmospheric Administration (NOAA). HSPF also used computed hourly potential evapotranspiration (PET) from daily estimated PET data using the Hargreaves's method (Hargreaves and Samani, 1985) and daily recorded minimum and maximum temperatures at the NOAA Sanford station. In addition, HSPF also used recorded and gap-filled daily groundwater levels at S-0975 for simulating vertical fluxes exchange between the lake and Upper Floridan Aquifer (UFA) systems.

## Model Domain and Sub-watershed Delineation

We modified the District's detailed basins boundary for the CCL, based on the information obtained from the Interconnected Channel and Pond Routing (ICPR) model of the Monroe basin developed by Camp Dresser and McKee (CDM) (2002) and a site visit conducted on 6/10/2021. The final watershed boundaries for the CCL are shown in Figure B - 2. We first delineated the watershed boundary using the catchment boundaries used in the ICPR model of CDM (2002). We further sub-divided the watershed into 13 sub-watersheds (Figure B - 2). As CDM (2002) used detailed sub-catchments in their ICPR model, we merged some of the CDM's sub-catchments into one sub-watershed and thus simplified the sub-watersheds representation in the HSPF model. In addition, we further refined certain part of the CDM's watershed boundary based on our findings during the site visit of 6/10/2021. We particularly made boundary refinements for sub-watersheds 1 and 4 (Figure B – 2). We also limited the sub-watersheds delineation up to the Deforest Lake outlet (represented as sub-watershed 13 in Figure B - 2).

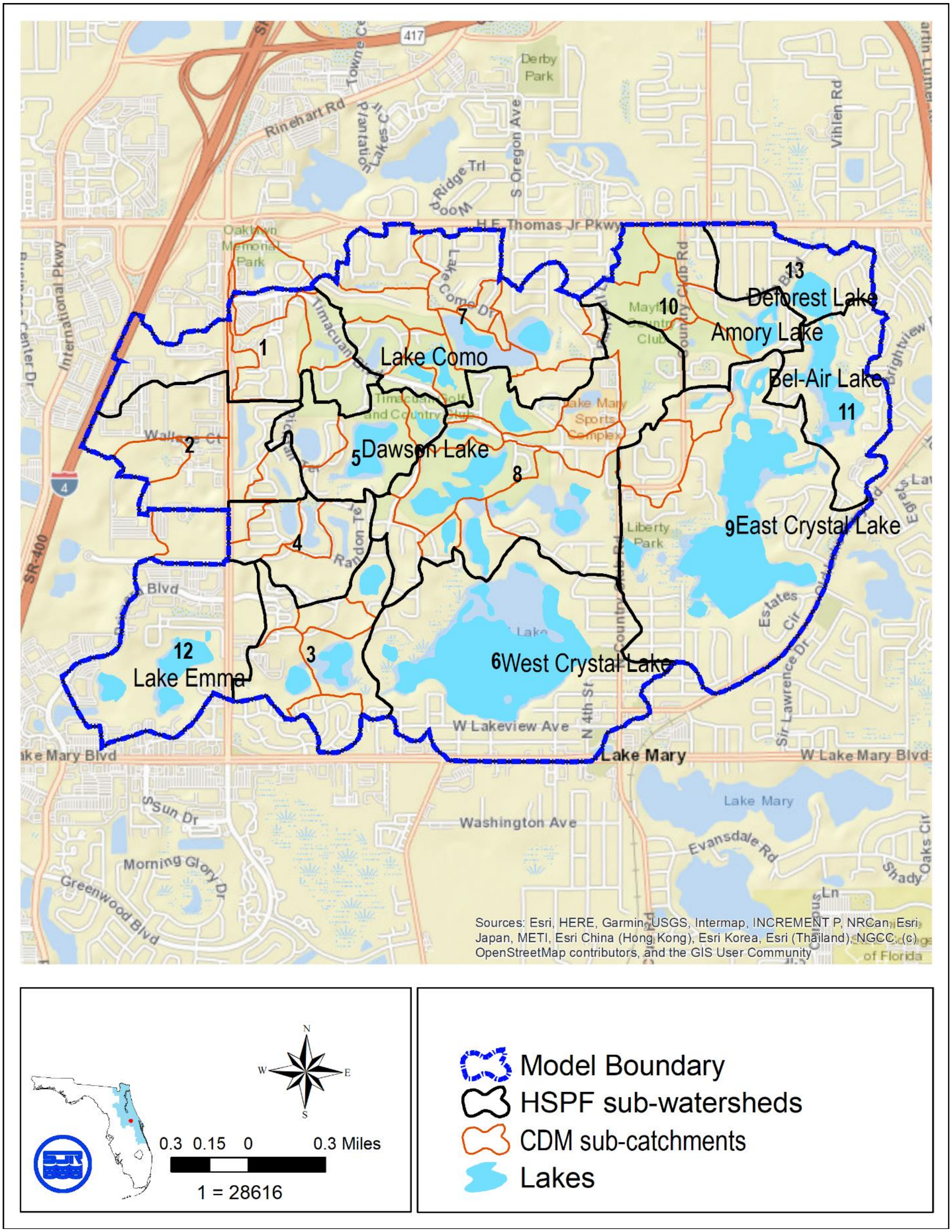


Figure B - 2. Delineated sub-watersheds of Crystal chain of Lakes for the HSPF model. Numbers represent sub-watersheds

## Land use/Land cover

The CCL HSPF model used the SJRWMD's land use/land cover (LULC) map. Figure B - 3 shows the spatial distribution of the study area's LULC map whereas Table B - 1 summarizes the acreage of each LULC within the study area. While mixed residential and commercial LULC cover about 57% of the study area, water and wetland approximately account for 25% of the area. To determine the area of each LULC within a sub-watershed, we intersected the LULC map with the delineated sub-watersheds of the HSPF model (Figure B - 2).

Table B - 1. Land use/land cover (LULC) acreage of the study area.

| Land use/land cover | HSPF code | Area (acres) | Percentage |
|---|---|---|---|
| Low density residential | 1 | 226.9 | 6.9 |
| Medium density residential | 2 | 850.2 | 25.8 |
| High density residential | 3 | 400.0 | 12.1 |
| Commercial/Industrial | 4 | 400.2 | 12.1 |
| Open | 6 | 65.0 | 2.0 |
| Pasture | 7 | 0.3 | 0.0 |
| General agriculture | 8 | 293.7 | 8.9 |
| Range/Shrub | 10 | 95.1 | 2.9 |
| Forest | 11 | 147.7 | 4.5 |
| Water | 12 | 253.6 | 7.7 |
| Wetland | 13 | 564.8 | 17.1 |
| **Total** | | **3297.4** | **100.0** |

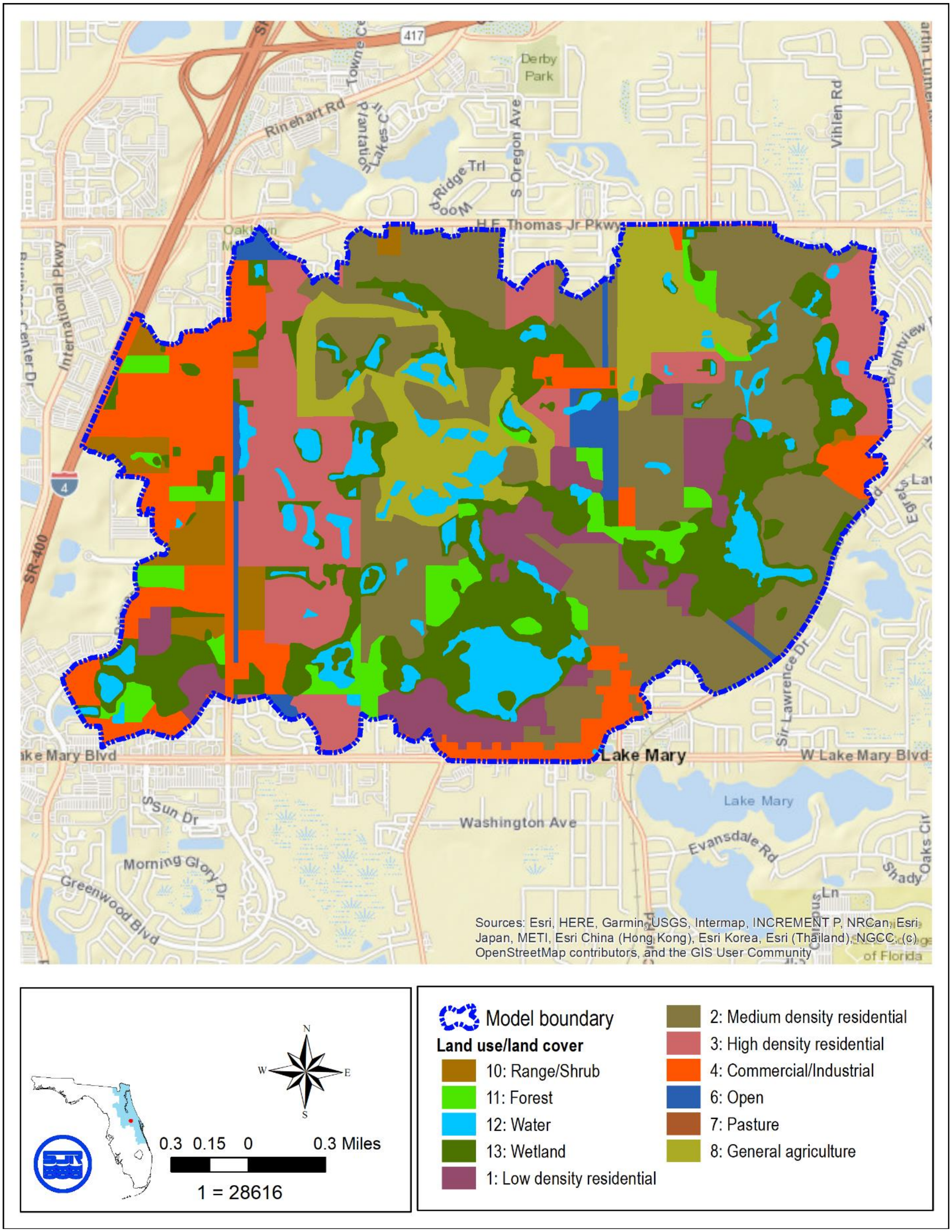


Figure B - 3. Land use/land cover map of the study area

## Imperviousness Values

We used the typical imperviousness fractions used at the SJRWMD for the HSPF models. Table B - 2 presents those values used in the HSPF models for the SJRWMD's thirteen-land use/land cover (LULC) codes.

Table B - 2. Imperviousness fractions. Numbers in first column represent District's 13 land use/land cover codes.

| Land use/land cover | Imperviousness (%) |
|---|---|
| 1: Low density residential | 5 |
| 2: Medium density residential | 15 |
| 3: High density residential | 35 |
| 4: Commercial/Industrial | 50 |
| 5: Mining | 0 |
| 6: Open | 0 |
| 7: Pasture | 0 |
| 8: General agriculture | 0 |
| 9: Groves | 0 |
| 10: Range/Shrub | 0 |
| 11: Forest | 0 |
| 12: Water | 0 |
| 13: Wetland | 0 |

## Hydrologic Soil Group

The soil hydrologic groups (SHG) distribution within the HSPF model domain is shown in Figure B - 4. Table B - 3 presents the percentage coverage of each SHG, whereby type A soil covers about 60% of the model domain followed by type A/D soil. While type A soil is generally characterized with high infiltration rate and well drain condition, type A/D soil experiences high infiltration rate and well drain during dry condition but become low infiltration rate and poorly drained condition when surface soil gets wet. It should be noticed that we will not use the soil data directly to estimate the infiltration parameters in the model but derive the parameters based on the approach used in other HSPF models at the SJRWMD.

Table B - 3. Soil hydrologic group of the HSPF model domain

| Soil hydrologic group | Area (acres) | Percentage |
|---|---|---|
| A | 1966.6 | 59.6 |
| A/D | 920.8 | 27.9 |
| Urban land | 70.3 | 2.1 |
| Water | 339.7 | 10.3 |
| **Total** | **3297.4** | **100.0** |

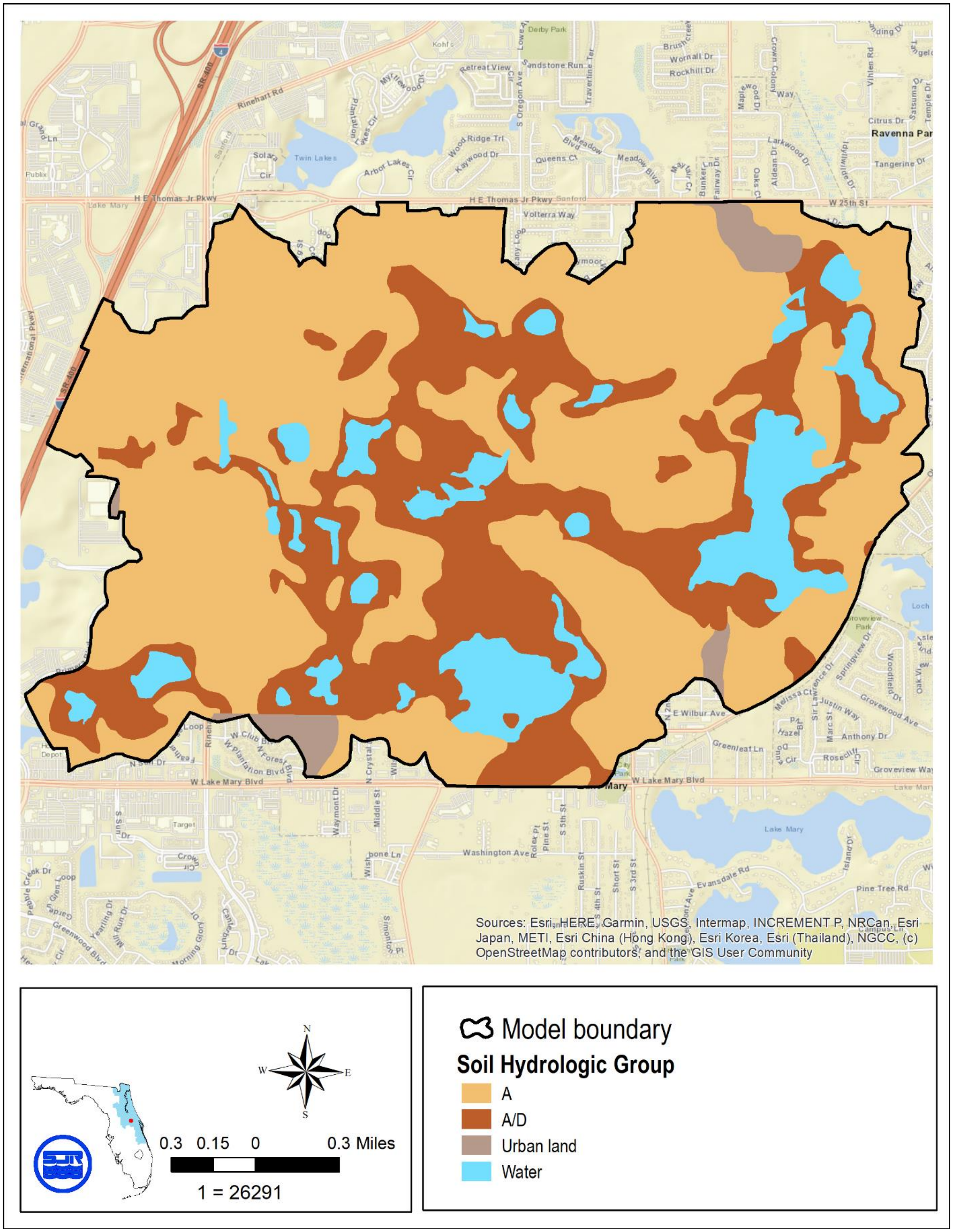


Figure B - 4. Soil hydrological group distribution with the HSPF model domain

## FTABLE and Flow Simulations

In HSPF, the streams and lakes within a sub-watershed are grouped and represented as a river reach or reservoir segment called RCHRES. As sub-watersheds and RCHRES share the same numbering, the sub-watersheds' numbers displayed in Figure B - 2 represent the RCHRES's numbers referred hereafter. The relationships between stage, surface area, volume, and discharge for a RCHRES are represented by a hydraulic function table called an FTABLE, a piecewise-linear function table. Due to a lack of bathymetry data, we did not derive stage-area-volume-discharge curves directly from the available DEM. Instead, the model set up focused on the use of stage-area-volume-discharge data retrieved from the ICPR model of the Monroe basin (CDM, 2002). We estimated the curves based on the simulated stages and discharges by the CDM's model for 2-year and 100-year storm events. We used these derived curves to represent storage volumes and outflows from the lakes. For East Crystal Lake, Bel-Air Lake, Amory Lake, and Deforest Lake, we obtained the bathymetry data from the East Crystal Chain-of-Lakes Hydrologic/Nutrient Budgets & Management Plans study (Environmental Research & Design, 2014) and derived the stage-area-volume curves for the bathymetry portions of the FTABLEs.

We used the Special Action (SA) module of HSPF to simulate the effect of tailwater on upstream RCHRES. Discharge from an upstream RCHRES to a downstream RCHRES only happens when the upstream stage is above the downstream stage. When the downstream stage is higher, the discharge from the upstream RCHRES is set to zero and the backflow from downstream to upstream is calculated. The schematic representation of HSPF RCHRES and water control structure is shown in Figure B - 5.

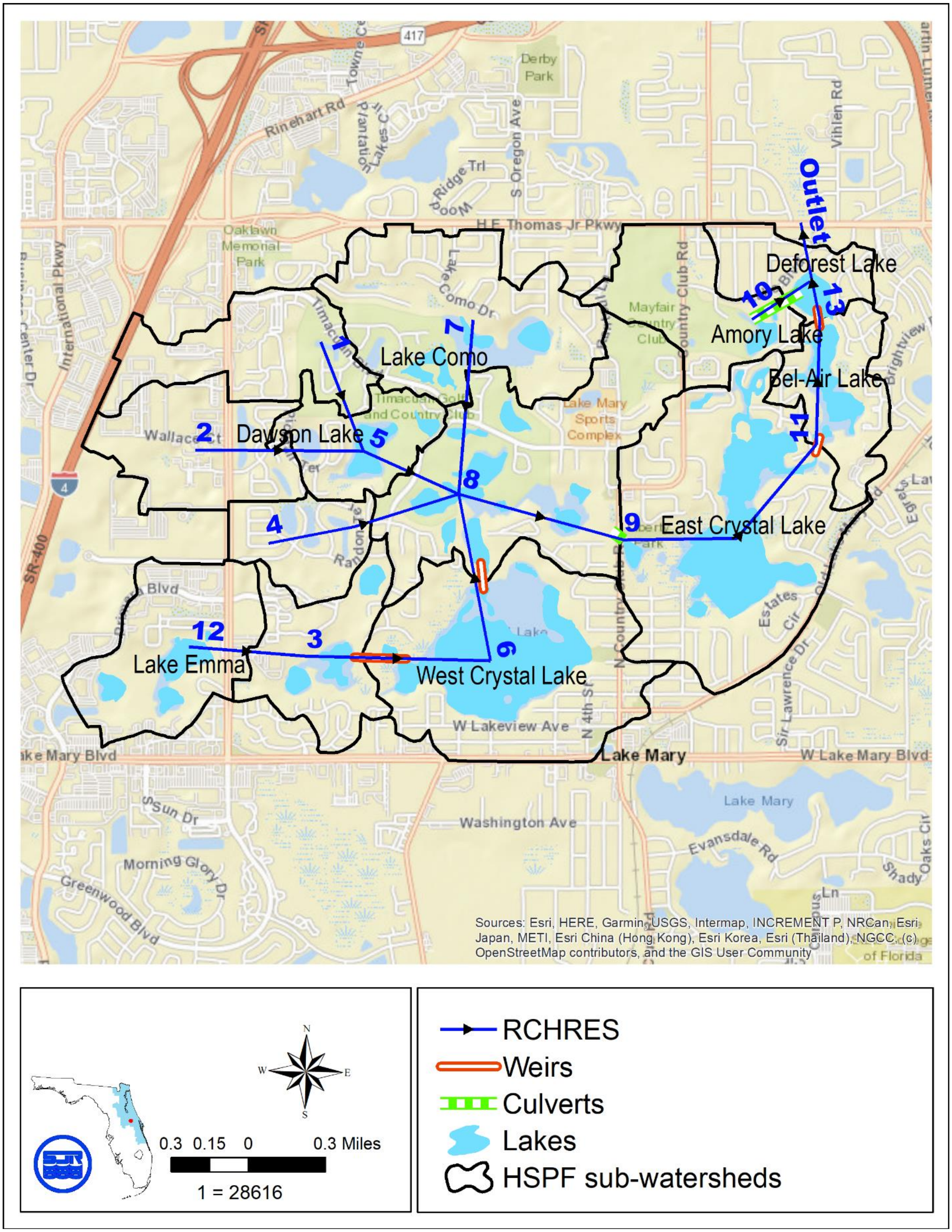


Figure B - 5. Schematic representation of the HSPF model

We simulated the connections between RCHRES 3 and RCHRES 6 (West Crystal Lake), RCHRES 6 and RCHRES 8, RCHRES 9 (East Crystal Lake), and RCHRES 11 (Bel-Air Lake), RCHRES 11 and RCHRES 13 (Deforest Lake) using rectangular weirs. When the downstream stage is below the weir invert, flow is calculated using the standard weir equation (French, 1985):

$$Q = CLH^{1.5}$$

Where:

Q is flow rate (cfs);

C is weir flow coefficient (-);

L is weir length (ft);

H is upstream head above invert (ft, NAVD88).

When the downstream stage is above the weir invert, flow is calculated using the Villemonte's equation (Villemonte, 1947):

$$Q = CLH_1^{1.5}(1 - \frac{H_2^{1.5}}{H_1^{1.5}})^{0.385}$$

Where:

H1 is upstream head above invert (ft);

H2 is downstream head above invert (ft).

Table B - 4 shows the weir flow coefficient, weir length, and invert values used for the weir flow calculations. The weir flow coefficients are based on the typical range of 0.2 – 1.0 for non-elevated overbank terrain and natural high ground barrier reported in Table 3-1 of the Hydrologic Engineering Center River Analysis System (HEC-RAS) 2D Modeling User's Manual (USACE, 2020). We estimated the weir lengths and inverts based on the DEM data (RCHRES 3, 6, and 8) and field data collection (RCHRES 9, 11, and 13), which are summarized in Table B - 4.

Table B - 4 . Weir coefficient, length, and invert used for flow calculations in HSPF Special Actions (SA)

| Upstream RCHRES | Downstream RCHRES | C | L (ft) | Invert (ft NAVD) |
|---|---|---|---|---|
| 3 | 6 | 0.2 | 200 | 42.5 |
| 6 | 8 | 0.2 | 100 | 39.5 |
| 9 | 11 | 0.5 | 25 | 38.6 |
| 11 | 13 | 1.0 | 25 | 36.0 |

We simulated flows through the culverts between RCHRES 8 and RCHRES 9 (East Crystal Lake) and between RCHRES 10 (Amory Lake) and RCHRES 13 (Deforest Lake) using multiple rating curves implemented in SA of the HSPF model. We developed the rating curves by first setting up an ICPR4 model of these culverts and using the geometric and hydraulic parameters obtained from the CDM's ICPR model (CDM, 2002). Then we ran the model with a range of tailwater conditions. Table B - 5 shows the culvert data. Table B - 6 and Table B - 7 present the ICPR4 developed rating curves.

Table B - 5 . Culvert data for rating curve calculations

| Culvert Characteristics | Between RCHRES 8 and 9 | Between RCHRES 10 and 13 |
|---|---|---|
| Shape | Arch | Circular |
| Manning's n | 0.013 | 0.018 |
| Size (ft) | 9 (rise) × 13 (span) | 3 |
| Length (ft) | 37 | 33 |
| Number of Barrels | 1 | 2 |
| Upstream Invert (ft, NAVD88) | 42.3 | 41.0 (north barrel) |
| Downstream Invert (ft, NAVD88) | 42.1 | 39.0 (north barrel) |

Depending on the simulated tailwater stages, the model chooses an appropriate rating curve at run time for flow calculation. Because the rating curves 1 – 4 for the culvert between RCHRES 8 and RCHRES 9 give similar flow values when the headwater stage is above the tailwater stage (Table B - 6), we combined these four curves into one curve. The model uses the rating curve 1 when the simulated tailwater stage is ≤ 43.5 ft, and uses the rating curve 5 when the simulated tailwater stage is > 43.5 ft. Similarly, we merged the rating curves 1 – 5 for the culverts between RCHRES 10 and RCHRES 13 (Table B - 7). The model uses the rating curve 1 when the simulated tailwater stage is below 43.5 ft, uses the rating curve 6 when the simulated tailwater stage is between 43.5 ft and 44.0 ft, and uses the rating curve 7 when the simulated tailwater stage is ≥ 44.0 ft.

Table B - 6 . Rating curves estimated by ICPR4 model and used in HSPF model to estimate flows between RCHRES 8 and RCHRES 9 (East Crystal Lake).

| **Headwater** | **Tailwater Stage (ft, NAVD88)** | | | | |
|---|---|---|---|---|---|
| **Stage (ft, NAVD88)** | **Curve 1** | **Curve 2** | **Curve 3** | **Curve 4** | **Curve 5** |
| | **42.4** | **42.5** | **43.0** | **43.5** | **44.0** |
| 41.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.5 | 1.9 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.6 | 3.7 | 3.7 | 0.0 | 0.0 | 0.0 |
| 42.7 | 5.9 | 5.9 | 0.0 | 0.0 | 0.0 |
| 42.8 | 8.4 | 8.4 | 0.0 | 0.0 | 0.0 |
| 42.9 | 11.2 | 11.2 | 0.0 | 0.0 | 0.0 |
| 43.0 | 14.1 | 14.1 | 0.0 | 0.0 | 0.0 |
| 43.1 | 17.3 | 17.3 | 15.2 | 0.0 | 0.0 |
| 43.2 | 20.7 | 20.7 | 20.7 | 0.0 | 0.0 |
| 43.3 | 24.4 | 24.4 | 24.4 | 0.0 | 0.0 |
| 43.4 | 28.0 | 28.0 | 28.0 | 0.0 | 0.0 |
| 43.5 | 31.5 | 31.4 | 31.5 | 0.0 | 0.0 |
| 43.6 | 35.1 | 35.1 | 35.1 | 29.5 | 0.0 |
| 43.7 | 39.0 | 39.0 | 39.0 | 40.9 | 0.0 |
| 43.8 | 44.2 | 44.2 | 44.2 | 46.8 | 0.0 |
| 43.9 | 49.2 | 49.2 | 49.2 | 53.2 | 0.0 |
| 44.0 | 55.0 | 55.0 | 55.0 | 59.6 | 0.0 |
| 44.1 | 60.8 | 60.8 | 60.8 | 64.3 | 46.1 |

| | | | | | |
|---|---|---|---|---|---|
| 44.2 | 66.5 | 66.5 | 66.5 | 68.9 | 74.1 |
| 44.3 | 72.5 | 72.5 | 72.5 | 72.8 | 81.3 |
| 44.4 | 79.3 | 79.3 | 79.3 | 79.3 | 84.7 |
| 44.5 | 86.4 | 86.5 | 86.4 | 86.4 | 93.1 |
| 44.6 | 92.3 | 92.3 | 92.3 | 92.3 | 100.6 |
| 44.7 | 99.4 | 99.4 | 99.4 | 99.4 | 107.1 |
| 44.8 | 106.6 | 106.6 | 106.6 | 106.6 | 113.6 |
| 44.9 | 114.5 | 114.5 | 114.5 | 114.5 | 119.5 |
| 45.0 | 121.3 | 121.3 | 121.3 | 121.3 | 125.2 |

Table B - 7. Rating curves estimated by ICPR4 model and used in HSPF model to estimate flows between RCHRES 10 (Amory Lake) and RCHRES 13 (Deforest Lake).

| **Headwater** | **Tailwater Stage (ft, NAVD88)** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Stage (ft, NAVD88)** | **Curve 1 41.1** | **Curve 2 41.5** | **Curve 3 42.0** | **Curve 4 42.5** | **Curve 5 43.0** | **Curve 6 43.5** | **Curve 7 44.0** |
| 41.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.2 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.3 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.4 | 1.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.5 | 2.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.6 | 3.2 | 3.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.7 | 4.5 | 4.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.8 | 6.0 | 6.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.9 | 7.6 | 7.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.0 | 9.4 | 9.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.1 | 11.3 | 11.3 | 10.8 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.2 | 13.5 | 13.5 | 13.5 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.3 | 15.9 | 15.8 | 15.7 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.4 | 18.0 | 18.0 | 18.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.5 | 20.6 | 20.6 | 20.6 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.6 | 23.2 | 23.2 | 23.2 | 23.2 | 0.0 | 0.0 | 0.0 |
| 42.7 | 25.7 | 25.7 | 25.7 | 25.7 | 0.0 | 0.0 | 0.0 |
| 42.8 | 28.5 | 28.5 | 28.5 | 28.5 | 0.0 | 0.0 | 0.0 |
| 42.9 | 31.3 | 31.3 | 31.3 | 31.3 | 0.0 | 0.0 | 0.0 |
| 43.0 | 34.2 | 34.2 | 34.2 | 34.2 | 0.0 | 0.0 | 0.0 |
| 43.1 | 37.2 | 37.2 | 37.2 | 37.2 | 31.3 | 0.0 | 0.0 |
| 43.2 | 40.1 | 40.1 | 40.1 | 40.1 | 40.1 | 0.0 | 0.0 |
| 43.3 | 43.0 | 43.0 | 43.0 | 43.0 | 43.0 | 0.0 | 0.0 |
| 43.4 | 45.9 | 45.9 | 45.9 | 45.9 | 45.9 | 0.0 | 0.0 |
| 43.5 | 49.2 | 49.2 | 49.2 | 49.2 | 49.2 | 0.0 | 0.0 |
| 43.6 | 52.1 | 52.1 | 52.1 | 52.1 | 52.1 | 31.9 | 0.0 |
| 43.7 | 55.3 | 55.3 | 55.3 | 55.3 | 55.3 | 43.4 | 0.0 |
| 43.8 | 58.5 | 58.5 | 58.2 | 58.2 | 58.2 | 52.7 | 0.0 |
| 43.9 | 61.4 | 61.4 | 61.4 | 61.4 | 61.4 | 58.1 | 0.0 |
| 44.0 | 64.5 | 64.5 | 64.5 | 64.5 | 64.5 | 63.1 | 0.0 |
| 44.1 | 67.5 | 67.5 | 67.5 | 67.5 | 67.5 | 67.3 | 29.2 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 44.2 | 70.7 | 70.7 | 70.8 | 70.8 | 70.8 | 70.8 | 42.6 |
| 44.3 | 73.6 | 73.6 | 73.9 | 73.9 | 73.9 | 73.9 | 51.9 |
| 44.4 | 76.8 | 76.8 | 76.8 | 76.8 | 76.8 | 76.8 | 59.4 |
| 44.5 | 79.8 | 79.8 | 79.8 | 79.8 | 79.8 | 79.8 | 66.2 |
| 44.6 | 82.9 | 82.9 | 82.9 | 82.9 | 82.9 | 82.9 | 72.8 |
| 44.7 | 85.8 | 85.8 | 85.8 | 85.8 | 85.8 | 85.8 | 78.7 |
| 44.8 | 88.9 | 88.9 | 88.7 | 88.7 | 88.7 | 88.7 | 83.2 |
| 44.9 | 91.8 | 91.8 | 91.8 | 91.8 | 91.8 | 91.8 | 87.0 |
| 45.0 | 94.6 | 94.6 | 94.7 | 94.7 | 94.7 | 94.7 | 91.2 |

## Riparian Wetland Simulations

As riparian wetlands fluctuate with the rise and fall of the lake stage, we used the SA module of HSPF to simulate this interaction. The module helps to account for area change due to lake shrinking and expanding by dynamically computing the current remaining riparian wetland area from the maximum estimated area of water and wetland. We estimated the maximum riparian areas by summing up the areal coverage of water and wetland in the LULC map per sub-watershed.

## Lake and Upper Floridan Aquifer (UFA) Interaction

Lake can lose water to or gain water from UFA depending on the head difference between the lake and UFA stages. HSPF simulates the exchange of fluxes between the lake and UFA based on the Darcy's law equation (Maidment, 1998) defined as:

$$Q = k\frac{\Delta h}{b}A$$

Where:

Q is seepage flow rate (cfs);

k is the coefficient of permeability of hydraulic conductivity (-);

$\Delta h$ is the difference in stage between UFA potentiometric surface and lake (ft);

b is the thickness of sediments between the lake bottom and the UFA groundwater level (ft);

A is the cross-sectional area of the material through which water seeps from lake to aquifer, which is assumed to be the lake surface area simulated by HSPF, varying with time.

Using the above equation, HSPF simulates seepage rates from CCL to UFA. This concept is a simplified representation of reality in HSPF, which is handled by the SA module of the model. At each time step, the model calculates the stage difference between the simulated lake and observed UFA stage values. Then, it determines fluxes (seepages) are vertically upward (gain water) or downward (lose water) to/from the lake depending on the stage gradient. Since neither k nor b are well known for the lake, HSPF uses the combined value of k/b into a constant term, commonly called a leakance, which will be optimized during model calibration process. Replacing k/b with the leakance term L yields the following equation:

$$Q = L * A * \Delta h$$

To represent UFA time series stages, we used the daily recorded UFA stages at well S-0975, which is located inside the model domain (see Task A report for detail). Given insignificant spatial variability of UFA stages within the model domain (see Task A report), we did not apply any offset values to move the observed UFA stages at well S-0975 to beneath the lakes. We used the observed stages along with leakance values. We estimated the average leakance values per lakes' polygon based on the values used in the East-Central Florida Transient Expanded (ECFTX) model of the Central Florida Water Initiative (CFWI) (CFWI, 2020) and using the zonal statistics tool of ArcGIS. Then, we assigned the estimated average leakance values to the RCHRES part of the HSPF model. The Upper Floridan Aquifer (UFA) levels are needed for the HSPF model to simulate leakage rates beneath the lakes. We collected, reviewed, and analyzed a number of daily UFA wells data within and around the watershed for the period 1953 to 2019. Location of the wells are shown in Figure A - 10. S-0975 is located inside the watershed and therefore, selected to be used in the HSPF model. Figure A - 11 presents observed water levels for S-0975 and nearby wells. S-0206 and S-0123 had short-term POR but show similar water levels with S-0975 (Figure A - 11). S-0125 had long-term POR (since 10/25/1951) and generally shows similar temporal pattern and evolution with S-0975's data.

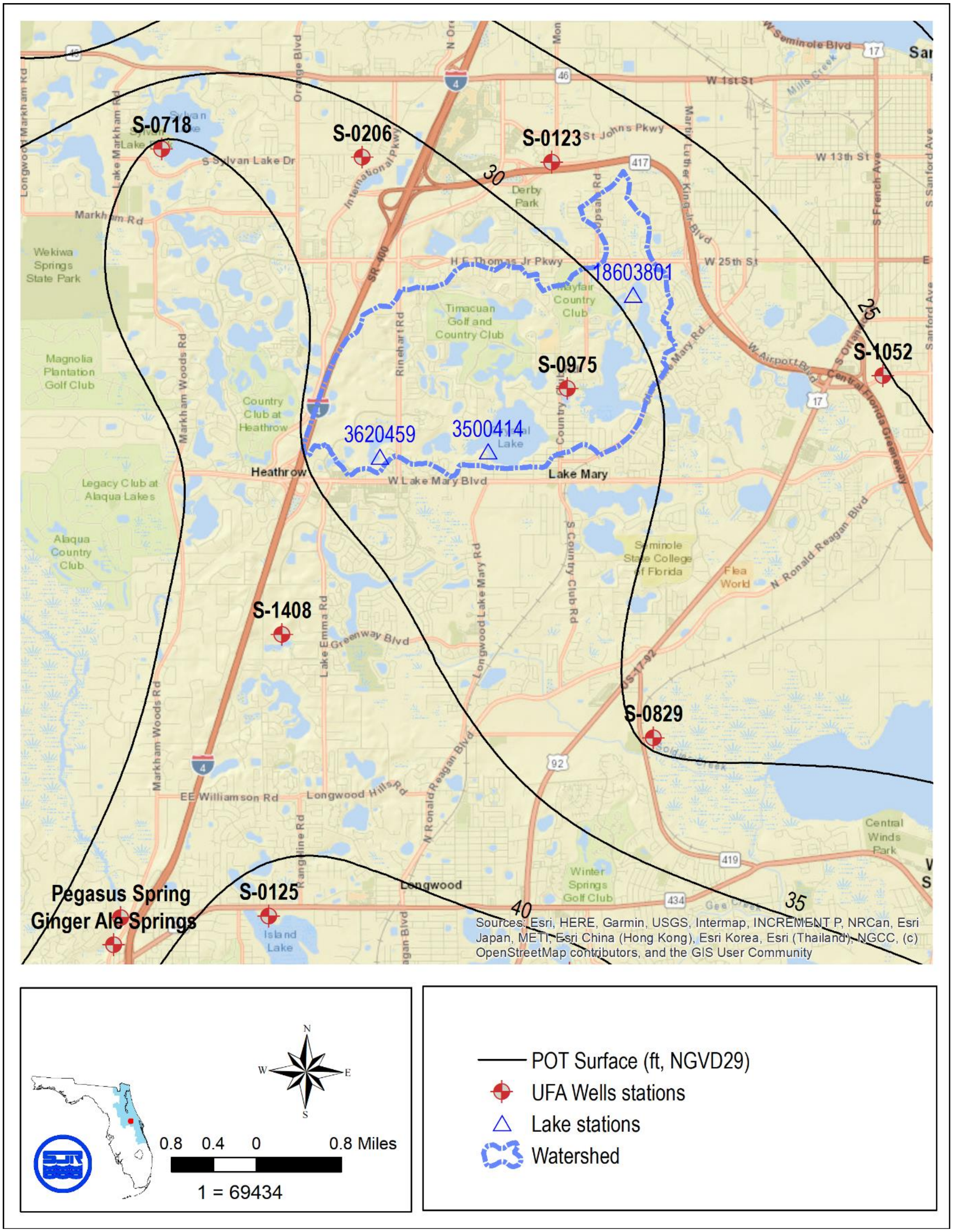


Figure A - 10. Location of UFA wells and lakes stations, and Potentiometric levels of September 2010 (NGVD29).

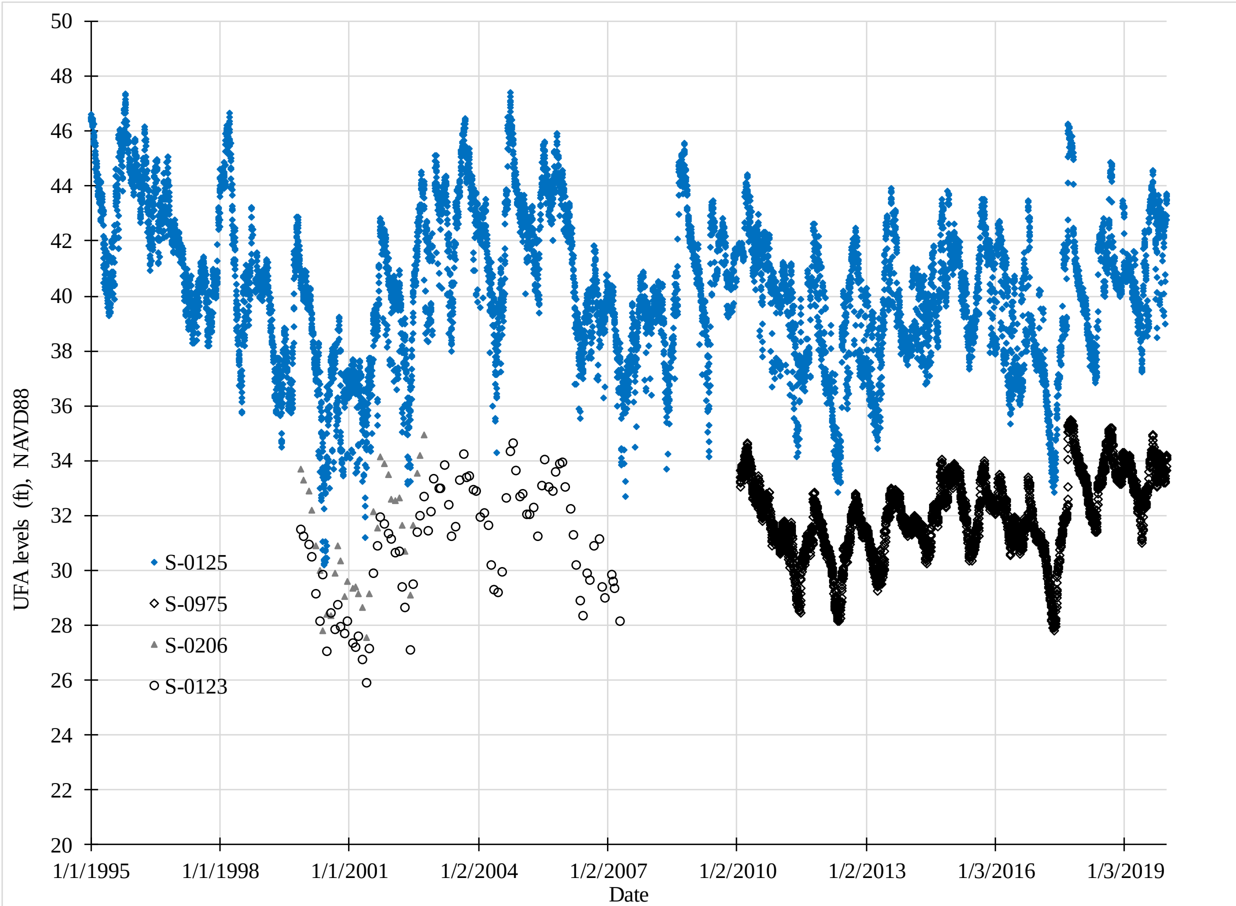


Figure A - 11. The daily observed UFA levels for wells within and around the watershed of East Crystal Lake

As S-0975 had irregularly recorded water levels since 1/29/2010 (Figure A - 11), we subsequently extended this well's data to the period from 1953 to 2019 based on the recorded values at well S-0125, which is located approximately 6 miles southwest of S-0975 and had a reasonable correlation with S-0975 (R2 = 0.71). The scatter plot between observed water levels at S-0125 and S-0975 for the overlapping POR is shown in Figure A - 12. With similar temporal patterns between the two wells, water levels at S-0125 are averagely higher by approximately 8 ft (Figure A - 12). Due to long-term records at S-0125 and a reasonable correlation with S-0975, we used S-0125 to fill long-term missing values at S-0975. We filled the long-term missing values at S-0975 based on monthly offset values and line of organic correlation (LOC), including simple linear regression (SLR). We computed the monthly offsets and regression equations from the observed water levels at S-0975 and S-0125 for the overlapping POR.

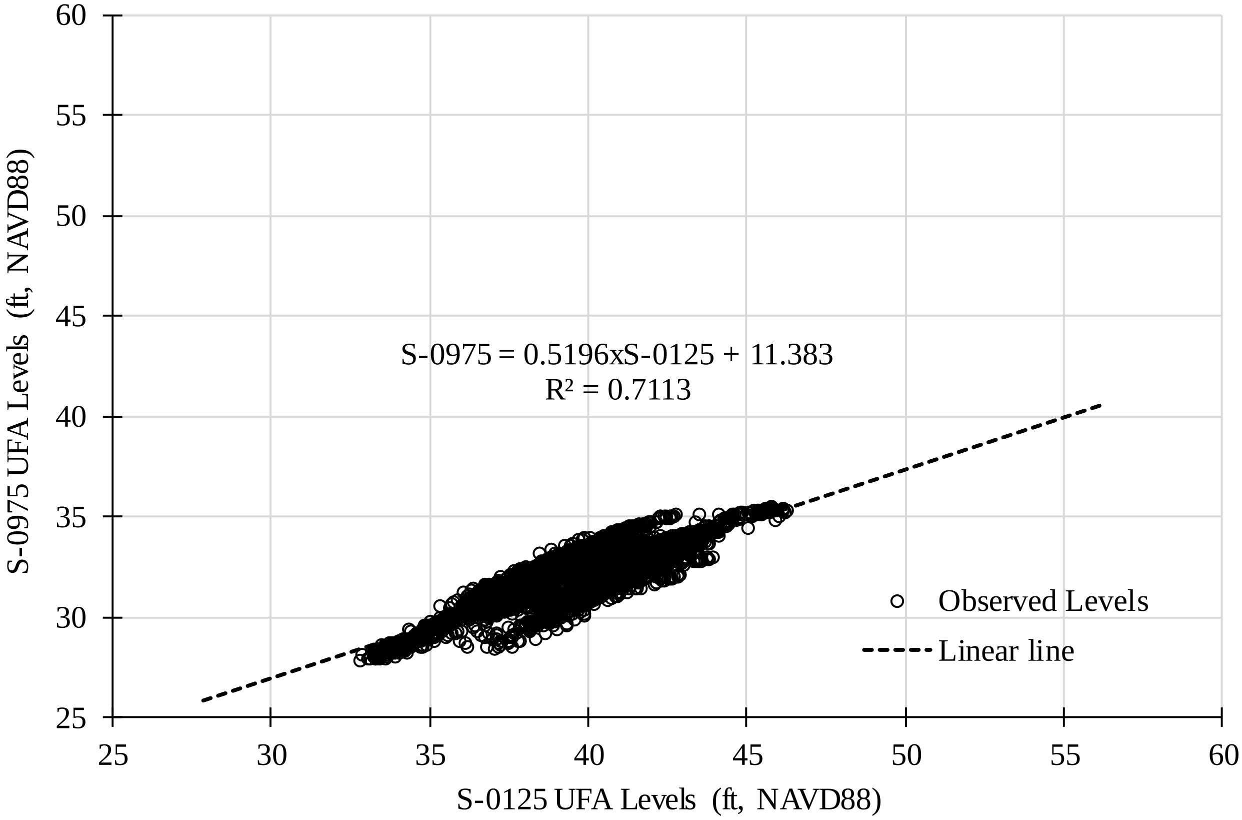


Figure A - 12. Observed UFA levels scatter plot between S-0125 and S-0975

Table A - 5 presents the monthly estimated offset values between the two wells. We estimated still missing values using linear interpolation technique. Figure A - 13 presents the gap-filled water levels at S-0975 along with the observed values.

Table A - 5. Summary of monthly offset values (S-0125 minus S-0975)

| Month | Offsets (ft) |
|---|---|
| 1 | 7.33 |
| 2 | 7.43 |
| 3 | 7.20 |
| 4 | 7.14 |
| 5 | 7.04 |
| 6 | 8.17 |
| 7 | 7.59 |
| 8 | 8.22 |
| 9 | 8.73 |
| 10 | 8.48 |
| 11 | 7.44 |
| 12 | 7.41 |

Figure A - 13 clearly indicates that the variance of the extended water levels using the monthly offset values is higher than that of observed data while the LOC and SLR methods provide reasonable values. Consequently, we will use the gap-filled data of S-0975 based on the LOC method, which is the commonly used method at the SJRWMD because it preserves the variance in the record.

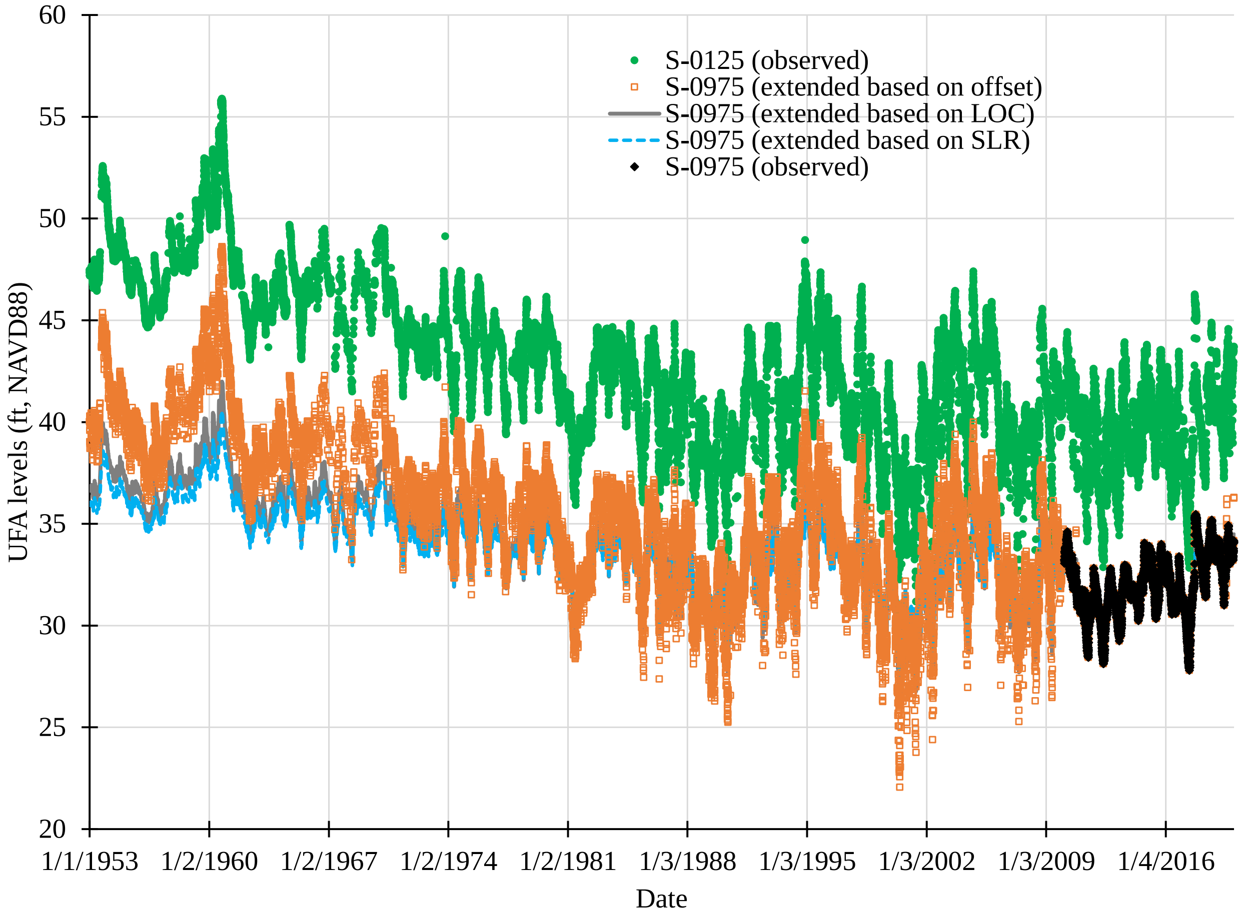


Figure A - 13. Observed and estimated UFA levels for Well S-0975

## Lake Levels

We retrieved water level data for Crystal Chain of Lakes within the watershed from the SJRWMD's and Seminole's county hydrologic databases. The lakes had irregularly POR data since 1993 as summarized in Table A - 6.

Table A - 6. Summary of lake water levels data. Values are in ft.

| Lake | Station ID | POR | Min | Max | Mean | Median | Standard deviation | Source |
|---|---|---|---|---|---|---|---|---|
| East Crystal | 7541 | 1/27/1993 to present | 32.10 | 42.95 | 39.02 | 39.10 | 1.99 | Seminole county |
| West Crystal | 3500414 | 9/13/1995 to 1/10/2007 | 32.03 | 42.62 | 38.22 | 38.57 | 3.00 | SJRWMD |
| DeForest | 18603801 | 10/22/2003 to present | 35.99 | 42.97 | 39.20 | 39.12 | 1.20 | SJRWMD |
| Emma | 3620459 | 5/11/1995 to 9/23/2007 | 37.02 | 42.44 | 40.89 | 41.41 | 1.25 | SJRWMD |

Historical water levels at all lakes show similar pattern and order of magnitudes (Figure A - 14). We will use the observed water levels of the lakes for model calibration and validation.

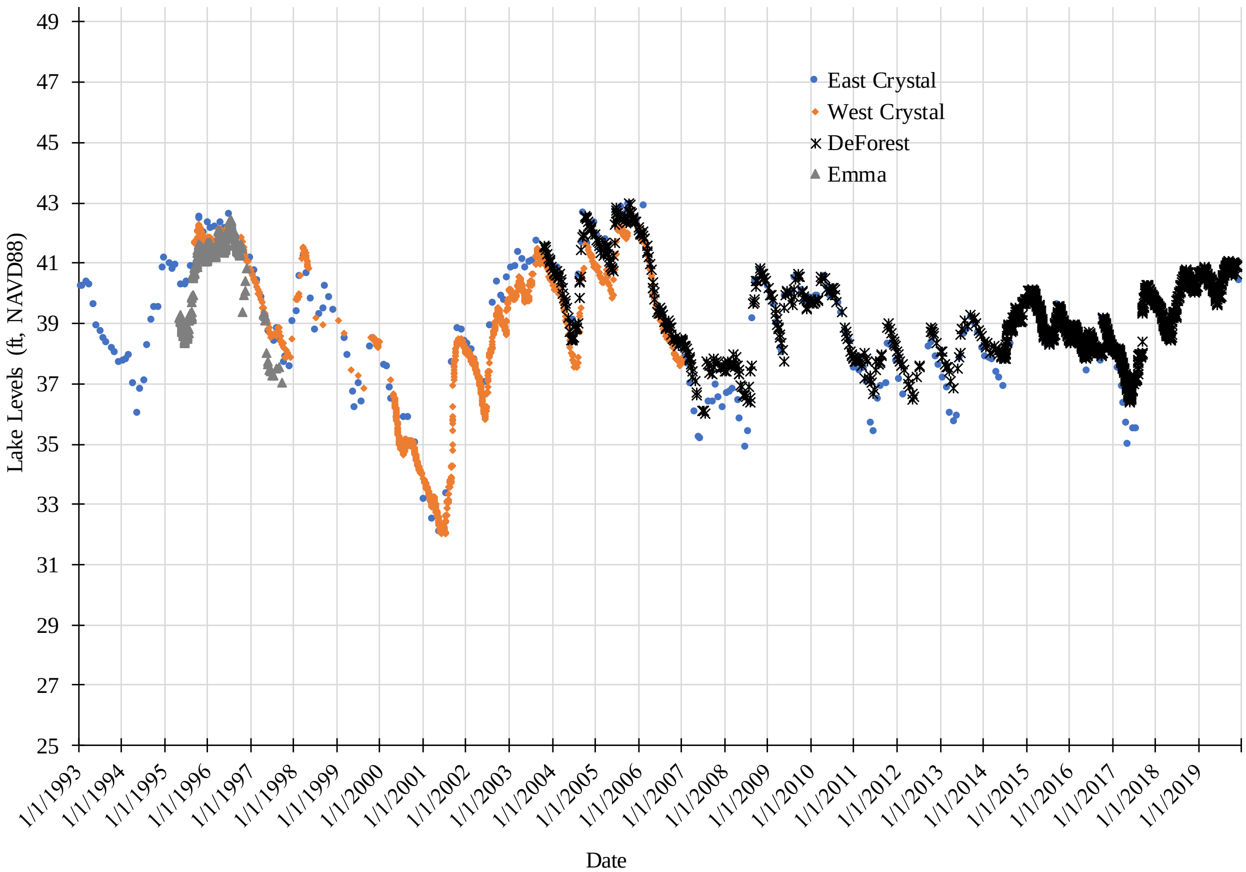


Figure A - 14. Observed water levels of Crystal Chain of Lakes

shows the average leakance values for the 13 RCHRES of the CCL HSPF model. We used these values as a starting point, and thus will adjust them during model calibration process.

Table B - 8 . RCHRES leakance values as derived from ECFTX model

| RCHRES | Leakance (per day) |
|---|---|
| 1 | 0.0000169 |
| 2 | 0.0000134 |
| 3 | 0.0000973 |
| 4 | 0.0000288 |
| 5 | 0.0000162 |
| 6 | 0.0001672 |
| 7 | 0.0000249 |
| 8 | 0.0000911 |
| 9 | 0.0001806 |
| 10 | 0.0002012 |
| 11 | 0.0002171 |
| 12 | 0.0000664 |
| 13 | 0.0002388 |

# Summary

For hydrological and MFLs modeling of the Crystal Chain of Lakes, we set up an HSPF model based on the available geo-spatial and hydro-meteorological data. The simulation period is from 1/1/1995 to 12/31/2019. The model simulates the hydrological processes at hourly time scale. We will split the simulation period into model validation (1995 to 2006) and calibration (2007 to 2019) periods. We will perform model calibration and validation in the next task of the project.

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# Appendix C – Model Calibration and Validation

# TECHNICAL MEMORANDUM

**DATE:** October, 2021

**SUBJECT:** Crystal Chain of Lakes HSPF Model Calibration and Validation

## Introduction

The St. Johns River Water Management District (SJRWMD) has been establishing Minimum Flows and Levels (MFLs) for Crystal Chain of Lakes (CCL), located in Seminole County, Florida (Figure C - 1). The chain includes Lake Como, Dawson Lake, West Crystal Lake, East Crystal Lake, Bel-Air Lake, Amory Lake, and Deforest Lake (Figure C - 1). The MFLs program designates the minimum hydrologic conditions that must be maintained for these lakes to avoid significant harm to water resources values, resulting from permitted water withdrawals. The program is scheduled for completion in 2024.

In support of the MFLs modeling, we set up an HSPF model (Bicknell et al., 1997) for the CCL that covered the period from 1995 to 2019 (see Task B report). We calibrated and validated the model for the period from 1/1/2007 to 12/31/2019 and 1/1/1995 to 12/31/2006, respectively. This technical memorandum summarizes the calibration and validation processes and presents the corresponding results.

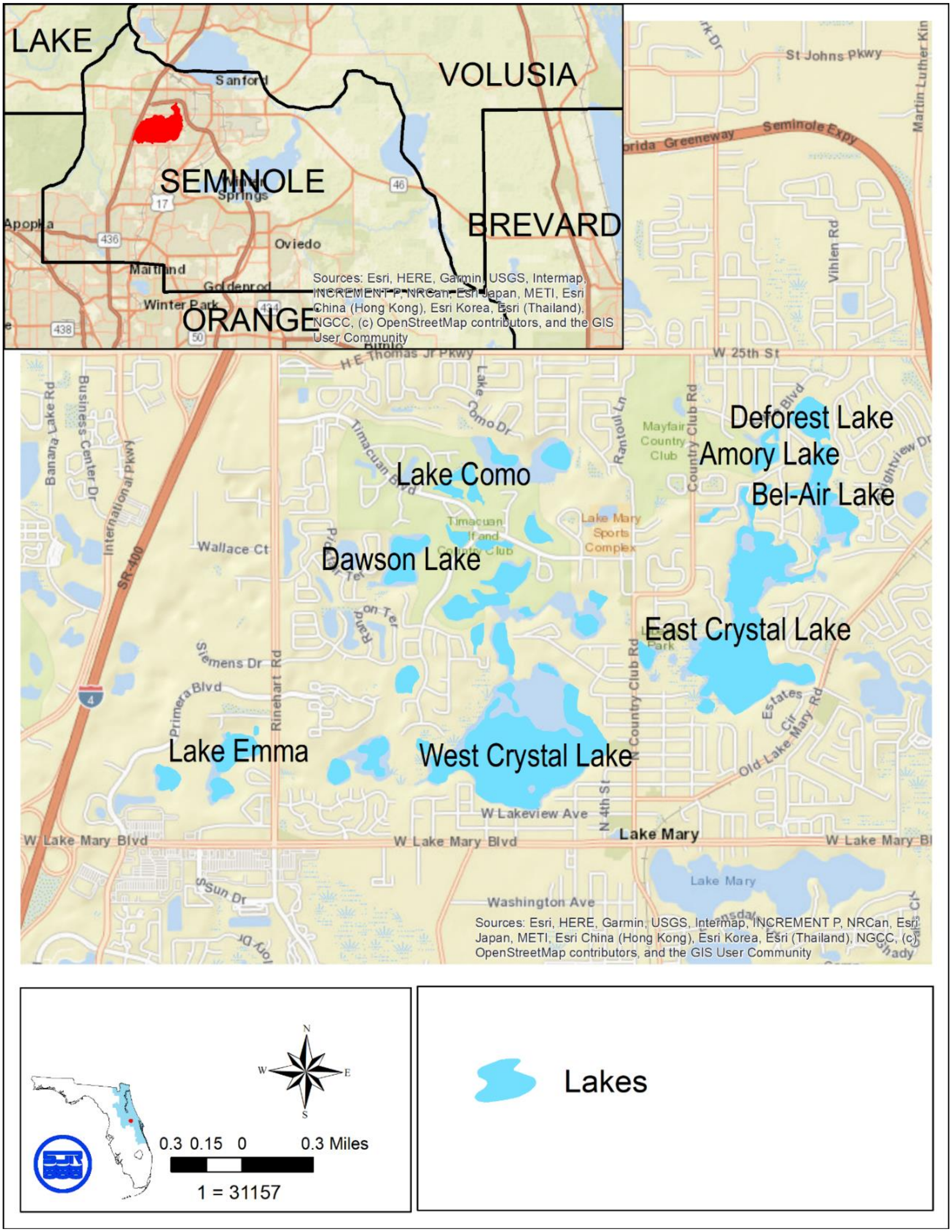


Figure C - 1. Location of Crystal Chain of Lakes (top left corner) in Seminole County

# Model Calibration and Validation

Using the non-continuous observed daily stages at Amory, Bel-Air, Deforest, East Crystal, and West Crystal Lakes (see Task B report for detail), we manually calibrated the HSPF model of CCL. We used the period 2007 to 2019 for calibration and 1995 to 2006 for validation. During model calibration and validation processes, we evaluated the performance of the model by consistently using multiple statistical indices with targeted values (Table C - 1). Model evaluation also included graphical methods, such as plotting and visualizing the daily observed against simulated stage hydrographs and duration curves.

Table C - 1. Statistical metrics used for model evaluation with targeted values for monthly time scale.

| **Statistics** | **Description** | **Target (Calibration)** | **Target (Validation)** |
|---|---|---|---|
| NSE | Nash-Sutcliffe Efficiency | $\geq 0.80$ | $\geq 0.70$ |
| RMSE | Root Mean Squared Error | $\leq 1$ ft | $\leq 1$ ft |
| ME | Mean Error | $\leq \lvert \pm 0.5 \rvert$ ft | $\leq \lvert \pm 1 \rvert$ ft |
| ±1ft (%) | % of observations bracketed | $\geq 85$ | $\geq 75$ |

# Results and Discussion

## Initial Conditions

We assessed the effect of initial hydrologic conditions (e.g. soil moisture) of the system on simulated lake stages. Using a 2-year period as a model warm up significantly improved the simulated lake stages of the first two years of the calibration period (2007-2008), as shown in Figure C - 2 for the East Crystal Lake (ECL). We also noticed similar impacts for the other lakes. Consequently, we used the period from 2005 to 2006 and 1993 to 1994 as a model warm up period for the calibration and validation periods, respectively.

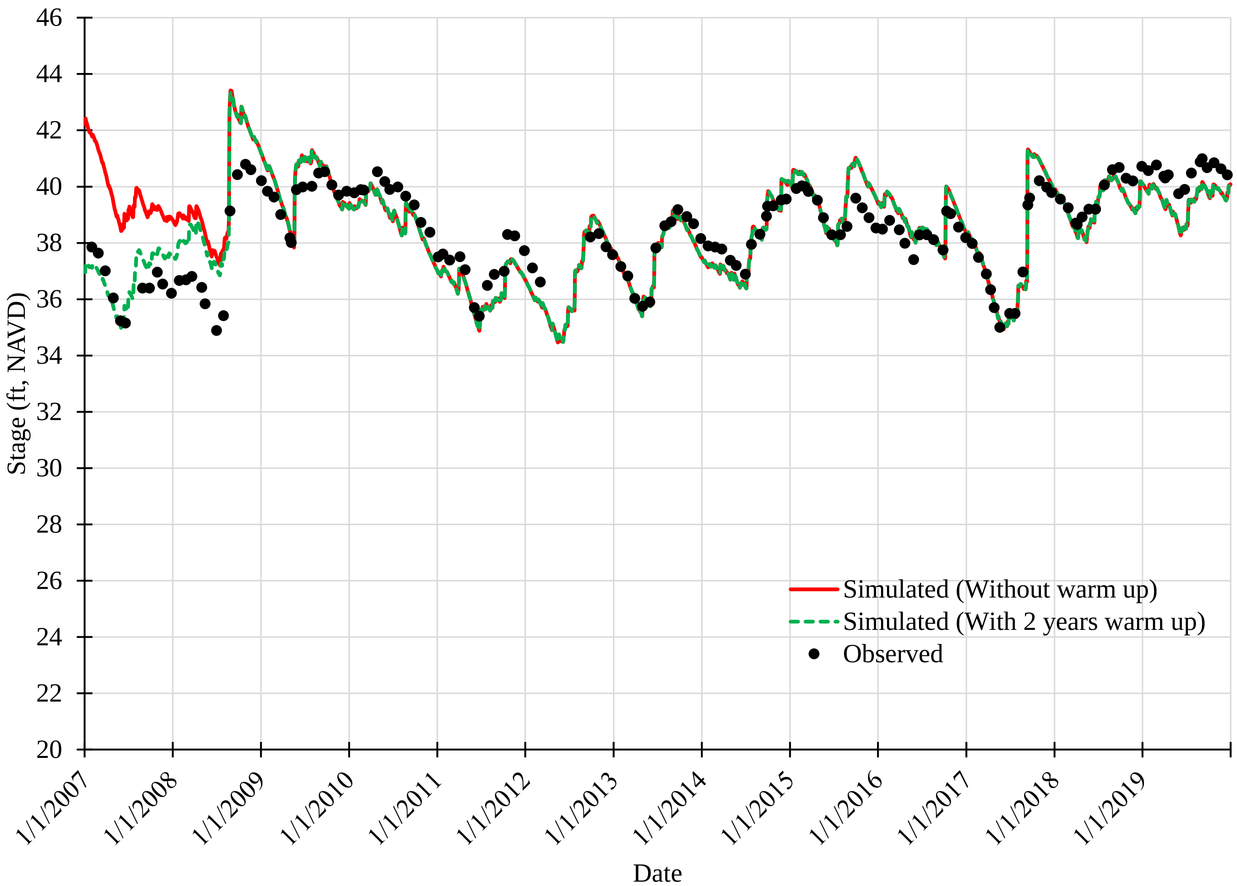


Figure C - 2. Effect of using a warm up period on simulated stages of East Crystal Lake

## Effect of Rainfall on Simulated Lake Stages

We evaluated the implication of using the nearby National Oceanic and Atmospheric Administration (NOAA) Sanford rain gauge and NEXRAD data (see Figure A - 7 of Task A report) on the simulated lake stages. While some periods (e.g., 2007-2008) of the observed stages might be captured well with the NEXRAD data, the Sanford station data reasonably reproduced the observed stages of West and East Crystal Lakes (Figure C - 3 and Figure C - 4). Overall, the model performance is generally better using the station data as compared to the NEXRAD data, especially for the West Crystal Lake (WCL) (Table C - 2). Since the subsequent long-term simulations will utilize the station data, model calibration and validation also used hourly rainfall values from the Sanford station.

Table C - 2. Performance evaluation statistics using rain gauge and NEXRAD data over the calibration period

| Statistics | West Crystal Lake | | East Crystal Lake | |
|---|---|---|---|---|
| | **Rain gauge data** | **NEXRAD data** | **Rain gauge data** | **NEXRAD data** |
| NSE | 0.28 | -0.09 | 0.69 | 0.72 |
| RMSE | 1.38 | 1.70 | 0.87 | 0.83 |
| ME | -0.59 | -1.02 | 0.24 | -0.25 |
| ±1ft (%) | 44.53 | 36.50 | 81.01 | 73.42 |

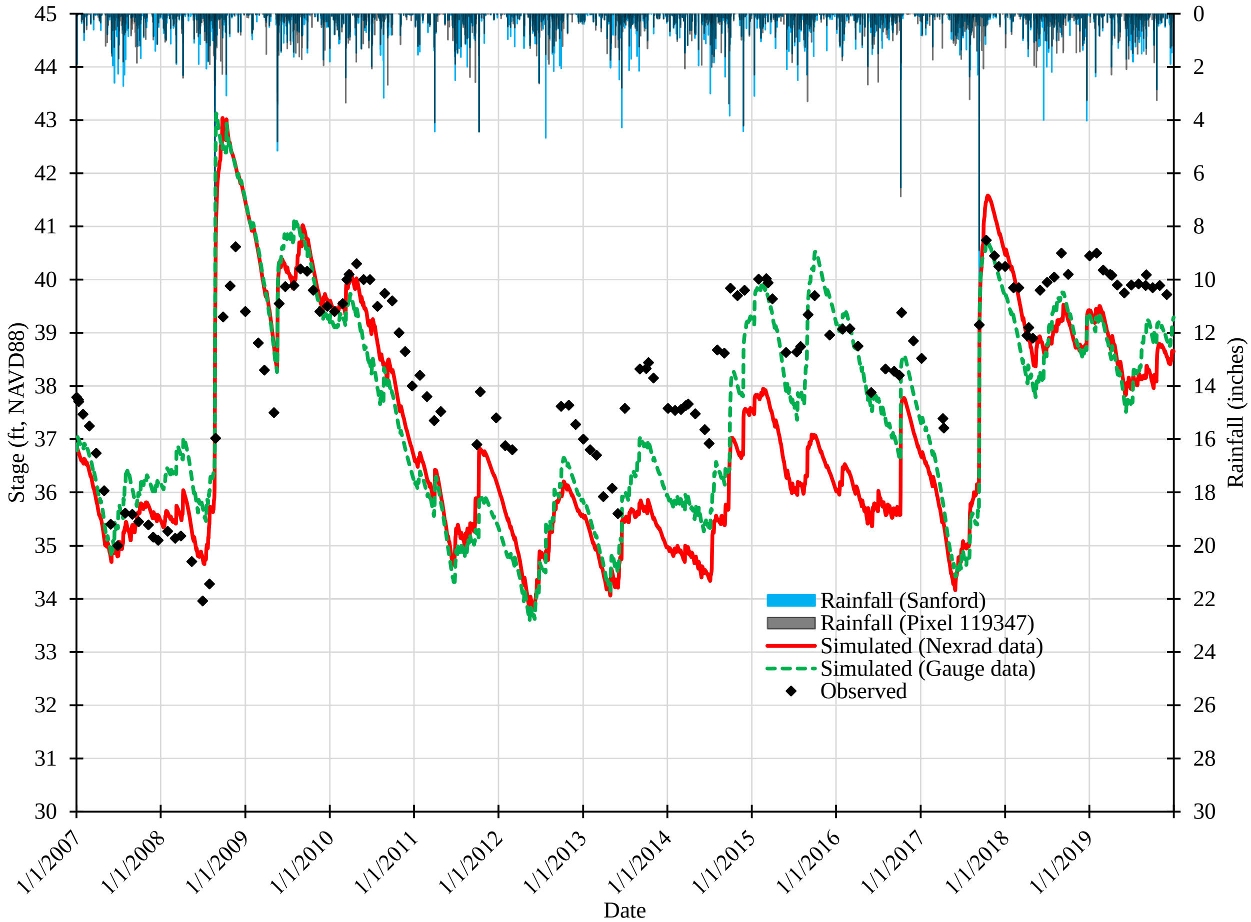


Figure C - 3. Effect of rain gauge and NEXRAD rainfall data on simulated stages of West Crystal Lake

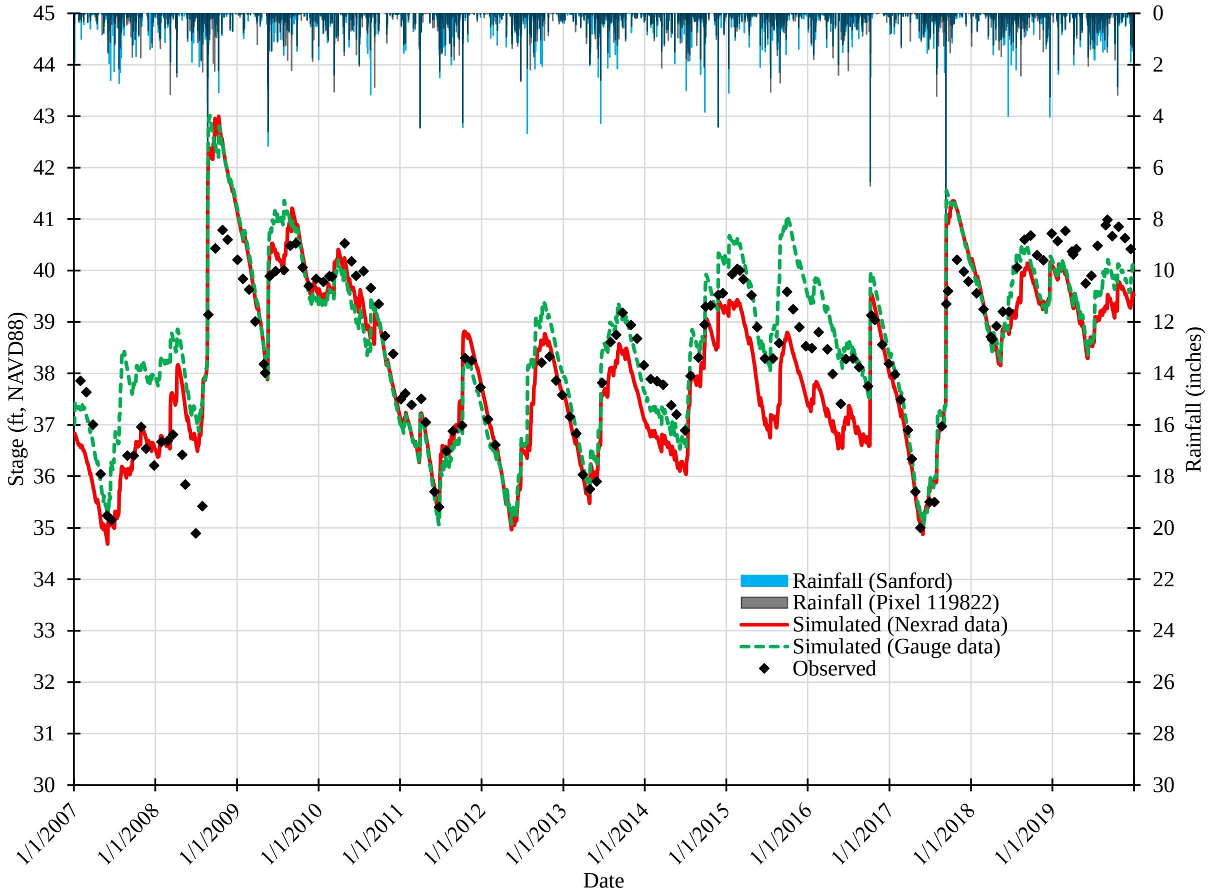


Figure C - 4. Effect of rain gauge and NEXRAD rainfall data on simulated stages of East Crystal Lake

## Calibrated Parameters

As a starting point, we used the calibrated parameter values of the Middle St. Johns River Basin (MSJRB)'s HSPF model. Because the CCL is in high recharge area, further calibrating those parameters that control surface runoff processes showed minimal effects on simulated lake stages. Consequently, we fixed the surface runoff related parameter values to the values used in the HSPF model of MSJRB. Thus, the model calibration process focused on optimizing those parameters that control lake and groundwater interaction processes, mainly leakance values beneath the lake and amount of recharge to the deep aquifer (UFA) from the upland areas. We calibrated the "DEEPFR" parameter of HSPF, which controls the amount of water recharge to the UFA from the upland areas.

We spatially varied the leakance values for the 13 RCHRES shown in Figure C - 5. The model using leakance values from the ECFTX model of the Central Florida Water Initiative, CFWI (2020) as a starting point significantly overestimated the observed stages of all lakes. Therefore, we further adjusted and fine-tuned the leakance values. Table C - 3 presents the calibrated leakance values and compares them with the values from the ECFTX model. The leakance values used by the ECFTX model are generally low compared to the values used in the HSPF model. Given the coarse resolution of the ECFTX model, the HSPF calibrated values are believed to be more reasonable.

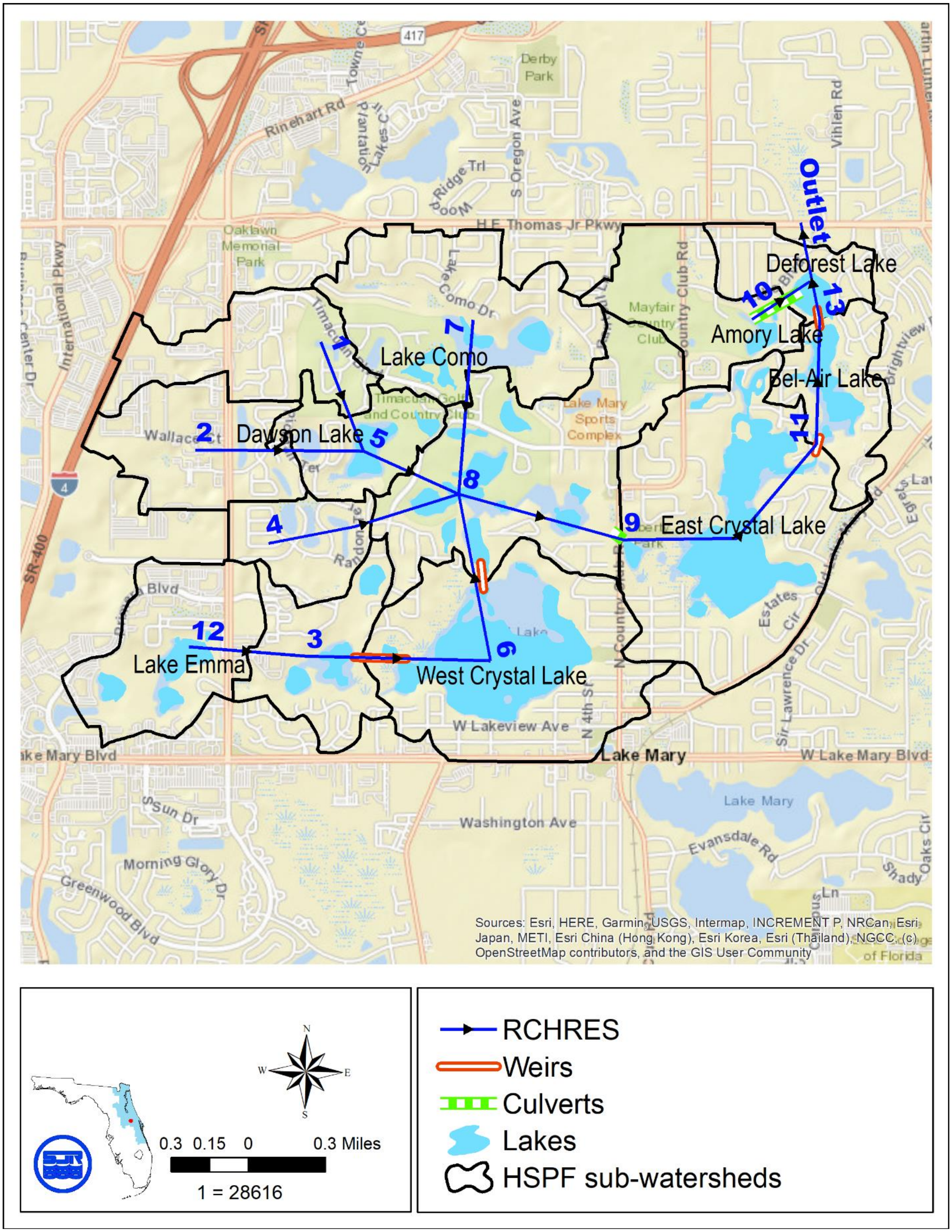


Figure C - 5. The 13 sub-watersheds or RCHRES of the HSPF model of CCL.

For flow calculations between RCHRES 9 (East Crystal Lake) and RCHRES 11 (Bel-Air Lake) and between RCHRES 11 and RCHRES 13 (Deforest Lake) (see Figure C - 5), we adjusted the weir discharge coefficients in the Special Actions module of HSPF to the low end of typical range reported in the literature (USACE, 2020). The adjusted values are summarized in Table C - 4 and are lower than the values in Table B – 4 of the Task B report. We used such low values to avoid numerical instability issues.

Table C - 3. Calibrated leakance values of the HSPF model

| RCHRES | ECFTX leakance (per day) | HSPF leakance (per day) |
|---|---|---|
| 1 | 0.000017 | 0.0018 |
| 2 | 0.000013 | 0.0018 |
| 3 | 0.000097 | 0.0020 |
| 4 | 0.000029 | 0.0023 |
| 5 | 0.000016 | 0.0023 |
| 6 | 0.000167 | 0.0023 |
| 7 | 0.000025 | 0.0023 |
| 8 | 0.000091 | 0.0023 |
| 9 | 0.000181 | 0.0024 |
| 10 | 0.000201 | 0.0027 |
| 11 | 0.000217 | 0.0024 |
| 12 | 0.000066 | 0.0024 |
| 13 | 0.000239 | 0.0014 |

Table C - 4. Adjusted weir coefficient for RCHRES 9, 11, and 13

| Upstream RCHRES | Downstream RCHRES | Coefficient |
|---|---|---|
| 3 | 6 | 0.2 |
| 6 | 8 | 0.2 |
| 9 | 11 | 0.2 |
| 11 | 13 | 0.2 |

According to Boniol and Mouyard (2016), the WCL's sub-watersheds (sub-watersheds 3 and 6) are geographically in medium recharge zone (annual average recharge of 5 to 10 inches per year) as compared to the rest of the sub-watersheds that are in high recharge zone (greater than 10 inches per year). Based on this information, we reduced the deep aquifer recharge value (DEEPFR) used in the HSPF of MSJRB from 0.5 to 0.4 for the two sub-watersheds to improve the underestimation of observed stages during the calibration period. Such change also improved the performance of the model, such as NSE, RMSE, and PBIAS values. In contrast, we increased the DEEPFR value of sub-watershed 10 from 0.5 to 0.6 as this value improved the calibration at Amory Lake. The slightly increased DEEPFR value of sub-watershed 10 reduced the amount of inflows to Amory Lake, which most likely compensated the effect of some of the spatially scattered retention ponds/wetland areas in the upstream part of the lake (Figure C - 1 and Figure C - 5). Otherwise, the model seemingly overestimated the observed stages.

We also updated the rating curves documented in model set up (see Table B – 6 and Table B – 7 of Task B report), based on information obtained from a site visit conducted on 06/10/2021. During the visit, we noticed about 0.4 and 0.7 ft sedimentation in the downstream side of the culverts between RCHRES 8 and 9 (East Crystal Lake) and between RCHRES 10 (Amory Lake) and RCHRES 13 (Deforest Lake), respectively. We considered the sedimentation effects by using the bottom clip option of the Interconnected Channel and Pond Routing version 4 (ICPR4) model (Streamline Technologies, 2018), which was used to estimate the rating curves. The updated rating curves are reported in Attachment C - 1 (between RCHRES 8 and 9) and Attachment C - 2 (between RCHRES 10 and 13).

## Simulated Stages

We carried out model calibration and validation processes at multiple locations, but this report will only present graphic results for the two major lakes of the system (West and East Crystal Lakes), where MFLs modeling and evaluation processes are expected to be implemented. However, the goodness-of-fit statistics are summarized in Table C - 5 for all lakes that have observed stages. It should be noted that although the target values of NSE reported in Table C - 5 are for monthly time scale, we calculated the performance metric only for daily values due to the sporadic nature of observed stages. Such data may lose their meaning when converted to monthly average values. Therefore, the monthly target values of NSE could be relaxed for daily model performance evaluations. In general, most of the targeted values are met except NSE and percent of observations bracketed at ± 1 foot (Table C - 5).

Table C - 5. Daily goodness-of-fit statistics for the calibration and validation periods. Bold signifies targeted values not achieved.

| Period | Statistics | Target | West Crystal | East Crystal | Bel-Air | Amory | Deforest |
|---|---|---|---|---|---|---|---|
| Calibration (2007-2019) | NSE | ≥ 0.80 | **0.01** | **0.73** | **0.39** | **0.06** | **0.59** |
| | RMSE | ≤ 1 ft | **1.62** | **0.82** | 1.11 | 0.82 | 0.70 |
| | ME | ≤ │±0.5│ ft | **-0.81** | 0.17 | 0.51 | 0.33 | 0.08 |
| | ±1ft (%) | ≥ 85 | **24.09** | **81.01** | **68.54** | **76.92** | **82.04** |
| Validation (1995-2006) | NSE | ≥ 0.70 | 0.84 | 0.76 | **0.66** | **0.58** | **0.48** |
| | RMSE | ≤ 1 ft | 1.17 | 1.14 | **1.39** | 1.04 | 0.99 |
| | ME | ≤ │±1│ ft | 0.40 | -0.06 | 0.01 | -0.24 | -0.77 |
| | ±1ft (%) | ≥ 75 | **53.64** | **58.96** | **55.21** | **67.18** | **64.10** |

The simulated stages generally match the observed stages in terms of temporal evolutions and variations for both the calibration and validation periods (Figure C - 6 and Figure C - 8). However, we noticed that HSPF systematically underestimated the observed stages of the West Crystal Lake (WCL) after 2009 (Figure C - 6). On the other hand, those periods were well simulated for the East Crystal Lake (ECL) as shown in Figure C - 8, and for the other lakes too. It should be noticed that due to the lack of observed data from the SJRWMD's hydrologic databases (since 2007), the calibration of WCL used sparsely recorded stages (mostly once in a month) from the Seminole County.

Comparison of the two datasets from the Seminole County and SJRWMD for the overlapping period of record (POR) (1993 to 2006) showed noticeable discrepancies. For example, we noticed up to 2 feet difference between the two data sources. Further calibration of WCL did not provide fruitful results as it caused additional overestimation before 2009. Given the sparsity of observed data, large discrepancies between Seminole and SJRWMD datasets for the overlapping POR, and the model's reasonable simulation of the other lakes, the quality of observed stages of WCL from the Seminole County might be questionable for that period. The performance of the model is thus poor during the calibration period, especially for NSE, RMSE, and percent of observations bracketed within ± 1ft (Table C - 5). This effect is also clearly observed in the stage duration curves of the calibration period especially for medium to high stages (Figure C - 7). However, the model adequately simulated observed stages of WCL during the validation period and thus the statistical metrics significantly improved (Table C - 5).

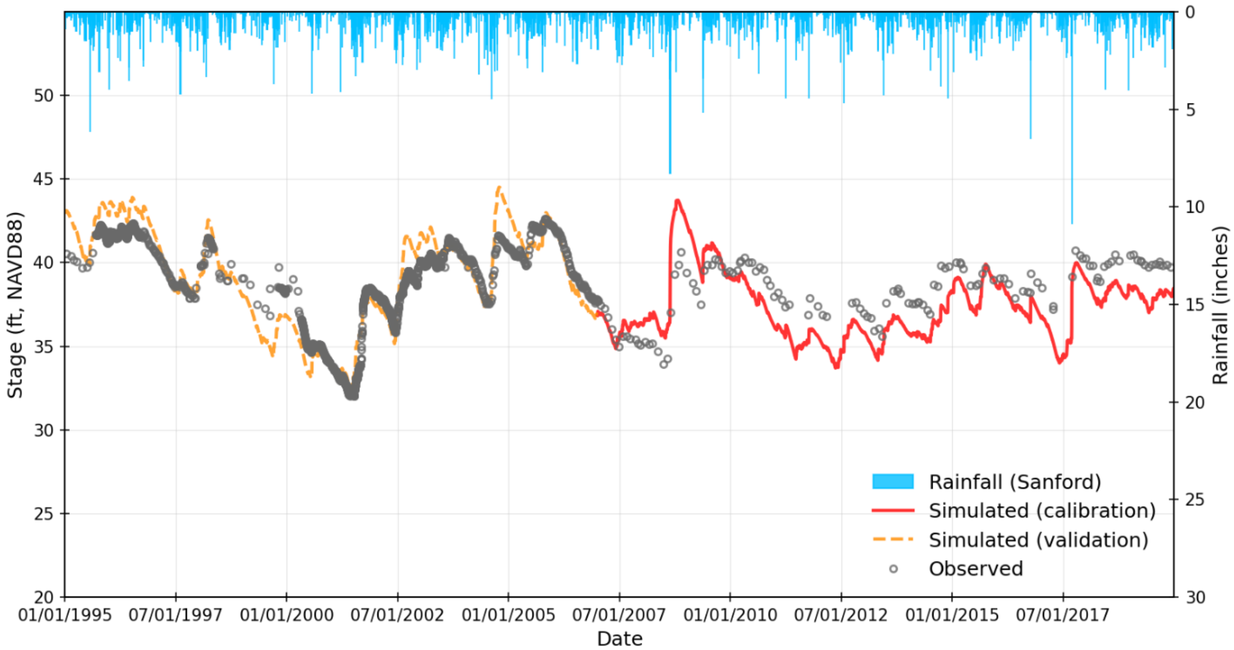


Figure C - 6. Daily observed and simulated stages for West Crystal Lake

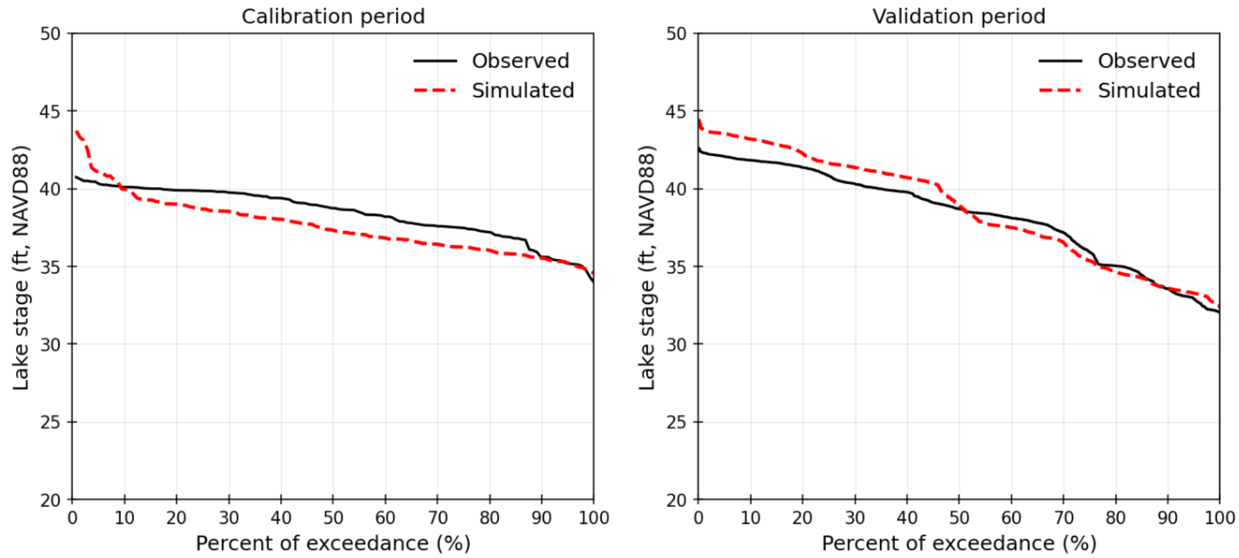


Figure C - 7. Observed and simulated stages duration curves for calibration and validation periods of West Crystal Lake

The observed stage duration curves of the ECL are well replicated by the HSPF model for both the calibration and validation periods (Figure C - 9). Overall, HSPF reasonably reproduced the temporal variation and magnitude of the observed stages (Figure C - 6 and Figure C - 8) except for the late calibration period of WCL.

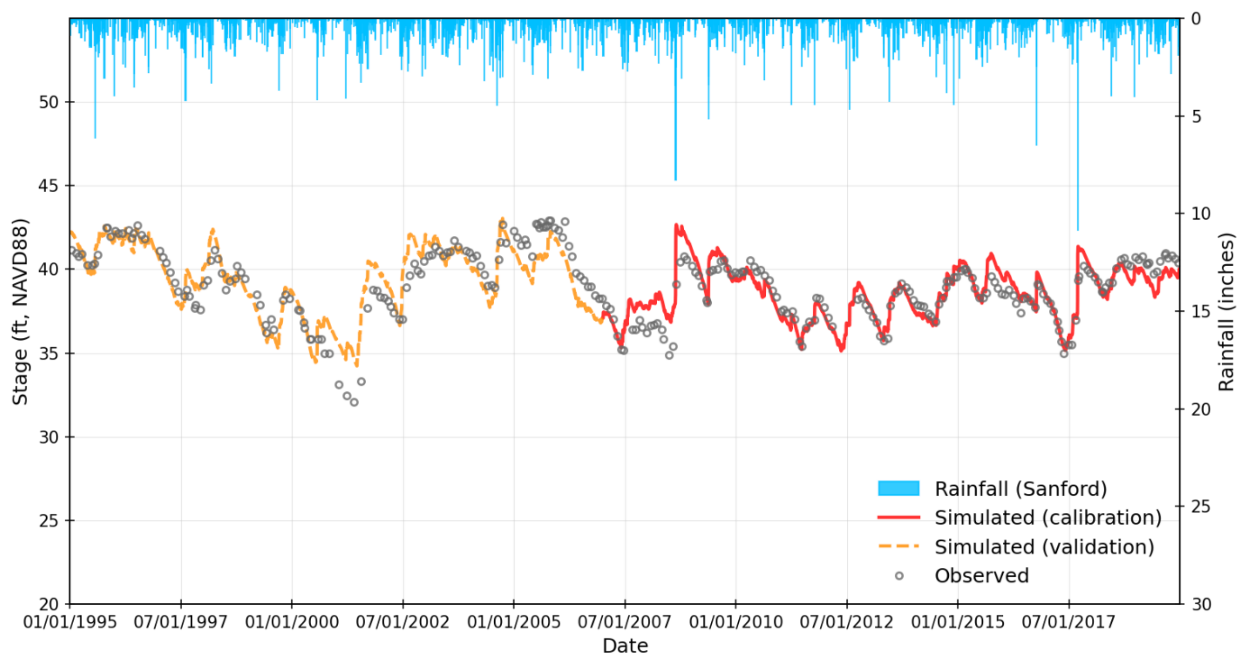


Figure C - 8. Daily observed and simulated stages of East Crystal Lake

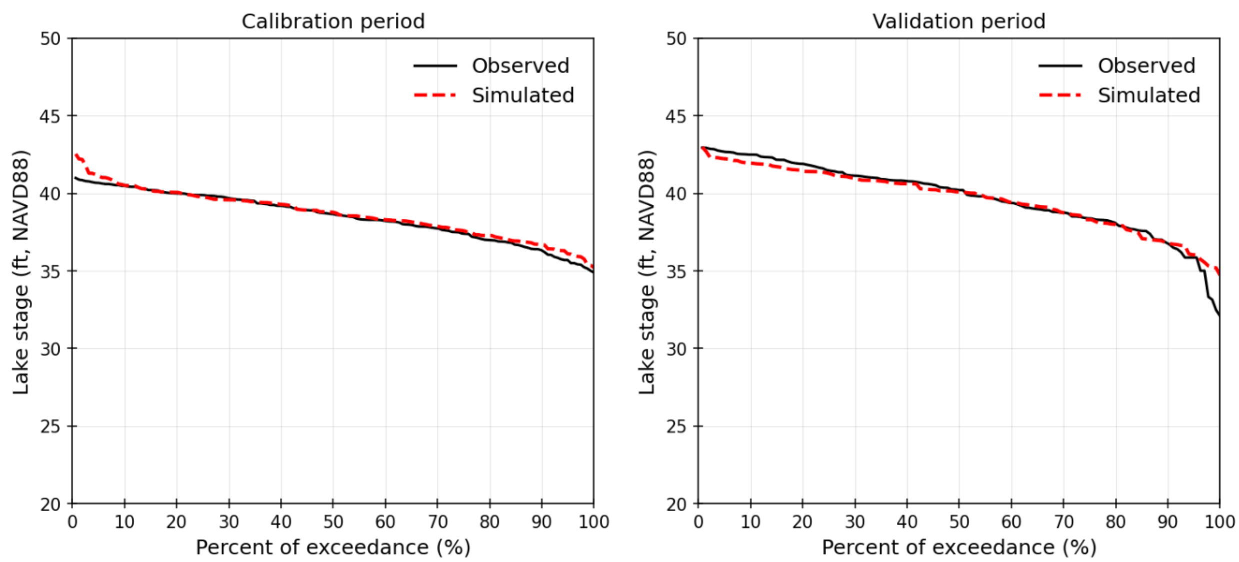


Figure C - 9. Observed and simulated stages duration curves for calibration and validation periods of East Crystal Lake

## Water Balance

We assessed the simulated water balance components, such as annual average actual evapotranspiration (AET), runoff, baseflow, and recharge to deep aquifer for both the calibration and validation periods. The values are reported in Table C - 6 for each land use land cover (LULC) and the entire watershed. The simulated AET values of each LULC are close to the target values commonly used at the SJRWMD. In addition, recharge values to the deep aquifer are reasonably simulated when compared to the values reported by Boniol and Mouyard (2016). AET accounts for more than 50% of the annual average rainfall values. Overall, the simulated water balance components are reasonable.

Table C - 6. Annual average water balance summary (inches per year)

| Period | Description | LDR | MDR | HDR | CI | OPN | PAS | AGR | RNG/SHB | FRS | WTL | Watershed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calibration (2007-2019) | Rainfall | 52.8 | 52.8 | 52.8 | 52.8 | 52.8 | 52.8 | 52.8 | 52.8 | 52.8 | 52.8 | 52.8 |
| | Deep recharge | 5.9 | 6.1 | 5.8 | 6.1 | 10.2 | 6.6 | 6.4 | 6.3 | 4.8 | 7.0 | 5.3 |
| | AET | 35.0 | 32.5 | 27.5 | 23.8 | 26.4 | 37.2 | 39.0 | 37.7 | 41.2 | 42.9 | 34.0 |
| | Runoff | 12.2 | 15.1 | 21.4 | 25.9 | 16.2 | 8.9 | 7.2 | 8.7 | 6.6 | 2.6 | 13.4 |
| | Baseflow | 6.7 | 6.5 | 6.8 | 6.5 | 10.6 | 6.5 | 5.6 | 6.4 | 5.7 | 2.5 | 4.7 |
| Validation (1995-2006) | Rainfall | 53.9 | 53.9 | 53.9 | 53.9 | 53.9 | 53.9 | 53.9 | 53.9 | 53.9 | 53.9 | 53.9 |
| | Deep recharge | 6.4 | 6.6 | 6.3 | 6.6 | 10.4 | 7.3 | 7.4 | 7.1 | 5.9 | 7.0 | 5.7 |
| | AET | 34.3 | 31.9 | 27.1 | 23.5 | 26.5 | 36.5 | 38.2 | 36.9 | 40.3 | 43.4 | 33.6 |
| | Runoff | 13.7 | 16.5 | 22.8 | 27.2 | 17.1 | 10.3 | 8.6 | 10.1 | 8.1 | 4.6 | 14.9 |
| | Baseflow | 7.4 | 7.1 | 7.4 | 7.2 | 10.9 | 7.4 | 6.7 | 7.3 | 7.2 | 4.5 | 5.6 |

**Note:** LDR = low density residential; MDR = medium density residential; HDR = high density residential; CI = commercial-industrial; OPN = open land; PAS = pasture; RNG/SHB = rangeland/shrubland; FRS = forest; WTL = wetland; AET = Actual Evapotranspiration.

Table C - 7 summarizes the lake water budget of the two major lakes (WCL and ECL) for both the calibration and validation periods. The table clearly indicates that seepage to groundwater generally dominates the outflow components of the two lakes, followed by evaporation. Higher surface outflows are simulated during the validation period, which could be due to the wetter conditions and higher direct rainfall amount, compared to the calibration period (Table C - 6 and Table C - 7).

Table C - 7. West and East Crystal Lakes annual average water budget (acres-feet). Percent represents to the total inflow

| Lake | Period | Direct Rainfall | Watershed Inflow | Evaporation | Seepage | Surface Outflow | Total Inflow | Total Outflow | Storage Change |
|---|---|---|---|---|---|---|---|---|---|
| West Crystal | Calibration | 486.3 | 741.6 | 463.3 | 531.3 | 218.9 | 1227.9 | 1213.4 | 14.5 |
| | Percent | **39.6** | **60.4** | **37.7** | **43.3** | **17.8** | | | **1.2** |
| | Validation | 662.1 | 2303.4 | 613.3 | 854.3 | 1579.8 | 2965.4 | 3047.4 | -82.0 |
| | Percent | **22.3** | **77.7** | **20.7** | **28.8** | **53.3** | | | **-2.8** |
| East Crystal | Calibration | 428.9 | 800.5 | 402.9 | 576.3 | 227.3 | 1229.4 | 1206.5 | 22.9 |
| | Percent | **34.9** | **65.1** | **32.8** | **46.9** | **18.5** | | | **1.9** |
| | Validation | 549.1 | 1301.6 | 493.9 | 730.1 | 679.6 | 1850.7 | 1903.6 | -52.9 |
| | Percent | **29.7** | **70.3** | **26.7** | **39.5** | **36.7** | | | **-2.9** |

# Summary

For hydrological and MFLs modeling of the Crystal Chain of Lakes, we calibrated and validated the HSPF model for the period from 1/1/2007 to 12/31/2019 and 1/1/1995 to 12/31/2006, respectively. We used a 2-year warm up period for both calibration and validation periods. We used non-continuous daily observed lake stages at different locations and calibrated and validated the model. During model calibration and validation processes, we evaluated the performance of the model by consistently using multiple statistical indexes and graphical methods. HSPF adequately reproduced the observed data. Overall, the model performance improved during the validation period, highlighting the suitability of the model in simulating the hydrological processes of the system outside the calibration period. Therefore, the model can be used for the long-term simulations, which is in the next task of the project.

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# Attachment

Attachment C - 1. Rating curves estimated by ICPR4 model and used in HSPF model to estimate flows between RCHRES 8 and RCHRES 9 (East Crystal Lake)

| **Headwater** | **Tailwater Stage (ft, NAVD88)** | | | | |
|---|---|---|---|---|---|
| **Stage (ft, NAVD88)** | **Curve 1 42.4** | **Curve 2 42.5** | **Curve 3 43.0** | **Curve 4 43.5** | **Curve 5 44.0** |
| 41.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.8 | 2.5 | 2.5 | 0.0 | 0.0 | 0.0 |
| 42.9 | 4.0 | 4.0 | 0.0 | 0.0 | 0.0 |
| 43.0 | 5.8 | 5.8 | 0.0 | 0.0 | 0.0 |
| 43.1 | 7.9 | 7.9 | 7.2 | 0.0 | 0.0 |
| 43.2 | 10.2 | 10.2 | 10.3 | 0.0 | 0.0 |
| 43.3 | 12.7 | 12.7 | 12.7 | 0.0 | 0.0 |
| 43.4 | 15.4 | 15.4 | 15.4 | 0.0 | 0.0 |
| 43.5 | 18.4 | 18.4 | 18.4 | 0.0 | 0.0 |
| 43.6 | 22.3 | 22.3 | 22.3 | 19.4 | 0.0 |
| 43.7 | 26.4 | 26.4 | 26.4 | 27.4 | 0.0 |
| 43.8 | 30.8 | 30.8 | 30.8 | 33.2 | 0.0 |
| 43.9 | 35.7 | 35.7 | 35.7 | 38.2 | 0.0 |

| | | | | | |
|---|---|---|---|---|---|
| 44.0 | 40.7 | 40.7 | 40.7 | 42.4 | 0.0 |
| 44.1 | 45.8 | 45.8 | 45.8 | 46.2 | 34.5 |
| 44.2 | 51.2 | 51.2 | 51.2 | 51.2 | 48.7 |
| 44.3 | 56.9 | 56.9 | 56.9 | 56.9 | 58.7 |
| 44.4 | 62.7 | 62.7 | 62.7 | 62.7 | 67.2 |
| 44.5 | 68.4 | 68.4 | 68.4 | 68.4 | 74.0 |
| 44.6 | 75.0 | 75.0 | 75.0 | 75.0 | 80.6 |
| 44.7 | 81.2 | 81.2 | 81.2 | 81.2 | 86.2 |
| 44.8 | 88.2 | 88.2 | 88.2 | 88.2 | 91.6 |
| 44.9 | 94.7 | 94.7 | 94.7 | 94.7 | 97.1 |
| 45.0 | 101.9 | 101.9 | 101.9 | 101.9 | 101.9 |

Attachment C - 2. Rating curves estimated by ICPR4 model and used in HSPF model to estimate flows between RCHRES 10 (Amory Lake) and RCHRES 13 (Deforest Lake).

| **Headwater** | **Tailwater Stage (ft, NAVD88)** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Stage (ft, NAVD88)** | **Curve 1** | **Curve 2** | **Curve 3** | **Curve 4** | **Curve 5** | **Curve 6** | **Curve 7** |
| | **41.1** | **41.5** | **42.0** | **42.5** | **43.0** | **43.5** | **44.0** |
| 41.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.3 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.4 | 1.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.5 | 1.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.6 | 3.0 | 3.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.7 | 4.3 | 4.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.8 | 5.8 | 5.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 41.9 | 7.5 | 7.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.0 | 9.2 | 9.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.1 | 11.2 | 11.2 | 10.9 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.2 | 13.3 | 13.3 | 13.3 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.3 | 15.4 | 15.4 | 15.4 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.4 | 17.8 | 17.8 | 17.8 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.5 | 20.3 | 20.3 | 20.3 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42.6 | 22.9 | 22.9 | 22.9 | 20.4 | 0.0 | 0.0 | 0.0 |
| 42.7 | 25.5 | 25.5 | 25.5 | 25.2 | 0.0 | 0.0 | 0.0 |
| 42.8 | 28.2 | 28.2 | 28.2 | 28.2 | 0.0 | 0.0 | 0.0 |
| 42.9 | 31.0 | 31.0 | 31.0 | 31.0 | 0.0 | 0.0 | 0.0 |
| 43.0 | 33.9 | 33.9 | 33.9 | 33.9 | 0.0 | 0.0 | 0.0 |
| 43.1 | 36.8 | 36.8 | 36.8 | 36.8 | 23.6 | 0.0 | 0.0 |
| 43.2 | 39.7 | 39.7 | 39.7 | 39.7 | 33.1 | 0.0 | 0.0 |
| 43.3 | 42.8 | 42.8 | 42.8 | 42.8 | 40.1 | 0.0 | 0.0 |
| 43.4 | 45.8 | 45.8 | 45.8 | 45.8 | 45.4 | 0.0 | 0.0 |
| 43.5 | 48.6 | 48.6 | 48.6 | 48.6 | 48.7 | 0.0 | 0.0 |
| 43.6 | 51.7 | 51.7 | 51.7 | 51.7 | 51.7 | 25.0 | 0.0 |
| 43.7 | 54.9 | 54.9 | 54.9 | 54.9 | 54.9 | 34.3 | 0.0 |
| 43.8 | 58.0 | 58.0 | 58.0 | 58.0 | 58.0 | 42.0 | 0.0 |
| 43.9 | 60.9 | 60.9 | 60.9 | 60.9 | 60.9 | 48.1 | 0.0 |
| 44.0 | 64.0 | 64.0 | 64.0 | 64.0 | 64.0 | 53.5 | 0.0 |
| 44.1 | 67.2 | 67.2 | 67.2 | 67.2 | 67.2 | 58.0 | 23.4 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 44.2 | 70.3 | 70.3 | 70.3 | 70.3 | 70.3 | 62.6 | 33.8 |
| 44.3 | 73.4 | 73.4 | 73.4 | 73.4 | 73.4 | 66.9 | 41.0 |
| 44.4 | 76.5 | 76.5 | 76.5 | 76.5 | 76.5 | 70.5 | 47.5 |
| 44.5 | 79.6 | 79.6 | 79.6 | 79.6 | 79.6 | 73.9 | 52.8 |
| 44.6 | 82.6 | 82.6 | 82.6 | 82.6 | 82.6 | 77.3 | 57.9 |
| 44.7 | 85.5 | 85.5 | 85.5 | 85.5 | 85.5 | 80.3 | 62.6 |
| 44.8 | 88.5 | 88.5 | 88.5 | 88.5 | 88.5 | 83.5 | 66.7 |
| 44.9 | 91.4 | 91.4 | 91.4 | 91.4 | 91.4 | 86.7 | 70.9 |
| 45.0 | 94.1 | 94.1 | 94.1 | 94.1 | 94.1 | 89.6 | 74.6 |

# Appendix D – Long-term Simulations

# TECHNICAL MEMORANDUM

**DATE:** January, 2022

**SUBJECT:** Crystal Chain of Lakes HSPF Model Long-term Simulations

## Introduction

The Crystal Chain of Lakes (CCL) is located in Seminole County, Florida (Figure D - 1). The chain includes Lake Como, Dawson Lake, West Crystal Lake, East Crystal Lake, Bel-Air Lake, Amory Lake, and Deforest Lake (Figure D - 1). The St. Johns River Water Management District (SJRWMD) has been establishing Minimum Flows and Levels (MFLs) for the CCL, which is scheduled for completion in 2023. The MFLs program designates the minimum hydrologic conditions that must be maintained for these lakes to avoid significant harm to water resources values, resulting from permitted water withdrawals. As minimum levels are usually based on hydrologic events with associated durations and return periods, MFLs assessment requires frequency analysis of the lake levels. Due to the presence of short- and long-term climatic cycles (e.g., El Nino Southern and Atlantic Multidecadal Oscillations), the frequencies of lake levels could be significantly different in the wet periods than those in the dry periods. Therefore, it is important to perform frequency analysis using long-term continuous lake levels so that the effect of short- and long-term climatic variations can be captured in the lake levels frequency analysis. Long-term observed lake level time series can be used for such analyses, but such data are usually discontinuous and sometimes sparse. Thus, long-term lake levels need to be simulated by using hydrologic and hydraulic models. This is also important for a better understanding of the lakes' water budget elements.

In support of the MFLs modeling, SJRWMD used the Hydrological Simulation Program – FORTRAN (HSPF) model (Bicknell et al., 1997) for hydrologic and hydraulic processes, surface water – groundwater interactions, and water budget elements modeling of the CCL. The set up HSPF model covered the period from 1995 to 2019 (see Task B report for detail). The model was calibrated and validated for the period from 1/1/2007 to 12/31/2019 and 1/1/1995 to 12/31/2006, respectively (see Task C report for detail). We subsequently extended the calibrated and validated model to the period from 1/1/1953 to 12/31/2019 for long-term simulation and MFLs modeling. This technical memorandum summarizes the long-term simulation processes and presents the corresponding results.

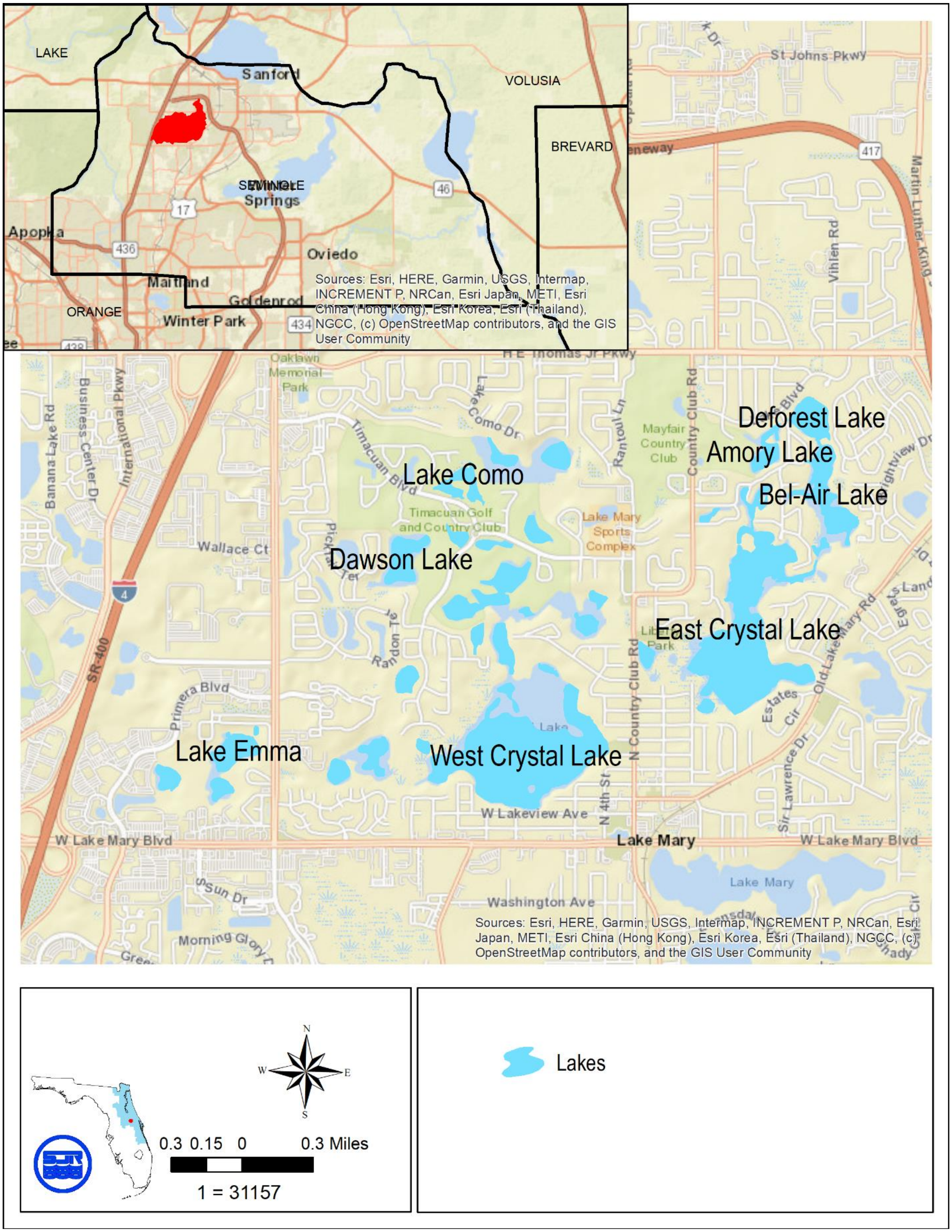


Figure D - 1. Location of Crystal Chain of Lakes (red polygon in the top left corner) in Seminole County

# Hydro-meteorological Data

For long-term hydrologic simulations, we extended rainfall, potential evapotranspiration, and groundwater stages based on the available data from nearby stations. Figure D - 2 presents the locations of the available stations. The extended data covered the period from 1953 to 2019.

## Rainfall

As detailed in model calibration and validation report (see Task C report), we compared the performance of the HSPF model with NEXRAD and gauged data. Due to the reasonable performance of the model using one rain gauge data recorded at Sanford station for both the validation (1995 – 2006) and calibration (2007 – 2019) periods, available hourly NEXRAD data in the SJRWMD's hydrologic databases was not used. As a result, the long-term simulation model used hourly rainfall data computed from daily rainfall records at the Sanford station (ID#: GHCND:USC00087982) of the National Oceanic Atmospheric Administration (NOAA) (Figure D - 2). SJRWMD disaggregated recorded daily rainfall values at Sanford station into hourly values based on hourly NEXRAD (since 1995) and nearby NOAA station (before 1995) data. The annual rainfall values derived from the computed hourly data are shown in Figure D - 3. The figure indicates that the lowest annual rainfall value was reported in 2000.

## Potential Evapotranspiration

Long-term estimated PET data based on the Hargreaves's method (Hargreaves and Samani, 1985) and recorded daily maximum and minimum temperatures (since 1/1/1948) is available at the NOAA Sanford station. HSPF used computed hourly potential evapotranspiration (PET) from daily estimated PET data of the Sanford station. Annual PET values used in the HSPF model are shown in Figure D - 3.

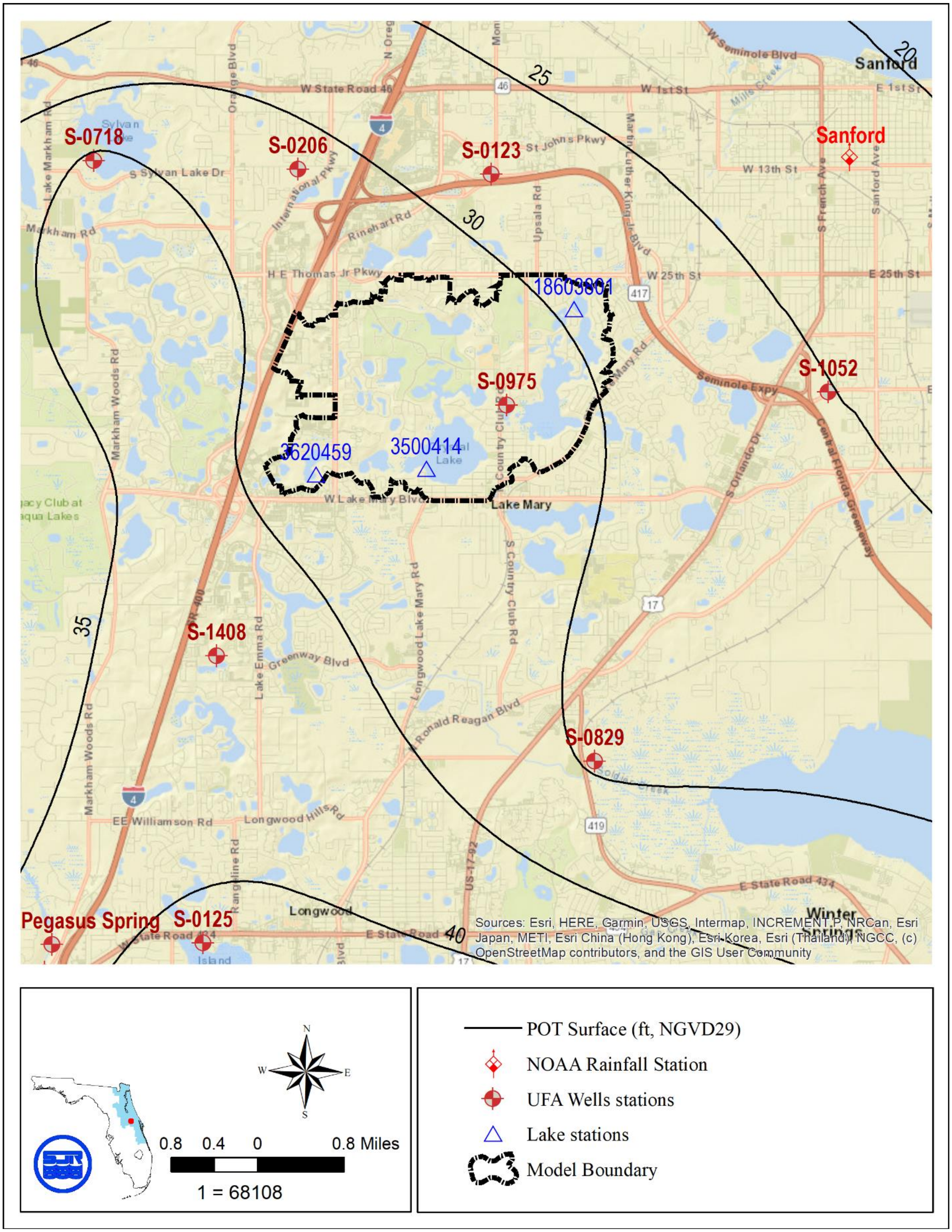


Figure D - 2. Hydro-meteorological stations of Crystal Chain of Lakes along with September 2010 potentiometric (POT) level.

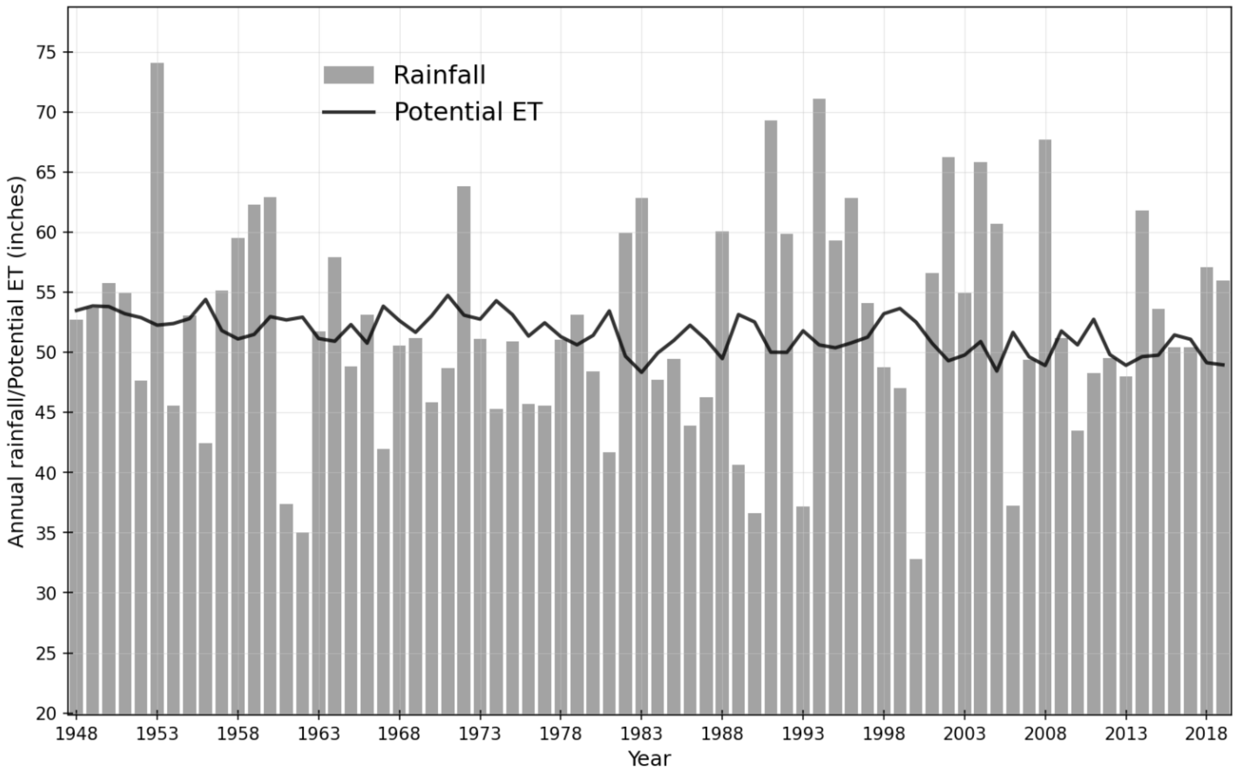


Figure D - 3. Annual rainfall and potential evapotranspiration (ET) values at Sanford station

## Groundwater Stages

Long-term lake stage simulation required daily time series Upper Floridan Aquifer (UFA) stage data. We collected, reviewed, and analyzed several UFA wells data within and around the watershed. Location of the available wells are shown in Figure D - 2. S-0975 is located inside the watershed and therefore used in the HSPF model. S-0975 had irregularly recorded water stages since 1/29/2010, and other wells that are closer to S-0975 had short-term period of record (POR) as documented in Task A report. S-0125 station, which is roughly located at 6 miles from S-0975, had a long-term POR (since 10/25/1951). This station also showed reasonable correlation with S-0975 with a coefficient of determination $R^2$ of 0.71 (Figure D - 4). Although S-0125 had data since 10/25/1951, we excluded the period 10/25/1951 to 12/31/1952 during data extension due to infrequent records (once per month) and missing values for two consecutive months.

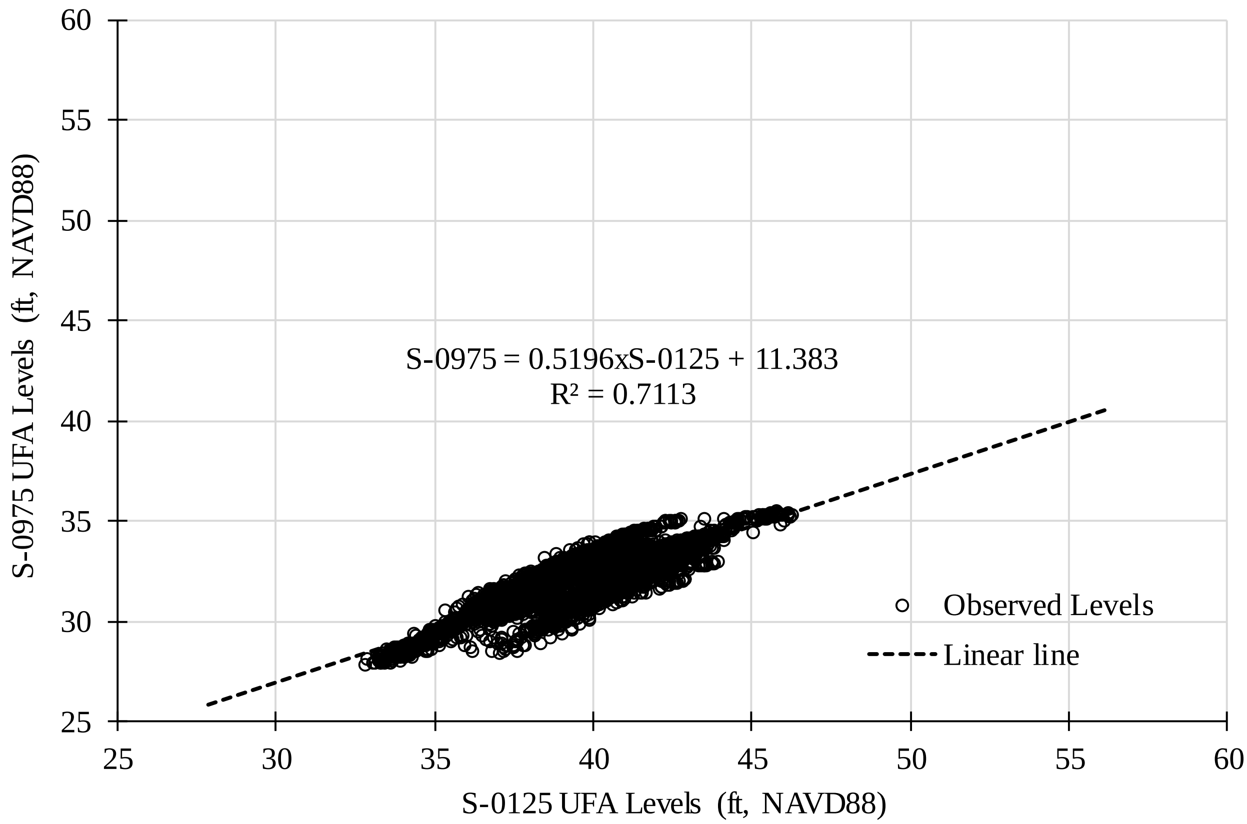


Figure D - 4. Scatter plot of observed Upper Floridan Aquifer (UFA) stages between S-0125 and S-0975

With similar temporal evolution between S-0125 and S-0975 stations, as evidently seen in Figure D - 5, water stages at S-0125 are on average higher by approximately 8 ft. Given the reasonable correlation of S-0125 with S-0975 ($R^2$ = 0.71), we chose S-0125 to extend the data at S-0975 back to 1/1/1953 that based on the Line of Organic Correlation method (Helsel & Hirsch, 2002) and recorded values at S-0125. We filled remaining missing values by linear interpolation. Figure D - 5 presents the extended daily groundwater stages at S-0975 along with observed stages. Figure D - 6 compares the monthly estimated UFA stages with the May and September potentiometric surfaces of 1978 to 2017. The figure indicates that the potentiometric values scattered around the monthly estimated stages except for a few values during the period 2001 to 2008. Since the simulated lake stages match the observed stages of 2001 to 2008 and the estimated UFA stages follow the variation of observed lake stages (see Figure D - 7 and Figure D - 8), the potentiometric values might not be representative for this period. Therefore, the estimated UFA stages are believed to be reasonable.

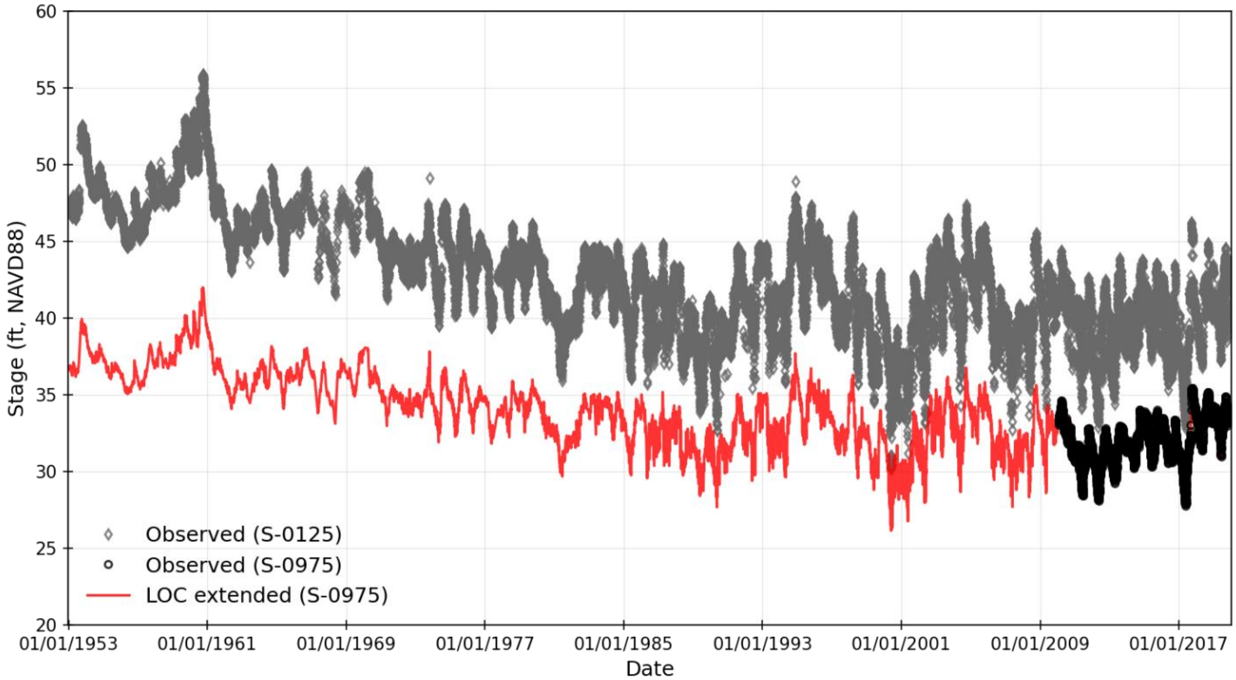


Figure D - 5. Daily observed and extended groundwater stages at S-0975 based on the Line of Organic Correlation (LOC)

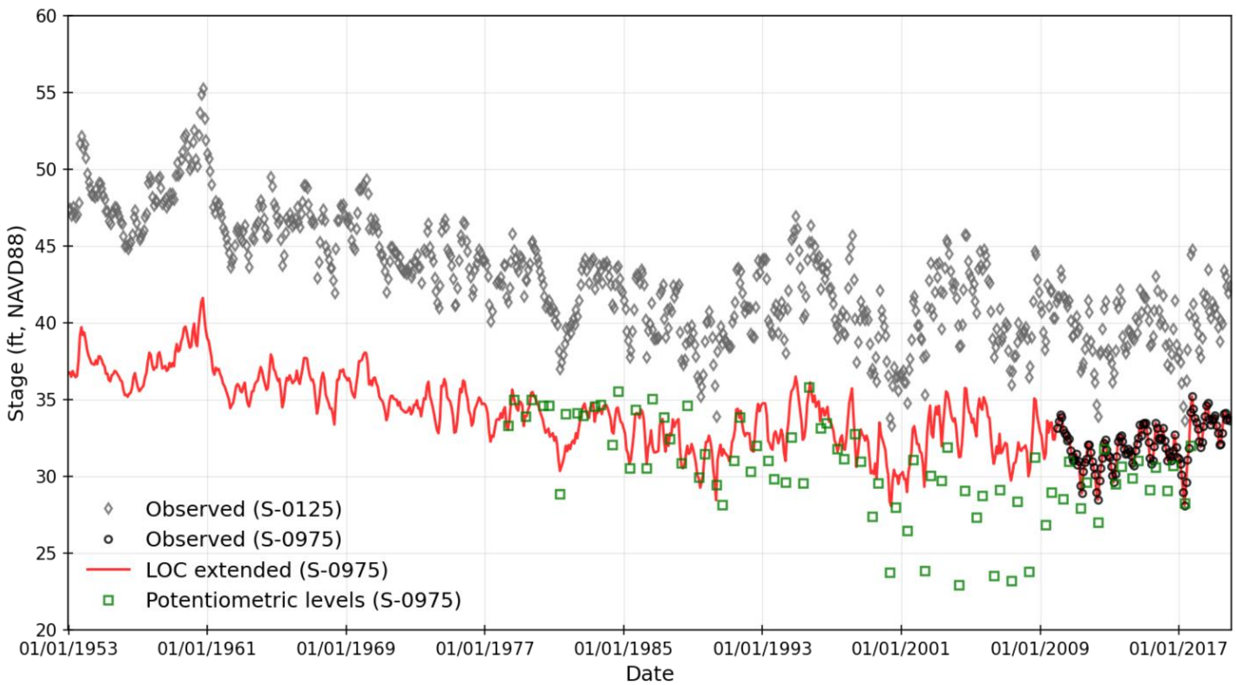


Figure D - 6. Monthly observed and extended groundwater stages along with potentiometric values at S-0975

# Long-term Simulation

## Results and Discussion

### Simulated Stages

We carried out a long-term simulation for the entire lake chain, but this report will only present graphical results for the two major lakes of the system (West and East Crystal Lakes), where MFLs evaluation is expected to be implemented. However, the long-term goodness-of-fit statistics are summarized in Table D - 1 for all lakes that have observed stages. We calculated the performance metric only for daily values due to the sporadic nature of observed stages. Such data may not be directly comparable when converted to monthly average values. In general, the calculated statistical values are reasonable for long-term simulations (Table D - 1).

Table D - 1. Daily goodness-of-fit statistics for the long-term period.

| Statistics | Description | West Crystal | East Crystal | BelAir | Amory | Deforest |
|---|---|---|---|---|---|---|
| NSE | Nash-Sutcliffe Efficiency | 0.83 | 0.76 | 0.63 | 0.48 | 0.64 |
| RMSE | Root Mean Squared Error | 1.20 | 0.97 | 1.26 | 0.96 | 0.72 |
| ME | Mean Error | 0.30 | 0.07 | 0.25 | -0.03 | 0.02 |
| ±1ft (%) | % of observations bracketed | 52.34 | 72.15 | 61.62 | 70.88 | 80.87 |

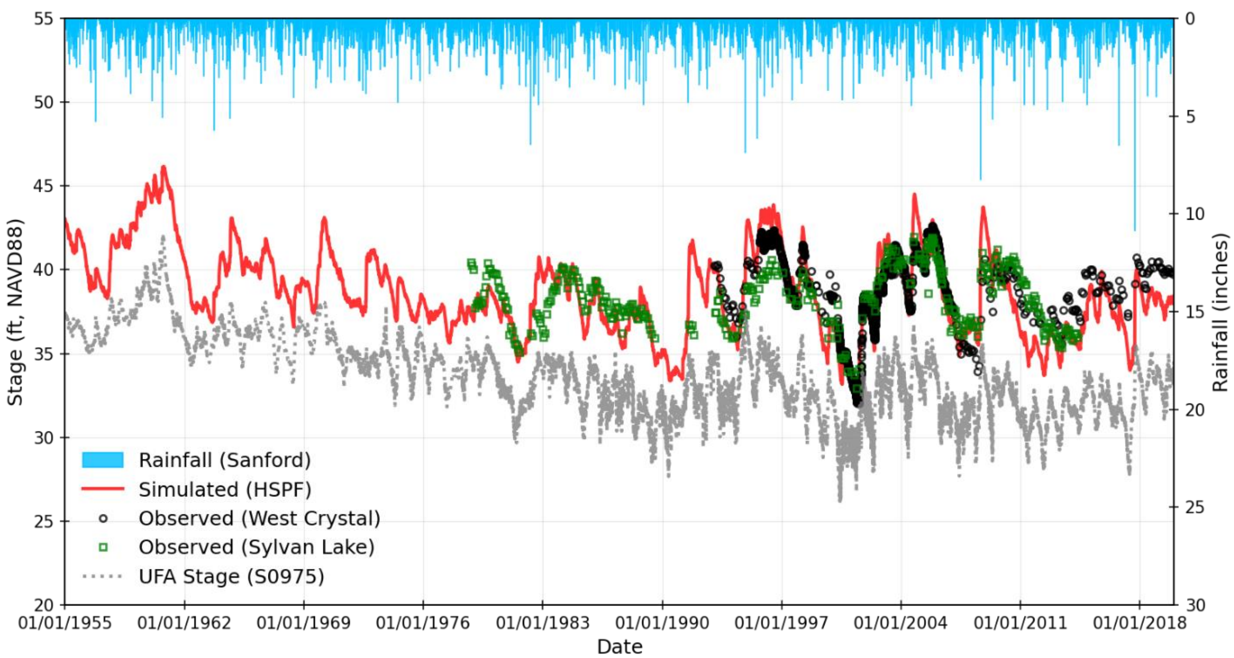


Figure D - 7. Daily long-term observed and simulated stages of West Crystal Lake

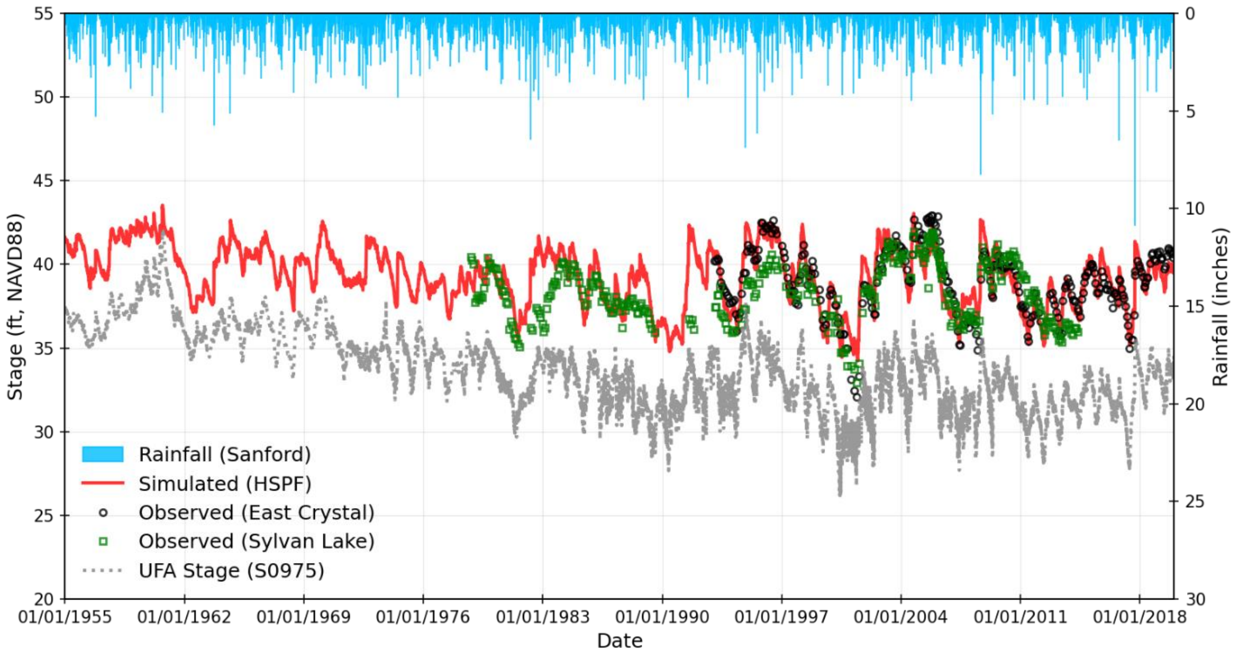


Figure D - 8. Daily long-term observed and simulated stages of East Crystal Lake

The simulated stages generally match the observed stages in terms of temporal variation for the period 1993 to 2019 (Figure D - 7 and Figure D - 8). However, due to the lack of observed data before 1993, we were not able to compare and evaluate the simulated stages before that time. For the period before 1993, we compared the simulated stages with the observed stages at a nearby lake. Sylvan Lake is the only nearby lake that had long-term daily stage records, which seems to track the East and West Crystal stages closely. Both Figure D - 7 and Figure D - 8 compare the simulated stages of West and East Crystal Lakes with observed data of Sylvan Lake, respectively. The model adequately tracked the observed stages of Sylvan Lake, indicating the long-term stages of East and West Crystal Lakes produced by the HSPF model are reasonable. This also highlighted the capability of the HSPF model in simulating stages outside the calibration (2007-2019) and validation (1995-2006) periods.

## Water Balance

We assessed the simulated water balance components, such as annual average actual evapotranspiration (AET), runoff, baseflow, and recharge to deep aquifer. The values are reported in Table D - 2 for each land use land cover (LULC) and the entire watershed. The simulated AET values of each LULC are close to the target values commonly used at SJRWMD. In addition, recharge values to the deep aquifer are reasonably simulated when compared to the values (5 to 10 inches per year) reported by Boniol and Mouyard (2016). AET accounts for more than 50% of the annual average rainfall. Overall, the simulated water balance components are reasonable.

Table D - 2. Annual average water balance summary (inches per year)

| Period | Description | LDR | MDR | HDR | CI | OPN | PAS | AGR | RNG/SHB | FRS | WTL | Watershed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1955-2019 | Rainfall | 51.9 | 51.9 | 51.9 | 51.9 | 51.9 | 51.9 | 51.9 | 51.9 | 51.9 | 51.9 | 51.9 |
| | Deep recharge | 5.8 | 6.0 | 5.7 | 6.0 | 10.0 | 6.5 | 6.3 | 6.2 | 4.7 | 6.5 | 5.2 |
| | AET | 34.7 | 32.3 | 27.4 | 23.7 | 26.5 | 36.9 | 38.7 | 37.4 | 40.8 | 42.7 | 33.8 |
| | Runoff | 11.6 | 14.5 | 20.8 | 25.2 | 15.4 | 8.5 | 6.9 | 8.2 | 6.3 | 2.7 | 13.0 |
| | Baseflow | 6.6 | 6.4 | 6.7 | 6.4 | 10.4 | 6.5 | 5.6 | 6.3 | 5.7 | 2.6 | 4.7 |

**Note:** LDR = low density residential; MDR = medium density residential; HDR = high density residential; CI = commercial-industrial; OPN = open land; PAS = pasture; RNG/SHB = rangeland/shrubland; FRS = forest; WTL = wetland; AET = Actual Evapotranspiration.

Table D - 3 summarizes the lake water budget components of the two major lakes for the long-term simulation period (1955-2019). The table clearly indicates that seepage to groundwater generally dominates the outflow components of the two lakes, followed by evaporation. This is reasonable as the lakes are in high recharge area (Boniol and Mouyard, 2016). The storage change is less than 1%, indicating the reasonable simulation of lake's water budget elements (Table D - 3).

Table D - 3. East & West Crystal Lakes average water budget (acres-feet per year). Percent represents to the total inflow

| Lake | Period | Direct Rainfall | Watershed Inflow | Evaporation | Seepage | Surface Outflow | Total Inflow | Total Outflow | Storage Change |
|---|---|---|---|---|---|---|---|---|---|
| West Crystal | 1955-2019 | 586.7 | 1722.8 | 578.6 | 590.8 | 1152.3 | 2309.5 | 2321.7 | -12.2 |
| | Percent | **25.4** | **74.6** | **25.1** | **25.6** | **49.9** | | | **-0.5** |
| East Crystal | 1955-2019 | 502.4 | 1084.0 | 486.9 | 565.0 | 537.9 | 1586.4 | 1589.8 | -3.4 |
| | Percent | **31.7** | **68.3** | **30.7** | **35.6** | **33.9** | | | **-0.2** |

# Summary and Conclusions

SJRWMD set up (1995-2019), calibrated (2007-2019), and validated (1995-2006) an HSPF model for the Crystal Chain of Lakes (CCL). SJRWMD then extended the hydro-meteorological data such as rainfall, potential evapotranspiration, and groundwater stages of the set up period back to 1953 using available time series data from the nearby stations. We subsequently extended the calibrated and validated model to the period 1953 to 2019 for long-term simulation and MFLs modeling. HSPF adequately represented the long-term daily observed stages of CCL with acceptable statistical evaluation values and performance ratings. The HSPF model also reasonably simulated the water budget elements of the lakes. Therefore, it is concluded that the model can be used for MFLs modeling and scenario analysis.

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# Appendix E – Sensitivity Analysis

# TECHNICAL MEMORANDUM

**DATE:** February, 2022

**SUBJECT:** Crystal Chain of Lakes HSPF Model Parameter Sensitivity Analysis

## Introduction

The Crystal Chain of Lakes (CCL) is located in Seminole County, Florida (Figure E - 1). The chain includes Lake Como, Dawson Lake, West Crystal Lake, East Crystal Lake, Bel-Air Lake, Amory Lake, and Deforest Lake (Figure E - 1). The St. Johns River Water Management District (SJRWMD) has been establishing Minimum Flows and Levels (MFLs) for the CCL, which is scheduled for completion in 2023. In support of the MFLs program of the CCL, the Hydrological Simulation Program – FORTRAN (HSPF) model (Bicknell et al., 1997) was used for hydrologic and hydraulic processes, surface water – groundwater interactions, and water budget elements modeling of the lakes. The model was calibrated and validated for the period from 1/1/2007 to 12/31/2019 and 1/1/1995 to 12/31/2006, respectively. The calibrated and validated model was subsequently extended to the period from 1/1/1953 to 12/31/2019 for long-term simulation. The calibration period of the extended model was used for parameter sensitivity analysis (SA). This technical memorandum focuses on the sensitivity analysis of the HSPF model for five selected parameters and presents the corresponding results.

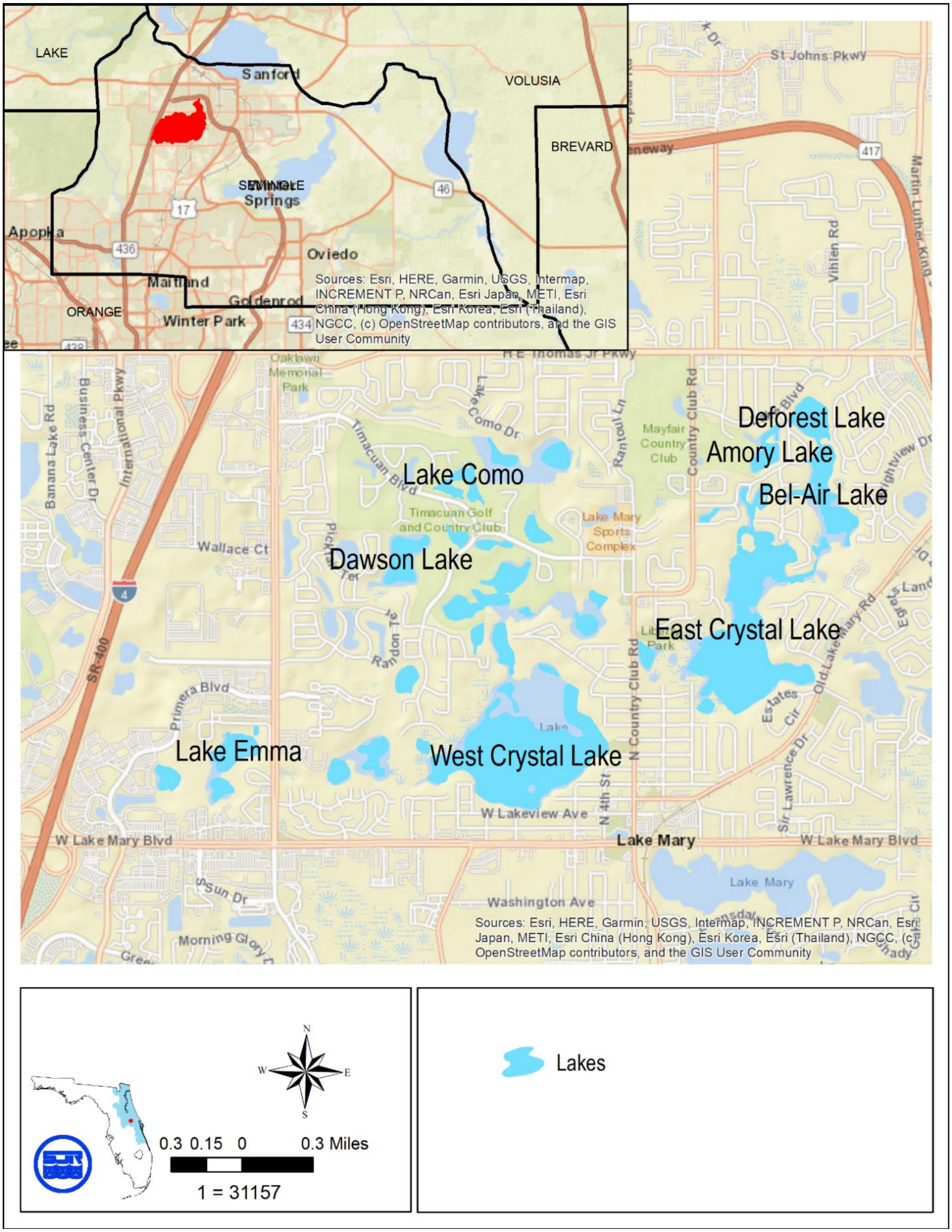


Figure E - 1. Location of Crystal Chain of Lakes (red polygon in the top left corner) in Seminole County

# Sensitivity analysis

The HSPF model parameter sensitivity analysis used a one-factor-at-a-time (OAT) method (Campolongo et al., 2010), which varies one parameter value at a time while keeping the other parameter values remain constant. Since the OAT method does not simultaneously vary all the model parameter values, it is more informative if there is minimal interaction among the parameters (Link et al., 2018; Saltelli et al., 2004). To identify the important/sensitive parameters of the HSPF model, we ran the model several times by changing one parameter value at a time and evaluated the influence of each parameter on model goodness-of-fit (GOF) statistics and simulated stages with respect to the calibration results. Table E - 1 summaries the change (perturbation) factors applied to the calibrated values of five selected parameters as outlined in the scope of work (SOW).

Table E - 1. Five selected parameters with applied change methods.

| Parameter | Description | Calibrated value | Change |
|---|---|---|---|
| DEEPFR | Fraction of groundwater inflow to deep aquifer | Varied with sub-watershed | Decreased by 10% or 20%<br>Increased by 10% or 20% |
| INFILT | Soil infiltration capacity index | Varied with LULC type | Decreased by 10% or 20%<br>Decreased by 10% or 20% |
| LZSN | Lower zone nominal storage | Varied with LULC type | Decreased by 10% or 20%<br>Increased by 10% or 20% |
| LZETP | Lower zone Evapotranspiration | Varied with LULC type | Decreased by 10% or 20%<br>Increased by 10% or 20% |
| k | Leakance | Varied with RCHRES | Divided by 2 or 3<br>Multiplied by 2 or 3 |

Note: LULC = land use-land cover; RCHRES = river reach or reservoir segment

As proposed in the SOW, we used three GOF statistics that include the Nash-Sutcliffe efficiency (NSE), Root Mean Squared Error (RMSE), and Percent Bias (PBIAS). We also used percent change in simulated stages with respect to the calibrated stages, including graphical method such as stage duration curves to assess the sensitivity of low, medium, and high simulated stages as compared to the calibrated stages.

# Results and Discussion

We performed SA for both East and West Crystal Lakes. However, due to similarity in SA results, including the better performance of the model for the East Crystal Lake calibration period, we only present results from the East Crystal Lake.

## Sensitivity of model performance statistics

The effect of increasing or decreasing the calibrated parameter values on the model performance metrics is summarized in Table E - 2. The table indicates that increasing or decreasing the calibrated soil infiltration capacity index (INFILT) and lower zone nominal storage (LZSN) values by 10-20% have minimal effect on model performance metrics. Changing the lower zone evapotranspiration parameter (LZETP) and fraction of groundwater inflow to deep aquifer (DEEPFR) values by 10-20%

is expected to have medium effect on model performance metrics. However, increasing or decreasing the calibrated leakance values shows the highest impact on NSE, RMSE, and PBIAS. For example, increasing the calibrated leakance value by a factor of 2 and 3 significantly lowers the NSE values from 0.73 to -2.22 and -4.09, respectively (Table E - 2). In general, leakance is the only parameter that has showed significant effect on the HSPF model performance metrics and thus identified as the most important parameter for the study area. Overall, when compared to the calibration period GOF statistics, none of the perturbed values of the five selected parameters improved the model performance metrics except the increased values of the DEEPFR, INFILT, LZSN, and LZETP parameters. However, the increased values of these parameters showed insignificant improvements on the RMSE and PBIAS values (Table E - 2).

Table E - 2. Sensitivity of goodness-of-fit statistics compared to calibrated values. Bold indicates ≥ |±1| change

| Parameter | Calibrated value | Calibration statistics | | | Sensitivity statistics | | | Absolute change | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | NSE | RMSE | PBIAS | NSE | RMSE | PBIAS | NSE | RMSE | PBIAS |
| DEEPFR | Decreased by 10% | 0.73 | 0.82 | 0.45 | 0.71 | 0.85 | 0.75 | -0.02 | 0.03 | 0.30 |
| | Decreased by 20% | | | | 0.68 | 0.89 | 1.04 | -0.05 | 0.07 | 0.58 |
| | Increased by 10% | | | | 0.73 | 0.81 | 0.15 | 0.01 | -0.01 | -0.30 |
| | Increased by 20% | | | | 0.73 | 0.82 | -0.15 | 0.00 | 0.00 | -0.60 |
| INFILT | Decreased by 10% | 0.73 | 0.82 | 0.45 | 0.72 | 0.83 | 0.50 | -0.01 | 0.01 | 0.05 |
| | Decreased by 20% | | | | 0.71 | 0.84 | 0.56 | -0.02 | 0.02 | 0.11 |
| | Increased by 10% | | | | 0.73 | 0.81 | 0.41 | 0.01 | -0.01 | -0.04 |
| | Increased by 20% | | | | 0.74 | 0.80 | 0.38 | 0.01 | -0.02 | -0.07 |
| LZSN | Decreased by 10% | 0.73 | 0.82 | 0.45 | 0.72 | 0.83 | 0.53 | 0.00 | 0.01 | 0.07 |
| | Decreased by 20% | | | | 0.72 | 0.83 | 0.61 | -0.01 | 0.02 | 0.16 |
| | Increased by 10% | | | | 0.73 | 0.81 | 0.39 | 0.00 | -0.01 | -0.06 |
| | Increased by 20% | | | | 0.73 | 0.81 | 0.33 | 0.01 | -0.01 | -0.12 |
| LZETP | Decreased by 10% | 0.73 | 0.82 | 0.45 | 0.70 | 0.86 | 0.82 | -0.03 | 0.04 | 0.37 |
| | Decreased by 20% | | | | 0.66 | 0.91 | 1.18 | -0.07 | 0.09 | 0.72 |
| | Increased by 10% | | | | 0.73 | 0.81 | 0.30 | 0.01 | -0.01 | -0.15 |
| | Increased by 20% | | | | 0.73 | 0.81 | 0.14 | 0.01 | -0.01 | -0.32 |
| k | Divided by 2 | 0.73 | 0.82 | 0.45 | -1.50 | 2.47 | 6.08 | **-2.22** | **1.65** | **5.63** |
| | Divided by 3 | | | | -3.36 | 3.27 | 7.97 | **-4.09** | **2.45** | **7.51** |
| | Multiplied by 2 | | | | -0.78 | 2.09 | -4.65 | **-1.50** | **1.27** | **-5.11** |
| | Multiplied by 3 | | | | -2.44 | 2.90 | -6.93 | **-3.17** | **2.09** | **-7.38** |

## Sensitivity of simulated stages

Table E - 3 presents the effect of changing calibrated parameter values on simulated minimum, mean, and maximum stages. Compared to the calibrated stages, the percent change on minimum, maximum and mean stages are small (< 1%) except for the leakance values. As expected, leakance value shows the highest effect on the simulated minimum stages. For example, reducing the calibrated leakance value by a factor of 3 is expected to increase the simulated minimum stage by approximately 12% (Table E - 3). This is reasonable, as the CCL is in the high recharge area to the Upper Floridan Aquifer (UFA) (Boniol and Mouyard, 2016) and such process largely dominates during the dry period.

Table E - 3. Sensitivity of minimum, maximum, and mean simulated stages. Bold indicates ≥ |±1%| change

| Parameter | Calibrated value | Calibration | | | Sensitivity | | | Percent change | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Min** | **Max** | **Mean** | **Min** | **Max** | **Mean** | **Min** | **Max** | **Mean** |
| INFILT | Decreased by 10% | 35.12 | 42.68 | 38.53 | 35.13 | 42.71 | 38.55 | -0.02 | 0.11 | 0.05 |
| | Decreased by 20% | | | | 35.14 | 42.75 | 38.57 | -0.05 | 0.23 | 0.11 |
| | Increased by 10% | | | | 35.12 | 42.64 | 38.51 | -0.10 | 0.03 | -0.04 |
| | Increased by 20% | | | | 35.11 | 42.61 | 38.50 | -0.17 | 0.04 | -0.07 |
| LZSN | Decreased by 10% | 35.12 | 42.68 | 38.53 | 35.15 | 42.70 | 38.56 | 0.01 | 0.49 | 0.37 |
| | Decreased by 20% | | | | 35.18 | 42.73 | 38.59 | 0.02 | 0.98 | 0.73 |
| | Increased by 10% | | | | 35.10 | 42.65 | 38.50 | -0.21 | 0.00 | -0.15 |
| | Increased by 20% | | | | 35.09 | 42.63 | 38.48 | -0.43 | -0.01 | -0.31 |
| LZETP | Decreased by 10% | 35.12 | 42.68 | 38.53 | 35.26 | 42.74 | 38.67 | -0.01 | 0.13 | 0.07 |
| | Decreased by 20% | | | | 35.40 | 42.79 | 38.81 | -0.01 | 0.26 | 0.16 |
| | Increased by 10% | | | | 35.07 | 42.65 | 38.47 | -0.11 | 0.01 | -0.06 |
| | Increased by 20% | | | | 35.02 | 42.63 | 38.41 | -0.21 | 0.01 | -0.12 |
| DEEPFR | Decreased by 10% | 35.12 | 42.68 | 38.53 | 35.21 | 42.72 | 38.64 | 0.03 | 0.39 | 0.29 |
| | Decreased by 20% | | | | 35.30 | 42.77 | 38.75 | 0.06 | 0.74 | 0.58 |
| | Increased by 10% | | | | 35.04 | 42.63 | 38.41 | -0.39 | -0.03 | -0.30 |
| | Increased by 20% | | | | 34.95 | 42.57 | 38.30 | -0.75 | -0.07 | -0.60 |
| k | Divided by 2 | 35.12 | 42.68 | 38.53 | 37.88 | 43.67 | 40.71 | 0.73 | **8.12** | **5.73** |
| | Divided by 3 | | | | 39.21 | 45.73 | 41.48 | **1.72** | **11.84** | **7.76** |
| | Multiplied by 2 | | | | 32.59 | 42.07 | 36.58 | **-7.26** | **-1.20** | **-5.06** |
| | Multiplied by 3 | | | | 31.39 | 41.71 | 35.71 | **-10.66** | **-2.14** | **-7.32** |

Increasing or decreasing the calibrated INFILT and LZSN values barely changes the stage duration curves of the East Crystal Lake as respectively shown in Figure E - 2 and Figure E - 3. In addition, perturbing the calibrated LZETP and DEEPFR values by 10 or 20% also shows the second minimal effect on simulated stage duration curves of the lake (Figure E - 4 and Figure E - 5), with a maximum change of about 1%. Nevertheless, decreasing and increasing leakance is expected to significantly shift the simulated stage duration curves upward and downward, respectively (Figure E - 6).

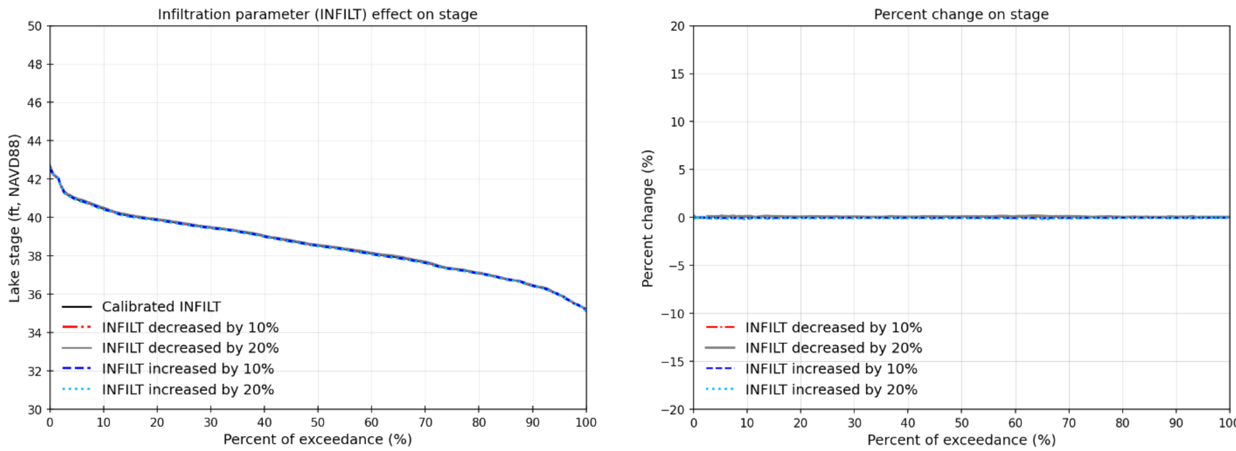


Figure E - 2. Stage duration curves sensitivity to changed infiltration capacity of the soil

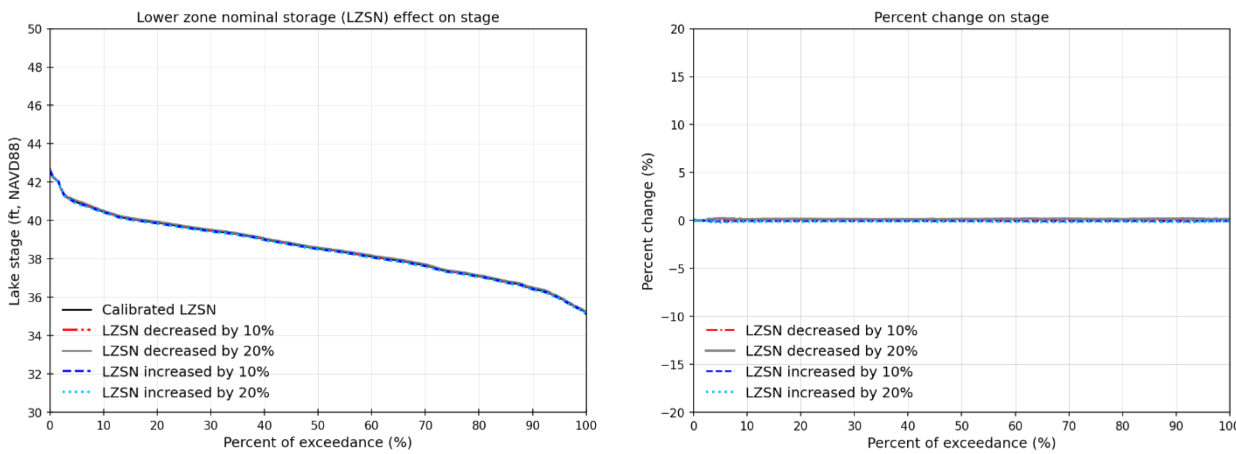


Figure E - 3. Stage duration curves sensitivity to changed lower zone nominal storage

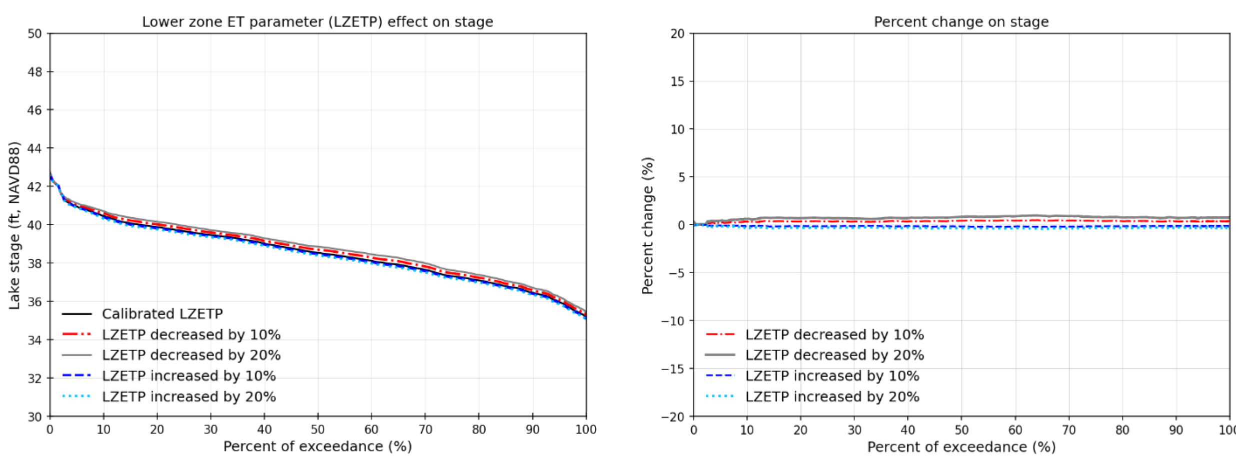


Figure E - 4. Stage duration curves sensitivity to changed lower zone evapotranspiration parameter

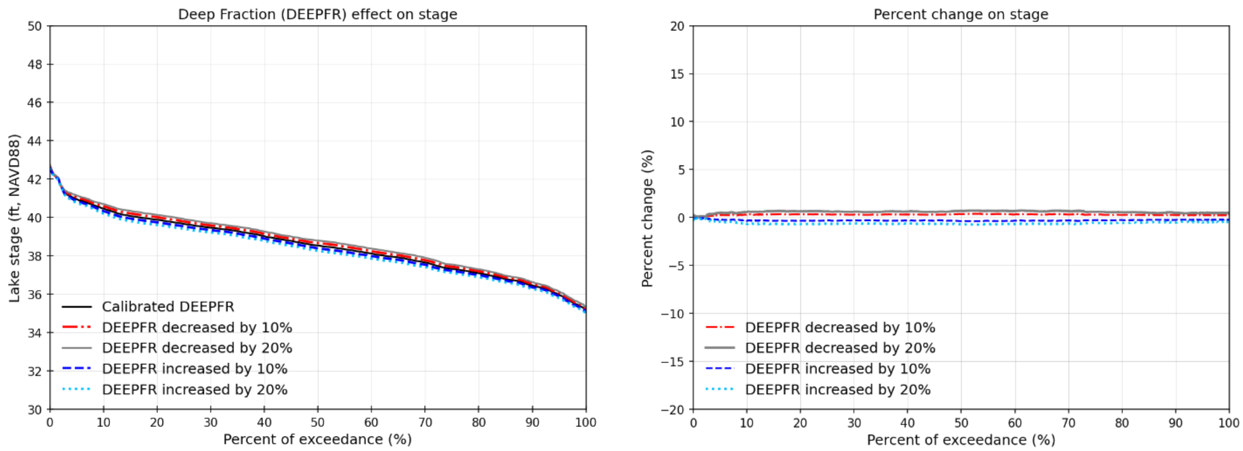


Figure E - 5. Stage duration curves sensitivity to changed fraction of groundwater inflow to deep aquifer

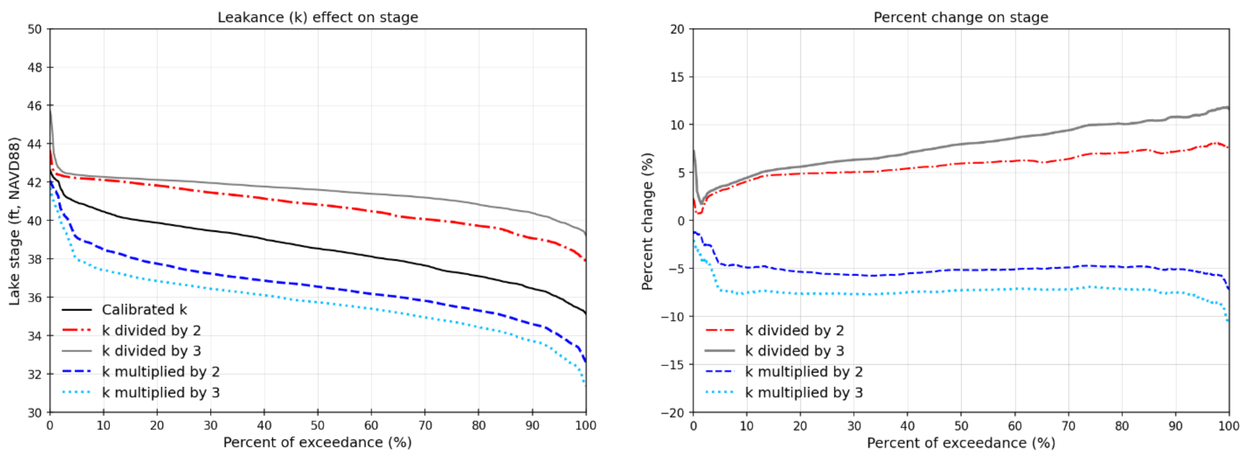


Figure E - 6. Stage duration curves sensitivity to changed leakance values

In general, the simulated stages of East Crystal Lake are highly sensitive to leakance value, followed by fraction of groundwater inflow to deep aquifer and lower zone evapotranspiration parameter (Table E - 3). This indicates that if the leakance values are not well identified during the calibration process, they may drive most of the uncertainty on the simulated stages of the lake. SJRWMD also reached similar conclusions for the West Crystal Lake. Overall, SA results generally indicate that the surface runoff related parameters are insensitive as compared to sub-surface processes related parameters, which is also consistent with the calibration results. This highlights that the hydrologic processes of the lake are dominated by rainfall, evapotranspiration, and leakage components.

# Summary and Conclusions

Using the calibrated HSPF model of the Crystal Chain of Lakes (CCL), we performed one-factor-at-a-time (OAT) sensitivity analysis for soil infiltration capacity index (INFILT), lower zone nominal storage (LZSN), lower zone evapotranspiration parameter (LZETP), fraction of groundwater inflow to deep aquifer (DEEPFR), and leakance (k) parameters. While we increased or decreased the calibrated INFILT, LZSN, LZETP, and DEEPFR values by 10 and 20%, we divided or multiplied the calibrated k values by 2 and 3. Then, we assessed and compared the sensitivity of the parameters on the simulated stages and model performance metrics with respect to the calibrated stages and model performance metrics.

INFILT and LZSN are identified as the least sensitive parameters to simulated stages and model performance evaluation metrics followed by LZETP and DEEPFR. Consequently, their effect on the simulated stage is minimal. On the other hand, we found that the simulated stages and model performance metrics are highly sensitive to the k value. This signifies that the latter parameter is highly important for simulating the hydrologic system of the lake. While increasing the values of DEEPFR, INFILT, LZSN, and LZETP by 10 and 20% insignificantly improved the RMSE and PBIAS values, none of the remaining perturbed parameter values improved the simulated stages and model performance metrics when compared to the calibrated stages and model performance evaluation metrics. Overall, evapotranspiration and leakage related parameters are the most important/sensitive parameters for the CCL.

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