Revised Minimum and Guidance Levels Based on Reevaluation of Levels Adopted for Crooked Lake in Polk County, Florida

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Resource Evaluation Section
Water Resources Bureau
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Cover: Photograph of Crooked Lake, 2016 (Southwest Florida Water Management District files).

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Introduction

Reevaluation of Minimum Flows and Levels

This report describes the development of revised minimum levels for Crooked Lake in Polk County, Florida. These revised levels were developed based on the reevaluation of minimum and guidance levels approved by the Southwest Florida Water Management District (District) Governing Board in December 2007 and subsequently adopted into District rules. The revised minimum and guidance levels represent necessary revisions to the previously adopted levels.

Crooked Lake was selected for reevaluation based on development of modeling tools used to simulate natural water level fluctuations in lake basins that were not available when the previously adopted minimum levels for the lake were developed. Adopted levels for Crooked Lake were also reevaluated to support ongoing District assessment of minimum flows and levels and the need for additional recovery in the Southern Water Use Caution Area (SWUCA), a region of the District where recovery strategies are being implemented to support recovery to minimum flow and level thresholds.

Following Board approval on October 25, 2016, the revised levels became effective on March 2, 2017.

Minimum Flows and Levels Program Overview

Legal Directives
Section 373.042, Florida Statutes (F.S.), directs the Department of Environmental Protection or the water management districts to establish minimum flows and levels (MFLs) for lakes, wetlands, rivers and aquifers. Section 373.042(1)(a), F.S., states that “[t]he minimum flow for a given watercourse shall be the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area." Section 373.042(1)(b), F.S., defines the minimum water level of an aquifer or surface water body as "…the level of groundwater in an aquifer and the level of surface water at which further withdrawals would be significantly harmful to the water resources of the area." MFLs are established and used by the Southwest Florida Water Management District (SWFWMD or District) for water resource planning, as one of the criteria used for evaluating water use permit applications, and for the design, construction and use of surface water management systems.

Established MFLs are key components of resource protection, recovery and regulatory compliance, as Section 373.0421(2) F.S., requires the development of a recovery or prevention strategy for water bodies “[i]f the existing flow or level in a water body is below, or is projected to fall within 20 years below, the applicable minimum flow or level established pursuant to S. 373.042.” Section 373.0421(2)(a), F.S., requires that recovery or prevention strategies be developed to: "(a) [a]chieve recovery to the established minimum flow or level as soon as practicable; or (b) [p]revent the existing flow or level from falling below the established minimum flow or level." Periodic reevaluation and, as necessary, revision of established minimum flows and levels are required by Section 373.0421(3), F.S.

Minimum flows and levels are to be established based upon the best information available, and when appropriate, may be calculated to reflect seasonal variations (Section 373.042(1), F.S.). Also, establishment of MFLs is to involve consideration of, and at the governing board or department’s discretion, may provide for the protection of nonconsumptive uses (Section 373.042(1), F.S.). Consideration must also be given to "…changes and structural alterations to watersheds, surface waters and aquifers, and the effects such changes or alterations have had, and the constraints such changes or alterations have placed, on the hydrology of the affected watershed, surface water, or aquifer…", with the requirement that these considerations shall not allow significant harm caused by withdrawals (Section 373.0421(1)(a), F.S.). Sections 373.042 and 373.0421 provide additional information regarding the prioritization and scheduling of minimum flows and levels, the independent scientific review of scientific or technical data, methodologies, models and scientific and technical assumptions employed in each model used to establish a minimum flow or level, and exclusions that may be considered when identifying the need for MFLs establishment.

The Florida Water Resource Implementation Rule, specifically Rule 62-40.473, Florida Administrative Code (F.A.C.), provides additional guidance for the establishment of MFLs, requiring that "…consideration shall be given to natural seasonal fluctuations in water flows or levels, nonconsumptive uses, and environmental values associated with coastal, estuarine, riverine, spring, aquatic and wetlands ecology, including: a) Recreation in and on the water; b) Fish and wildlife habitats and the passage of fish; c) estuarine resources; d) Transfer of detrital material; e) Maintenance of freshwater storage and supply; f) Aesthetic and scenic attributes; g) Filtration and absorption of nutrients and other pollutants; h) Sediment loads; i) Water quality; and j) Navigation."

Rule 62-40.473, F.A.C., also indicates that "[m]inimum flows and levels should be expressed as multiple flows or levels defining a minimum hydrologic regime, to the extent practical and necessary to establish the limit beyond which further withdrawals would be significantly harmful to the water resources or the ecology of the area as provided in Section 373.042(1), F.S." It further notes that, “…a minimum flow or level need not be expressed as multiple flows or levels if other resource protection tools, such as reservations implemented to protect fish and wildlife or public health and safety, that provide equivalent or greater protection of the hydrologic regime of the water body, are developed and adopted in coordination with the minimum flow or level.” The rule also includes provision addressing: protection of MFLs during the construction and operation of water resource projects; the issuance of permits pursuant to Section 373.086 and Parts II and IV of Chapter 373, F.S.; water shortage declarations; development of recovery or prevention strategies, development and updates to a minimum flow and level priority list and schedule, and peer review for MFLs establishment.

Development of Minimum Lake Levels in the Southwest Florida Water Management District

Programmatic Description and Major Assumptions

Since the enactment of the Florida Water Resources Act of 1972 (Chapter 373, F.S.), in which the legislative directive to establish MFLs originated, and following subsequent modifications to this directive and adoption of relevant requirements in the Water Resource Implementation Rule, the District has actively pursued the adoption, i.e., establishment of MFLs for priority water bodies. The District implements established MFLs primarily through its water supply planning, water use permitting and environmental resource permitting programs, and through the funding of water resource and water supply development projects that are part of a recovery or prevention strategy. The District's MFLs program addresses all relevant requirements expressed in the Florida Water Resources Act and the Water Resource Implementation Rule.

A substantial portion of the District's organizational resources has been dedicated to its MFLs Program, which logistically addresses six major tasks: 1) development and reassessment of methods for establishing MFLs; 2) adoption of MFLs for priority water bodies (including the prioritization of water bodies and facilitation of public and independent scientific review of proposed MFLs and methods used for their development); 3) monitoring and MFLs status assessments, i.e., compliance evaluations; 4) development and implementation of recovery strategies; 5) MFLs compliance reporting; and 6) ongoing support for minimum flow and level regulatory concerns and prevention strategies. Many of these tasks are discussed or addressed in this minimum levels report; additional information on all tasks associated with the District's MFLs Program is summarized by Hancock *et al.* (2010).

The District's MFLs Program is implemented based on three fundamental assumptions. First, it is assumed that many water resource values and associated features are dependent upon and affected by long-term hydrology and/or changes in long-term hydrology. Second, it is assumed that relationships between some of these variables can be quantified and used to develop significant harm thresholds or criteria that are useful for establishing MFLs. Third, the approach assumes that alternative hydrologic regimes may exist that differ from non-withdrawal impacted conditions but are sufficient to protect water resources and the ecology of these resources from significant harm.

Support for these assumptions is provided by a large body of published scientific work addressing relationships between hydrology, ecology and human-use values associated with water resources (e.g., see reviews and syntheses by Postel and Richter 2003, Wantzen *et al.* 2008, Poff *et al.* 2010, Poff and Zimmerman 2010). This information has been used by the District and other water management districts within the state to identify significant harm thresholds or criteria supporting development of MFLs for hundreds of water bodies, as summarized in the numerous publications associated with these efforts (e.g., SFWMD 2000, 2006, Flannery *et al*. 2002, SRWMD 2004, 2005, Neubauer *et al.* 2008, Mace 2009).

With regard to the assumption associated with alternative hydrologic regimes, consider a historic condition for an unaltered river or lake system with no local groundwater or surface water withdrawal impacts. A new hydrologic regime for the system would be associated with each increase in water use, from small withdrawals that have no measurable effect on the historic regime to large withdrawals that could substantially alter the regime. A threshold hydrologic regime may exist that is lower or less than the historic regime, but which protects the water resources and ecology of the system from significant harm. This threshold regime could conceptually allow for water withdrawals, while protecting the water resources and ecology of the area. Thus, MFLs may represent minimum acceptable rather than historic or potentially optimal hydrologic conditions.

Consideration of Changes and Structural Alterations and Environmental Values

When establishing MFLs, the District considers "…changes and structural alterations to watersheds, surface waters and aquifers, and the effects such changes or alterations have had, and the constraints such changes or alterations have placed, on the hydrology of the affected watershed, surface water, or aquifer…" in accordance with Section 373.0421(1)(a), F.S. Also, as required by statute, the District does not establish MFLs that would allow significant harm caused by withdrawals when considering the changes, alterations and their associated effects and constraints. These considerations are based on review and analysis of best available information, such as water level records, environmental and construction permit information, water control structure and drainage alteration histories, and observation of current site conditions.

When establishing, reviewing or implementing MFLs, considerations of changes and structural alterations may be used to:

- adjust measured flow or water level historical records to account for existing changes/alterations;
- model or simulate flow or water level records that reflect long-term conditions that would be expected based on existing changes/alterations and in the absence of measurable withdrawal impacts;
- develop or identify significant harm standards, thresholds and other criteria;
- aid in the characterization or classification of lake types or classes based on the changes/alterations;
- evaluate the status of water bodies with proposed or established MFLs (i.e., determine whether the flow and/or water level are below, or are projected to fall below the applicable minimum flow or level); and
- support development of lake guidance levels (described in the following paragraph).

The District has developed specific methodologies for establishing minimum flows or levels for lakes, wetlands, rivers, estuaries and aquifers, subjected the methodologies to independent, scientific peer-review, and incorporated the methods for some system types, including lakes, into its Water Level and Rates of Flow Rule (Chapter 40D-8, F.A.C.). The rule also provides for the establishment of Guidance Levels for lakes, which serve as advisory information for the District, lakeshore residents and local governments, or to aid in the management or control of adjustable water level structures.

Information regarding the development of adopted methods for establishing minimum and guidance lake levels is included in Southwest Florida Water Management District (1999a, b) and Leeper *et al.* (2001). Additional information relevant to developing lake levels is presented by Schultz et al. (2004), Carr and Rochow (2004), Caffrey *et al.* (2006, 2007), Carr *et al.* (2006), Hoyer *et al*. (2006), Leeper (2006), Hancock (2006, 2007) and Emery *et al.* (2009). Independent scientific peer-review findings regarding the lake level methods are summarized by Bedient *et al.* (1999), Dierberg and Wagner (2001) and Wagner and Dierberg (2006).

For lakes, methods have been developed for establishing Minimum Levels for systems with fringing cypress-dominated wetlands greater than 0.5 acre in size, and for those without fringing cypress wetlands. Lakes with fringing cypress wetlands where water levels currently rise to an elevation expected to fully maintain the integrity of the wetlands are classified as Category 1 Lakes. Lakes with fringing cypress wetlands that have been structurally altered such that lake water levels do not rise to levels expected to fully maintain the integrity of the wetlands are classified as Category 2 Lakes. Lakes with less than 0.5 acre of fringing cypress wetlands are classified as Category 3 Lakes.

Categorical significant change standards and other available information are developed to identify criteria that are sensitive to long-term changes in hydrology and can be used for establishing minimum levels. For all lake categories, the most sensitive, appropriate criterion or criteria are used to develop minimum levels. For Category 1 or 2 Lakes, a significant change standard, referred to as the Cypress Standard, is developed. The Cypress Standard is 1.8 feet below the normal pool elevation. For Category 3 lakes, six significant change standards are typically developed. Other available information, including potential changes in the coverage of herbaceous wetland and submersed aquatic plants is also considered when establishing minimum levels for Category 3 Lakes. The standards and other available information are associated with the environmental values identified for consideration in Rule 62-40.473, F.A.C., when establishing MFLs (Table 1). The specific standards and other information evaluated to support development of revised minimum levels for Crooked Lake are provided in subsequent sections of this report. More general information on the standards and other information used for consideration when developing minimum lake levels is available in the documents identified in the preceding sub-section of this report.

Table 1. Environmental values identified in the state Water Resource Implementation Rule for consideration when establishing minimum flows and levels and associated significant change standards and other information used by the District for consideration of the environmental values.

Environmental Value	Associated Significant Change Standards and Other Information for Consideration
Recreation in and on the water	Basin Connectivity Standard, Recreation/Ski Standard, Aesthetics Standard, Species Richness Standard, Dock-Use Standard, Herbaceous Wetland Information, Submersed Aquatic Macrophyte Information
Fish and wildlife habitats and the passage of fish	Cypress Standard, Wetland Offset, Basin Connectivity Standard, Species Richness Standard, Herbaceous Wetland Information, Submersed Aquatic Macrophyte Information
Estuarine resources	NA[1]
Transfer of detrital material	Cypress Standard, Wetland Offset, Basin Connectivity Standard, Lake Mixing Standard, Herbaceous Wetland Information, Submersed Aquatic Macrophyte Information
Maintenance of freshwater storage and supply	NA[2]
Aesthetic and scenic attributes	Cypress Standard, Dock-Use Standard, Wetland Offset, Aesthetics Standard, Species Richness Standard, Herbaceous Wetland Information, Submersed Aquatic Macrophyte Information
Filtration and absorption of nutrients and other pollutants	Cypress Standard Wetland Offset Lake Mixing Standard Herbaceous Wetland Information Submersed Aquatic Macrophyte Information
Sediment loads	NA[1]
Water quality	Cypress Standard, Wetland Offset, Lake Mixing Standard, Dock-Use Standard, Herbaceous Wetland Information, Submersed Aquatic Macrophyte Information
Navigation	Basin Connectivity Standard, Submersed Aquatic Macrophyte Information

NA[1] = Not applicable for consideration for most priority lakes;
NA[2] = Environmental value is addressed generally by development of minimum levels based on appropriate significant change standards and other information and use of minimum levels in District permitting programs

Lake Classification

Lakes are classified as Category 1, 2, or 3 for the purpose of Minimum Levels development. Those with fringing cypress wetlands greater than 0.5 acre in size where water levels currently rise to an elevation expected to fully maintain the integrity of the wetlands (i.e. the Historic P50 (HP50), or the 50th percentile of historic data, is equal to or higher than an elevation 1.8 feet below the Normal Pool elevation) are classified as Category 1 Lakes. Lakes with fringing cypress wetlands greater than 0.5 acre in size that have been structurally altered such that the Historic P50 elevation is more than 1.8 feet below the Normal Pool elevation are classified as Category 2 Lakes. Lakes without fringing cypress wetlands or with cypress wetlands less than 0.5 acre in size are classified as Category 3 Lakes.

According to Rule 40D-8.624, F.A.C., Crooked Lake meets the classification as a Category 3 lake, with less than 0.5 acre of fringing cypress wetlands. The standards associated with Category 3 lakes described below will also be developed in a subsequent section of this report.

Lake-specific significant change standards and other available information are developed for establishing Minimum Levels for Category 3 Lakes. The standards are used to identify thresholds for preventing significant harm to cultural and natural system values associated with lakes in accordance with guidance provided in the Florida Water Resource Implementation Rule (62-40.473, F.A.C.). Other information taken into consideration includes potential changes in the coverage of herbaceous wetland vegetation and aquatic plants.

The <u>Recreation/Ski Standard</u> is developed to identify the lowest elevation within the lake basin that will contain an area suitable for safe water skiing. The standard is based on the lowest elevation (the Ski Elevation) within the basin that can contain a 5-foot deep ski corridor delineated as a circular area with a radius of 418 feet, or a rectangular ski corridor 200 feet in width and 2,000 feet in length, and use of Historic lake stage data or region-specific reference lake water regime statistics where Historic lake data are not available.

The <u>Dock-Use Standard</u> is developed to provide for sufficient water depth at the end of existing docks to permit mooring of boats and prevent adverse impacts to bottom-dwelling plants and animals caused by boat operation. The standard is based on the elevation of lake sediments at the end of existing docks, a two-foot water depth for boat mooring, and use of Historic lake stage data or region-specific reference lake water regime statistics.

The <u>Wetland Offset Elevation</u> is developed to protect lake fringing non-cypress wetlands. Based on the rationale used to develop the Cypress Wetland Standard for Category 1 and 2 lakes (1.8 feet below the Normal Pool elevation), a Wetland Offset Elevation for Category 3 Lakes was developed. Because Hydrologic Indicators of sustained inundation used to determine the Normal Pool elevation usually do not exist on Category 3 Lakes, another datum, in this case the Historic P50 elevation, was used in the development of the Wetland Offset Elevation. Based on an evaluation of the relationship of the Cypress Wetland Standard with the Historic P50 for hydrologically unimpacted cypress wetlands, the Wetland Offset Elevation for Category 3 Lakes was established at an elevation 0.8 feet below the Historic P50 elevation (Hancock, draft report, 2007).

The <u>Aesthetics Standard</u> is developed to protect aesthetic values associated with the inundation of lake basins. The standard is intended to protect aesthetic values associated with the median lake stage from diminishing beyond the values associated with the lake when it is staged at the Low Guidance Level. The Aesthetic Standard is established at the Low Guidance Level. Water levels equal or exceed the standard ninety percent of the time during the Historic period, based on the Historic, composite water level record.

The <u>Species Richness Standard</u> is developed to prevent a decline in the number of bird species that may be expected to occur at or utilize a lake. Based on an empirical relationship between lake surface area and the number of birds expected to occur at a lake, the standard is established at the lowest elevation associated with less than a fifteen percent reduction in lake surface area relative to the lake area at the Historic P50 elevation.

The <u>Basin Connectivity Standard</u> is developed to protect surface water connections between lake basins or among sub-basins within lake basins to allow for movement of aquatic biota, such as fish, and support recreational use of the lake. The standard is based on the elevation of lake sediments at a critical high spot between lake basins or lake sub-basins, identification of water depths sufficient for movement of biota and/or watercraft across the critical high spot, and use of Historic lake stage data or the region-specific Reference Lake Water Regime statistics where Historic lake data are not available.

The <u>Lake Mixing Standard</u> is developed to prevent significant changes in patterns of wind-driven mixing of the lake water column and sediment re-suspension. The standard is established at the highest elevation at or below the Historic P50 elevation where the dynamic ratio (see Bachmann *et al.* 2000) shifts from a value of <0.8 to a value >0.8, or from a value >0.8 to a value of <0.8.

Herbaceous Wetland Information is also taken into consideration to determine the elevation at which changes in lake stage would result in substantial changes in potential wetland area within the lake basin (i.e., basin area with a water depth of four feet or less) (Butts *et al*. 1997). Similarly, changes in lake stage associated with changes in lake area available for colonization by rooted submersed or floating-leaved macrophytes are also evaluated, based on water transparency values. Using methods described in Caffrey (2006), mean secchi disk depth (SD) is used to calculate the maximum depth of colonization (MDC) for aquatic plants using the regression equation log(MDC) – 0.66log(SD) + 0.30, where all values are represented in meters. The MDC depth is then used to calculate the total acreage at each lake stage that is available for aquatic plant colonization.

Minimum Levels

Two Minimum Levels and two Guidance Levels are typically established for lakes. Upon completion of a public input/review process and, if necessary completion of an independent scientific review, either of which may result in modification of the proposed levels, the levels are adopted by the District Governing Board into Chapter 40D-8, F.A.C. (see Hancock *et al.* 2010 for more information on the adoption process). The levels, which are expressed as elevations in feet above the National Geodetic Vertical Datum of 1929 (NGVD29), may include the following (refer to Rule 40D-8.624, F.A.C.).

- A **High Guidance Level** that is provided as an advisory guideline for construction of lake shore development, water dependent structures, and operation of water management structures. The High Guidance Level is the elevation that a lake's water levels are expected to equal or exceed ten percent of the time on a long-term basis.

- A **High Minimum Lake Level** is the elevation that a lake's water levels are required to equal or exceed ten percent of the time on a long-term basis.

- A **Minimum Lake Level** that is the elevation that the lake's water levels are required to equal or exceed fifty percent of the time on a long-term basis.

- A **Low Guidance Level** that is provided as an advisory guideline for water dependent structures, information for lakeshore residents and operation of water management structures. The Low Guidance Level is the elevation that a lake's water levels are expected to equal or exceed ninety percent of the time on a long-term basis.

The District is in the process of converting from use of the NGVD29 datum to use of the North American Vertical Datum of 1988 (NAVD 88). While the NGVD29 datum is used for most elevation values included within this report, in some circumstances, notations are made for elevation data that was collected or reported relative to mean sea level or relative to NAVD88 and converted to elevations relative to NGVD29.

Development of Minimum and Guidance Levels for Crooked Lake

Lake Setting and Description

Crooked Lake, which has been known as Lake Caloosa in the past, is located in south-central Polk County, Florida (Sections 25, 35 and 36, Township 30 South, Range 27 East; Sections 28, 29, 30, 31, 32 and 33, Township 30 South, Range 28 East; Sections 6, 7 and 18, Township 31 South, Range 28 East; and Sections 1, 2, 11, 12, 13, 14, 23, and 24, Township 31 South, Range 27 East) (Figure 1) in the Kissimmee River Basin within the Southwest Florida Water Management District. The lake is composed of several sub-basins, with the southernmost two basins known collectively as Little Crooked Lake (Figure 3). Crooked Lake was classified as an Outstanding Florida Water by the State in 1987.

Within the Kissimmee River primary basin, the lake is in the Crooked Lake Outlet sub-basin, which is within the Crooked Clinch Reedy Watershed (Figure 2), and has a drainage area of 32.7 square miles (Florida Board of Conservation 1969, Foose 1981). Inlets include ditches that drain uplands and wetlands located west of U.S. Highway 27 (Figure 3). An outlet ditch, which was reportedly constructed in the 1880s and modified in the 1940s and 1950s (Bradbury *et al.* 1978), drains the basin from the southeast shore of Little Crooked Lake to Lake Clinch when the lake stage higher than 120 ft. above the National Geodetic Vertical Datum of 1929 (NGVD29) (Figure 3, Figure 4). Several canals have been dredged through residential areas along the north shore of the large, middle basin of the lake to provide private lake access. Public access to the lake is available along the east shore of the lake at Crooked Lake Prairie, an Environmental Land Property owned and maintained by Polk County, and at a public boat ramp site located on the south shore of Little Crooked Lake. Boats may also be launched from a private ramp site in Cody's Bay, a small embayment along the east shore of the lake.

The "Gazetteer of Florida Lakes" (Florida Board of Conservation 1969, Shafer *et al.* 1986) lists the size of Crooked Lake as 5,538 acres. A stage-area-volume relationship generated in support of minimum levels development indicates that the lake extends over 5,574 acres when it is staged at 118 ft.

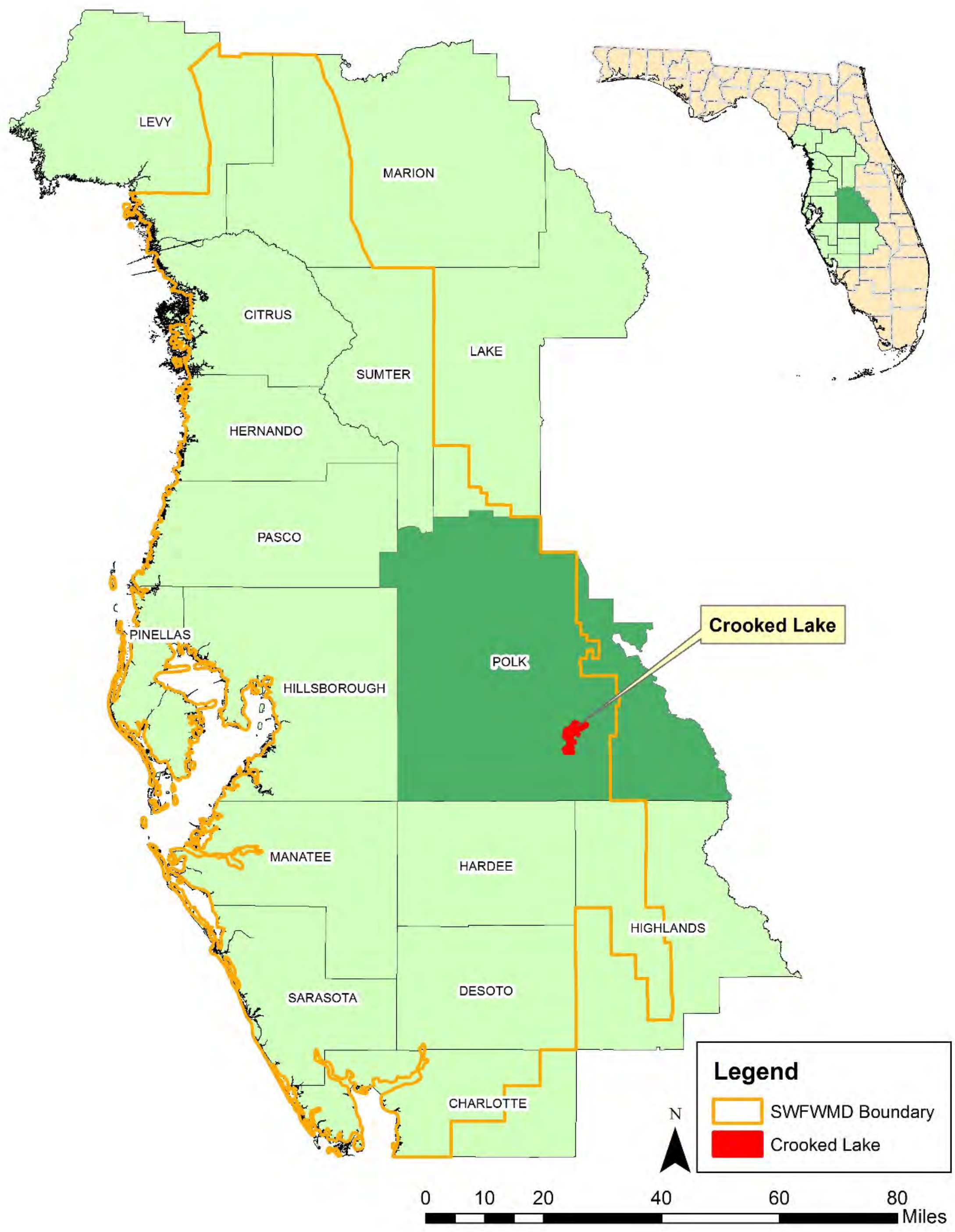

Figure 1: Location of Crooked Lake in Polk County, Florida.

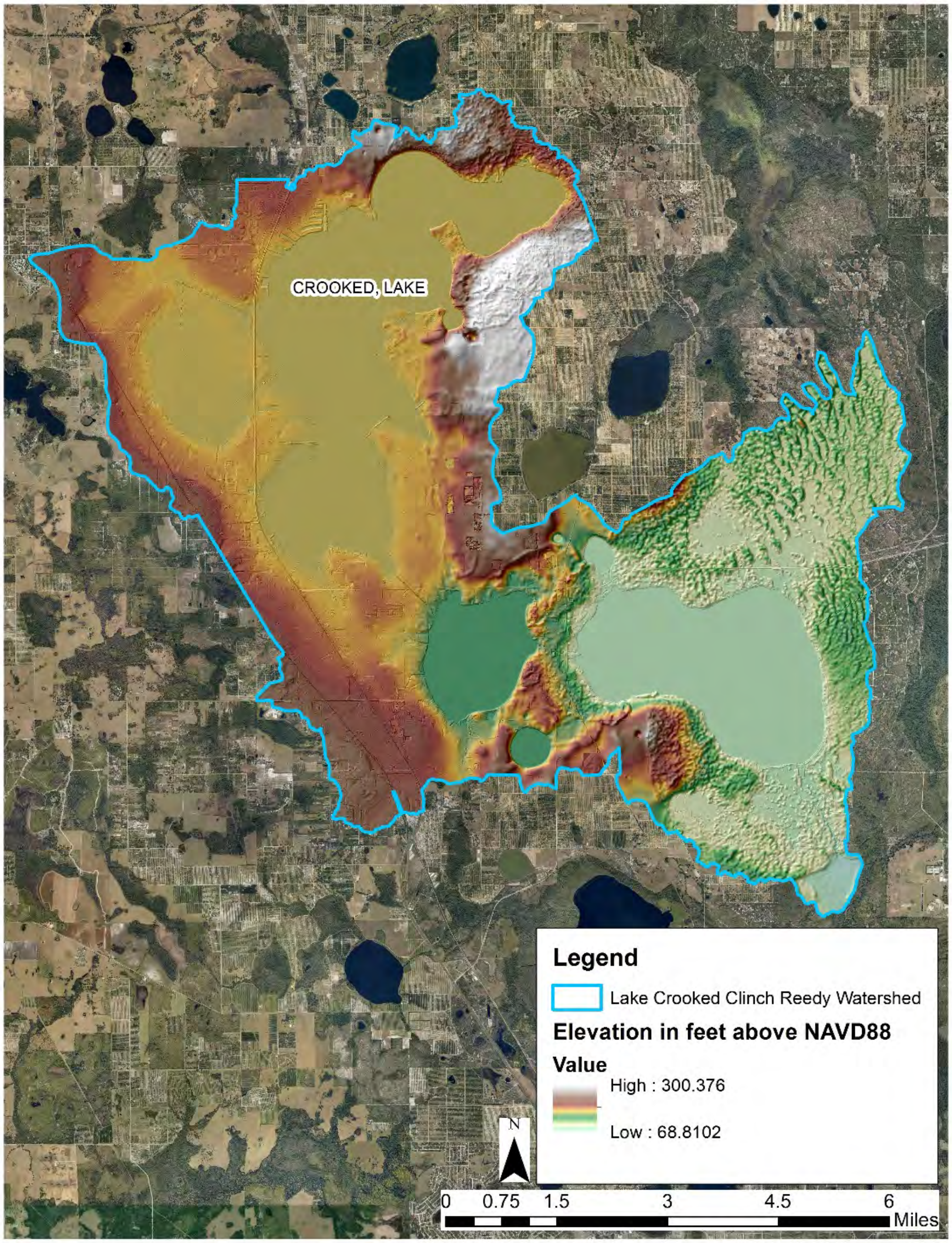

Figure 2: Watershed Delineation and Topography.

Figure 3: General Location of Inflows and Outflow.

Figure 4: Historic aerial photograph (1968) showing the outlet from the southern portion of Crooked Lake (Little Crooked Lake) to Lake Clinch (image source: United States Department of Agriculture 1968a).

Land Use Land Cover

An examination of the 1990 and more current 2011 Florida Land Use, Cover and Forms Classification System (FLUCCS) maps, as well as historic aerial photographs, revealed that there had been little change to the landscape in the vicinity of Crooked Lake in the recent past (Figure 5 - Figure 11). In 1990, agriculture dominated the land use, with lesser amounts of urban build up, wetlands, and rangeland (Figure 5). By 2011, agriculture continued to dominate the landscape, while much of the rangeland had been replaced with wetlands and the footprint of Crooked Lake increased (Figure 6). These differences could be partially attributed to differences in mapping and photointerpretation between 1990 and 2011. Urban and built-up lands increased minimally between 1990 and 2011 (Figure 5, Figure 6). Figure 7 through Figure 11 aerial photography chronicle landscape changes to the immediate lake basin from the 1970's through 2011.

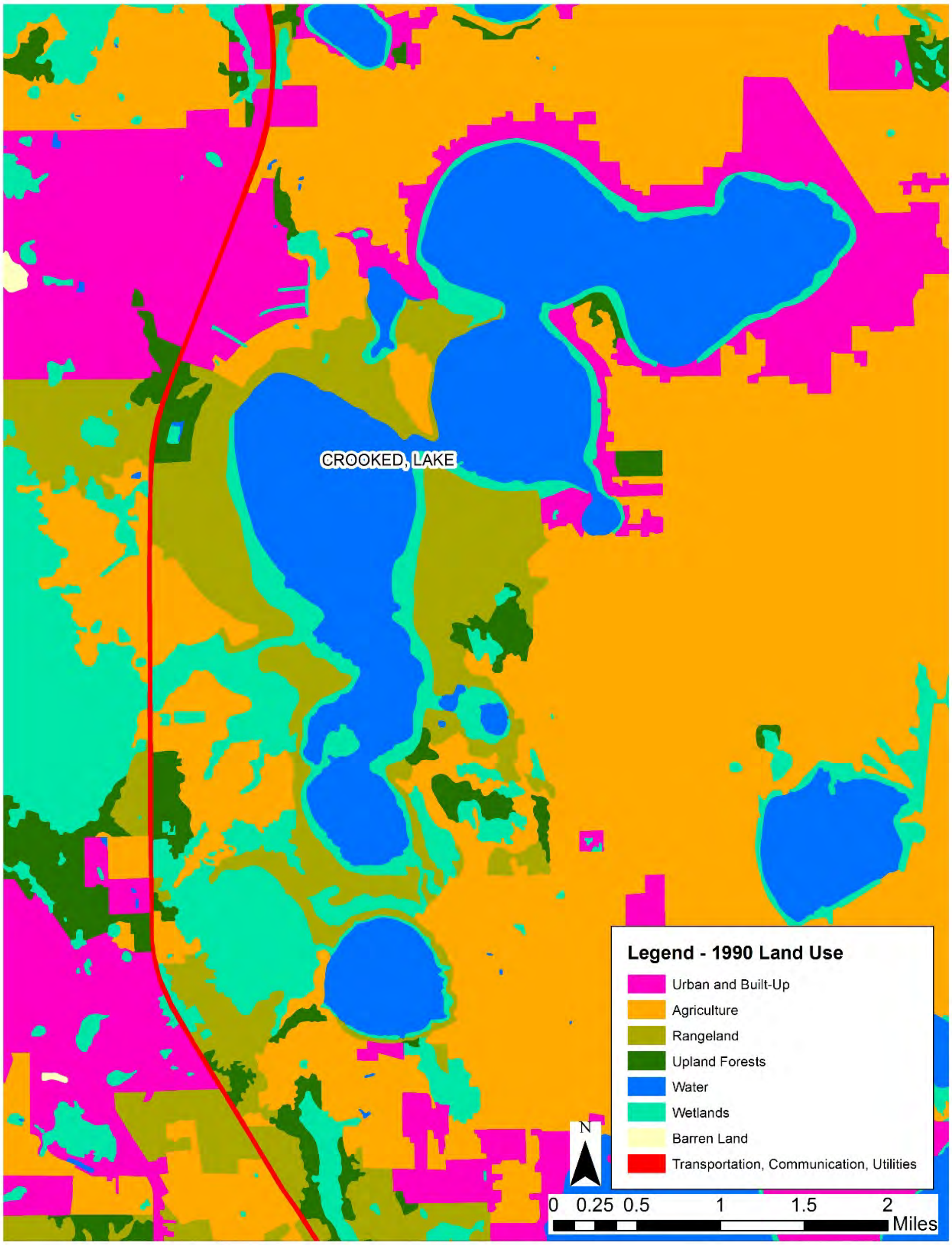

Figure 5: 1990 Land Use Land Cover Map of the Crooked Lake Vicinity.

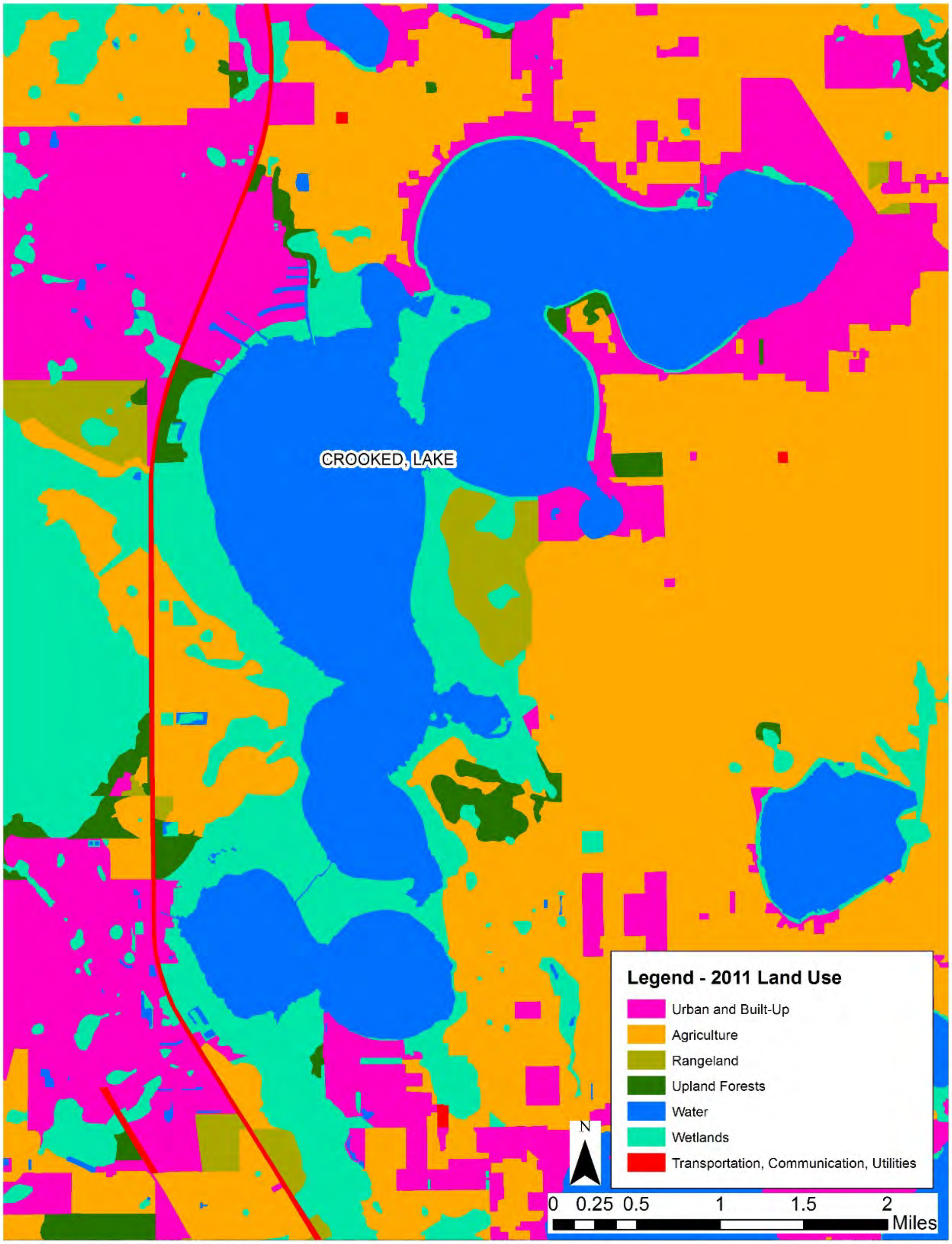

Figure 6: 2011 Land Use Land Cover Map of the Crooked Lake Vicinity.

Figure 7: 1970's Aerial Photograph of Crooked Lake

Figure 8: 1984 Aerial Photograph of Crooked Lake

Figure 9: 2004 Aerial Photograph of Crooked Lake

Figure 10: 2006 Aerial Photograph of Crooked Lake

Figure 11: 2011 Aerial Photograph of Crooked Lake

Bathymetry Description and History

One-foot interval bathymetric data gathered from recent field surveys resulted in lake-bottom contour lines from 73 ft. to 131 ft. (Figure 12). These data revealed that the lowest lake bottom contour (73 ft.) is located in a very small hole in the most northwest lobe of the lake (approximately 81°34'6.432"W, 27°50'2.841"N). Additional morphometric or bathymetric information for the lake basin is discussed in the Methods, Results and Discussion section of this report.

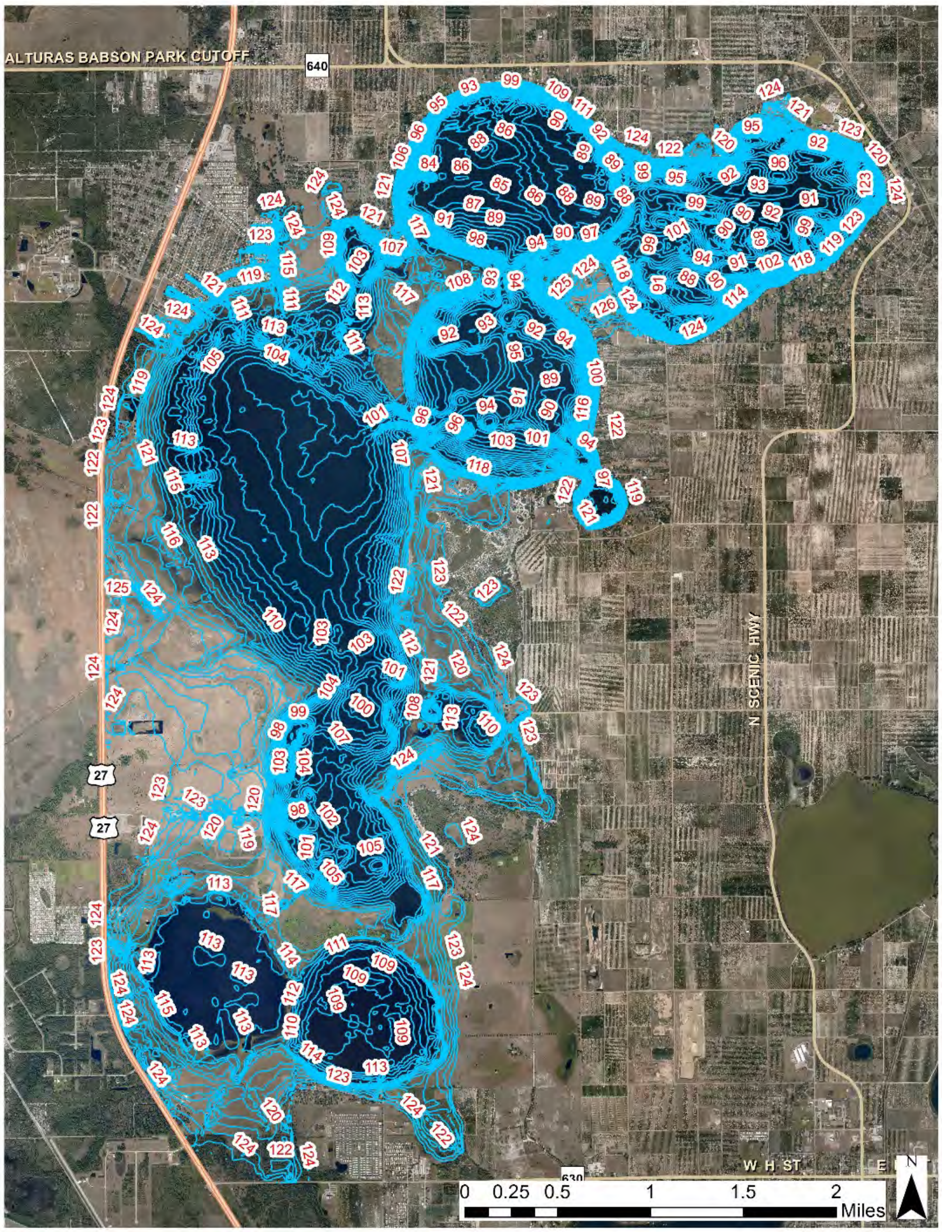

Figure 12: Lake Bottom Contours (ft., NGVD29) on a 2014 Natural Color Aerial Photograph

Water Level (Lake Stage) Record

Lake stage data, i.e., surface water elevations, are available for Crooked Lake (SID 23857) and Little Crooked Lake (SID 23866) from the District's Water Management Information System (Figure 13). For Crooked Lake, data collection began on April 29, 1945 from staff gauge SID 23857. At the time of this report,the District continues to monitor the water levels on a monthly basis from this gauge. The highest lake stage elevation on record was 123.98 ft. and occurred in October 1948. The lowest lake stage elevation on record was 106.1 ft. and occurred in May 1991. For Little Crooked Lake, data collection began on May 4, 1981 from staff gauge SID 23866. At the time of this report, the District continues to monitor the water levels on a monthly basis from this gauge. The highest lake stage elevation on record was 123.51 ft. and occurred in September 2005. The lowest lake stage elevation on record was 112.8 ft. and occurred in June 1991.

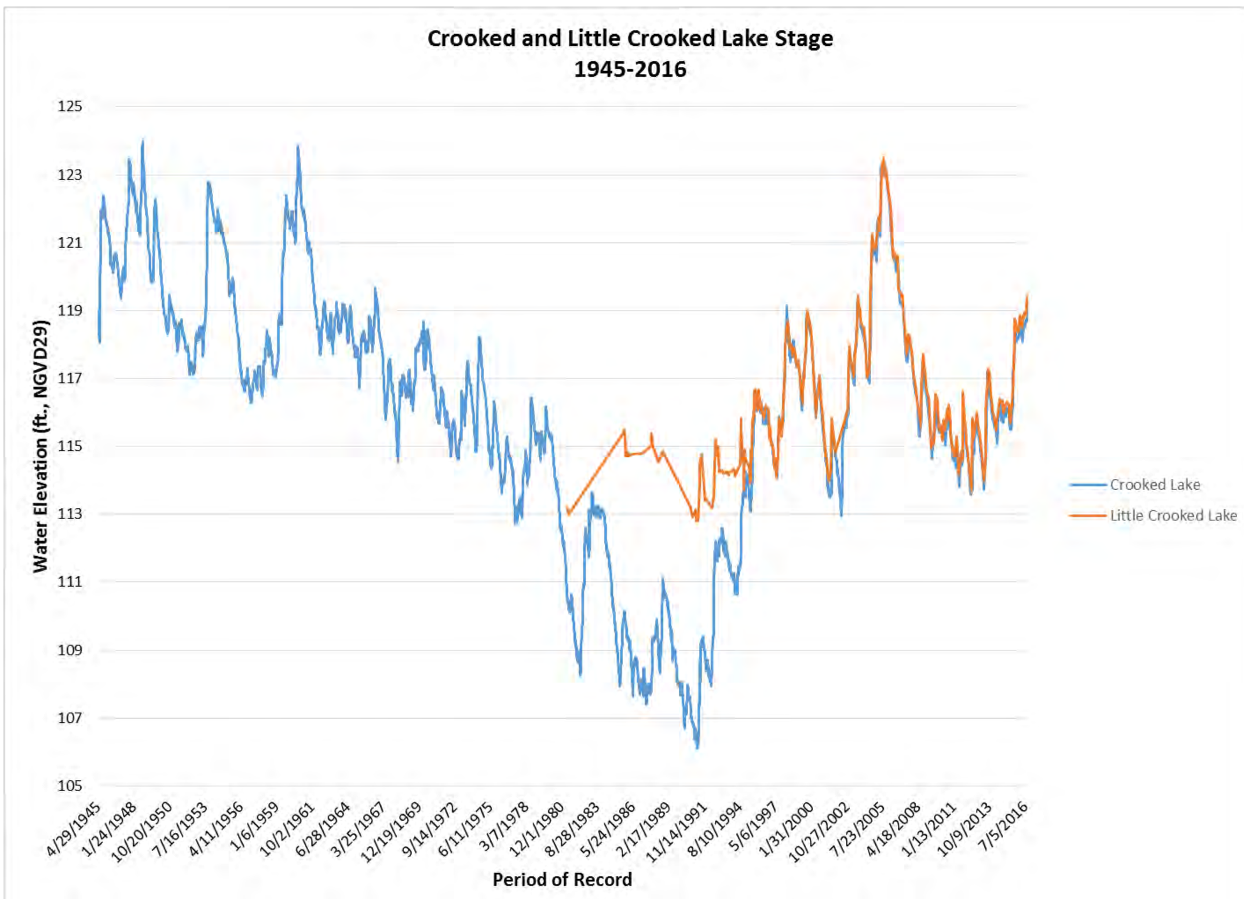

Figure 13: Crooked and Little Crooked Lake Period of Record Water Elevation Data (SID 23857 & 23866).

Historic Management Levels

The District has a long history of water resource protection through the establishment of lake management levels. With the development of the Lake Levels Program in the mid-1970s, the District began establishing management levels based on hydrologic, biological, physical and cultural aspects of lake ecosystems. By 1996, management levels for nearly 400 lakes had been adopted into District rules.

The District Governing Board approved Guidance and Minimum levels for Crooked Lake (Table 2) in December 2007, which were subsequently adopted into Chapter 40D-8, Florida Administrative Code on January 28, 2008 using the methodology for Category 3 Lakes described in SWFWMD (1999a and 1999b). Revised levels (Table 3) have since been incorporated into rule and have replaced those listed in Table 2.

Table 2. Guidance and Minimum levels adopted January 2008 for Crooked Lake

Level	Elevation (ft., NGVD)
High Guidance Level	121.2
High Minimum Level	120.8
Minimum Level	117.9
Low Guidance Level	116.4

Methods, Results and Discussion

Revised Minimum and Guidance Levels were developed for Crooked Lake using the methodology for Category 3 lakes described in Chapter 40D-8, F.A.C. The levels, along with lake surface area for each level, are listed in Table 3 along with other information used for development of the revised levels. Detailed descriptions of the development and use of these data are provided in subsequent sections of this report.

Table 3. Revised Minimum and Guidance Levels, Lake Stage Percentiles, Normal Pool and Control Point Elevations, Significant Change Standards, and associated surface areas for Crooked Lake.

Levels	Elevation in Feet NGVD 29	Lake Area (acres)
Lake Stage Percentiles		
Historic P10 (1946 to 2014)	121.5	6,578
Historic P50 (1946 to 2014)	118.5	5,690
Historic P90 (1946 to 2014)	115.9	5,059
Revised Normal Pool and Control Point		
Normal Pool	NA	NA
Control Point	120.0	6,077
Significant Change Standards		
Recreation/Ski Standard	92.6	705
Dock-Use Standard	118.8	5,745
Wetland Offset Elevation	117.7	5,527
Aesthetics Standard	115.9	5,059
Species Richness Standard	115.1	4,903
Basin Connectivity Standard	120.6	6,313
Lake Mixing Standard	84.5	8
Revised Minimum and Guidance Levels		
High Guidance Level	121.5	6,578
High Minimum Lake Level	120.7	6,335
Minimum Lake Level	117.7	5,527
Low Guidance Level	115.9	5,059

NA - not appropriate

Bathymetry

Relationships between lake stage, inundated area, and volume can be used to evaluate expected fluctuations in lake size that may occur in response to climate, other natural factors, and anthropogenic impacts such as structural alterations or water withdrawals. Long term reductions in lake stage and size can be detrimental to many of the environmental values identified in the Water Resource Implementation Rule for consideration when establishing MFLs. Stage-area-volume relationships are therefore useful for developing significant change standards and other information identified in District rules for consideration when developing minimum lake levels. The information is also needed for the development of lake water budget models that estimate the lake's response to rainfall and runoff, outfall or discharge, evaporation, leakance, and groundwater withdrawals.

Stage-area-volume relationships were determined for Crooked Lake by building and processing a digital elevation model (DEM) of the lake basin and surrounding watershed. Elevations of the lake bottom and land surface elevations were used to build the model through a series of analyses using LP360 (by QCoherent) for ArcGIS, ESRI® ArcMap 10.2 software, the 3D Analyst ArcMap Extension, Python, and XTools Pro. The overall process involves merging the terrain morphology of the lake drainage basin with the lake basin morphology to develop one continuous 3D digital elevation model. The 3D digital elevation model is then used to calculate area of the lake and the associated volume of the lake at different elevations, starting at the largest size of the lake at its peak or flood stage, and working downward to the base elevation (deepest pools in the lake).

Two elevation data sets were used to develop the terrain model for Crooked Lake. Light Detection and Ranging Data (LiDAR) was processed with LP360 for ArcGIS and merged with bathymetric data collected with both sonar and mechanical (manual) methods. These data were collected using a LEI HS-WSPK transducer (operating frequency = 192kHz, cone angle = 20) mounted to a boat hull, a Lowrance LMS-350A sonar-based depth finder, and the Trimble GPS Pathfinder Pro XR/Mapping System (Pro XR GPS Receiver, Integrated GPS/MSK Beacon Antenna, TDC1 Asset Surveyor and Pathfinder Office software).

The DEM created from the combined elevation data sets was used to develop topographic contours of the lake basin and to create a triangulated irregular network (TIN). The TIN was used to calculate the stage areas and volumes using a Python script file to iteratively run the Surface Volume tool in the Functional Surface toolset of the ESRI® 3D Analyst toolbox at one-tenth of a foot elevation change increments. Selected stage-area-volume results are presented in Figure 14.

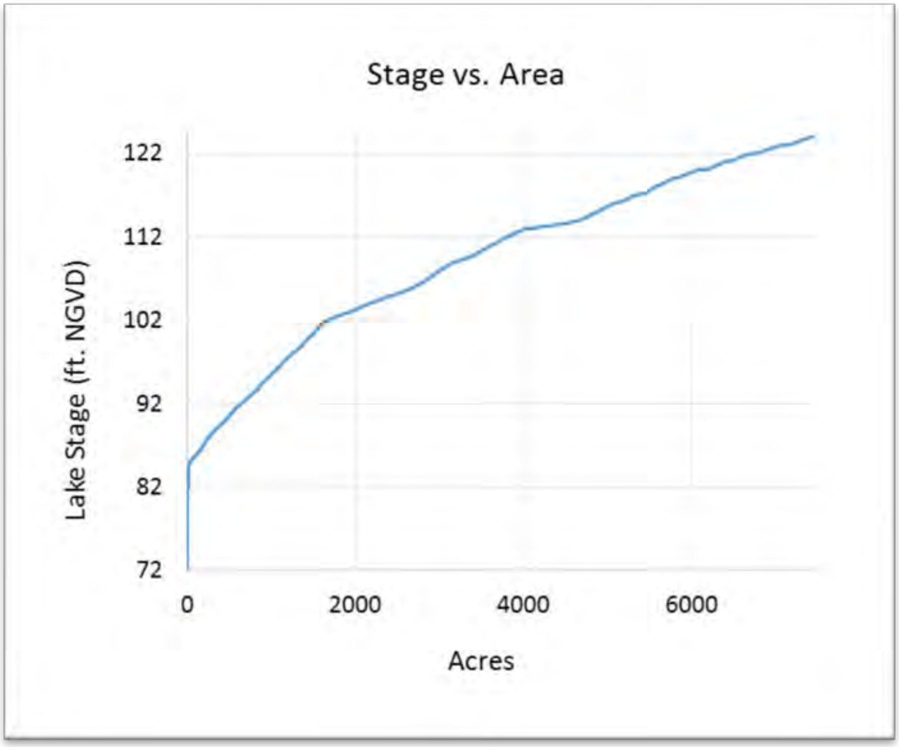

Figure 14: Lake Stage (Ft. NGVD29) to Surface Area (Acres) for Crooked Lake.

Development of Exceedance Percentiles

A key part of establishing Minimum and Guidance Levels is the development of exceedance percentiles based on Historic water levels (lake stage data). For the purpose of minimum levels determination, lake stage data are categorized as "Historic" for periods when there were no measurable impacts due to water withdrawals, and impacts due to structural alterations were similar to existing conditions. In the context of minimum levels development, "structural alterations" means man's physical alteration of the control point, or highest stable point along the outlet conveyance system of a lake, to the degree that water level fluctuations are affected.

Based on water-use estimates and analysis of lake water levels and regional ground water fluctuations, a modeling approach (Appendix A) was used to estimate Historic lake levels. This approach was considered appropriate for extending the period of record for lake stage values for developing Historic lake stage exceedance percentiles. Development of this stage record was considered necessary for characterization of the range of lake-stage fluctuations that could be expected based on long-term climatic cycles that have been shown to be associated with changes in regional hydrology (Enfield et al. 2001, Basso and Schultz 2003, Kelly 2004).

The initial approach included developing a water budget model which incorporated the effects of precipitation, evaporation, overland flow (run-off), and groundwater interactions (Appendix A). Using the results of the water budget model, regression modeling for lake stage predictions was conducted using a linear line of organic correlation statistical model (LOC) (see Helsel and Hirsch 1992). The procedure was used to derive the relationship between daily water surface elevations for Crooked Lake and composite regional rainfall.

A combination of measured data for the period 1946 to 1964 and model data for the remainder of the period produced a hybrid model which resulted in a 68-year (1946-2014) Historic water level record. Based on this hybrid data, the Historic P10 elevation, i.e., the elevation of the lake water surface equaled or exceeded ten percent of the time, was 121.5 ft. The Historic P50, the elevation the lake water surface equaled or exceeded fifty percent of the time during the historic period, was 118.9 ft. The Historic P90, the lake water surface elevation equaled or exceeded ninety percent of the time during the historic period, was 115.9 ft. (Figure 15 and Table 3).

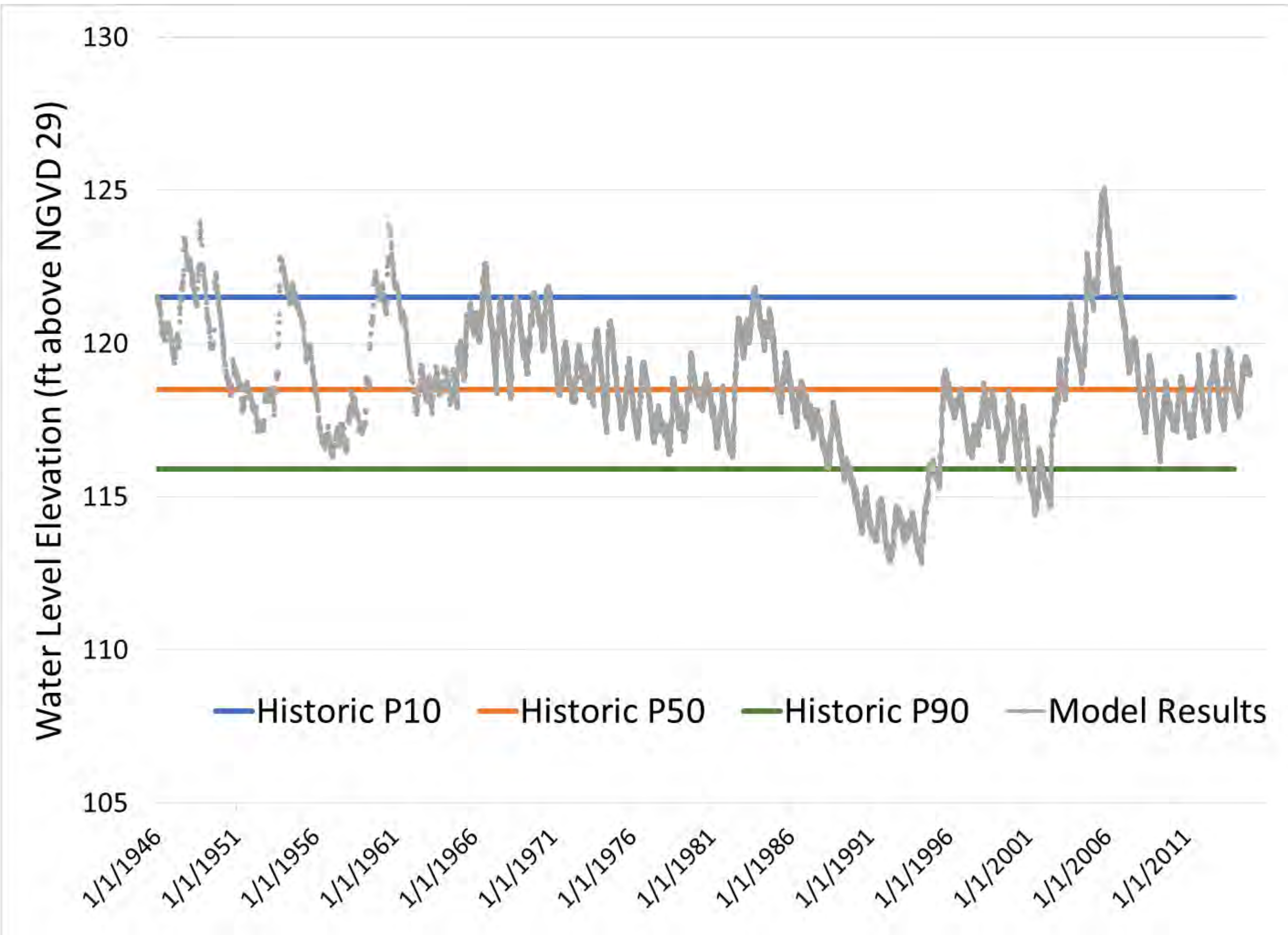

Figure 15: Historic Water Levels (hybrid) Used to Calculate Percentile Elevations Including P10, P50, and P90 for Crooked Lake.

Normal Pool Elevation and Additional Information

The Normal Pool elevation, a reference elevation used for development of minimum lake and wetland levels, is established based on the elevation of hydrologic indicators of sustained inundation. The inflection points (buttress swelling) and moss collars on the trunks of cypress trees have been shown to be reliable biologic indicators of hydrologic Normal Pool (Carr et al. 2006). As Crooked Lake does not have sufficient cypress trees with adequate hydrologic indicators, a Normal Pool elevation was not determined.

Additional information to consider in establishing Minimum and Guidance Levels are the Control Point elevation and the lowest building floor (slab) elevation within the lake basin (determined by field survey data). The Control Point elevation is the elevation of the highest stable point along the outlet profile of a surface water conveyance system that can principally control the lake water level fluctuations at the high end. A weir in the ditch leading from the southeast corner of Little Crooked Lake to Lake Clinch serves as the control point at 120.0 ft. The lowest floor slab, as identified by field survey, was 118.23 ft.

Revised Guidance Levels

The High Guidance Level is provided as an advisory guideline for construction of lakeshore development, water dependent structures, and operation of water management structures. The High Guidance Level is the expected Historic P10 of the lake, and is established using Historic data if it is available, or is estimated using the Current P10, the Control Point elevation and the Normal Pool elevation. Based on the availability of Historic data developed for Crooked Lake, the revised High Guidance Level was established at the Historic P10 elevation, 121.5 ft. The High Guidance Level has been exceeded a few times in the Historic data, primarily between the 1940's – early 1960's, and again in 2005 following a heavy rain season. The highest peak was 123.98 ft. in October 1948.

The Low Guidance Level is provided as an advisory guideline for water dependent structures, and as information for lakeshore residents and operation of water management structures. The Low Guidance Level is the elevation that a lake's water levels are expected to equal or exceed ninety percent of the time on a long-term basis. The level is established using Historic or Current lake stage data and, in some cases, reference lake water regime statistics. Reference lake water regime statistics are used when adequate Historic or current data are not available. These statistics represent differences between P10, P50 and P90 lake stage elevations for typical, regional lakes that exhibit little or no impacts associated with water withdrawals, i.e., reference lakes. Reference lake water regime statistics include the RLWR50, RLWR90 and RLWR5090, which are, respectively, median differences between P10 and P50, P10 and P90, and P50 and P90 lake stage percentiles for a set of reference lakes. Based on the availability of Historic data for Crooked Lake, the revised Low Guidance Level was established at the Historic P90 elevation, 115.9 ft. The gaged period of record indicates the lowest recorded elevation was 106.1 ft., below the low guidance level, in May 1991 (Figure 13). The lake elevation was consistently below the Low Guidance Level during the late 1960's through 2002, and again from 2008-2015. The most recent record of the water level dropping below the low guidance level was in June 2015, with a recorded level of 115.49 ft.

Significant Change Standards

Category 3 significant change standards were established for Crooked Lake based on the stage-volume relationship which was developed. These standards include a Recreation/Ski Standard, Dock-Use Standard, Wetland Offset Elevation, Aesthetics Standard, Species Richness Standard, Basin Connectivity Standard, and Lake Mixing Standard. Each was evaluated for minimum levels development for Crooked Lake and presented in Table 3.

- The **Recreation/Ski Standard** was established at an elevation of 92.6 ft. based on a ski elevation of 90.0 ft.
- The **Dock-Use Standard** was established at 118.8 ft. based on the elevation of lake sediments at the end of 73 docks on the lake.
- The **Wetland Offset Elevation** was established at 117.7 ft., or 0.8 ft. below the historic P50 elevation.
- An **Aesthetic-Standard** for Crooked Lake was established at the Low Guidance Level elevation of 115.9 ft.
- The **Species Richness Standard** was established a 115.1 ft., based on a 15% reduction in lake surface area from that at the Historic P50 elevation.
- The **Basin Connectivity Standard** was established at 120.6 ft., based on the addition of 1 ft. plus the difference between the Historic P50 and P90 elevations (1.7 ft.) to the critical high spot elevation of 116 ft. This is the highest elevation where Crooked Lake splits into two basins.
- The **Lake Mixing Standard** was established at an elevation of 84.5 ft., where the dynamic ratio shifts from a value of > 0.8 to < 0.8, indicating that potential changes in basin susceptibility to wind-induced sediment resuspension would not be of concern for minimum levels development (see Bachmann *et al.* 2000).

Review of changes in potential herbaceous wetland area associated with change in lake stage (Figure 16), and potential changes in area available for aquatic plant colonization (Figure 17) did not indicate that use of any of the identified standards would be inappropriate for minimum levels development. Figure 16 shows that as the lake stage increases, the acres available for herbaceous wetland area (i.e., acres <4 ft. deep) also increase, up until around 106 ft. NGVD. The acres available for herbaceous wetlands then decrease as the lake becomes deeper, and then continue to increase and decrease according to the bathymetry of the lake and surrounding wetland areas. Similarly, the area available for aquatic plant colonization (acres < 10.6 ft. deep) generally increases as lake stage increases as well (Figure 17). The changes in the slope of the lines reflect the variation in lake bottom contours and the area which it contains.

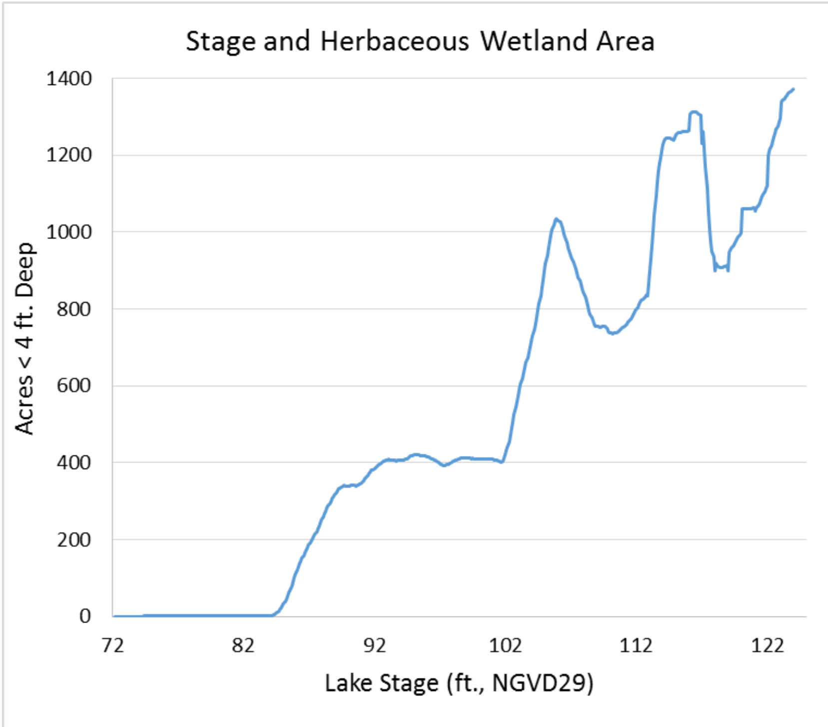

Figure 16: Lake Stage Compared to Available Herbaceous Wetland Area.

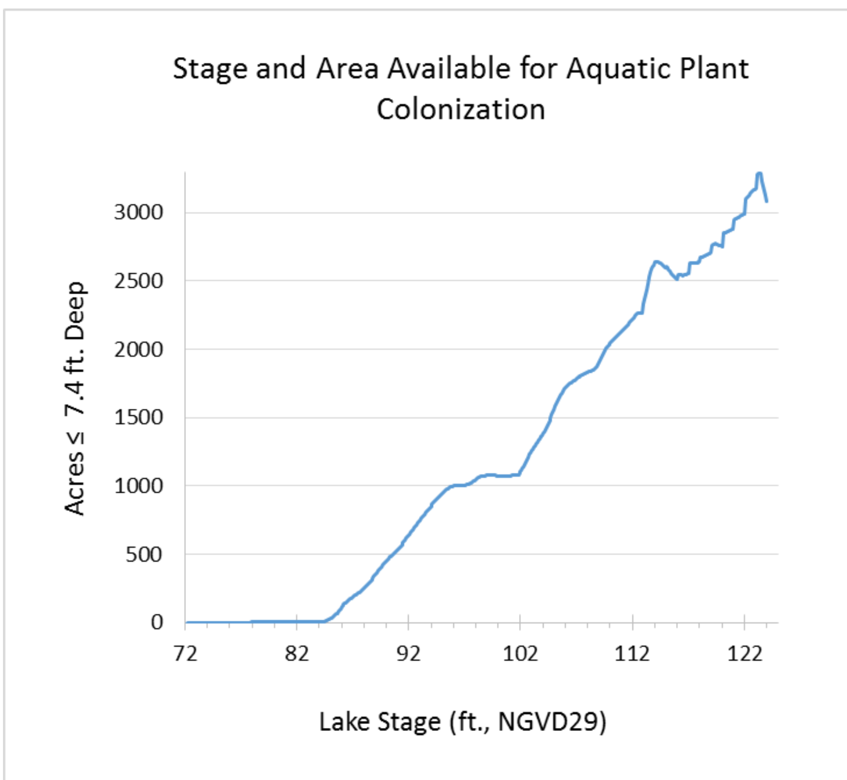

Figure 17: Lake Stage and Area Available for Aquatic Plant Colonization.

Revised Minimum Levels

The Minimum Lake Level (MLL) is the elevation that a lake's water levels are required to equal or exceed fifty percent of the time on a long-term basis. For a Category 3 lake, the MLL is established using a process that considers applying professional experience and judgement, and the Standards listed previously. The revised MLL for Crooked Lake is established at the Wetland Offset elevation of 117.7 ft.

The High Minimum Lake Level (HMLL) is the elevation that a lake's water levels are required to equal or exceed ten percent of the time on a long-term basis. For Category 3 lakes, the HMLL is developed using the Minimum Lake Level, Historic data, or reference lake water regime (RLWR) statistics. If Historic Data are available, the HMLL is established at an elevation corresponding to the Minimum Lake Level plus the difference between the Historic P10 and Historic P50. Given the availability of Historic data for Crooked Lake, the revised HMLL was set at 120.7 ft.

Revised Minimum and Guidance levels for Crooked Lake are plotted on the Historic water level record as well as actual water level elevations collected in the field (Figure 18). To illustrate the approximate locations of the lake margin when water levels equal the revised minimum levels, the levels are imposed onto a 2014 natural color aerial photograph in Figure 19.

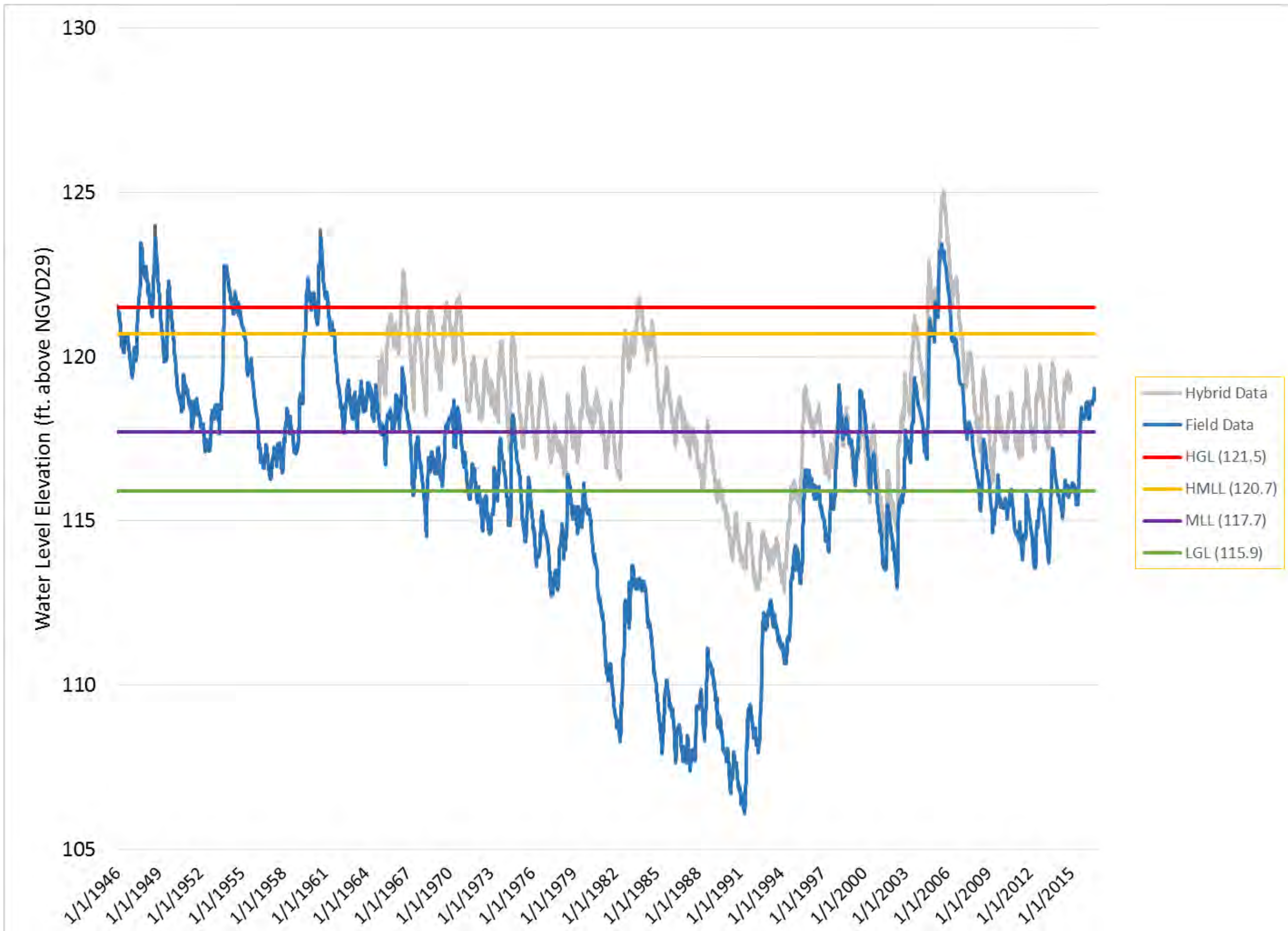

Figure 18: Historic water levels used to calculate the Revised Minimum and Guidance Levels along with field collected water level data, Guidance, and Minimum lake levels for Crooked Lake.

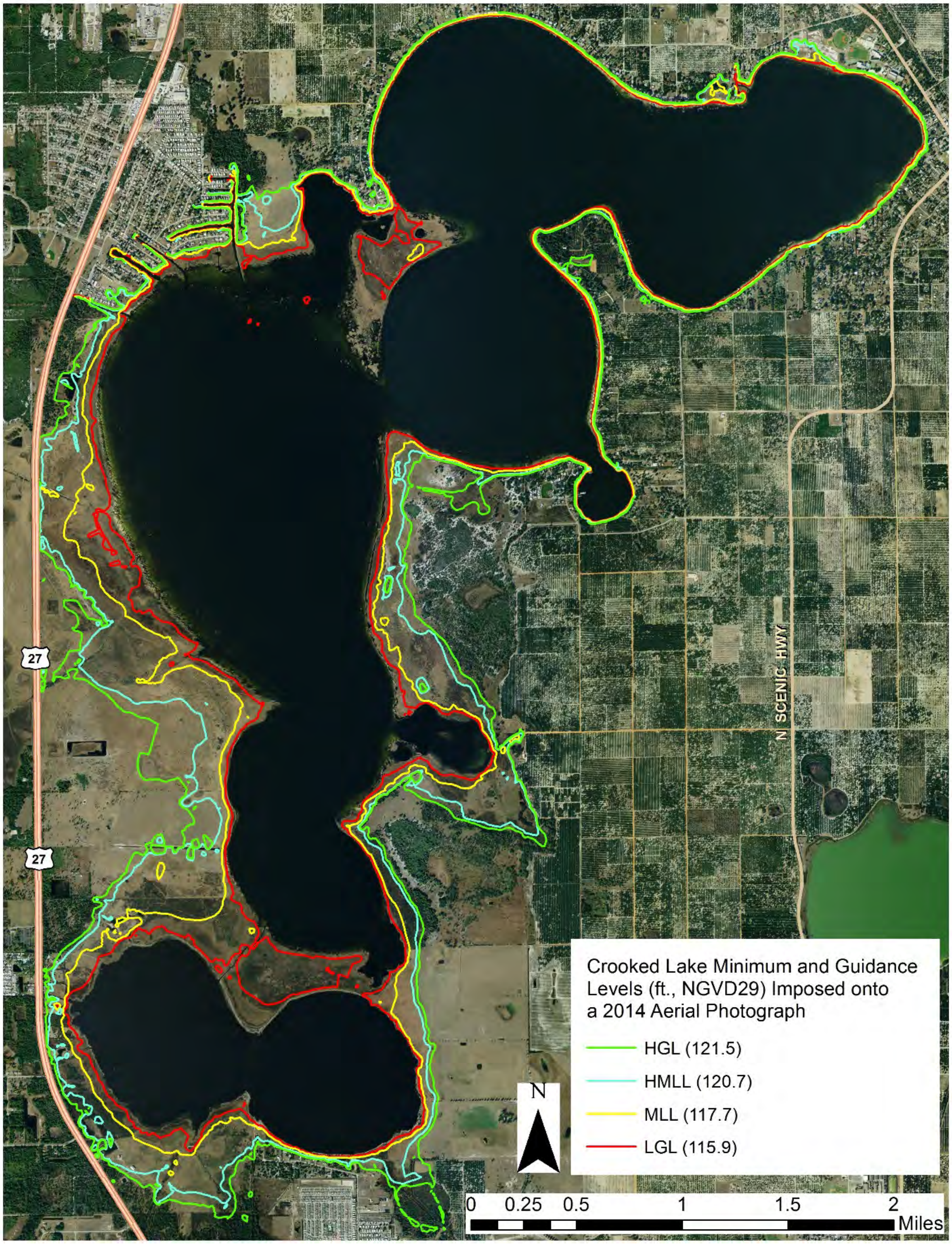

Figure 19: Crooked Lake Revised Minimum and Guidance Level Contour Lines Imposed onto a 2014 Natural Color Aerial Photograph.

Many federal, state, and local agencies, such as the U.S. Army Corps of Engineers, the Federal Emergency Management Agency, United States Geological Survey, and Florida's water management districts are in the process of upgrading from the National Geodetic Vertical Datum (NGVD29) standard to the North American Vertical Datum (NAVD88) standard. For comparison purposes, the revised MFLs for Crooked Lake are presented in both datum standards (Table 5). The datum shift was calculated based on third-order leveling ties from vertical survey control stations with known elevations above the North American Vertical Datum of 1988. The NGVD29 datum conversion to NAVD88 is -1.03 ft. for SID 23857 on Crooked Lake, and -0.98 ft. for SID 23866 on Little Crooked Lake.

Table 5. Revised Minimum and Guidance Levels for Crooked Lake in NGVD29 and NAVD88.

Minimum and Guidance Levels	Elevation in Feet NGVD29	Elevation in Feet NAVD88 (SID 23857)	Elevation in Feet NAVD88 (SID 23866)
High Guidance Level	121.5	120.47	120.52
High Minimum Lake Level	120.7	119.67	119.72
Minimum Lake Level	117.7	116.67	116.72
Low Guidance Level	115.9	114.87	114.92

Consideration of Environmental Values

The revised minimum levels for Crooked Lake are protective of relevant environmental values identified for consideration in the Water Resource Implementation Rule when establishing minimum flows and levels (see Rule 62-40.473, F.A.C.). As presented above, when developing minimum lake levels, the District evaluates categorical significant change standards and other available information to identify criteria that are sensitive to long-term changes in hydrology and represent significant harm thresholds. The Wetland Offset Elevation was used for developing revised Minimum Levels for Crooked Lake based on its classification as a Category 3 lake. This standard is associated with protection of several environmental values identified in Rule 62-40.473, F.A.C., including: fish and wildlife habitats and the passage of fish, transfer of detrital material, aesthetic and scenic attributes, filtration and absorption of nutrients and other pollutants, and water quality (refer to Table 1).

In addition, the environmental value, maintenance of freshwater storage and supply is also expected to be protected by the minimum levels based on inclusion of conditions in water use permits that stipulate permitted withdrawals will not lead to violation of adopted minimum flows and levels.

Two environmental values identified in the Water Resource Implementation Rule were not considered relevant to development of revised minimum levels for Crooked Lake. Estuarine resources were not considered relevant because the lake is not connected to an estuarine resource. Sediment loads were similarly not considered relevant for minimum levels development for the lake, because the transport of sediments as bedload or suspended load is a phenomenon typically associated with flowing water systems.

Comparison of the Revised and Previously Adopted Levels

The revised High Guidance Level is 0.3 ft. higher than the previously adopted High Guidance Level, while the Low Guidance Level is 0.5 ft. lower than the previously adopted Low Guidance Level (Table 6). These differences are primarily due to the application of a new modeling approach for characterization of Historic water level fluctuations within the lake, and additional data since the last evaluation.

The revised High Minimum Lake Level for Crooked Lake is 0.1 ft. lower than the previously adopted High Minimum Lake Level. The revised Minimum Lake Level is 0.2 ft. lower than the previously adopted Minimum Lake Level (Table 6). These differences are due to the same factors listed for the changes in the guidance levels.

Table 6. Revised Minimum and Guidance Levels for Crooked Lake compared to previously adopted Minimum and Guidance Levels.

Minimum and Guidance Levels	Revised Elevation (in Feet NGVD29)	Previously Adopted Elevation (in Feet NGVD29)
High Guidance Level	121.5	121.2
High Minimum Lake Level	120.7	120.8
Minimum Lake Level	117.7	117.9
Low Guidance Level	115.9	116.4

Minimum Levels Status Assessment

To assess if the revised Minimum and High Minimum Lake Levels are being met, observed stage data in Crooked Lake were used to create a long-term record using a Line of Organic Correlation (LOC) model, similar to what was developed for establishing the Minimum Levels (Appendix A). For the status assessment, the lake stage data used to create the LOC must be from a period representing a time when groundwater withdrawals and structural alterations are reasonably stable, and represent current conditions, referred to as the “Current” period. Current stage data observed on Crooked Lake were determined to be from 1995 through 2015. Using the Current stage data, the LOC model was created. The LOC model resulted in a 68-year long-term water level record (1946-2015). For evaluation of compliance, the LOC model results for the period 1995 to 2015 were replaced with actual measured lake levels data to create a hybrid model for use in determining the state of lake levels.

For the status assessment, cumulative median (P50) and cumulative 10th percentile (P10) water elevations were compared to the revised Minimum Lake Level and High Minimum Lake Level to determine if long-term water levels were above the revised levels. Results from these assessments indicate that Crooked Lake water levels are above the revised High Minimum Lake Level, and just below the revised Minimum Lake Level (see Appendix B).

The lake lies within the region of the District covered by an existing recovery strategy for the Southern Water Use Caution Area (Rule 40D-80.074, F.A.C.). The District plans to continue regular monitoring of water levels in Crooked Lake and will also routinely evaluate the status of the lake’s water levels with respect to adopted minimum levels for the lake included in Chapter 40D-8, F.A.C.

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APPENDIX A

Draft Technical Memorandum

October 3, 2016

TO: Donna Campbell, Environmental Scientist, Resource Evaluation Section

THROUGH: Jerry L. Mallams, P.G., Manager, Resource Evaluation Section

FROM: Mark D. Barcelo, P.E. Chief Professional Engineer, Resource Evaluation Section

Subject: Crooked Lake Water Budget Model, Rainfall Regression Model, and Historic Percentile Estimations

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A. Introduction

Water budget and rainfall regression models were developed to assist the Southwest Florida Water Management District (District) in the reassessment of minimum levels in 2016 for Crooked Lake in east-central Polk County. This document will discuss the development of the hydrologic analysis and models used for development of Historic lake stage exceedance percentiles.

B. Background and Setting

Crooked Lake is located near the town of Babson Park in east-central Polk County, about 12 miles south of the intersection of U.S. Highway 27 and State Road 60 in the City of Lake Wales (Figure 1). The lake is located on the Lake Wales Ridge and is within the Kissimmee River watershed. There are no major surface water systems draining into the lake basin however, surface outflows to Lake Clinch occur from the southern end of the lake when water elevations rise above 120 feet National Geodetic Vertical Datum of 1929 (NGVD29). Drainage into the lake is a combination of overland flow, flow through drainage swales and conveyance systems, and groundwater inflow from the surficial aquifer. Though withdrawals from the lake occur for lawn irrigation, there are no permitted surface water withdrawals from the lake. There are numerous permitted groundwater withdrawals in the vicinity of the lake.

Physiography

Crooked Lake lies within two physiographic provinces. The northeastern portion of the lake extends into the western portion of the Lake Wales Ridge, the most prominent topographic feature in the area, is a north-south oriented sand ridge that is approximately 100 miles long, ranges from four to ten miles wide, and has elevations along the crest that range from about 150 feet to 300 feet above sea level (Figure 1). The southern and western portions of the lake lie within the Polk Uplands, a broad, elevated, sandy area that ranges in elevation from about 100 to 245 feet above sea level. The Lake Wales Ridge area is predominantly well-drained with internal drainage caused by numerous karst features; hence, it is an uplands recharge area for the Upper Floridan aquifer in Central Polk and Highlands counties. Dissolution of the underlying limestone creates the relief seen along the Lake Wales Ridge. The Lake Wales Ridge Complex is a remnant of a broader upland that has been eroded and lowered by sea level fluctuations, fluvial erosion, and aeolian redistribution of sediments (Green et al., 2012). The lake straddles the center of a north-south trending ridge that slopes downward to the east and west. Elevations within the immediate watershed range from the lake edge at about 115 feet to nearly 300 feet NAVD 88 on the eastern side of the lake.

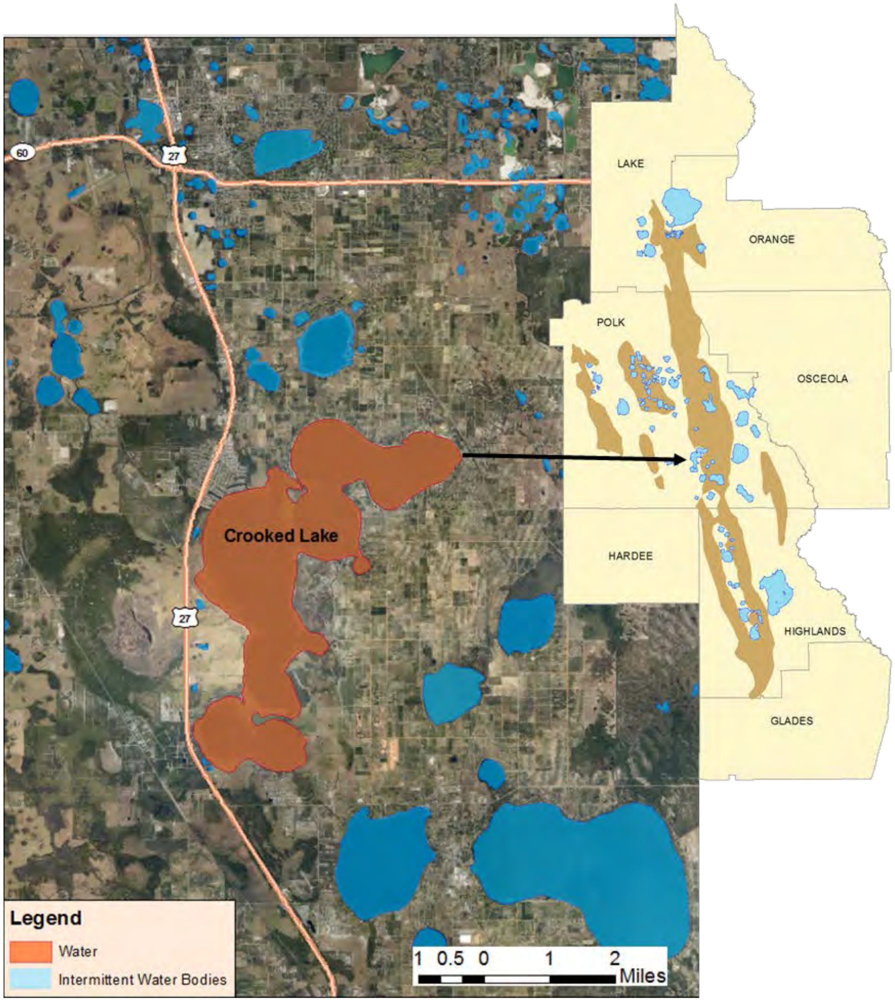

Figure 1. Location of Crooked Lake and the Lake Wales Ridge in Polk County, Florida.

Hydrogeology

The hydrogeology of the area includes a sand, surficial aquifer; a clay confining unit perforated by karst features (sinkholes); and the thick carbonate Upper Floridan aquifer (Spechler and Kroening, 2007). Sinkholes are numerous along the Lake Wales Ridge and range in size from small depressions to large lakes. The circular shoreline, especially in northern portions of Crooked Lake are evidence of karst or sinkhole activity. Sinkholes provide more direct avenues for water from the surficial aquifer to move downward and recharge the underlying Upper Floridan aquifer. The surficial aquifer is recharged by area rainfall; however, much of the rain that falls drains into lakes or is lost to evapotranspiration. Other sources of recharge that are applied to land include wastewater, reclaimed water, septic effluent, and irrigation of agricultural land or landscape areas (Spechler and Kroening, 2007). In elevated areas, such as the Lake Wales Ridge, the water table generally is a subdued reflection of land-surface topography (Yobbi, 1996). The Hawthorn aquifer system that consists mostly of interbedded clay, silt, phosphate, and sand is present at Crooked Lake and serves as a confining unit except where breached by sinkholes.

Hydrogeology and stratigraphy near Crooked Lake at the ROMP CL-1 wellsite are described in Decker (1987). This site is located in the northeastern portion of the watershed near Webber College. The surficial aquifer at this site consists of undifferentiated, unconsolidated quartz sand and clayey quartz sand deposits present from land surface datum (LSD) to 132 feet below LSD (10 feet below NGVD 29). The stratigraphy at the ROMP CL-1 wellsite is typical of the area, as the surficial aquifer generally thickens moving from west to east across Polk County, especially along the southern part of the Lake Wales Ridge where the thickness can exceed 200 feet (Spechler and Kroening, 2007). The surficial aquifer generally exhibited moderate to high porosity and permeability at the ROMP CL-1 wellsite. The water table at ROMP CL-1 has ranged from about 99 feet to 121 feet NGVD29 and typically responds fairly quickly to precipitation and groundwater withdrawals. Some area surficial aquifer wells declined to record or near-record lows in 2000 and 2001, when annual rainfall averaged about 21 and 27 inches below normal at the Mountain Lake and Avon Park rainfall stations, respectively (Spechler and Kroening, 2007).

Spechler and Kroening (2007) report that the intermediate confining unit (more recently referred to as the Hawthorn aquifer system) is present throughout much of northern and eastern Polk County and is locally absent or thin in the extreme northwestern part of Polk County. The Hawthorn aquifer system was present at ROMP CL-1 from 132 feet below LSD (10 feet below NGVD 29) to 200.5 feet below LSD (78.5 feet below NGVD 29). It is primarily composed of clayey/sandy limestones and sandy clays grading to clayey dolomites. The unit exhibited low to moderate porosity values with low permeability values. Preliminary comparisons of water levels for the surficial and Floridan aquifer system indicated that the Hawthorn aquifer system exhibits characteristics of a semi-leaky confiner (Decker, 1987).

Below the Hawthorn aquifer system lies the limestone of the Upper Floridan aquifer that ranges from approximately 300 feet thick in eastern Polk County to more than 1,200 feet thick in the southwestern part of the county (Spechler and Kroening, 2007). The Upper Floridan aquifer is the principal source of water in the area and the well at the ROMP CL-1 site was open from 200.5 feet below LSD (-78.5 NGVD 29) to 349 feet below LSD (-227 feet NGVD 29). The Upper Floridan aquifer here consisted mainly of calcarenitic limestone with some dolomite lenses. Porosity and permeability were moderate to high.

Data

Regular water level data collection at Crooked Lake (SID 23857) began in 1946 (Figure 2). The frequency of data collection averaged about five (5) times per month until 2004 when data collection was reduced to an average of about two (2) times per month. Data collection for Little Crooked Lake also (SID 23866) was sporadic in the 1980s and became more regular in the early 1990s. Based on data collected, the lakes are generally well connected and have the same elevation at water levels at or above 115 feet; but, they were as much as seven (7) feet different during the 1980s.

The Upper Floridan aquifer monitor well used in this analysis is the ROMP CL-1 well (SID 23873), with regular daily data collection beginning in November 1987 (Figures 3 and 4). Data gaps in the well were infilled with estimated data generated using a linear regression of the ROMP CL-1 well with the Coley Deep monitor well (SID 25339). The Coley Deep well monitor well is located in the town of Frostproof (Figure 3).

Data from three surficial aquifer monitor wells were used: ROMP CL-1 (SID 23875), ROMP 44 (SID 23891), and Ridge WRAP CLP-1 (SID 23893). The data for the surficial well start in November 1987 and are generally daily, with the exception of a few data gaps and a period from November 1994 through October 2003 when data collection was monthly. Missing data were linearly infilled since the gaps were relatively short.

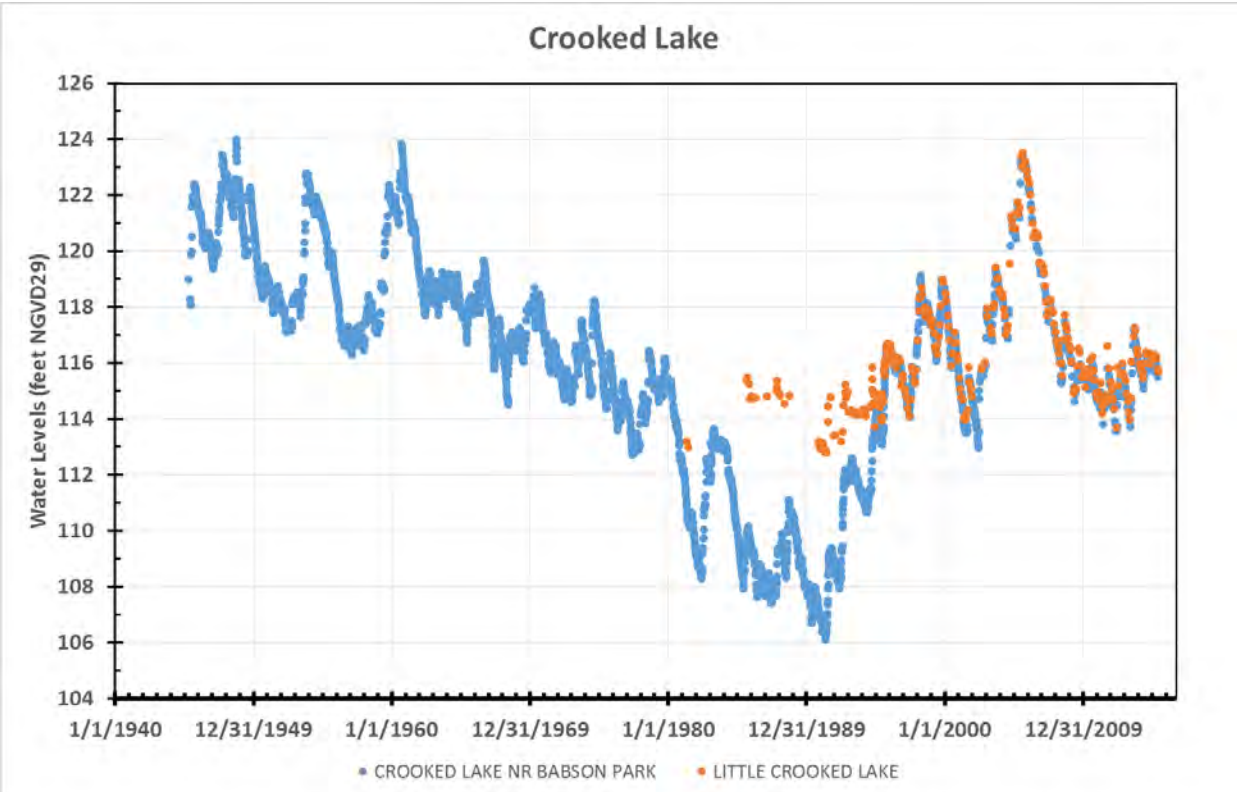

Figure 2. Crooked Lake water levels.

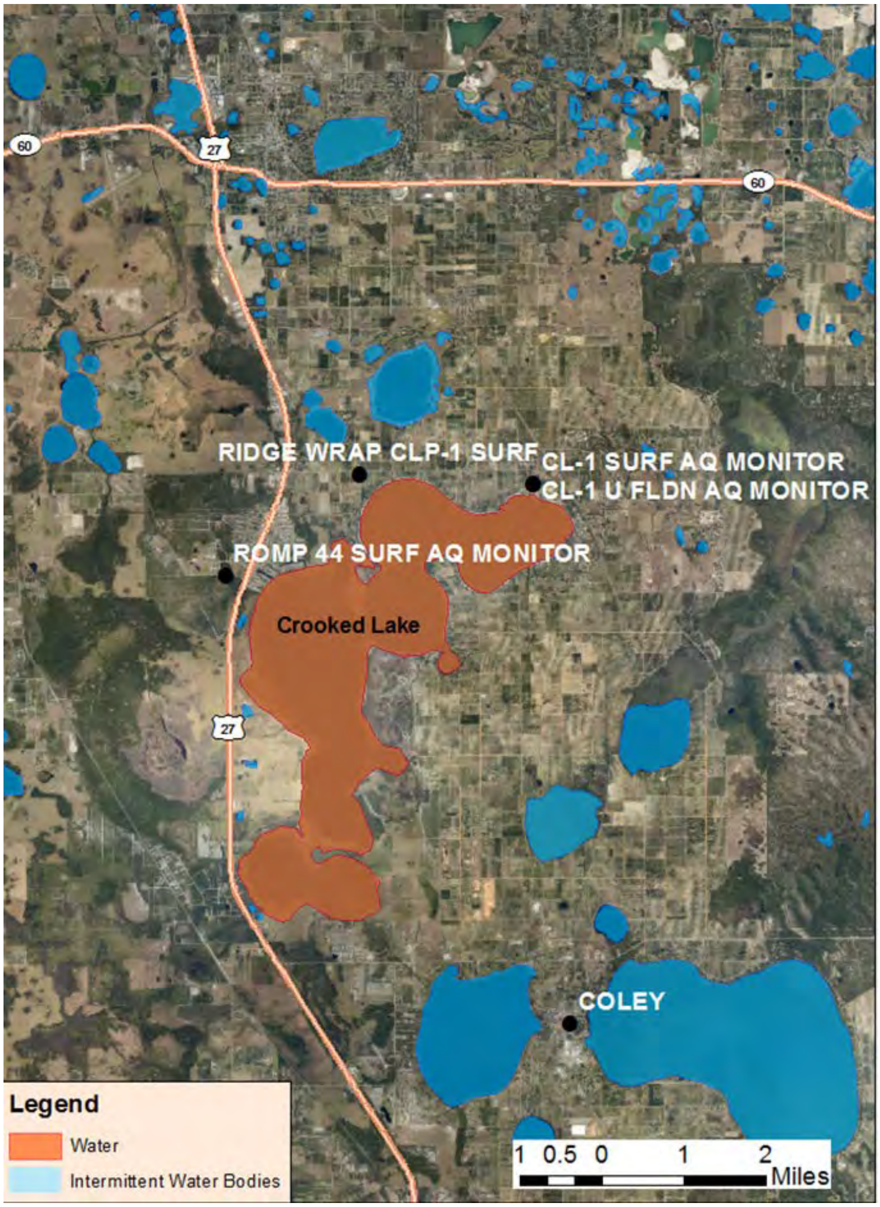

Figure 3. Location of monitoring wells near Crooked Lake.

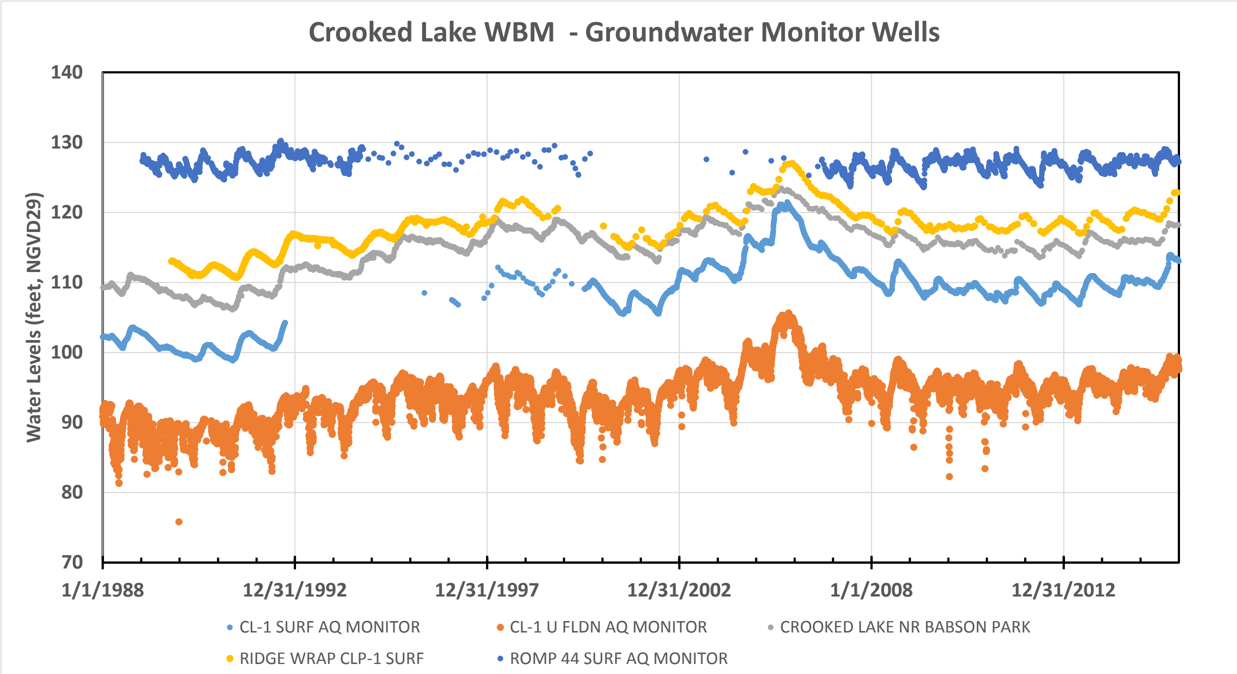

Figure 4. Water levels in monitoring wells used in the Crooked Lake water budget model.

<u>Land and Water Use</u>

Land and water use in the Crooked Lake watershed has changed over the years, though some areas have remained the same for the past several decades. Figure 5 shows land use in the watershed as it currently exists. Much of the agricultural land use is for citrus. In general, irrigation of citrus groves became more prevalent in the 1960s when it was determined that it could greatly improve crop yield. Though not shown, water use by the phosphate industry, centered in an area approximately 30 miles to the west/southwest of Crooked Lake, began to increase significantly throughout the late 1960s and 1970s, but has since declined. Locations and relative magnitudes of water withdrawals near Crooked Lake are shown in Figure 6 and summarized in Table 1. From 2008 to 2012, the total estimated groundwater use within one mile of the lake was approximately 3.96 million gallons per day (mgd), of which approximately 87 percent was for agriculture. Within 5 miles of the lake, the estimated total groundwater use for the same time period was approximately 26 mgd, of which 83 percent was agricultural use, 4 percent for commercial/industrial use, 10 percent for public supply use, approximately 3 percent for recreation use, and less than 1 percent for mining/dewatering use.

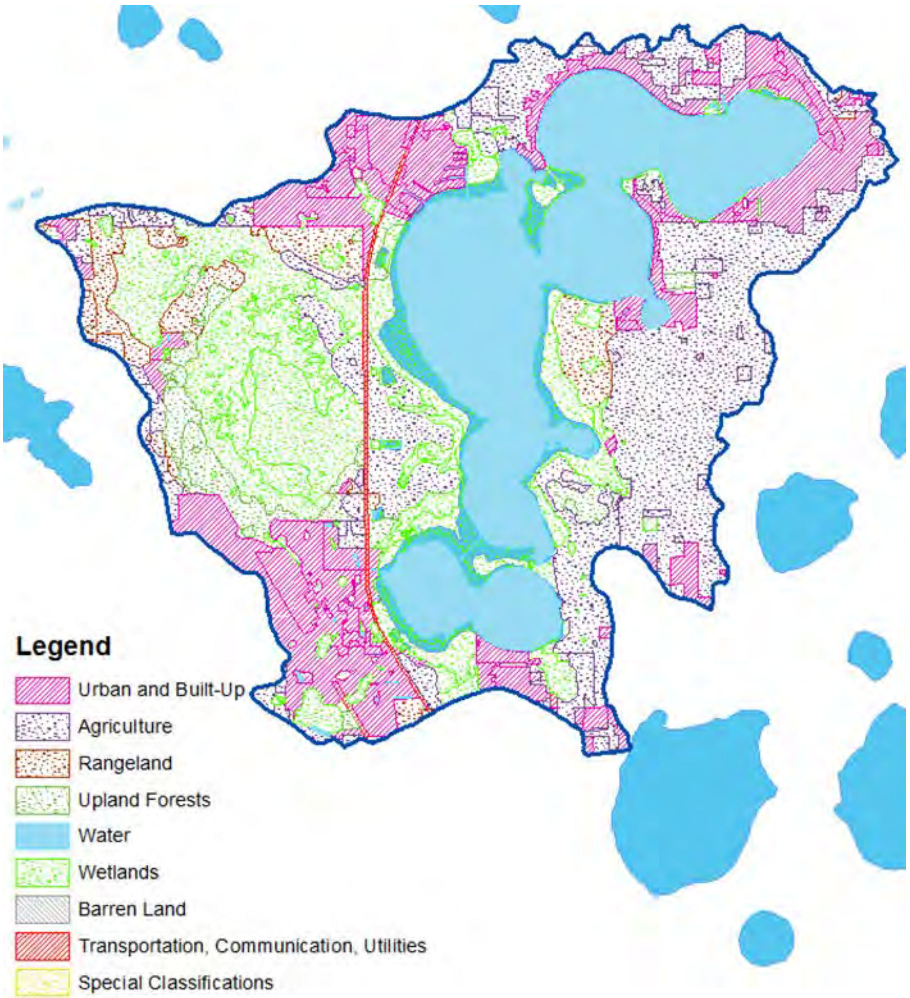

Figure 5. Land use in the Crooked Lake Watershed (2011).

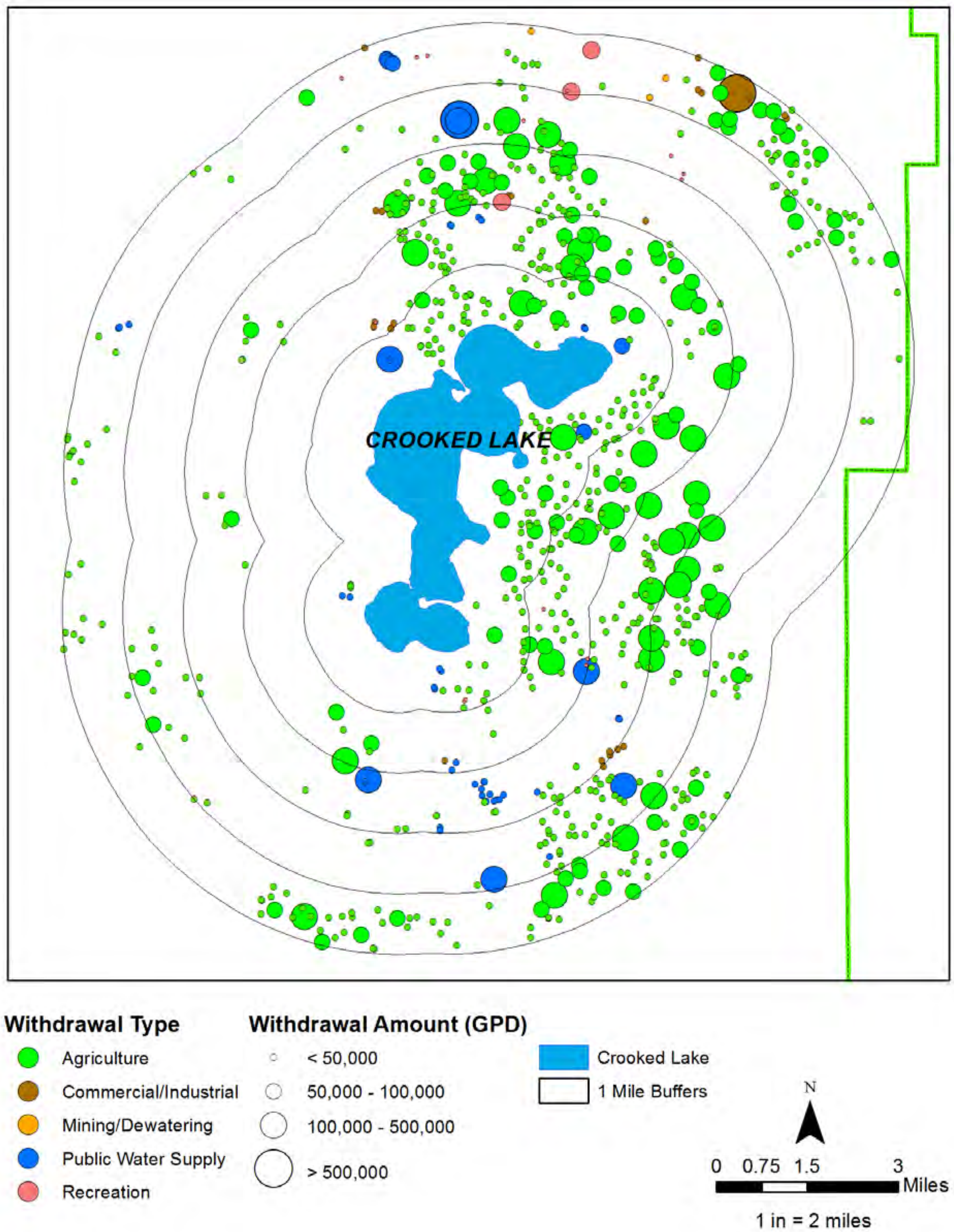

Figure 6. Locations and relative magnitudes of withdrawals in the vicinity of Crooked Lake over the period 2008-2012

Table 1. Water Use in the Crooked Lake area (2008-2012 average).

Water Use Within 1 Mile of Crooked Lake (GPD)			
Use Type	**SW**	**GW**	**Total**
Agriculture	3,328	3,459,762	3,463,091
Commercial/Industrial			-
Mining/Dewatering			-
Public Supply		462,012	462,012
Recreation		36,505	36,505
Total	3,328	3,958,279	3,961,608
Water Use Within 5 Miles of Crooked Lake (GPD)			
Use Type	**SW**	**GW**	**Total**
Agriculture	1,249,175	20,385,304	21,634,480
Commercial/Industrial	64	987,678	987,742
Mining/Dewatering	62	1,349	1,411
Public Supply	22,229	2,650,404	2,672,632
Recreation		868,376	868,376
Total	1,271,530	24,893,111	26,164,640

Figure 7 presents total estimated and measured groundwater withdrawals in Polk County since the 1930s (updated from Southwest Florida Water Management District, 2006). Significant groundwater withdrawals began in the area throughout the 1940s and 1950s, and peaked in the late 1960s and early 1970s. Groundwater withdrawals in Polk County have been relatively stable since the early to mid-1990s, although this period includes both extreme dry (2000) and wet (2004/2005) conditions. Since 1994, estimated groundwater withdrawals in Polk County averaged about 218 mgd and ranged from 172 mgd in 2011 to 274 mgd in 2000.

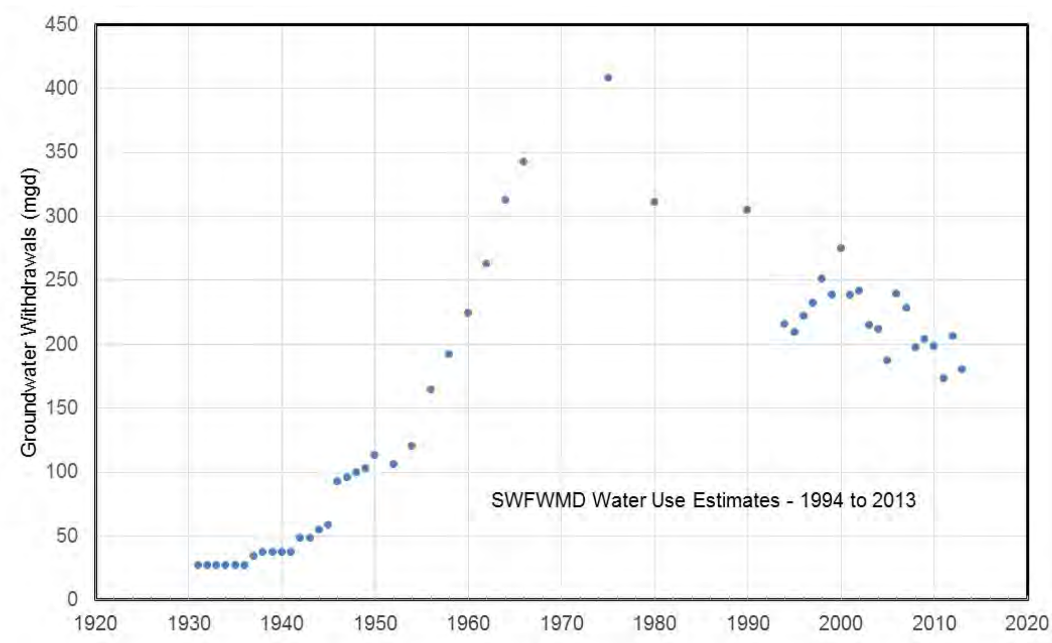

Figure 7. Total groundwater withdrawals in Polk County.

Figure 8 summarizes groundwater withdrawals in the SWFWMD portion of Polk County since 1994 by major water use type. Over this period, withdrawals for agriculture and mining/dewatering have steadily declined. Public supply withdrawals, however, increased until 2006 but since that time have returned to withdrawal levels experienced during earlier portions of the period. Factors that have been cited for declines in agricultural use include uncertainties associated with citrus greening and canker and increased urbanization, which is evidenced by reductions in citrus acreage that have occurred in the county. With respect to public supply, the economic recession that began in 2006 has been cited as a potential influence in the recent reductions that have occurred. Because permitted groundwater withdrawal quantities have remained fairly constant (with the exception of how agriculture has been permitted in the Southern Water Use Caution Area (SWUCA) since 2003), the permanancy of these declines is uncertain. As part of the SWUCA Recovery Strategy, the District continues to work with users to develop alternative water supplies to meet water demands while reducing groundwater withdrawals when possible.

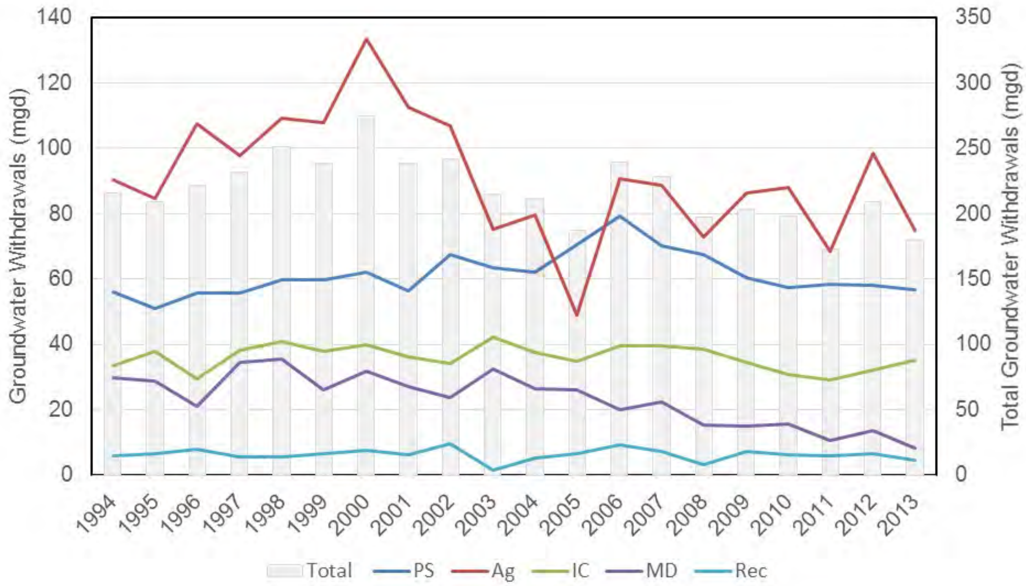

Figure 8. Estimated groundwater use in Polk County by use type (1994-2013)

The long-term response of groundwater levels to changes in the different hydrologic factors were assessed through use of cumulative mass plots where cumulative groundwater levels were plotted versus cumulative Polk County rainfall totals (county-wide averages from several stations published by the District). A straight-line relationship between these plotted values is an indication that the relationship between them is unchanged for the period evaluated. If a long-term change in groundwater withdrawals were to occur, a deviation from the straight line would be expected. Figure 9 is a cumulative mass plot of water levels in the ROMP 57 Upper Floridan aquifer monitor well (SID 25343) versus county rainfall. The plot shows a small break in the early 1990s, and then a stable period since. Because consistent data collection doesn't begin at this well until the late 1980s, very little data prior to the break can be presented. Figure 10 presents a similar cumulative mass plot using data from the Coley Deep (SID 25339) Upper Floridan aquifer monitor well, located several miles south and east of ROMP 57. This well has significantly more data, but a similar break can be seen in the early 1990s (along with other breaks prior to the early 1990s). Both Figures 9 and 10, along with the withdrawal data seen in Figures 7 and 8, show evidence of the general change in water withdrawals in Polk County starting in the early 1990s.

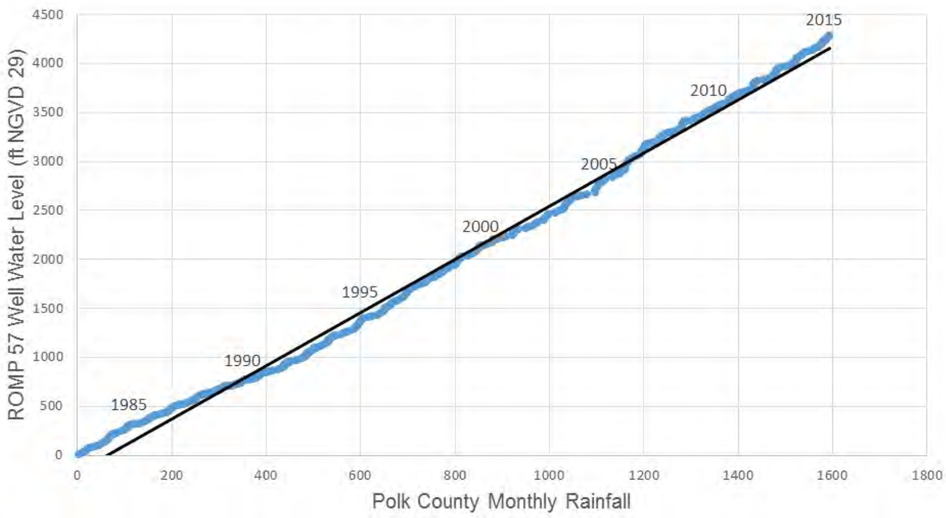

Figure 9. Cumulative double mass curve of ROMP 57 Upper Floridan aquifer monitoring well and Polk County-wide rainfall (1983 to 2014).

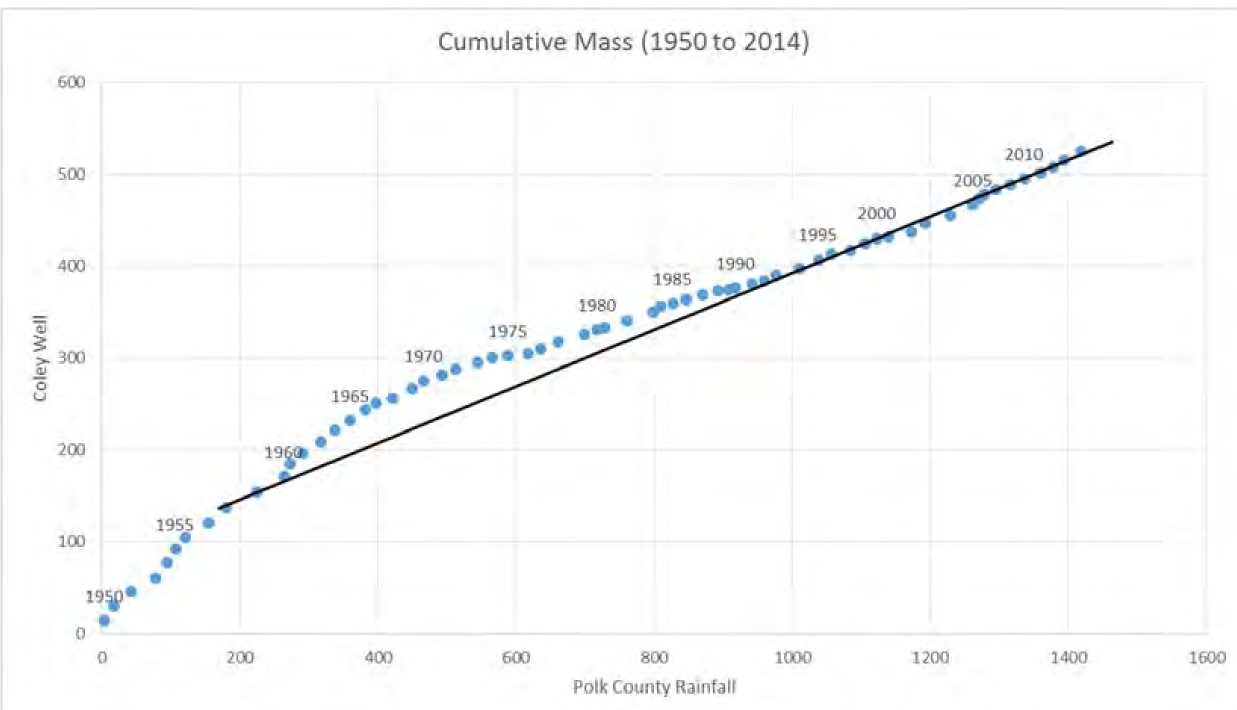

Figure 10. Cumulative double mass curve of the Coley Deep Upper Floridan aquifer monitoring well and Polk County-wide rainfall (1950 to 2014).

C. Purpose of Models

Prior to establishment of Minimum Levels, long-term lake stage percentiles are developed to serve as starting elevations for determination of the lake's High Minimum Lake Level and the Minimum Lake Level. A critical task in this process is the delineation of a Historic time period. The Historic time period is defined as a period of time when there is little to no groundwater withdrawal impact on the lake, and the lake's structural condition is similar or the same as present day. The existence of data from a Historic time period is significant, since it provides the opportunity to establish strong predictive relationships between rainfall, groundwater withdrawals, and lake stage fluctuation that represent the lake's natural state in the absence of groundwater withdrawals. This relationship can be used to calculate long-term Historic lake exceedance percentiles such as the P10, P50, and P90, which are, respectively, the water levels equaled or exceeded ten, fifty, and ninety percent of the time. If data representative of a Historic time period do not exist, or available Historic time period data is considered too short to represent long-term conditions, then a model is developed to approximate long-term Historic data.

In the case of Crooked Lake, withdrawals throughout the area have potentially affected water levels in the lake since about the early 1960s. The development of a water budget model coupled with a rainfall regression model of the lake was considered essential for estimating long-term Historic percentiles, accounting for changes in the lake's drainage system, and simulating effects of changing groundwater withdrawal rates.

D. Water Budget Model Overview

The Crooked Lake water budget model is a spreadsheet-based tool that includes natural hydrologic processes and engineered alterations acting on the control volume of the lake. The control volume consists of the free water surface within the lake extending down to the elevation of the greatest lake depth. Using LiDAR and bathymetry data, a stage-volume curve was derived for the lake that produced a unique lake stage for any total water volume within the control volume.

The hydrologic processes in the water budget model include:

a. Rainfall and evaporation
b. Overland flow
c. Inflow and discharge via channels
d. Flow from and to the surficial aquifer
e. Flow from and to the Upper Floridan aquifer

The water budget model uses a daily time step, and tracks inputs, outputs, and lake volume to calculate a daily estimate of lake levels. The model was calibrated for the period 1988 to 2014. This period provides the best balance of using available data for all components of the water budget and the desire to develop a long-term water level record.

E. Water Budget Model Components

Lake Stage/Volume

Lake stage-area and stage-volume estimates were determined by building a terrain model of the lake and surrounding watersheds. Lake bottom elevations and land surface elevations were used to build the model with LP360 (by QCoherent) for ArcGIS, ESRI's ArcMap 10.1, the 3D Analyst ArcMap Extension, Python, and XTools Pro. The overall process involves merging the terrain morphology of the lake drainage basin with the underlying lake basin morphology to develop one continuous three-dimensional (3D) digital elevation model. The 3D digital elevation model was then used to calculate area of the lake and the associated volume of the lake at different elevations, starting at the extent of the lake at its flood stage and working downward to the lowest elevation within the basin.

Precipitation

After a review of several rain gages in the area and NEXRAD (Next Generation Weather Radar), a composite dataset of rainfall data was established (Figure 11). Distance from the lake, data availability and reasonableness, and effects on model calibration were considered when creating the composite dataset. The data used from January 1, 1988 through December 31, 2000 were the Coley gage (SID 25155), ROMP 44 Warner Southern College gage (SID 25544), Avon Park 2W NWS gage (25508) and NEXRAD.

Data from the ROMP 44 gage were prioritized for use in the model, then the Coley gage and finally the Avon Park gage. Because the ROMP 44 gage doesn't begin until 2001, the Coley gage was mostly used from 1998 until 2001. Beginning in 2007 rainfall used was obtained from an average of NEXRAD rainfall over the watershed. Several different combinations of rainfall gages were used throughout the process of building the model. A difficult factor for Crooked Lake is the size of the lake. It is easy to see that a rainfall event on one end of the lake may not occur at the other end of the lake. The selection of these gages for use in the final model were based on how well they matched the response of the lake. The useful aspect of the NEXRAD data is that you are able to obtain an area weighted rainfall over the watershed versus a point estimate at a gage.

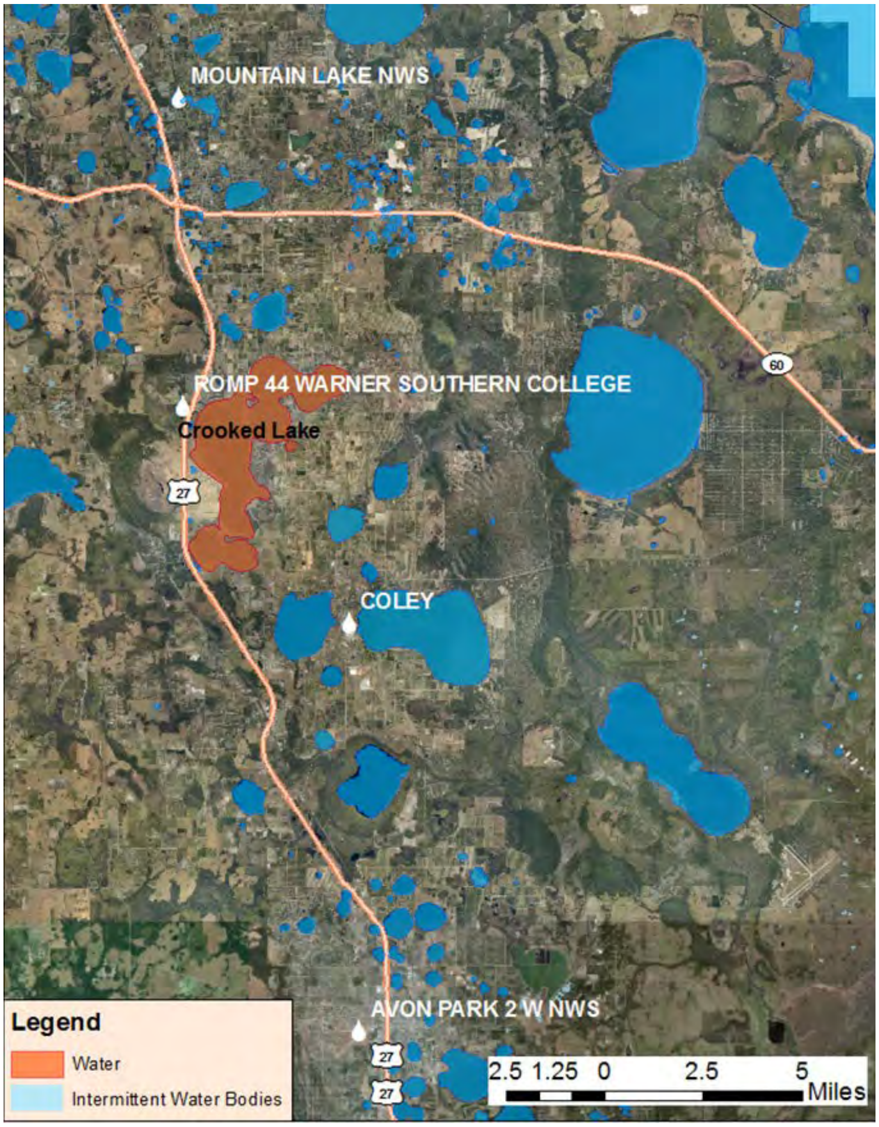

Figure 11. Rain gages used in the Crooked Lake water budget model.

Lake Evaporation

Lake evaporation was estimated through use of monthly energy budget evaporation data collected by the U.S. Geological Survey (USGS) at Lake Starr in Polk County (Swancar et al., 2000) (Figure 12). Lake Starr is located approximately 3.5 miles to the northwest of Lake Wales. The data were collected from August of 1996 through July of 2011. Monthly Lake Starr evaporation data were used in the water budget model when available, and monthly averages for the period of record were used for those months when Lake Starr evaporation data were not available.

Jacobs (2007) produced daily potential evapotranspiration (PET) estimates on a 2-square kilometer grid for the entire state of Florida. The estimates began in 1995, and are updated annually. These estimates, available from the USGS, were calculated through use of solar radiation data measured by a Geostationary Operational Environmental Satellite (GOES). Because PET is equal to lake evaporation over open water areas, using the values derived from the grid nodes over the modeled lake was considered. A decision was made to instead use the Lake Starr evaporation data since the GOES data nodes typically include both upland and lake estimates, with no clear way of subdividing the two. It was thought that using the daily PET estimates based on the GOES data would increase model error more than using the Lake Starr data directly.

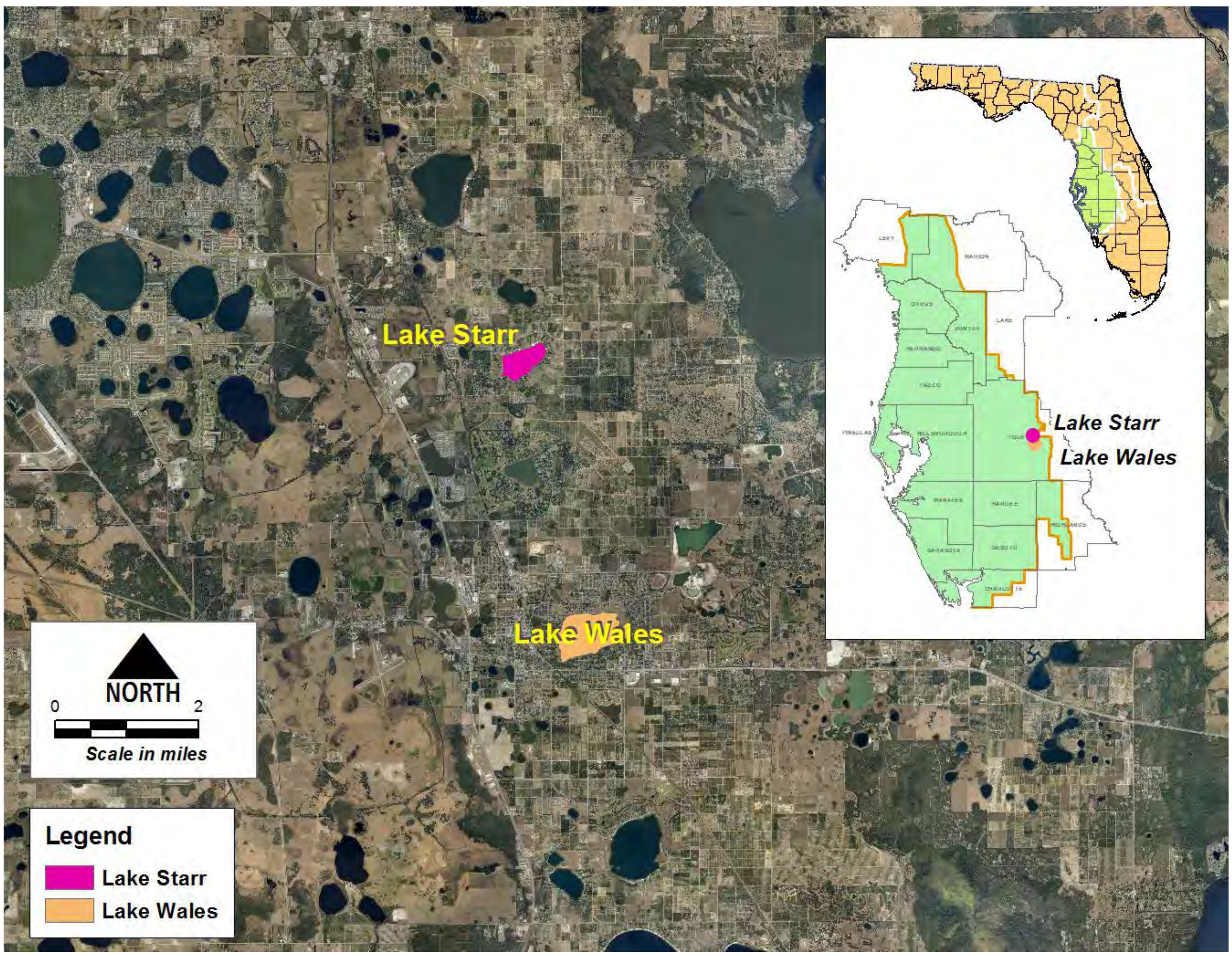

Figure 12. Location of Lake Starr north of Lake Wales.

Overland Flow

The water budget model was set up to estimate overland flow via a modified version of the U.S. Department of Agriculture, Soil Conservation Service (SCS) Curve Number method (SCS, 1972), and via directly connected impervious area calculations. The free water surface area of the lake was subtracted from the total watershed area at each time step to estimate the watershed area contributing to surface runoff. The directly connected impervious area (DCIA) is subtracted from the watershed area for the SCS calculation, and then added to the lake water budget separately. Additionally, the curve number (CN) chosen for the watershed of the lake only represents the portion of the watershed not accounted for with DCIA.

The modified SCS method was described and suggested for use in Florida by CH2M HILL (2003), and has been used in several other analyses. The modification adds a fourth category of antecedent moisture condition (AMC) to the original SCS method (SCS, 1972) to account for Florida's frequent rainfall events.

The northern and eastern portions of the lake are adjacent areas of relatively high land surface elevations (150 feet to about 300 feet) and slopes associated with the Lake Wales Ridge whereas the area contributing runoff to the western and southern portions of the lake have lower elevations (120 feet to 130 feet) and much gentler slopes. The watershed for Crooked Lake was based on identifying the topographic drainage area (Figure 13). At a lake elevation of 118 feet, the lake covers an area of about 5,574 acres (8.7 square miles) and the contributing area covers an area of about 15,299 acres (23.9 square miles) for a total area of about 20,873 acres (32.6 square miles).

The DCIA and SCS CNs used for the direct overland flow portion of the watershed are listed in Table 2. The soils in the immediate lake watershed are mostly either "A" or "A/D" soils, with some smaller areas of "B/D" and "C/D" soils (Figure 14). The northern and eastern contributing areas are mostly associated with the A soils except along the lake shoreline where much of the area is associated with the A/D soils. The B/D and C/D soils are mostly found in western portions of the contributing area. In the water budget model, surface runoff was broken into two contributing area, one representing the northern and eastern portions of the watershed (about 40 percent of the area) and the other representing the western and southern portions of the watershed (about 60 percent of the area). Land use in the watershed is mostly agricultural, urban/built up, and wetlands. A curve number (model calibration parameter) of 50 was used for the northern and eastern portions of the watershed and a curve number of 80 was used to represent the western and southern portions of the watershed to represent the respective soil types and land uses. The DCIA parameter was used in addition to the curve number parameter to account for connected impervious areas that provide direct runoff to the lake through storm water systems. While there are no significant natural surface water inflows to the lake, there are several directly connected drains in the area. It was estimated that 16 percent of the watershed (model calibration parameter) is directly connected impervious area, which was considered reasonable given current land use types. At elevations above 118 feet this value was increased to 25 percent to account for additional contributions from the western portion of the contributing area, an area consisting of man-made drainage canals in pasture lands.

Table 2. Model inputs for the Crooked Lake water budget model.

Input Variable	Value
Lake area at 118 feet	5,574
Contributing area for lake at 118 feet	15,299
Total area (lake and contributing area)	20,873
SCS CN for watershed	50 and 80
Percent Directly Connected Area	17 percent (25 percent – lake above 118)
UFA Monitor Well Used	ROMP CL-1
Surf. Aq. Monitor Wells Used to Simulate surficial aquifer inflow/outflow	ROMP CL-1 ROMP 44 Ridge WRAP CLP-1
FL Aq. Leakance Coefficient (ft/day/ft)	0.00033
Surf. Aq. Conductance – ROMP CL-1 (ft/day/ft)	0.0014
Surf. Aq. Conductance – ROMP 44 (ft/day/ft)	0.00001
Surf. Aq. Conductance – RW CLP-1 (ft/day/ft)	0.0025
Outflow K	0.0035
Outflow Invert (ft NGVD 29)	120
Inflow K	0.001
Inflow Invert (ft NGVD 29)	113

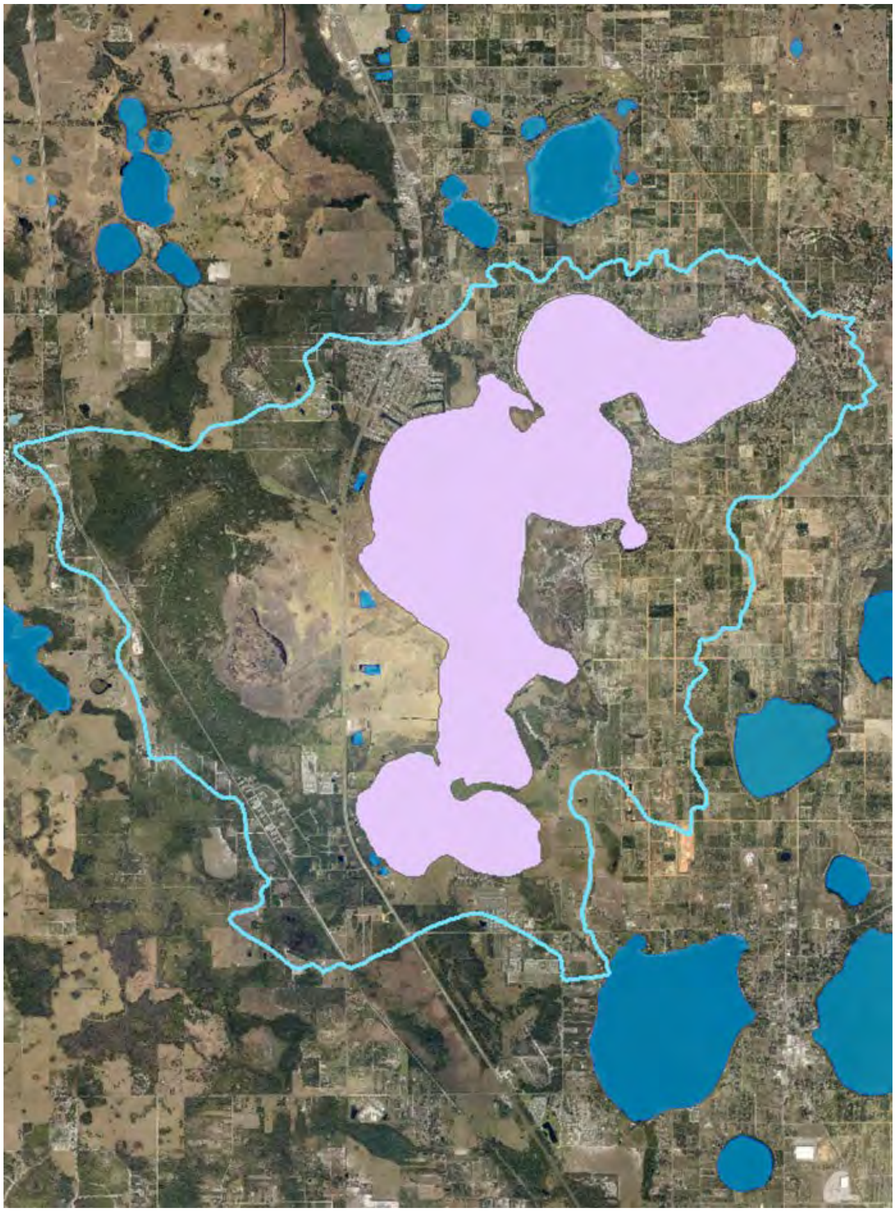

Figure 13. The Crooked Lake watershed.

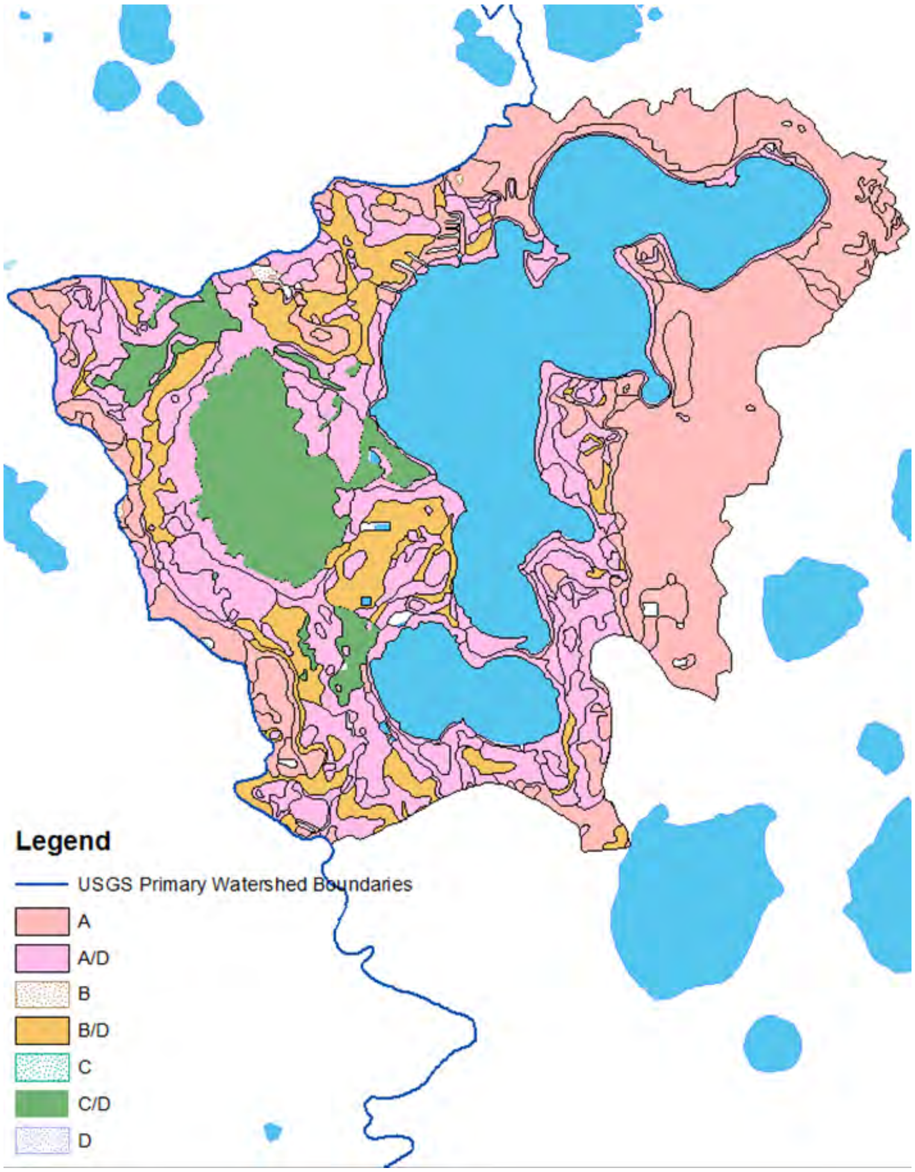

Figure 14. Soil types within the Crooked Lake watershed.

Inflow and Discharge via Channels from Outside Watersheds

Though there is no surface water inflow from outside the watershed, the water budget model was set-up to simulate water levels associated with “Big” Crooked Lake as separate from Little Crooked Lake (the two southerly lobes) at elevations below 115 feet. Flow from little Crooked Lake would occur via a small channel that connects the western lobe to the bigger lake at elevations above 113 feet and at elevations of 115 or greater, all lobes of the lake were assumed to be sufficiently connected to simulate one lake.

Surface water outflow occurs via an open ditch at the southern end of Little Crooked Lake (eastern love). The invert elevation of the ditch is 120 feet. The ditch is reported (Jeff Spence, Polk County Natural Resources Division, personal communication) to have been constructed in the 1880s and modified in the 1940s and 1950s (Bradbury et. al., 1978)

Flow from and into the surficial aquifer and Upper Floridan aquifer

Water exchange between Crooked Lake and the underlying aquifers is estimated using a vertical leakance coefficient and the head difference between the lake and aquifer levels. For each day of the simulation period, the volumes of water exchanged between the lake and surficial aquifer and the lake and Upper Floridan aquifer were calculated independently. The surficial aquifer conductance terms and Upper Floridan aquifer leakance coefficient were then determined through calibration.

Data from three different areas around the lake were used to simulate surficial aquifer leakage for each model time step. Water level data from ROMP CL-1 surficial aquifer well and Ridge WRAP CLP-1 were used to simulate interactions with the surficial aquifer to the north and east. Interaction in remaining portions of the watershed were represented using the ROMP 44 surficial aquifer well.

F. Water Budget Model Approach

The primary reason for development of the water budget model was to estimate Historic lake stage exceedance percentiles that could be used to support development of Minimum and Guidance Levels for the lake. Model calibration was therefore focused on matching long-term percentiles based on measured water levels, rather than short-term high and low levels. Model calibration statistics that are reported are based on comparison of pairs of daily measured and modeled water levels.

Figure 15 presents the model calibration results. Table 3 presents a comparison of the percentiles of the measured data versus the model results. Table 4 presents the modeled water budget components for the calibration period.

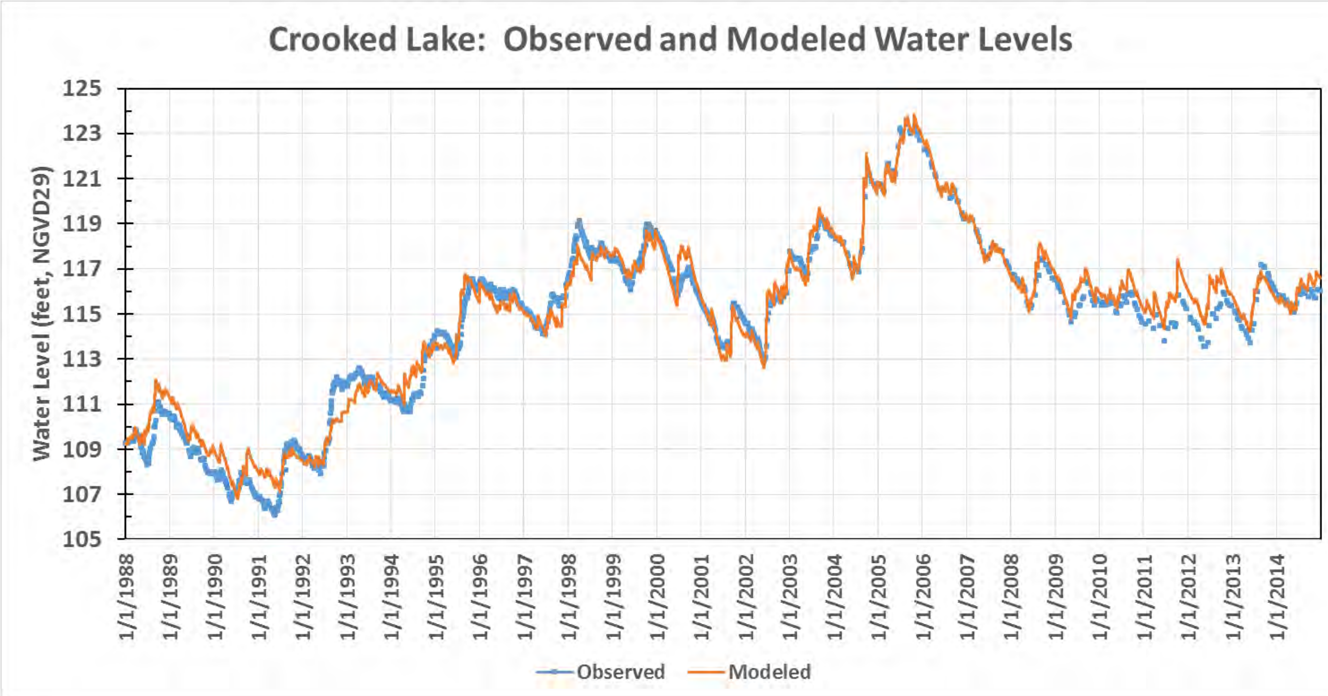

Figure 15. Comparison of observed and modeled lake levels.

Table 3. Comparison of percentiles for observed and modeled lake levels for the period 1988 to 2014 (feet NGVD 29).

	Observed	Modeled
P10	118.3	118.1
P50	115.8	115.9
P90	113.1	113.0

Table 4. Crooked Lake Water Budget (1988-2014): Summary of average annual inflows and outflows represented over the average lake surface area

Inflows	Rainfall	Surficial Aquifer Ground-water Inflow	Floridan Aquifer Ground-water Inflow	Runoff	DCIA Runoff	Inflow via channel	Total
In/yr	47.2	32.2	0.0	20.1	25.4	1.6	126.5
%	37.3	25.5	0.0	15.9	20.1	1.3	100.0

Outflows	Evap-oration	Surficial Aquifer Ground water Outflow	Floridan Aquifer Ground-water Outflow			Outflow via channel	Total
In/yr	55.7	38.1	26.9			2.7	123.4
%	45.1	30.9	21.8			2.2	100.0

Area of lake at 115 feet is 7.63 mi^2
Average area contributing runoff when lake is at 115 feet is 25.08 mi^2
Total area is 32.71 mi^2

G. Water Budget Model Calibration Discussion

Based on visual inspection of Figure 15 the model appears to be reasonably well calibrated. There are a few periods when the peaks or lows in the modeled hydrograph are higher or lower than the measured values, and these differences contributed to minor differences between the modeled and measured percentiles associated with the P90 percentile. Data limitations in the extreme ranges of the topography/bathymetry used to develop stage-volume estimates may also have contributed to the percentile difference.

A review of Table 3 shows that the observed percentiles were 0.2 feet higher for the P10, 0.1 feet lower for the median or P50 percentile and 0.1 feet higher for the P90. These minor difference could be attributed to inaccuracies in rainfall estimates caused by the distance between rainfall gages and the lake during certain time periods or data collection frequency issues. Other measures of calibration were also used to characterize model performance. The mean absolute error (MAE) was 0.5 feet, the Root Mean Square Error (RMSE) was 0.63 feet and the Nash-Sutcliffe Efficiency (NSE) was 0.97.

The water budget model results are best viewed in terms of inches per year over the average lake area for the period of the model run, which can be difficult to comprehend at first (Table 4). For example, runoff for the entire watershed is applied to the smaller lake area, which makes the value appear high until the differences in application area are considered. For example, whereas the amount of leakage to the Upper Floridan aquifer was 26.9 inches per year over the lake surface area at an elevation of 115 feet, when converted to the total area (lake plus contributing area) the same volume of water is equivalent to 6.3 inches per year. Professional judgement and decisions were used to match the modeled lake levels with observed data and arrive at the ultimate goal of developing a calibrated model. Even though data gaps as well as uncertainties in the values of model parameters have caused some differences between the model and observed data, the model is reasonably well calibrated and can be used to estimate the long term historic percentiles. Following is a summary of major items evaluated during model calibration to judge model results:

- The leakance coefficient used to represent the interconnection between the lake and underlying Upper Floridan aquifer was determined to be 0.00033 day^{-1}, which is comparable to modeled values reported for this area by Sepulveda (2012) and Yobbi (1996).
- Leakage to the UFA (6.3 inches over the total area) combined with surficial groundwater outflow (38.1 inches over the lake area or 8.9 inches over the total area) represents potential recharge to the UFA ranging from 6.3 to 15.2 inches per year over the entire area. These numbers are in the expected range of values reported in previous studies.
- Surficial aquifer inflow is within the range of estimate recharge to the water table for estimated evapotranspiration rates ranging from 25 to 30 inches per year.

H. Water Budget Model Results

Groundwater withdrawals are not directly included in the Crooked Lake water budget model, but are indirectly represented by their effects on water levels in the Upper Floridan aquifer. When a relationship between withdrawal rates and Upper Floridan aquifer potentiometric levels can be established, the effect of changes in groundwater withdrawals can be estimated by adjusting Upper Floridan aquifer levels in the model.

Determining the amount of Upper Florida aquifer drawdown that has occurred due to groundwater withdrawals involved the use of a regional groundwater model and analysis of water level data. The East-Central Florida Transient (ECFT) groundwater model (Sepulveda, et al., 2012 and CFWI, 2014) was used to quantify changes in water levels in response to changes in groundwater withdrawals. This was accomplished using a series of model runs whereby recent withdrawals and irrigation amounts were reduced by 25 percent, 50 percent, and 75 percent. This approach enabled the model to be used within the range of withdrawals that were used during the calibration phase. For the reassessment of minimum levels, the reduced pumping scenarios used a Reference Condition as a basis for comparing model reduction scenarios. The Reference Condition was based on the amount of groundwater withdrawals needed to meet the demands for water that existed as of 2005. Pumping amounts for each year and month of the 12 year transient model run were varied according to rainfall that occurred during each month. Based on the model scenarios it was estimated that modeled groundwater withdrawals have lowered Upper Floridan aquifer water levels about 7 feet beneath Crooked Lake.

During evaluation of the reduced pumping scenarios, an assessment of long-term changes in water levels was also conducted to verify model results. The evaluation focused on water levels in the ROMP 57 and ROMP 57X Upper Floridan aquifer wells located near Lake Wales; the Coley Deep well (SID 25339), located near the City of Frostproof; the ROMP 60 Upper Floridan aquifer abandoned (SID 17974) and replacement (SID 77757) wells located near the City of Mulberry; and the Claude Hardin Upper Floridan aquifer well (SID 17966), located near the City of Mulberry. This was done using water level data averaged over different periods, for example annual and monthly, and single months such as September, May and December. For each regression analysis, the regression parameters were determined using data for the period 1988 to 2014, which is the time period used for the water budget model. These parameters were then used to estimate water levels for the period available for the respective independent well levels (Coley Deep and ROMP 60 Upper Floridan aquifer). For the regression analyses, estimates of long-term changes in groundwater levels ranged from about 3.5 feet to 9 feet. It was ultimately determined that 6.2 feet of drawdown at the CL-1 site obtained from the ECFT model would be used in this analysis. With respect to the surficial aquifer, the relationship between the leakance coefficient and the ratio of surficial aquifer to Upper Floridan aquifer drawdowns established for previous modeling efforts was used. From the water budget model, the leakance coefficient was 0.00033 feet/day/feet which resulted in a ratio of surficial to Upper Floridan drawdown of 0.25. The resulting recovery in the surficial aquifer was then estimated as the product of this ratio and the estimated Upper Floridan aquifer recovery amount (6.2 feet) or 1.55 feet. Because the ECFT model indicated only small drawdown amounts in the west/southwest portions of the watershed, the surficial aquifer drawdown was not applied to the ROMP 44 well in the recovery analysis.

Figure 16 presents the results of the calibrated water budget model for Crooked Lake with and without the effects of groundwater withdrawals. Table 5 presents the percentiles based on model output.

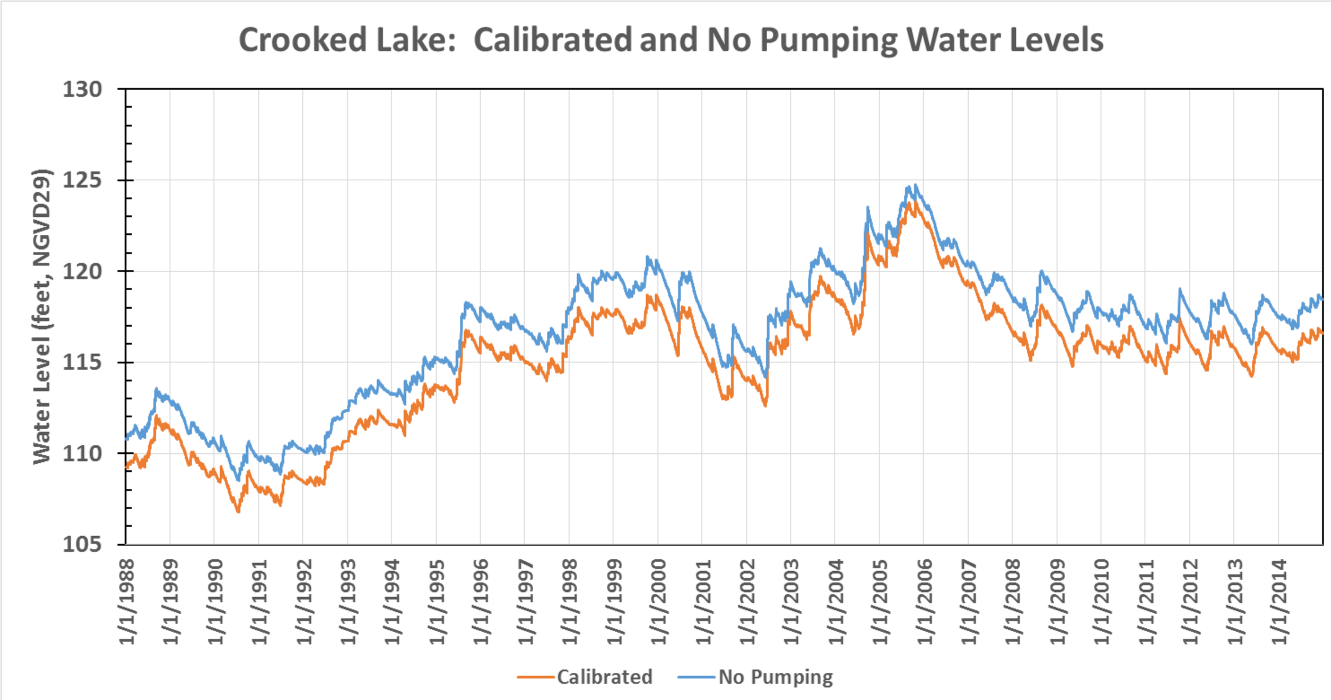

Figure 16. Calibrated Water Budget Model for Crooked Lake with and without the effects of withdrawals.

Table 5. Lake level percentiles determined using the water budget model with withdrawal effects removed for the period 1988-2014 (feet NGVD 29).

Percentile	Elevation
P10	120.5
P50	117.5
P90	110.5

I. Rainfall Regression Model

In an effort to extend the period of record of water levels used to determine the Historic percentiles to be used in the development of the Minimum Levels, a line of organic correlation (LOC) was performed using the results of the water budget model and long-term rainfall data. The LOC is a linear fitting procedure that minimizes errors in both the x and y directions and defines the best-fit straight line as the line that minimizes the sum of the areas of right triangles formed by horizontal and vertical lines extending from observations to the fitted line (Helsel and Hirsch, 2002). LOC is preferable for this application since it produces a result that best retains the variance (and therefore best retains the "character") of the original data. By using this technique, the limited years of calibrated model water levels can be projected back to create a simulated data set representing over 60 years of lake levels, based on the relationship between modeled water levels and actual rainfall.

In this application, the simulated lake water levels representing Historic conditions were correlated with long-term rainfall data. For the rainfall regression analysis, additional representative rainfall records were added to the rainfall data used in the water budget model (1988-2014), extending the rainfall record back to 1930. The record consisted of daily rainfall measurements from the closest rain gage and, missing daily data values were infilled from the next closest gage with available data until all days were populated with rainfall data. The data used for the period 1988 to 2014 were the same as used in the water budget model and described previously. Prior to 1988 the data used were the Avon Park 2W NWS gage (25508) infilled with data from the Mountain Lake NWS gage (SID 25147). It was necessary to use the Avon Park and Mountain Lake gages for the historic information because the other rainfall data did not exist prior to 1988.

Rainfall data were correlated to lake level data by applying a linear inverse weighted sum to the rainfall using a concept described by Merritt (2001). The weighted sum gives higher weight to more recent rainfall and less weight to rainfall in the past. In this application, weighted sums varying from 6 months to 10 years were separately used, the results were compared, and the weighted rainfall series with the highest coefficient of determination (R^2) was chosen as the best model.

Rainfall was correlated to the water budget model results for the current period, 1995 to 2014, and the results from 1946-2014 (69 years) were produced. The final 6-year weighted model had the highest coefficient of determination, with R^2 of 0.83. The results are presented in Figure 17.

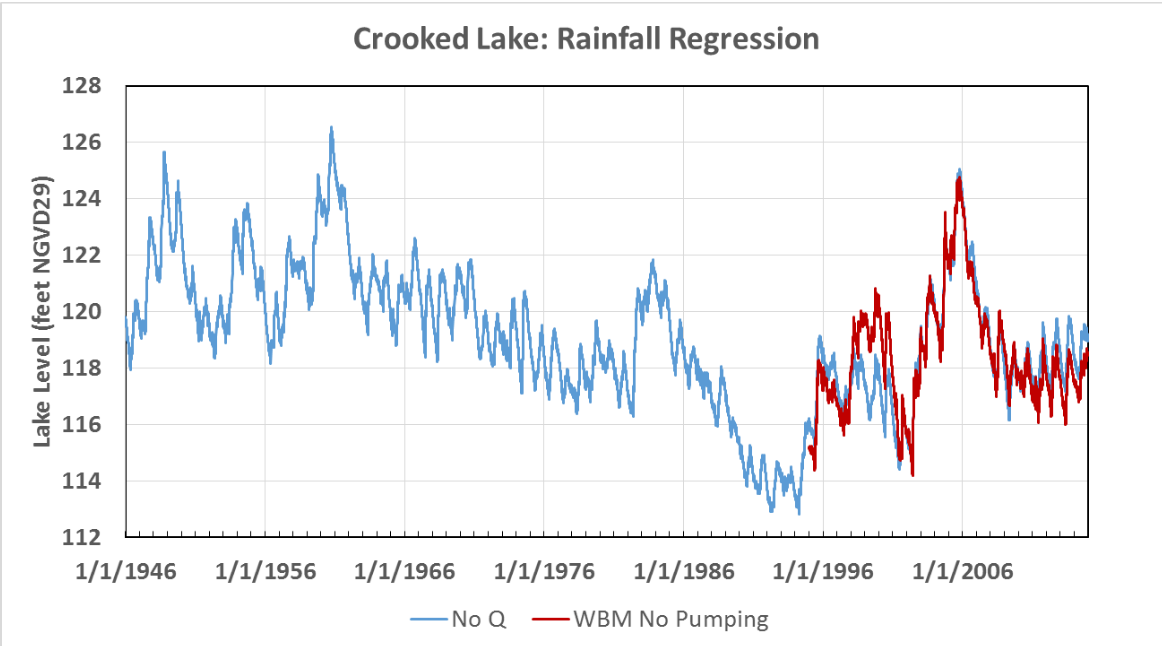

Figure 17. LOC model results for Crooked Lake, calibrated using water budget model results for the period 1995 to 2014 with pumping effects removed.

Because Crooked Lake has measured lake level data going back to 1946, and the period from 1946 to 1964 is considered to be minimally influenced by pumping, the rainfall regression analysis was modified in order to produce the final Historic percentiles. That is, data from the regression was replaced with actual measured lake levels data for the period 1946 to 1964. This was done to minimize potential error in estimating historical levels. Figure 18 depicts the final Historic water levels and the resulting Historic percentiles are presented in Table 6.

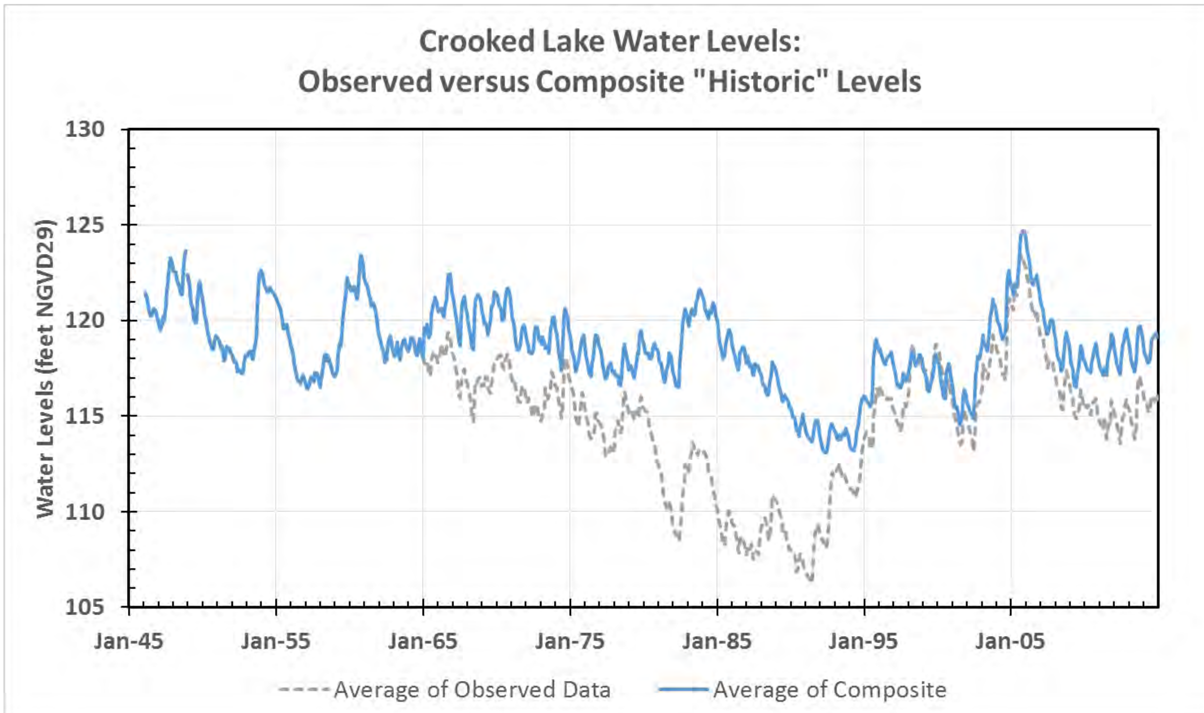

Figure 18. Composite Historic lake levels (hybrid model results) using actual data (1946 to 1964) and rainfall regression results (1965 to 2014).

Table 6. Historic percentiles as estimated using the hybrid model from 1946 to 2014 (feet NGVD 29).

Percentile	Crooked Lake
P10	121.5
P50	118.5
P90	115.9

J. Conclusions

Based on the model results and the available data, the Crooked Lake water budget and LOC rainfall models are useful tools for assessing long-term percentiles in the lake. Based on the same information, lake stage exceedance percentiles developed through use of the models appear to be reasonable estimates for Historic conditions.

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APPENDIX B

Draft Technical Memorandum

October 3, 2016

TO: Jerry L. Mallams, P.G., Manager, Resource Evaluation Section

FROM: Mark D. Barcelo, P.E., Chief Professional Engineer, Resource Evaluation Section

Subject: Crooked Lake Initial Minimum Levels Status Assessment

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A. Introduction

The Southwest Florida Water Management District (District) is reevaluating adopted minimum levels for Crooked Lake and is proposing revised minimum levels for the lake, in accordance with Section 373.042 and 373.0421, Florida Statutes (F.S). Documentation regarding development of the revised minimum levels is provided by McBride and Barcelo (2015) and Ghile and others (2015).

Section 373.0421, F.S. requires that a recovery or prevention strategy be developed for all water bodies that are found to be below their minimum flows or levels, or are projected to fall below the minimum flows or levels within 20 years. In the case of Crooked Lake and other waterbodies with established minimum flows or levels in the Southern Water Use Caution Area (SWUCA), an applicable regional recovery strategy, referred to as the SWUCA Recovery Strategy, has been developed and adopted into District rules (Rule 40D-80.074, F.A.C.). One of the goals of the SWUCA Recovery Strategy is to achieve recovery of minimum flow and level water bodies such as Crooked Lake. This document provides information and analyses to be considered for evaluating the status of the revised minimum levels proposed for Crooked Lake and any recovery that may be necessary for the lake.

B. Background

Crooked Lake is located near the town of Babson Park in east-central Polk County, about 12 miles south of the intersection of U.S. Highway 27 and State Road 60 in the City of Lake Wales (Figure 1). The lake is located on the Lake Wales Ridge and is within the Kissimmee River watershed.

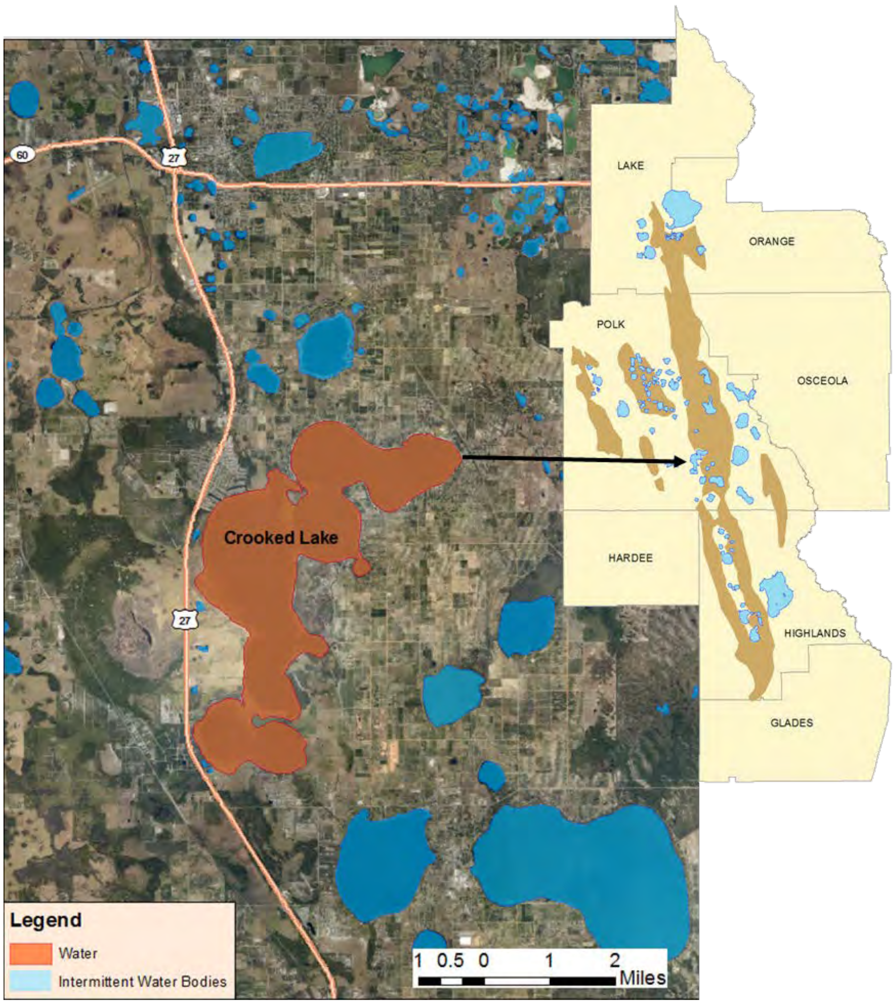

Figure 1. Location of Crooked Lake in Polk County, Florida

C. Revised Minimum Levels Proposed for Crooked Lake

Revised minimum levels proposed for Crooked Lake are presented in Table 1 and discussed in more detail by Campbell and others (2016). Minimum levels represent long-term conditions that, if achieved, are expected to protect water resources and the ecology of the area from significant harm that may result from water withdrawals. The Minimum Lake Level is the elevation that a lake's water levels are required to equal or exceed fifty percent of the time on a long-term basis. The High Minimum Lake Level is the elevation that a lake's water levels are required to equal or exceed ten percent of the time on a long-term basis. The Minimum Lake Level therefore represents the required 50th percentile (P50) of long-term water levels, while the High Minimum Lake Level represents the required 10^{th} percentile (P10) of long-term water levels. To determine the status of minimum levels for Crooked Lake or minimum flows and levels for any other water body, long-term data or model results must be used.

Table 1. Proposed Minimum Levels for Crooked Lake.

Proposed Minimum Levels	Elevation in Feet NGVD 29
High Minimum Lake Level	120.7
Minimum Lake Level	117.7

D. Status Assessment

The lake status assessment approach involves using actual lake stage data for Crooked Lake from 1995 through 2015, which was determined to represent the “Current” period. The Current period represents a recent “Long-term” period when hydrologic stresses (including groundwater withdrawals) and structural alterations are reasonably stable. “Long-term” is defined as a period that has been subjected to the full range of rainfall variability that can be expected in the future. As demonstrated in Barcelo (2016), groundwater withdrawals during this period were relatively consistent. To create a data set that can reasonably be considered to be “Long-term,” a rainfall regression model, using the line of organic correlation (LOC), was developed using lake level data from the Current period. The LOC is a linear fitting procedure that minimizes errors in both the x and y directions and defines the best-fit straight line as the line that minimizes the sum of the areas of right triangles formed by horizontal and vertical lines extending from observations to the fitted line (Helsel and Hirsch, 2002). The LOC is preferable for this application since it produces a result that best retains the variance (and therefore best retains the "character") of the original data. This technique was used to develop the minimum levels for Crooked Lake (Campbell, 2016). By using this technique, the limited years of Current lake level data can be projected back to create a simulated data set representing over 60 years of lake levels, based on the current relationship between lake water levels and actual rainfall.

The same rainfall data set used for setting the minimum levels for Crooked Lake was used for the status assessment. The best resulting correlation for the LOC model created with measured data was the 6-year weighted period (the best correlation for the LOC analyses created with Historic data to set the Crooked Lake MFL was 6 years), with a coefficient of determination of 0.81. The LOC model was then modified to create an LOC/hybrid model by replacing modeled data with actual measured data for the period 1995 to 2015. The resulting lake stage exceedance percentiles are presented in Table 2.

As an additional piece of information, Table 2 also presents the same percentiles calculated directly from the measured lake level data for Crooked Lake for the period from 1995 through 2015. A limitation of these values is that the resulting lake stage exceedance percentiles are representative of rainfall conditions during only the past 21 years, rather than the longer-term rainfall conditions represented in the 1946 to 2015 LOC model simulations.

Table 2. Comparison of lake stage exceedance percentiles for Crooked Lake.

Percentile	Status: Long-term LOC/Hybrid Model Calibrated to Current Conditions[a] (feet NGVD 29)	1995 to 2015 Data (feet NGVD 29)[b]	Proposed Minimum Levels (feet NGVD 29)
P10	121.1	119.9	120.7
P50	117.6	116.1	117.7

[a]Values represent percentiles for the period 1946 to 2015. LOC calibrated using actual data from 1995 to 2015. Daily values converted to monthly average values
[b]Based on monthly averages of available measured data for the period 1995 to 2015

A comparison of the LOC/hybrid model with the revised minimum levels proposed for Crooked Lake indicates the Long-term P10 is 0.4 feet higher than the proposed High Minimum Lake Level, and the Long-term P50 is 0.1 feet lower than the proposed Minimum Lake Level. The P10 elevation derived directly from the 1995 to 2015 lake data is 0.8 feet lower than the proposed High Minimum Lake Level and the P50 elevation is 1.6 feet lower than the proposed Minimum Lake Level. Differences in rainfall between the two periods (1995 to 2015 versus 1946 to 2015), likely contribute to the differences between derived and measured lake stage exceedance percentiles. Additionally, differences between actual withdrawal rates and those used in the models may have contributed to some of the differences in the percentiles.

E. Conclusions

Based on the information presented in this memorandum, it is concluded that Crooked Lake water levels are currently below the revised Minimum Lake Level, and above the revised High Minimum Lake Level proposed for the lake. These conclusions are supported by comparison of percentiles derived from LOC modeled lake stage data with the proposed minimum levels.

Minimum flow and level status assessments are completed on an annual basis by the District and on a five-year basis as part of the regional water supply planning process. In addition, Crooked Lake is included in the Recovery Strategy for the Southern Water Use

Caution Area Recovery Strategy (40D-80.074, F.A.C). Therefore, the analyses outlined in this document will be reassessed by the District as part of this plan.

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