APPENDIX A— PHYSIOGRAPHY OF LAKES BROOKLYN AND GENEVA, BRADFORD AND CLAY COUNTIES, FLORIDA

Lakes Brooklyn and Geneva are among the most studied and modeled in the St. Johns River Water Management District (SJRWMD; Table 1). The following provides a brief summary of the physiographic setting of Lakes Brooklyn and Geneva.

PHYSIOGRAPHY

The physiography of Florida, as described by Brooks (1981), is broken up into districts and subdivisions based on soil taxonomy, geological structure of native rocks, geomorphic processes, and topography. Districts and subdivisions tend to have defining vegetative communities distinctive to each subdivision. The Keystone Heights area, where lakes Brooklyn and Geneva are located, is situated in the Interlachen Sand Hills subdivision of the Central Lakes District. Characteristics of the Central Lake District include undulating surficial sand depth overlying the Floridan Aquifer along with areas of rapid hydraulic conductivity caused by sinkhole formation connecting lakes to the aquifer system (Brooks, 1981). The Interlachen Sand Hills subdivision is defined by direct hydraulic connectivity between lakes and the aquifer system (Schiffer, 1998, Kindinger, 1999). This leads to lake stage and potentiometric surface of the Floridan Aquifer being intimately intertwined.

The main physiographic features in Clay County are the St. Johns River, Trail Ridge, and Floridan Aquifer. The Floridan aquifer is thin, confined (USGS HA 730), and exhibits an elevated potentiometric surface (Annable and Motz, 1996) in this region. This confinement can restrict aquifer recharge and enhance surficial aquifer flow in areas surrounding the lakes, while the lakes themselves act as rapid hydrological conduits. Rapid conductivity to the aquifer is evident in the Keystone Heights area due to a doming of the potentiometric surface of the Upper Floridan Aquifer (Motz et al., 1994).

SANDHILL LAKE SOILS

The high stage variability and missing stable seasonally flooded wetland communities found in sandhill lakes lead to a lack of organic soils, soil organic matter, and inconsistent delineation of some hydric soil indictors. Much work has been done on attempting to correlate soil indicators with lake stage for MFL’s determination on sandhill lakes (Nkedi-Kizza and Richardson, 2007; Richardson, 2006; Ellis, 2002; Jones Edmunds, 2006; Hurt et al., unpublished). The efficacy of this method is tenuous and the relevance of using minimum average, frequent low, and frequent high on sandhill lakes is lacking. Out of 20 studied sandhill lakes only 2 had soil indicators present at the minimum average position (Hurt et al., unpublished data). The identification of soil indicators to locate the frequent high and frequent low was also “problematic” according to Hurt et al. (unpublished data) due to inconsistent results in pine-dominated communities and seepage slopes. While identification of soil morphology and hydric indicators is important to preserve these systems, additional metrics must be used to determine MFLs on sandhill lakes.

Table 1 Index of previous studies into the Etonia Creek Basin from 1963 through present

Author	Title	Journal / Agency	Year
Clark et al.	Hydrology of Brooklyn Lake near Keystone Heights	USGS	1963
Clark et al.	Water Resources of Alachua, Bradford, Clay, and Union Counties, Florida	USGS	1964
Army Corps of Engineers	Flood Plain Information Upper Etonia Creek Basin, Southwest Clay and Northwest Putnam Counties, Florida; Department of the Army, Jacksonville District , Corps of Engineers, Jacksonville, Florida	SJRWMD	1975
D.K. Yobbi and G.C. Chappell	Summary of the Upper Etonia Creek Basin	SJRWMD	1979
Miller	Hydrogeologic Framework of the Floridan Aquifer System in Florida, and in Parts of Georgia, Alabama, and South Carolina	USGS	1986
Motz et al.	Upper Etonia Creek Hydrologic Study Phases I and II	SJRWMD	1991 & 1994
Robison	Surface Water Modeling Study of the Upper Etonia Creek Chain of Lakes	SJRWMD	1992
Subsurface Detection Investigations, Inc.	High Resolution Seismic Reflection Profiling in Selected Lakes in SJRWMD	SJRWMD	1992
Kindinger et al.	High Resolution Single-Channel Seismic Reflection Surveys of Orange Lake and Other Selected Sites of North Central Florida	USGS	1994
Motz and Dogan	North-Central Florida Active Water-Table Regional Groundwater Flow Model	SJRWMD	1994
Annable and Motz	Investigation of Lake and Surficial Aquifer System Interaction in the Upper Etonia Creek Basin	SJRWMD	1996
Kindinger et al.	Geology and Evolution of Lakes in North-Central Florida	Environmental Geology	1999
Dykehouse	Water Budget and Vertically Averaged Vertical Conductance for Lake Geneva	University of Florida	1998
Goodrich	Water Budget and Vertically Averaged Vertical Conductance for Lake Brooklyn	University of Florida	1999
Hirsch and Randazzo	Hydraulic Seepage Within an Astatic Karst Lake, North-Central Florida	Groundwater: Past Achievements and Future Challenges	2000
Golder Associates Inc.	Hydrologic Assessment of the South Trail Ridge Mine and Upper Etonia Creek Basin	DuPont	2001
Watson et al.	Water Budget and Vertical Conductance for Magnolia Lake	American Society of Civil Engineers	2001
Motz et al.	Water Budget and Vertical Conductance for Lowry Lake	Journal of Hydrology	2001
Merritt	Simulation of the Interaction of Karstic Lakes Magnolia and Brooklyn with the Upper Floridan Aquifer, Southwestern Clay County	USGS	2001
Schreuder, Inc	Investigation and Conceptual Design of Options for the Lake Brooklyn Watershed, Clay County, Florida	SJRWMD	2002
CH2MHILL	Preliminary Evaluation Criteria in Support of Minimum Flows and Levels for Sandhill Lakes	SJRWMD	2003
Jones, Edmunds, and Associates , Inc.	Sandhill Lakes Minimum Flows and Levels: Values, Functions, Criteria and Thresholds for Establishing and Supporting Minimum Levels; Jones, Edmunds and Associates, Inc.	SJRWMD	2006
Eichler and Doyle	Aquifer Performance Test Clay County Utility Authority Lower Floridan Aquifer	CCUA, Connect Connecting, Inc.	2009
Robison	Upper Etonia Chain of Lakes Minimum Flows and Levels Hydrologic Methods Report	SJRWMD	2011

Hendrickson et al.	Assessment of State Water Quality Standards: Proposed Augmentation of Lake Brooklyn with Lower Floridian Aquifer Water; John Hendrickson, Sherry Brandt-Williams, Erich Marzolf	SJRWMD	2012
Gordu et al.	Have We Been Here Before?: Hindcasting Lake Levels for Minimum Flows and Levels Evalucations Using a Rainfall Decay Model	Florida Water Resources Journal	2014
Neubauer	Minimum Levels Determination for Lake Brooklyn, Bradford and Clay Counties	SJRWMD	2015
Neubauer	Minimum Levels Determination for Lake Geneva, Bradford and Clay Counties	SJRWMD	2016
Gordu et al.	A Challenging Site for Aquifer Recharge: Keystone Heights Rapid Infiltration Basins Feasibility study	Florida Water Resources Journal	2016

LITHOLOGY

Geologic stratification in the Keystone Heights region has been extensively studied. A comprehensive summary was presented by Motz et al. (1994; Table 1). From the surface downward, the stratigraphy consists of post-Hawthorne deposits, Pliocene deposits, the Hawthorne group, Ocala Limestone, Avon Park Formation, Oldsmar Formation, and the Cedar Keys Formation (Figure A-1).

The Cedar Keys Formation represents the oldest strata within the Cenozoic era and described by this report. It lies above the Lawson and Pine Key formations of the Cretaceous period (Faulkner and Applegate 1986). This stratum represents the lower confining unit of the lower Floridan Aquifer (Scott, 1988). Deposition of the Cedar Keys Formation occurred while peninsular Florida was a shallow ocean bordered by the Rebecca Shoal Barrier Reef (Winston, 1994). Winston (1994) further describes the Cedar Keys formation as containing dolomite and anhydrite due to Rebecca Shoal causing a restriction in circulation within its borders leading to increased salinity. The degree to which older strata influence the aquifer system within Keystone Heights is not well known.

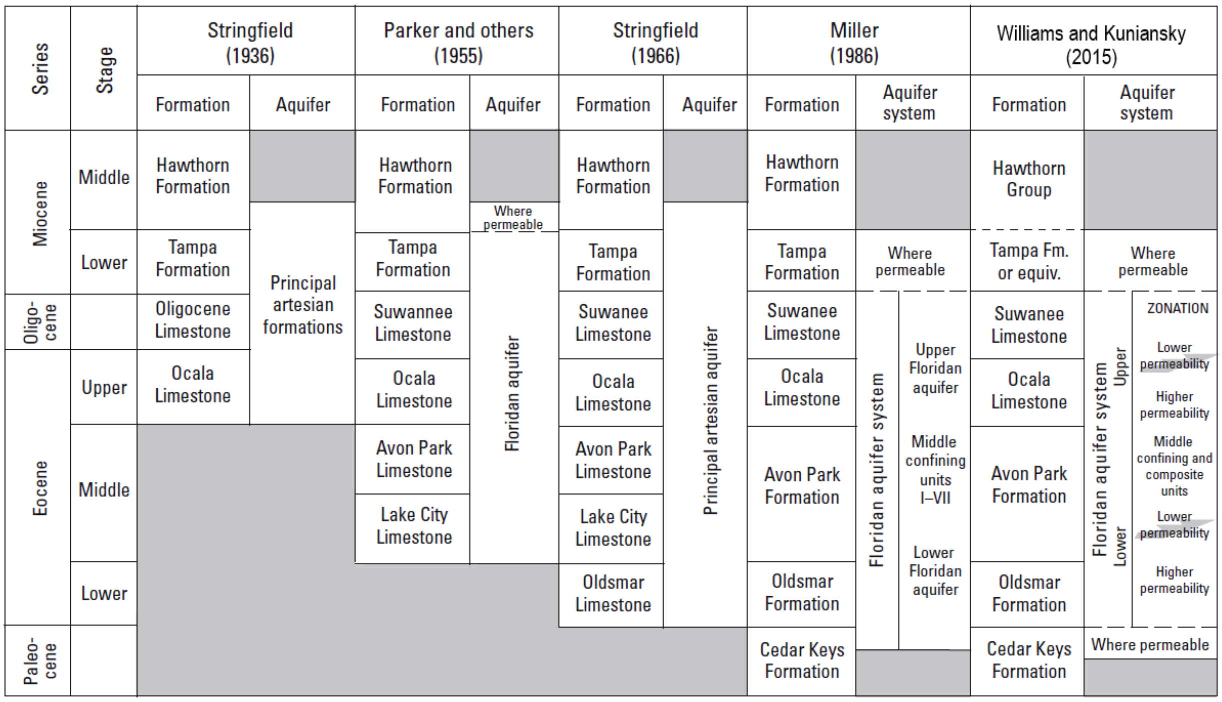
The Oldsmar Formation formed during the early Eocene and traverses peninsular Florida into the panhandle. The shallow-marine paleoenvironment of the Oldsmar formation was similar to the Cedar Keys formation, with the exception being that ocean circulation was improved (Powell, 2010). Circulation may have improved due to sea level rise caused by thermal expansion during the Paleocene–Eocene Thermal Maximum event that is represented in the geologic record between the Oldsmar and Avon Park Formation (Sluijs et al., 2014).

The Avon Park Formation, originally described by Applin and Applin (1944), formed during the middle Eocene and is the oldest exposed layer in Florida. The paleoenvironment of the Avon Park Formation was similar to the Oldsmar Formation, but is distinguishable by the prevalence of larger foraminifera, denoting deeper ocean depth (Powell, 2010). The Avon Park Formation represents a continuation of increasing sea level from the paleoenvironment of the Cedar Keys Formation.

The Avon Park Formation along with the Ocala Limestone act as confining units on the Floridan Aquifer. The boundary between the Avon Park Formation and Ocala Limestone also acts as a tenuous boundary between the upper and lower Floridan Aquifer (Figure A-2).

Table 2 Lithology of the Keystone Heights area according to studies by Bermes et al., 1963; Clark et al., 1964; Fairchild, 1972; Hoenstine and Lane, 1991; Leve, 1966; Miller, 1986; and Scott, 1988

Geologic Age	Stratigraphic Unit	Approximate thickness (ft)	Lithology
Pleistocene and recent	Post-Hawthorne Deposits	10-100	Discontinuous beds of loose sand, sandy clay, marl, and shell
Pliocene	Post-Hawthorne Deposits/ Pliocene Deposits	10-100	Clay, clayey sand, sandy clay, shell, and limestone
Miocene	Hawthorne Group	100-400	Interbedded clay, quartz, sand, carbonate, phosphate
Late Eocene	Ocala Limestone	200-400	Porous limestone
Middle Eocene	Avon Park Formation	500-1200	Interbedded limestone and dolomite
Early Eocene	Oldsmar Formation	300-800	Interbedded limestone and dolomite
Paleocene	Cedar Keys Formation	unknown	Interbedded dolomite and anhydrite



Series	Stage	Stringfield (1936)		Parker and others (1955)		Stringfield (1966)		Miller (1986)		Williams and Kuniansky (2015)	
		Formation	Aquifer	Formation	Aquifer	Formation	Aquifer	Formation	Aquifer system	Formation	Aquifer system
Miocene	Middle	Hawthorn Formation		Hawthorn Formation	Where permeable	Hawthorn Formation		Hawthorn Formation		Hawthorn Group	
	Lower	Tampa Formation	Principal artesian formations	Tampa Formation	Floridan aquifer	Tampa Formation	Principal artesian aquifer	Tampa Formation	Where permeable	Tampa Fm. or equiv.	Where permeable
Oligo-cene		Oligocene Limestone		Suwannee Limestone		Suwannee Limestone		Suwanee Limestone	Floridan aquifer system: Upper Floridan aquifer	Suwannee Limestone	Floridan aquifer system, ZONATION: Upper: Lower permeability Higher permeability
Eocene	Upper	Ocala Limestone		Ocala Limestone		Ocala Limestone		Ocala Limestone		Ocala Limestone	
	Middle			Avon Park Limestone Lake City Limestone		Avon Park Limestone Lake City Limestone		Avon Park Formation	Middle confining units I–VII	Avon Park Formation	Middle confining and composite units
	Lower					Oldsmar Limestone		Oldsmar Formation	Lower Floridan aquifer	Oldsmar Formation	Lower: Lower permeability Higher permeability
Paleo-cene								Cedar Keys Formation		Cedar Keys Formation	Where permeable

Figure A-1. Comparison of stratigraphic units from various studies.

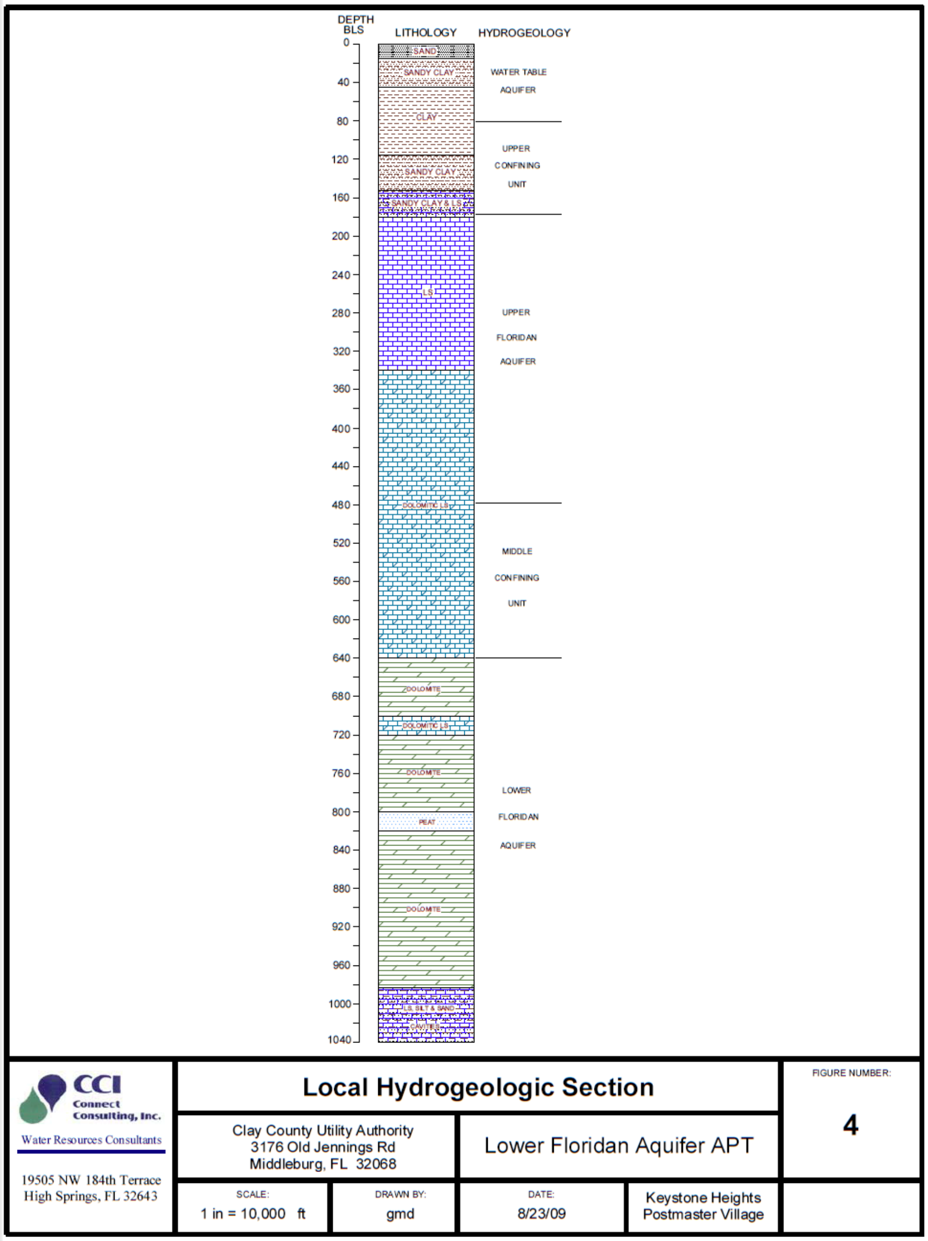


Figure A-2. From Eichler and Doyle: Aquifer Performance Test Lower Floridan Aquifer Clay County Utility Authority

SINKHOLE FORMATION

Rainwater reacting with soil CO_2 can lead to low pH groundwater. Groundwater flowing through geological features leads to dissolution of karst confining units. The $CaCO_3$ content dissolves, neutralizing groundwater and leads to a fractured structure. Sinkholes form when the pressure of higher strata exerts enough force on fractured bedrock to collapse lower strata. The predominance of karst bedrock, high annual rainfall, and extensive groundwater flow, make Florida prone to sinkhole formation.

Lake stage in the UECB is largely influenced by connectivity to the aquifer. Many of the lakes in the basin formed by sinkhole formation and act as conduits to the aquifer. The Hawthorne group is thin, fractured by sinkholes, or absent in much of the UECB, leading to spatial variability in connectivity to the aquifer (SDI 1992). Lake Geneva (Figures A-3 and A-4) and Lake Brooklyn (Figures A-5 and A-6) have been mapped through high definition seismic reflection profiling (SDI 1992). Several areas were observed as having collapse features with localized high conductivity to the aquifer likely. In these regions, the lithology is altered relative to surrounding areas. Lake stage can suffer from decreases in the potentiometric surface of the aquifer due to the localized high conductivity found in lakes of the UECB. It is also likely that Alligator Creek has a lithology that fosters connectivity to the aquifer (Jones Edmunds, 2014).

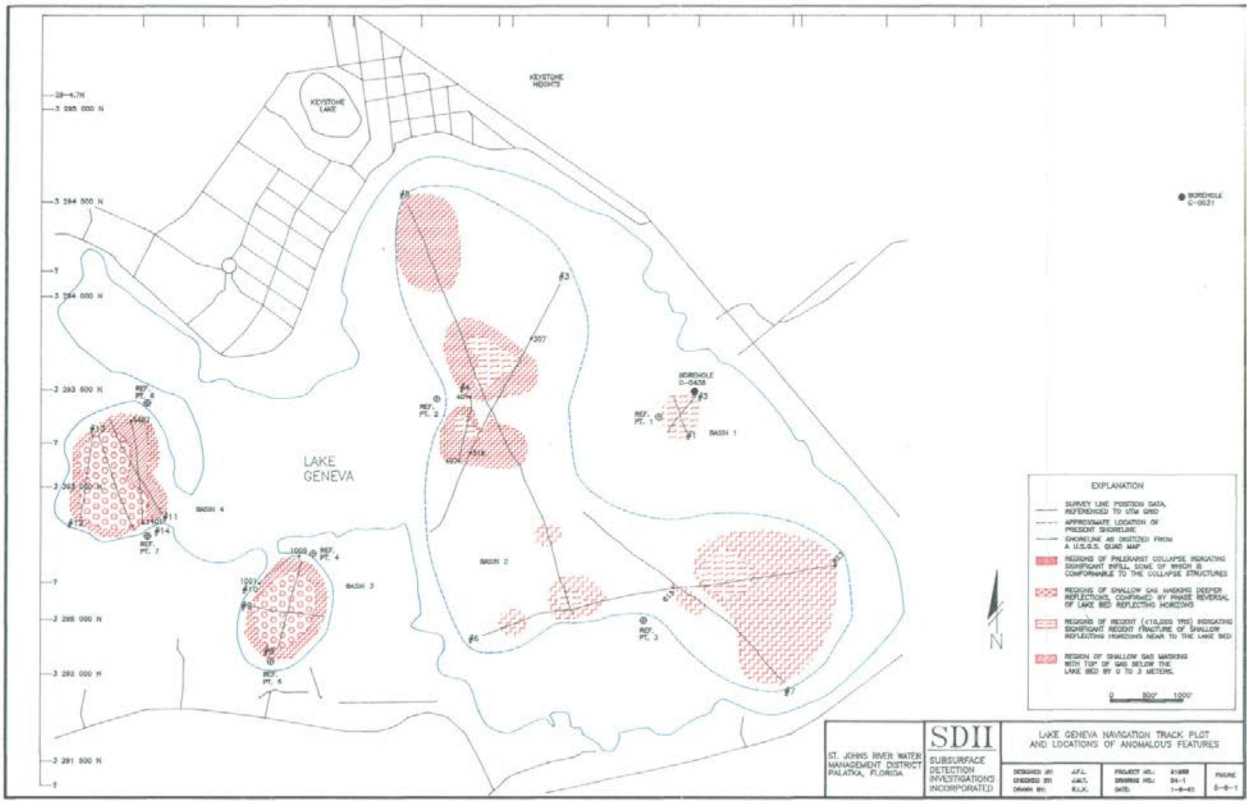


Figure A-3 Anomalous features in the stratigraphy of the lake bed in Lake Geneva, as determined by Marine reflection seismic profiling

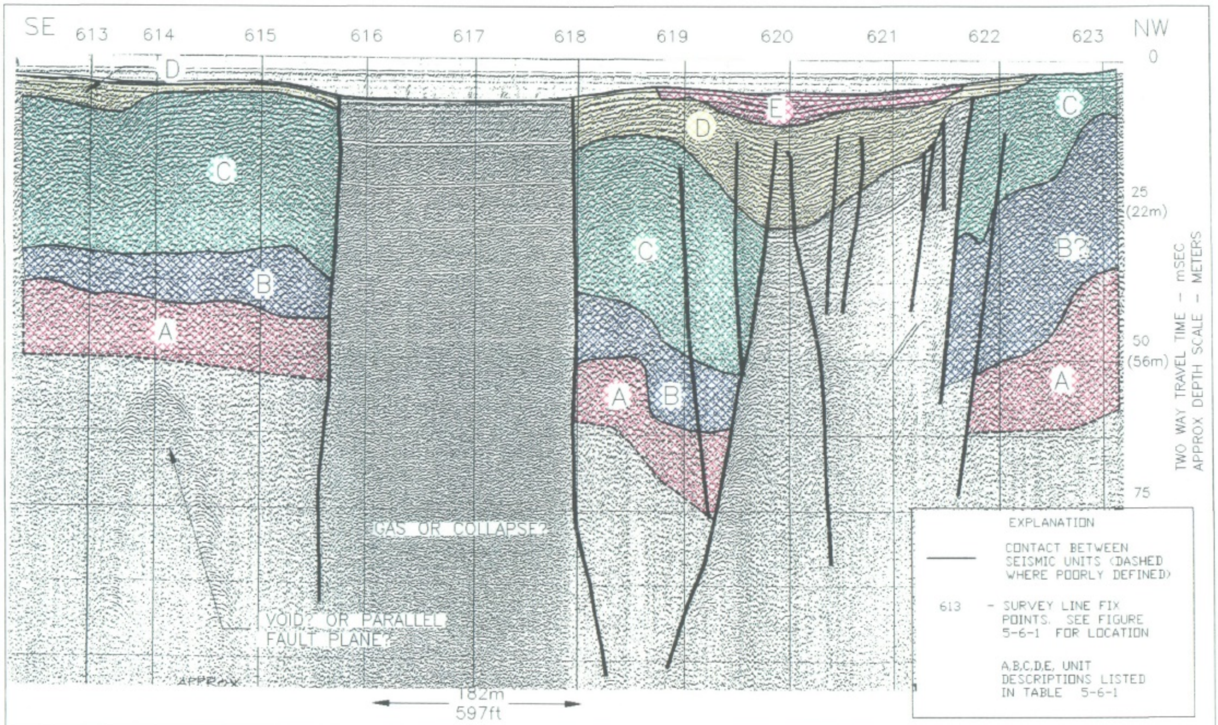


FIGURE 5-6-3 Example seismic record from survey line 6 in Basin 2 of Lake Geneva showing the range of acoustic units.

Figure A-4. Collapse feature in the stratigraphy of the lake bed in Lake Geneva, as determined by Marine reflection seismic profiling

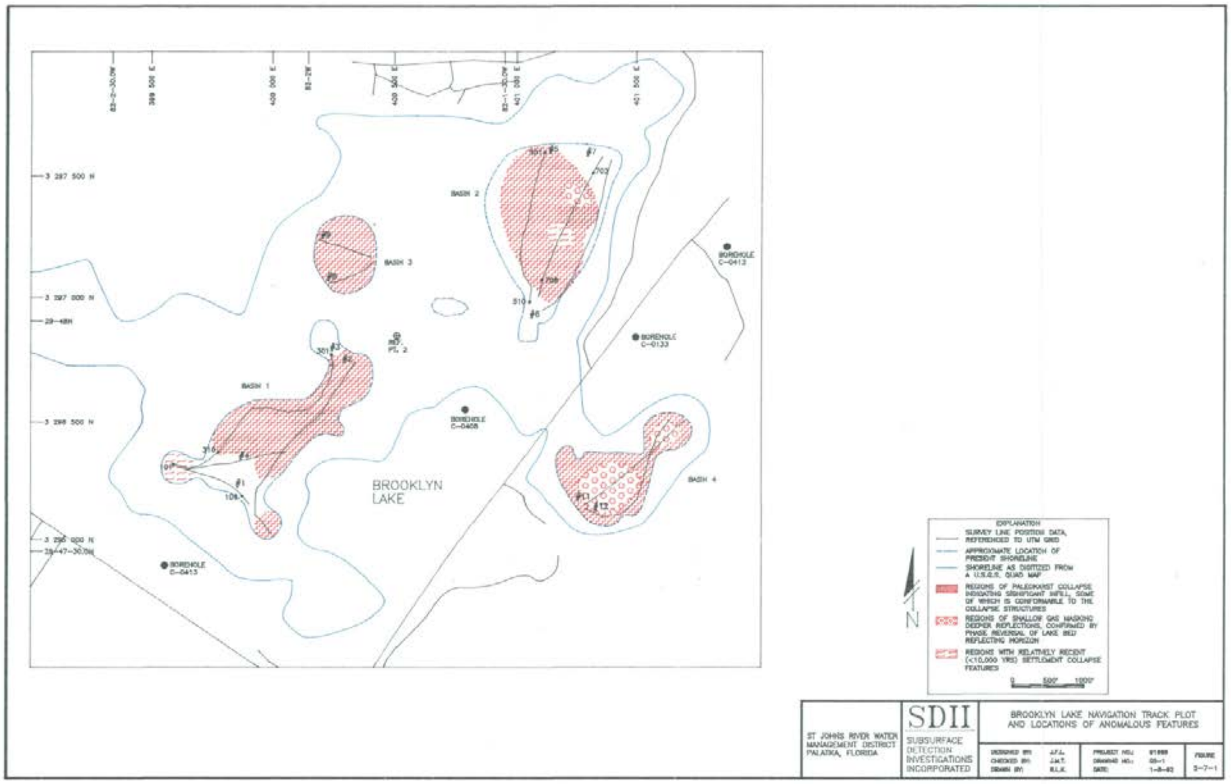


Figure A-5 Anomalous features in the stratigraphy of the lake bed in Lake Brooklyn, as determined by Marine reflection seismic profiling

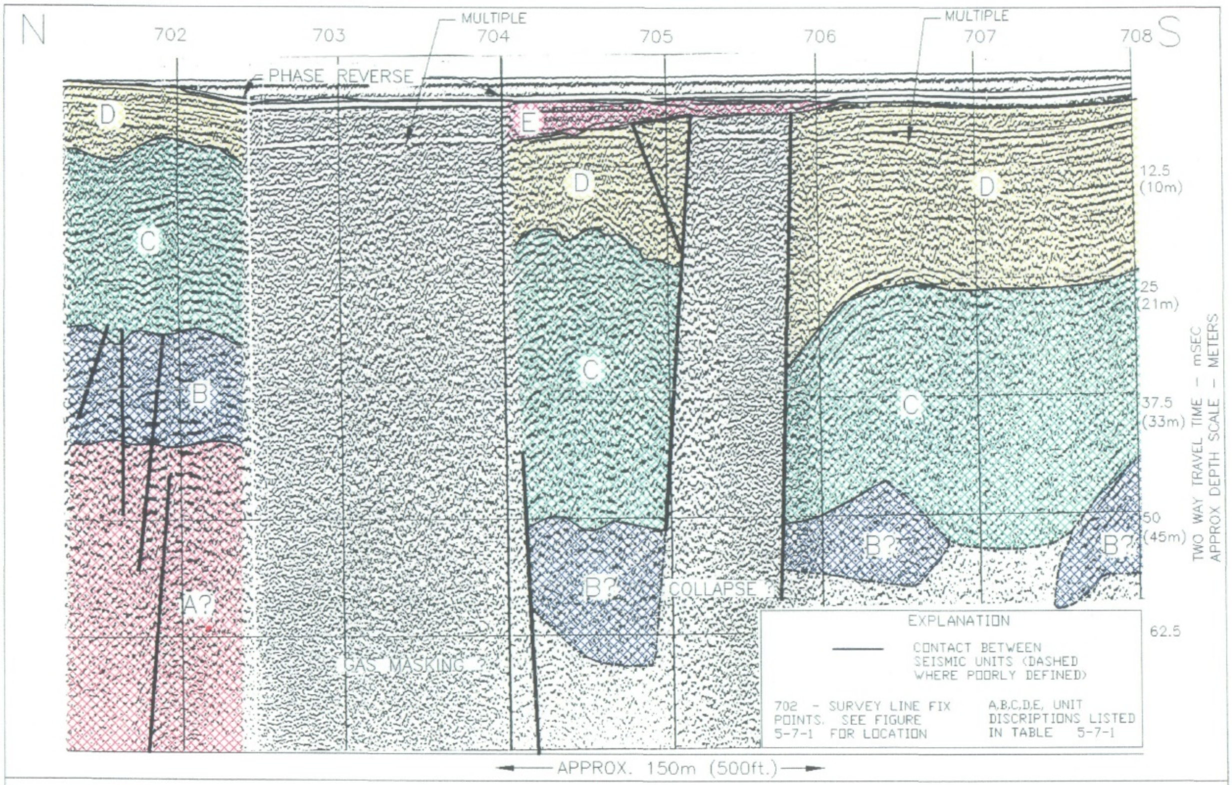


FIGURE 5-7-5 Example record from survey line 7 in Basin 2 of Brooklyn Lake, showing two high reflectivity masking zones. The northern zone shows apparent phase reversal (gas) while the southern zone shows infill possibly indicating collapse activity.

Figure A-6. Collapse feature in the stratigraphy of the lake bed in Lake Brooklyn, as determined by Marine reflection seismic profiling

Literature Cited

Applin, P.L., and E.R. Applin. 1944. Regional subsurface stratigraphy and structure of Florida and southern Georgia. American Association of Petroleum Geologists. 28(12):1673-1753.

Annable, M.D., and L.H. Motz. 1996. Investigation of lake and surficial aquifer interaction in the Upper Etonia Creek Basin; SJRWMD Special Publication SJ96-SP15.

Bermes, B.J. 1963. Geology and groundwater resources of Flagler, Putnam, and St. Johns Counties, Florida; Florida Geological Survey, Tallahassee Florida.

Brooks, H.K. 1981. Physiographic Divisions of Florida; University of Florida Institute of Food and Agricultural Sciences, Gainesville, Florida.

CHM2HILL. 2003. Preliminary evaluation criteria in support of minimum flows and levels for sandhill lakes; SJRWMD special publication SJ2005-SP7.

Clark, W.E., R.H. Musgrove, C.G. Menke, and J.W. Cagle Jr. 1963. Hydrology of Brooklyn Lake near Keystone Heights, Florida: Florida Geological Survey Report of Investigations no. 33, 43 p.

Clark, W.E., R.H. Musgrove, C.G. Menke, and J.W. Cagle. Jr. 1964. Water Resources of Alachua, Bradford, Clay and Union Counties, Florida. Florida Geologic Survey Report of Investigations No. 3.

Dykehouse, T.L. 1998. Water budget and vertically averaged vertical conductance for Lake Geneva in Keystone Heights, Florida, U.S.A. (Master's Thesis). Retrieved from SJRWMD library.

Eichler, G.E., and G.M. Doyle. 2009. Aquifer performance test lower Floridan Aquifer Clay County Utility Authority; Connect Connecting, Inc., High Springs, Florida.

Ellis, L.R. Investigation of hydric and sub-aqueous soil morphologies to determine Florida sandhill lake stage fluctuations (Master's Thesis). Retrieved from http://intraweb/comm/library/files/pubs/Ellis_thesis_2002.pdf

Fairchild, R.W. 1972. The shallow-aquifer system in Duval County, Florida; Florida Department of Natural Resources Bureau of Geology, Tallahassee, Florida.

Faulkner, B.M., and A.V. Applegate. 1986. Hydrocarbon exploration evaluation of Pulley Ridge area, offshore South Florida basin. Gulf Coast Association of Geological Societies Transactions. 36:83-95

Golder Associates. 2001. Hydrologic assessment of the south Trail Ridge mine and Upper Etonia Creek Basin. Golder Associates Inc., Jacksonville, Florida.

Goodrich, C.A. 1999. Water budget and vertically averaged vertical conductance for Lake Brooklyn in North Central Florida, U.S.A. (Master's Thesis). Retrieved from SJRWMD library.

Gordu, F., M. Hays, and L.H. Motz. 2016. A challenging site for aquifer recharge: Keystone Heights rapid infiltration basins feasibility study. Florida Water Resources Journal. 67(2):32-38.

Gordu, F., B. Goodman, T. Cunningham, and A.B. Munson. 2014. Have we been here before?: hindcasting lake levels for minimum flows and levels evaluations using a rainfall decay model. Florida Water Resources Journal. 66(2):50-55.

Hendrickson, J., S. Brandt-Williams and E. Marzolf. 2012. Assessment of state water quality standards: proposed augmentation of Lake Brooklyn with lower Floridan aquifer water. SJRWMD unpublished draft. March 2012.

Hirsch, J.D., and A.F. Randazzo. 2000. Hydraulic seepage within an astatic lake, North-Central Florida. In: *Groundwarer: Past Achievements and Future Challenges* (ed. By O. Sillio), 159-164. A. A. Balkema, Rotterdam, The Netherlands.

Hoenstine, R.W., S.M. Spencer, and T. O'Carrol. 1990. Geology and ground-water resources of Madison County, Florida; Florida Geological Survey and SRWMD, Tallahassee, Florida.

Jones Edmunds. 2006. Sandhill lakes minimum flows and levels: values, functions, criteria, and thresholds for establishing and supporting minimum levels; Jones Edmunds & Associates Inc., Gainesville, Florida.

Jones Edmunds. 2014. Black Creek literature and data review; Jones Edmunds & Associates Inc., Gainesville, Florida.

Kindinger, J.L., J.B. Davis and J.G. Flocks. 1999. Geology and evolution of lakes in north-central Florida. Environmental Geology 38(4):301-321.

Kindinger, J.L., J.B. Davis, and J.G. Flocks. 1994. High-resolution single-channel seismic reflection surveys of Orange Lake and other selected sites of north central Florida.

Leve, G.W. 1966. Ground water in Duval and Nassau counties, Florida. Florida Geological Survey Report of Investigations no. 43

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

Miller, J.A. 1986. Hydrogeologic framework of the Floridan Aquifer system in Florida, and in parts of Georgia, Alabama, and South Carolina. U.S. Geological Survey Professional Paper 1403-B.

Motz, L.H., and A. Dogan. 2004. North-central Florida active water-table regional groundwater flow model. SJRWMD Special Publication SJ2005-SP16.

Motz, L.H., J.P. Heaney, W.K. Denton, and G. Leiter. 1991. Upper Etonia Hydrologic Study Phase I Final Report. University of Florida Departments of Civil Engineering and Environmental Engineering Sciences; SJRWMD Special Publication SJ91-SP5

Motz, L.H., J.P. Heaney, W.K. Denton, M.S. Fowler, and G. Leiter. 1994. Upper Etonia Hydrologic Study Phase II Final Report. University of Florida Departments of Civil Engineering and Environmental Engineering Sciences; SJRWMD Special Publication SJ92-SP18

Motz, L.H., G.D. Sousa, and M.D. Annable. 2001. Water budget and vertical conductance for Lowry (Sand Hill) Lake in north-central Florida, USA. Journal of Hydrology 250(1-4):134-148

Neubauer, C.P. 2015. Minimum levels reevaluation for Lake Geneva, Bradford and Clay counties, Florida. SJRWMD unpublished draft. 2015.

Neubauer, C.P. 2015. Minimum levels reevaluation for Lake Brooklyn, Bradford and Clay counties, Florida. SJRWMD unpublished draft. 2015.

Nkedi-Kizza, P, and T.C. Richardson. 2007. Characterization of sandhill lake soils: in support of St. Jogns River Water Management District's minimum flows and levels program. SJRWMD Special Publication SJ2007-SP7.

Parker, G.G., G.E. Ferguson, and S.K. Love. 1955. Water resources of southeastern Florida, with special reference to the geology and ground water of the Miami area; U.S. Geological Survey Water-Supply Paper. 1255.

Powell, J.B. 2010. Larger foraminiferal biostratigraphy, systematics and paleoenvironments of the Avon Park Formation and Ocala Limestone, Highlands County, Florida. (Ph.D. Dissertation). Retrieved from http://digitalcommons.fiu.edu/cgi/viewcontent.cgi?article=1374&context=etd

Richardson, T.C. 2006. Relationships of Florida sandhill lake soil parameters with the capillary fringe, oxidation-reduction potential, and air entry values (Master's Thesis). Retrieved from http://etd.fcla.edu/UF/UFE0017324/richardson_t.pdf

Robison, C.P. 2011. Upper Etonia Chain of lakes minimum flows and levels hydrologic methods report. SJRWMD unpublished draft. 2011.

Robison, C.P. 1992. Surface Water Modeling Study of the Upper Etonia Creek Chain of Lakes, Clay County, Florida. SJRWMD Technical Publication SJ92-3

(SDI) Subsurface Detection Investigations, Inc. 1992. High resolution seismic reflection profiling in selected lakes in the St. Johns River Water Management District. Final Report prepared for SJRWMD. April 1992.

Schiffer, D.M., 1998, Hydrology of Central Florida Lakes - A Primer: U.S. Geological Survey Circular 1137, 38 p.

Schreuder. 2001 Investigation and conceptual design of restoration options for Upper Lake Brooklyn watershed; Schreuder Inc., Tampa, Florida.

Scott, T.M. 1988. The lithostratigraphy of the Hawthorn Group (Miocene) of Florida; Florida Geological Survey, Tallahassee, Florida.

Sluijs, A., van Roij, L., Harrington, G.J., Schouten, S., Sessa, J.A., LeVay, L.J., Reichart, G.-J. and Slomp, C.P. (2014). Warming, euxinia and sea level rise during the Paleocene–Eocene Thermal Maximum on the Gulf Coastal Plain: implications for ocean oxygenation and nutrient cycling. Climate of the Past 10:1421-1439.

Stringfield, V.T. 1936. Artesian water in the Florida peninsula; U.S. Geological Survey Water-Supply Paper 773:524–529.

Stringfield, V.T. 1966. Artesian water in Tertiary limestone in the southeastern States; U.S. Geological Survey Professional Paper 517.

U.S. Army Corps of Engineers. 1975. Flood Plain Information Upper Etonia Creek Basin, southwest Clay and northwest Putnam Counties, Florida. Department of the Army, Jacksonville District, Corps of Engineers, Jacksonville, Florida.

USGS. 2000. Ground-water atlas of the United States; U.S. Geological Survey, Reston, Virginia. Retrieved from https://pubs.usgs.gov/ha/730/report.pdf

Watson, B., L.H. Motz, and M. Annable. 2001. Water budget and vertical conductance for Magnolia Lake. Journal of Hydrologic engineering 6(3)

Williams, L.J., and E.L. Kuniansky. 2015. Revised hydrogeologic framework of the Floridan Aquifer system in Florida and parts of Georgia, Alabama, and South Carolina; U.S. Geological Survey Professional Paper 1807.

Winston, G.O. 1994. Lithostratigraphy of the Cedar Keys Formation of Paleocene and upper Cretaceous age peninsular Florida and environs; Miami Geological Society, Coral Gables, Florida.

Yobbi, D.K. and G.C. Chappell. 1979. Summary of the Hydrology of the Upper Etonia Creek Basin. SJRWMD Technical Publication SJ79-5