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Joint Assessment of the Regional Changes in the Level and Configuration of the Potentiometric Surface of the Upper Floridan Aquifer in Southeast Georgia and Northeast Florida

September 2015

St. Johns River and Suwannee River Water Management Districts

Suwannee River and St. Johns River Water Management District Aquifer Decline Literature Review

A Joint Assessment of Regional Changes in the Level and Configuration of the Potentiometric Surface of the Upper Floridan Aquifer in Southeast Georgia and Northeast-North Central Florida

INTRODUCTION

Effective water management in northeast Florida requires close coordination between the Suwannee River and St. Johns River Water Management Districts (SRWMD and SJRWMD, respectively) to ensure resource protection while equitably regulating consumptive water uses in both districts. In order to focus coordination efforts, the districts and Florida Department of Environmental Protection (Department) executed an Interagency Agreement (IAA) on September 13, 2011. The IAA outlined the focus areas requiring close intra-district coordination in order to better understand, manage and plan for the sustainability of shared water resources.

One specific task of the IAA requires the SRWMD and SJRWMD to develop and implement a scope of work to study changes in the regional level and configuration of the potentiometric surface of the Upper Floridan aquifer (UFA) through an analysis of historic literature. Both SRWMD and SJRWMD acknowledge that there have been changes in the potentiometric surface in northeast Florida and southeast Georgia and concede that additional data and analysis will be necessary to better understand the factors that have caused these changes and resulting resource impacts. Figure 1 illustrates the primary UFA study area for this effort.

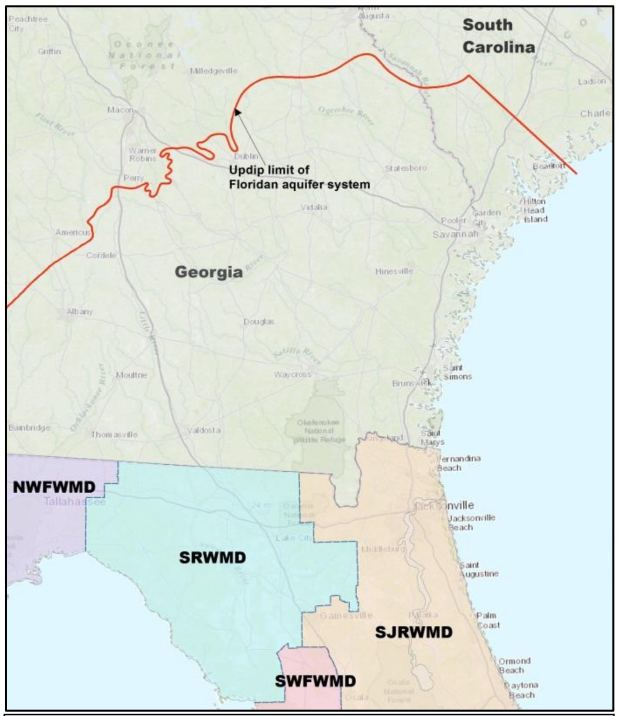


Figure 1: Primary study area for the joint assessment of regional changes in the potentiometric surface of the UFA

The scope of work was limited to a review of published scientific literature related to the UFA or entire Floridan aquifer system (FAS). Reviewed documents covered the time period from the mid-1930s to the present day in order to assimilate sufficient information related to trends in the potentiometric surface. Subject material included groundwater levels, water quality, modeling and predictive simulations, the role of climatic fluctuations, and water use. The districts realized that a common understanding of the factors affecting the level and configuration of the potentiometric surface would benefit their collective management efforts of shared water resources. This summary report represents the combined interpretation of both districts related to the literature review; including methodology, findings, conclusions, and recommendations for further analysis.

GENERAL GEOLOGY / HYDROGEOLOGY OF THE UFA IN THE AREA OF STUDY

The FAS is one of the most productive aquifers in the world covering a total area of approximately 100,000 square miles (Figure 2). As indicated in Figure 2, the FAS pinches out where it outcrops in south-central Georgia and thickens moving downdip into northeast – north-central Florida where it ranges from approximately 1,400 feet (SRWMD) to over 2,000 feet thick (SJRWMD near the northeast coast).

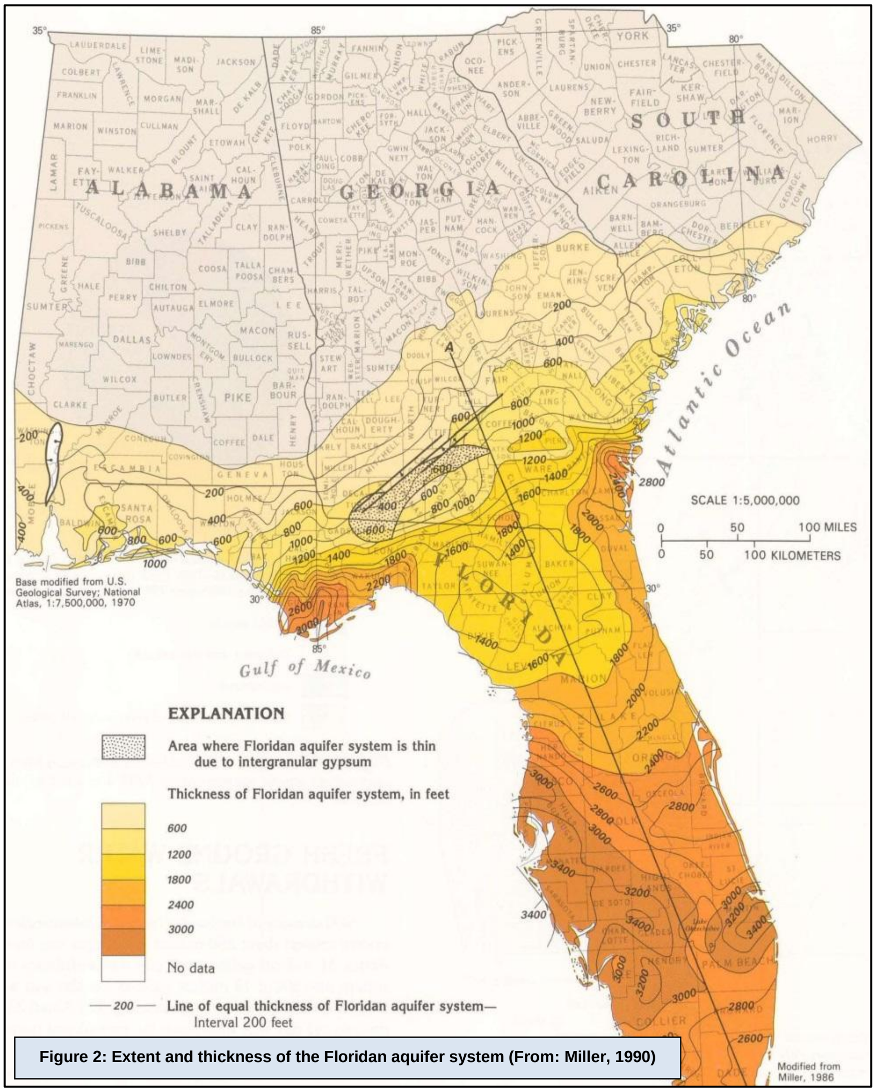


Figure 2: Extent and thickness of the Floridan aquifer system (From: Miller, 1990)

The FAS in southeast Georgia and northeast/ north-central Florida generally consists of Eocene-age carbonate rocks (limestone and dolostone) of varying thickness and permeability. In some areas, the FAS is confined by overlying low-permeability Miocene-age clastic and carbonate sediments or rocks known throughout most of the area as the Hawthorn Group. Where confined, recharge to the FAS from precipitation is inhibited and recharge rates are minimal. Where the Hawthorn Group is absent, the FAS is unconfined and is rapidly recharged by precipitation. Figure 3 indicates the general confined and unconfined areas of the FAS in the study area. As Figure 3 illustrates, a large portion of the FAS in the SRWMD is under semi-confined or unconfined conditions, and southeast Georgia and northeast Florida is generally under confined conditions.

In some areas, the FAS is divided into the UFA and Lower Floridan aquifer (LFA) based on the presence of low to relatively impermeable rocks within the FAS. These sub-regionally extensive units are referred to as Middle Floridan confining units, or MFCUs. Previous work[1] recognized the presence of eight mappable MCFUs throughout the entire FAS. In general, three MFCUs were identified in the study area. As a result, the FAS in the SJRWMD and coastal Georgia is

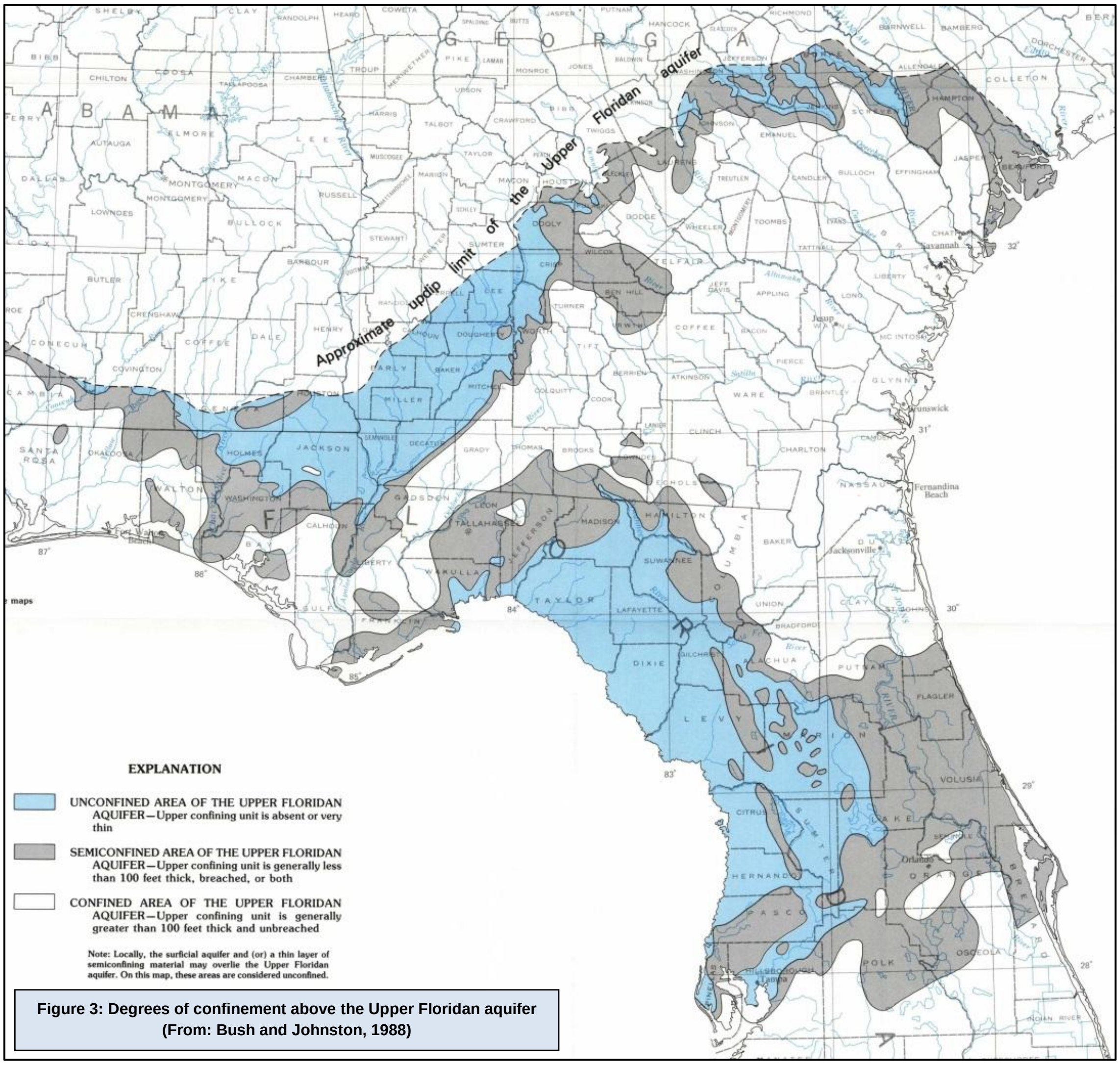


Figure 3: Degrees of confinement above the Upper Floridan aquifer (From: Bush and Johnston, 1988)

divided into an UFA and LFA, as is a portion of north-central Florida extending into southern Georgia. While work continues to refine the hydrostratigraphy of the FAS in the study area (the USGS is currently updating the hydrostratigraphy of the FAS as part of the Floridan Aquifer System Groundwater Availability Study), the FAS is still considered to be a single hydrostratigraphic unit in most of the SRWMD and southeastern Georgia.

[1] Miller, 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, U.S. Geological Survey, Washington D.C.

METHODOLOGY

District staff developed five key questions in order to guide the literature review process and focus the study. The five questions were:

1. What are the factors driving changes in the level and configuration of the potentiometric surface of the UFA in the study area?
2. To the extent possible, what is the proportional effect of each factor driving changes in the level and configuration of the potentiometric surface of the UFA in the study area?
3. What are the trends in the level and configuration of the potentiometric surface of the UFA in the study area?
4. To the extent possible, which hydrologic features are most susceptible to changes in the level and configuration of the potentiometric surface of the UFA in the study area?
5. To what extent are the hydrologic features being affected by changes in the level and configuration of the potentiometric surface of the UFA in the study area?

A master list of 65 scientific publications to which the key questions would be applied was compiled and provided in Appendix A. This list comprised a comprehensive body of evidence from various fields of study directly or indirectly related to the level and configuration of the potentiometric surface of the UFA and represented expertise from a wide range of agencies, including the United States Geological Survey (USGS), the Florida Geological Survey (FGS), the SJRWMD, the Georgia Department of Natural Resources, and the University of Florida.

In the interest of time, the master list was then reduced to a manageable number of documents believed to be the most relevant to the scope of work. Staff from both districts deliberated on the merits of each document to produce the resulting list of 30 publications contained in Appendix B. In selecting these 30 documents, the districts were careful to select documents that covered a broad range of subject areas related to the UFA potentiometric surface; including (as previously mentioned) groundwater levels, water quality, modeling and predictive simulations, the role of climate cycles, and water use. Most of the publications addressed two or more of these subject areas; however, one subject area was often the primary focus. Table 1 (Appendix C) categorizes the 30 documents according to the primary and secondary subject areas discussed by the author(s) and evaluated by district staff.

In rare instances, documents from the Master Reference List may be cited in this summary report to provide clarification. In those cases, the citation will provide the reference followed by "Appendix A". If a reference is mentioned in the text and cited in a footnote, it is not present in either the Master List or final 30 references but was added to supplement discussion. All other references should be assumed to have come from the final list of 30 documents.

A document review template was used to evaluate each of the 30 documents (Appendix D). Each document was reviewed by staff most qualified to evaluate and comment on the subject matter. District staff independently reviewed each document and provided comments on the template. Following independent review, the districts discussed opinions, findings, and issues pertaining to each document and a consensus summary opinion was prepared. The consensus summary opinions for all 30 documents are presented in the following section. The opinions are presented in the order indicated in Table 1 (Appendix C).

REVIEW AND EVALUATION OF DOCUMENTS

Introduction: The wide range of subject matter and temporal distribution of reviewed reference material allowed a unique opportunity to analyze the factors affecting the level and configuration of the UFA over time. Publishing dates of the reference list ranged from 1936 to 2012, and therefore contained over seven decades of perspectives and knowledge pertaining to aquifer conditions.

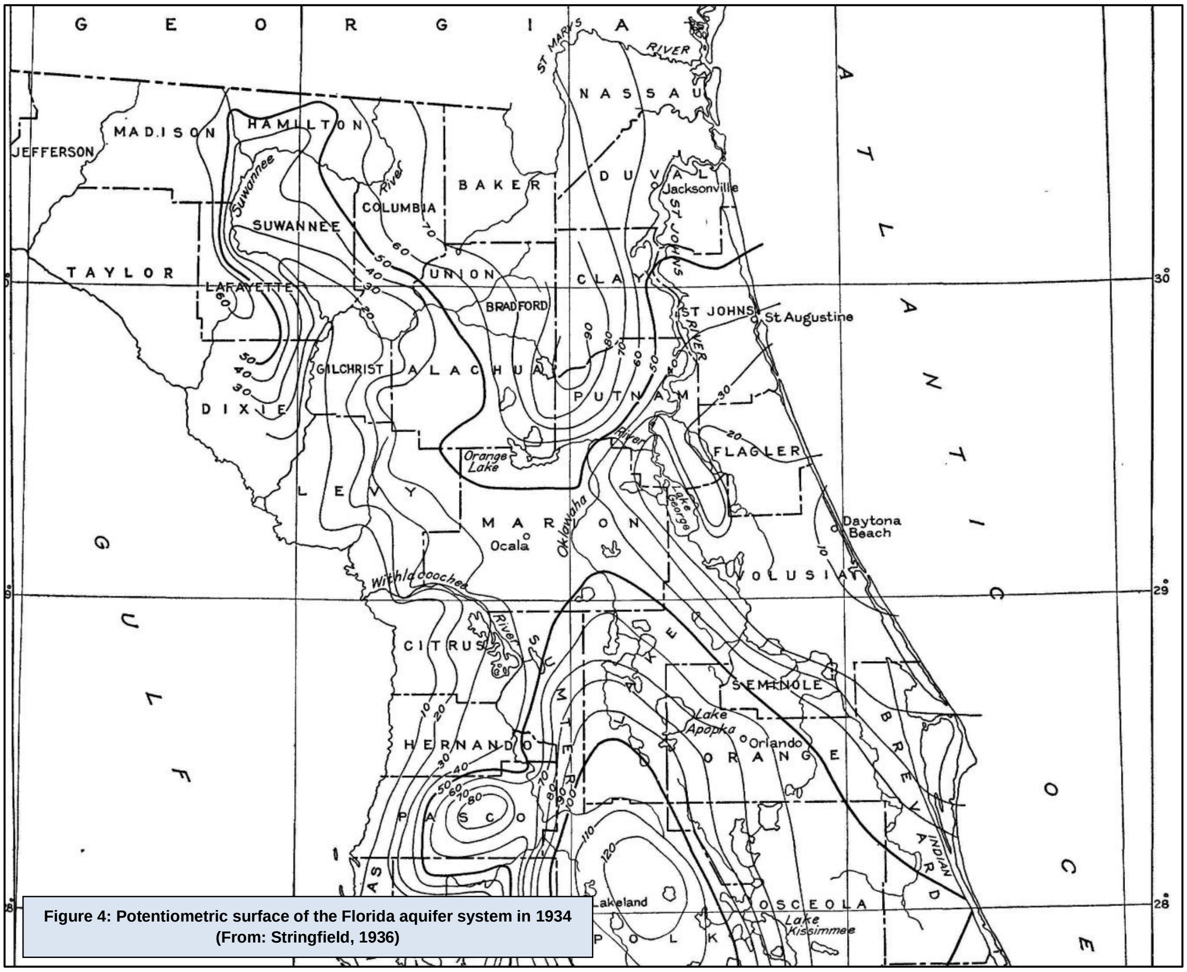


Figure 4: Potentiometric surface of the Florida aquifer system in 1934 (From: Stringfield, 1936)

One of the first efforts to represent the potentiometric surface of the FAS was by Stringfield (1936; Appendix B, Reference 60). The inferred 1934 potentiometric surface (Figure 4) was based on water levels collected from artesian wells. In the study area, a potentiometric high was located in southwest Clay / southeast Bradford counties with maximum interpolated water level elevations greater than 90 feet above sea level. The groundwater flow direction was radially outward from the high into the SJRWMD and SRWMD. A broad, generally flat "saddle", bracketed by the 70-foot contour line, extended northward from the potentiometric high through Bradford, Union, and Baker counties. From a hydrologic standpoint, the midline of the saddle (between the 70 foot contours) can be interpreted as a "no-flow boundary" and was the inferred general position of the groundwater basin boundary between the two districts in 1934.

Although Stringfield (1936) noted the susceptibility of changes in FAS potentiometric levels due to pumping and hydrogeologic conditions (e.g., level of confinement in the FAS), the role of climatic variations and interaction between surface and groundwater were not evaluated. More importantly, Stringfield's publication was the first regional map representing the potentiometric surface of the FAS based on water levels collected from artesian wells and provided a basis for representing the configuration of the potentiometric surface.

Summary Opinions:

As mentioned above, the following summaries are the consensus opinions of both districts related to the UFA / FAS and factors affecting the level and configuration of the potentiometric surface over time. Full citations of the following summary opinions are included in Appendix B.

- Reference Correspondence 1: *USGS letter dated June 8, 2011 – Evaluation of the Floridan aquifer system regional groundwater flow divide migration since predevelopment*.
  This communication is a professional opinion from the USGS Florida Water Science Center (Ft. Lauderdale, FL) related to the regional westward migration of the groundwater basin boundary between the SRWMD and SJRWMD. The USGS provided evidence to support a westward migration of the boundary since predevelopment conditions based upon sound hydrogeologic principles. Presented evidence includes:

  1. Withdrawals in northeast Florida probably caused a westward expansion of the 'early' depressions in the post-development potentiometric surface. The declines and the outward expansion of the cones of depression from these withdrawals are consistent with concepts that a westward-moving basin boundary is impacting the area of recharge, reducing groundwater head, and potentially causing declines in spring flow to the west.
  2. Groundwater withdrawals in the coastal counties of northern Florida and southern Georgia always have been much larger than in the counties west of the groundwater basin boundary. These withdrawals combined with a thickly-confined FAS and low recharge rates northeastern Florida contrast with the unconfined aquifer conditions and relatively higher recharge rates of counties to the west. It is unlikely that groundwater levels fell at the same rate east and west of the divide, a hydrologic condition required in order to maintain the divide position during a transient post- development period (pre-1980).
  3. The western discharges in the FAS caused by the Suwannee, Ichetucknee and the Lower Santa Fe Rivers are much more prominent than the eastern discharges in the form of leakage from the FAS through confining layers to the St. Johns River and Atlantic Ocean. This suggests that the predevelopment groundwater basin boundary was probably located east of the midway point between these two sinks under predevelopment conditions.

  The USGS also recognized the tool that could more accurately predict changes in the position of the basin boundary and associated water resource impacts would be a calibrated regional-scale transient model, which does not yet exist. Discharges from the groundwater system in any form and location with respect to the groundwater basin boundary affect the position of the boundary. In addition to the groundwater withdrawals, climate also plays an important role. The present stability of the boundary (since approximately 1980) would seem to indicate the system has achieved a new steady-state condition. A comparison of pre- and post-development baseflows and pumping on each side of the boundary using good quality data may provide additional insight.

- Reference 3: *Impact of development on availability and quality of ground water in eastern Nassau County, Florida, and southeastern Camden County, Georgia (1984)*. Groundwater pumping from the UFA increased 60 million gallons per day (mgd) from 1940 to 1980 and resulted in an estimated decline in the potentiometric surface (since predevelopment) of 25 feet in the western portion of the study area to as much as 100 feet in the eastern portion due to industrial pumping centers near the coast, with the greatest declines occurring between 1940 and 1960 (Figure 5). Decline in the potentiometric surface of the UFA increased the head difference among other water-bearing zones of the FAS, thereby increasing leakage from deeper zones of higher artesian heads to the upper zone. An expanding cone of depression also is believed to

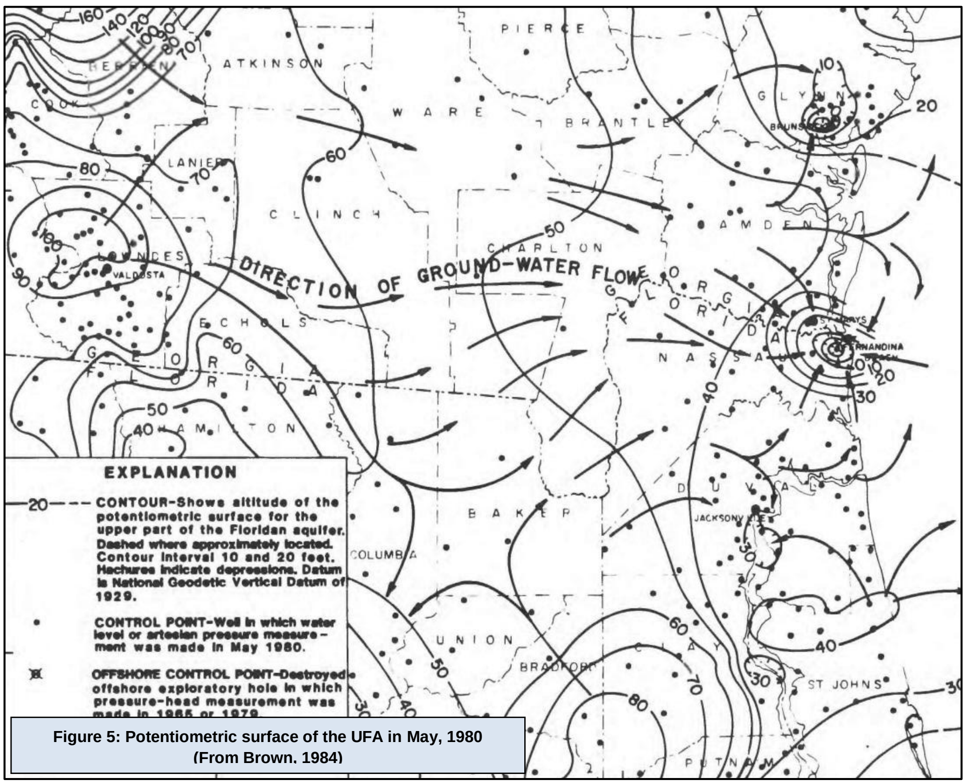


Figure 5: Potentiometric surface of the UFA in May, 1980 (From Brown, 1984)

increase lateral movement from adjacent areas in the FAS and downward leakage of water from the surficial aquifer system (SAS). The author found no indication of saline intrusion into the UFA under 1980 withdrawal rates and was unable to estimate the maximum sustainable pumpage from this zone that may cause significant water quality deterioration. Nevertheless, he believed future development of the FAS may at some point be limited to the UFA as a result of degradation of water quality in the middle-Floridan and LFA, with increasing chloride concentrations in several middle-zone wells from less than 100 milligrams per liter (mg/L) to more than 1,000 mg/L since 1952. The author did not draw comparisons between hydrologic conditions within study area to hydrologic features of interest outside the study area in this report.

- Reference 4: *Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida and parts of Georgia, South Carolina, and Alabama (1988)*.
  Groundwater level declines coalesced to form a regional-scale cone of depression (Figure 6). This cone of depression shifted the ground-water basin boundary between the SRWMD and northern SJRWMD towards the southwest; which diverted a portion of the groundwater that, in predevelopment times, flowed towards the SRWMD to pumping centers in northeastern Florida and southeastern Georgia. Pumpage resulted in significant movement of the groundwater basin boundary separating the Suwannee Groundwater Basin from the southeast Georgia/ northeast Florida/ South Carolina Groundwater Basin. Increases in recharge and decreases in discharge generally balanced pumping stresses, resulting in approximate steady-state conditions within the FAS as a whole.

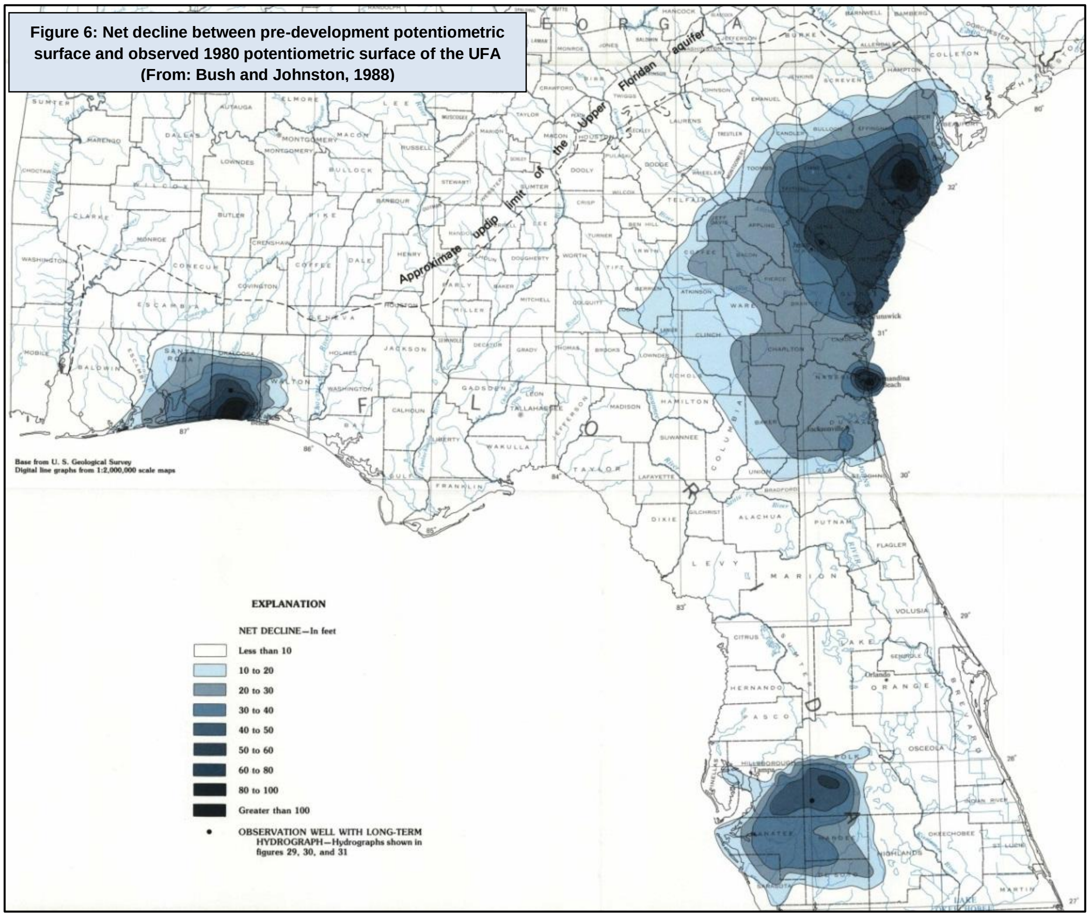


Figure 6: Net decline between pre-development potentiometric surface and observed 1980 potentiometric surface of the UFA (From: Bush and Johnston, 1988)

- Reference 7: *Hydrology of Brooklyn Lake near Keystone Heights, Florida (1963)*.
Brooklyn Lake receives significant inflow from the SAS. During a period of deficient rainfall (1955 – 1958), Brooklyn Lake receded approximately 20 feet below a desirable stage. The lake also loses water to the UFA, since it is hydraulically connected. Since leakage is proportional to the head difference between the lake level and the potentiometric surface of the UFA, water table lakes subsequently recede when the potentiometric surface in the UFA is lowered, especially those that are the surface expression of filled sinkholes (such as Brooklyn Lake). Seepage losses to the UFA of approximately three to eight mgd were calculated in the case of Lake Brooklyn. Additionally, FAS and SAS well hydrographs compared to the lake stage in 1960 show head differences are greatest at low stages resulting in increased seepage.

- Reference 11: *Water level changes in aquifers of the Atlantic Coastal Plain, predevelopment to 2000 (2008)*.
UFA water levels in the confined coastal areas, where the highest pumping occurred between predevelopment and 1980, were most affected by pumpage (Figure 6). After 1980, groundwater levels stabilized and recovered at the major cones of depression at Savannah, Brunswick, and Jessup, Georgia (Figure 7). The drawdowns remained about the same in St. Marys, Georgia and Fernandina Beach, Florida, and were stable to slightly declining in Jacksonville, Florida. In general, the distribution of withdrawals shifted inland after 1980 allowing for stable and recovering water levels along the coast and moderate water level declines further inland (Figure 7). The author applied constant values for precipitation and aquifer recharge for the time periods studied.

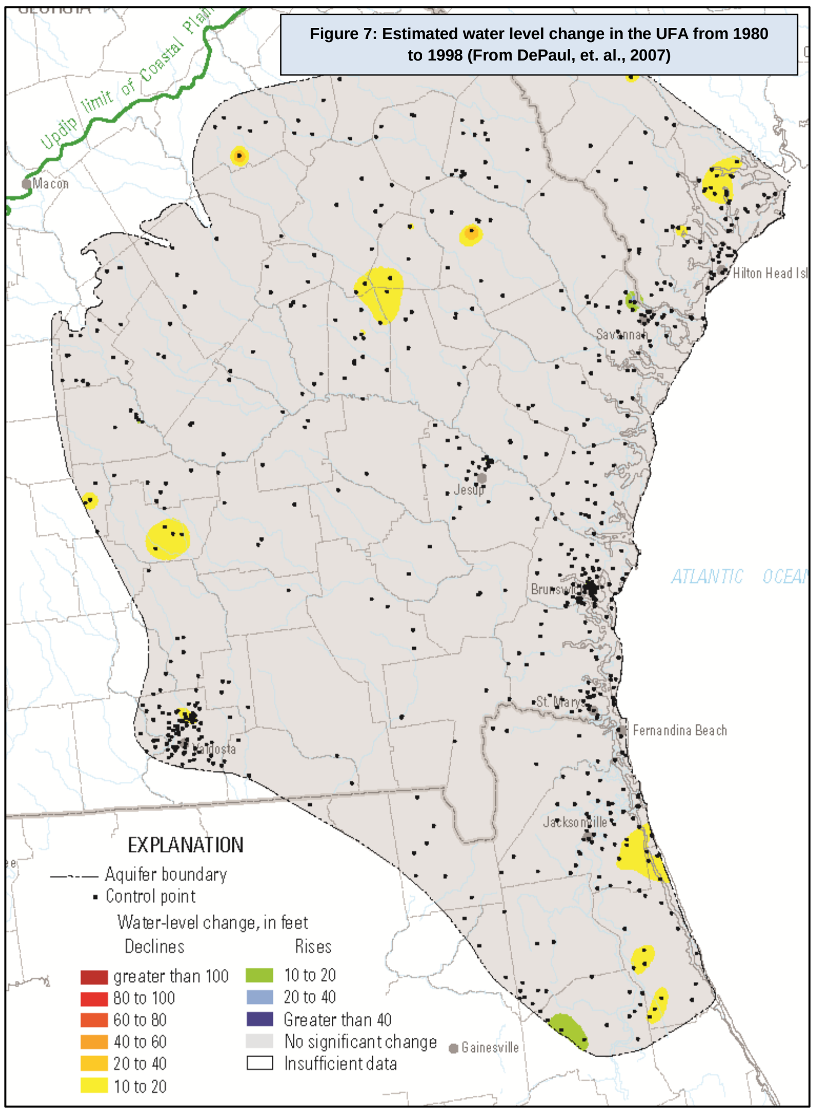


Figure 7: Estimated water level change in the UFA from 1980 to 1998 (From DePaul, et. al., 2007)

- Reference 13: *Finite-difference simulation of the Floridan aquifer system in Northeast Florida and Camden County, Georgia (1997)*.

  The author detailed the development and application of a regional steady-state UFA model in northeast Florida and Camden County, Georgia (Figure 8). Predevelopment (prior to the onset of major pumpage), 1985, and projected (2010) simulations were considered. Mass-balance analysis showed postdevelopment conditions led to a significant increase in groundwater flux relative to predevelopment conditions. Within the FAS, the greatest amount of flux occurred in the LFA, a significant source of recharge to the UFA within the model domain. The greatest source of influx to the UFA, LFA, and Fernandina permeable zone was recharge entering the model from outside the model domain through the western model boundary.

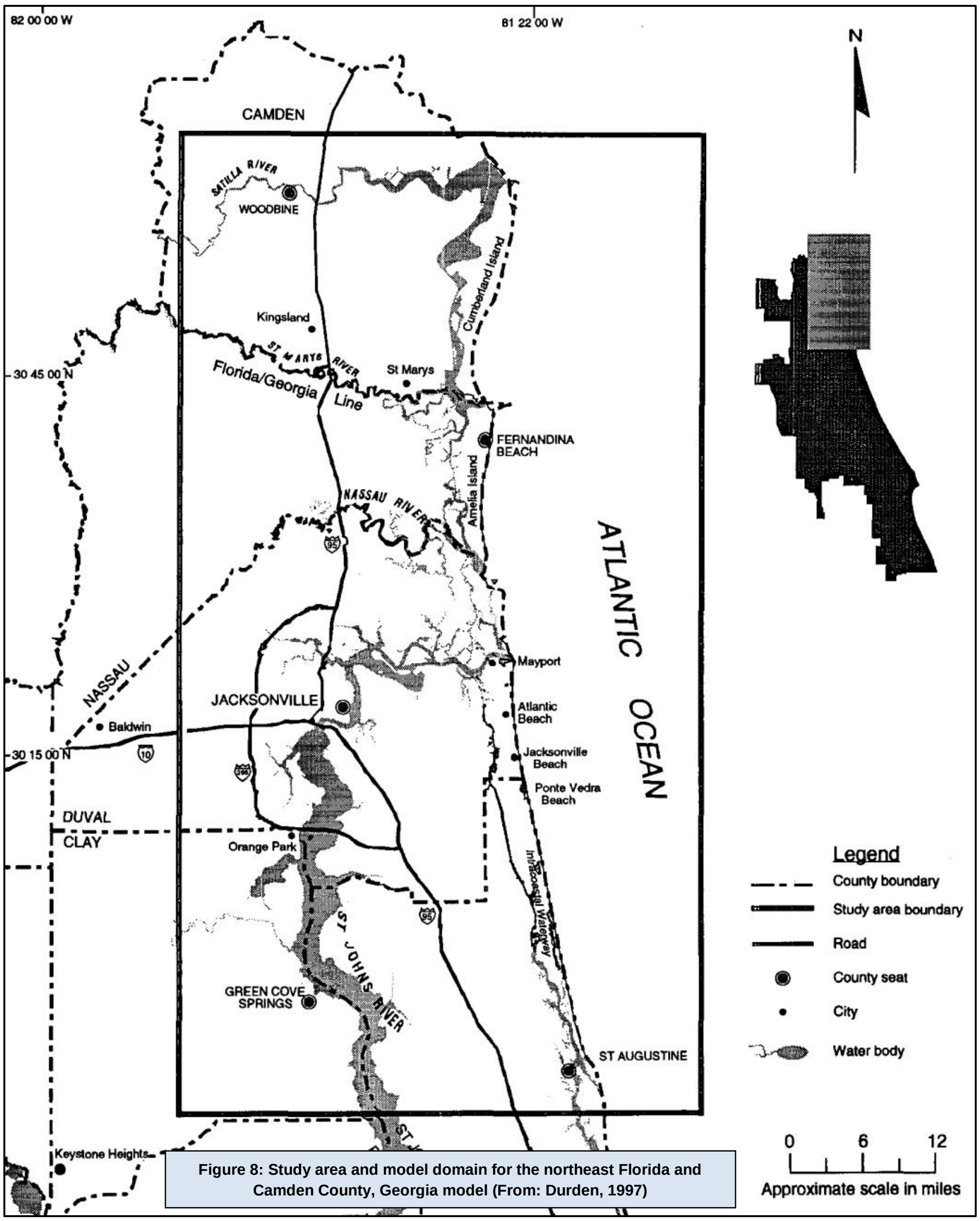


Figure 8: Study area and model domain for the northeast Florida and Camden County, Georgia model (From: Durden, 1997)

Pumping was a significant outflow from both the UFA and LFA and resulted in a significant reduction in flux to offshore areas and in an increase in downward flux from the overlying SAS, which is inhibited by thick clay beds of the intermediate aquifer system. As a result, influx from areas west of the model domain was the major contribution of additional flux necessary for supplying water to wells under postdevelopment conditions. Predictive simulations indicated that, by 2010, the potentiometric surface of the UFA would decline by 0 to 5 feet relative to predevelopment conditions throughout most of the study area, and decline by 5 to 20 feet in parts of the southern half of the study area due to projected groundwater withdrawals. The role of changing climatic conditions was not considered in the analysis.

- Reference 17: *Water use in Georgia by county for 2005; and water-use trends, 1980 – 2005 (2009)*.

  Trends in water use in Georgia generally followed trends in climate, with more water use during the 1998-2002 drought period and decreasing use leading up to the 2005 wet period. The state-wide 2005 surface water use (4.3 billion gallons per day, or bgd) exceeded 2005 groundwater use (1.2 bgd) and accounted for 78 percent of Georgia's overall water use, with the primary surfacewater use type being power generation. Water use in southern Georgia was predominantly from UFA withdrawals for agricultural uses and accounted for at least 75 percent of the water use from counties bordering SRWMD and SJRWMD (Figure 9). The authors noted a 32 percent increase in total irrigated acres (agricultural and landscape-recreation-aesthetics) between 1995 and 2005.

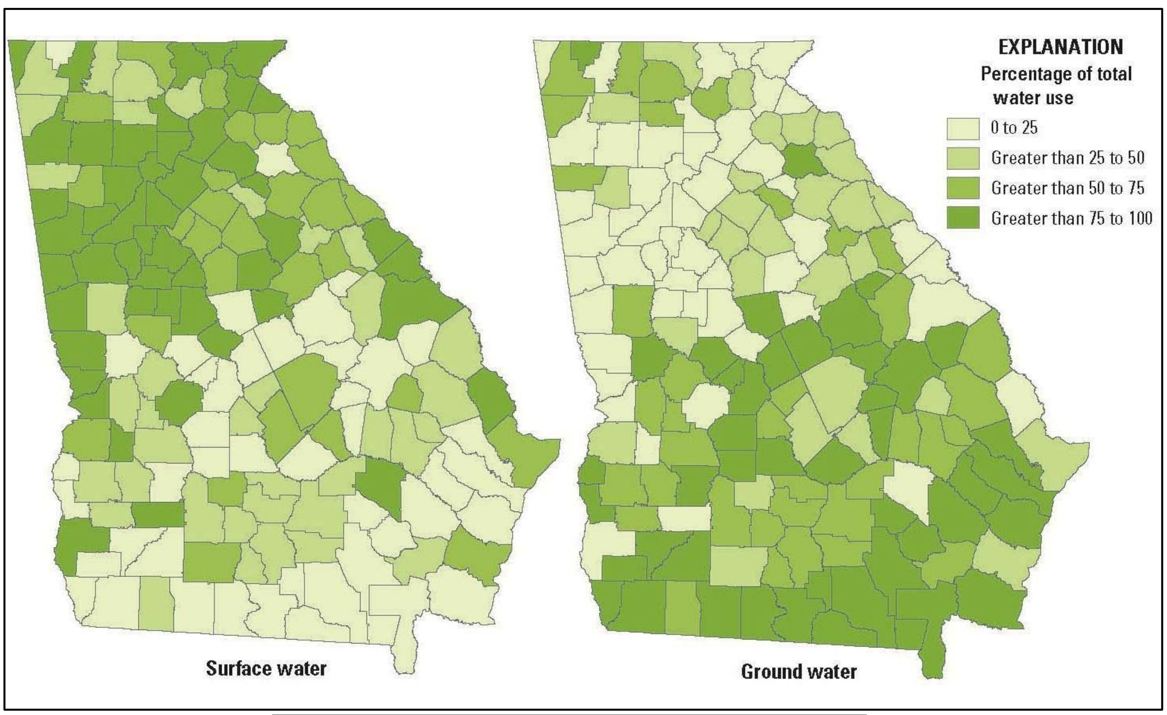


Figure 9: Percentage of total water use by county and source in 2005 (From: Fanning and Trent, 2009)

- Reference 20: *Estimated drawdowns in the Floridan aquifer due to increased withdrawals, Duval County, Florida (1979)*.

  In 1975, groundwater withdrawals from the UFA were approximately 150 mgd in Duval County, which resulted in artesian water level declines of about 0.5 foot/year. Steady-state distance-drawdown curves were compiled for a range of withdrawal rates (3, 5, 20, and 50 mgd) using a range of transmissivity (T) values (20,000 to 200,000 feet squared per day, or ft^2/d) estimated from more than 20 aquifer performance tests in Duval County. It was concluded that the spatial arrangement of pumping centers is a critical consideration for managing the influence of drawdown; which could be as much as 40 feet of drawdown 5,000 feet from a 50 mgd withdrawal point.

  Predicted aquifer drawdowns were not entirely consistent with observed localized historic water-level declines. However, the author cited possible errors in transmissivity and leakance estimates, paucity of historic water use data (i.e., errors in drawdown are directly related to errors in withdrawal estimates), the presence of long-term regional declines, and fluctuations in climate masked by significant pumpage as possible reasons. However, the estimated aquifer parameters (i.e., T, storage, and leakance) were considered representative and could be used to evaluate aquifer response to future pumping rates. The author also concluded that increased UFA withdrawals would be accompanied by further head decline in the LFA; which could facilitate further UFA saltwater intrusion.

- References 21 and 22: *Gao, et. al, 2010 (SJ2010-SP11) and Gao, et. al., 2010 (SJ2010-SP12)*.

  Both references involved collection, compilation, and statistical trend analyses of historic hydrologic data (groundwater levels, rainfall, streamflow, spring discharge) and groundwater withdrawal records in counties in the Suwannee River Basin in Florida and Georgia. Reference 21 looked at the time period from 1980 to 2007. Of the UFA stations, 9 of 52 in the SRWMD had statistically significant downward trends, four of seven in Georgia, and 18 of 73 in the SJRWMD. Of these, 12 groundwater wells exhibited “very certain” downward trends (one SRWMD, three Georgia, and eight SJRWMD). Probable correlations existed between two of the SRWMD wells and one of the nearest rainfall stations. Also, probable correlations are shown between three Florida (SRWMD) and two Georgia wells and nearest streamflow stations. Annual rainfall did not show a trend over the same period but was not analyzed for seasonal or monthly trends. Trend analysis on groundwater withdrawal data suggests that the data were not of sufficient quality to draw any conclusions or show relationships with other hydrologic time series. Correlation analysis suggested that annual rainfall was correlated to groundwater levels. Cluster analysis identified a number of wells exhibiting downward trends are in the vicinity of Northeast Florida as well as central Georgia.

  Using the entire period of record (POR) in Reference 22 (as opposed to the 27-year POR in Reference 21), the statistical analyses identified more trends in groundwater levels in both Florida and Georgia, mainly in the Jacksonville area. The SRWMD showed 13 downward-trending wells (six “very certain”), Georgia had five downward-trending wells (three “very certain”), and SJRWMD had 28 downward-wells (21 “very certain") with statistically significant trends. Cluster analysis for Georgia, SJRWMD, and SRWMD trending wells was similar to Reference 21 findings.

- Reference 23: *Exchanges of water between the Upper Floridan aquifer and the Lower Suwannee and Lower Santa Fe rivers, Florida (2007)*.
  This reference examined the exchange of groundwater between the UFA and the lower Suwannee and lower Santa Fe Rivers in the SRWMD. The primary study area, and focus for the development of a transient hydrologic model, was the southern portion of the SRWMD and included the lower Suwannee River and lower Santa Fe River. The author referred to this area as the subregional study area boundary. Results of the study identified climate as a significant hydrologic factor driving the rates of groundwater inflow into the subregional study area.

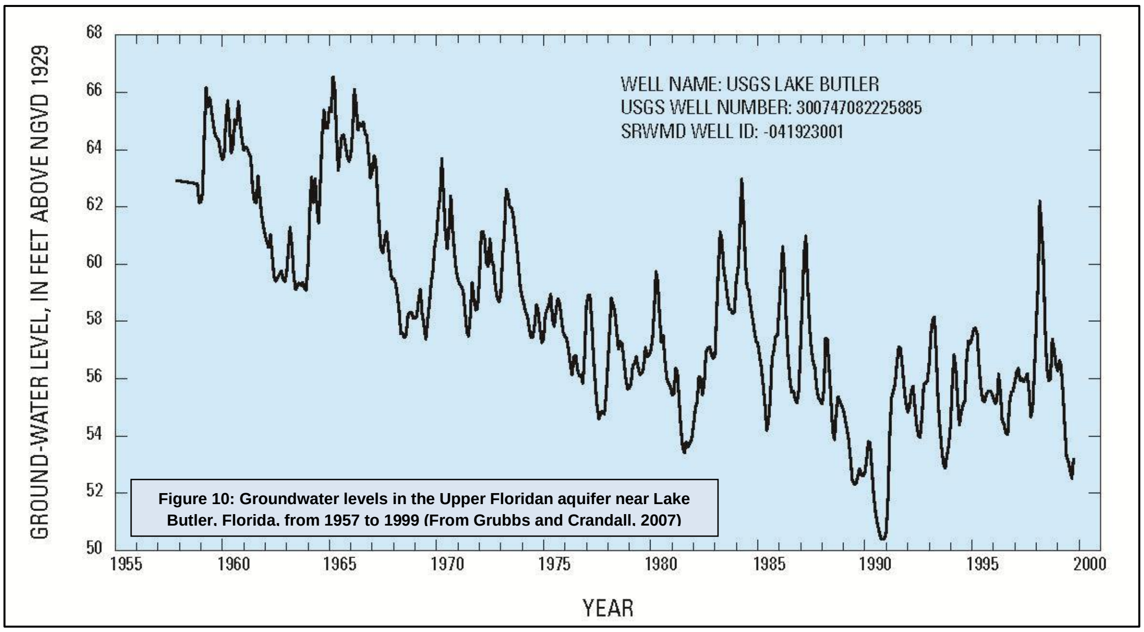


Figure 10: Groundwater levels in the Upper Floridan aquifer near Lake Butler, Florida, from 1957 to 1999 (From Grubbs and Crandall, 2007)

Also mentioned were large regional UFA drawdowns due to groundwater pumpage in the northeastern portion of the regional study area resulting in the westward migration of the groundwater basin flow boundary between the SJRWMD and SRWMD. However, groundwater levels in the USGS Lake Butler monitor well (Figure 10) indicated the rate of drawdown slowed or perhaps stopped in recent times and the boundary may have currently reached equilibrium.

- Reference 24: *Analysis of long-term trends in flow from a large spring complex in northern Florida (2011)*.
  Water levels and configurations of the regional predevelopment and May 1980 UFA potentiometric surface maps were compared.

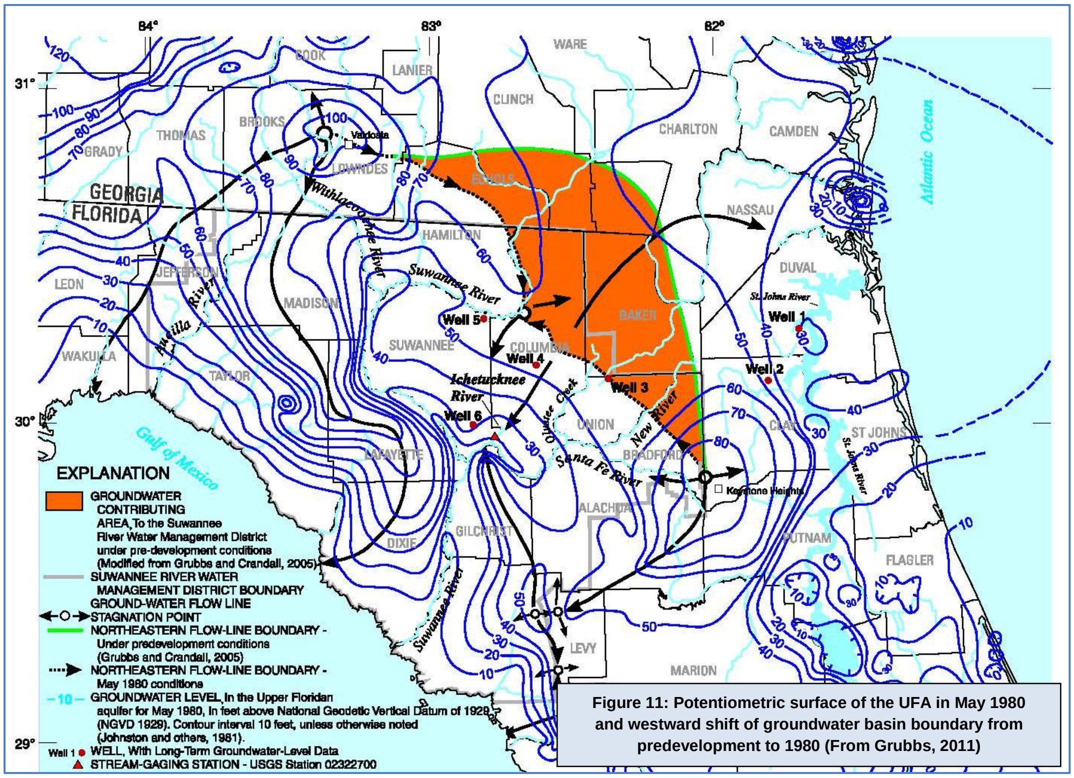


Figure 11: Potentiometric surface of the UFA in May 1980 and westward shift of groundwater basin boundary from predevelopment to 1980 (From Grubbs, 2011)

The author suggested that large regional withdrawals in the UFA in the northeastern portion of the study area resulted in a westward migration of the northeastern groundwater flow-line boundary between the two water management districts from predevelopment to 1980 (Figure 11). Comparison between predevelopment and May 1980 potentiometric surface maps indicated groundwater level declines were negligible near the Ichetucknee River becoming more pronounced toward the northeast. Average groundwater levels declined 4 to 12 feet in selected wells east and west of the groundwater flow boundary from 1960 to 2009 (Figure 12).

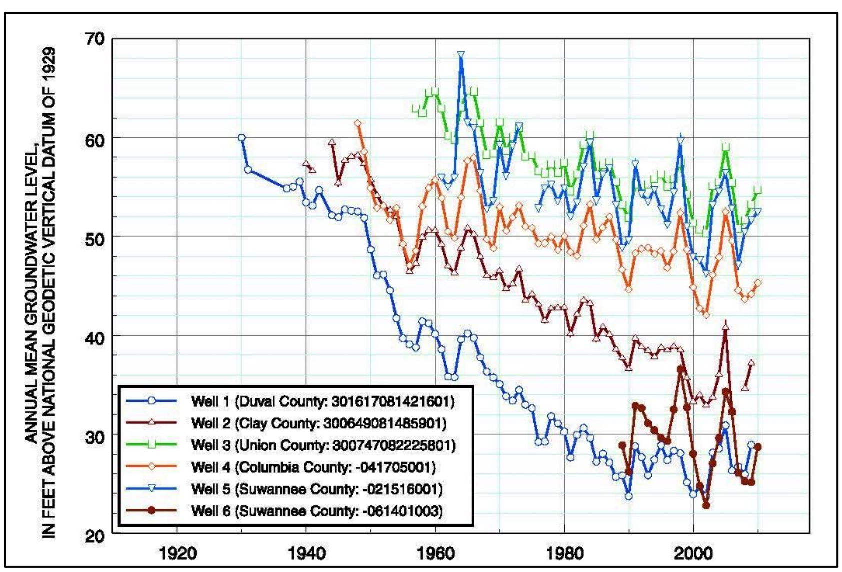


Figure 12: Time series of groundwater levels from selected wells in northern peninsular Florida (From: Grubbs, 2011)

While the exact position of the northeastern groundwater basin flow-line boundary for both time periods is subject to interpretation, an overall decline of the UFA potentiometric surface over the long term is well documented in other sources. However, the general configuration of the potentiometric surface has been relatively stable since approximately 1980.

The author also identified an increase in the rate of decline in flow of the Ichetucknee River that was not consistent with the historic relationship between flow and short term rainfall, thus concluding that groundwater withdrawals in and around the modern groundwater contributing basin were the likely cause.

- <u>References 27 and 28</u>: *Healy, 1962 (1961 FAS potentiometric surface map) and Healy, 1974 (1974 FAS potentiometric surface map)*.
  Maps of the FAS potentiometric surface and areas of artesian flow generated from data collected July 6-17, 1961 (Reference 27), and May 1974 (Reference 28) were compared and contrasted. The comparison of areas of artesian flow in both documents reveals that these areas decreased in size only slightly from 1961 to 1974 when considering the entire FAS. There were major declines in the potentiometric surface locally (i.e., in the north-central / northeast Florida area), but not regionally (Figure 13).

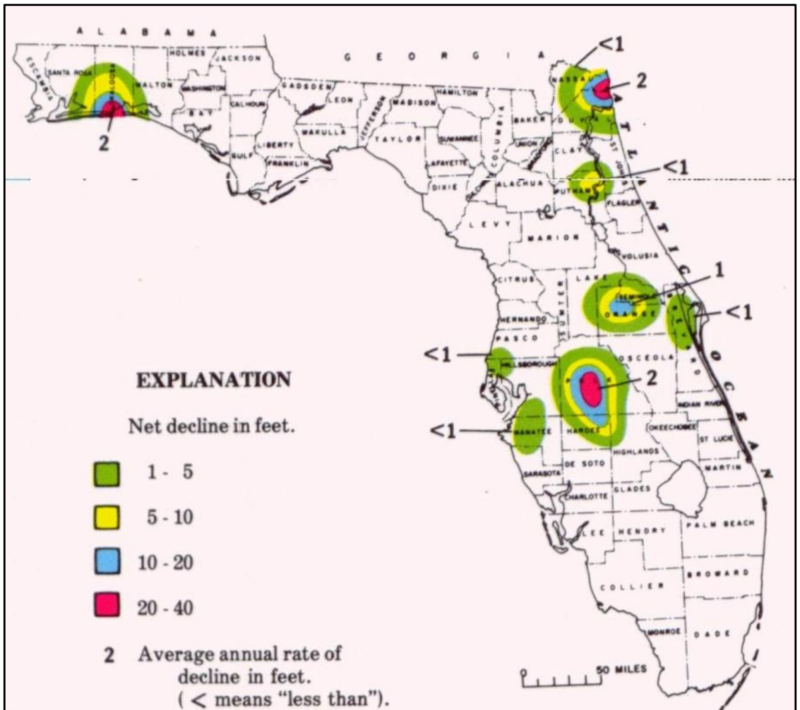


Figure 13: Decline of the potentiometric surface of the FAS in areas of heavy groundwater withdrawal, 1961 – 1974 (From: Healy, 1974)

Additionally, the configuration of major features of the potentiometric surface did not change appreciably from 1961 to 1974 (e.g., recharge areas). Comparatively, the potentiometric surface was lower in 1974 than 1961, which was attributed to differences in regional groundwater use, climate, and an admitted lack of data 'control' due to a low density of monitoring wells in some areas.

- Reference 32: *Adaptation of the USGS MegaModel for the prediction of 2030 groundwater impacts (2012)*.
  Predictive simulations of the effects of projected increases in groundwater withdrawals between the years 1995 and 2030 were performed using the modified USGS MegaModel. Results showed that a major portion of anticipated water level declines in both the SAS and FAS will be due to projected increases in groundwater withdrawals in the SJRWMD (Figure 14).

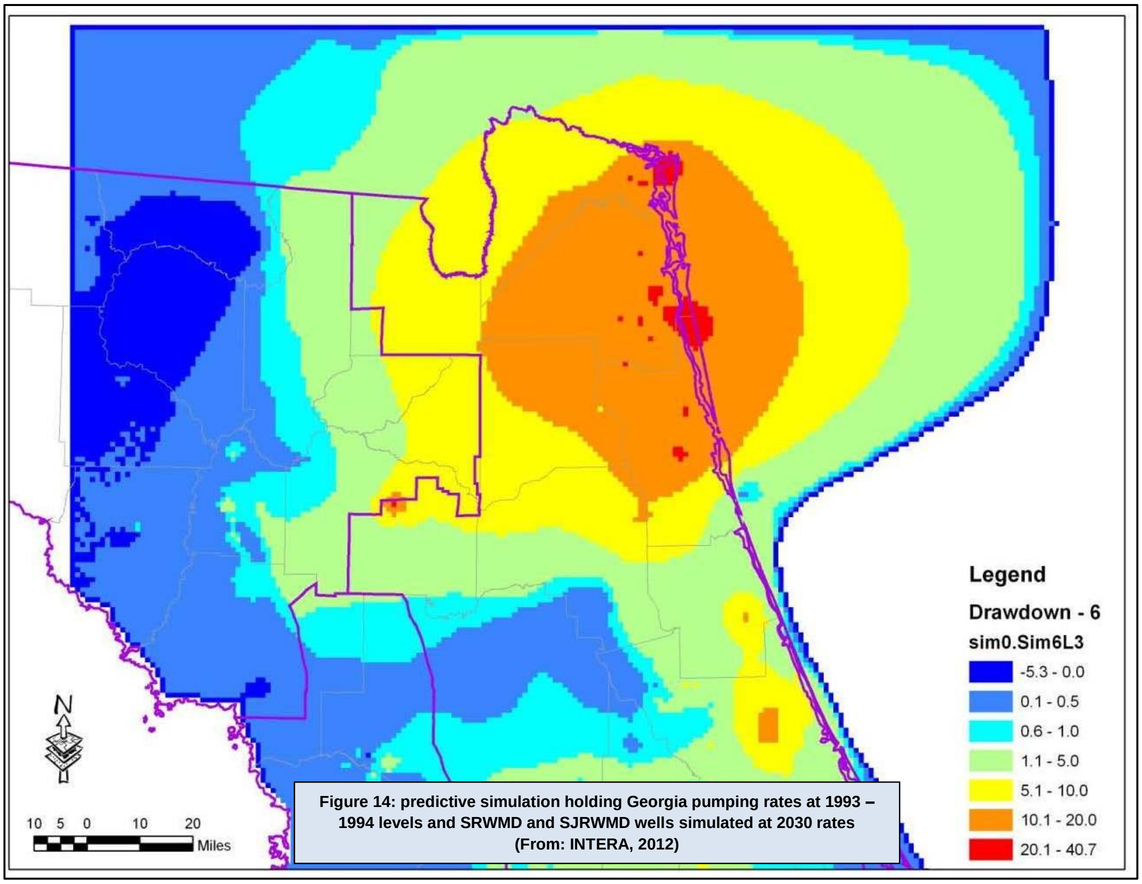


Figure 14: predictive simulation holding Georgia pumping rates at 1993 – 1994 levels and SRWMD and SJRWMD wells simulated at 2030 rates (From: INTERA, 2012)

These predicted declines extend well into the SRWMD and indicate the potential for significant inter-district withdrawal impacts. Model results also indicated that the PCS phosphate mine in the SRWMD had a significant impact on White Sulphur Springs, as removal of the withdrawal effects caused the spring to reverse from being an inflow to the FAS to an outflow from the FAS. The model did not include an evapotranspiration (ET) package; therefore, changes in ET as a function of the change in the water-table level are not represented in the modified MegaModel and water that would have gone to the atmosphere is diverted to other outflows (the SAS in this case). By excluding the ET package, drawdown estimates may be larger than would otherwise be the case. Estimated recharge rates were negative in many instances, indicating the need for additional adjustments. Two errors in the dataset used to generate the artificial neural network estimation of White Sulphur Springs flow were also identified. Specifically, groundwater withdrawals at the PCS phosphate mine in Hamilton County used in the model were approximately 42% higher than actual water use data collected later by SRWMD.

- Reference 34: *Summary of the hydrology of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama (1988)*.
  The dominant feature of the FAS flow system, both before and after groundwater development, is discharge from UFA springs (Figures 15 and 16).

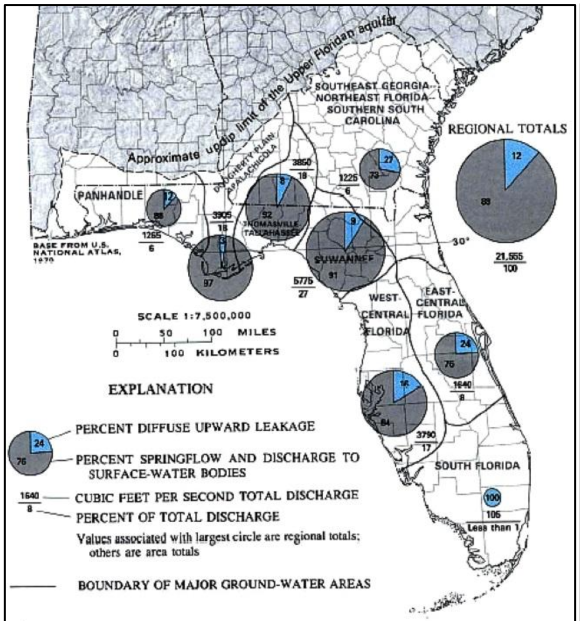


Figure 15: Estimated predevelopment discharge from major groundwater basins of the UFA (From: Johnston and Bush, 1988)

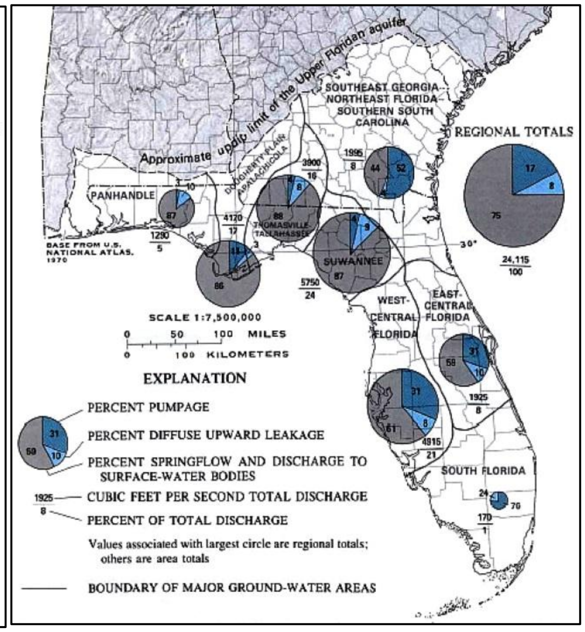


Figure 16: Estimated discharge from major groundwater basins of the UFA, approximately 1980 (From: Johnston and Bush, 1988)

  The approximately three billion gallons per day pumped from the FAS in 1980 regionally resulted in water level declines of more than 10 feet; and is supplied primarily by diversion of natural outflow from the system and induced recharge, rather than by loss of water from aquifer storage. On a subregional scale, pumpage has produced steep cones of depression in areas of lower transmissivity, changes in the natural groundwater flow direction, increased recharge rates, and saltwater encroachment. Inconsistent with findings in USGS Professional Paper 1403-C (Reference 4), this report found pumpage has not resulted in significant movement of the groundwater basin boundary separating the Suwannee Groundwater Basin from the southeast Georgia/ northeast Florida/ South Carolina Groundwater Basin; and the configuration of the UFA potentiometric surface was considered to be approximately at equilibrium, except during periods following sustained increases in pumping. The stability of groundwater flow boundaries is largely the result of water being readily available from increases in induced recharge (i.e., vertical leakage) or from adjacent areas within the aquifer (i.e., diversion of natural discharge, [e.g., springs]).

- Reference 33: *Estimated potentiometric surface for the Tertiary limestone aquifer system, south-eastern United States prior to development (1980)*.

A predevelopment potentiometric surface was estimated based on past measurements in areas where water levels had already changed (primarily due to pumpage), and present-day (early 1980's) water levels in relatively undeveloped areas. Previous maps showing water levels in the 1930s, 1940s, and 1960s were also used. Areas of high recharge show up as potentiometric highs and areas experiencing significant groundwater withdrawals result in depressions in the surface. A potentiometric high does not necessarily receive its recharge directly from the same location as recharge can also originate laterally. Most notable was an estimated predevelopment potentiometric high in the Keystone Heights region of 90 feet or more.

- Reference 36: *Interactions between groundwater and surface water in the Suwannee River basin (1997)*.
  This document represents one of the first significant studies in the SRWMD using water chemistry and statistical parameters to quantitatively describe and define surface water/ groundwater mixing. In the upper Suwannee and upper Santa Fe basins, the groundwater basins do not coincide with the surface water drainage basins due to aquifer confinement.

- Reference 37: *Hydrology of the Floridan aquifer system in Southeast Georgia and adjacent parts of Florida and South Carolina (1989)*.
  In terms of alterations to the level and configuration of the UFA, the report focused primarily on the coastal areas of southeast Georgia and northeast Florida. Intense pumping in this area resulted in significant drawdowns in the UFA and some localized saltwater intrusion by the early 1980s (Figure 17).

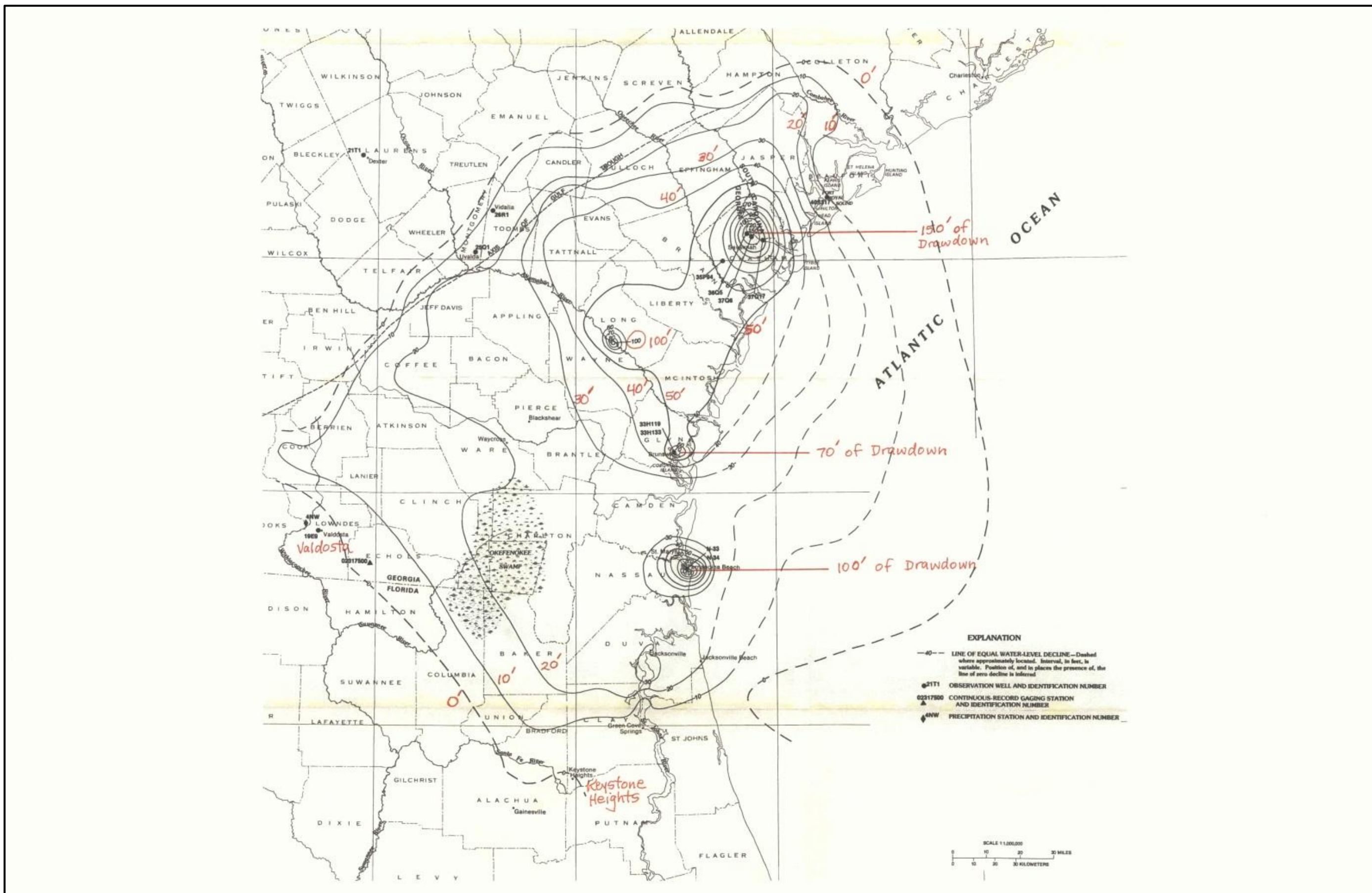


Figure 17: Estimated decline in the potentiometric surface of the UFA from 1880 to 1980 (After: Krause and Randolph, 1989)

Aquifer recharge in some areas (Valdosta and Keystone Heights for example) appeared to temper the head decline caused by regional pumping. In these recharge areas, groundwater levels respond more to changes in precipitation and stream flow with limited long-term decline (Figure 18).

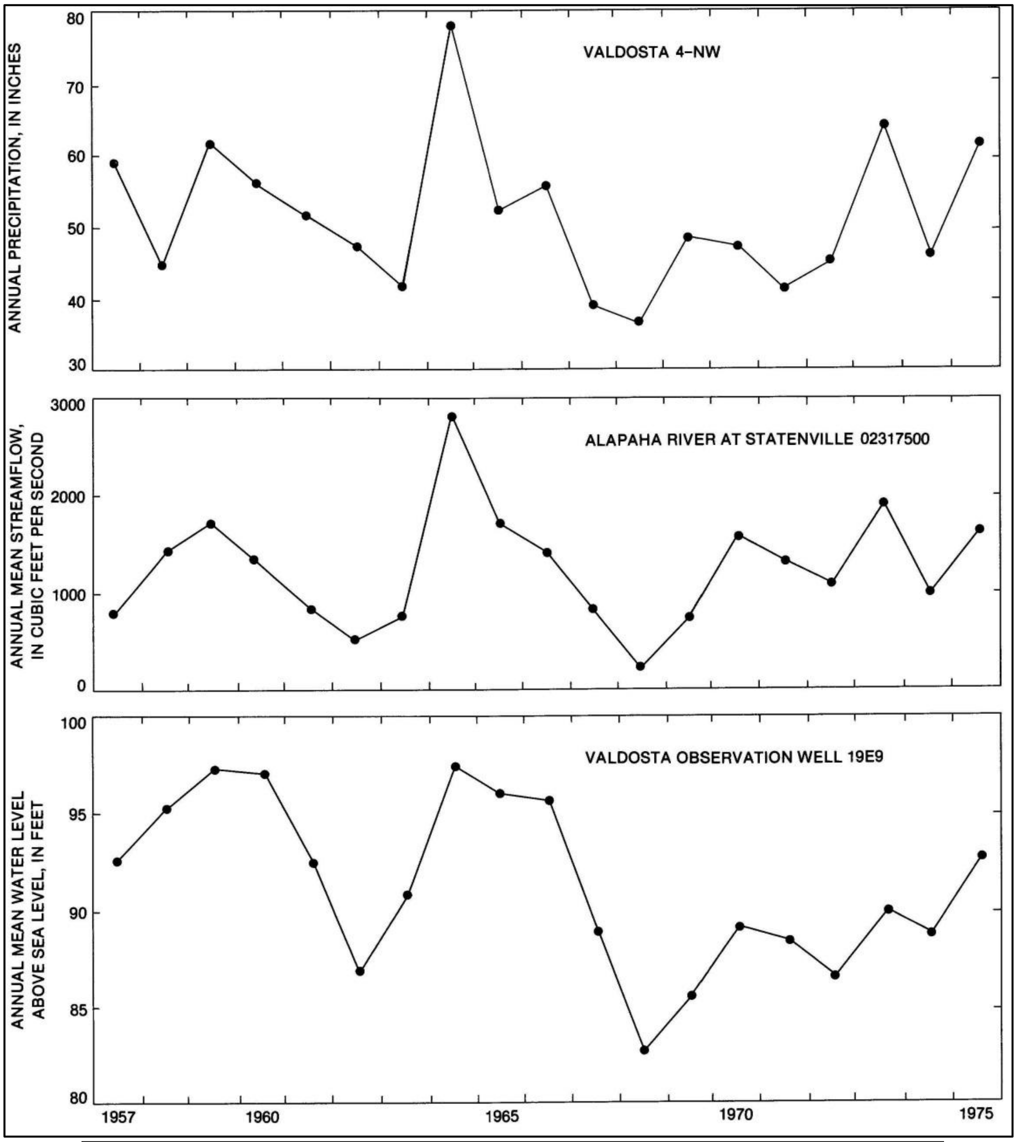


Figure 18: Relation of precipitation, streamflow, and water level in the UFA, Valdosta, GA area, 1957 – 1975 (From: Krause and Randolph, 1989)

- <u>References 44 and 45</u>: *Water withdrawals and trends from the Floridan aquifer system in the southeastern United States, 1950 – 2000* (Reference 44, 2005); and *Water withdrawals, use and trends in Florida, 2005* (Reference 45, 2009).
  Overall, fresh groundwater withdrawals increased steadily from 1950 to 2000 (peaking in 2000) and declined from 2000 to 2005, probably from the effects of climate, water conservation efforts and alternative water supplies. Water use is typically inversely proportional to rainfall and directly affects the level and configuration of the

potentiometric surface. Where implemented, inclining block (tiered) water utility rate structures and watering restrictions help reduce water use.

- Reference 47: *Ground water atlas of the Unites States, Alabama, Florida, Georgia, and South Carolina (1990)*.

  The degree of confinement in the FAS controls the shape and smoothness of the contour lines as well as the magnitude of water level fluctuation. Pumpage can create cones of depression in the potentiometric surface and can cause flow direction to change and even reverse. By 1980, in the vicinity of Fernandina Beach, Florida and Brunswick, Georgia, the UFA potentiometric surface had declined from 30 feet to greater than 80 feet from predevelopment conditions, and groundwater levels in the area of the groundwater basin boundary between the SRWMD and SJRWMD generally declined 10 to 30 feet from predevelopment to 1980 (Figure 19).

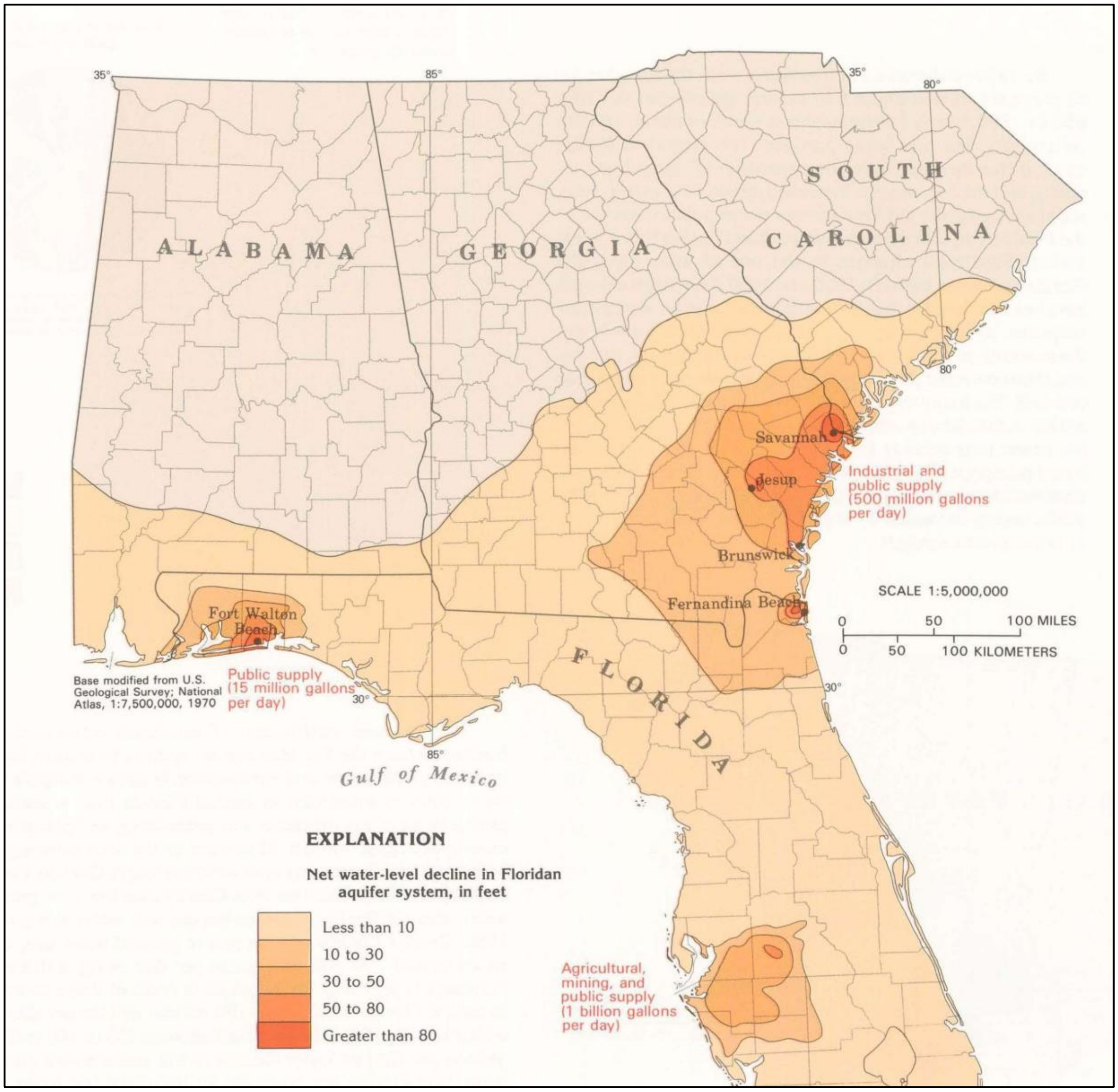


Figure 19: UFA potentiometric surface decline between predevelopment conditions and 1980 (From: Miller, 1990)

However, the configuration of the potentiometric surface (e.g., the position and shape of recharge and discharge areas) had not been significantly altered by groundwater development. Discharge from the FAS from predevelopment to 1980 was predominantly through springflow and discharge to streams. In 1980, withdrawals accounted for only 20 percent of the total discharge from the system.

- <u>Reference 50</u>: *Simulation of ground-water flow in coastal Georgia, and adjacent parts of South Carolina and Florida – predevelopment, 1980, and 2000 (2005)*.
  This report documented the development and application of a regional groundwater flow model that focuses primarily on southeastern Georgia, but also includes a small portion of northeastern Florida. It addressed temporal changes between predevelopment, 1980, and 2000 in the FAS, SAS, and the Brunswick aquifer system (an intermediate aquifer system within the Hawthorn Group located exclusively in Georgia). Simulated pumping resulted in increased recharge to the FAS while decreasing the rate of base flow to streams, and reversal of seaward lateral gradients back towards land in the coastal Georgia area between Chatham and Camden counties and parts of northeastern Florida. The rate at which groundwater flowed from the seaward to landward direction exceeded the predevelopment landward to seaward rates. Hydraulic gradient reversals resulted from declines in groundwater levels in the FAS of the coastal areas of Georgia and northeastern Florida.

- <u>Reference 51</u>: *Potentiometric surface of the Upper Floridan aquifer in Georgia and adjacent parts of Alabama, Florida, and South Carolina, May 1998 (1999)*.
  The potentiometric surface map, developed from water level measurements collected from 2,000 wells throughout May 1998 in Georgia, was described according to four geographic areas generally based on factors such as degree of confinement and aquifer recharge/ discharge zones: 1) southwestern area, 2) south-central area, 3) north-central area, and 4) coastal area (Figure 20).

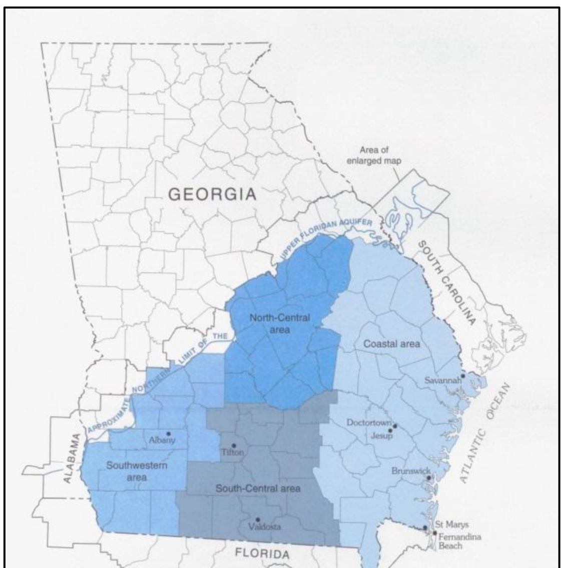


Figure 20: Geographic areas (From: Peck, et. al., 1999)

Water levels from selected wells in each of the four areas were evaluated for trends for the time period 1990 to 1998. Coastal area water levels were generally higher in 1998 than 1990 due to a decrease in pumpage from about 369 mgd in 1990 to 347 mgd in 1997. Furthermore, groundwater levels were generally higher in 1998 than 1990 in the south-central area. In the south-central area, seasonal water levels were generally highest in the late winter and early spring and declined from late summer to fall (primarily in response to precipitation. The most notable potentiometric feature in the south-central area (bordering SRWMD) is the Valdosta High recharge area, which receives approximately 70 mgd in direct UFA recharge via sinkholes along the Withlacoochee River.

- Reference 52: *Ground-water conditions and studies in Georgia, 2006 – 2007 (2009)*.
  The authors evaluated the changes in the level and configuration of the potentiometric surface of the UFA in the study area from 2006 – 2007. Where the FAS is semiconfined, water levels fluctuated seasonally in response to variations in climate-related recharge and pumping. Where the aquifer is confined, water levels responded primarily to pumping and fluctuations related to climate were less pronounced. The authors' approach to representing POR percentiles with as little as three years of data and defining percentiles based on different PORs was cause for concern.

- Reference 53: *Water resources of Duval County, Florida (1994)*.
  The author identified a declining trend in the UFA potentiometric surface from pre-development to 1989 (Figures 21 and 22).

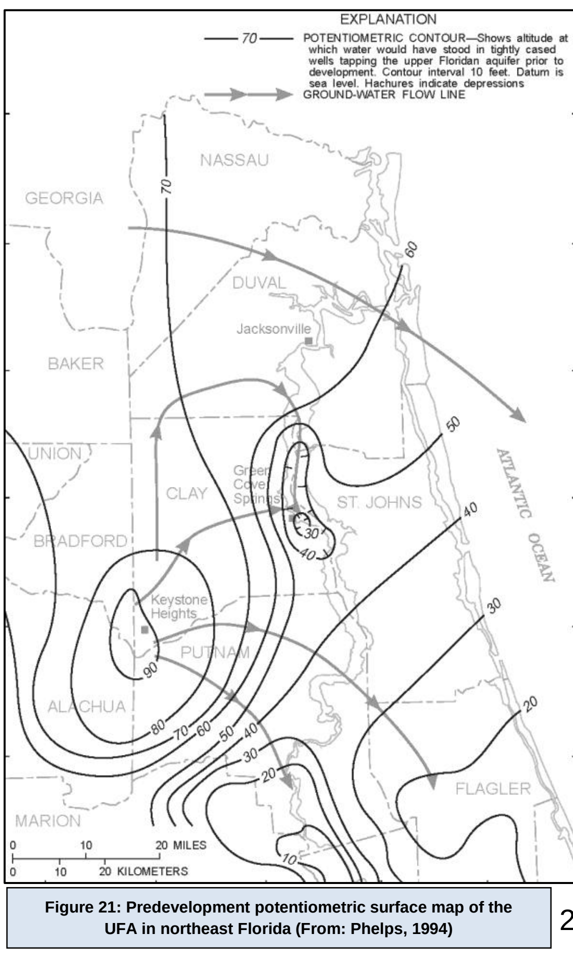


Figure 21: Predevelopment potentiometric surface map of the UFA in northeast Florida (From: Phelps, 1994)

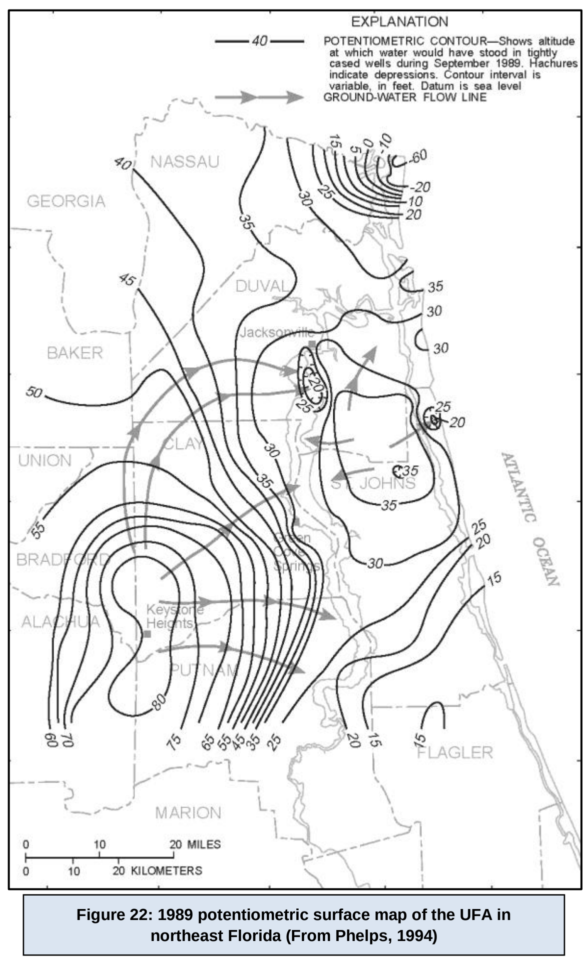


Figure 22: 1989 potentiometric surface map of the UFA in northeast Florida (From Phelps, 1994)

In the recharge areas of western Duval County, sediments overlying the FAS are thick and clayey, and the rate of recharge is low to moderate. Recharge in Duval County is not sufficient to replace the amount of water withdrawn there from the FAS. As a result, withdrawn groundwater is replaced by water moving laterally from an unstressed part of the aquifer to the west and southwest of the county, in particular the Keystone Heights potentiometric high (Figure 22).

Also noted was a potentiometric high in southeastern Duval County, likely the result of diffuse upward leakance that is not present on the pre-development potentiometric surface map. In this area, a declining UFA potentiometric surface increases the head difference between the UFA and LFA (which has a higher artesian head); thereby increasing the recharge potential from the overlying SAS.

- <u>Reference 55</u>: *Simulation of regional ground-water flow in the Suwannee River basin, northern Florida and southern Georgia (2007)*.
  The author noted that the groundwater basin boundary between the two districts migrated southwesterly since the onset of heavy pumping in Fernandina Beach and Jacksonville, Florida since the late 1800's. However, he observed that from 1980 through 2004 water levels in the FAS in the area of the groundwater basin boundary generally stabilized. Consequently, the configuration of the potentiometric surface may have also reached stability. The eastern model boundary (Figure 23) was set as a "no-flow" boundary for modeling purposes, which prohibited the simulation of flux across the boundary. The author recommended changing the eastern boundary from a no-flow to a general-head boundary condition in follow-up studies to account for additional increases in pumpage to the east.

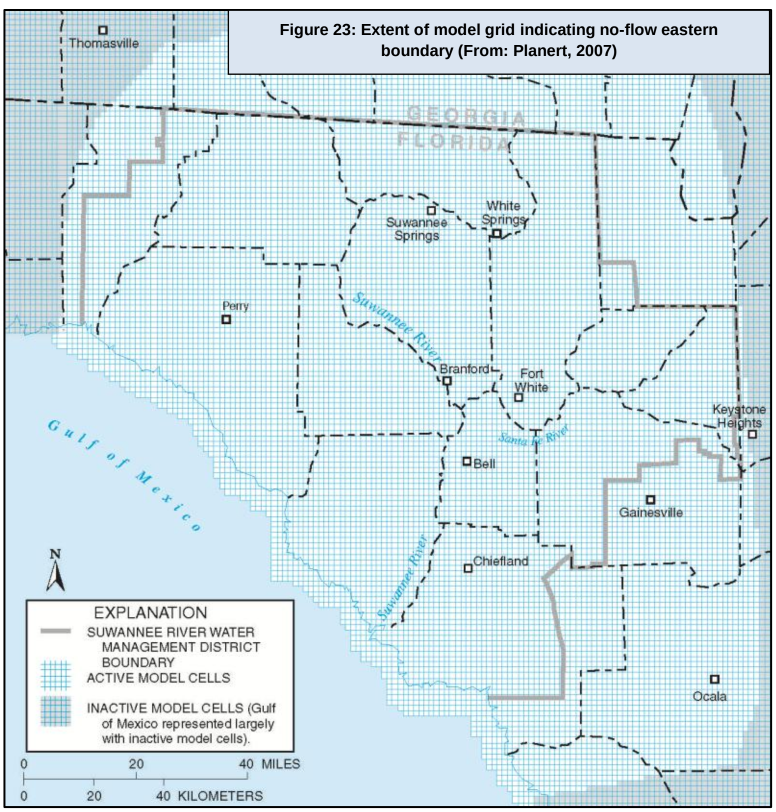


Figure 23: Extent of model grid indicating no-flow eastern boundary (From: Planert, 2007)

- Reference 60: *Artesian water in the Florida peninsula (1936)*.
  Reference 60 was previously discussed in the Introduction to this section (REVIEW AND EVALUATION OF DOCUMENTS). Please refer to pages 5 and 6.

- Reference 61: *Artesian water in Tertiary limestone in the southeastern States (1966)*.
  Withdrawal of water from wells is balanced by a combination of decrease in storage, decrease in discharge, and increased recharge. When the effects of withdrawal reach a recharge area, the rate of recharge is increased and any rejected recharge is captured. Rejected recharge could be in the form of runoff or ET. The most noticeable fluctuations in the potentiometric surface are the result of groundwater withdrawals; and, in the late 1950s, levels were trending downward with appreciable decreases in coastal Georgia and Northeast Florida (Figure 24). Except for those areas of heavy pumping, most of the major features of the potentiometric surface of the FAS remained essentially the same as in 1934 (see Stringfield, 1936 and Figure 4).

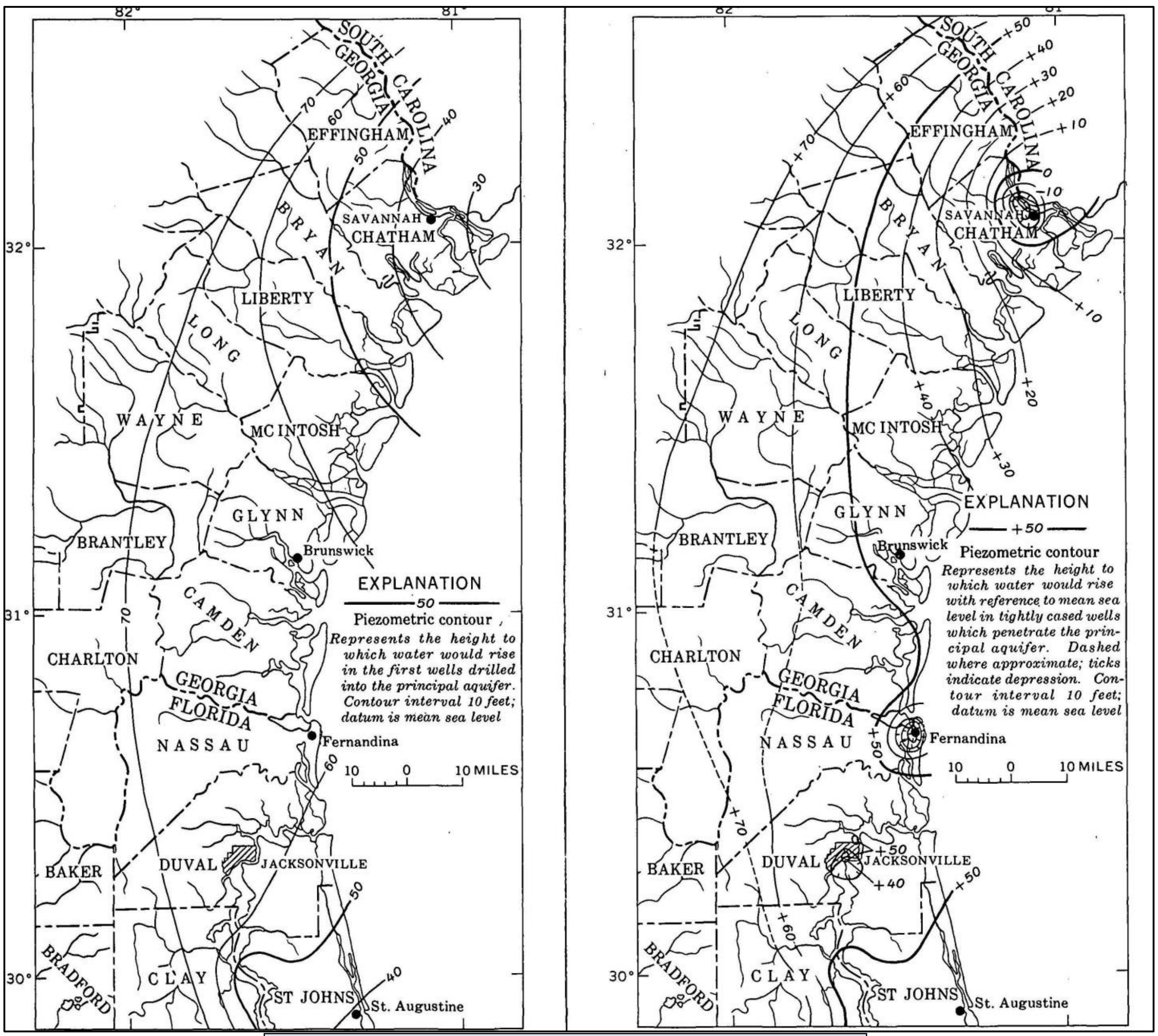
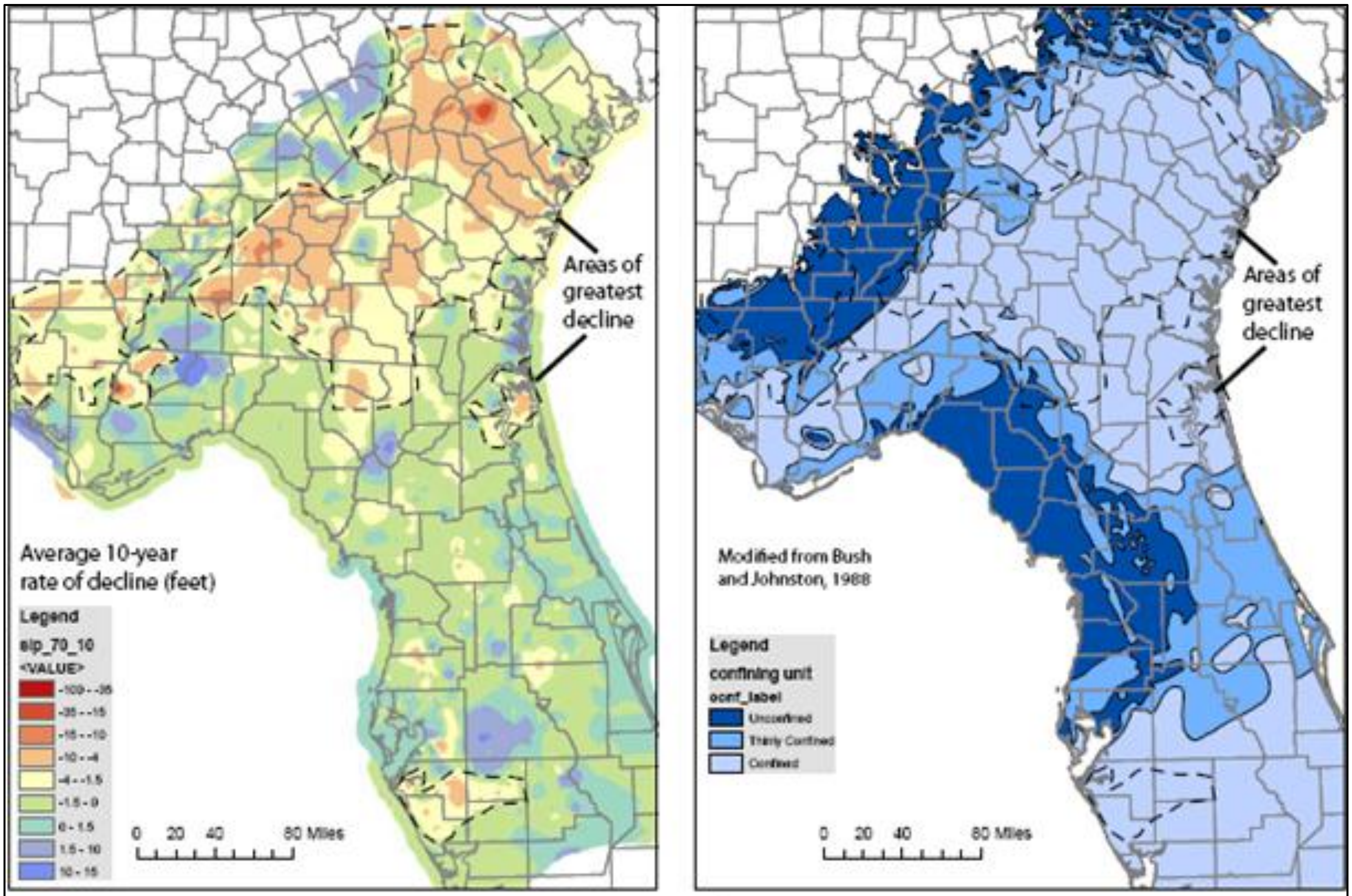


Figure 24: Interpreted UFA potentiometric levels in 1885 (left) and 1940 (right) (From: Stringfield, 1966)

- Reference 62: *PowerPoint presentation – Relation of aquifer confinement and long-term groundwater level decline in the Floridan aquifer system (2011)*.
  An analysis of spatial and temporal groundwater levels in the UFA indicates that, in general, regional groundwater level declines in the confined regions are three times greater over a 40-year period (1970 – 2010) than declines in the unconfined regions (Figure 25). The author contributes the long-term water level declines in the confined areas to lower recharge rates through the upper confining unit, increases in annual pumpage, and long pronounced drought coupled with pumping. The author also states that the declining areas have expanded to unconfined areas and may be affecting spring flows (Figure 26).



A. Long-term rate of decline map for 1970 to 2010. Reds and yellows indicate declines; blues indicate relative rises in water levels; greens indicate no signficant changes over the past 40 years.

B. Relative confinment of the Floridan Aquifer System Light blue indicates confined areas and darker blues indicate thinly confined and unconfined areas respectively.

Figure 25: Relationship between FAS potentiometric surface decline and aquifer confinement (From: Williams, et. al., 2011)

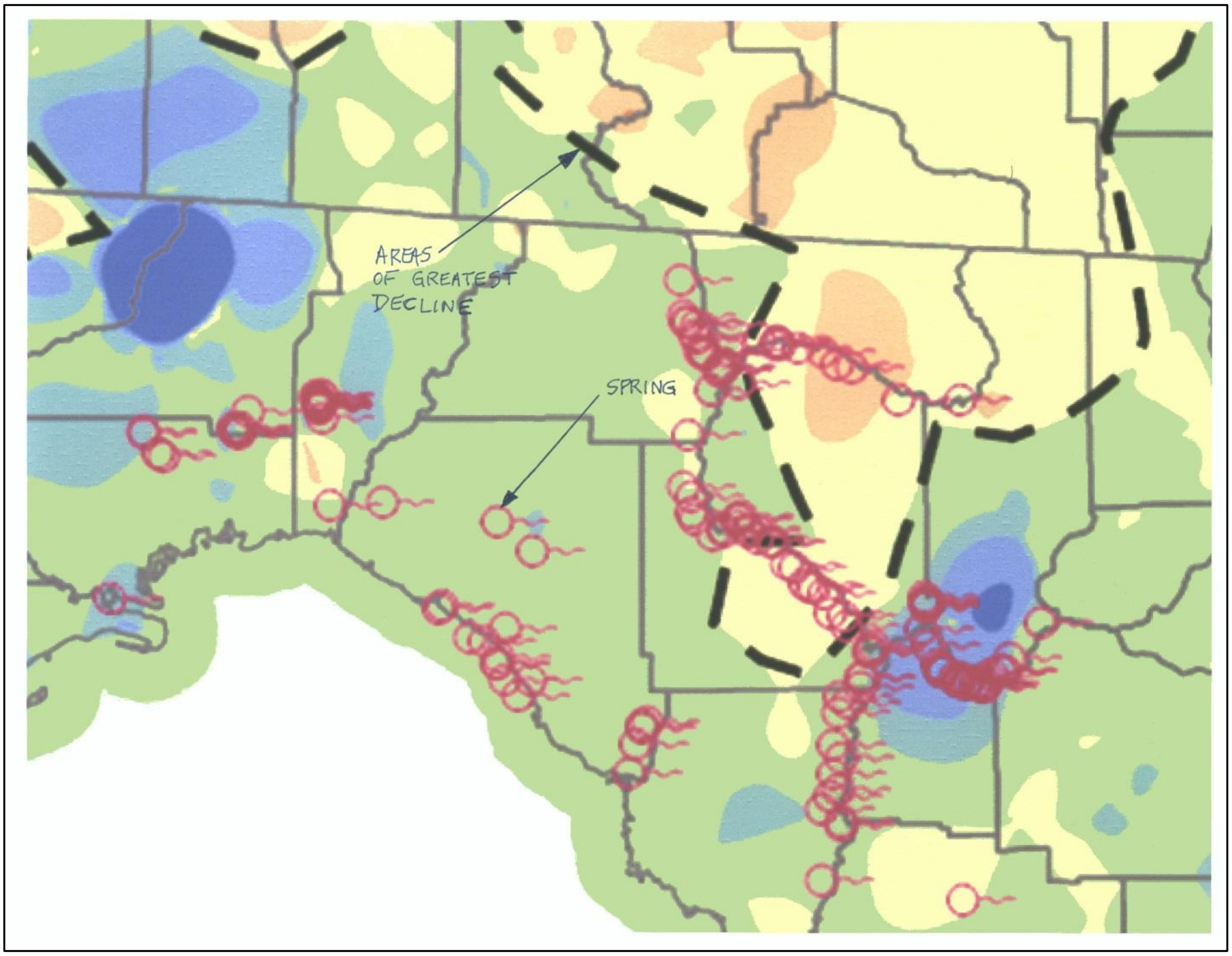


Figure 26: Relationship of FAS potentiometric surface declines and springs in the SRWMD (After Williams, et. al., 2011)

CONCLUSIONS

Thirty professional publications were reviewed by the SRWMD and SJRWMD in order to evaluate regional and temporal changes in the level and configuration of the potentiometric surface of the UFA. The factors responsible for these changes and the proportional effect of these factors were assessed and included groundwater withdrawals and climatic effects on recharge. Another factor to consider is land-use changes over time; however, this was not addressed specifically in the documents and would be considered a minor effect on a regional scale when compared to withdrawals and precipitation.

Based upon the body of evidence provided in the consensus summaries prepared by the SRWMD and SJRWMD, groundwater withdrawals, especially withdrawals from confined portions of the UFA in north Florida, appear to be one of the factors responsible for changes in the potentiometric surface over time. However, it must be stated that the role of climatic variations on the regional configuration of the UFA potentiometric surface has not been thoroughly considered. For example, the distributions of precipitation inside and outside of recharge areas such as the Valdosta and Keystone Heights potentiometric highs.

In addition to this joint assessment report, other work tasks initiated by the two districts since execution of the IAA in September 2011 (see INTRODUCTION) to more fully understand the changes in the potentiometric surface and to cooperatively optimize management of groundwater resources include:

- Sharing and collecting hydrologic data, including construction of additional monitor wells in the area of the groundwater basin boundary.
- Building the North Florida – Southeast Georgia Regional Groundwater Flow Model (or NFSEG Model). The NFSEG Model is a steady-state regional model with boundary conditions that include the FAS to its updip limit in Georgia, as well as the nine northernmost counties in the SJRWMD and the entire SRWMD. This is the first regional model including all water use and the most recent hydraulic, climatic, and hydrogeologic properties in both districts and southeast Georgia. The NFSEG Model is scheduled for completion in 2015.
- Prioritizing the establishment and reassessment of minimum flows and levels (MFLs) in the area of the groundwater basin boundary.
- Developing prevention and recovery strategies for MFLs in the area of the groundwater basin boundary.
- Initiating the Joint North Florida Regional Water Supply Plan (or Plan). The Plan is scheduled for completion in 2015 and will utilize the NFSEG to assess the sustainable limits of fresh groundwater in the 2015 – 2035 planning period based on potential impacts of projected groundwater use to natural systems such as MFLs.

RECOMMENDATIONS

Notwithstanding the knowledge gained through this joint assessment and other efforts to more fully understand regional changes in the potentiometric surface of the UFA, this study also identified the need to better understand the proportional impact of factors responsible for the regional changes. This need is well-stated by the USGS (Reference 'Correspondence 1'):

> *"A fundamental problem in this discussion regarding a hydrologic analysis of the groundwater divide is that several parameters have not been adequately quantified. The appropriate tools for a hydrologic analysis are not currently available. …..'A better approach for evaluating impacts of withdrawals to the system is to develop a regional-scale transient numerical groundwater model of the Floridan aquifer system with an active surficial layer and lateral model boundaries that are sufficiently far from the area of interest and are conceptually realistic'. …..'Model predictions using a calibrated regional-scale transient model could be used to investigate the extent and transient movement of the historical divide. Furthermore, a calibrated transient flow model could be used to quantify relative impacts that different pumping centers have on divide movement and assess future withdrawal impacts on the groundwater divide.'"*

A regional scale, transient numerical groundwater model of the FAS is unquestionably the necessary tool for assessment of the changes to the UFA potentiometric surface. To that end, development of the steady-state NFSEG Model is the first step in the process. The NFSEG Model will contain an active surficial layer and model boundaries sufficient in extent to eliminate current boundary-related issues. Both districts are compiling all available data to enable a transition to a regional transient model. Completion of the steady-state NFSEG model is expected by the end of 2015, with development of the transient model two to three years after that.

APPENDIX A

Assessment of Regional changes in the Level and Configuration of the Potentiometric Surface of the Upper Floridan Aquifer in Southeast Georgia and Northeast-North Central Florida

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Correspondence:

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APPENDIX B

Assessment of Regional changes in the Level and Configuration of the Potentiometric Surface of the Upper Floridan Aquifer in Southeast Georgia and Northeast-North Central Florida

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22. Gao, B., et al. 2010. *Statistical evaluation of long term groundwater levels in northeastern Florida and southern Georgia*. Special Publication SJ2010-SP12, St. Johns River Water Management District, Palatka, Fla.

[1] The numbering system for each reference is maintained from the numbered reference in the Master Reference List – see Appendix A.

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Correspondence:

1. Letter dated June 8, 2011 from the U.S. Geological Survey to the St. Johns River Water Management District. Subject: *Evaluation of the Floridan aquifer system regional groundwater flow divide migration since predevelopment*.

APPENDIX C

Table 1
Regional Drawdown Reference List Subject-Area Matrix

Reference Number	Primary Subject Area					Secondary Subject Area					Reference Authors and Brief Citation
	Water Levels (L)	Quality (Q)	Modeling (M)	Water Use (U)	Climate (C)	Water Levels (L)	Quality (Q)	Modeling (M)	Water Use (U)	Climate (C)	
3	X						X		X		Brown, 1984; Nassau County
4	X			X			X	X			Bush & Johnston, 1988; USGS 1403-C
7	X										Clark, 1963; Brooklyn Lake
11	X								X		DePaul, et al, 2008; Atlantic Coastal Plain
13			X			X			X		Durden, 1997; NE FL and SE GA simulation
17				X						X	Fanning & Trent, 2009; GA water use 2005 & trends
20	X			X			X	X			Franks & Phelps, 1979; drawdown in FAS - Duval Co.
21	X				X				X		Gao, et al, 2010; statistical eval. hydrol. data NE FL / southern GA
22	X				X				X		Gao, et al, 2010; statistical eval. long-term GW levels NE FL / southern GA
23	X		X	X						X	Grubbs & Crandall, 2007; lower Suwannee & SF - USGS 1656-C
24	X				X			X	X		Grubbs, 2011; long-term trends - Ich R., Karst Proceedings
27	X[2]										Healy, 1962; Piezo surface FAS in 1961
28	X[3]										Healy, 1974; Pot surface FAS in 1974
32			X								Intera, 2012; MegaModel for prediction of 2030 Impacts
34	X			X			X				Johnston & Bush, 1988; USGS 1403-A
33	X										Johnston, et al, 1980; estimated pre-development pot surface
36		X									Katz, et al, 1997; GW-SW interactions in Suwannee Basin
37	X			X			X	X		X	Krause & Randolf, 1989; USGS 1403-D
44				X							Marella & Berndt, 2005; FAS WDs & trends in SE USA - 1950 - 2000
45				X							Marella, 2009; water WDs & trends in FL: 2005
47	X			X							Miller, 1990; GW Atlas AL, FL, GA, & SC
50			X			X					Payne, et al, 2005; GW simulation in SE GA / NE FL; PD, 1980, & 2000
51	X									X	Peck, et al, 1999; pot surface 1988 & GA WL trends 1990-1998
52	X	X							X	X	Peck, et al, 2009; GW conditions / studies in GA from 2006-2007
53	X	X									Phelps, 1994; water resources of Duval County
55			X			X					Planert, 2007; regional GW flow simulation: Suwannee River Basin
60	X									X	Stringfield, 1936; artesian water in FL peninsula
61	X			X			X				Stringfield, 1966; artesian water in Tertiary limestone in SE USA
1	X			X				X			USGS letter 2011: USGS to SJRWMD - GW divide migration since PD
62	X								X	X	Williams, et al, 2011; relation of confinement to long-term GWL decline

1: The reference numbers correspond to the Master List numbering system (see Appendix A).

2: Water Levels when used in conjunction with Reference #28.

3: Water Levels when used in conjunction with Reference #27.

APPENDIX D
Assessment of Regional changes in the Level and Configuration of the Potentiometric Surface of the Upper Floridan Aquifer in Southeast Georgia and Northeast-North Central Florida

Coordinated Document Review Template

Document Number:

Document Title:

Complete Document Citation:

Date of Review:

SRWMD Reviewer(s):

SJRWMD Reviewer(s):

Author's Major Conclusions in Document Related to the Principle Questions (major concepts)

Synthesis (Reviewer's interpretation of concepts or assumptions)

Analysis

1. What are the factors that drive changes in the level and configuration of the potentiometric surface of the Upper Floridan aquifer in the study area?

2. What is the proportional effect of each factor driving changes in the level and configuration of the potentiometric surface of the Upper Floridan aquifer in the study area?

3. What are the trends in the level and configuration of the potentiometric surface of the Upper Floridan aquifer in the study area?

4. Which hydrologic features are most susceptible to changes in the level and configuration of the potentiometric surface of the Upper Floridan aquifer in the study area?

5. To what extent are these hydrologic features affected by changes in the level and configuration of the potentiometric surface of the Upper Floridan aquifer in the study area?

Differing interpretations

References cited in document review (Other references considered to further support reviewer's interpretations. These would likely be references also cited in the document being reviewed, not completely new material.)