Regional, Passive Saline Encroachment in Major Springs of the Floridan Aquifer System in Florida (1991 -2020)

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November 24, 2022

Abstract

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1. INTRODUCTION

Florida has over 1,000 documented springs (Florida Department of Environmental Protection (FDEP), 2016). As Florida's population grows, spring-water quality and quantity changes have been observed (Florida Spring Task Force, 2000). FDEP, Florida's water management districts (WMDs) (Figure 1), and the United States Geological Survey (USGS) standardized efforts to monitor spring water and increased the number of springs being monitored, beginning in the early 1990s. Increasing nutrient concentrations were the initial focus of spring water-quality studies, but later studies expanded the indicator lists to include discharge, along with major ions, including two saline indicators, sodium (Na^+) and chloride (Cl^-). The two indicators are abbreviated "Na" and "Cl" respectively. Copeland et al. (2011) discovered that between 1991 and 2003, spring discharge decreased while concentrations of Na and Cl increased in most of the monitored springs A possible driver for the increased saline trend is saltwater encroachment, which has been a documented issue in Florida for decades (Black et al., 1953; Krause and Randolph, 1989; Spechler, 1994; Prinos, 2013: Prinos et al., 2014; and Prinos, 2016). These reasons prompted FDEP leadership to recommend a follow-up study to investigate if the changes have been occurring over a longer period.

The sequel investigation (Copeland and Woeber, in press) included most of the same springs used in the earlier study but extended the period from 1991 through 2011. During this period, discharge continued to decrease, while concentrations of Na and Cl continued to rise. Copeland and Woeber (in press) postulated the major drivers of the observed changes were: (1) declining rainfall and subsequent declines in recharge, (2) sea-level rise and (3) groundwater extraction. The major sources of Na and Cl were suspected to be saline groundwater near Florida's coasts and relict sea water from the deeper portions of the Floridan aquifer system (FAS).

Considering the statewide interest in springs and saltwater encroachment, this investigation is the third examination of trends in spring discharge, plus Na, and Cl concentrations. The period of study is from 1991 through 2020. The springs are primarily in north-central Florida (Figure 1) and occur where the FAS is unconfined or thinly confined (Figure 2). Related to driver (1) above, it should be noted that climatic variability is now recognized as affecting rainfall and river discharge as well as lake chemistry and is due to teleconnections like the Atlantic Multidecadal Oscillation (AMO) and the El Nino southern oscillation (ENSO) (Enfield et al., 2001; Kelly and Gore, 2008; Goly and Teegavarapu, 2014; Canfield et al., 2018). The oscillations affect rainfall, influence spring discharge, and likely influence concentrations of both Na and Cl in spring water.

2. FLORIDAN AQUIFER SYSTEM

Florida has three freshwater aquifer systems, from deep to shallow: (1) the Floridan aquifer system (FAS), (2) the intermediate aquifer system and confining unit, and (3) the surficial aquifer system (Southeastern Geological Society (SEGS, 1986)). The largest in terms of areal extent and thickness is the FAS. According to the SEGS, it is a thick carbonate sequence which includes all or parts of Paleocene to early Miocene formations. It can exist under unconfined or confined conditions, depending on the extent of low permeability sediments lying above it. Miller (1986) and Williams and Kuniansky (2016) indicated the FAS is one of the most productive aquifer systems in the world. It underlies all of Florida and portions of South Carolina, Georgia, and Alabama. Klein (1976) mentioned that it can be over 900 meters (m) thick in places. Scott (2016), along with Budd and Vacher (2004), mentioned that the FAS is a multi-porosity aquifer: fractured and porous where it is confined, and karstic, fractured, and porous where it is unconfined. Scott et al. (2004) indicated that most of Florida's springs are in portions of the state where the FAS is unconfined or thinly confined (Figure 2).

In most places, the FAS can be divided into the Upper Floridan aquifer and the Lower Floridan aquifer, separated by several semi-confining units (Miller, 1986). However, in some places the two aquifers cannot be differentiated. For this reason, no attempt is made to differentiate the aquifer system and the undifferentiated term, FAS, is used.

3. ENCROACHMENT

Black et al. (1953) mentioned that from the early 1900s through the early 1950s, saltwater had encroached into municipal water supply systems in at least 19 of Florida's coastal counties. Since that report, other authors have reported saline encroachment in Florida. Krause and Randolph (1989) and Spechler (1994) described several possible mechanisms that can drive saltwater encroachment that occurred in northeast Florida. Potential mechanisms included: the landward movement of the freshwater/saltwater interface, the regional upconing of saltwater below pumped wells, and the upward leakage of saltwater from deeper, saline water–bearing zones through confining units. The latter can occur where the units are thin or breached by joints, fractures, collapse features, or other structural anomalies. Movement can also occur because of failed, damaged, or improperly installed well casings, and as mentioned previously, encroachment can occur by the upward movement of unflushed pockets of relict seawater in the FAS.

In discussions regarding south Florida aquifers, Prinos (2013), Prinos et al. (2014), and Prinos (2016) discussed pathways for saltwater encroachment similar to those mentioned above. However, Prinos (2016) discussed two additional pathways. First, along Florida's coasts, saltwater can flow inland though canals, rivers, boat basins, and coastal marshes, and subsequently leak into the freshwater portions of aquifers. This type of encroachment has been observed in the south Florida aquifers, but can also occur in other areas of Florida where the FAS is under unconfined conditions. Second, Prinos mentioned that encroachment can occur laterally from the coast, moving inland along the base of an aquifer and then upward.

Using conductivity and potentiometric head measurements, Xu et al. (2016) found strong evidence that periodically, under both normal and low-rainfall conditions, sea water has moved inland through cave conduits in the FAS in northwest Florida as much as 11 miles. However, under high-rainfall conditions, when aquifer potentials are high, sea water reverses flow and moves seaward.

As modified from Neuendorf et al. (2005), saltwater encroachment is the displacement of fresh groundwater by the advance of saltwater caused by its greater density. Note, using this definition, there is no requirement distinction that encroachment is due to human activity.

4. STUDY AREA, MATERIALS, AND METHODS

The portion of Florida where the FAS is under unconfined to thinly confined conditions (Figures 2) will be referred to as the "Spring Area". The springs and discharge sites used in this study are essentially the same ones used in Copeland et al. (2011) and Copeland and Woeber (in press). A total of 32 springs and three stream discharge sites were used (Figure 1). Spring and discharge station names, along with their locational information (WMD, latitude and longitude) are found in Table 1. Of the 35 sites, 31 had sufficient water quality data and 24 had sufficient discharge data, for trend analysis.

Water quality and discharge data were obtained from either the FDEP, local WMD or USGS online databases [Suwannee River Water Management District (SRWMD) (2021); St. Johns River Water Management District (SJRWMD) (2021); Southwest Florida Water Management District (SWFWMD) (2021); and the U.S. Geological Survey (2021)]. Data are available by contacting the major author. It should be noted that by law [(Florida Statues 373.026(2)], state agencies, WMDs, and local agencies are required to cooperate with FDEP in making water quality data available in a central database. Recently, FDEP developed the Water

Information Network (WIN)] database (Florida Department of Environmental Protection, 2021). At the time of publication, the uploading of groundwater data to WIN is incomplete. However, when complete, efforts to retrieve data in a common format for analyses will be greatly reduced and will increase the efficiency managing Florida's springs.

All sample collection and all field and laboratory analyses were conducted in accordance with Chapter 62-160, Florida Administrative Code. All agencies supplying analytical information did so under FDEP-approved quality assurance project plans. Regarding Na and Cl ions, for the study, laboratory analyses vary between reporting the total and the dissolved species. Total was the most frequently reported, and for this reason, the authors selected the total species to use whenever possible. However, to make the time series as complete as possible, the dissolved species was used whenever the total species was not reported.

Scott et al. (2004) reported on the chemical analysis and discharge of many of Florida's springs. Reiterating comments from an earlier and similar report (Ferguson et al., 1947), Scott et al. indicated the springs in the report represent the "major" and "most important" springs in the state. The terms "major" and "most important" have been historically based on discharge. For the springs with available discharge data, the current authors calculated median discharge for each spring and then summed the total discharge of the medians for 92 onshore springs in the Scott et al. report [230 m^3/sec (8,122 $feet^3$/sec) (ft^3/sec)]. Next, the current authors summed the total median discharge from each of the 24 discharge sites used in this report but restricted it to the 1991 – 2020 timeframe, for a calculated total of 89 m^3/sec (3,124 ft^3/sec). This represents about 39% of the total discharge; a substantial proportion.

Statewide estimates of groundwater extraction from the FAS are generally reported on 5- or 10-year frequencies by the USGS. Statewide data are available for 1990, 2000, 2010, and 2015, but not 2020. A discussion will be presented later.

Mean annual precipitation data for all of Florida and for selected sites were supplied by the Florida Climate Center (2021). During the study, greater than 99 percent of all precipitation was rain. For this reason, precipitation will often be referred to as rain or rainfall.

Eight rainfall sites (Figure 2) reported by the Climate Center are located within the Spring Area. Figure 3 displays annual rainfall and spring discharge for the period (1991 – 2020). The solid squares represent annual mean precipitation totals for all of Florida (Florida Climate Center, 2021). The solid circles represent annual means of the eight sites in the Spring Area. Two rainfall Lowess smoothing curves are also in Figure 3. The dashed line (upper) curve represents the annual Florida totals, while the dotted line (middle) curve identifies the Spring Area. They decrease through the first half of the study. Beginning in the late 2000s, and continuing through 2020, both curves increase. The Pearson correlation (r) between the Florida and Spring Area sites is 0.620 (p-value <0.001), and for this reason, only the data from the Spring Area sites are used for the remainder of this report.

Spring discharge annual means were either provided by the monitoring agencies or were calculated by the authors. The annual means are displayed in Figure 3 as solid triangles. The Lowess curve (solid line) decreases slightly in the E period and increases during the L period. The correlation (r) between the Spring Area rainfall and spring discharge is 0.309 (p-value = 0.097).

Recall, one of the major drivers of the observed trends for the 1991 – 2011 timeframe is believed to be a decrease in precipitation (and a subsequent decrease in recharge). If so, have increases in rainfall reversed the earlier trends? In part, the current investigation was initiated to address this question. This investigation evaluates trends in precipitation, discharge, and concentrations of both Na and Cl in the Springs Area for the entire period (1991 – 2020), along with an early (E) period (1991 – 2011) and a late (L) period (2006 – 2020). It also revisits the major driving forces of the observed changes. Note, the E period used in this report, coincides with the one used by the Copeland and Woeber report (in press). The L period begins in 2006, approximately when rainfall began to increase, and continues through 2020.

For each spring, annual means and medians were calculated for Na and Cl. Figure 4 displays the annual means, along with corresponding Lowess curves. Note how the curves do not track rainfall and discharge (Figure 3). This topic will be discussed.

5. STATISTICAL METHODS

Most statistical analyses were conducted using the “EnvStats”, “nortest”, and “rkt” packages of the R programming language (R. Core Team, 2021). Additional analyses were conducted using the NCSS software (2020).

Data distributions were checked for normality using the Anderson-Darling test (NCSS, 2020). Both rainfall and spring discharge were normally distributed. In addition, data suppliers often provided data for these variables as annual means. For these reasons, the annual means were used for data analysis. Distributions of Na and Cl were strongly and positively skewed (compare their corresponding means to their median values in Table 2). Consequently, their annual medians were used for most analytical procedures in this report.

The nonparametric tests [the Mann-Kendall (MK) (Mann, 1945) test and the regional-Kendall (RK)] test (Helsel and Frans, 2006) were used for trend analyses. The null hypothesis was of no change in the slope and alpha was pre-set at 0.10. All tests were two sided. As needed, the Benjamini and Hochberg procedure (1995) was used to test for potential adverse effects of multiple comparisons. None of the tests of tests were adversely affected.

Regarding the RK test, it works best if there are a minimum of 10 years of data are available from each site (Helsel and Frans, 2006). For each RK test, this criterion was met. The RK test computes the p-value for the test and a Sen slope (Sen, 1968) for the region.

By using annual means and medians for trend analysis, potential adverse effects of serial autocorrelation (AC), such as seasonality, were reduced. To reduce the effects of spatial AC, a modification of the work completed in the St. Johns River WMD (Figure 1) by Boniol (2002) was used. Boniol determined that spatial AC was sufficiently reduced in groundwater of the FAS in the WMD for Cl at a distance of 15,240 m (50,000 ft). Copeland and Woeber expanded the efforts of Boniol. Using an ArcGIS script tool (Whiteaker, 2015), they generated a coverage of 1,173 equal area hexagons, each with a diameter of 15,240 m, for the entire state. They plotted locations of 56 FAS springs that that had been sampled at least once for Cl during the period 2005–2011. A spatial join was then performed with the hexagons (polygon layer) containing a unique identifier and the spring locations. The median Cl concentration was determined for each spring. The median Cl values from the 56 springs, including those in this study, were compared to all possible nearest-neighbor springs. To determine nearest neighbors, the "point distance" tool in ArcMap 10.6 was utilized. This tool was chosen to allow comparisons of feature layers directly. The tool compares the distances between two sets of points. The process involves comparing a point location with all other point locations in the feature layer. This comparison can be performed with either the same layer or different layers and a search radius can be set to limit processing and search at specific distances for neighboring points. Additional joins are performed to identify the hexagon identifier associated with each point location for further statistical analysis.

At a distance of up to 15,240 m there were 79 pairs of nearest neighbors. At distances greater than 15,240 m and up to 30,480 m there were 117 nearest neighbors. For distances greater than 30,480 m up to 45,720 m, there were 1,289 nearest neighbors. Using each set of paired stations, Pearson correlations (Triola and Lossi, 2018) were determined. The correlations for the three distance groupings were 0.273, 0.118, and -.006, respectively. Thus, the effects of spatial AC are reduced considerably at distances greater than 15,240 m. With this in mind, Copeland and Woeber (in press) randomly selected one spring if more than one existed within any single hexagon. As a result, 31 springs were selected for water quality analyses. In addition, 24 discharge stations were located in separate hexagons.

For this investigation, the Sen slope was not used for further statistical analyses unless the RK test inferred the existence of a trend (p-value ≤ 0.10). Nevertheless, inspections of the direction of Sen slopes were used to assist in interpreting causes of observed changes.

Tidal fluctuations can potentially influence trend analyses in springs located near the coast. Annual median or mean values were used for each indicator at each site. Thus, adverse effects of serial correlation are considered minor. In addition, regarding discharge, depending on the site, annual mean data from USGS sites were adjusted for tidal influences.

6. RESULTS

Summary statistics for annual means for rain and discharge, and median (Q2) values for Na and Cl are presented in Table 2. Note, Na and Cl concentrations vary considerably in the 31 springs, depending on their location relative to the coast. In mg/L, median Na and Cl concentrations range from a minimum 1.23 and 3.00 in a spring located in Florida's interior to a maximum of 3,950 and 5,960 for the two variables in a spring located near Florida's coast. Based on 815 observations from 31 springs used in this study, in mg/L, the median and mean for Na were 8.51 and 165.83, respectively (Table 2). For Cl, the median and mean were 12.55 and 280.40.

Previously, it was mentioned that Pearson correlation between rainfall and discharge was 0.309 (p-value = 0.097). The nonparametric Spearman correlation between Na and Cl was 0.956 (p-value <0.001). The correlations indicate a significant positive correlation between rainfall and discharge and a much stronger positive correlation between Na and Cl. There may be several reasons for the lower rainfall-discharge correlation. First, it was based on a sample size of 30 (annual means), compared to the Na-Cl correlation that was based on the 815 median values (Table 2). Second, rainfall sites were not necessarily located close enough to spring discharge sites to have strong correlations. Third, the variances of both rainfall and discharge were slightly greater in the E, relative to the L period. The coefficient of variation (CV) (standard deviation divided by the mean), the was used was used to make comparisons. For rainfall, the CV in the E period was 0.13 and 0.12 in the L period. For discharge, the CVs were 0.13 and 0.11 respectively.

Figure 1 displays the locations of the springs by WMD. With only two springs in the Northwest Florida Water Management District (NWFWMD), they are included with those in the SRWMD. The region is referred to as the NWFWMD and SRWMD region. The remaining regions are the SJRWMD and the SWFWMD. Table 3 display the results of the RK tests for the entire study (1991 – 2020) for the four variables for the Spring Area and WMD Regions. Table 4 does the same for both the E and L periods. In both tables, significant p-values are in bold font.

For 1991 – 2020 for the Spring Area and the WMDs for both rainfall and discharge there were no statistical trends (Table 3) with two exceptions. Discharge decreased in the SJRWMD and rain increased in the SWFWMD. Concentrations of Na and Cl increased significantly in the

Spring Area and within each WMD region (p-values <0.001); the most compelling finding of the study.

During the E period (Table 4) for the Spring Area and each WMD, there were no trends in rainfall or discharge. Na concentrations increased significantly in the Spring Area, and in each WMD region. Concentrations of Cl did the same, except for the SJRWMD where they did not increase significantly. During the L (Table 4) period, rainfall increased in the NWFWMD and SRWMD region, plus the SJRWMD. Discharge increased in the Spring Area, the NWFWMD and SRWMD region, plus the SWFWMD. Na concentrations did not change in the Spring Area. They increased in the SJRWMD and the SWFWMD but decreased in the NWFWMD and /SRWMD region. The decrease in Na in this region plausibly explains why the Spring Area did not experience a significant change. Concentrations of Cl increased in the Spring Area and each WMD.

In the Spring Area, for the study, concentrations of Na and Cl increased by about 0.056 and 0.135 mg/L per year (Table 3). During the E period, Sen slopes for Na and Cl rates increased by 0.086 and 0.138 mg/L per year, respectively (Table 4). During the L period, discharge increased by (0.550 m^3)/(sec) per year. Concentrations of Cl increased by 0.135 mg/L per year (Table 4).

From 1991 through 2020, the estimated total change in the concentrations of Na and Cl were 1.68 (0.056 x 30) and 4.05 (0.135 x 30) mg/L (Table 3). To estimate the percent rate of change, the total changes for the two variables were compared to the grand median concentrations (8.51 and 12.55 mg/L respectively) found in Table 2. To one significant figure, the percent annual rates of change for the two indicators were 0.7% and 1.1 %. For entire study, the percent changes were 19.7% and 33.0%, respectively.

7. DISCUSSION

7.1 Conceptual Model

The term saline is used to indicate that the source water has greater concentrations of Na and Cl than the receiving groundwater. To assist in understanding the observed changes in spring water, the Ghyben-Herzberg relationship (Freeze and Cherry, 1979) was used. Fetter (2001), and Freeze and Cherry, indicated that in the ideal Ghyben-Herzberg relationship, for each meter of drawdown the saltwater/ freshwater interface rises by 40 meters as a sharp line.

Figure 5 presents a conceptual model, based on the Ghyben-Herzberg relationship. All of Florida's freshwater aquifers and confining units are conceptually lumped together into a freshwater lens. The irregularly shaped lens is generally thickest in the central portion of the state and narrows toward Florida's coastlines. The top part of Figure 5 (A) represents the lens during normal times. The bottom part of Figure 5 (B) represents long periods of below-normal rainfall. After a lag in rainfall, (aquifer) potentials (Hubbert, 1940), including spring discharge, decline. In addition, the freshwater lens decreases in size (exaggerated in Figure 5). In the FAS, deep groundwater is enriched in carbonate rock-matrix indicators such as calcium (Ca^{+2}), magnesium (Mg^{+2}), potassium (K^{+1}), alkalinity, and sulfate (SO_4^{-2}), along with both Na and Cl (Upchurch et al. 2019; and Sprinkle, 1989). During periods of extended below-normal rainfall, the deep enriched groundwater can migrate horizontally from the edges of the lens and vertically upward from the transition zone at the bottom of the lens.

Krause and Randolph (1989), and Spechler (2001) hypothesized that deep, relict sea water may be a major source for increased saline indicator concentrations in portions of the FAS in northeastern Florida. In an investigation of spring water chemistry in the SRWMD (Figure 1), Moore et al. (2009) observed that upward movement of groundwater from deep within the Upper Floridan aquifer of the FAS may, at times, deliver up to 50% of spring discharge. The proportion of deep water is dependent on head gradients within the aquifer. The authors stated that the deep water provides the major source of Na, Cl, potassium, magnesium, and sulfate. Berndt et al. (2005) indicated that spring discharge water can originate from both shallow and deep sources. For springs with relatively high TDS concentrations, Berndt et al. speculated that the spring water may have first circulated with deeper groundwater and had a relatively long residence time prior to discharge from springs.

Although not displayed in Figure 5, it is implied that if a period of above-normal rainfall prevails, and if recharge exceeds discharge for a long enough time, the lens will increase in size, and concentrations of Na and Cl, along with FAS rock-matrix indicators, will eventually decline. However, as previously stated, some saline water may not be totally flushed (Sprinkle, 1989). Scott et al. (2004) mentioned that during the Pleistocene Epoch, beginning 2.6 million years ago, continental glaciers waxed and waned in the Earth's northern latitudes. In Florida, the potentiometric surfaces and water tables of the aquifers are hypothesized to have dropped with the advancing continental glaciers and then to have risen when the glaciers retreated. The range of sea-level changes may have been up to 140 m (460 ft). Upchurch et al. (2019) indicated that this action would result in saltwater encroachment into the aquifers when sea level rose, and a flushing out of the saltwater when sea level dropped. Although the geological time scale discussed by these authors are considerably different from the decades-scale in this study, the processes remain unchanged.

7.2 Passive Encroachment

When a well, located near the coast in an unconfined aquifer is pumped, the cone of depression around the well can cause upconing of saline groundwater into the well from below in general accordance with the Ghyben-Herzberg principle. When this type of encroachment occurs, it is an example of active encroachment (Fetter, 2001). Fetter also discussed the term passive encroachment. It occurs when some fresh groundwater has been diverted from the aquifer, yet the hydraulic gradient is still sloping toward the saltwater–freshwater boundary. In this situation, the boundary will slowly shift landward until it reaches an equilibrium position based on the new discharge conditions. The mechanisms controlling passive encroachment are the same as active encroachment. However, the rate of encroachment is much slower. Fetter stated, "Movement is slow. It may take hundreds of years for the boundary to shift a significant distance." Fetter mentioned that passive encroachment can occur inland, as well as in coastal areas. Werner (2017) stated that encroachment can be active, passive, or a combination of the two. Significant increasing trends in the concentrations of both Na and Cl (Tables 3 and 4) support the hypothesis that passive encroachment is occurring across the Spring Area of Florida.

Recall, during the state's periodic dry periods, when aquifer recharge is reduced and aquifer potentials decline, the freshwater zone shrinks. Younger groundwater is replaced by groundwater with a longer residence time. As a result, groundwater has a greater ionic strength, including increased concentrations of saline indicators such as Na and Cl. This conclusion is supported by Upchurch (1992) and Katz (2004). During times of declining potentials, the likelihood that saline groundwater migrates inland and upward into the freshwater zone is increased.

8. Potential Drivers of the Observed Passive Encroachment

Copeland et al. (2011) and Copeland and Woeber (in press) listed several potential drivers of the changes described above. The most significant were: (1) below-normal rainfall and subsequent declines in recharge, (2) groundwater extraction, and (3) rising sea-level.

8.1 Decreasing Rainfall and Consequent Decreases in Recharge

Verdi et al. (2006) mentioned that Florida suffered a severe drought from 1999-2002 that affected Florida's water resources. Copeland et al. (2011) indicated the drought was the major driver of change for the period 1991 – 2003.

During either the E or L periods (Table 4), there were no confirmed trends in rainfall and the only significant trend for discharge occurred in the L period. It was upward. Nevertheless, the decreasing Sen slopes of rain and discharge during the E period, and the increasing slopes in the L periods (Figure3 and Table 4) support the concept that rainfall was an important driver of observed changes for the Spring Area.

The decrease in rainfall and followed by an increase are probably related to climatic oscillations (Figure 3). The Atlantic Multidecadal Oscillation (AMO) and the El Nino southern oscillation (ENSO) influence rainfall in Florida (Enfield et al., 2001; Kelly and Gore, 2008; Goly and Teegavarapu, 2014; Canfield et al., 2018). AMO cycles are quasi-periodic, lasting up to 60 and possibly 80 years (Kerr, 2005). Climate Data Guide (2021) indicated the North Atlantic sea surface temperature (an index for the AMO) increased from the mid-1970s through the late 2000s and has decreased since that time. Of note, the change in the direction of the AMO coincided with the change in rainfall observed in this investigation.

It is important to note the relationships between rainfall and subsequent recharge/discharge in an aquifer system. They can be complex. Theis (1940) and Ponce (2007) stated that under equilibrium conditions in a pristine aquifer, discharge is equal to recharge. To maintain steady-state conditions, Ponce (2007) mentioned that an increase in discharge must be balanced by: (1) an increase in recharge to the aquifer from another source (e.g., from an overlying aquifer if the aquifer is confined), (2) a decrease in natural discharge from the aquifer, (3) a loss of storage in the aquifer, or (4) a combination of all three.

Ponce (2007) mentioned that where the aquifer is unconfined, extended periods of below-normal rainfall result in water table decline. Where it is confined, these conditions can lower the potentiometric surface and groundwater storage. However, below-normal rainfall still can result in additional recharge where the aquifer is thinly confined. The recharge rate will be less than it would be under normal or above-normal rainfall conditions, leading to an overall decrease in storage. In addition, with a sufficient increase in rainfall and recharge for a long enough time, the potentiometric surfaces will eventually increase.

Regarding recharge quantity to the FAS, Bellino et al. (2018) reported the mean annual rate to be 19.0 cm/year. Variations over time were not determined.

8.2 Groundwater Extraction

Based on periodic five- and 10-year summaries by the USGS, groundwater extraction from the FAS in Florida had a net decrease during the study. In units of million m^3/d, 1990 it was reported as 10.46 (Marella, 1992). It rose to 11.72 in 2000 (Marella and Berndt, 2005), but then declined to 9.64 in 2010 (Marella, 2014), and to 8.85 in 2015 (Marella, 2019). Statewide data were not available for 2020. The declines in extraction coincide with efforts by the WMDs to conserve groundwater extraction (U.S. Environmental Protection Agency, 2017a).

Copeland and Woeber (in press) converted the groundwater extraction data from 2010 (Marella, 2014) to a flux in cm/year. They estimated extraction was about 2.4 cm or about 13% of the mean recharge estimate of Bellino et al. (2018). They concluded the effect of extraction was relatively minor, compared to rainfall and subsequent recharge. The net decrease in extraction during this study suggests it was not a major driver of the observed changes in this study.

8.3 Sea-Level Rise

In a study of former sea-level rises in Florida, Gully and Florea (2016) indicated that rising sea-levels eventually result in rising aquifer potentials. This can result in a reduction in fresh groundwater in an aquifer (a reduction of the freshwater lens, especially in areas where the FAS is unconfined. As previously noted, as discharge increases older and more saline groundwater, originating from the deeper portions of the aquifer, can result in increased concentrations of Na and Cl in discharge water.

Walton (2007) indicated that in Florida, between 1950 and 1999, sea level rose between 8.0 and 23.0 cm. Using linear extraction, an estimate of sea level increase was between (0.15 and 0.46 cm) per year from 1991 through 2011 (E period). The National Oceanographic and Atmospheric Administration (NOAA) (2021) stated that between 1993 and 2019 (27 of the 30 years of the current investigation), sea level rose by 8.76 cm. Using the more recent NOAA data, on an annual basis, sea-level rose by about 0.32 cm/yr. Using this rate for the entire duration of the current study, rising sea levels represent about 2% of the recharge estimates presented earlier [0.32 cm (sea-level rise) / 19.0 cm (recharge)]. With a limited sea-level rise data set, it is unknown whether the rise in sea level played a significant role in changing the observed indicator concentrations during this investigation. However, Walton predicted sea level in Florida could rise another 25 cm by 2080. By 2100, Wigley and Raper (1992), the US Environmental Protection Agency (2017b), and Lindsey (2019) predict that globally, sea level could rise as much as 1.2 m (4.0 ft), while the NOAA (2021) projects that as an extreme estimate, sea levels could rise as much as 2.5 m). In southeastern Florida, Bloetcher et al. (2011) predicts sea level rise to be between 0.5 and 1.0 m by the end of the 21st century. Unfortunately, as the twenty first century proceeds in time, it appears that sea-level rise will play a more important role as a driver of changes in concentrations of Na and Cl.

A question was posed earlier. Although many of the observed changes in this investigation, mostly in the concentrations of Na and Cl, are statistically significant, do the changes have practical significance? The fact that the changes occurred over multiple decades and over an area as large as the spring area (Figure 1), suggests they do.

9. **Unresolved Issues and Need for Additional Encroachment Monitoring**

9.1 Unresolved Issues

The changes observed in this report support the conceptual model, but several questions remain unanswered. There was a direct positive correlation between rainfall and spring discharge. During the E period with declining rainfall, spring discharge declined. As predicted by the conceptual model, concentrations of Na and Cl increased. During the L period, when rainfall, discharge and recharge began to increase, the model predicted a decrease in Na and Cl concentrations would eventually follow. For Na, the slope decreased in the Spring Area and decreased significantly in the NWFWMD and SRWMD region. However, concentrations continued to increase in the SJRWMD and the SWFWMD. Regarding Cl concentrations, they increased in the Springs Area and the three WMD regions. As of 2020, evidence suggests Florida may be experiencing the beginning of the reversal process of encroachment. Unfortunately, this remains uncertain because of continued increases in the Cl concentrations.

Rainfall is the major driver of the observed changes during the time frame of this investigation and may be tied to climatic cycles such as the AMO. Recall, the AMO is a driver of Florida’s rainfall and influences surface-water flows (Enfield et al., 2001; Kelly and Gore, 2008; Goly and Teegavarapu, 2014; Canfield et al., 2018). The correlation of rainfall and spring discharge in this study suggests a similar relationship with Florida’s spring water.

If the AMO is a major driver of rainfall, then Florida will likely experience increased rainfall for the next several decades. During this period, Floridians will likely be more concerned with surface-water flooding than passive encroachment. Nevertheless, passive encroachment did occur over the course of this study, and as of 2020, encroachment had not abated, at least for Cl. Unfortunately, rainfall will, again, eventually enter a declining stage. When it does, along with the probable increase in the rate of sea-level rise, passive encroachment will likely follow. And again, if the rate of sea-level rise increases, encroachment is likely to be greater than that observed in this study. Floridians would benefit from additional research efforts on the effects that encroachment will have on Florida's groundwater, drinking water, and surface water resources.

9.2 Need for Increased Saline Encroachment Monitoring

Passive encroachment observed in this study, along with rising sea levels indicate the state needs to continue to monitor spring discharge and saline indicator concentrations. As presented, springs represent good monitoring sites and should be incorporated into saline monitoring efforts whenever possible. It should be noted that the Florida Water Resources Monitoring Council formed a Salinity Network Workgroup in 2011. Key workgroup members include the FDEP, the five WMD's, the USGS, and several counties (Florida Water Resource Monitoring Council, 2019a). One workgroup objective is to improve Florida's ability to monitor for potential saltwater encroachment into major aquifer systems. To this end, the Workgroup established a statewide Coastal Salinity Monitoring Network (Florida Water Resource Monitoring Council, 2019b). It is mostly composed of monitoring wells but does contain a few springs. As sea level continues to rise, it is anticipated that additional springs will be added to the network in the future.

10. **KEY FINDINGS**

At a 90% confidence level, from 1991 through, 2020, concentrations of Na and Cl increased in the Florida Spring Area. For multiple decades, the region encountered passive saltwater encroachment, as defined by Fetter (2001). To the nearest percent, the rates of change for the concentration of Na and Cl were approximately 20% and 33% respectively for the duration of the study, or about 7% and 11% per decade.

Evidence suggests the primary driver of the observed changes is below-normal rainfall and a subsequent reduction in recharge to the FAS. Evidence also suggests sea-level rise played a minor role as a driver for changes in Na and Cl concentrations for this investigation. However, several investigators have indicated the rate of sea-level rise is increasing and the rate will continue to increase in the future and therefore become a more important driver of changes in groundwater quality in Florida.

Evidence suggests that an important origin of the saline indicators is from saltwater along Florida's coasts and from saline water located at depth within the FAS. The decrease in spring discharge during the study allowed older and deeper groundwater, located below the freshwater lens, and from the coastal regions of Florida, to migrate inward and upward into the springs.

There are several important aspects of this investigation that need emphasis. First, small increases in concentrations of Na and Cl have been observed in major Florida springs for multiple decades. Second, the changes meet the definition of passive saline encroachment. Third, the area of encroachment covers a significant geographical area of the state. And fourth, with increasing rates of sea-level rise predicted in the future, additional monitoring efforts by Florida's water agencies will be needed, including the inclusion of springs.

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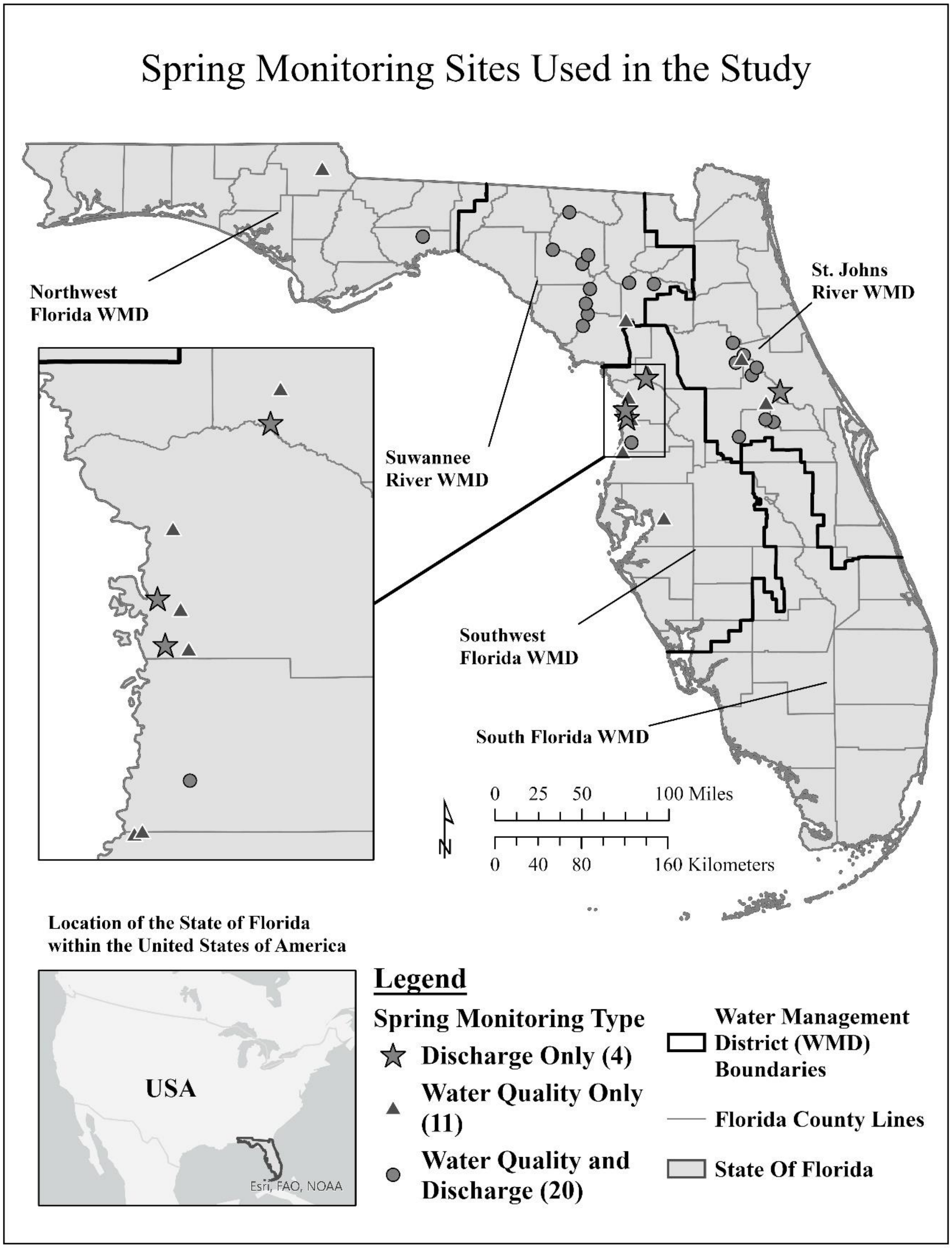


Figure 1. Florida, Water Management Districts and Monitoring Sites.

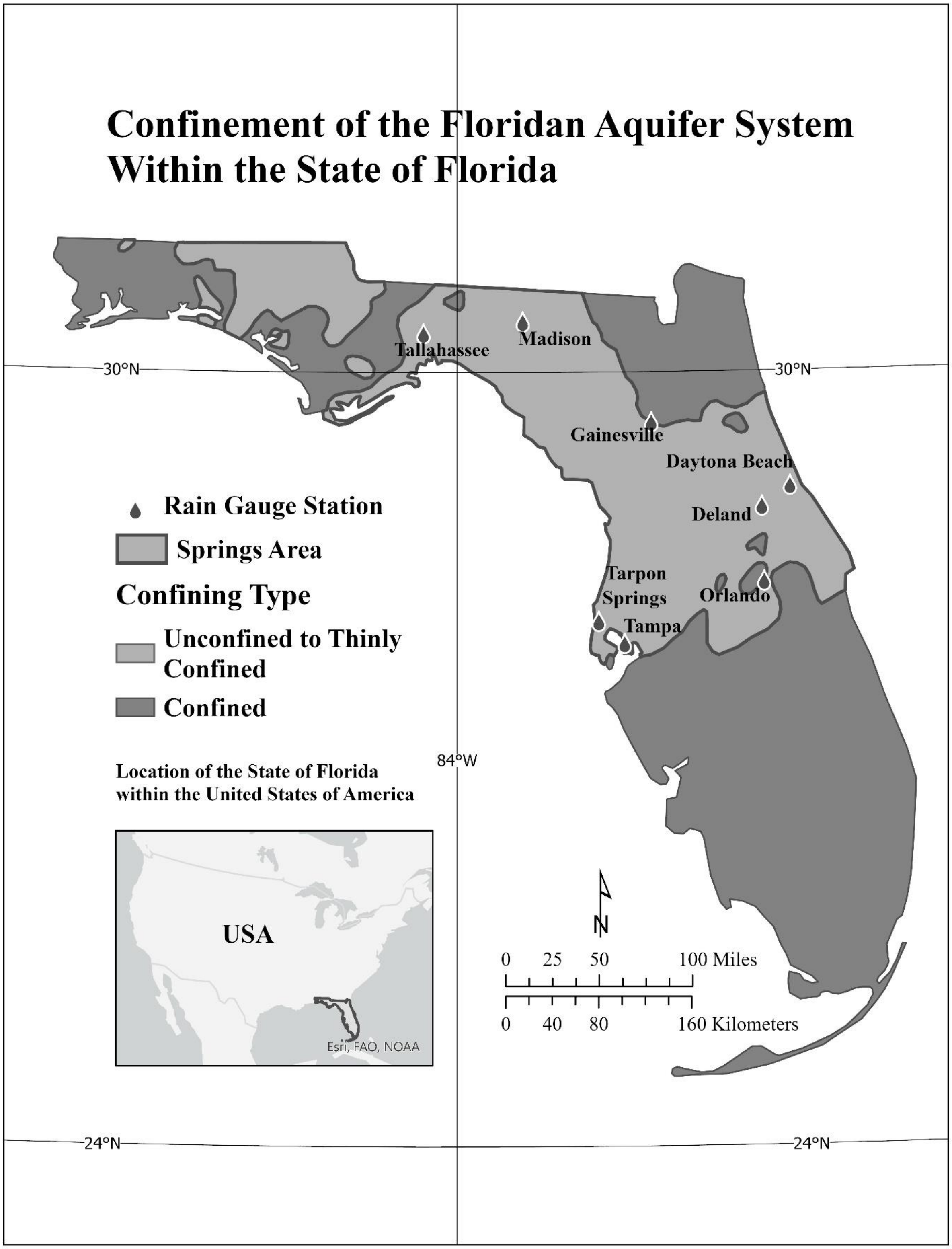


Figure 2. Floridan aquifer system in Florida with confinement. Study area is the portion of Florida with unconfined to thinly confined conditions. Solid tear-drop symbols represent rain gauge stations in Spring Area. (Modified from Williams and Dixon, 2015)

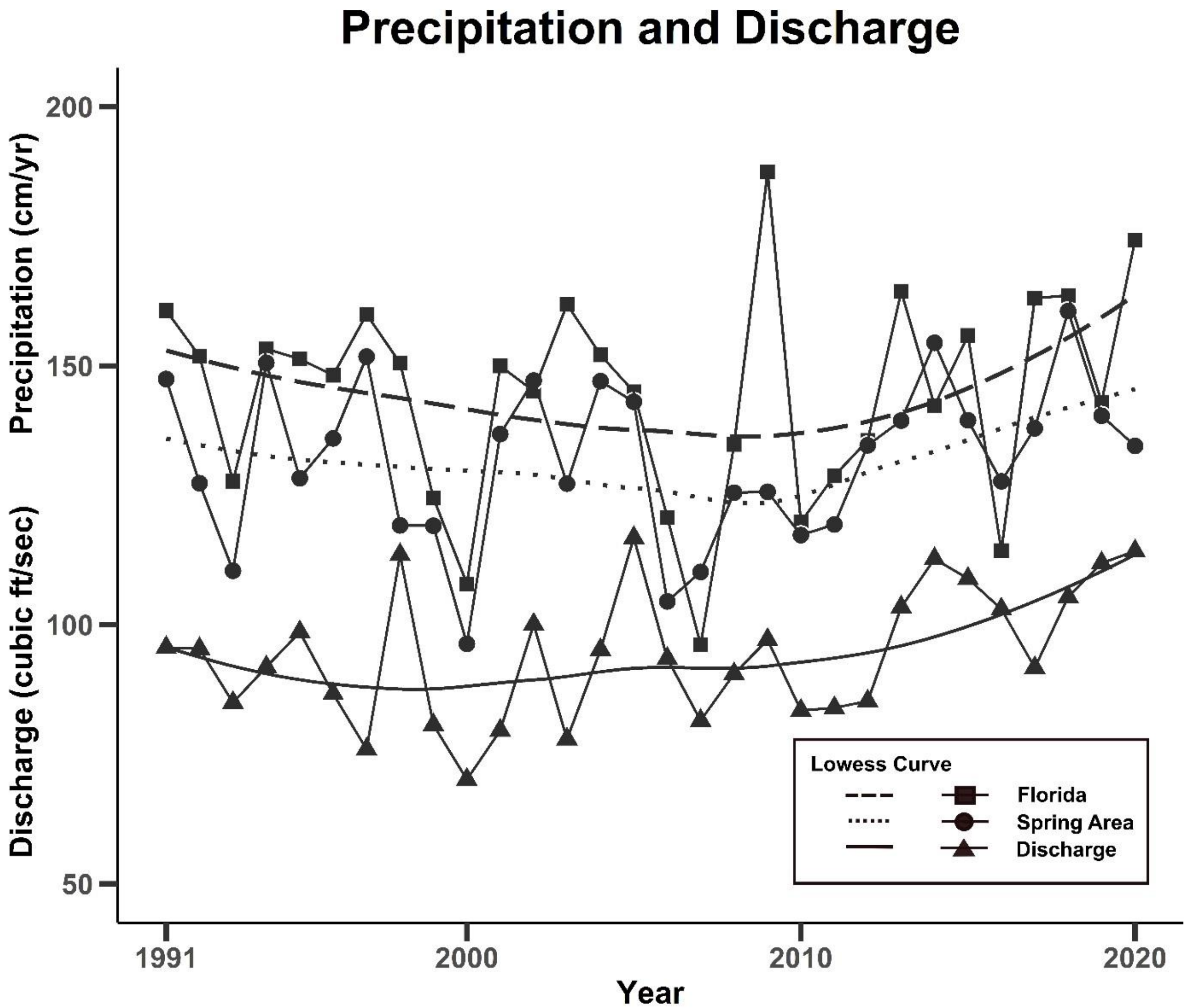


Figure 3. Annual Precipitation and Spring Discharge (1991 – 2020). Solid circles represent annual statewide means (Florida Climate Center, 2021). Solid squares represent annual means of eight rainfall stations and solid triangles represent annual means of 24 discharge sites in Spring Area. Three Lowess curves are: (1) dashed line – Florida rainfall, (2) dotted line – Spring Area rainfall, and (3) solid line – spring discharge in Spring Area.

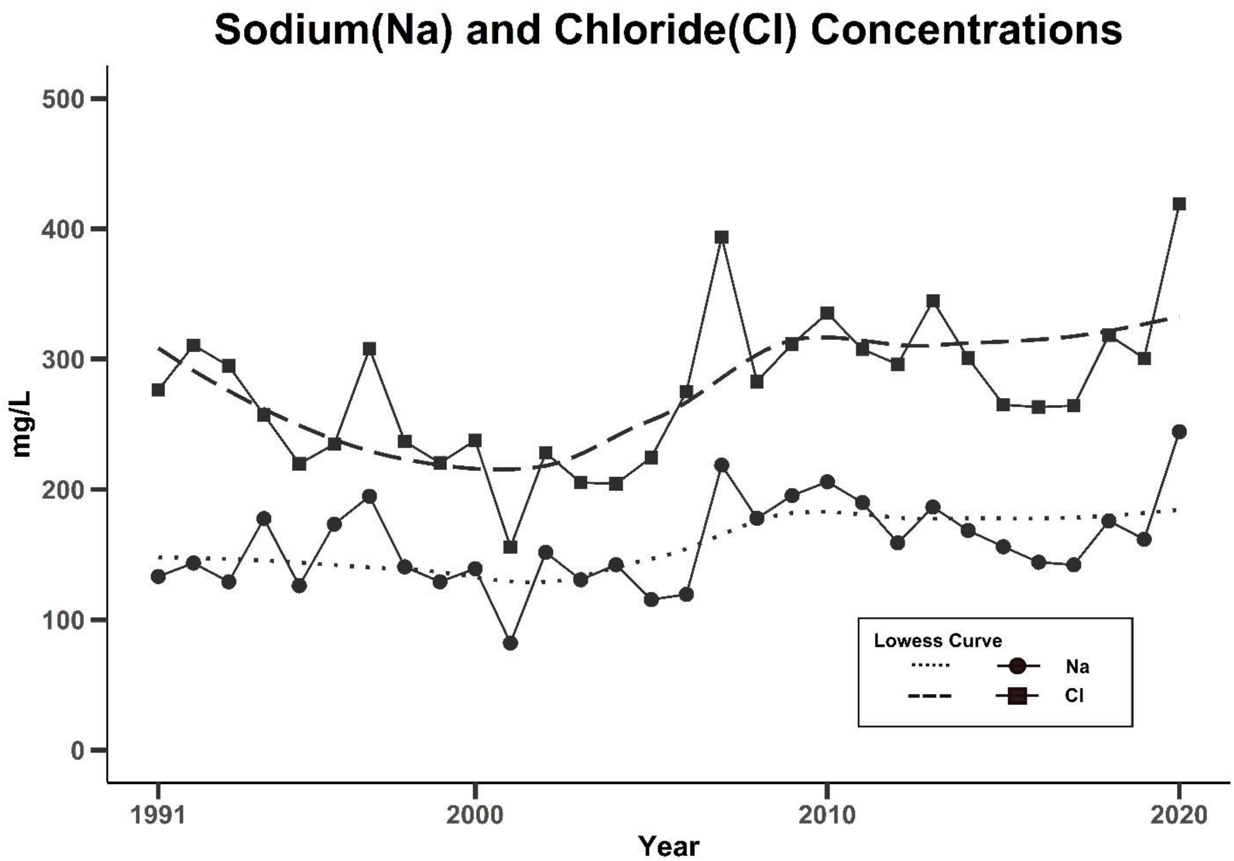
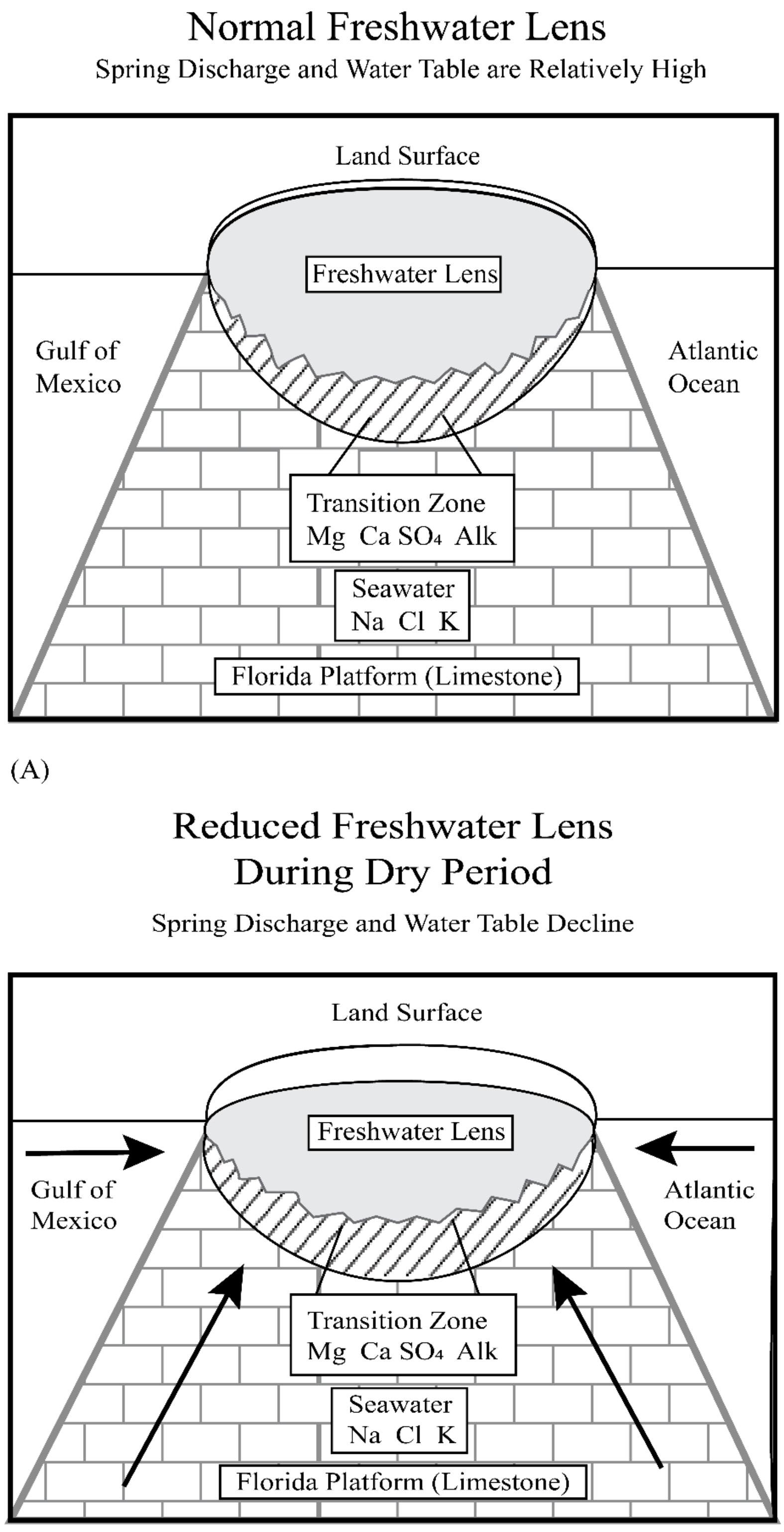


Figure 4. Annual Mean Concentration of Na and Cl (1991 – 2020) from 31 Springs in Spring Area. Solid circles represent annual Na concentrations. Solid squares represent annual Cl concentrations. Lowess curves are represented by dotted line (Na) and dashed line (Cl).



(B)

Figure 5. Fresh groundwater lens changes over a long dry period.
(A). Lens after a long period of average or above average rainfall.
(B). Lens after a long period of below-average rainfall.

Table 1. Monitoring Sites used in this report. (The term spring is not included in spring name.)

Water Management District location and Station Name	Latitude	Longitude	Water Management District location and Station Name	Latitude	Longitude
Northwest Florida WMD			**St. Johns River WMD (continued)**		
Jackson Blue[2]	30.7913	-85.1401	Ponce De Leon[1]	29.1343	-81.5294
Wakulla[1]	30.2238	-84.3037	Sanlando[1]	28.6808	-81.3882
Suwannee River WMD			Silver Glen[1]	29.2366	-81.6363
Alapaha Rise[1]	30.4267	-83.0861	Sweetwater[2]	29.2096	-81.6528
Fanning[1]	29.5782	-82.9318	Wekiwa[1]	28.7040	-81.4535
Gilchrist Blue[1]	29.8299	-82.3829	Volusia Blue[3]	29.9387	-81.3319
Hart[1]	29.6660	-82.9482	**Southwest Florida WMD**		
Hornsby[1]	29.8398	-82.5883	Boat[2]	28.4305	-82.6531
Lafayette Blue[1]	30.1146	-82.2233	BobHill[2]	28.4347	-82.6411
Manatee[1]	29.4804	-82.9736	Buckhorn Main[2]	27.8844	-82.2989
Rock Bluff[1]	29.7889	-82.9149	Catfish[2]	28.8906	-82.5950
Ruth/Little Sulfur[1]	29.9956	-82.9770	Chassahowitzka Main[2]	28.7093	-82.5713
Suwannee Blue[1]	30.0704	-82.9310	Hernando Salt[2]	29.5330	-82.6152
St. Johns River WMD			Hidden River No. 2[2]	28.7691	-82.5835
Alexander[1]	29.0724	-81.5687	Rainbow No. 1[2]	29.1014	-82.4330
12Apopka[1]	28.5593	-81.6745	Weeki Wachee[1]	28.5108	-82.5694
Fern Hammock[1]	29.1745	-82.7013	Chassahowitzka River near Chassahowitzka[3]	28.7150	-82.6064
Marion Salt[1]	29.3411	-81.7257	Homosassa River at Homosassa[3]	28.7850	-82.6181
Palm[2]	28.8437	-81.4501	Rainbow River at Dunnellon[3]	29.0492	-82.4478

[1]Water quality and discharge (n = 20) [2]Water Quality only (n = 11) [3]Discharge only (n = 4)

Table 2. Statistical Summaries for Rain, Discharge, Sodium and Chloride.

Rain and Discharge								
	Units	**[1]n**	**Min**	**Mean - 1 SD**	**SD**	**Mean**	**Mean + 1 SD**	**Max**
Rain	cm/yr	30	96.32	116.48	15.50	131.98	147.48	160.55
Discharge	m^3/sec	30	70.16	79.43	15.53	94.96	110.49	146.82
Na and Cl								
		[2]n	**Min**	**[3]Q1**	**[3]Q2**	**Mean**	**[3]Q3**	**Max**
Na	mg/L	815	1.23	4.29	8.51	165.83	125.23	3950
Cl	mg/L	815	3.00	8.00	12.55	280.40	233.75	5960

[1]n = number of annual grand means for the eight rainfall and 24 discharge sites. [2]n = number of available pairs.
[3]Q1= 25th percentile, Q2 = 50th percentile = median, Q3 = 75th percentile.

Table 3. Results of Regional Kendall Tests for Springs for the Entire Study Period (1991 – 2020).

Indicator	Station n[1]	Annual n[2]	Sen Slope Units	Sen Slope	p-value
Rain	8	30	cm/year	-0.049	0.594
Discharge	24	30	(m^3)/(sec)/yr	-0.045	0.459
Sodium	31	30	(mg/L)/yr	0.056	**<0.001**
Chloride	31	30	(mg/L)/yr	0.135	**<0.001**
Northwest Florida and Suwannee River Water Management Districts					
Rain	3	30	cm/year	0.119	0.302
Discharge	11	30	(m^3)/(sec)/yr	0.330	0.281
Sodium	12	30	(mg/L)/yr	0.005	**<0.001**
Chloride	12	30	(mg/L)/yr	0.135	**<0.001**
St. Johns River Water Management District					
Rain	3	30	cm/year	-0.298	0.377
Discharge	9	30	(m^3)/(sec)/yr	-0.136	**0.020**
Sodium	10	30	(mg/L)/yr	0.111	**<0.001**
Chloride	10	30	(mg/L)/yr	0.170	**<0.001**
Southwest Florida Water Management District					
Rain	2	30	cm/year	0.358	**0.014**
Discharge	4	30	(m^3)/(sec)/yr	0.659	0.224
Sodium	9	30	(mg/L)/yr	0.085	**<0.001**
Chloride	9	30	(mg/L)/yr	0.248	**<0.001**

[1]Number of stations in region [2]Number of years in period

Table 4. Results of Regional Kendall Tests for the E and L Period by Region. (See Table 3 for units.)

	Station n[1]	Annual n[2]	Sen Slope	p-value	Station n[1]	Annual n[2]	Sen Slope	p-value
Period	**Early**				**Late**			
	Spring Area							
Rain	8	21	-0.237	0.293	8	15	0.270	0.364
Discharge	24	21	-0.670	0.226	24	15	0.550	**0.019**
Na	31	21	0.086	**<0.001**	31	15	**0.015**	0.244
Cl	31	21	0.138	**<0.001**	31	15	0.135	**<0.001**
	Northwest Florida and Suwannee River Water Management Districts							
Rain	3	21	-0.281	0.129	3	15	1.200	**0.011**
Discharge	11	21	-0.849	0.133	11	15	0.163	**0.007**
Na	12	21	0.083	**<0.001**	12	15	-0.028	**0.024**
Cl	12	21	0.071	**0.002**	12	15	0.075	**0.006**
	St. Johns River Water Management District							
Rain	3	21	-1.104	0.253	3	15	2.460	**0.006**
Discharge	9	21	-0.062	0.497	9	15	0.100	0.131
Na	10	21	0.086	<0.001	10	15	0.085	**0.011**
Cl	10	21	0.103	0.164	10	15	0.224	**<0.001**
	Southwest Florida Water Management District							
Rain	2	21	-0.237	0.293	2	15	0.270	0.364
Discharge	4	21	-0.990	0.220	4	15	6.050	**<0.001**
Na	9	21	0.089	**<0.001**	9	15	0.067	**0.006**
Cl	9	21	0.200	**<0.001**	9	15	0.163	**<0.001**

[1]Number of stations in region [2]Number of years in period