Water and Climate Resilience Metrics

PHASE 1: LONG-TERM OBSERVED TRENDS

Final Report December 17, 2021

PROJECT TEAM

Akintunde Owosina	Hydrology and Hydraulics
Alan Buzard	Hydro Data Management
Amanda Kahn	Applied Science – Coastal Ecosystems
Brian Turcotte	Applied Science – Data Management
Carol Ballard	Hydrology and Hydraulics Modeling
Cassondra Armstrong	Applied Science – Water Quality Treatment
Christian Avila	Water Quality - Compliance Assessment & Reporting
Christopher Madden	Applied Science – Everglades Systems
Fred Sklar	Applied Science – Everglades Systems
Heather Kostura	Geospatial Services
Hongying Zhao	Hydrology and Hydraulics Modeling
Jeffrey Iudicello	Hydrology and Hydraulics Modeling
Jenifer Barnes	Hydrology and Hydraulics Modeling
Jenni Hiscock	District Resiliency
Jennifer Reynolds	Ecosystem Restoration and Capital Projects
Jesse Markle	Environmental Resources and Regulation Support
Jessica Frost	Applied Science – Coastal Ecosystems
Jill Margolius	Communication and Public Affairs
John Raymond	Hydro Data Management
Juli LaRock	Water Quality - Compliance Assessment & Reporting
Kris Esterson	Water Supply Planning
Lawrence Glenn	Water Resources
Mandy McDonald	Applied Science – Everglades Systems
Mark Elsner	Water Supply
Matthew Morrison	Ecosystem Restoration
Michael Brown	Hydrology and Hydraulics Modeling
Patricia Burke	Water Quality Monitoring
Ronda Albert	IT Applications
Sarah Noorjahan	Hydro Data Management
Sean Sculley	Applied Science - Lake and River Ecosystems
Sean Williams	Hydro Data Management
Seyed Hajimirzaie	Hydrology and Hydraulics Applied Hydrology
Shimelis Setegn	Applied Science – Coastal Ecosystems
Stuart Van Horn	Water Quality
Suelynn Kirkland	Operations
Toni Edwards	Applied Science – Coastal Ecosystems
Walter Wilcox	Hydrology and Hydraulics Modeling

Technical Leads

Alaa Ali	Hydrology and Hydraulics Modeling
Carlos Coronado	Applied Science – Everglades Systems
Christine Carlson	Geospatial Services
Karin Smith	Water Supply Planning
Nenad Iricanin	Water Quality - Compliance Assessment & Reporting
Tibebe Dessalegne	Hydrology and Hydraulics Applied Hydrology
Yibing Kevin Zhu	Hydro Data Management

Overall Coordination

Carolina Maran	District Resiliency
Nicole Cortez	District Resiliency

EXECUTIVE SUMMARY

BACKGROUND

The South Florida Water Management District (District or SFWMD) is strongly committed to addressing the impacts of a changing climate, including sea level rise. The District's resilience efforts support its mission of safeguarding and restoring South Florida's water resources and ecosystems, protecting communities from flooding, and ensuring we are able to meet South Florida's water needs. In the context of establishing water and climate resilience metrics, it is important to introduce the current resilience actions being prioritized by the District according to its mission elements:

> *Resiliency and Flood Protection:* As a key focus of its resiliency strategy, the District continues assessing the status of its flood control infrastructure and advancing adaptation strategies necessary to continue providing primary flood protection for South Florida and other mission critical services as part of its Sea Level Rise and Flood Resiliency Plan and its Flood Protection Level of Service (FPLOS) Program. SFWMD is also seeking to advance a partnership with the U.S. Army Corps of Engineers (USACE) to initiate the Central and Southern Florida (C&SF) Flood Resiliency Study. This study would analyze the current C&SF Project and revisit the 72-year old design, which forms the basis of the series of flood protection canals, levees and structures that exist today. It will identify which infrastructure is at the highest risk of impact from a changing climate and evaluate flood vulnerabilities, water supply needs, and surge protection. A phased approach is being proposed, focusing on the critical project features and coastal structures which can reduce the most immediate flood risk, based on a broad C&SF system overview, resulting in actionable recommendations to decision makers.
>
> *Resiliency and Water Supply*: The District also supports the development of alternative water supply projects and promotes water conservation to increase the security and diversity of its water resources, such as withdrawing less water from aquifers which helps to prevent saltwater intrusion. The District is actively monitoring, modeling and mapping the location of the underground saltwater interface in freshwater aquifers. The mapping identifies movement of saltwater inland which could increase risks to water supply. The modeling, currently under development, will expand the District's ability to assess current and future water supply vulnerabilities. Given a range of sea level rise scenarios, District staff is also studying the possible use of coastal canals for additional storage alternatives to manage groundwater levels and slow saltwater intrusion.
>
> *Resiliency and Everglades Restoration*: Everglades Restoration supports the District's efforts to reduce the effects of climate change, including sea level rise. Completed water storage projects that are part of the Comprehensive Everglades Restoration Plan (CERP) will increase SFWMD's ability to better manage water for the benefit of the environment and people. Completed CERP projects will also increase the District's ability to better manage anticipated extreme weather events. In addition, these projects will increase the ecosystem's future resilience in the face of warmer temperatures and other climate change impacts.

OBJECTIVES

As part of the above introduced resiliency initiatives, the District is laying out a plan to develop a set of water and climate resilience metrics districtwide. These science-based metrics are being advanced with the goal of tracking and documenting shifts and trends in District-managed water and climate observed data. The effort supports the assessment of current and future climate condition scenarios, related operational decisions, and District resiliency investment priorities. As part of the District's communication and public engagement priorities, the results of this work will provide continued information to stakeholders, the general public, and partner agencies about the District's resilience initiatives, while supporting local resiliency strategies.

Phase I of the Water and Climate Resilience Metrics consists of analyzing and determining the relevance of trends in observed water and climate records that are part District's DBHydro and other related databases. This report summarizes the recommendations of the District's Water and Climate Resilience metrics Internal Workgroup, and lays out a plan to detect long-term trend observations districtwide, leveraging extensive work already advanced in assessing water resources and climate data by Water Management Districts in Florida and many of our partner organizations.

An initial set of 50 metrics were identified and evaluated as representative for observed climate change impacts. Fifteen were prioritized by the District's Water and Climate Resilience Metrics Internal Workgroup, and are included in this report:

- Tidal elevations at Coastal Structures
- High Tide Elevations
- Groundwater Elevations
- Saltwater Interface – Chloride Levels
- Minimum Flows and Minimum Water Levels
- Flooding Events
- Rainfall
- Evapotranspiration
- Water Temperature
- Dissolved Oxygen
- pH
- Specific Conductance
- Estuarine Inland Migration
- Soil Subsidence
- Salinity in the Everglades

For the trend analysis, the District's Internal Workgroup recommended the Srivastava And Kubokawa Test For Equal Mean (SK) as part of statistical approaches to support the assessment of available data, including length and frequency, the identification and validation of observed trends, and the determination of significance in the analysis of the selected metrics.

In this context, it is important to evolve the understanding of potential contributing factors and key interrelations that influence observed trends and their association with climate change impacts, not yet fully advanced as part of this report. Alternative mapping, chart, and graph options are proposed for the selected metrics to display and communicate observation results. Additional statistical and spatial analysis tools are essential in establishing improvements to data interpretation and visualization.

NEXT STEPS AND PHASE II

The Water and Climate Resilience Metrics are an important step towards planning for the future with consideration of long-term observed trends and their impacts on the Districts mission. The set of selected water and climate resilience metrics are currently being automated for publication through an interactive web portal providing navigation to different locations districtwide and access to real time data. The portal will generate alternative mapping, chart, and graph options to display and communicate trend results, supported by a story map.

In addition, a new section to highlight the major scientific findings related to the development of water and climate resilience metrics is being incorporated into Volume I – Chapter 2 of the South Florida Environmental Report (SFER), which provides the public with the science and data used to drive decisions at the District. The report also documents restoration, water quality, scientific and engineering accomplishments in South Florida during each water year. It is expected that this scientific reporting effort will allow for research advancement, along the years, to identify potential contributing factors and key interrelations that influence observed trends shifts and anomalies, and their association with climate change impacts, including inflection-point and multidecadal oscillation analyses.

Future efforts will continue to determine better ways to assess and communicate climate trends and associated scientific observations., and will serve as the basis for the introduction of Phase II, which will be advancing the development of future scenario projections for the selected metrics, their application in additional planning efforts. and the development of guidance references for the modernization of design standards .

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ACRONYMS AND ABBREVIATIONS

Compact	Southeast Florida Regional Climate Change Compact
District	South Florida Water Management District
ET	evapotranspiration
MFL	Minimum Flow and Minimum Water Level
NOAA	National Oceanic and Atmospheric Administration
SFWMD	South Florida Water Management District
SK	seasonal Kendall (test)
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

INTRODUCTION

The South Florida Water Management District (SFWMD or District) is responsible for safeguarding and restoring South Florida's water resources and ecosystems, protecting communities from flooding, and meeting the region's water needs, while connecting with the public and stakeholders.

The District is strongly committed to addressing the impacts of climate change, including sea level rise, as well as changes in population growth and land development that affect its mission. As part of a series of resiliency initiatives to evaluate these changing conditions and non-stationary stressors, the District is determining water and climate resilience metrics. These science-based metrics are being developed with the goals of tracking and documenting trends in District-managed water and climate observed data. These efforts support the assessment of current and future climate condition scenarios, related operational decisions, and District resiliency priorities. As part of the District's communication and public engagement priorities, the results of this work will provide continued information to stakeholders, the general public, and partner agencies on water resilience aspects and support local resiliency strategies.

The benefits of advancing water and climate resilience metrics include a stronger planning capacity, by documenting and publishing observed trends District-wide, based on the best available data analysis and science-based approaches. The results will serve to better validate modeling assumptions and risk-informed operational decisions, including future infrastructure investment decisions.

It is important to emphasize that in its Phase I, the Water and Climate Resilience Metrics efforts focus on observed data that might be used to support assumptions of future conditions. As part of Phase II, the water and climate resilience metrics will include the development or more scientifically robust data extrapolation approaches to determine future scenario projections, and a guidance for the modernization of the District's design standards.

This report summarizes the recommendations of the District's Water and Climate Resilience metrics Internal Workgroup, and lays out a plan to automate the trend analyses districtwide. Its main outcomes include the following:

- Description and examples of trend analysis results for the set of prioritized metrics
- Recommended approaches to statistical and data analyses
- Alternative mapping, chart, and graph options to display and communicate results

This report is organized in five main sections:

1) background and existing climate metrics and indicators from partner agencies;

2) proposed water and climate resilience metrics;

3) description of recommended statistical and data analysis approaches and districtwide automation of the metrics trend analyses;

4) reporting and communication strategies; and

5) final remarks and proposed next steps.

BACKGROUND

The District has a robust monitoring program, with more than 3,800 active hydrometeorological stations and approximately 1,750 active water quality stations. The monitoring program represents a vast amount of historical and current scientific data on South Florida's water resources, including hydrologic, hydrogeologic, meteorological, and water quality data. However, the District has not established a recurrent formal process to document long-term trends and shifts in observed data as a result of non-stationary stressors, mainly sea level rise in a changing climate. Obeysekera et al. (2011) elaborated on past and projected trends in climate for South Florida, including an in-depth analysis of precipitation, temperature, and sea level rise data, while highlighting associated challenges. Recurring reports published by the District, such as the annual *South Florida Environmental Report*, examine seasonality, short-term trends and anomalies, impacts of intense storm events, and multidecadal variability, but do not yet incorporate analysis on long-term climate trends. In addition, there has not been a consensus on uniform, science-based metrics to support future climate conditions planning and related operational decisions and communication. Also missing is an established data analysis process to support the definition and continuous update of such water resilience metrics.

As part of its commitment to ensure the resiliency of the South Florida water resources and environment—now and in the future—and to make sustainable infrastructure investments, the District has been assessing the status of its flood control infrastructure and defining what adaptation strategies may be needed to continue providing flood protection in the future. This effort is integrated into the District's capital improvement program to ensure its structures, pumps, and canals are functioning as designed and will remain serviceable in the event of major events and disasters. The District also has been supporting development of alternative water supply projects and promoting water conservation to increase the security and diversity of regional water sources. It is actively monitoring and mapping the location of the underground saltwater interface within freshwater aquifers. From an operations perspective, the District is exploring options ranging from smart operations, increased efficiency, to enhanced remote control capabilities. Structural solutions include hardening infrastructure, updating controls and backup generators, and installing pumps. In addition, restoration of freshwater volumes into the Everglades slows saltwater intrusion, which promotes more sustainable aquifer recharge rates, healthier estuaries and bays, more stable coastlines, and reduced increased hydroperiod lengths.

In this context, the District recognizes the importance of a comprehensive analysis of the impacts of climate change, including sea level rise, on water resources management. Such an analysis must be based on the best available data and a collaborative and mutual understanding of observed trends and shifts associated with non-stationary stressors. Therefore, the District is developing a set of water and climate resilience metrics, primarily composed in its Phase I by observed trends in selected key variables — such as evaporation, sea level, salinity intrusion, and rainfall — that will be used as decision input for the development and prioritization of local and regional resilience strategies For instance, once one or more observed trends demonstrate significant upward or downward signal with implications on water management, appropriate actions will need to be prioritized by the District to ensure resiliency of South Florida water resources and environment. Such actions include the development of robust hydrologic and hydraulic models to evaluate current and future conditions and estimate impacts into water management objectives. These modeling efforts are advanced based on the determination of scenarios that represent these observed trends, as well as projections into the future. As stated above, Phase II of the water and climate resilience metrics will include the development or more scientifically robust data extrapolation approaches to determine future scenario projection.

Reasonable information on observed water and climate trends, as well as projections, are existent, as local, regional, State and Federal partner agencies have been documenting sea level rise, changes in rainfall patterns, and other climate impacts in South Florida and nationwide. These efforts demonstrate how climate metrics are being organized and used by multiple agencies, and the District is planning to take advantage of existing efforts and established science, to evaluate its own data and validate local and regional relevant information, while avoiding duplication of efforts. A summary of the available information and work performed by other agencies to detect trends in past observation, as well as determine future projections is provided below.

The Southeast Florida Regional Climate Change Compact (2020) has established a set of climate indicators including sea level rise, flooding, and saltwater intrusion. Graphics of observed and projected data from the four counties within the Compact (Palm Beach, Broward, Miami-Dade, and Monroe) include the number of high tide events over an established threshold (**Figure 1**) and groundwater levels and associated trends (**Figure 2**). With regards to flooding events, the Compact has been documenting the locations of major occurrences as an ad hoc process but does not have a comprehensive and detailed database with magnitude, duration, and extent of flooding events. One of the most important contributions of the Compact, that goes beyond solely documenting observations, has been its regional unified sea level rise projections, updated every 5 years. **Figure 3** illustrates the 2019, most recent unified projection. A new set of more comprehensive and updated climate indicators is currently available at the Southeast Florida Regional Climate Change Compact Website (2020).

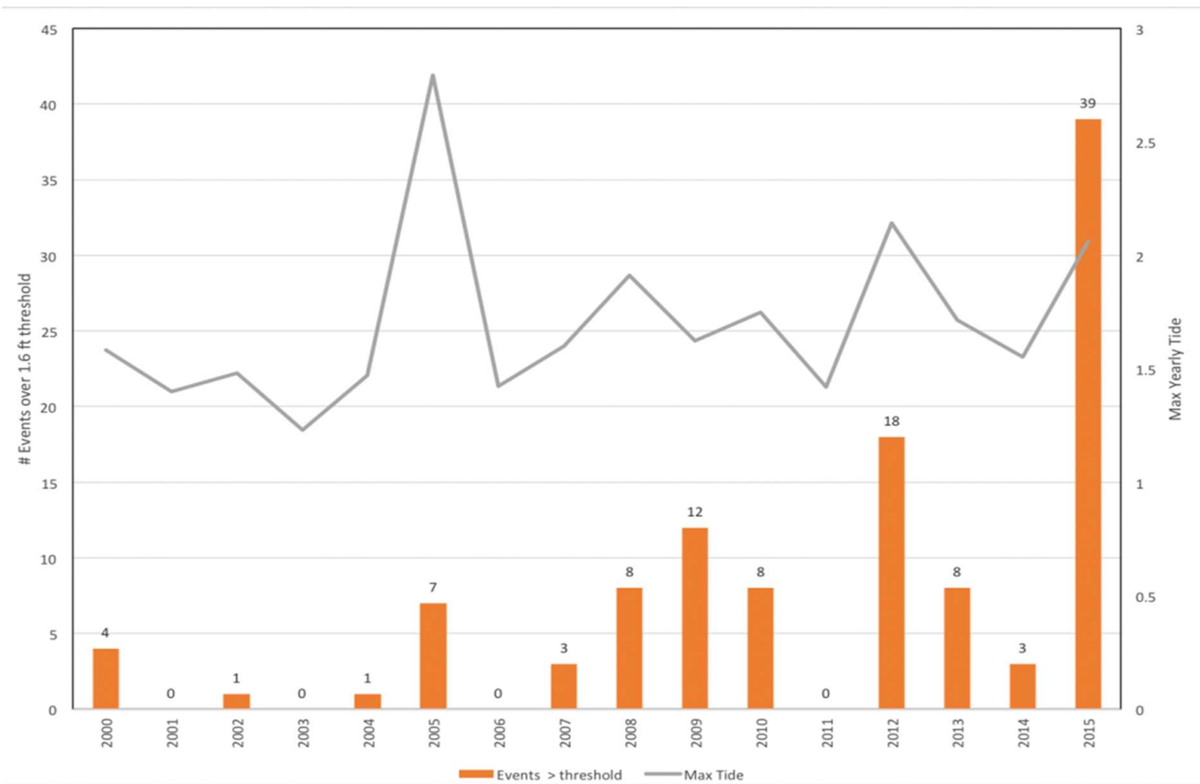


Figure 1. Number of high tide events over threshold (From: Southeast Florida Regional Climate Change Compact 2020).

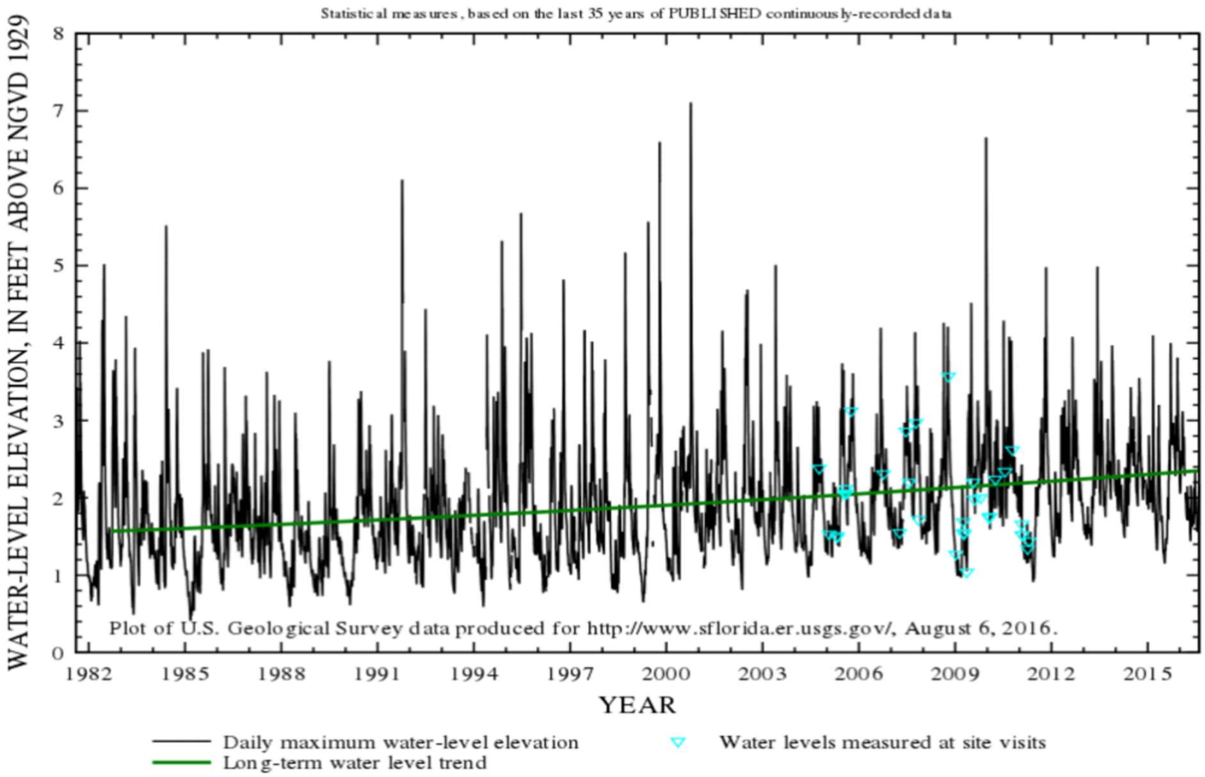


Figure 2. Water level elevations from the past 35 years at well F-291 (From: Southeast Florida Regional Climate Change Compact 2020).

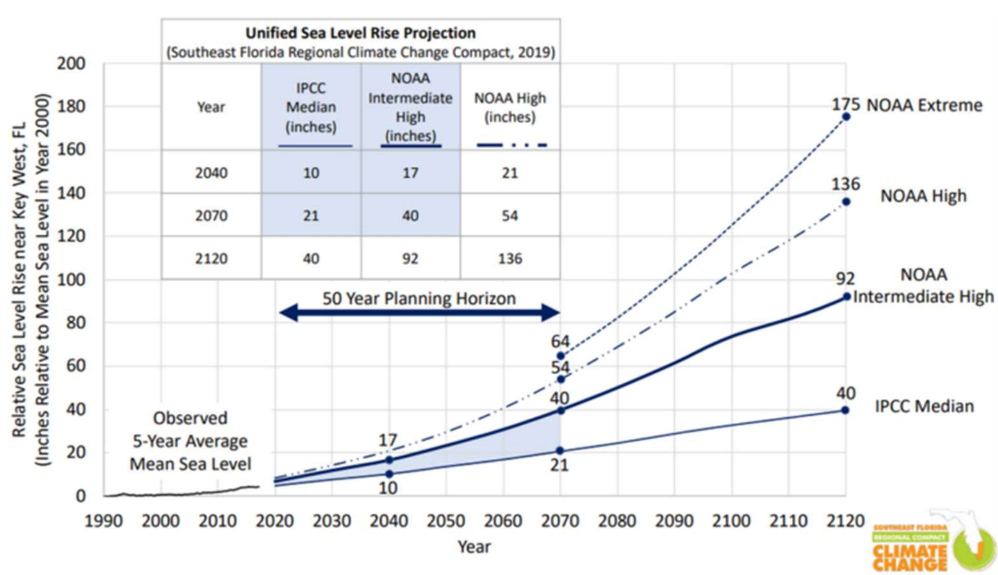


Figure 3. 2019 unified sea level rise projection (From: Southeast Florida Regional Climate Change Compact 2020).

The U.S. Climate Resilience Toolkit (2020) Water Resources Dashboard provides access to maps and data related to extreme rainfall and drought events and is organized into two main sections: 1) current observations, and 2) forecasts, outlooks, and future projections, and contains several interactive map products. The dashboard is a hub for various sources of data from multiple agencies and provides a brief summary of each tool. Most datasets available through the Water Resources Dashboard include advanced data analyses, displaying trends, anomalies, and current conditions percentiles, among others.

Built to support the U.S. Climate Resilience Toolkit, the Climate Explorer (2020) provides easy access to different types of climate data, including maps and charts, for temperature, tide, and precipitation variables, with past and projected values, and associated uncertainty ranges. The mapping tool, once a zip code or locality is selected, allows the user to interactively select low or high emissions scenarios, adjust the time horizon, and compare historical observations and future projections (**Figure 4**).

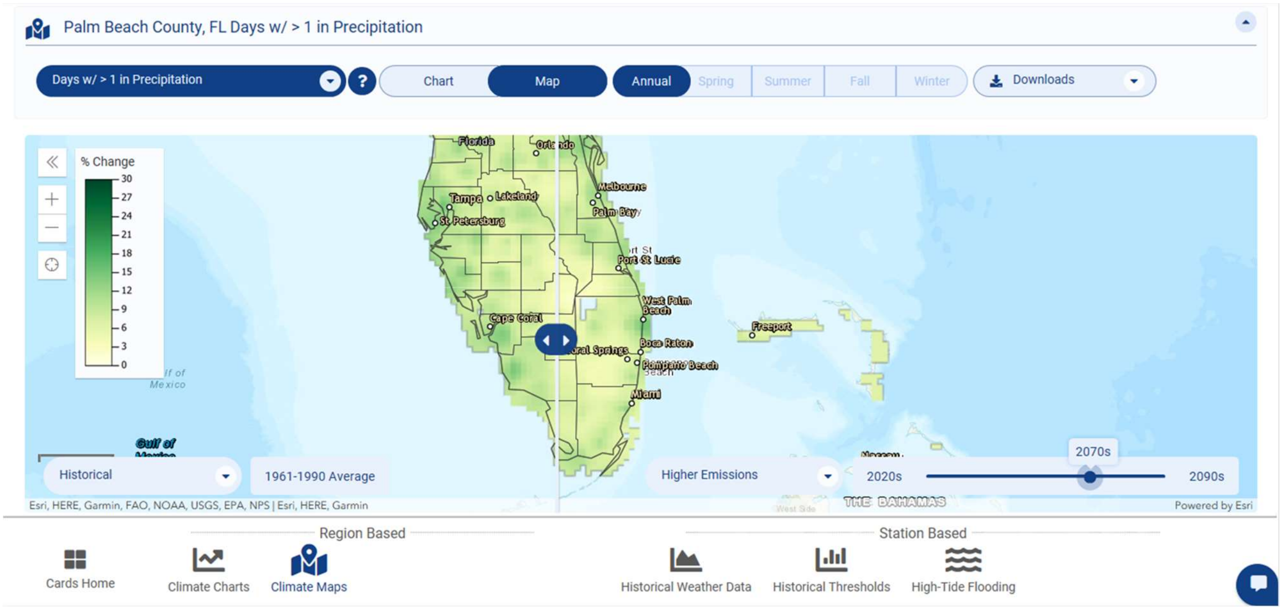


Figure 4. Map of the percentage change in days with more than 1 inch of precipitation in Palm Beach County (and surrounding counties) by 2070, in contrast with historical averages, Climate Explorer tool illustration.

The United States Geological Survey (USGS) maintains a network of surface water stations nationwide that provide current water data at regular intervals. **Figure 5** shows surface water stations in Florida with at least 30 years of data and the associated percentiles representing daily streamflow conditions (USGS 2020). The USGS (2020) website provides easy access to real-time data and the time series used for the analysis.

The U.S. Drought Monitor is produced through a partnership between the National Drought Mitigation Center at the University of Nebraska-Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration. Data and maps of current and forecasted conditions are available through the U.S. Drought Monitor website. Current conditions from the U.S. Drought Monitor are included as part of the District's weekly water and environmental conditions analyses (**Figure 6**).

Created by the National Weather Service, the Advanced Hydrologic Prediction Service provides real-time data and maps largely based on observed water level data collected by the USGS. The suite of forecasting products available are helpful tools for resource and risk managers. **Figure 7**0 presents an example map of river observations and forecasts for predicted flood status in South Florida.

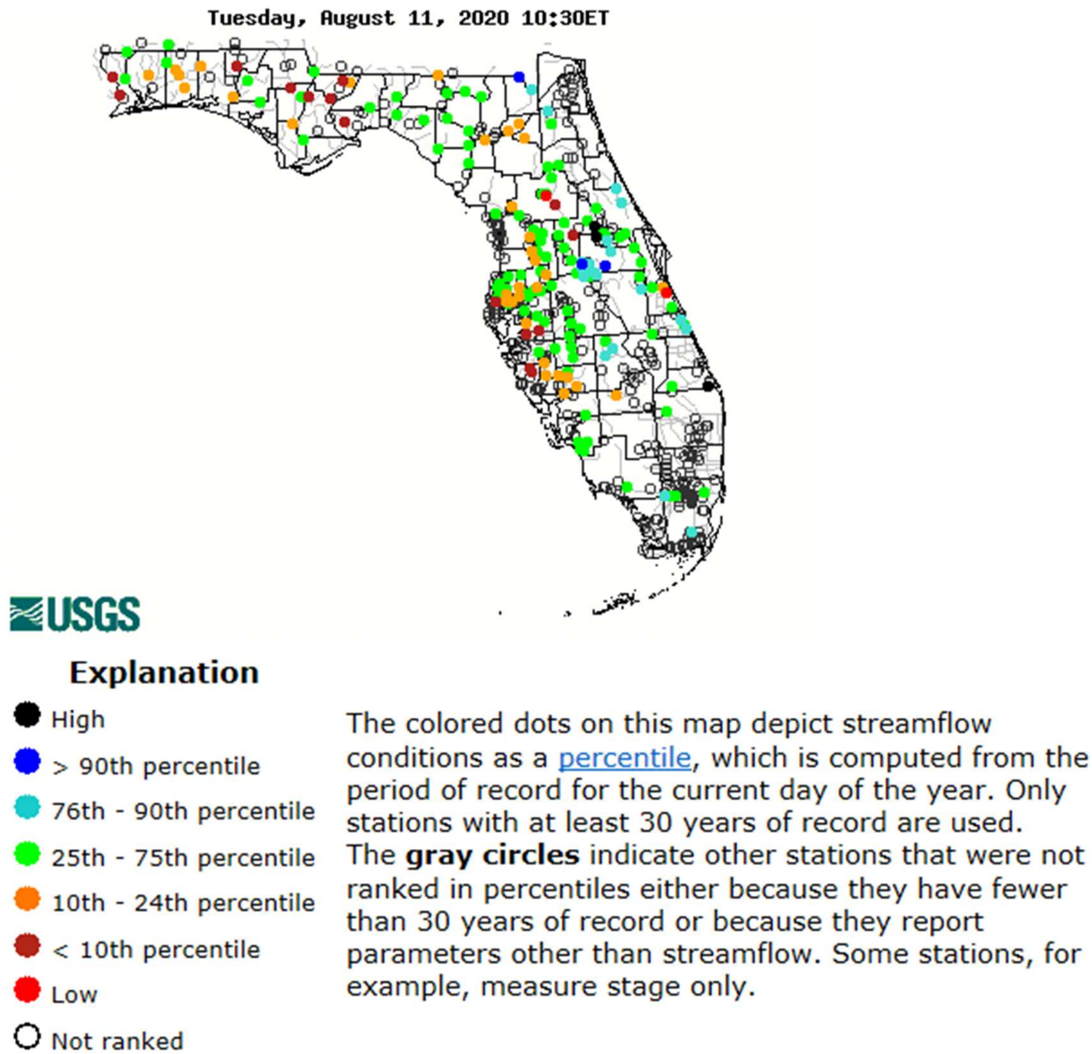


Figure 5. Daily streamflow conditions and associated percentiles at surface water stations in Florida (From: USGS 2020).

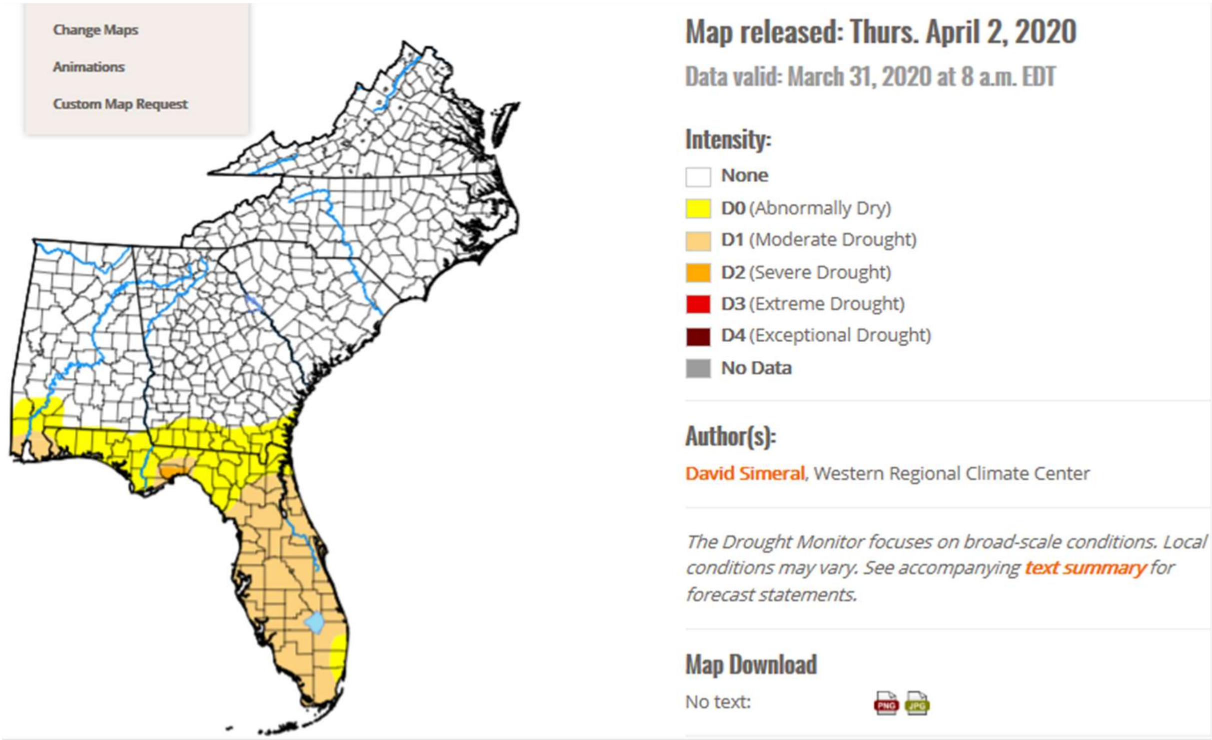


Figure 6. Example of drought intensity map for the southeastern United States available through the U.S. Drought Monitor website (From: Simeral 2020).

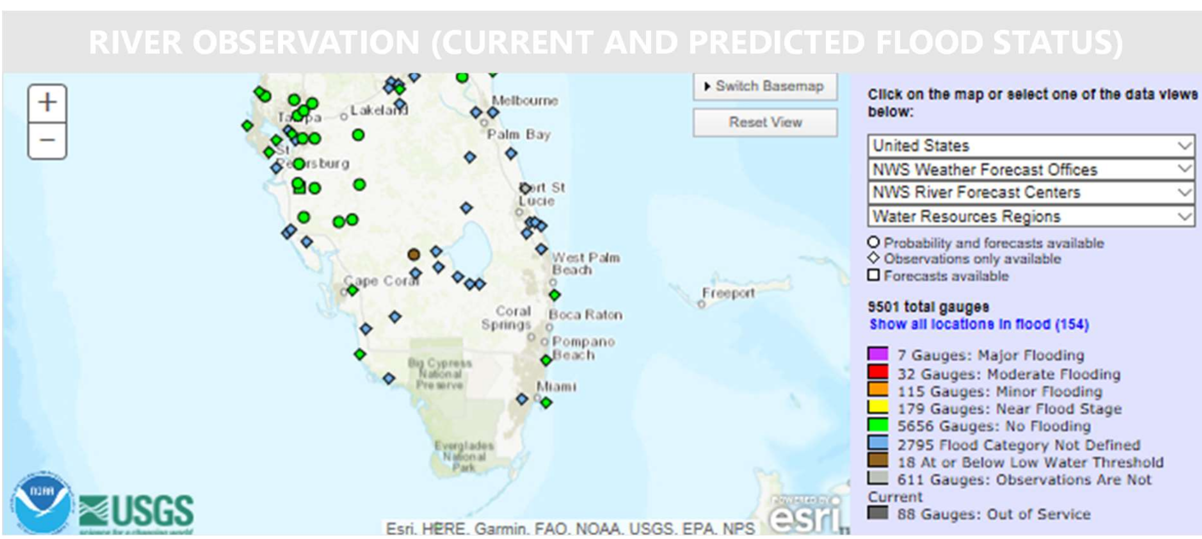


Figure 7. Example of river observations and forecasts for predicted flood status (From: National Weather Service 2020).

The U.S. Climate Extremes Index, available through the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information, is another indicator used to indicate climate changes based on temperature and precipitation data. **Figure 8** shows extremes in the number of days with/without precipitation in the southeastern United States.

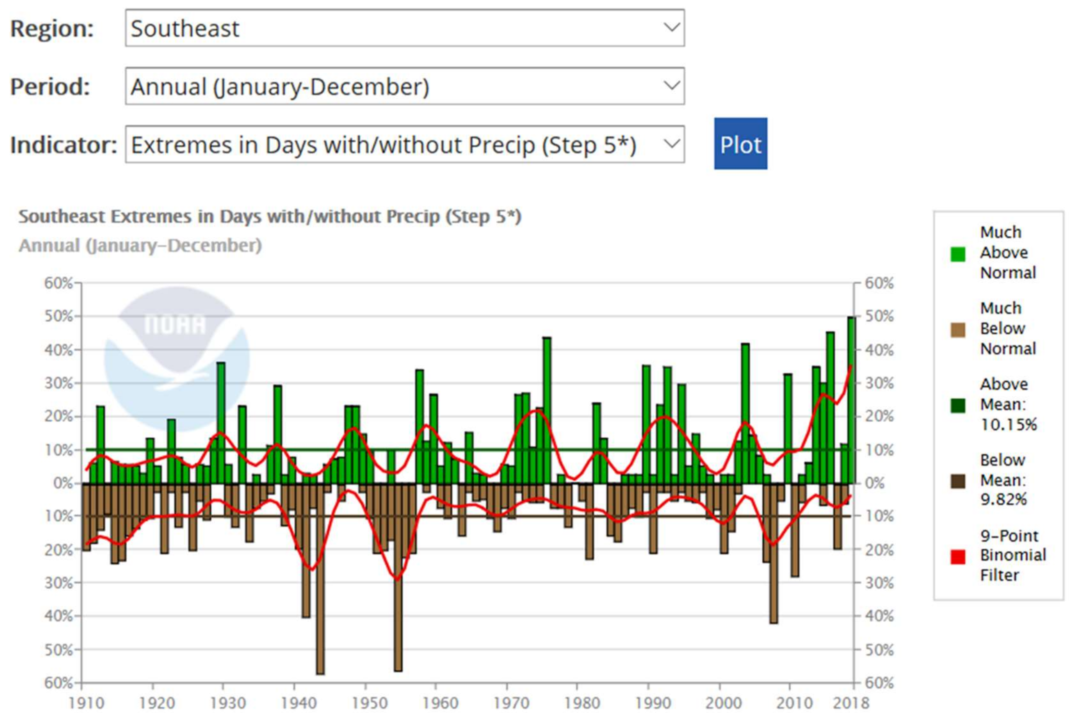


Figure 8. Extremes in days with/without precipitation in the southeastern region of the United States (From: NOAA National Centers for Environmental Information 2020a).

The United States Environmental Protection Agency (USEPA) has cultivated a list of climate change indicators, including high and low temperatures, precipitation, tropical cyclone activity, and drought events. Heavy precipitation is exemplified in **Figure 9**, showing extreme one-day precipitation events, with relevant information about upward trends in percent of land area in the contiguous United States.

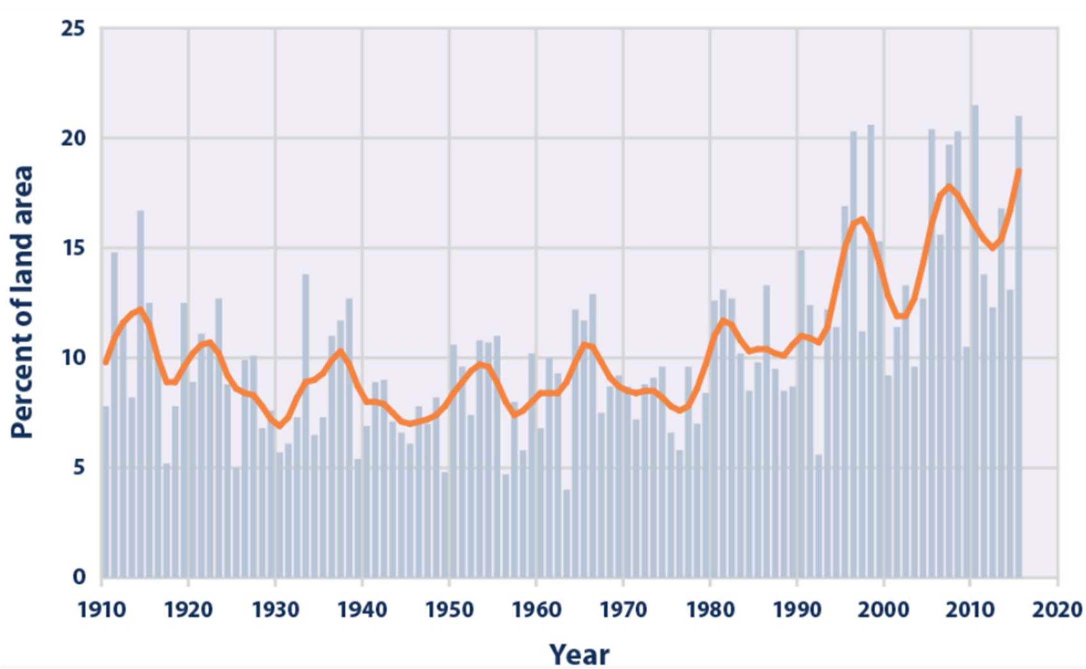


Figure 9. Extreme one-day precipitation events in the contiguous United States in percent of land area from 1910 to 2015, along with smooth trend line in orange (From: USEPA 2016).

The federal U.S. Global Change Research Program is a collaborative effort of 13 federal agencies with the goal of understanding the natural and anthropogenic forces changing the global environment and the impacts of those changes on society. The program has created a catalog of climate-related indicators with static countrywide charts and maps in a visually appealing summary page (**Figure 10**). The data included in this catalog are used for the National Climate Assessments. **Figure 11**, from the U.S. Global Change Research Program indicator catalog, shows the annual global average surface temperature in relation to the 20th century average, for land and ocean, with an evident upward trend.

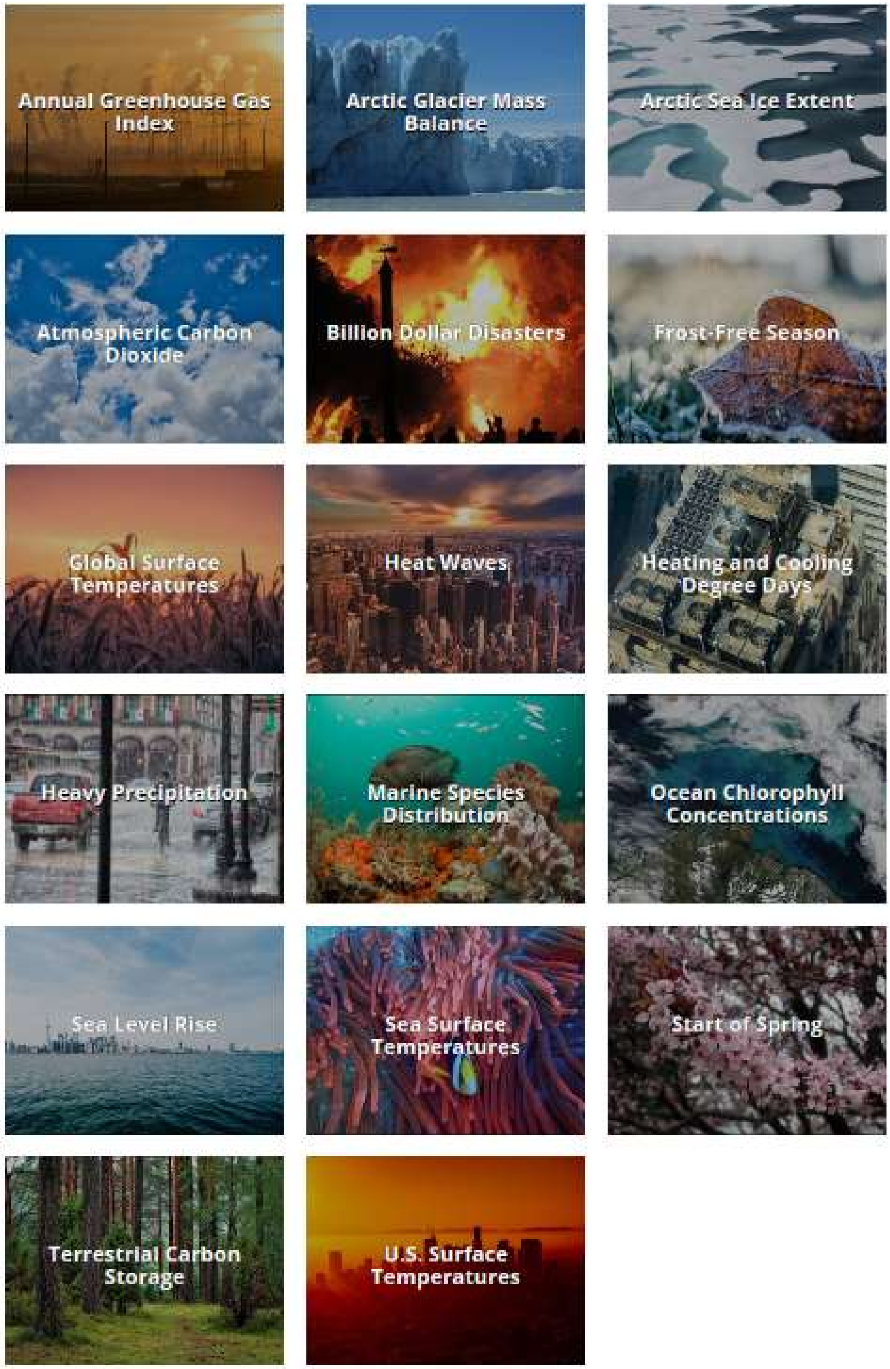


Figure 10. Indicators related to climate and environmental changes (From: U.S. Global Change Research Program n.d.).

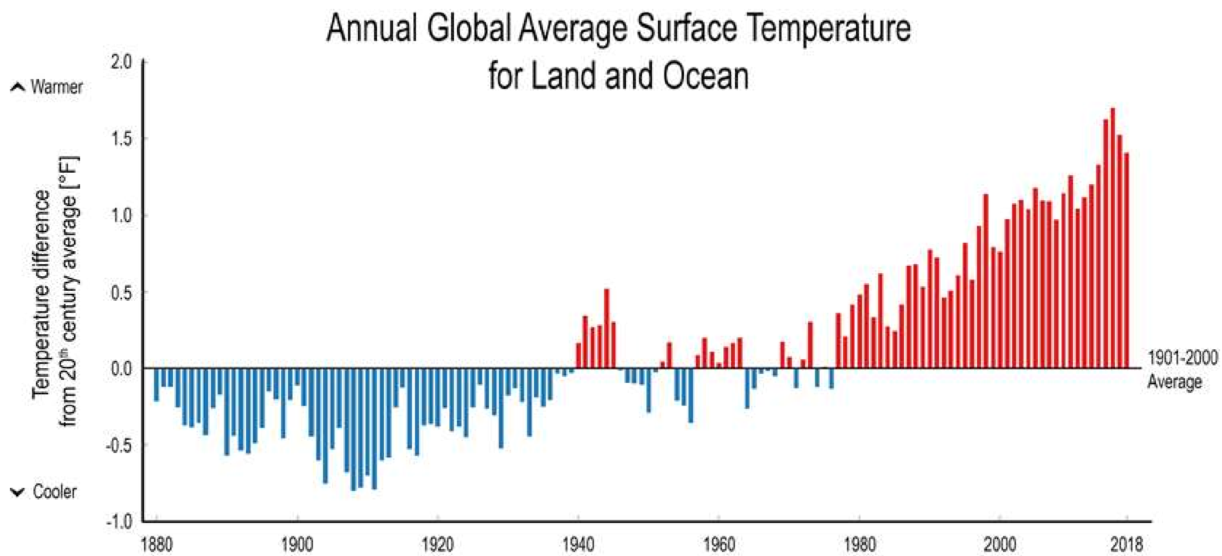


Figure 11. Annual global average surface temperature for land and ocean, 1880–2020 (From: U.S. Global Change Research Program n.d.).

The National Centers for Environmental Information, which is the central repository of climate data from NOAA, provides a climate database with monthly averages and anomalies of temperature, precipitation, and drought indices for all climate divisions in the United States back to 1895, based on a 5-kilometer grid based on the Global Historical Climatology Network. Raw station data are available for select stations through user-friendly "time series" and "mapping" functions. **Figure 12** shows an upward trend in minimum temperatures since 1895 in Miami-Dade County. **Figure 13** illustrates global temperature anomalies in a grid format. NOAA uses information from the National Centers for Environmental Information for the 'State of the Climate' monthly reports, as illustrated in **Figure 14**.

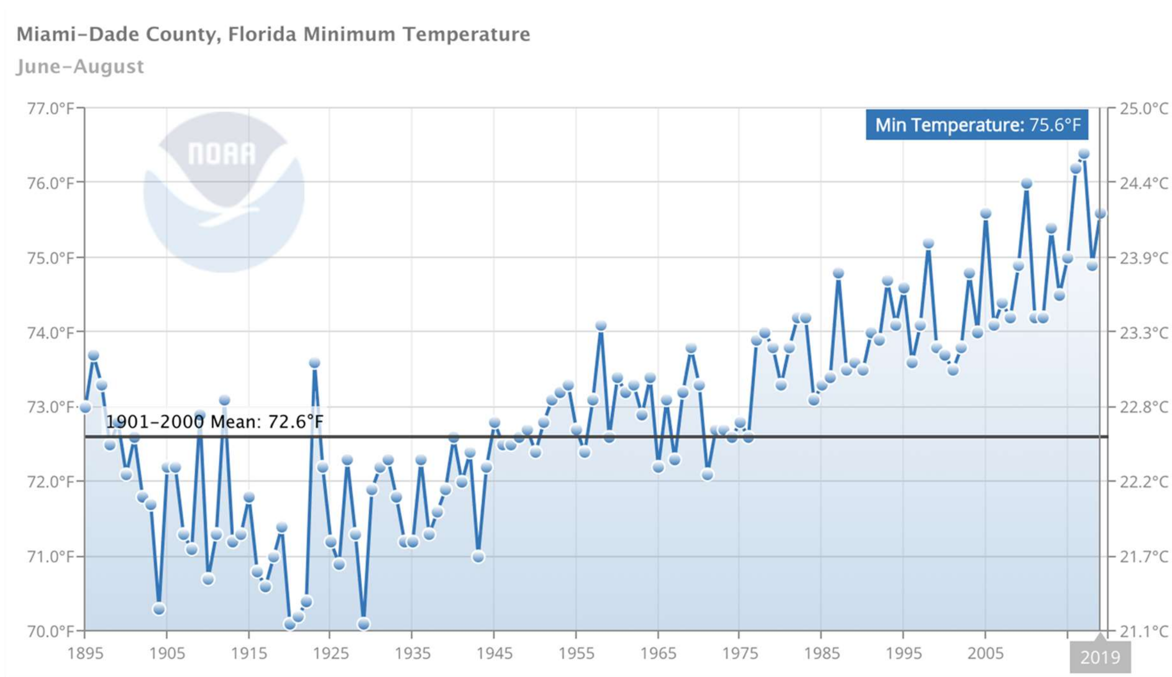


Figure 12. Minimum recorded temperatures, June to August, in Miami-Dade County, Florida (From: NOAA National Centers for Environmental Information 2020b).

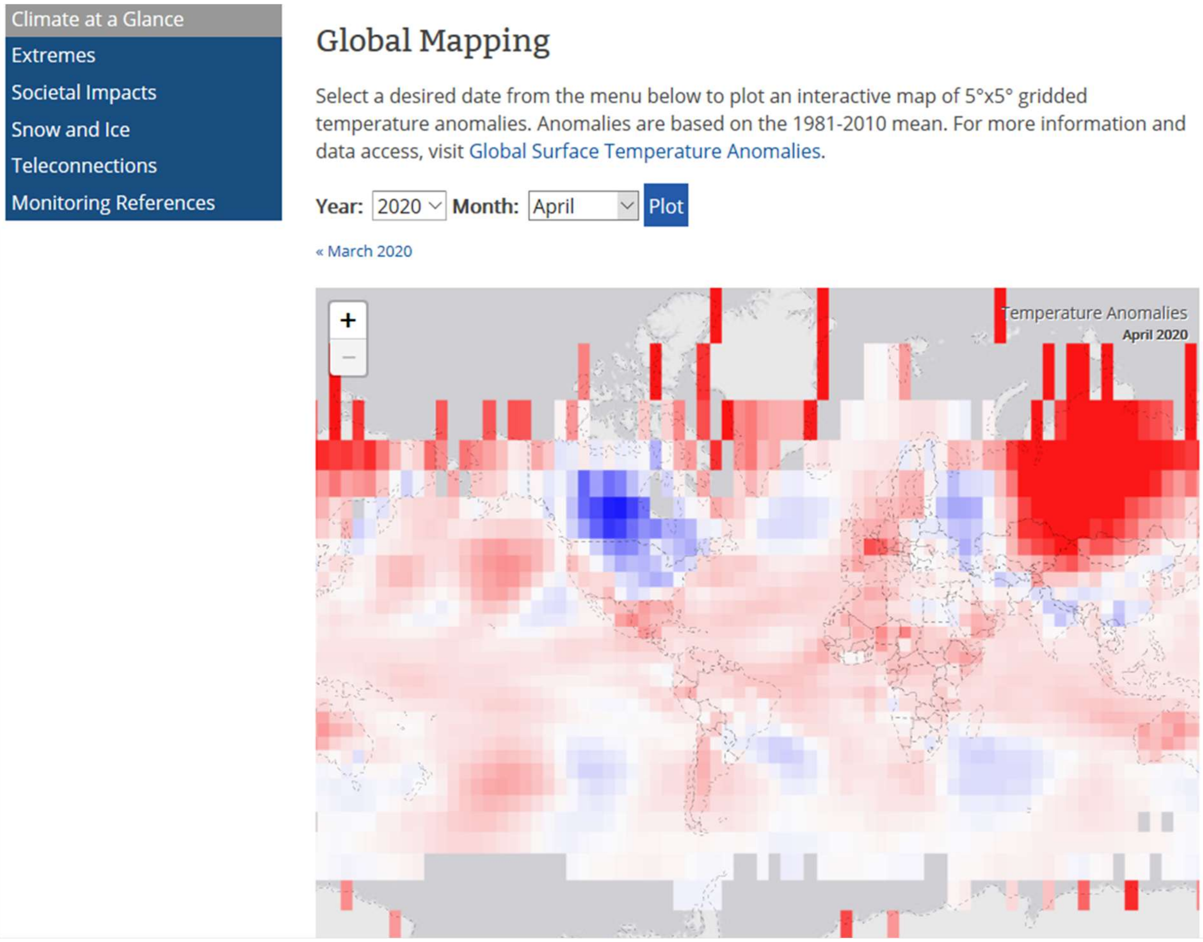
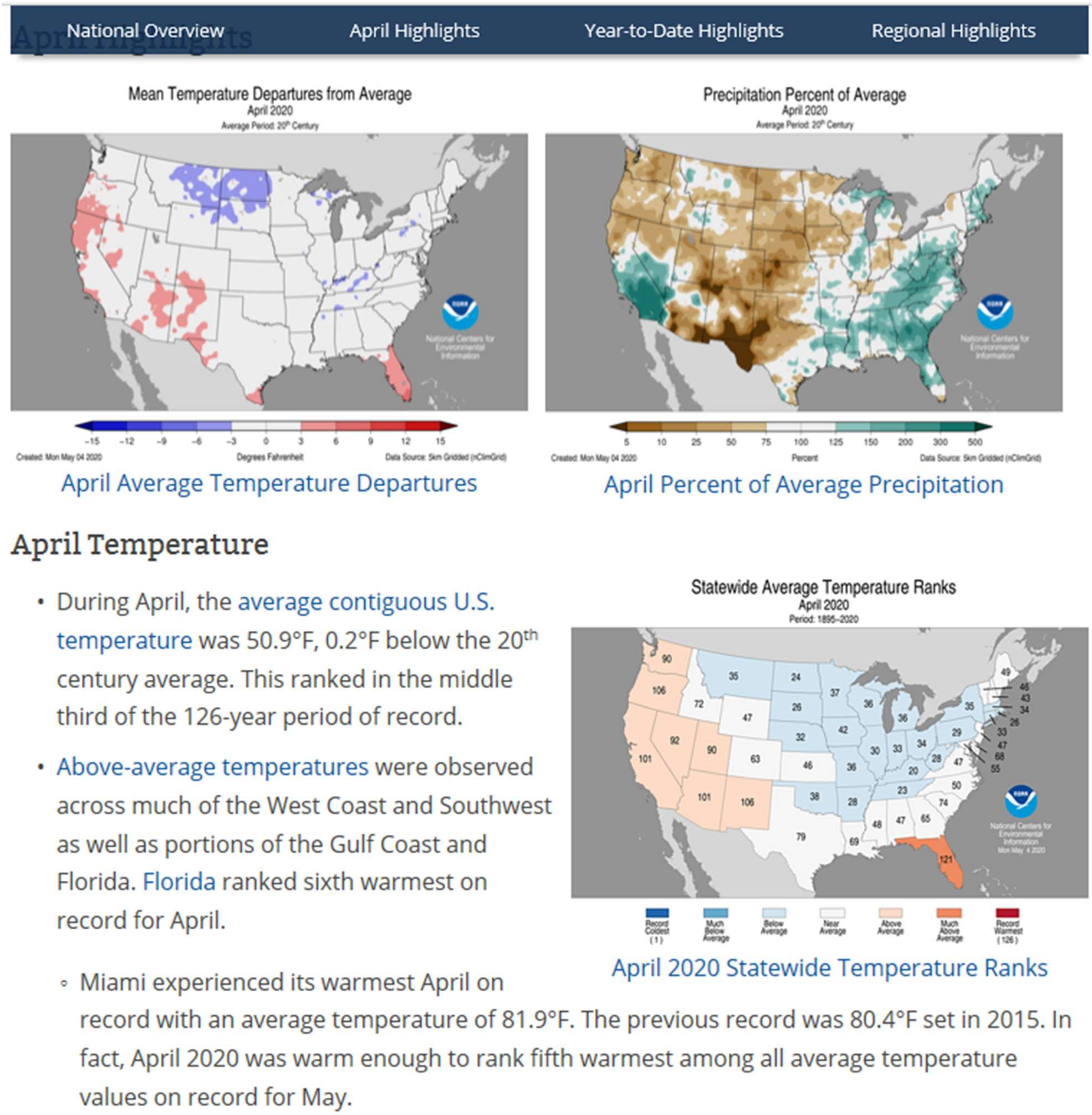


Figure 13. Global mapping of temperature anomalies in April 2020 (From: NOAA National Centers for Environmental Information 2020c).



- During April, the average contiguous U.S. temperature was 50.9°F, 0.2°F below the 20th century average. This ranked in the middle third of the 126-year period of record.
- Above-average temperatures were observed across much of the West Coast and Southwest as well as portions of the Gulf Coast and Florida. Florida ranked sixth warmest on record for April.
    - Miami experienced its warmest April on record with an average temperature of 81.9°F. The previous record was 80.4°F set in 2015. In fact, April 2020 was warm enough to rank fifth warmest among all average temperature values on record for May.

Figure 14. Illustration of NOAA state of the climate monthly report for April 2020 (From: NOAA National Centers for Environmental Information 2020d).

The NOAA Tides and Currents website (NOAA Center for Operation Oceanographic Products and Services 2020a, 2020b) provides a suite of tools for looking at oceanographic data. The section on Water Levels can be used to monitor current water levels and compare them to predicted values. The function "Sea Level Trends" provides information on long-term trends at different tide stations. **Figure 16** illustrates an upward trend in sea level at Mayport, Florida, since the 1930s.

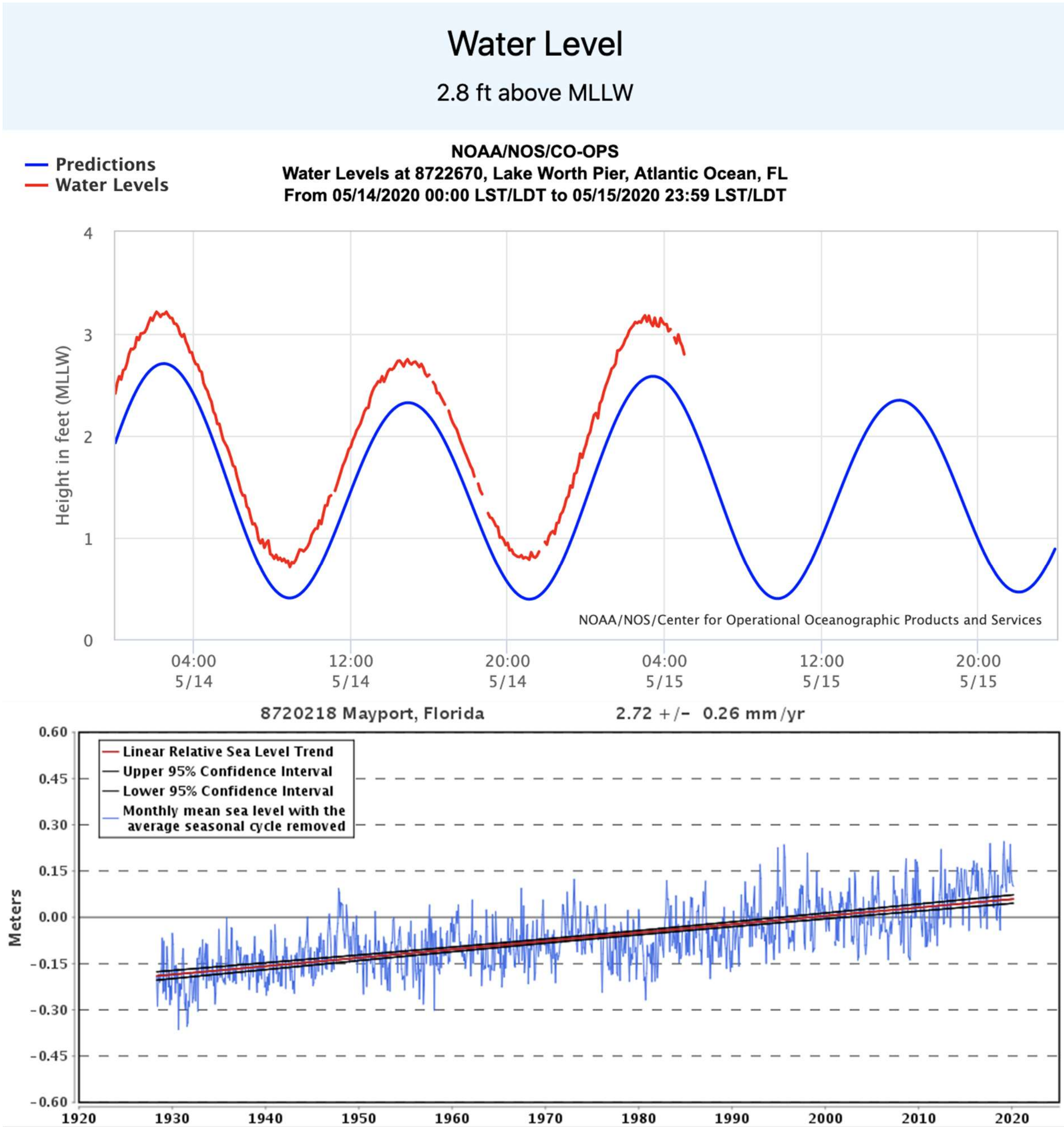


Figure 16. Sea Level Upward Trend at Mayport, Florida, since 1930s, NOAA "Sea Level" tool illustration. (From: NOAA Center for Operation Oceanographic Products and Services 2020b).

The NOAA Sea Level Rise Viewer (NOAA Office for Coastal Management 2020) is a web map that allows the user to view potential flood inundation from various levels of sea level rise by moving the sliding bar on the side. **Figure 17** illustrates the potential flood inundation scenario resulting from a 3-foot sea level rise in South Florida.

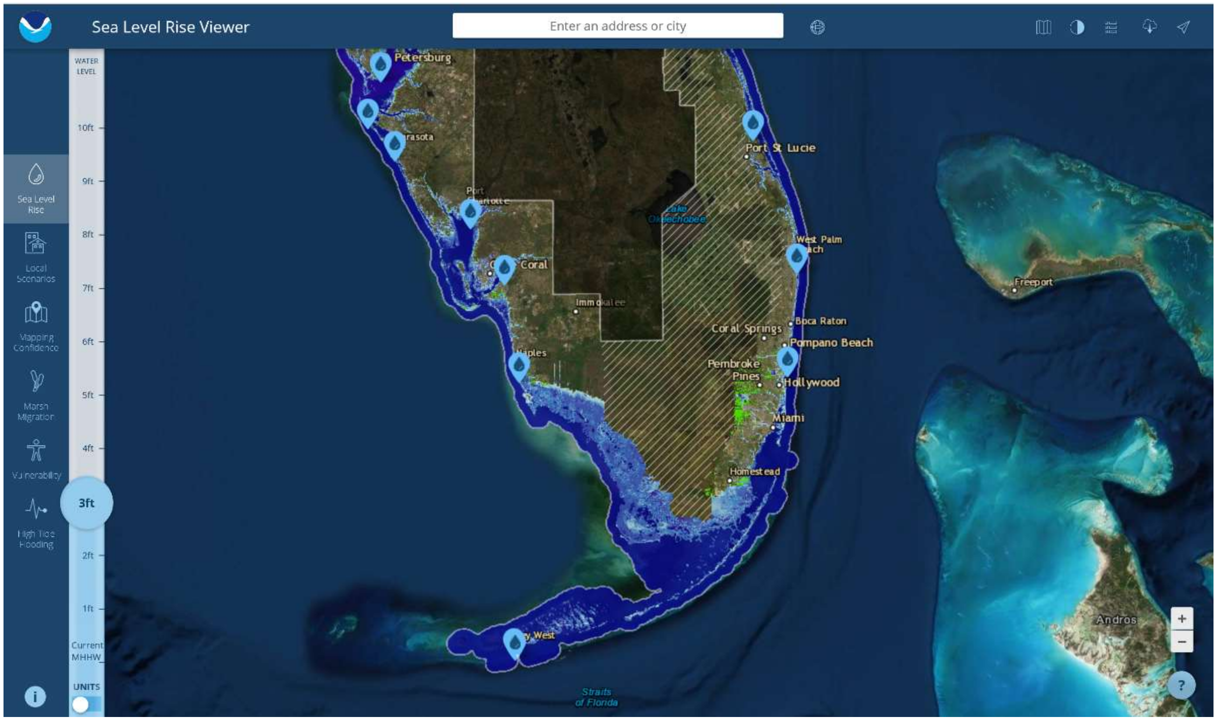
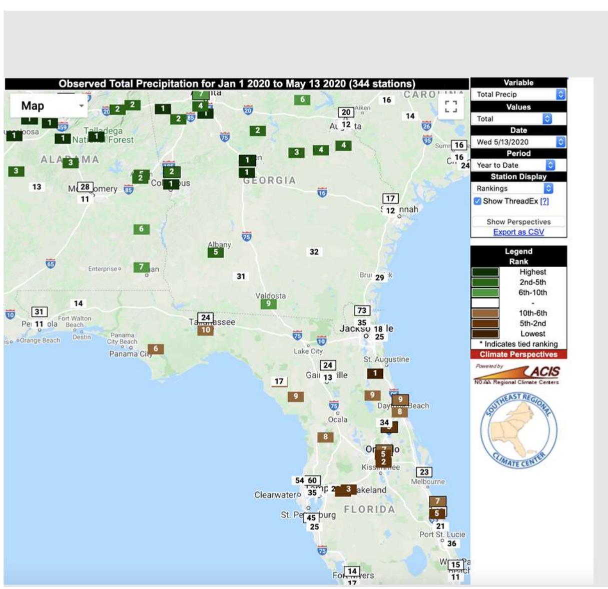


Figure 17. Inundation scenario from a 3-foot sea level rise in South Florida, NOAA Sea Level Rise Viewer illustration (From: NOAA Office for Coastal Management 2020).

Climate Perspectives (The Southeast Regional Climate Center, 2020) accesses the NOAA Applied Science Information System and compares recent conditions to historical climates. There is both a map version for viewing many stations across the regions and a station-by-station tabular version for more detailed information (**Figure 18**).



Past Climatological Periods
At Miami Intl Ap in Miami, FL (085663)
Period of record: 1937-03-01 to 2020-05-13 (current) - 84 Year(s)
Normals values based on 1981-2010 normals data from this station
This data was pregenerated on Friday, May 15th, 2020 at 3:02 AM EDT

Date(s)	Data (%) # of Obs Used		Avg High Temp (°F)	Avg Low Temp (°F)	Avg Mean Temp (°F)	Total Precip (in)	Most similar city
Wednesday May. 13th, 2020 View History	100% 1 Daily	Value	84 °F	75 °F	79.5 °F	0 in	Key West, FL Max: 84.7 °F Min: 75.3 °F
		DFN	-2.7 °F	+2.5 °F	-0.1 °F	-0.1 in	
		Ranking	T-23rd coldest	T-10th warmest	T-31st warmest	T-1st driest	
		Similar DOY	Apr 23	May 31	May 13	-	
Past 2 Days 05/12/20 - 05/13/20 View History	100% 2 Daily	Value	84.5 °F	74 °F	79.3 °F	0 in	Key West, FL Max: 84.7 °F Min: 75.3 °F
		DFN	-2.2 °F	+1.6 °F	-0.3 °F	-0.3 in	
		Ranking	T-29th coldest	T-19th warmest	35th warmest	T-1st driest	
		Similar DOY	Apr 26-Apr 27	May 22-May 23	May 10-May 11	-	
Past Week 05/07/20 - 05/13/20 View History	100% 7 Daily	Value	84.6 °F	71.1 °F	77.9 °F	0.26 in	Honolulu, HI Max: 84 °F Min: 70.3 °F
		DFN	-1.8 °F	-0.9 °F	-1.3 °F	-0.7 in	
		Ranking	T-29th coldest	T-39th warmest	T-35th coldest	39th driest	
		Similar DOY	Apr 24-Apr 30	May 2-May 8	Apr 29-May 5	-	
Month to Date 05/01/20 - 05/13/20 View History	100% 13 Daily	Value	85.5 °F	70.5 °F	78 °F	0.26 in	Miami, FL Max: 85.9 °F Min: 71.5 °F
		DFN	-0.4 °F	-1.0 °F	-0.7 °F	-1.3 in	
		Ranking	T-37th warmest	T-40th coldest	41st coldest	19th driest	
		Similar DOY	Apr 29-May 11	Apr 25-May 7	Apr 27-May 9	-	
Past 2 Weeks 04/30/20 - 05/13/20 View History	100% 14 Daily	Value	85.7 °F	70.6 °F	78.1 °F	1.23 in	Miami, FL Max: 85.9 °F Min: 71.4 °F
		DFN	-0.1 °F	-0.9 °F	-0.5 °F	-0.4 in	
		Ranking	35th warmest	T-41st warmest	T-40th warmest	38th driest	
		Similar DOY	Apr 29-May 12	Apr 25-May 8	Apr 27-May 10	-	
Past 3 Weeks 04/23/20 - 05/13/20 View History	100% 21 Daily	Value	86.6 °F	71.7 °F	79.2 °F	2.62 in	Miami, FL Max: 85.4 °F Min: 70.9 °F
		DFN	+1.2 °F	+0.8 °F	+1.0 °F	+0.2 in	
		Ranking	16th warmest	26th warmest	T-17th warmest	T-40th wettest	
		Similar DOY	May 2-May 22	Apr 28-May 18	Apr 30-May 20	-	
Past Month 04/14/20 - 05/13/20 View History	100% 30 Daily	Value	88.2 °F	73.2 °F	80.7 °F	2.62 in	San Juan, PR Max: 86.7 °F Min: 75.2 °F
		DFN	+3.4 °F	+3.0 °F	+3.2 °F	-0.8 in	
		Ranking	1st warmest	T-8th warmest	T-1st warmest	T-36th driest	
		Similar DOY	May 13-Jun 12	May 3-Jun 2	May 7-Jun 6	-	
Season to Date 03/01/20 - 05/13/20 View History	100% 74 Daily	Value	86.3 °F	72.1 °F	79.2 °F	4.22 in	San Juan, PR Max: 85.8 °F Min: 74 °F
		DFN	+3.8 °F	+4.7 °F	+4.3 °F	-3.5 in	
		Ranking	1st warmest	1st warmest	1st warmest	19th driest	

Figure 18. Climate perspectives dataset (From: The Southeast Regional Climate Center 2020).

Finally, Climate Central is an independent organization of leading scientists and journalists that researches and reports the facts about climate change and its impacts. The diverse set of climate indicator graphics (**Figure 19**) are visually appealing and focus on communicating key messages.

Figure 19. Example graphics of climate indicators (From: Climate Central 2020).

Internal Survey Results

As part of the initial workgroup efforts, a District staff survey was conducted with the goal of capturing internal knowledge and experience in developing, analyzing, and using water and climate resilience data. Among the 35 responses, 68% affirmed to be currently involved in documenting trends and shifts in water and climate observed data (**Figure 20**). The most common types of data being analyzed include:

- Sea level rise and impact to coastal structures
- Seasonal and interannual water stages and flows
- Extreme events (i.e., droughts and floods)
- Salinity, temperature, and other water quality data
- Exceedances and violations of Minimum Flows and Minimum Water Levels (MFLs)
- Ecological variables (e.g., seagrass, sediment, nutrient, oyster beds, fish abundance)
- Evaporation
- Water use and groundwater levels
- Saltwater intrusion and chloride concentrations

The second survey question was related to the utilization of past observations and future projections as part of current work efforts. Approximately 60% of the responses (**Figure 20**) were affirmative, and the major sources of data listed are:

- DBHYDRO (the District's corporate environmental database)
- Southeast Florida Regional Climate Change Compact
- NOAA/National Hurricane Center
- USGS
- United States Army Corps of Engineers
- National Climate Assessment
- Regulatory databases
- Florida International University (monitoring partnerships)

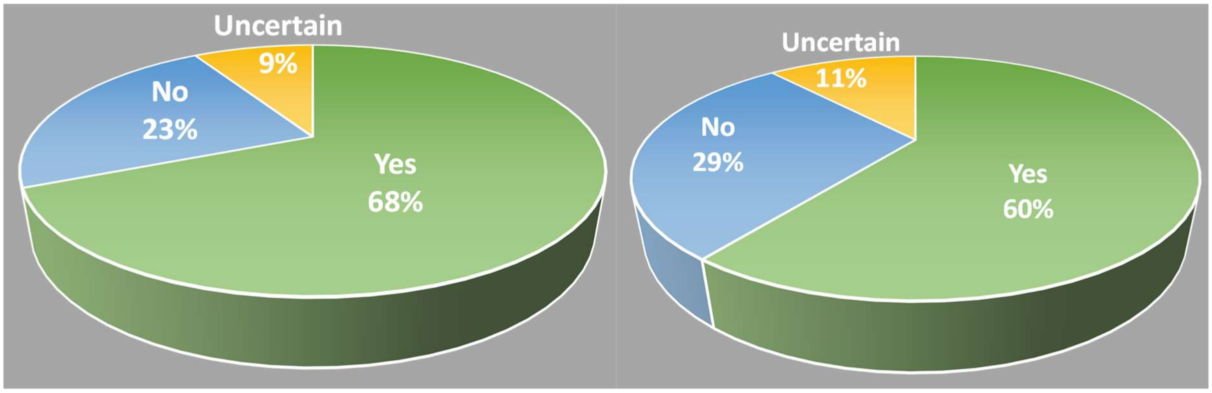


Figure 20. Percentage of respondents currently involved in documenting trends/shifts in water and climate observed data (left) and utilizing climate change observations and projections as part of responsibilities (right).

Regarding the tools being used to search and display data, about 34% of the responses (**Figure 21**) were affirmative. Examples of tools include:

- DBHYDRO
- Graphical verification analysis
- MFL compliance tool
- Sediment elevation table
- USGS Water Level and Salinity Analysis Mapper
- NOAA web services
- NEXRAD and BAT tool
- GIS visualization tools, Python scripts
- DHI visualization tools
- Custom scripts, Excel tools

A strong consensus of 80% agreement (**Figure 21**) verified the importance of creating a publication format to periodically report on selected water and climate resilience metrics. Suggestions of reporting and publication formats include:

- Real-time interactive web-based tool (links to raw data and technical information)
- Monthly/quarterly/annual consolidated report/technical publication
- Mid-level audience technical document (science in appendices or via weblinks)
- Visual summary (data values and graphs/charts)
- Weekly environmental conditions and operations meetings/report
- South Florida Environmental Report
- Synopsis of work of partner agencies
- Observations and projections (potential seasonal shifts and uncertainty ranges)

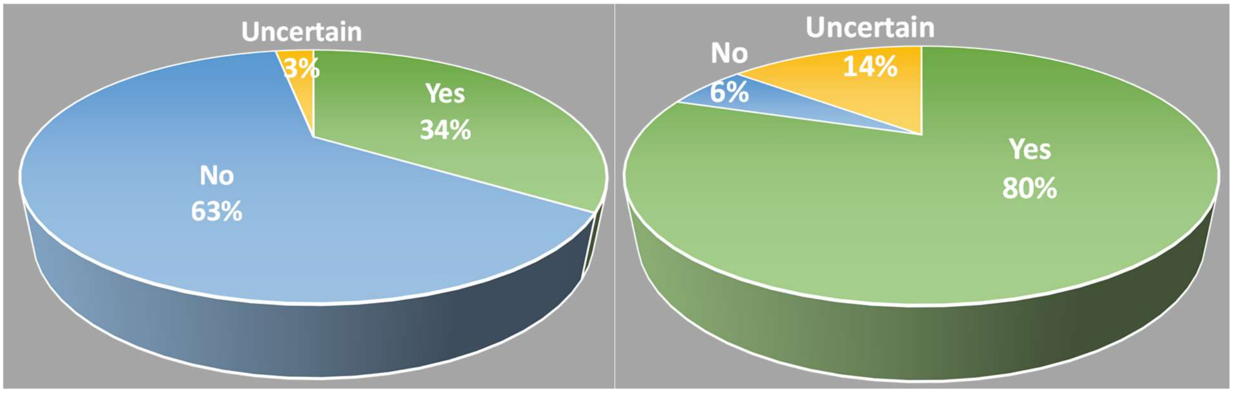


Figure 21. Percentage of respondents currently using innovative tools to search and display data (left) and supporting the establishment of a periodic water and climate resilience metrics report (right).

Finally, about 60% of respondents expressed interest in supporting the workgroup efforts, and 74% wanted to learn more about water and climate resilience aspects associated with the District's mission.

RELEVANT WATER AND CLIMATE RESILIENCE METRICS

A comprehensive list of potentially relevant water and climate resilience metrics was developed as part of the survey responses and in follow-up workgroup discussions. The initial workgroup effort focused on identifying metrics relevant to the District's mission that could be associated with climate change impacts, including sea level rise. For each identified metric, the length and frequency of available data were confirmed, and the main District mission elements were identified. Additional observations and justifications were provided for each metric, as well as alternative options for data interpretation and visualization (**Appendix 1**).

The objectives of this step were to 1) accomplish a comprehensive analysis of the available data sets currently monitored and maintained by the District, and 2) initiate investigation of trends, anomalies, and shifts in observed data. Multiple departments within the District provided a variety of data sources being used in their scientific analyses and technical work and that are anticipated to be influenced by changing climate patterns. These initial discussions were fundamental in identifying potential water and climate resilience metrics, as they reflect valuable expertise from the workgroup members and the relevance of the suggested data to the projects and priorities being implemented by the District.

The initial list of suggested metrics and summarized information is organized into the following categories:

- Sea level
- Groundwater levels
- Rainfall
- Flooding
- Drought/water supply
- Saltwater intrusion
- Temperature
- Stormwater
- Water quality
- Ecology/habitat

Evaluation of the Association with Climate Change Impacts

Workgroup discussions emphasized the importance of evaluating the association of each suggested metric with climate change impacts based on scientific assumptions, and in terms of available data robustness and the identification of other associated factors that can influence these observed changes. One example is the association of saltwater intrusion with rates of sea level rise. In South Florida, several water supply wellfields are located within the coastal zones and, therefore, vulnerable to saltwater intrusion. Sea level rise, as a result of climate change impacts, has been identified as a significant contributing factor to the increasing saltwater vulnerability of coastal wellfields. In addition, well-field pumping rates can be an important factor in determining coastal wellfield saltwater vulnerability. In 2016, the USGS published the results of a study on the distribution of salinity in the Biscayne Aquifer in Broward County and how salinity levels in 2011 could be related to wellfield pumping and sea level rise rates (Hugues et al., 2016). The study used a MODFLOW model to simulate changes in the salinity curve, if pumping had not occurred and if sea level rise, separately, had not occurred. The left map in **Figure 22** shows differences in simulated groundwater levels, in feet, if pumping had not occurred, resulting in higher water tables, as expected. The red areas in the middle map show the differences in simulated groundwater levels, in feet, if sea level rise had not occurred, resulting in lower water tables. The right map illustrates the results of the simulation in which both pumping and sea level rise were ignored, resulting in a combination of areas with higher and lower water tables. This demonstrates that both factors combined, influence how fresh groundwater levels are affected and how saltwater intrusion can be exacerbated. The study results also support the association between sea level rise and movement of the saltwater interface.

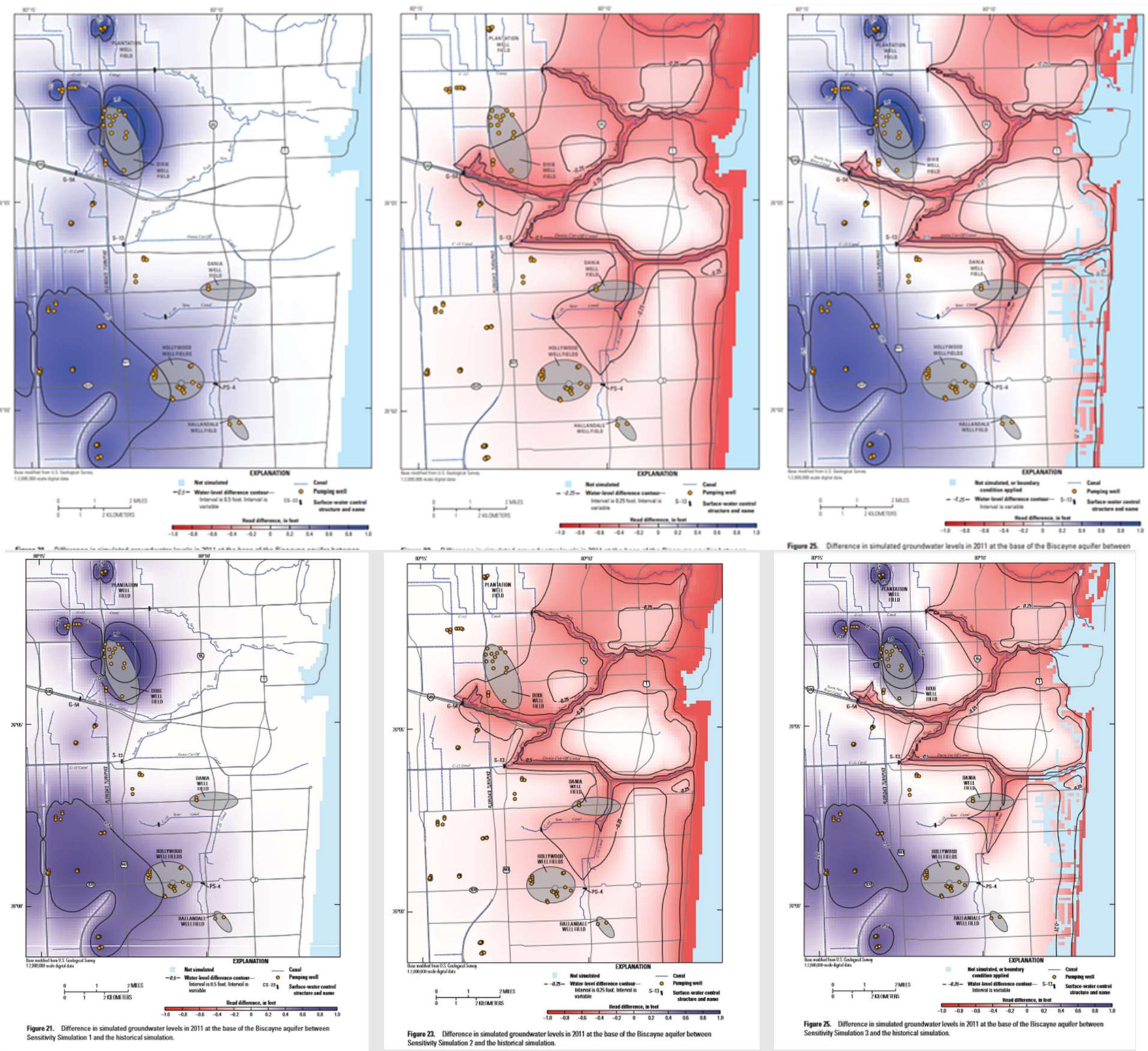


Figure 22. Map of simulated differences in groundwater levels in the Biscayne Aquifer in Broward County without pumping (left), without sea level rise (middle) and without both (right) (From: Hughes and others, 2016).

Subsequent scientific analyses will be undertaken for the selected metrics to analyze the relationship between observations and changing climate patterns. The association between climate change impacts and some of the observed trends in District data might require additional monitoring efforts and development of new scientific approaches as part of future resiliency project efforts. In some cases, it is important to identify other contributing factors associated with observed trends and shifts, especially if they result from changes in operational decisions, structural and physical conditions, and other controlled variables.

DATA AND TREND ANALYSIS APPROACH

A key element in the implementation of water and climate resilience metrics is to determine the best data analysis approach to support the assessment of available data, including length and frequency, the identification and validation of observed trends, and the determination of relevant metrics. In the context of this effort, it is important to understand potential contributing factors and reveal key interrelations that might influence observed trends and their association with climate change impacts. Robust statistical and spatial analysis tools are essential in establishing alternative options of data interpretation and visualization. Several methods are used throughout this document to identify trends. These methods include ordinary least squares (or linear) regressions, and non-seasonal and seasonal Mann Kendall (MK and SK, respectively).

<u>**Linear Regression**</u>

A linear regression estimates the relationship between one or more independent variables and a dependent variable by minimizing the sum of the squared residuals (differences between observed and predicted values).

The following assumptions underlie the linear regression:

- A linear relationship exists between the independent variable (x), and the dependent variable (y).
- The residuals are independent.
- The residuals have constant variance at every level of x (homogeneous).
- The residuals of the model are normally distributed.

These assumptions are not necessary if statistical significance is not being tested.

<u>**Non-seasonal and Seasonal Mann Kendall**</u>

The MK and SK tests (as described in Hirsch et al. 1982, Gilbert 1987, and Helsel and Hirsch 1992) are used to identify monotonic trends of variables collected over time. Monotonic upward trends mean the variable consistently increases over time, while monotonic downward trends mean the variable is consistently decreasing over time. The MK and SK tests were developed by the USGS in the 1980s to identify surface water quality trends throughout the United States (Helsel et al. 2006).

While the MK test is appropriate for data with no statistically significant seasonal patterns, most water quality data from surface water sampling typically exhibit strong seasonal patterns. Surface water flow, rainfall, and evapotranspiration also are greatly affected by seasonality that affect water quality. Both the MK and SK tests are a nonparametric test that do not require the data to follow a particular distribution. Additionally, the tests are robust against outliers and large data gaps. The SK test was proposed by Hirsch et al. (1982) for use with 12 seasons (months). However, the SK test also may be used for other seasons, for example: the four quarters of the year, the three 8-hour periods of the day, or the wet and dry seasons. Events that occur once per season (e.g., rainfall during the months of January) or exceed a given threshold (rainfall peak over a threshold) do not exhibit seasonal patterns hence they may be modeled using MK.

The following assumptions underlie the MK and SK tests:

- When no trend is present, the observations are not serially correlated over time (MK and SK).
- When no trend is present, the observations are serially correlated over time with adjusted probability value (SK).
- The sample collection, handling, and measurement methods provide unbiased and representative observations of the underlying populations over time (MK and SK).
- One observation per time point (MK and SK)
- Seasonality (seasonal cycles) is not statistically significant (MK).
- Seasonal cycles are statistically significant (SK).

Hirsch and Slack (1984) developed a modification of the SK test that can be used when serial correlation is present over time.

The MK and SK tests results included in the Water Quality section earlier were performed using the FORTRAN code developed by Reckhow et al. (1993) for the USEPA. This code is used to compute the tau statistic, unadjusted and adjusted probability values (p-values) for the tau statistic, and slope (Sen) of observed trend. The adjusted p-value accounts for covariance caused by serial correlation. SAS code is used to produce statistics (correlograms) to identify potential serial correlation. Additionally, modifications to the code were made to output the intercept, as described in Helsel et al. (2006).

As with any statistical analyses, anomalous results can occur. For instance, in rare cases, a trend that is statistically significant (tau statistic with a p-value $<\alpha$) can be associated with a Sen slope of zero. To understand how this may occur with the MK and SK tests, an understanding how tau and Sen slope are calculated is necessary. The tau statistic is calculated based on the differences of all possible adjacent pairs (X2-X1, X3-X2, X4-X3, etc.). These differences will contain positive, negative, and zero values. The tau statistic is the result of the number of positive minus negative differences, which are indicative of the trend direction. The Sen slope estimator (magnitude of the slope) is calculated by determining the median of the differences used to calculate the tau statistic. The p-values for the MK and SK tests are determined from the tau statistic, not the Sen slope. Thus, a Sen slope of zero with a statistically significant tau statistic can occur when many adjacent values are equal (e.g., difference of adjacent pairs equals zero).

Correlation with multi-decadal oscillations will be incorporated as part of yearly technical reports to be included in the SFER - Chapter 2, and change-point statistical techniques will be incorporated accordingly.

KEY METRICS AND ASSOCIATED TREND EXAMPLES

Extensive discussions were promoted to evaluate the availability and relevance of existing District's data to be associated with potential impacts from climate change such as sea level rise. About 50 metrics were compiled as part of these Internal Workgroup discussions. The next step adopted by the Workgroup was to prioritize an initial set of relevant science-based resilience metrics, supported with suitable data sets and periods of record to be implemented Districtwide. A second survey effort and follow-up workgroup discussions assessed the initial metrics and identified a set of relevant metrics. **Appendix 1** summarizes the main discussions and assumptions suggested by the Workgroup for each of the metrics. **Figure 23** summarizes the results of the survey to identify the importance of each of the suggested metrics in informing the District's resiliency efforts.The listed metrics included in the survey do not match exactly the list of metrics included in Appendix 1 because some metrics were combined or added during the following workgroup meetings and the development of this report.

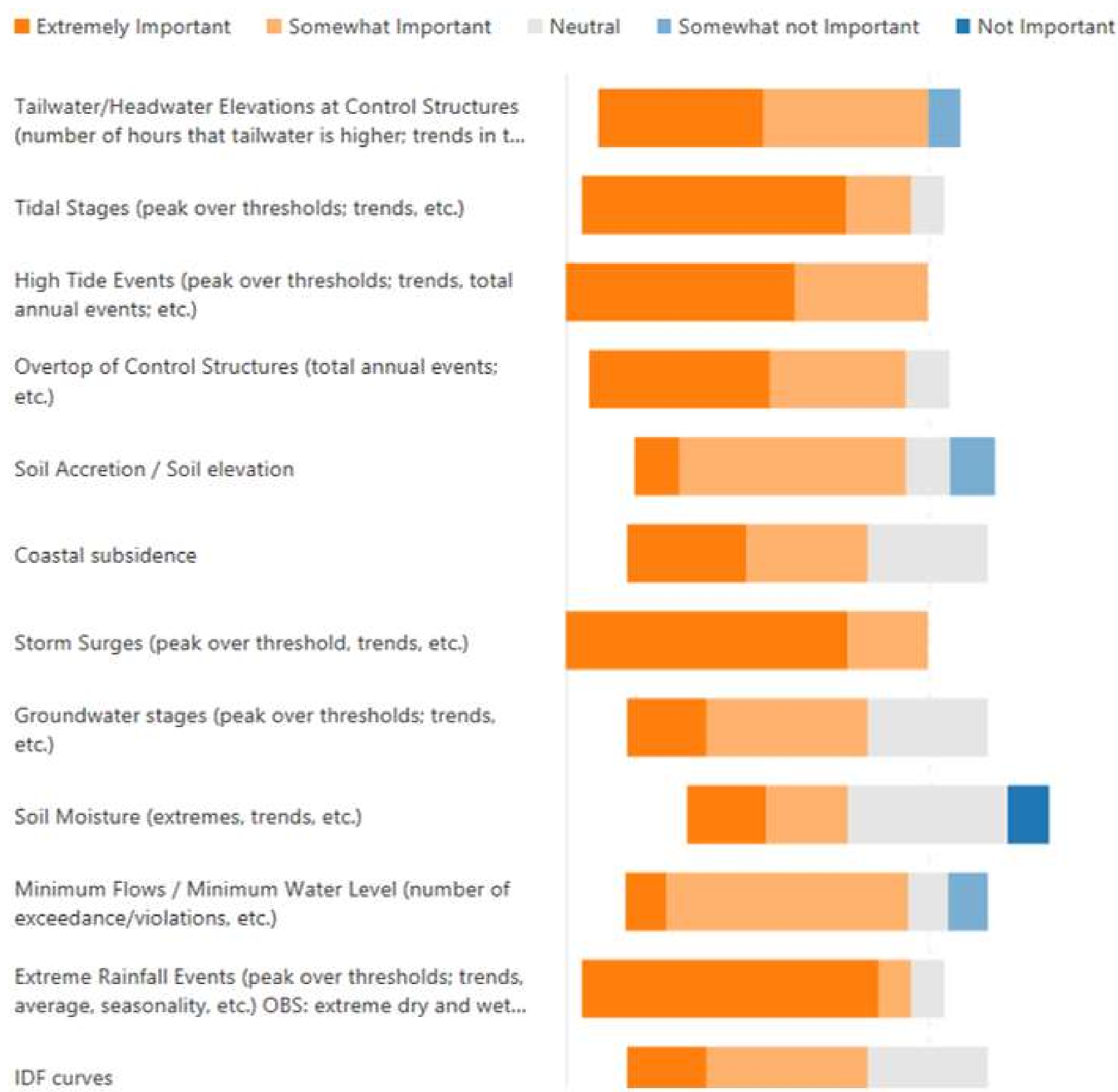


Figure 23. Assessment of the importance of the initial list of resilience metrics, workgroup survey results.

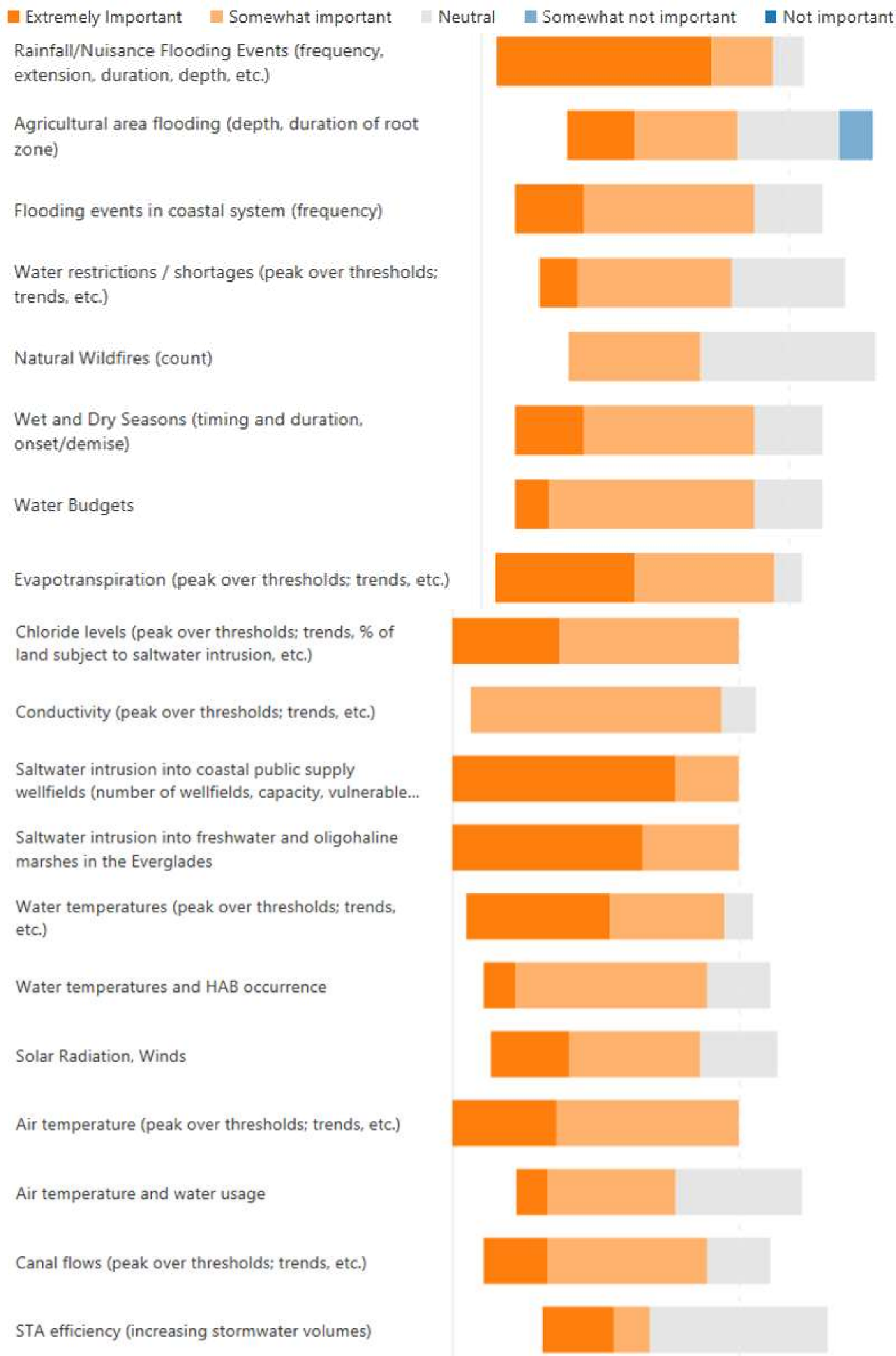


Figure 23 (cont.). Assessment of the importance of the initial list of resilience metrics, workgroup survey results.

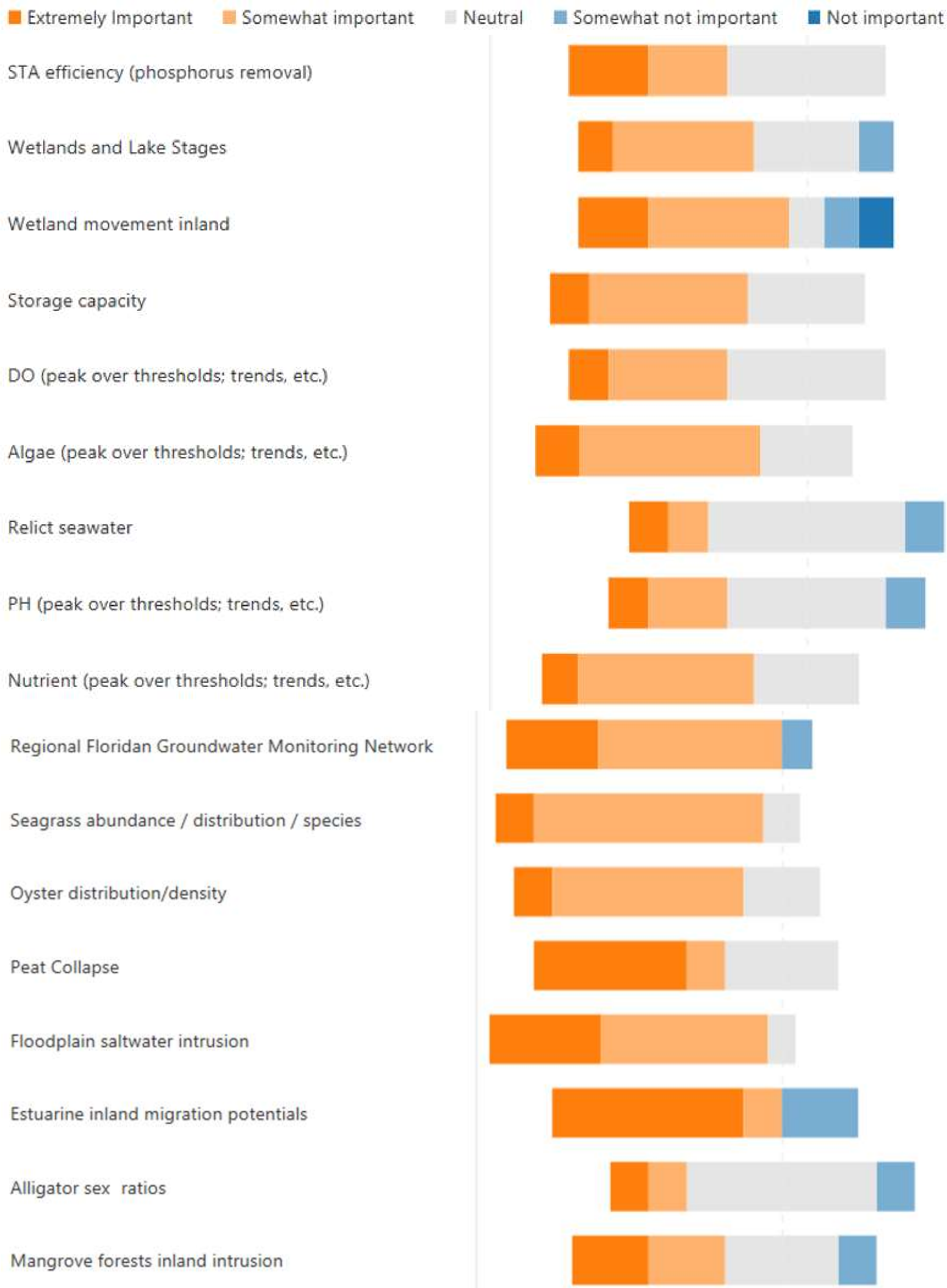


Figure 23 (cont.). Assessment of the importance of the initial list of resilience metrics, workgroup survey results.

Table 1 presents a list of the water and climate resilience metrics that were prioritized as part of the survey results, highlighting metrics that most survey responses classified as extremely important, and considering additional follow-up workgroup discussions and technical presentations. This initial list of priority water and climate resilience metrics was formulated considering the following criteria:

- Potential association with climate change impacts
- Length and frequency of available data
- Initial observed trends
- Association with District's mission elements
- Alternative options of data interpretation and visualization
- Additional observations and justifications

Table1. List of priority water and climate resilience metrics (not ranked).

Set of Priority Water and Climate Resilience metrics
Tailwater Elevations at coastal structures
Tidal stages and high tide events
Groundwater levels
Saltwater intrusion – chloride levels
Minimum Flows and Minimum Water Levels – exceedances/violations
Flooding events
Rainfall (average and wet extremes)
Evapotranspiration
Water temperature
Dissolved oxygen
pH
Specific conductance
Estuarine inland migration
Soil subsidence
Salinity in the Everglades

In the following subsections, each priority metric is briefly introduced, with draft graphics, alternatives for data interpretation and visualization, and a summary of initially observed trends. The analysis focuses on oscillations that significantly influenced climate variability in the 20th and early 21st centuries. This document, including the following subsections, is not intended to advance scientific analyses of the association between each metric and climate change impacts or the comprehensive validation of initially observed trends. Full implementation of the selected metrics District-wide will be developed in the next steps of this project. In addition, the metrics focus on observed District-maintained data that can support assumptions of anticipated future conditions. Data extrapolation into future projections will be developed as a separate future effort.

Tailwater Elevations at Coastal Structures

Tailwater elevations at District coastal structures represent how sea level rise is already affecting stormwater discharge capacity in critical locations in South Florida. The basic function of the region's stormwater management system is based on pre-determined operational ranges at which canal reaches are maintained. When it rains, canals fill up and the coastal structures open to discharge stormwater to the tide via gravity. The gravity characteristic of the system means the discharge capacities at these structures are determined based on the elevation difference between inland canals (i.e., headwater) and the tide elevation (i.e., tailwater). The coastal structures need to be opened to release stormwater as part of flood control operations, and they need to be closed during high tailwater conditions to prevent saltwater intrusion inland, risking groundwater and drinking water system impacts. Closing the structures for longer periods of time due to high tailwater conditions may impact the structure's ability to provide flood control at the design headwater. The increased length of time that coastal structures must be closed due to high tailwater conditions negatively impacts the efficiency of these structures to provide flood control, increasing flooding risks.

As seen in **Figures 24** and **25**, this metric shows an upward trend over the past 35 years, as gates needed to be closed during high tailwater conditions. This data set is unique to the District and constitutes an important metric, mainly in respect to coastal structures. Beyond flood protection, coastal structures are critical to protect water supply from inland saltwater intrusion and increasing vulnerability at coastal wellfields.

There are several options to display these observations, including the monthly/daily tailwater long-term time series plots, with the associated trend line, as illustrated in **Figures 24** and **25** for the S27 and S22 structures, respectively. Other data visualization alternatives to be evaluated during project implementation are the total number or percentage of hours that each coastal structure is closed as a result of high tailwater elevations, as well as the number of occurrences over an established threshold value at each structure, considering the structures operation schedule.

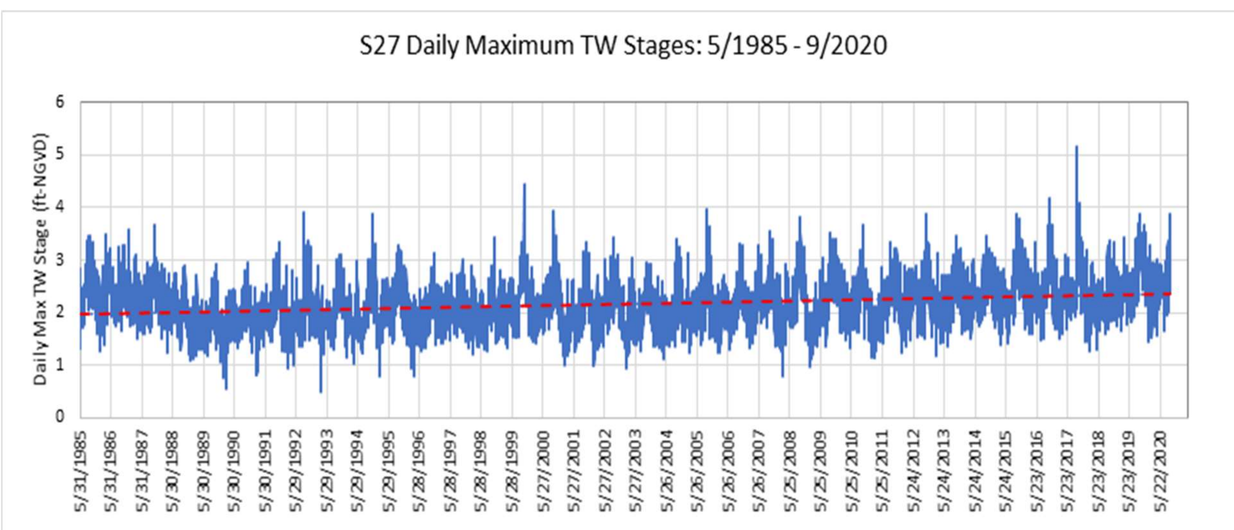


Figure 24. Daily maximum tailwater stages upward trend at the S27 coastal structure in Miami Dade

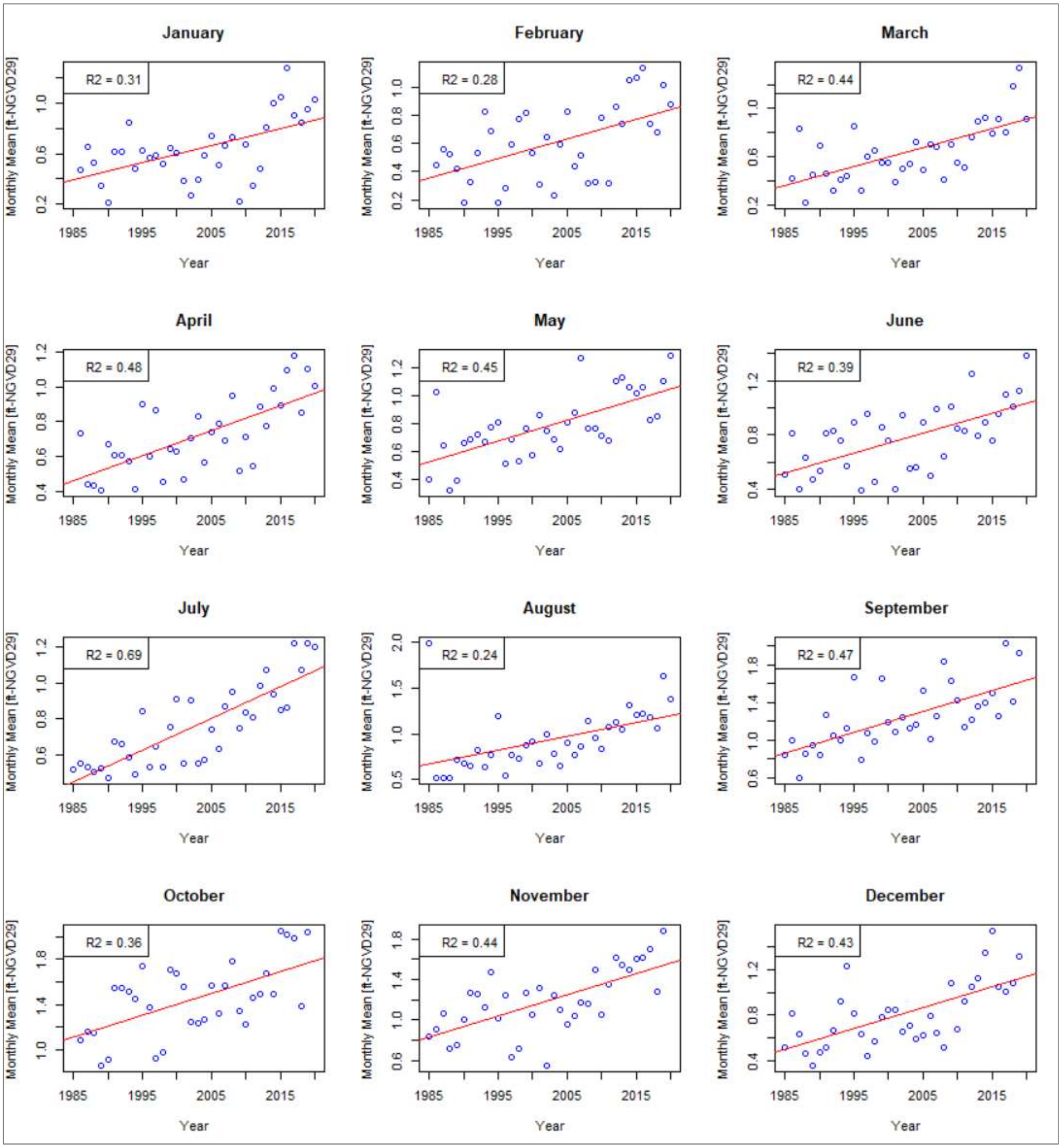


Figure 25. Monthly mean tailwater stages showing upward trend at the S22 coastal structure in Miami Dade.

Tidal Stages and High Tide Events

Tidal stages are a traditional metric used by several agencies to assess sea level rise. The occurrence of tidal stages exceeding predetermined design standards is becoming more intense and frequent. This is an indication that flood risk, risk of saltwater intrusion impacts to drinking water and aquifers, and risk of impact to restoration efforts will also increase. **Figure 26** illustrates the monthly average mean sea level at NOAA's Key West tidal monitoring station.

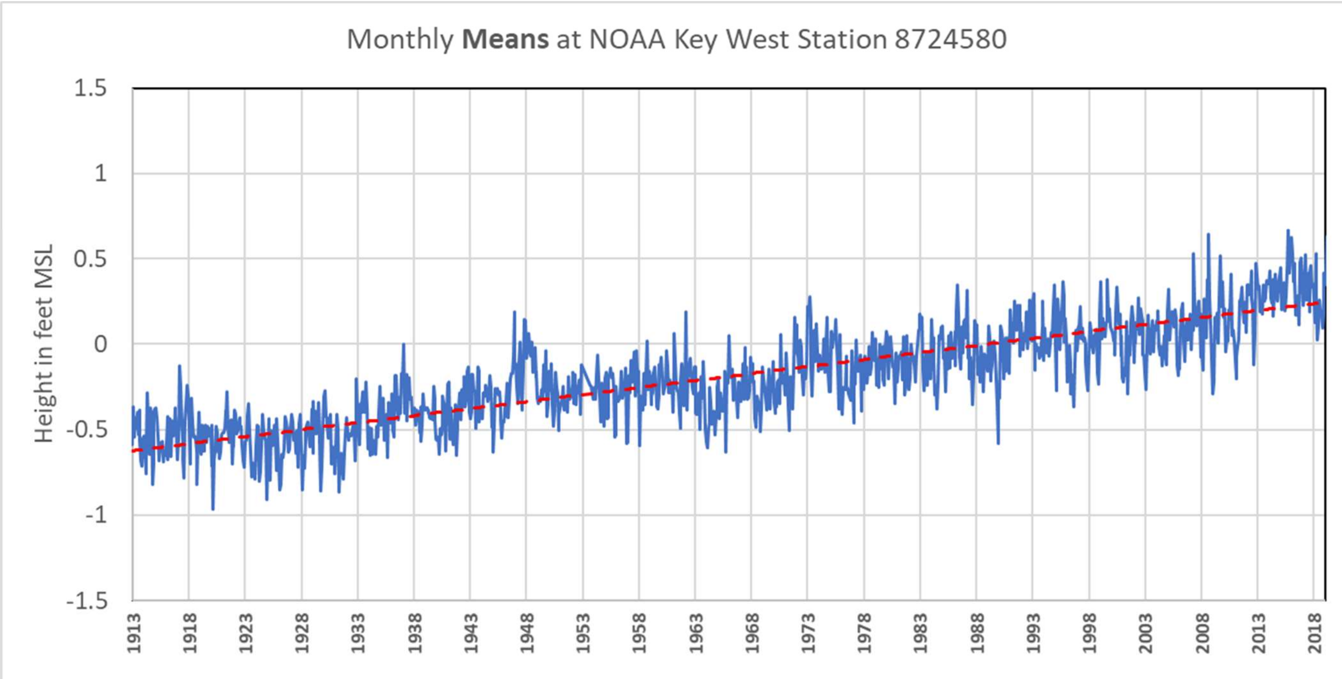


Figure 26. Monthly average mean sea level upward trend at NOAA's Key West monitoring station.

Seasonal variation of sea level occurs due to seasonal oceanographic and atmospheric processes such as fluctuations in coastal ocean temperature, salinity, winds, atmospheric pressure, and ocean currents (Southeast Florida Regional Climate Change Compact. 2020). High tide events represent extreme values of the tidal stage analysis. High tide levels above tidal stage thresholds, also associated with storm surge, typically will increase the risk of saltwater reaching farther inland, especially where not blocked by coastal structures. Where structures are at low elevations, there is an increased risk of structure overtopping. Similar to the previous metric, the magnitude of a high tide and duration over a particular stage is indicative of increasing flood hazard and risk to water supply and restoration projects.

Exceptionally high tides, commonly known as king tides, can result in "sunny day" or nuisance flooding events in low-lying coastal areas. These higher than normal tidal elevations occur due to increasing gravitational pull of the moon, typically during the fall, with the peak elevations usually occurring in October. Twice a day, the higher tidal elevations during these events can cause ocean water to backflow through drainage pipes, flow over seawalls and coastal structures, or even seep up through the ground due to the higher water pressure. These flooding conditions can last for hours, resulting in significant damage to critical infrastructure and property, especially when subject to corrosion from the saltwater. Higher tides can be particularly dangerous and lead to significantly flooding if an extreme rainfall event storm surge occurs during the same time, limiting the discharge capacity of coastal structures.

Figure 27 illustrates the 23-year time series of maximum daily sea levels at another NOAA station – Virginia Key. High tide events are shown in burgundy, along with the total number of events to the right of each year plot. This figure exemplifies an alternative graphic format to communicate the increase in the number of higher tide events above an established threshold.

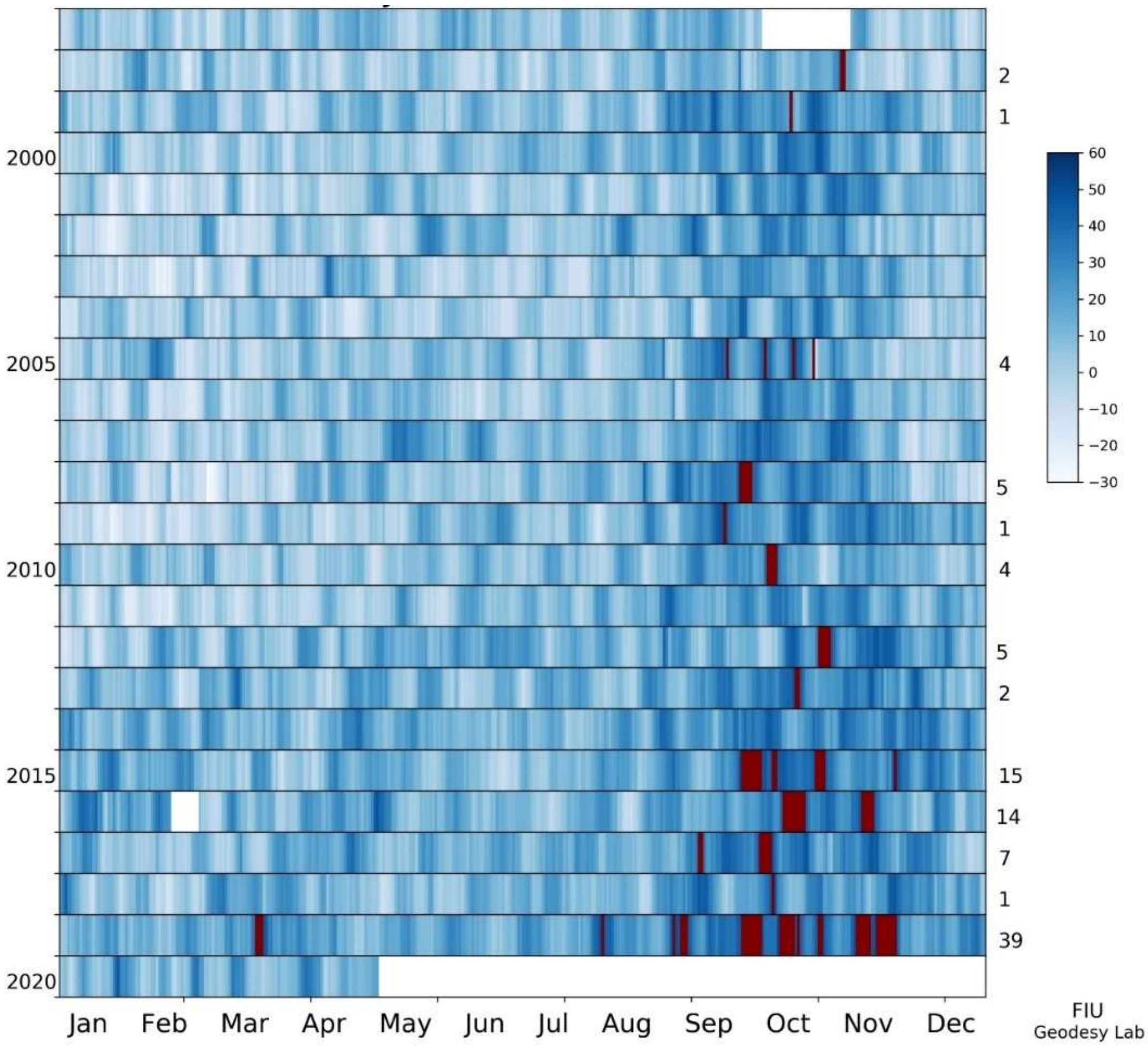


Figure 27. Maximum daily sea level, in centimeters North American Vertical Datum of 1988, at NOAA's Virginia Key tidal monitoring station (From: Florida International University Geodesy Lab 2020).

Groundwater Levels

Groundwater monitoring programs guide operations, provide early warning of threats to water supply, protect existing users and natural systems, and provide data for regional surface water and groundwater models as well as permitting reviews. Groundwater and surface water level data are used to establish MFL criteria and to monitor compliance with those criteria to protect natural systems. Average wet season groundwater levels are used to determine soil storage capacity as part of stormwater permitting, and dry season groundwater levels are monitored for potential impacts on water availability, existing users, and wetlands in water use permitting reviews. Groundwater levels at key sites are evaluated weekly as indicators of potential water shortages.

Monitoring data are collected by state and federal agencies as well as private entities, primarily permittees. For example, **Figure 28** identifies shallow groundwater monitoring within the Lower East Coast Planning Area. Data collected by the SFWMD and Everglades National Park are available from DBHYDRO; data collected by water use permittees is stored in the District's Regulatory database; and data collected by the USGS are available from the National Water Information System Mapper[13] online tool, with many stations' data also copied to DBHYDRO.

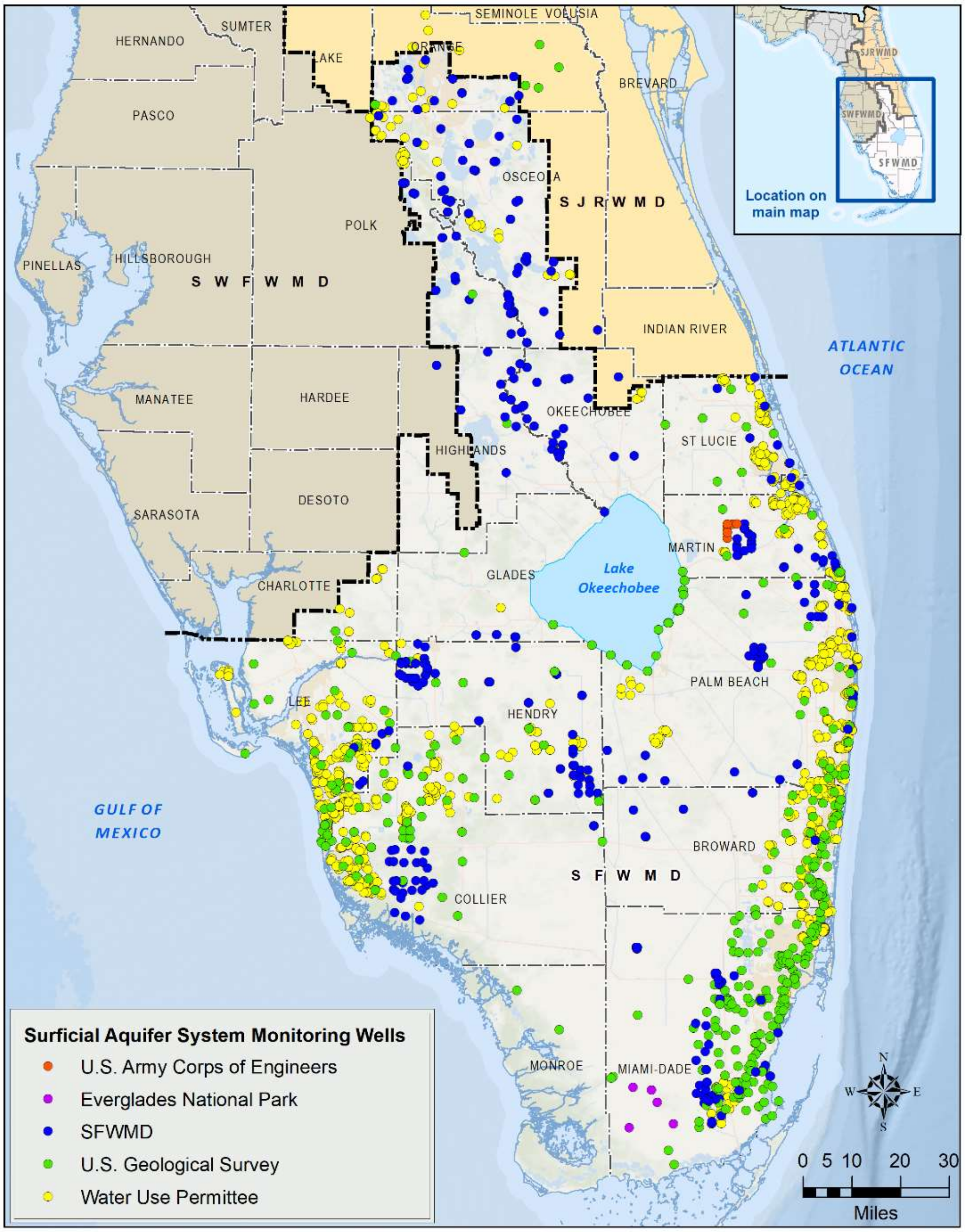


Figure 28. Surficial aquifer system monitoring well locations in SFWMD and monitoring entity.

Increasing groundwater stages are being observed as a result of sea level rise, especially at coastal monitor wells, as well as at several inland locations. Data are collected at different times and frequencies, and there is a need to determine appropriate trend analysis (see section on Data and Trend Analysis below). Increasing groundwater levels at the coast as a result of sea level rise reduce the freshwater head gradient from inland areas towards the coast, which could exacerbate saltwater intrusion.

Figure 29 shows a comparison of groundwater stage time series at wells from coastal to inland locations and associated changes in water level gradient. The trendlines were calculated using the linear least squares method. This example demonstrates increasing groundwater stages near the coast as a result of sea level rise and provides information on the extent of inland effects. In the late 1980s, four wells (the upper trend lines) had water levels highest inland and declining towards the coast, indicating a seaward gradient. That has gradually shifted, and the gradient is now opposite, with water levels higher at the coast than inland. This is expected with sea level rise because denser saltwater pushes up the overlying fresh water along the coast. The overall trend in all four wells is an increase in water levels, with the well closest to the coast (F-291) showing the largest increase. c The sea level has increased about half a foot, measured south of the wells at the downstream side of the S-29 water control structure. The establishment of numerous straight-line, perpendicular-to-coast, shallow (or depth-nested) monitoring well transects is recommended.

A District-wide analysis will support assessment of sea level rise impacts, the timing and extent of such impacts, additional monitoring needs, and the increased flooding potential as a result of reduced soil storage. Alternative data visualization options include the number of peaks over an established threshold to demonstrate increasing frequency of higher groundwater stages, and the mapping of the shift in the wet season average groundwater level over the past 20 years.

Saltwater Intrusion – Chloride Levels

The District is actively monitoring and mapping the location of the underground saltwater interface within freshwater aquifers. Completed every 5 years (**Figure 30**), the mapping effort identifies any movement of saltwater inland, which can put water supply at risk. Increasing chloride levels can impact water supply operations and have large implications on ecosystems. The District periodically conducts groundwater chloride sampling, contracts with the USGS for additional sampling, and analyzes data submitted by water use permittees to produce saltwater interface maps throughout most of the District's coastal areas. Data are available for long-term chloride concentrations in monitor wells in different aquifer systems.

In addition to mapping movement of the saltwater interface, the saltwater intrusion metric can be represented by the percent increase change of inland territorial extent or time series chloride concentration data showing upward trends, as illustrated in **Figure 31**, at USGS monitor well G-3949. This figure was obtained through the USGS Water Level and Salinity Analysis Mapper online tool, as illustrated in **Figure 32**, displaying trends over the past 5 years, chloride concentrations, and the approximate inland extent of saltwater intrusion. In addition to chloride data from grab sampling, time series electromagnetic-induction log datasets are collected by the USGS from PVC cased monitor wells to evaluate changes in water conductivity throughout an aquifer over time and are used to monitor saltwater intrusion (Valderrama 2017). These datasets can be used monitor changes in water conductivity throughout the full thickness of an aquifer, without the need for long open-interval wells, which have allowed, in some instances, vertical water flow within the well bore that has biased water conductivity profiles. An increase in bulk conductivity (typically greater than 67 millisiemens per meter) represents a change from fresh water to saltwater (**Figure 33**). Note that electromagnetic induction log units are bulk conductivity in millisiemens per meter and field water samples units are specific conductance in microsiemens per centimeter or chloride concentration in milligrams per liter.

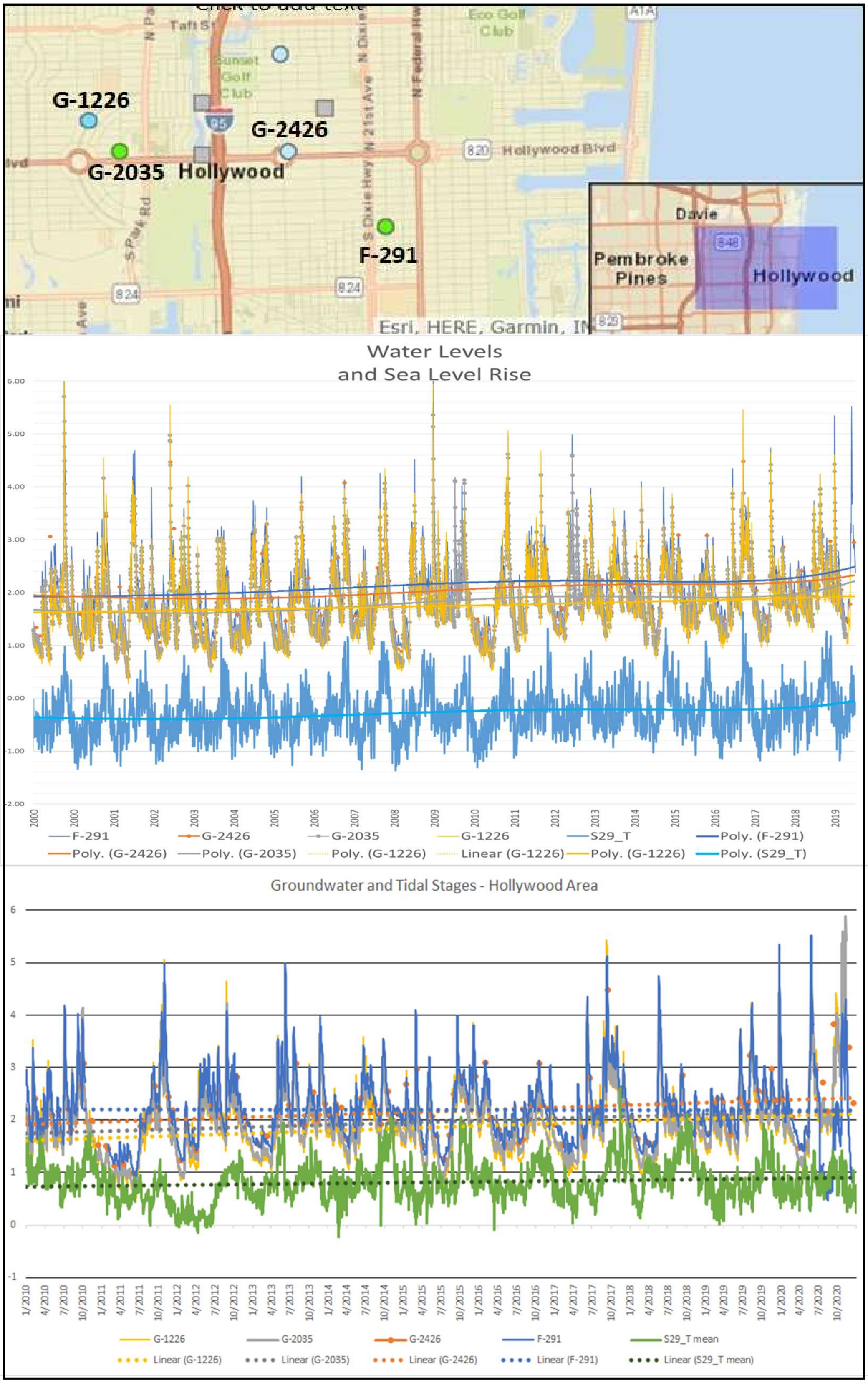


Figure 29. Location and groundwater stage time series at coastal and inland monitor wells and coastal canal structure, showing different upward trends.

Figure 30. Freshwater/saltwater interface mapping in 2009, 2014, and 2019, represented by isochlor lines (most recent lines overlay previous lines, where coincident)

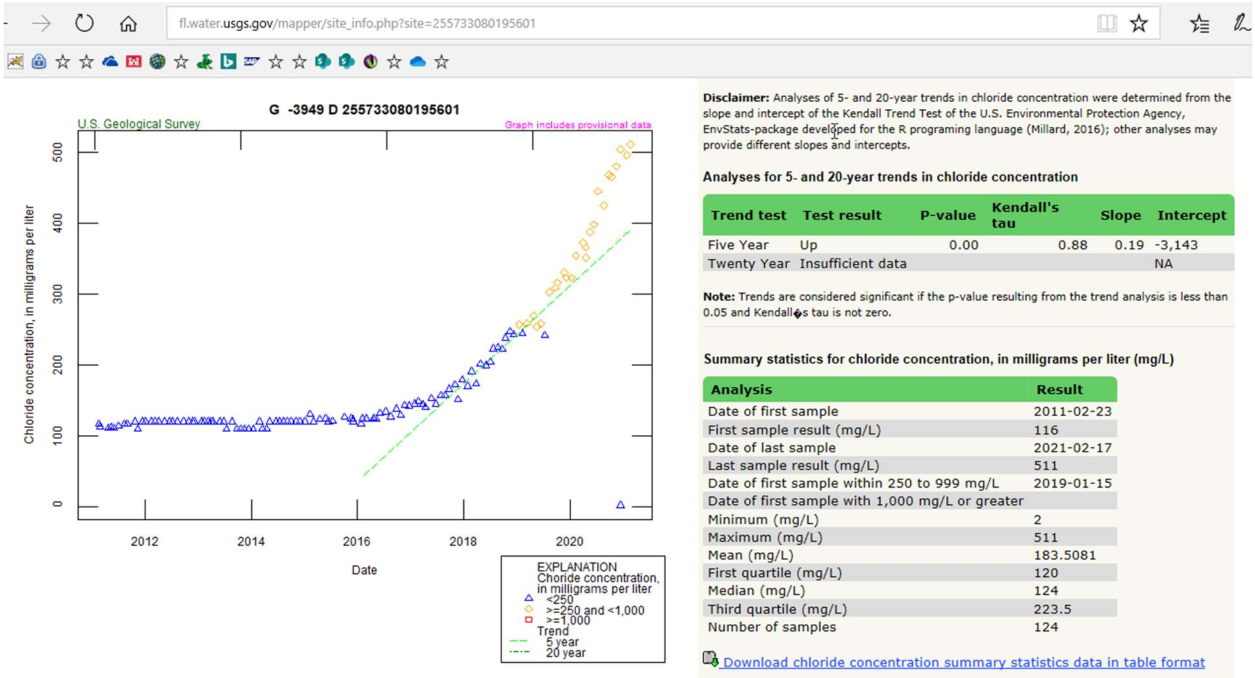


Figure 31. Example of 5-year upward trend in chloride concentrations at the G-3949 monitor well (From: USGS n.d.).

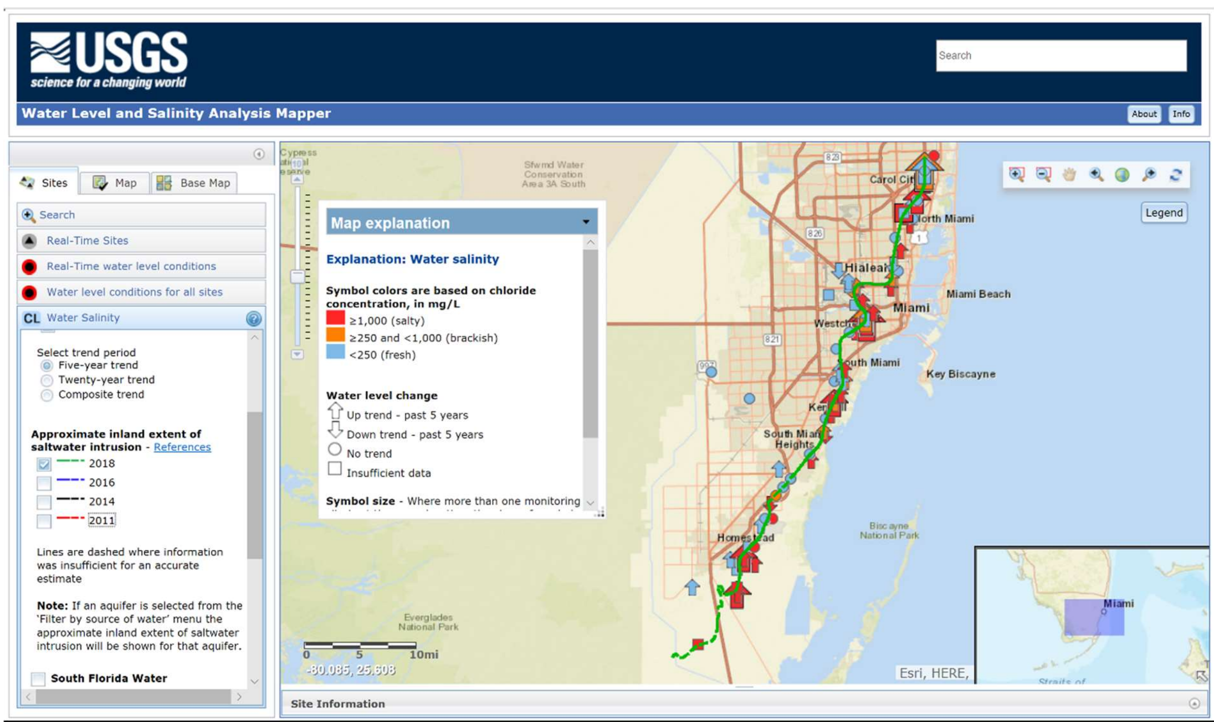


Figure 32. USGS Water Level and Salinity Analysis Mapper, displaying the Miami-Dade 2018 saltwater interface, 5-year observed trends and chloride concentrations (From: USGS n.d.).

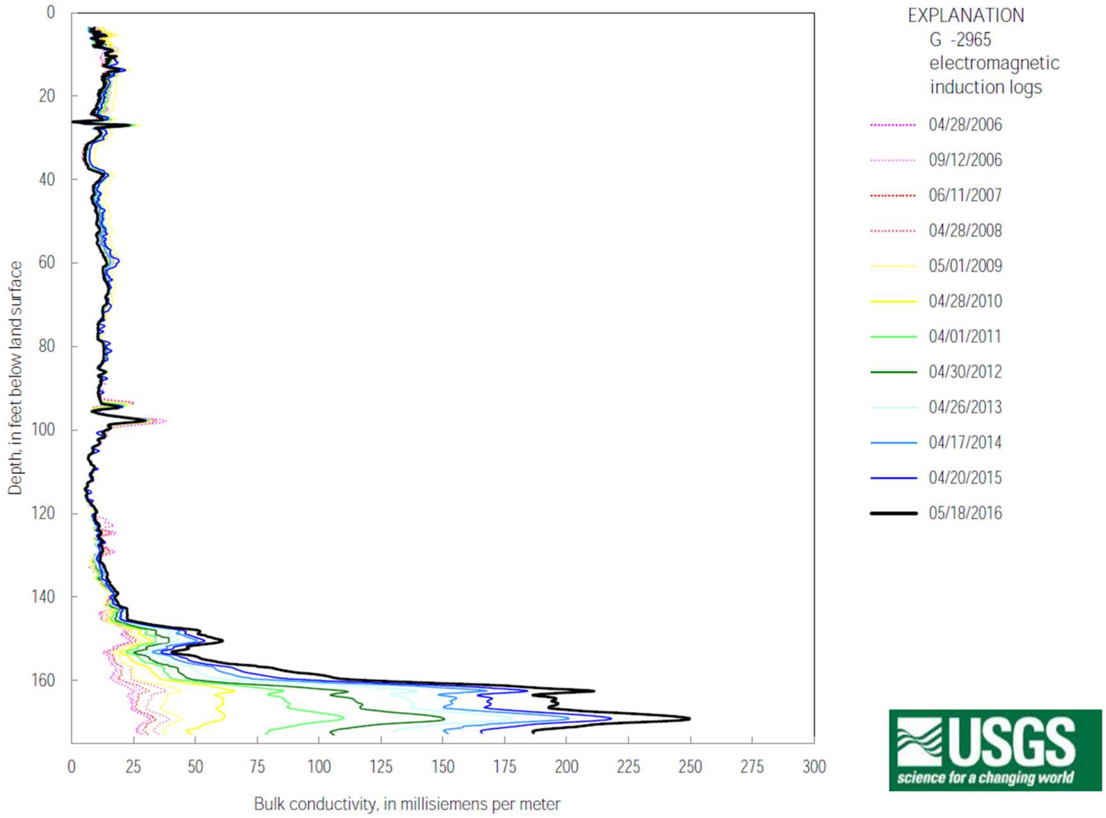


Figure 33. Induction logs for monitor well G-2965 (175 feet deep) in Hallandale, eastern Broward County (From: Valderrama 2017).

Vulnerability Analysis (Backward Looking)

Water use permit records can be used to identify the number of utilities that experienced well loss due to inland movement of saltwater (**Table 2**) based on a defined timeline (past 15 to 20 years). The analysis will include the influencing factors regionally such as: location of wellfield in relation to the salinity control structure, stormwater management/control elevations at the neighborhood canal system, and sea level rise (in association with the changing Gulf Stream current conditions being observed). Local factors including aquifer characteristics, well depths and pumping rates also inform the analysis. Conclusions about reactive versus proactive actions from utilities could be relevant.

Table 2. Public water supply wells abandoned due to saltwater intrusion since 2000.

Utility Wellfield	# of Wells Abandoned
Deerfield Beach Public Water Supply	2
Dania Beach Public Water Supply	1
Broward County 3A/3B Wellfields	9
Broward County 2A Wellfield	3
Lake Worth Utilities – East Wells	7
Manalapan Public Water Supply	3

Vulnerability Analysis (Forward Looking)

The District identifies public water supply utilities with water supply sources near the saltwater interface that could be vulnerable to saltwater intrusion or reduced availability during severe drought conditions. Considerations include whether the utility has wellfields near a saltwater source (e.g., ocean, relict seawater, hypersaline plume), the availability of other water sources (e.g., inland wellfield, alternative water supply sources, interconnects with other utilities), and the ability of alternative water supply sources to meet demands. Utilities with wellfields near the saltwater interface that do not have an inland wellfield, have not developed alternative water supply sources, and/or have limited ability during a drought to meet user needs through interconnects with other utilities are considered more vulnerable. Some utilities that have a surficial aquifer system wellfield near the saltwater interface have access to other water sources during drought conditions. These are considered vulnerable utilities due to the potential for loss of sufficient capacity to meet demands (**Table 3**).

Table 3. Number of utilities vulnerable to saltwater intrusion, by water supply planning region.

Water Supply Planning Region	Utilities Identified in Most Recent Water Supply Plan		
	Total Utilities	More Vulnerable Utilities	Vulnerable Utilities
Lower East Coast	52	6	8
Lower West Coast	22	0	4
Upper East Coast	17	0	4

Minimum Flows and Minimum Water Levels – Exceedances/Violations

This metric represents shifts in determining if a water body is meeting its MFL, and the need to develop a recovery or prevention strategy, supported by the observed number of exceedances and violations. For the Biscayne aquifer (**Figure 34**) MFL, exceedances occur when canal stages fall below specified levels and become violations if they occur for more than 180 consecutive days. Canal stages upstream of salinity control structures are available through DBHYDRO, as illustrated on **Figure 35**, which also displays MFL violation occurrences at gauge S25-B. Minimum canal operation levels upstream of the salinity control structures, as established in the MFL, are listed in **Table 4**, as well as statistical data for the period of record (POR). Maintaining a groundwater monitor network and conducting research in areas where saltwater is near potable water sources are other prevention strategies.

MFLs are reviewed and updated, and recovery and prevention strategies are described in the District's regional water supply plans. MFLs for the Biscayne aquifer and Lower West Coast aquifers are discussed in the Lower East Coast and Lower West Coast water supply plans, respectively. Maximum Developable Limits for aquifers included in the Lower West Coast aquifers MFL prevention strategy are an associated metric. The District performs weekly analyses during water shortages for key Maximum Developable Limit monitoring stations throughout the Lower West Coast. Further evaluations are needed to ensure the MFL complies over a 20-year planning horizon (required by statute).

In the context of establishing MFL exceedances and violations as a resiliency metric, there is a need to differentiate natural processes that could be associated with climate change from related system operational decisions, which the upstream stage mainly depends on. The analysis of difference between the upstream and downstream stages at each MFL structure is included as part of the Tailwater Elevation at Control Structures metric discussed earlier. These observations show a reduction in the protective head, which impacts saltwater intrusion. Insufficient upstream head already is evident at some southern control structures in Miami-Dade County. The Ghijben-Herzberg theory (Verrjuit 1968) describes the relationship between saltwater and freshwater bodies; it specifically states that the thickness of the freshwater lens is directly related to the elevation of the water table above sea level. In this area, the base of the Biscayne aquifer is about 80 feet below mean sea level, which requires an overlying freshwater head of 2 feet to be preventive. In the four southernmost structures, the 2-foot head is maintained, and the saltwater line is not moving inland. In structures where only 1.7 feet of head are maintained, the saltwater front is moving farther inland.

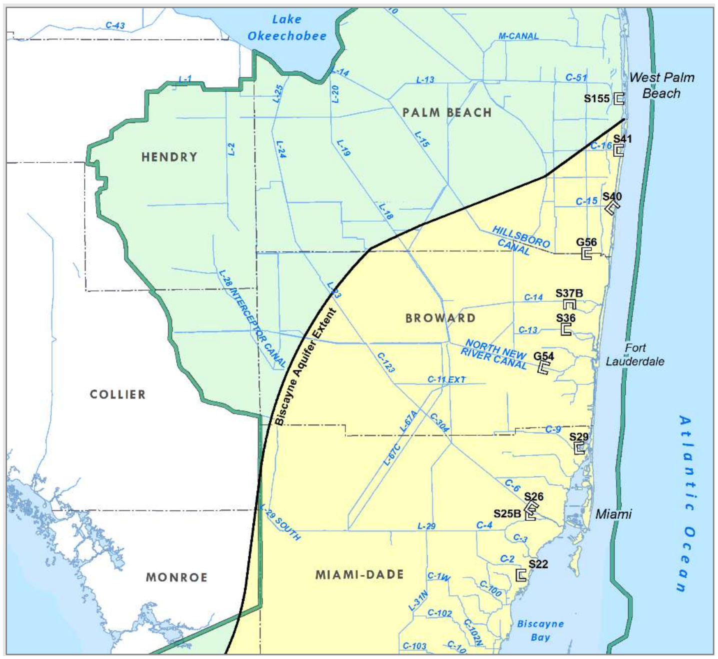


Figure 34. Location of Biscayne aquifer Minimum Flow and Minimum Water Level salinity control structures.

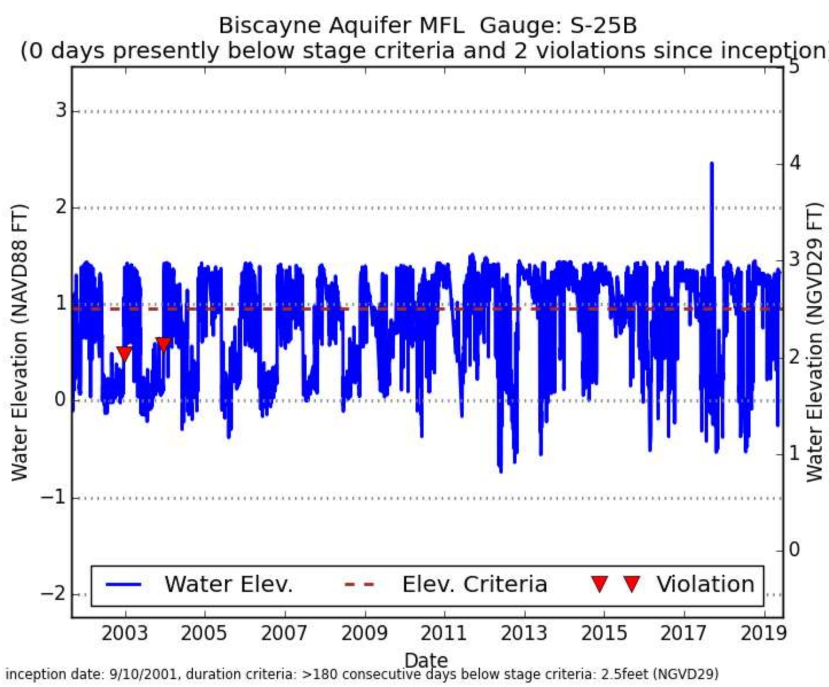


Figure 35. Biscayne aquifer MFL violation occurrences at gauge S-25B.

Table 4. Summary of data for salinity control structures monitored for Biscayne aquifer MFL.

Station	S155_H	S41_H	S40_H	G56_H	S37B_H	S36_H	G54_H	S29_H	S26_H	S25B_H	S22_H
MFL (Ft NGVD)	7.80	7.80	7.80	6.75	6.50	4.00	3.50	2.00	2.50	2.50	2.50
Total days below MFL*	1,321	1,312	2,679	2,332	2,258	1,758	2,059	3,524	5,538	6,633	3,001
% of days below MFL	10%	10%	21%	18%	18%	14%	16%	28%	44%	53%	24%
Days beyond 180 (POR)	0	0	0	0	0	0	0	0	34	101	12
# of Events > 180 days	0	0	0	0	0	0	0	0	2	4	1
Average annual WL	8.19	8.10	8.00	7.23	6.81	4.37	3.98	2.10	2.35	2.35	2.77
Average Wet WL**	8.18	8.14	8.02	6.98	6.72	4.26	4.03	1.97	2.22	2.17	2.69
Average Dry WL**	8.20	8.09	7.98	7.39	6.87	4.44	3.94	2.19	2.43	2.47	2.82
*POR 5/1985 to 12/2019 12,633 days			**Wet Season: June - Oct Dry Season: Nov - May								

Flooding Events

The District has an internal editable web map and a viewable web map created in June 2017 (**Figure 36**) to track and report major flooding events, usually associated with hurricane and tropical storm events. The tool was tailored to assist in transferring flood occurrence information, compiled from email and phone calls reported from the community, to the application for immediate needs. The Citizens Information Line, designed to receive calls from the public, was deactivated in 2017.

A crowdsourcing tool is proposed to replace the system put in place 2017 with the intent of streamlining the collection of reports, standardizing the reported information, providing a means to submit digital images, and centralizing information in a repository for long-term maintenance and evaluation. Crowd sourcing applications require an outreach and communications strategy and should be targeted based on the intended use of the collected information. The intent of this data collection is to obtain pictures and information about local flooding that can be used to supplement quantitative data and validate model results. Although our gauge network is vast, it does not provide measurements for all areas across South Florida. Where quantitative measurements are available, water surfaces can be interpolated and used in combination with high resolution elevation data to estimate flood extent and depth. Where those quantitative data do not exist, crowd sourced depth estimates can be used to do the same. If captured during an event, pattern analysis of such estimates can be used to deploy reconnaissance teams to collect more precise measurements. In pursuing a crowd sources application to assist in data collection, decisions need to be made about audience and quality review of collected information. Should the audience be the general public or local municipalities and water control districts? Who should review and validate reports? How should collected data be managed? SFWMD will need to address these questions as part of their implementation strategy. The intent is to provide a systematic data collection strategy to supplement and improve existing data acquisition methods.

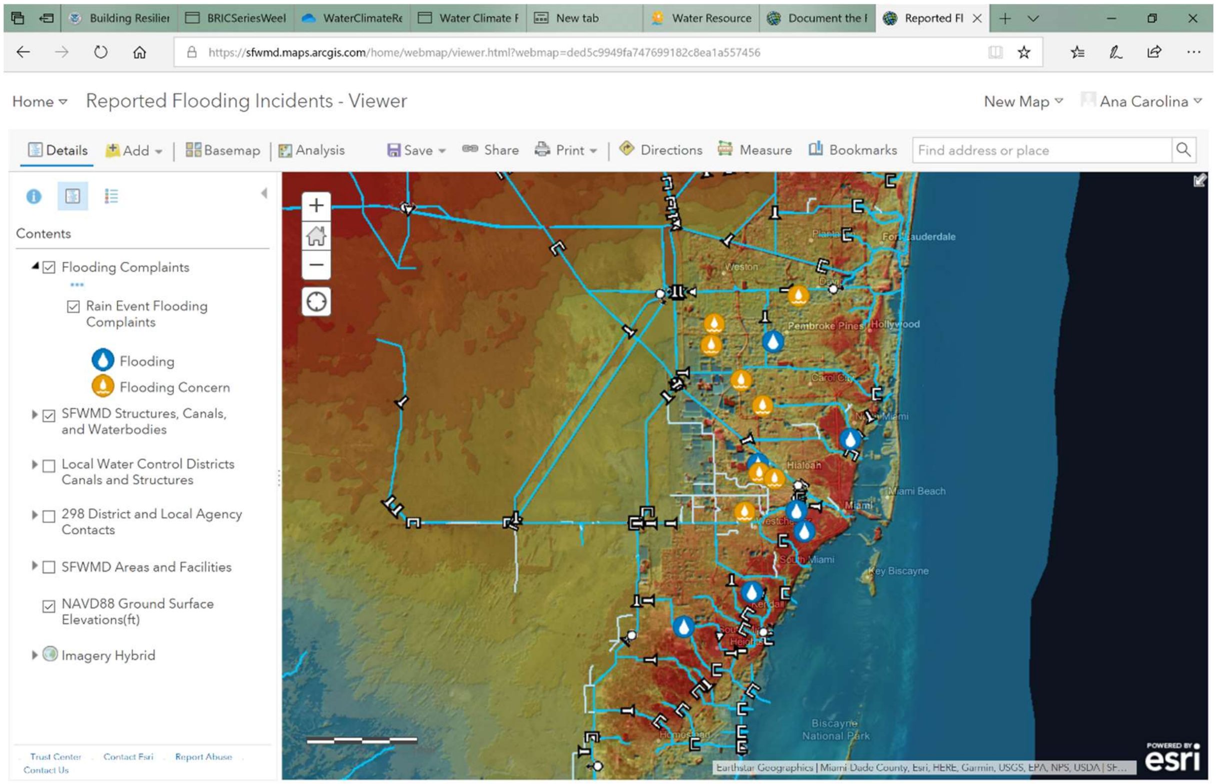


Figure 36. Reported flooding incidents viewer.

In addition to public flood reports, the District prepares post-storm reports that document storm characteristics and impacts. The format is not standardized and the data collection is not systematic and may only focus on particular areas of interest. The primary purpose is to brief the organization on the event and the state of the water management system and operations. Reports are not compiled for all major events. Some of these reports can be found in the District's technical report archive but these information are not comprehensive or in a format that can be used to systematically evaluate flood occurrence. Other storm reporting and documentation are available across district business units. This information should be collected and consolidated into a single document repository and standard reporting procedures should be implemented. The Areas of Interest layer in the District's Emergency Management web layer (**Figure 37**) was compiled to highlight areas that consistently reported flooding. These were identified by District subject matter experts and supported by diagnostic modeling work. The layer originally was developed for -remote sensing application, and the plan included having a geographic information systems (GIS) Emergency Operations Center team member available to determine areas likely to be impacted by given a storm track, rainfall forecasts, and trigger monitoring conditions, including radar/satellite data acquisition, high-water marks collection, and other requested information about ground conditions. Partner agencies have additional information, such as the Federal Emergency Management Agency (FEMA) flood claims database and the USGS high-water marks event-specific database, available for consultation. The District should coordinate with these agencies and the Florida Department of Emergency Management to better integrate available information into reporting and evaluation.

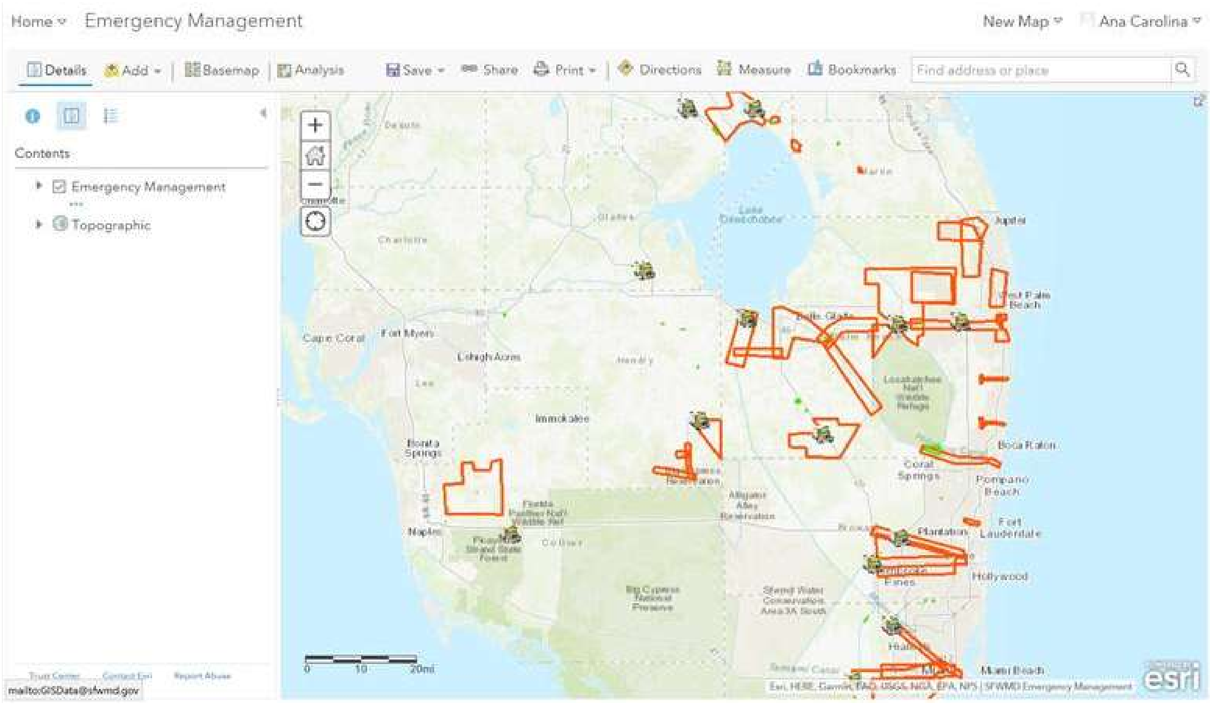


Figure 37. Areas of Interest layer in the Emergency Management web layer, SFWMD

To better assess the pattern, extent, and depth of flooding associated with rainfall events, the District should investigate use of open source remote sensing data and/or subscription services that can be acquired/ activated prior to or during an event. The advantages of such services are their availability, extent of coverage and spectral range. Access to these data over the entire event area will allow for more holistic evaluations of system response including interdependent responses within urban, rural, and natural systems. Pre- and post-event imagery can be used to document and differentiate antecedent conditions from storm related flooding and can be used to correlate rainfall distribution with system response. Landscape is an important factor in flood response and remote sensing data can be used to identify short- and long-term landscape changes. These data can also be used to develop machine-learning models to rapidly and accurately calculate short- and long-term streamflow forecasts.

As part of the Water and Climate Resilience metrics effort, information about flooding occurrences, driven by rainfall or high tides, is an important metric to support prioritization of investments and refinement of flood depth and duration performance metrics, beyond modeling results alone. Formally tracking trends of reported flooding and comparing to other trends, such as rainfall, will help determine if observed changes are part of a long-term trend or represent a shift in climate.

As an initial flood metric, an interactive map will be used to show locations and content related to frequently flooded areas and flood reports. This strategy allows this information to be viewed in association with monitoring and other geospatial sea level rise and climate data. Other information can be incorporated as it becomes available. Content will be configured to support filtering by event and other key attributes. End users have requested the ability to download records by filters and areas of interest. This is more advanced functionality and requirements will need to be further developed prior to implementation.

Rainfall (Average and Wet Extremes)

South Florida has a very flat and low topography and a semi-tropical climate. Based on rainfall amount, the climate is divided into three seasons: dry, transitional, and wet. The 6 months from November through April are considered the dry season, when monthly rainfall is around 2 inches per month. May and October are considered transitional months, when monthly rainfall is approximately 4 inches per month. The remaining 4 months from June through September are considered the wet season, when monthly rainfall is above 7 inches per month (Ali and Abtew 1999). Long-term averages indicate South Florida has an annual rainfall of 52 to 53 inches, and three-quarters of it occurs in the wet season and transitional months. Spatial variability of rainfall is large and highly influenced by the oceans surrounding the peninsula and the large lakes within. Typically, sea breezes from both coasts over the hot land surface form convective storms inland. In addition, tropical storms and hurricanes often bring heavy rainfall to the region (Pathak 2001). The southeastern coast (Palm Beach, Broward, and Miami-Dade counties) receives the highest annual rainfall, whereas the Lower Kissimmee Basin and Lake Okeechobee receive the lowest amount of rainfall. The southwestern coast (Collier County) has a unique rainfall pattern, receiving the highest amount of rain in the District during the wet season and the lowest amount of rain during the dry season (Pathak 2001).

Changes in rainfall pattern could impact stormwater volumes and the amount of available fresh water, potentially causing more frequent flooding events or prolonged periods of drought. Natural climate variability in Florida is partially a result of climate oscillations at global scales. Rainfall changes could be cyclical and affected by the variability of continental climatic phenomena over decades, such as the Atlantic Multidecadal Oscillation, the Pacific Decadal Oscillation, and the El-Niño Southern Oscillation (Obeysekera et al. 2011). Due to the varied connections to Florida climate and weather, identifying trends in rainfall observations involves a series of complex analyses.

Regional trend analysis was performed using District model input rainfall data, based on the District gauge network rainfall data sets nearest to each of the District's two-by-two model grid cells, and summarized by the District's existing fourteen operations and maintenance rainfall basins (Ali et al. ,2006), as shown in **Figure 46**.

Long-term rainfall data is available beginning as early as 1985. Although rainfall data in the early period of record has undergone extensive quality assurance and quality control analysis, data gaps exist. To ensure consistent rainfall estimates in the region, data gaps in the period of record are often interpolated using available data across the spatial domain or adjusted using Areal Reduction Factors (ARF). Filling data gaps is essential to ensure continuous records; however, it is rarely done for rainfall data because it assumes a homogeneously reliable data set early in the period of record and yield a high degree of uncertainty. Additionally, these data gaps often exist during periods when rainfall monitoring systems changed. Overtime, rainfall monitoring moved away from the use of rainfall gates to rainfall gauges, and the number of deployed and active monitoring stations also grew. Early in the period of record, the location and quantity of data available may not accurately represent rainfall in a spatial context.

To ensure a sufficiently large and reliable data set, long-term rainfall data collected between January 1935 and December 2018 were analyzed for the trend analyses, as described below. Three types of trend analyses were performed: 1) Monthly, seasonal and annual analysis to check for a trend of average rainfall volume over longer durations, 2) one, three and 5 day rainfall maxima analysis to check for a trend of rainfall extreme events over shorter durations and 3) Peak Over Threshold analysis to check for trend of the frequency of rainfall events exceeding a determined thresholds. Trend analyses significance tests were performed using Mann-Kendall Tau test with 95% confidence band around the trend slope. A trend is considered significant if a double-sided Z test rejects the null hypothesis that there is no trend. All variables tested are assumed to be independently identically distributed. An introduction about Mann-Kendall was presented in a specific section, above in this report. In this section, we present regional trend analysis to provide an overall characterization of rainfall trend covering all district areas using long term historical data. Additional site-specific analysis is provided in Appendix B.

The results of the monthly, seasonal and annual analysis in this section are illustrated in Figures 47-50. The monthly results exhibit insignificant trend in all months for all rainfall basins, except upward trends observed in the Caloosahatchee, Southwest Coast, Martin-St. Lucie and Big Cypress in August; and downward trend observed in the Upper Kissimmee, Lake Okeechobee and Dade Basins in July. October exhibits a noticeable downward trend in most of all water conservation areas, Broward, Dade, Palm Beach, Martin-St. Lucie, East EAA basins. The wet season results exhibit significant upward trends for the East Caloosahatchee and Southwest Coast basins and a slight downward trend for East EAA basin. The annual results exhibit a slight downward trend for East EAA basin.

In the one-, three- and five-day rainfall maxima trend analysis, Lognormal Distribution was fit for annual 1, 3 and 5-day maxima for the 1935-2018 period of record (Ali et. Al., 2006). Frequency results were obtained for 2, 5, 10, 25, 50 and 100-year return periods. A trend analysis was then performed for each of these frequencies. For the 5-year return period, results are illustrated in Figures 51-53, where insignificant trend is generally observed. In general, results are sensitive to the frequency and type of distribution being fit. The higher the return period the fewer observations and hence higher uncertainty in trend analysis. The daily annual maxima results exhibit significant upward trends for the East Caloosahatchee, Martin-St. Lucie and Upper Kissimmee basins. The 3-day annual maxima results did not exhibit significant trends. The 5-day annual maxima results exhibit significant downward trend for the Broward Basin.

This One-, three-, five-day Peak Over Threshold Analysis (POT) technique is another way to assess trend analysis of extreme values frequency where a subset of the data that exceeds certain threshold is secluded and is modeled using an appropriate distribution. In this study for each of the abovementioned durations, we identify 6 thresholds. Two thresholds correspond to K largest observations considering two formulas [k=sqrt(n), k=n^(2/3)/log(log(n))], while the remaining thresholds are higher values in ½ inch increments. We fit Poisson distribution to the event count exceeding the threshold and we fit Pareto distribution to the event exceedance. In this report, we present the event exceedance results for 5-day duration 2-year return period. Figures 54-59 show trend analysis for thresholds of 3.1", 3.9", 4.0, 4.5, 5.0" and 5.5".

Results show upward trend in the Big Cypress basin for 4.0" and 4.5" thresholds, an upward trend for West Agricultural Area Basin for thresholds of 5" and 5.5", and an upward trend at the SW Coast Basin for 3.9and 4.0" thresholds . These results emphasize the need for continuous rigorous rainfall frequency and trend analysis on daily maxima, daily minima, and peaks over/under thresholds, for selected return frequencies and durations, in the context of resiliency studies. Additional regional threshold trend analysis is needed for the annual maxima 25-, 50- and 100-year return frequencies, as well as a peak over threshold analysis to further support the assessment of extreme wet and extreme dry events. These will be included as part of the next steps of the work currently in progress.

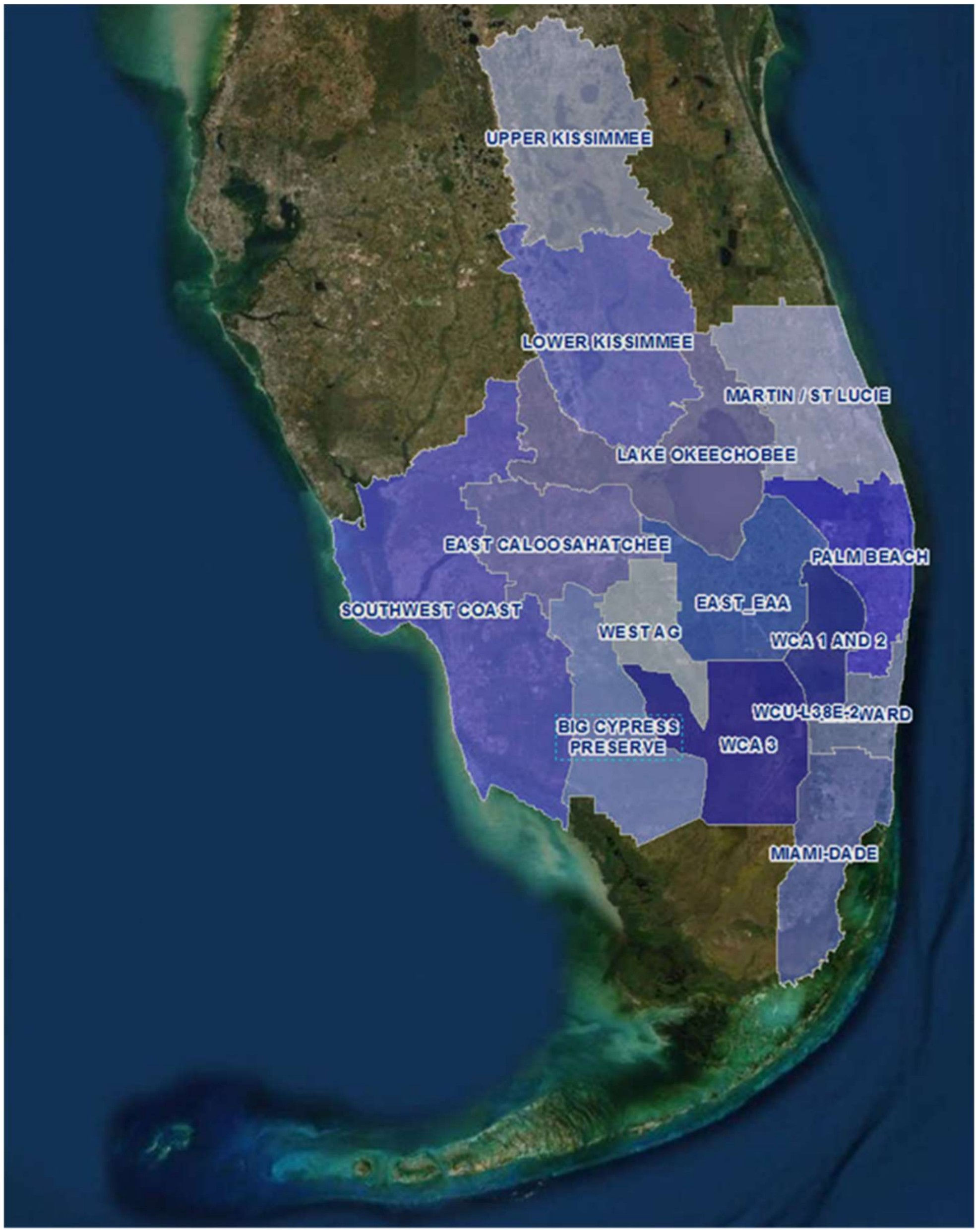


Figure 46: Map of Rainfall Basins adopted in the Rainfall Frequency and Trend Analysis

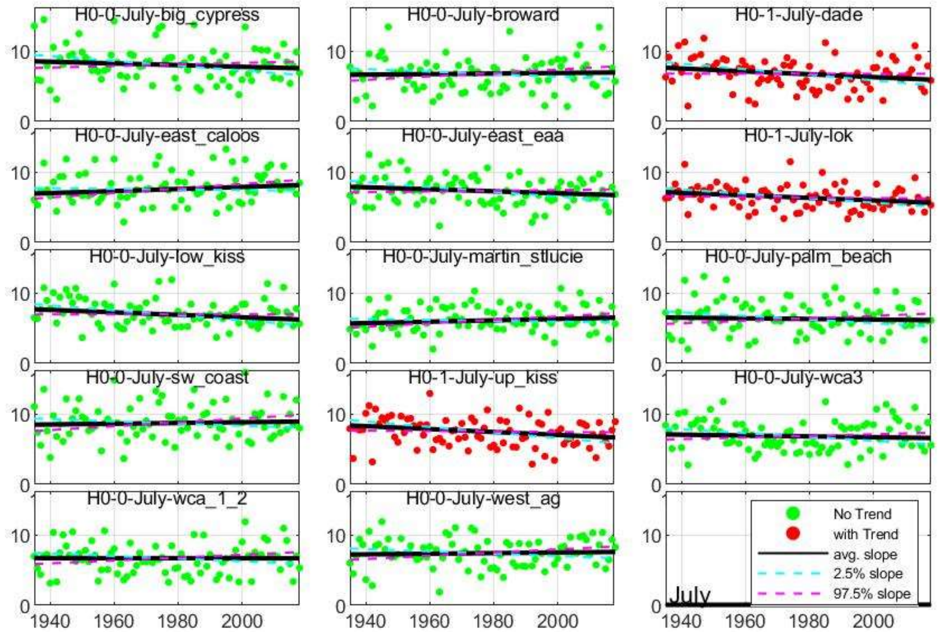


Figure 47: Monthly Rainfall Trend Analysis results for the month of July (1935-2018).

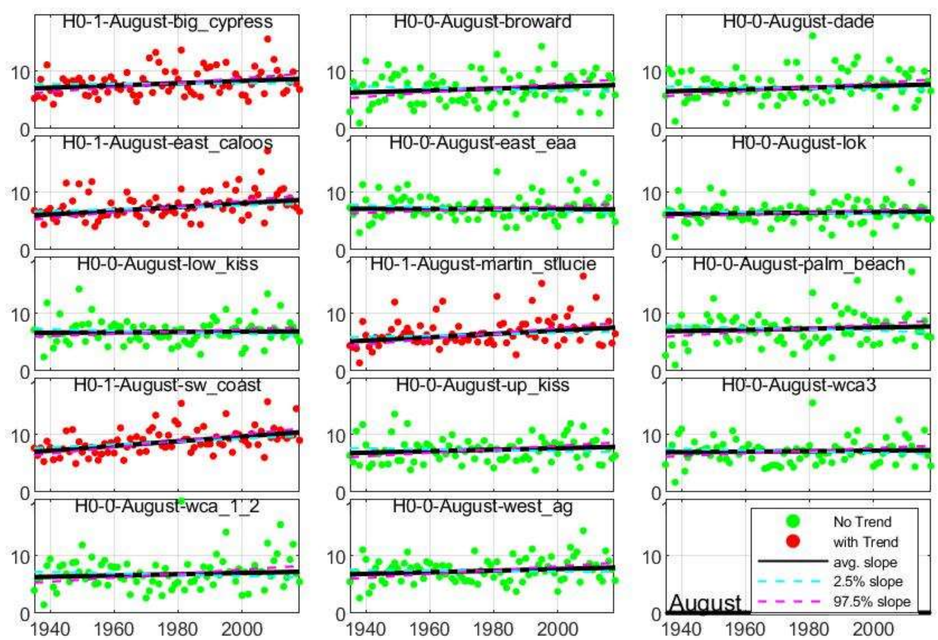


Figure 48: Monthly Rainfall Trend Analysis results for the month of August (1935-2018).

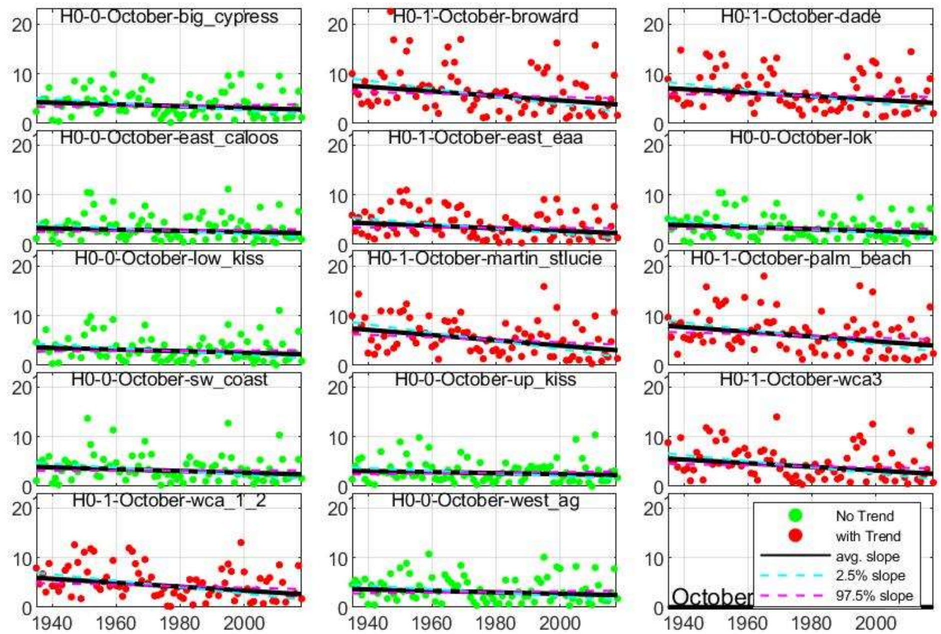


Figure 49: Monthly Rainfall Trend Analysis results for the month of October (1935- 2018).

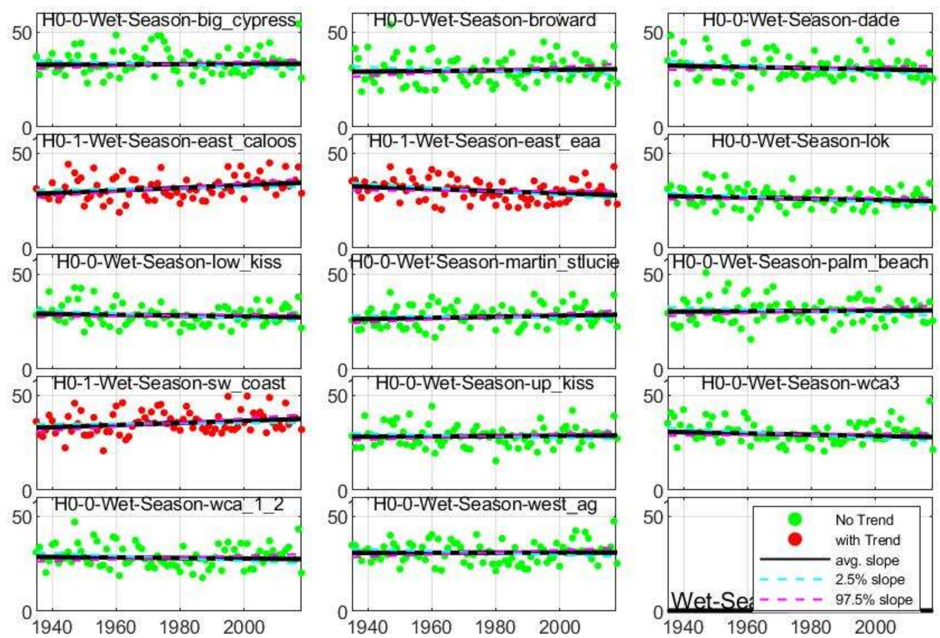


Figure 48: Wet Season Trend Analysis results (1935-2018).

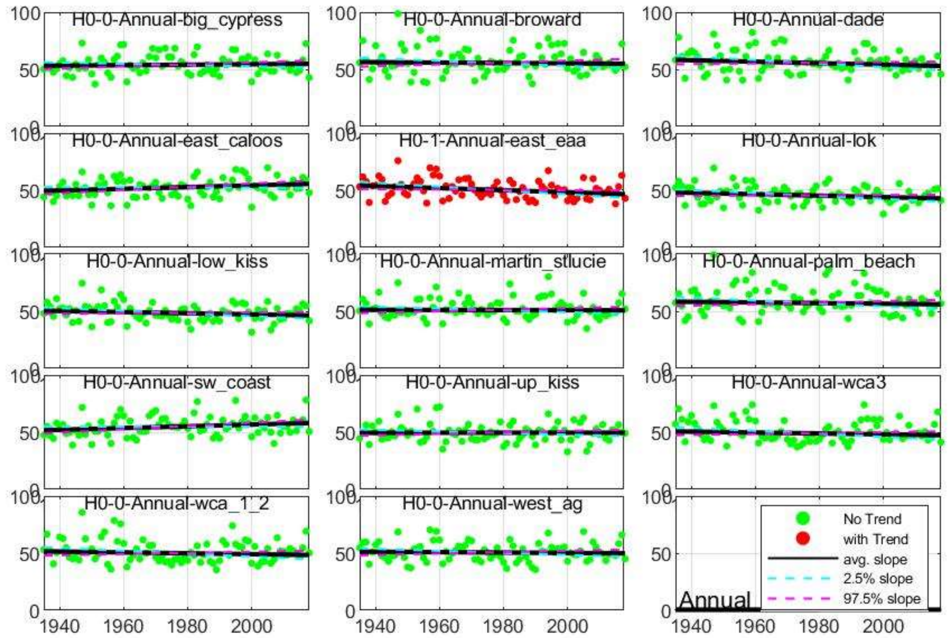


Figure 50: Annual Rainfall Trend Analysis results (1935-2018).

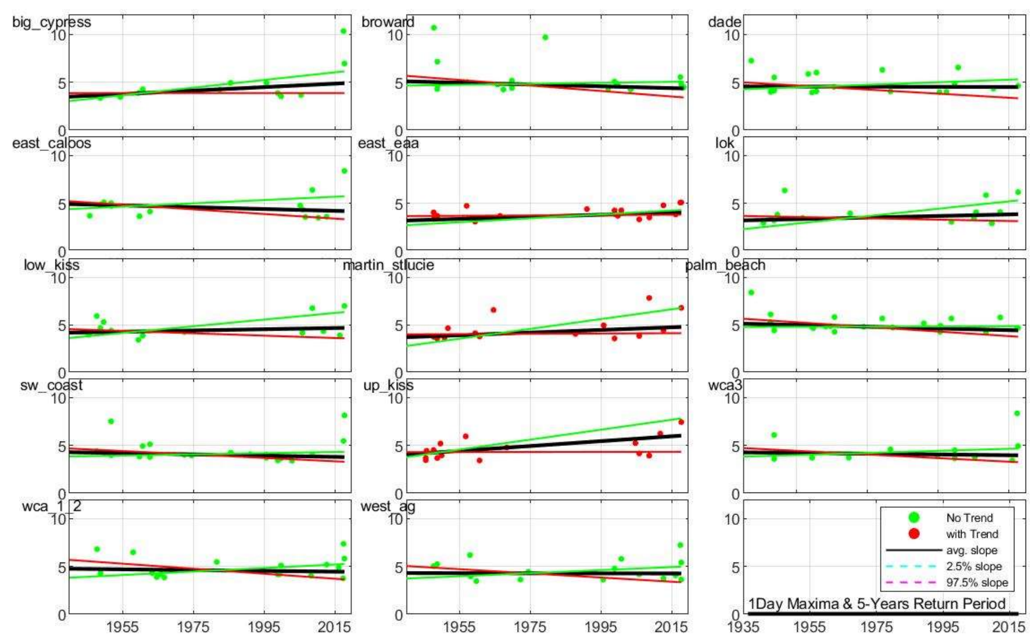


Figure 51: Daily Annual Maxima Rainfall Trend Analysis results for a 5-year return period between 1935-2018.

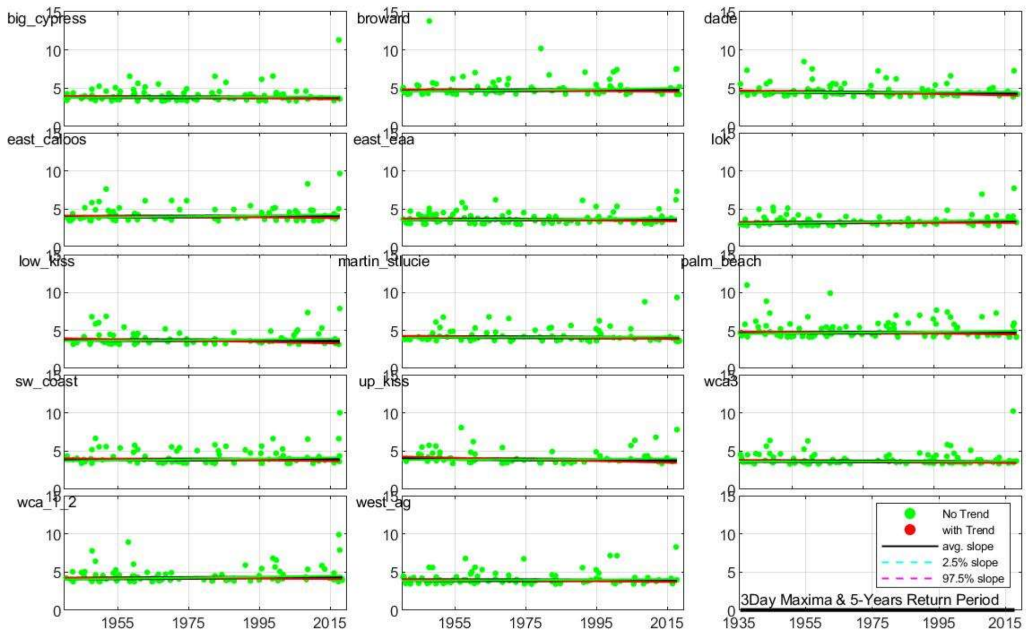


Figure 52: 3-day Annual Maxima Rainfall Trend Analysis results for a 5-year return period between 1935-2018.

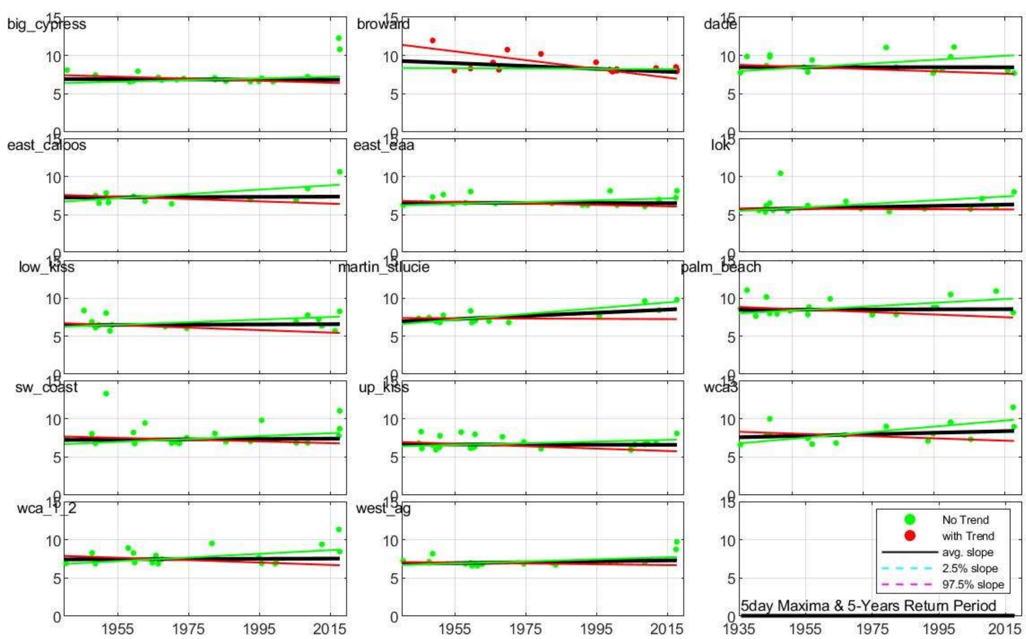


Figure 53: 5-day Annual Maxima Rainfall Trend Analysis Results for a 5-year return period between 1935-2018.

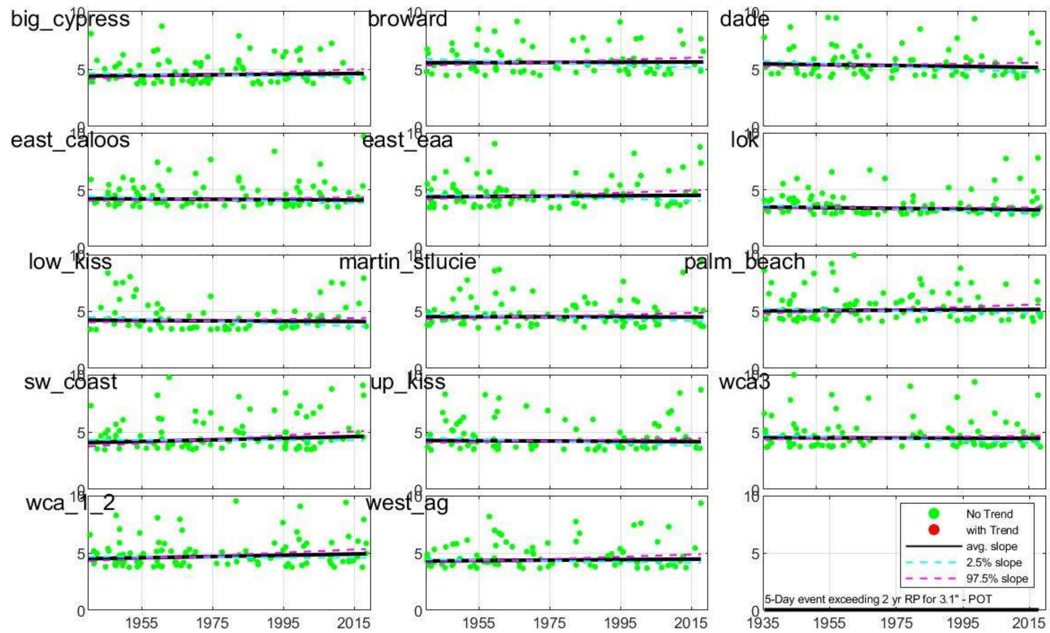


Figure 54: Peak Over Threshold trend analysis results for a 5-day exceeding 3.1 inches of rainfall for a 5-year return period between 1935-2018.

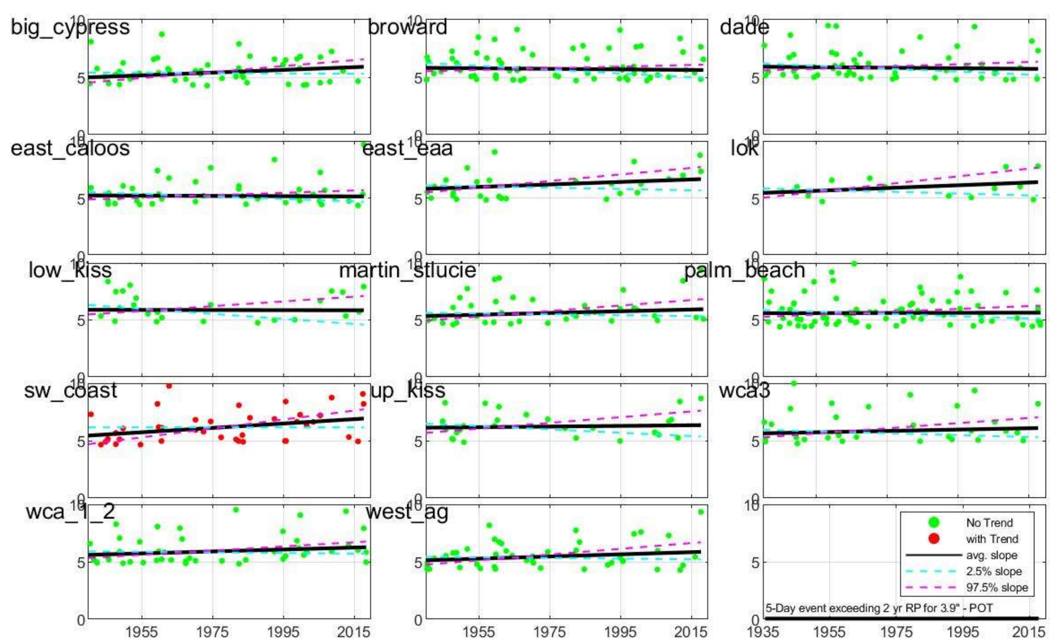


Figure 55: Peak Over Threshold trend analysis results for a 5-day exceeding 3.9 inches of rainfall for a 5-year return period between 1935-2018.

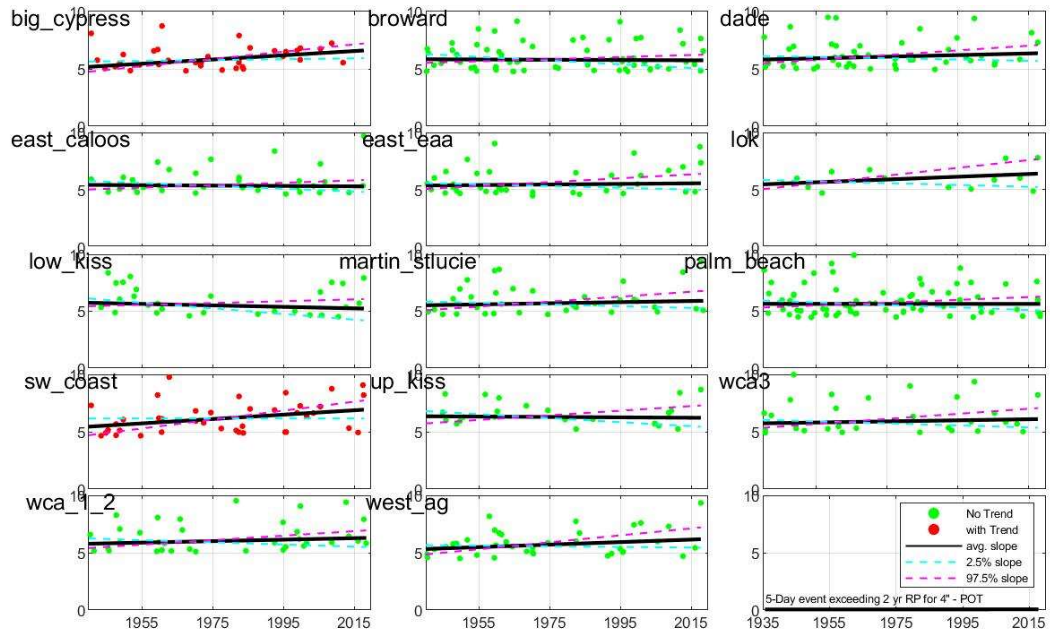


Figure 56: Peak Over Threshold trend analysis results for a 5-day exceeding 4.0 inches of rainfall for a 5-year return period between 1935-2018.

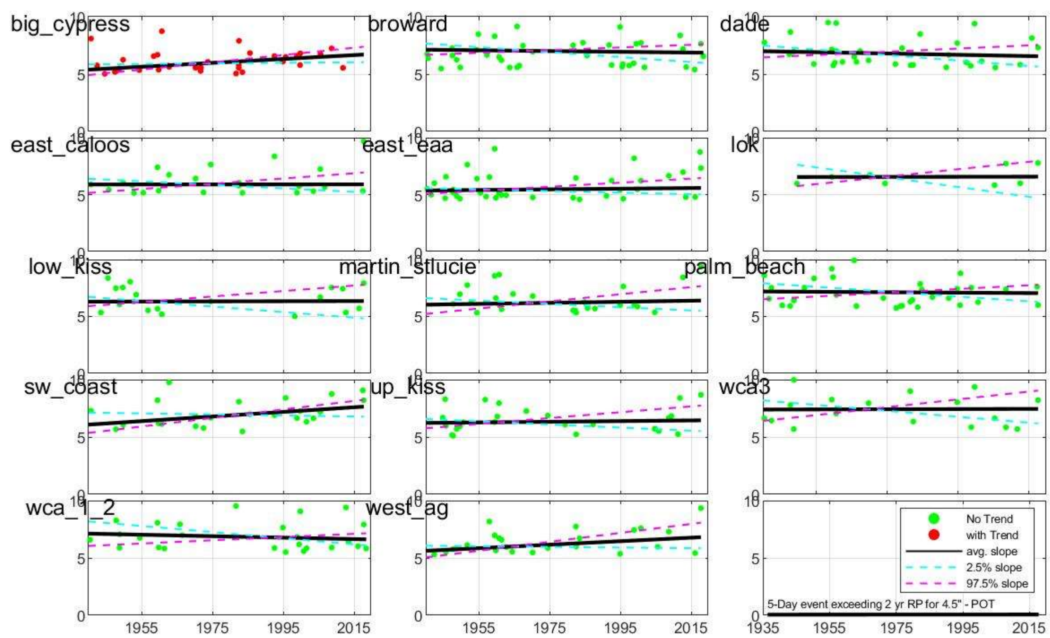


Figure 57: Peak Over Threshold trend analysis results for a 5-day exceeding 4.5 inches of rainfall for a 5-year return period between 1935-2018.

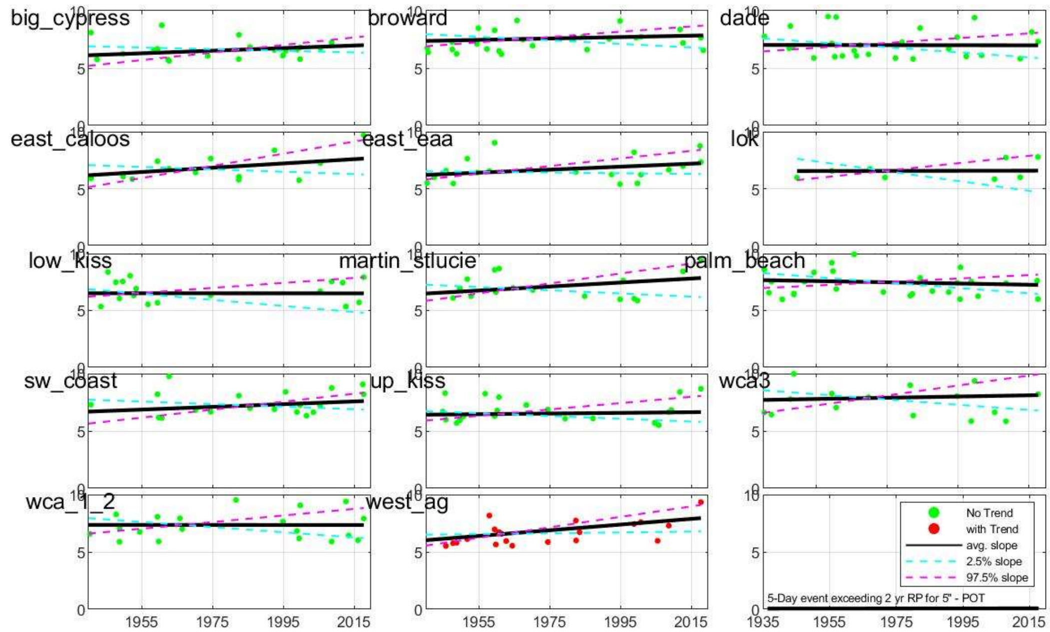


Figure 58: Peak Over Threshold trend analysis results for a 5-day exceeding 5.0 inches of rainfall for a 5-year return period between 1935-2018.

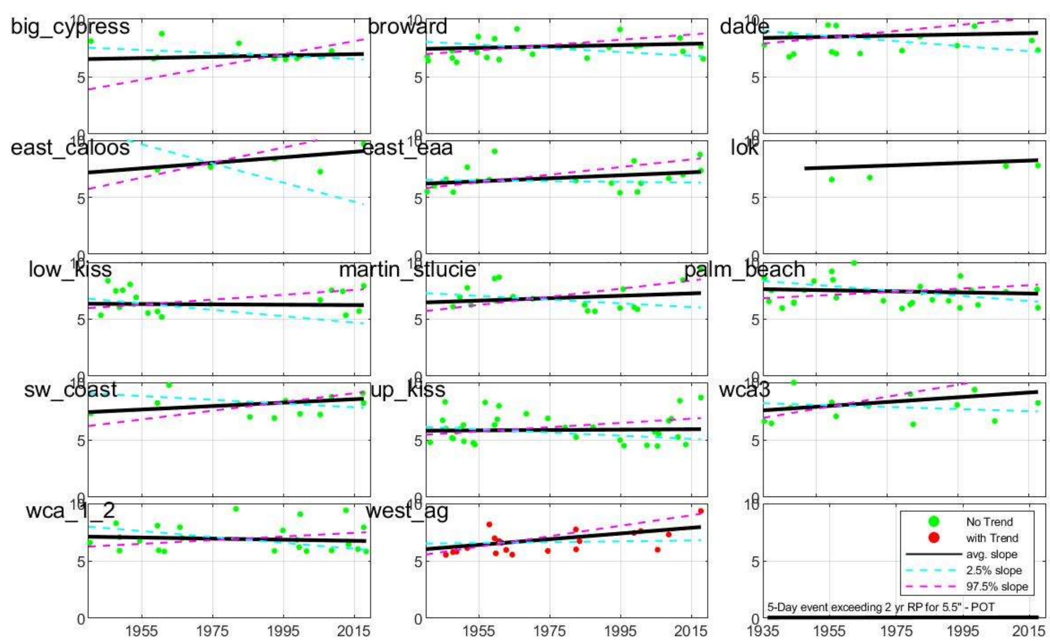


Figure 59: Peak Over Threshold trend analysis results for a 5-day exceeding 5.5 inches of rainfall for a 5-year return period between 1935-2018.

Evapotranspiration

Besides rainfall in South Florida, evapotranspiration (ET) is the other most significant component of the hydrologic cycle and water budget, and it has a magnitude comparable to rainfall (about 70%). Within the conterminous United States, the annual ET is greatest in the Southeast (Hanson, 1991), where Florida is located. ET includes two parts: 1) evaporation from the ground surface, and 2) transpiration from plants (whose root systems absorb water from the soil and release it through leaves). ET rate is mainly affected by solar radiation, along with wind speed, air temperature, and relative humidity, and it represents changes in drought vulnerability. During a drought, the significance of ET is magnified, as it continues to deplete the limited remaining water supplies in water bodies and the soil (Hanson, 1991). From a water supply perspective, the ET metric is as important as rainfall. Obeysekera et al. (2011) affirmed that ET rates are a result of meteorological and landscape factors, and the balance between rainfall and ET results in the quantity of water available in the system.

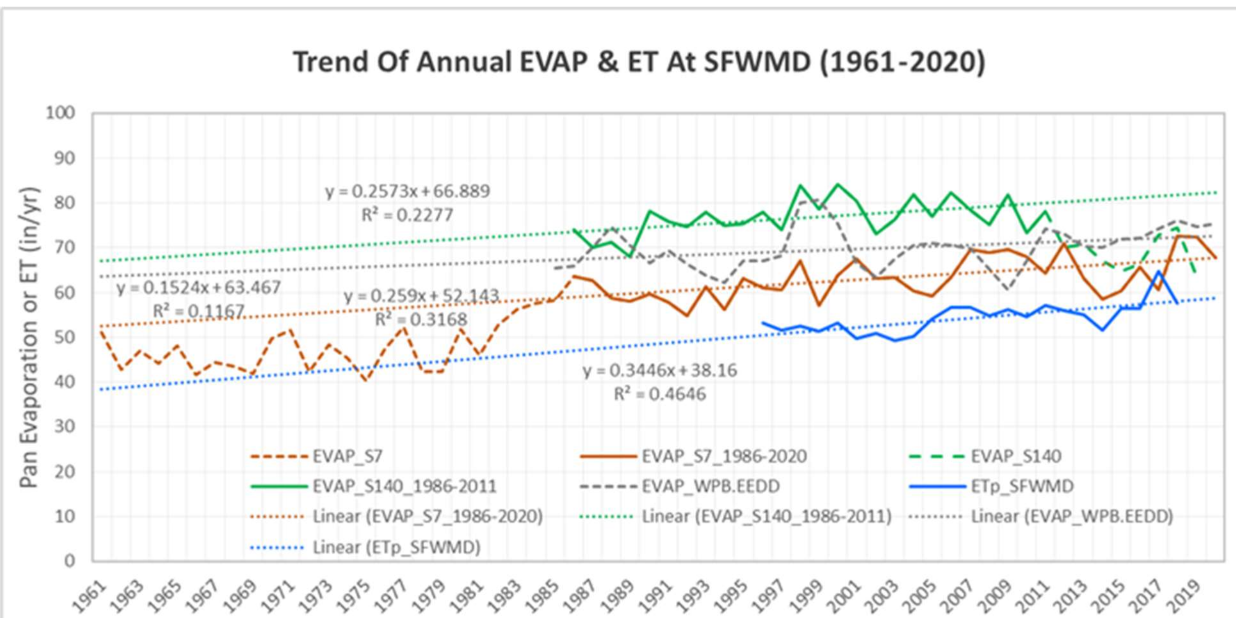
ET rate is hard to measure directly, especially transpiration, because of the difficulty in isolating the observation object. Evaporation can be measured directly to some extent with the help of a pan, which holds water for evaporation to occur, and the water level change represents the evaporation rate. A lysimeter provides the most practical way for direct ET measurement, but it is expensive to operate and maintain. Therefore, in practice, ET rate usually is calculated by empirical equations or models, with input of the other environmental parameters like solar radiation (the primary driving factor), air temperature, relative humidity, and wind speed.

The most commonly used evaporation pan in the United States is the “Class A” of the National Weather Service, and it is adopted in the District as well. The cylinder pan is 47.5 inches (120.7 centimeters) in diameter and 10 inches (25 centimeters) in depth. Water level in the pan is required to be maintained at 2 inches (5 centimeters) from the rim, after each measurement. The pan usually is accompanied by a rain gauge to factor out the contribution of concurrent rainfall to the stage variation for the actual value of evaporation. The pan is made of metal and rests on a wood platform, which is carefully leveled, and the platform surface is about 5.9 inches (15 centimeters) from the ground. Because the pan has more exposure to the air (at its sides and bottom) than any natural water body, it absorbs more heat from the surroundings. This gives higher evaporation values than other measurements like lake evaporation and ET, under the same weather conditions.

ET usually is referred to as potential ET, which means the maximum rate that only occurs when water availability in the soil is non-limiting. Actual ET is the ET that actually takes place, and it is strongly influenced by the level of soil moisture. The actual ET of wetlands in South Florida is equal or close to the potential ET, especially during the wet season.

Although there are different methods for ET or evaporation rate measurement or estimation, which may lead to different magnitudes in values, the data of any method can be trusted for trend analysis as long as the measurement/estimation has been kept consistent throughout.

Figure 59 shows three annual data sets from three manual evaporation pans and one data set of potential ET from the USGS. The data sets illustrate a clear upward trend, not only by the slope of linear regression trendlines but also by the Mann-Kendall test. All three evaporation pans are still in operation, but they have different start dates, from 1961 to 1986. The S7 station has the longest period of record at 60 years. The pan data from the S140 station were altered since 2012 for the experiment of automation, so trend analysis was only applied to its records up to 2011 (26 years). Among the three evaporation pans, the WPB.EEDD is operated by the City of West Palm Beach, while the other two (S7 and S140) are operated by the District. In addition, the evaporation data from S7 and S140 have been used to produce the weekly Shark River Report since 1985 (for water releases from Water Conservation Area 3A to Everglades National Park, based on water budget analysis of rainfall, evaporation, and stage regulation). The weekly data check for the report and the feedback between District headquarters and the field stations makes the manual measurements at S7/S140 as consistent as possible (or at least better than others without regular checks). Measurement errors at daily or weekly scales are unavoidable and random; however, when the data are pooled to monthly or yearly scales, the errors follow a normal distribution, and the monthly or annual values should be reliable for analysis. The USGS potential ET data (average over the entire District) have a period of record of 23 years (1996 to 2018) and were generated based on satellite estimates of insolation calibrated to ground pyranometers (with coefficient of determination $R^2 = 0.93$); thus, they are spatially consistent and temporally continuous (Mecikalski et al. 2018). The direct pan observations and the generation of satellite-based ET data were conducted independently; therefore, they can be used as cross check to each other. The slope values of linear regression trendlines for S7 (evaporation), S140 (evaporation), and USGS (potential ET) are quite close to each other. (Note: Data from 1986 to 2020 were used in statistics for S7.) The WPB.EEDD linear regression trendline, however, has a more gradual slope but in the same direction (positive or up). The Mann-Kendall test proves all four data sets show an upward trend at a significance level of 0.05. The background of statistics used here is described in DATA AND TREND ANALYSIS section above.



EVAP_S7_1986-2020
Mann-Kendall Test

alpha	0.05
MK-stat	**197**
s.e.	67.4562
z-stat	2.9056
p-value	**0.0037**
trend	yes

EVAP_S140_1986-2011
Mann-Kendall Test

alpha	0.05
MK-stat	**101**
s.e.	45.3689
z-stat	2.2042
p-value	**0.0275**
trend	yes

EVAP_WPB.EEDD
Mann-Kendall Test

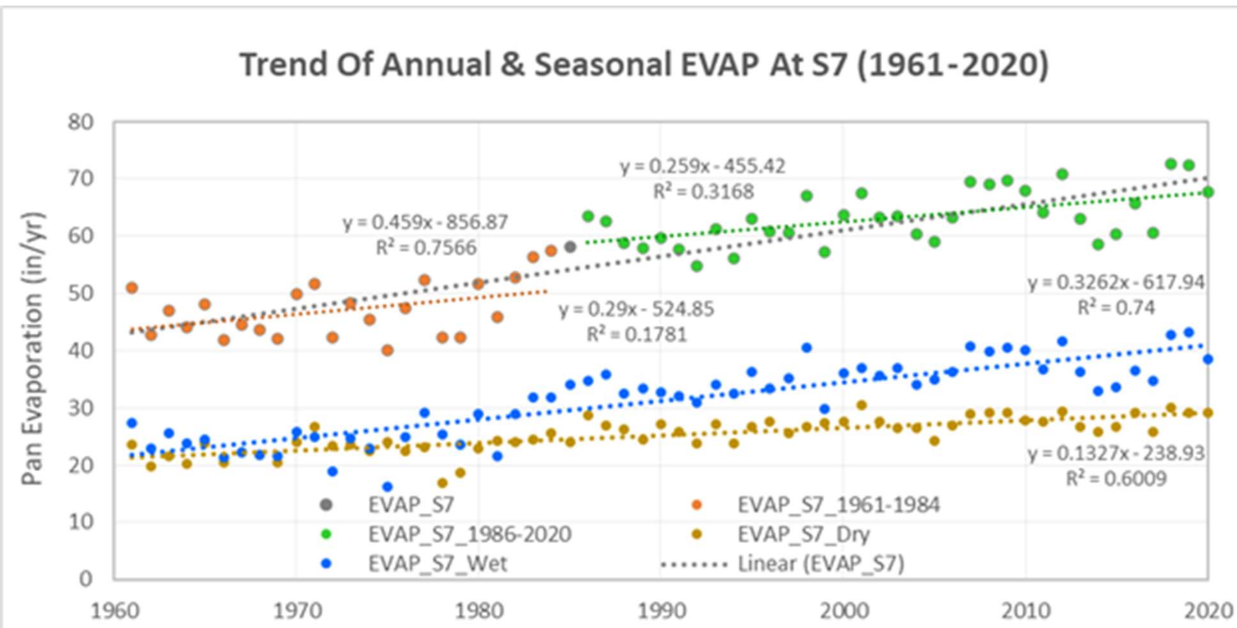
alpha	0.05
MK-stat	**168**
s.e.	70.4083
z-stat	2.3719
p-value	**0.0177**
trend	yes

ETp_EntireDistrict
Mann-Kendall Test

alpha	0.05
MK-stat	**121**
s.e.	37.8638
z-stat	3.1693
p-value	**0.0015**
trend	yes

Figure 59. Trend of annual pan evaporation and evapotranspiration across the District (1961 to 2020).

Figure 60 illustrates the annual and seasonal pan evaporation data at S7, with more details. The orange and green dots in the upper part of the chart represent the annual sub-data sets of 1961 to 1984 and 1986 to 2020, respectively, to account for the measurement schedule change from every day to weekdays only in 1985. Both sub-periods show an upward trend. The two groups of dots in the lower part of the chart are the seasonal summaries over the 60-year period of record. The blue ones represent the wet season (May to October), and the brown ones represent the dry season (November to April). The wet season has a steeper slope than the dry season, while the latter has less variation, or more stable tendency. The Mann-Kendall test proves that both seasons have an upward trend at a significance level of 0.05. The data quality of pan evaporation suffers during heavy or intense rain events due to overflow; this typically occurs during the wet season. If the dry season shows the same direction, the conclusion of an overall trend should be reliable with less uncertainty.



EVAP_S7_1961-2020
Mann-Kendall Test

alpha	0.05
MK-stat	**1129**
s.e.	152.9172
z-stat	7.3765
p-value	**0.0000**
trend	**yes**

EVAP_S7_Dry-SZN
Mann-Kendall Test

alpha	0.05
MK-stat	**1035**
s.e.	152.9172
z-stat	6.7618
p-value	**0.0000**
trend	**yes**

EVAP_S7_Wet-SZN
Mann-Kendall Test

alpha	0.05
MK-stat	**1125**
s.e.	152.9172
z-stat	7.3504
p-value	**0.0000**
trend	**yes**

Figure 60. Trend of pan evaporation data at S7 from 1961 to 2020; annual totals and seasonal summaries.

Figure 61 shows the monthly pan evaporation data at S7, including the identification of extreme occurrences with 1-in-10 and 1-in-25 return frequencies. The green dashed line represents the linear regression trendline on the maximum monthly value of a year over the 60-year period of record and illustrates a clear upward trend.

Possible causes for the upward trend include increasing temperatures and better air quality from tighter regulations on exhaust emissions (e.g., less aerosols from coal-burning power plants and diesel engines), which results in stronger solar radiation (Hidy et al. 2014). Land use and land cover changes also may contribute to increases in solar radiation across the southeastern United States (Ellenburg et al. 2016).

Figure 62 presents a side-by-side comparison of District-wide average monthly ET and rainfall (over the past 25 years), and the differences are presented in **Figure 63**. At the start of the wet season, May has twice as much rain as April; however, May also has the highest ET rate for the year, and the deficit between ET and rainfall may put it (May) under threat of drought sometimes. In terms of the (ET – Rainfall) values, the dry and wet seasons could be re-defined as 7 months of dry season from November through May, and 5 months of wet season from June through October.

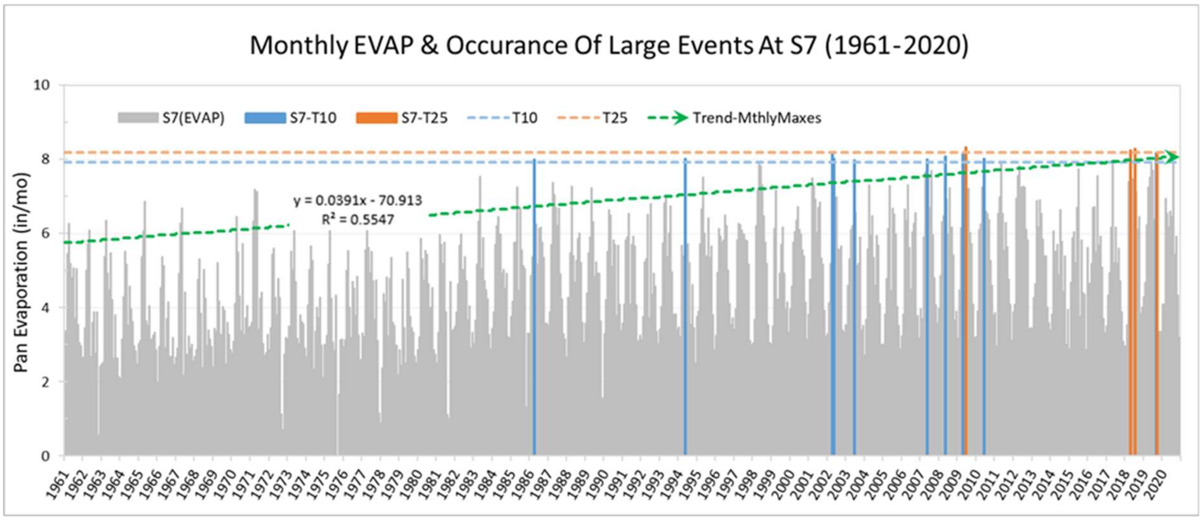


Figure 61. Monthly pan evaporation at S7, highlighting events above 1-in-10 and 1-in-25 return frequencies.

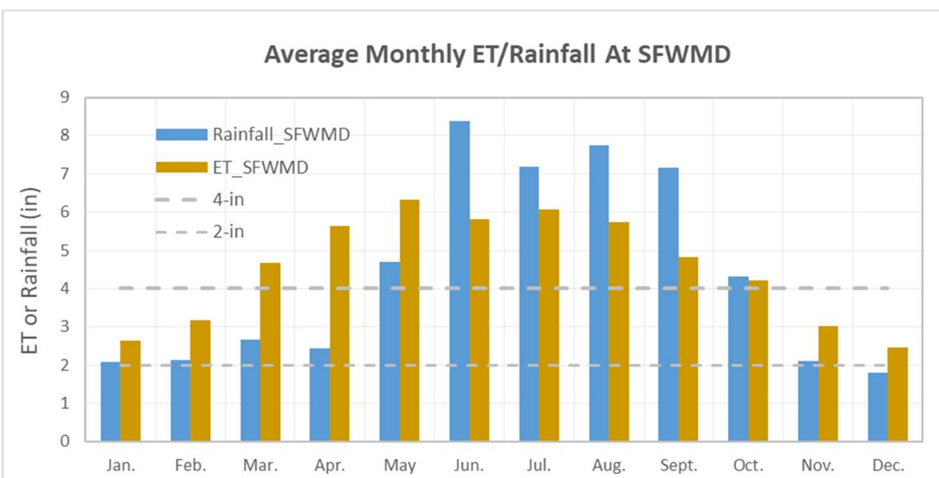


Figure 62. Average monthly evapotranspiration and rainfall across the District (over the past 25 years).

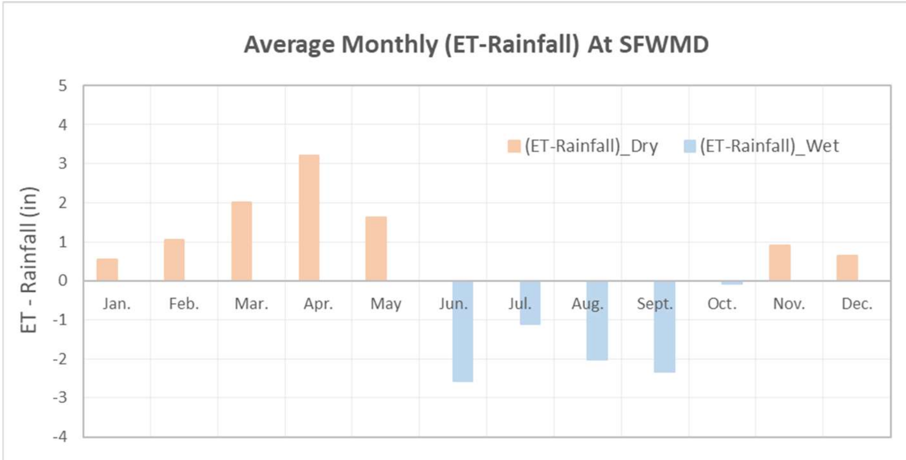


Figure 63. Average monthly differences between evapotranspiration and rainfall across the District.

Water Quality

Several projects monitor water quality parameters at various inland non-estuarine and coastal estuarine locations throughout the District. Frequency of data collection varies among projects. Project names and areas of interest are as follows: Biscayne Bay Coastal Wetlands, Caloosahatchee Estuary, Caloosahatchee Fresh Water – Upstream of Structures, Florida Bay, Indian River Lagoon, Kissimmee River Restoration, Picayune Strand Manatee Mitigation, Picayune Strand Restoration Project, Rookery Bay, St. Lucie Estuary, St. Lucie Tributaries, St. Lucie River Watershed Upstream, Ten Thousand Islands, Water Quality Monitoring – Northern Estuary Structures.

As an example of potential uses of water quality as a metric for climate change, observations for several parameters collected between November 1972 and June 2020 were compiled in this report at six stations within Lake Okeechobee (**Figure 64**). These water quality observations include data for water temperature, dissolved oxygen, pH, specific conductance, and total phosphorus. The monthly values were aggregated as arithmetic means (specific conductance, dissolved oxygen, pH and temperature) and geometric means (total phosphorus) across the six stations. The presentation of these water quality data is to be strictly used to demonstrate if potential effects from climate change could be observed using a long period of record.

While water quality parameters could be influenced by climatic changes, water quality changes are more directly affected by physical and biological processes. Therefore, any analysis of the selected parameters needs to differentiate natural processes from those associated with climate change. An additional consideration is the frequency and time of data collection. All manual water quality samples are collected during the day at various times of day. As a result, these sampling regimes can have an impact on associating climate change with changes in water quality.

Figures 59 – 62 show two sets of plots for each water quality parameter of interest. The top plot in each figure (labeled as A) depicts monthly averages over the period of record. Also presented in each of the top plots are a trend line based on seasonal Mann Kendall (SK) results (in blue) and a local estimated scatter smoothing (LOESS) line. Additionally, statistical results of each SK test are provided to identify and validate trends for each parameter over the period of record, with months used as seasons. The Sen slope and Kendall tau statistics are used to determine the direction and amount of annual change. Negative values indicate a parameter level is decreasing over the observed period, while positive values suggest an increase. Probability values (p-values) are provided to indicate if the observed change and direction are

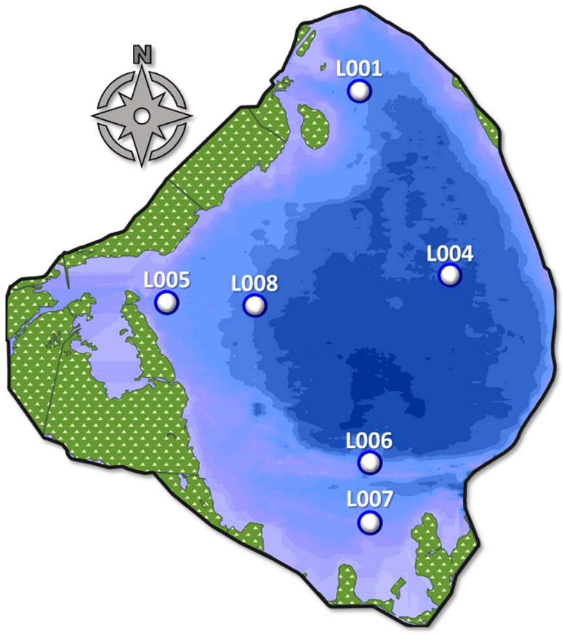


Figure 64. Location of the six water quality stations used in summarizing water quality data in Lake Okeechobee.

statistically significant. Periods of severe drought (shaded regions) and tropical events (yellow arrows = tropical storms; red arrows = hurricanes) are also identified The bottom set of plots (labeled as B) associated with each figure show annual changes for each parameter as an average within each season (month). As with the time series plots, LOESS lines are provided in association with Kendall tau (τ) correlation coefficients to indicate the direction of the observed trend. This rank correlation was chosen to establish if the tested variables are statistically dependent. Additionally, the Kendall τ correlation is non-parametric and does not rely on any assumptions regarding the distribution of the data. The associated p-values indicate whether the observed trend is statistically significant. A significance level of 0.05 was used for these analyses. Thus, when the p-value is less than 0.05, the observed trend is statistically significant.

Water Temperature

Figure 65A shows the average monthly water temperatures measured in Lake Okeechobee. A seasonal signal can be observed with lower water temperatures occurring during cooler months (December – March) and higher temperatures observed during warmer months. While the water temperature data exhibit a slight increasing trend based on SK analysis, the trend is not statistically significant (p-value = 0.68). Generally, the annual changes by season (**Figure 65B**) do not exhibit any significant trends except for June, which exhibits a significant decreasing trend in water temperatures (p-value = 0.03). Dry season months (November to April) exhibit greater variability in water temperatures compared to wet season months (May to October). Also, January exhibited a visible, although not significant, increasing trend over the period and may offer a subtle indicator of some potential climatic effect.

Dissolved Oxygen

Dissolved oxygen is a measure of the amount of oxygen that is dissolved in the water and available for living aquatic organisms. Dissolved oxygen concentrations change over diel cycle because of changes in water temperatures, primary productivity (e.g., photosynthesis), respiration and other biochemical interactions. Additionally, inhibition of light penetration resulting from suspended material can affect photosynthetic activity and increase respiration resulting in reduced dissolved oxygen concentrations. Dissolved oxygen levels exhibit a seasonal signal with higher concentrations occurring during cooler months, as cooler water can hold more dissolved oxygen, and lower concentrations during warmer months.

A

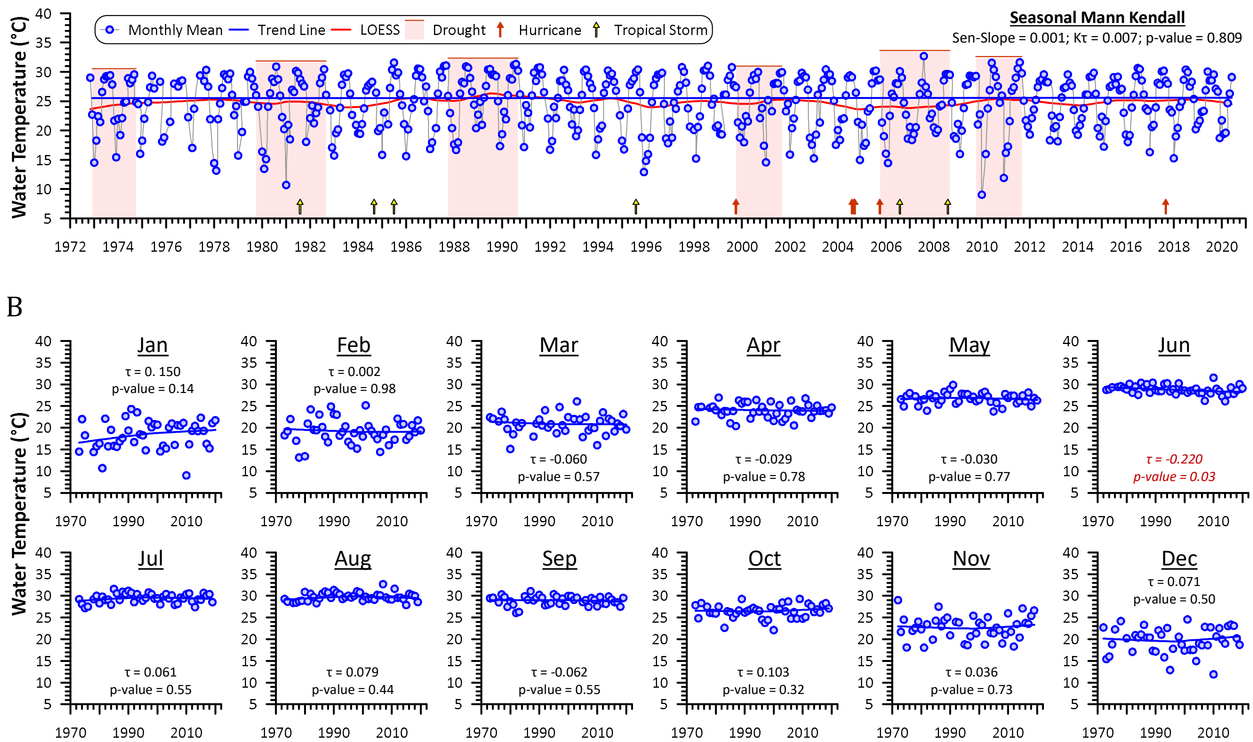


Figure 65. (A) Monthly mean water temperature at six stations in Lake Okeechobee with seasonal Kendall trend analysis results. (B) Annual trends in seasonal water temperature. Statistically significant trends identified in red.

Figure 66A shows the time series plot of mean monthly dissolved oxygen concentrations in Lake Okeechobee over the 48-year period. Based on the SK test performed on monthly data, a statistically significant (p = 0.04) decreasing trend was observed. Given a resolution of 0.01 mg/L typically associated with dissolved oxygen probes, it is highly questionable if the observed decreasing trend (0.004 mg/L per year) would be environmentally significant.

Over the period of record, the average dissolved oxygen concentrations for these monitoring stations is 8.4 ± 1.0 mg/L (± standard deviation) and is higher than observed in more than 60% of Florida lakes (Hand 2016). Annual seasonal changes, as illustrated in **Figure 66B**, show downward trends (negative τ statistics) for most months. October is the only month with a statistically significant decreasing trend (p-value = 0.02).

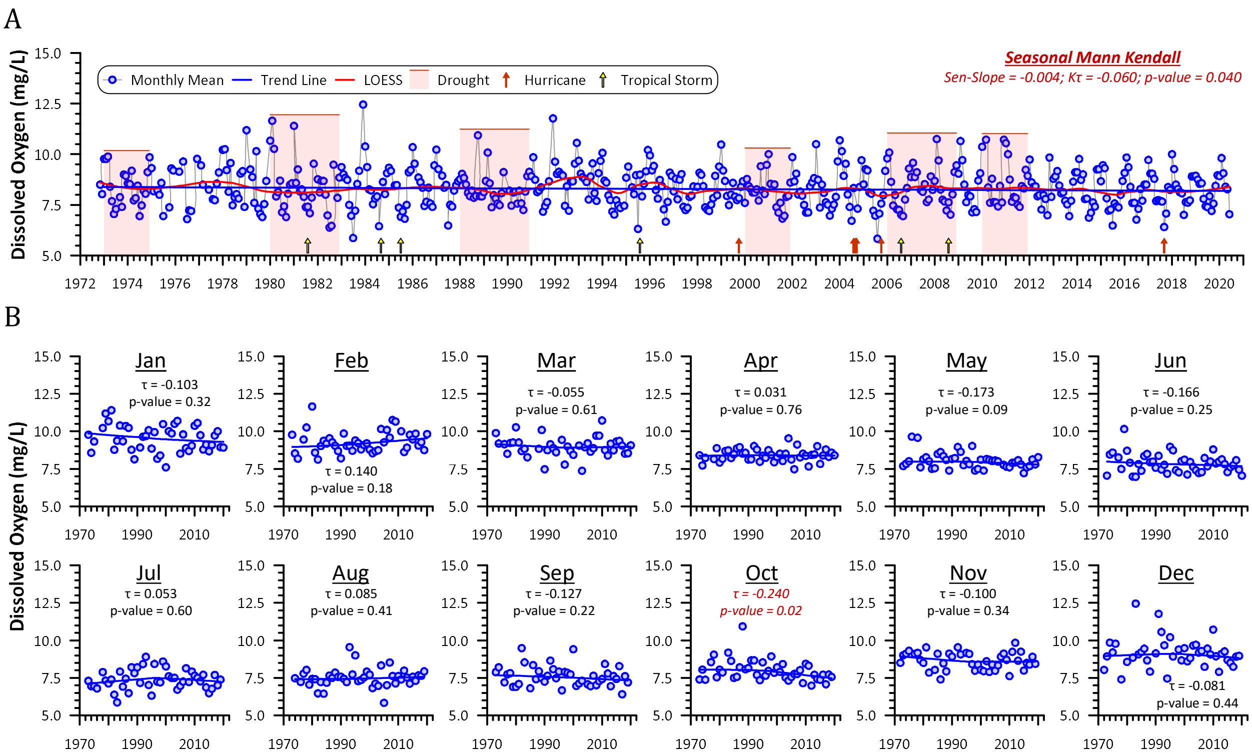


Figure 66. (A) Monthly mean dissolved oxygen concentrations at six stations in Lake Okeechobee with seasonal Kendall trend analysis results. (B) Annual trends in seasonal dissolved oxygen concentrations. Significant trends identified in red.

Water pH

Water pH is a measure of the acidity/basicity of water with respect to hydrogen ions. pH is measured on logarithmic scale ranging from 0 to 14, with each whole number representing a 10-fold decrease in hydrogen ion content. A pH of 7 is neutral (neither acidic nor basic). In surface waters, pH can be affected by geology, rainfall, chemical interactions, photosynthetic activity, and respiration, including bacterial decomposition of organic matter. In general, organisms (especially aquatic organisms) have a pH tolerance range of 6 to 9.

The time series variation of pH values is calculated as a monthly mean of the six in-lake monitoring stations (**Figure 67A**) as well as the annual variation by season (**Figure 67B**). From 1972 to 2020, the average water pH in Lake Okeechobee was 8.1 ± 0.1 and varied by less than 8%. Based on the period mean, Lake Okeechobee is in the 70th percentile of typical lakes in Florida with respect to pH (Hand 2014). Water pH levels of 7.6 represent the 50th percentile of Florida lakes (Hand 2014). The SK results show that pH appeared to increase over the period of record. The observed increase in pH was just outside the statistically significance level of 0.05 (p-value = 0.051). Typically, pH sensors have a resolution of 0.01 pH units. The observed increasing trend (0.001 year) would not have an environmental impact over the period of record. Annual seasonal changes (**Figure 67B**) generally show an upward trend with the only month significant trend observed for August (p-value = 0.04).

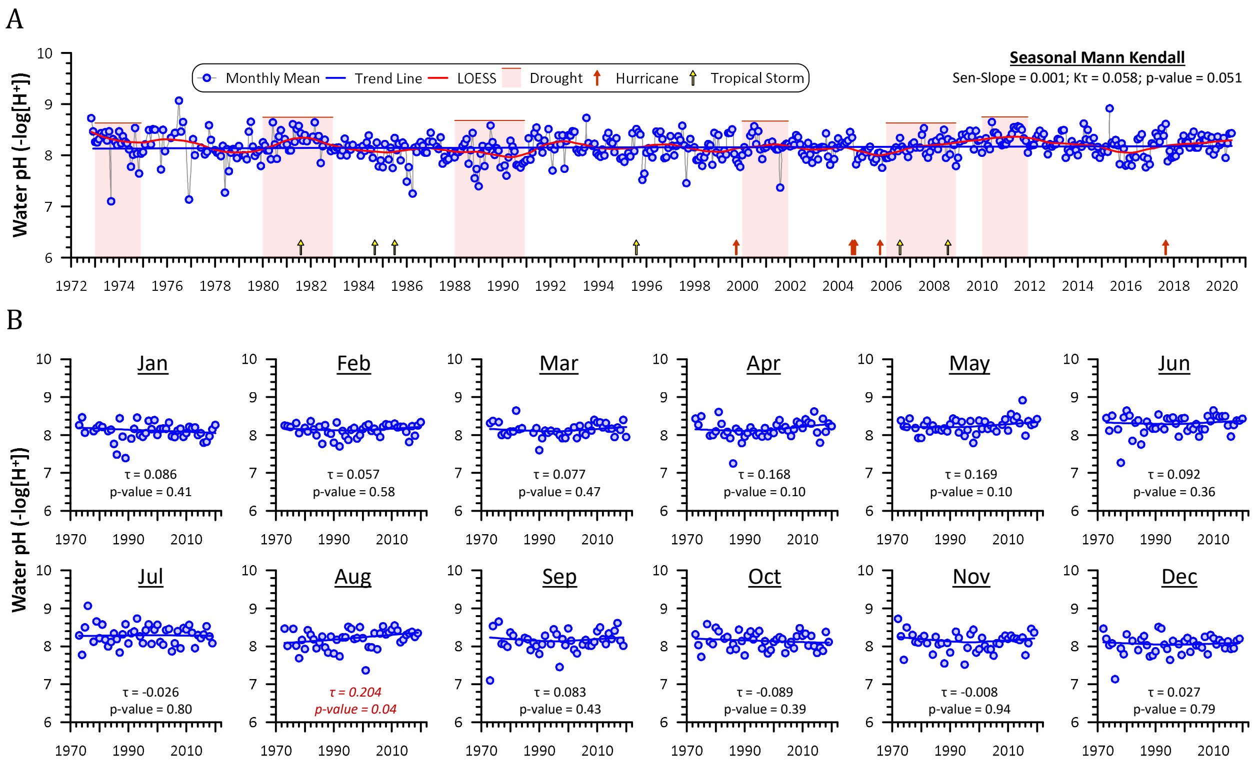


Figure 67. (A) Monthly mean water pH at six stations in Lake Okeechobee with seasonal Kendall trend analysis results. (B) Annual trends in seasonal water pH. Significant trends identified in red.

Specific Conductance

Specific conductance measures the ability of water to carry an electrical current, varying by types and amounts of ions present in solution, and is an indirect measure of the presence of dissolved solids (e.g., Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, HCO_3^{-}, SO_4^{2-}, NO_3^{-}, and PO_4^{3-}). Variations in specific conductance levels are caused by evaporation, rainfall, geology of a watershed, and groundwater interactions. Additionally, anthropogenic activities (e.g., agriculture, industry) can influence specific conductance levels. Specific conductance is one of the most frequently measured water quality parameters and is used as a conservative tracer.

Figure 68A shows the time series plot of mean monthly specific conductance for six in-lake stations from December 1972 to June 2020. The annual change in specific conductance on a seasonal or monthly basis is shown in **Figure 68B**. The time series plot, shown in **Figure 68A**, illustrates seasonal changes in specific conductance, with lower values typically observed during the wet season and higher values occurring during the dry season. In addition, climatic events, such as droughts and tropical events, affect observed specific conductance levels in Lake Okeechobee with specific conductance increasing during droughts and decreasing following tropical events, as a result of increased rainfall and watershed runoff.

A highly statistically significant decreasing trend (p-value <0.01) was observed for specific conductance in Lake Okeechobee. Over the 48-year period, specific conductance decreased by approximately 40%, from a mean of 680 microsiemens per centimeter (µS/cm) in December 1972 to approximately 400 µS/cm in June 2020. Annual changes in specific conductance over the 12 months also exhibit significant decreases (**Figure 62B**). It is important to note that during the period from 1973 through 1983, specific conductance averaged 624 ± 100 µS/cm. Specific conductance averaged 396 ± 42 µS/cm from 2013 to 2020 and reflects typical specific conductance levels observed in Florida lakes (Hand 2014).

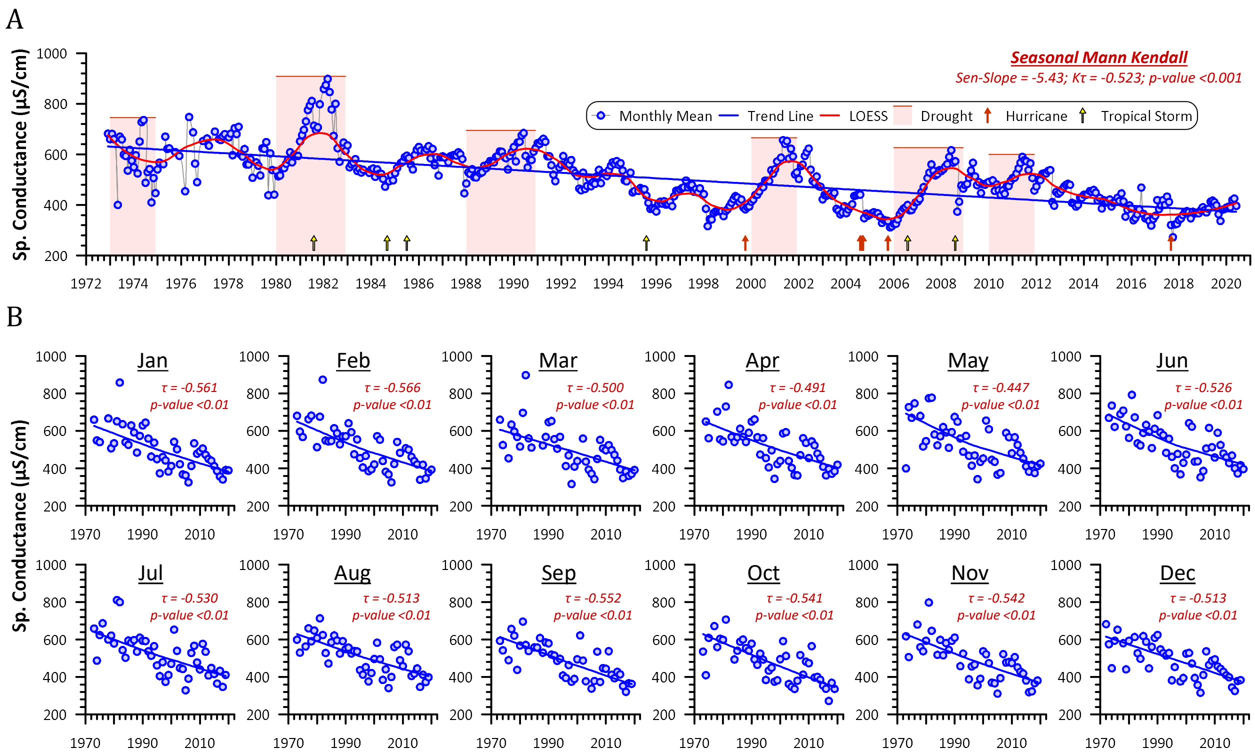


Figure 68. (A) Monthly mean specific conductance at six stations in Lake Okeechobee with seasonal Kendall trend analysis results. (B) Annual trends in seasonal specific conductance. Significant trends identified in red.

An important question regarding this highly significant decrease in specific conductance is what produced the observed trend? Is the observed trend associated with climate change or other influences? A discussion pertaining to the potential causes of the observed trend in specific conductance is provided in Appendix C.

Changes in air and water temperature, as well as precipitation, have predictable effects on water quality. However, attributing variations in water quality as a function of climate change is more complicated due to multiple cascading factors that exert great influence on water quality such as changes in land use, hydro-management, and other anthropogenic activities. Therefore, it is suggested that the water quality metric should be used more as a response variable to confirm results for metrics that are more directly connected to climate change. Further, water quality trend analysis, including additional water quality sites and more frequent data collection, will seek to provide supporting evidence for potential influences due to climate change.

Estuarine Inland Migration

During the mid-1940s, the marshes in the southeastern saline Everglades were arranged in well-defined plant communities running parallel to the coast, with shrub mangroves dominating the along the coast and graminoid-mangrove communities and *Cladium* dominating farther inland (Ross et al. 2000). However, by 1994, the boundary of the mixed graminoid-mangrove and *Cladium* communities had shifted inland by 3.3 kilometers (**Figure 69**). The current plant community distribution within the southeastern saline Everglades is shown in **Figure 70**. The interior boundary of a low-productivity zone, appearing white in both black-and-white and color-infrared photos, moved inland by 1.5 kilometers on average. A smaller shift in this "white zone" was observed in an area receiving freshwater overflow through gaps in one of the southeastern saline Everglades canals, while greater change occurred in areas cut off from upstream water sources by roads or levees. These large-scale vegetation dynamics apparently are the combined result of sea level rise (approximately 10 centimeters since 1940) and water management practices in the southeastern saline Everglades.

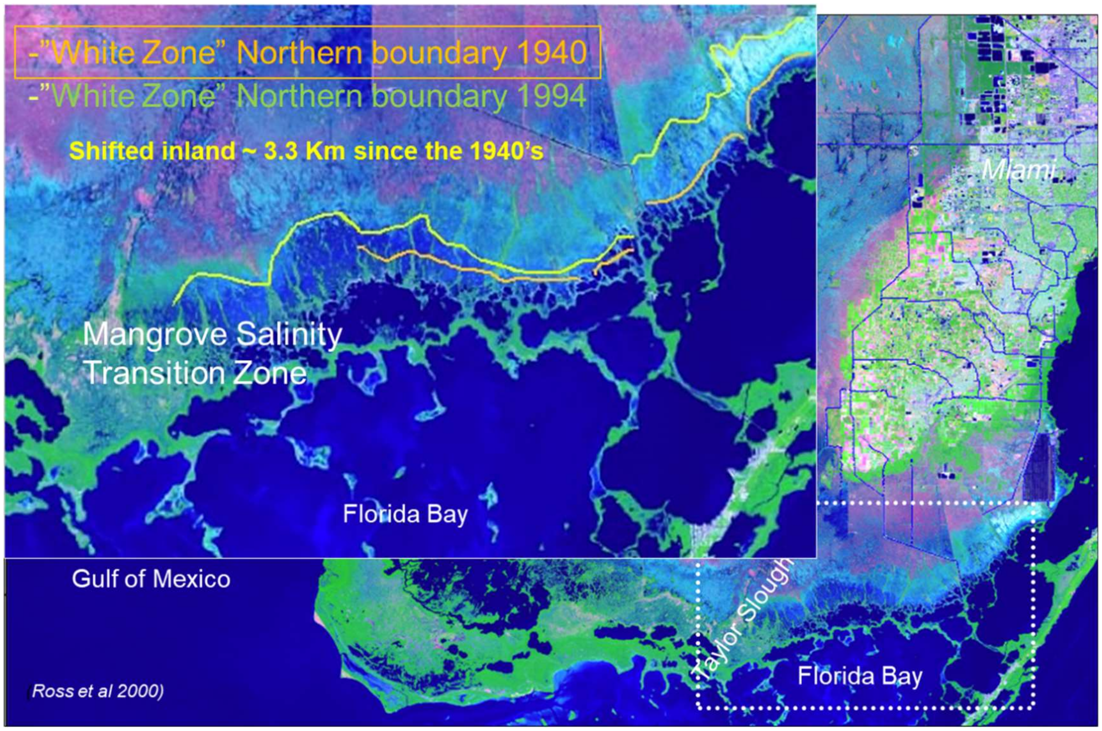


Figure 69. Estuarine inland migration in the southeastern saline Everglades. Modified from Ross et al.2000

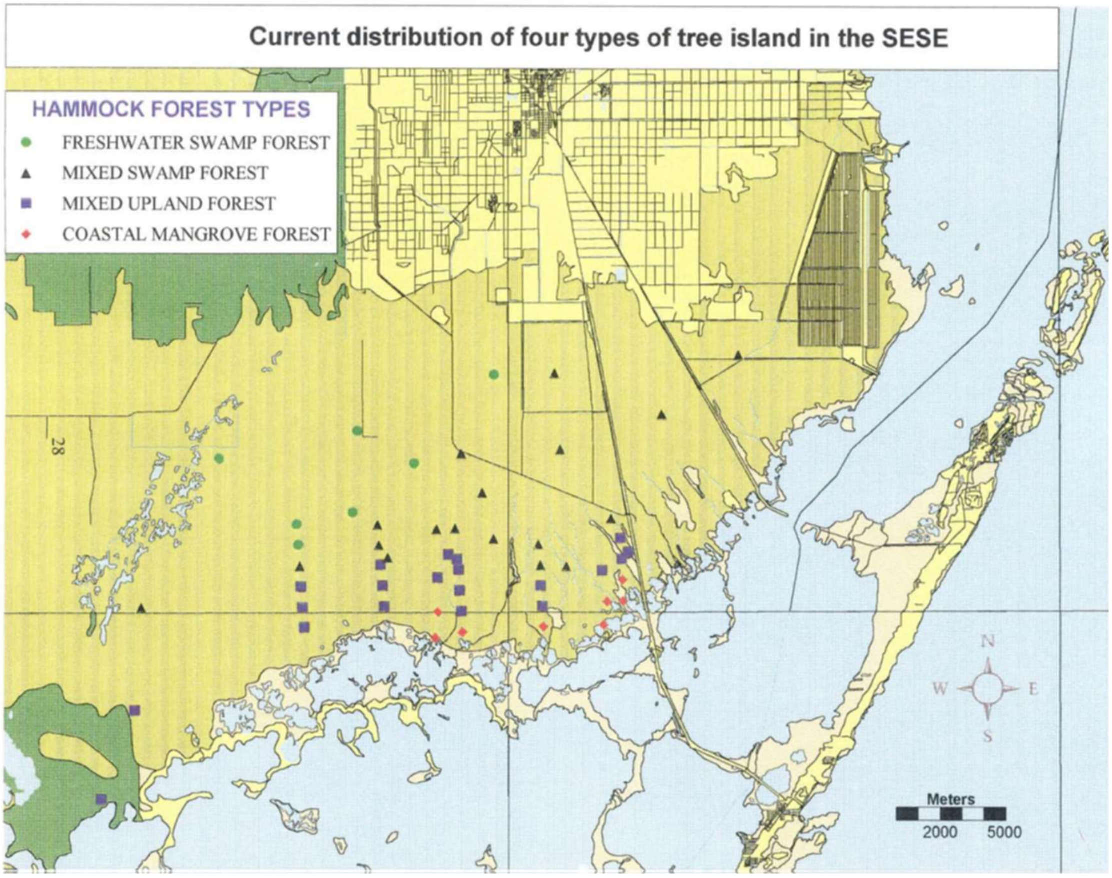


Figure 70. Distribution of four types of tree island in the southeastern saline Everglades in the 1990s. Source: Ross et al. 2000

Paleoecology studies confirm the transgressive encroachment of coastal mangroves into historically freshwater marshes. **Figure 71** illustrates the core locations from Upper Joe Bay, approximately 5 kilometers north of the Florida Bay coastline (Sklar et al. 2019), displaying a transgressive stratigraphic sequence of sawgrass peat-marl to marl to mangrove peat-marl and documenting saltwater encroachment in the southeastern saline Everglades. Arrows represent breaks in soil types. The date is based on 210Pb dating of mangrove peat-marl soils producing an accretion rate of 3.2 millimeters per year (Sklar et al. 2019). **Figure 71** also illustrates mangroves retreating past a freshwater tree island in the southeastern saline Everglades in response to the Current Marine Transgression. Mangrove clumps range between 1 and 3 meters in diameter.

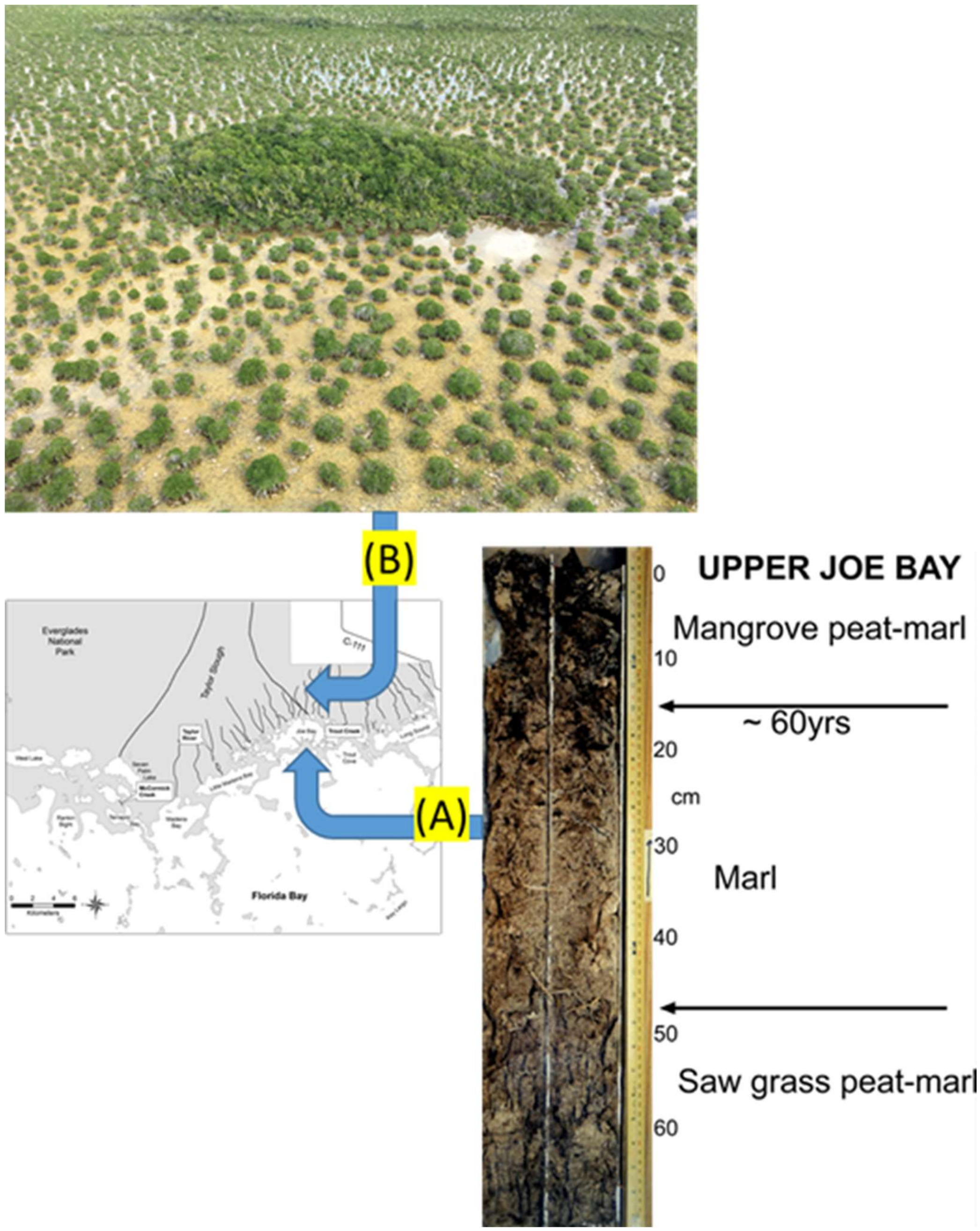


Figure 71. Upper Joe Bay Core locations displaying mangrove retreating. Source: Sklar et al. 2019

Figure 72 presents the 1940 and 1994 images of the coastal gradient between U.S. Highway 1 and Card Sound Road, showing a shift in the interior boundary of the white zone over time. The vertical line on the left side of the 1994 image is from a contrast difference between National Aerial Photography Program (NAPP) photos.

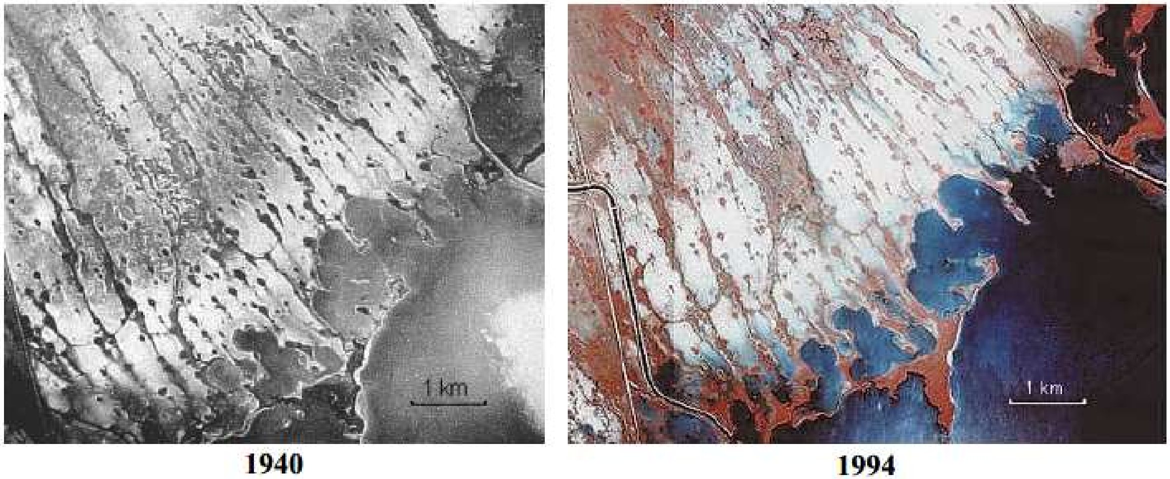


Figure 72. Coastal gradient between U.S. Highway 1 and Card Sound Road. Source; Ross et al. 2000

Figure 73 illustrates that the pre-drainage Everglades had a peat depth of 2 meters, a peat volume of 20 billion cubic meters, and a carbon content of about 900 million metric tons. On the right, the current conditions of the Everglades have a peat depth of 0.75 meter, a peat volume of 5 billion cubic meters, and a carbon content of approximately 200 million metric tons.

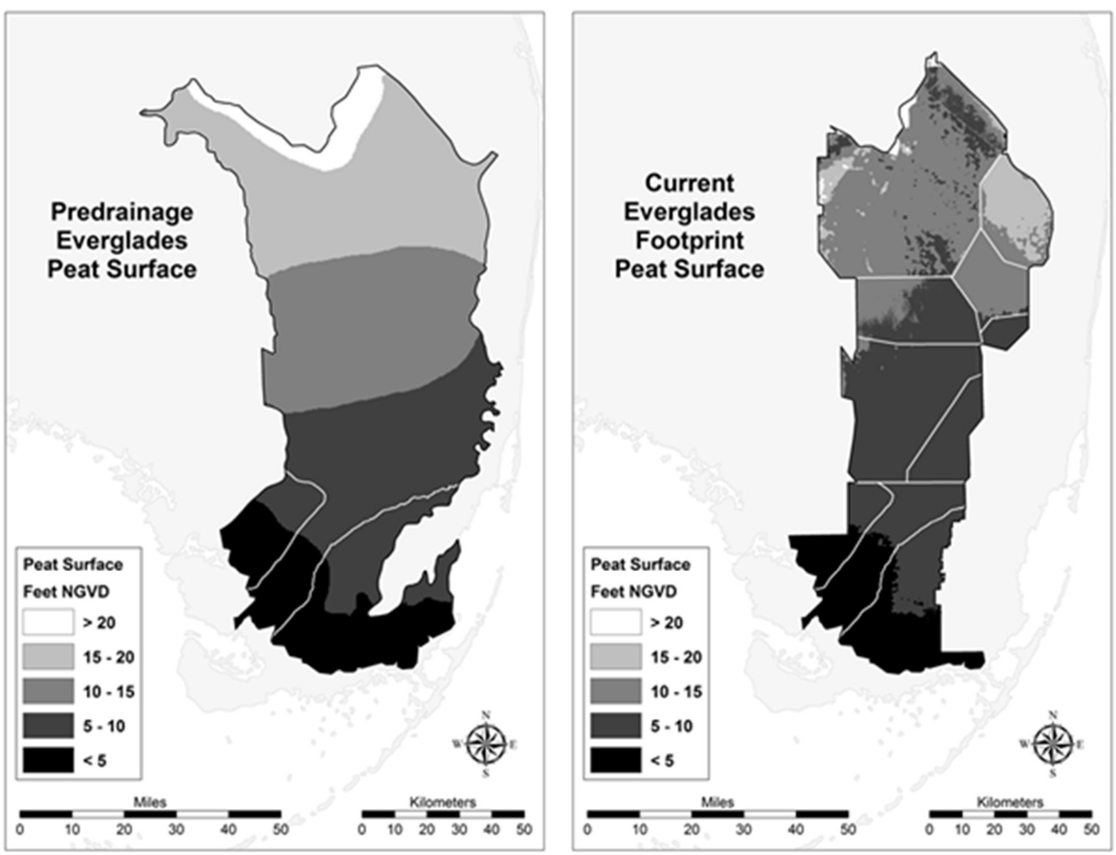


Figure 73. Pre-drainage and current Everglades peat surface. Source: Hohner and Dreschel, 2015

Soil Subsidence

Soil subsidence or expansion is the result of elevation change minus accretion rate, incorporating both surface and subsurface processes. The District has been studying mangrove environments in northeastern Florida Bay and Taylor River (**Figure 74**) to determine soil subsidence at non-flooded, frequently flooded, and permanently flooded areas. The main objective of the study is to determine whether mangrove soil surface elevation can keep pace with increasing sea level rise. **Figure 75** illustrates soil elevation change and soil accretion at Shark River and Lostmans River in southwestern Florida. **Figure 76** illustrates elevation changes and soil accretion rates in non-flooded, frequently flooded, and permanently flooded areas, showing a higher elevation change rate in frequently flooded areas and higher soil accretion rate in permanently flooded areas. **Figure 77** presents the total rates at these locations. The non-flooded environment was not as stable as previously reported. Erosion and oxidation dominate the biogeochemical processes of soil formation and loss in the Florida Bay coastal mangrove environment. Pulsing events, such as hurricanes and thunderstorms, likely play an important role in nourishing mangrove sites closer to the coast with inorganic matter imported from Florida Bay, as has been observed and measured.

Surface elevation table-marker horizon (SET-MH) data indicate some mangrove sites are not keeping pace with sea level rise rates, but other sites are keeping pace, underlying the importance of microtopography and hydrology to better determine the fate of mangrove forests along the Taylor River. Previous studies (e.g., Sklar et al. 2019) show mangrove forests could migrate inland into freshwater environments. This migration has been attributed to a response to increasing sea level and decreasing freshwater input into the salinity transition zone of Taylor Slough.

Figure 74. Northeastern Florida Bay and Taylor River.

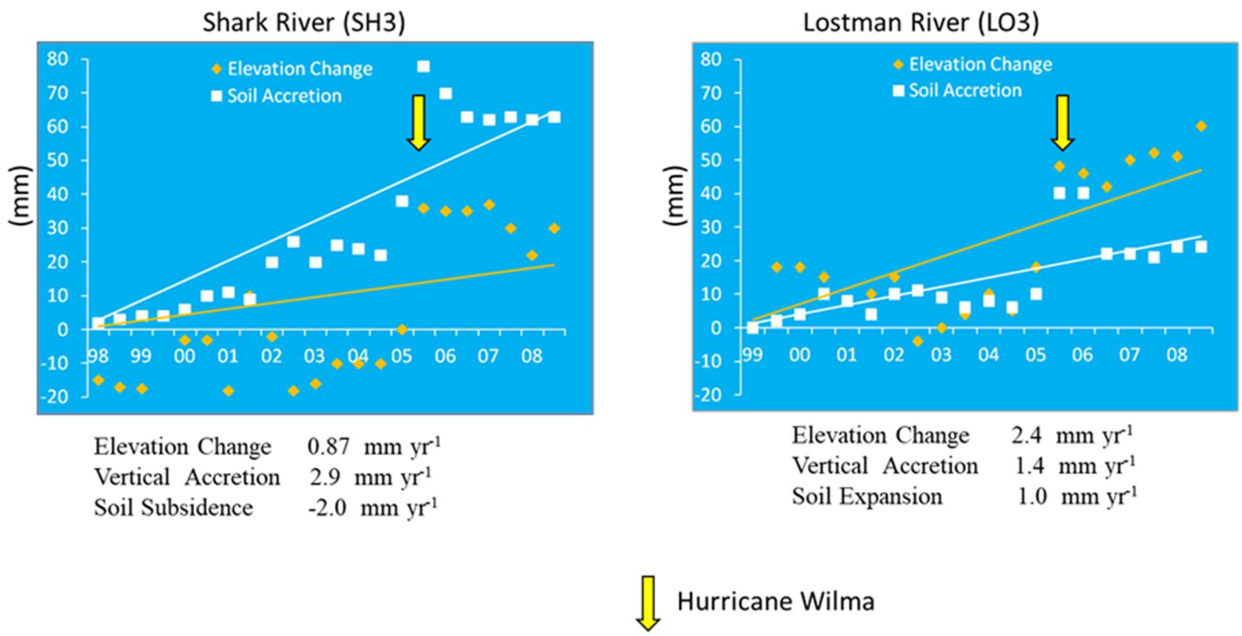


Figure 75. Soil subsidence/expansion rates in Shark River and Lostman River. Source: Smith et al. 2009

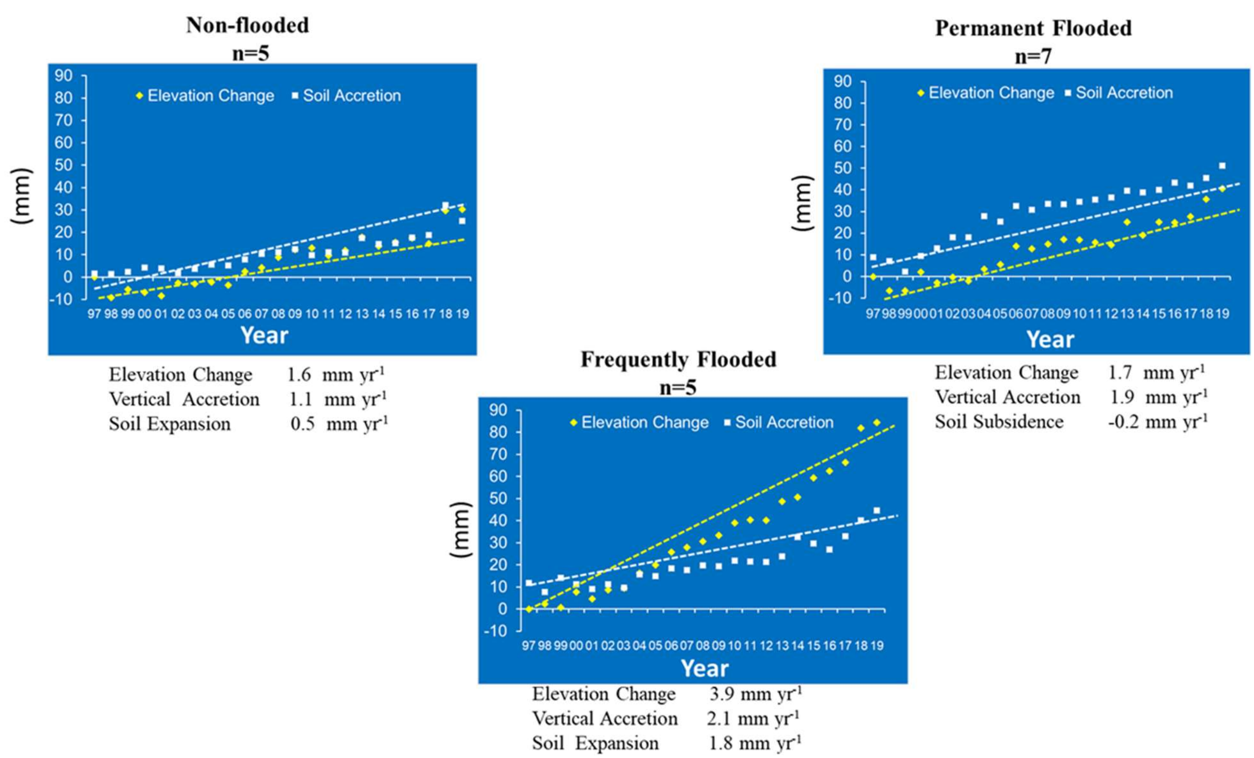


Figure 76. Soil subsidence/expansion rates in northeastern Florida Bay and Taylor River. Unpublished data

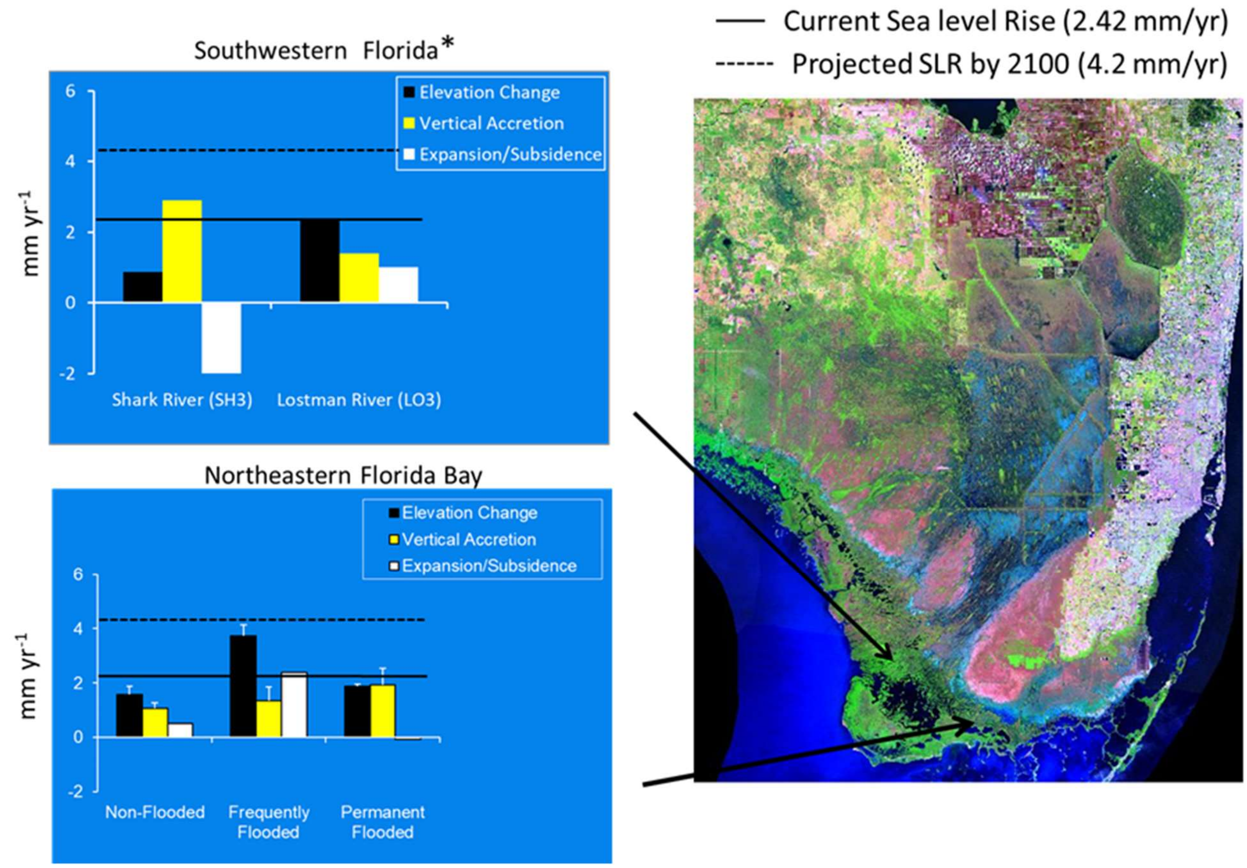


Figure 77. Total soil subsidence/expansion in southwestern Florida and northeastern Florida Bay. Unpublished data

Salinity in the Everglades

The District contracts with Audubon's Tavernier Science Center for monitoring of the coastal creeks along the northern Florida Bay shoreline as part of the Restoration Coordination and Verification (RECOVER) program. The metrics included as part of this contract include water stage, salinity, submerged aquatic vegetation (SAV), and prey fish community. **Figure 78** illustrates the locations of the regions, including long-term monitoring sites, with data from 1995 to 2020; short-term sites, with data from 2002 to 2020 and from hydrostation and SAV sites only.

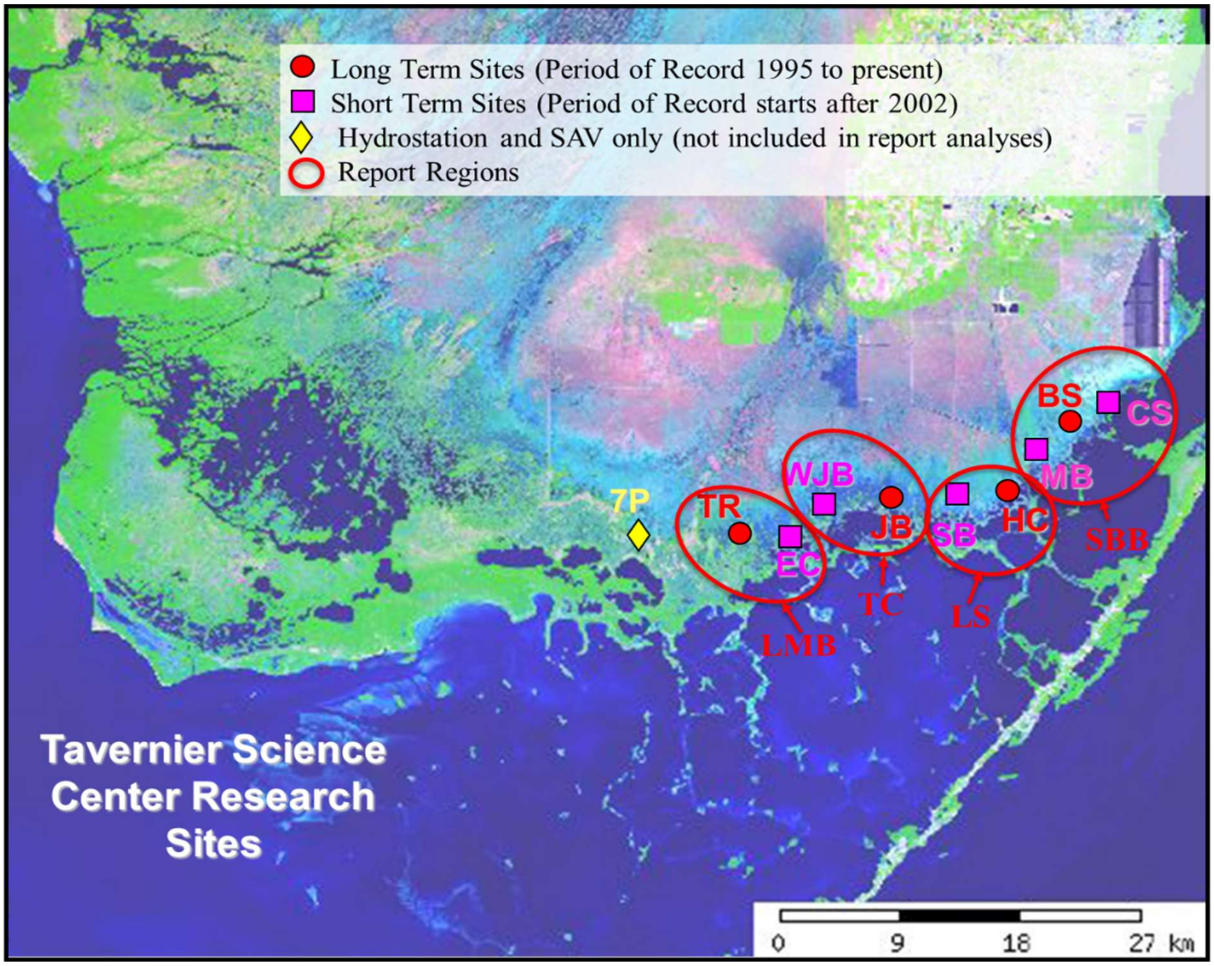


Figure 78. Map showing the regions and monitoring sites. Source: Audubon's Tavernier Science Center.

The District oversees a comprehensive ecological monitoring program in the southern Everglades wetland marshes, Florida Bay mangrove transition zone, and estuarine waters of Florida Bay to evaluate the effects and benefits of Everglades restoration. Specifically, the program monitors the C-111 Spreader Canal Western Features project, which has been in operation since 2012. Ecological monitoring conforms to the Project Monitoring Plan (SFWMD 2011), which outlines protocols for assessing hydrology, nutrients, water quality, vegetation, and fauna and their interactions in the footprint of, and downstream of, C-111 project operations. The restoration project is designed to retain or increase freshwater flow within Taylor Slough and into northern Florida Bay by construction of a hydrologic seepage barrier to retain water that formerly flowed out of Taylor Slough and eastward into the C-111 basin. Retaining water in Taylor Slough is expected to increase water levels and hydroperiod in the slough, increase freshwater discharge towards the southern wetland and into Florida Bay, and reduce extreme salinity levels in wetland and estuarine habitats. Measures of water quality at mouths of major creeks discharging to Florida Bay showed general salinity declines during project operations during the wet seasons since project implementation. Salinity declines began prior to pump operation, indicating an important local rainfall effect. Total nitrogen and TP showed significant decreases in concentrations in discharges from Taylor River, but increases of TP in creeks in western Taylor Slough. In the coming years, it will be important to monitor the effects of increased flow and associated nutrient burdens on downstream systems.

Figure 79 illustrates the location of fixed autosampler sites in Taylor Slough and the C-111 basin to monitor salinity and nutrients. **Figure 80** illustrates the 11-year record of salinity in upstream and downstream Taylor Slough, measured daily.

No clear trend is indicated yet as part of the data analysis, as there is a need to differentiate natural processes that could be associated with climate change, from restoration strategies and related operational decisions as well as other physical and biological activities, as part of future efforts.

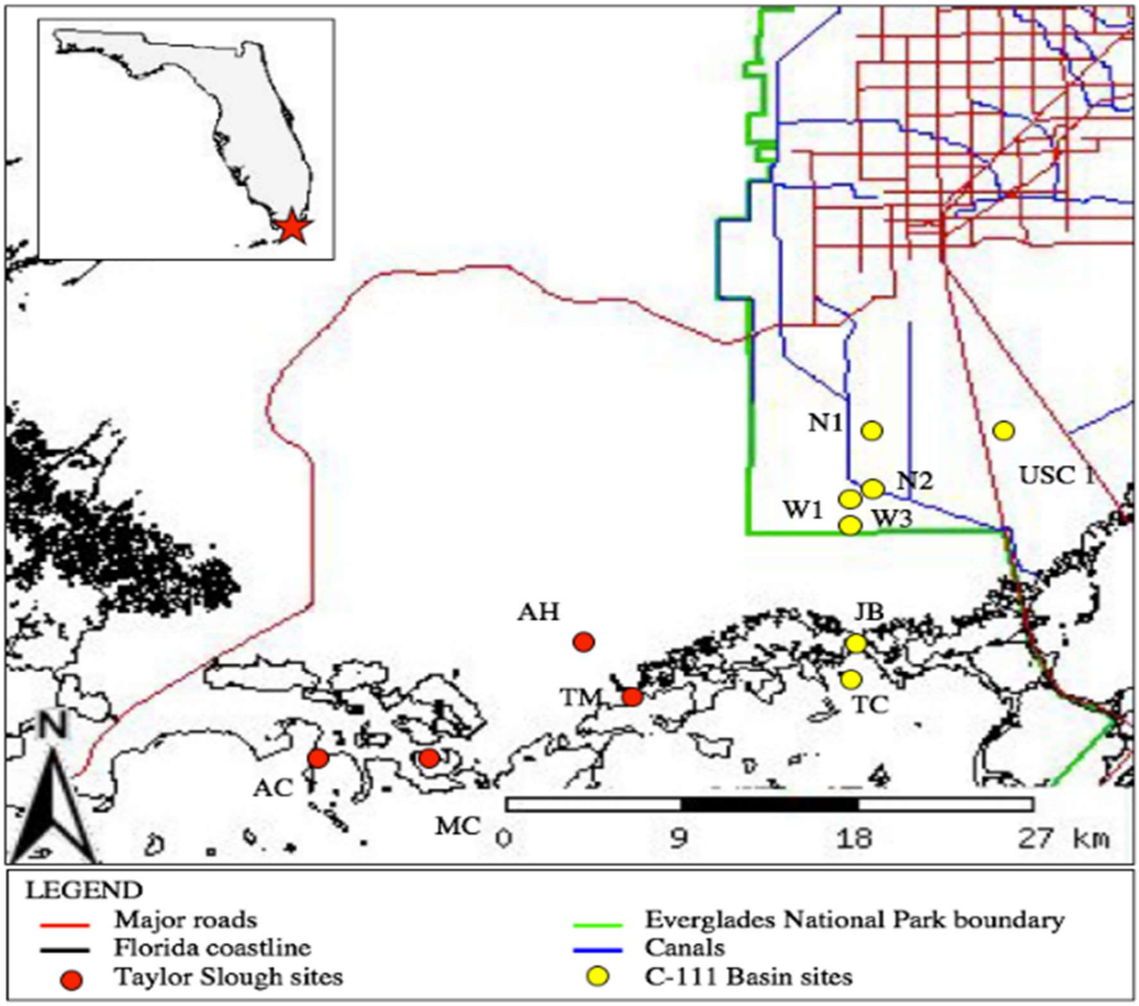


Figure 79. Location of fixed salinity and nutrient autosampler sites.

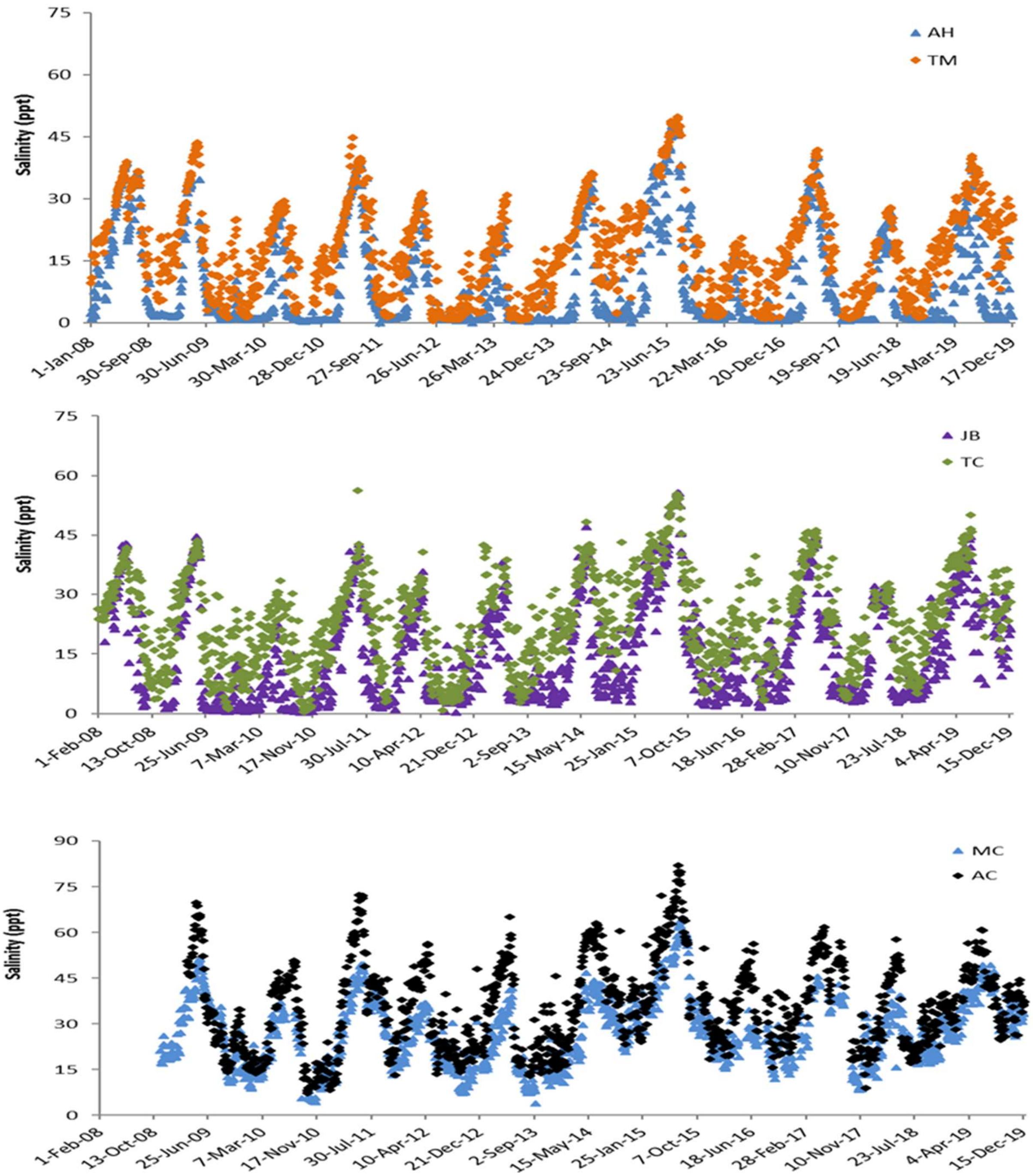


Figure 80. Salinity in upstream and downstream Taylor Slough, measured daily. Argyle Henry (AH), Taylor Mouth (TM), Joe Bay (JB), Trout Creek (TC), McCormick Creek (MC), Alligator Creek (AC).

REPORTING AND PUBLICATION

The set of selected water and climate resilience metrics will be automated and published by the District in an interactive web portal that provides navigation to different locations Districtwide as well as alternative mapping, chart, and graph options to display and communicate results.

The proposed format for the data web publication includes innovative solutions to assess and display data and gather and download target data in different formats and from multiple sources with consistent units, as appropriate, through a database designed for maximum versatility to perform spatial joins and cross-link files. This will allow for a more robust evaluation of trends and patterns and for performing spatial analyses to reveal key interrelations and support communication of relevant metrics.

The web portal will be developed using story maps, as illustrated in **Figure 81**, infographics, and interactive dashboards tools to support communication. Portions of the data with limited access will have appropriate security protocols in place, including access-privileged control tools.

A summarized report will be developed annually to highlight the latest changes and most important information collected during the respective period and is currently being proposed to be incorporated as part of the South Florida Environmental Report.

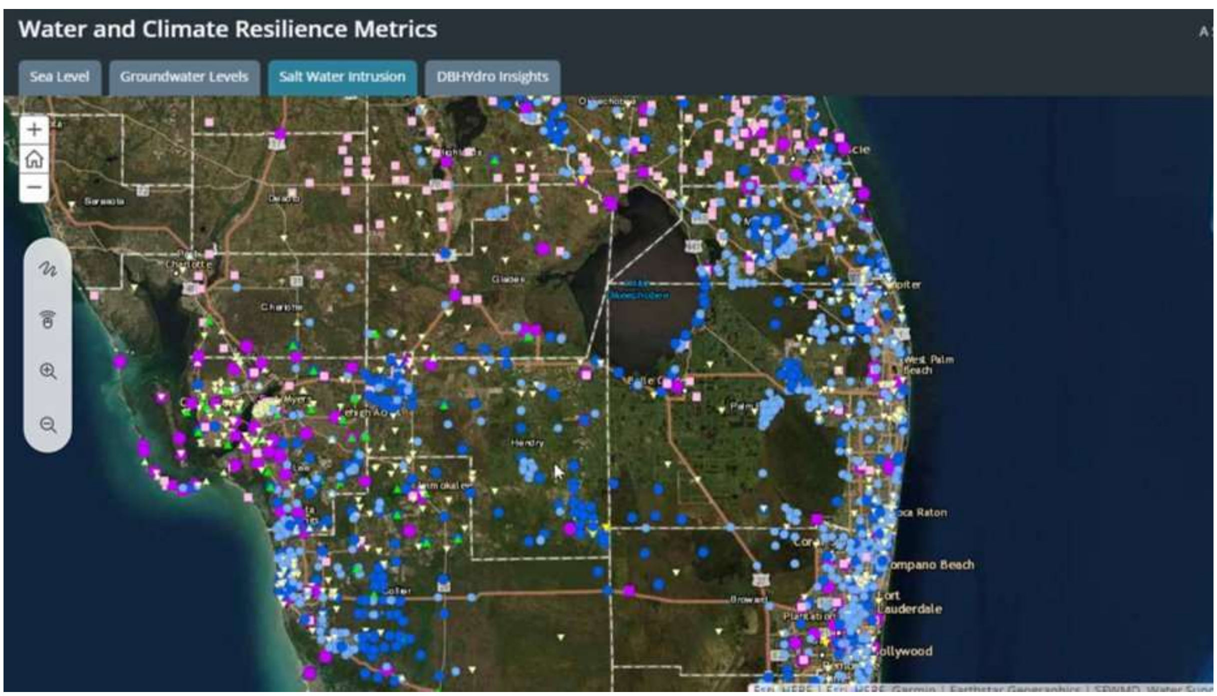


Figure 81. Prototype of water and climate resilience metrics story map interface.

DBHYDRO Insights

The DBHYDRO Insights tools (**Figure 82**) can support assessment of trends, shifts, and anomalies in selected data and automate the display and access of the selected metrics. DBHYDRO Insights is where publicly available District data are integrated, reimagined, and rebuilt in the context of how data are used by end users.

The tool has data mining algorithms embedded in the existing analyses to determine trends and potential climate impacts association. In addition, the tool was developed such that it provides the user with an easy interface linked to a spatial format, allowing the user to zoom to areas of interest and obtain pertinent data. Automation of the water and climate resilience metrics should be possible using the existing infrastructure and resources developed as part of DBHYDRO Insights.

Subject to the evaluation and approval from the Hydro-governance Committee, a Climate Resiliency Lens might be developed, through which the prepared metrics data can be visualized. Additional data mining techniques would need to be built into the metrics data generation.

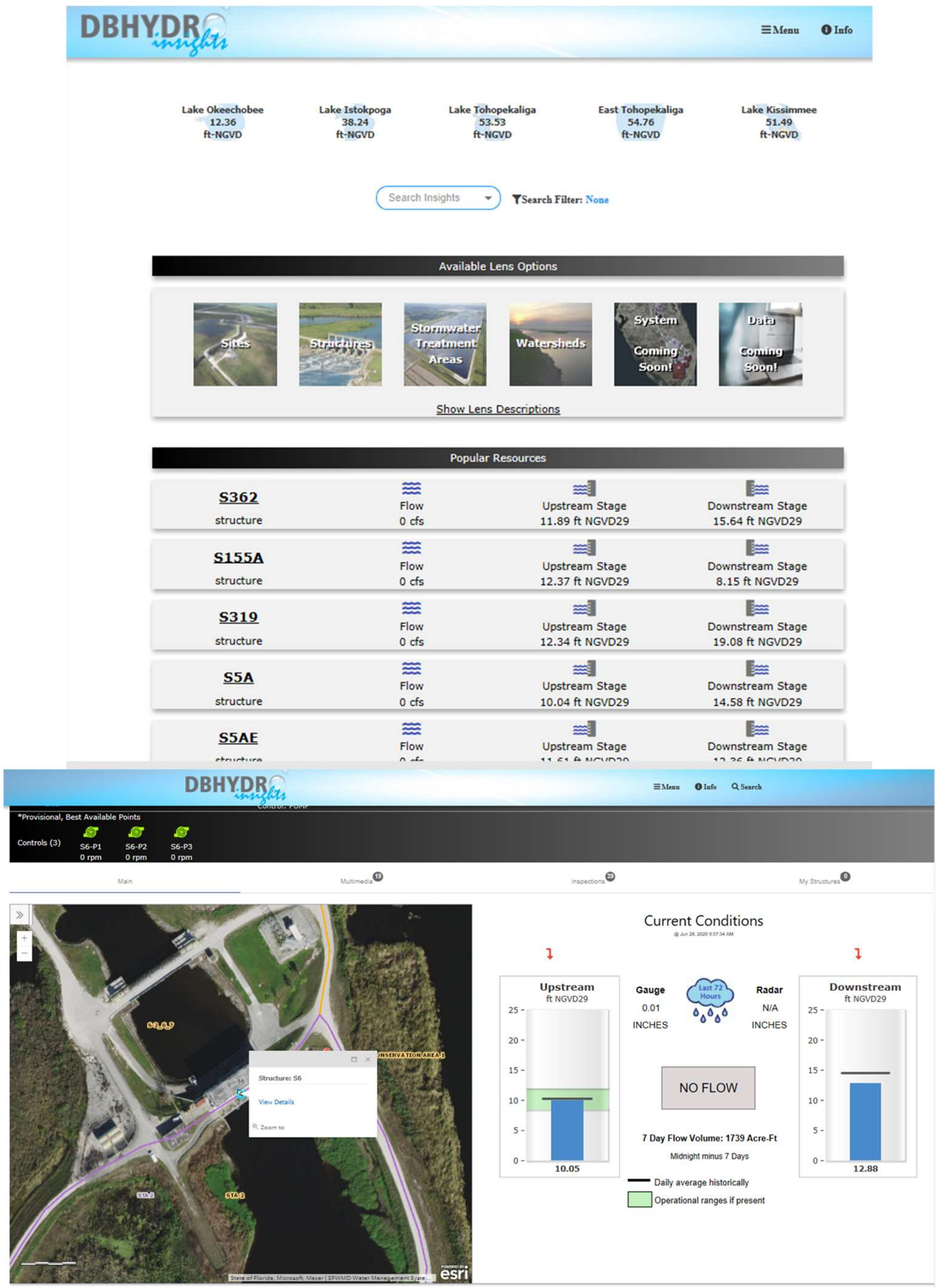


Figure 82. DBHYDRO Insights interface.

FINAL COMMENTS AND NEXT STEPS

SFWMD continues to be a leader in resiliency efforts and routinely works with stakeholders, local governments and experts to develop strategies and project plans to ensure the District's infrastructure can respond to the changing conditions like increased sea level rise and rainfall. The District's resilience efforts support its mission of safeguarding and restoring South Florida's water resources and ecosystems, protecting communities from flooding, and ensuring we are able to meet South Florida's water needs.

As summarized in this report, observed trends in metrics associated with flood protection will pinpoint critical areas to enhance the evaluation and assessment of effectiveness and resilience of the flood control system infrastructure, and continuous long-term effects on levels of service. They may also help to identify C&SF system adaptation and mitigation strategies necessary to continue providing primary flood protection for South Florida. Observed trends in water supply and water quality metrics, including the movement of the saltwater interface, will help in the continuous development of alternative water supply projects and promotion of additional water conservation efforts to increase the security and diversity of water resources, for their multiple uses. Observed trends in ecosystem will increase the District's ability to better manage water for the benefit of the environment and people, as part of restoration efforts.

The selection of appropriate science-based water and climate resilience metrics, and associated data analysis processes, allows the tracking and documentation of long-term observed trends and shifts in District data, supporting the assessment of current and future climate condition scenarios and related operational decisions. They also provide a sound basis for District resiliency priorities. Communication of the information, data and trends identified in this report will update the District's stakeholders, general public and partner agencies and provide support in outlining resilience strategies to achieve the best solutions to future water and climate problems identified in South Florida. Periodic review of current and future results of this effort will be conducted as part of the South Florida Environmental Report.

The District is fortunate to have some of the premier subject matter experts in the fields of Hydrology and Hydraulics, Applied Sciences – Coastal, Lake, River, and Everglades Systems, Water Supply and Planning, Water Quality, and Hydro Data Management. Experts from these areas have attended initial informational gathering and planning meetings. These interactive exchanges and additional prioritization have defined an initial list of metrics including tailwater elevations at coastal structures, tidal stages and high tide events, groundwater levels, saltwater intrusion, minimum flows and minimum water levels, flooding events, rainfall, evapotranspiration, water temperature, dissolved oxygen, pH, specific conductance, estuarine inland migration, soil subsidence, and salinity in the Everglades. In addition, a selected group of representatives from partner agencies, stakeholders, and the general public have agreed to provide initial comments, which were incorporated in this report, and as part of the implementation steps.

Currently, the initial set of selected water and climate resilience metrics is being automated to be published into an interactive web portal, that provides navigation all the locations where data is available districtwide, as well as alternative mapping, chart, and graph options to display and communicate results. Future efforts will continue to determine better ways to assess and communicate climate trends and associated scientific observations, and will serve as the basis for the introduction of Phase II, which will be advancing the development of future scenario projections for the selected metrics, and a guidance for the modernization of the District's design standards.

In addition, the South Florida Environmental Report, beginning in 2022, will contain a new chapter – Chapter 2B – to summarize the technical results and scientific findings associated with the development and implementation of the Resilience Metrics. The content, to be rotated among the selected metrics each year, will be addressing the more complex analyses that seek to identify and describe the correlation with additional datasets and other influencing factors; observed shifts, inflection points, and multidecadal factors; contribution from population increase, land development and water management operations; and others. As data continue to be collected, new observations, trends, and interpretations will emerge, and it is anticipated these would be addressed as part of the annual South Florida Environmental Report. Initial recommendations for enhancing data monitoring were formulated as part of the analysis and interpretation the data, including the identification of spatial or type data gaps, suggesting revisions of the type, spatial distribution, or frequency of data collection.

While it's not the direct purpose of this project, stakeholder comments suggested whether the District could publish risk-based resilience metrics, for example the level of flood protection provided by the system in certain basins, or available water storage available in the system. The importance of also bring stormwater volumes as part of the set of resilience metrics, either through flow discharges, pumping rates, and/or canal stages were also included in several stakeholder comments. Wet season pumping increase, along with empirical evidence of flooding, have been document in critical basins and might serve as an indicator of increasing flooding risks and the need for infrastructure investments.

A final summary table is presented below, which categorizes the initial set of priority metric presented in this report as a climate metric or as a resilience metric. Climatic metrics are defined as the primary drivers of change. Resilience metrics are defined as the consequences of climate change. This determination has been included to support the understanding about the role of the District in directing a course of action capable of influencing system changes, and to what extent that control exists with regards to the other contributing factors.

The future of successful water resources management in South Florida will be determined by the understanding of how climate-related long-term trends, and other associated changed conditions, are impacting its multiple objectives and needs, and the ability of the Region to provide flood protection, water supply and ecosystem restoration. The continuous assessment and availability of the water and climate metrics being established as part of this effort will be essential in achieving this understanding and informing South Florida's Resiliency Priorities.

> *"The report represents a comprehensive and insightful review of available data that will help guide the South Florida Water Management District in their many critical directives in water-resources management over the long term. Pulling all this information together and providing the data analysis makes this document invaluable not just for the District, but also many of the stakeholders and other resource-managers within the district boundaries. It may also serve as a template in pointing to data and analysis needed for long-term planning under changing conditions".* (Comment from stakeholder review)

Summary Table of the Water and Climate Resilience Metrics

Climate Metrics | Resilience Metrics

Metric	District Role/Control	Use (What It Is and What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)	Observed Trend & Influencing Factors & Recommendations
Rainfall	The District cannot control Rainfall. The effects on rainfall as a consequence of societal activities and regulatory policies set forth by other agencies are not controlled by the District.	Rainfall is used to determine the water budget, forecast inflows to the system, plan the management of water resources, and drives water management operations.	Annual trend analysis provides insights about the overall annual average rainfall. Regional trend analyses on daily maxima, daily minima, and peaks over/under thresholds for selected return frequencies and durations are necessary to fully understand impacts of rainfall on flooding, water supply, and droughts.	Regional trend analyses of 83 years of data show that rainfall trends vary between the District's 14 rainfall regions and within the wet, dry, and transitional seasons on a monthly and annual basis. Spatial variability of rainfall is large and highly influenced by the oceans surrounding the Florida peninsula, the large lakes within it, and the inland flow of coastal sea breezes as well as tropical storms and hurricanes that typically bring heavy rainfall to the regions The results emphasize the need for continuous rainfall frequency and total rainfall trend analysis as well as model projections.
Evapotranspiration	The District cannot control Evapotranspiration. The effects on rainfall as a consequence of societal activities and regulatory policies set forth by other agencies are not controlled by the District.	Together with Rainfall, Evapotranspiration drives the hydrologic cycle and water budget.	Evapotranspiration will increase in a warming climate and impact seasonal patterns and trends in precipitation. During prolonged rain events increased Evapotranspiration will contribute to seasonal rainfall amount, increasing demand on the water management system (due to associated canal levels, flooding, etc.). During drought events Evapotranspiration will deplete already limited water supply. Evapotranspiration data trends inform the District system requirements.	Historical data from 1961 to 2020 shows an upward trend in Evapotranspiration, specifically potential ET. Enhanced Evapotranspiration monitoring that is uniform and consistent during collection is needed to develop more reliable trend analyses for future projections.
Tidal Elevations at Coastal Structures	Tidal elevations at coastal structures are partially controlled by the District. Tidal Elevations at Coastal structures impacted by the activities of other jurisdictional agencies are not controlled by the District.	Headwater (freshwater canal levels) and tailwater (tidal levels) elevations are the drivers of stormwater discharge operations. Coastal structures need to be opened to release stormwater as part of flood control operations and they need to be closed during high tailwater conditions to prevent saltwater intrusion inland. Coastal structures are a vital component of the maintenance and compliance strategy for the Biscayne aquifer Minimum Flow and Minimum Water Level (MFL).	Long-term data trends concurrently with flood level of service performance data inform the District on the limitations and deficiencies of flood control infrastructure. This information provides guidance on the priority investments where resources are most needed for adaptation planning and mitigation strategies.	Over the past 35 years, an upward trend in high tailwater conditions was observed at various coastal structures using long-term time series plots of daily tailwater elevations/stages.
High Tide Events	Tidal Stages and High Tide Events cannot be controlled by the District.	High tide events represent extreme values of the tidal stages used to assess trends in sea level rise and identify potential flooding hazards, risks to water supply, and impacts to structural design standards.	Long-term data trends in tidal stages and high-tide events, future projections, and level of service performance inform the District on the limitations and deficiencies of natural and structural assets. This information provides guidance on where the District might allocate resources for adaption strategies and planning.	High tide events and increased tidal stages exceeding predetermined design standards at coastal structures are becoming more frequent and more intense as observed in daily maximum sea level time series and upward trending monthly average mean sea levels.
Groundwater Levels / Elevations / Stages	Groundwater Levels may partially be controlled by the District. In urban areas water levels can be manipulated in canal systems. Higher sea levels that increase hydrostatic pressure and impact groundwater cannot be controlled.	Groundwater level data is used to monitor water supply, for surface water and groundwater modeling, to establish MFL criteria and compliance, and permitting reviews. Groundwater levels at key sites are evaluated weekly as indicators of potential water shortages.	Trends in groundwater level data inform a broader understanding of the impacts of sea level rise in terms of timing and extent of groundwater stages during the wet season, threats to water supply, the need for additional monitoring, mitigation strategies, and places the need for communicating risks through visualization at the forefront of resilience planning. Data are available for long-term groundwater level trends for the surficial, intermediate, and Floridan aquifer systems. Data also are available through the USGS Water Level and Salinity Analysis Mapper online tools, showing trends over the past 20 years.	Since the late 1980s, a gradual shift in the hydraulic gradient (of groundwater) between inland areas and coastal areas has been observed. Historically, higher groundwater levels were observed inland and lower groundwater levels were observed along the coast, indicating a seaward gradient. Today, increasing groundwater levels and groundwater stages are being observed at coastal monitoring sites and several inland monitoring sites as a result of sea level rise. These increased groundwater levels at the coast diminish the freshwater head inland, reversing the gradient from coastal areas towards inland areas and exacerbating saltwater intrusion. This trend is expected to continue as denser saltwater pushes up the overlying fresh water along the coast due to sea level rise .
Saltwater Intrusion / Saltwater Interface - Chloride Levels	The Saltwater Interface may partially be controlled by the District. The water management system has some/limited/variable capacity to maintain higher elevations in inland canal systems to stall saltwater intrusion.	Analytical chloride data is used to monitor freshwater aquifers and map the inland movement of saltwater.	Historical and projected movement of saltwater inland together with current water use data and future water use projections identifies vulnerabilities to public water supply utilities. Saltwater Intrusion has a larger impact in water use permitting as an increased number of wells/wellfields/utilities vulnerable to loss of supply or reduced availability during droughts are identified to be at risk or of concern.	Between 2004 and 2019, isochlar line data has shown a persistent inland movement of the saltwater interface during each mapping/map publication interval. Chloride concentration time series data and graphics from the USGS Water Level and Salinity Analysis Mapper webtool show upward trends at various monitoring wells and supports/agrees/is in line with District findings.
Minimum Flows and Minimum Water Levels (MFLs) – Exceedances/Violations	The District monitors exceedances and violations of MFLs within each water supply region to identify priority water bodies and develop recovery and prevention strategies. Through water management, operational, and regulatory practices the District may achieve recovery status.	MFLs identify a range of water levels and/or flows above which water could be permitted for consumptive use and are established to protect water resources from any harm that may result from permitted water withdrawals and to safeguard water quantities necessary for navigation and recreation and for fish and wildlife habitat. Minimum levels have been established for lakes, wetlands and aquifers. Minimum flows have been set for rivers, streams and estuaries. Flow and level data are used to ensure that waterbody's are in compliance with their minimum requirements and identify the occurrence of exceedances and violations.	MFL data identify threats to water supply and ecosystems, and the need to develop recovery or prevention strategies in cases where a water body currently does not or will not meet an established MFL. The MFLs program supports the District's regional water supply planning process, permitting criteria for the consumptive use permitting program, and the environmental resource permitting program. MFLs are used in decision making and affect permit applications as water uses cannot be permitted that cause any MFL to be violated. MFL data is also used in assessments of water supply sources and declarations of water shortages.	To establish MFL criteria/compliance/exceedances and violations as a resiliency metric there is a need to differentiate natural processes that could be associated with climate change from processes related to operational decisions within the system which the upstream stage mainly depends on. Waterbodies in compliance with their MFLs maintain the water levels required upstream to prevent the movement of salt water downstream in coastal areas. In Miami-Dade County, at MFL structures where there is reduced/insufficient upstream freshwater head the saltwater interface has been observed moving farther inland. Enhancing the groundwater monitoring network and applying observational research in areas where saltwater is near potable water sources is recommended.
Flooding Events	The number of flooding events may be reduced through adaptation strategies and accounting for observed trends in driver metrics.	Flood data is used to assess and monitor (pattern, extent, and depth) flooding events that take place after storms and heavy rainfall, and extreme tides.	Comprehensive analysis of flood event data, together with other resilience metrics to determine long-term trends and possible shifts in climate, identifies where investments and reinforcements in flood control systems are necessary. Formally tracking trends of reported flooding and comparing to other trends, such as rainfall, will help determine if observed changes are part of a long-term trend or represent a shift in climate.	There is not a standardized and systematic process in place to collect flood occurence data.

Metric	District Role/Control	Use (What It Is and What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)	Observed Trend & Influencing Factors & Recommendations
Water Temperature	The District may partially control water temperature in the system through operational and management decisions.	Together with other water quality parameters water temperature is used to monitor water supply and aquatic and marine ecosystems.	Water temperature along with other water quality parameters inform effective water management practices and help asses restoration efforts. Resilience-driven interventions may reduce the impacts of poor water quality in critical areas and help identify areas that require the implementation of restoration strategies.	Monthly water quality data collected between November 1972 and June 2020 at six monitoring stations within Lake Okeechobee exhibits an increased trend in water temperature, however it is not statistically significant. Attributing variations in water temperature as a function of climate change is complex due to multiple cascading factors that influence water quality. Analyses of water quality parameters must differentiate between natural processes, anthropogenic activities, and operational rules from those associated with climate change.
Dissolved Oxygen	The District may control DO levels in the system through operational and management decisions.	Together with other water quality parameters dissolved oxygen is used to monitor water supply and availability for uptake in aquatic and marine ecosystems.	DO along with other water quality parameters inform effective water management practices and help asses restoration efforts. Resilience-driven interventions may reduce the impacts of poor water quality in critical areas and help identify areas that require the implementation of restoration strategies.	Monthly water quality data collected between November 1972 and June 2020 at six monitoring stations within Lake Okeechobee exhibited a statistically significant decreasing trend in DO. DO levels are controlled by physical and biological activities, analyses of water quality parameters must differentiate between natural processes, anthropogenic activities, and operational rules from those associated with climate change.
pH	The District may control pH in the system through operational and management decisions.	Water pH is an indicator that signals the chemical state and chemical changes within a waterbody. Together with other water quality parameters water pH is used to monitor water supply and aquatic and marine ecosystems.	Water pH along with other water quality parameters inform effective water management practices and help asses restoration efforts. Resilience-driven interventions may reduce the impacts of poor water quality in critical areas and help identify areas that require the implementation of restoration strategies.	Monthly water quality data collected between November 1972 and June 2020 at six monitoring stations within Lake Okeechobee did not exhibit a significantly change in pH. multiple cascading factors that influence water quality. Analyses of water quality parameters must differentiate between natural processes, anthropogenic activities, and operational rules where a shift or trend is observed from those associated with climate change.
Specific Conductance	The District may control specific conductance in the system through operational and management decisions.	Specific conductance is used to monitor water supply and aquatic and marine ecosystems. Analyses of specific conductance allows for the removal of altering variables and accounts for fluctuations in water temperature. High levels of specific conductance indicate a high amount of substances and chemicals dissolved in water. Conductivity may also be used as a conservative tracer to monitor the movement of water and contamination.	Specific conductance inform effective water management practices that promote resilience and helps asses restoration efforts. This metric identifies critical areas that require the implementation of restoration strategies.	Monthly water quality data collected between November 1972 and June 2020 at six monitoring stations within Lake Okeechobee exhibited a statistically significant decreasing trend in specific conductance levels. Over this period, specific conductance decreased by 40% from 680 µS/cm to 400 µS/cm. Analyses of water quality parameters must differentiate between natural processes, anthropogenic activities, and operational rules from those associated with climate change. The consistency in the ionic composition of dissolved substances in water must be considered in monitoring trends in specific conductance monitoring.
Estuarine Inland Migration - Everglades	The District can control the extent of Estuarine Inland Migration through water management by maintaining higher freshwater levels inland.	Estuarine and Mangrove Inland Migration is used to monitor shifts in species composition in freshwater marshes. Trends in Estuarine Inland Migration provide insights to the impacts of sea level rise in coastal areas and the Everglades.	Estuarine Inland Migration informs the District on the efficacy of water management practices in creating favorable conditions for marshes and mangroves to keep up with SLR. Together with the other climate metrics, information on Estuarine Inland Migration provides guidance to align/plan (future?) practices to adapt and mitigate for SLR and other climate change impacts.	Historical data show that between the mid-1940s and 1994, the boundary of inland mixed graminoid-mangrove and sawgrass communities had shifted inland by 3.3 kilometers. More recent data are limited and vegetation dynamics (composition, structure, and function) are influenced by changes in water quality and water management practices, oceanographic and atmospheric factors, and hardened shorelines, sea walls, and other coastal development prevent the inland migration of coastal habitat with sea level rise.
Soil Subsidence	The District can control the extent of Soil Subsidence through water management by maintaining higher freshwater levels inland and improving the physical and biological processes that promote accretion and subsurface root and peat accumulation.	Soil subsidence, or expansion, is the result of elevation change minus accretion rate, incorporating both surface and subsurface processes. The District has been studying mangrove environments in northeastern Florida Bay and Taylor River to determine soil subsidence at non-flooded, frequently flooded, and permanently flooded areas. The main objective of the study is to determine whether mangrove soil surface elevation can keep pace with increasing sea level rise.	The rate of Soil Subsidence informs the District on the effectiveness and benefits of Everglades restoration. This information guides water management practices that aim to uplift land to reduce the impacts of sea level rise and promote the seaward migration of coastlines (i.e. increasing freshwater input into the salinity transition zone of Taylor Slough).	Surface elevation table-marker horizon (SET-MH) data indicate some mangrove sites are not keeping pace with sea level rise rates, but other sites are keeping pace, underlying the importance of microtopography and hydrology to better determine the fate of mangrove forests in the Everglades. Trend analyses of soil subsidence are needed to better understand the rate of collapse or the mechanisms contributing to soil. While erosion and oxidation dominate the biogeochemical processes of soil formation and loss in the Florida Bay coastal mangrove environment, pulsing events, such as hurricanes and thunderstorms, likely play an important role in nourishing mangrove sites closer to the coast with inorganic matter imported from Florida Bay.
Salinity in the Everglades	The District can control Salinity through water management by maintaining higher freshwater levels inland.	Salinity is used to monitor water quality and evaluate the effectiveness of restoration strategies.	Salinity, along with various other metrics, inform the District on the effectiveness and benefits of Everglades restoration and guide water management practices.	Current data analysis does not indicate a clear trend. There is a need to differentiate natural processes, that could be associated with climate change and other physical and biological activities, from the influence of restoration strategies and related operational decisions.

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Appendix A
List of Relevant Water and Climate Resilience Metrics

Table 1. List of relevant water and climate resilience metrics, as indicated by the District's Internal Workgroup, along with data description and additional comments

Metric	Length of Data	Frequency	Agency	Data Options	District Mission	Additional Comments, Justification
Sea Level						
Tailwater (TW)/ headwater (HW) elevations at coastal structures	(1) HW, earliest start: 1966 HW, latest start: 2019 TW, earliest start: 1966 TW, latest start: 2019 HW: 17 years on average TW: 18 years on average Count HW: 451 Count TW: 415	Daily breakpoint Also gate opening time series	SFWMD	Trends – raw data, peak-over-threshold analysis	Water supply, flood control	Coastal structures need to be opened to release stormwater as part of flood control operations, and they need to be closed during high tailwater conditions to prevent saltwater intrusion inland, risking groundwater and drinking water system impacts. If the structures are closed for longer periods of time due to higher tailwater conditions, this may impact the ability to discharge and provide flood control at the design headwater. The increased length of time that coastal structures must be closed due to high tailwater conditions negatively impacts the efficiency of these structures to provide flood control, increasing flooding risks. This metric shows an upward trend over the past, with gates needing to be closed during higher tailwater conditions. This data set is unique to the SFWMD, and constitutes an important metric, mainly in respect to tidal coastal structures. Beyond flood protection, coastal structures have a very important function in protecting water supply from inland saltwater intrusion and increasing vulnerability at coastal wellfields. In the Lower East Coast, coastal structures are part of the prevention strategy for avoiding violations of the Biscayne aquifer Minimum Flow and Minimum Water Level (MFL).
Tidal stages	(2) TW, earliest start: 1984 TW, latest start: 2010 TW: 30 years Count TW: 30	Daily breakpoint	NOAA/SFWMD	Trends – raw data, peak-over-threshold analysis, % associated with storm surges and hightides	Water supply, flood control, ecosystem restoration	Tidal stages constitute a traditional metric being used by several agencies to monitor sea level rise. The occurrence of tide stages exceeding predetermined design standards is becoming more intense and frequent. This is an indication that flood risk, risk of saltwater intrusion impacts to drinking water and aquifers, as well as risk of impact to restoration efforts will also increase.
High tide events (extreme)	Data analysis from (2)	Daily breakpoint	SFWMD	Trends - raw data, peak-over-threshold analysis, duration	Water supply, flood control, ecosystem restoration	High tide events represent extreme values of the tidal stage. Tide levels above determined thresholds, also associated with storm surge, typically will increase the risk of saltwater reaching farther inland, especially where not blocked by coastal structures. In some cases, where structures are at a low elevation, there is increased risk of structure overtopping. The magnitude of high tides and duration over a particular stage is indicative of increasing flood hazard and risk to water supply and restoration.
Overtop of control structures (extreme)	Data analysis from (1) using bypass stage in structure	Daily breakpoint	SFWMD	Count, elevation duration extension	Water supply, flood control	This metric is associated with the tailwater/headwater elevation metric and might be impacted by physical changes in the control structures (e.g., raising of the gates, other hardening). There is a need to evaluate if information is captured in other metrics, with a more continuous series, over time.

Metric	Length of Data	Frequency	Agency	Data Options	District Mission	Additional Comments, Justification
Soil subsidence (elevation and accretion rates)	20 years	Annual	SFWMD	Trend elevations	Ecosystem restoration	Soil subsidence or expansion is the result of elevation change minus accretion rates, incorporating both surface and subsurface processes. The SFWMD has been studying mangrove environments in northeastern Florida Bay and Taylor River and in Shark River and Lostmans River in southwestern Florida to determine changes in soil elevation, accretion, and expansion rates. There are monitoring sites in several parts of Florida Bay and other areas in ENP. Data indicate some mangrove ecosystems are not keeping pace with current sea level rise rates and are migrating inland.
Coastal subsidence	6 years		SFWMD & FIU		Water supply, flood control, ecosystem restoration	This metric represents the effect of saltwater intrusion into freshwater and oligohaline marshes in the Everglades. The SFWMD is working with FIU's research team to measure coastal subsidence by artificially adding salt into freshwater soils and tracking salt intrusion in freshwater environment.
Storm surge		Event-based	NHC & NOAA	Peak-over-threshold analysis	Water supply, flood control, ecosystem restoration	This metric is related to the abnormal rise of water above predicted astronomical tides. The storm surge values can be accounted for as part of high tide metrics or separately.
Groundwater Levels						
Groundwater Levels	8 to 71 years (more robust from 1970s, some stations from 1950s)	Continuous monthly, bimonthly, quarterly, semi-annually, annually	USGS/SFWMD	Trends, peak-over-threshold analysis, sea level rise association in coastal locations – spatial extension, loss of soil storage	Water supply, flood control, ecosystem restoration	Groundwater level monitoring at key locations throughout the SFWMD for water shortage and wet season stages, as part of environmental resource protection regulation. Groundwater levels at key sites are evaluated weekly as indicators of potential water shortages. Data are available for long-term groundwater level trends for the surficial, intermediate, and Floridan aquifer systems. Data also are available through the USGS Water Level and Salinity Analysis Mapper online tools, showing trends over the past 20 years. Increasing groundwater stages are being observed as a result of sea level rise, including their inland extent.
Soil moisture	Since 2008	Daily, monthly	NOAA	Trends, peak-over-threshold analysis	Water supply, flood control, ecosystem restoration	This metric is related to drought conditions, including agriculture issues. It also can be linked to demands on the system for water supply. There may be a correlation with groundwater levels, through the establishment of peak-over-threshold analysis. This metric also can be linked to flood risks, as antecedent groundwater conditions.

Metric	Length of Data	Frequency	Agency	Data Options	District Mission	Additional Comments, Justification
MFL exceedance/ violation	Since 2002 (Biscayne aquifer, LWC aquifers, and Everglades – peat/marl gauges, Lake Okeechobee)	Daily	SFWMD	Count or duration of MFL criteria exceedance and violation events	Water supply, ecosystem restoration	This metric represents shifts in determining whether a water body is meeting its MFL, and the need to develop a recovery or prevention strategy, supported by the observed number of exceedances and violations. Maintaining a groundwater monitoring network and conducting research in areas where saltwater is near potable water sources are other prevention strategies. The MFLs for the Biscayne aquifer and Lower West Coast aquifers are reviewed and strategies are defined in water supply plans. Maximum Developable Limits for aquifers in the Lower West Coast aquifers. MFL prevention strategy is an associated metric. The SFWMD performs weekly analysis during water shortages for key Maximum Developable Limit monitoring stations throughout the Lower West Coast. There is a need for further evaluation to ensure the MFL complies over a 20-year planning horizon (required by statute).
Rainfall						
Wet and dry extreme events	(3) Earliest start: 1957 Latest start: 2020 22 years on average Count: 263	Daily breakpoint	SFWMD	Peak-over-threshold analysis, trends (extreme wet and extreme dry)	Water supply, flood control, ecosystem restoration	Spatial variability of rainfall is large and highly influenced by the oceans surrounding the Florida peninsula and the large lakes within. Typically, sea breezes from both coasts over the hot land surface form convective storms inland. In addition, tropical storms and hurricanes often bring heavy rainfall to the region. While annual trend analysis provides insights about the overall annual average behavior, it is important to perform regional trend analysis on daily maxima, daily minima, and peaks over/under thresholds for selected return frequencies and durations, with emphasis on flooding, water supply, and droughts.
Intensity, duration, and frequency curves	Data analysis from (3)	Daily breakpoint	SFWMD	Changes in intensity, duration, and frequency of storms	Water supply, flood control, ecosystem restoration	Similar to the previous metric (wet and dry extreme events), and represented in terms of changes in intensity, duration, and frequency of observed rainfall events.
Rainfall average, seasonality	Data analysis from (3)	Daily breakpoint	SFWMD	Changes in seasonality, average rainfall (increase/decrease)	Water supply, flood control, ecosystem restoration	While annual trend analysis provides insights about the overall annual average behavior, it is important to perform seasonality analysis and evaluate if shifts are observed in onset and demise dates.

Metric	Length of Data	Frequency	Agency	Data Options	District Mission	Additional Comments, Justification
Flooding						
Flooding events	Event-based data sets (not comprehensive)	Event-based	SFWMD/USGS/ FEMA	Frequency, extension, duration, depth	Flood control	The SFWMD has internal mapping tools to track and report major flooding events, usually associated with hurricane and tropical storm events. The tool was tailored to assist in transferring flood occurrences information, compiled from email and phone calls reported from the community, to the application for immediate needs. Formally tracking trends of reported flooding and comparing to other trends (such as rainfall) will help determine if observed changes are part of a long-term trend or represent a shift in climate. In order to track the duration, depth, and extension of flooding events Districtwide, it is necessary to create innovative solutions to map flooding occurrences, with the use of available drones, satellites, and radar images, in addition to establishing a crowdsourcing tool more widely advertised to support community reporting.
Agricultural area flooding	Event-based	Event-based	SFWMD	Depth and duration of inundation in root zone	Flood control	Some USGS wells in the South Dade Agricultural Area are monitored as part of the Combined Operating Plan. In addition, zoot zone control data is available in the EAA.
Drought						
Water restrictions/ shortages	Event-based	Weekly analysis during droughts	SFWMD/USGS	Number of events below certain thresholds, severe/extreme/ exceptional drought events frequency	Water supply, ecosystem restoration	Under warmer temperatures and increasing evaporating rates, severe/extreme/ exceptional drought events also show increasing frequency. There is a need to identify risk status for groundwater and surface water supply and implement water shortage orders, as needed. The SFWMD currently has multiple spreadsheets tracking occurrences, in addition to MFLs (see groundwater metrics above).
Natural wildfires	Event-based	Event-based	SFWMD	Frequency of occurrence?	Water supply, ecosystem restoration	Occurrence of natural wildfires is subject to increasing frequency. There is a need to determine if South Florida is becoming more vulnerable. This problem has been verified at Big Cypress National Preserve.
Water budgets/ wet and dry seasons	Daily breakpoint	Daily breakpoint	SFWMD	Changes in seasonality, trends	Water supply, ecosystem restoration	The timing and duration of the wet and dry seasons will affect SFWMD operations. There is a need to evaluate changes in monthly water budgets and assess trends, including changes in onset and demise dates. Also, historical data may be “muting” more recent climate trends and affecting the volume of water permitted.
Saltwater Intrusion						
Chloride Concentrations	Data from 1970s (most)	quarterly, annual	SFWMD, USGS, & others	Concentration time series trends, % of land subject to saltwater intrusion	Water supply, ecosystem restoration	The SFWMD is actively monitoring and mapping the location of the underground saltwater interface within freshwater aquifers. Increasing chloride concentrations impact water supply operations and have large implications over ecosystems. The SFWMD periodically conducts groundwater chloride sampling, contracts with the USGS for additional sampling, and analyzes data submitted by permittees to produce saltwater interface maps throughout most of the coastal regions. Data are available for long-term chloride concentrations in monitor wells in different aquifer systems.

Metric	Length of Data	Frequency	Agency	Data Options	District Mission	Additional Comments, Justification
Conductivity	Data from 1970s (most)	quarterly, annual	SFWMD, USGS, & others	Concentration time series trends, % of land subject to saltwater intrusion	Water supply, ecosystem restoration	Increasing conductivity (chloride conversion) levels impact water supply operations and have large implications over ecosystems. Additional data sets provided by utilities, the marine influence, and ratios of various ions to chloride (sodium/calcium/potassium) need to be assessed. Conductivity probes can give real-time data unlike chloride concentrations, which require sample testing.
Lateral saltwater intrusion into coastal public supply wellfields	Data from 1970s (most)	quarterly, annual	SFWMD & others	Number of wellfields relocated/vulnerable to saltwater intrusion and associated capacity	Water supply, ecosystem restoration	The total number of wells or wellfields within the saltwater front (including a 2- to 3-mile buffer zone to account for spatial and time variability). The Biscayne aquifer MFL prevention strategy includes conducting research in high-risk areas where the saltwater interface is adjacent to potable water sources.
Everglades marshes – saltwater intrusion			SFWMD/FIU	Trends, peak-over-threshold analysis, extension	Water supply, ecosystem restoration	The effect of saltwater intrusion into freshwater and oligohaline marshes in the Everglades.
Temperature						
Water temperatures	(4) Earliest start: 1988 Latest start: 2019 12 years on average Count: 62	Daily Breakpoint	SFWMD & others	Peak-over-threshold analysis, trends, seasonality	Water supply, ecosystem restoration	Trend analysis of water temperatures in ocean, lakes, canals, etc., as a result of increasing atmospheric temperature.
Algae (microalgae, phytoplankton)	Data analysis from (4)	Daily breakpoint	SFWMD & others	Peak-over-threshold analysis, raw data trends, duration, seasonality	Water supply, ecosystem restoration	Algae occurrence can be determined in association to water temperature and other variables. Data are only available for the last couple years on species composition. There is no long-term time series of chlorophyll a concentration, which would provide information on the types of microalgae present. The SFWMD is supporting the LOMS network, with more continuous monitoring in Lake Okeechobee. At times when there are no other inhibiting factors present (i.e. wind), warmer temperatures during bloom months could create conditions that allow algal blooms to occur more intensively and frequently, possibly as result of climate change. The SFWMD is increasing monitoring in lakes and estuaries. There is a need to evaluate available information from other agencies to relate species of algae growth versus temperature. There is not enough data to perform an analysis at this time.
Evapotranspiration	(5) Earliest start: 1992 Latest start: 2008 18 years on average Count: 35	Daily breakpoint	SFWMD & others	Peak-over-threshold analysis, raw data trends, seasonality	Water supply, ecosystem restoration	Besides precipitation or rainfall in South Florida, evapotranspiration (ET) is the other most significant component of the hydrologic cycle and water budget. ET rate is mainly affected by solar radiation, along with air temperature, relative humidity, and wind speed, and it represents changes in drought vulnerability. During a drought, the significance of ET is magnified. From a water supply perspective, the ET metric is as important as rainfall.

Metric	Length of Data	Frequency	Agency	Data Options	District Mission	Additional Comments, Justification
Solar Radiation, Winds			USGS	Trends, peak-over-threshold analysis	Water supply, flood control, ecosystem restoration	As part of hurricane and storm surge studies, some research projects aim to estimate the association of winds, radiation, etc., as a result of changing climate. The USGS radar rainfall dataset also includes solar radiation, that goes back to 1995 or earlier.
Air temperatures	(6) Earliest start: 1988 Latest start: 2008 23 years on average Count: 23	Daily breakpoint	SFWMD & others	Trend, seasonality, days over threshold values	Water supply, ecosystem restoration	This is a traditional climate resiliency metric. The link with water use rates should be evaluated, as increasing temperatures result in increasing water use.
Stormwater						
Canal flows	(7) Earliest start: 1961 Latest start: 2020 19 years on average Count: 687	Daily breakpoint	SFWMD	Extreme values, frequency of flow type changes at coastal spillways	Water supply, flood control, ecosystem restoration	This metric represents changes in stormwater volumes and overall operation of primary canals, including changes in canal discharge capacity (primary system and sub-basins, at critical control points). Pump stations are especially important, as they move water from low to high, and if they are deficient, flooding can overwhelm the pump capacity and flood mitigation takes longer.
River Channel flows	Baseline data water years 1970s - 1999. Reference conditions water years 1930s – 1960s.	?	SFWMD	Extreme values, frequency of flow type changes, variability of flow	Water supply, flood control, ecosystem restoration	Continuous river channel flows data are available at Kissimmee Basin. Changes in seasonal weather patterns (El Niño, for example) can result in altered restoration performance. Regulation schedules assume the start of the wet season is June 1. Extreme dry spells, possible to occur in the future, will make it very difficult to achieve 210 continuous days of floodplain inundation (flows above 1400 cfs). Climate change may result in weather patterns different than years of which were used in hydrologic simulations to estimate performance. Altered flow patterns could alter the District's ability to replicate historic stage hydrograph conditions. Atypical dry season weather can cause either too steep a recession, reversals, or both.
Stormwater treatment area efficiency/ biological/ ecological functions		Daily, hourly	SFWMD	Increasing stormwater volumes and efficiency? Phosphorus removal rates/exceedance?	Water supply, flood control, ecosystem restoration	Stormwater treatment area efficiency can be a metric to represent the changing biological and ecological functions impacted by shifting temperature and potential increasing stormwater volumes. Ecological variables are more difficult to tease out of data than physical effects of increasing water volumes, and it could take many years to be evaluated. The SFWMD has some ecological data sets that can be analyzed to assess climate change impact. Determining a climate change signal might be complex. Some considerations need to be evaluated regarding how data are collected, which would result in additional investigations.

Metric	Length of Data	Frequency	Agency	Data Options	District Mission	Additional Comments, Justification
Lake and wetlands stages	Data analysis from (7)	Daily breakpoint	SFWMD	Trends, peak-over-threshold analysis	Water supply, flood control, ecosystem restoration	This metric represents the wetland health and changes in regional hydrology over a multi-decadal time frame. It can be linked to water quality indicators and influenced by inland migration of the salt waterfront as a result of sea level rise. Kissimmee Upper Basin and Lake Okeechobee stages and storage capacity are affected by changes in extremal rainfall (and runoff) patterns, which may result in more frequent and extreme high and low stage events. Intensity of rainfall will further inhibit management of Spring recessions. Operational decisions and controlled elevations have large influence on water levels.
Storage capacity	Data analysis from (7)	Daily breakpoint	SFWMD & 298 Districts	Trends, peak-over-threshold analysis	Water supply, flood control, ecosystem restoration	This metric represents the total storage volumes available and variations in response to extreme events. The metric can also represent the water available for water supply deliveries to coastal canals for salinity control, aquifer recharge, etc.
Water Quality						
Dissolved oxygen	1972 – 2020 (Lake Okeechobee)	Varies	SFWMD & others	Concentration time series, peak-over-threshold analysis, trends (critical locations)	Ecosystem restoration	Dissolved oxygen (DO) is a measure of the amount of oxygen dissolved in water and available for aquatic organisms. DO concentrations change over the diel cycle because of changes in water temperatures, primary productivity (e.g., photosynthesis), respiration, and other biochemical interactions. DO concentrations exhibit a seasonal signal, with higher concentrations during cooler months (when saturation increase) and lower concentrations during warmer months. DO levels are controlled by physical and biological activities, and analyses need to differentiate natural processes that could be associated with climate change. At Kissimmee River, temperature and more extreme rainfall events causing rapid increase in water depth, discharge rate or both can cause reductions in river channel DO. Several projects monitor this parameter at various inland, non-estuarine and coastal estuarine locations throughout the SFWMD. Frequency of collection varies among projects.
Total maximum daily load (TMDL)	Varies	Varies	SFWMD & others	Concentration time series (and water volumes), peak-over-threshold analysis, trends, change in maximum loads	Ecosystem restoration	TMDLs are set by the Florida Department of Environmental Protection to establish limits of pollutants in water bodies that do not meet water quality standards and are identified as “impaired” for pollutants of concern. Assimilative capacities of pollutants and loading rates could be changing as a result of increasing stormwater volumes. For instance, Lake Okeechobee levels and TMDLs in relationship to downstream lake releases and net loading would need to be evaluated.
Relict seawater	Varies	Varies	SFWMD & others	Trends, peak-over-threshold analysis	Water supply	This metrics is related to upconing occurrences and associated high conductivity in dry/wet events at public water supply wellfields (e.g., Wellington, Seacoast, Piccolo), intersecting regional canals in western Palm Beach County (Everglades Agricultural Area, water conservation areas, L-8 flow equalization basin).

Metric	Length of Data	Frequency	Agency	Data Options	District Mission	Additional Comments, Justification
Salinity (see above, under Saltwater intrusion)	Varies	Varies	SFWMD, USGS, & others	Trends, peak-over-threshold analysis	Ecosystem restoration	Several projects monitor this parameter at various coastal and estuarine locations throughout the SFWMD. Frequency of collection varies among projects.
Algae (microalgae, phytoplankton)	Varies	Varies	SFWMD & others	Concentration time series, peak-over-threshold analysis, trends, duration, seasonality	Ecosystem restoration	This metric represents microalgae occurrence linked to water quality aspects, water temperature, and association with climate change impacts. Data only are available for the last few years (there is no significant time series). The SFWMD is supporting the LOMS network, with more continuous monitoring in Lake Okeechobee and Kissimmee Upper Basin. At times when there are no other inhibiting factors present (i.e. wind), warmer temperatures during bloom months could create conditions that allow algal blooms to occur more intensively and frequently, possibly as result of climate change. Wind associated with tropical disturbances conversely can reduce HAB frequency. The SFWMD is increasing monitoring in lakes and estuaries. Information may be available from other agencies to relate species of algae growth versus temperature. It might be possible to perform an analysis for an initial set, but there may not be enough data at this time. One observation is the removal of the "Harmful Algae Bloom" designation as a metric. Not all algal blooms are designated as harmful and there are no well-developed correlations made to predict the dominating toxin-producing algae in these regions and specific environmental triggers. Algal blooms are very complex to understand because it takes very little in terms of environmental condition (e.g., temperature, flow, season, precipitation) and water quality (namely nitrogen and phosphorus) changes to stimulate an algal population. In general, excess nutrients, warmer water temperatures, and increased residence times drive algal population growth. However, less is known about the combined forces that stimulate an algal bloom, harmful or otherwise. Additionally, many toxin-producing algae can be discriminant in whether they produce toxins or not and at what concentration. Harmful algae bloom data from the SFWMD are limited, primarily event-driven, and collected in coordination with other agencies.
pH	1972 – 2020 (Lake Okeechobee)	Varies	SFWMD & others	Concentration time series, peak-over-threshold analysis, trends, discharge to estuaries	Ecosystem restoration	Water pH is a measure of the acidity/basicity of water with respect to hydrogen ions. In surface waters, pH can be affected by the geology, rainfall, chemical interactions, photosynthetic activity, and respiration, which includes bacterial decomposition of organic matter. Estuarine pH shifts with increasing saltwater, and pH likely will decrease with increases in atmospheric carbon dioxide. pH is controlled by physical and biological activities, and analyses need to differentiate natural processes that could be associated with climate change. Several projects monitor this parameter at various inland, non-estuarine and coastal estuarine locations.

Metric	Length of Data	Frequency	Agency	Data Options	District Mission	Additional Comments, Justification
Specific conductance	1972 – 2020 (Lake Okeechobee)	Varies	SFWMD & others	Concentration time series	Ecosystem restoration	Specific conductance measures the ability of water to carry an electrical current, varying by types and amounts of ions present in solution, and is an indirect measure of the presence of dissolved solids. Variations in specific conductance levels are caused by evaporation, rainfall, geology of a watershed, and groundwater interactions. Anthropogenic activities can influence specific conductance levels. Specific conductance is controlled by physical and biological activities, and analyses need to differentiate natural processes that could be associated with climate change. Several projects monitor this parameter at various inland, non-estuarine and coastal estuarine locations.
Nutrients (total phosphorus)	1972 – 2020 (Lake Okeechobee) Water Year 1981 to Present (Lake Okeechobee Watershed) 2005 – present (Kissimmee Upper Basin)	Varies	SFWMD & others	concentration time series, peak-over-threshold analysis, trends, discharge to estuaries	Ecosystem restoration	Phosphorus is an essential nutrient for aquatic organisms in surface water bodies. Excessive phosphorus levels will lead to eutrophic conditions and result in an imbalance of flora and fauna. High phosphorus levels in Lake Okeechobee have been associated with anthropogenic sources (including septic systems) and driven by rainfall amount overall. Peak total phosphorus concentrations typically occur during the dry season, as wind activity associated with winter fronts occur, as well as resuspension of bottom sediments along with stormwater inflows associated with tropical storm events. Increases in nutrients in tidal areas may indicate saltwater intrusion influence as a result of sea level rise. Total phosphorus is controlled by physical and biological activities, and analyses need to differentiate natural processes that could be associated with climate change. Several projects monitor this parameter at various inland, non-estuarine and coastal estuarine locations. Total Nitrogen, Total Phosphorus, Pelagic Total Phosphorus, Pelagic Total Nitrogen and Nearshore Total Phosphorus data are also available for Lake Okeechobee and its Watershed. At Kissimmee Upper basin, altered rainfall patters may also directly affect Total Phosphors and other water quality parameters.
Regional Floridan Groundwater Monitoring Network			SFWMD	trends, peak-over-threshold analysis	Ecosystem restoration, water supply	The SFWMD samples the Floridan aquifer system annually to evaluate baseline conditions and identify trends in groundwater quality. Overexploitation of this resource will show up as declines in water quality. The Floridan aquifer system is an alternative public water supply source when the surficial aquifer system is limited by saltwater intrusion or Everglades/Loxahatchee MFLs.

Metric	Length of Data	Frequency	Agency	Data Options	District Mission	Additional Comments, Justification
Ecology/Habitat						
Seagrass	1998 – Present	Varied: monthly transects, biannual in estuary survey, biennial aerial map surveys	SFWMD	Shifts in composition, abundance and distribution, frequency, extension, and density	Ecosystem restoration	Seagrass data contain important metrics that can be explored by assessing shifts in species composition due to temperature and/or salinity changes; duration to recolonization after extreme climatic events; displacement by other benthic habitat types; and declines due to water quality, specifically high color and turbidity causing shading. Research indicates that increases of carbon dioxide could favor seagrass development. Check RECOVER reports for all habitat parameters.
Submerged aquatic vegetation	1991 - 2019	?	SFWMD	Shifts in composition and distribution, frequency, extension, and density	Ecosystem restoration	Submerged aquatic vegetation is monitored at Lake Okeechobee and Kissimmee Upper Basin, and might be affected by changes in turbidity, wind and other variables. Increasing tropical disturbance frequency and strength, possibly as a result of climate change, might affect turbidity. Other altered environmental conditions (temperature, rainfall, stages) will also cause changes in the abundance, distribution, and species composition of submerged vegetation. This metric is also relevant to other estuaries within the District boundaries.
Oyster distribution/ density	2005 – Present	Varied: monthly spat, disease, quarterly or biannual density	SFWMD	Shifts in distribution, frequency of shifts, extension, density	Ecosystem restoration	Monitoring the status of oyster populations in South Florida requires collecting data concerning spatial and temporal changes in oyster density, health, and reproductive status at established sentinel locations. This includes the prevalence of parasitic infections, which respond to changes in salinity and temperature, the recruitment rate, growth, survival, and repopulation after extreme climatic events or high discharge events.
Peat collapse	2014 – 2019	Monthly	FIU & SFWMD	Elevation trends, peak-over-threshold analysis, extension	Ecosystem restoration	Pre-drainage Everglades had a peat depth of 2 meters, a peat volume of 20 billion cubic meters, and a carbon content of about 900 million metric tons. Currently, the Everglades have a peat depth of 0.75 meters, a peat volume of 5 billion cubic meters, and a carbon content of about 200 million metric tons. Ongoing research, funded by SeaGrant, is conducting salt dosing experiments in ENP and data from the past 5 years show the elevation change in mangrove environments.
Nutrients and salinity at Everglades	1995 – Present	Daily	FIU & SFWMD	Shifts in distribution, density, extension	Ecosystem restoration	The SFWMD oversees a comprehensive ecological monitoring program in the southern Everglades wetland marshes, Florida Bay mangrove transition zone, and estuarine waters of Florida Bay to evaluate the effects and benefits of Everglades restoration funded through RECOVER. Metrics include water stages, salinity, submersible aquatic vegetation, and prey fish community. Increased salinity and nutrients into the Everglades and other fresh water might alter habitat both in the water and on the floodplain (i.e., cypress getting replaced with mangrove in the Loxahatchee).

Metric	Length of Data	Frequency	Agency	Data Options	District Mission	Additional Comments, Justification
Estuarine and Mangrove forests inland migration	1940 – 1994 – 2017	Pre- and post-conditions, about every 10 years	SFWMD, FIU, ENP	Shift in extension, density, distribution	Ecosystem restoration	This metric represents estuarine and mangrove inland migration, where natural habitat is available, and to the north, including shifts in species composition in freshwater marshes. In the mid-1940s, the marshes in the southeastern saline Everglades were arranged in well-defined plant communities running parallel to the coast, with shrub mangroves dominating along the coast. By 1994, the boundary of the inland mixed graminoid-mangrove and *Cladium* communities had shifted inland by 3.3 kilometers. Recent data are limited. Hardened shorelines, sea walls, and other coastal development prevent the inland migration of coastal habitat with sea level rise.
Alligator sex ratios		Bi-annual		Shift in distribution.	Ecosystem restoration	RECOVER-supported monitoring effort.
Floodplain and Littoral Vegetation	Reference condition 1952 - 1954; baseline data 1973 - 1974	?	SFWMD	Shift in annual distribution / extension / density	Ecosystem restoration	At Kissimmee River, broadleaf marsh requires particular floodplain inundation frequency and duration to flourish and meet expectation. At Kissimmee Upper Basin, altered environmental conditions (temperature, rainfall, stages) will likely cause changes in the abundance, distribution, and species composition of littoral vegetation.
Birds, fish and threatened and endangered species	Baseline 1996 - 1998; no reference condition data	?	SFWMD	Shifts in annual / season totals	Ecosystem restoration	Birds, Fish and threatened and endangered species metrics are included as part of Kissimmee River restoration goals. Increased temperatures and extreme rainfall, possible to occur in the future, can reduce the suitability of river channel and fish nursery environments at the river floodplain. Climate change may have a "domino effect" on bird populations, beginning with altered rainfall patterns, that can reduce floodplain inundation frequency and duration, altering floodplain vegetation, reducing prey base and reducing bird foraging.
Invertebrates, Herpetofauna	Limited Data	?	SFWMD	Shift in annual distribution	Ecosystem restoration	Changes in temperature and rainfall may alter invertebrates and herpetofauna habitat suitability at Kissimmee River.

ENP = Everglades National Park; FEMA = Federal Emergency Management Agency; FIU = Florida International University; NHC = National Hurricane Center; NOAA = National Oceanic and Atmospheric Administration; SFWMD = South Florida Water Management District; USGS = United States Geological Survey.

APPENDIX B
Site Specific Rainfall Analysis

Site Specific Rainfall Analysis

Rainfall observation and data collection have been significantly improved over the past 30 years. The District has the up-to-date Thiessen polygon-averaged rainfall data in the DBHYDRO database (starting 1992, period of record = 28 years), as illustrated in **Figure B01**. Radar rainfall also are available through DBHYDRO, starting with 1996 (period of record = 24 years). Next Generation Radar (NEXRAD) or Weather Surveillance Radar 88 Doppler (WSR-88D) data provide complete spatial coverage of rainfall amounts at a grid resolution of 2x2 km^2. While NEXRAD cannot measure rainfall directly, it does measure raindrop reflectivity, which is then converted to water depth by matching the rainfall volume measured at ground rain gauge(s). Once the calibration is established, NEXRAD provides an opportunity to improve the spatial estimation of rainfall amounts and has used for comparison in **Figure B02**, which shows a high correlation between the Thiessen polygon averaged and the NEXRAD data. Years with low rainfall correspond well to drought years with high insolation index (e.g., 1996, 2000, 2006, 2007).

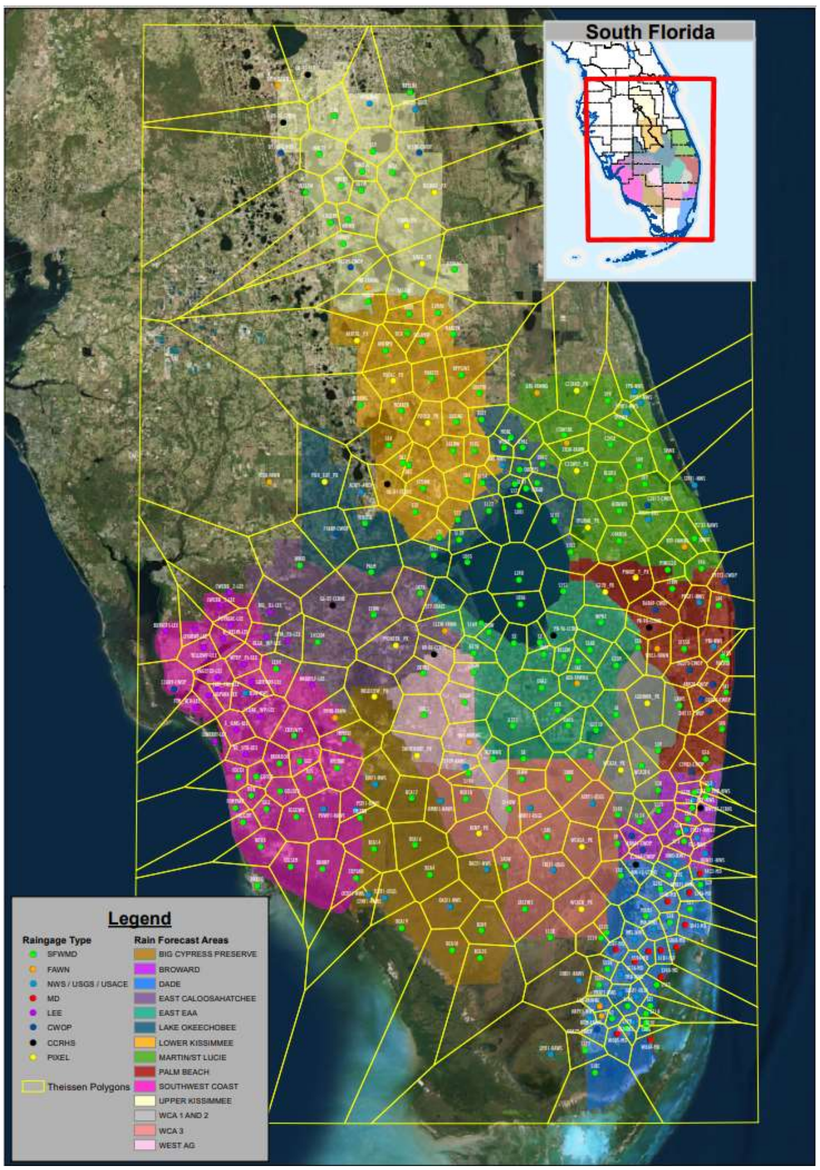


Figure B01.Ground rain gauges and Thiessen polygons covering the District's jurisdiction.

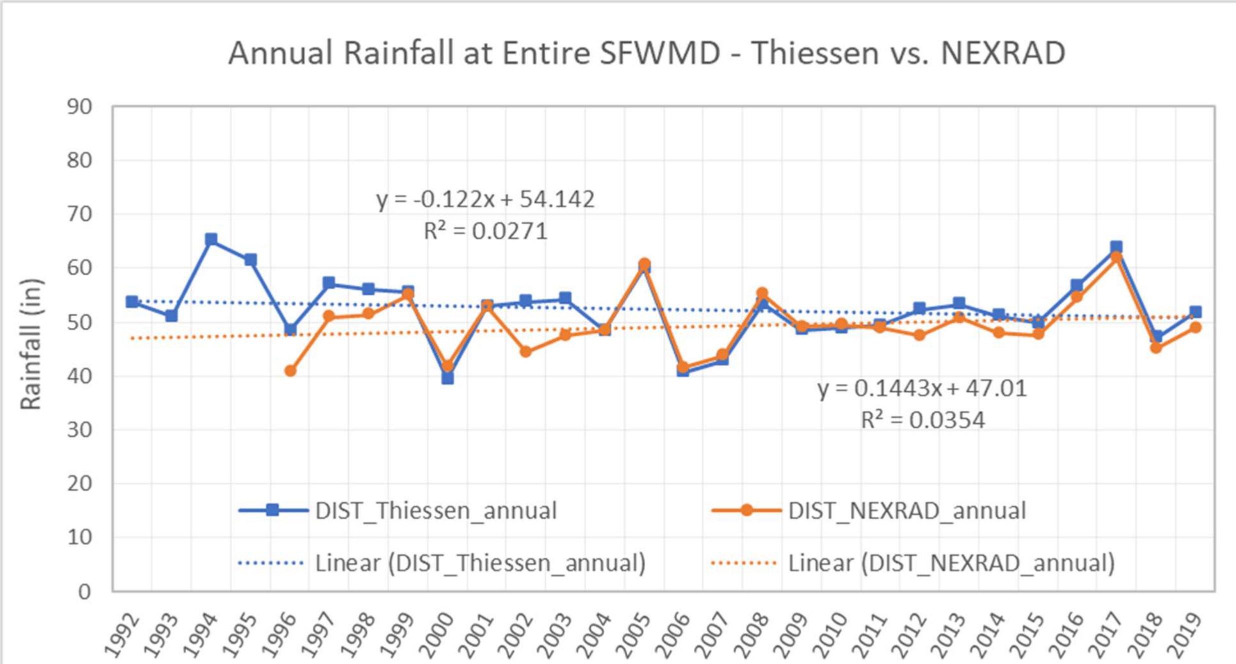
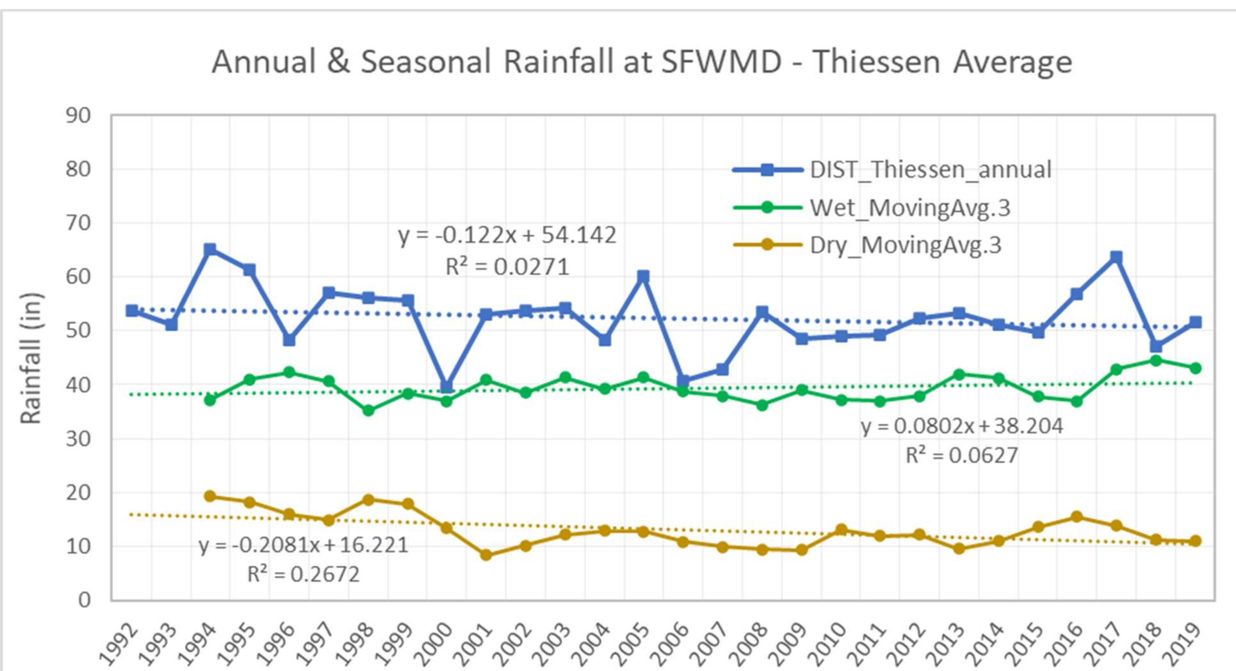


Figure B02.Comparison of annual rainfall between Thiessen polygon averaged and NEXRAD data.

Figure B03 presents the trend analysis of the Thiessen polygon-averaged rainfall over the entire District. The annual data show an overall downward trend at 10-year moving averages. The dry season shows a clear downward trend, while the wet season has no detectable trend. This conclusion conflicts with the one inferred from the analysis of the six stations. This may be due to the different periods of record (28 years versus 50+ years); therefore, the most recent regional rainfall data need to be combined with the historical data for more thorough analysis. The background of statistics used here is described in DATA AND TREND ANALYSIS section above.



Rainfall_DIST_Thiessen
Mann-Kendall Test

alpha	0.05
MK-stat	-52
s.e.	50.6162
z-stat	-1.0076
p-value	0.3137
trend	no

MovingAvg.5
Mann-Kendall Test

alpha	0.05
MK-stat	-58
s.e.	40.3154
z-stat	-1.4139
p-value	0.1574
trend	no

MovingAvg.10
Mann-Kendall Test

alpha	0.05
MK-stat	-59
s.e.	28.5832
z-stat	-2.0292
p-value	0.0424
trend	yes

DIST_Thiessen_Dry
Mann-Kendall Test

alpha	0.05
MK-stat	-62
s.e.	50.6162
z-stat	-1.2051
p-value	0.2281
trend	no

MovingAvg.2
Mann-Kendall Test

alpha	0.05
MK-stat	-73
s.e.	47.9687
z-stat	-1.5010
p-value	0.1334
trend	no

MovingAvg.3
Mann-Kendall Test

alpha	0.05
MK-stat	-97
s.e.	45.3689
z-stat	-2.1160
p-value	0.0343
trend	yes

DIST_Thiessen_Wet
Mann-Kendall Test

alpha	0.05
MK-stat	6
s.e.	50.6162
z-stat	0.0988
p-value	0.9213
trend	no

MovingAvg.5
Mann-Kendall Test

alpha	0.05
MK-stat	46
s.e.	40.3154
z-stat	1.1162
p-value	0.2643
trend	no

MovingAvg.10
Mann-Kendall Test

alpha	0.05
MK-stat	-9
s.e.	28.5832
z-stat	-0.2799
p-value	0.7796
trend	no

Figure B03.Trend analysis of Thiessen polygon-averaged rainfall throughout the District.

An initial analysis of rainfall observations was conducted at selected locations, , the result presents great variations in rainfall patterns and trends. Stations were selected based on two criteria: 1) still in operation, so they can be used for trend watch in the future; and 2) continuous period of record lasting more than 50 years. Six rain gauge stations in the DBHYDRO database met the criteria and were chosen for analysis. The six stations have various periods of record from 57 to 79 years, and **Figure B04** shows their annual and seasonal time series. The Mann-Kendall test indicates the annual data of four stations have no trend at the significance of 0.05, while one station (Pahokee 1) shows an overall downward trend and one station (S6) shows an overall upward trend.

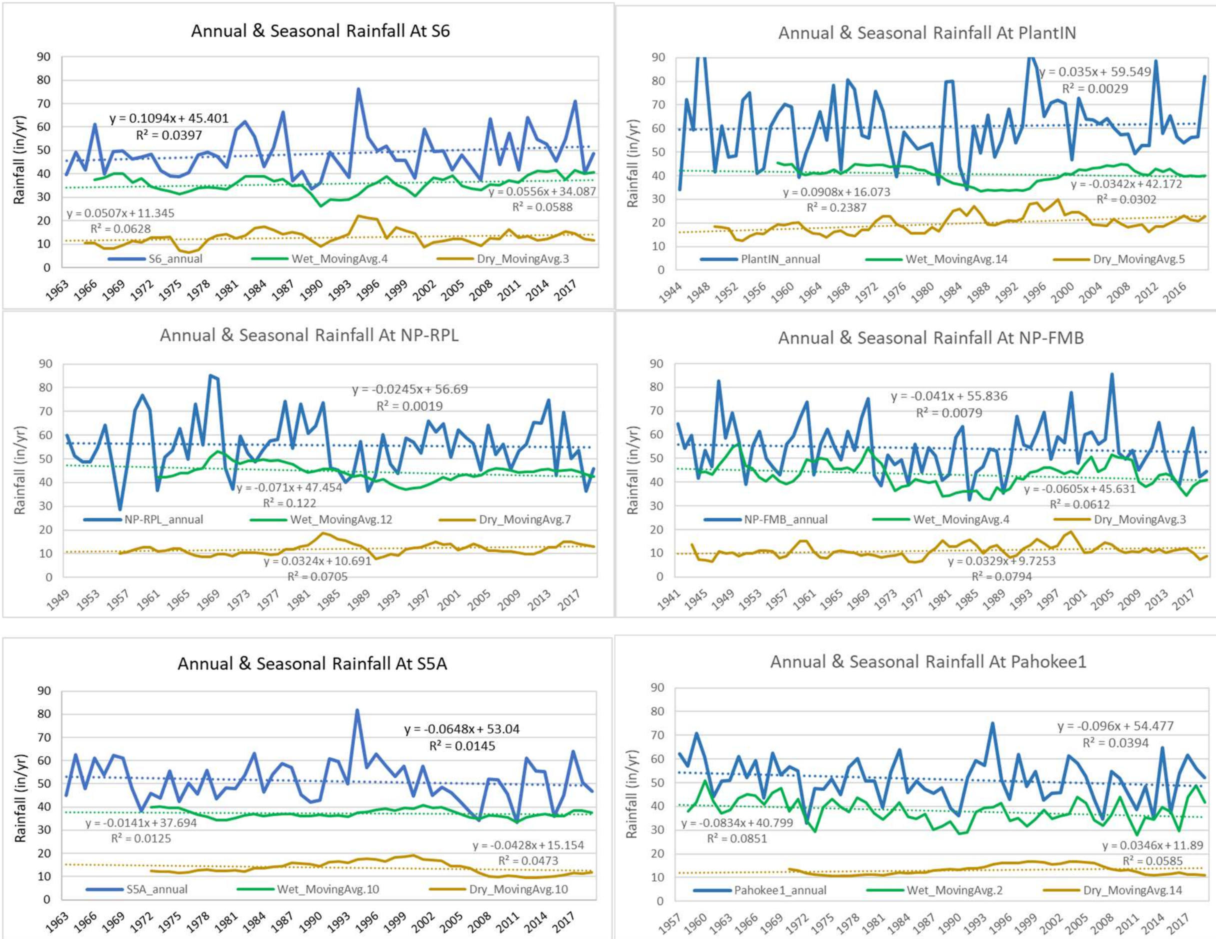


Figure B04.Annual and seasonal rainfall time series of six stations in the District. Trend at significance of 0.05 often shows up on moving average data, and the number of years.

Analysis of the seasonal data tells a different story, as summarized in **Table B01**. Color shading in the table displays the degree of tendency. Blue indicates an upward trend (+/wetter), orange indicates a downward trend (-/drier), and “No” means no trend at the significance of 0.05. The numbers in light gray indicate the number of years the moving average has trend; thus, the deeper the tone, the stronger the trend. All six stations show an upward trend during the dry season, except S5A, which shows no annual or seasonal trend. Most stations show a downward trend during the wet season, except S6, which shows an upward trend at the annual and seasonal levels (two seasons).

Table B01.Trends of annual and seasonal time series at six stations in the District.

Sort	County	Station	Annual	SZN-Dry	SZN-Wet
1	Miami-Dade	NP-FMB	No	3	-4
2	Miami-Dade	NP-RPL	No	7	-11
3	Palm Beach	Pahokee1	-2	14	-2
4	Palm Beach	PlantIN	No	1	-14
5	Palm Beach	S5A	No	No	No
6	Palm Beach	S6	2	3	[illegible]

Blue = rainfall trend upward (+/wetter); Orange = rainfall trend downward (-/drier); No = no trend at significance of 0.05; Number of years' moving average, where the trend shows up.

In addition to the annual and seasonal rainfall analysis, **Figure B05** presents daily rainfall peak over threshold analysis at the S6 station as well as the associated trends for occurrences above 1-in-10 return frequency events (in blue) and 1-in-25 return frequency events (in orange). **Figure B06** presents daily rainfall peak over threshold analysis at the NP_FMP station and the associated trends for occurrences above 1-in-10 return frequency events (in blue) and 1-in-25 return frequency events (in orange). Statistically significant trend (upward) are observed in either case, while no significant trends are observed at other four stations. Trend analyses were performed using Mann-Kendall Tau test with 95% confidence band around the trend slope. A trend is considered significant if a double sided Z test rejects the null hypothesis that there is no trend.

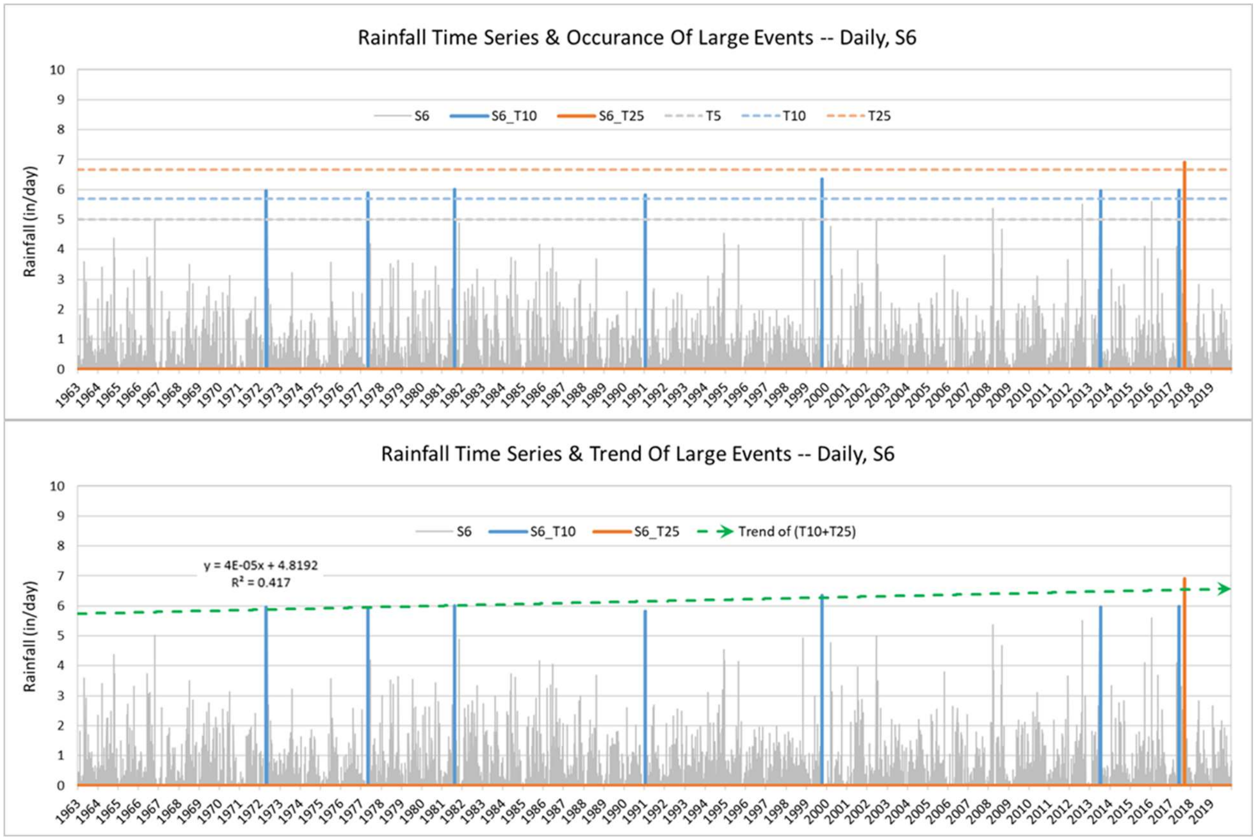


Figure B05.Daily rainfall occurrence at S6, highlighting events above a 1-in-10 and 1-in-25 return frequency. The green dash line is linear regression trendline on the large events (T10 & T25).

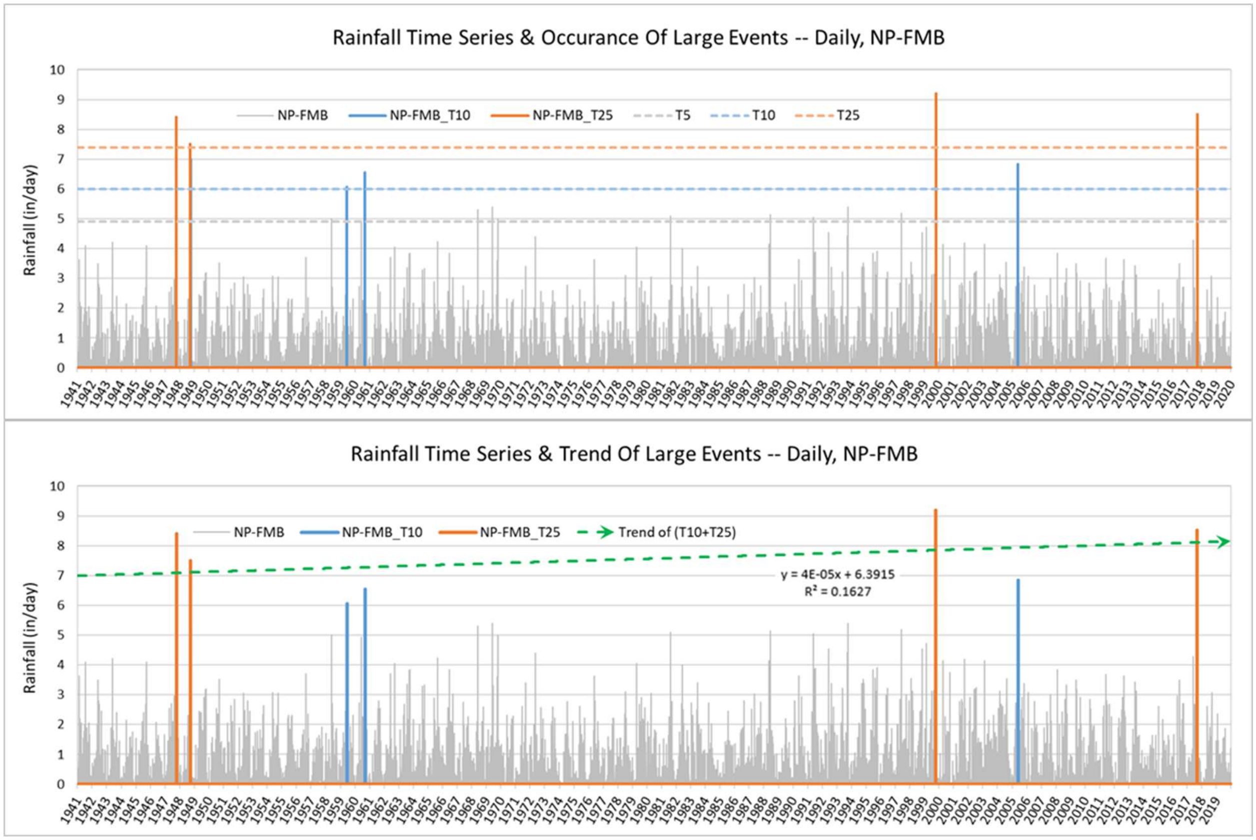


Figure B06.Daily rainfall occurrence at NP-FMP, highlighting events above a 1-in-10 and 1-in-25 return frequency. The green dash line is linear regression trendline on the large events (T10 & T25).

With emphasis in extreme dry events, the analysis of the occurrence of most dry events, as illustrated in **Figure B07**, highlights monthly events below the 1-in-10 return frequency. No statistically significant trend is observed at the two selected stations (S6, NP-FMB). Alternative data visualization options include the seasonal yearly maximum number of consecutive dry days or number of days below a threshold.

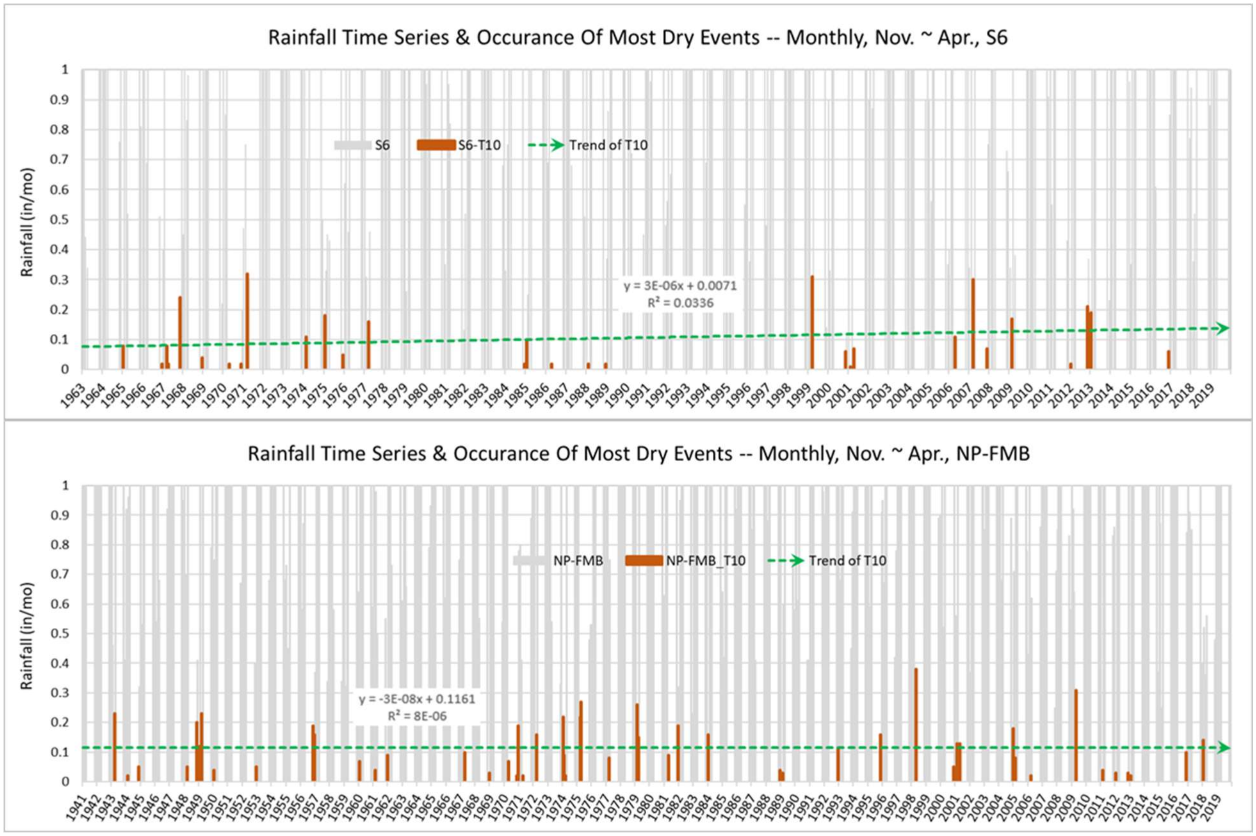


Figure B07. Monthly rainfall occurrence at NP-FMP, highlighting events below a 1-in-10 return frequency. Only the low portion of data between 0 and 1 in/mo is shown. The green dash line is linear regression trendline on the T10 events.

In addition to the analysis of extreme dry events (rainfall only), relative dryness commonly is assessed using available temperature and precipitation data to calculate the Palmer Drought Severity Index, a standardized index that generally ranges from -10 (dry) to +10 (wet), with the most common range of -4 to +4. **Figure B08** illustrates the index calculated for Florida, between 1895 and 2020, showing a downward trend of -0.10 per decade. The decrease in the Palmer Drought Severity Index represents increasing dry conditions throughout Florida. It is important to note that Florida has different climate zones that experience different rainfall and the Palmer Index varies among these zones.

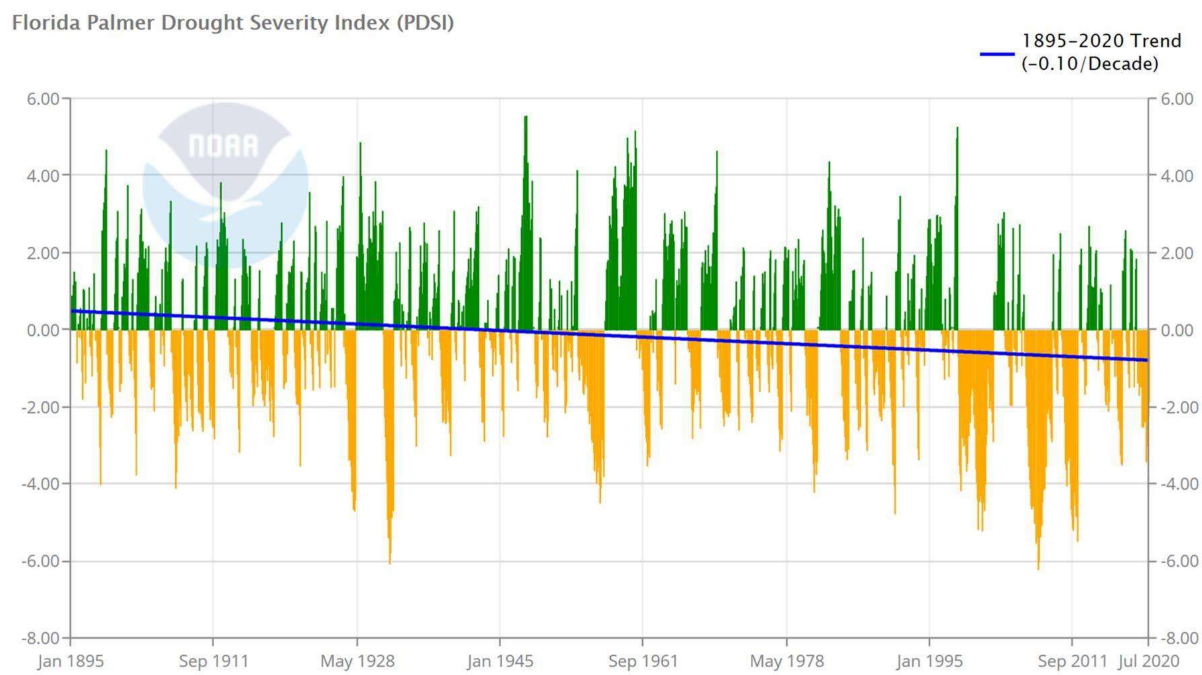


Figure B08.Florida Palmer Drought Severity Index (From: NOAA 2020).

Appendix C

Water Quality - Observed Specific Conductance Trends in Lake Okeechobee

Observed Specific Conductance Trends in Lake Okeechobee

Major ion data (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, HCO_3^{-}, and SO_4^{2-}) were used to provide insight regarding the observed change of specific conductance levels in Lake Okeechobee. If the observed change resulted from dilution, then the ionic composition and inter-ionic ratios remain relatively unaltered. However, if the ionic composition changes over time, then the resulting trend may be associated with a change in the source water to the lake.

As stated above, specific conductance is affected by the types and amounts of ions present in solution. Therefore, it is highly correlated with the ionic content of the solution being measured. **Figure C.1** shows the strong relationship (r = 0.94) between monthly specific conductance and total ionic concentrations (as cations or positively charged ions and anions or negatively charged ions) in Lake Okeechobee for the period of record. Ion concentrations were converted from mg/L to meq/L to account for the ionic valence or charge and to determine if the cations and anions in solution are balanced. All aqueous solutions must satisfy the law of electroneutrality (Sawyer and McCarty 1978; Snoeyink and Jenkins 1981; Stumm and Morgan 1982). Two methods, Shoeller plots and Stiff diagrams, were applied to visually determine if the ionic composition of Lake Okeechobee water changed over time and potentially influenced the observed specific conductance trend.

Shoeller plots are typically used to demonstrate different hydro-chemical water types by showing cation and anion concentrations (in meq/L) on a semi-log plot. These plots were developed in the 1960s and have been used for both surface and ground water analyses to identify dominant ion pairs.

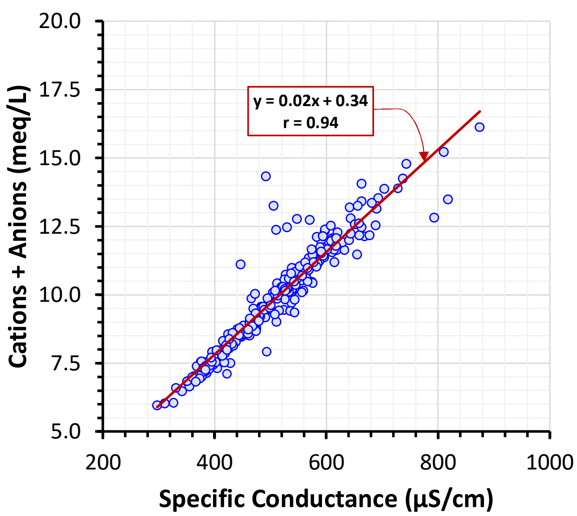


Figure C.1. Correlation between monthly specific conductance and cation and anion concentrations in Lake Okeechobee from 1973 to 2020

Stiff diagrams provide a graphical representation of chemical constituent in solution. By convention, cations are plotted on the left side with anions plotted on the right. The resulting polygon shape provides a useful method for comparing potential ionic compositional differences between samples.

Figure C.2 shows the Shoeller plot (left) of ionic concentrations in Lake Okeechobee calculated over a variety of specific conductance ranges for the period of record. The same plot also presents Stiff diagrams (right) of the ionic composition in lake water over the same specific conductance ranges depicted in the Shoeller plots.

At higher specific conductance levels (as observed during the late 1970s and early 1980s, Lake Okeechobee ionic composition appears to be co-dominated by Na-Cl and Ca-HCO_3 with the Na-Cl component being slightly higher than the Ca-HCO_3 fraction. At the lower specific conductance levels, such as those observed in the more recent period, the ionic composition has shifted to a more Ca-HCO_3 dominated fraction.

Further, Stiff diagrams were used to characterize the ionic composition in Lake Okeechobee over decadal intervals (**Figure C.3**). As shown by these diagrams, ionic composition in the lake has changed over the period of record with the observed change being associated with changes in specific conductance. Also shown in **Figure C.3** are the monthly ratios of Na:K and Na:Ca. These ratios are useful in providing additional support for identifying potential sources affecting ionic compositions in Lake Okeechobee. For example, Na:K ratios in the 1970s and early 1980s averaged approximately 22:1. In contrast, the average ratio for these two ions is approximately 8:1 in more recent years. Over the period of record, an incremental decrease in Na:K ratios is observed. High Na:K ratios may be indicative of a more marine-like source. The average seawater Na:K ratio is approximately 46. One possible source of this marine-like water is the connate seawater (i.e., entrapped relic seawater) underlying portions of the watershed (Chen et al. 2006; Pollman and James 2011) that is being flushed from the system. Pollman (2012) observed evidence of connate seawater influx at several structures to the Water Conservation Areas using Na:K and SO_4:Cl ratios. The ratio anomalies were observed under low to no flow conditions.

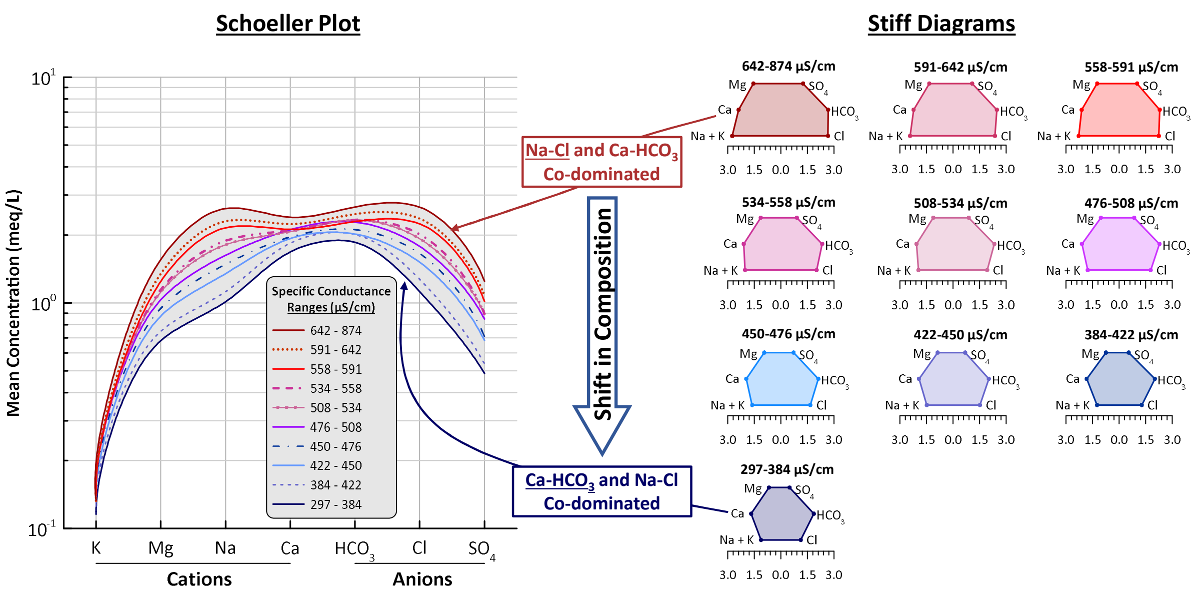


Figure C.2. (left) Shoeller plot and (right) Stiff diagrams show ionic composition of Lake Okeechobee water under various specific conductance ranges for the period 1973 to 2020. Compositions are based on monthly mean ionic and specific conductance data.

Additionally, the Na:Ca ratios support that the early period of record was more dominated by Na-Cl ions than the latter period with the latter period being less dominated by Na-Cl and more influenced by Ca-HCO_3 ions as shown in both the Shoeller plot and Stiff diagrams. Based on these observations and analyses, the significant decreasing trend observed in specific conductance is believed to have resulted from a change in source water to the lake.

Finally, higher water pH levels can generally be associated with a more Ca-HCO_3 dominant aquatic system. While the SK trend analysis for pH (Figure 61) is not conclusive, it is noteworthy that the trend analysis presented suggests that pH levels in Lake Okeechobee have increased over the period of record as the system shifted from a Na-Cl to a Ca-HCO_3 system.

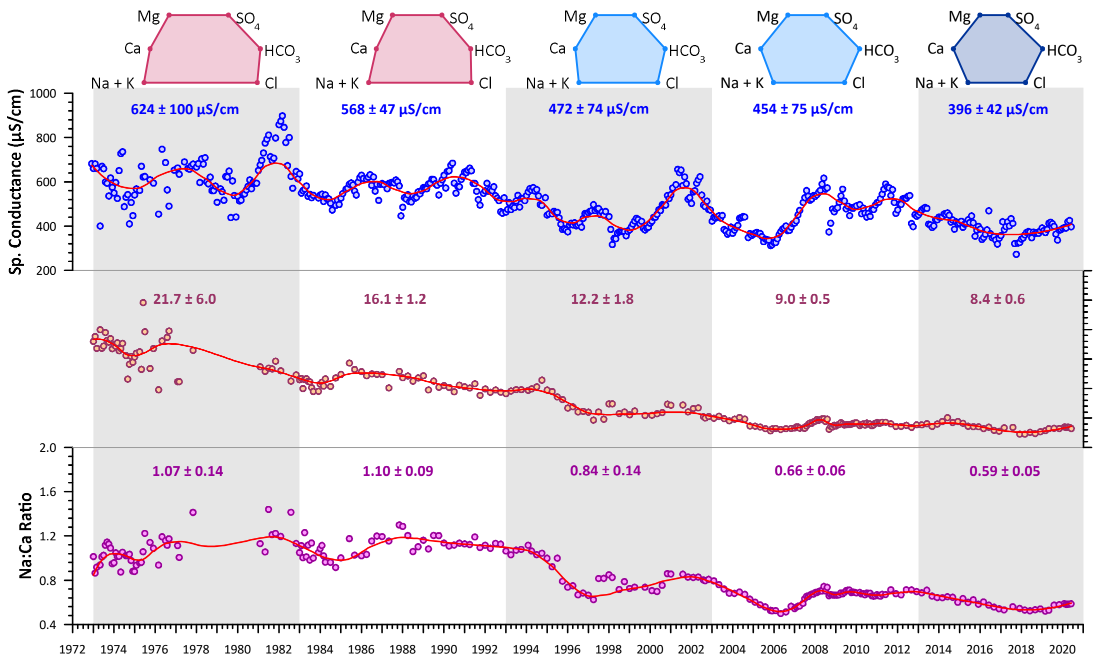


Figure C.3. Monthly mean specific conductance at six stations in Lake Okeechobee with seasonal Kendall trend analysis results.