Chapter 2B: Water and Climate Resilience Metrics

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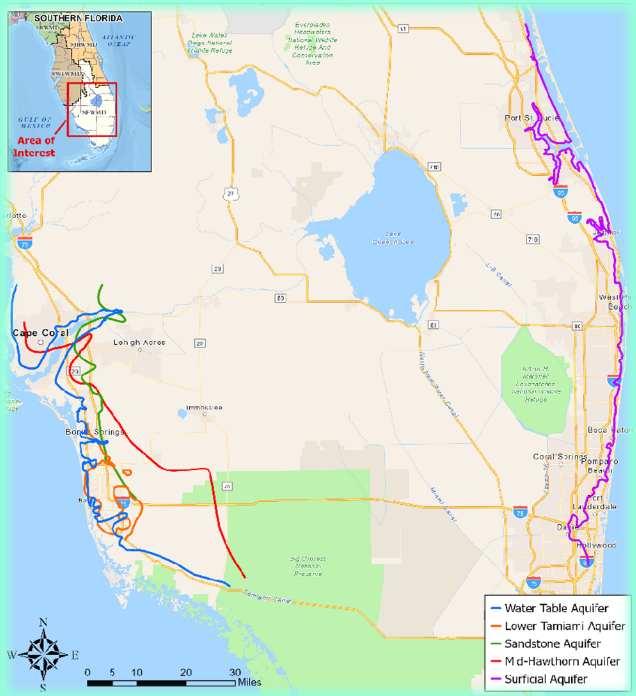

Isochlor lines showing the saltwater-freshwater interface for aquifers within the SFWMD region.

HIGHLIGHTS

In this year's Water and Climate Resilience Metrics chapter, the following metrics are discussed:

- Rainfall
- Meteorological drought
- High tide events at coastal structures
- Saltwater intrusion

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RAINFALL

The South Florida Water Management District (SFWMD) conducted its 5-year update of the rainfall metric trend and frequency analyses using gridded daily data from 1935 to 2024, extending the previous 2022 analysis by six years. The methodology remained consistent, focusing on analyzing trends within each of the region's hydrologically delineated rainfall areas. This extended data set revealed shifts from previously observed trends. Frequency analysis showed increasing occurrences of short- to medium-duration extreme rainfall events in some areas. These results highlight the influence of recent climate variability and the need for continuous monitoring to inform resilience planning for water management and flood risk reduction strategies.

Additionally, SFWMD analyzed spatial rainfall patterns in South Florida, across the region's 14 rainfall areas as a whole, during both periods of record from 1935 to 2018 and the updated period from 1935 to 2024. The method used identified dynamic rainfall clusters based on spatial and temporal exceedance characteristics. By testing multiple rainfall thresholds (4.00 to 6.00 inches), the analysis distinguished between persistent clusters and emerging clusters. Trend analysis of peak-over-threshold events revealed intensifying rainfall behavior areas across Central and Southern Florida, particularly in inland and southern areas. These findings highlight the importance of distinguishing between gradual baseline changes and variability from recent events contributing to shifts in evolving hydrologic conditions for effective adaptive infrastructure planning and risk reduction strategies.

METEOROLOGICAL DROUGHT

SFWMD analyzed meteorological drought conditions in South Florida using gridded precipitation and evapotranspiration data from 1948 to 2022. Events were characterized based on duration, severity, and intensity. Trend analysis revealed no statistically significant changes in drought severity or duration across the 14 rainfall areas. However, alignment was observed between drought anomalies and droughts identified by the U.S. Drought Monitor classifications and SFWMD-issued water shortage declarations. These findings support the utility of the method used for retrospective drought identification and confirm its relevance for water supply planning, even in the absence of long-term trends.

HIGH TIDE EVENTS AT COASTAL STRUCTURES

SFWMD assessed high tide events (HTEs) in South Florida using paired headwater and tailwater data from coastal structures to evaluate closure requirements and associated risks of reverse flow and saltwater intrusion. High tide events at coastal structures were defined based on both tidal and inland water levels, characterized by periods when tailwater came within 0.1 feet of the headwater. Visualization using frequency heatmaps and hourly time series allowed identification of extreme tides, storm impacts, and site-specific vulnerabilities. Maximum HTEs typically occurred during the king tide season, though a few structures in Miami-Dade and Collier counties peaked in the spring. Coastal structures across the region showed notable variation in both trends and frequency of HTEs, with several structures frequently experiencing HTE conditions. These results provide a data-driven framework to support adaptive coastal water management and infrastructure planning.

SALTWATER INTRUSION

As part of its ongoing monitoring program, SFWMD completed its 2024 five-year update of saltwater interface maps using dry season chloride data from over 1,000 wells to assess seawater encroachment into the surficial aquifer system, along the eastern and western coastlines of South Florida. Compared to the 2019 maps, interface movement varied by region, showing retreat toward the coast, minor or notable inland movement, or no change. These patterns reflect the influence of local water use, recharge practices, and coastal hydrology. Areas with notable inland movement are now being prioritized for enhanced monitoring to support future water supply planning and protect vulnerable wellfields.

www.sfwmd.gov/our-work/district-resiliency

SUMMARY

The South Florida Water Management District (SFWMD) continues to be strongly committed to addressing the impacts of land development, population growth, sea level rise, extreme rainfall, and other changing conditions. SFWMD's resiliency planning efforts focus on assessing how sea level rise (SLR) and extreme events, including flood and drought events, happen under current and future hydrologic and climate conditions, and how they affect water resources management. In this context, resiliency is the capacity for natural and man-made systems to cope with and adapt to acute and chronic stressors, now and in the future, as climate conditions evolve.

As part of its resilience planning initiatives, SFWMD has established an initial set of water and climate resilience metrics to track and document trends and shifts in water and climate monitored data. This data assessment supports enhanced understanding of the current and predicted impacts of changing hydrologic and climate conditions on South Florida's ecosystems and water resources, informs modeling scenario formulation, adaptation planning, operational decisions, and the resiliency projects prioritization.

In this year's chapter, the following metrics are examined:

- Rainfall
- Meteorological drought
- High tide events at coastal structures
- Saltwater intrusion

The chapter includes discussions and explorations of the drivers influencing the observations of the selected metrics, delves into their relevance to resiliency in water management, and addresses next steps in ongoing data analysis efforts.

INTRODUCTION

As part of its resilience planning initiatives, SFWMD has established an initial set of water and climate resilience metrics to track and document trends and shifts in the water and climate data. This collaborative effort is led by the SFWMD Water and Climate Resilience Metrics initiative, supported by technical leads and subject matter experts from various internal bureaus. Reporting the latest information about SFWMD's water and climate resilience metrics ensures scientific findings are memorialized to preserve institutional knowledge and disseminated to stakeholders, the public, and partner agencies to support local and regional resilience strategies.

The analysis of these data is essential for understanding the current and predicted impacts of changing conditions on South Florida's ecosystems and water resources and to support risk-informed decision making. While uncertainties persist regarding climate change, evaluating changes in water and climate variables like rainfall, temperature, and evapotranspiration as well as their consequences on SLR, saltwater intrusion, groundwater elevation, and ecosystem dynamics is important. These assessments provide the foundation for more robust infrastructure planning and operational decisions in water management and ecosystem restoration projects, ensuring SFWMD's resilience planning is grounded in the best available science.

The comprehensive risk-informed approach supports SFWMD's mission and resiliency goals, ensuring ecosystem restoration, flood protection, and water supply mission while considering current and future hydrological and climate conditions.

BACKGROUND

As part of its resilience planning initiatives, SFWMD implemented an initial set of water and climate resilience metrics to track and document shifts and trends in SFWMD-monitored water and climate data. Referred to as Phase I, this effort focused on fifteen mission-driven parameters that provide actionable information to support decision-making and resiliency planning. This year's chapter marks the completion of the documentation of data sources, analyses, and results for all Phase I metrics and initiates the scheduled reanalysis of these metrics. It also introduces the scope and direction of Phase II of the water and climate resilience metrics initiative.

Building on the foundation established in Phase I, Phase II focuses on refining and expanding the assessment of changing water and climate conditions. It includes three primary efforts:

- **New data analysis:** Identifies and evaluates new data sources to support the development of additional metrics and includes the formal establishment of an internal Future Scenarios Workgroup.
- **Enhanced analysis:** Integrates new data sets and establishes additional monitoring stations to strengthen SFWMD's data collection capabilities.
- **Metric updates:** Supports the ongoing monitoring of long-term trends in the original metrics and maintains automated tools to ensure continued tracking and identification of emerging patterns.

Table 2B-1 summarizes key aspects of the water and climate resilience metrics under evaluation. Each metric is categorized as a climate metric or a resilience metric. Climate metrics are the primary drivers of observed changes in climate conditions that impact the hydrologic cycle, while resilience metrics represent the observed consequences of changing conditions and can be directly or indirectly managed or mitigated through operation of the water management system or implementation of adaptation strategies.

The selected statistical approaches for consistent analyses across the set of initial set of metrics include linear regression analysis and seasonal and non-seasonal Mann-Kendall tests, complemented by geographic information system (GIS) analyses for identifying spatial patterns of specific metrics. More detailed information on the selection of the initial set of metrics and approaches to data analysis can be found in the *Water and Climate Resilience Metrics Phase I: Long-term Observed Trends* (SFWMD 2021b).

This chapter, introduced in Volume I of the *2022 South Florida Environmental Report* (SFER; Cortez et al. 2022), aims to continuously advance water and climate data analysis and deepen the understanding of the influence of changing conditions on observations and findings. This year's report includes additional technical analysis and scientific considerations for four water and climate resilience metrics: rainfall, drought, high tide events (HTEs) at coastal structures, and saltwater intrusion.

Examining the factors that influence resilience metrics is crucial for correlating trends and identifying potential relationships between climate factors and resilience outcomes. Analyzing how changes in one factor may impact resilience metrics supports informed decision-making and prioritization of interventions to enhance overall resilience. Monitoring these factors also supports the observation of any shifts in established trends over time and enables water managers to adapt and respond to changing conditions, ensuring resilience planning and implementation strategies remain effective and relevant in the face of dynamic challenges.

Table 2B-1. Summary of the water and climate resilience metrics.

Metric	Type of Metric	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Rainfall	Climate	Rainfall intensity, duration, extension, and frequency cannot be controlled by SFWMD.	Rainfall is used to estimate the water budget, forecast inflows to the system, plan the management of water resources, and determine water management operations.	Annual trend analysis provides insights regarding 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 the impacts of rainfall on flooding, water supply, and ecosystem restoration.
Evapotranspiration (ET)	Climate	ET cannot be controlled by SFWMD.	Together with rainfall, ET drives the hydrologic cycle and water budget.	ET is projected to increase in a warming climate and impact seasonal patterns and trends in precipitation. Increasing ET might contribute to increasing demand on the water management system (due to associated canal levels, flooding, etc.). During drought events, ET might deplete already limited water supplies. ET data trends inform SFWMD operation and planning efforts.
Tidal Elevations at Coastal Structures [a]	Climate	Tidal elevations cannot be controlled by SFWMD. Tidal elevations at coastal structures can be partially influenced by SFWMD operations. Activities of other jurisdictional agencies cannot be controlled by SFWMD.	Headwater (freshwater canal levels) and tailwater (tidal levels) elevations are the drivers of stormwater discharge operations. Coastal structures must be opened to release stormwater as part of flood control operations and closed during high tailwater conditions to prevent saltwater intrusion inland.	Long-term data trends, combined with flood level-of-service performance data, inform SFWMD 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. For instance, coastal structures are a vital component of the prevention strategy for the Biscayne Aquifer Minimum Flow and Minimum Water Level (MFL).
High Tide Events at Coastal Structures [a]	Climate	Tidal stages and HTEs cannot be controlled by SFWMD.	HTEs represent extreme values observed in tidal water level data used to assess trends in SLR and identify potential flood hazards, risks to water supply, and impacts to structural design standards.	Long-term data trends in tidal stages, HTEs, and level-of-service performance inform SFWMD on the limitations and deficiencies of natural and structural assets. This information guides planning and where SFWMD might allocate resources for adaptation strategies.
Groundwater Levels	Resilience	Groundwater levels can be indirectly controlled by SFWMD via operation of water control structures and pump stations along canals of the Central and Southern Florida Flood Control Project (C&SF Project). Higher sea levels that increase hydrostatic pressure and allow inland movement of seawater into aquifers cannot be controlled by SFWMD.	Groundwater level data are used to monitor water supply, as inputs to surface water and groundwater modeling, for the establishment of and compliance with MFL criteria, and for 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 SLR in terms of timing and extent of groundwater stages during the wet season, threats to water supply, the need for additional monitoring, urgency of 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 United States Geological Survey (USGS) Water Level and Salinity Analysis Mapper online tools, showing trends over the past 20 years.

Table 2B-1. Continued.

Metric	Type of Metric	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Saltwater Intrusion/ Saltwater Interface – Chloride Concentrations	Resilience	The saltwater interface can partially be controlled by SFWMD. The water management system has limited/variable capacity to maintain higher elevations in inland canal systems to impede saltwater intrusion.	Analytical chloride data from groundwater wells are used to monitor salinity in freshwater aquifers and map the inland movement of salt water.	Historical and projected movement of salt water inland and current water use data and future water use projections identify vulnerabilities to public water supply utilities. Saltwater intrusion has a large impact on water use permitting as an increased number of wells/wellfields/utilities are vulnerable to loss of supply or reduced availability during droughts.
Minimum Flows and Minimum Water Levels (MFLs) – Exceedances/ Violations	Resilience	SFWMD adopts MFL criteria for key water bodies where there is the existence of, or potential for, significant harm to the water resources or ecology within SFWMD boundaries. When establishing an MFL, SFWMD considers structural changes and alterations to the watersheds of MFL water bodies and the effects and constraints of these changes and alterations on their hydrology. SFWMD monitors exceedances and violations of adopted MFLs to determine compliance and to develop recovery or prevention strategies, respectively. Through water management, operational, and regulatory practices, SFWMD may achieve adequate MFL status. MFL rules and criteria contained in Chapter 40E-8, Florida Administrative Code, are based on the best available information, and are periodically reevaluated and revised by SFWMD as appropriate.	MFL criteria are the minimum flows or water levels at which water resources, or the ecology of the area, would experience significant harm from further permitted water withdrawals. MFL criteria are developed individually for the affected water bodies and define the minimum flow or minimum water level for surface water bodies, or minimum water level for groundwater in aquifers. Flow and water level data are used to ensure water bodies are in compliance with their minimum requirements and to identify the occurrence of exceedances and violations.	MFL monitoring data identify threats to water supply sources and ecosystems, and the need to develop recovery or prevention strategies in cases where a water body currently does not or will not meet adopted MFL criteria. The MFL program supports SFWMD's regional water supply planning process, and involves the consumptive use permitting program, and the environmental resource permitting program. Applications for consumptive use permits for water uses that directly or indirectly withdraw water from MFL water bodies must meet the requirements of the recovery or prevention strategy at the time of permit issuance. MFL data are also used in assessments of water supply sources and declarations of water shortages.
Flooding Events	Resilience	SFWMD has the capacity and mission to control and protect communities from flooding events through effective operation and maintenance of its water management system and through infrastructure investments to implement flood adaptation and mitigation strategies.	Flood data are used to assess and monitor (pattern, extent, and depth) flooding events that occur after storms, heavy rainfall, and extreme tides.	Comprehensive analysis of flood event data 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.

Table 2B-1. Continued.

Metric	Type of Metric	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Water Temperature	Resilience	SFWMD can indirectly control water temperature in the system through operational and management decisions, and through coordination with state and local agencies as part of basin management action plan (BMAP) implementation.	Water temperature is used to monitor water supply and aquatic and marine ecosystems.	Water temperature informs effective water management practices and helps assess restoration efforts. Assessment of water temperature can help identify areas that require implementation of restoration strategies.
Dissolved Oxygen (DO)	Resilience	SFWMD can indirectly control DO in the system through operational and management decisions, and through coordination with state and local agencies as part of BMAP implementation.	DO is used to monitor water supply sources and availability for uptake in aquatic and marine ecosystems.	DO informs effective water management practices and helps assess restoration efforts. Resilience-driven interventions may reduce the impacts of poor water quality in critical areas and help identify areas that require implementation of restoration strategies.
pH	Resilience	SFWMD can indirectly control pH in the system through operational and management decisions, and through coordination with state and local agencies as part of BMAP implementation.	Water pH is an indicator of the chemical state and changes within a water body. Water pH is used to monitor water supply sources and aquatic and marine ecosystems.	Water pH informs effective water management practices and helps assess restoration efforts. Resilience-driven interventions may reduce the impacts of poor water quality in critical areas and help identify areas that require implementation of restoration strategies.
Specific Conductance	Resilience	SFWMD can indirectly control specific conductance in the system through operational and management decisions, and through coordination with state and local agencies as part of BMAP implementation.	Specific conductance is used to monitor water supply sources and aquatic and marine ecosystems. Analyses of specific conductance allow for the removal of altering variables and account for fluctuations in water temperature. High specific conductance values 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 informs effective water management practices that promote resilience and helps assess restoration efforts. This identifies critical areas that require implementation of restoration strategies.
Estuarine Inland Migration – Everglades	Resilience	SFWMD can partially control the extent of estuarine inland migration through water management by maintaining higher freshwater levels inland.	Estuarine inland migration is used to monitor shifts in species composition in freshwater marshes. Trends in estuarine inland migration provide insights into the impacts of SLR in coastal areas and the Everglades.	Estuarine inland migration informs SFWMD on the efficacy of water management practices in creating favorable conditions for marshes and mangroves to keep up with SLR. Information on estuarine inland migration provides guidance to align/plan practices to adapt and mitigate for SLR and other climate change impacts.

Table 2B-1. Continued.

Metric	Type of Metric	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Soil Subsidence	Resilience	SFWMD can partially 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. SFWMD 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 SLR.	The rate of soil subsidence informs SFWMD on the effectiveness and benefits of Everglades restoration. This information guides water management practices that aim to uplift land to reduce the impacts of SLR and promote the seaward migration of coastlines (i.e., increasing freshwater input into the salinity transition zone of Taylor Slough).
Salinity in the Everglades and Biscayne Bay	Resilience	SFWMD can partially 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 informs SFWMD on the effectiveness and benefits of Everglades restoration, impacts in Biscayne Bay, and guides water management practices.
Drought	Climate	SFWMD cannot control meteorological droughts and may partially influence hydrological droughts through operational adjustments, water shortage declarations, and regional water supply planning.	Drought characteristics (frequency, duration, and intensity) are used to assess and monitor water supply conditions, activate drought response actions, and support regulatory and planning decisions.	Drought trend analysis informs risk-based planning and understanding changing drought patterns guides water management and supports investments in water supply sources.
Freshwater Lens	Resilience	SFWMD can indirectly control the depth and thickness of the freshwater lens through groundwater levels operation.	Freshwater lens characterization is used to monitor salinity in freshwater aquifers and map the lateral and vertical movement of salt water.	Long-term changes in lens thickness and salinity boundaries inform aquifer vulnerability assessments, permitting decisions, and adaptive water supply strategies. Trends support the need for enhanced recharge, protective canal operations, or alternative water source development.
Stormwater Volume and Flow	Resilience	SFWMD has the capacity and mission to manage stormwater within its jurisdiction through effective operation and maintenance of its water management system and through infrastructure investments to implement flood adaptation and mitigation strategies.	Stormwater data are used to assess and monitor flow dynamics, system capacity, drainage performance, recharge potential, and localized flooding risks, particularly in flood prone areas.	Comprehensive analysis of stormwater dynamics data identifies where investments and reinforcements in flood control systems are necessary.
Algal Blooms	Resilience	SFWMD can indirectly control algal blooms in the system through operational and management decisions, and through coordination with state and local agencies as part of BMAP implementation.	Algal blooms are an indicator of the chemical state and changes within a water body. Algal blooms are used to monitor water supply sources aquatic and marine ecosystems health, and risks to human use.	Algal blooms inform effective water management practices and help assess restoration efforts. Assessment of algal blooms can help identify areas that require implementation of restoration strategies.

Table 2B-1. Continued.

Metric	Type of Metric	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Atlantic Multidecadal Variability (AMV)	Climate	AMV cannot be controlled by SFWMD.	AMV is a global climate pattern characterized by fluctuations in sea surface temperatures in the North Atlantic Ocean. It is used to monitor changes in the frequency and intensity of regional climate patterns, including rainfall, droughts, and hurricanes.	AMV-related trends help inform projections of hydrologic extremes and long-term planning scenarios. Understanding AMV supports adaptive strategies for infrastructure design, flood risk management, and water supply planning under future climate conditions.

a. The 'Tidal Elevations at Coastal Structures' and 'High Tide Events at Coastal Structures' metrics reflect tidal conditions at gravity-driven coastal control structures that are influenced by both tidal forces and the operation of water management infrastructure. Therefore, in the context of this report, these tidal elevations and high tide events are not purely ocean-driven tidal parameters. Additionally, while these structures are located directly upstream of tidally dominated water bodies, the observed water levels upstream and downstream are also shaped by operational decisions, discharges, and the complex engineered nature of the regional water management system. For this reason, the terms 'Tidal Elevations at Coastal Structures' and 'High Tide Events at Coastal Structures' are used with the understanding that the metrics are inherently reflective of the interconnection and management of South Florida's water control infrastructure.

Understanding and tracking these factors can lead to the development and implementation of novel indicators for monitoring resilience, providing more comprehensive insights into the system's ability to withstand and recover from short- and long-term disturbances. New data and associated analysis would contribute to a more nuanced and holistic understanding of complex interactions and can help address limitations in existing metrics.

Initially identified influencing factors for each analyzed metric are outlined in this chapter, as their understanding supports the development of well-informed and effective strategies to enhance resilience in South Florida's regional water management system.

The following four sections provide background information for each metric, outline the findings of these metrics, discuss influencing factors, recommend enhancements to data monitoring, and additional analyses that can aid in distinguishing between climate and non-climate driven change. Evaluating these metrics is an important step in planning for the future. The observed trends in long-term water and climate data shed light on the consequences of changing conditions, guiding water management and resiliency priorities.

RAINFALL

BACKGROUND

Rainfall is the primary driver of hydrology and water management in South Florida, a region characterized by a humid, subtropical climate and extremely flat topography. The interaction of intense solar heating, surrounding oceans, large inland lakes like Lake Okeechobee, and frequent convective storms results in highly variable rainfall patterns both seasonally and spatially (Cortez et al. 2022). Annual rainfall across South Florida averages 53 inches (1991–2020) with nearly three-quarters of that total falling during the wet season and transitional months (SFWMD 2021a).

Chapter 2B in the 2022 SFER – Volume I (Cortez et al. 2022) presented an initial analysis of historical rainfall trends using data from 1935 through 2018. That analysis included three components: (1) long-term trends in monthly, seasonal, and annual rainfall volumes; (2) frequency trends of one-, three-, and five-day maximum rainfall events; and (3) peak-over-threshold (POT) analyses to identify extreme rainfall values exceeding defined thresholds. These analyses were conducted using SFWMD's model input rainfall data set, which is derived from gauge data interpolated across two-mile-by-two-mile grid cells and summarized within the 14 rainfall areas (Ali et al. 2006).

Building on that work, this report presents an update of the 2022 analysis and new results including a refined step in the approach. First, the rainfall trend and frequency analysis will extend the previous 2022 assessment to incorporate six additional years of data (2019–2024). This component will include (1) updated monthly, seasonal, and annual volume trends using the non-parametric Mann-Kendall Tau test, and (2) updated extreme rainfall frequency analyses, based on 1-, 3-, and 5-day maxima fitted to log-normal distributions for 2-, 5-, and 10-year return periods. Second, a cluster analysis will be introduced to identify areas of similar rainfall trends across the SFWMD region without being limited by the boundaries of the 14 rainfall areas. Clusters will be defined based on shared rainfall characteristics, and long-term trends will then be assessed within each cluster for the 1935–2018 and 1935–2024 periods of record (PORs). Together, these analyses aim to improve understanding of long-term trends in rainfall across South Florida, supporting adaptive water management strategies in the face of ongoing climate change and hydrologic uncertainty.

TREND AND FREQUENCY ANALYSIS UPDATE

To continuously support SFWMD's resilience planning initiatives, long-term trends in historical rainfall across SFWMD's 14 rainfall areas are periodically evaluated to identify emerging patterns. This report, in addition to the novel cluster analysis summarized above, presents an updated rainfall trend analysis using daily gridded rainfall data spanning from 1935 to 2024, extending the POR used in the previous 2022 analysis, which ended in 2018. The methodology for this update remains consistent with previous efforts (Cortez et al. 2022), relying on spatially interpolated gridded rainfall data, originally developed by Ali et al. (2006), that ensures spatial and temporal consistency across the POR.

Two types of rainfall trend analyses are presented:

1. **Monthly, Seasonal, and Annual Volume Trends**: Identified using the non-parametric Mann-Kendall Tau test (p-value = 0.05).
2. **Frequency Analysis of Extreme Rainfall Events:** Conducted for 1-, 3-, and 5-day maxima, with log-normal distributions fit to estimate trends across multiple return periods (2-, 5-, and 10-year).

Results and Discussion

This updated analysis provides new insights into the evolution of rainfall trends over an extended POR. The comparison between the 1935–2018 and 1935–2024 results highlight how extending the data set by six additional years (2019–2024), which includes both recent dry and wet periods, had a substantial impact on the analysis, with several trends either emerging or disappearing. Only statistically significant results at the 95% confidence level are reported.

Table 2B-2Error! Reference source not found. presents the comparative results for the monthly, seasonal, and annual trend analyses, for both the 1935–2018 and 1935–2024 PORs. For figures corresponding to the 1935–2018 analysis, see Cortez et al. (2022). For the complete set of figures from the updated analysis, see Appendix 2B-1.

While most monthly trends remain statistically insignificant across both periods, some changes are noteworthy:

- In March, a new downward trend emerges in the Upper Kissimmee, as shown in **Figure 2B-1**, indicating a recent decrease in early spring rainfall not previously evident.
- In July, the existing downward trends in Miami-Dade, Lake Okeechobee, and Upper Kissimmee now extend to Lower Kissimmee, as shown in **Figure 2B-2**, suggesting a strengthening and geographic expansion of mid-summer drying across the region.
- In August, the previously observed upward trend in Big Cypress is no longer statistically significant. This shift likely reflects a reduction in rainfall in recent years that has weakened the previously consistent late summer increases in that basin. Meanwhile, upward trends continue in East Caloosahatchee, Martin – St. Lucie, and Southwest Coast. As shown in **Figure 2B-3**.
- October continues to show persistent downward trends in Broward, Miami-Dade, East Everglades Agricultural Area, Martin – St. Lucie, Palm Beach, and Water Conservation Areas 1, 2, and 3, as shown in **Figure 2B-4**, reinforcing a long-term pattern of declining rainfall across southeastern basins in the late wet season.
- For the wet season, upward trends in East Caloosahatchee and the Southwest Coast remain, while the previously noted downward trend in the East Everglades Agricultural Area is no longer significant, as shown in **Figure 2B-5**. This change likely indicates increased rainfall in recent years that has offset the long-term decline in that basin.
- On an annual scale, the downward trend in the East Everglades Agricultural Area persists, while a new upward trend in East Caloosahatchee emerges, as shown in **Figure 2B-6**. This divergence underscores increasing regional variability, with long-term drying in some eastern areas and intensifying rainfall in western basins.

Table 2B-22. Monthly, seasonal, and annual trend analyses results.

Trend Analysis	Observed Trend for POR 1935–2018	Observed Trend for POR 1935–2024
January	No significant trend	No significant trend
February	No significant trend	No significant trend
March	No significant trend	Downward trend: Upper Kissimmee
April	No significant trend	No significant trend
May	No significant trend	No significant trend
June	No significant trend	No significant trend
July	Downward trend: Miami-Dade, Lake Okeechobee, Upper Kissimmee	Downward trend: Miami-Dade, Lake Okeechobee, Upper Kissimmee, Lower Kissimmee
August	Upward trend: Big Cypress, East Caloosahatchee, Martin – St. Lucie, Southwest Coast	Upward trend: East Caloosahatchee, Martin – St. Lucie, Southwest Coast
September	No significant trend	No significant trend
October	Downward trend: Broward, Miami-Dade, East Everglades Agricultural Area, Martin – St. Lucie, Palm Beach, Water Conservation Areas 1, 2, and 3	Downward trend: Broward, Miami-Dade, East Everglades Agricultural Area, Martin – St. Lucie, Palm Beach, Water Conservation Areas 1, 2, and 3
November	No significant trend	No significant trend
December	No significant trend	No significant trend
Wet Season	Upward trend: East Caloosahatchee, Southwest Coast Downward trend: East Everglades Agricultural Area	Upward trend: East Caloosahatchee, Southwest Coast
Annual	Downward trend: East Everglades Agricultural Area	Upward trend: East Caloosahatchee Downward trend: East Everglades Agricultural Area

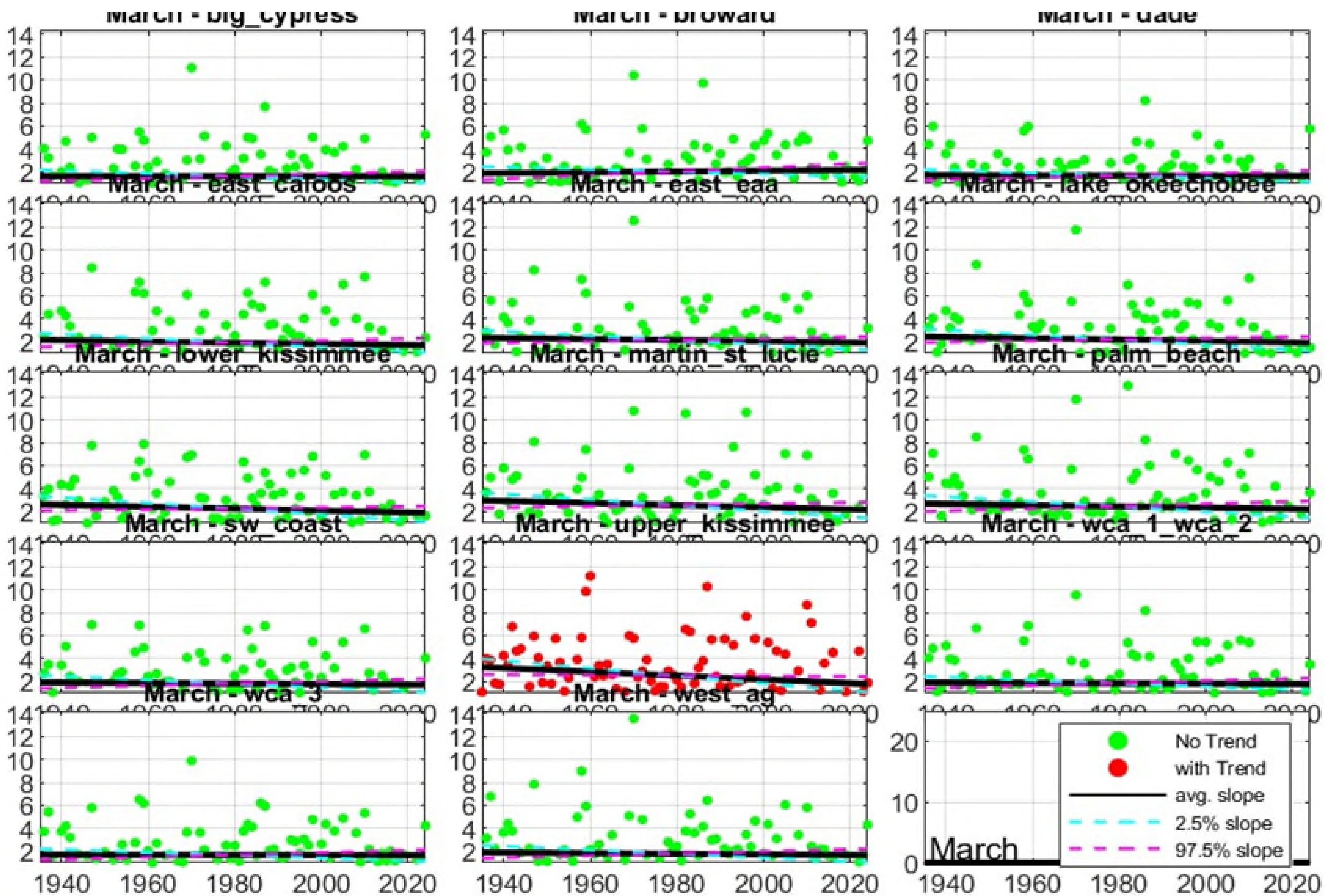

Figure 2B-1. Results of the rainfall trend analysis for March, POR from 1935 to 2024.

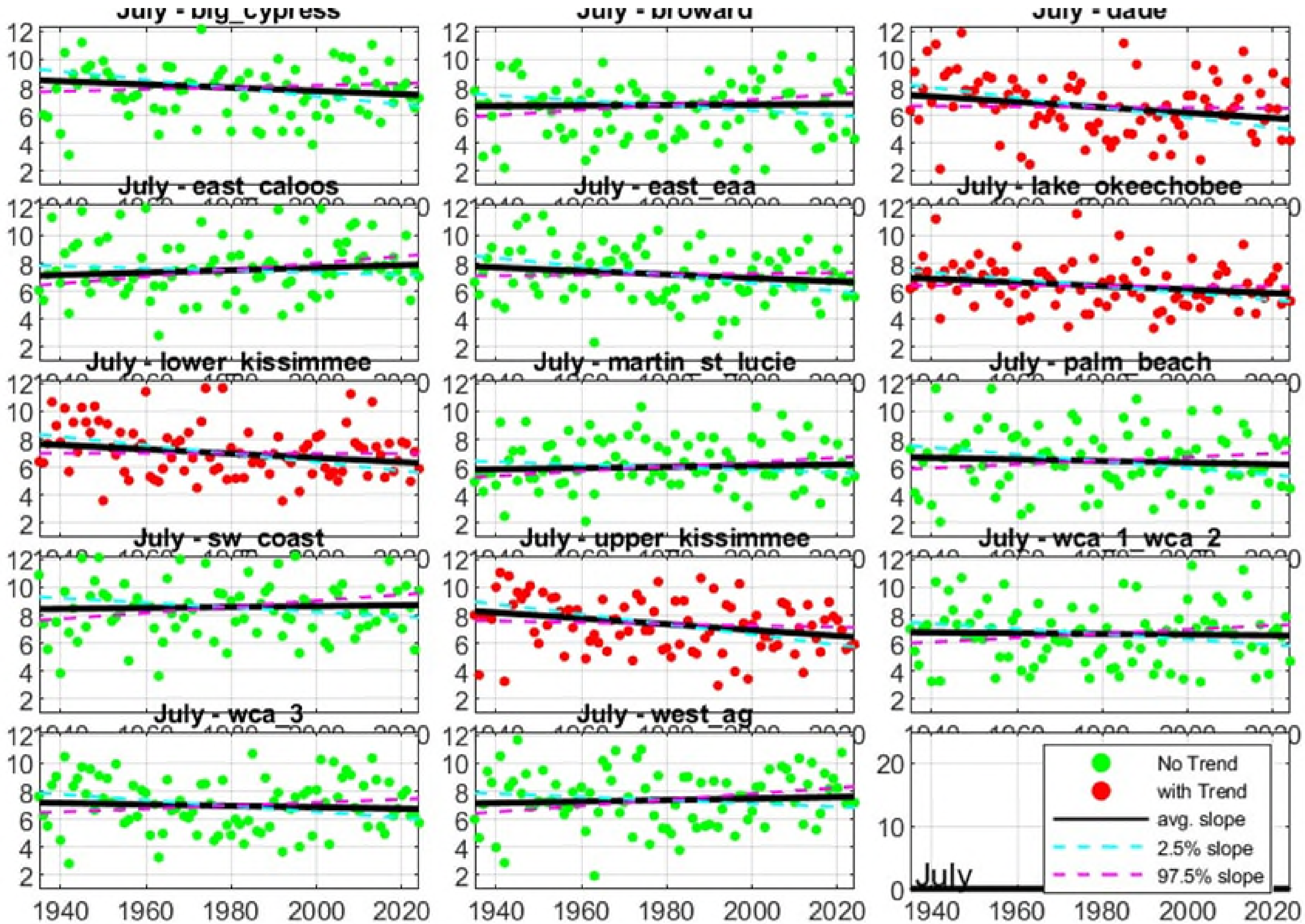

Figure 2B-2. Results of the rainfall trend analysis for July, POR from 1935 to 2024.

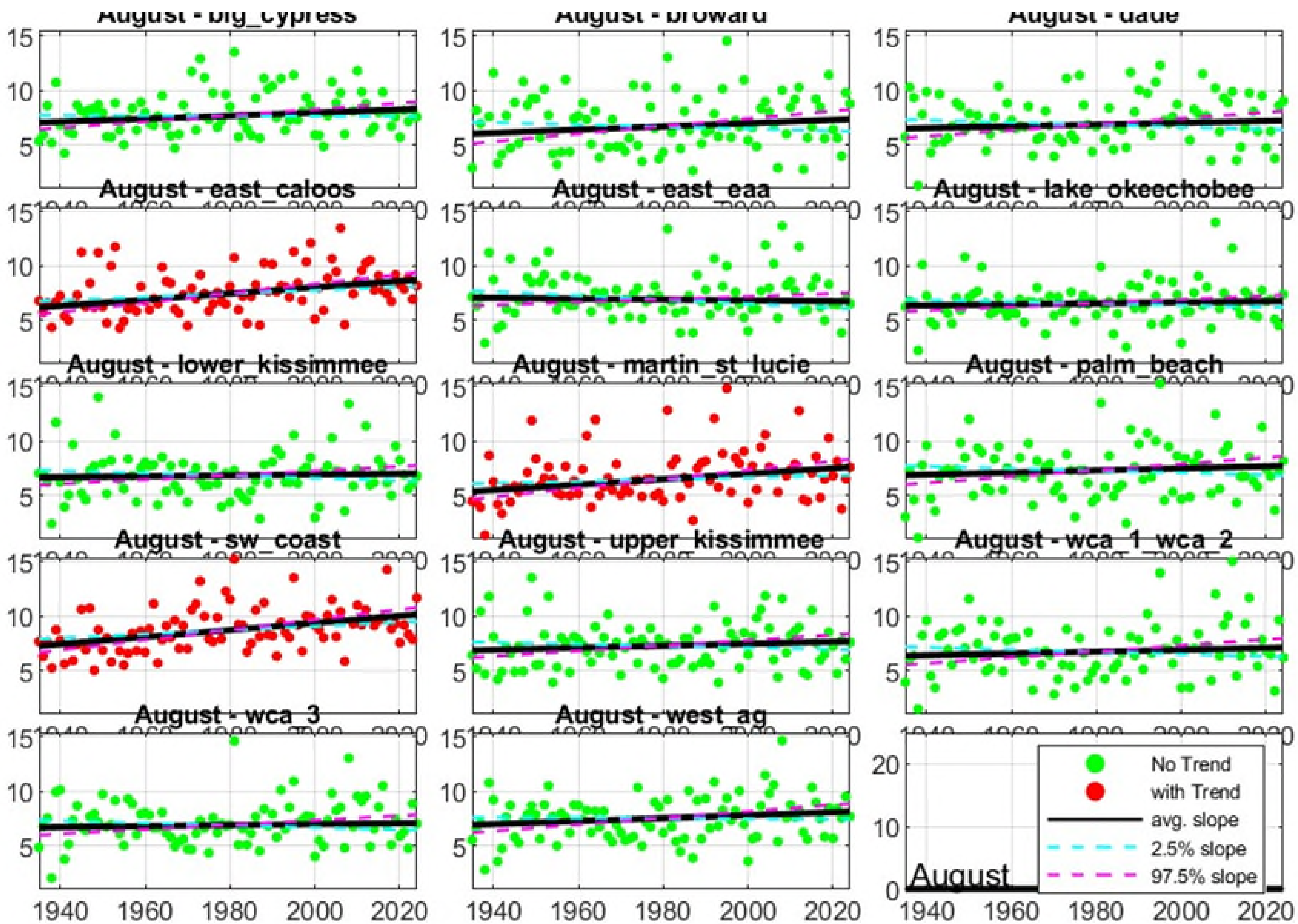

Figure 2B-3. Results of the rainfall trend analysis for August, POR from 1935 to 2024.

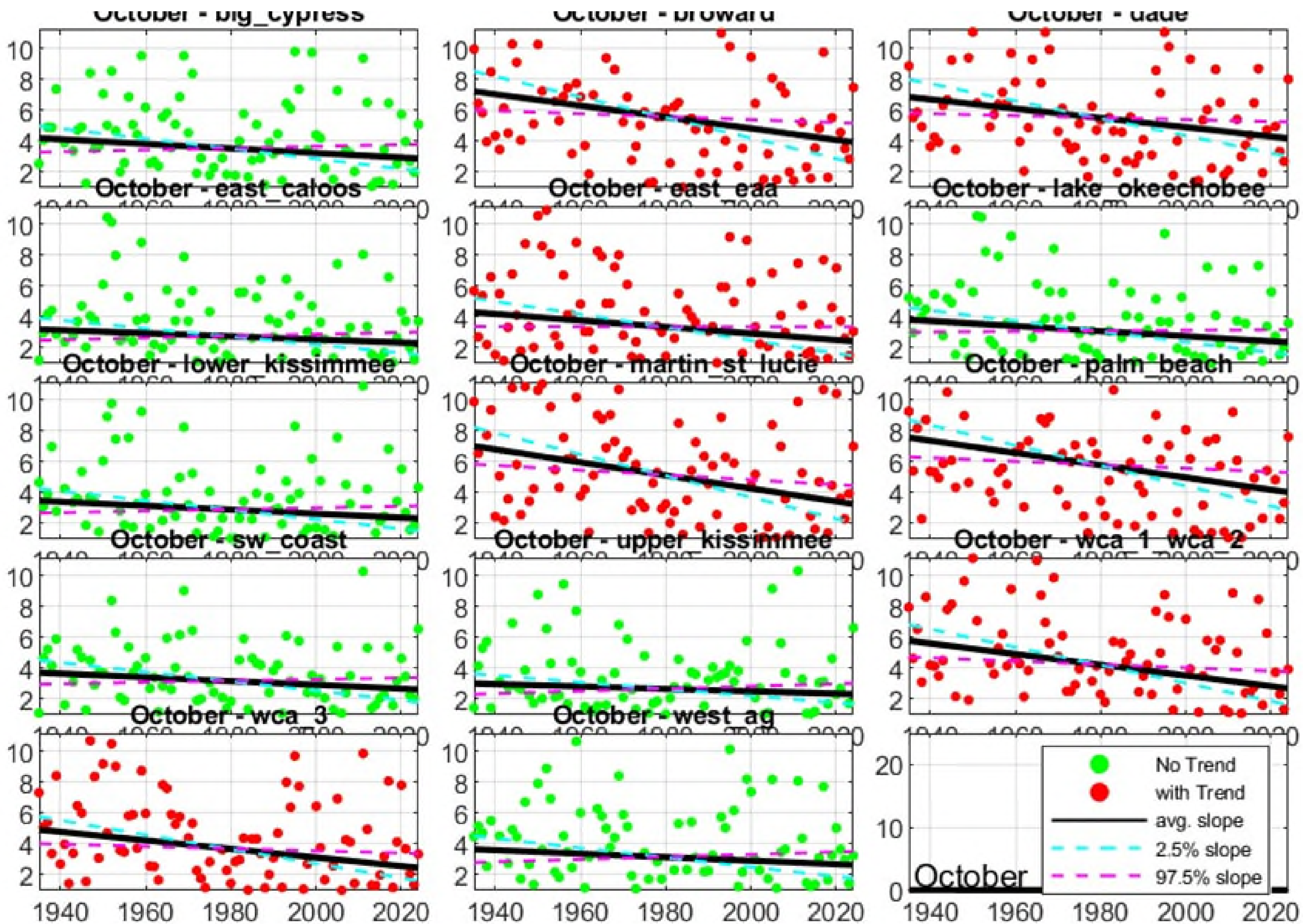

Figure 2B-4. Results of the rainfall trend analysis for October, POR from 1935 to 2024.

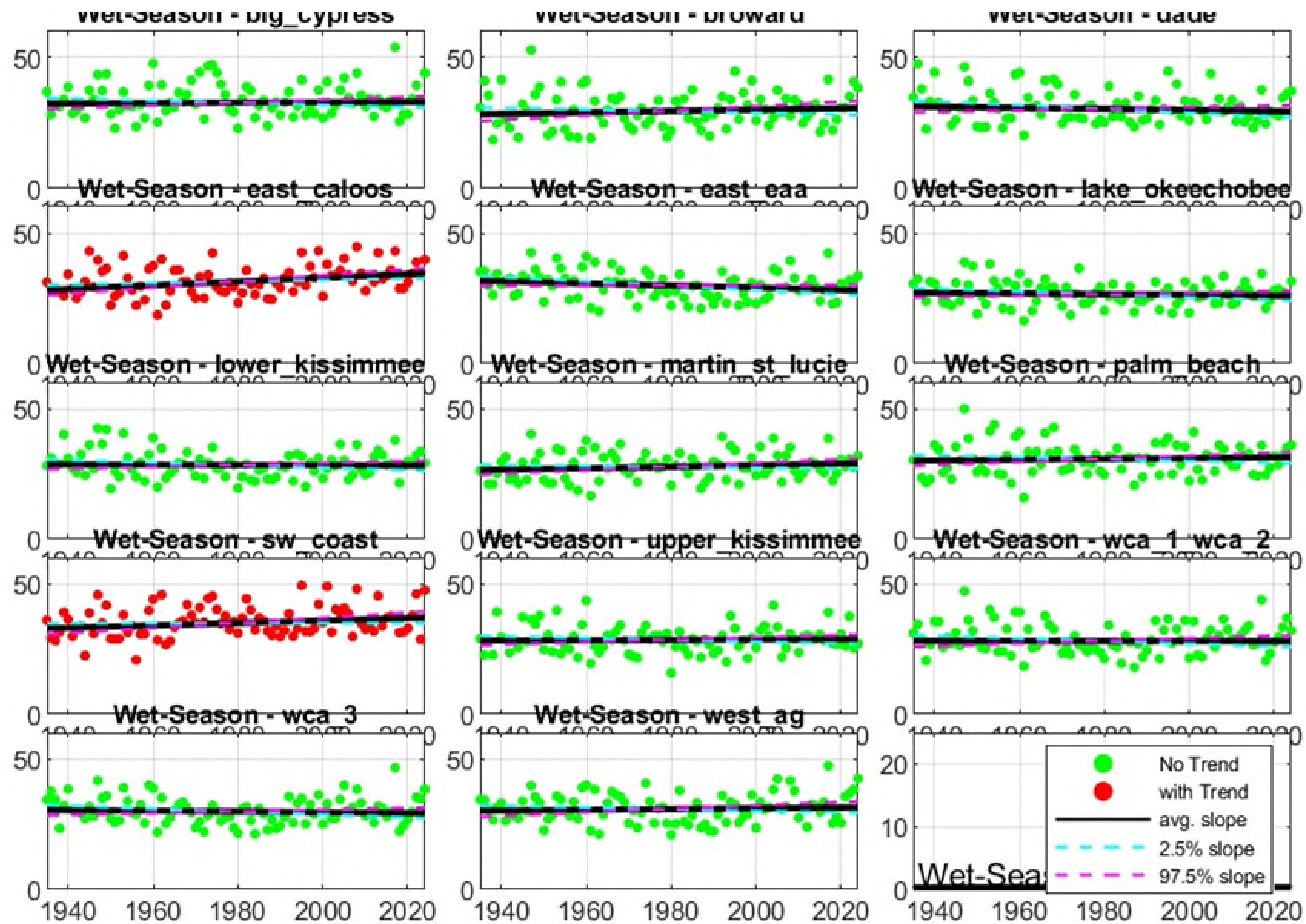

Figure 2B-5. Results of the rainfall trend analysis for the wet season, POR from 1935 to 2024.

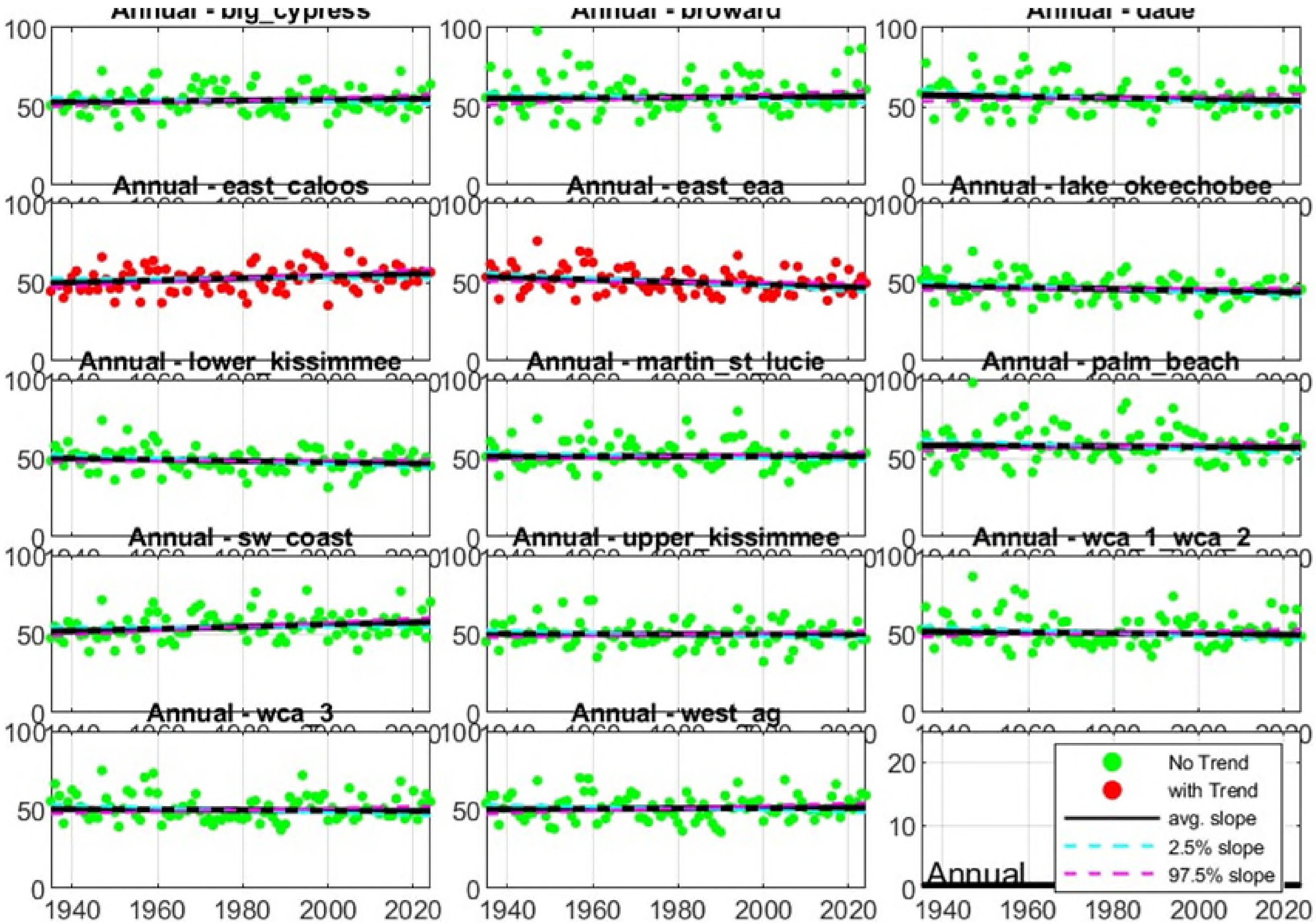

Figure 2B-6. Results of the annual rainfall trend analysis, POR from 1935 to 2024.

Table 2B-3 Error! Reference source not found. presents the comparative results for the maxima frequency trend analyses for both the 1935–2018 and 1935–2024 PORs. For figures corresponding to the 1935–2018 analysis, see Cortez et al. (2022). For the complete set of figures from the updated analysis, see Appendix 2B-1.

Table 2B-33. Annual 1-, 3-, and 5-day maxima frequency trend analyses results.

Frequency Trend Analysis	Observed Trend for POR 1935–2018	Observed Trend for POR 1935–2024
1-day, 2-year	Upward trend: Water Conservation Area 1 and 2 Downward trend: Upper Kissimmee	No significant trend
1-day, 5-year	Upward trend: Martin – St. Lucie Downward trend: Palm Beach	Upward trend: Big Cypress, Martin – St. Lucie, Upper Kissimmee Downward trend: Palm Beach
1-day, 10-year	Upward trend: Upper Kissimmee	Upward trend: Big Cypress, Upper Kissimmee
3-day, 2-year	No significant trend	Upward trend: Southwest Coast
3-day, 5-year	Downward trend: Miami-Dade	No significant trend
3-day, 10-year	Upward trend: Big Cypress	Upward trend: Broward
5-day, 2-year	No significant trend	Upward trend: Broward
5-day, 5-year	Downward trend: Broward	Upward trend: Martin – St. Lucie, Water Conservation Area 3
5-day, 10-year	No significant trend	Upward trend: East Caloosahatchee

The frequency analysis reveals a broader distribution of significant trends in the updated data set, particularly for short-to-intermediate return periods.

- For the 1-day maxima, the previously observed 2-year upward trends in Water Conservation Areas (WCAs) 1 and 2 and downward trend in Upper Kissimmee are no longer significant. These changes suggest reduced and increased rainfall intensity in recent years, respectively, which has weakened the strength of those earlier trends. At the same time, the 5-year upward trends in Martin – St. Lucie have expanded to include Big Cypress and Upper Kissimmee (as shown in **Figure 2B-7**), and the 10-year trend in Upper Kissimmee now also includes Big Cypress (as shown in **Figure 2B-8**), indicating increased frequency of more extreme short-duration events in some basins.
- For the 3-day maxima, a new 2-year upward trend appears in the Southwest Coast (as shown in **Figure 2B-9**), suggesting more frequent medium-duration rainfall events in that region. Meanwhile, the 5-year downward trend previously noted in Miami-Dade is no longer present, likely due to increased rainfall in recent years that has counteracted the earlier decline. The 10-year upward trend in Big Cypress from the prior analysis is now observed in Broward (as shown in **Figure 2B-10**), reflecting spatial shifts in extreme rainfall patterns.
- For the 5-day maxima, a new 2-year upward trend appears in Broward (as shown in **Figure 2B-11**), while the previously observed 5-year downward trend in the same region has been replaced by upward trends in Martin – St. Lucie and WCA-3 (as shown in **Figure 2B-12**). In addition, a new 10-year upward trend is observed in East Caloosahatchee (as shown in **Figure 2B-13**), reinforcing the idea of increasing longer-duration rainfall extremes in that area.

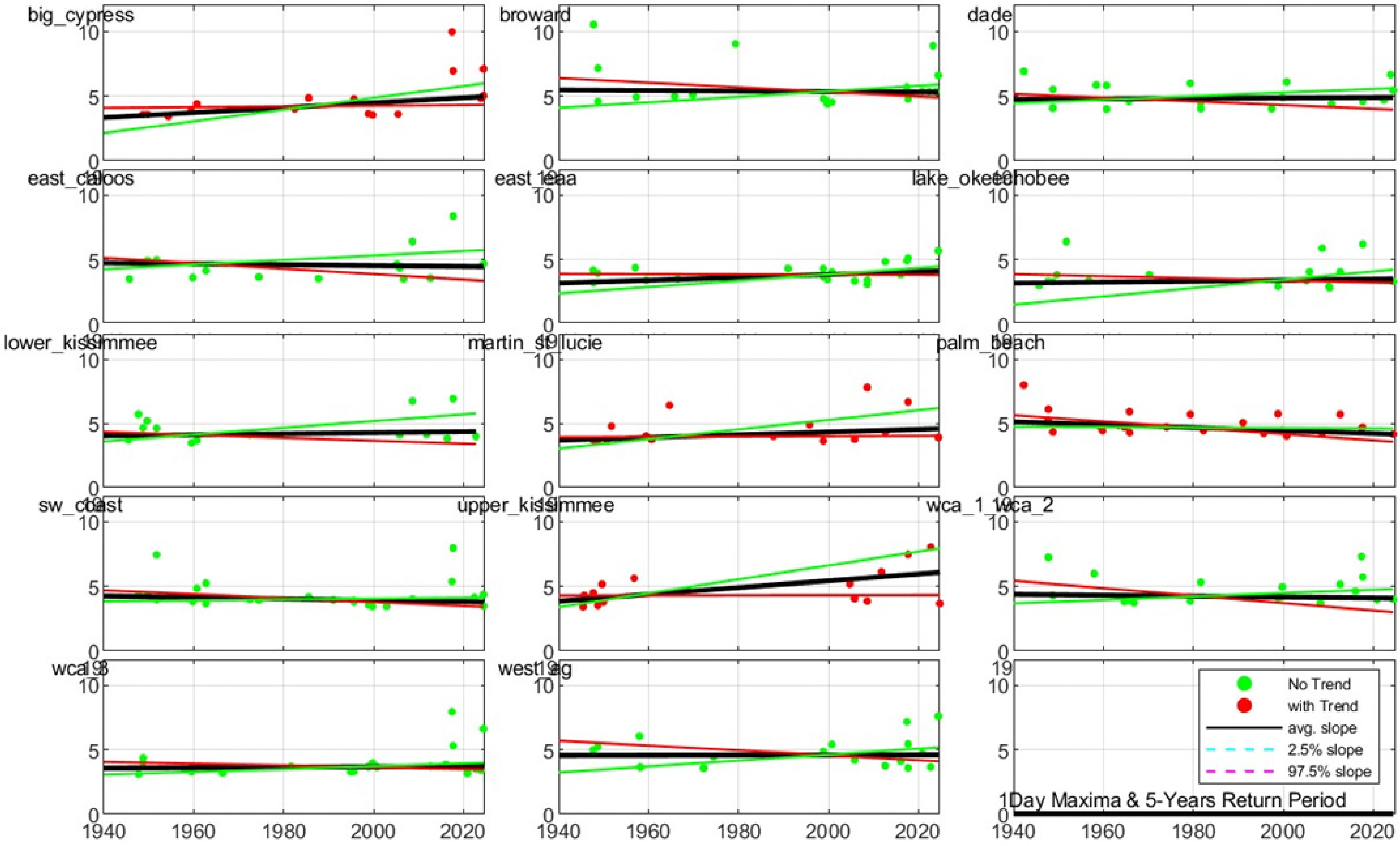

Figure 2B-7. Results of the 1-day maxima, 5-year return frequency trend analysis, POR from 1935 to 2024.

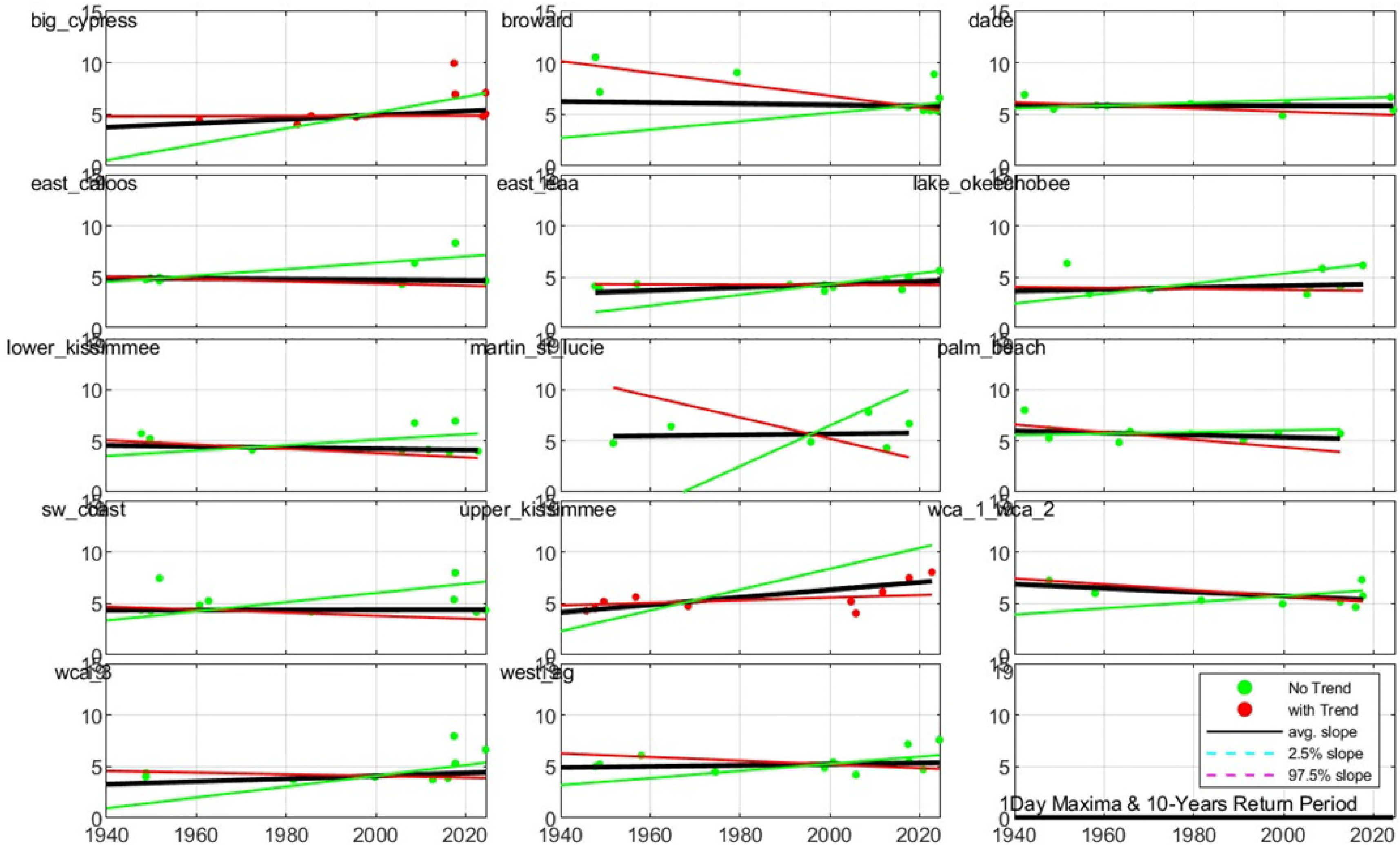

Figure 2B-8. Results of the 1-day maxima, 10-year return frequency trend analysis, POR from 1935 to 2024.

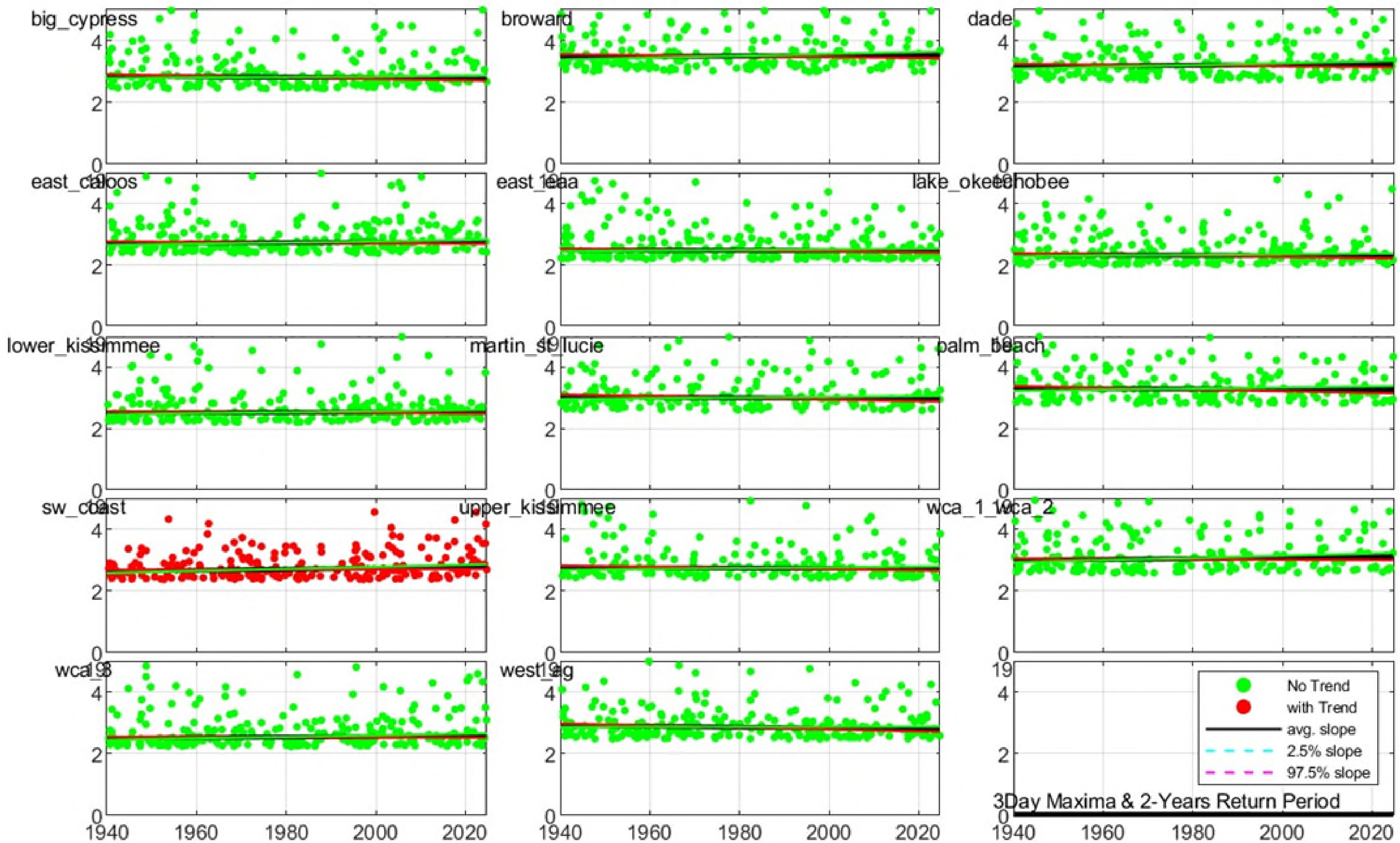

Figure 2B-9. Results of the 3-day maxima, 2-year return frequency trend analysis, POR from 1935 to 2024.

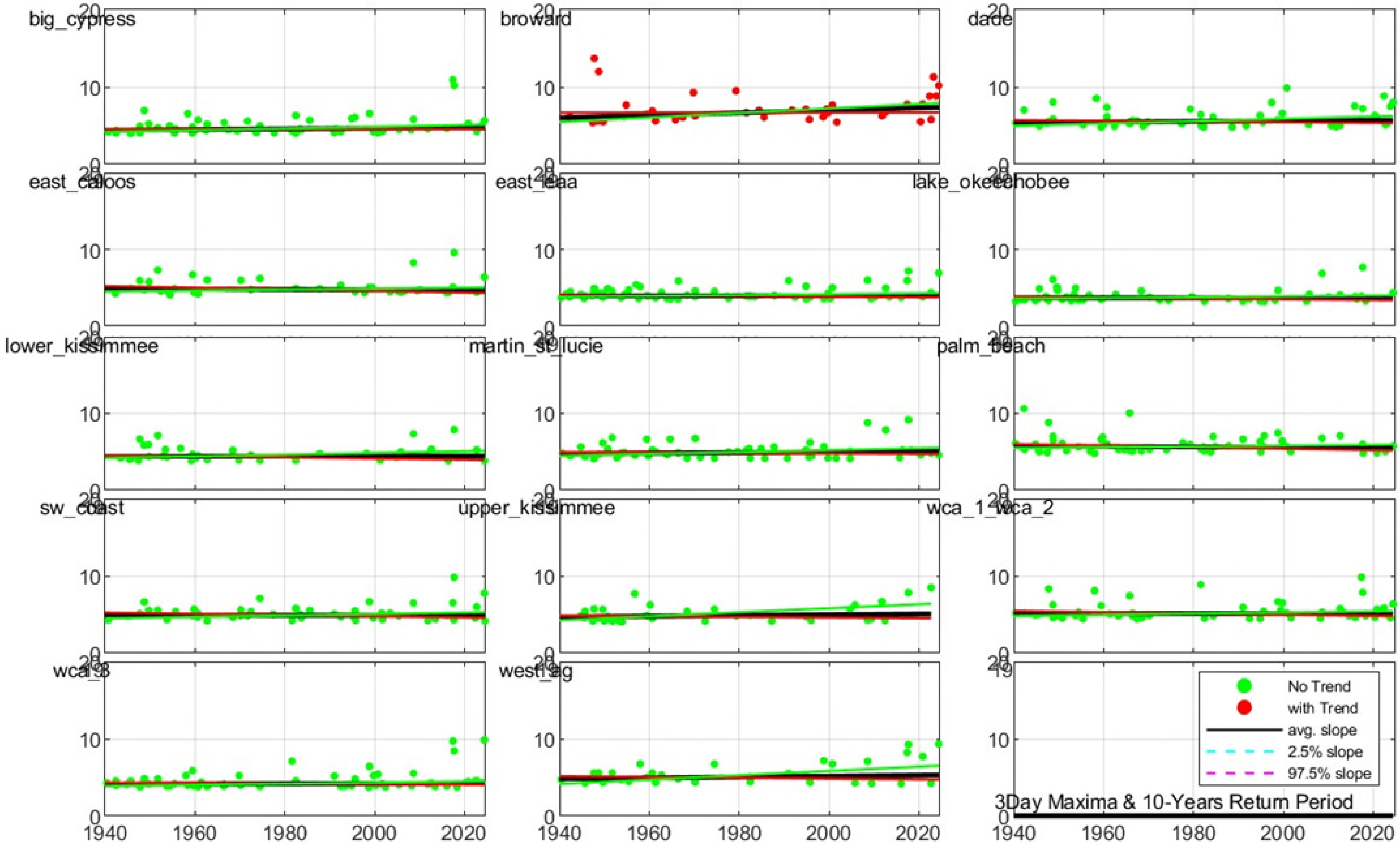

Figure 2B-10. Results of the 3-day maxima, 10-year return frequency trend analysis, POR from 1935 to 2024.

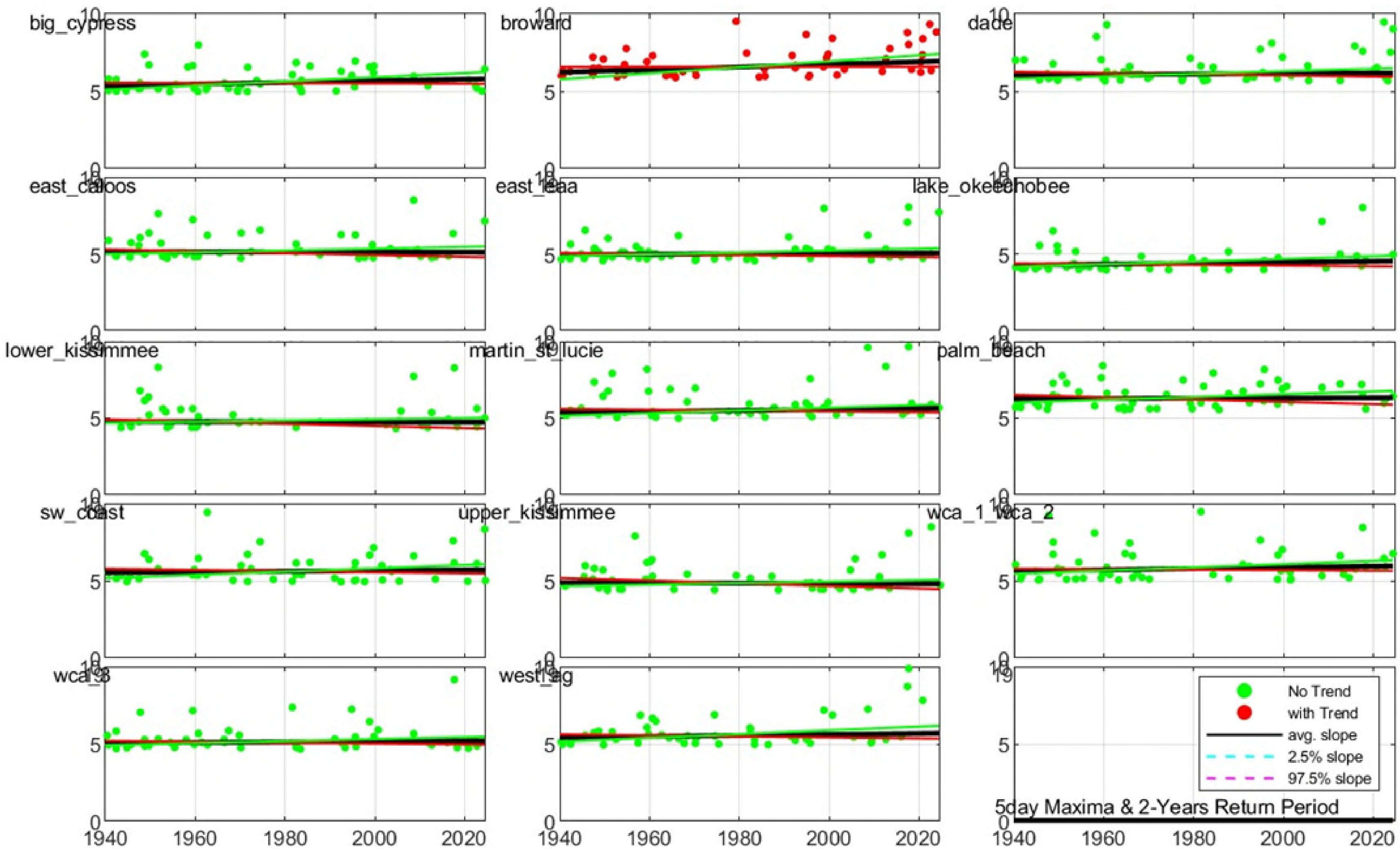

Figure 2B-11. Results of the 5-day maxima, 2-year return frequency trend analysis, POR from 1935 to 2024.

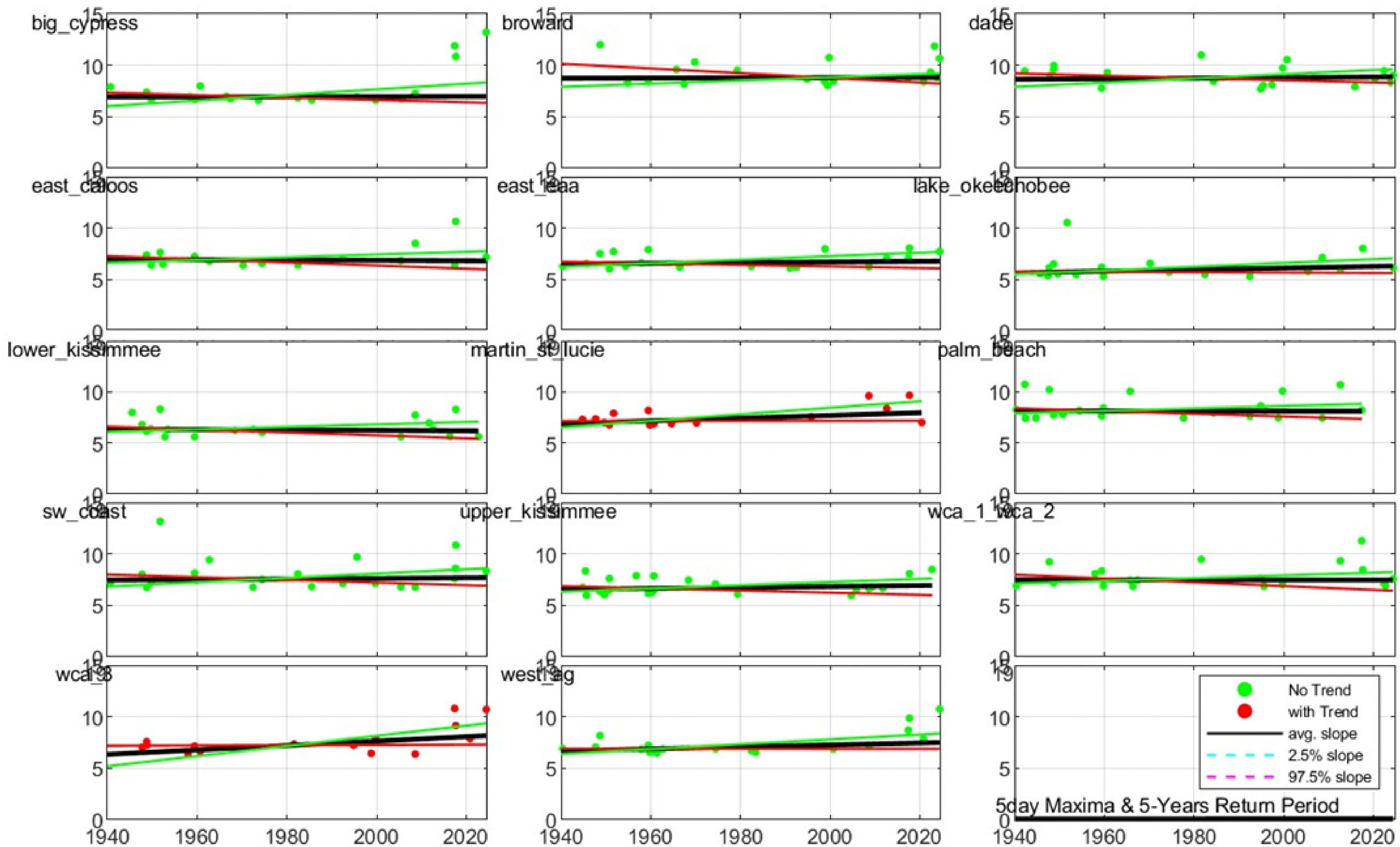

Figure 2B-12. Results of the 5-day maxima, 5-year return frequency trend analysis, POR from 1935 to 2024.

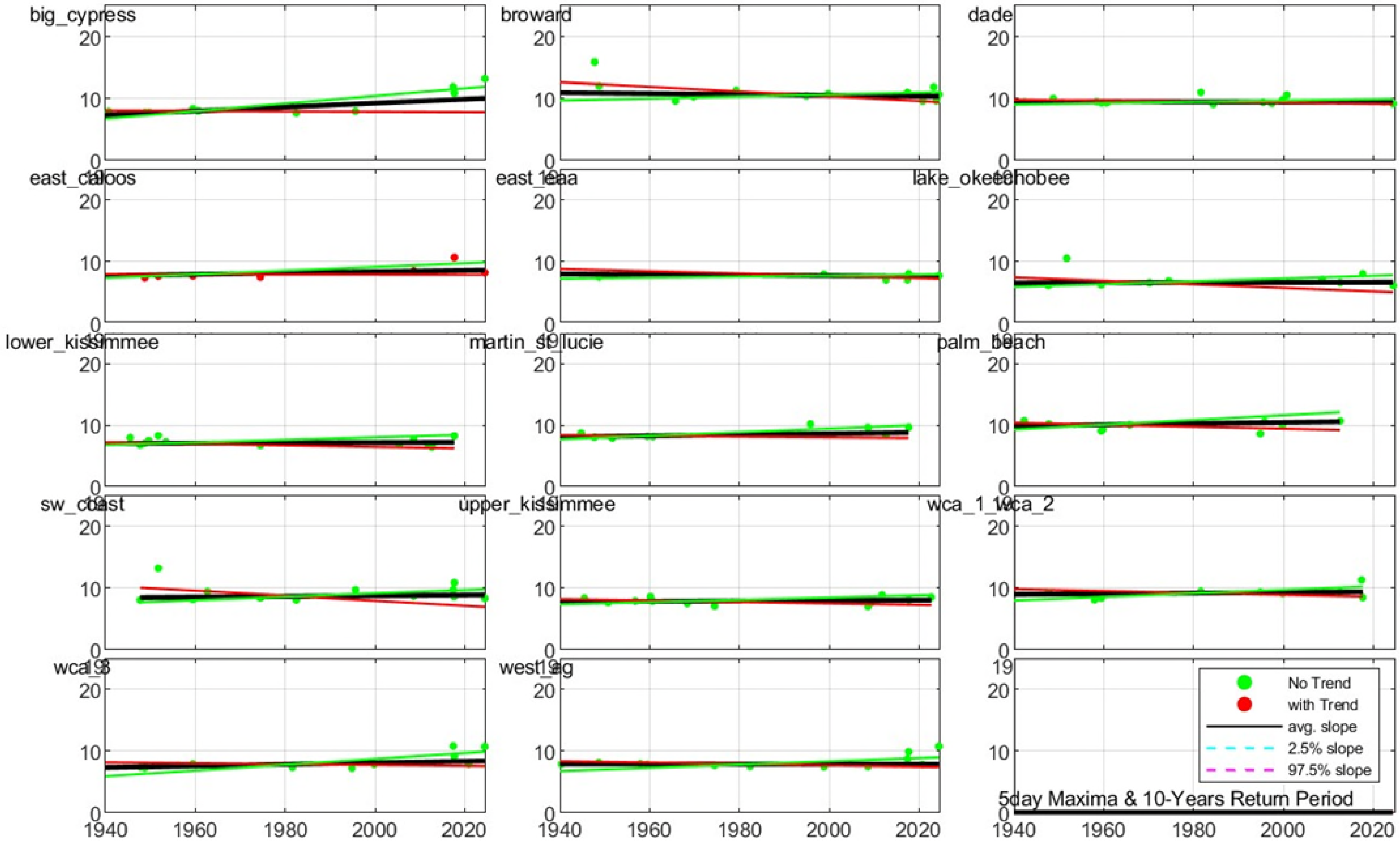

Figure 2B-13. Results of the 5-day maxima, 10-year return frequency trend analysis, POR from 1935 to 2024.

The integration of six additional years of rainfall data (2019–2024) has altered both trend and frequency analyses, demonstrating that regional hydrologic patterns are dynamic and sensitive to recent climate variability. The updated findings emphasize the importance of continuous monitoring and periodic reassessment to capture evolving rainfall patterns that may affect water management infrastructure and operations, flood risk, and ecosystem health across South Florida.

CLUSTER ANALYSIS

In addition to the update of the rainfall analysis described in the preceding subsection—which focuses on assessing long-term rainfall trends within each of the region's 14 rainfall areas, delineated according to hydrologic components within the regional water management system—an analytical approach is introduced to enhance the assessment of long-term spatial rainfall patterns in South Florida. This approach enhances regional rainfall analysis by expanding the capability to identify localized trends in extremes, particularly low-density occurrences of extreme rainfall values within a pre-determined rainfall grid. By applying specific rainfall thresholds to define clusters of such observations (grid cell values), the method enables examination of rainfall patterns both across the region's rainfall areas and through a more granular assessment of spatial variability and localized deviations.

The analysis employs density-based spatial clustering of applications with noise (DBSCAN), a non-parametric clustering algorithm that applies user-defined thresholds to large data sets. DBSCAN is particularly suited for rainfall studies because it can detect clusters of arbitrary shape, does not require predefined cluster counts, and effectively handles noise. These capabilities make it well adapted to threshold-sensitive rainfall behavior, providing a flexible alternative to conventional fixed-grid or station-based statistical methods.

Applied to regional rainfall grid data, DBSCAN identified locations (grid cell values) where rainfall thresholds deemed extreme are consistently exceeded, referred to as persistent clusters. This framework also enables detection of emerging clusters as climate conditions evolve. To assess temporal significance, peaks-over-threshold (POT) analysis was integrated, allowing evaluation of whether these regions exhibit statistically significant trends. By combining spatial clustering with temporal trend detection and aligning results interpretation with rainfall area analyses and overall metrics effort, the study establishes a robust, scientifically grounded framework to support resilience planning, infrastructure adaptation, and risk reduction strategies.

Methodology

This study employs DBSCAN to detect rainfall clusters by leveraging density and spatial-temporal proximity of grid cell values (observed rainfall). The algorithm groups locations that exhibit dense similarities in annual maximum rainfall thresholds, while filtering out low-density outliers (noise). Multiple thresholds were tested to capture behavior under normal and extreme conditions. Each threshold produced distinct cluster formations, revealing how rainfall zones evolve with increasing intensity. This methodology enables the identification of persistent clusters (zones that appear across multiple thresholds) and emerging clusters (zones that appear only under specific high-threshold conditions). The process involves several steps: (1) data and preprocessing, (2) DBSCAN clustering, and (3) clusters identification. These steps are discussed in more detail in the following subsections.

Data and Preprocessing

The rainfall data set spans from January 1, 1935, through December 31, 2024. Daily rainfall values are represented across a gridded domain, with each grid cell defined by row and column coordinates. For this analysis, the POR was restricted to 1935–2024 to ensure sufficient data density and completeness.

DBSCAN Clustering

In this study, each rainfall grid cell is treated as a ‘point” in DBSCAN terminology. The algorithm groups together points that are closely packed based on key parameters:

- **Rainfall threshold (in inches):** Minimum daily rainfall value considered an “extreme” event.
- **Minimum exceedance days:** Minimum number of days within the POR a grid cell must exceed the threshold to be considered active.
- **Minimum points:** Minimum number of cells required to form a cluster.
- **Epsilon:** Maximum distance between neighboring grid cells (in grid units).
- **Alpha:** Significance level for statistical trend analysis (e.g., 0.05).
- **Core point:** Grid cell with the minimum required number of neighboring exceedance cells (MinPts) within span epsilon.
- **Border point:** Not a core point but is within epsilon distance to a core point.
- All other points are noise.

Optimal clusters were identified through iterative adjustments of the above parameters; results are presented in Appendix 2B-1**.** *Epsilon* was internally calculated as the distance to the nearest neighbor of the *minimum points* in each parameter scenario, which is in essence defined as spatial proximity combined with temporal rainfall similarity. The method helps isolate meaningful hydrological zones that consistently behave similarly across different rainfall intensity thresholds. This clustering method supports SFWMD’s ability to identify both persistent and emerging spatial behaviors essential for tiered resilience planning.

Clusters Identification

All grid cells that exceed a given *rainfall threshold* (e.g., 4.00 inches) are first extracted from the data set. From this subset, only grid cells surpassing the *minimum exceedance days* are retained, forming a refined set of exceedance cells (exceedance cells). The DBSCAN algorithm is then applied to group these spatially adjacent *exceedance cells* into contiguous rainfall clusters. Each resulting cluster is assigned to a unique identifier and is individually analyzed. Grid cells that do not conform to any cluster formation are labeled as ‘-1’, indicating that they are classified as noise and do not belong to any defined rainfall cluster. This way, a set of clusters are identified to provide insights about significant patterns (as shown in Appendix 2B-1). For these clusters, daily rainfall is aggregated into threshold exceedance time series for each cluster ready for trend analysis.

Results and Discussion

The key outcomes from the cluster-based analysis of rainfall extremes across different time periods and intensity thresholds are presented below. This analysis provides a coherent narrative of how rainfall behavior evolves spatially and temporally, offering a structured view of the observed patterns.

Threshold Sensitivity

When applying a lower rainfall threshold (e.g., 4.00 inches), the clustering algorithm revealed widespread spatial clustering, identifying numerous rainfall hotspots (as shown in **Figure 2B-14** below). This broad spatial footprint indicates areas regularly impacted by moderate to high rainfall. In contrast, raising the threshold to 6.00 inches yielded smaller, more focused clusters that aligned with the most intense rainfall events (as shown in **Figure 2B-26** below). Despite the reduced footprint, certain clusters consistently appeared across both low and high thresholds, indicating persistent rainfall hotspots. These findings support a tiered resilience strategy: widespread zones inform base-level planning, while high-threshold clusters guide preparations for extreme events.

Temporal Changes (Period of Record Effect)

A comparative analysis between the 1935–2018 period and the updated 1935–2024 period reveals notable changes in spatial rainfall patterns. In particular, the recent period (post-2018) introduced new clusters not observed in the earlier record, highlighting emerging rainfall zones (as shown in **Figures 2B-14** through **2B-29**). This trend suggests a possible intensification of rainfall in recent years, supporting concerns over possible climate change-driven shifts. These temporal changes validate the use of updated data sets for real-time planning and underscore the need to identify and reassess particular zones regularly.

Cluster Stability and Spatial Behavior

The spatial stability of clusters varies across regions; while some clusters remain fixed across time and threshold changes, others shift or disappear (as shown in **Figures 2B-14**, **2B-18**, **2B-22**, and **2B-26**). This dynamic behavior illustrates the non-stationary nature of extreme rainfall zones. It underscores the value of adaptive planning and monitoring rather than relying on static zoning. DBSCAN's ability to detect evolving spatial patterns proves essential for proactive risk mitigation and planning that accounts for future climate variability.

Temporal Trend Analysis

In addition to spatial clustering, temporal trends in POT rainfall are analyzed to assess how rainfall extremes are evolving over time. These trends were derived from annual series of POT rainfall values across the same thresholds (4.00, 4.80, 5.00, and 6.00 inches) and two PORs: 1935–2018 and 1935–2024.

- **4.00-inch threshold:** The trend analysis for the earlier period (1935–2018) showed relatively flat or mildly increasing patterns. However, in the extended period (1935–2024), upward trends became more prominent in several inland and southern zones, indicating intensification in rainfall frequency and volume driven by rainfall patterns in the last 6 years of the POR. These are discussed in more detail in the following subsections. **Figures 2B-16** and **2B-17**.
- **4.80-inch threshold:** This threshold exhibited clearer positive trends in the updated period, particularly in mid-basin areas where POT rainfall shows moderate increases. The emerging trend aligns with spatial cluster growth in these areas, as shown in **Figures 2B-18** and **2B-19**.
- **5.00-inch threshold:** While 4.80-inch POT exhibited positive trends in the updated period, the 5.00-inch POT did not exhibit any noticeable change, indicating the nonstationary mentioned above, as shown in **Figures 2B-22** and **2B-23**.
- **6.00-inch threshold:** While trends are more scattered, some regions with recent clustering show strong positive trends, confirming that cluster emergence is often tied to intensifying extremes, as shown in **Figures 2B-28** and **2B-29**.

Overall, the trend analysis validates the cluster-based findings, adds a temporal dimension to risk assessment, and reinforces the importance of using updated records to detect accelerating patterns in rainfall extremes.

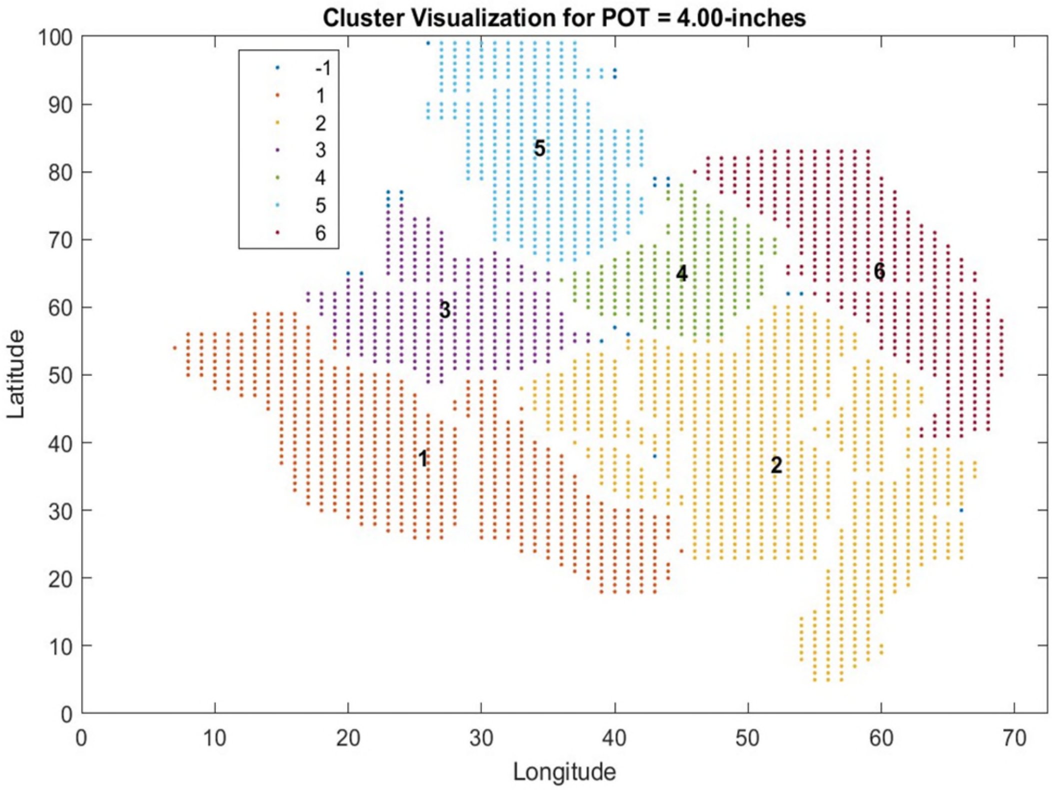

Figure 2B-14. Spatial clustering pattern for threshold 4.00 inches, POR from 1935 to 2018.

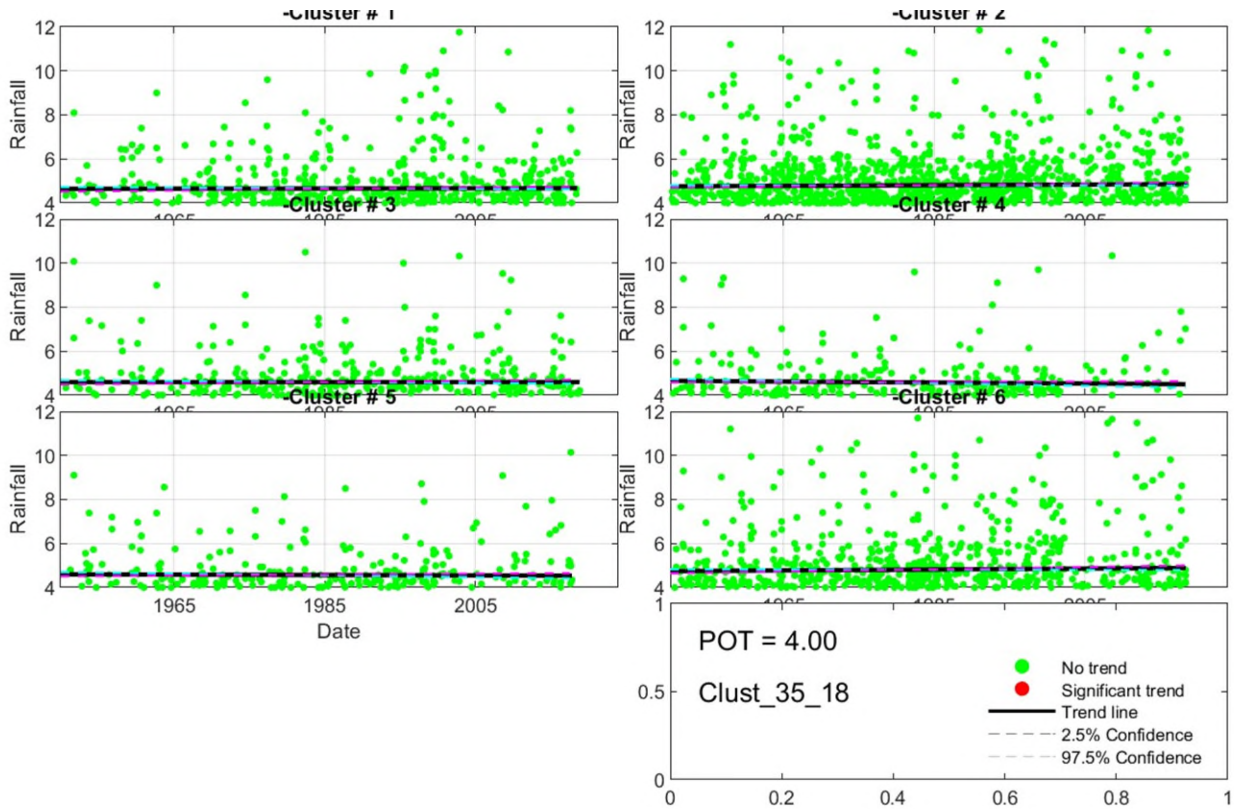

Figure 2B-15. POT trend analysis for threshold 4.00 inches, POR from 1935 to 2018.

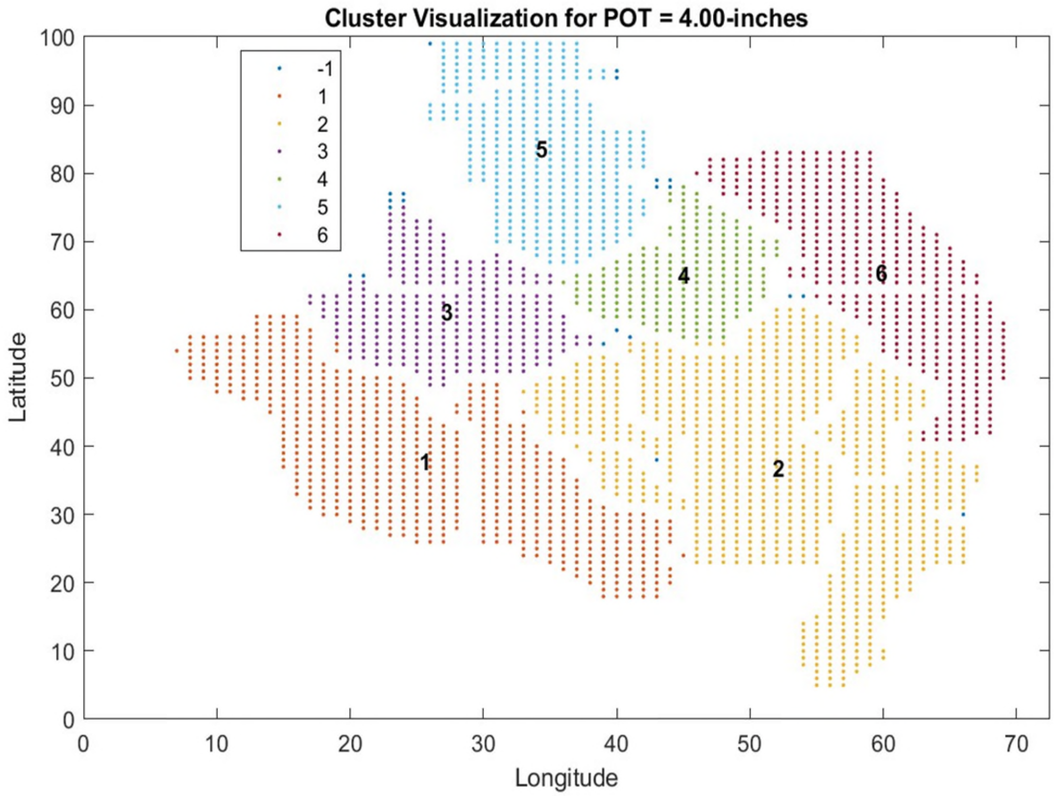

Figure 2B-16. Spatial clustering pattern for threshold 4.00 inches, POR from 1935 to 2024.

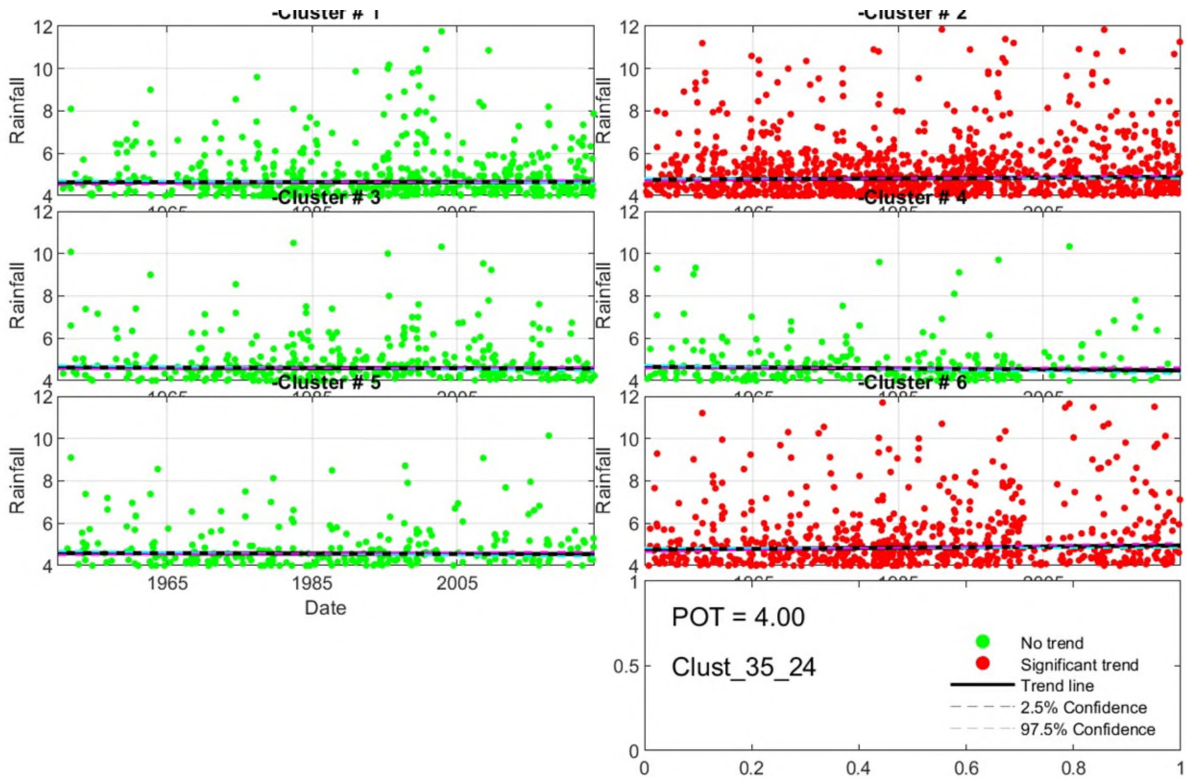

Figure 2B-17. POT trend analysis for threshold 4.00 inches, POR from 1935 to 2024.

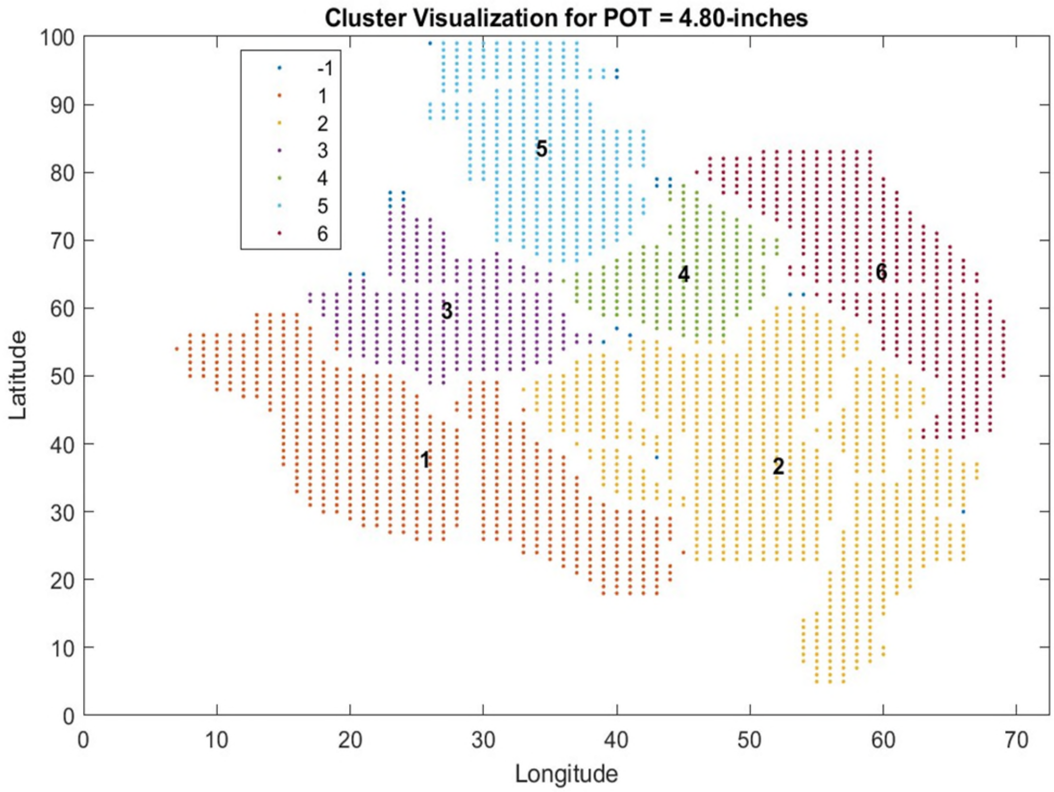

Figure 2B-18. Spatial clustering pattern for threshold 4.80 inches, POR from 1935 to 2018.

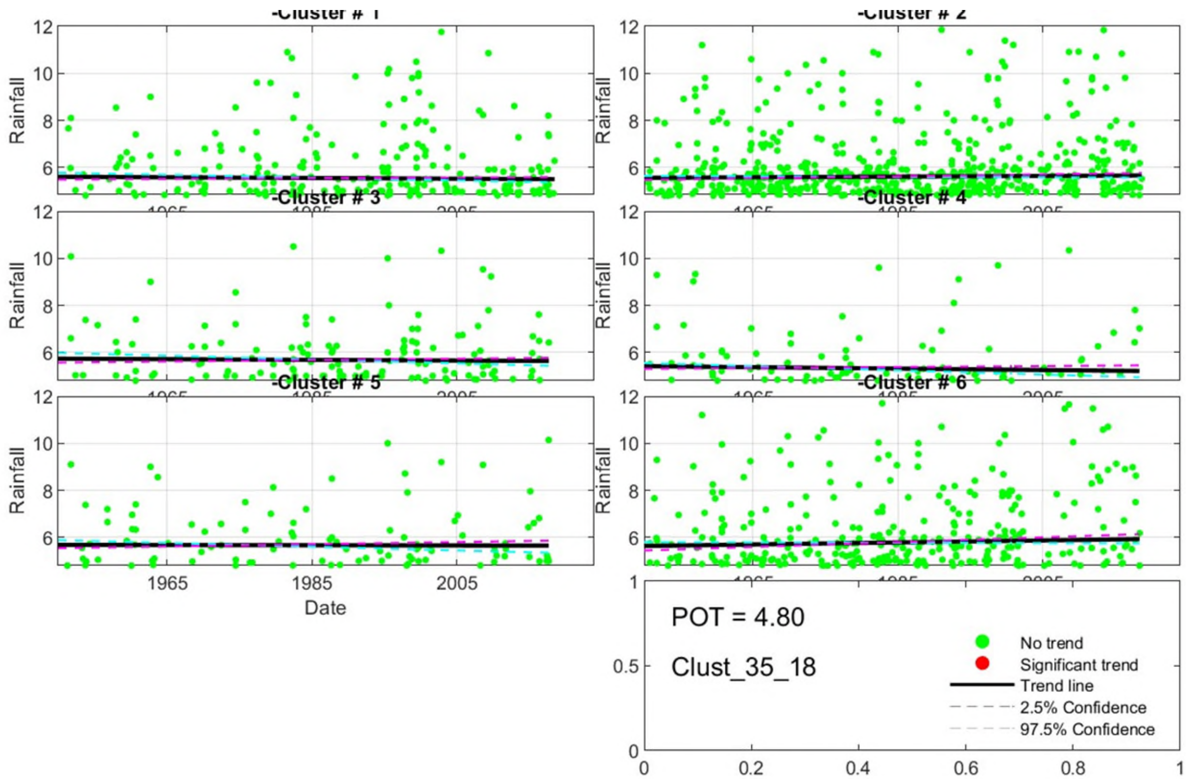

Figure 2B-19. POT trend analysis for threshold 4.80 inches, POR from 1935 to 2018.

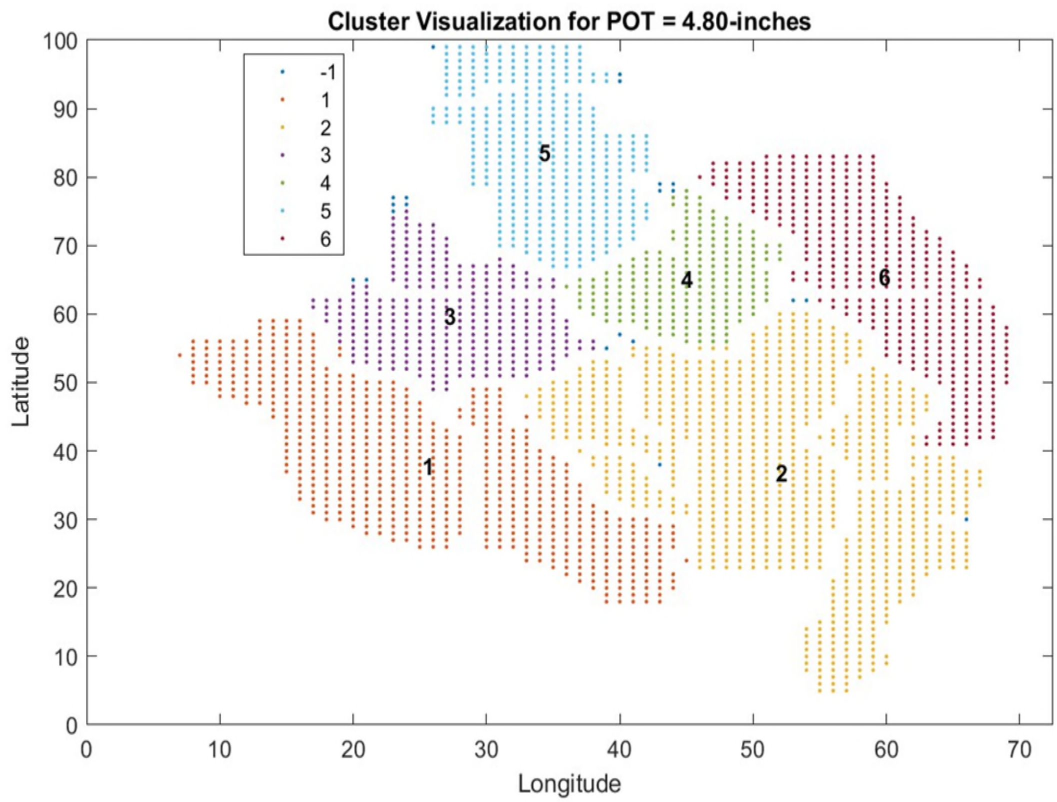

Figure 2B-20. Spatial clustering pattern for threshold 4.80 inches, POR from 1935 to 2024.

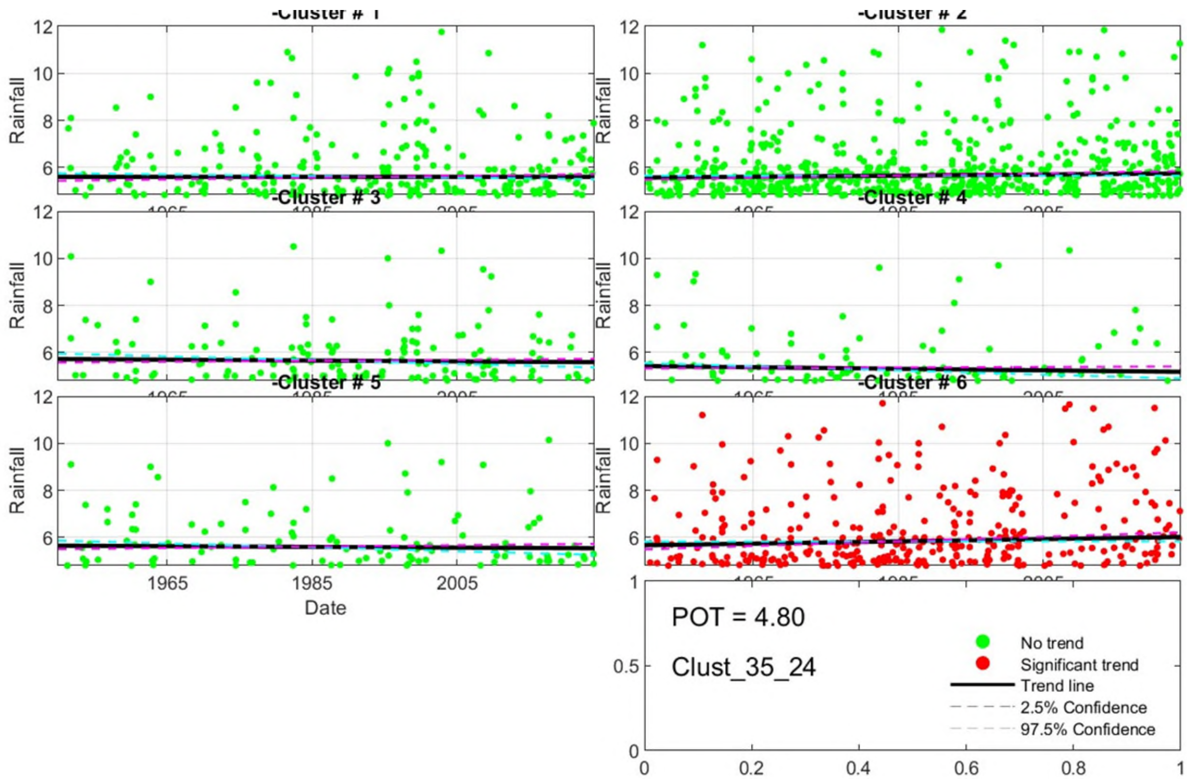

Figure 2B-21. POT trend analysis for threshold 4.80 inches, POR from 1935 to 2024.

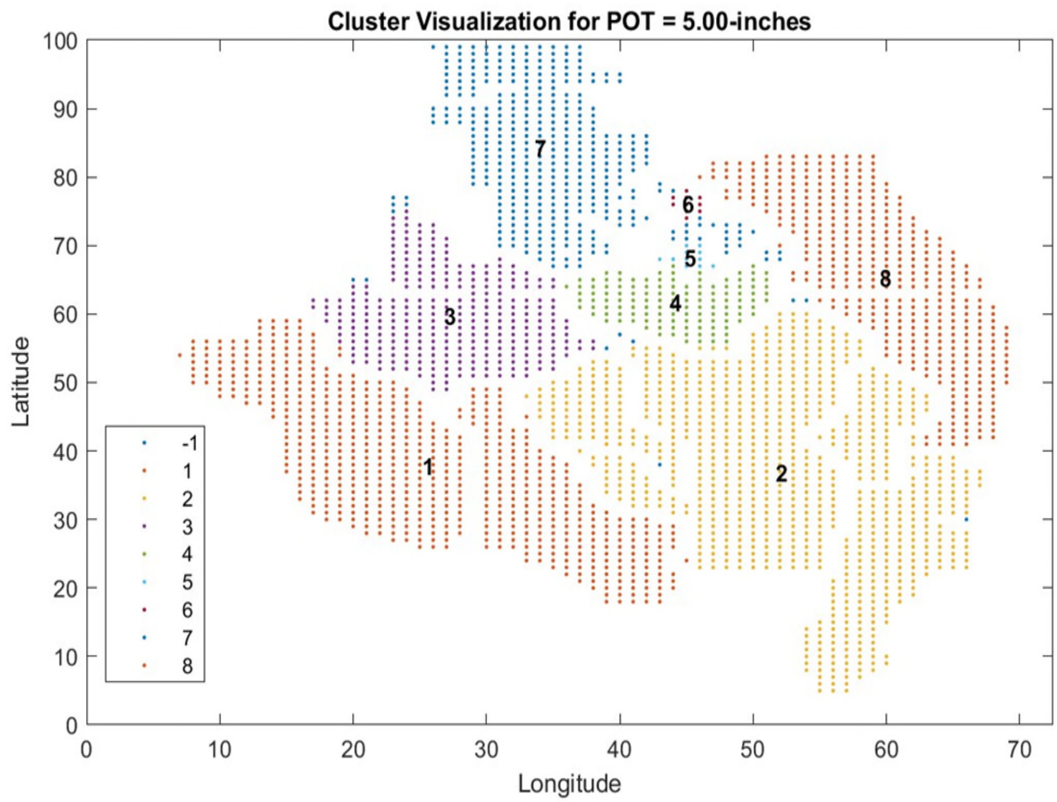

Figure 2B-22. Spatial clustering pattern for threshold 5.00 inches, POR from 1935 to 2018.

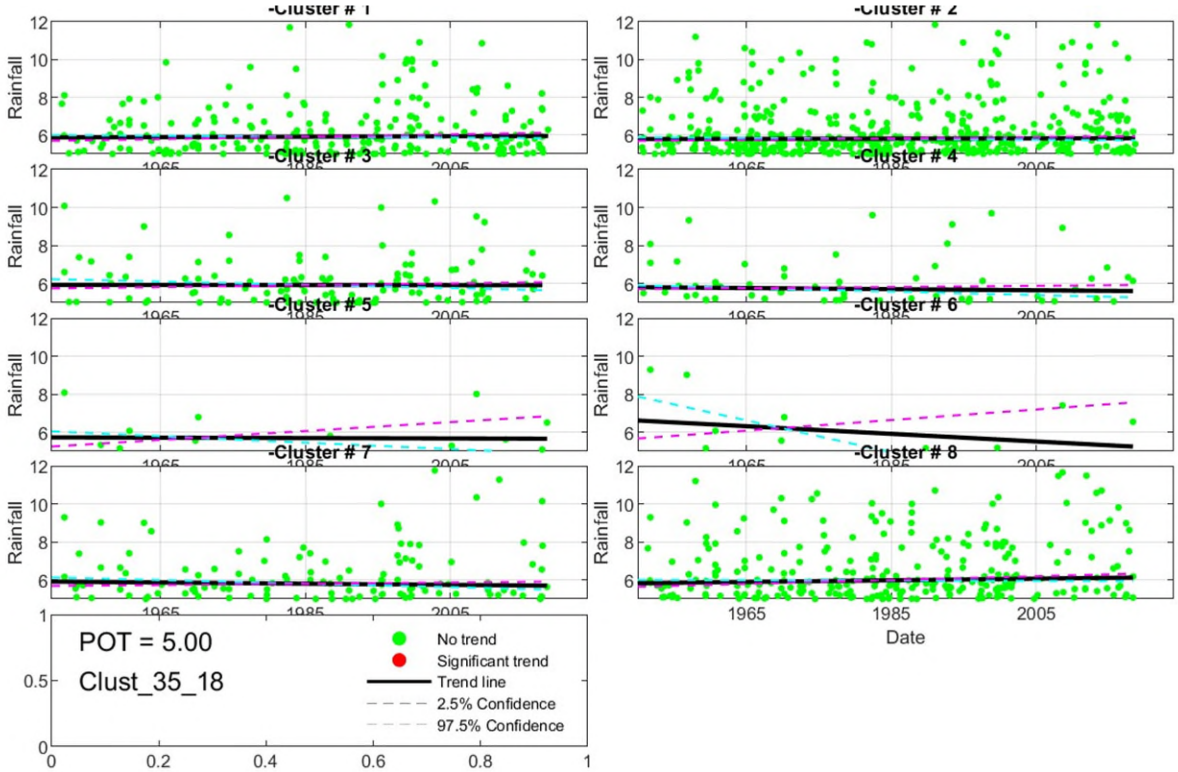

Figure 2B-23. POT trend analysis for threshold 5.00 inches, POR from 1935 to 2018.

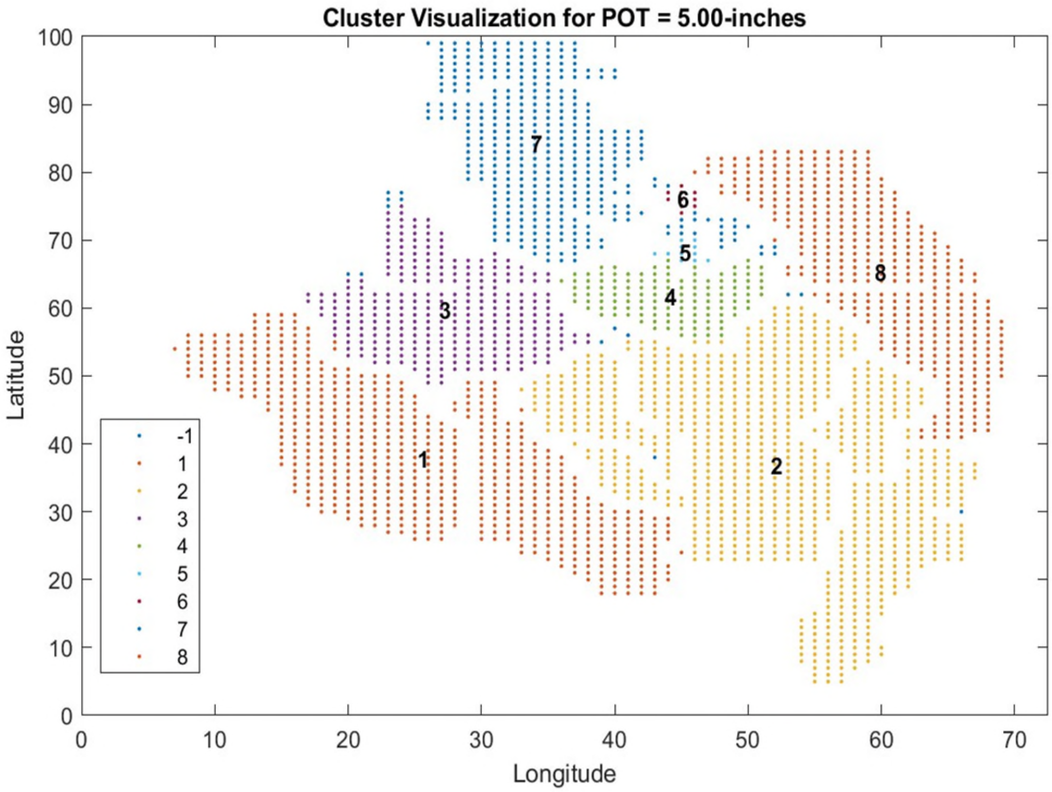

Figure 2B-24. Spatial clustering pattern for threshold 5.00 inches, POR from 1935 to 2024.

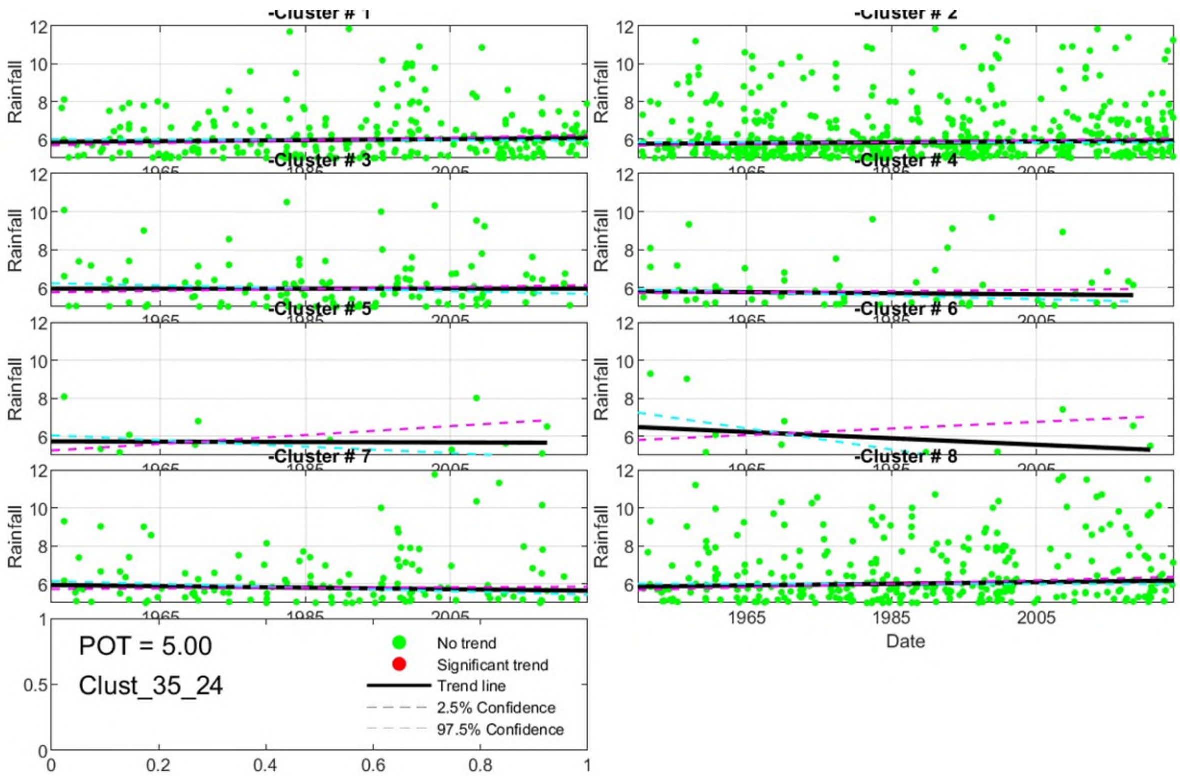

Figure 2B-25. POT trend analysis for threshold 5.00 inches, POR from 1935 to 2024.

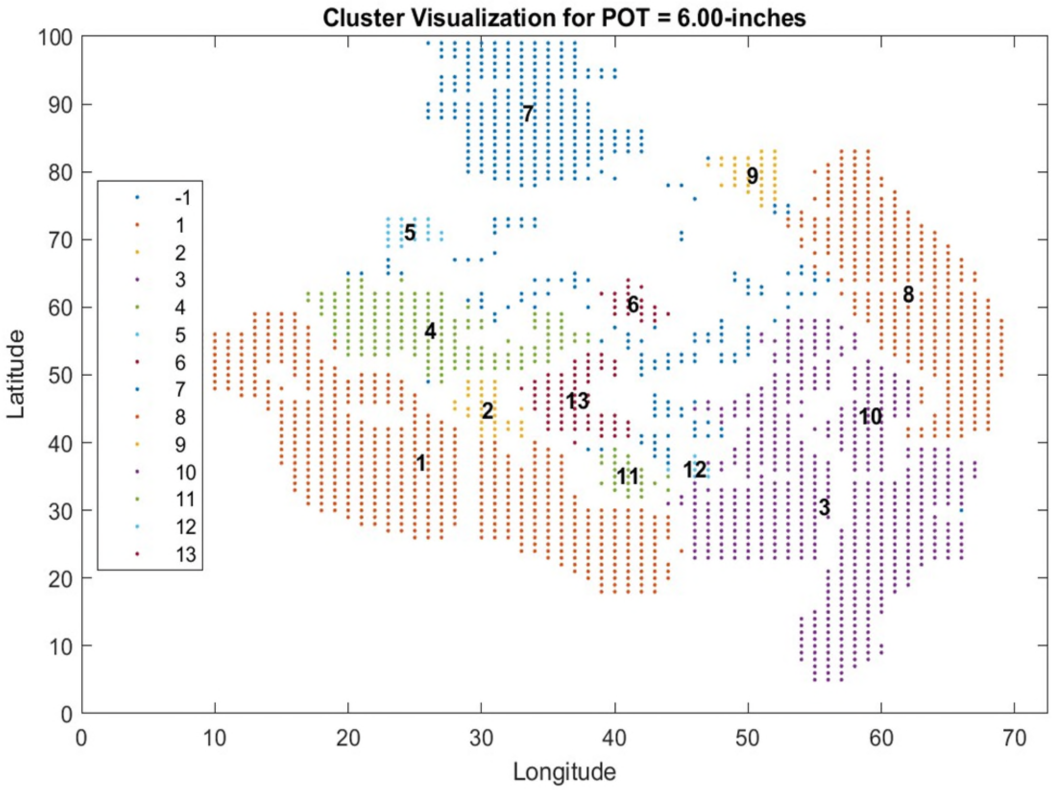

Figure 2B-26. Spatial clustering pattern for threshold 6.00 inches, POR from 1935 to 2018.

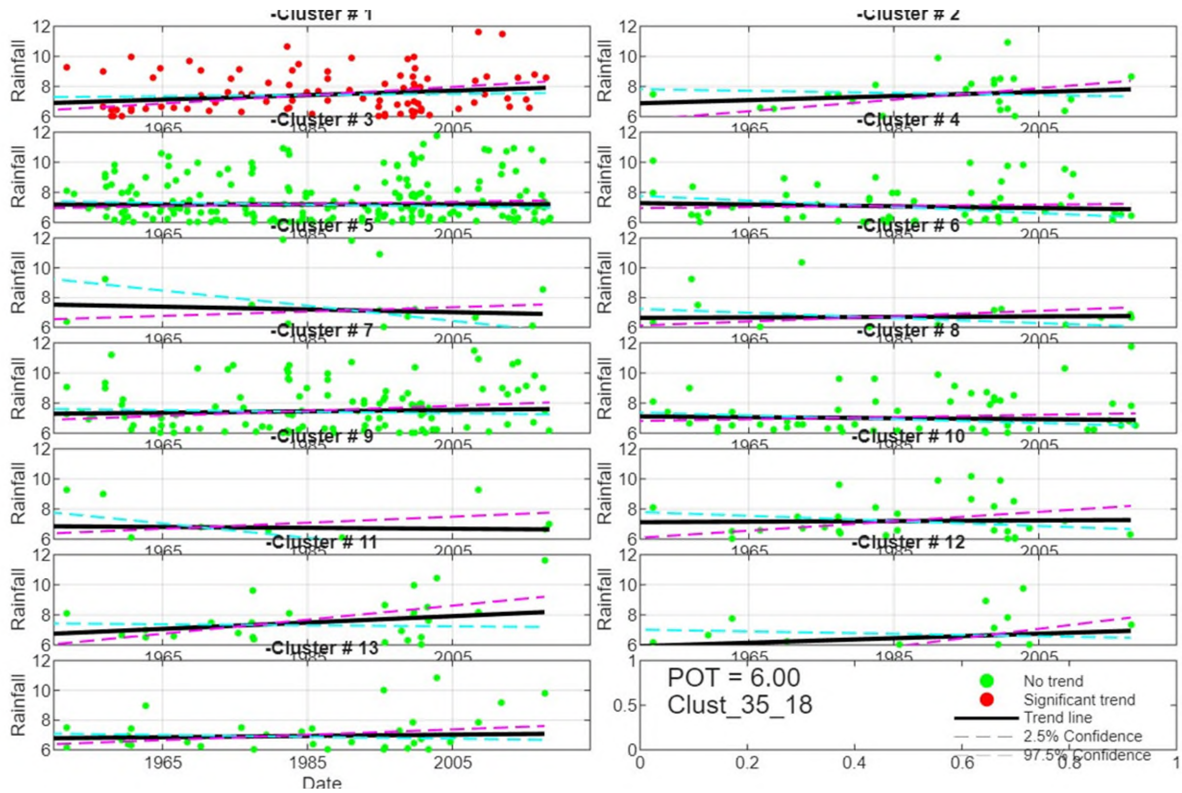

Figure 2B-27. POT trend analysis for threshold 6.00 inches, POR from 1935 to 2018.

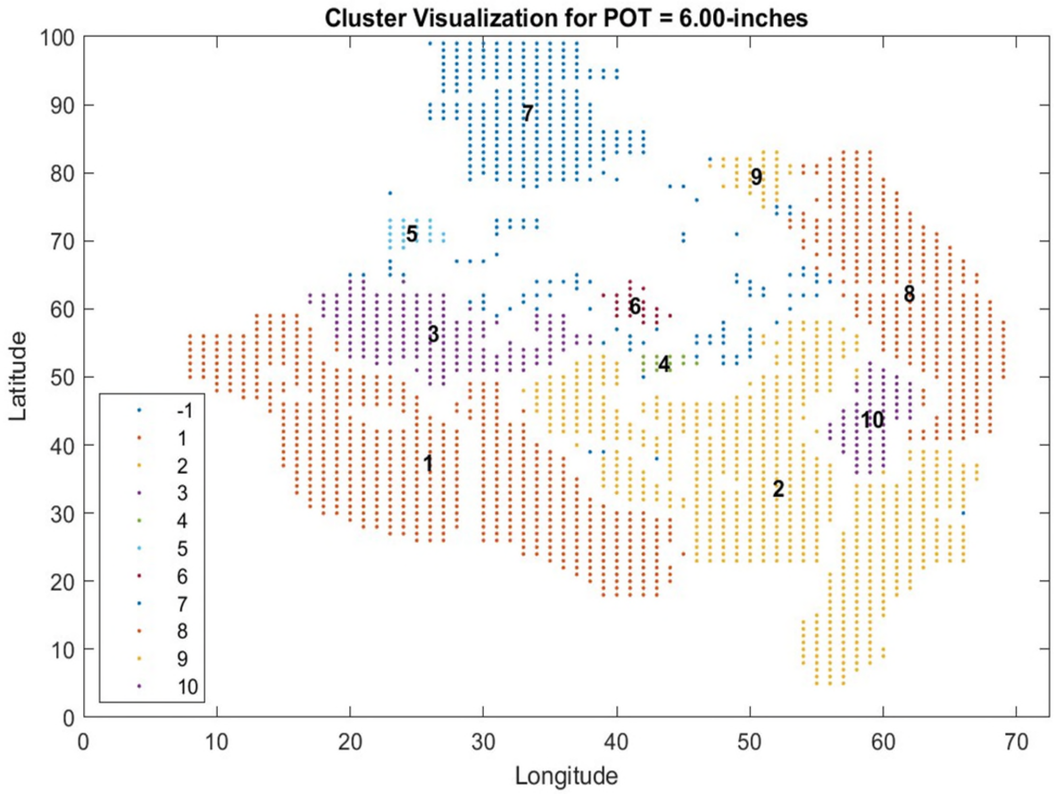

Figure 2B-28. Spatial clustering pattern for threshold 6.00 inches, POR from 1935 to 2024.

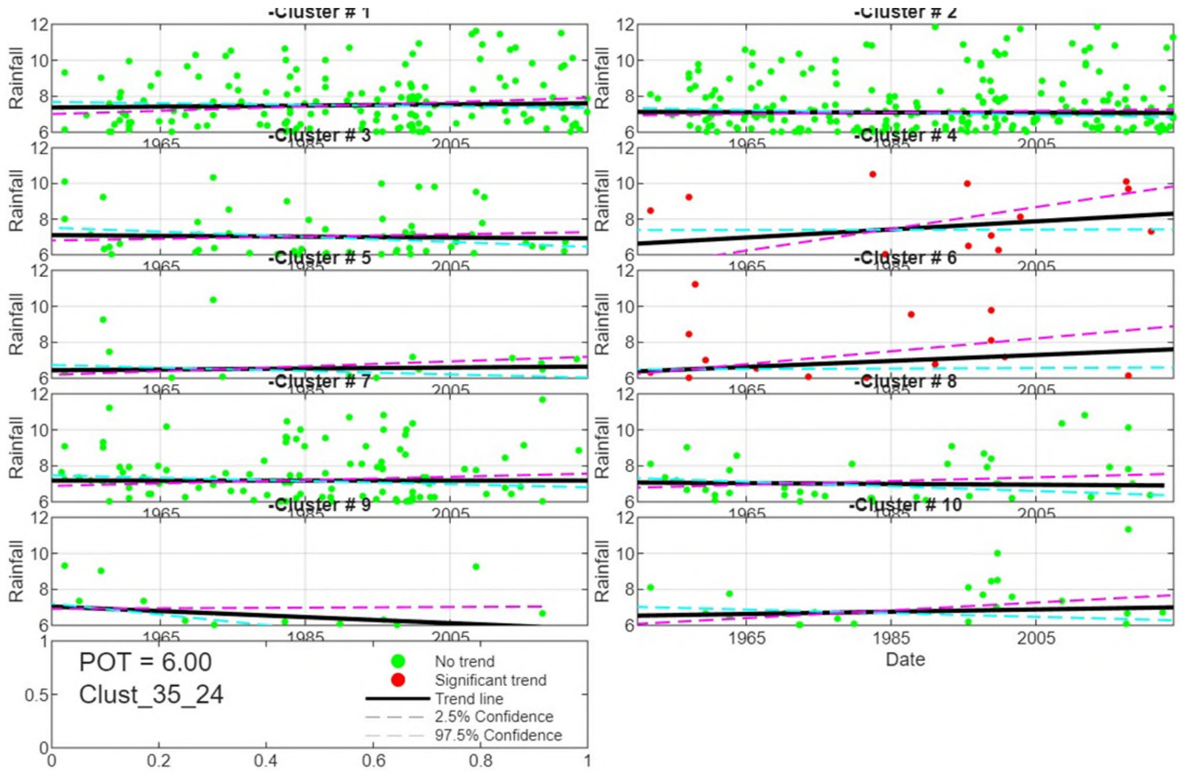

Figure 2B-29. POT trend analysis for threshold 6.00 inches, POR from 1935 to 2024.

Table 2B-4 presents the results of the cluster analysis, indicating the number of clusters obtained for each threshold across both analyzed periods (1935–2018 and 1935–2024), and among these, the number of clusters exhibiting a statistically significant trend.

Table 2B-4. Rainfall clusters across thresholds and time periods.

POR	Clusters	Threshold			
		4.00 Inches	4.80 Inches	5.00 Inches	6.00 Inches
1935–2018	Total	6	6	8	13
	With significant trend	0	0	0	1
1935–2024	Total	6	6	8	10
	With significant trend	2	1	0	2

Drawing from the individual results presented in **Figures 2B-14** through **2B-29**, **Table 2B-5** summarizes the trend behavior of the most persistent clusters, based on their repeated appearance across thresholds and PORs. The listed locations are approximate, reflecting general areas where clustering remained stable. The cluster number corresponding to each threshold is indicated in parentheses and aligns with the respective figures.

Table 2B-5. Spatially persistent rainfall clusters across thresholds and time periods.

Location	POR	Threshold			
		4.00 Inches	4.80 Inches	5.00 Inches	6.00 Inches
Lower west coast	1935–2018	No significant trend (Cluster 1)	No significant trend (Cluster 1)	No significant trend (Cluster 1)	Upward trend (Cluster 1)
	1935–2024	No significant trend (Cluster 1)	No significant trend (Cluster 1)	No significant trend (Cluster 1)	No significant trend (Cluster 1)
Lower east coast	1935–2018	No significant trend (Cluster 2)	No significant trend (Cluster 2)	No significant trend (Cluster 2)	No significant trend (Cluster 3)
	1935–2024	Upward trend (Cluster 2)	No significant trend (Cluster 2)	No significant trend (Cluster 2)	No significant trend (Cluster 2)
Upper east coast	1935–2018	No significant trend (Cluster 6)	No significant trend (Cluster 6)	No significant trend (Cluster 8)	No significant trend (Cluster 8)
	1935–2024	Upward trend (Cluster 6)	Upward trend (Cluster 6)	No significant trend (Cluster 8)	No significant trend (Cluster 8)
Kissimmee	1935–2018	No significant trend (Cluster 5)	No significant trend (Cluster 5)	No significant trend (Cluster 7)	No significant trend (Cluster 7)
	1935–2024	No significant trend (Cluster 5)	No significant trend (Cluster 5)	No significant trend (Cluster 7)	No significant trend (Cluster 7)

Conclusions

The analysis utilized DBSCAN, a density-based clustering algorithm, to objectively delineate spatial patterns of exceedance without predefining the number of clusters or assuming rigid geometric shapes. DBSCAN is effective at detecting arbitrarily shaped clusters and filtering out noise, which is particularly useful in the complex spatial dynamics of rainfall behavior. However, the algorithm is sensitive to parameter selection (epsilon and minimum points), which may affect consistency across thresholds and periods.

The study also combines spatial clustering with temporal trend analyses of extreme rainfall events using the POT method. Four rainfall intensity thresholds (4.00, 4.80, 5.00, and 6.00 inches) were evaluated over two periods (1935–2018 and 1935–2024) to identify zones of hydrologic risk. Persistent clusters, which consistently exhibit elevated rainfall exceedances across thresholds and years, are identified as key targets for assessing resilience infrastructure planning needs. In contrast, emerging clusters, more pronounced in the updated period (1935–2024) and for higher thresholds (5.00 and 6.00 inches), reflects shifts in climate patterns and highlight potential areas of increasing vulnerability.

Temporal trend analysis of POT events further reinforced these spatial observations. Several locations showed new clustering behavior and upward trends in the frequency and mean magnitude of rainfall exceedances. This alignment of spatial and temporal patterns underscores the need to further assess risks in identified zones as part of adaptive planning and targeted interventions.

Comments and Recommendations

The findings of this study provide critical insights into the spatial and temporal changes in rainfall patterns, establishing a robust foundation for informed resilience planning. By applying clustering techniques, the analysis distinguishes between persistent and emerging rainfall risk zones. Persistent clusters, representing zones with stable hydrological behavior over time, are identified as potentially critical for long-term risk planning. In contrast, emerging clusters, which represent emerging hotspots where rainfall intensity is increasing during extreme weather events, may require specific action in resiliency planning and risk reduction strategies as their variability could present challenges to the water management infrastructure system.

The findings of this rainfall analysis offer valuable insights for advancing climate resilience planning and water management. Therefore, stakeholders are encouraged to leverage these results as a foundation for integrated resilience strategies that reflect the evolving risks driven by changing precipitation patterns and intensifying extreme weather events.

A key recommendation is the use of clustering outputs as a natural, data-driven method to delineate rainfall management zones, as these zones provide a scientific basis for refining drainage system designs, informing flood risk zoning, and guiding emergency preparedness initiatives. Furthermore, the spatial behavior uncovered in this study supports a tiered resilience strategy: persistent zones for foundational planning and emerging zones for adaptive or contingent investment. To that end, the recommendations should be embedded within broader hazard mitigation planning frameworks and infrastructure prioritization efforts, particularly in alignment with the Federal Emergency Management Agency (FEMA) and United Nations Office for Disaster Risk Reduction (UNDRR) recommendations.

RELEVANCE TO RESILIENCY IN WATER MANAGEMENT

Rainfall is the primary driver of South Florida's hydrologic processes, and understanding its behavior over time provides a critical foundation for risk informed planning and decision making related to water supply, flood risk, and ecosystem sustainability.

Long-term analyses of rainfall patterns, especially those that account for both spatial and temporal variability, support resiliency planning. By identifying how rainfall trends shift over time and across geographic areas, water managers can better understand regional climate dynamics and their implications for resource availability. This spatial awareness is particularly valuable in informing resiliency planning for adapting infrastructure and developing targeted strategies for risk mitigation.

In addition, trend analyses support the evaluation and refinement of existing water management practices. Recognizing whether extreme rainfall events are becoming more frequent or intense helps agencies assess flood vulnerabilities and whether current systems are adequate or need adjustment. This insight is especially important for flood control, drainage systems design, and the development of resilient infrastructure.

Rainfall monitoring also plays a key role in supporting ecosystem health. Hydrologic trends directly influence habitat conditions, and understanding changes in precipitation helps guide restoration and conservation efforts to ensure long-term sustainability.

Ultimately, integrating rainfall trend data into water management practices strengthens the capacity to adapt to future climate conditions as it enables a shift from static approaches to dynamic data-informed strategies that reflect a changing environment.

METEOROLOGICAL DROUGHT

BACKGROUND

A drought is defined as a period of abnormally dry weather long enough to cause a serious hydrological imbalance (Matthews 2018). Droughts are generally categorized into four types: meteorological, agricultural, hydrological, and socioeconomic drought. These types are interconnected through atmospheric and land-ocean processes, meaning that the occurrence of one can trigger the development of others—a phenomenon known as drought propagation.

Meteorological drought, often initiated by prolonged precipitation deficits and intensified evapotranspiration (ETo), typically begins this sequence. Reduced rainfall limits the replenishment of soil moisture, leading to agricultural drought, characterized by water stress in crops and vegetation. A continued lack of surface water inflow and groundwater recharge can then result in hydrological drought. Together, these forms of drought can impair municipal, industrial, and agricultural water supply systems, ultimately reducing the ability of these systems to meet the water demands necessary for socioeconomic development—a condition referred to as socioeconomic drought (Wang et al. 2024).

Regions that depend primarily on surface water sources may experience more immediate effects from meteorological drought, as surface water storage can deplete rapidly. In contrast, hydrological droughts tend to be more significant in areas where groundwater serves as a primary source of water supply, such as in South Florida. In 2023, 67% of the total water used per day in the region came from groundwater sources, while 33% came from surface water sources (SFWMD 2023). The two largest water use categories in the region were public supply and agriculture, accounting for 79% of total water use. Within individual planning areas, the proportions of groundwater and surface water use may differ from regional averages due to a variety of factors, including the characteristics of local water supply systems, hydrologic conditions (e.g., precipitation, surface water availability, and recharge), water management practices (such as storage in canals, reservoirs, or other impoundments), the availability of alternative water supply sources, and variations in water demand.

Droughts often result in extensive ecological, economic, and environmental losses over large spatial and temporal scales (Huang et al. 2017). In the state of Florida, at least one severe and widespread drought has occurred each decade since 1900, highlighting the region's long-standing vulnerability (Collins et al. 2017). While global-scale trends in drought remain uncertain due to inconsistencies in observation networks, differing drought definitions, and regional variability (Pachauri and Meyer 2014), anticipating future changes in drought patterns remains a priority for water resource management and climate adaptation.

To address this challenge, the United States Geological Survey (USGS) and SFWMD have collaborated to analyze droughts in South Florida. Their study focuses on identifying and characterizing projected future droughts across South Florida (2056–2095) using a method based on historical record and available downscaled global climate model data and the determination of a timescale-averaged precipitation-minus-evapotranspiration, or (P – ETo), anomalies (Irizarry-Ortiz et al. 2025). This report follows the methodology introduced in Irizarry-Ortiz et al. (2025) to support the identification of meteorological droughts between 1948 and 2022, and incorporates trend analysis to examine potential long-term shifts in drought behavior within SFWMD's 14 rainfall areas.

DRIVERS AND INFLUENCING FACTORS

Meteorological, agricultural, hydrological, and socioeconomic droughts are each shaped by distinct natural and human factors. Meteorological drought is primarily driven by deficits in precipitation, along with increased temperatures and elevated ETo rates, which together reduce atmospheric moisture availability and alter the surface energy balance (Vicente-Serrano et al. 2010). In contrast, agricultural drought is influenced not only by reduced rainfall and ETo, but also by soil moisture availability, root-zone storage capacity, crop water demand, and the timing of precipitation during sensitive phenological stages (Dai 2011). Hydrological drought evolves over longer timeframes and is influenced by antecedent hydrological conditions, groundwater and surface water storage levels, land use change, and human water management practices such as reservoir operations and water withdrawals (Van Loon 2015). Finally, socioeconomic drought occurs when the demand for water exceeds available supply, shaped by factors such as population growth, infrastructure capacity, governance and policy responses, and economic resilience.

Given the interconnected nature of these drought types, the triggering role of meteorological drought is particularly important. In South Florida, average annual precipitation is approximately 53 inches (1991–2020) with about 65% occurring during the wet season and transitional months from June through October (SFWMD 2021a). More than 75% of annual precipitation is lost to the atmosphere through ET (Obeysekera et al. 2011, Reitz et al. 2017), leaving a limited portion for aquifer recharge and runoff. This creates a system that is highly sensitive to even modest declines in precipitation or increases in evaporative demand.

The region's low topographic relief and highly permeable aquifers further compound this vulnerability, making South Florida particularly susceptible to prolonged and severe meteorological droughts (Obeysekera et al. 2017).

In addition to local hydrologic features, large-scale climate patterns modulate Florida's drought risk. For example, El Niño Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation (AMO), and Pacific Decadal Oscillation are key regional climate anomalies influencing rainfall variability on seasonal to multidecadal scales (Infanti et al. 2020). Climate change is expected to intensify these effects by increasing ETo and altering precipitation patterns (Scheff and Frierson 2014), potentially exacerbating both the duration and severity of meteorological droughts in the region.

CHARACTERIZING DROUGHTS

Different definitions of drought exist, and resulting estimates of drought duration and severity can vary significantly depending on the definition used. For this study, drought conditions are assessed using the Irizarry-Ortiz et al. (2025) definition, which considers a drought to occur when timescale-averaged (P – ETo) anomalies are negative for three or more consecutive months. Considering physical conditions unique to South Florida, this definition should identify dry periods, including ones of significant duration and intensity to affect water supply availability. Further analysis discussed below reinforces the method's retrospective drought identification applicability. Based on this definition, approximately 50% of the period from 1948 to 2022 is classified as experiencing varying intensities of drought conditions. It is important to note that the approach identifies meteorological droughts, not specifically hydrological droughts significant enough to impact water supplies and are typically more relevant in water management, which the public typically considers a drought.

To characterize and assess historical drought patterns in South Florida, high-resolution observational data sets, applying a structured methodology that includes the estimation of balance anomalies and trend assessments, were used.

Observational Climate Data Sets

SFWMD produced gridded data sets for precipitation and ETo in South Florida. The SFWMD precipitation super-grid covers daily data from 1914 to 2022 with a 2-mile (3.2 kilometer or km) resolution, using TIN-10 interpolation of rainfall gauge data until May 2002 and gauge-corrected National Oceanic and Atmospheric Administration (NOAA) Next Generation Weather Radar (NEXRAD) data from May 2002 onward.

The SFWMD ETo Super-grid, covering the 1948–2022 period with the same resolution, was developed using meteorological data from the National Aeronautics and Space Administration (NASA) North American Land Data Assimilation System 2 (NLDAS-2; Xia et al. 2012) and Hydro51 reanalysis (Fan et al. 2006) data sets. These were used to estimate ETo via the standardized American Society of Civil Engineers (ASCE) Penman-Monteith equation, which is equivalent to the FAO-56 method when applied daily. A separate gridded ETo data set (2-km resolution, 1985–2021), developed by USGS for Florida, based largely on solar radiation estimates from NOAA's Geospatial Satellite Server (GOES) satellite data, was used for bias correction of ETo.

Methodology

As illustrated in **Figure 2B-30**, the process for estimating timescale-averaged balance anomalies involves several steps: (1) monthly balances (P – ETo) are calculated for the 1948–2022 period using gridded data and averaged over a region of interest; (2) the historical mean balance for each month from January to December is computed for the reference period 1948–2022; (3) the historical mean balance is subtracted from each monthly balance in the entire 1948–2022 time series to obtain monthly balance anomalies; (4) moving averages of these anomalies are computed over 6- and 12-month periods, resulting in timescale-averaged balance anomalies for each month in the 1948–2022 series. These anomalies are assigned to the ending month of the averaging period (e.g., June 1950 for a 6-month average from January to June) (Irizarry-Ortiz et al. 2025).

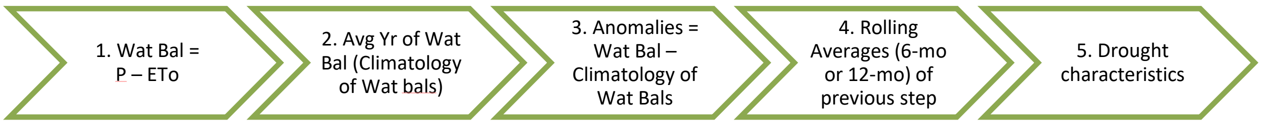

Figure 2B-30. Steps used in calculating timescale-averaged balance anomalies. (Note: Avg – Average, mo – month, Wat Bal – Water Balance, and Yr – Year.)

The timescale-averaged balance anomalies are then used to (5) define drought events using run theory where drought events are defined as consecutive months when the timescale-averaged balance anomaly is below zero (cumulative ETo exceeds cumulative rainfall). Only droughts lasting at least 3 months are considered. For each drought event, characteristics like start and end dates, duration, severity, and intensity are extracted. Event duration is the number of consecutive months below the threshold, intensity is the mean balance anomaly during the event, and severity is the area under the curve of the anomaly (Irizarry-Ortiz et al. 2025). An example of drought event characteristics is provided in **Figure 2B-31**.

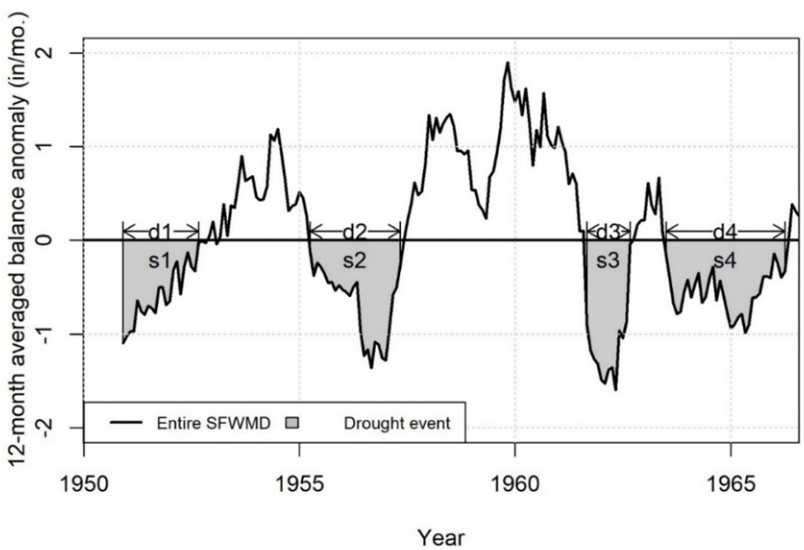

Figure 2B-31. Drought-event characteristics (s – severity and d – duration) extracted from 12-month averaged balance anomaly timeseries for a limited period (1950–1966) for illustration purposes (Irizarry-Ortiz et al. 2025).

Trend Analysis

A trend analysis was conducted using the non-parametric Mann-Kendall test to evaluate long-term patterns in drought conditions. This analysis was applied to the 6-month and 12-month average balance anomalies for each of SFWMD's 14 rainfall areas (**Figure 2B-32**). The objective was to identify statistically significant trends that may indicate increasing or decreasing drought conditions (duration and severity) over time across the region. Graphs for the observed net rainfall anomaly for 6-month and 12-month rolling averages for each of the 14 rainfall areas in **Figure 2B-32** are presented in Appendix 2B-2.

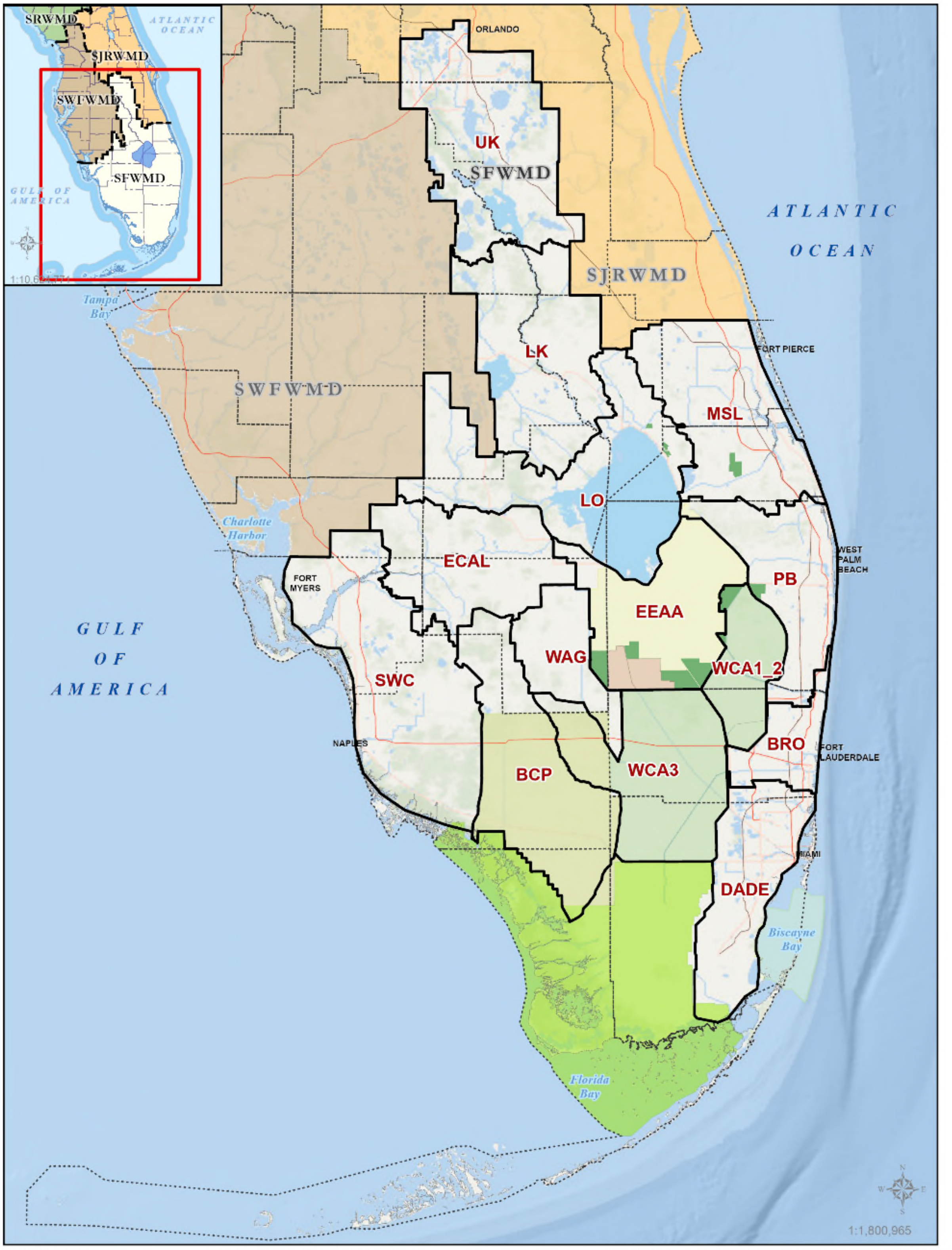

Figure 2B-32. SFWMD's 14 rainfall areas.

RESULTS AND DISCUSSION

The Mann-Kendall trend analysis applied to the 6-month and 12-month (P – ETo) anomaly time series revealed no statistically significant trends for any of the 14 rainfall areas evaluated across South Florida. This suggests that, under the selected meteorological drought metric, there has been no consistent long-term increase or decrease in drought duration or severity over the 1948–2022 analysis period.

To assess the operational relevance of the (P – ETo) anomaly method, additional analysis was conducted comparing the timing and magnitude of 12-month anomalies with two key indicators: the U.S. Drought Monitor from 2020 onward and water shortage declarations issued by SFWMD from 1980 onward. The results showed alignment between significant drought anomalies and both drought monitor categories and declared water shortages, supporting the method's applicability for retrospective drought identification and water supply planning.

The U.S. Drought Monitor data set (https://droughtmonitor.unl.edu/Data.aspx), produced jointly by the National Drought Mitigation Center at the University of Nebraska-Lincoln, NOAA, and the United States Department of Agriculture, classifies drought into six levels: normal, abnormally dry (D0), and four stages of increasing severity: moderate (D1), severe (D2), extreme (D3), and exceptional (D4). Classifications are determined weekly through a combination of physical indicators, field observations, local insight, and expert interpretation (NOAA 2025). **Figure 2B-33** shows the percentage of land area within each drought category, overlaid with the SFWMD district-wide balance anomaly plot, indicating a good correlation in both occurrence and intensity of drought conditions within the available time frame.

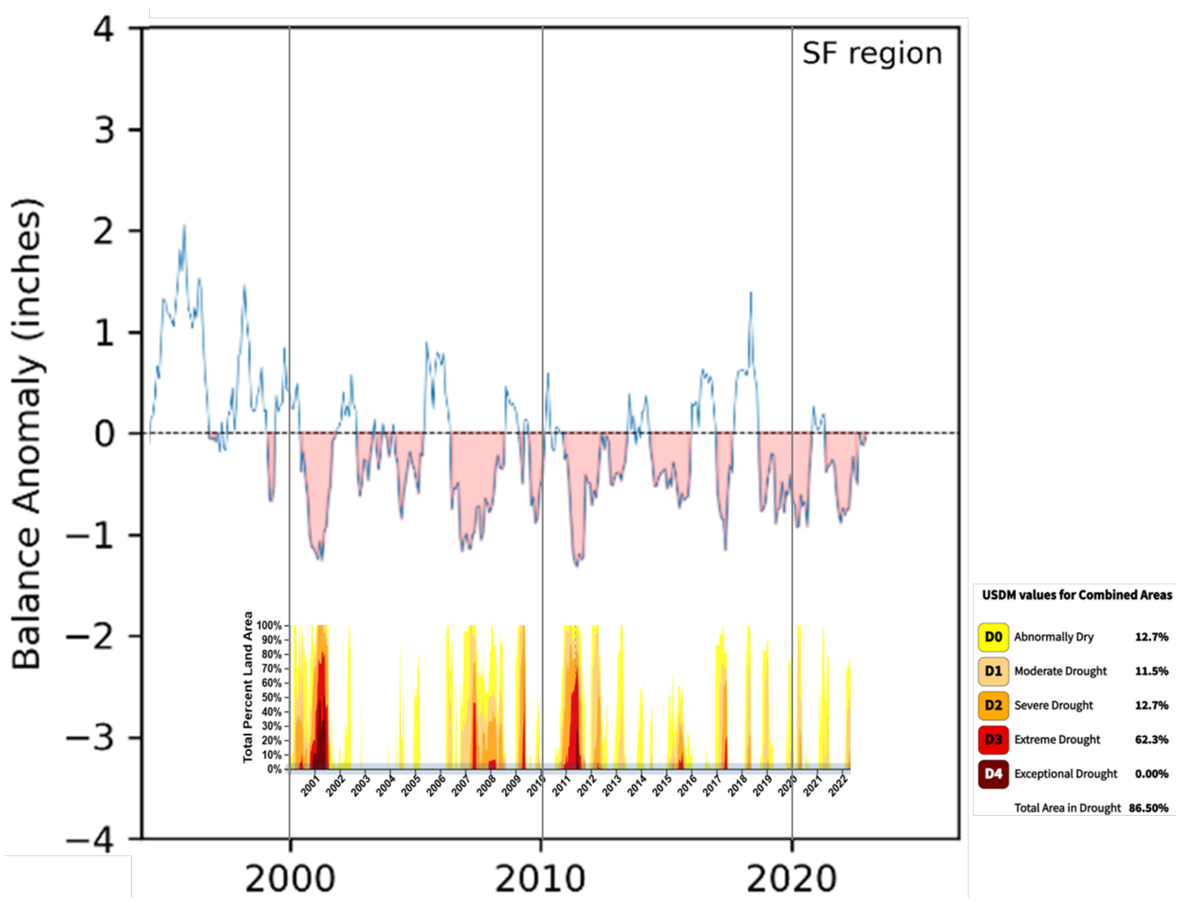

Figure 2B-33. Drought anomalies in South Florida from 1995 to 2022 and U.S. Drought Monitor classifications from 2000 to 2022.

A water shortage is a temporary declaration made by a water management district Governing Board or the Executive Director when water conditions in parts or all of the district are deemed insufficient to meet the present and anticipated needs of residents and other water users and natural systems. Such a declaration is made to help reduce impacts on water resources and equitably distribute available supplies. A water shortage usually occurs due to drought and is rescinded once wetter conditions return to the affected areas (SFWMD 2025). SFWMD has four water shortage phases (Chapter 40E-21, Florida Administrative Code or F.A.C.): Phase I (Moderate), Phase II (Severe), Phase III (Extreme), and Phase IV (Critical). The water shortage declarations shown in the following inset bar graphs are summarized for the water supply planning areas, which includes specific restrictions for water sources or irrigation types (i.e., agriculture, landscape, recreation) but does not reflect local area restrictions if they are the only place in the planning area with a higher phase (e.g., City of West Palm Beach Phase III restrictions in 2011). There is some degree of subjectivity and professional judgment in declaring and rescinding the water shortages. Therefore, balance anomalies may not always align with declared shortages.

For the Lower East Coast Service Area, water shortages were declared consistent with most of the significant drought anomalies in the Palm Beach and Miami-Dade rainfall areas (as shown in **Figures 2B-34** and **2B-35**, respectively). The severity of the water shortage phase does not always align with the intensity of the drought anomaly. This area has a large regional canal network (i.e., the Central and Southern Florida Flood Control Project or C&SF Project) which, if adequate stored water is available, can be moved to and hydrate dry areas and areas with low groundwater levels to help prevent saltwater intrusion. This influences whether and how severe water shortage cutbacks are declared. The bar graph also shows how some of the water shortage declarations extend past the event to allow time for water supplies to recover. Note that on the balance anomaly plots, drought anomalies from 2000 to 2015 appear to be more intense and have a longer duration in the Palm Beach than the Miami-Dade rainfall area.

Similarly, significant drought anomalies in the Lake Okeechobee rainfall area aligned with declared water shortages in the Lake Okeechobee Service Area (LOSA) (as shown in **Figure 2B-36**). Note that the water shortage phase in 1990/1991 was more severe than the drought balance anomaly, which is opposite of what was seen in the Miami-Dade region (**Figure 2B-35**). In 2001, the intensity of the drought anomaly and water shortage phase are consistent with each other in LOSA.

Significant drought anomalies in the Southwest Coast rainfall area correlate well with declared water shortages in the Lower West Coast Service Area (LWCSA) as shown in **Figure 2B-37**). This is also the case in the Martin–St. Lucie rainfall area with water shortages in the Upper East Coast planning area (as shown in **Figure 2B-38**). In these regions, the local canal networks are less extensive and do not connect back to a large water storage source. Consequently, note that more of the declared water shortages correspond to the drought anomaly's timing.

Finally, significant drought anomalies in the Upper Kissimmee rainfall area also corresponded with declared water shortages in the Kissimmee area (as shown in **Figure 2B-39Figure 2B-**).

Overall, while no long-term trends were detected, the timing and location of significant drought anomalies demonstrated consistency with historical water management decisions with respect to declared water shortages. This confirms the utility of the (P – ETo) anomaly-based approach for drought monitoring and reinforces its value as a diagnostic tool for historical drought event analysis across different water supply areas in South Florida.

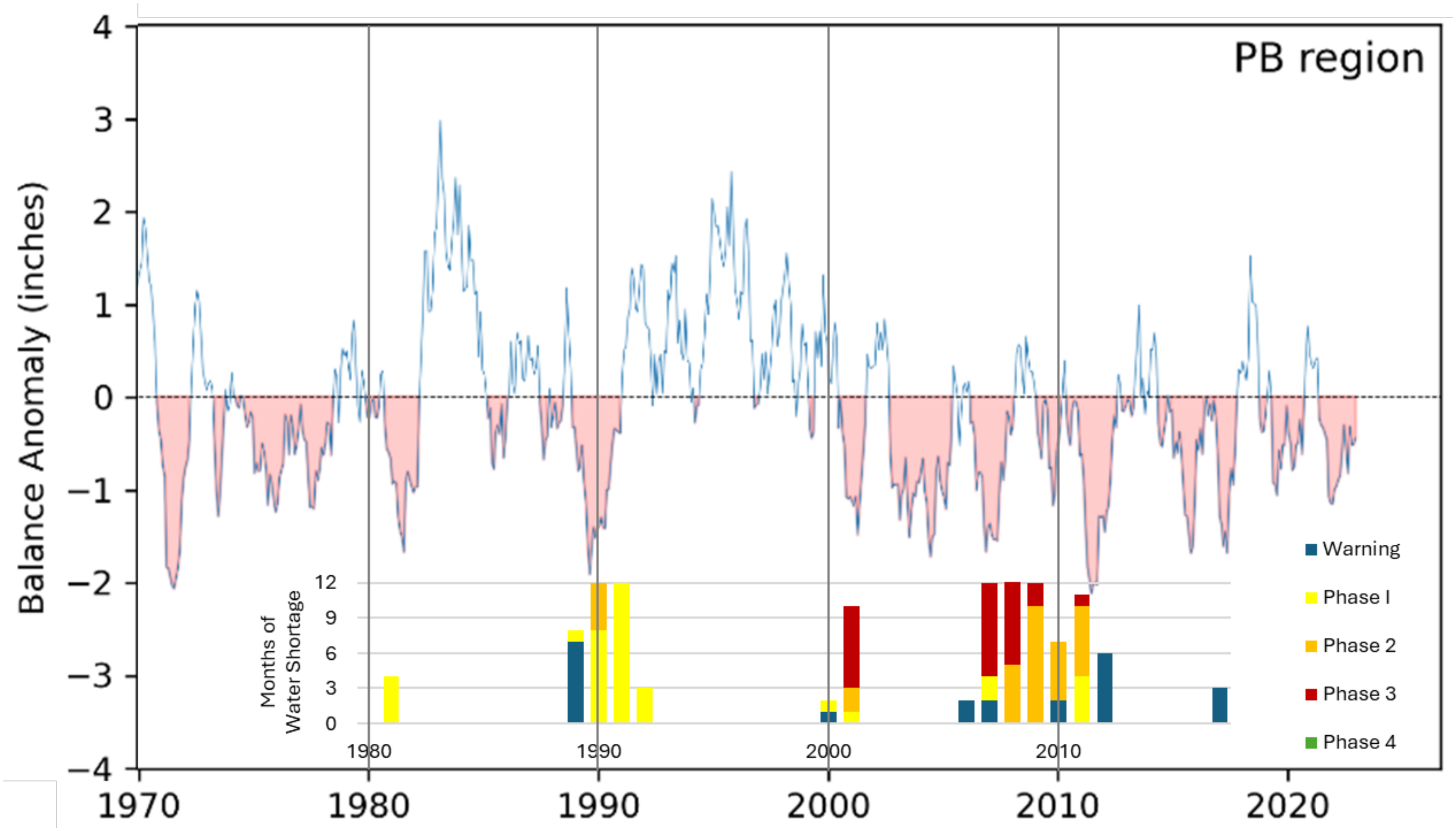

Figure 2B-34. Meteorological drought anomalies in the Palm Beach (PB) rainfall area from 1970 to 2022 and declared water shortages in the Lower East Coast Service Area from 1980 to 2017.

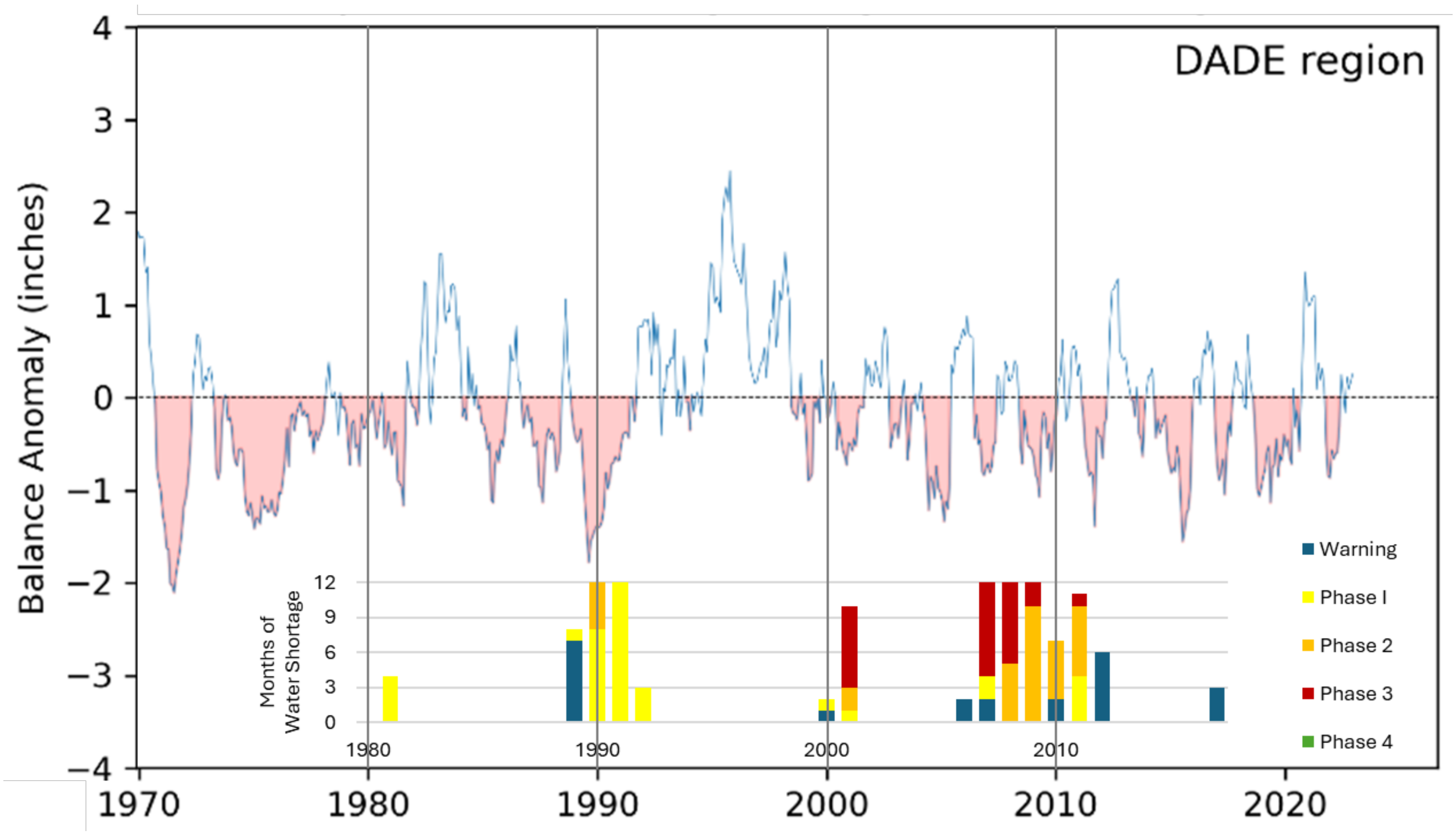

Figure 2B-35. Meteorological drought anomalies in the Miami-Dade rainfall area from 1970 to 2022 and declared water shortages in the Lower East Coast Service Area from 1980 to 2017.

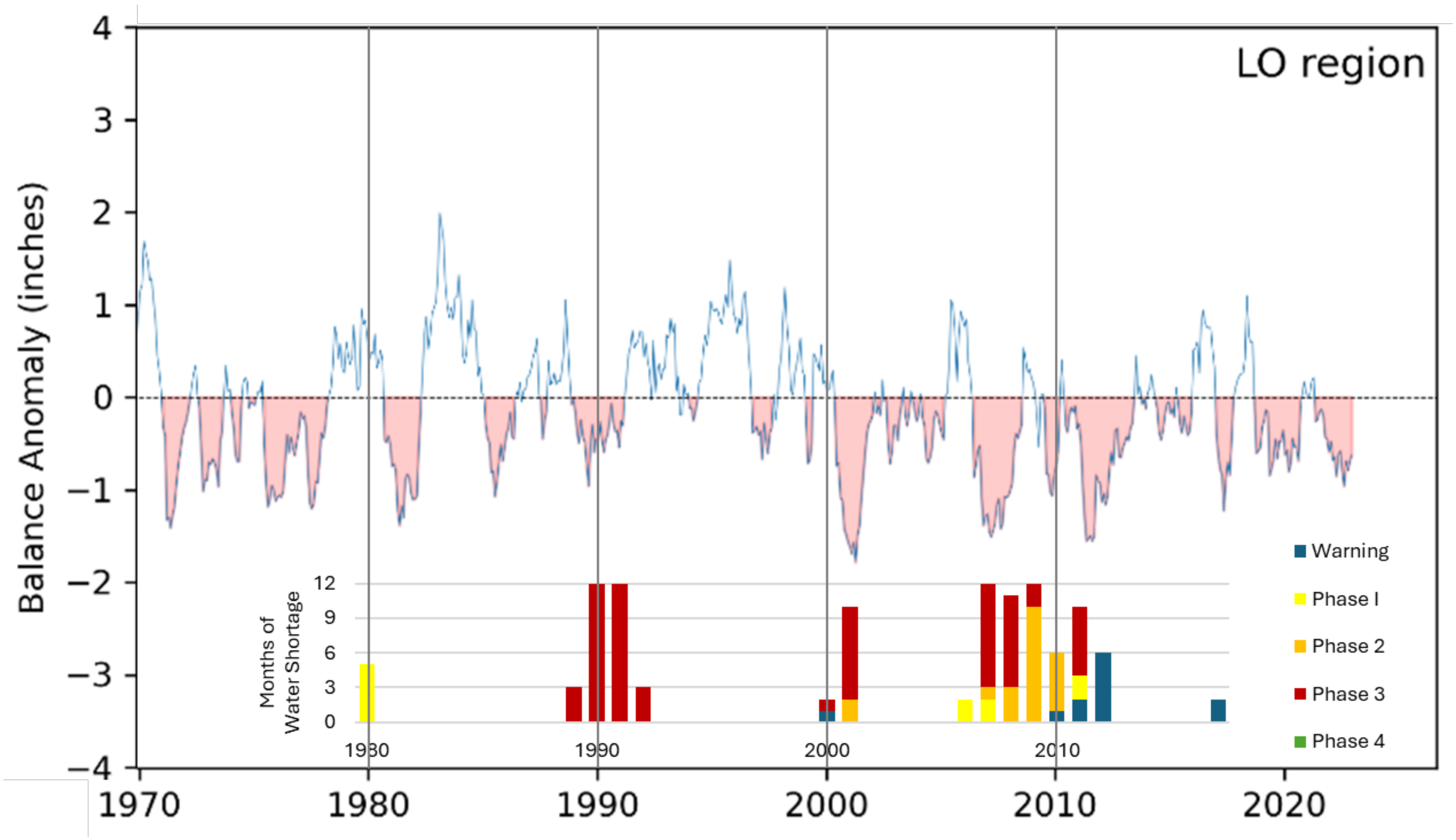

Figure 2B-36. Meteorological drought anomalies in the Lake Okeechobee (LO) rainfall basin from 1970 to 2022 and declared water shortages in LOSA from 1980 to 2017.

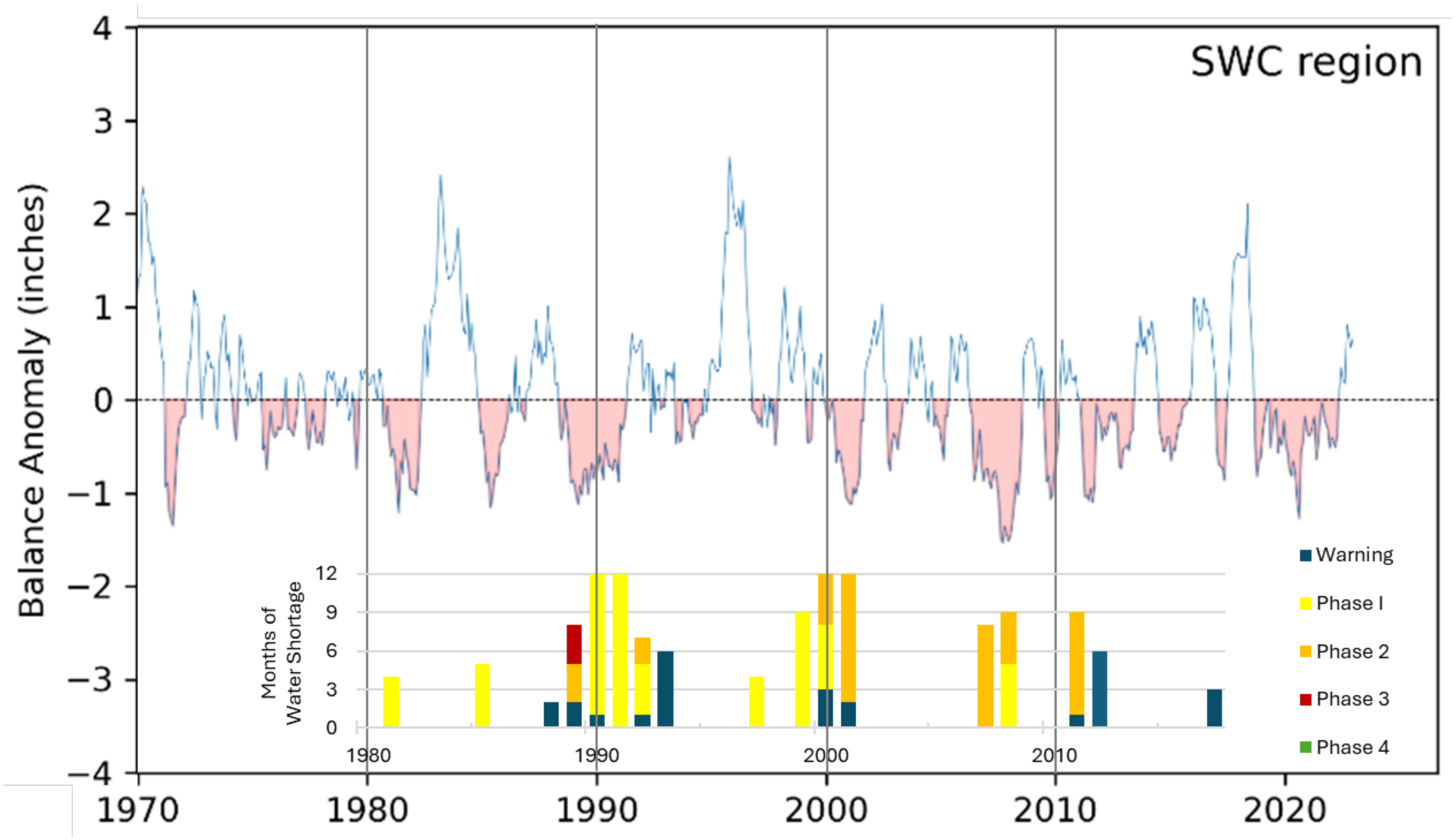

Figure 2B-37. Meteorological drought anomalies in the Southwest Coast (SWC) rainfall basin from 1970 to 2022 and declared water shortages in LWCSA from 1980 to 2017.

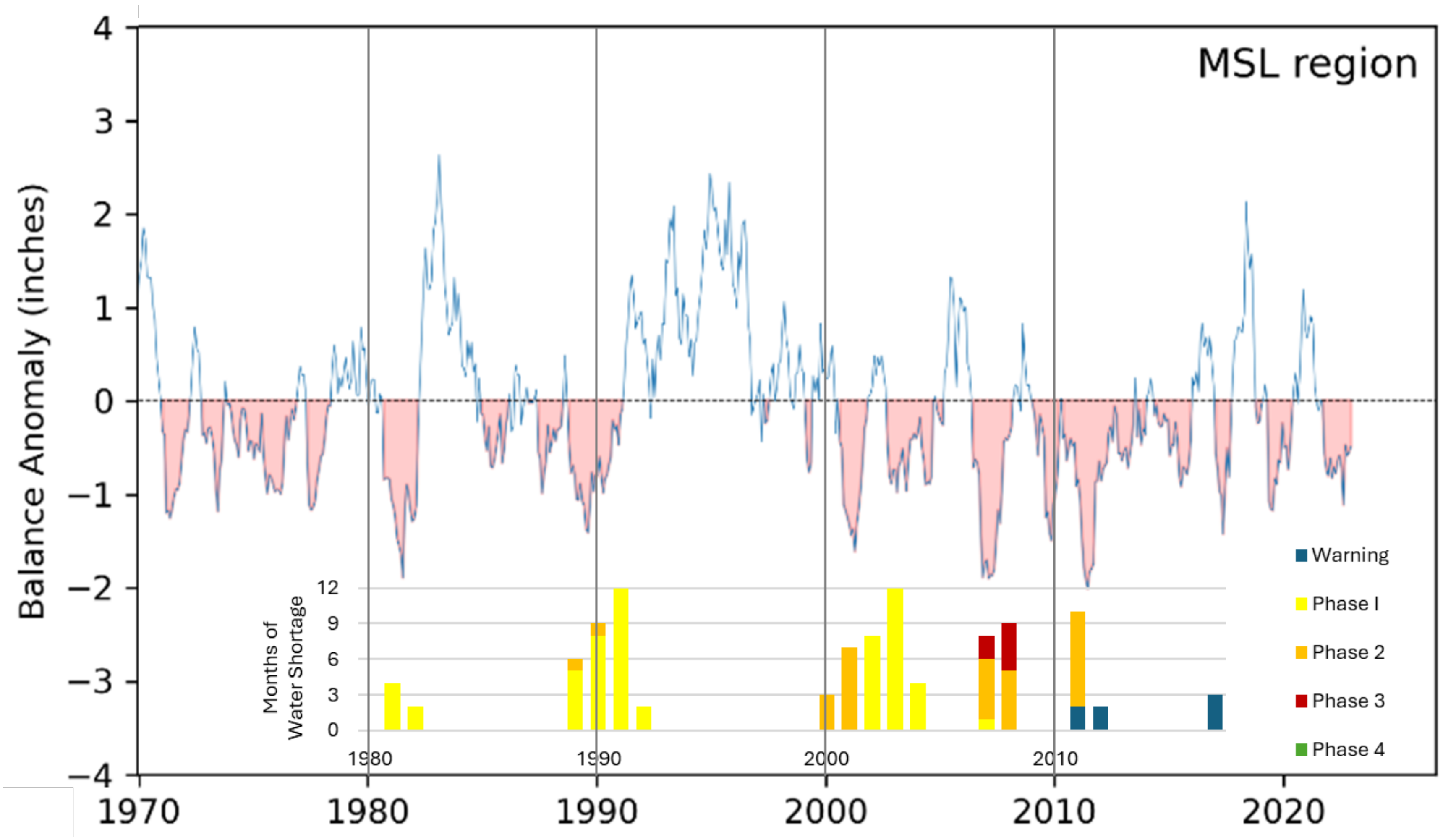

Figure 2B-38. Meteorological drought anomalies in the Martin and St. Lucie (MSL) rainfall area from 1970 to 2022 and declared water shortages in the Upper East Coast planning area from 1980 to 2017.

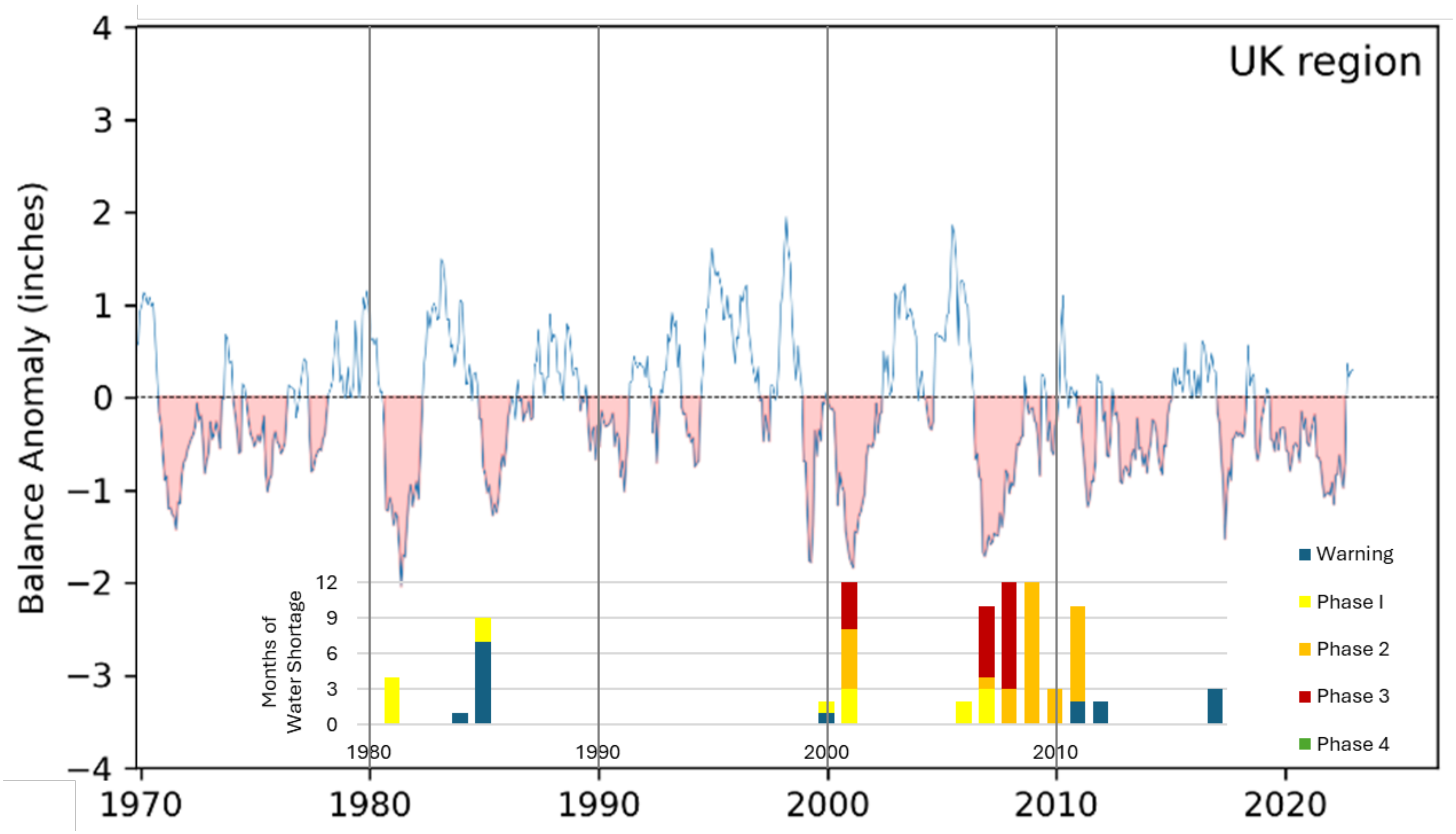

Figure 2B-39. Meteorological drought anomalies in the Upper Kissimmee (UK) rainfall area from 1970 to 2022 and declared water shortages in the Kissimmee area from 1980 to 2017.

COMMENTS AND RECOMMENDATIONS

The analysis presented demonstrates the utility of the (P – ETo) anomaly method for identifying and characterizing meteorological droughts in South Florida, with alignment to historical U.S. Drought Monitor classifications and SFWMD water shortage declarations. However, it is important to recognize that the resulting drought conditions can vary significantly depending on the definition used. For this study, drought duration and severity were assessed using the Irizarry-Ortiz et al. (2025) definition, which considers a drought to occur when timescale-averaged (P-ETo) anomalies are negative for three or more consecutive months. While this approach provides consistency for meteorological drought identification, future studies should evaluate the sensitivity of results to alternative thresholds, as they may capture varying drought conditions.

Establishing permanent weather stations capable of recording both rainfall and ETo in each rainfall area would improve spatial resolution and reduce reliance on modeled data. Integrating available temperature measurements at these sites is also critical, as increasing temperatures can drive up ET and intensify drought severity under projected climate change scenarios. Integrating these high-resolution, site-specific data sets would strengthen regional drought diagnostics and support adaptive and resilient water resource management strategies moving forward.

RELEVANCE TO RESILIENCY IN WATER MANAGEMENT

SFWMD manages the water resources of South Florida for water supply, flood control, and environmental purposes. Droughts not only affect water withdrawals for public, agricultural, commercial, and industrial users, and the environment in the short-term, but also threaten existing water supply infrastructure and limiting available freshwater sources by increasing saltwater intrusion as a result of declining groundwater levels that reduce freshwater recharge to coastal aquifers. This issue is compounded by increasing population, land development, SLR, and other changing climate and hydrologic conditions, which may result in abandonment or relocation of existing surficial aquifer wells, and the need to develop alternative water supplies (SFWMD 2024). New alternative water supply projects, interconnections with neighboring utilities, implementing water conservation practices, and compliance with water restrictions all help reduce drought impacts.

Post-drought assessments have been used to better understand how drought has affected water users and to document responses and outcomes. Crop and landscape losses due to drought-reduced water supply sources are costly to agriculture, nursery, and recreation industries. State, county, and federal programs help evaluate irrigation systems for these industries and promote high-efficiency irrigation practices, making them more resilient in drought conditions. Efficient irrigation practices also help water utilities reduce the water use demand due to population growth. Low water levels affect the stability of surface water management infrastructure, including lakes and canals and their ability to move water throughout the regional canal system. SFWMD is undergoing a review of its regional canal system to recommend necessary improvements to improve resiliency for flood control as well as water supply.

Freshwater habitats located close to the coast and estuaries are also affected by decreased freshwater flows associated with droughts. In partnership with the United States Army Corps of Engineers, SFWMD has been developing and implementing a series of ecosystem restoration projects that are designed to improve the quantity, timing and distribution of freshwater flows, which will increase the ecosystem's future resilience.

HIGH TIDE EVENTS AT COASTAL STRUCTURES

BACKGROUND

The SFWMD manages over 936 water control structures across the region. Among these, a subset consists of coastal structures—gravity-dependent gated spillways, culverts, and weirs—that allow water to flow from the landside headwater (HW) to the oceanside tailwater (TW). These coastal structures directly interact with the tides and play a key role in protecting inland areas from flooding and saltwater intrusion. **Figure 2B-40** shows the locations of the coastal structures analyzed in this study.

These coastal structures must be closed when the TW level is very close to or above the HW level to prevent flooding and/or saltwater intrusion. The operation of these structures becomes increasingly critical during extremely dry or wet conditions. During severe droughts, the HW level can be abnormally low, and levels upstream need are maintained even higher. Conversely, during widespread heavy rain, water needs to be drained to prevent flooding, but routine high tides can reduce or even eliminate opportunities to open the spillways and alleviate flooding upstream. Additionally, significant weather events such as hurricanes present a unique challenge to water management due to the combination of significant rain inland and elevated tide levels along the coast due to storm surge.

The low-lying topography of South Florida makes most of these gravity-driven structures very sensitive to slight changes in water levels. TW is higher during high tides, so even with a fixed HW, the hydraulic gradient decreases across the structure and the discharge capacity (potential flow rate) also decreases. Regardless of inland weather patterns, SLR is exacerbating the risk by increasing the TW level and decreasing stormwater discharge capacity and the amount of time the structures can be open.

This analysis seeks to analyze trends and vulnerabilities associated with high tide events (HTEs) at coastal structures. Although the highest tides of the year typically occur during "King Tide season" (September–November), defining a relevant HTE, in this case, is more complicated because the HW level must also be considered. Therefore, for this study, a HTE (at coastal structures) is defined as any time when the TW comes within 0.1 feet (ft) of the HW, prompting the closure of the structure.

The 'High Tide Events at Coastal Structures' metric reflects tidal conditions at gravity-driven coastal control structures that are influenced by both tidal forces and the operation of water management infrastructure. Therefore, in the context of this report, these high tide events are not a purely ocean-driven tidal parameter. Additionally, while these structures are located directly upstream of tidally dominated water bodies, the observed water levels upstream and downstream are also shaped by operational decisions, discharges, and the complex engineered nature of the regional water management system. For this reason, the term 'High Tide Events at Coastal Structures' is used with the understanding that the metric is inherently reflective of the interconnection and management of South Florida's water control infrastructure.

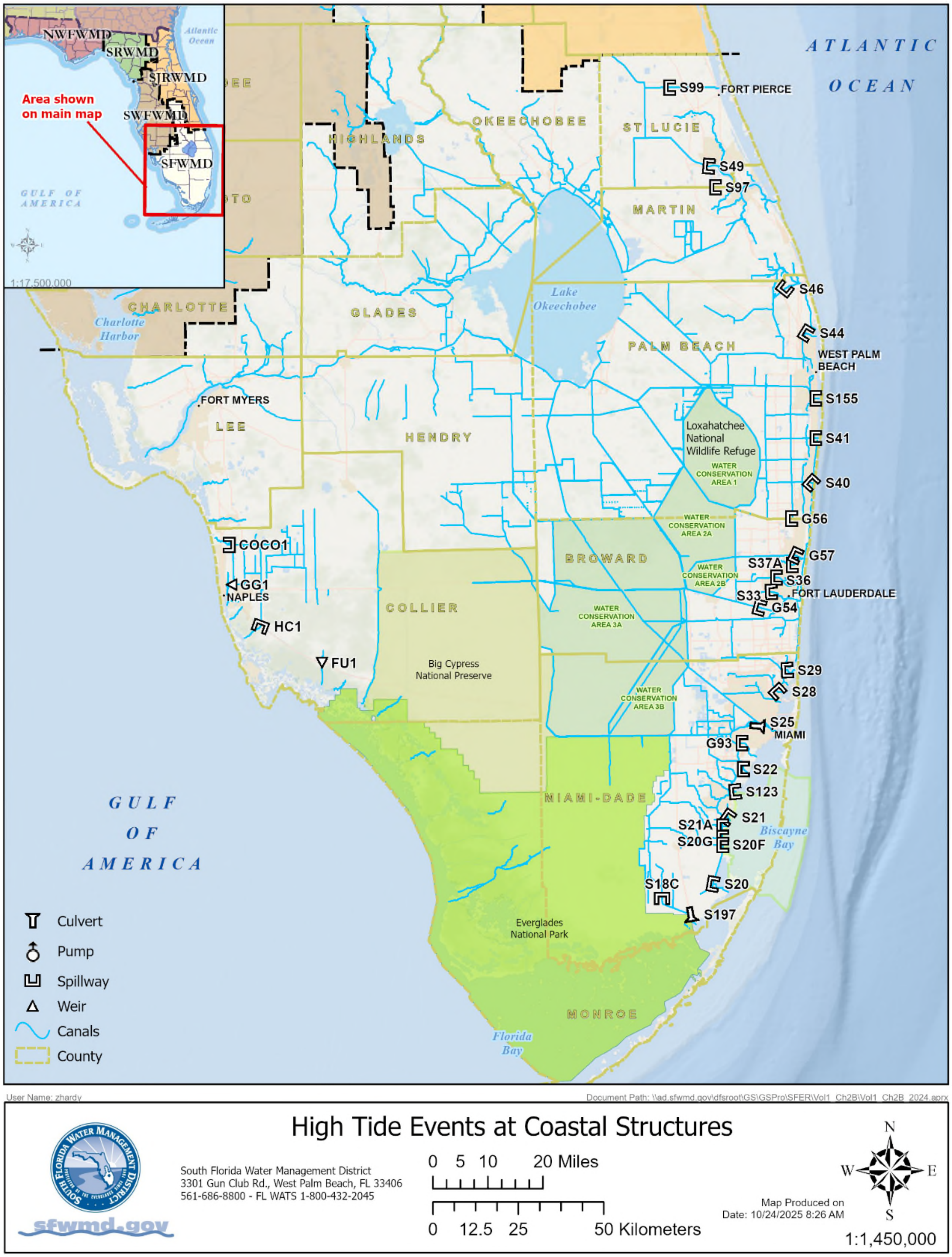

Figure 2B-1. SFWMD coastal structures used for analysis of HTEs.

DRIVERS AND INFLUENCING FACTORS

Most of the SFWMD's coastal structures were designed and built several decades ago and, even then, in some parts of southeast Florida, the available hydraulic gradient across the structure was minimal due to the low topography. Since then, SLR has further reduced that gradient, with an average rate of SLR in South Florida reaching roughly 3.2 inches/decade (8.2 millimeters per year or mm/yr) over the past two decades (see Table 2B-3 in SFWMD 2024). Additionally, all SLR projections indicate an acceleration trend, meaning that extrapolating that linear rate will significantly underestimate future impacts, placing even more structures at risk in the coming decades.

The Florida Flood Hub's statewide projection (FDEP 2024), which falls between NOAA's "intermediate low" and "intermediate" scenarios (Sweet et al. 2022), indicates the increase in TW relative to 2020's level will be 5.0 to 5.6 inches (12.7 to 14.2 centimeters or cm) by 2040 and 12.9 to 17.8 inches (32.8 to 45.2 cm) by 2070, as shown in **Figure 2B-41**. As an example, in Miami-Dade County, the difference between the HW and TW design elevations ranges from 18 inches (45.7 cm) at G-93 to just 1.2 inches (3.0 cm) at S-25, with most structures designed for at a 6-inch design differential. Given the projected increases, even the least vulnerable structures in the county will be at risk under future conditions without mitigating actions.

HW levels across SFWMD might also be affected by increasing rainfall intensities, as documented in 2022 SFER – Volume I (Cortez et al. 2022). These changes are expected to coincide with ongoing occurrences of impactful weather events, such as tropical disturbances and cyclones, which often occur during the King Tide season, and produce both large rainfall totals and elevated tides. As shown in **Figure 2B-42**, the significant warming of the water surrounding South Florida during the summer months further reinforces the trend of increasing available moisture and rainfall across the region. Furthermore, regional SLR might be exacerbated by ocean warming, due to thermal expansion of the water (Domingues et al. 2018). Future studies, under the Water and Climate Metrics effort, will confirm the actual effects of these potential influencing factors, particularly for the South Florida region.

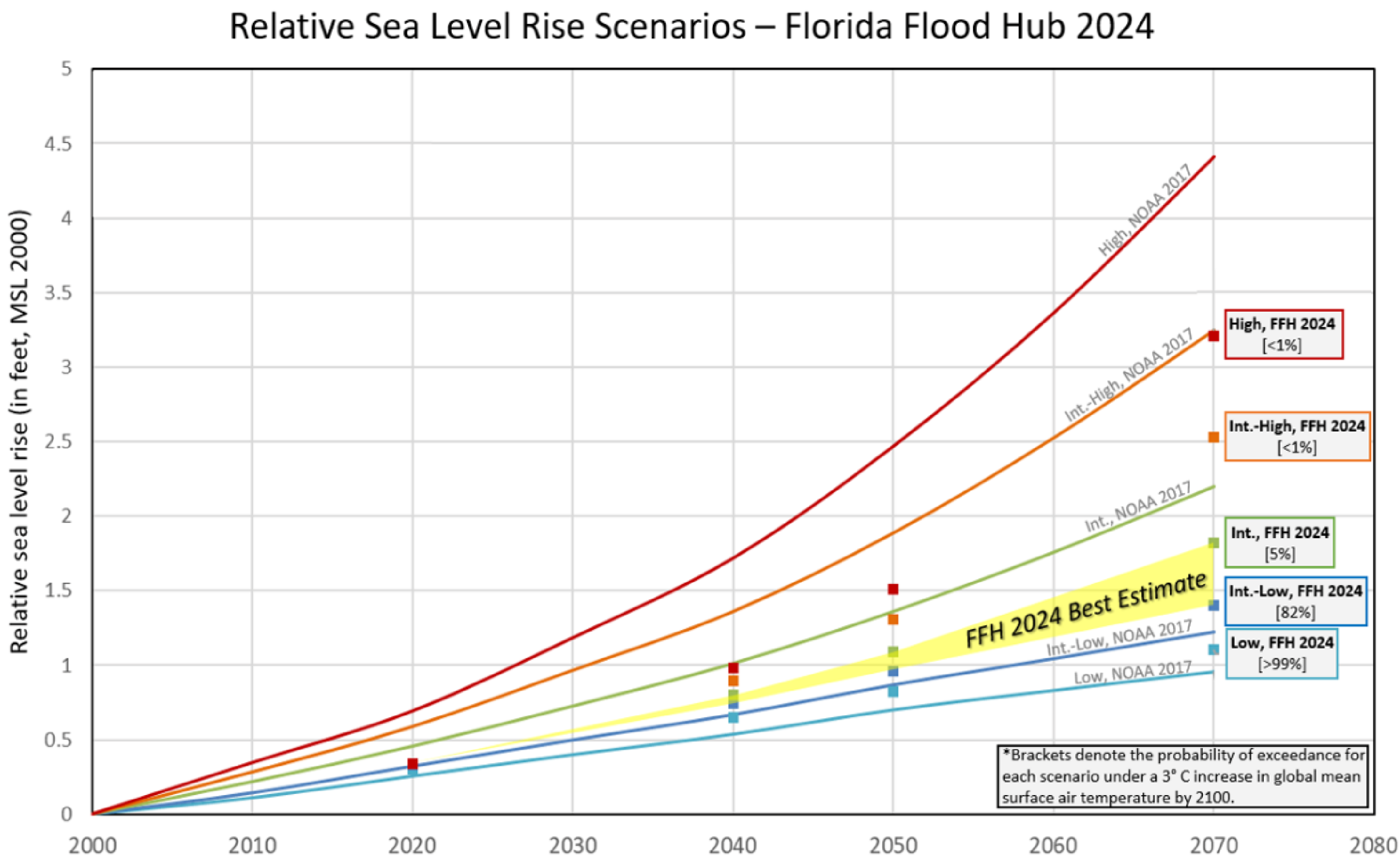

Figure 2B-41. SLR projections for the state of Florida from the Florida Flood Hub (FFH) (FDEP 2024). (Note: °C – degrees Celsius, MSL – mean sea level.)

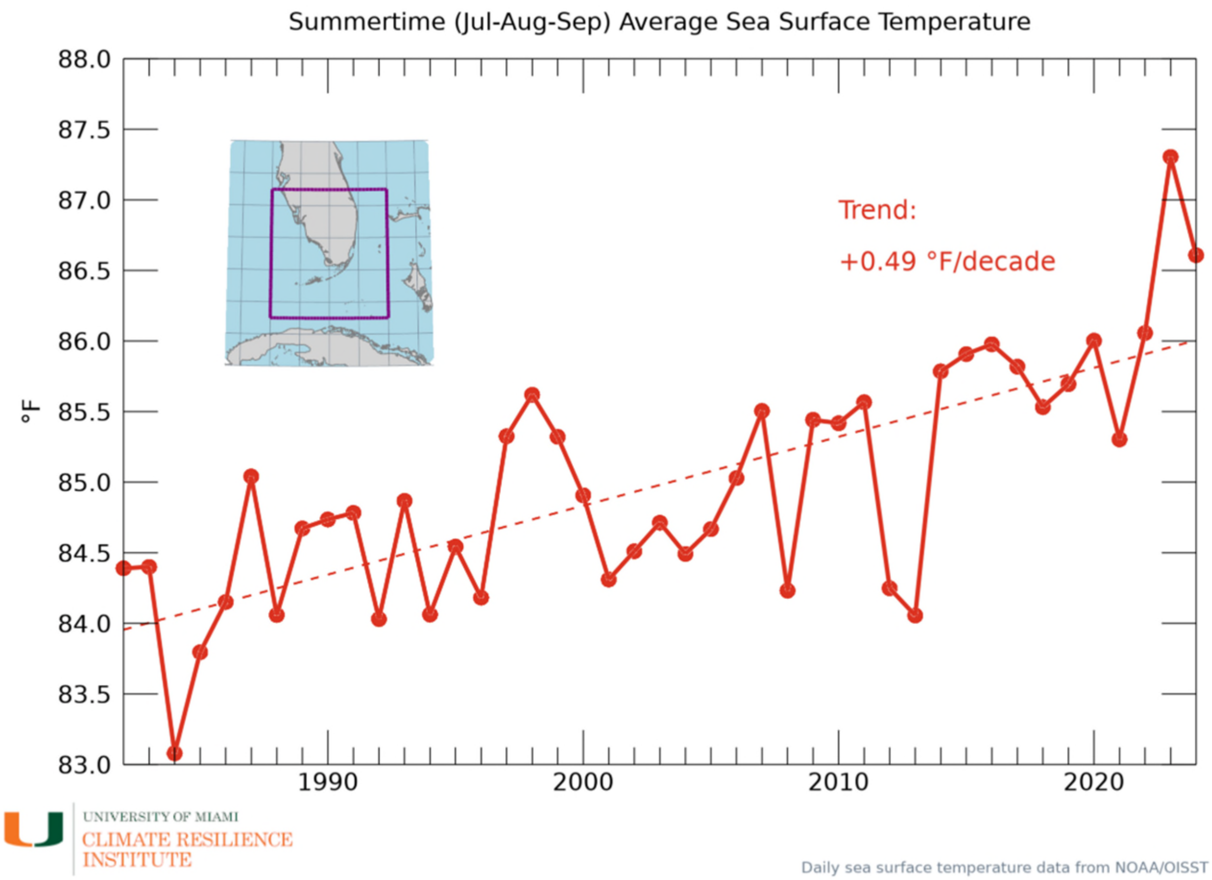

Figure 2B-42. Summertime sea surface temperature averaged in a region surrounding South Florida, from 1981 to 2024. (Raw daily data are from NOAA processed by Brian McNoldy for the University of Miami's Climate Resilience Institute). (Note: °F – degrees Fahrenheit.)

METHODOLOGY

For the analysis, high temporal resolution breakpoint data for all the coastal structures were considered, including design HW elevation, high and low operating ranges, flow rates, and HW and TW levels. The TW and HW breakpoint data were typically not available at matching times; thus, to facilitate calculations, all TW data were used and HW data were interpolated to align with those times. At least 75% of data in a month was needed for the month to be considered. **Figure 2B-40** provides the names and locations of the coastal structures analyzed in this study.

The seasons were defined in this analysis as September–October–November (SON, fall, or king tide season), December–January–February (DJF or winter), March–April–May (MAM or spring), and June–July–August (JJA or summer). King tide flooding does occasionally occur outside of those three months (e.g., late August or early December), but with a climatological peak in mid-October in South Florida, the SON period encompasses the vast majority of king tide events.

Frequency heatmaps are presented to visualize temporal aspects of the results of the HTEs analysis. One type of heatmap illustrates the percentage of hours each month that the TW was above the HW design elevation. This effectively shows tide levels since the TW elevation is directly associated with the ocean side of the structure, and the design HW is a fixed elevation at each structure that indicates how much buffer (freeboard) is available for flood protection from canal bank elevation. Therefore, this reference elevation supports the identification of the variation within the seasonal cycle of tides, periods of extremely high tides, and the gradual trend toward higher extreme occurrences due to SLR. However, at some structures, the design HW elevation is much higher than the tidal elevations, and as a result, the calculated percentages are zero or near-zero and the heatmap looks blank. **Figures 2B-43**, **2B-44**, and **2B-45Figure 2B-** present the results for S-28, S-22, and S-20F, respectively, all located in Miami-Dade County. During the king tide season, the frequencies for the complete period of record (POR) were 23% at S-28, 1% at S-22, and 28% at S-20F, increasing in the last 10 years to 38, 4, and 46%, respectively.

On a monthly average basis, it can be difficult to pick out specific events such as hurricane-related storm surges as they generally occupy up to a day out of the entire month. But two large hurricanes in 2005 (Rita in September and Wilma in October) contributed to a few days of elevated water levels at S-28 and S-22. It does not take a direct hurricane landfall to influence coastal water levels, hundreds of miles away is sufficient and, in some exceptional cases, even thousands of miles. However, not all high percentages on the heatmap are associated with weather events. Sometimes, a perigean full or new moon can generate elevated tides for many days or even a couple weeks during high/king tide season. Perigee is when the moon is at its closest approach to the Earth in its 27.3-day elliptical orbit around the Earth. One example of this influence is August and September 2019, with perigee dates on August 2, August 30, and September 28. These ideal alignments will inevitably cause elevated tides around the world, without any influence from the weather.

Since the HW is controlled by both inland rainfall, evaporation, and upstream managed structures, HTEs are not simply when there is a high tide. A HTE, in this study, is defined at any time in which the control structure gate must be closed to prevent reverse flow and saltwater intrusion. During the king tide season, the frequencies for the complete POR were 38% at S-28, 8% at S-22, and 37% at S-20F, increasing over the last 10 years to 49, 15, and 50%, respectively, as shown in **Figures 2B-46**, **2B-47**, and **2B-48**, respectively.

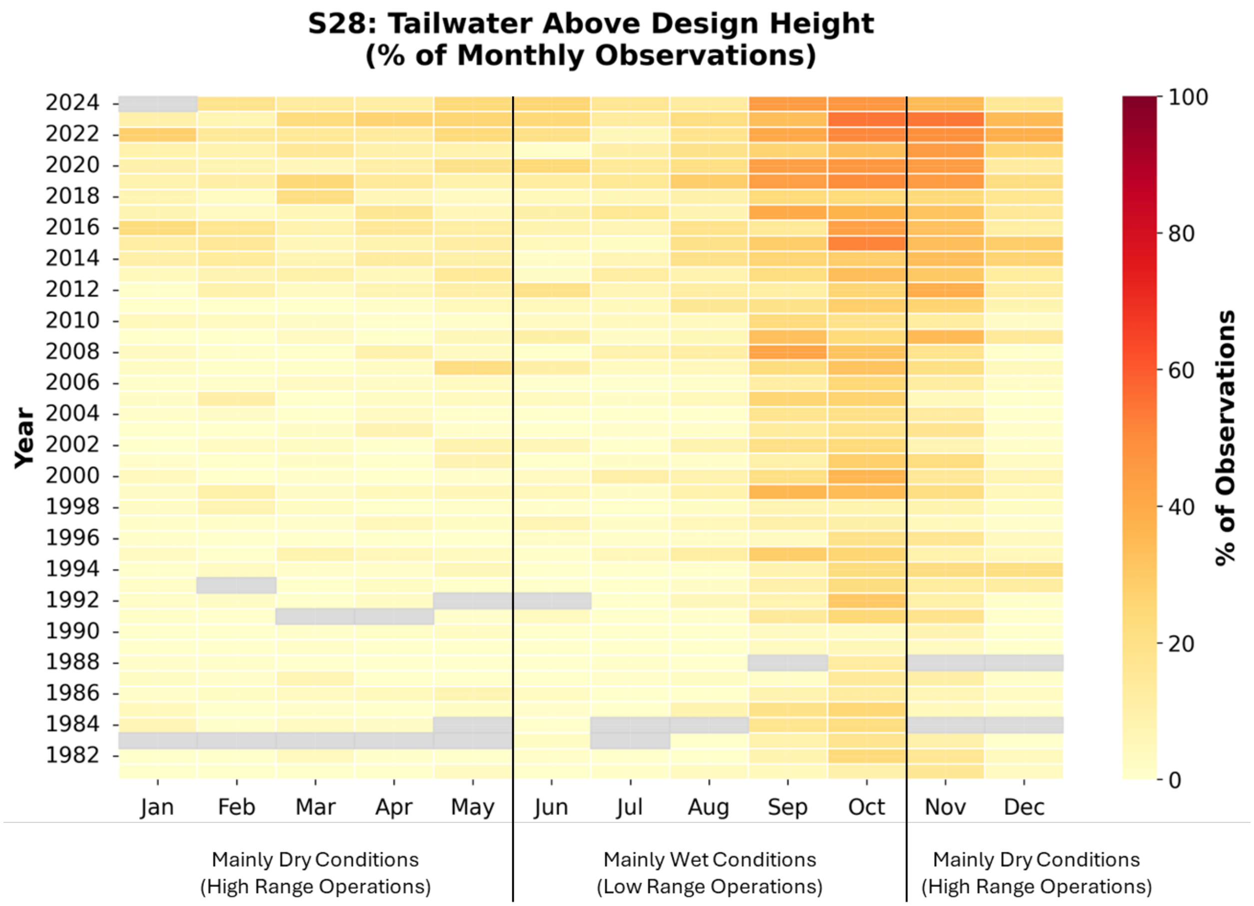

Figure 2B-2. Heatmap diagram showing the percentage of hours each month that the TW was above the HW design elevation at the S-28 structure.

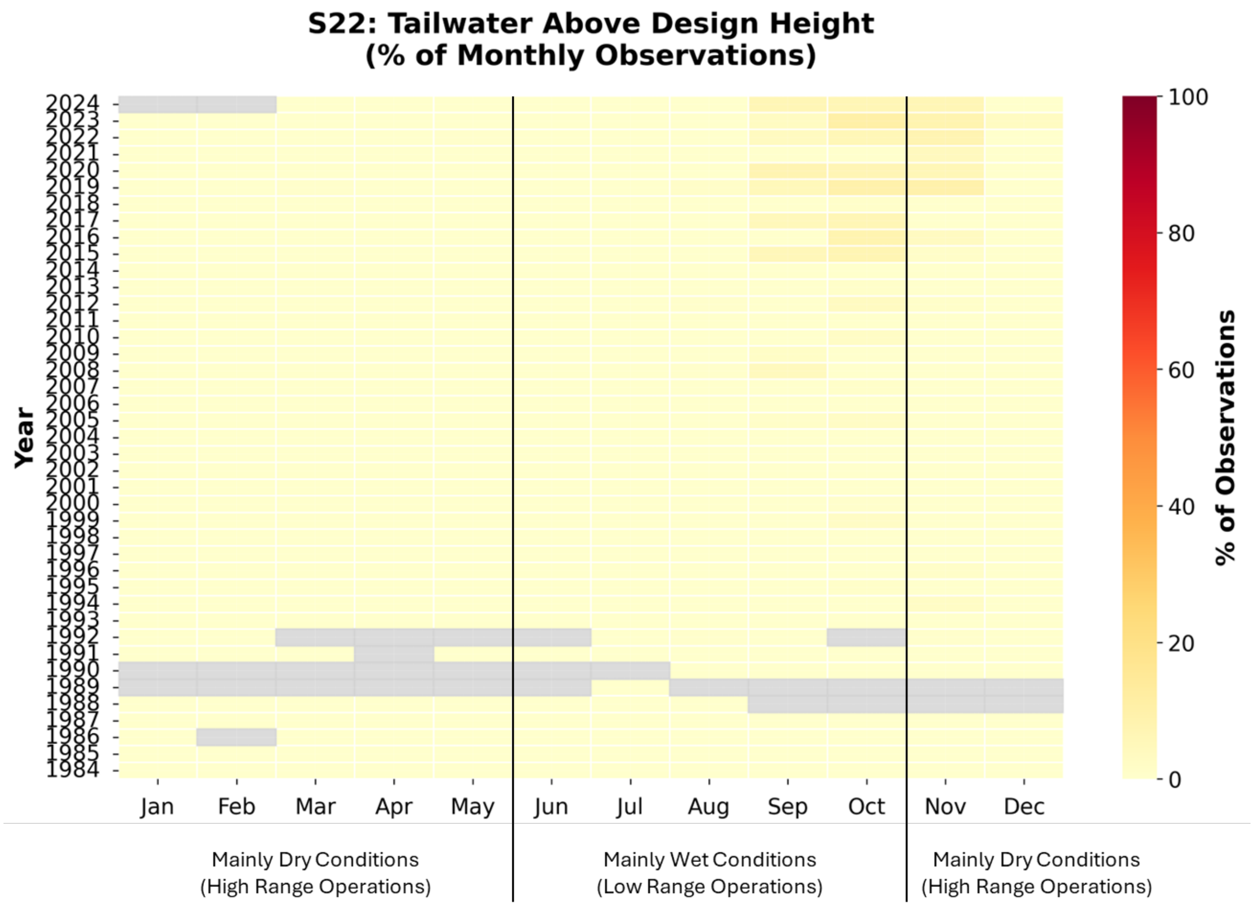

Figure 2B-34. Heatmap diagram showing the percentage of hours each month that the TW was above the HW design elevation at the S-22 structure.

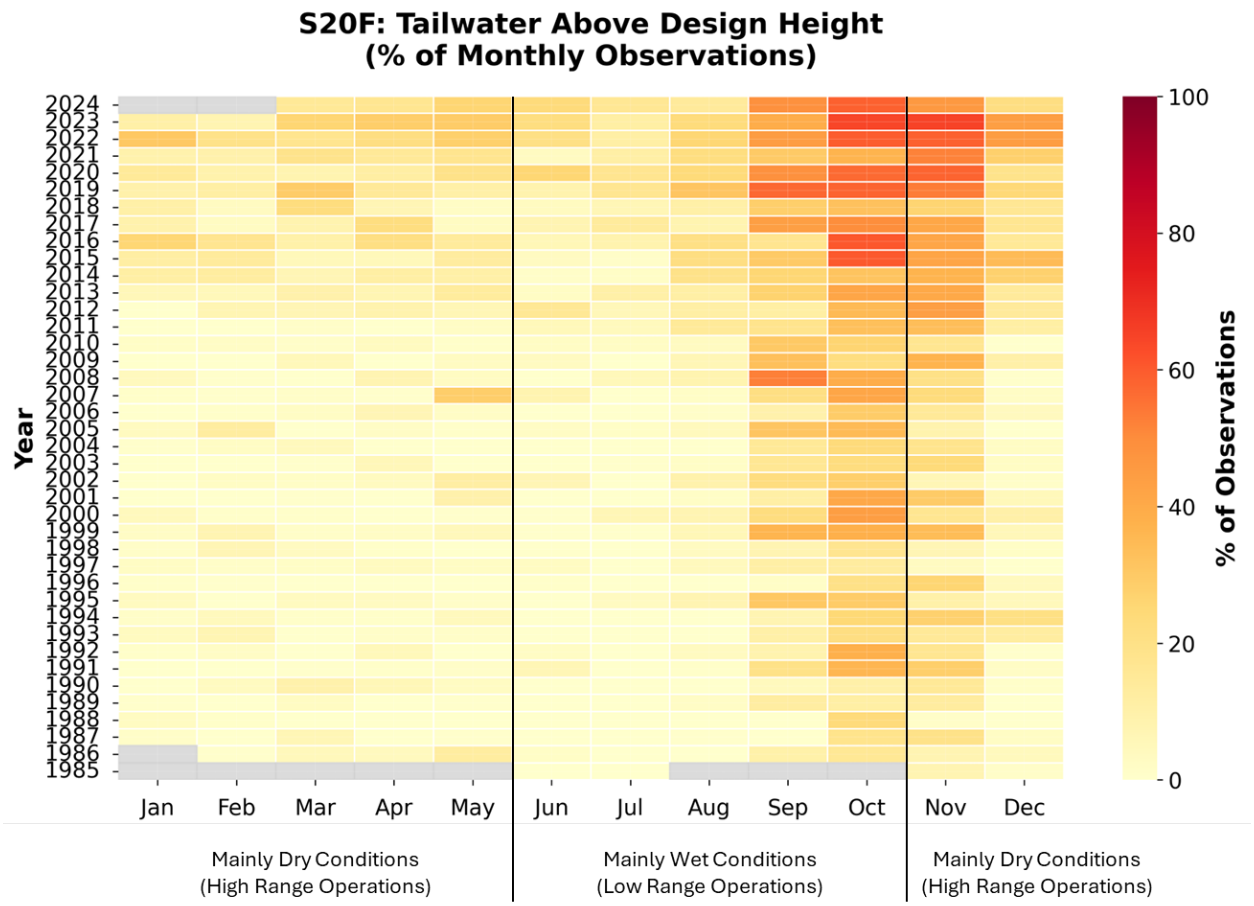

Figure 2B-45. Heatmap diagram showing the percentage of hours each month that the TW was above the HW design elevation at the S-20F structure.

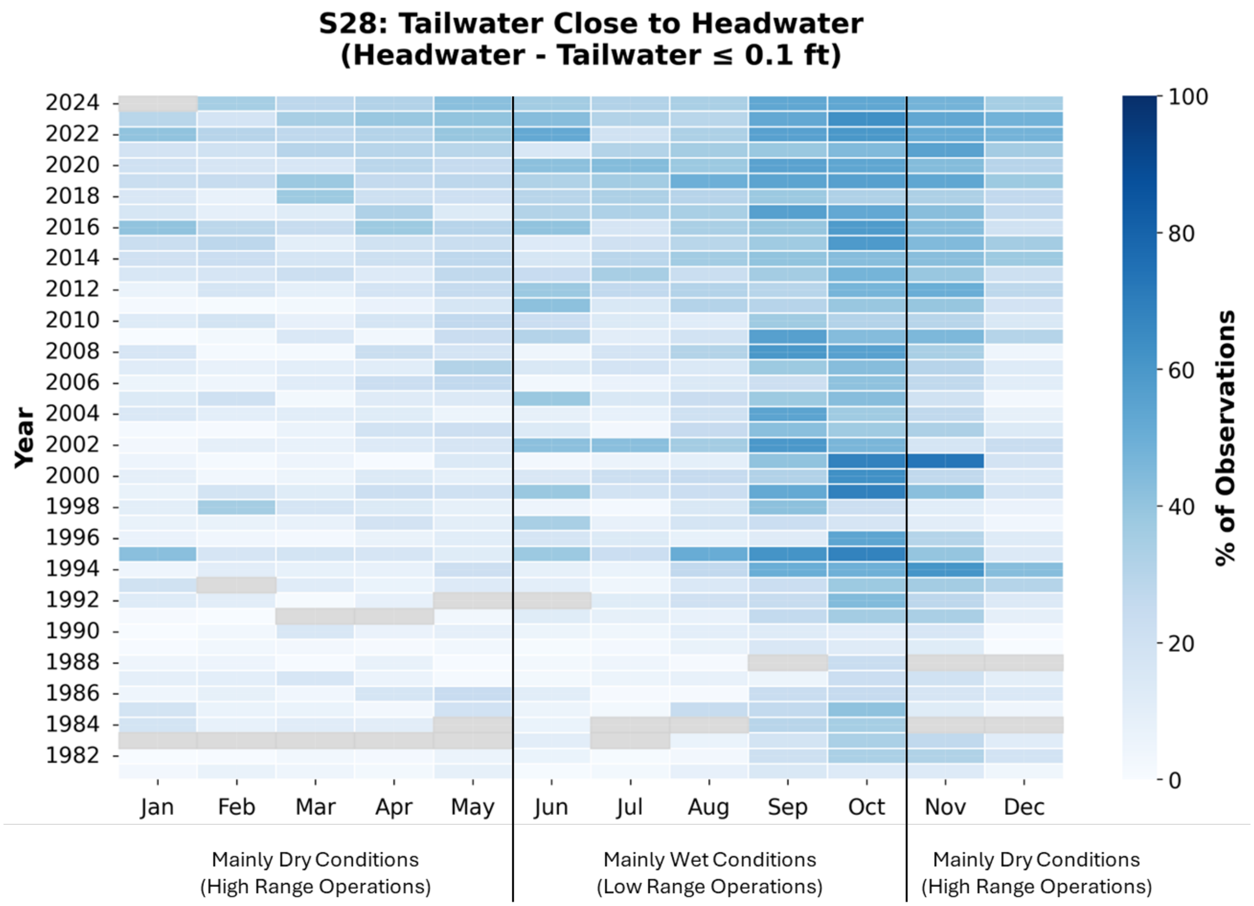

Figure 2B-46. Heatmap diagram showing the percentage of hours each month that the TW was within 0.1 ft of the HW, the definition of an HTE in this study, at the S-28 structure.

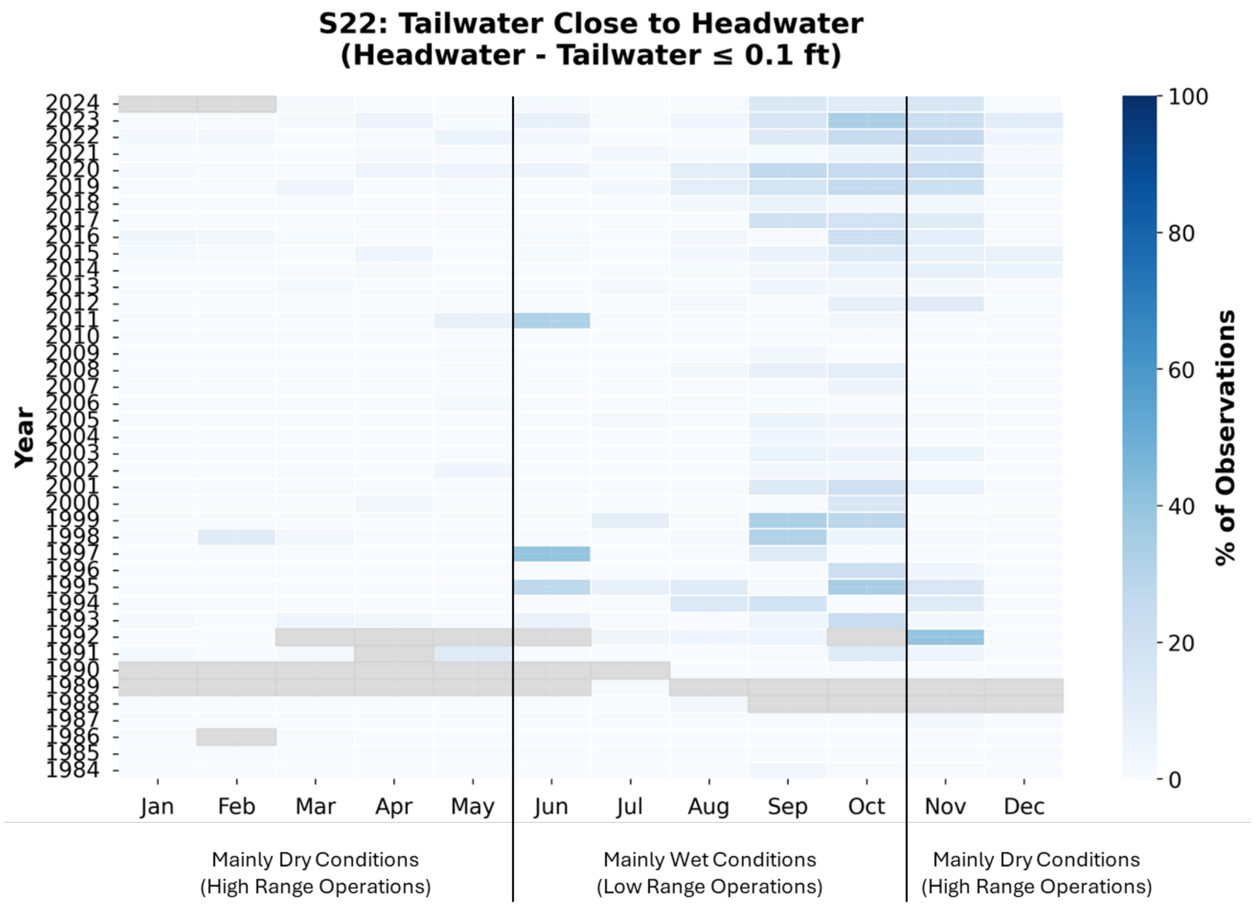

Figure 2B-47. Heatmap diagram showing the percentage of hours each month that the TW was within 0.1 ft of the HW, the definition of an HTE in this study, at the S-22 structure.

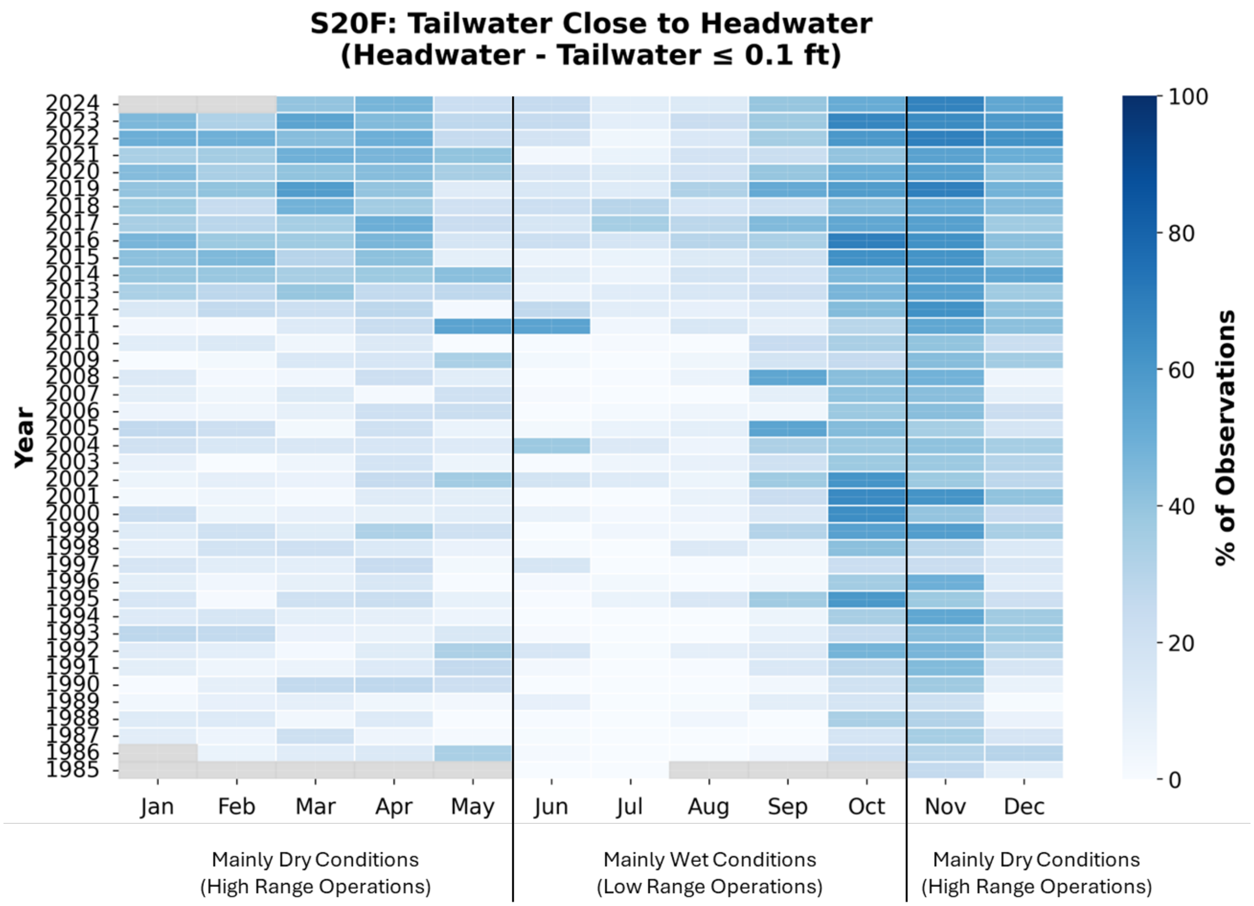

Figure 2B-48. Heatmap diagram showing the percentage of hours each month that the TW was within 0.1 ft of the HW, the definition of an HTE in this study, at the S-20F structure.

From the HTEs frequency data, the percentage of time that condition was met during each of the seasons was calculated, and a linear trend line was fitted to the data over the POR. As shown in **Figure 2B-49**, during king tide season, structures S-28, S-22, and S-20F exhibited statistically significant increases in the number of hours tailwater elevation was close to headwater elevation (HTEs), with p-values below 0.01. The estimated trend slopes were approximately 0.8% per year for S-28 and S-20F, and 0.3% per year for S-22. Similar figures for each season are available in Appendix 2B-3.

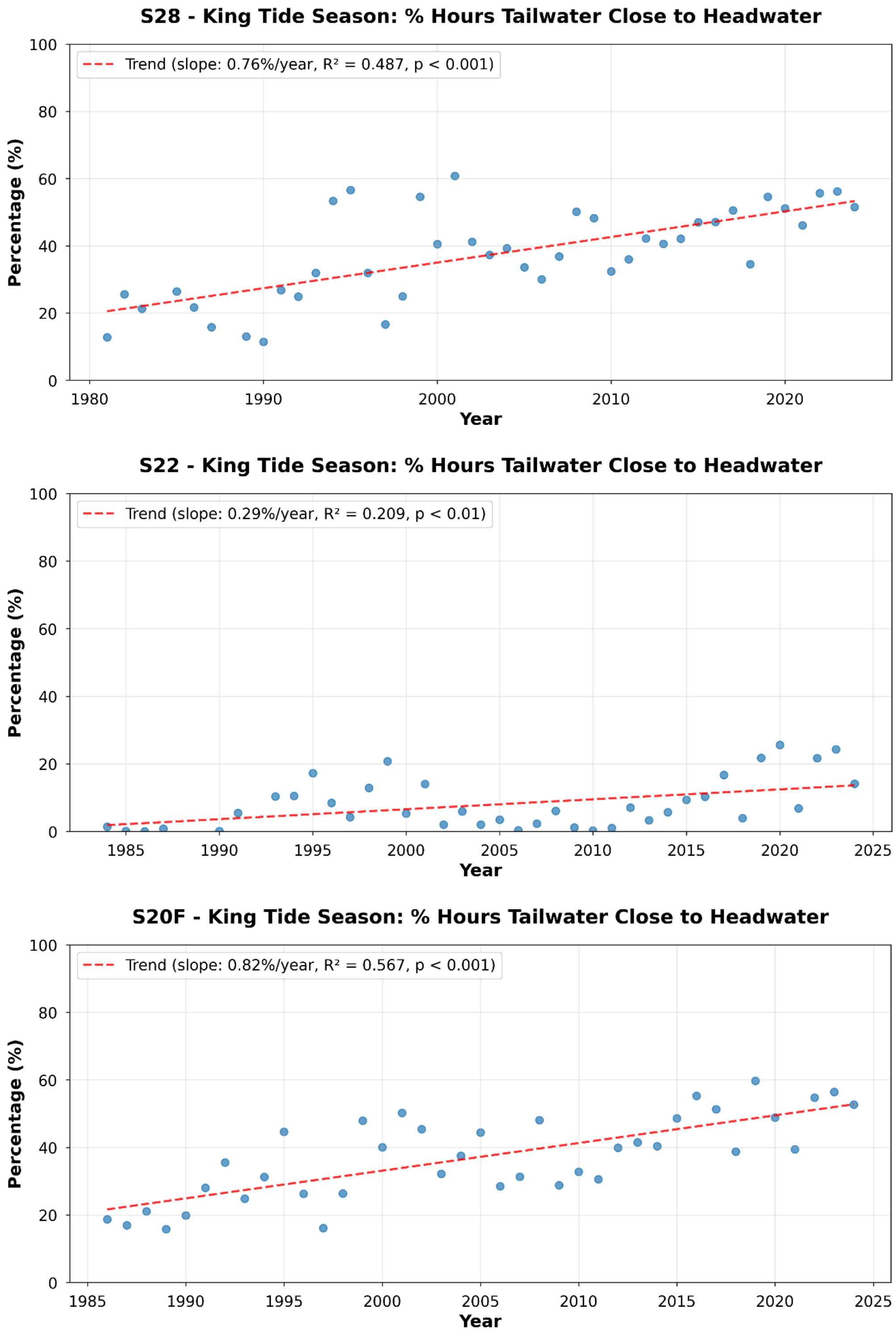

Figure 2B-49. Annual time series of the frequency of HTEs during king tide season at the S-28, S-22, and S-20F structures. The red dashed line shows a linear trend through the data.

A third type of heatmap shows the percentage of hours each month when the TW is above the low range maximum HW height. Many structures have their own unique operating ranges defined as low, normal, and high, with corresponding maximum and minimum HW heights. During the wet season, which overlaps with the king tide and hurricane seasons, the coastal structures typically operate in low range mode to accommodate preventative action during those vulnerable periods when very heavy rain could fall, or very high tides could occur. The maximum HW height within that range is shown in **Table 2B-6** at the end of this subsection. Since the TW is relative to a fixed elevation at a particular location, **Figures 2B-50**, **2B-51**, and **2B-52** are similar to **Figures 2B-43**, **2B-44**, and **2B-45** in primarily showing the effect of tides. During the king tide season, for the complete POR, the frequencies were 69% at S-28, 13% at S-22, and 52% at S-20F, with these values increasing in the last 10 years to 81, 26, and 68%, respectively.

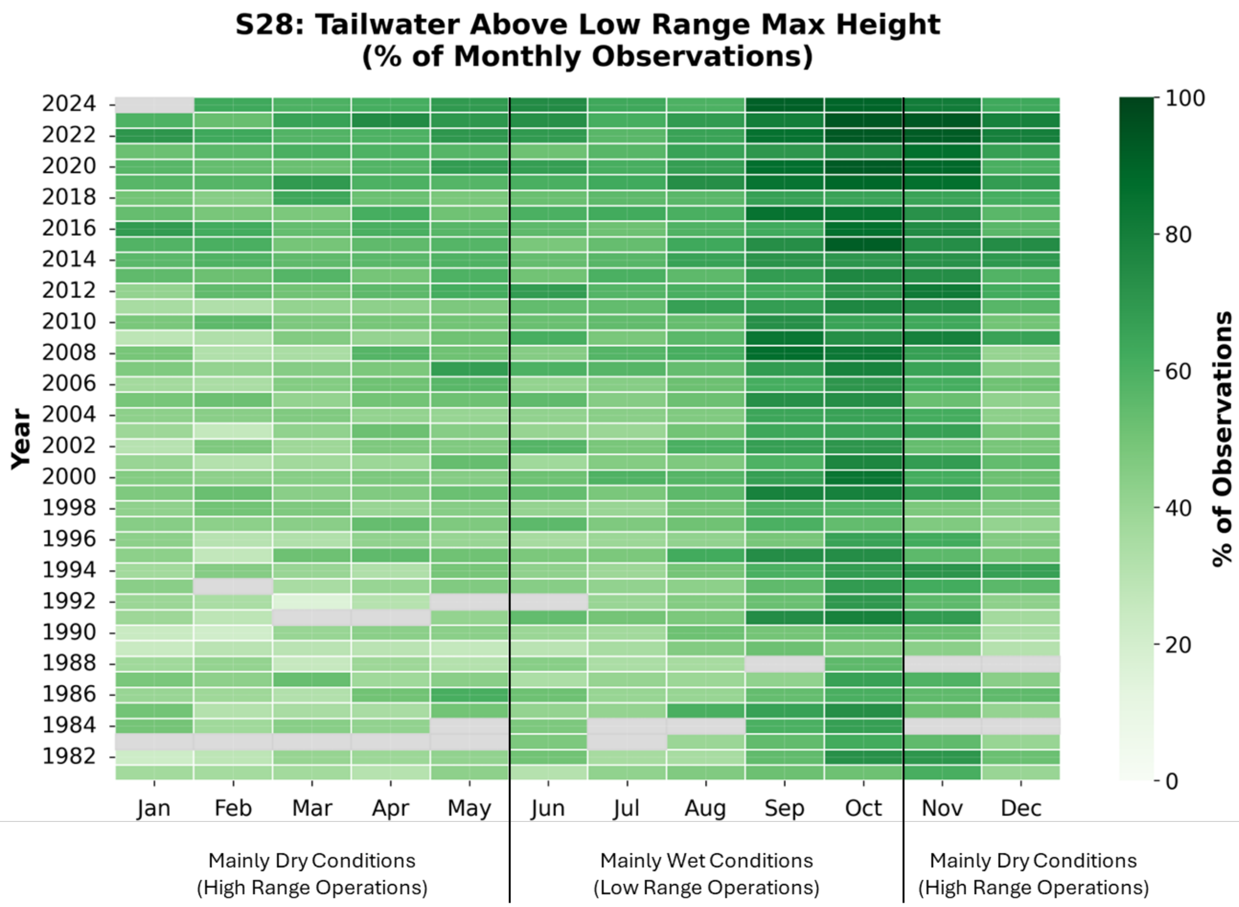

Figure 2B-50. Heatmap diagram showing the percentage of time each month that the TW was above the low range maximum HW height at the S-28 structure.

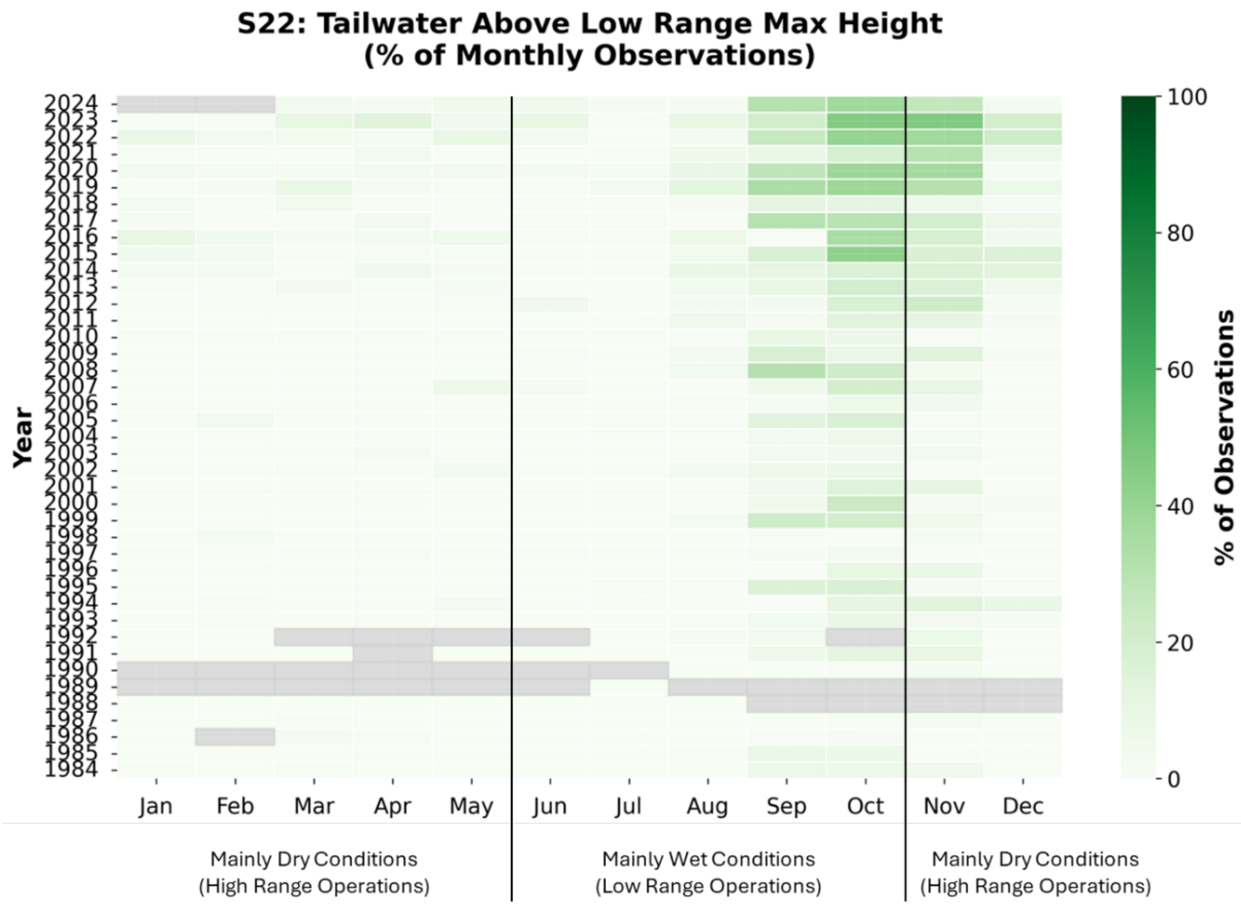

Figure 2B-51. Heatmap diagram showing the percentage of time each month that the TW was above the low range maximum HW height at the S-22 structure.

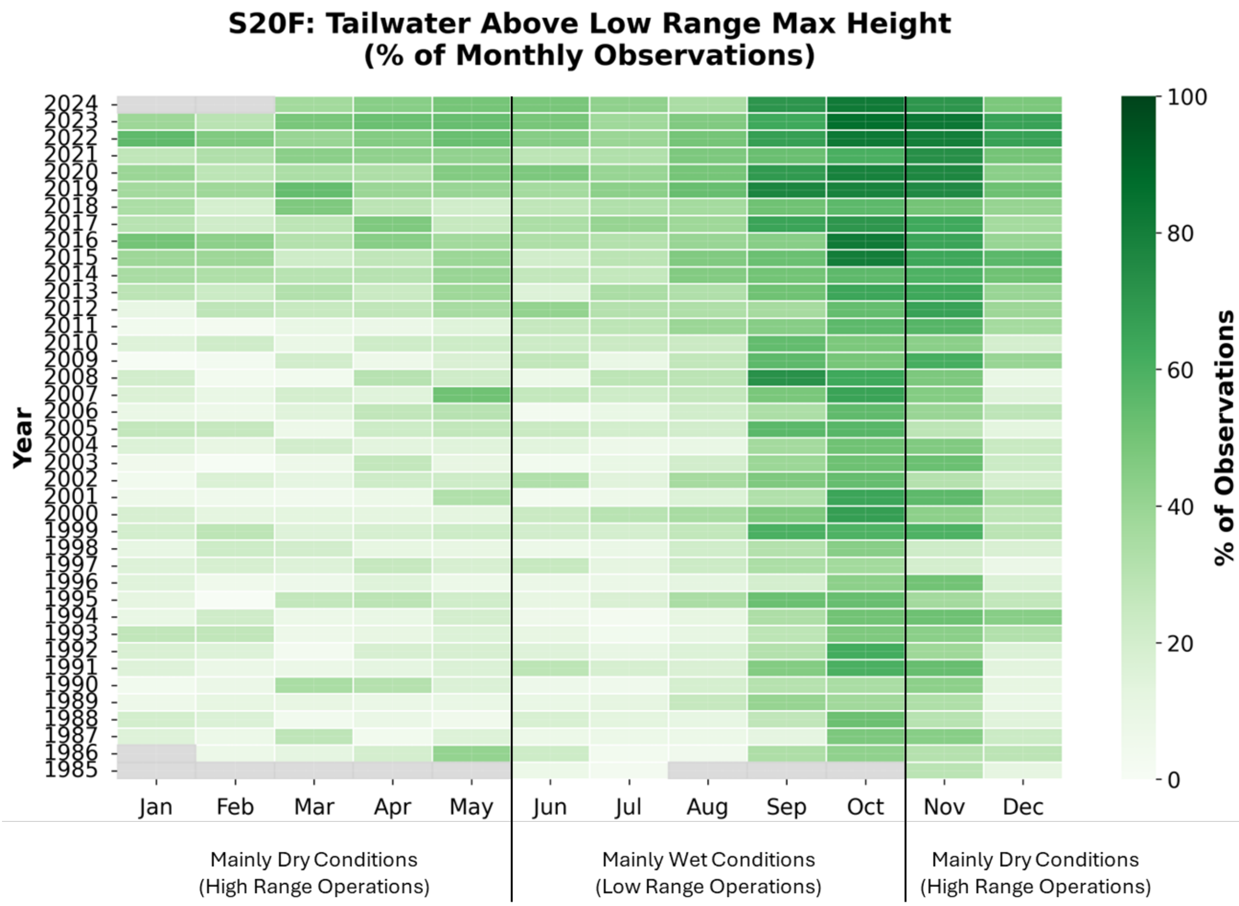

Figure 2B-52. Heatmap diagram showing the percentage of time each month that the TW was above the low range maximum HW height at the S-20F structure.

Finally, an hourly analysis of the entire POR is presented in **Figure 2B-53**. With hourly values of HW and TW, the difference is simply plotted as a time series. If the TW is within 0.1 ft or above the HW (defined to be an HTE), the data point for that hour is colored red. At S-28 and S-20F, it is becoming increasingly difficult to identify and count discrete "events" because the condition is satisfied almost continuously. However, some notable tropical cyclone events stand out, such as Andrew in August 1992, Erin in August 1995, Frances and Jeanne in September 2004, Katrina in August 2005, Wilma in October 2005, and Nicole in November 2022, to name a few. Appendix 2B-3 includes the complete set of figures for the analyzed coastal structures.

To summarize the analysis, the HTEs condition was calculated as the average of the HTE percentages for in each of the four seasons and over the past 20 years (2005–2024, when possible). Since the TW level is governed by tides, a period of ~20 years (related to the 18.6-year lunar nodal cycle) is commonly used when calculating trends and averages.

Table 2B-6 presents the details for the analyzed coastal structures, organized by county and sorted from north to south. The first column lists the structure name, followed by the POR, with stations still active as of this report indicated by an end of 2024. The next column shows the percentage of hours with valid data during the POR. This is followed by the design HW elevation, and then the difference between the HW and TW design elevations, which reflects the structure's sensitivity to water level fluctuations. The subsequent columns provide the HTEs trend for each season. Finally, the last columns display the HTEs condition for each season considering the past 20 years of data (2005–2024, if available).

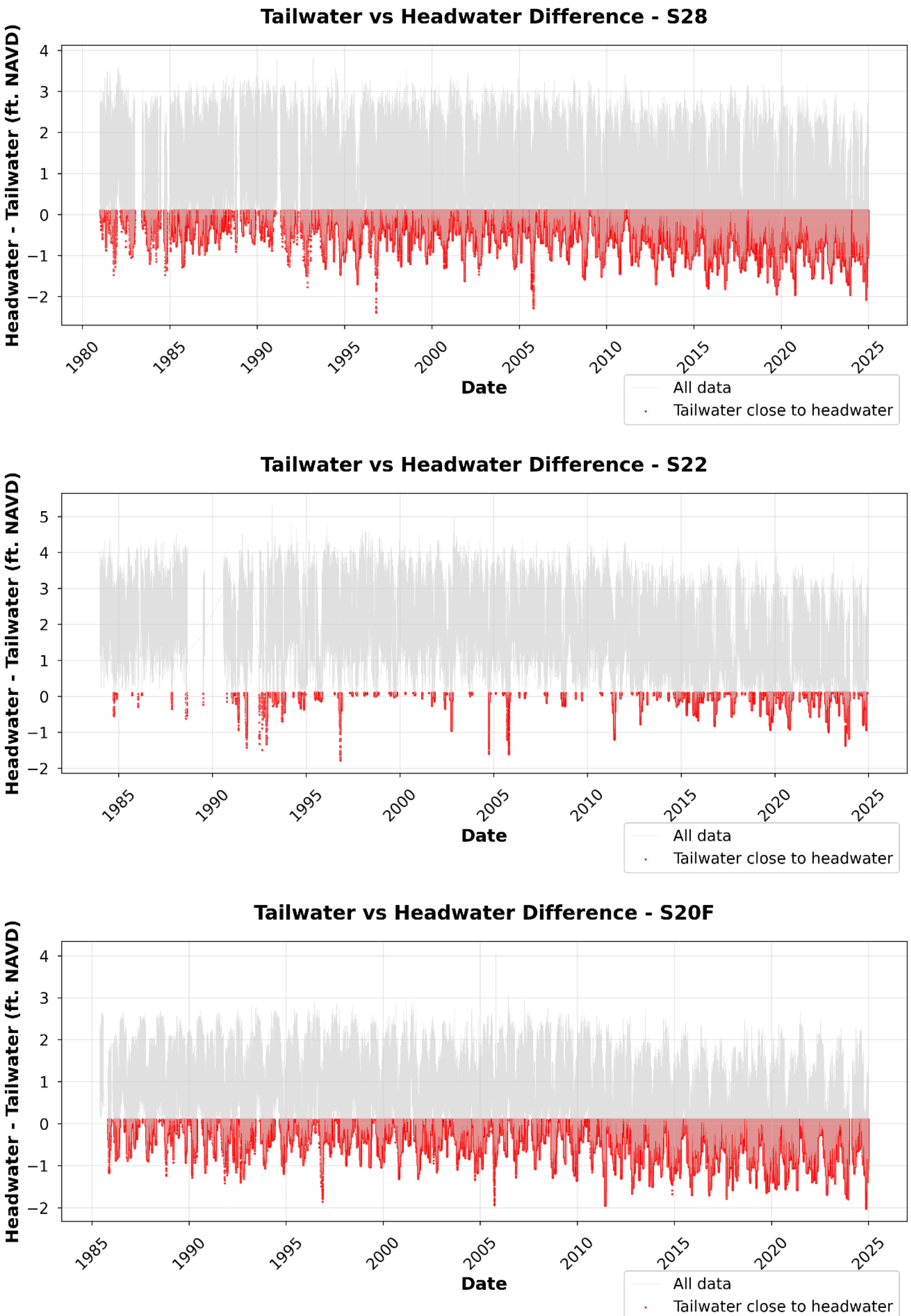

Figure 2B-53. Hourly differences between the HW and TW levels at the S-28, S-22, and S-20F structures. The data point is colored red if the HTE threshold was met. Negative values indicate the TW was above the HW.

Table 2B-64. Summary of data for coastal structures analyzed in this study, organized by county and sorted north-to-south.

Structure	POR	Average Data Coverage (%)	Design HW Elevation (ft NAVD88)	Design HW-TW Elevation (ft)	HTEs Regression Results (% per year)				HTEs Condition (% of time)			
					SON	DJF	MAM	JJA	SON	DJF	MAM	JJA
St Lucie County (East Coast)												
S-99	1966–2024	94.9	18.54	0.50	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
S-49	1994–2024	99.7	14.81	14.60	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
S-97	1986–2024	99.4	17.02	4.50	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
Palm Beach County (East Coast)												
S-46	1996–2016	99.5	11.30	10.60	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
S-44	1982–2024	99.1	7.49	8.90	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
S-155	1987–2024	99.4	6.97	9.50	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
S-41	1985–2024	97.9	6.54	8.30	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
S-40	1985–2024	98.6	6.65	5.50	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
Broward County (East Coast)												
G-56	1991–2024	99.3	6.04	0.70	**-0.05**	-0.01	0.00	**-0.05**	0.0	0.0	0.0	0.0
G-57	1991–2024	97.8	3.42	0.50	0.00	0.00	0.00	**-0.01**	0.3	0.0	0.0	0.0
S-37A	1986–2024	98.3	1.42	3.40	**0.07**	**0.01**	0.02	0.03	1.9	0.1	0.6	0.7
S-36	1986–2024	97.6	3.72	0.50	0.00	0.00	0.00	0.00	0.6	0.0	0.0	0.1
S-33	1991–2024	99.6	4.32	1.00	0.08	0.01	**0.08**	0.03	3.2	0.3	1.5	1.6
G-54	1991–2024	98.7	3.00	0.30	-0.02	-0.01	0.00	-0.06	0.8	0.0	0.1	0.1
Miami-Dade County (East Coast)												
S-29	1986–2024	98.8	0.84	0.50	0.17	0.15	**0.30**	0.22	29.6	6.9	10.2	15.6
S-28	1986–2024	97.6	0.66	0.50	**0.76**	**0.55**	**0.60**	**0.76**	44.3	19.3	22.1	27.1
S-27	1986–2024	98.8	1.46	0.50	0.27	0.19	0.26	0.32	51.4	27.2	28.7	38.1
S-25	1977–2024	97.5	0.26	0.10	**0.69**	**0.44**	**0.50**	**0.67**	44.5	19.4	22.2	31.3
G-93	1992–2024	97.2	2.94	1.50	-0.04	**0.09**	0.06	-0.10	16.7	1.6	2.0	4.7
S-22	1984–2024	98.9	1.66	0.50	**0.29**	**0.05**	**0.03**	0.00	9.3	0.9	0.9	1.7
S-123	1980–2024	97.8	0.47	0.50	**0.51**	**0.13**	**0.18**	**0.09**	14.6	2.7	4.8	3.2
S-21	1985–2024	99.4	0.43	0.50	**0.58**	**0.25**	**0.22**	**0.21**	28.8	7.5	6.5	8.2
S-21A	1974–2024	98.4	0.57	0.50	**0.86**	**0.86**	**0.43**	**0.40**	45.6	28.7	23.3	13.4
S-20G	1985–2024	98.3	0.47	0.50	**0.68**	**0.69**	**0.85**	**0.49**	43.5	24.8	26.3	14.9
S-20F	1985–2024	99.1	0.37	0.50	**0.82**	**0.98**	**0.84**	**0.50**	43.6	29.9	28.2	12.6
S-20	1969–2024	94.5	-0.03	0.50	-0.06	**0.26**	**0.41**	0.08	24.6	9.2	29.1	8.3
S-18C	1987–2024	99.2	1.74	0.50	**2.73**	**4.15**	0.41	**2.60**	74.6	33.6	12.4	62.4
S-197	1998–2024	98.9	-0.15	0.80	**0.43**	-0.01	-0.59	-0.06	6.7	1.4	14.2	2.9
Collier County (West Coast)												
COCO1	1995–2024	98.8	5.91	0.65	0.00	0.00	0.00	0.00	0.2	0.0	0.0	0.1
GG1	2005–2024	99.8	5.73	0.10	-0.04	0.00	0.05	0.00	0.6	0.0	0.6	0.3
HC1	2001–2024	99.3	5.33	1.78	**0.01**	-0.07	-1.14	**-0.68**	0.0	0.3	11.7	4.1
FU1	1987–2024	95.1	-	-	**0.17**	**0.19**	**0.82**	**0.24**	4.3	3.8	21.8	7.1

Note: Bolded HTEs trend values indicate a statistically significant relationships at the 0.05 significance level, with increasing values presented in green and decreasing values shown in red.

RESULTS AND DISCUSSION

Coastal structures managed by SFWMD display considerable variation in both the regression results and the percentage of time that the HTEs conditions are met, and as discussed in the background section, operational water management decisions used in this analysis play a key role in shaping observed patterns. In St. Lucie and Palm Beach counties, which overall present higher average ground elevations, structures consistently maintain design TW elevations well above tidal levels, resulting in infrequent HTEs. In Broward County, structures S-37A and S-33 showed statistically significant increasing relationships. Structure S-33 recorded the highest rate of increase during the MAM season at 0.08% per year, and a maximum HTE occurrence of 3.2% during the king tide season. In Collier County, structures HC1 and FU1 also exhibited statistically significant increasing relationships, with FU1 showing the most pronounced results, an increase of 0.82% per year and a peak HTEs occurrence of 21.8% during the MAM season which may primarily reflect a transition to lower operational ranges rather than a tidal signal. The higher HTEs results were observed in Miami-Dade County, where all structures except S-27[3] demonstrated statistically significant increasing relationships. Structure S-18C on Canal 111E exhibited the highest rate of increase at 4.15% per year during the DJF season and recorded the highest percentage of time under HTEs conditions, reaching 74.6% during the king tide season. Additionally, six structures in Miami-Dade County (S-28, S-27, S-25, S-21A, S-20G, and S-20F) experienced HTEs conditions approximately 50% of the time during the king tide season, highlighting the county's vulnerability to high tides.

The maximum HTEs condition is almost always observed during king tide season (SON), however, there are four locations at which it is observed during MAM season: S-20 and S-197 in Miami-Dade County, and HC1 and FU1 in Collier County. These variations can be attributed to the specific operational regimes of the structures, particularly during dry conditions, when water conservation is prioritized. For example, in addition to its role in preventing saltwater intrusion and providing flood control, S-20 is designed to maintain optimal water levels in the upstream agricultural, industrial, and wetland areas. Similarly, when upstream water levels are low, HC1 remains closed to conserve water for nearby water supply withdrawals, resulting in no reserve flow and higher headwater levels. At FU1, which functions as a fixed-crest weir, HTEs are more frequent in MAM season due to lower headwater levels influenced by water redistributions from the Picayune Strand Restoration Project and tidal effects.

Although HTEs are influenced by both TW and HW levels, the dominant factor is the increasing TW associated with SLR, which is already presenting challenges to SFWMD's water management operations and infrastructure performance, and these challenges may intensify as conditions evolve. Beyond SLR, other natural factors contributing to coastal vulnerability are considered in this analysis. These include hurricanes, perigean new and full moons, the 18.6-year lunar nodal cycle, climatological surface pressure, and wind, topography, and estuarine tide behavior. However, the observed seasonal differences and trends may also reflect transitions between operational ranges rather than a purely tidal signal. Furthermore, even with these complexities, this analysis does not evaluate rainfall patterns, droughts, or other upstream water management factors that influence HW elevations.

Overall, this analysis aligns closely with the SLR assessment reported in SFWMD (2024). While SLR remains a leading factor in the HTEs impact score described in this study (summarized in **Table 2B-6**), the results differ slightly due to the inclusion of weather events, lunar influences, and structure-specific HW elevations.

[3] Data analysis for structure S-27 is ongoing to improve result accuracy; further verification will be carried out.

COMMENTS AND RECOMMENDATIONS

The analysis was originally intended to assess the frequency of HTEs, specifically how many occur now compared to decades ago, or how many occur in each month or season, and how those patterns have evolved. However, at several sites, this approach becomes less meaningful because the criteria to trigger the onset of an HTE can be met, but the event may last for days or even weeks. In such cases, this could count as a single event. Meanwhile, a site closer to the threshold could trigger an HTE at every high tide and then return below the threshold at low tide hours later. In that scenario, this could count as multiple events in a single day. Given this wide variation, the analysis instead focuses on the percentage of time the HTE condition was met. Thus, regardless of how many times the threshold was crossed in a month, the total number of hours the threshold was exceeded is what matters in this analysis.

Furthermore, this study provides a bridge between the tidal elevations analysis provided in SFWMD (2024) and forthcoming analyses on rainfall extremes. Although TW level is the dominant influence on triggering an HTE, inland rainfall, drought, and upstream water management are also components that could influence the vulnerability to HTEs.

RELEVANCE TO RESILIENCY IN WATER MANAGEMENT

Effective water management in low-lying coastal regions, such as those found throughout South Florida, depends on a sound understanding of tidal dynamics and their interaction with the managed hydrologic system, particularly in the context of rising sea levels and changing climate conditions. Evaluating tidal behavior is essential for identifying patterns and anticipating challenges related to flood risk, saltwater intrusion, infrastructure performance, and overall water management objectives.

Long-term analyses of HTEs provide valuable insight into how SLR and tidal variability influence the performance of coastal structures. Increases in the frequency and duration of elevated TW levels, particularly during king tide periods, can reduce the capacity of coastal structures to discharge inland stormwater, thereby increasing the potential for upstream flooding. Identifying and understanding these trends supports risk-informed decision-making for both operational planning and long-term infrastructure investments.

Monitoring tidal water levels also supports ongoing efforts to mitigate saltwater intrusion. When coastal structures remain closed for extended periods due to elevated TW levels, the hydraulic gradient that helps limit inland saltwater movement is reduced. Understanding the relationship between HW and TW levels improves the ability to anticipate and manage intrusion risks, thereby contributing to the protection of freshwater resources and estuarine ecosystems.

Many of South Florida's coastal structures were designed under historical hydrologic and sea level conditions that are increasingly challenged by rising sea levels as well as changing rainfall and ET patterns. Site-specific analysis of tidal patterns inform structure and basin performance studies and help identify locations where design modifications or operational adjustments is needed to meet water management objectives under future conditions.

Integrating HTE data into water management planning and operational strategies enhances the ability to adapt to climate-driven hydrological and sea level changes. In this context, tools such as the HTEs impact score provide data-drive, risk-based approaches for assessing evolving conditions at SFWMD's coastal structures. The current and future operational capacity of South Floria's coastal structures will depend on site-specific design parameters, system-wide operations, and ongoing resiliency enhancement prioritized by SFWMD.

SALTWATER INTRUSION

BACKGROUND

SFWMD established the saltwater interface monitoring and mapping program to evaluate the extent of seawater encroachment into the surficial aquifer system (SAS) along the eastern and western coastlines of South Florida. Water quality data (e.g., chlorides, total dissolved solids, and specific conductance) collected during the dry season (March 1–May 31) by SFWMD, stakeholders, counties, and other entities are compiled by SFWMD every 5 years and used to update the location of the SAS saltwater interface (including the Biscayne aquifer) on the east coast of Florida, and the water table aquifer (WTA) and Lower Tamiami aquifer (LTA) in SFWMD's Lower West Coast (LWC) planning region. Chloride concentration data from 1,135 wells were used to create the 2024 saltwater interface maps presented in Zumbro and Coonts (2025).

Water supply plans for each planning area within SFWMD are updated every 5 years, as required by Chapters 373 and 187, Florida Statutes. Saltwater intrusion monitoring is an important component of water management, as the location and movement of the saltwater interface is for water supply planning. For example, if coastal wellfields are over pumped, saltwater can be drawn into wells either laterally or vertically from deeper aquifers, causing public water supply (PS) wells to be shut down, resulting in the need for new wells to be installed farther inland or for an alternative water supply source to be identified and developed. Coastal utilities also use these maps to monitor potential impacts to PS wellfields.

SFWMD's regulatory staff use the saltwater interface maps when evaluating applications for consumptive use permits. Projects located in areas vulnerable to saltwater intrusion are required to implement a saline water monitoring program and periodically report chloride concentrations, from groundwater samples collected from their wells to SFWMD.

The main objective of this monitoring and mapping effort is to evaluate changes in the location of the saltwater interface every 5 years. The saltwater interface is defined as the 250-milligrams per liter (mg/L) isochlor (i.e., a line of equal chloride concentrations) on the associated maps. Saltwater intrusion is considered harmful when the chloride concentrations consistently exceed 250 mg/L, above and beyond seasonal fluctuations in chloride concentrations (SFWMD 2022). A concentration of 250 mg/L is the United States Environmental Protection Agency's drinking water secondary maximum contaminant level for chloride. The collected chloride concentration data are used to map the location and extent of saltwater intrusion, show the changes in the position of the saltwater interface that have occurred over the past 5 years, and help determine the causes of those changes. Chloride data from sampled wells can vary between the dry and wet seasons. This mapping effort is focused on the location of the saltwater interface during the dry season as it will reflect the farthest inland extent of the interface.

DRIVERS AND INFLUENCING FACTORS

The factors that influence and drive saltwater intrusion include a combination of natural factors and human activities. Proper management of these factors is essential to preserve the aquifer's ecological health and prevent further saltwater intrusion. Among the main influencing factors are the following:

- **Rainfall:** Groundwater levels within the aquifer systems are influenced by local rainfall. Increased rainfall contributes to higher groundwater levels, while drought conditions can lead to lower groundwater levels.
- **Canal operations:** The canals and structures operated by SFWMD play a significant role in determining the elevation of freshwater levels in the Biscayne aquifer across South Florida.

- **Distance from canals:** Groundwater dynamics are more influenced by canals and less by rainfall as one moves closer to the primary canal network. The aquifer becomes more rainfall-driven and less canal-dependent as distance from the canals increases.
- **Secondary and tertiary canals:** Local canals and water storage in the secondary and tertiary canal systems also play a significant role in influencing groundwater dynamics and the surficial aquifer's water levels.
- **Wellfield pumpage:** Pumping water from wellfields for various purposes, including municipal water supply and irrigation, affects groundwater levels in the aquifer. High pumpage can lead to lower groundwater levels and increased potential for saltwater intrusion.
- **Seasonal variations:** Short-term variations in groundwater levels can temporarily affect the position of the saltwater interface but the interface typically retreats to its former position once groundwater levels return to normal ranges.
- **Long-term low water levels:** Historical data indicate that when water levels in the canals and aquifer remain low for an extended period, significant inland migration of the freshwater-saltwater interface may occur, potentially resulting in permanent movement of the interface even after water levels return to normal or above normal conditions.
- **Saltwater intrusion:** As the aquifer experiences increased sea levels or freshwater withdrawals or faces prolonged shortages in inland water levels or drought conditions, the saltwater interface can advance inland, threatening the aquifer's freshwater quality. Over time, the intrusion may cause permanent displacement of the saltwater interface, even after water levels return to normal or above-normal conditions.
- **Water supply management:** Water supply releases from regional storage sources, such as the Everglades Water Conservation Areas, are utilized to achieve dry season drought management targets, which, in turn, influence the adjacent dry season groundwater elevations within the surficial aquifer.
- **Consumptive use permits:** The consumptive use permit conditions for coastal users aim to maintain a groundwater divide between the withdrawal point and the source of saline water, further protecting the surficial aquifer from saltwater intrusion.

2024 SALTWATER INTERFACE MAPS AND INTERPRETATION

The SFWMD saltwater interface monitoring and mapping program was established to evaluate the extent of seawater encroachment into aquifers along the South Florida coastline except for Miami-Dade County, which has retained the USGS to conduct its mapping (Prinos et al. 2014, Prinos 2017, Zhang and Renshaw 2024). SFWMD began mapping the approximate location of the saltwater interface in its coastal aquifers in 2009, with updated maps produced every 5 years (2014, 2019, and 2024 to date). For all the maps, the round dots represent monitor wells and hexagons represent pumping well locations. The color of the dots represents the range of chloride values including green (< 100 mg/L), yellow (101 to 250 mg/L), orange (251 to 1,000 mg/L) and red (> 1,000 mg/L). The stars on the map indicate wells that did not exist, or no data was available from those wells prior to the 2024 maps.

The 2024 SFWMD saltwater interface maps are available on SFWMD's webpage at https://www.sfwmd.gov/documents-by-tag/saltwaterinterface. The associated interpretation report (Zumbro and Coonts 2025) is available at https://www.sfwmd.gov/sites/default/files/documents/WS-67_2024_swi_mapping_report.pdf. The approximate inland extent of saltwater intrusion for the Biscayne aquifer in Miami-Dade County are available at https://doi.org/10.5066/P13TSEEA.

St. Lucie and Martin Counties – Surficial Aquifer System

Chloride concentration data from 183 SAS groundwater samples and 30 surface water samples were used to draw the 2024 saltwater interface in St. Lucie and Martin counties. There has been little movement of the interface in this region. The coastal area north of the City of Fort Pierce lacks monitor well data. However, the chloride concentrations in the four SAS wells in this area are all well below 250 mg/L, and the chloride concentrations in three of these four wells have decreased since 2019. Between the City of Fort Pierce and Jensen Beach, there is only one monitor well located close to the coastline, and no monitor wells are located seaward of the City of Fort Pierce–Lawnwood PS wellfield in St. Lucie County.

The 2024 interface near the South Martin Regional Utility–South PWS wellfield in Hobe Sound has migrated approximately 500 ft inland since 2019 but is farther seaward than it was in 2014 and 2009 (**Figure 2B-54**). This result is based primarily on the chloride concentration of 2,350 mg/L reported at Well-R4 ID 280521 (Map ID 176 in **Figure 2B-54**) in May 2024 as well as the chloride concentration at SW-13D ID 156278 (Map ID 169 in **Figure 2B-54**), which increased from 42 mg/L in 2019 to 282 mg/L in 2024. Review of pumpage data from this wellfield showed that the total pumpage from the wellfield has increased each year since 2014. The total reported pumpage was approximately 560.92 million gallons in 2014, 626.39 million gallons in 2020, 763.87 million gallons in 2021, 786.24 million gallons in 2022, and 795.07 million gallons in 2023. These increased pumping volumes likely caused reduced freshwater heads near the wellfield and inland movement of the saltwater interface from 2019 to 2024 and could continue to do so in the future.

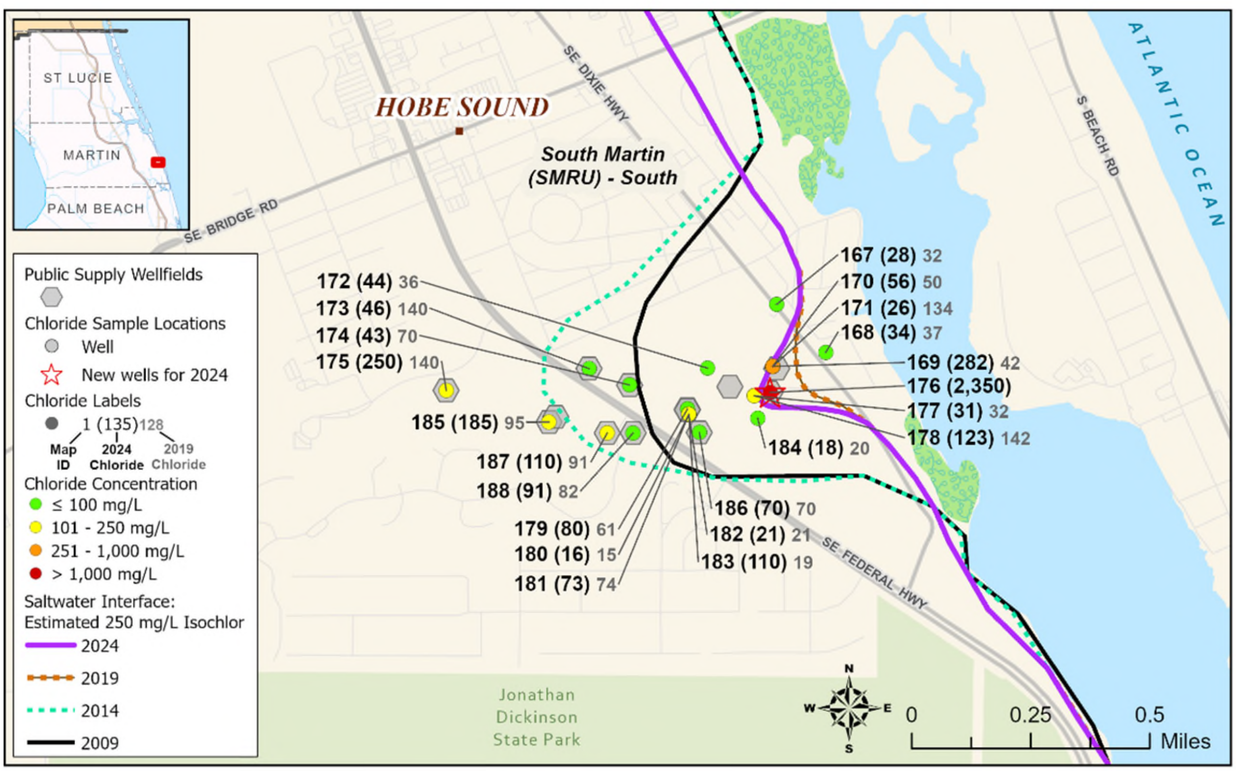

Figure 2B-54. Position of the 2024 saltwater interface in the SAS at the South Martin Regional Utility–South PS wellfield in Hobe Sound in Martin County.

Palm Beach County – Surficial Aquifer System

Chloride concentration data from 306 SAS groundwater samples and two surface water samples were used to draw the 2024 saltwater interface in Palm Beach County. New groundwater chloride concentrations were obtained from three monitor wells in Jonathan's Landing Golf Club (Map IDs 30, 38, 43 on **Figure 2B-55**). The three wells in Jonathan's Landing Golf Club appear to be replacement monitor wells for historical wells with long periods of record that are in approximately the same locations as the three wells shown in **Figure 2B-55**. The 2024 chloride concentrations for these wells were 1,005 mg/L (JLOW-08R, Map ID 30), 340 mg/L (JLOW-04R, Map ID 38), and 336 mg/L (JLOW-5R, Map ID 43), from north to south, respectively.

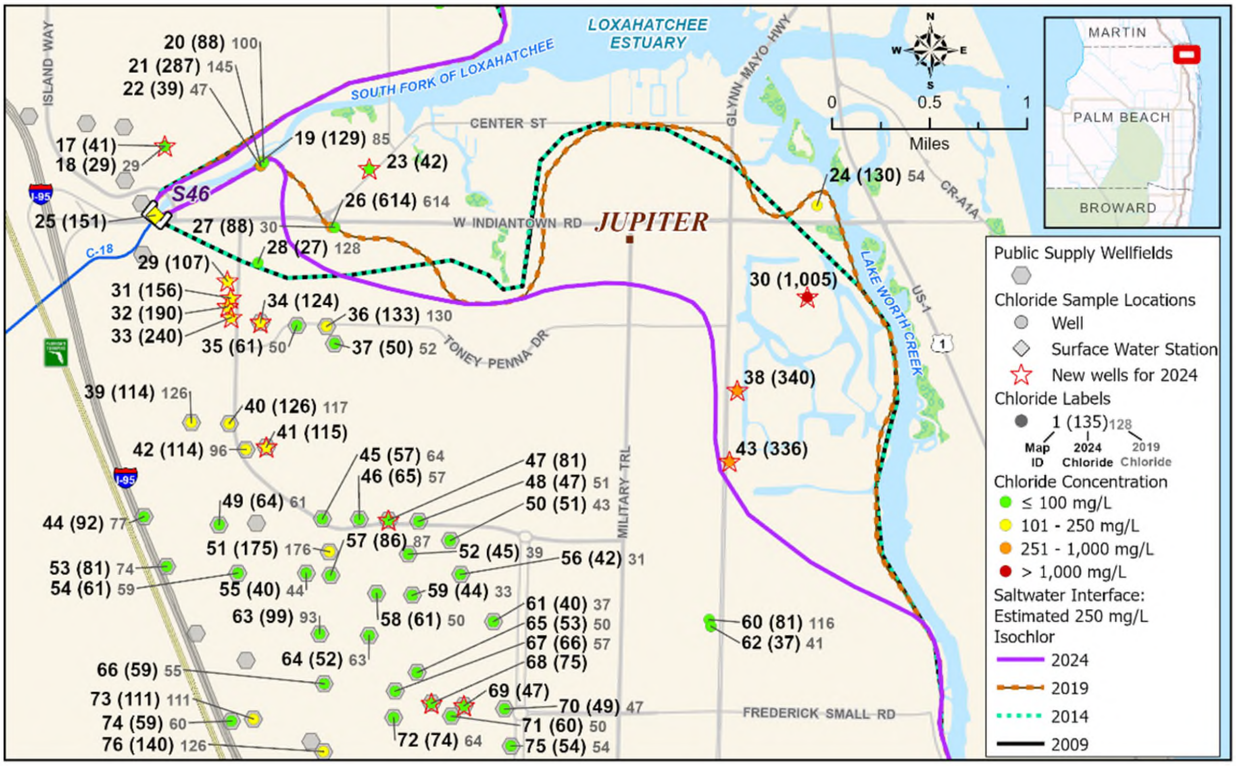

Figure 2B-55. Position of the 2024 saltwater interface in the SAS in the Town of Jupiter in Palm Beach County.

Fifteen miles south of Jonathan's Landing Golf Club, the saltwater interface moved inland beneath the Good Samaritan Medical Center in the City of West Palm Beach between 2019 and 2024 (**Figure 2B-56**). The chloride concentrations at two of the three monitor wells in this area have increased since 2019. For the well closest to the Intracoastal Waterway (PBV ID 155268 [Map ID 106]), chlorides increased from 9,510 mg/L in 2019 to 11,000 mg/L in 2024. This well is open from 192 to 212 ft below land surface (bls). The saltwater interface likely extends beneath the two monitoring wells to the west of PBV ID 155268, which have significantly shallower open intervals of 45 to 65 ft bls at the northern well (PB3 ID 17073 [Map ID 105], chloride concentration of 62 mg/L), and 60 to 80 ft bls at the southern well (PB2R ID 45047 [Map ID 107], chloride concentration of 37 mg/L).

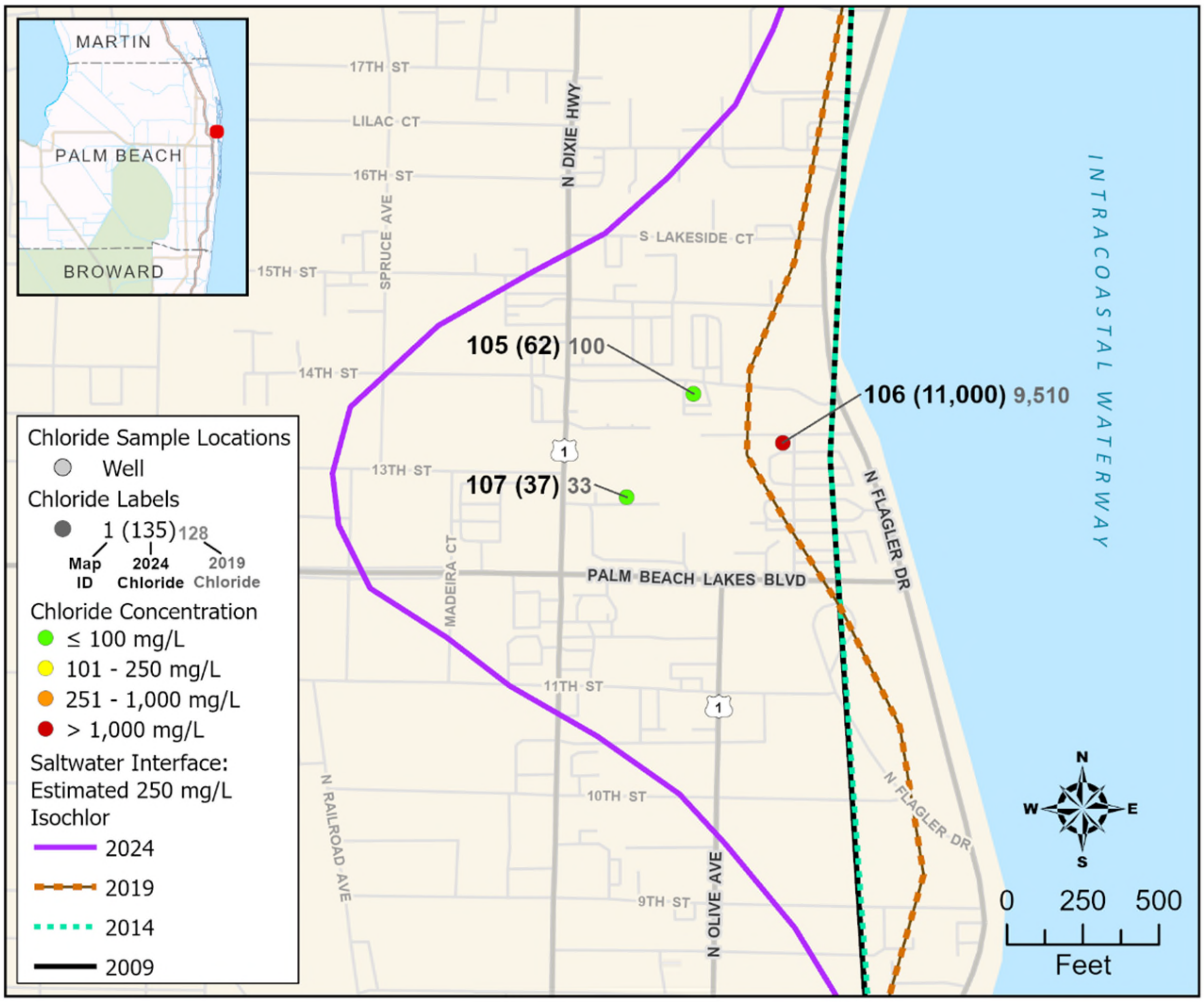

Figure 2B-56. Position of the 2024 saltwater interface in the SAS beneath the Good Samaritan Medical Center in the City of West Palm Beach in Palm Beach County.

No notable changes were made to the saltwater interface between the Good Samaritan Medical Center and the City of Lake Worth Beach, primarily due to the lack of monitor wells along this 8-mile section of coastline. Near the City of Lake Worth Beach Utilities PS wellfield, slight inland movement of the saltwater interface was mapped southwest of LWMW-9 ID 192495 (Map ID 127), where chloride concentrations increased from 1,880 mg/L to 2,000 mg/L between 2019 and 2024 (**Figure 2B-57**). The total depth of LWMW-9 ID 192495 is 328 ft bls, with no open interval information. The monitor wells to the southwest of the 2024 isochlor have 2024 chloride concentrations in the 17 to 31 mg/L range and have slightly shallower total depths and open intervals. To the south in **Figure 2B-57**, the saltwater interface moved slightly seaward due to decreasing chloride concentrations in most of the wells on either side of the 2019 isochlor.

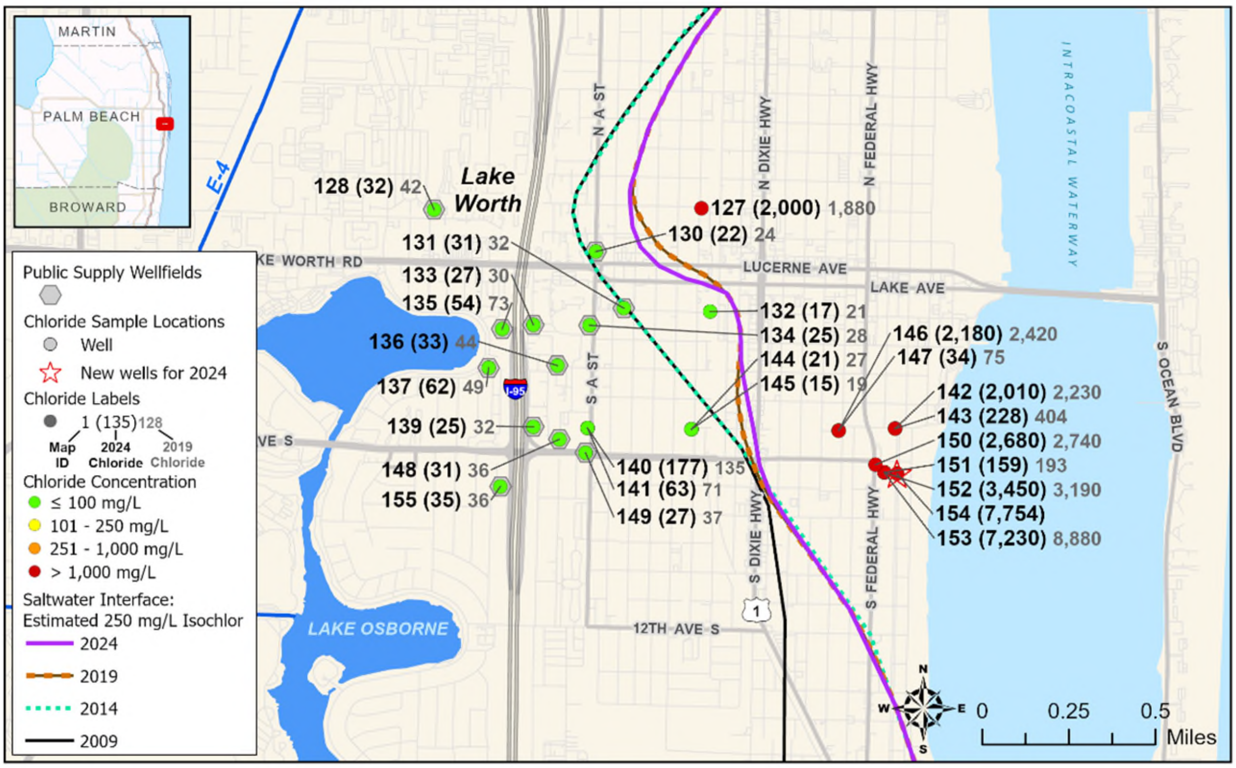

Figure 2B-57. Position of the 2024 saltwater interface in the SAS near the City of Lake Worth Beach Utilities PS wellfield in Palm Beach County.

The leading edge of the 2024 interface extends beneath the Town of Lantana PS wellfield (**Figure 2B-58**) but does not extend as far inland as it did in 2009. LT4-C ID 137788 (Map ID 174) is adjacent to Dixie Highway/U.S. Route 1. At this well, chloride concentrations increased from 1,715 mg/L in 2019 to 2,160 mg/L in 2024 (**Figure 2B-58**). This well has an open interval extending from 150 to 160 ft bls.

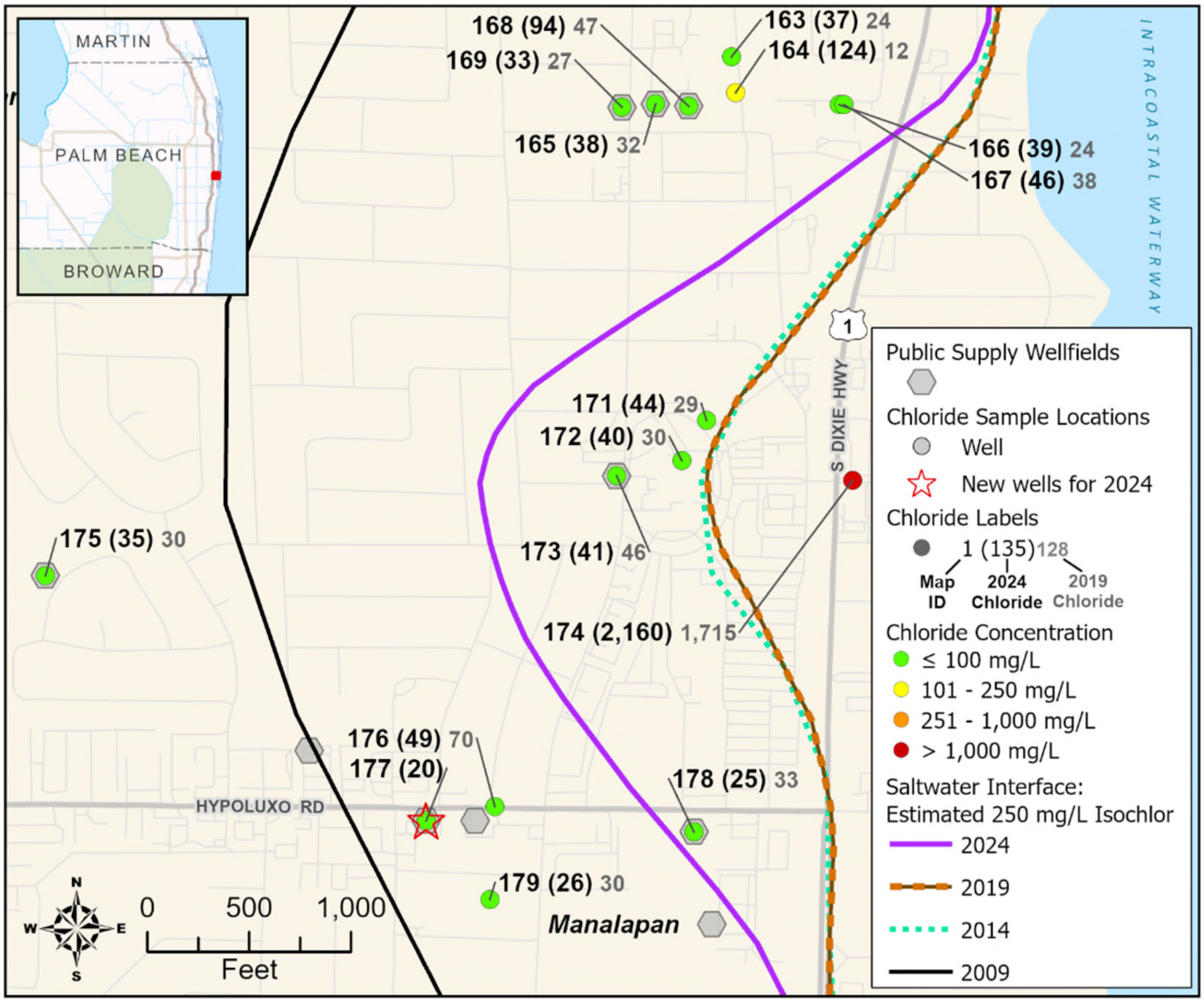

Figure 2B-58. Position of the 2024 saltwater interface in the SAS near the Town of Lantana PS wellfield in Palm Beach County.

The leading edge of the 2024 saltwater interface beneath the City of Boynton Beach PS wellfield in **Figure 2B-59** is defined by the 350-ft deep BYHP1 ID 152794 (Map ID 202), which had a 2024 dry season chloride concentration of 1,520 mg/L. The PS wells in this area range in depth from 54 to 273 ft bls, with the deeper wells being located primarily west of Interstate 95. BYHP1 ID 152794 has an open interval extending from 340 to 350 ft bls. Since 2010, however, the overall trend of chloride concentrations at BYHP1 ID 152794 has been gradually increasing, possibly indicating slow migration of the saltwater interface through this well. The PS wells west of BYHP1 ID 152794 are about 117 to 150 ft shallower and reported 2024 dry season chloride concentrations in the 34 to 46 mg/L range. The wells with the largest chloride concentrations (i.e., red dots) are Map ID 208 (BYHP4, total depth of 285 ft bls, chloride concentration 12,300 mg/L) and Map ID 195 (DM1, total depth 186 ft bls, chloride concentration 16,050 mg/L).

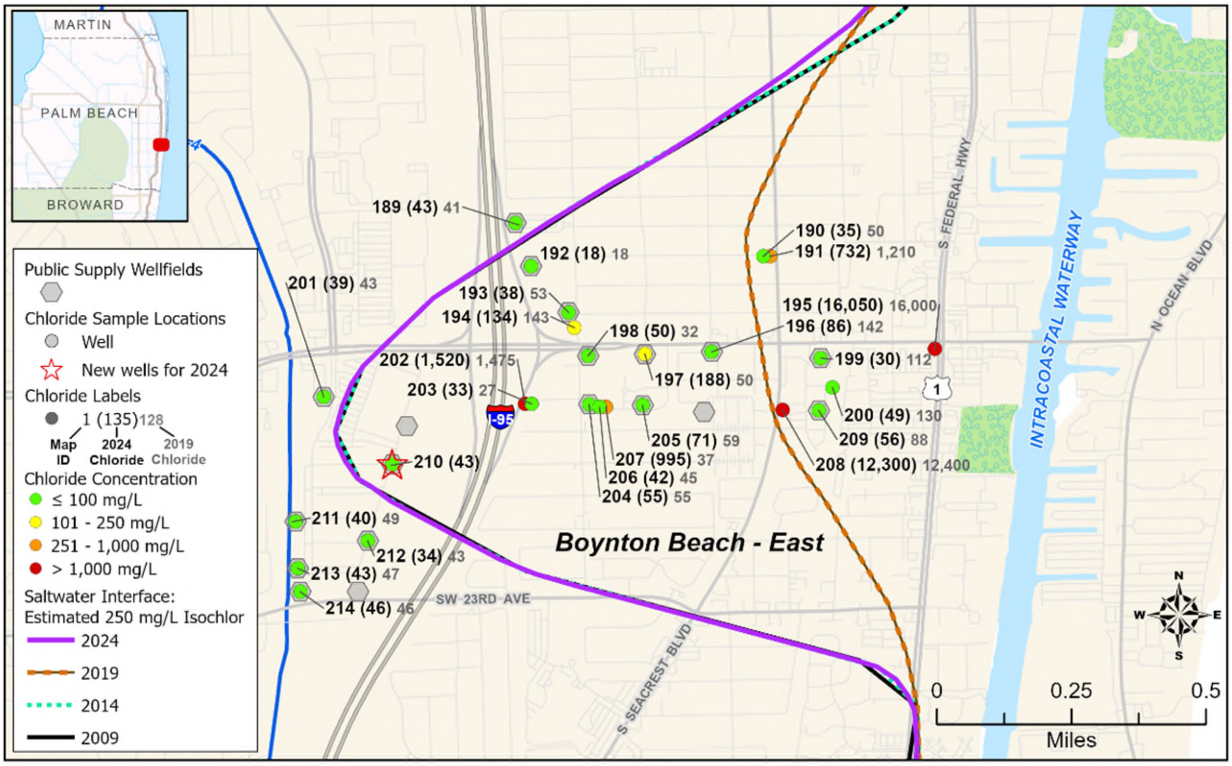

Figure 2B-59. Position of the 2024 saltwater interface in the SAS near the City of Boynton Beach PS wellfield in Palm Beach County.

Figure 2B-60 shows that the 2024 interface has apparently moved inland beneath the easternmost City of Delray Beach PS wellfield. The 12 City of Delray Beach PS wells located adjacent to the 2024 interface are completed to depths ranging from 76 to 115 ft bls. The three wells to the west of the 2024 isochlor with elevated chloride concentrations are completed deeper in the aquifer than the shallow PS wells with low chloride concentrations.

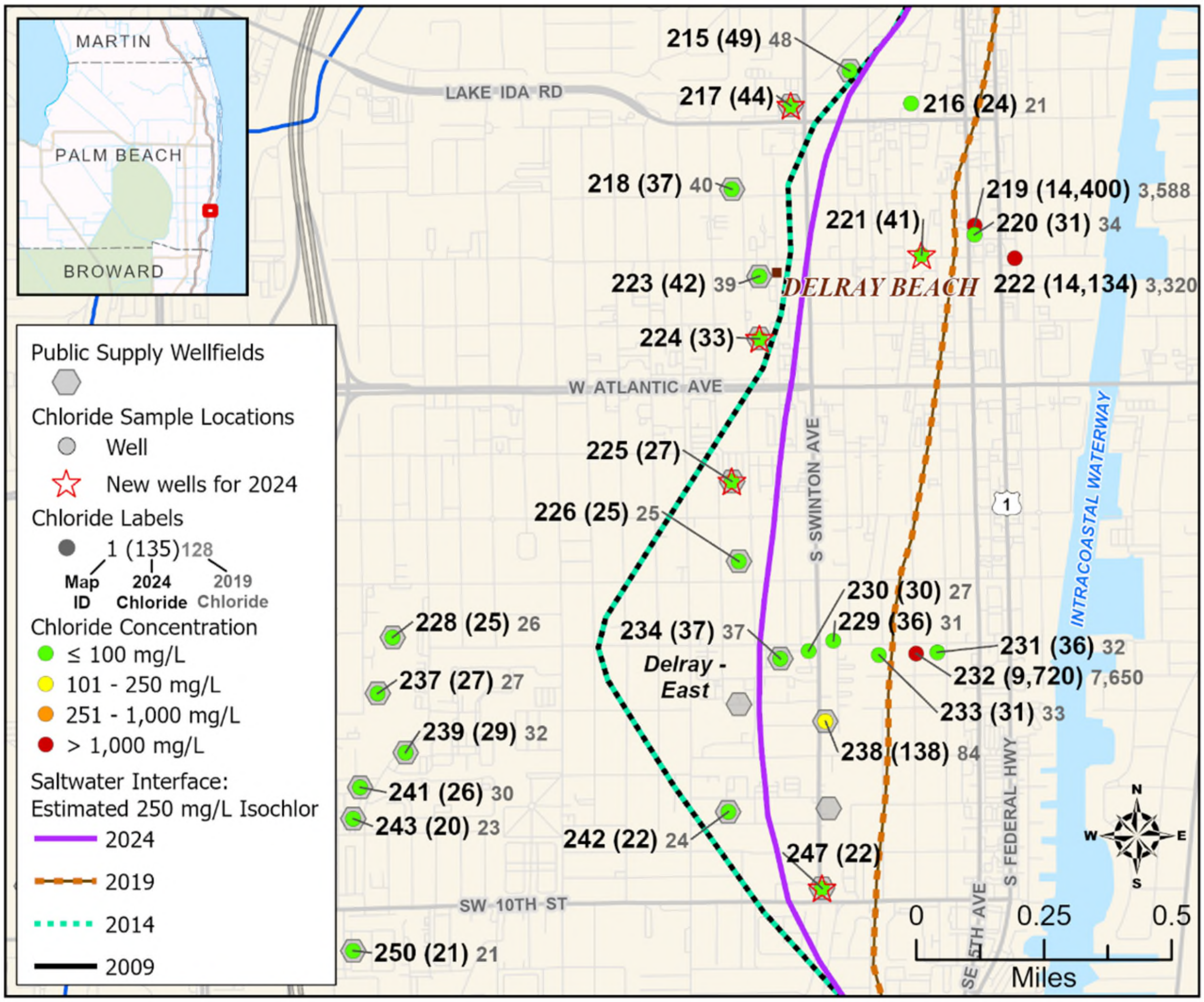

Figure 2B-60. Position of the 2024 saltwater interface in the SAS near the City of Delray Beach Utilities PS wellfield in Palm Beach County.

Broward County – Surficial Aquifer System

Chloride concentration data from 122 SAS groundwater samples and two surface water samples were used to draw the 2024 saltwater interface in Broward County. **Figure 2B-61** shows that the saltwater interface has retreated approximately 1 mile seaward in the City of Pompano Beach since 2019 due to decreasing chloride concentrations at SWI9-S ID 136333 (130 ft deep, Map ID 46) and SWI9-D ID 136332 (140 ft deep, Map ID 45). The decreasing chloride concentrations are likely the result of reduced pumpage from the city's eastern wellfield coupled with reduced domestic irrigation withdrawals in areas where reclaimed water is being used for irrigation.

Figure 2B-61 also shows the location of newly installed saltwater intrusion monitoring well BS-3 (Map ID 43) located on the western bank of the G-16 Canal near the West Atlantic Boulevard southbound on-ramp to Interstate 95. This well was installed in February 2023 by SFWMD to fill a spatial data gap where inland migration of the saltwater interface could be detected before it reaches the City of Pompano Beach PS wellfield to the west. This well was installed with a 10-ft long screen at the base of the SAS with a 10-ft long sump extending into the underlying Hawthorn Group sediments to allow for future dual induction geophysical logging of the entire aquifer and detection of the encroaching saltwater interface along the base of the SAS. A groundwater sample collected from this well in 2024 was fresh with a chloride concentration of 19 mg/L.

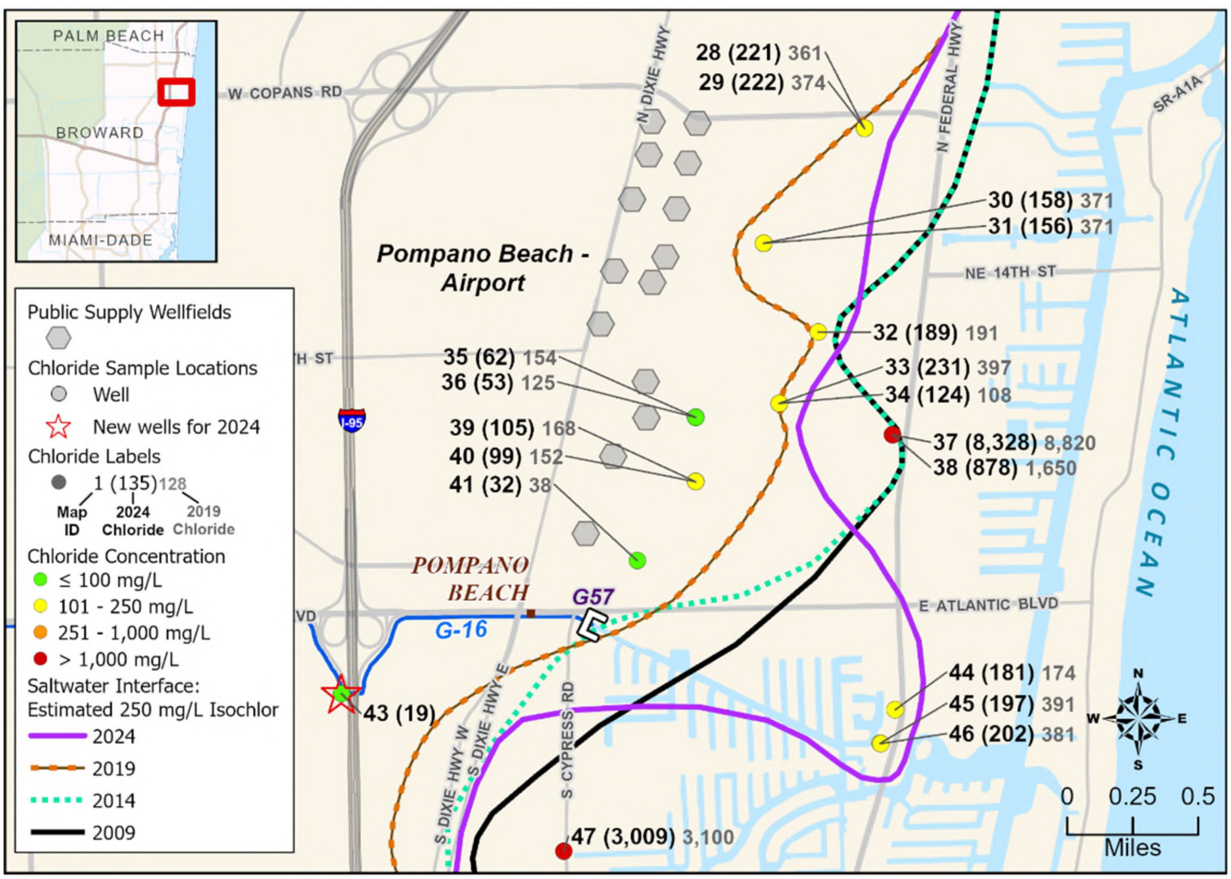

Figure 2B-61. Position of the 2024 saltwater interface near the City of Pompano Beach Utilities Eastern PS wellfield in Broward County. Newly installed monitor well BS-3 (Map ID 43) had a 2024 chloride concentration of 19 mg/L.

Figure 2B-62 shows the location of the interface near the City of Fort Lauderdale Dixie PS wellfield since 2019. The data are interpreted to indicate that the interface exists beneath the wellfield, but the exact location is not known, so the dashed line is used to represent that uncertainty. The Dixie PS wellfield production wells are Biscayne aquifer wells screened from 90 to 120 ft bls. The City of Fort Lauderdale has installed 10 saltwater intrusion monitor wells in the general vicinity of the Dixie PS wellfield (**Figure 2B-62**). All 10 of these monitor wells have long well screens that start at a depth of 5 ft bls and extend to depths ranging from 200 to 280 ft bls. Rather than collecting groundwater samples from these wells for laboratory analyses, the City of Fort Lauderdale performs vertical, specific conductance profiling, once at the end of the wet season and once at the end of the dry season, at each of its 10 saltwater intrusion monitor wells. For this report, the largest specific conductance values recorded in each well (often at or near the bottom of the well) were converted to chloride concentrations using the methodology outlined in Zumbro and Coonts (2025).

Northeast of the Dixie PS wellfield, the 2024 interface has moved inland (**Figure 2B-62**), primarily due to chloride concentrations increasing at G-2899 (Map ID 58). At this well, chloride concentrations increased from 1,020 mg/L in 2019 to 1,622 mg/L in 2024. The 250 mg/L interface passed through G-2899 sometime between January 2005 and April 2005, when the chloride concentration reached 270 mg/L, and continued to increase, reaching a concentration of 1,622 mg/L in 2024.

South of the Dixie PS wellfield, in the area south of Interstate 595 (**Figure 2B-62**), the 2024 saltwater interface was adjusted inland compared to the 2019 interpretation because the two Ferncrest Water Treatment Plant wells (MW5 ID 136755 [Map ID 72] and MW6 ID 136756 [Map ID 73]) at the Tindall Hammock PS wellfield are shallow wells that are not completed at or near the base of the aquifer. Therefore, these wells are not detecting the saltwater interface that likely lies underneath them based on the other wells in the area. Well MW5 ID 136755 is open from 10 to 20 ft bls, and MW6 ID 136756 is open from 72 to 82 ft bls. Town of Davie well MW-4 (Veterans Park DW-4) ID 137073 (Map ID 74) farther to the south (**Figure 2B-62**) helps bracket the location of the interface, as this well is completed with an open interval from 165 to 175 ft bls and has a 2024 chloride concentration of 270 mg/L.

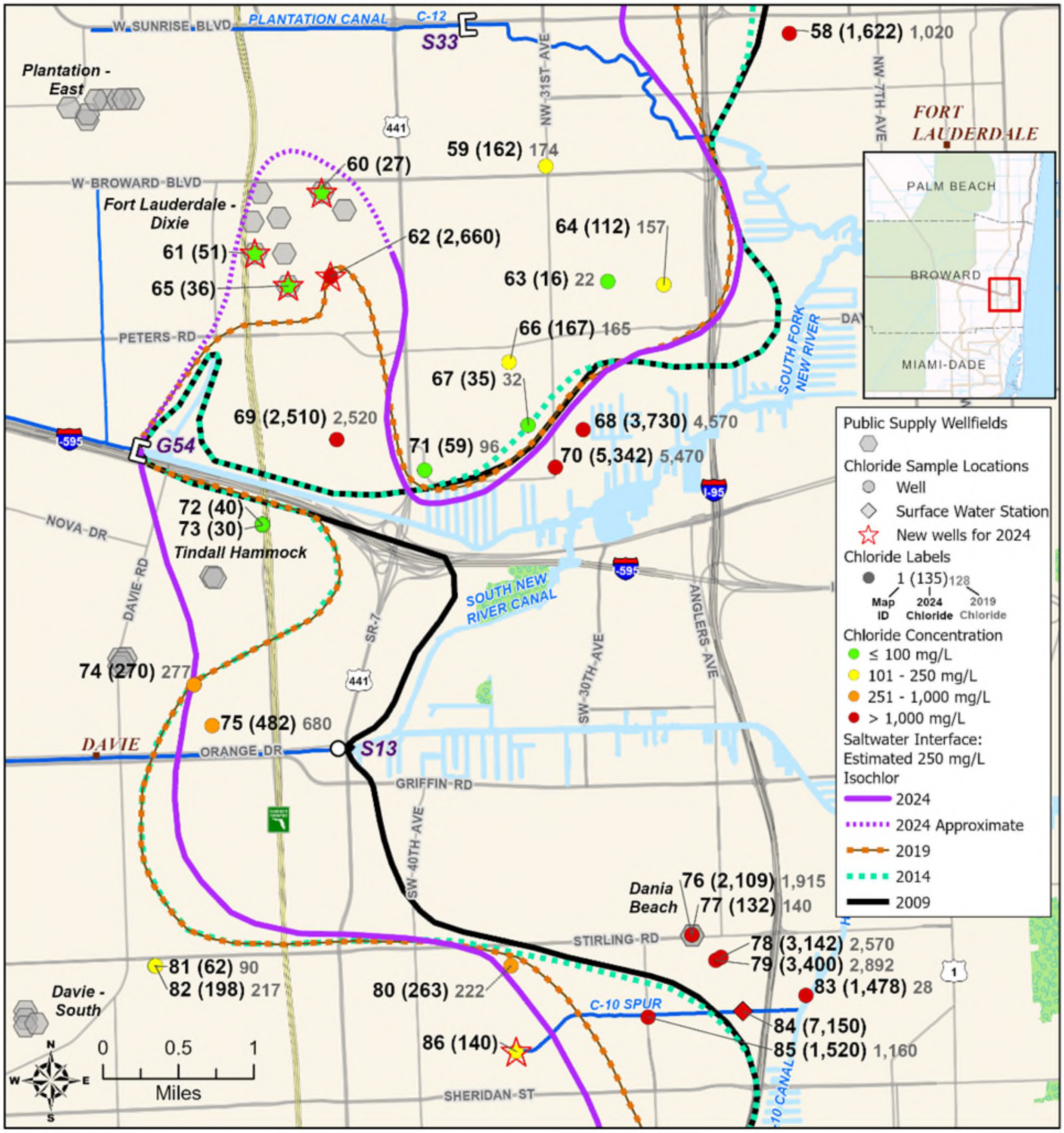

Figure 2B-62. Position of the 2024 saltwater interface in the Biscayne aquifer near the City of Fort Lauderdale Dixie PS wellfield in Broward County.

The 2024 interface has moved inland through the remainder of southern Broward County down to the Miami-Dade County line (**Figure 2B-63**). Large increases in chloride concentrations have been reported east of the 2024 interface. The chloride concentrations reported for the cities of Hollywood–Hallandale Beach and Hollywood–South PS wellfields, located west of the 2024 interface, show that chloride concentrations have decreased slightly in all the wells since 2019 (**Figure 2B-63**).

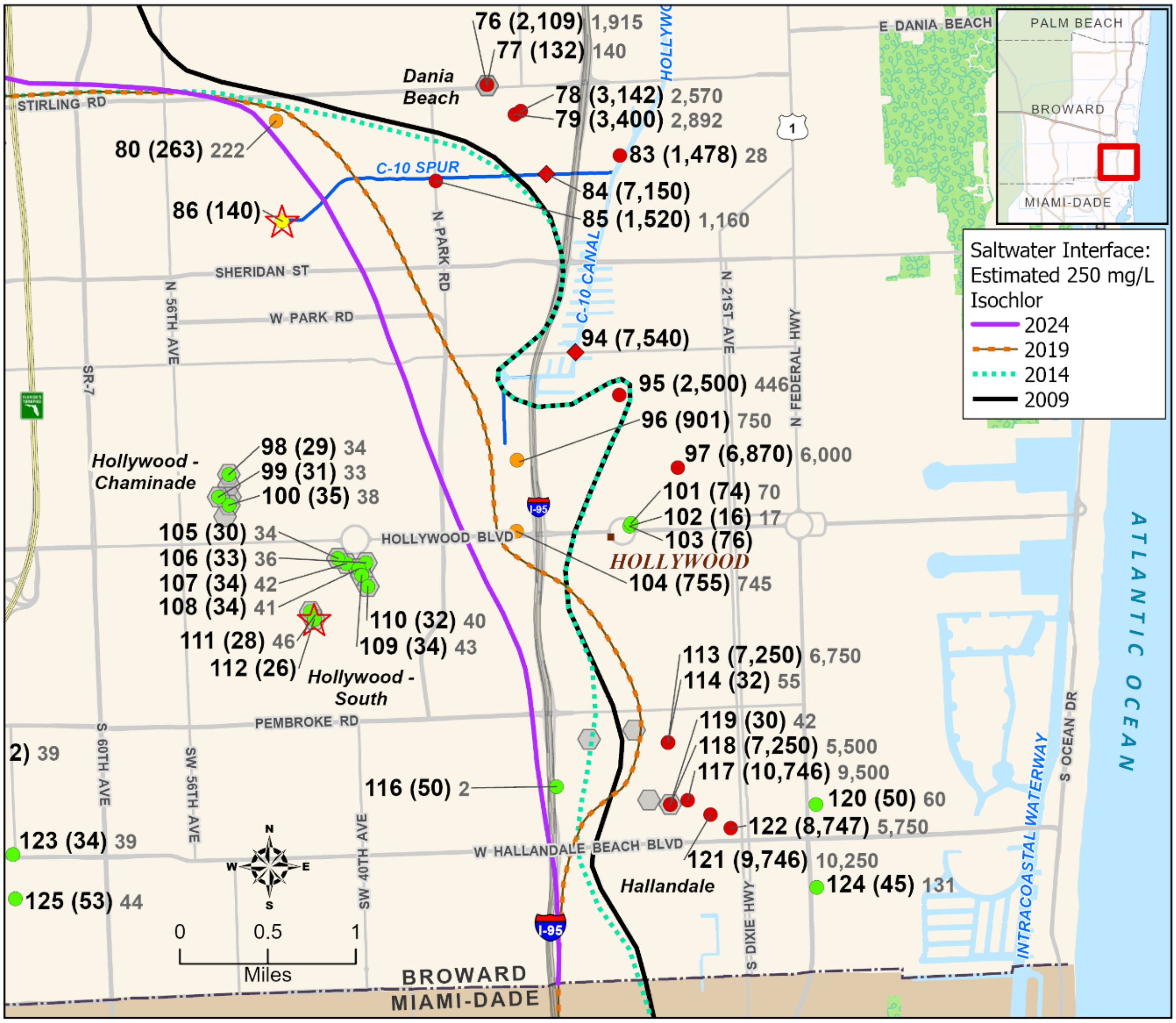

Figure 2B-63. Position of the 2024 saltwater interface in the Biscayne aquifer near the cities of Dania Beach, Hollywood, and Hallandale Beach PS wellfields in Broward County. Map ID 86 is the newly installed saltwater intrusion monitor well BS-2 in the City of Hollywood.

Lee County – Water Table Aquifer

Chloride concentration data from 95 WTA groundwater samples and 14 surface water samples were used to draw the 2024 saltwater interface in Lee County. The 2024 interface has advanced landward in some areas and remained stable in others, compared to 2009, 2014, and 2019. The interface near the City of Cape Coral was previously drawn with boxy-shaped corners. For 2024, the WTA isochlor has been smoothed out and moved closer to the coastline to more accurately reflect the shape and position of the interface (**Figure 2B-64**).

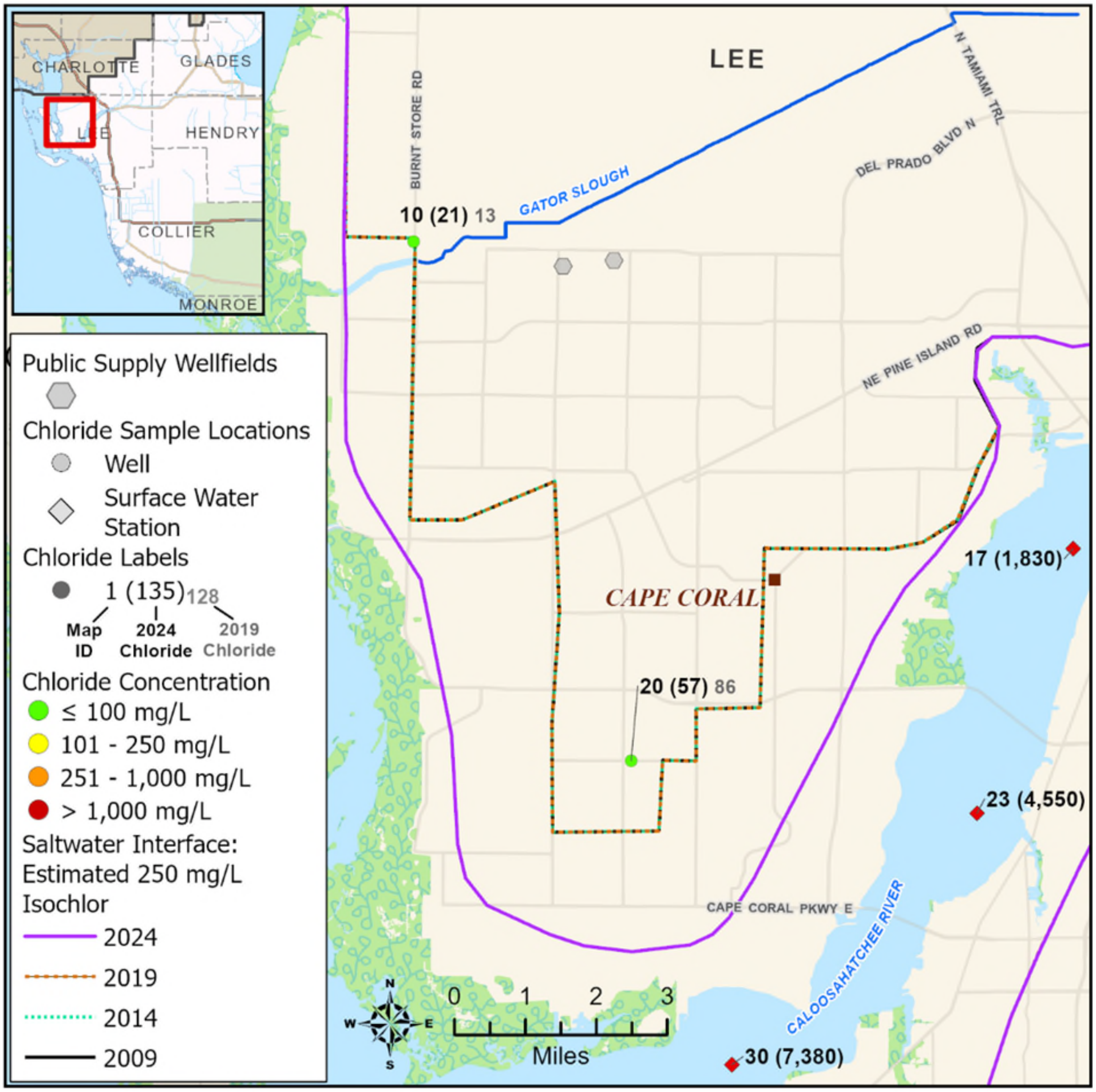

Figure 2B-64. Position of the 2024 saltwater interface in the WTA in the City of Cape Coral in Lee County.

Between an area north of the Estero River and the City of Bonita Springs, the WTA interface has moved inland in three areas since 2019 (**Figure 2B-65**). The wells in the region generally reported increasing chloride concentrations between 2019 and 2024. To the east of this area are the Lee County Corkscrew, Lee County Pinewoods, and the City of Bonita Springs–West PS wellfields, which pump from the WTA and LTA. This pumping may be causing the movement of the interface.

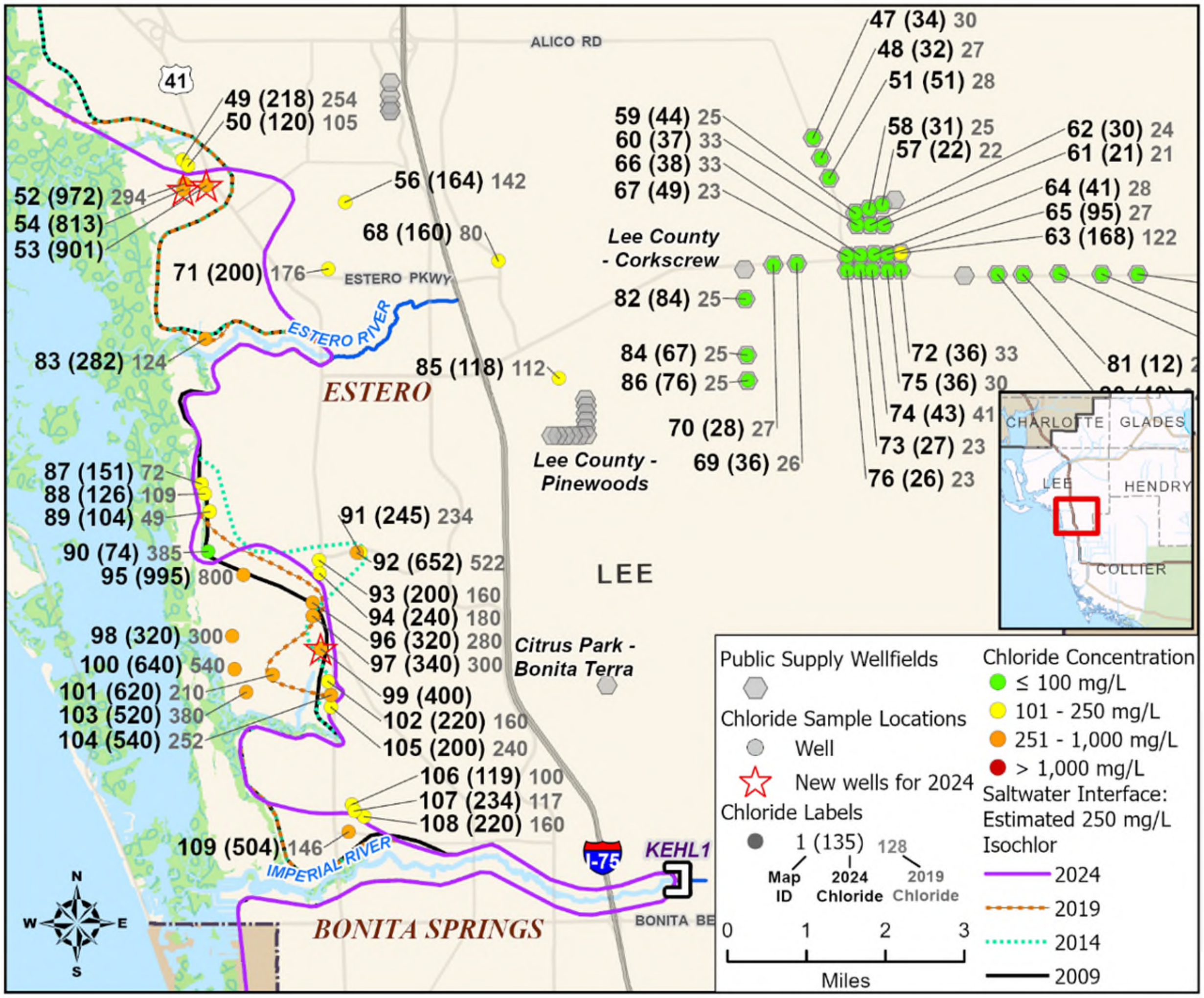

Figure 2B-65. Position of the 2024 saltwater interface in the WTA in coastal Lee County.

Collier County – Water Table Aquifer

Chloride concentration data from 95 WTA groundwater samples and 31 surface water samples were used to draw the 2024 saltwater interface in Collier County. Unlike on the east coast of Florida where salinity control structures are present and often act as a divide to prevent saltwater from freely flowing inland, the LWC planning area typically does not have such structures. Thus, areas adjacent to uncontrolled freshwater creeks, such as Haldemen Creek, Lely Canal, and Henderson Creek Canal, have indicated landward movement of the saltwater interface. **Figure 2B-66** shows the Cocohatchee River and its control structure COCO1. The 2024 interface is farther inland than it was in 2009, 2014, and 2019, likely due to new chloride data from CCN5 (Map ID 12) and CCN11 (Map ID 26).

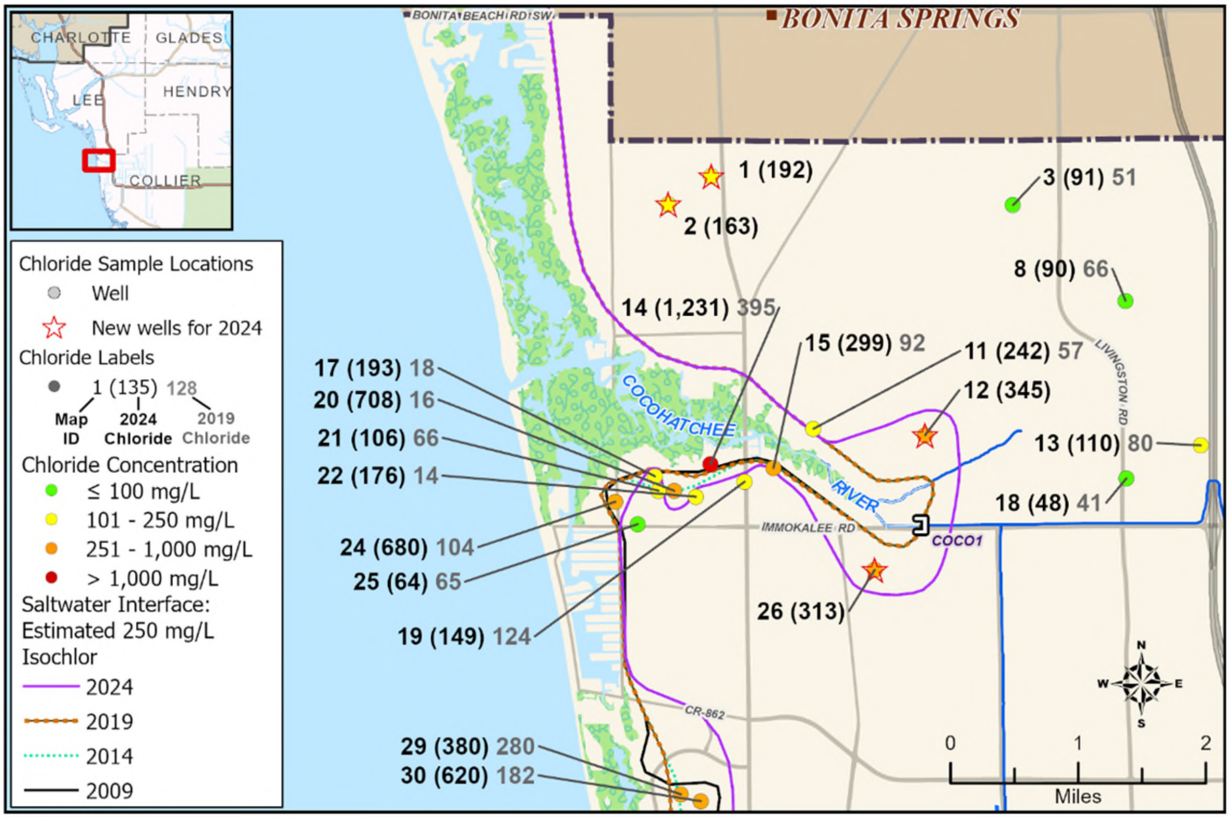

Figure 2B-66. Position of the 2024 saltwater interface in the WTA near the Cocohatchee River in Collier County.

However, in the Lely Canal area in Collier County, additional movement of the saltwater interface was noted (**Figure 2B-67**). The area around the Lely Canal outfall is a coastal natural habitat influenced by tidal changes. Lely Canal lacks a control structure, so saltwater can flow inland through the canal. In 2019, the saltwater interface wrapped inland around Lely Canal, but a new inland data point from C-1276 (Map ID 60 in **Figure 2B-67**) shows that elevated chloride concentrations have been recorded at the Collier County South Hawthorn WTA PS wellfield, much farther inland than was mapped in 2019.

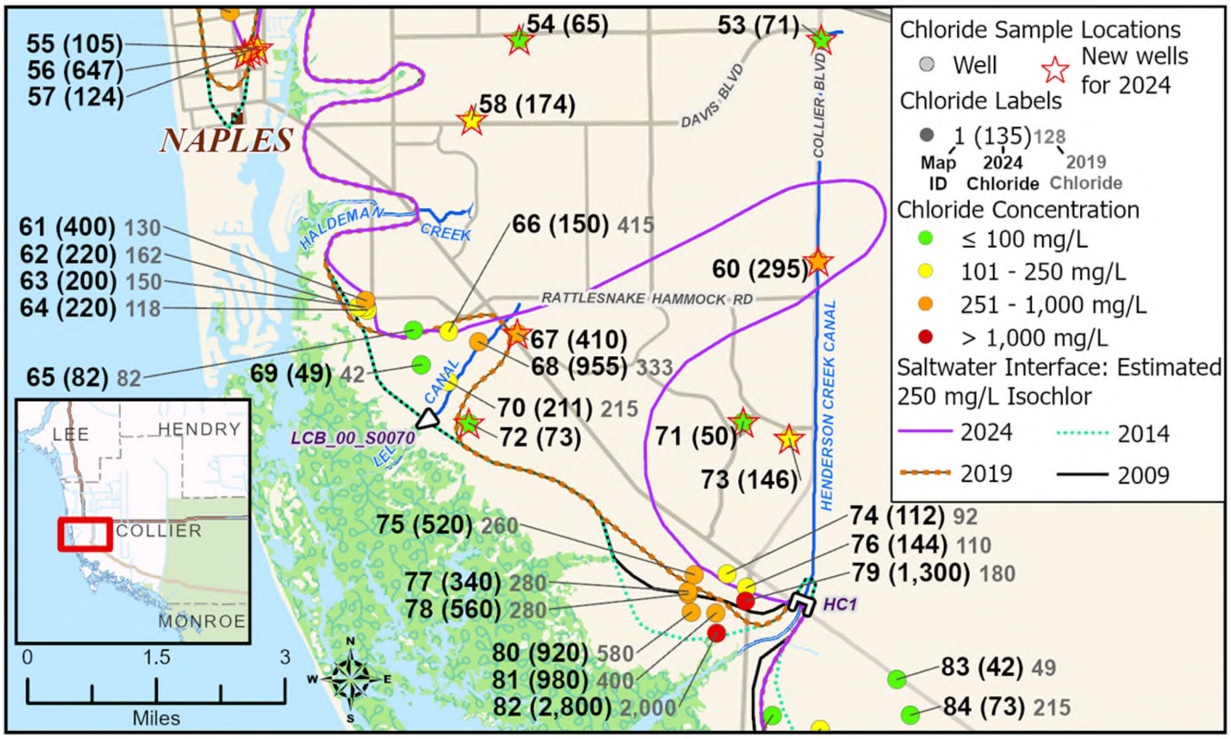

Figure 2B-67. Position of the 2024 saltwater interface in the WTA near Henderson Creek Canal in central Collier County.

The WTA interface in southern Collier County moved both inland and seaward since 2019. Inland movement is seen on the western side of **Figure 2B-68** due to the new surface water data point TMBR37 (Map ID 94). Seaward retreat/movement of the saltwater interface has occurred on the eastern side of **Figure 2B-68** near the Port of the Islands. In this area, MW-1 ID 229836 (Map ID 95) freshened significantly since 2019, with chloride concentrations decreasing from 262 mg/L in 2019 to 93 mg/L in 2024.

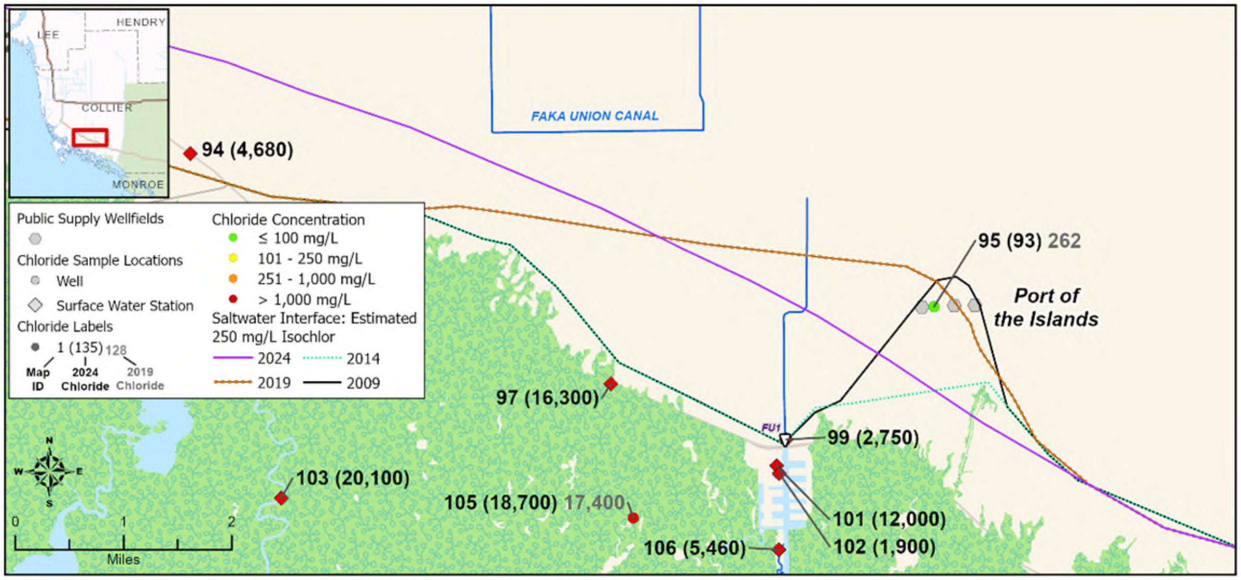

Figure 2B-68. Position of the 2024 saltwater interface in the WTA east of Marco Island and the Ten Thousand Islands in southern Collier County.

Lee and Collier Counties – Lower Tamiami Aquifer

Chloride concentration data from 160 LTA groundwater samples were used to draw the 2024 saltwater interface in Lee and Collier counties. The 2024 LTA interface in Lee and Collier counties exhibited some movement due to changes in chloride concentrations over time compared to previous years. Large changes in the 2024 LTA interface were due to new data points allowing for an updated interpretation to the interface location.

In north Collier County, near the Cocohatchee Canal, the saltwater interface showed some movement seaward and landward (**Figure 2B-69**). Well 1 ID 104175 (Map ID 39), Well 2 ID 10946 (Map ID 40), and Well 3 ID 104186 (Map ID 44) are three new data points that allowed for a better understanding of the inland extent of the saltwater interface, resulting in the interface being farther inland from where it was in 2019. CO-14 ID 144235 (Map ID 32) freshened from a chloride concentration of 317 mg/L in 2019 to 153 mg/L in 2024. Near that well, the saltwater interface retreated toward the coast.

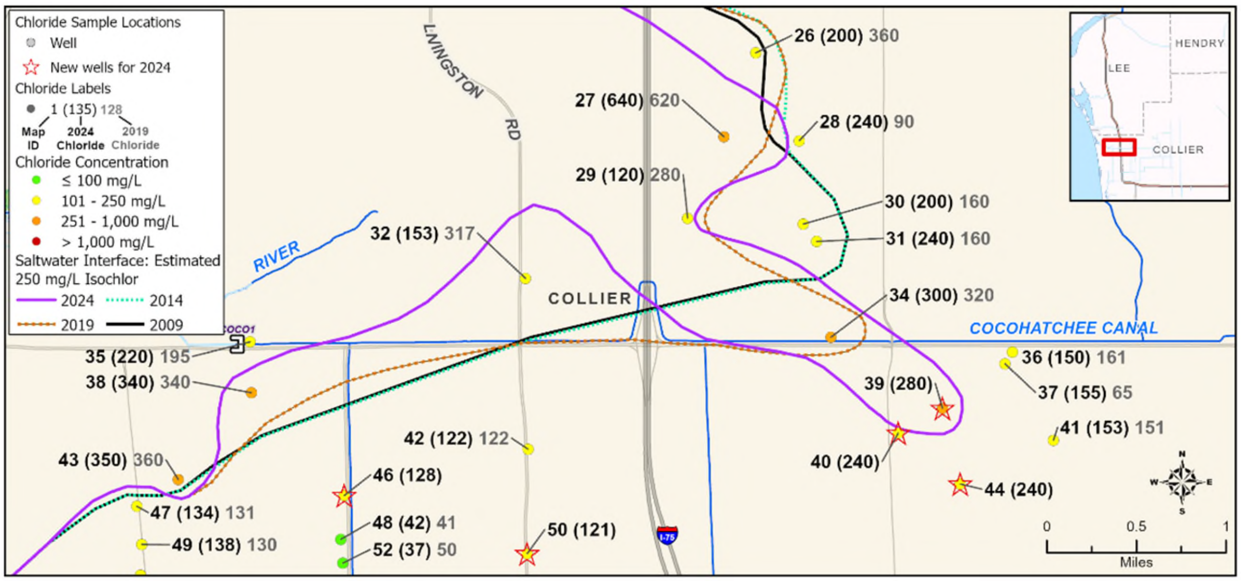

Figure 2B-69. Position of the 2024 saltwater interface in the LTA near the Cocohatchee Canal in Collier County, primarily due to newly obtained data.

Based on new chloride concentration data, the 2024 interface near the City of Naples Coastal Ridge PS wellfield was interpreted to be closer to the coastline compared to 2019 (**Figure 2B-70**). Monitor wells in this area that had 2019 chloride concentration data did not show significant changes in chloride concentrations.

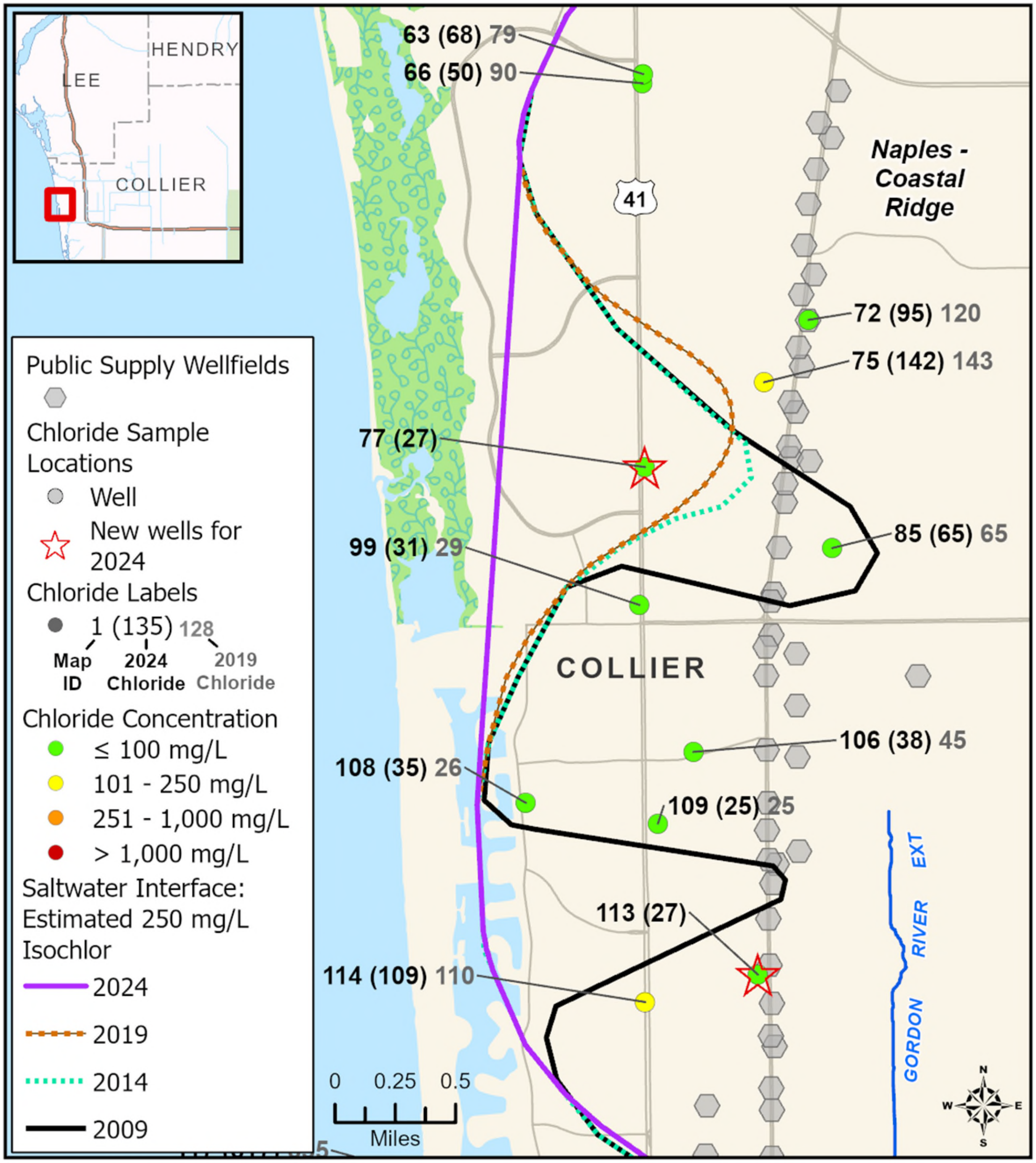

Figure 2B-70. Position of the 2024 saltwater interface in the LTA in the City of Naples area in Collier County, primarily due to newly obtained data.

The 2024 LTA saltwater interface moved inland in the area east of the City of Naples and the Gordon River (**Figure 2B-71**). The interface location was modified because the chloride concentrations at C3 ID 2997 (Map ID 122) increased from 119 mg/L in 2019 to 161 mg/L in 2024.

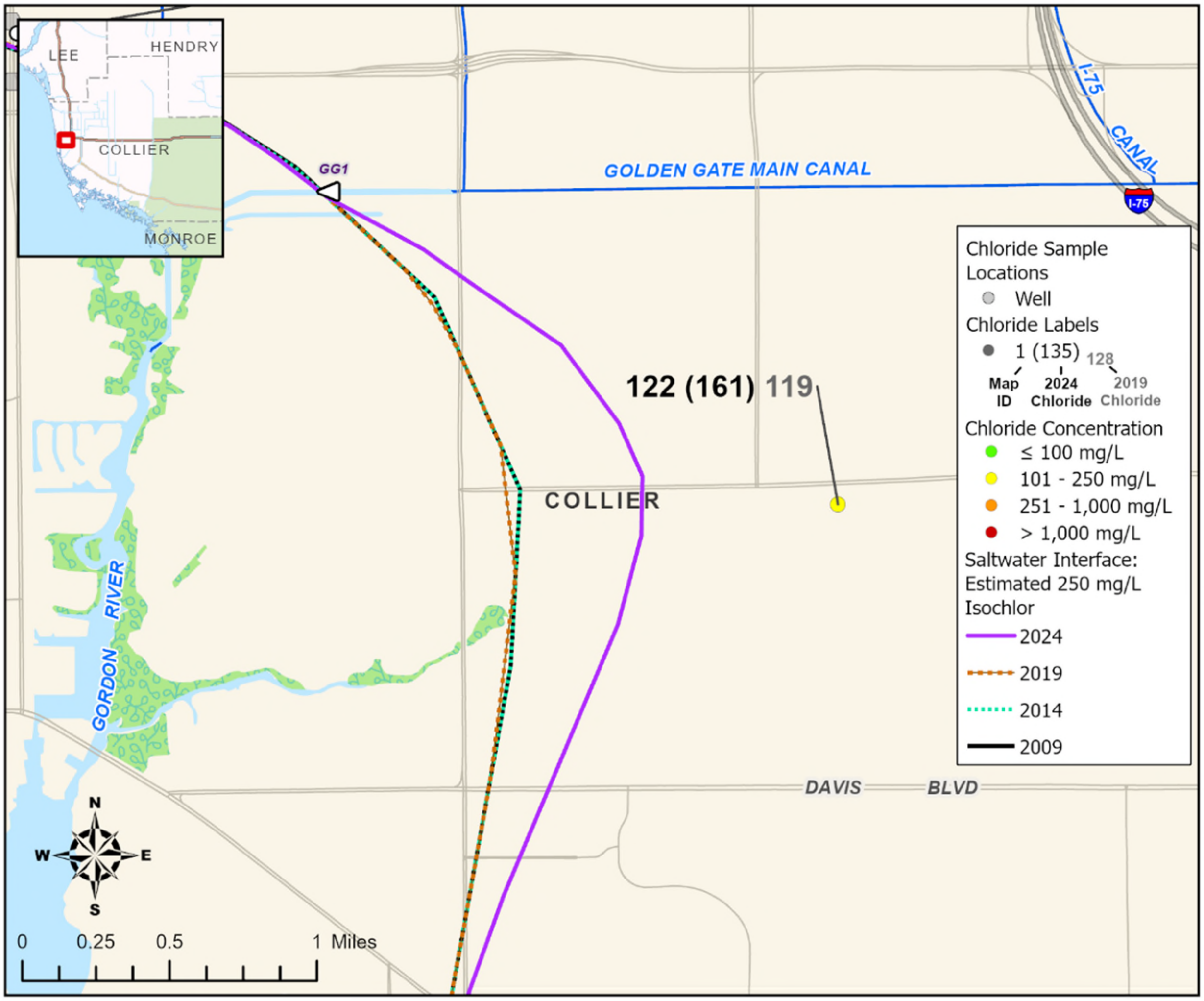

Figure 2B-71. Position of the 2024 saltwater interface in the LTA east of the City of Naples and the Gordon River in Collier County, due to increasing chloride concentrations at C3 ID 2997 Map ID 122.

Within the Lely Resort Community, the LTA interface moved northwest relative to its 2019 position (**Figure 2B-72**). Most of the wells at the Lely Resort Community are relatively shallow (30 to 50 ft bls) compared to the bottom depth of the LTA in this area (approximately 100 ft NAVD88 or approximately 110 ft bls). However, LRCMW-3 (Map ID 148) is 135 ft bls and should provide more representative groundwater chemistry data for the deeper LTA. The March 6, 2024, groundwater sample collected from LRCMW-3 ID 259157 had a chloride concentration of 320 mg/L, so the 2024 saltwater interface was positioned to the north-northwest to encompass this well (**Figure 2B-72**).

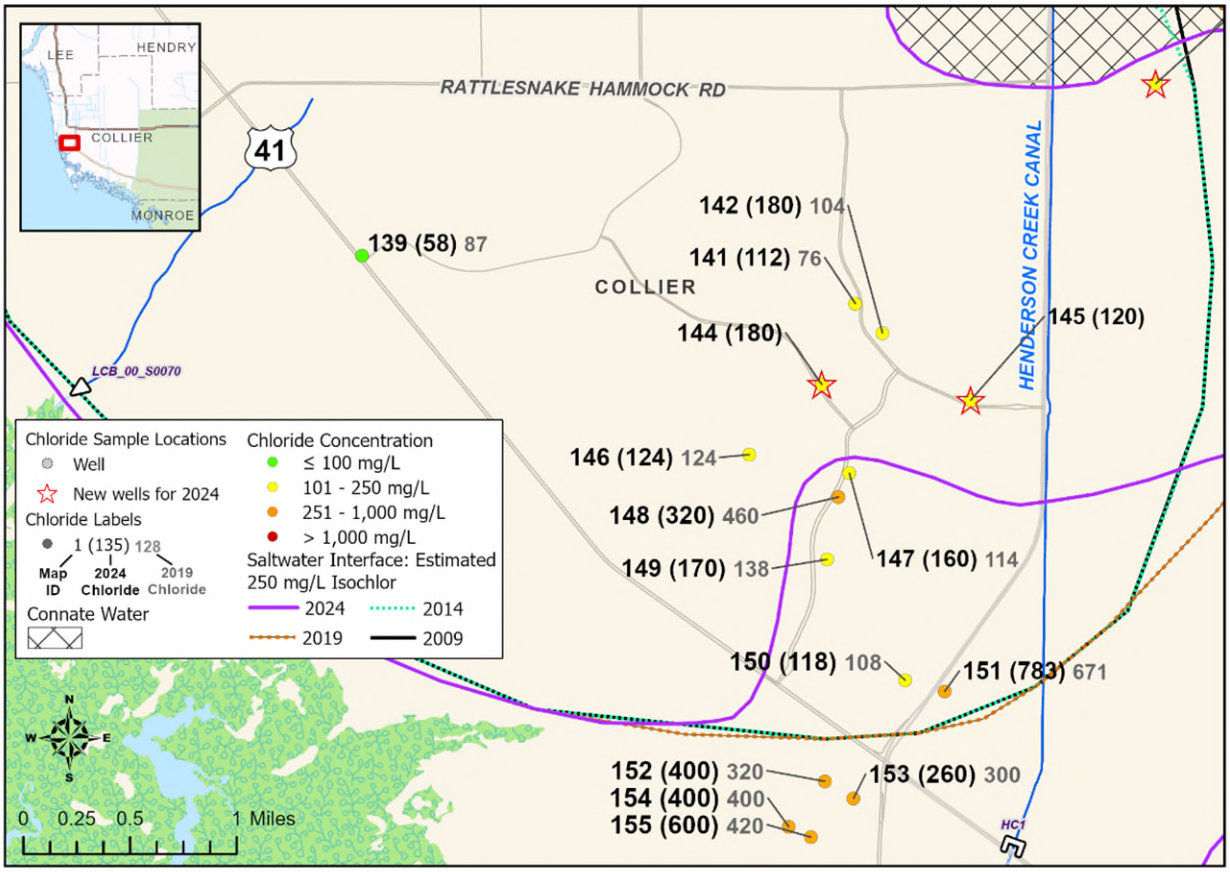

Figure 2B-72. Position of the 2024 saltwater interface in the LTA near the Lely Resort Community in Collier County.

RESULTS AND DISCUSSION

Based on the updated map excerpts presented in the previous section, **Table 2B-7** qualitatively summarizes the current situation with respect to saltwater intrusion in the coastal SAS of South Florida. A more detailed description of the interface status from a qualitative perspective is provided below:

- **No appreciable movement**: The interface did not move between 2019 and 2024 as evidenced by little to no change in chloride concentrations in the monitor wells upon which the interface position was interpreted.
- **Retreated towards the coast:** In areas where the interface retreated, the cause is likely due to factors including reduction of pumpage from coastal wellfields or from domestic wells due to implementation of a wastewater reuse project, with aquifer recharge from the reuse project as well.
- **Minor inland movement:** The interface was interpreted to have moved inland between 2019 and 2024. The amount of movement is considered minor in relation to the magnitude of the chloride concentrations of the monitor wells upon which the interface position was interpreted.
- **Notable inland movement:** This is defined as interface movement that was notable due to it being persistent from 2009 to 2024 (e.g., south Broward) or significant interface movement followed by stability (e.g., Delray Beach), or inland movement specific to the most recent 5-year period from 2019 to 2024.

Table 2B-75. Summary of areas where the saltwater interface changed from the 2019 mapped location.

Area	Interface Status (2019 to 2024)
Deerfield, Pompano Beach, Naples Coastal Ridge LTA, Lee County WTA, Port of the Islands WTA	Retreated towards the coast
Martin and St. Lucie counties SAS	No appreciable movement
South Martin County, Jupiter, Lake Worth Beach, Boynton Beach, Bonita Springs, Northern Collier County WTA, Southern Collier County LTA	Minor inland movement
Lantana, West Palm Beach, Delray Beach, Fort Lauderdale, South Broward	Notable inland movement

Areas classified as having "notable inland movement" are strong candidates for additional monitoring. SFWMD will develop and implement strategies to conduct this additional monitoring as described in the *Comments and Recommendations* subsection.

Challenges and Limitations

There are multiple challenges to mapping the location or movement of the 250 mg/L isochlor:

- The saltwater interface is a three-dimensional surface that must be represented on a two-dimensional plan view map.
- The interface is a dynamic surface, moving due to changes in hydraulic head and chloride concentration differentials within the aquifer as well as rising sea levels. Reclaimed water use, wellfield pumping, domestic water usage, and infiltration from canals and surface water bodies can all affect the movement and location of the saltwater interface.

- A fixed point in time must be selected to represent the isochlor location.
- The saltwater interface is a diffuse saltwater-freshwater mixing zone that must be represented by a single line on plan view maps.
- Different pathways for saltwater intrusion or pathways along the top of confining units may complicate mapping of the isochlor.
- Monitor wells that were appropriately designed and constructed to detect the saltwater interface are not always available in certain areas.
- Wells used in previous years maps are not always available 5 years later (due to being destroyed during urban development or road construction, no longer required to be monitored, or have not been sampled in the last 3 to 5 years), making comparisons between mapping efforts more challenging.
- New wells may be installed between mapping efforts, providing data in areas previously lacking data. Data from those wells can alter the mapped position of the saltwater interface and change the interpretation from previous maps. These changes in the saltwater interface position may not represent actual movement of the interface because no data was available in that area during previous mapping effort.

Proper well construction is an important factor for detection of the saltwater interface. Monitor wells consist of both blank casing (solid casing with no slots in the casing) installed above either a well screen consisting of machined slots or, in some instances, an uncased open section of the borehole to allow water to enter the well. Whether or not a groundwater sample collected from a monitor well "detects" the saltwater interface can be directly related to the total well depth and the length and location of the open or screened interval of the well. If a shallow well is installed in the aquifer, groundwater samples collected from that well may not indicate the presence of salt water, while a well screened just above the base of the aquifer in the same location could provide groundwater samples containing elevated chloride concentrations, indicating that the saltwater interface has passed beneath both wells. In an ideal saltwater monitoring program, all saltwater intrusion wells would be installed with short (5- to 10-ft long) well screens at the base of the aquifer, eliminating groundwater mixing between aquifer flow zones of differing salinities. Since a districtwide saltwater intrusion monitoring well network consisting of hundreds of perfectly designed saltwater intrusion monitoring wells does not exist, SFWMD relies, where possible, upon the best available groundwater quality sample data from the most reliable wells.

The Florida Department of Environmental Protection has standard methods for sampling monitor wells; however, the methods for saltwater intrusion monitoring may not be consistently implemented. This is unavoidable due to the challenges mentioned earlier. Well construction and sampling methods affect the quality of groundwater samples. Additionally, not all samples are analyzed for chloride concentrations. Instead, some surface and groundwater samples are analyzed for specific conductance, total dissolved solids, or salinity. These data were converted to chloride concentrations so that they could be used for mapping purposes. The details of the specific conductance to chloride conversion methodology are discussed in Section 3.3 of Zumbro and Coonts (2025).

Finally, there is the issue of the timing of groundwater sample collection. Ideally, all wells to be used for saltwater interface mapping would be sampled every 5 years during the dry season when freshwater heads in the aquifer are lowest (March 1–May 31). However, not all wells were sampled during this preferred time frame. In some cases, particularly in an area lacking data or near PS wellfields, a chloride concentration reported from outside this time frame, but as close to the time frame as possible, was used. This often occurs due to regulatory requirements that specify when certain facilities must collect and submit sampling data to SFWMD or other agencies. On the 2024 saltwater interface maps, chloride concentration data from outside the dry season time frame are denoted using an asterisk in the well data tables at the bottom of each map.

COMMENTS AND RECOMMENDATIONS

Increased chloride sample collection from coastal monitoring wells, electromagnetic induction logging of select wells, and regional saltwater interface mapping efforts are being conducted to respond to the increasing threat of saltwater intrusion. In addition, density-dependent groundwater models are being developed to more explicitly simulate saltwater intrusion and the effects of sea level rise and climate change. These technological advances will enable SFWMD to better protect the resource by proactively identifying areas of concern, providing time to manage wellfield operations and identify alternative water supply sources to meet future water demands. As a result, future operational strategies may be developed.

With increased impacts due to SLR, local governments, utilities, and private entities will need to develop adaptive strategies to combat further saltwater intrusion (as well as regional flood protection). Potential strategies include the construction of defensive barriers and pumping systems, improvement of infrastructure, and changes to land use. With the inland movement of the saltwater interface, local investigations of the interface position could be warranted in some areas, depending on the network of monitor wells available, land available for installing new monitor wells, the proximity of saltwater sources to wellfield locations, and withdrawal rates.

Consumptive water use permitting requires and water supply plans concur that utilities must design wellfield locations, configurations, and pumping regimes to avoid saltwater intrusion. Implementation of groundwater recharge systems could help prevent inland movement of the saltwater interface. The SFWMD, USGS, and local governments should continue to coordinate saltwater intrusion monitoring efforts to delineate the location and movement of the saltwater interface and identify areas of concern. Meanwhile, SFWMD should periodically review existing groundwater monitoring networks and enhance them as appropriate (SFWMD 2024).

RELEVANCE TO RESILIENCY IN WATER MANAGEMENT

The saltwater interface monitoring and mapping program is an important component of water supply planning and resiliency, particularly in coastal areas. SFWMD water supply planning areas applicable to this mapping effort are named the Upper East Coast, Lower East Coast, and Lower West Coast. Existing coastal salinity control structures, along with operational strategies, have helped stabilize the saltwater interface in some areas, but there is evidence of inland migration in areas, particularly coastal Broward and Miami-Dade counties. A few coastal PS wellfields located seaward of salinity control structures are no longer operating due to saltwater intrusion (SFWMD 2024).

SLR can increase landward movement of the saltwater interface. As sea level continues to rise, some coastal wellfields may have to relocate farther inland, decrease pumpage, change water treatment processes, or be replaced with alternative water sources (SFWMD 2024). The continued collection of groundwater elevation and groundwater chloride concentration data is critical to understanding the location and extent of saltwater intrusion, particular in areas near PS wellfields.

Freshwater heads in coastal areas must be maintained at high enough elevations to prevent saltwater encroachment into the fresh groundwater system. To help protect wellfields and prevent inland movement of saltwater through coastal canals, salinity control structures have been constructed near the coast in main canals, as part of the C&SF Project, in the 1950s. These control structures allow SFWMD to raise and maintain the upstream canal stage and the groundwater elevation in the surrounding water table (particularly during the dry season), to raise the inland freshwater head to prevent saltwater intrusion.

Over time, some coastal wellfields have been replaced by wellfields farther inland as the saltwater interface has moved landward and impacted wellfield operations and water quality. Significant ongoing population increases in South Florida and the associated increase in water use present challenges for water supply and require careful monitoring of the location of the saltwater interface. Ongoing SLR also requires continued saltwater interface monitoring and mapping so that adaptation strategies can be developed and implemented to protect the freshwater aquifers and the water supply of South Florida.

Saltwater Intrusion Monitoring and Mapping

Saltwater intrusion monitoring and mapping helps with management of the following:

- **Groundwater recharge:** Identifies areas where intrusion is occurring, recognizing the need for increased groundwater recharge in those areas. Groundwater recharge helps raise groundwater elevations, which acts as a buffer during dry spells, helping communities and ecosystems withstand prolonged droughts.
- **Water quality:** The saltwater intrusion monitoring and mapping program helps protect water quality by providing permittees and regulatory staff with the data needed to guide decisions that will prevent further degradation of the coastal freshwater aquifers relied upon for water supply. Water resources (such as wetlands and the aquifers themselves) can act as natural purifiers, enhancing water quality for both human consumption and agricultural use.
- **Drought management:** The saltwater intrusion monitoring and mapping program identifies areas of concern and can point to the need for increased monitoring and water resource management during droughts in areas where saltwater intrusion has already occurred.
- **Adaptation to changing conditions:** As water bodies face stressors, like changing rainfall patterns, SLR, and anthropogenic impacts, the saltwater intrusion monitoring and mapping program provides a framework for adaptive management. It allows for adjustments in response to changing conditions, ensuring that aquifers and the water bodies that recharge them can maintain their functionality.
- **Climate resilience:** As climate changes, the frequency and severity of extreme weather events, such as droughts and floods, may increase. The saltwater intrusion monitoring and mapping program acts as a safeguard by identifying areas of concern, resulting in the need for increased monitoring, modified wellfield operations, and canal recharge operations. During droughts, these operations ensure there is enough water to sustain the aquifer, reducing the impact of prolonged dry spells.

CONCLUSIONS

The future of successful water resource management in South Florida will be influenced by the understanding of how hydrologic and climate-related long-term trends and other associated changing conditions are impacting SFWMD's mission and the region's ability to provide flood protection, water supply, and ecosystem restoration. The continuous assessment and availability of water and climate resilience metrics established as part of this effort will be essential in achieving this understanding.

The inaugural Water and Climate Resilience Metrics chapter in the 2022 SFER – Volume I (Cortez et al. 2022) presented trend analyses for rainfall and ET in South Florida, tidal elevations at selected coastal structures, and four key water quality metrics in Lake Okeechobee. The 2023 SFER – Volume I, Chapter 2B (Cortez et al. 2023) expanded on this by detailing spatial trends in saltwater intrusion and trends in three ecological metrics: estuarine salinity, soil accretion/subsidence, and estuarine inland migration. The 2024 SFER – Volume I, Chapter 2B (Cortez et al. 2024) reported on trend analyses of tidal elevations at coastal structures, flood occurrences in South Florida, and the Minimum Flows and Minimum Water Levels

(MFLs) in the Biscayne Aquifer. The 2025 SFER – Volume I, Chapter 2B (Cortez and Zhu 2025), focused on spatial trends in ETo in South Florida and salinity patterns in Florida Bay.

This chapter presents the data and analyses, potential influencing factors, and future monitoring considerations for four metrics: rainfall, drought, HTEs, and saltwater intrusion. The goal is to identify trends across relevant water and climate metrics, enhance prior analyses, and develop a clearer understanding of the contributing factors, particularly in distinguishing climate-related impacts from non-climatic influences. Further evaluation and correlation of these metrics is necessary to determine whether observed changes are attributable to identifiable climatic factors or other drivers.

Overall findings for each metric included in this chapter are presented below:

- The updated rainfall trend analysis (1935–2024) revealed several notable shifts compared to the previous analysis ending in 2018. While most monthly trends remained statistically insignificant, emerging or expanded trends were identified in specific basins. October continued to show widespread declines across southeastern rainfall areas. Wet season trends remained upward in the East Caloosahatchee and Southwest Coast, while the previously observed decline in the East Everglades Agricultural Area was no longer significant. Annual trends revealed continued divergence, with new drying in the East Everglades Agricultural Area and new wetting in the East Caloosahatchee. Frequency analyses of extreme rainfall events indicated increasing intensity and occurrence of short- to medium-duration maxima, with upward trends for 1-day, 3-day, and 5-day events observed in multiple basins.

- The newly introduced cluster analysis revealed both persistent and emerging spatial patterns in extreme rainfall across South Florida. Lower rainfall thresholds (e.g., 4.00 inches) produced widespread clusters, while higher thresholds (e.g., 6.00 inches) identified more localized zones associated with the most intense events. Several areas—the Southwest Coast, Southeast Coast, Northeast Coast, and Kissimmee—exhibited persistent clusters across multiple thresholds and both PORs, indicating long-standing rainfall hotspots. In the extended 1935–2024 period, new clusters emerged particularly in inland and mid-basin regions, reflecting shifts in rainfall behavior in recent years. Trend patterns within clusters were mixed: the Northeast Coast, for instance, showed new upward trends at lower thresholds, while other persistent clusters showed limited trend changes.

- The analysis did not find statistically significant long-term trends in meteorological drought across South Florida based on the 6- and 12-month (P – ETo) anomaly from 1948–2022. However, the timing and severity of significant drought anomalies generally aligned with historical U.S. Drought Monitor data and SFWMD-issued water shortage declarations, particularly in the Lower East Coast, Lake Okeechobee, Southwest Coast, Martin–St. Lucie, and Kissimmee rainfall areas. This alignment confirms the method's operational relevance for retrospective drought assessment and water resource planning.

- The HTEs at coastal structures analysis demonstrated increasing tidal impacts in South Florida, particularly at structures in the southeast coast. Structures at higher-elevation areas like St. Lucie and Palm Beach experienced minimal occurrences, while structures at Broward and Collier counties showed statistically significant increasing relationships. Structures at Miami-Dade County demonstrated the highest vulnerability, with several structures frequently experiencing HTEs conditions. Rising sea levels were the primary driver of these trends, amplified by hurricanes, lunar cycles, climatological pressure, and wind. Local structure parameters, including the difference between design HW and TW elevations, further explained variability at site level.

- The 2024 saltwater interface mapping effort revealed mixed patterns of interface movement along the South Florida coast. Certain areas—including Deerfield, Pompano Beach, and parts of Naples and Lee County—showed retreat of the interface toward the coast, likely due to reductions in groundwater withdrawals or increased aquifer recharge. Other areas, including Martin and St. Lucie counties, exhibited no appreciable change. Minor inland movement was observed in locations such as Hobe Sound and Bonita Springs, while notable inland movement was identified in areas like Delray Beach, West Palm Beach, Fort Lauderdale, and South Broward. Areas exhibiting persistent or significant inland migration in recent years were prioritized for additional monitoring.

In future SFERs, the Water and Climate Resilience Metrics chapter will present developments on these and other water and climate resilience metrics, quantification of influencing factors, and correlation with other selected metrics. Future chapters will also explore expanded resiliency monitoring requirements. These efforts provide a means to evaluate the significance of water and climate observations, and how they compare to historical trends as climate conditions evolve.

Additionally, the links between major findings in Chapter 2A: South Florida Hydrology and Water Management of this volume and this chapter will continue to support the understanding of how the observations summarized in Chapter 2A are part of long-term trends or represent evolving conditions documented in Chapter 2B, and how these long-term trends or shifts may be associated with climate change and other evolving conditions.

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