Chapter 2B: Water and Climate Resilience Metrics[1]

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Florida Bay. Photo credit: Mark Cook, SFWMD

Highlights

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

- Evapotranspiration (ET)
- Salinity in Florida Bay

EVAPOTRANSPIRATION

Previously reported in the *2022 South Florida Environmental Report – Volume I*, evapotranspiration (ET) indicates a statistically significant upward trend in South Florida over the past three decades. The assessment presented in this year's report updates the correlation analysis with newly found data of air temperature. The rising solar radiation and air temperature contribute to the ET trend most, followed by the decreasing relative humidity. Multi-variable correlation analysis is added to this year's report for the first time. Both the two-variable model (solar radiation and air temperature) and four-variable model (solar radiation, air temperature, relative humidity, and wind speed) yield higher correlation coefficients than the single-variable models. In relation to rainfall, the upward ET

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trend is well correlated to the downward rainfall trend. The findings underscore the need for continued monitoring to understand and manage ET's impact on water resources.

SALINITY IN FLORIDA BAY

The analysis presented in this chapter section identifies the long-term trends in available historical salinity data for Florida Bay. The 2023 analysis found that salinity in western Florida Bay (Alligator Creek and McCormick Creek) is more influenced by tidal inputs, while salinity in eastern Florida Bay (Joe Bay and Trout Creek) is mainly affected by wind, freshwater flows, and ET; however, no significant trends were observed in the annual water year data. In the 2024 analysis, statistically significant seasonal upward trends in daily salinity data at all monitoring sites in Florida Bay were identified, while no significant trends were identified in wet and dry season averages or transitional month averages. This suggests, while salinity exhibits seasonal patterns, the influence of multiple factors year-to-year complicates the ability to isolate specific trends. Ultimately, while more comprehensive analyses are in development, ongoing monitoring plays a critical role in understanding and managing the dynamic salinity conditions in Florida Bay. By providing current and relevant data, it supports informed decision-making and adaptive management in response to evolving conditions.

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, and climate change. SFMWD's resiliency efforts focus on assessing how sea level rise and extreme events, including flood and drought events, happen under current and future 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.

SFWMD is making significant infrastructure adaptation investments needed to successfully implement its mission of safeguarding and restoring South Florida's water resources and ecosystems, protecting communities from flooding, and ensuring an adequate water supply for all of South Florida's needs. Working to ensure the region's water resources and ecosystems resiliency, now and in the future, is part of everything SFWMD does.

As part of its resilience 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 the enhanced understanding of the current and predicted impacts of climate change 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:

- Evapotranspiration (ET)
- Salinity in Florida Bay

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 also addresses next steps in ongoing data analysis efforts.

BACKGROUND

As part of its resilience 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 it monitors. This collaborative effort is led by the SFWMD Water and Climate Resilience Metrics Workgroup, comprising technical staff 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. While uncertainties persist regarding climate change, evaluating changes in water and climate variables like rainfall, temperature, evapotranspiration, and sea level as well as their consequences on sea level rise, saltwater intrusion, groundwater elevation, and ecosystem dynamics is crucial. 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 approach supports SFWMD's mission and resiliency goals, ensuring ecosystem restoration, flood protection, and water supply mission while considering current and future climate conditions.

INTRODUCTION

As part of its resilience 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. **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 includes 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 Final Report* (SFWMD 2021).

This chapter, introduced in Volume I of the *2022 South Florida Environmental Report* (SFER), aims to continuously advance water and climate data analysis and deepen the understanding of the influence of changing conditions on observations and findings. It includes additional technical analysis and scientific considerations for two water and climate resilience metrics: evapotranspiration (ET) and salinity.

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.

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 to provide a comprehensive understanding of the underlying drivers shaping resilience trends. This approach supports the development of well-informed and effective strategies to enhance resilience in South Florida's regional water management system.

The following two sections provide background information for each metric, outline the findings of these two metrics, and discusses influencing factors, recommended 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.

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 about 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	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	Climate	Tidal stages and high tide events cannot be controlled by SFWMD.	High tide events represent extreme values of the tidal stages used to assess trends in sea level rise and identify potential flooding hazards, risks to water supply, and impacts to structural design standards.	Long-term data trends in tidal stages and high tide events and level-of-service performance inform SFWMD on the limitations and deficiencies of natural and structural assets. This information provides guidance on where SFWMD might allocate resources for adaption strategies and planning.
Groundwater Levels/Elevations/ Stages	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 sea level rise in terms of timing and extent of groundwater stages during the wet season, threats to water supply, the need for additional monitoring, 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 Levels	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 saltwater.	Historical and projected movement of saltwater inland and current water use data and future water use projections identify vulnerabilities to public supply utilities. Saltwater intrusion has a large impact in 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 accounts 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 to the impacts of sea level rise 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 sea level rise. Information on estuarine inland migration provides guidance to align/plan practices to adapt and mitigate for sea level rise 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 sea level rise.	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 sea level rise 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.

EVAPOTRANSPIRATION

BACKGROUND

Evapotranspiration (ET) involves the combined processes of evaporation from earth surface (e.g. soil and water bodies), as well as transpiration from plants through their leaves. It is a significant component of the hydrological cycle and plays a key role in regulating water availability, energy balance, agriculture, and ecosystem functioning.

Across the contiguous United States, about two-thirds of precipitation returns to the atmosphere through ET, with the highest rates observed in the southeast (Hanson 1991). South Florida is characterized by its subtropical climate and high temperatures, humidity, and precipitation levels. The region is home to diverse ecosystems, including wetlands, forests, and coastal areas, all of which are sensitive to changes in climate and hydrological conditions. The impacts of sea level rise and alterations in precipitation patterns pose significant challenges to the region's water management and ecological resilience.

A side-by-side comparison of the region's average monthly potential ET (ET_p) and rainfall over the past 25 years is presented in **Figure 2B-1**. In terms of rainfall distribution, a year is evenly divided into two seasons: the wet season, spanning from May to October (six months), and the dry season from November to April (six months). Upon closer examination of monthly differences between ET and rainfall, the wet season spans from June to October (five months), while the dry season extends from November to May (seven months). Notably, during drought periods, the significance of ET is magnified as it accelerates the depletion of the remaining, often limited, water supplies in water bodies and the soil (Hanson 1991).

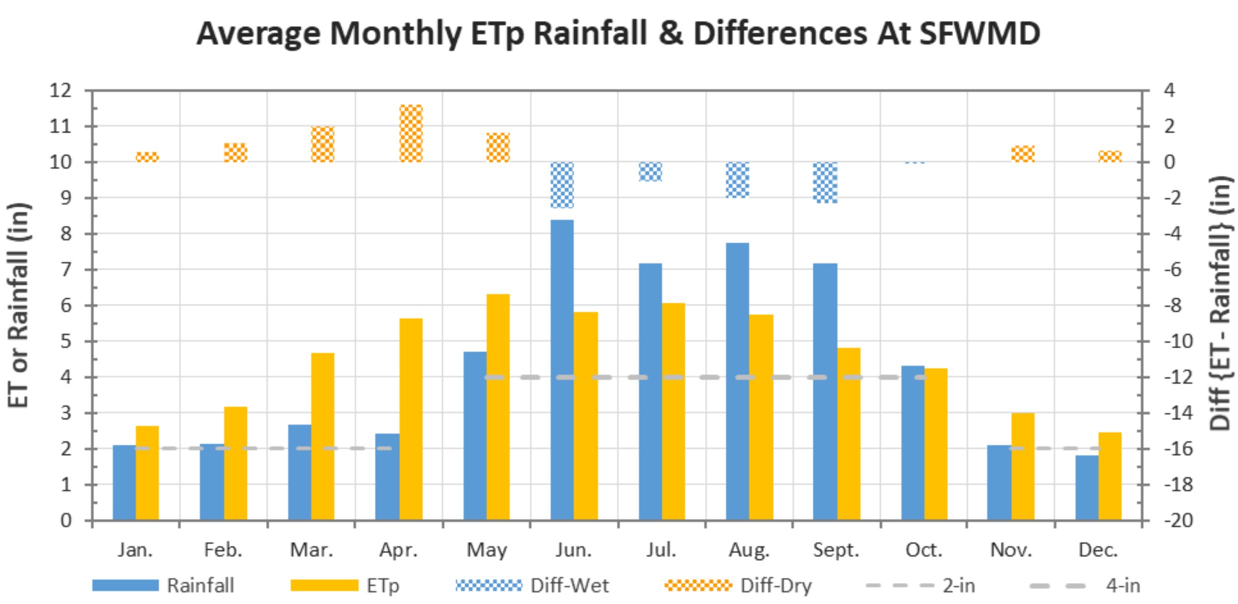


Figure 2B-1. Average monthly potential ET and rainfall across SFWMD, and their differences. (Data source: Next Generation Radar or NEXRAD.)

Considering these factors, understanding long-term trends in ET provides valuable insights into shifts in regional climate patterns, water availability, and overall regional dynamics over time. The analysis of ET trends informs water resource management strategies, aligns with SFWMD's mission, and guides agricultural practices and environmental conservation efforts. Historical ET data for South Florida are typically obtained from evaporation pans, meteorological stations, and satellite remote sensing.

The inaugural water and climate resilience chapter in the 2022 SFER explored various aspects of ET in South Florida, including its upward trend correlated to four meteorological variables individually. The key updates being reported this year include the incorporation of air temperature data from the National Oceanic and Atmospheric Administration (NOAA) and its correlation to ET_p. In addition, multi-variable correlation analysis is added to this year's report for the first time. Rainfall observations were also analyzed in relation to ET variation and trends.

DRIVERS AND INFLUENCING FACTORS

ET is a physical process that demands energy to drive. The major meteorological variables behind ET rate include solar radiation, air temperature, wind speed and relative humidity, which are described below.

- **Solar Radiation**: Solar radiation is a primary driver of ET, providing the energy necessary to initiate the process of evaporation and transpiration.
- **Air Temperature**: Higher air temperatures generally lead to increased ET rates as warmer temperatures accelerate the vaporization of water from surfaces and enhance transpiration rates from plant leaves.
- **Wind Speed**: Wind speed affects the rate of evaporation by removing water vapor from surfaces, thereby enhancing the drying effect, and increasing ET rates.
- **Relative Humidity (Vapor Pressure Deficit)**: Relative humidity, or vapor pressure deficit, represents the difference between the amount of moisture in the air and the maximum amount of moisture the air can hold at a given temperature. Lower relative humidity values result in higher ET rates due to increased moisture gradient, facilitating faster evaporation and transpiration.

Solar radiation is called the radiative energy budget, while air temperature, wind speed, and relative humidity are sometimes collectively called the advective budget. Usually, multiple factors or drivers determine an ET rate simultaneously, with different weights. For example, solar radiation contributes most during a sunny day, while it has zero impact overnight. The other three major factors can engage in the ET process whenever their magnitude is beyond the threshold (e.g., wind speed > 0). Some environmental features may have indirect influence on ET rates, for example, land use/cover, groundwater level, soil moisture content, vegetation type/density, and so on.

MEASURING ET AND ET DATA CONSIDERATIONS

Unlike the directly measurable components of a hydrological cycle, namely precipitation and streamflow, ET rate is hard to directly measure, particularly the transpiration part, because of the difficulty in isolating the observation object (i.e., moisture or water vapor). Evaporation can be measured directly to some extent with the help of a pan that holds water for evaporation to occur, and the water level change reflects the evaporation rate. A lysimeter provides the most practical way for direct measurement of ET_p, but it is expensive to operate and maintain. Empirical equations and models have been developed to estimate ET rate, with input of the four driving parameters (solar radiation, wind speed, relative humidity, and air temperature).

ET_p, an upper limit to ET, means the maximum rate that only occurs when water availability in the soil is non-limiting. Actual ET (ET_a) is the ET that actually takes place, and it is strongly influenced by the level of soil moisture or precipitation and the type of vegetation coverage. ET_a rates are often estimated by multiplying ET_p with a proportion of water depth to the saturated soil zone and crop coefficients. However, regional averages of ET_a can be derived through a water budget by subtracting the surface water outflow, groundwater outflow, and consumptive use from the precipitation.

Where wetlands are extensive (e.g., in South Florida), ET_p is dominated by the radiative energy budget, and the evaporative conditions are known as energy limited (Abtew 1996). Where the available water is not sufficient to meet the evaporative demand (e.g., in Arizona), ET_a will be less than the upper limit (i.e. ET_p), and the conditions are said to be water limited. In water-limited environments, over annual or longer periods, the trend in ET_a is usually very close to the trend in precipitation. By definition, ET_p and pan evaporation (E_{pan}) are two measurements fit to energy-limited conditions. E_{pan} measurements are widely used to estimate evaporative demand because the equipment is readily available, affordable, and simple to operate (Roderick et al. 2009). Daily variations in E_{pan} do not necessarily resemble the ET_p from well-watered vegetation ground. However, over longer periods such as months to years, E_{pan}, when multiplied by the pan coefficient (discussed below), is a good measure of ET_p in the same location or area (McIllroy and Angus 1964, Rose et al. 1972, Stanhill 1976).

The most commonly used evaporation pan in the United States is the "Class A" of the National Weather Service. The cylinder pan is 47.5 inches in diameter and 10 inches in depth. Water level in the pan is required to be maintained at 2 inches below the rim, after each measurement. The pan usually is accompanied by a rain gauge to factor out the contribution of concurrent rainfall to the stage variation for the actual value of evaporation. The pan is made of metal and rests on a wooden platform, which is carefully leveled. The platform surface is about 5.9 inches from the ground. Because the pan has more exposure to the air (at its sides and bottom) than any natural water body, it absorbs more heat from the surroundings. This gives higher evaporation values than other measurements (e.g., lake evaporation, ET_p) under the same weather conditions. Therefore, the pan coefficient (ET_p/E_{pan}) for a Class A pan is usually less than one and mostly around 0.7.

Background of Previous Analyses: ET Data and Trend Analyses

Monitoring stations were selected for trend analyses based on two criteria: (1) active status (still in operation), ensuring they can continue to be used for future trend observations; and (2) a period of record (POR) longer than 25 years. As the result, two E_{pan} stations (WPB.EEDD and S7) and one ET_p data set (from the United States Geological Survey or USGS) were included in this study.

The WPB.EEDD pan station, operated by the City of West Palm Beach, has been active since 1984, but the POR used for the statistical trend analysis was 37 years (1984–2020). The S7 pan station, operated by SFWMD, has the longest POR, and has been active since 1961. Evaporation data from the S7 station have been used to produce the weekly Shark River Report since 1986 (for water releases from Water Conservation Area 3A to Everglades National Park, based on water budget analysis of rainfall, evaporation, and stage regulation). The weekly data quality check for the report and staff communication have made the manual measurements at S7 as consistent as possible. The POR used for the statistical trend analysis at S7 was 35 years (from 1986 to 2020).

The measurement quality of E_{pan} is subject to many potential errors, including pan environment bias (e.g., distance to surrounding trees or buildings, bird guard, platform material and height to ground, algae in water), operation bias (e.g., reading and recording errors of water level), rainfall estimation (e.g., different diameters of rain gauge and pan), among others (Gunderson 1989). E_{pan} often is measured manually, so the measurement frequency depends on staff availability. For example, the measurements are not conducted over weekends or holidays, and an accumulated value is obtained on the next workday. Also, a heavy rain event can cause overflow in the pan, resulting in a missing data point for that day. Large measurement errors at daily or weekly scales are unavoidable and random; however, when they are pooled up to monthly or yearly scale, the errors follow a normal distribution and lead to less biased summaries. Therefore, the monthly or annual values are more suitable for statistical analysis. The raw data for this study went through quality assurance (QA) before being used in any statistical analysis.

Theoretically, annual evaporation rate should not vary much spatially and temporally because the meteorological variables (i.e., solar radiation, wind speed, relative humidity, and air temperature) in the region do not fluctuate widely on a yearly basis. Large variation between years is most likely due to operation errors; however, its influence on the evaporation trend will diminish with a longer POR. Large difference between stations (e.g., S7 and WPB.EEDD) are likely due to a combination of local environment, equipment settings, and operation bias. Although there are different magnitudes in values, the data from any station can be trusted for trend analysis as long as they have been consistently maintained (i.e., no change of location, surrounding, or equipment over the POR).

ET_p data from USGS were generated using insolation, retrieved from satellite images of cloud cover, with a POR of 25-year (1996–2020) for the trend analysis. The calculated ET_p values (based on Priestley-Taylor equation with net radiation, which is a function of land-surface albedo, as the major input) were calibrated to ground pyranometers, with a high coefficient of determination (R^2 = 0.93). The pyranometers measure solar radiation, which is the primary contributor to ET. As a result, the ET_p data set is both spatially consistent and temporally continuous (Mecikalski et al. 2018). The annual ET_p data shown in **Figure 2B-2** are the averages over the entire SFWMD jurisdiction.

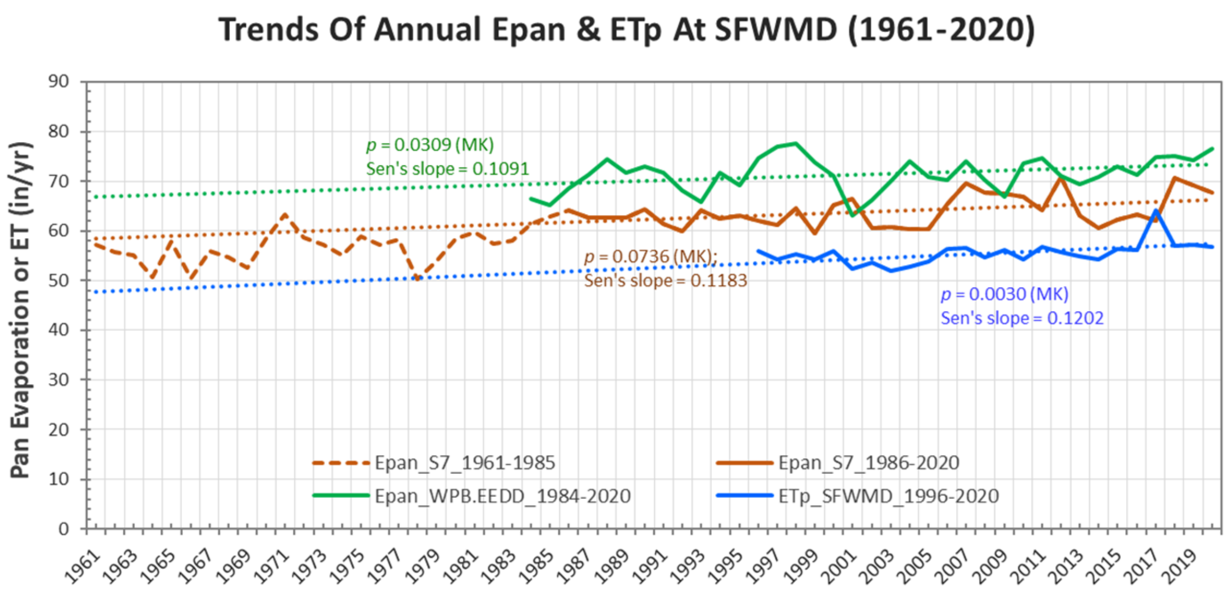


Figure 2B-2. Trend of annual E_{pan} and ET_p across SFWMD, 1961–2020. (Note: Statistics of S7 are based on data from 1986 through 2020 and WPB.EEDD are based on data from 1984 through 2020.)

Mann-Kendall test was used to detect trends in each of the ET data sets based on annual averages. All the three data sets illustrate upward trends, with significance levels less than p = 0.05 at WPB.EEDD and ET_p_SFWMD, and a significance level of p = 0.07 at S7 (**Figure 2B-2**). Their trends are all considered statistically significant.

The two direct pan observations and the satellite-based ET_p data set were collected independently; therefore, they can be used to cross-check each other. The statistics of annual E_{pan} and ET_p are presented in **Table 2B-2**. The averaged ET_p rate of 55 inches/year is close to the long-term rainfall rate in South Florida (approximately 53 inches/year). The change rate of the upward trend is approximately 0.1 inch/year.

Table 2B-2. Statistics of annual E_{pan} and ET_p.

Data Set	Agency	Period of Record	Period of Analysis	No. of Samples	Mean (inch/yr)	Ratio of ET_p/E_{pan}	Standard Deviation	Change Ratio (inch/yr)
E_{pan}_S7	SFWMD	1961–2024	1986–2020	35	63.97	0.87	3.17	+0.1183
E_{pan} WPB. EEDD	City of WPB	1984–2024	1984–2020	37	71.51	0.78	3.41	+0.1091
ET_p_SFWMD	USGS	1996–2024	1996–2020	25	55.48	1	2.35	+0.1202

Figure 2B-3 illustrates the annual and seasonal E_{pan} data at S7. The orange and green dots in the upper part of the chart represent the annual data subsets of 1961 to 1984 and 1986 to 2020, respectively, to account for the measurement schedule change from every day to workdays only in 1985. Both subperiods before and after 1985 show a statistically significant upward trend (for both p= < 0.001), the statistics shown in Figure 2B-3 are based on the 60-year POR. The two groups of dots in the lower part of the chart are the seasonal summaries over the 60-year POR. The blue dots represent the wet season (May–October), and the brown dots represent the dry season (November–April).

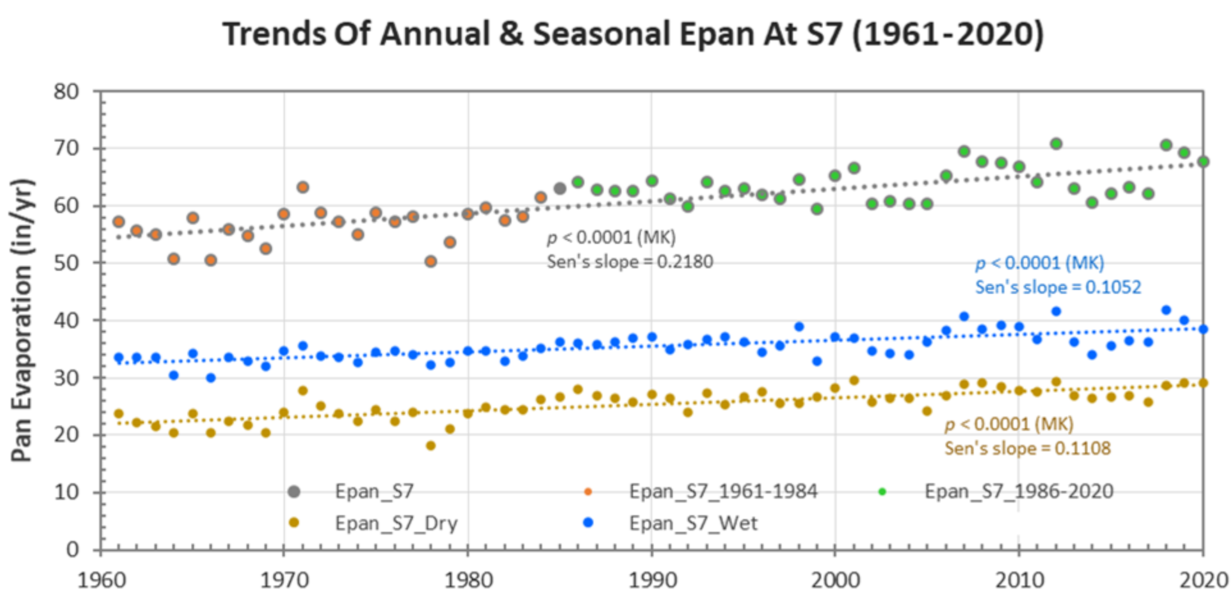


Figure 2B-3. Trend of E_{pan} data at S7 from 1961 to 2020: annual totals and seasonal summaries.

Figure 2B-4 shows the monthly E_{pan} data at S7 over the 60-year POR, including extreme occurrences with 1-in-10-year and 1-in-25-year return frequencies. The green dashed line represents the trendline of every year's maximum monthly values over the 60 years, and it illustrates an upward trend as well.

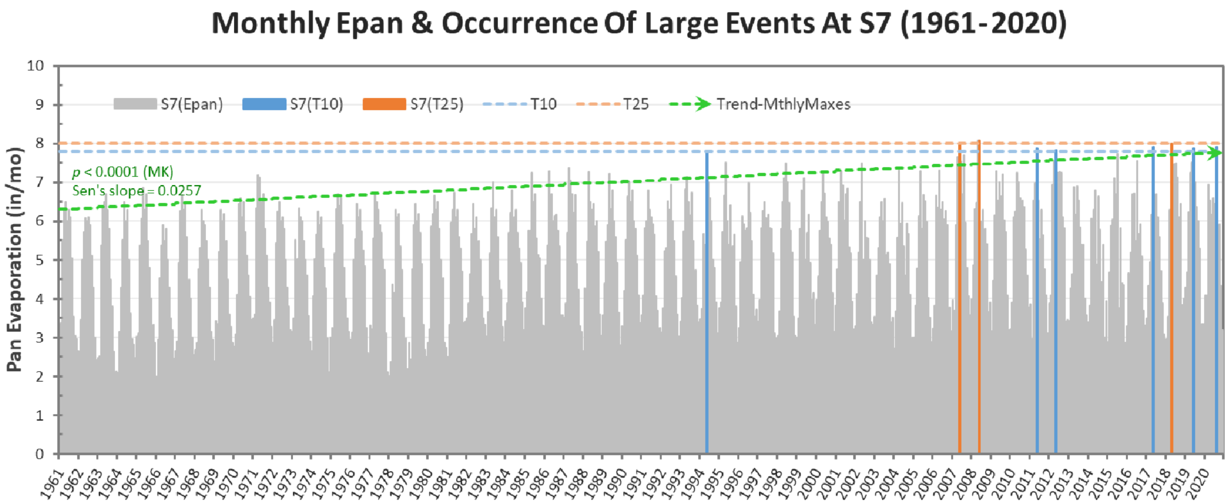


Figure 2B-4. Monthly E_{pan} data at S7 (gray), highlighting events above 1-in-10-year (blue) and 1-in-25-year (orange) return frequencies. The green dashed line represents the trendline of every year's maximum monthly values over the 60 years.

Transpiration in ET

Transpiration is difficult to measure in practice; therefore, there is no monitoring system for it at the local level; in other words, there is no field data that can directly confirm a trend of transpiration in South Florida. However, other dedicated studies may help understand its magnitude and tendency.

Large-scale or global studies show that plant transpiration accounts for about 60% of global terrestrial ET. The ratio varies largely among different landscapes, from more than 90% in tropical rainforests to less than 10% in deserts (Schlesinger and Jasechko 2014, Good et al. 2015, Zhang et al. 2016, Wei et al. 2017). For most of the United States, evaporation returns less moisture to the atmosphere than transpiration (Hanson 1991). In Florida, evaporation and transpiration roughly share a 50/50 composition in total ET (Wei et al. 2017), as there are many wetlands and open water bodies (e.g., lakes, ponds, canals), where evaporation dominates over transpiration. In urban areas, hard surfaces (e.g., pavement, roofs) also contribute to greater evaporation than transpiration. In agricultural areas, transpiration is dominant during the growing season, while evaporation is prevalent during fallow periods.

Climate change theory has linked global warming to rising concentration of carbon dioxide (CO_2) in the atmosphere. The global mean atmospheric concentration of CO_2 is 410 parts per million, which is 45% more than the concentration in 1750 (Arias 2021). The rising CO_2 concentration appears to influence transpiration rates due to less need for plants to open their stomates to obtain sufficient CO_2 for photosynthesis. With higher CO_2 concentrations, plants have evolved to have less stomatal density over recent centuries. However, it was also found that stomatal density decreases as CO_2 concentrations increase up to about 310 parts per million, but there is no effect to density found above this concentration (Woodward and Bazzaz 1988). Different plant species also show large differences in response of stomatal density to elevated CO_2 concentrations. For example, the stomatal density of rice and bean leaves is positively correlated to CO_2 concentrations (O'Leary and Knecht 1981, Rowland-Bamford et al. 1990). Stomatal functioning (opening and closing) also responds to other environmental cues, such as radiation or light intensity, leaf water status (drought), vapor pressure deficit, air pollution, and air temperature (van de Geijn and Goudriaan 1996). For example, air temperatures rise due to the greenhouse effect, and the associated increases in vapor pressure deficit may stimulate transpiration, or open the stomata (Urban et al. 2017, Kirschbaum and McMillan 2018).

ET_a versus ET_p

All else equal, ET_p and ET_a have a complementary relationship (**Figure 2B-5**). During dry conditions or in water-limited environments, ET_p is at its highest values and ET_a is at its lowest values. With increased precipitation or humidity, water limitation on the evaporative process gives way to an energy limitation. When the ET_p decreases, the ET_a increases, and they converge under the wettest circumstances (Hobbins et al. 2001, Hobbins and Ramirez 2004). Therefore, the humid climate in South Florida results in a close relationship between ET_p and ET_a, especially in wetlands and lakes, or during the wet season.

Although there are no transpiration monitoring networks or established ET_a data sets for South Florida, some independent, large-scale studies support that the southeastern United States has been experiencing an upward trend in transpiration and ET_a due to climate warming and vegetation restoration, among other reasons (Zhang et al. 2016).

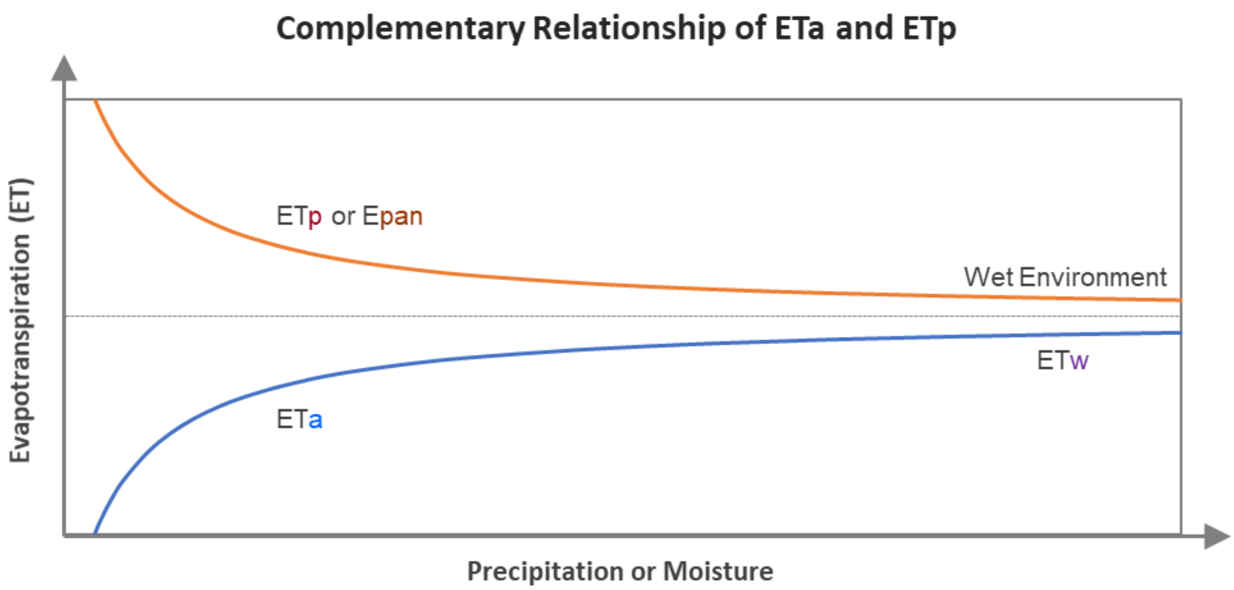


Figure 2B-5. Complementary relationship of ET_a and ET_p.

Updated Analyses: Correlations to Meteorological Variables

The SFWMD's systematic weather monitoring network was established in the 1990s and includes ET-driving variables like solar radiation, wind speed, relative humidity, and air temperature. Examining trends in these components can help explain the ET trends. There are 15 active weather stations operated by SFWMD. Seven stations were selected for trend analysis because they have longer PORs than the other eight stations. The seven weather stations, from north to south, are S61W, S78W, CFSW, Belle GL, LOXWS, S140W, and S331W. The raw data for air temperature, relative humidity, and wind speed are daily mean values, while the total solar radiation is a daily summary. The raw data went through QA for missing gaps and abnormal values. Annual values at the seven stations were averaged to represent the whole region.

In addition, data from other agencies (like USGS and NOAA) were also explored and utilized for their better quality than the SFWMD counterparts. For example, the solar radiation data from USGS were used in analyses to replace the SFWMD data in this and Chapter 2B of the 2022 SFER, and the newly found air temperature data from NOAA are used in this year's update, replacing the SFWMD data used in the 2022 report. The air temperature data downloaded from NOAA website (downloaded from https://www.ncei.noaa.gov/data/nclimdiv-monthly/access/) are monthly county averages over the 16 counties falling in SFWMD jurisdiction, and are considered better quality since their values at different counties are harmonic over years and recorded recent heat peaks (see Vose et al. 2014 for methodology used in data quality improvement). Two more analyses are also added into this year's report to further explore the ET's correlations to multi-variable effects, and to the region's rainfall pattern and trend.

Figure 2B-6 depicts the trends of air temperature and relative humidity. The air temperature (NOAA) shows an upward trend, and it is statistically significant (Mann-Kendall [MK] Test probability (p) = 0.0012, which is more significant than the SFWMD counterpart). The relative humidity (SFWMD) shows a downward trend (MK Test p = 0.0973). A downward relative humidity means there is an upward vapor pressure deficit, which contributes to an upward ET trend. Studies show that evaporation or ET rate is not very sensitive to air temperature variations when the vapor pressure deficit is constant; instead, it typically is more sensitive to variations in radiation, humidity, and wind speed (Monteith and Unsworth 1990). Relative humidity and air temperature are inversely proportional, if the moisture stays the same. As air temperature increases, its relative humidity decreases; when temperature drops, relative humidity increases (Thomson 1986). **Figure 2B-6** shows the trends of monitored relative humidity and air temperature match their theoretical relationship, though moisture was not considered. The discrepancy in statistical significance (p = 0.0012 versus 0.0973) is assumed to be a result of data quality issues (i.e., monitoring accuracy and consistency).

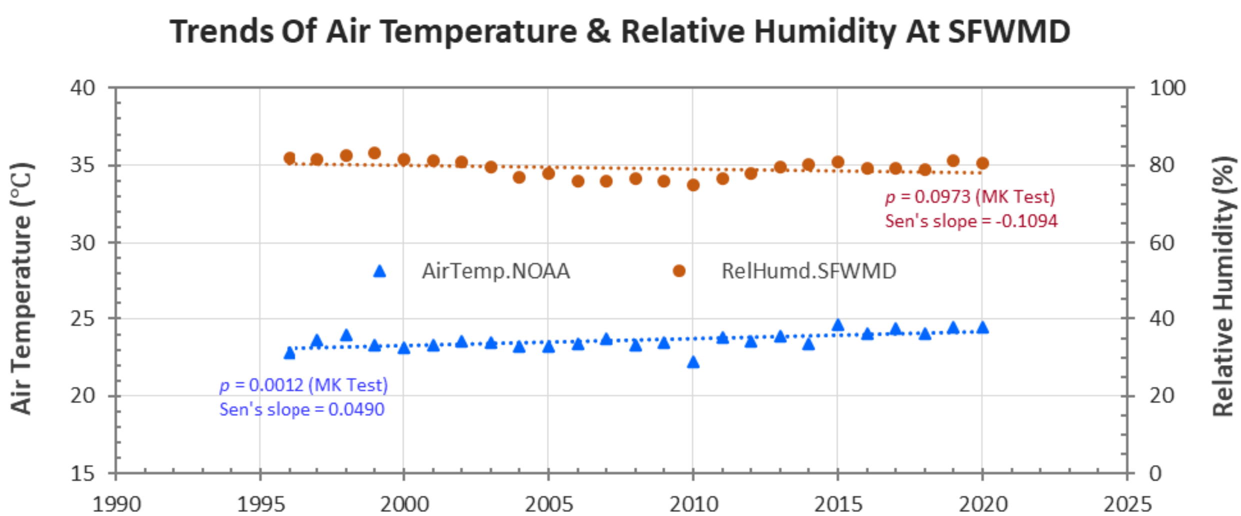


Figure 2B-6. Trends of air temperature and relative humidity across the SFWMD region, 1996–2020.

Figure 2B-7 depicts the trends of solar radiation and wind speed. Wind speed data (NOAA) do not show a trend (MK Test p = 0.9441; nor does the SFWMD counterpart). The total solar radiation data are from USGS (the SFWMD counterpart was considered less reliable, as it did not catch the peaks in some severe drought years like 2006/2007). The USGS data set was derived from insolation indices, which were retrieved with scanning satellite images for cloud coverages. From 1996 to 2015, the average insolation of the second 10 years is approximately 1 megajoule per square meter per day ($MJ/m^2/d$) or 0.011574-kilowatt days per square meter ($kW\text{-}day/m^2$) greater than the first 10 years (Mecikalski et al. 2018). The solar radiation data show an upward trend with a MK Test p = 0.0628, which is considered statistically significant for its trend.

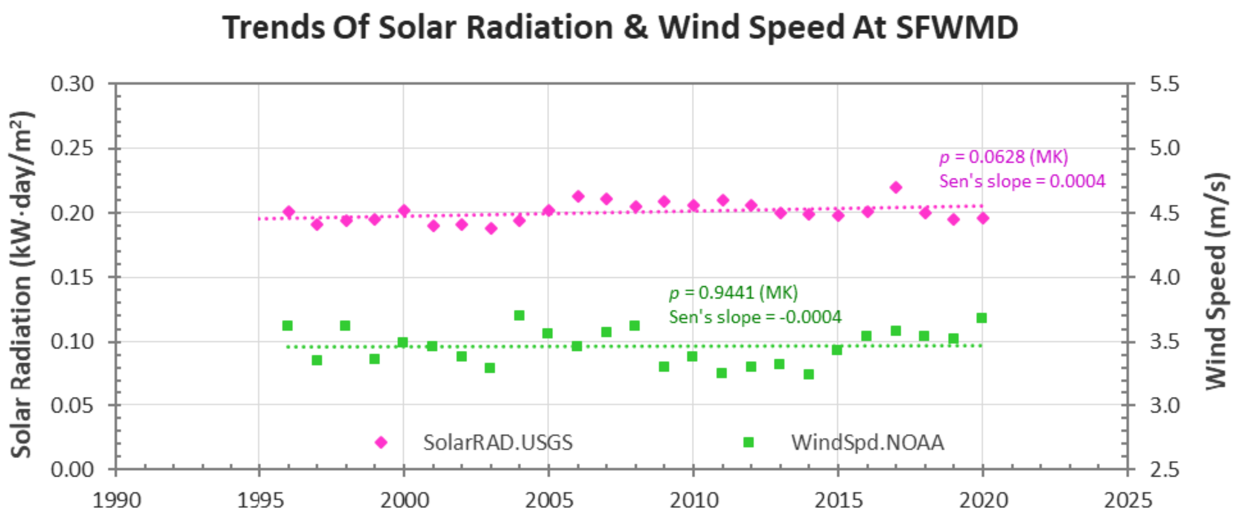
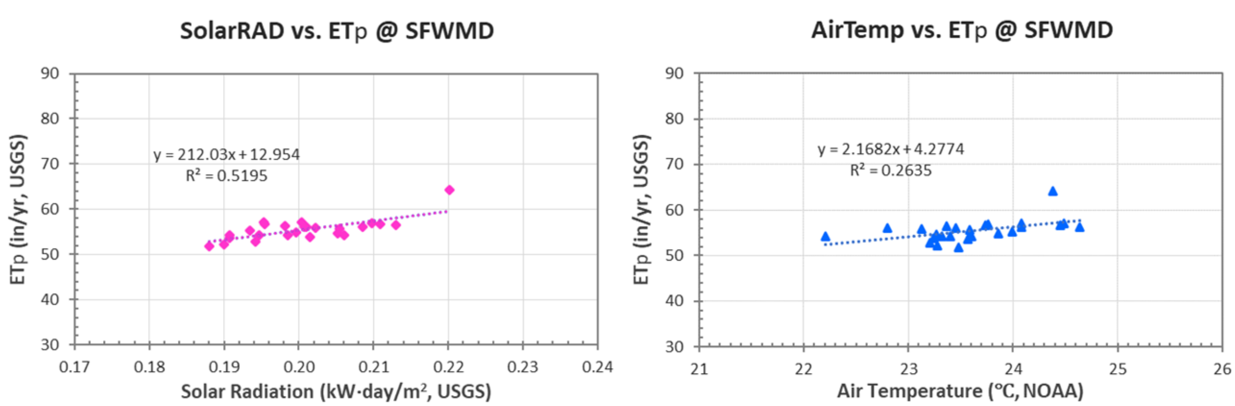


Figure 2B-7. Trends of total solar radiation and wind speed across the SFWMD region, 1996–2020.

Increasing solar radiation (insolation) and increasing air temperature were the two driving forces behind the upward ET trend in South Florida, while relative humidity and wind speed have not had a strong impact on the trend (**Figure 2B-8**). Possible causes for increasing solar radiation include better air quality from stricter regulations on exhaust emissions (e.g., less aerosols from coal burning power plants and diesel engines), which results in less cloud cover and stronger ray penetration (Hidy et al. 2014). Changes in land use and land cover may also contribute to increases in solar radiation across the southeastern United States (Ellenburg et al. 2016). Changes (i.e., increases/decreases) in relative humidity and the rate of change is dependent on the interaction between temperature and the amount of water vapor (moisture) in the air. The increasing air temperature certainly contributes to the decreasing relative humidity; on the other hand, there is a lack of moisture data; therefore, the exact proportion of the contribution to decreasing relative humidity cannot be determined at this point and should be further assessed in the future.



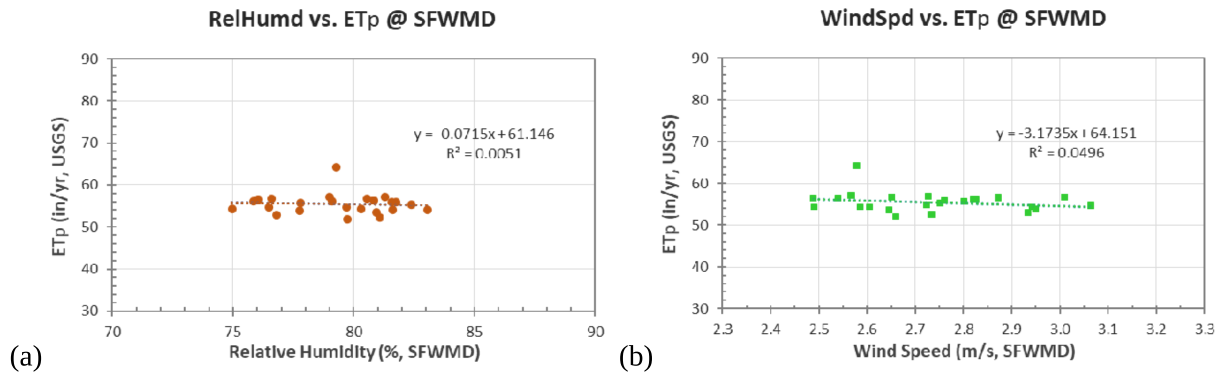


Figure 2B-8. Correlations between annual ET_p and individual environmental variables—solar radiation (SolarRAD), air temperature (AirTemp), relative humidity (RelHumd), and windspeed (WindSpd)—1996–2020.

ET is actually the effect of compositive processes; therefore, it is probably better correlated to multi-variables than individual ones. For example, the correlations of two major driving variables (solar radiation and air temperature) and all four variables (plus relative humidity and wind speed) are shown in **Figure 2B-9**. Their correlation coefficients (R^2 = 0.79 and 0.91) are both noticeably higher than the ones with a single variable (R^2 = 0.005, 0.05, 0.26, and 0.52). **Figure 2B-9a** shows positive coefficients for the two variables, which aligns with the single-variable regression models. **Figure 2B-9b** also displays positive coefficients for all four variables. However, the coefficient for relative humidity is changed from negative in the single-variable model. This discrepancy could suggest the presence of multicollinearity in the multi-variable model or indicate that the inclusion of additional variables has altered the effect of relative humidity on evapotranspiration. Multicollinearity is the occurrence of high intercorrelations among two or more variables in a multiple regression model; for example, relative humidity is closely related to air temperature in this case.

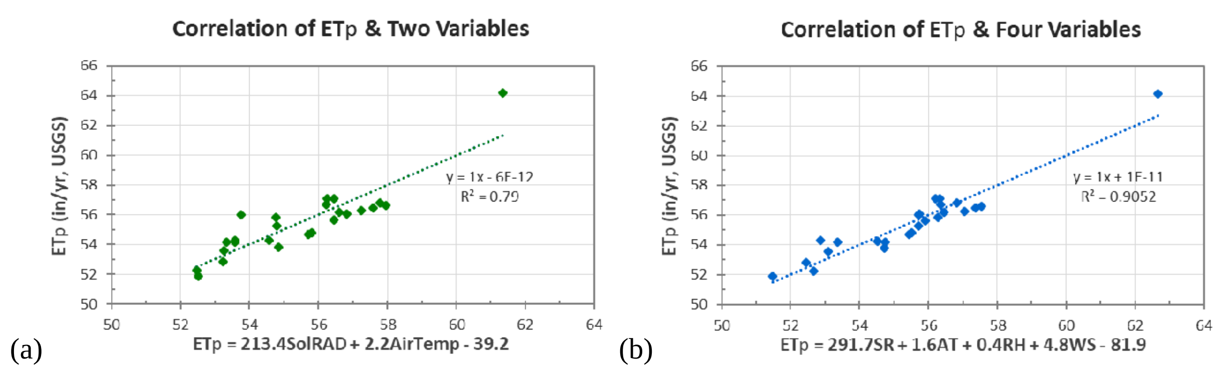


Figure 2B-9. Correlations between annual ET_p in inches per year (in/yr) and multiple environmental variables, 1996–2020.

Insolation or solar radiation is inversely proportional to cloud coverage, consequently rainfall amount (as convective rainfall is dominant in South Florida). More cloud cover means less insolation but more rainfall; and less cloud cover (sunnier) means more insolation but less rainfall. During the dry seasons, the observed solar radiation and rainfall have a good inverse relationship (**Figure 2B-10**). During the wet seasons, a hurricane or a tropical storm brings in excessive or disproportional rainfall over a short period (2 to 3 days), followed by sunny days. Removing the excessive rainfall (from hurricanes and tropical storms) out of the seasonal summary, their correlation of solar radiation and rainfall is similar to the dry seasons. Over the 25 years from 1996 to 2020, the annual rainfall series in South Florida had a decreasing tendency, while the solar radiation was on an increasing trend. This inverse relationship meets the expectation in general.

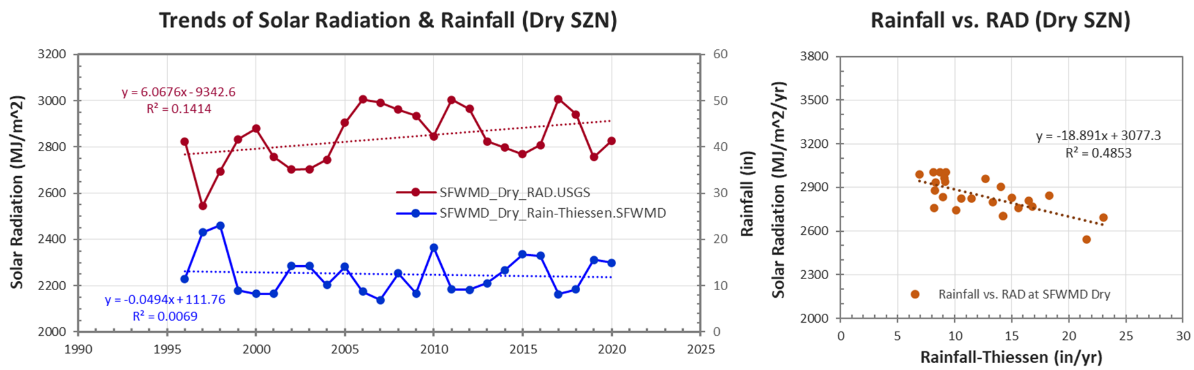


Figure 2B-10. Trends and correlation of solar radiation and rainfall in the dry season, 1996–2020.

Two other environmental factors (solar cycle and ozone depletion) were also reviewed for their roles in hydrological change at South Florida, but no significant contributions were found from them.

The sun has an 11-year cycle of solar activities characterized by the rise and fall in the numbers and area of sunspots. Total solar irradiance is the radiant energy emitted by the sun at all wavelengths outside Earth's atmosphere. Annual values of total solar irradiance vary slightly with the solar cycle, from 1,365.5 to 1,366.6 watts per square meter (W/m^2), only a 0.1% variation (Hathaway 2015). The amount reaching Earth's surface (as insolation) is reduced by atmospheric attenuation (e.g., reflection, absorption), which varies with location, time, and weather condition. The solar cycle plays a negligible role in driving global climate change because its magnitude is much smaller than the impact from greenhouse gases (Arias 2021).

Ozone is a gas that absorbs ultraviolet (UV) radiation from the sun, especially UV-B (280 to 315 nanometers) and UV-C (100 to 280 nanometers), the shorter wavelength or higher energy rays that are harmful to all life forms. About 90% of Earth's ozone resides in the stratosphere (altitude 10 to 50 kilometers). Ozone distribution generally increases from the tropics (0 to 20°) to the mid-latitudes (30 to 60°) and polar regions (60 to 90°). There is little seasonal variation in tropics, but large variation in high-latitude regions. Ozone depletion was observed throughout the 1980s due to increases in reactive halogen gases (e.g., chlorine, bromine) resulting from human activities. In both hemispheres, ozone depletion is greater toward the poles and less near the equator. In the early 1990s, global ozone was depleted by 5% relative to the 1964–1980 average, but the depletion ratio has been declining since then due to the Montreal Protocol (1987), which controls the production and consumption of ozone-depleting substances. The abundance of total ozone is now 2 to 3% below the 1964–1980 average, and it is projected to recover back to the 1964–1980 level around the middle of the 21^{st} century. Although ozone depletion has led to increased UV radiation on Earth's surface, it is not the principal cause of global climate change because of its small volume compared to other potent greenhouse gases like CO_2 (Salawitch et al. 2019). Because of Florida's location between the tropics and mid-latitudes, the state's climate should not be heavily influenced by ozone depletion. In summary, the ET trend in Florida should be guided by interactive elements (e.g., humidity, cloudiness) within the troposphere (altitude 0 to 10 kilometers), rather than higher layers of the atmosphere.

RELEVANCE TO RESILIENCY IN WATER MANAGEMENT

Monitoring trends in ET as part of resilience and adaptation planning in water management supports the following:

- **Understanding of Regional Climate Patterns:** Monitoring trends in ET helps assess changes in regional climate patterns and water availability over time.
- **Water Supply Vulnerability:** Monitoring ET trends informs water management strategies by identifying changing patterns in water supplies and guiding adaptive measures.
- **Ecosystem Restoration:** Assessing ET trends supports ecosystem health and resilience by informing habitat restoration and conservation efforts.
- **Infrastructure Management:** ET data aids in evaluating the effectiveness of water resource management practices.
- **Adaptation Planning:** Long-term ET monitoring contributes to resiliency planning by identifying shifts in hydrological cycles and informing resilient infrastructure development.

RESULTS AND DISCUSSIONS

The assessment presented in this chapter examines the long-term data of ET in South Florida, which indicates a statistically significant upward trend over the past three decades. The correlation analyses reveal that rising solar radiation and air temperature contribute to the upward ET trend most, followed by the decreasing relative humidity. Multi-variable correlation analysis is added to this year's report for the first time. Both the two-variable model (solar radiation and air temperature) and four-variable model (solar radiation, air temperature, relative humidity, and wind speed) yield higher correlation coefficients than the single-variable models. In relation to rainfall, the upward ET trend is well correlated to the downward rainfall trend. The findings underscore the need for continued monitoring to understand and manage ET's impact on water resources.

COMMENTS AND RECOMMENDATIONS

Quality data are the backbone of trend analysis. While all the parameters or variables involved in measurement, estimation, or assessment of ET come from a modern monitoring system, some need special attention or improvement. For example, solar radiation measured on the ground is extremely important because it is directly used in ET estimation and to calibrate other solar radiation estimating methods (e.g., the satellite image method). However, there are many data gaps and anomalies in the SFWMD weather stations, which impaired data usability; therefore, a more thorough monitoring scheme is under development for data enhancement. Air temperature is used globally to gauge climate change, and its importance cannot be overstressed. Besides the continuity of the current practice, its consistency among SFWMD weather stations should be improved with a tighter calibration procedure. The E_{pan} measurement has been collected at the S7 station for more than 60 years since 1960, the longest continuous observation in South Florida. This is a great asset to SFWMD's monitoring network and should be preserved for continuous trend analysis. A moisture (absolute) measurement currently is not in the monitoring system, but it is critical in assessing the trend of relative humidity; therefore, it should be considered for future monitoring plans to help understand the causes of the declining trend in relative humidity.

SALINITY IN FLORIDA BAY

BACKGROUND

South Florida's estuaries and bays are vulnerable to the impacts of climate change, including sea level rise and the changes in rainfall patterns, and rely on water management practices to deliver adequate freshwater flows. SFWMD monitors and reports ecosystem response to water management, climate conditions, and restoration projects. The salinity of surface water is used to monitor water quality, guide water management practices, and evaluate the effectiveness of restoration strategies. In Florida and Biscayne bays, salinity and nutrient loads are the main drivers of ecosystem change and vegetation dynamics. The salinization of previously freshwater and brackish habitats leads to habitat loss of tidal marshes, poses a threat to the flora and fauna that inhabit them, and impacts soil dynamics and local geologic processes. While other chapters of the SFER detail annual salinity totals for the purposes of monitoring and reporting, this chapter introduces the analysis of historical salinity data as part of the water and climate resilience metrics effort. The analysis presented in this chapter section identifies the long-term trends in available historical salinity data for Florida Bay. Improved monitoring and understanding of the impacts to coastal systems, and their response, to the effects of climate change is critical to identifying adaptive management opportunities and resiliency planning.

DRIVERS AND INFLUENCING FACTORS

Fluctuations in salinity are most noticeable in South Florida's estuaries and shallow bays where the physical and chemical characteristics of surface water are directly connected to saltwater inputs from the ocean's tides, freshwater inputs from inland flows, and precipitation and tropical storm events, as well as antecedent and current conditions. In northeastern Florida Bay, the influence of tidal inputs is relatively low due to the presence of keys that act as physical barriers to water exchanges. Instead wind, freshwater flows, and evaporation are dominating factors, at least at the mouth of creeks where salinity is measured. The influence of tidal inputs might be greater along the western areas of Florida Bay. The salinity of surface water in any given period of time ultimately depends on how much evaporation is taking place and how much fresh water, primarily from rainfall and inland freshwater discharge, enters the system. Spatially, surface water salinity is generally lower in areas of freshwater runoff, such as was described for mouths of rivers by Cortez et al. (2023), and temporarily during the wet season when rainfall increases. Surface water salinity is generally higher during the dry season and drought events, when evaporation rates are highest, rainfall is lower, and freshwater flows are low because more water is held in the Everglades Water Conservation Areas (WCAs). Water and climate elements in the bays exhibit a positive feedback loop during drought events when more water is held within the WCAs and the lack of freshwater flows into the bays leads to increased salinity levels as tidal influences become the more dominant factor. Salinity levels are further exacerbated when air temperatures and ET increase. Altogether, these conditions increase the likelihood of further encroachment of sea water in freshwater inland areas.

Over time, the factors that increase salinity are be counterbalanced by the processes that decrease salinity in a continuous cycle. The average salinity of sea water is about 35. It is nearly zero in fresh water and can range from 0.5 to 35 in estuaries where inland fresh water and seawater meet (USGS 2004). In the lower estuary region, where the bay meets the ocean, salinity may be even higher, especially during the dry season when freshwater flow is low and evaporation increases (USGS 2004). By virtue of their transitional nature and interconnectedness with terrestrial and marine habitats, estuaries and bays are highly susceptible to impacts from anthropogenic practices and changes to upstream land uses and physical and chemical oceanic changes downstream. Variations in rainfall, which are dependent on short-term local weather patterns and long-term climatic variability, influence surface water salinity. Therefore, water management is a key component in maintaining adequate salinity levels by establishing higher freshwater levels inland. As conditions continue to evolve, it becomes more important to monitor the effects of increased freshwater flow as part of water management practices as well as climate variables that impact salinity to understand the impacts of rising sea level in critical coastal habitats and ensure adequate water management practices and planning in coastal waters.

Several drivers and influencing factors interact dynamically to determine the salinity regime within shallow estuaries and bays, shaping the ecological structure and function of these important coastal ecosystems.

- **Precipitation and ET:** Precipitation directly adds fresh water to estuarine systems, reducing salinity levels. ET removes water from the system, concentrating salt and increasing salinity levels.
- **Freshwater Inputs:** Freshwater flow from uplands and wetlands, such as Taylor Slough in Florida Bay and man-made canals in Biscayne Bay, can significantly affect salinity levels. Altered freshwater discharges due to land development, extreme weather conditions or water management practices can disrupt natural salinity gradients.
- **Seasonal Variations**: Seasonal changes in temperature and precipitation can impact evaporation rates and freshwater inflows, leading to fluctuating salinity levels throughout the year.
- **Tidal Dynamics:** Tidal cycles and variations in tidal amplitude influence the mixing of fresh and salt water in estuaries, affecting salinity levels. Changes in tidal patterns due to factors such as sea level rise can alter salinity gradients and distribution.
- **Storm Events:** Storms and hurricane surges can rapidly alter estuarine salinity levels. Heavy rainfall and runoff from these events often lower salinity temporarily, while storm surges can introduce salt water into freshwater areas, causing abrupt salinity changes that may disrupt habitats and impact ecosystem health over time.
- **Sea Level Rise:** Rising sea levels alter the depth and extent of estuarine water bodies, affecting salinity levels.
- **Climate Change:** Changing atmospheric patterns can influence precipitation and ET rates, impacting freshwater input and salinity levels.
- **Landscape Effects and Physical Features:** Proximity to freshwater inputs influences salinity levels, with areas closer to freshwater sources experiencing lower salinity. Physical features of the landscape, such as elevation and topography and key islands, can affect the distribution and movement of fresh and saline water within estuarine systems.
- **Anthropogenic Activities:** Human activities, such as urban development, agriculture, and water withdrawals, can modify freshwater inputs and alter salinity levels in estuarine environments. Pollution and nutrient runoff from urban and agricultural areas can impact water quality and salinity dynamics.

SALINITY DATA AND TREND ANALYSIS

SFWMD manages a comprehensive ecological monitoring program in the southern Everglades marshes, mangrove transition zone, and estuarine waters of Florida and Biscayne bays to assess the impacts and benefits of Everglades restoration. This program specifically monitors the C-111 Spreader Canal Western Project, which has been operational since 2012. Monitoring follows the project's plan (SFWMD and USACE 2011), which details protocols for evaluating hydrology, nutrients, water quality, vegetation, and fauna, as well as their interactions within and downstream of the C-111 Spreader Canal Western Project area.

The restoration project aims to retain or increase freshwater flow within Taylor Slough and into northern Florida Bay by constructing a hydrologic seepage barrier. This barrier is intended to capture water that previously flowed out of Taylor Slough and east into the C-111 Basin. Expected outcomes include higher water levels and extended hydroperiods in Taylor Slough, increased freshwater discharge to southern wetlands and Florida Bay, and reduced frequency, duration, and extent of elevated salinity in the bay and estuarine habitats.

The *Water and Climate Resilience Metrics Phase I: Long-term Observed Trends* (SFWMD 2021) report introduced salinity data from 2008 to 2021 for sites in Florida Bay, and Chapter 2B of the 2023 SFER – Volume I (Cortez et al 2023) expanded the analysis by examining trends in water year averages. These data are critical for monitoring the influence of fresh and tidal water into the bay and nearshore salinity levels, helping to identify extended periods of high salinity (35 or higher) that could impact the shallow bay ecosystem. These data also guide water managers in directing freshwater flows where they are most needed.

Based on the findings reported in these previous publications, this chapter provides an expanded statistical analysis of the available data from Florida Bay, as illustrated in **Figure 2B-11**. Monitoring stations include Alligator Creek and McCormick Creek in western and central Florida Bay, respectively, which represent salinity in Taylor Slough; and Joe Bay and Trout Creek in eastern Florida Bay, representing salinity in the C-111 Basin.

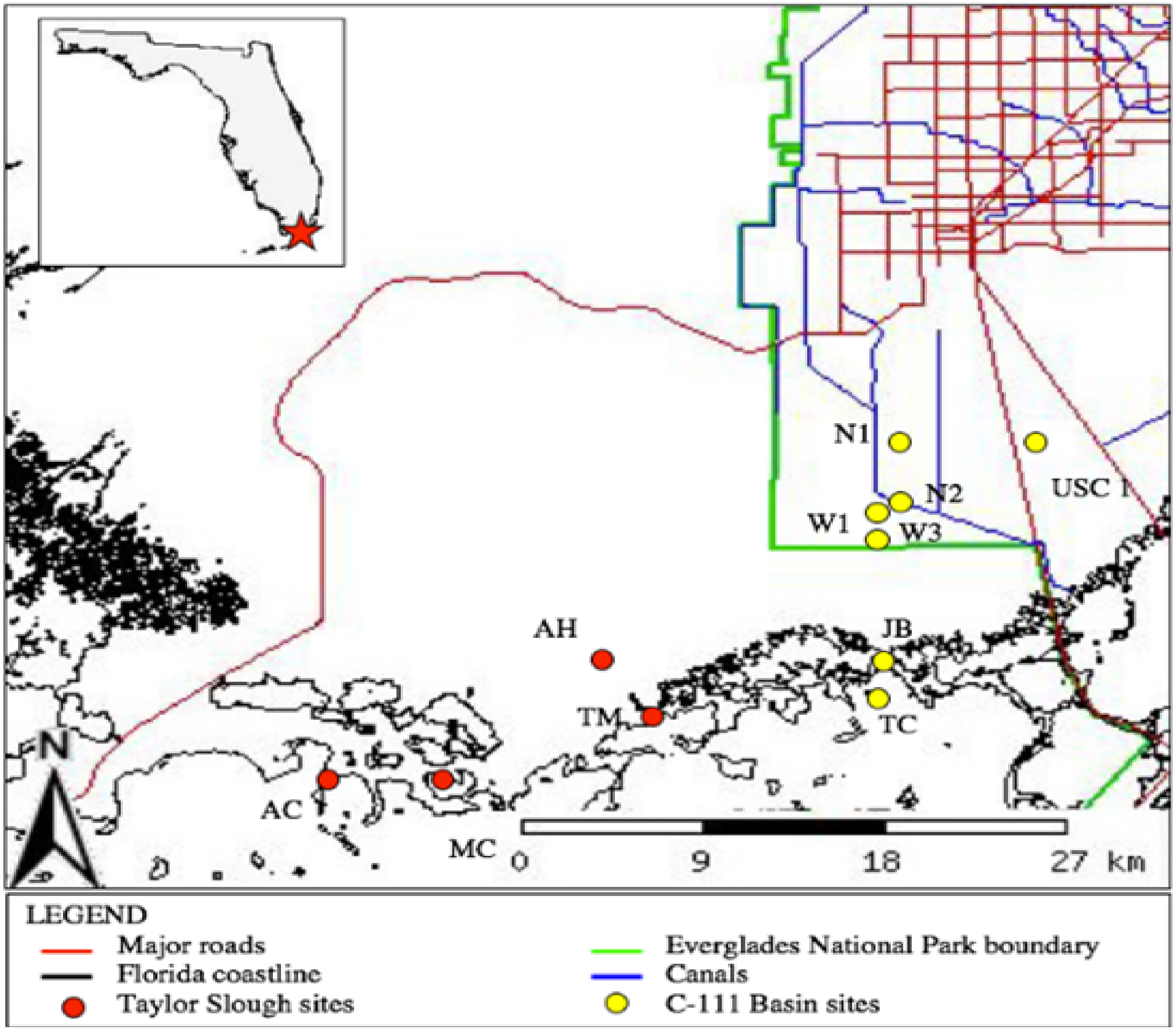


Figure 2B-11. Locations of salinity monitoring sites in Florida Bay evaluated as part of the trend analysis. The sites used in this evaluation were Alligator Creek (AC), McCormick Creek (MC), Joe Bay (JB), and Trout Creek (TC).

Overview of Previous Assessment

The 2023 analysis (Cortez et al. 2023) examined long-term trends in annualized salinity data by water year, which starts in May as the wet season approaches and ends during the dry season in April of the following calendar year, which were averaged to smooth out daily seasonal variations. Only water years with complete data sets were included in the analysis. No significant trends were observed at any of the monitoring sites in Florida Bay. However, AC and MC, located in the western and central regions of Florida Bay, showed the highest average daily salinity and the greatest variability between minimum and maximum daily salinity concentrations.

Current Refined Assessment and Results

Available salinity time series data show salinity concentrations exhibit seasonal variations, increasing and decreasing over time. To confirm the seasonal influence that may have affected the 2023 analysis (which found no trends in annualized data), it is important to examine the spatial findings at the seasonal level and determine if trends are more apparent seasonally. This involves updating the long-term trend analysis of annual water year salinity averages with recent data and conducting detailed seasonal, wet, and dry season trend analyses. Performing Mann-Kendall tests on isolated seasonal averages will help identify trends specific to each season and compare trends between the wet and dry seasons to understand seasonal shifts.

Trend analyses were carried out using both Seasonal Mann-Kendall and Mann-Kendall tests to detect salinity trends at each site based on daily and seasonal data, respectively. Sen's Slope was used to determine whether these trends are positive or negative. The data were assumed to be independent and normally distributed, with missing values excluded. The tests were conducted with a 95% confidence interval around the trend slope. A trend is considered significant if the probability value is less than the significance level of 0.05, thus rejecting the null hypothesis of no significant trend.

As with the daily and water year salinity averages, the seasonal salinity averages are higher in the western Florida Bay sites (Alligator Creek and McCormick Creek) compared to the eastern sites (Joe Bay and Trout Creek). As expected, seasonal salinity averages are generally lower during the wet season, although some years have shown higher averages (**Tables 2B-3** through **2B-6** and Figures **2B-12** and **2B-13**).

Table 2B-3. Summary of statistics and Seasonal Mann Kendall trend analyses results for daily salinity in Florida Bay.

Site	Alligator Creek	McCormick Creek	Joe Bay	Trout Creek
POR	WY2009–WY2023	WY2009–WY2023	WY2008–WY2023	WY2008–WY2023
Minimum	5.60	4.00	0.20	0.40
Maximum	96.70	63.40	55.70	56.30
Mean	35.31	27.38	15.05	23.18
Magnitude	91.10	59.40	55.50	55.90
p-value	0.013	0.031	0.000	0.030
Sen's Slope	0.059	0.044	0.050	0.038
Trend	Upward	Upward	Upward	Upward

Table 2B-4. Summary of statistics and Mann Kendall trend analyses results for average wet season salinity in Florida Bay.

Site	Alligator Creek	McCormick Creek	Joe Bay	Trout Creek
POR	WY2009–WY2023	WY2009–WY2023	WY2008–WY2023	WY2008–WY2023
Minimum	19.61	11.97	2.35	6.28
Maximum	63.66	50.77	38.72	45.09
Mean	36.13	30.46	13.22	22.28
Magnitude	44.04	38.80	36.37	38.81
p-value	0.956	0.956	0.067	0.067
Sen's Slope	N/A [a]	N/A	N/A	N/A
Trend	None	None	None	None

a. N/A – not applicable.

Table 2B-5. Summary of statistics and Mann Kendall trend analyses results for average dry season salinity in Florida Bay.

Site	Alligator Creek	McCormick Creek	Joe Bay	Trout Creek
POR	WY2009–WY2023	WY2009–WY2023	WY2008–WY2023	WY2008–WY2023
Minimum	20.43	15.08	3.33	14.00
Maximum	45.68	35.29	35.29	33.79
Mean	32.83	24.79	14.76	23.25
Magnitude	25.25	20.20	31.95	19.79
p-value	0.055	0.071	0.586	0.586
Sen's Slope	N/A [a]	N/A	N/A	N/A
Trend	None	None	None	None

a. N/A – not applicable.

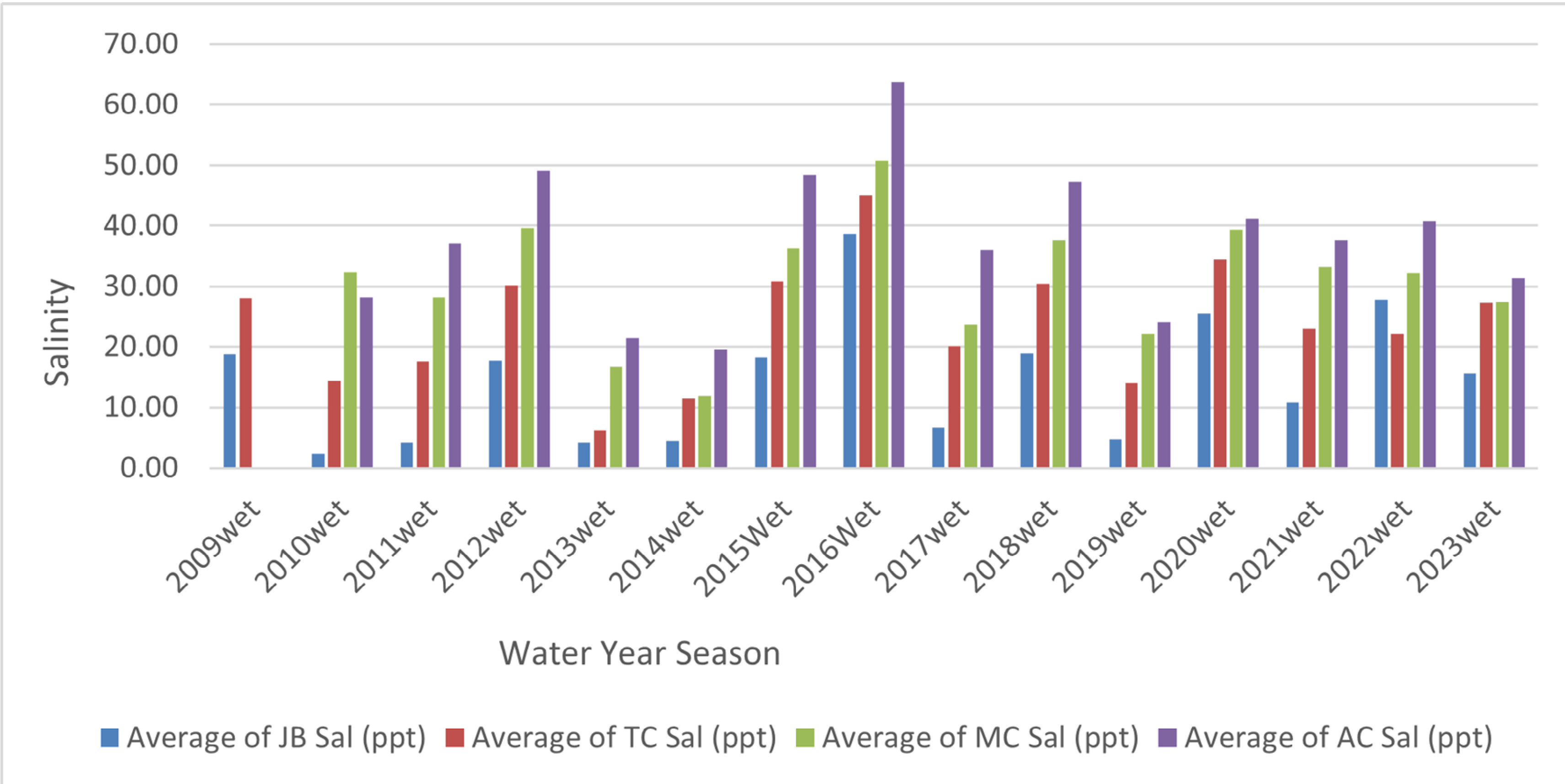


Figure 2B-12. Wet season averages in Florida Bay. Sites used in the evaluation are Joe Bay (JB), Trout Creek (TC), McCormick Creek (MC), and Alligator Creek (AC). (Note ppt – parts per thousand.)

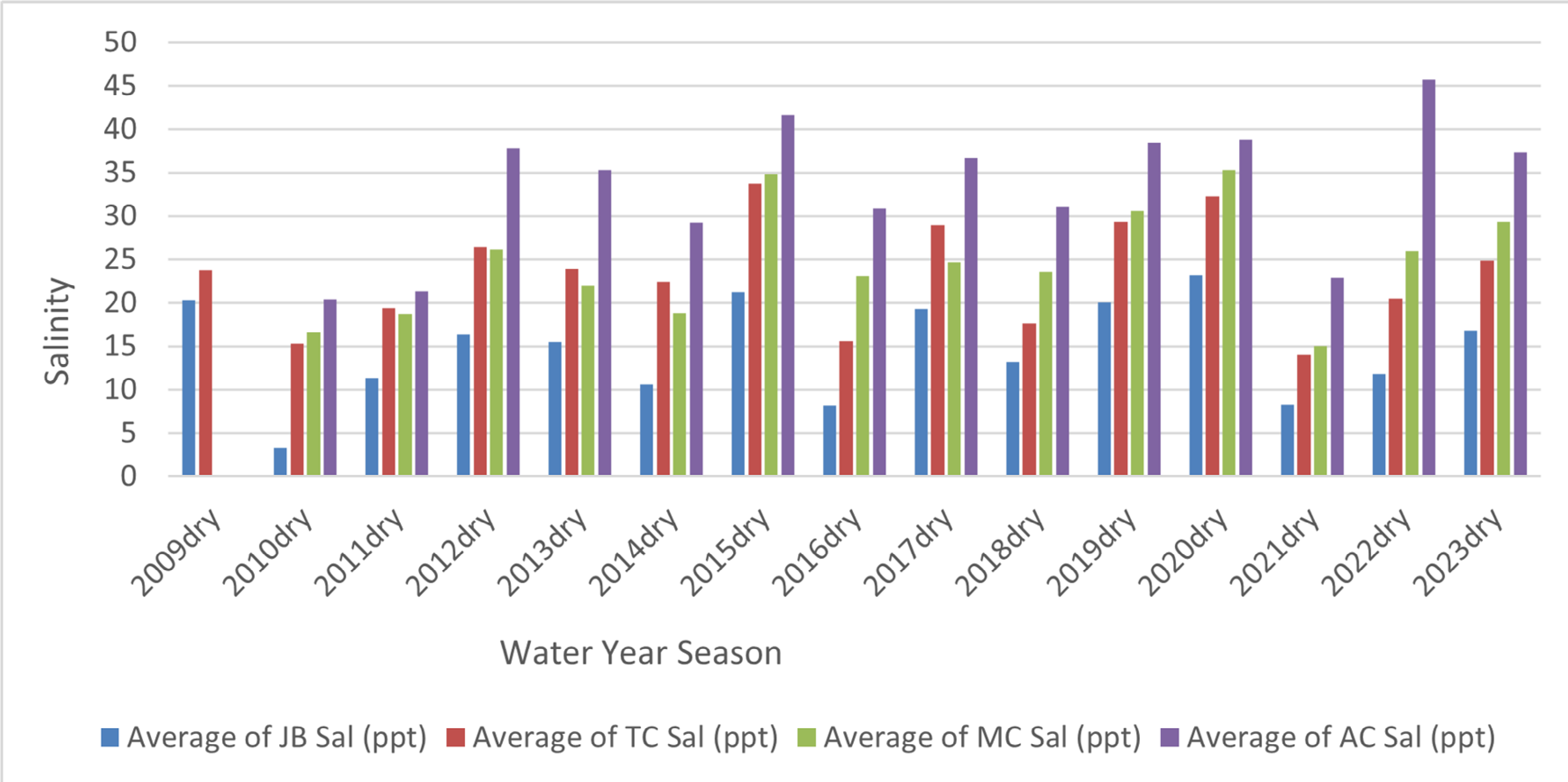


Figure 2B-13. Dry season averages in Florida Bay. Sites used in the evaluation are Joe Bay (JB), Trout Creek (TC), McCormick Creek (MC), and Alligator Creek (AC). (Note ppt – parts per thousand.)

Results and Discussion

The 2023 analysis revealed salinity concentrations at Alligator Creek and McCormick Creek in western Florida Bay appear to be more influenced by tidal inputs compared to the central and eastern regions of the bay, as noted in the *Drivers and Influencing Factors* sub-section. In contrast, Joe Bay and Trout Creek, located in eastern Florida Bay and the C-111 Basin, are primarily influenced by wind, freshwater flows, and ET. These sites exhibited lower average daily salinity concentrations and smaller fluctuations between minimum and maximum daily salinity levels. However, no statistically significant trends were observed in annualized water year data for the available POR. A water year, beginning May 1 and ending April 30 of the following year, is used for hydrological analysis to capture the entered of the wet season and dry season each year.

Key updates in this report included seasonal trend analysis of daily salinity data and trend analyses of seasonal average salinity data, revealing statistically significant seasonal trends at all monitoring sites in Florida Bay. The seasonal Mann-Kendall test, which examines trends within 12-month periods of daily data, confirmed the presence of seasonal variations. However, no significant trends were identified in wet and dry season averages or transitional month averages. This suggests, while salinity exhibits seasonal patterns, the influence of factors such as ET, rainfall, and freshwater and tidal inputs at shorter time scales complicates the ability to isolate seasonal trends.

RELEVANCE TO RESILIENCY IN WATER MANAGEMENT

Understanding salinity trends in Florida Bay is critical for effective water resource management and ecosystem restoration, particularly in the context of resilience planning. The relevance of these trends is outlined as follows:

- **Ecosystem Health**: Monitoring salinity variations is essential for evaluating the health of key ecosystems such as wetlands, estuaries, and mangroves. Salinity fluctuations can also impact aquatic species distributions and abundance, which in turn affects overall biodiversity and ecosystem functions.
- **Habitat Protection**: Tracking salinity changes aids in the protection of critical habitats. High salinity levels can negatively affect sensitive species and alter habitat structures, making it essential to manage salinity to maintain habitat quality and support wildlife populations.
- **Restoration Effectiveness**: Salinity data are crucial for assessing the success of restoration projects. For instance, projects aimed at enhancing freshwater flow into estuaries must be evaluated based on their impact on salinity levels.
- **Adaptive Management**: Resilience planning requires the ability to adapt to environmental changes and uncertainties. Salinity trends inform adaptive management by illustrating how ecosystems react to variations in freshwater inputs, sea level changes, and other factors. This information supports the development of flexible management strategies.
- **Predictive Modeling**: Accurate salinity data are vital for predictive modeling of future scenarios. Understanding how salinity patterns may shift due to changing conditions enables planners to forecast potential challenges and implement proactive measures.

COMMENTS AND RECOMMENDATIONS

To gain a deeper understanding of how salinity is correlated with specific influences and pulse events, and to effectively monitor how regional conditions evolve amid climate change and sea level rise, several strategies can be pursued/are necessary.

First, a focused analysis of key events that significantly impact salinity, such as major storms, droughts, or substantial freshwater inflows, is essential. Identifying these pivotal events and examining their correlation with changes in salinity can provide insights into how these factors influence salinity levels. Statistical methods, such as correlation studies and time series analysis, can then be employed to quantify these relationships and understand the temporal dynamics.

In addition, advanced statistical techniques can be used to predict salinity changes based on historical data and external factors. Multiple regression analyses can further demonstrate how various predictors, including rainfall, temperature, and sea level, affect salinity. These approaches allow for a more nuanced understanding of how different variables interact to influence salinity.

To complement these analyses, integrated modeling approaches can be employed. Hydrodynamic models, which simulate the effects of freshwater inflows, tidal actions, and sea level changes on salinity, provide insights into how these factors influence salinity under different conditions. Similarly, incorporating climate models can help project future changes in rainfall patterns and sea levels, allowing for predictions about their potential impacts on salinity.

Expanding and enhancing monitoring networks are also critical. By increasing the number of monitoring sites and measuring additional parameters that affect salinity, such as evaporation rates and freshwater inputs, researchers can collect more comprehensive data. Remote sensing technologies can provide high-resolution, large-scale data on environmental conditions, further enriching the data set.

Real-time monitoring facilitates the early detection of shifts or anomalies in salinity. Such early detection is important, as it can indicate significant environmental changes or the emergence of new influencing factors. This proactive approach enables timely responses and adjustments to management strategies.

Scenario and sensitivity analyses will enable researchers to explore various future conditions. Developing and analyzing different climate and water management scenarios, such as increased rainfall or higher sea levels, along with water management strategies can reveal potential future impacts on salinity. Sensitivity analyses can assess how salinity might respond to changes in key influencing factors under these scenarios.

Finally, collaboration with experts and stakeholders is vital. Engaging with climate scientists, hydrologists, and oceanographers can integrate diverse expertise and data, leading to a more comprehensive understanding of salinity dynamics. Working with local stakeholders can also provide valuable observational data and insights into regional changes and impacts.

As plans are developed for more detailed analyses, continuing to monitor current trends remains essential for understanding how salinity conditions in Florida Bay and other areas such as Biscayne Bay are evolving. Ongoing monitoring will support the tracking of changes and identify emerging patterns as they occur.

This continuous observation allows for immediate insights into current salinity conditions, ensuring any significant changes are promptly noted and analyzed. By maintaining an up-to-date record of salinity levels, researchers can validate and refine the trends identified in earlier analyses, confirming whether these patterns persist over time.

CONCLUSIONS

The future of successful water resource management in South Florida will be influenced by the understanding of how 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.

This chapter detailed the data and analyses, potential influencing factors, and future monitoring considerations for one climate and two resilience metrics related to sea level and hydrology—tidal elevations at coastal structures, MFLs, and flood occurrence—to identify trends for specific water bodies, enhance previous analyses, and develop an understanding of influencing factors to begin differentiating the influences of climate and non-climate factors. The evaluation of these metrics and correlation with other metrics may be required to determine if observed changes are associated with identifiable climatic changes or other influencing factors.

Overall findings for each of the two metrics included in this chapter are presented below:

- Previous analyses of E_{pan} and ET_p data have shown statistically significant upward trends at stations like WPB.EEDD and S7. These trends show significant correlations with rising solar radiation and air temperatures data from NOAA. Additionally, multi-variable correlations to the ET trend were explored, including two-variable models (solar radiation and air temperature) as well as four-variable models (solar radiation, air temperature, relative humidity, and wind speed). The correlation coefficients for these multi-variable models are higher than those for single-variable models. Rainfall observations were also analyzed in relation to ET variation and trends, showing the relationship between ET_p and ET_a are closely tied to water availability, with both increasing during wetter periods. The findings highlight the need for continued monitoring to better understand and manage ET's impact on water resources.
- Daily salinity data in Florida Bay exhibit statistically significant seasonal upward trends at all monitoring sites included in this analysis confirmed by the seasonal Mann-Kendall. No significant trends were identified in wet and dry season averages confirmed by the Mann-Kendall trend test. This suggests, while salinity exhibits seasonal patterns, the influence of multiple factors year-to-year complicates the ability to isolate specific trends. Ultimately, while more comprehensive analyses are in development, ongoing monitoring plays a critical role in understanding and managing the dynamic salinity conditions in Florida Bay. By providing current and relevant data, it supports informed decision-making and adaptive management in response to evolving conditions.

The inaugural Water and Climate Resilience Metrics chapter in the 2022 SFER – Volume I (Cortez et al. 2022) detailed the trend analyses of rainfall and ET in South Florida, tidal trends at select coastal structures, and the four selected water quality metrics in Lake Okeechobee. The 2023 SFER – Volume I chapter (Cortez et al. 2023), detailed spatial trends in saltwater intrusion, and trends in the three ecological metrics: salinity in estuaries, soil accretion/subsidence, and estuarine inland migration. This chapter details the refined analysis of ET and salinity.

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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