Corrections were made on April 11, 2023, to the highlighted text on page 2B-35.

Chapter 2B: Water and Climate Resilience Metrics

Nicole A. Cortez[1], Kristopher Esterson, Carlos Coronado, and Carolina Maran

Contributors: Karin Smith, Christine Carlson, Cassondra Armstrong, Nenad Iricanin, Laura Feher[2], Michael Ross[3], Tiffany Troxler[3], and Fred Sklar

Florida Bay mangrove habitat.

Highlights

The South Florida Water Management District (SFWMD and District) is strongly committed to addressing the impacts of climate change, including rising sea levels, changing rainfall, and flood patterns. Resiliency is the capacity for natural and man-made systems to withstand or to recover quickly from disturbances. The District'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. The District is also making significant infrastructure adaptation investments that are 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 the District 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 data monitored by SFWMD. The District is assessing these data to better understand the current and predicted impacts of climate change on South Florida's ecosystems and water resources. In this year's chapter, the focus is on the following metrics:

- Groundwater levels in South Florida
- Coastal saltwater intrusion trends South Florida
- Salinity trends in the South Florida ecosystems
- Soil subsidence (loss of elevation) trends in South Florida
- Estuarine inland migration trends in South Florida

[1]Workng under contract with the South Florida Water Management District.
[2]United States Geological Survey, Wetland and Aquatic Research Center, Lafayette, Louisiana.
[3] Florida International University, Miami, Florida.

GROUNDWATER LEVELS AND COASTAL SALTWATER INTRUSION TRENDS IN SOUTH FLORIDA

South Florida's coastal aquifers are vulnerable to saltwater intrusion (invasion of a body of fresh water by a body of salt water) and the challenge of maintaining these aquifers as sustainable sources for water supply will be compounded by the effects of sea level rise. Aquifers are underground water-bearing layer of porous rock, sand, or gravel. Rising sea levels, in addition to driving saltwater intrusion, have the potential to increase elevation of coastal aquifer water levels. Sea level rise-driven elevation of the coastal water table, known as shoaling, along with groundwater emergence in low-lying areas, will present challenges for maintaining flood protection and the survival of freshwater plant communities in the future. Groundwater shoaling occurs when rising sea level drives inland water tables up toward the ground surface, whereas groundwater emergence occurs when the water table rises above the ground surface resulting in flooding.

Drilling a well to measure saltwater intrusion.

The inland impacts of sea level rise, including both migration of the saltwater interface and groundwater shoaling and emergence, will require that water managers carefully consider the following factors: water supply impacts and adaptation planning; flooding impacts and adaptation planning; trade-offs between water supply and flood protection; and need for continued/enhanced monitoring and data management.

Resiliency planning and future water management for this metric will rely on accurate data collected in the right places, in the right formats, and archived in a way that allows for future statistical and modeling analysis. To meet these needs, SFWMD should continue to cultivate and support a regional network of saltwater intrusion monitoring wells. Coordination with other government agencies will continue to be important considering that many of the wells utilized for monitoring and mapping saltwater intrusion are owned by other entities. As data is collected, it must be processed and stored so that the data sets will be accessible over the long term while being useful for future statistical and modeling applications. Given the complexities of spatially analyzing the effects of sea level rise in the South Florida environment, the development and refinement of appropriate modelling tools will be an ongoing focus.

Results from current data analyses show that chloride data collected between 1990 and 2020 at four utility monitoring wells in the lower east coast surficial aquifer identify areas of westward (inland) saltwater movement and areas of eastward (seaward) saline water movement. These observed trends in the movement of the saltwater interface along the coast highlight the influence of withdrawals for water use, sea level rise, and freshwater/saltwater interactions. Water managers must consider these factors as part of long-term planning.

In addition, groundwater level data coupled with chloride data reveal how the relationship between fresh and saltwater dynamics in coastal aquifers influences the position of the saltwater interface and informs options for resiliency and adaptation planning. Continued and enhanced monitoring and data management are recommended to inform planning for water supply and flood protection.

SALINITY TRENDS IN SOUTH FLORIDA ECOSYSTEMS

Changes in surface water salinity drive the characteristics of South Florida's estuaries and bays, which 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. The increase in salinity of previously freshwater and brackish (containing a mixture of salt water and fresh water) habitats leads to habitat loss of tidal marshes, poses a threat to the plants and animals that inhabit them, and impacts the soil dynamics and local geologic processes.

Salinity monitoring in Florida and Biscayne bays provides insight into the influence of saltwater inputs from tidal levels and freshwater inputs from upstream sources as well as the influence of rainfall and storms, which is critical feedback for water management decision making. The impacts of climate change, including sea level rise and changing rainfall patterns, will require water managers carefully consider ecological vulnerabilities brought on by climate change and various aspects of water management. Water managers must leverage the availability of fresh water in the system and the ability to move that water south toward Florida Bay and east toward Biscayne Bay. Pathways to reducing the reliance on infrastructure to freshen the system through long-term restoration must be developed and timely and enhanced monitoring and data management are needed.

A surface water and groundwater monitoring station in Biscayne Bay

The challenge of maintaining low salinity levels in in nearshore areas is complex due to the uncertainties of climate change and the fact that any significant changes in weather (short-term) and climate (long-term) patterns, mainly air temperature and rainfall, could limit the effectiveness of existing and planned restoration efforts. As part of future efforts, long-term monitoring data and continued analyses that look more closely at seasonal trends, correlations with flows and other freshwater inputs, and consider landscape characteristics and spatial patterns are needed to track and document how salinity trends evolve in the future and to differentiate natural processes that could be associated with climate change from operational water management practices and restoration strategies. To achieve this, data should encompass a longer period of record, a wide range of conditions, and look at pre- and post-project conditions.

Daily surface water salinity data collected between 2008 and 2022 at six stations within central and eastern Florida Bay and between 2009 and 2021 at two stations in southern Biscayne Bay do not exhibit any statistically significant long-term trends. In Florida Bay, the role of ambient temperature, rainfall, and freshwater inputs are apparent in the daily observed data at all central and eastern sites and point to the relevance of site location within the landscape relative to distance from freshwater inflows and physical barriers to capture the role of tidal inputs in the western bay. In southern Biscayne Bay, ambient factors also influence surface water salinity; however, the proximity to nearby freshwater sources highlight how water management can direct freshwater flows to minimize the impacts of increased temperatures and changing rainfall patterns on the bay.

SOIL SUBSIDENCE TRENDS IN SOUTH FLORIDA

South Florida's coastal ecosystems are exhibiting changes in soil dynamics due to sea level rise, including soil subsidence at both freshwater and oligohaline (having a salinity between 0.5 and 5.0) environments. Soil subsidence is the loss of ground elevation generally associated with saltwater intrusion into freshwater dominated environments. Vertical soil accretion is the process of growth or increase in ground elevation by increasing soil volume. The District has been studying mangrove environments in northeastern Florida Bay and Taylor River to quantify soil accretion and subsidence at various red mangrove-dominated sites throughout the region. The main objective of the monitoring program is to determine whether processes associated with soil surface elevation can keep pace with increasing sea level rise. On the other hand, the rate of soil subsidence informs the District on the effectiveness and benefits of Everglades restoration. This information guides water management practices that aim to reduce the impacts of sea level rise by increasing freshwater input into the salinity transition zone of Northeast Florida Bay. The impacts on soil dynamics might lead to inland migration of coastal habitats and diminish the protection provided by coastal habitats to inland freshwater habitats. Soil subsidence coupled with an increasing rate of sea level rise will likely result in increasing flood hazards in coastal communities, increasing storm surge during storm events, threats to water supply, and shoreline retreat in low-lying coastal areas. This chapter section discusses quantifiable observations in soil elevation change and accretion as part of the SFWMD's water and climate resilience metrics monitoring effort. Improved monitoring and understanding of the response of coastal systems to the effects of climate change is critical to identifying adaptive management opportunities and resiliency planning. Adaptive management is the application of scientific information and explicit feedback mechanisms to refine and improve future management decisions.

A surface elevation table for measuring soil accretion and subsidence (source: John Lynch, United States Geological Survey).

For coastal habitats to persist, the rate of accretion must exceed the rate of sea level rise. Historical tide data reveal increases in tidal elevation have become more rapid over the last 20 years than is observed over the full period of record. The analyses of elevation and accretion data collected between 1997 and 2019 indicate that while accretion rates at some frequently flooded mangrove sites are keeping pace with the historical rate of sea level rise, accretion rates at most sites, mainly at rarely and permanently flooded sites, are not keeping pace with the historical rate of sea level rise. Furthermore, the current rates of accretion and elevation change also suggest coastal habitats would likely not keep up with accelerated rates of current sea level rise. These results underscore the importance of adaptive opportunities for restoration and the extent to which increasing freshwater inputs will benefit the persistence of mangrove forests along the Taylor River and in Florida Bay. Identifying ecological vulnerabilities to sea level rise and other climate change impacts informs restoration efforts and water management practices that minimize land loss to saltwater intrusion.

Restoration efforts that increase freshwater flows and maintain adequate salinity levels in Florida Bay, key influencing factors of soil dynamics, are necessary to stave off the threats of sea level rise and preserve coastal habitat ecosystem services. Monitoring the response of soil dynamics in coastal mangrove forests to changing conditions is critical in determining the extent to which coastal habitats can remain intact and resilient.

ESTUARINE INLAND MIGRATION TRENDS IN SOUTH FLORIDA

Mangroves in Biscayne Bay.

The distribution of coastal mangrove forests and adjacent estuarine ecosystems in South Florida is determined by tidal fluctuation, salinity, and sediment elevation. These forests are important buffer zones between land and sea that contribute to the formation of soil and stabilization of coastlines, acting as natural defense systems against hurricanes and tidal surge protecting inland habitats and coastal communities from flooding. Mangrove forests provide habitat for many marine and terrestrial (on or relating to the earth) animals by providing refuge and nursery grounds and reduce atmospheric carbon through photosynthesis and sinks of carbon stored in peat. Inland freshwater flows entering South Florida's shallow bays is improved as mangroves filter upland runoff.

These habitats are responding to global climate change and changes in historical water flows by moving inland into higher elevations dominated by freshwater plant communities. Mangrove inland migration informs SFWMD on the ability of water management practices to create favorable conditions for coastal marshes and mangrove forests to keep up with sea level rise.

Due to its low elevation and proximity to the coast, the vegetation mosaic in the wetlands of Northeastern Florida Bay is extremely vulnerable to changes caused by the encroaching sea. Much of this region is a flat coastal plain that ascends from sea level to approximately one meter above sea level at the base of the uplands. Soil substrates are mostly marls produced under freshwater conditions, or peats, or some combination of the two. Marl is an unconsolidated (not cemented together) sedimentary rock or soil consisting of clay and lime. Peat is the surface organic layer of a soil that consists of partially decomposed organic matter, derived mostly from plant material, which has accumulated over time. The coastal wetland landscape can respond to sea level rise in three potential ways: (1) peat and sediment accretion that allows coastal wetlands to keep pace with sea level rise, (2) submergence with landward migration of coastal vegetation and wetland habitat, or (3) submergence and loss of coastal wetland habitat, without migration. The third possibility, which will result in the mangrove forests becoming an open estuarine water body, would represent the condition of highest vulnerability to human interests further inland.

Coastal marsh and mangrove communities have persisted through a steady slow rise in sea level by retreating approximately 3 kilometers (1.86 miles) inland since the mid-1940s into historically freshwater marshes. This inland migration was due to an estimated 10 centimeters (1.18 inches) in sea level rise coupled with reductions in freshwater inputs from the altered upland watershed due to development. Insight regarding the response of mangrove ecosystems as sea level begins to rise more rapidly can be obtained by comparing the historical record with current trends.

Mapped vegetation data collected in 1940 and 1994 illustrate significant inland retreat of coastal marshes and mangrove communities occurring in parallel with increasing sea level in eastern Florida Bay. Inland retreat varied within the landscape, with the greatest observed retreat occurring in areas cut off from upstream water sources by roads or levees. The data also illustrate the role of water management in staving off the impacts of sea level rise through freshwater inputs that promote lower surface water salinity, the establishment of mangrove propagule, and soil accretion. The results emphasize the need for continued and enhanced monitoring in Florida Bay and additional monitoring in other areas managed by SFWMD. Expanding hydrological restoration efforts will continue to be important considering projected climate changes.

BACKGROUND

As part of its resilience initiatives, the South Florida Water Management District (SFWMD or District) has established an initial set of water and climate resilience metrics to track and document trends and shifts in water and climate data monitored by SFWMD. This effort supports the SFWMD's mission and resiliency goals of ensuring ecosystem restoration, flood protection, and water supply mission elements while accounting for current and future climate conditions. The District is assessing these data to better understand the current and predicted impacts of climate change on South Florida's ecosystems and water resources. Although many aspects of climate change are still uncertain and a combination of changes to climate variables (e.g., rainfall, temperature, evapotranspiration [ET]) and their consequential impacts (e.g., sea level rise, saltwater intrusion, groundwater elevation, ecosystem changes) could substantially alter water management system operations and infrastructure needs. The analysis of trends and shifts in observed data, along with the collective experience and best professional judgment of SFWMD technical staff, ensures the District's resilience planning and projects are founded on the best available science and serves as the foundation for more robust infrastructure planning and operational decisions in water management and ecosystem restoration. Along with data assessment and integration into resiliency planning efforts, the SFWMD provides the latest information about the water and climate resilience metrics to stakeholders, the public, and partner agencies to support local and regional resilience strategies.

INTRODUCTION

As part of its resilience initiatives, the SFWMD implemented an initial set of water and climate resilience metrics to track and document shifts and trends in District-monitored water and climate data. **Table 2B-1** summarizes key aspects of the water and climate resilience metrics. 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 hydrological cycle. Resilience metrics are the observed consequences of changing climate conditions and can be directly or indirectly managed or mitigated through operation of the water management system or implementation of adaptation strategies. Additional findings of the initial trends observed from historical data, along with a more detailed description of the adopted approaches to data analysis, are reported in the *Water and Climate Resilience Metrics Phase I: Long-term Observed Trends* final report (SFWMD 2021).

With the goal of continuously advancing water and climate data analysis and developing a better understanding of the extent by which these observations may be influenced by climate change and other determinant factors, this chapter was inaugurated in the *2022 South Florida Environmental Report – Volume I*. This year's chapter contains additional technical analysis and scientific considerations for the following five water and climate resilience metrics:

- Water Supply
  - Groundwater Stages
  - Saltwater Intrusion
- Ecosystem Restoration
  - Salinity
  - Soil Subsidence
  - Estuarine Inland Migration

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

Metric	Category (Climate or Resilience Metric)	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Rainfall	Climate Metric	Rainfall intensity, duration, extension, and frequency cannot be controlled by the District.	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	Climate Metric	Evapotranspiration cannot be controlled by the District.	Together with rainfall, evapotranspiration drives the hydrologic cycle and water budget.	Evapotranspiration is projected to increase in a warming climate and impact seasonal patterns and trends in precipitation. Increasing evapotranspiration might contribute to increasing demand on the water management system (due to associated canal levels, flooding, etc.). During drought events, evapotranspiration might deplete already limited water supplies. Evapotranspiration data trends inform District operation and planning efforts.
Tidal Elevations at Coastal Structures	Climate Metric	Tidal elevations cannot be controlled by the District. Tidal elevations at coastal structures can be partially influenced by District operations and the activities of other jurisdictional agencies that cannot be controlled by the District.	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 the District on the limitations and deficiencies of flood control infrastructure. This information provides guidance on the priority investments where resources are most needed for adaptation planning and mitigation strategies. For instance, coastal structures are a vital component of the prevention strategy for the Biscayne aquifer minimum flow and minimum water level (MFL).

Table 2B-1. Continued.

Metric	Category (Climate or Resilience Metric)	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
High Tide Events	Climate Metric	Tidal stages and high tide events cannot be controlled by the District.	High tide events represent extreme values of the tidal stages used to assess trends in sea level rise and identify potential flooding hazards, risks to water supply, and impacts to structural design standards.	Long-term data trends in tidal stages and high tide events and level-of-service performance inform the District on the limitations and deficiencies of natural and structural assets. This information provides guidance on where the District might allocate resources for adaption strategies and planning.
Groundwater Levels/ Elevations/Stages	Resilience Metric	Groundwater levels can partially be controlled by the District. In urban areas, water levels can be manipulated in canal systems. Higher sea levels that increase hydrostatic pressure and impact groundwater cannot be controlled by the District.	Groundwater level data are used to monitor water supply, as inputs to surface water and groundwater modeling, for the establishment of 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.
Saltwater Intrusion/ Saltwater Interface – Chloride Levels	Resilience Metric	The saltwater interface can partially be controlled by the District. The water management system has limited/variable capacity to maintain higher elevations in inland canal systems to stall saltwater intrusion.	Analytical chloride data are used to monitor 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 water supply utilities. Saltwater intrusion has a large impact in water use permitting as an increased number of wells/wellfields/utilities vulnerable to loss of supply or reduced availability during droughts are identified to be at risk or of concern.

Table 2B-1. Continued.

Metric	Category (Climate or Resilience Metric)	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Minimum Flows and Minimum Water Levels (MFLs) – Exceedances/ Violations	Resilience Metric	MFLs are defined as the minimum flows or minimum water levels, adopted by the District Governing Board pursuant to Sections 373.042 and 373.0421, Florida Statutes, at which further withdrawals would be significantly harmful to the water resources or ecology of the area. The District monitors exceedances and violations of MFLs within each of its five water supply planning areas to identify priority water bodies and develop recovery and prevention strategies. Through water management, operational, and regulatory practices, the District may achieve adequate MFL status.	MFLs identify a range of water levels and/or flows above which water could be permitted for consumptive use and are established to protect water resources from harm that may result from permitted water withdrawals and to safeguard water quantities necessary for ecosystem resilience. Minimum levels have been established for lakes, wetlands, and aquifers. Minimum flows have been set for rivers, streams, and estuaries. Flow and water level data are used to ensure that water bodies are in compliance with their minimum requirements and to identify the occurrence of withdrawal exceedances and violations.	MFL 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 MFLs that are adopted. The MFL program supports the District's regional water supply planning process, the consumptive use permitting program, and the environmental resource permitting program. MFLs are used in decision making and affect permit applications as water uses cannot be permitted if they cause any MFL to be violated. MFL data are also used in assessments of water supply sources and declarations of water shortages.
Flooding Events	Resilience Metric	The District 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	Category (Climate or Resilience Metric)	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Water Temperature	Resilience Metric	The District 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. Resilience-driven interventions may reduce the impacts of poor water quality in critical areas and help identify areas that require implementation of restoration strategies.
Dissolved Oxygen	Resilience Metric	The District can indirectly control dissolved oxygen in the system through operational and management decisions, and through coordination with state and local agencies as part of BMAP implementation.	Dissolved oxygen is used to monitor water supply sources and availability for uptake in aquatic and marine ecosystems.	Dissolved oxygen 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 Metric	The District 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.

Table 2B-1. Continued.

Metric	Category (Climate or Resilience Metric)	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Specific Conductance	Resilience Metric	The District 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 metric identifies critical areas that require implementation of restoration strategies.
Estuarine Inland Migration – Everglades	Resilience Metric	The District 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 the District 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	Category (Climate or Resilience Metric)	SFWMD Role	Use (What It Is & What It Is Used For)	Application (How Observed Trends Inform Resilience Efforts)
Soil Subsidence	Resilience Metric	The District 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. The District has been studying mangrove environments in northeastern Florida Bay and Taylor River to determine soil subsidence at non-flooded, frequently flooded, and permanently flooded areas. The main objective of the study is to determine whether mangrove soil surface elevation can keep pace with increasing sea level rise.	The rate of soil subsidence informs the District on the effectiveness and benefits of Everglades restoration. This information guides water management practices that aim to uplift land to reduce the impacts of sea level rise and promote the seaward migration of coastlines (i.e., increasing freshwater input into the salinity transition zone of Taylor Slough).
Salinity in the Everglades	Resilience Metric	The District 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 the District on the effectiveness and benefits of Everglades restoration and guides water management practices.

The following sections provide background information, describe the main findings of these five metrics, and include discussion on influencing factors, recommended improvements to data monitoring, and additional analyses that could help differentiate influences from climate and non-climate factors. Assessment of these metrics is an important step toward planning for the future. Observed trends in long-term water and climate data demonstrate the implications of a changing climate and inform water management and resiliency priorities.

GROUNDWATER LEVELS AND COASTAL SALTWATER INTRUSION TRENDS IN SOUTH FLORIDA

BACKGROUND

South Florida's coastal aquifers are vulnerable to saltwater intrusion and the challenge of maintaining these aquifers as sustainable sources for water supply will be compounded by the effects of sea level rise. Rising sea levels, in addition to driving saltwater intrusion, have the potential to elevate coastal aquifer water levels absent intervening management projects or limiting natural drainage. Sea level rise-driven elevation of the coastal water table, known as shoaling, along with groundwater emergence in low-lying areas, will present challenges for maintaining flood protection and the survival of freshwater plant communities in the future. Conducting a thorough vulnerability analysis of these effects is hampered by the traditionally decoupled nature of analysis where the coastal flooding effects of sea level rise are often reviewed or modeled separately from saltwater intrusion and from groundwater shoaling and emergence. Improved understanding of the multifaceted response of coastal aquifers in South Florida to sea level rise will help in preparing for resiliency and adaptation planning.

DRIVERS AND INFLUENCING FACTORS

Elevation of the inland water table in natural (i.e., unmanaged) coastal areas is in dynamic equilibrium with sea level. As sea level rises, however, this equilibrium is upset. Inland water levels will rise in response and the saltwater interface will migrate inland. The principle that describes this dynamic balance is known as the Ghyben-Herzberg principle. The Ghyben-Herzberg principle (**Figure 2B-1**) states that for every foot of fresh water above sea level (h) in an unconfined coastal aquifer, there will be forty feet of fresh water in the aquifer below sea level (z). Given this relationship, modest reductions of water table elevation (i.e., reduced freshwater head) relative to sea level could therefore result in substantial inland movement of the saltwater interface.

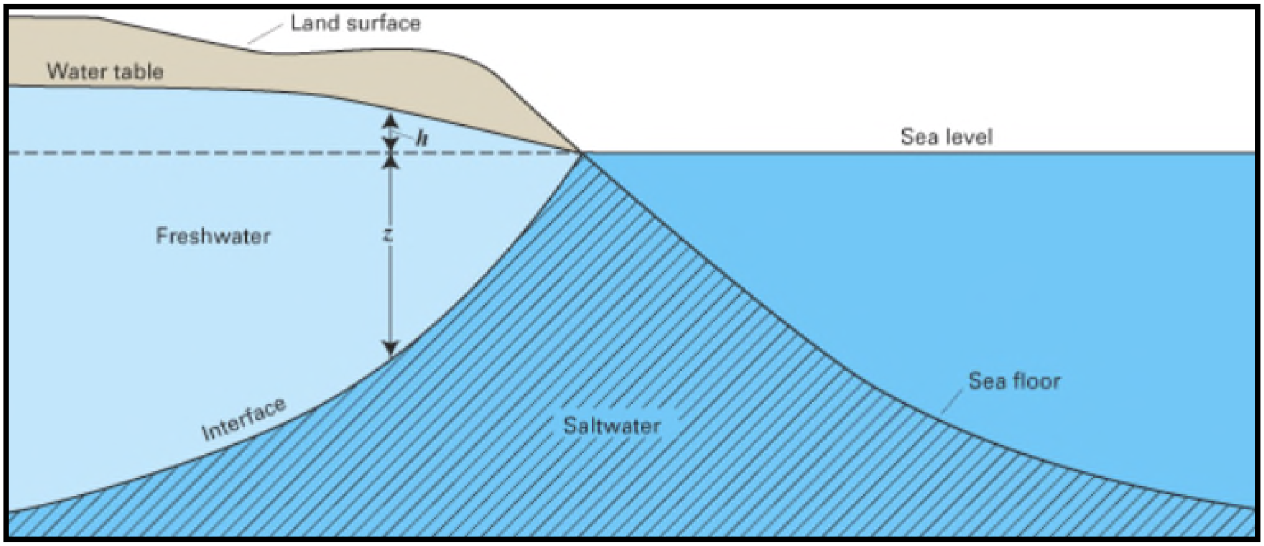

Figure 2B-1. Ghyben-Herzberg relationship between fresh and salt water in an unconfined coastal aquifer.

The Ghyben-Herzberg relationship between fresh and saltwater is dynamic, and the position of the interface, will shift in response to various natural and anthropogenic factors (**Figure 2B-2**).

Factors that may shift the saltwater interface inland in a typical South Florida setting undergoing sea level rise include the following:

- Less aquifer recharge from rain
- Higher ET losses
- Groundwater extraction for water supply
- Pumping, ditching, or channeling for flood control
- Port dredging

Factors that may shift the saltwater interface seaward in a typical South Florida setting include the following:

- More aquifer recharge from rain or from recharge augmentation projects
- Lower ET losses
- Reduced or shifted groundwater extraction for water supply
- Reduced pumping for flood control
- Eliminating ditching and channeling
- Holding higher stages on conveyances and coastal canals

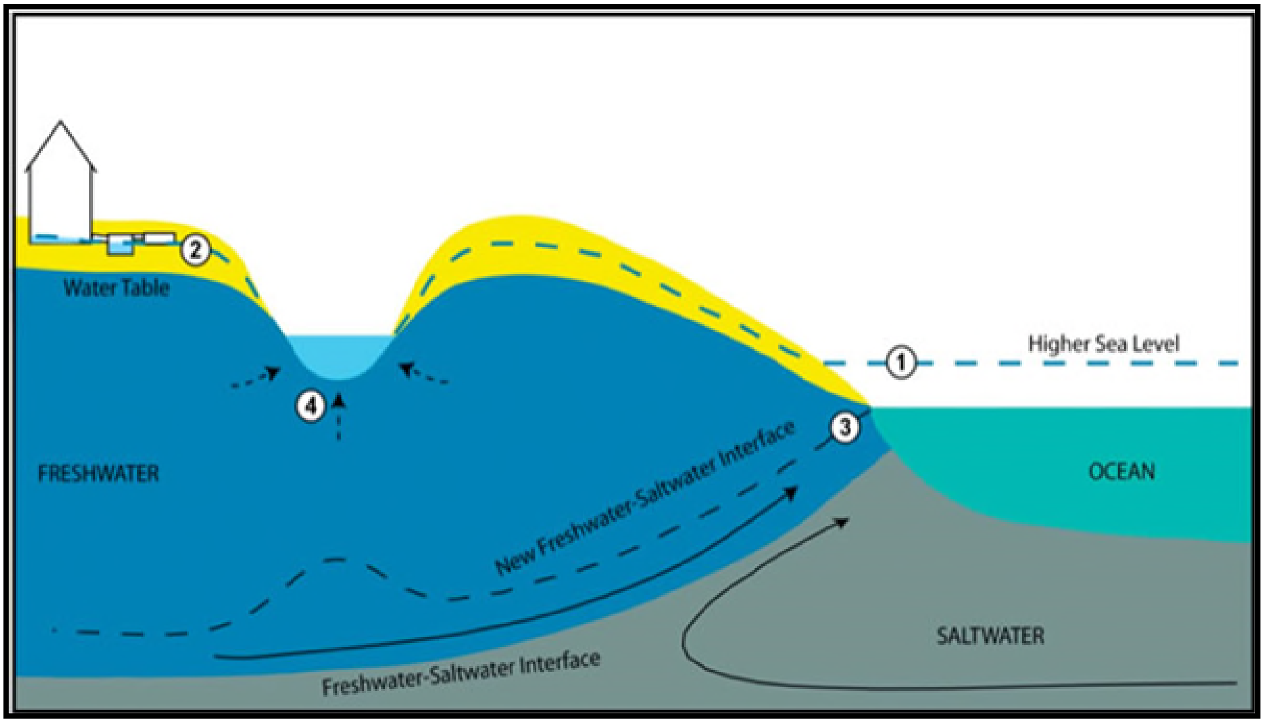

Figure 2B-2. Ghyben-Herzberg relationship between fresh and saltwater in an unconfined coastal aquifer with sea level rise. Source: United States Geological Survey (USGS).

The Ghyben-Herzberg relationship was originally studied as a simplified hydrostatic balance; however, this analytical solution is based on several assumptions that do not hold in all hydrogeologic settings. The Ghyben-Herzberg relationship was later expanded into a hydrodynamic context to accommodate groundwater flows and other complications. However, in order to define the current and potential future extent of saltwater intrusion in highly complex settings such as South Florida, the application of a modern variable density flow and solute transport model is required. While such models are not currently available for all of South Florida, a density-dependent groundwater model is currently under development by the District that will allow model runs to explicitly simulate the effects of sea level rise and some aspects of climate change on the groundwater system. This model, the East Coast Surficial Model (ECSM), includes most of the Lower East Coast (LEC) planning region and the entire Upper East Coast (UEC) planning region. In addition, the Lower West Coast planning region is included in the District's Lower West Coast Surficial/Intermediate Aquifer Systems Model (LWCSIM). In the future, following the completion of the ECSM, it is envisioned that the LWCSIM will be upgraded to be density dependent as well. In the future, as more advanced models are completed, increasingly detailed investigations of the impacts of sea level rise on both saltwater intrusion and inland water table levels will be possible.

There are two groundwater effects of particular interest in the South Florida coastal environment: groundwater shoaling and groundwater emergence. Groundwater shoaling occurs when rising sea level drives inland water tables up toward the ground surface, whereas groundwater emergence occurs when the water table rises above the ground surface resulting in flooding (Befus et al. 2020).

Sea level rise driven groundwater shoaling and emergence is a growing field of study with implications for both flood mitigation planning and water supply planning. As sea level rises, coastal water tables are elevated in response. Rising groundwater gradually fills the unsaturated zone thereby reducing aquifer recharge capacity and increasing runoff potential. Hydrologically, the unsaturated zone is often the main factor controlling water movement from the land surface to the aquifer as recharge.

Coastal topography is also a controlling factor. In locations where there is sufficient topography to allow for the presence of a thick unsaturated zone, sea level rise driven groundwater shoaling may simply result in a slightly thinner unsaturated zone. However, in low lying areas, which are common in coastal Florida, sufficient freeboard space may not be present in the unsaturated zone to accommodate groundwater shoaling due to sea level rise. Where the water table rises to meet topographic lows, newly inundated areas may form. This effect, groundwater emergence, will be an important consideration for coastal flood mitigation planning over the long term.

SALTWATER INTRUSION DATA AND SPATIAL TREND ANALYSIS

The District documents and maps the location of the saltwater interface every five years. The objective of the mapping effort is to evaluate movement of the saltwater interface and elucidate the causes of those changes where possible. The reports are used in multiple aspects of SFWMD's work including planning, resource evaluation, and regulation. The first report of the series was completed in 2009 and the most recent analysis was completed in 2019 (Shaw and Zamorano 2020). Due to the relatively slow movement of groundwater, and through review of the historical movement of the saltwater interface, it was determined that the five-year time interval between analyses is adequate for regional-scale mapping.

The maps display the farthest inland extent of the saltwater interface, defined as the 250 milligrams per liter (mg/L) isochlor that occurred over the 5-year period of analysis. The United States Environmental Protection Agency's (USEPA's) secondary drinking water standard for chloride concentrations is 250 mg/L. The saltwater interface is mapped for multiple aquifers within SFWMD's boundaries. The aquifers mapped include the surficial aquifer system (SAS), which includes the Biscayne aquifer, on the east coast of Florida and the water table, Lower Tamiami, Sandstone, and Mid-Hawthorn aquifers on the west coast of Florida. The District completes mapping for St Lucie, Martin, Palm Beach, Broward, Collier, and Lee counties. The United States Geological Survey (USGS) periodically maps saltwater intrusion for Miami-Dade and Monroe counties with the most recent analysis completed in 2018 (Prinos 2019). Water quality data used to generate the saltwater interface maps are compiled from multiple sources including cities, counties, the Florida Department of Environmental Protection (FDEP), water utilities permitted by FDEP and/or the District, and USGS. Water quality data from more than 1,000 wells were used to create SFWMD's 2019 saltwater interface maps.

SFWMD's saltwater interface mapping has shown that the rate and extent of saltwater intrusion is not uniform across all counties in South Florida. In many areas, the saltwater interface has been found to be nearly stable across multiple mapping events. However, in some areas the saltwater interface continues to move inland while in other locations the interface has moved back towards the coast.

Palm Beach County – Surficial Aquifer System

Overall, there has been no apparent inland movement of the saltwater interface in Palm Beach County between 2009 and 2019. In fact, near the City of Lake Worth Beach and the City of Lantana, there is an area of seaward migration of the saltwater interface (**Figure 2B-3a**). This also is evident in the time series plot representing USGS monitor well PB-1717 (**Figure 2B-3b**). These improvements (seaward movements) to the saltwater interface may be due to the shifting of pumpage among certain wells within a wellfield or the reduction of pumpage from SAS wells in favor of Floridan aquifer system wells.

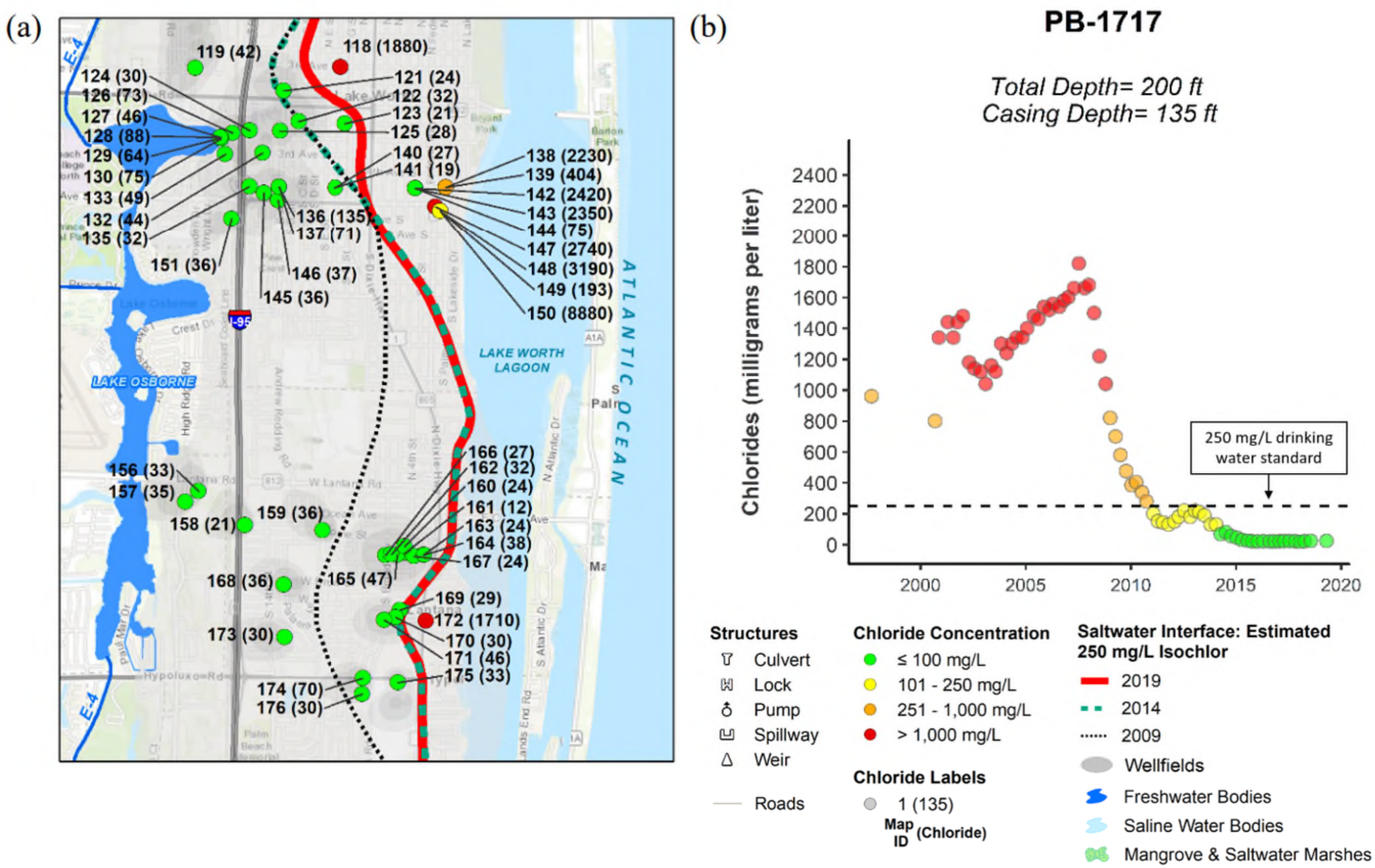

Figure 2B-3. (a) Evidence of eastward (seaward) saline migration around Lake Worth Beach and Lantana and (b) time series plot for monitor well PB-1717, which shows a decline in chloride concentrations. (Notes: ft – feet and source – Shaw and Zamorano 2020.)

Broward County – Surficial Aquifer System

Inland movement of the saltwater interface between 2009 and 2019 has been documented in Broward County (Shaw and Zamorano, 2020). This is evident in **Figure 2B-4a** where the three isochlors mapped in 2009, 2014, and 2019 are progressively moving west in Pompano Beach. In some cases, there is evidence of saltwater encroachment in the time series plot for a single monitor well. For example, in **Figure 2B-4b**, Map ID 48, which represents USGS monitor well G-2896, had a chloride concentration of approximately 750 mg/L in 2009, approximately 2,000 mg/L in 2015, and approximately 4,000 mg/L in 2019. These data represent the movement of the saltwater interface past a single monitoring well as the wedge of saltwater moves inland.

In southern Broward County, most of the Dania Beach wellfield was taken out of service as the saltwater interface moved into and beyond the wellfield. **Figure 2B-5a** shows that chloride concentrations in several wells (Map IDs 74 to 77) exceed 2,000 mg/L. Farther south, the Hallandale Beach wellfield is another impacted area where inland migration of the saltwater interface is observed (**Figure 2B-5a**). The time series plot in **Figure 2B-5b**) shows monitor well G-2478 (Map ID 108) was fresh prior to 2002 but as the saltwater interface moved westward, chloride concentrations increased to approximately 1,000 mg/L in 2009, approximately 2,500 mg/L in 2014, and is greater than 6,000 mg/L in 2019

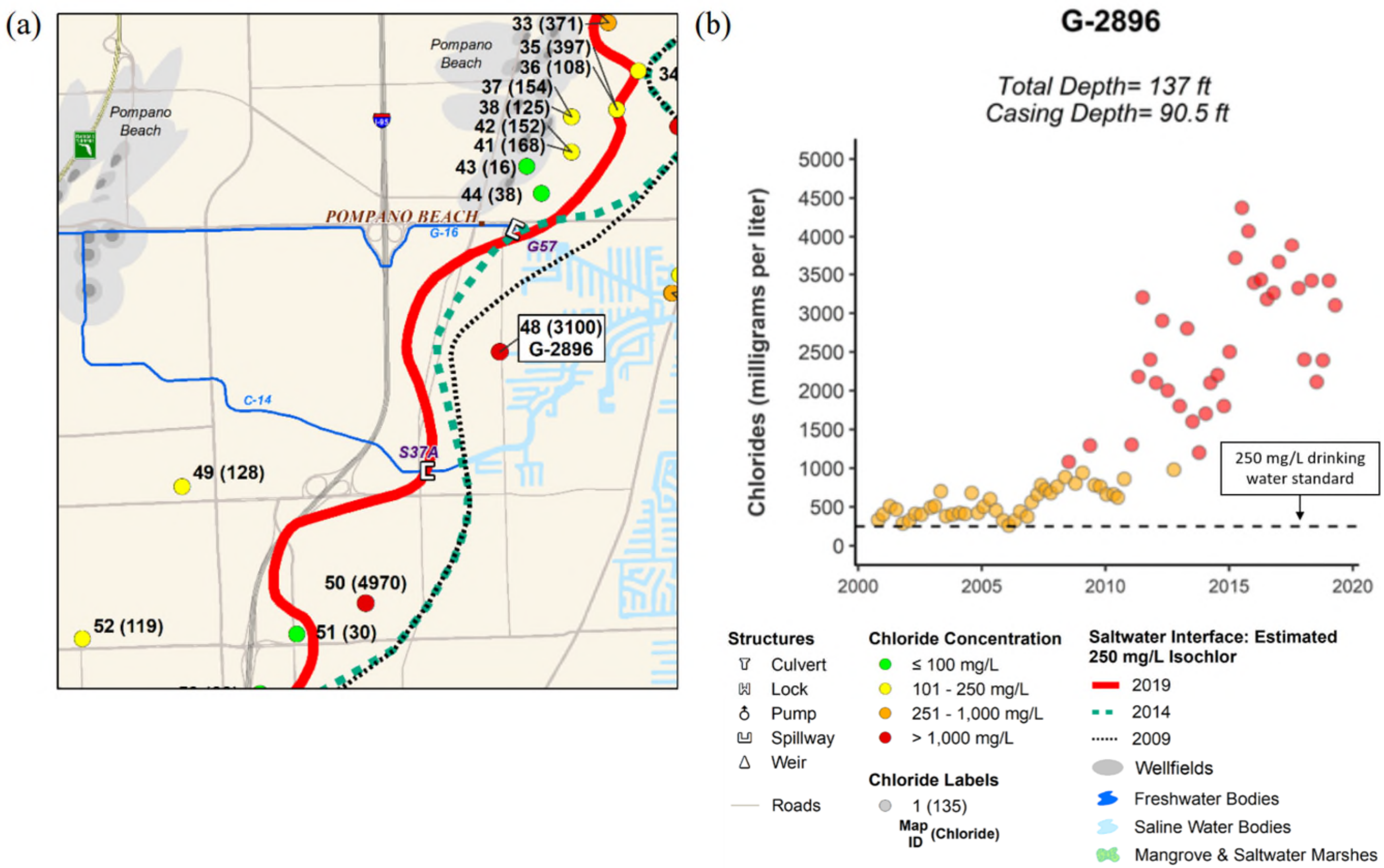

Figure 2B-4. (a) Evidence of westward (inland) saline migration in Pompano Beach and (b) time series plot showing the saltwater interface passing through monitor well G-2896. (Source: Shaw and Zamorano 2020.)

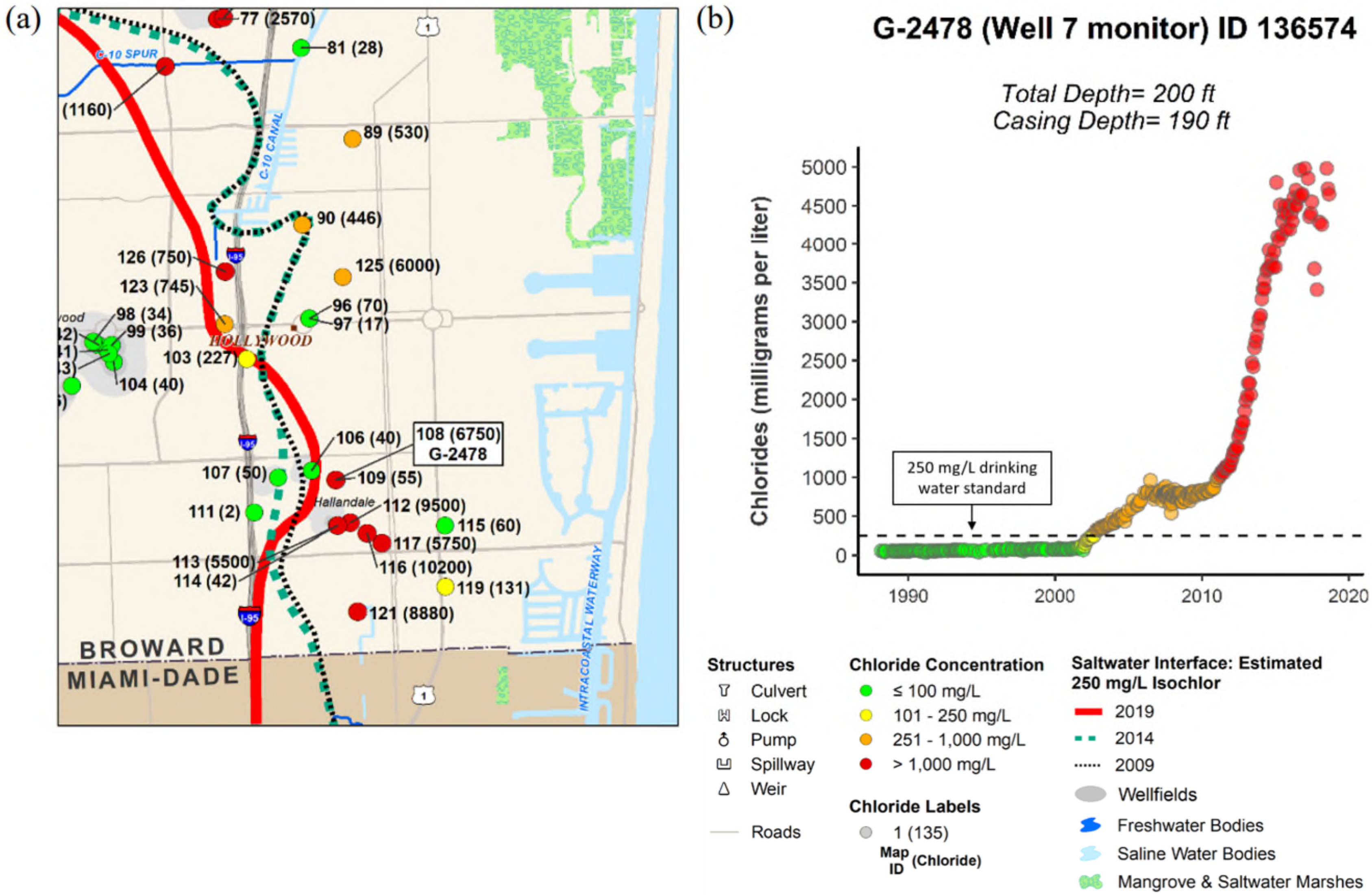

Figure 2B-5. (a) Westward (inland) movement of the saltwater interface impacting Dania Beach and Hallandale wellfields and (b) time series plot showing the saltwater interface passing through monitor well G-2478. (Source: Shaw and Zamorano 2020.)

Miami-Dade County – Biscayne Aquifer

In Miami-Dade County, the 2018 location of the saltwater interface (as measured at the base of the Biscayne aquifer) is, in most areas, further inland compared to its mapped position in 2011 (Prinos 2019). While this indicates that saltwater intrusion is actively occurring, attempts to quantify the inland movement rates of the saltwater interface are complicated by data scarcity. However, in one location within Miami-Dade County that contained a suitable collection of wells, and where the saltwater interface passed during the period of study, the interface moved inland at an estimated rate of 102 meters per year (Prinos 2019).

RELEVANCE TO RESILIENCY IN WATER MANAGEMENT

The inland impacts of sea level rise, including both migration of the saltwater interface and groundwater shoaling and emergence, will require that water managers carefully consider the following factors:

- Water supply impacts and adaptation planning.
- Flooding impacts and adaptation planning.
- Trade-offs between water supply and flood protection. We need to plan for flood mitigation projects while considering potential deleterious impacts of those projects to water supply objectives.
- Need for continued/enhanced monitoring and data management.

Water managers should consider the contribution of sea level rise to saltwater intrusion in long-term planning. As the saltwater interface approaches, and potentially reaches coastal wellfields, adaptation projects will be required to continue to meet water supply needs. As the water table rises due to groundwater shoaling, the unsaturated zone will be compressed, resulting in a greater portion of rainfall being lost to tide as run off rather than recharging the aquifer. This effect has implications for water supply as it may reduce the amount of recharge that replenishes aquifers and thereby limit the yield of some coastal wellfields.

Sea level rise-driven groundwater shoaling and emergence will exacerbate existing coastal flooding issues and create new concerns as well. As coastal water tables rise, there will be an increase in the frequency, depth, and duration of flooding, absent implementation of adaptation and mitigation projects (e.g., increased drainage pumping). One potential adaptation strategy to reduce flooding and maintain the flood protection level of service would be to implement a series of projects designed to lower the elevation of the water table. However, the potential resulting reduction in freshwater head would affect the dynamics of the saltwater interface moving the interface inland.

Adaptation and resiliency planners will need to consider the interplay, and potential trade-offs, between flood mitigation projects and water supply. Planning for additional flood challenges caused by rising coastal water levels may be complicated in some areas by the need to maintain higher freshwater heads in coastal aquifers for the purpose of protecting water supply for drinking and household needs, agriculture. recreation, and restoration. While flood mitigation efforts may seek to lower the water table elevation to address that concern, water supply interests may seek to increase the water table elevation (i.e., protective freshwater head) that keeps the saltwater interface away from coastal wellfields. Given this contrast in objectives, the potential trade-offs between flood mitigation and maintaining sustainable water supplies will need to be carefully balanced.

Changes in the position of the saltwater interface and water levels are captured by existing monitoring wells. These wells are owned by multiple entities and relatively few have been designed specifically for monitoring sea level rise impacts (e.g., inland migration of saltwater interface) over decades. For example, many wells that are utilized for SFWMD’s saltwater interface mapping products were constructed near water supply wellfields for regulatory purposes (i.e., ensuring the wellfield extractions do not adversely affect the position of the saltwater interface). Water managers tracking impacts across decades may need to consider construction of additional wells and enhancements in instrumentation or sampling protocols to ensure that the type of high quality data sets needed for planning will be available in the future. Similarly, the methods used for well sampling and data retention should be purposefully designed to accommodate future statistical analysis to detect and quantify changes on a multi-decadal time scale.

COMMENTS AND RECOMMENDATIONS

The challenges of sea level rise-driven change in groundwater levels and saltwater intrusion in South Florida are complex and multi-decadal in nature. Resiliency planning and future water management will rely on accurate data collected in the right places, in the right formats, and archived in a way that allows for future statistical and modeling analysis. To meet these needs, SFWMD should continue to cultivate and support a regional network of saltwater intrusion monitoring wells. Intergovernmental coordination will continue to be important considering that many of the wells utilized for monitoring and mapping saltwater intrusion are owned by many other entities. As data is collected it must be processed and stored so that the data sets will be accessible over the long term while being amenable for future statistical and modeling applications. Given the complexities of spatially analyzing the effects of sea level rise in the South Florida environment, the development and refinement of appropriate modelling tools will be an ongoing focus.

SALINITY TRENDS IN SOUTH FLORIDA ECOSYSTEMS

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 South Florida Environmental Report (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 and Biscayne bays. The two subsequent sections of this chapter discus observations in vegetation dynamics and soils processes as part of the District's water and climate resilience metrics monitoring effort. 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 minimal due to the presence of keys that act as physical barriers to water exchanges and 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 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 the mouths of rivers, 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 minimal 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 increase and increase evapotranspiration. Altogether, these conditions increase the likelihood of further encroachment of sea water in freshwater inland areas.

Over time, the factors that increase salinity should 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. While variations in rainfall, which are dependent on short-term local weather patterns and long-term climatic variability, which influence surface water salinity, water management is a key component in maintaining adequate salinity levels by establishing higher freshwater levels inland. In the coming years, it will be 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.

SALINITY DATA AND TREND ANALYSIS

The District oversees a comprehensive ecological monitoring program in the southern Everglades marshes, mangrove transition zone, and estuarine waters of Florida and Biscayne Bays to evaluate the effects and benefits of Everglades restoration. Specifically, the program monitors the C-111 Spreader Canal Western Project, which has been in operation since 2012. Ecological monitoring conforms to the project monitoring plan (SFWMD and USACE 2011), which outlines protocols for assessing hydrology, nutrients, water quality, vegetation, and fauna and their interactions in the footprint of, and downstream of, C-111 Spreader Canal Western Project operations. The restoration project is designed to retain or increase freshwater flow within Taylor Slough and into northern Florida Bay by construction of a hydrologic seepage barrier to retain water that formerly flowed out of Taylor Slough and eastward into the C-111 Basin. Retaining water in Taylor Slough is expected to increase water levels and hydroperiod in the slough, increase freshwater discharge towards the southern wetland and into Florida Bay, and lessen the frequency, duration, and extent of elevated salinity levels in the bay and estuarine habitats. The *Water and Climate Resilience Metrics Phase I: Long-term Observed Trends* (SFWMD 2021) final report introduced the salinity data available beginning in 2008 for sites in Florida Bay.

The District receives instantaneous (telemetered) water quality data and reports surface salinity levels as part of the Biscayne Bay Coastal Wetlands project for two stations located within the western boundary of Biscayne National Park (BNP), Biscayne Bay Coastal Wetland 8 (BBCW8), and Biscayne Bay Coastal Wetland 10 (BBCW10). Real-time water quality data informs water managers about flows into the bay and nearshore salinity levels and is critical for flagging extended periods of high salinity (35 or greater) that threaten the health of the shallow bay ecosystem. From an operational point of view, these data inform water managers of where freshwater flows are needed most. Historically, these stations were monitored by the SFWMD. In September 2021, BNP took over maintenance, monitoring, and reporting of station data. Additional sites in Biscayne Bay are monitored periodically under the Biscayne Bay Coastal Wetlands (BBCW) permit, as part of the Comprehensive Everglades Restoration Plan (CERP). The data for these stations are available in DBHYDRO, SFWMD’s corporate environmental database.

This chapter section provides expanded statistical analysis of the available data in Florida Bay and brings additional analysis of available data for Biscayne Bay operational reporting sites shown in **Figure 2B-6**. Alligator Creek (AC) monitoring station, located in western Florida Bay, and McCormick Creek (MC), Argyle Henry (AH), and Taylor Mouth (TM), located in central Florida Bay, represent salinity in Taylor Slough. Joe Bay (JB) and Trout Creek (TC), located in eastern Florida Bay, represent salinity in the C-111 Basin. The BBCW8 and BBCW10 monitoring stations are located on the western border of BNP, specifically in the northwest and southwest boundaries of the park near the outlet of two SFWMD spillways, S-123 and S-20F, respectively.

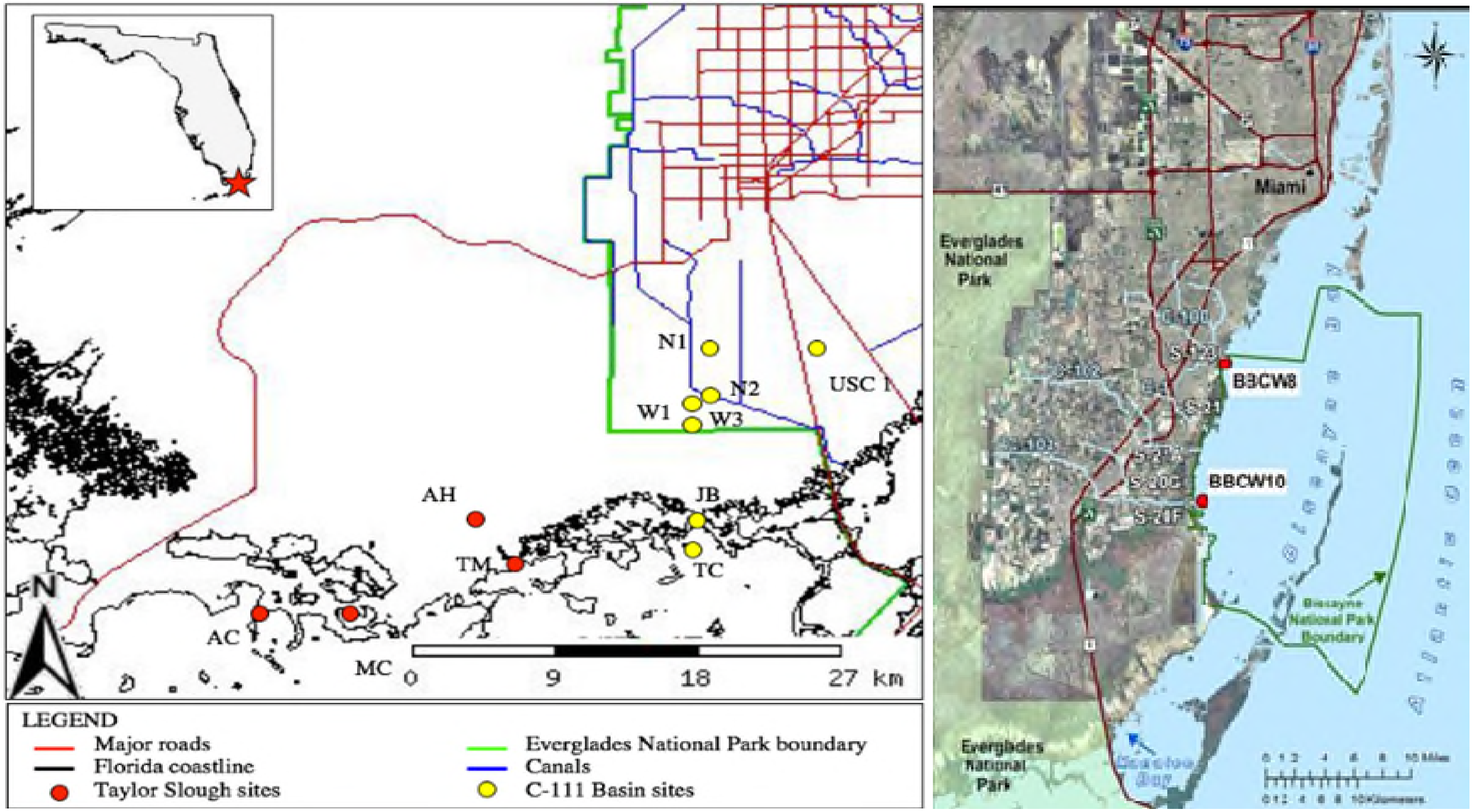

Figure 2B-6. Locations of salinity monitoring sites in Florida Bay (left) and Biscayne Bay (right) evaluated as part of this trend analysis.

Daily salinity was collected every 1 to 3 days and varies between monitoring sites. The available salinity time series data show seasonally influenced increasing and decreasing salinity concentrations over time. Trend analyses were performed using Mann-Kendall test to identify whether a trend in salinity exists at each of the selected sites and Sen's Slope was used to determine whether the trend is positive or negative. For the purposes of this assessment, salinity data were annualized (averaged) by water year to smooth out seasonality in daily data and only water years with a complete data set were included in the trend analyses. The data are assumed to be independent and normally distributed, and missing values were ignored. The test was performed using a 95% confidence band around the trend slope for the available salinity data. A trend is considered significant and rejects the null hypothesis that there is no significant trend in the series if the probability value is lower than the significance level of 0.05.

No significant trend was observed at any of the monitoring sites in Florida Bay. Alligator Creek (AC) and McCormick Creek (MC), located in the western and central regions of Florida Bay, exhibited the highest averages in daily salinity and greatest magnitude between minimum and maximum daily salinity concentrations. The results of this analysis support that observed salinity concentrations in western Florida Bay may be more greatly influenced by tidal inputs than the central and eastern regions of the bay, as noted in the *Drivers and Influencing Factors* subsection just above. The remaining sites: Argyle Henry (AH), Taylor Mouth (TM), Joe Bay (JB) and Trout Creek (TC), located in central and eastern Florida Bay and the C-111 Basin where wind, freshwater flows, and evapotranspiration are dominating factors influencing observed salinity concentrations, exhibited lower averages in daily salinity concentrations in addition to relatively smaller magnitudes between minimum and maximum daily salinity concentrations. **Table 2B-2** summarizes the daily salinity statistics and results of the trend analyses at upstream and downstream water quality monitoring sites in Taylor Slough and the C-111 Basin sites in Florida Bay. Plotted daily salinity time series data and trend line at each water quality monitoring site in Florida Bay are presented in **Figures 2B-7** through **2B-9**.

Table 2B-2. Summary of statistics and trend analyses results in Florida Bay.

	AC	MC	AH	TM	JB	TC
Period of Record	2009–2022	2008–2022	2008–2022	2008–2022	2008–2022	2008–2022
Minimum Value	5.60	4.00	0.00	0.40	0.20	0.40
Median Value	35.20	27.30	2.20	17.15	11.00	23.05
Maximum Value	82.00	63.40	47.90	49.70	55.70	56.30
Average	76.40	59.40	47.90	49.30	55.50	55.90
Magnitude	35.42	35.42	8.87	17.62	14.93	23.12
Probability value	0.74	0.55	0.87	0.55	0.30	0.70
Sen's Slope	0.14	0.35	0.05	0.32	0.70	0.29
Observed trend	No trend	No trend	No trend	No trend	No trend	No trend

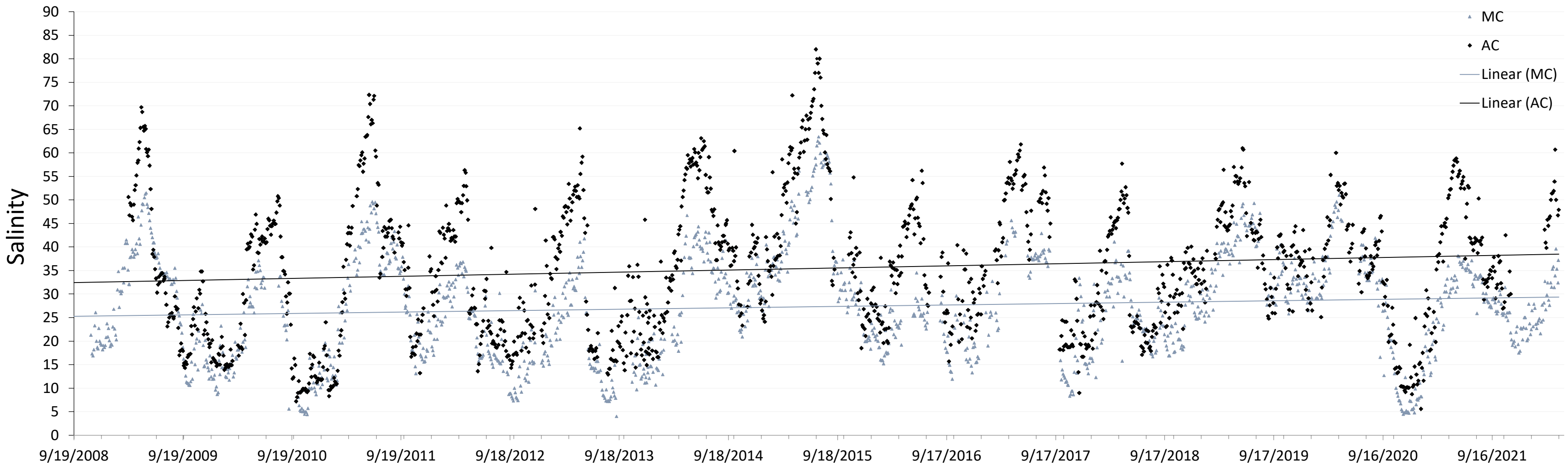

Figure 2B-7. Plotted daily salinity time series and trend line at Alligator Creek (AC) and McCormick Creek (TM).

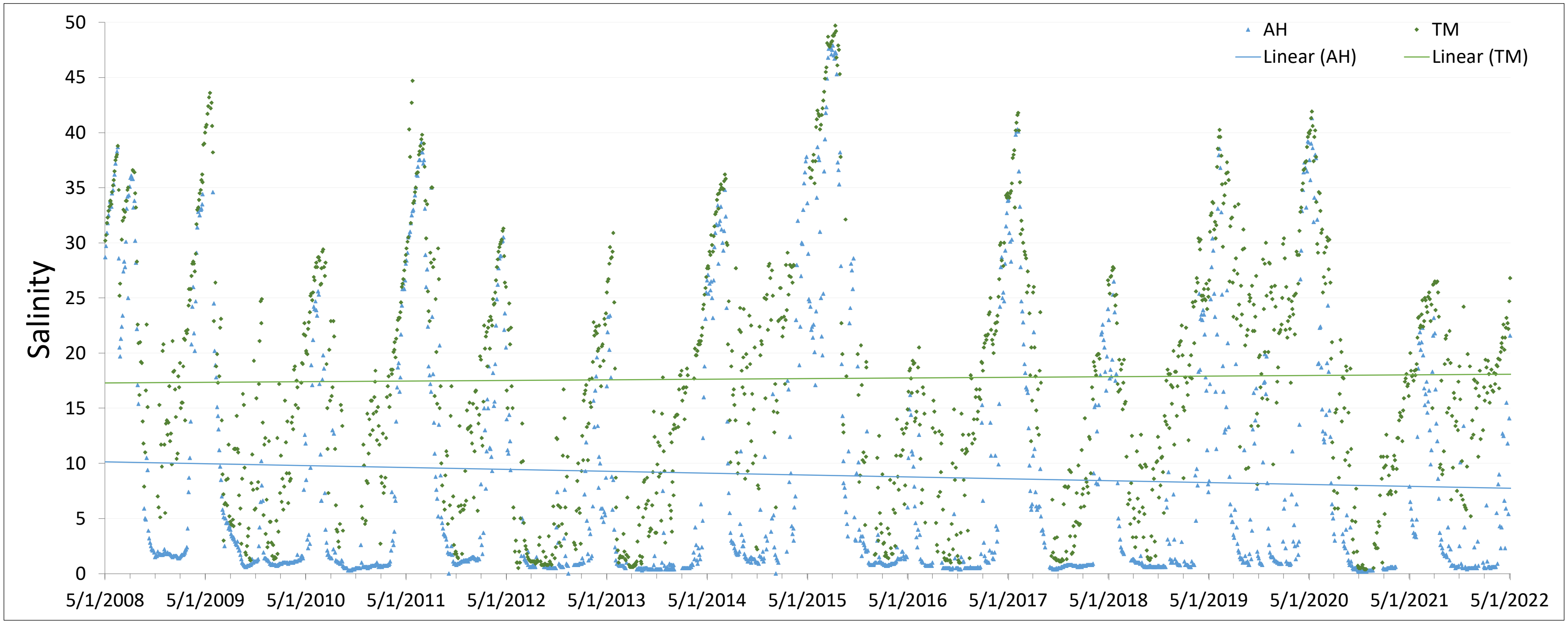

Figure 2B-8. Plotted daily salinity time series and trend line at Argyle Henry (AH) and Taylor Mouth (TM).

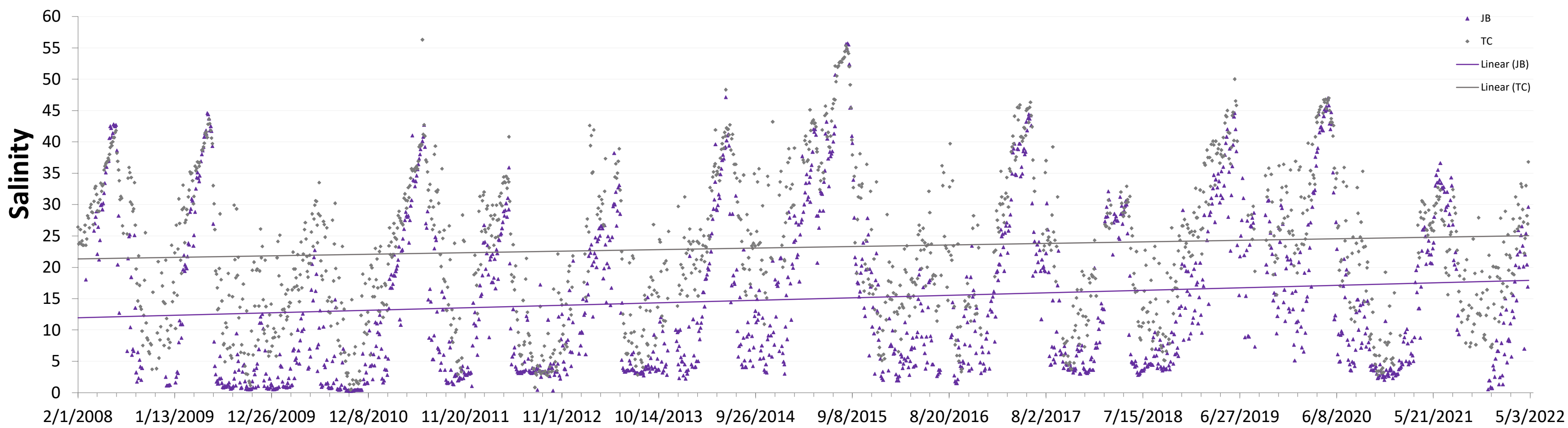

Figure 2B-9. Plotted daily salinity time series and trend line at Joe Bay (JB) and Trout Creek (TC).

No statistically significant trends were identified in annualized daily salinity concentrations observed at BBCW8 and BBCW10 for the available data and period of record. Average daily salinity concentrations at both sites are below 35, the operational monitoring high salinity threshold. The BBCW8 and BBCW10 monitoring stations are located on the northwest and southwest boundaries of BNP near the outlet of two SFWMD spillways, S-123 and S-20F, respectively. The location of these sites and the availability of instantaneous data reporting allows water managers to move water where it is needed most, north via the S-123 spillway or south via S-20F. The location and timely data availability also help water managers gauge system responses to freshening efforts as well as system responses to climate variables. **Table 2B-3** summarizes the daily salinity statistics and results of the trend analyses at each water quality monitoring site in Biscayne Bay. Plotted daily salinity time series data and trend line at each water quality monitoring site in Biscayne Bay are presented in **Figures 2B-10** and **2B-11**.

Table 2B-3. Summary of statistics and trend analyses results in Biscayne Bay.

	BBCW8	**BBCW10**
Period of Record	2009–2021	2009–2021
Minimum Value	9.24	6.84
Median Value	28.29	28.55
Maximum Value	46.29	49.10
Average	28.78	28.42
Magnitude	37.05	42.26
Probability value	0.12	0.84
Sen’s Slope	-0.35	-0.11
Observed trend	No trend	No trend

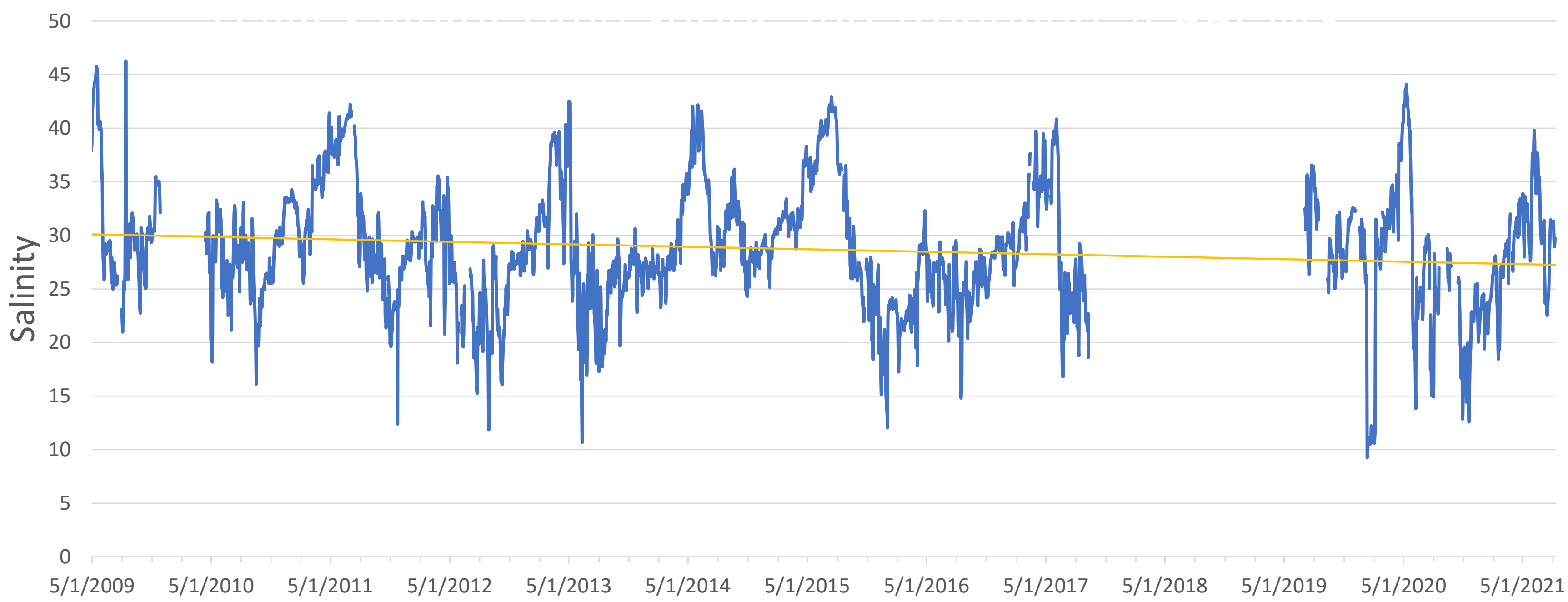

Figure 2B-10. Plotted daily salinity time series and trend line at BBSW8.

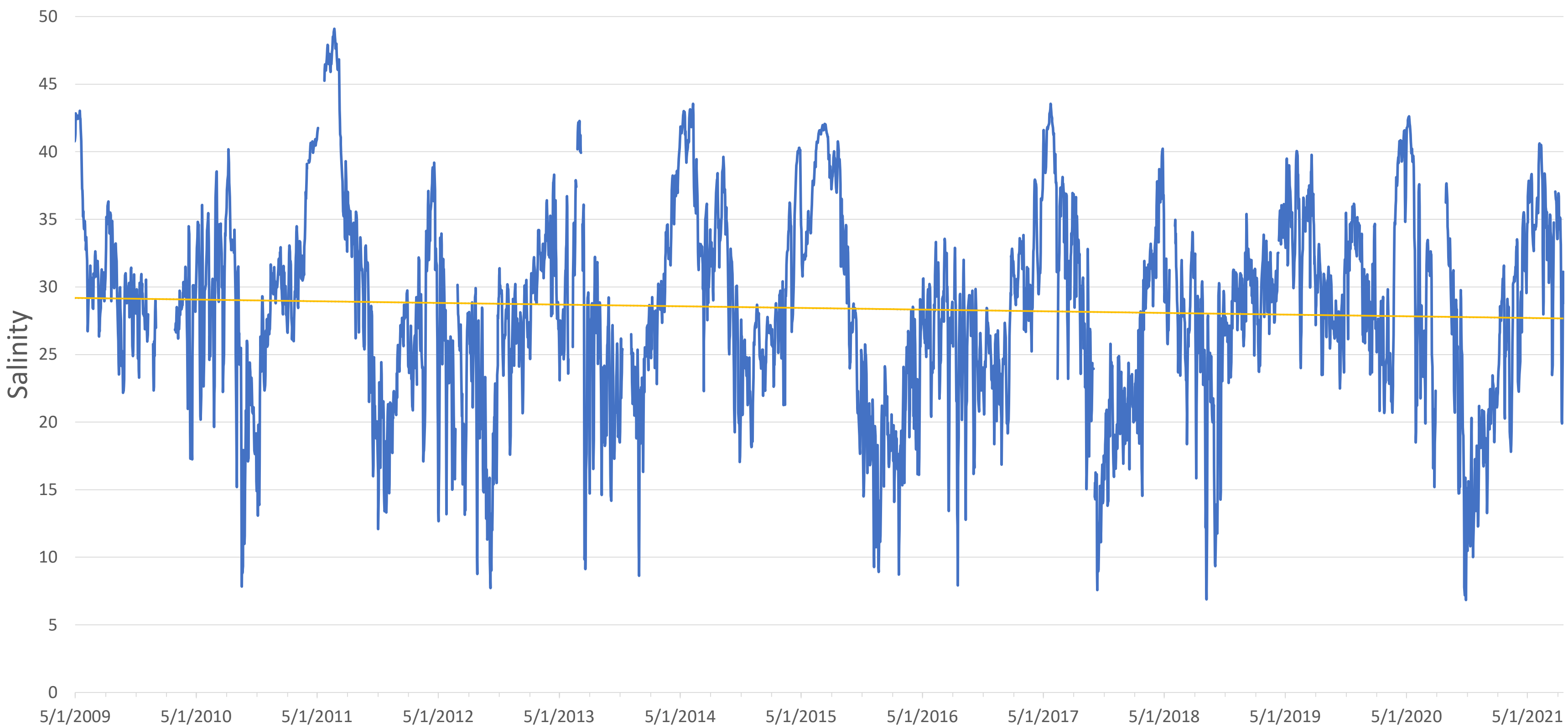

Figure 2B-11. Plotted daily salinity time series and trend line at BBSW10.

A correlation analysis was conducted to characterize the relationship between flow and daily salinity concentrations were averaged by water year to smooth out seasonal effects. Structure flow is the average daily total of flow through S-123, S-21, S-21A, S-20G, S-20F, and S-700. Statistically, the observed salinity at BBSW8 and BBSW10 is negatively correlated to flow at nearby SFWMD structures, as indicated by the negative correlation coefficients, so as flow increases, salinity decreases (**Figure 2B-12**). Since WY2010, flow through SFWMD structures has increased and daily salinity at each site has decreased (**Figure 2B-13**). Conversely, increases in salinity are observed during periods of lower flow (**Figure 2B-13**).

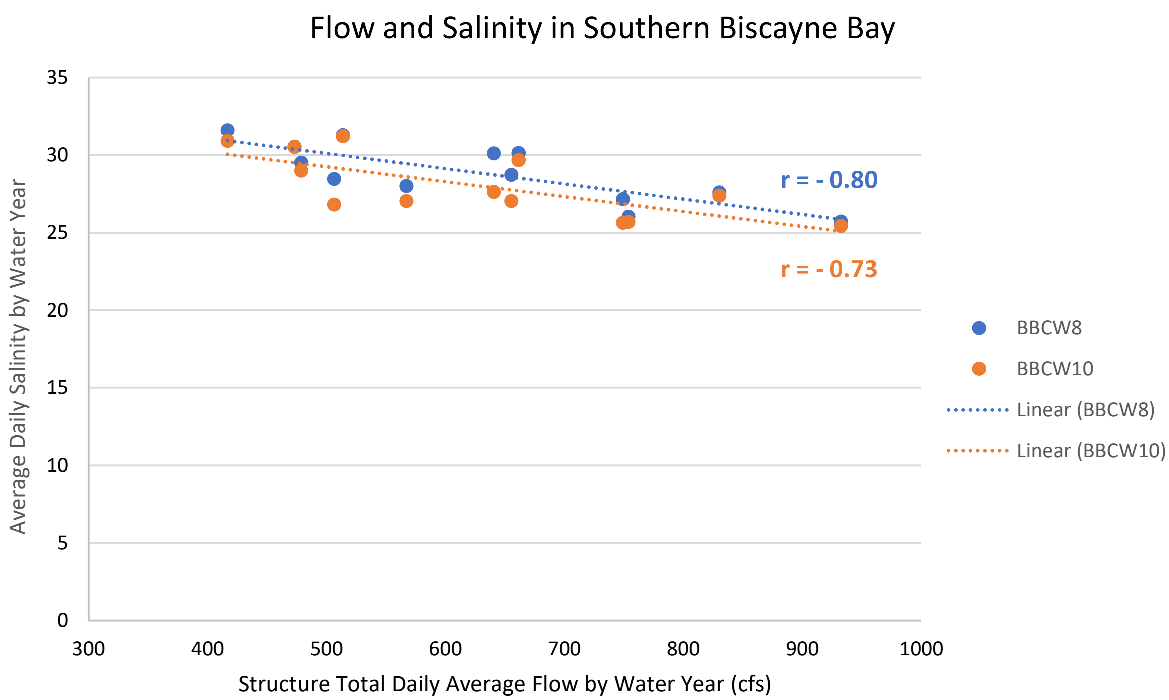

Figure 2B-12. Correlation between water year flow averages and water year daily salinity average at BBSW8 and BBSW10.

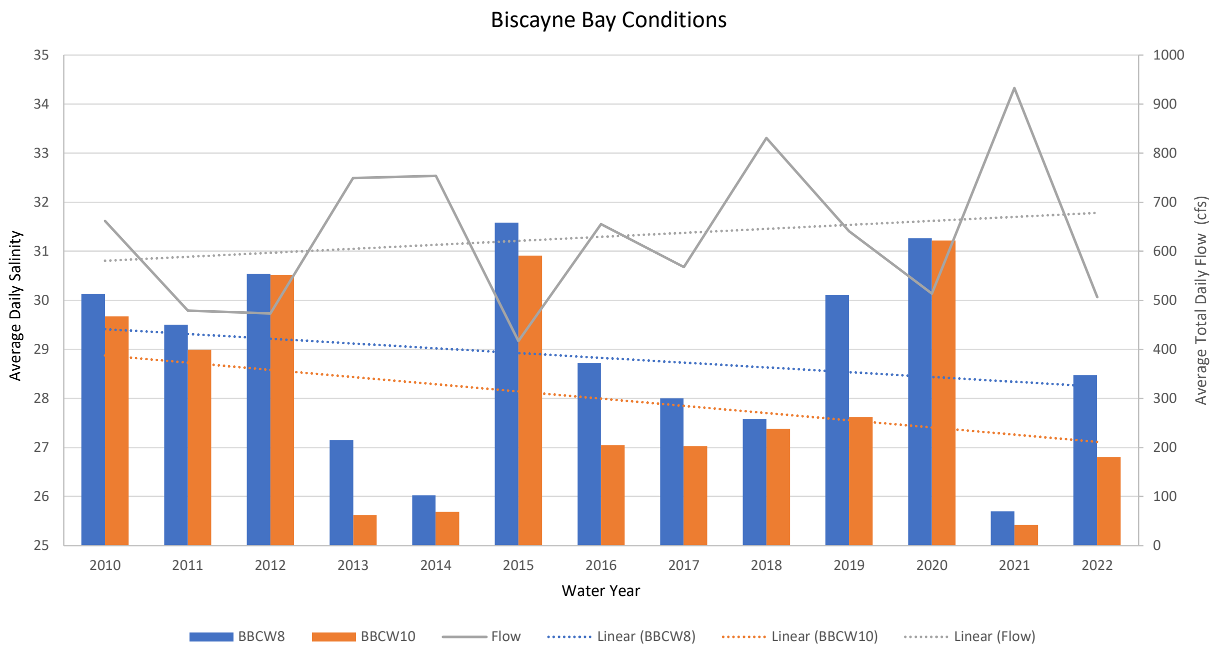

Figure 2B-13. Observed average daily salinity and average total daily flow between 2010 and 2022.

RELEVANCE TO RESILIENCY IN WATER MANAGEMENT

Changes in surface water salinity drive the hydrological and biological characteristics of South Florida's coastal ecosystems. Salinity monitoring in Florida and Biscayne bays provides insight into the influence of precipitation and storm events, freshwater inputs from upstream sources, and saltwater inputs from tidal levels in certain areas, which is critical feedback for water management decision making. With consideration for anticipated sea level rise and changing climate conditions in Florida and Biscayne bays, monitoring long-term trends in salinity is vital to supporting overall resiliency in South Florida's coastal ecosystems and achieving lower salinity as part of ongoing restoration efforts. The impacts of climate change, including sea level rise and changing rainfall patterns, will require that water managers carefully consider ecological vulnerabilities brought on by climate change and various aspects of water management. Operational changes have increased flows into Florida Bay and deliver adequate flows into Biscayne Bay for adaptive planning must continue to be prioritized. Water managers must leverage the availability of fresh water in the system and the ability to move that water south toward Florida Bay and east toward Biscayne Bay. Short-term and long-term examination of the effects of freshwater releases on downstream ecology are being conducted. Pathways to reducing the reliance on infrastructure to freshen the system through long-term restoration must be developed and timely and enhanced monitoring and data management are needed.

COMMENTS AND RECOMMENDATIONS

The challenge of maintaining low salinity levels in in nearshore areas is complex due to the uncertainties of climate change and the fact that any significant changes in weather (short-term) and climate (long-term) patterns, mainly air temperature and rainfall, could limit the effectiveness of existing and planned restoration efforts. As part of future efforts, long-term monitoring data and continued analyses that look more closely at seasonal trends, correlations with flows and other freshwater inputs, and consider landscape characteristics and spatial patterns are needed to track and document how salinity trends evolve in the future and to differentiate natural processes that could be associated with climate change from operational water management practices and restoration strategies. To achieve this, data should encompass a longer period of record, a wide range of hydrometeorological conditions, and look at pre- and post-project conditions.

SOIL SUBSIDENCE TRENDS IN SOUTH FLORIDA

BACKGROUND

South Florida's coastal ecosystems are exhibiting changes in soil dynamics due to sea level rise, including soil subsidence at both freshwater and oligohaline environments. Soil subsidence is the loss of ground elevation generally associated with saltwater intrusion into freshwater dominated environments. Vertical soil accretion is the accumulation of organic matter and sediment input that enhance expansion of total soil volume. The District has been studying mangrove environments in northeastern Florida Bay and Taylor River to quantify soil accretion and subsidence at various red mangrove-dominated sites throughout the region. The main objective of the monitoring program is to determine whether processes associated with soil surface elevation can keep pace with increasing sea level rise. On the other hand, the rate of soil subsidence informs the District on the effectiveness and benefits of Everglades restoration. This information guides water management practices that aim to reduce the impacts of sea level rise by increasing freshwater input into the salinity transition zone of Northeast Florida Bay. The impacts on soil dynamics might lead to inland migration of coastal habitats and diminish the protection provided by coastal habitats to inland freshwater habitats. Soil subsidence coupled with an increasing rate of sea level rise will likely result in increasing flood hazards in coastal communities, increasing storm surge during storm events, threats to water supply, and shoreline retreat in low-lying coastal areas. This chapter section discusses quantifiable observations in soil elevation change and accretion as part of the District's water and climate resilience metrics monitoring effort. Improved monitoring and understanding of the response of coastal systems to the effects of climate change is critical to identifying adaptive management opportunities and resiliency planning.

DRIVERS AND INFLUENCING FACTORS

Soil subsidence or expansion is driven by surface and subsurface processes directly associated with root dynamics, including root production, mortality and decomposition. Soil subsidence is calculated by subtracting the rate of vertical accretion from the rate of elevation change. Mechanisms that contribute to soil subsidence or expansion include compression of gas-filled pore spaces, deconsolidation of excessively waterlogged soil, compaction of aerenchyma tissue, and acceleration of soil mineralization (Chambers et al. 2019). Environmental conditions that contribute to soil subsidence or expansion include plant growth/turnover, flood depth and duration, freshwater flow, salinity, sea level and tides, and storm events (Cahoon 1998, 1999). Nutrient cycling and oxidation dominate the biogeochemical processes of soil formation and loss in the Florida Bay coastal mangrove environment. Pulse storm events play an important role in nourishing mangrove sites closer to the coast with inorganic matter imported from Florida and Biscayne bays but the extent of elevation gain or loss in coastal wetlands from storms varies locally (Cahoon

2003). Anthropogenic causes of soil subsidence in South Florida inlcude human-driven climate change and the reduction of freshwater flow south to Florida Bay.

SOIL ELEVATION DATA AND OBSERVED TREND

The District monitors land elevation changes and soil accretion at several sites in mangrove environments in northeastern Florida Bay and Taylor River to determine soil elevation change and subsidence (**Figure 2B-14**). Based on measured water depth data collected, mangrove sites have been grouped as non-flooded, frequently flooded and permanently flooded. Data are available as far back as 1997. The initial analyses of observed historical data, reported in the *Water and Climate Resilience Metrics, Phase I: Long-term Observed Trends* final report (SFWMD 2021), quantified combined elevation and accretion rates within the non-flooded, frequently flooded, and permanently flooded study areas. This chapter section expands the analysis by quantifying elevation and accretion rates at each individual site within the non-flooded, frequently flooded, and permanently flooded study areas shown in **Figure 2B-14**.

To determine total accretion rates at each sediment elevation table (SET) site for the period of record from 1997 to 2019, the rates of surface elevation change and vertical accretion were quantified using generalized additive models (GAMs), and a smoothing method called penalized regression splines from the Mixed GAM Computation Vehicle (mgcv) R package. In the GAMs, surface elevation and vertical accretion were the dependent variable and time was the independent variable. The basis function of the smoothing term for time was set to a maximum dimension of four, but its final value was determined by restricted maximum likelihood to prevent overfitting. We determined rates of change using the first derivatives of the GAMs. More specifically, we calculated the rate of surface elevation change or vertical accretion at each site as the mean of 200 equally-spaced first derivatives of the smoothing term of the fitted GAM models estimated by finite-difference approximation via the 'fderiv' function from the R package 'gratia'.

Figure 2B-15 illustrates the rates of soil elevation change at Shark and Lostmans rivers in southwestern Florida. Elevation change rates ranged between 1.28 and 2.00 millimeters per year (mm/yr) at rarely flooded sites, between 1.36 and 5.25 mm/yr at frequently flooded, and between 1.45 and 1.95 mm/yr at permanently flooded sites. The greatest elevation rate (5.25 mm/yr) was observed at TF10, which is a frequently flooded site. The lowest elevation rate (1.28 mm/yr) was observed at TF16 & TF17, which is a rarely flooded site. **Figure 2B-16** illustrates soil accretion rates at the sites. Vertical accretion rates ranged between 0.40 and 1.16 mm/yr at rarely flooded sites, between 0.95 and 4.22 mm/yr at frequently flooded sites, and 1.56 and 2.27 mm/yr at permanently flooded sites. The greatest accretion rate (4.22 mm/yr) was observed at TF10, which is a frequently flooded site where the greatest elevation change rate was also observed. The lowest accretion rate (0.40 mm/yr) was observed at TF1 & TF2, which is a rarely flooded site. The results highlight the importance of microtopography and hydrology in the soil dynamics of mangrove forests along the Taylor River and in Florida Bay.

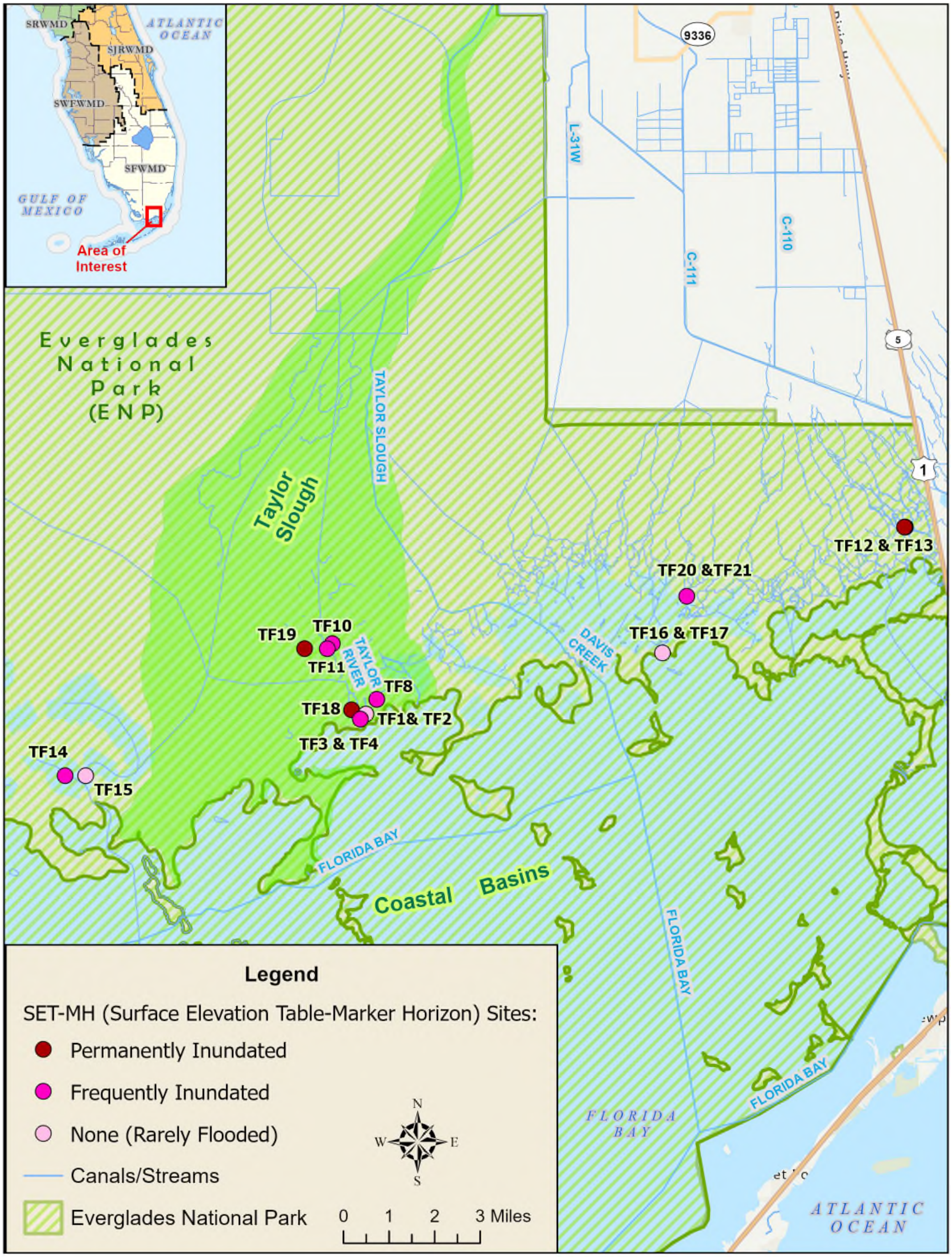

Figure 2B-14. Locations of non-flooded, frequently flooded, and permanently flooded soil monitoring sites in Florida Bay.

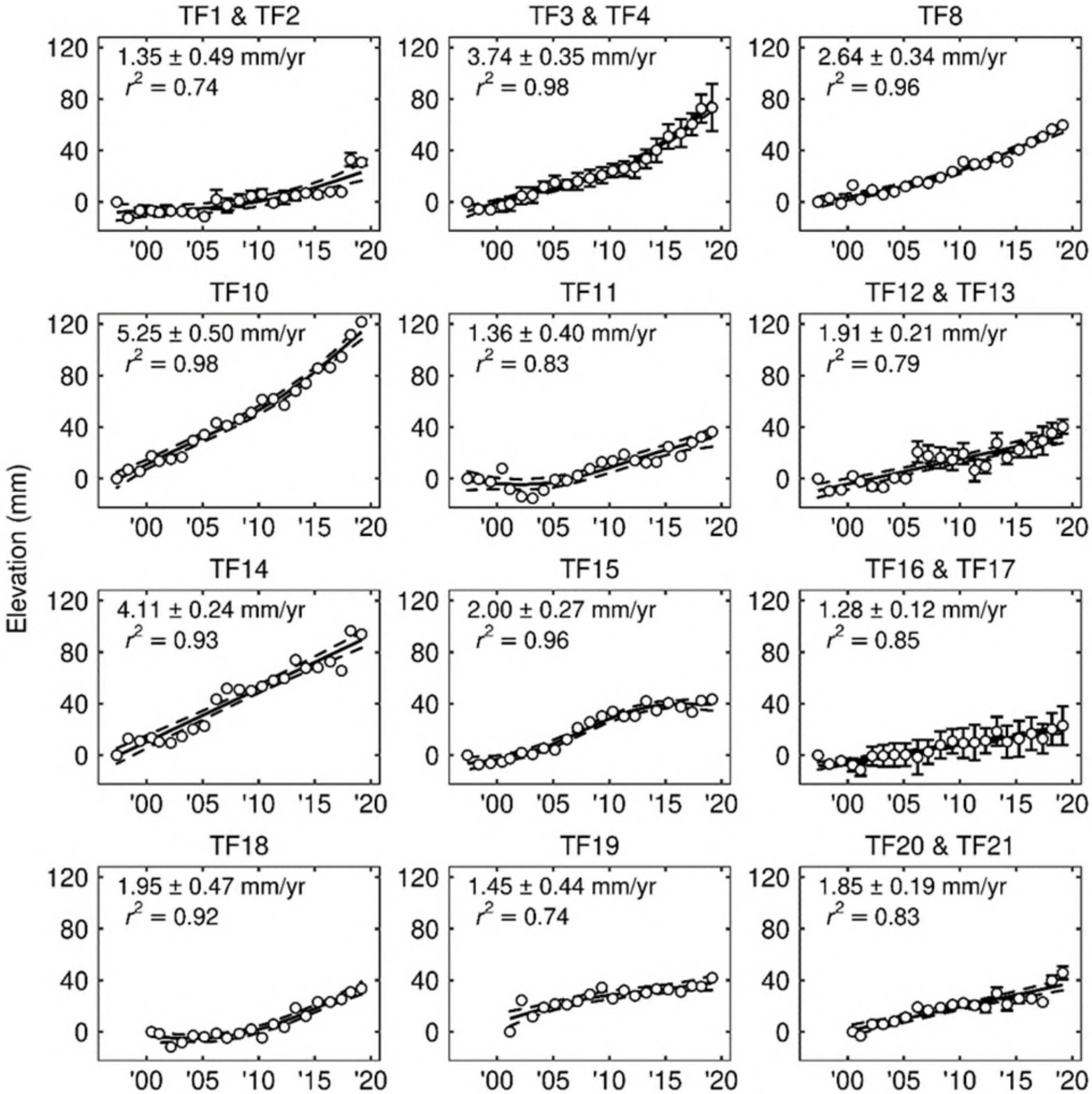

Figure 2B-15. Elevation change rates in millimeters per year (mm/yr).

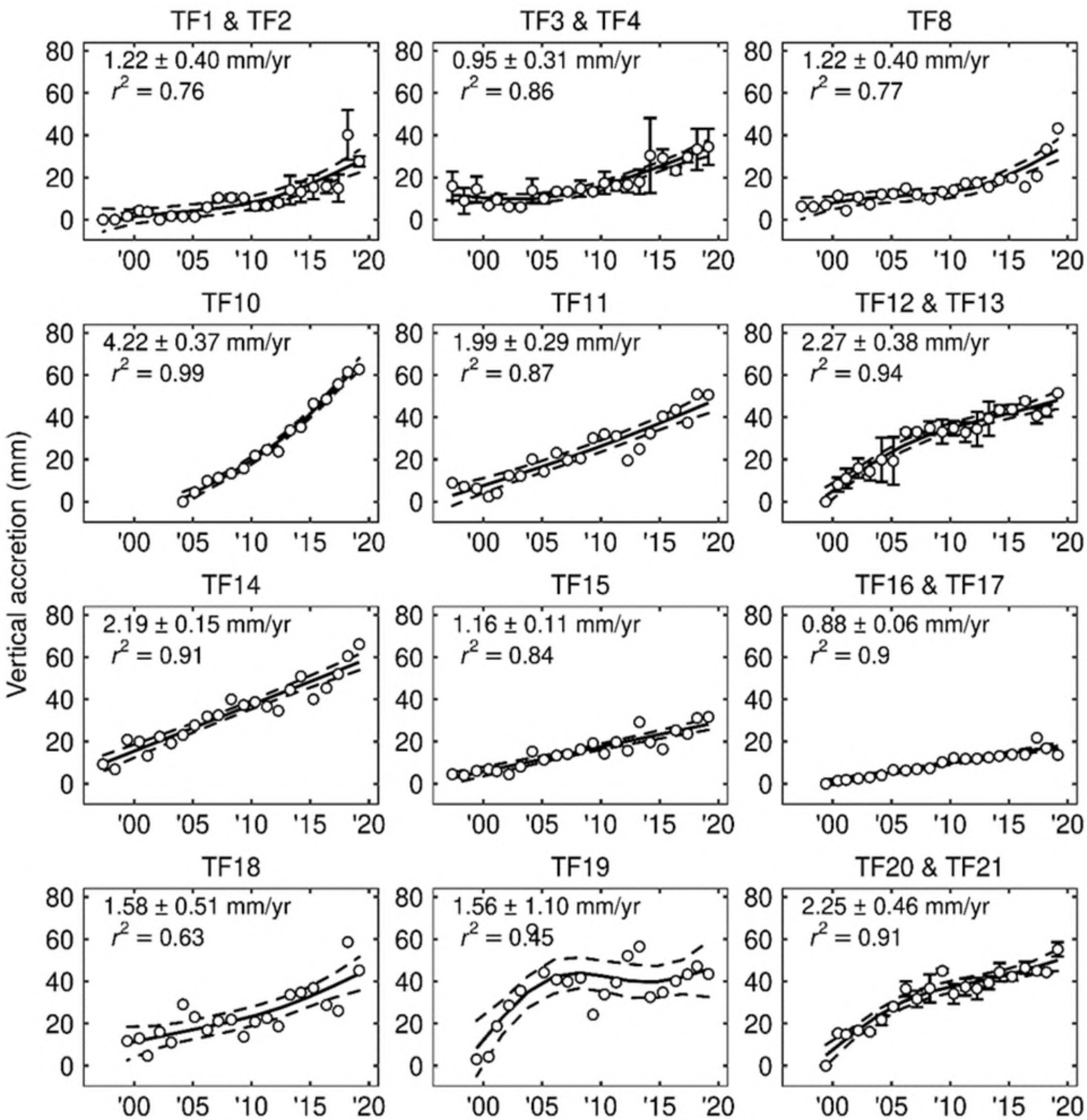

Figure 2B-16. Vertical accretion rates in mm/yr.

RELEVANCE TO RESILIENCY IN WATER MANAGEMENT

For coastal habitats to persist, the rate of accretion must exceed the rate of sea level rise. The historical rate of sea level rise at Key West, based on long-term monthly mean sea level derived from tide gauge data collected between 1913 and 2021 by the National Oceanic and Atmospheric Administration (NOAA), is 2.52 mm/yr (**Figure 2B-17**). The historical tidal data also reveal that the rate of increase in tidal elevation have become more rapid over the last 20 years than what is observed over the full period of record (Lindsey 2022). An analysis of four South Florida tide gauges indicates the average rate of sea level rise increasing from 3.9 mm/yr between 1900 and 2021 to 6.5 mm/yr between 2000 and 2021 and 9.4 mm/yr between 2010 and 2021 (Parkinson 2022). Studies consistently demonstrate increasing sea levels overall and accelerating rates of increase in more recent years, though the interpretation of particular values should be considered carefully as analytical approaches, site(s) selection, number of sites, periods of record, and periods of analysis, differ from one study to another.

The analyses of elevation and accretion data collected between 1997 and 2019 indicate that while accretion rates at some frequently flooded mangrove sites are keeping pace with the historical rate of sea level rise, accretion rates at most sites, mainly at rarely and permanently flooded sites, are not keeping pace with the historical rate of sea level rise. Furthermore, the current rates of accretion and elevation change also suggest coastal habitats would likely not keep up with accelerated rates of current sea level rise. These results underscore the importance of adaptive opportunities for restoration and the extent to which increasing freshwater inputs will benefit the persistence of mangrove forests along the Taylor River and in Florida Bay in the future. Identifying ecological vulnerabilities to sea level rise and other climate change impacts informs restoration efforts and water management practices that minimize land loss to saltwater intrusion.

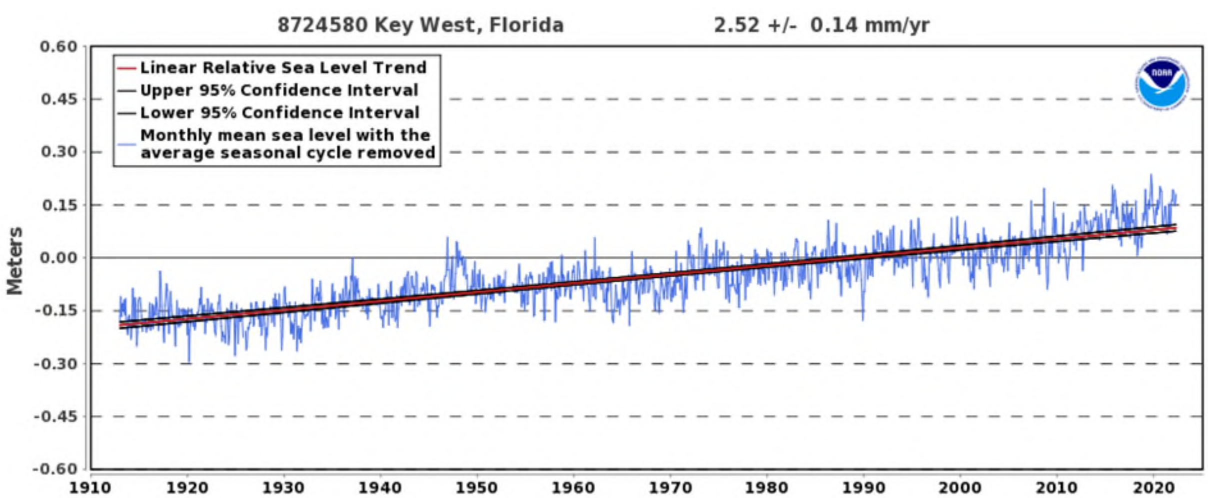

Figure 2B-17. Relative Sea Level Trend for Key West, Florida. (Source: https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8724580.)

COMMENTS AND RECOMMENDATIONS

Restoration efforts that increase freshwater flows and maintain adequate salinity levels in Florida Bay, key influencing factors of soil dynamics, are necessary to stave off the threats of sea level rise and preserve coastal habitat ecosystem services. Monitoring the response of soil dynamics in coastal mangrove forests to changing conditions is critical in determining the extent to which coastal habitats can remain intact and resilient.

ESTUARINE INLAND MIGRATION TRENDS IN SOUTH FLORIDA

BACKGROUND

The distribution of coastal mangrove forests and adjacent estuarine ecosystems in South Florida is determined by tidal fluctuation, salinity, and sediment elevation. They are important buffer zones between land and sea that contribute to the formation of soil and stabilization of coastlines, acting as natural defense systems against hurricanes and tidal surge protecting inland habitats and coastal communities from flooding. Mangrove forests provide habitat for many marine organism and terrestrial vertebrates and invertebrates alike by providing refuge and nursery grounds and reduce atmospheric carbon through photosynthesis and sinks of carbon stored in peat. Inland freshwater flows entering South Florida's shallow bays is improved as mangroves filter upland runoff. These habitats are responding to global climate change and changes in historical water flows by moving inland into higher topographic elevations dominated by freshwater plant communities. Mangrove inland migration informs SFWMD on the efficacy of water management practices in creating favorable conditions for coastal marshes and mangrove forests to keep up with sea level rise. Information on estuarine inland migration provides guidance to align planning practices toward adaption and mitigation from sea level rise and other climate change impacts.

DRIVERS AND INFLUENCING FACTORS

The most evident effect of global climate change on mangrove forests is the incidence of increasing sea levels, which are expected to be amplified in the coming decades (Lindsay 2022, Parkinson 2022, Sweet et al. 2022). Tidal fluctuation brings in salt water against the terrestrial outflow of fresh water and indirectly aids in the exclusion of freshwater plant species. Tidal flows help transport sediments, nutrients, and clean water inputs, and export organic carbon and reduced sulfur compounds. Sedimentation and the degree of wave energy provide the ideal conditions for propagule establishment since mangroves grow best in depositional environments with low wave energy. Ross et al. (2000) demonstrated that both sea level rise and freshwater discharge exerted important controls on the mangrove community dynamics, as well as on the relative proportions of organic and carbonate material in the coastal region of Northeastern Florida Bay. Field data support that areas receiving freshwater flows exhibit increased soil accretion relative to sites (areas) where water was stagnant, indicating that wetland plant communities are more productive when there is freshwater input and that increasing freshwater flow will have a positive effect on soil accretion and other biological metrics (i.e., biomass, leaf production, etc.). Ecological modifications associated with saltwater intrusion were greatest in coastal wetlands that were cut off from upstream freshwater sources. Data show that the interior border of the white zone, a zone of low productivity, in which a light-colored marl substrate is exposed by the low vegetation cover, is a broad but effective marker of coastal transgression (Ross et al., 2000). Because mangrove distribution is primarily determined by sea level and its fluctuations, such changes provide new more suitable environments for mangroves to migrate upland into what has historically been freshwater marsh habitat.

VEGETATION DATA AND SPATIAL-TEMPORAL TREND ANALYSIS

The latest vegetation type shapefiles for the C-111 and Model Land region were obtained from Miami-Dade County. These were transposed with vegetation data from Meeder et al. (1996) that was converted to a tagged image file format (.tif) and georeferenced in ArcGIS Pro using two locations: the intersection of Card Sound Road and US-1 and the southwest corner of the Turkey Point power plant cooling canals. Georegistration was verified using the C-111 canal. The 1940 and 1994 northern white zone boundaries were digitized from the saline Everglades data (Ross et al. 1996) georeferenced image. The historic mangrove migration area was created by joining the 1940 and 1994 boundaries lines and converting these lines to a polygon. Transects were generated along direction of flow between 1940 and 1994 white zone boundary line east and west of US 1.

Between the mid-1940s and the early 1990s, the boundary of the mixed graminoid-mangrove and sawgrass communities shifted inland. The interior boundary of a low productivity zone moved inland by up to 10,279.76 feet (ft; 3.13 kilometers [km]) and 6,807.65 feet (2.01 km) on average to the east of US 1 and 7,196.07 ft (2.19 km) and 2,726.61 ft (0.8 km) on average to the west of US 1 as shown in **Figure 2B-18** and listed in **Table 2B-4**. The smaller shift observed on the west side of US-1 was attributed to the area receiving more freshwater flows from the water management system, while greater change occurred in areas cut off from upstream water sources by roads or levees on the east side of US-1. These large-scale vegetation shifts are the combined result of changes to natural water flow in the Everglades and sea level rise.

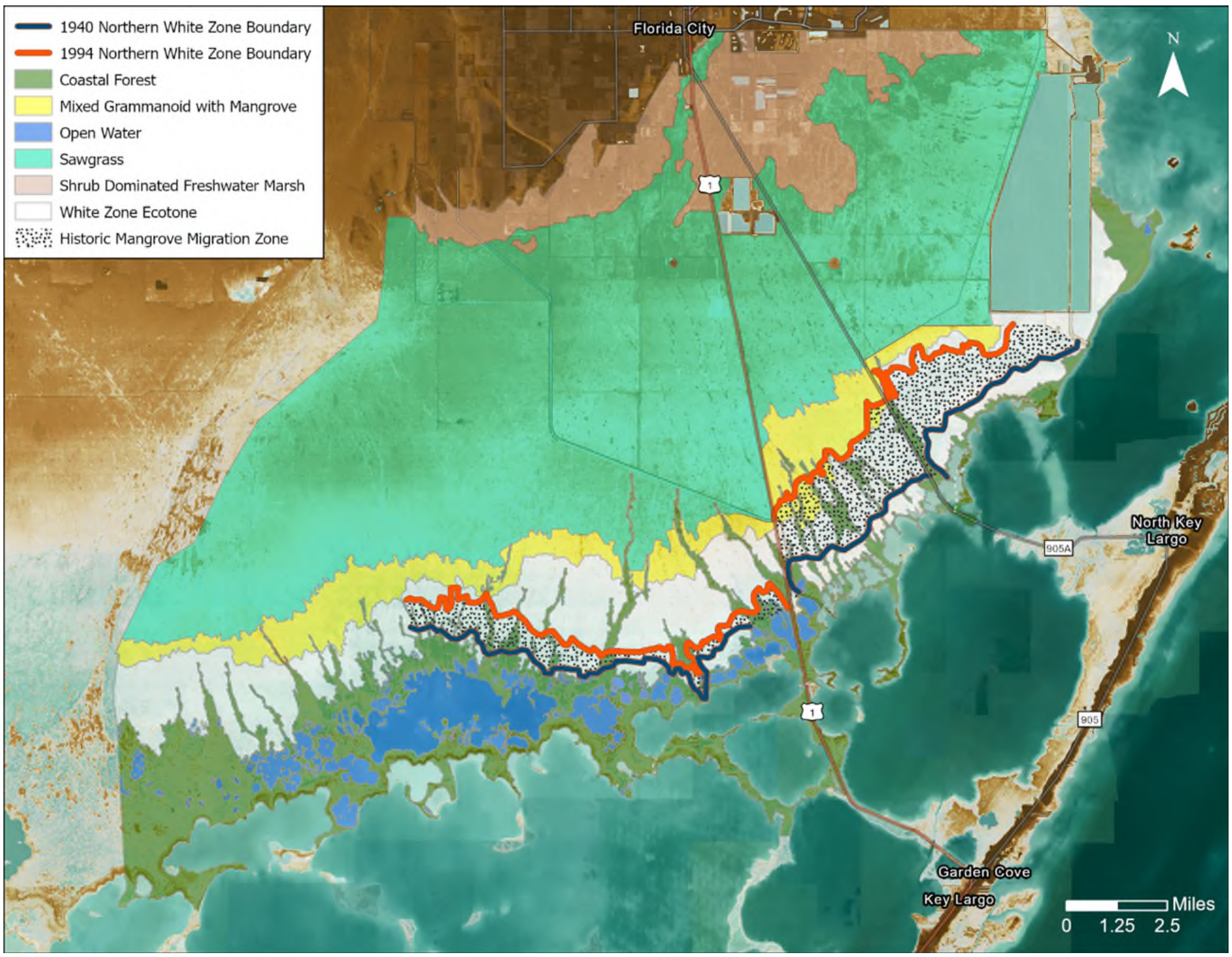

Figure 2B-18. Map of vegetation type in the southeastern glades showing the white zone, 1994 and 1940 northern white zone boundary, and historic mangrove migration zone.

Table 2B-4. Historic mangrove migration zone transect length statistics.

Location	Frequency (number of transects)	Minimum Transect Length (feet)	Mean Transect Length (feet)	Maximum Transect Length (feet)
East of US 1	19	2,613.89	6,807.65	10,279.76
West of US 1	26	799.76	2,726.61	7,196.07

RELEVANCE TO RESILIENCY IN WATER MANAGEMENT

Sea level change and changes in storm and rainfall patterns associated with climate change could have a potentially dramatic impact on the remaining natural areas in Florida. Due to its low elevation and proximity to the coast, the vegetation mosaic in the wetlands of Northeastern Florida Bay is extremely vulnerable to changes caused by the encroaching sea. Much of this region is a flat coastal plain that ascends from sea level to approximately one meter above sea level at the base of the uplands, more than 10 km distant throughout most of the region. Soil substrates are mostly marls produced under freshwater conditions, or peats, or some combination of the two (Leighty et al. 1965). The coastal wetland landscape can respond to sea level rise in three potential ways: (1) peat and sediment accretion that allows coastal wetlands to keep pace with sea level rise, (2) submergence with landward migration of coastal vegetation and wetland habitat, or (3) submergence and loss of coastal wetland habitat, without migration (Chambers et al. 2014). The third possibility, equating to a conversion to an open estuarine water body, would represent the condition of highest vulnerability to human interests further inland. A critical question for CERP is whether, and for how long, restoration of freshwater flows, depths and hydroperiods can mitigate salinity incursion related to sea level rise and associated soil subsidence and can facilitate a landward migration of coastal mangroves to counteract the effects of sea level rise.

COMMENTS AND RECOMMENDATIONS

Coastal marsh and mangrove communities have persisted through a steady slow rise in sea level by retreating approximately 3 kilometers inland since the mid-1940s into historically freshwater marshes. This inland migration was due to an estimated 10 centimeters in sea level rise as well as reductions in freshwater inputs from the altered upland watershed due to development. Insight regarding the response of mangrove ecosystems as sea level begins to rise more rapidly can be obtained by comparing the historical record with current trends. To slow down migration of the mangrove community into freshwater wetlands, facilitated by increasing freshwater input, tidal surge salt wedge incursion, and propagule recruitment (Raabe and Stumpf 2016, Cahoon et al. 2006) are adaptations that show some promise. The understanding of biological controls in mangrove forest dynamics can be expanded through the investigation of soil physical properties and the contribution of pulse events. It is important to identify ecological vulnerabilities from sea level rise and direct water management to minimize saltwater intrusion, soil subsidence, and estuarine inland migration to plan for resilient coastal systems. Expanding hydrological restoration efforts will continue to be important considering projected climate changes.

CONCLUSION

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 the District's multiple objectives 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 five resilience climate metrics—saltwater intrusion, groundwater levels, salinity, soil subsidence, and estuarian mangrove migration—to begin differentiating 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, mainly system operations and other anthropogenic activities.

Overall conclusions for each of the five metrics included in this chapter are presented below:

- Chloride data collected between 1990 and 2020 at four utility monitoring wells in the lower east coast surficial aquifer identify areas of westward (inland) saltwater movement and areas of eastward (seaward) saline water movement. These observed trends in the movement of the saltwater interface along the coast highlight the influence of withdrawals for water use, sea level rise, and freshwater/saltwater interactions. Water managers must consider these factors as part of long-term planning.
- Groundwater level data coupled with chloride data reveal how the relationship between fresh and saltwater dynamics in coastal aquifers influences the position of the saltwater interface and informs options for resiliency and adaptation planning. Continued and enhanced monitoring and data management are recommended to inform planning for water supply and flood protection.
- Daily surface water salinity data collected between 2008 and 2022 at six stations within central and eastern Florida Bay and between 2009 and 2021 at two stations in southern Biscayne Bay did not exhibit any statistically significant long-term trends. In Florida Bay, the role of ambient temperature, rainfall, and freshwater inputs are apparent in the daily observed data at all central and eastern sites and point to the relevance of site location within the landscape relative to distance from freshwater inflows and physical barriers to capture the role of tidal inputs in the western bay. In southern Biscayne Bay, ambient factors also influence surface water salinity; however, the proximity to nearby freshwater sources highlight how water management can direct freshwater flows to minimize the impacts of increased temperatures and changing rainfall patterns on the bay.
- Elevation change and vertical accretion data collected between 1997 and 2019 at twelve stations within Florida Bay show varying rates across monitoring sites in Florida Bay. While the highest elevation and soil accretion rates were both observed in rarely flooded sites, the results highlight the importance of microtopography and hydrology in the soil dynamics of mangrove forests along the Taylor River and in Florida Bay. The analysis indicates that elevation change and accretion rate at most sites are not keeping pace with the historically observed rate of sea level rise and are unlikely to keep pace with accelerated rates of sea level being observed at the present time. The results highlight the importance of increasing freshwater input as part of continued restoration activities and the of need to identify ecologically vulnerable areas where adaptation measures might be implemented.
- Mapped vegetation data collected in 1940 and 1994 illustrate significant inland retreat of coastal marshes and mangrove communities occurring in parallel with increasing sea level in eastern Florida Bay. Inland retreat varied within the landscape, with the greatest observed retreat occurring in areas cut off from upstream water sources by roads or levees. These large-scale vegetation shifts are the combined result of changes to natural water flow in the Everglades and sea level rise. The data also illustrate the role of water management in staving off the impacts of sea level rise through freshwater inputs that promote lower surface water salinity concentrations, the establishment of mangrove propagules, and soil accretion. The results emphasize the need for continued and enhanced monitoring in Florida Bay and additional monitoring in other areas managed by SFWMD.

The inaugural chapter in the 2022 SFER detailed the trend analyses of rainfall and evapotranspiration in South Florida and the four selected water quality metrics in Lake Okeechobee. This chapter details the enhanced analysis of chloride and groundwater levels in utility wells along Florida's lower east coast, surface water salinity in Florida Bay and Biscayne Bay, and soil accretion and estuarine migration in Florida Bay. In future South Florida Environmental Reports, Chapter 2B will present developments on the other water and climate resilience metrics, quantification of influencing factors, and correlation with other selected metrics. Future chapters will also explore additional resiliency monitoring considerations. These efforts provide a means to evaluate the significance of water and climate observations, and how they compare to historical trends. In addition, the links between major findings in Chapters 2A 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 shifts documented in Chapter 2B, and how these long-term trends or shifts may be associated with climate change.

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