Groundwater–surface water interaction and salinity responses to projected rainfall and sea-level rise in South Florida

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Abstract

Climate change, particularly sea-level rise (SLR) and rainfall patterns, poses a major challenge to coastal regions such as South Florida. The flat terrain and highly permeable aquifer increase risks of saltwater intrusion and flooding. However, assessments of these combined impacts using integrated hydrological models have been limited. We applied the density-dependent Biscayne and Southern Everglades Coastal Transport (BISECT) model, validated against daily groundwater levels and surface water stages. Simulations were forced with downscaled, bias-corrected rainfall from the best-performing CMIP6 model (ACCESS-CM2) and SLR projections from NASA IPCC AR6 tool, for a near-future (2051–2059) and far-future (2091–2099) under SSP2-4.5 and SSP5-8.5 scenarios. Results indicate substantial climate-driven shifts in hydrological processes. Groundwater levels are projected to rise by up to 1 m, especially in low-elevation coastal and inland wetland areas by the end of this century, reducing soil storage and thereby increasing flood risk. Groundwater recharge is expected to vary across the study area, with increases under moderate emissions but declines in some patchy areas in the far-future under high-emission scenarios. Both groundwater and surface-water salinity are projected to increase across scenarios, with chloride concentrations exceeding 30 g L^{-1} in parts of the Biscayne Aquifer, threatening municipal wellfields. Inland seawater intrusion is also projected to expand, reaching 40 g L^{-1} in the Everglades and concurrently reducing groundwater-driven evapotranspiration. The overall integrated modeling results highlighted the urgent need for nature-based adaptive strategies to protect freshwater resources, infrastructure, and ecosystems.

Plain Language Summary

South Florida is one of the most climate-vulnerable regions in the United States. Rising seas and shifting rainfall patterns are expected to affect the region's freshwater resources and flooding issues. We used an integrated model that links groundwater and surface water to understand how South Florida's water system may change by the mid and late 21st century. The model was tested against measurements and then used to simulate future projections. Our results show that groundwater levels are likely to rise by nearly a meter in some low-lying areas, reducing soil storage and increasing the risk of persistent flooding. Saltwater from the ocean is expected to move further inland, raising salinity in both surface water and underground aquifers. This threatens drinking water supplies from the Biscayne Aquifer and could damage wetlands such as the Everglades by killing freshwater vegetation and allowing mangroves to expand inland. These findings highlight the urgent need for integrated, nature-based strategies to protect water supplies, reduce flood risks, and protect ecosystems as the climate continues to change.

1. Introduction

Climate change including change in rainfall patterns and sea-level rise (SLR) are the most pressing global challenges, with far-reaching consequences for coastal communities, ecosystems, and freshwater resources (Michael et al., 2013; Werner et al., 2013; Dyring et al., 2023; Erostate et al., 2020; Puigserver et al., 2024; Xiao et al., 2021; Kh'ng et al., 2021 Yi Khet al., 2021). Through a feedback loop, climate change has accelerated the warming of the planet, leading to the widespread shrinking of the cryosphere, with mass loss from ice sheets and glaciers, which contribute to SLR (IPCC, 2019). The global mean sea level will continue to rise depending on different pathway scenarios (Zamrsky et al., 2024). Such changes will have significant implications for coastal zones, particularly in low-lying regions where even small increases in sea level can exacerbate flooding and saltwater intrusion into freshwater systems. The extent and severity of saltwater intrusion depend on several factors, including local hydrogeological conditions, groundwater extraction rates, and the magnitude of SLR (Costall et al., 2020; Sharan et al., 2024; Kretschmer et al., 2025). Beyond its direct impact on freshwater availability, SLR also interacts with other climate change drivers, such as changing precipitation patterns, storm surge, tides, and land subsidence, to amplify risks to coastal environments and human settlements (Day et al., 2024). Climate-driven change in groundwater recharge due to rainfall changes is a factor influencing the variability of saltwater intrusion (Adams et al., 2024). This impact can be observed on a local scale, adding to the global influence of SLR, which is a primary driver of widespread saltwater intrusion. The combined effects of these drivers pose significant challenges for water resource management, requiring integrated strategies that account for the complex interactions between climate, hydrology, and human activities.

Florida is often called "ground zero" for climate change in the United States, with coastal areas vulnerable to SLR and water supplies at risk from saltwater intrusion, changing precipitation patterns, and increased water demand due to higher temperatures (Maliva et al., 2021). It is more vulnerable to the impacts of the SLR, low elevation, and lack of topographic relief to promote drainage (Haque, 2023). In addition, saltwater intrusion threatens soil health and agriculture, requiring further study on its impact, especially in hydrologically connected (surface and groundwater) regions like South Florida with permeable limestone soils (Bayabil et al., 2021; Khoddamzadeh et al., 2023). Climate change will also affect future water resources through spatio-temporal shifts in its driving factors, potentially creating an imbalance between water supply and demand amid population growth. For example, Florida's population is projected to rise by 30.5% by 2045 relative to the 2018 population (Rayer & Wang, 2019). The

Florida Department of Environmental Protection (FDEP) also foresees a 27% increase in population by 2035 which will increase water demand by 18% (FDEP, 2019). This rising population can significantly impact ecological changes, potentially exacerbating the impacts of climate change.

Groundwater plays a crucial role in coastal areas like South Florida, serving as a primary freshwater source for water supply, irrigation and industrial use and maintaining ecological balance (Obeysekera et al., 2017). However, this vital resource faces significant threats from climate change and SLR, which exacerbate saltwater intrusion and groundwater salinity. Guha & Panday (2012) highlighted that SLR will impair freshwater resources in South Florida due to the significantly increasing chloride concentrations in groundwater. The region's groundwater-surface water (GW-SW) interactions are affected by climate changes due to the highly porous hydrogeological structure, which facilitates hydrological connectivity and enhances the risk of seawater intrusion. Moreover, rising sea levels increase groundwater tables, reducing soil storage capacity, which makes stormwater management systems difficult. Groundwater level rise significantly reduces the effectiveness of stormwater retention ponds (Davtalab et al., 2020), increasing the risk of flooding. The integration of groundwater and surface water models has shown crucial in assessing these challenges (Davtalab et al., 2020; Swain et al., 2019). However, many existing studies predominantly focus on SLR while overlooking the impact of changing precipitation patterns. Ignoring such factors could lead to an underestimation of flooding risks and freshwater depletion. Therefore, comprehensive, integrated GW-SW modeling approaches that incorporate both SLR and climate-driven spatio-temporal precipitation changes are essential for enhancing climate resiliency of groundwater resources in South Florida. Such a study is crucial for applying proper adaptation and mitigation solutions to be more compatible with the impacts at a variety of spatial and temporal scales.

Precipitation is the main climatic driver in integrated hydrological modeling. Projecting future precipitation is essential to model the future spatio-temporal GW-SW interaction dynamics. General Circulation Models (GCMs) are mathematical simulations used to predict future climate variables, including precipitation. However, the GCMs in the sixth Phase of Coupled Models Intercomparison Project (CMIP6) ensemble remains coarse for local and regional applications, requiring downscaling and bias correction methods (Shamir et al., 2019; Paz & Willems, 2022; Rahimi et al., 2024). This coarse resolution of the GCMs can be enhanced using process-based dynamical downscaling (Giorgi & Mearns, 1999) or empirical-based statistical downscaling (Wilby et al., 1998) methods to produce high-resolution climate projections that accurately capture fine-scale responses (Hou et al., 2019; Ashfaq et al., 2016; Ashfaq et al., 2022). Regional Climate Models (RCMs) are forced with projecting variables from coarse-resolution GCM simulations at their lateral boundaries in a high temporal resolution for dynamical downscaling. This allows RCMs to independently capture fine-scale climate responses, such as those influenced by topography, coastlines, and mesoscale convection, which are often missed by GCMs. Although dynamical downscaling requires higher computational costs than statistical downscaling, it offers the advantage of easier physical interpretation since it is based on fundamental physical principles. Dynamical downscaling provides high-resolution hydroclimate projections and independent precipitation series for hydrological modeling, but bias correction is often needed as precipitation is not constrained to observations (Potter et al., 2020). Statistical downscaling, on the other hand, relies on empirical relationships between simulated and observed climate data, making it computationally efficient for downscaling large GCM ensembles. However, it is limited to variables with long-term observational records and assumes stationarity in these relationships, which is a commonly cited limitation (Benestad, 2004). Both downscaling methods have inherent limitations and perform differently depending on hydroclimatic variations. Thus, despite decades of use in downscaling GCMs, the quantitative differences between the two approaches remain unclear (Rastogi et al., 2022). Srivastava et al. (2022) presented that dynamically downscaled RCMs generally underestimate the magnitude of monthly precipitation and fail to capture the seasonal phase of extreme precipitation across Florida. In contrast, Rahimi et al. (2024) demonstrated that the statistically downscaled approach showed substantial performance following the bias correction of the downscaled climatic variables. Such findings highlighted the need for validation and bias correction of downscaling approaches to ensure reliable climate projections before being used as input in any integrated hydrological models.

The SLR is the key boundary condition in a density-dependent groundwater-surface water flow model. This boundary condition significantly influences the interaction between surface water and groundwater systems, especially in coastal regions where saltwater intrusion and groundwater salinization are major concerns. As a result, SLR has been increasing at an accelerated rate over recent decades (Cazenave & Cozannet, 2014; Hay et al., 2015; Vaidya et al., 2023; M. Xiao et al., 2025). Future SLR can be estimated through observation-based extrapolations, which rely on historical records or climate model projections (Sweet et al., 2022). The observation-based extrapolation uses statistical techniques to project future sea levels based on observed trends. However, this approach may not fully account for future changes in climate dynamics. As a result, recent studies have increasingly focused on climate model projections, particularly those derived from the CMIP6 projections, which are based on different Shared Socio-economic Pathways (Bulgin et al., 2023; Sung et al., 2021).

The hydrologic system of South Florida is dynamic and complex, where climate change and SLR pose severe threats to this low-lying coastal region. The USGS developed the density-dependent Biscayne and Southern Everglades Coastal Transport (BISECT) model that accounts for this complexity (Swain et al., 2019). While studies have explored SLR impacts, there is a gap in understanding the combined effects of future SLR and changing rainfall patterns on surface and groundwater interactions, applying with such an integrated GW-SW modeling approach. Therefore, integrating future SLR and rainfall dynamics into density-dependent integrated hydrological modeling is crucial to enhance resilience and inform sustainable water resource management. The main objective of this study is to assess the combined impacts of projected SLR and changing rainfall patterns on GW-SW interactions, groundwater recharge, groundwater levels, and surface water and groundwater salinity affecting freshwater availability in hydrologically connected systems. This work is original in validating the BISECT model with independent data and analyzing its future impact, which, to the authors' knowledge, has not been previously done. This study is important to provide insights for policymakers and water resource managers to develop climate-resilient strategies that ensure sustainable water management in vulnerable coastal regions.

2. Methods

2.1. Study area

The study area encompasses the southern part of Florida (Fig. 1), which is the same boundary as the BISECT model (Swain et al., 2019). It covers Miami-Dade County except Water Conservation Areas 3A and 3B, Monroe County, and a small portion of southern Collier County. According to the 2020 U.S. Census Bureau data, the Miami-Dade County is one of the most populous counties in the state (Kim & Tepe, 2025). The study contains urban and suburban Miami, Everglades and Biscayne National Parks, Big Cypress National Preserve, agricultural lands, and diverse ecosystems. The terrain of the study area is nearly flat that ranges from land elevation of 10 m to -55 m in the marine waters, including parts of the Gulf of Mexico, Florida Bay, and the Atlantic Ocean (Swain et al., 2019).

South Florida is heavily influenced by fluctuations in sea surface temperatures, which plays a key role in shaping year-to-year climate variability. Its climate is humid subtropical, characterized by a wet season with high seasonal rainfall and occasional storm events, and a dry season with relatively low precipitation. The highest annual rainfall occurs in the extreme southeastern region (up to 3.7 m), with coastal areas tend to have slightly higher rainfall than the interior areas as a result of convective thunderstorms that form near the coasts (Upchurch et al., 2019). South Florida has experienced climatic extremes, such as hurricanes and heavy rainfall, which are expected to become more frequent and intense due to climate change (Rahimi et al., 2024). Rainfall is the main source of freshwater for southern Florida, which occurs about 75% during the wet season months from June to October (Langevin, 2001). This indicates that consideration of the spatio-temporal variability of rainfall is crucial. Inflows also occur through a water management canal system that regulates water levels in southern Florida.

The study area is divided into two subareas. The eastern subarea is primarily urban, containing most of the population, as well as Biscayne Bay, parts of the Florida Keys, and Biscayne National Park. The surface-water hydrology of much of this subarea is largely controlled by a network of canals and structures that are designed to manage floods, provide groundwater recharge, and mitigate saltwater intrusion (Swain et al., 2019). Despite its urbanization, the eastern subarea includes agricultural and wetland areas. The western subarea is largely undeveloped, consisting of wetlands in Everglades National Park and Big Cypress National Preserve. These subareas are highly modified and controlled freshwater delivery systems with complex and closely connected GW-SW components that can be contaminated by nearby seawater frequently (Swain et al., 2019). Both subareas share the impact of floods, droughts, and hurricanes.

The study area's surficial aquifer system is shallow and unconfined to semi-confined and composed primarily of the Biscayne aquifer in the east and the gray limestone aquifer in the west, both of which overlie the confined Floridan aquifer system (Swain et al., 2019). A layer of sand, silt, and clay separates these systems, limiting groundwater movement between the surficial and confined Floridan aquifers. The Biscayne Aquifer is a geologically young, highly productive carbonate aquifer with small karst features, where rapid and efficient natural recharge occurs through various openings and porous pathways in its limestone (Upchurch et al., 2019)

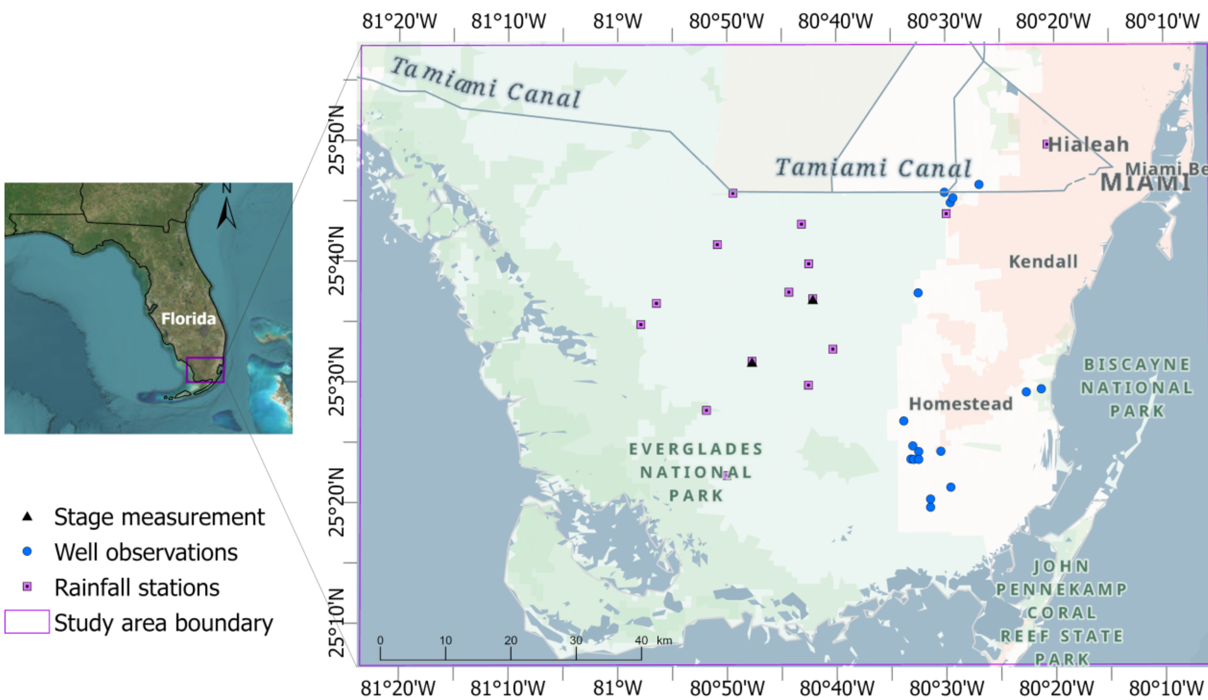

Fig. 1: Study area with station-based measurements of rainfall, stage and well used for validation in this study.

2.2. Data Sources

Future rainfall projection is crucial for reliable spatio-temporal representation in integrated hydrological models. This is because the accuracy of rainfall input directly influences the representation of hydrological variables at representative spatial and temporal scales by enhancing the model's ability to capture hydrological dynamics, leading to more effective water resource management and planning. The GCMs projections refined through downscaling approaches are the important sources of spatio-temporal rainfall. This study sourced the rainfall data from https://hydroshare.ornl.gov/files/9505/SWA9505V3/. This dataset presents a suite of high-resolution downscaled hydro-climate projections over the conterminous United States (CONUS) based on multiple selected GCMs from the CMIP6 (Kao et al., 2022). Each ensemble member spans the baseline period (1980–2019) and the near-future period (2020–2059) under the high-emission Shared Socioeconomic Pathway (SSP5-8.5) scenario. Additionally, using only Double Bias Correction Constructed Analogs (DBCCA) and Daymet, projections extend further to the far-future period (2060–2099) and include three additional emission scenarios of SSP3-7.0, SSP2-4.5, and SSP1-2.6. The Daymet and Livneh that have been widely used in many hydroclimate studies, are the meteorological reference observations in downscaling these climate projections. Daymet provides daily gridded surface weather parameters at a 1-km spatial resolution from 1980 to 2019 (Thornton et al., 2021). The Livneh dataset also offers daily gridded meteorological estimates at approximately 6-km spatial resolution (Livneh et al., 2015), with a recent update that addresses a timing adjustment issue and improves the representation of precipitation extremes (Pierce et al., 2021). These datasets were either aggregated or bilinearly interpolated to a common ~4-km resolution to facilitate downscaling and evaluation (Rastogi et al., 2022). The downscaled data sources have been used in various regional scale hydro-climate risk assessment, including but not limited to evaluations of climate change impacts on hydrology, reservoir operations, hydropower generation, future energy demand and climate extreme events (Rastogi et al., 2022).

The NASA Sea Level Projection Tool (Garner et al., 2021) was used as a source to the sea level projection locally at South Florida. This tool is used to visualize and download the SLR projection data from the IPCC 6th Assessment Report (AR6). Based on this projection, SLR under the SSP2-4.5 scenario is expected to reach approximately 0.37 m in the near-future and 0.72 m in the far-future periods. Under the higher-emission SSP5-8.5 scenario, SLR is projected to rise to around 0.41 m and 0.92 m over the near-future and far-future periods, respectively. Daily observed groundwater levels and surface stage were sourced from the South Florida Water Management District's (SFWMD) corporate environmental database that stores hydrologic, meteorologic, hydrogeologic and water quality data. Mean daily observations of these state variables were accessed at the DBHYDRO web-based application of SFWMD (2025).

2.3. Rainfall evaluation

The performance of the rainfall from the downscaled climate models was validated against the station-based rainfall at South Florida. This study utilized the statistically downscaled precipitation over CONUS which was based on six CMIP6 GCMs (Table 1). Each of the future GCM was bias corrected to the daily GCM output using a quantile mapping approach (Thrasher et al., 2012). This study applied the SSP5-8.5 and SSP2-4.5 scenarios. The SSP5-8.5 scenario is considered as the worst-case emission scenario (Wehner, 2020), while the SSP2-4.5 scenario provides more realistic predictions of global warming (Zhang et al., 2024). Considering these scenarios provides a framework for analyzing the range of possible future climate outcomes, from extreme impacts such as accelerated sea level rise to more moderate conditions, thereby supporting climate impact assessments and the development of informed adaptation strategies.

In-situ observations from 14 weather stations (Fig. 1) were used to evaluate the performance of the downscaled rainfall from six GCMs (Table 1). The performance of the downscaled data was evaluated using different distribution and statistical error metrics. To assess how well the downscaled simulations captured the characteristics of in-situ rainfall distributions, the skewness difference, Kolmogorov–Smirnov (KS) statistic, and the standard deviation ratio were utilized. Moreover, the Pearson correlation and error metrics (Eq. 1–3) were employed to analyze the quantile–quantile relationships between observed and GCM-derived rainfall data. Following the evaluation metrics, the best downscaled that represent the in-situ observations was selected as input to the BISECT model for the baseline and future projections. The BISECT original structured distinct zones were used to prepare the rainfall input Python packages for geospatial data processing and data manipulation were used during preprocessing and preparation of the spatio-temporal rainfall input.

Table 1: List of downscaled GCMs from the CMIP6 used for comparison station observations (Rastogi et al., 2022)

CMIP6 GCM	Spatial resolution	Ensemble number	GCM institute
ACCESS-CM2	144 × 192	r1i1p1f1	The commonwealth Scientific and Industrial Research Organization, Australia
BCC-CSM2-MR	160 × 320	r1i1p1f1	Beijing Climate Center
CNRM-ESM2-1	256 × 128	r1i1p1f2	French Center National de la Recherche Scientifique
MRI-ESM2-0	160 × 320	r1i1p1f1	Meteorological Research Institute Japan
MPI-ESM1-2-HR	192 × 384	r1i1p1f1	The German Climate Computing Center
NorESM2-MM	192 × 288	r1i1p1f1	Multi-institutional, coordinated climate research project in Norway

2.4. Model selection and discretization

The South Florida's hydrologic processes affecting the water balance resulted from interactions between the atmosphere, surface water, and groundwater systems. These processes are influenced by features such as inland and coastal streams, flooded freshwater marshes and sloughs, and man-made canals. The system is ultimately recharged with freshwater by rainfall throughout the entire area and freshwater inflows along the western part of the northern study boundary. Such complex hydraulic system requires a density-dependent integrated hydrological model that accurately represents the hydraulic connectivity among all these features. For this case, the USGS developed the BISECT model (Swain et al., 2019) to convert this complex conceptual modeling dynamics in South Florida into a numerical model, which was also applied in this study.

Two previous USGS modeling efforts have been developed in parts of the South Florida hydrologic system. These models were the Tides and Inflows to the Mangrove Everglades (TIME) by Wang et al. (2007), covers the undeveloped western part of the study area and the Biscayne (Lohmann et al., 2012) covers the highly developed eastern part. The BISECT model combined these two models modifying the Flow and Transport in a Linked Overland/Aquifer Density-Dependent System (FTLOADDS) simulator (Langevin et al., 2005). FTLOADDS is a computational framework that integrates two simulators, a two-dimensional surface-water model (SWIFT2D: Simulation of Surface-Water Integrated Flow and Transport in Two Dimensions) and a three-dimensional groundwater model (SEAWAT: Computer Program for Simulation of Three-Dimensional Variable-Density Ground-Water Flow). This integration enables the simulation of South Florida's complex hydrology, providing insights into potential hydrologic responses under future conditions. The BISECT model incorporates several parameters and algorithmic refinements that enhance simulation accuracy compared to the TIME and Biscayne models. It provides a more explicit representation of the hydrologic system through improved topographic detail, refined Manning's friction coefficients, enhanced evapotranspiration calculations using spatially variable albedo, increased vertical aquifer discretization, and an extended western boundary reaching farther offshore. Moreover, this model is applicable for hydrologic responses to possible future conditions, including SLR with future rainfall data downscaled from GCMs.

The BISECT model, horizontally discretized into a grid with 500 m, composed of 259 cells west to east and 186 cells south to north. The grid has 15 vertical layers to balance simulation efficiency and accurately represent the mixing zone in the surficial aquifer, which is highly susceptible to saltwater intrusion from SLR (Swain et al., 2019). In the BISECT aquifer representation, the bottom of the uppermost layer is set at 2 meters below NAVD 88. The next 10 layers, each uniformly 2 meters thick, provides high resolution, while the lower 4 layers have variable thicknesses to better approximate geological formations that are less critical to seawater intrusion concerns. Capturing groundwater movement and mixing at a 2-meter resolution in the uppermost aquifer enhances the accuracy of water and salt exchange calculations between groundwater and surface water.

2.5. Model validation

The BISECT model was calibrated by Swain et al. (2019), covering the period from 1996 to 2004. This calibration was conducted using a comprehensive dataset that included measured flow, water stage, and salinity for free-flowing streams discharging into coastal waters. Additionally, the calibration incorporated groundwater level observations from monitoring wells within the Biscayne aquifer, as well as wetland water levels recorded in various locations. Another crucial component of the calibration process was the general location of the saltwater-freshwater mixing zone within the Biscayne aquifer, which is essential for assessing saltwater intrusion and the impacts of SLR on the groundwater resources of the study area. Building upon this previous calibration, this study conducted an independent validation of the BISECT model using a different daily observational data from 2011 to 2019. The performance evaluation of the model validation was carried out through a combination of graphical and statistical analyses. The graphical analysis involved visual comparisons between observed and simulated hydrological variables, enabling the identification of trends, discrepancies, and temporal variations in model outputs. Quantitative assessment was performed using statistical error metrics, specifically the mean bias error (MBE) and mean absolute error (MAE) and root mean square error (RMSE) as presented in Eq.1, Eq. 2 and Eq. 3, respectively. The MBE provided an indication for the overall model overestimation or underestimation, while the MAE measured the overall magnitude of prediction errors, providing insights into the model’s accuracy and reliability. The RMSE is a quadratic scoring rule, which is more sensitive to outliers as it squares the errors.

$$MBE = \frac{1}{t}\sum_{i=1}^{t}(Sim_i - Obs_i) \qquad (1)$$

$$MAE = \frac{1}{t}\sum_{i=1}^{t}|Sim_i - Obs_i| \qquad (2)$$

$$RMSE = \sqrt{\frac{1}{t}\sum_{i=1}^{t}(Sim_i - Obs_i)^2} \qquad (3)$$

where Obs_i is observed state variables at day i; Sim_i is the model simulated variables corresponding to the observed ones at day i; t is the total number of data pairs (days).

2.6. Spatio-temporal surface water and groundwater variables

Once the BISECT model was validated against independent datasets, it was subsequently applied to assess future hydrological changes. The model was run for two distinct future time periods of the near-future (2051–2059) and the far-future (2091–2099). These simulations were driven by projected future rainfall patterns and SLR scenarios, which were derived from climate models. The future variables were then compared against baseline conditions to analyze expected changes in the future. This was analyzed by assessing the differences between the future and baseline variables, both spatially and temporally. Spatial analysis was conducted using a grid-based approach, where the difference between future and baseline variables was calculated at each model grid point. This method provided a detailed spatial representation of regions that are likely to experience increases or decreases in hydrological variables due to changing rainfall and SLR. Temporal analysis, on the other hand, involved examining how these changes evolved over time, allowing for a clearer understanding of seasonal variations in the hydrological processes.

3. Results

3.1. Rainfall validation and future variability

The spatial rainfall changes across the study area under the future climate scenarios using the six GCMs is presented in Fig. 2. The change in each model is derived from the difference between the annual spatial rainfall of the baseline and future periods. Rainfall projections show variability both between models and across scenarios. Under the near-future SSP2-4.5 scenario, ACCESS-CM2, MRI-ESM2-0 and MPI-ESM1-2-HR projects an increase in rainfall, while BCC-CSM2-MR CNRM-ESM2-1 and NorESM2-MM suggest decreasing. In the far-future SSP2-4.5 scenario, all models except ACCESS-CM2 and MRI-ESM2-0 project decreasing rainfall, particularly higher decrement projection by BCC-CSM2-MR and NorESM2-MM. Under SSP5-8.5, a high-emissions scenario, the pattern persists. ACCESS-CM2 continues to show notable increases, while BCC-CSM2-MR and NorESM2-MM project pronounced decreasing patterns, especially in the near-future period. Other models remain with smaller changes. These variations highlight the variation in climate projections, where model outputs differ even under the same emission scenarios. While using a multi-model ensemble remains important for capturing the range of possible futures, it is also crucial to assess how well each model reproduces the baseline rainfall patterns over the region of study. Selecting a best-performing model based on baseline comparison helps prioritize projections that are more regionally relevant. Accordingly, the performance of each model was assessed using different statistical metrics.

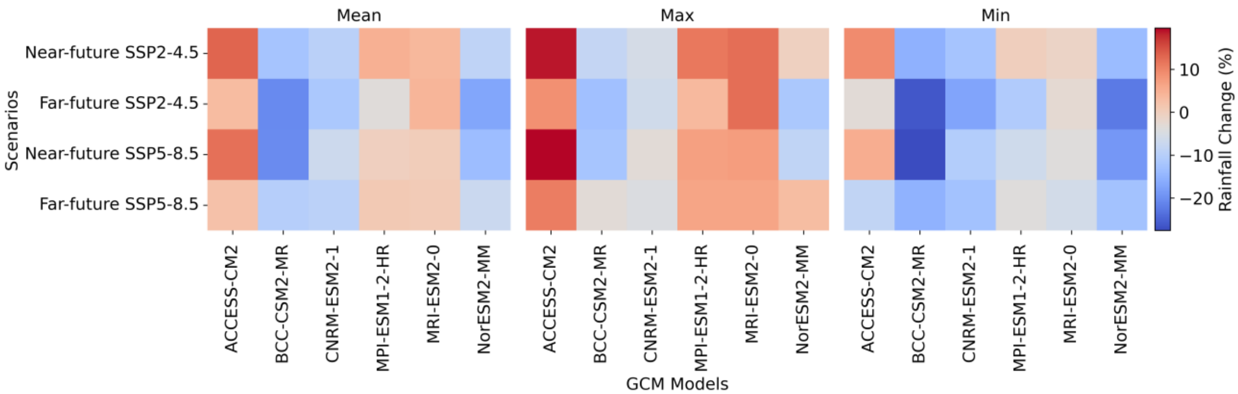

Fig. 2. Heatmap of spatial rainfall changes across the study area, representing differences between the baseline and future periods as projected by six GCMs under the medium and high climate emission scenarios.

The performance of the downscaled GCM rainfall assessed using a combination of distribution-based metrics and quantile–quantile error metrics is presented in Fig. 3. Among the six GCMs evaluated, ACCESS-CM2 consistently demonstrated relatively better performance across all metrics. In terms of distributional characteristics, ACCESS-CM2 showed the lowest station-mean skewness difference, indicating its ability to replicate the asymmetry of observed rainfall distributions compared to the other models. Moreover, its Kolmogorov–Smirnov (KS) statistic is relatively small, reflecting better alignment between the cumulative distributions of this GCM and observed rainfall. In terms of the standard deviation (STD) ratio, the BCC-CSM2-MR and NorESM2-MM exhibited slightly better average performance although the ACCESS-CM2 still captured the variability of observed rainfall across stations. In the quantile–quantile error analysis, ACCESS-CM2 maintained the better performance demonstrating the lowest station-averaged MAE and RMSE, outperforming all individual GCMs and the multi-model ensemble mean. These low error values indicate strong agreement between the simulated and observed rainfall quantiles. Although MRI-ESM2-0 showed a slightly lower mean bias error (0.55 mm day^{-1}), ACCESS-CM2 still showed a comparably low MBE (0.63 mm day^{-1}), indicating minimal systematic bias and balanced overall performance across error and distribution metrics. The ensemble means are also outperformed by ACCESS-CM2 in most metrics, particularly in representing distributional shape and variability. Therefore, ACCESS-CM2 was selected as the best performing downscaled model relative to other models for further use as input to the BISECT model.

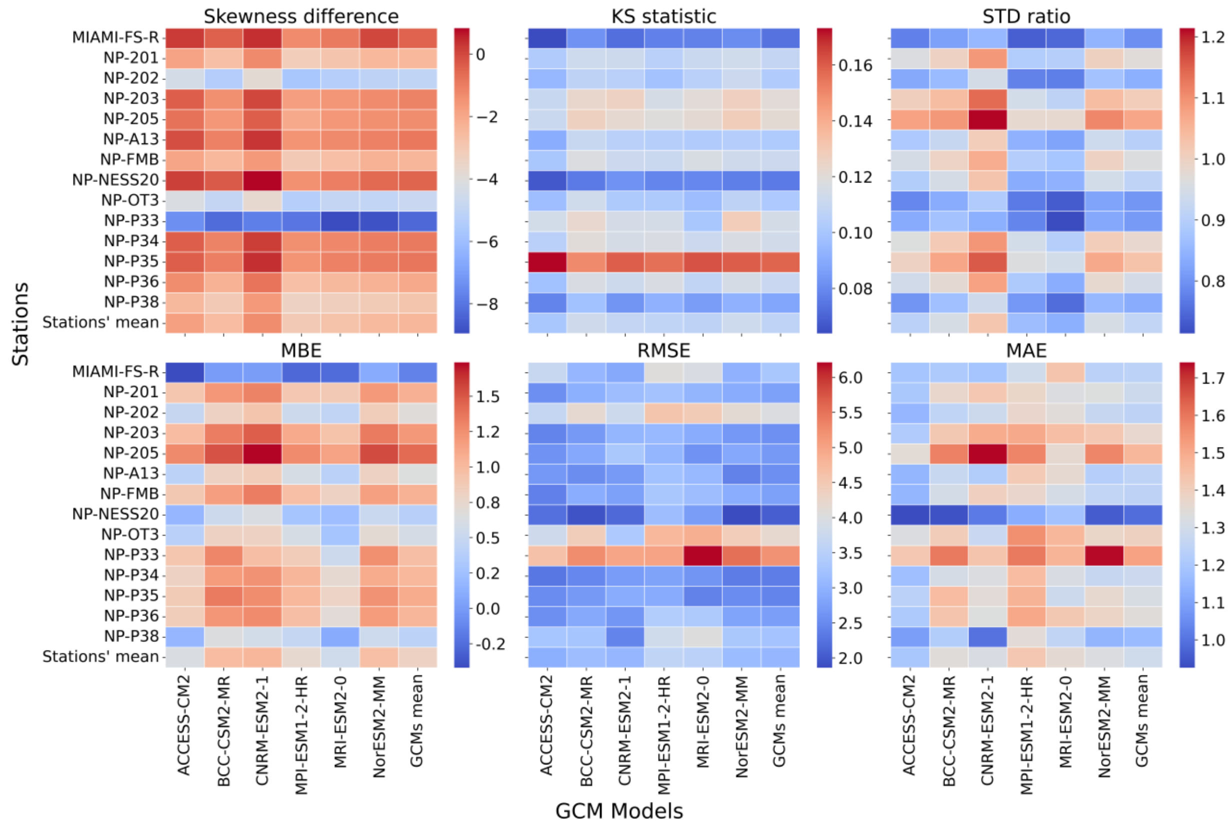

Fig. 3: Heatmaps showing the performance of downscaled GCM rainfall across in-situ station observations using distribution and error metrics. Metrics include skewness difference, Kolmogorov–Smirnov (KS) statistic, and standard deviation ratio (STD ratio) for evaluating distributional similarity, and mean absolute error (MAE), root mean square error (RMSE), and mean bias error (MBE) for quantile–quantile error analysis.

The ACCESS-CM2 model projects spatial and temporal rainfall variability under both the SSP2-4.5 and SSP5-8.5 emissions scenarios as presented in Fig. 4. The baseline period showed spatial rainfall distribution with higher totals in the central and eastern portions of the study area and lower values toward the western and southern parts. The near-future projection under SSP2-4.5 presented a noticeable increase in rainfall, particularly in the northern and central regions. This scenario projected a mean annual increase by about 13.3% relative to baseline. The maximum and minimum spatial variability of rainfall under this scenario also demonstrated an increasing pattern. Similarly, the near-future under SSP5-8.5 also indicates a general increase in rainfall relative to the baseline, but slight less scale relative to the corresponding period under SSP2-4.5. The mean annual rainfall in the near-future under SSP5-8.5 is expected to increase by about 12.1%, while the maximum and minimum by about 19.6% and 5.4%, respectively. These projections suggest that near-term climate change may increase regional water availability with increased extremes. In the far-future, the projections exhibit notable differences between scenarios, yet both suggest overall increases in mean and maximum annual rainfall. Under the far-future SSP2-4.5 scenario, rainfall shows a mean annual increase of 3.4%, a maximum increase of 8.9%, and a minimum decrease of 3.1% compared to the baseline. Similarly, the far-future SSP5-8.5 scenario indicates a 2.4% increase in mean annual rainfall and a 10.8% rise in maximum rainfall, though the minimum rainfall drops by 8.5%. Despite these overall gains, both far-future scenarios reveal areas of reduced rainfall, particularly in the central and western parts of the study area. These results highlight that while far-future rainfall may generally increase under both moderate and high emissions pathways, certain regions are still expected to experience localized declines, especially in minimum rainfall.

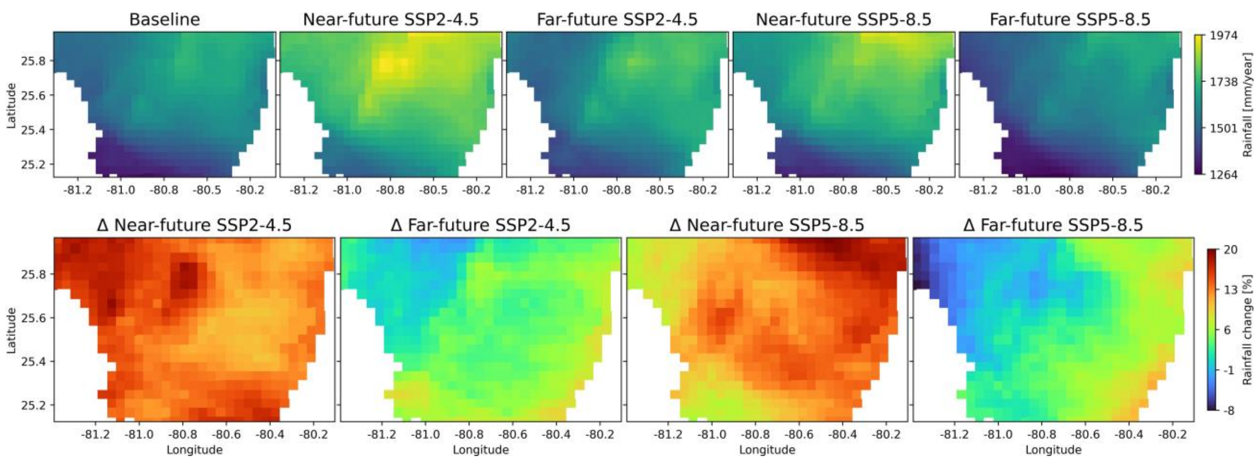

Fig. 4: ACCESS-CM2 model spatial mean yearly rainfall for baseline period and future periods. The change (∆) in the title of two future scenarios and periods represents the spatial differences in rainfall relative to the baseline period.

3.2. BISECT model validation

The BISECT model was validated for an independent period using observed groundwater levels at multiple well stations. The results, presented in Fig. 5, showed a comparison between observed and simulated groundwater levels at daily time scale over a period from 2011 to 2019. Graphical analysis indicated that the model captured the general trends of groundwater fluctuations at several well stations. The observed data showed some sharp fluctuations, while the simulated water level appears relatively smoother. Some wells, such C111AE, C111AK6, G-3338 and G-3339 demonstrate a relatively good agreement between observed and simulated values, suggesting the model replicated groundwater dynamics in these locations. However, notable discrepancies exist in other stations, such as ANGEL and C4GW1.

Most wells have MBE values close to zero, which indicates a minimal mean bias. However, BBCW3GW1 showed a relatively higher positive bias with an MBE of 0.19, indicating that the model overestimated groundwater levels in this location. Conversely, well S356GW4 has a slight underestimation with an MBE of -0.04. Based on the average magnitude of errors, the BISECT model performs well at locations such as G-3338 demonstrating minimal deviation between observed and simulated groundwater levels. However, higher MAE values at stations like ANGEL, C11W15 and C4GW1 suggest a relatively higher average discrepancy. The RMSE is a quadratic scoring rule, which is more sensitive to extremes (outliers) than the MAE. Like the MAE, the model showed good performance based on RMSE for some wells that include G-3338 and BBCMW4G2. On the other hand, ANGEL and C4GW1 presented relatively high RMSE values, indicating that simulated heads at these locations show larger deviations from the observed groundwater levels, particularly in cases with more extreme errors. The variation in model performance across different well locations suggested that several factors influence groundwater level fluctuations. Hydrogeological heterogeneity, boundary conditions such as nearby water bodies, pumping activities, and spatial scale differences can be among the factors that introduce the discrepancies between observed and simulated groundwater levels. Despite these biases, the BISECT model generally demonstrated a good agreement with observed groundwater levels.

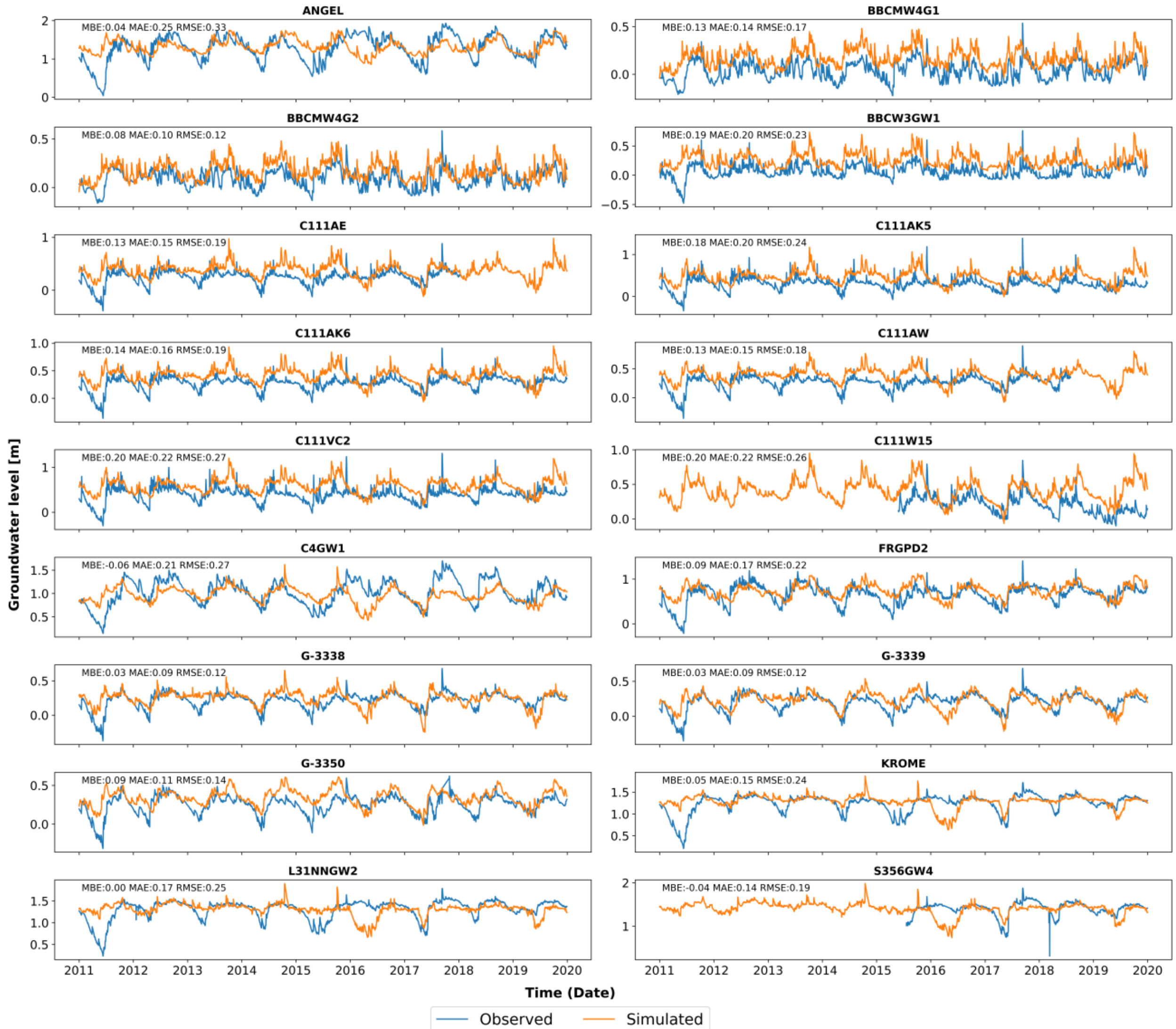

Fig. 5: Daily observed groundwater levels and simulated groundwater levels by the Biscayne and Southern Everglades Coastal Transport (BISECT) model for selected wells from the Miami-Dade County for the baseline period.

The BISECT model was also validated using surface water stage. The BISECT model validation performance using the surface water stage in the Shark River Slough demonstrated a good agreement between observed and simulated values, capturing the general trend (Fig. 6). The results indicated that the model replicated the seasonal and interannual variations in the surface water stage with some discrepancies exist. The error metrics of NP-P33 indicated that the model slightly overestimated the water stage but maintains a low overall error. The observed and simulated time series follow a similar pattern, particularly in capturing seasonal fluctuations and long-term trends. However, some periods show slight deviations, likely due to local hydrodynamic complexities and grid resolution discrepancies. Similarly, the BISECT model performs comparably for NP-P36 station with slight underestimation of the observed water level stage. Despite some discrepancies, the visual trend suggests that the BISECT model can reproduce surface water dynamics in the Shark River Slough. The relatively low ME, MAE, and RMSE also indicated that the model provides an ideal representation of hydrologic conditions. Therefore, this surface water validation also supports the reliability of BISECT as a tool for hydrological predictions and water management strategies, which also supports its applicability for future hydrological assessments in this region.

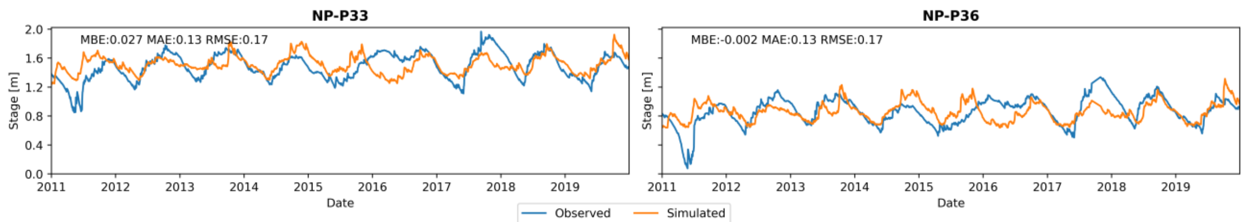

Fig. 6: Daily observed and simulated surface water stage by the Biscayne and Southern Everglades Coastal Transport (BISECT) model for selected stations for the baseline period.

3.3. Surface water salinity and temperature

The BISECT model simulates the surface water salinity which is a very important variable that could affect the ecology of the study area. A spatial distribution and temporal trend of surface salinity across a baseline period and four future climate scenarios is presented in Fig. 7. The spatial maps showed a clear transformation of coastal salinity patterns, especially in the Everglades and surrounding estuarine systems, highlighting the pressing impact of SLR on this ecologically sensitive region. In the baseline scenario, the spatial salinity distribution reveals a relatively well-preserved freshwater-dominated landscape in much of the coastal Everglades, with lower salinity values. However, the future scenarios reveal a dramatic change from this condition. Under near-future SSP2-4.5, there is a noticeable encroachment of higher surface salinity levels along all boundaries. This trend intensifies in the far-future SSP2-4.5 projection, where vast stretches of the southern Everglades transition into saline dominated areas, representing salinity levels up to 40 g L^{-1}. This surface salinity encroachment becomes even higher under the SSP5-8.5 pathway, particularly in the far-future scenario. Large parts of the southern and western Everglades exhibit increased surface salinity values, with freshwater areas shrinking dramatically.

Fig. 7 includes a time-series of salinity at two sample points, labeled P1 and P2, which further verify the spatial analysis. P1 marks the location of a well in Miami-Dade County with the station

ID G-3350, while P2 indicates the site of Mahogany Hammock within Everglades National Park. The salinity trend line in both locations reveals an increasing trend across all scenarios, with steeper increases under SSP5-8.5. This indicates not only a shift in average salinity but also greater seasonal variability, which could exacerbate ecological stress. In the near-future projections, the rise in surface salinity is gradual but consistent. By the far-future, however, salinity levels at both locations surpass current thresholds at 10 g L^{-1}. The variability observed in these plots also highlighted at complex interactions between tidal forcing and reduced freshwater discharge. The projected salinity increases clearly illustrate the potential risk of saltwater intrusion into the well field, which could compromise the quality and availability of freshwater resources. These findings have also reflective impact on the ecological integrity of the South Florida region, particularly the Everglades. This ecosystem is home to a variety of freshwater and brackish dependent plant and animal species. An increase in surface salinity, as shown in these projections, could accelerate the loss of freshwater marshes, promote mangrove encroachment, and diminish habitat suitability.

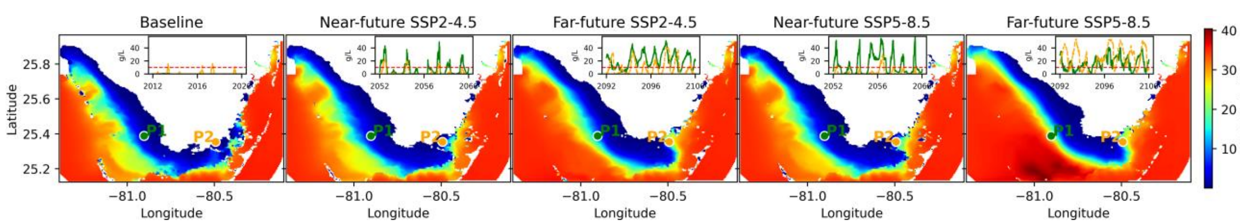

Fig. 7: Simulated spatial and temporal surface salinity under the baseline and four future climate scenarios using the Biscayne and Southern Everglades Coastal Transport (BISECT) model. The line graph in each scenario represents the temporal salinity at two locations P1 (G-3350 groundwater well in the Miami-Dade) and P2 (Mahogany Hammock site within Everglades National Park).

In regions like southern Florida, surface-water temperature can significantly impact the ecological balance of wetlands, estuaries, and coastal environments. The BISECT simulated spatial surface temperature presented important insights into the thermal dynamics under various climate scenarios (Fig. 8). The baseline conditions demonstrated the current surface temperature distribution, characterized by relatively moderate temperature gradients across the Everglades and adjacent coastal areas. In the near-future scenarios, slight variations are observed, but the general spatial pattern remains like the baseline. However, the far-future projections revealed a notable shift. A significant drop in surface temperatures is observed along the coastal margins of the Everglades, particularly under the SSP5-8.5 scenario. This cooling trend can be attributed primarily to increased inundation, driven by SLR and coastal hydrologic changes.

Despite the general cooling along the coasts, the simulation also revealed patches showing an increasing temperature trend. These localized hotspots may be due to reduced freshwater inflows or altered hydrodynamics under the influence of climate change. The presence of such contrasting thermal responses within the study area highlights the complex interaction in hydrology of the study area. Such varying hydrologic conditions and associated changes in surface-water temperature could have ecological implications.

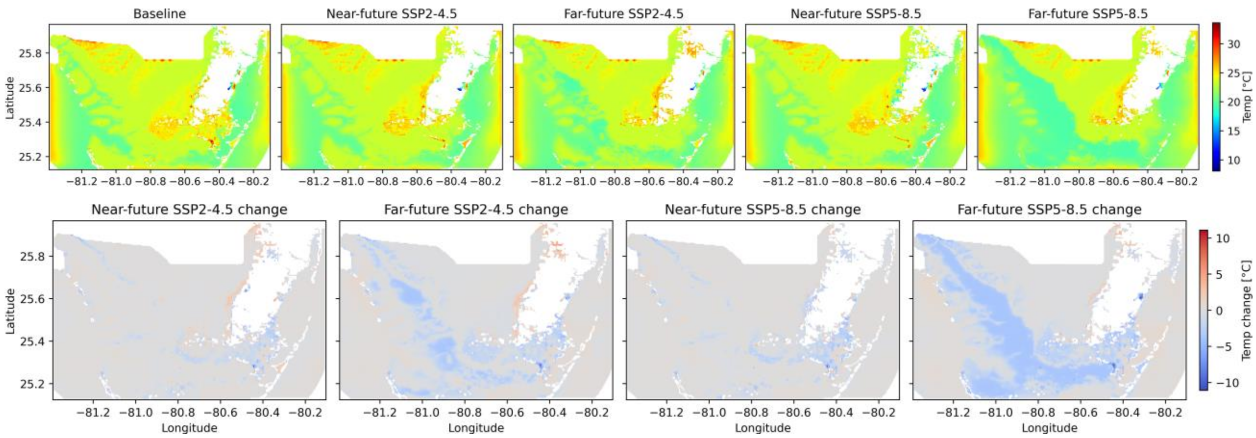

Fig. 8: Simulated spatial surface-temperature under the baseline and four future climate scenarios using the Biscayne and Southern Everglades Coastal Transport (BISECT) model.

3.4. Groundwater variables

The eastern part of the study area is characterized by agricultural areas, wetlands, networks of canals and structures that provide groundwater recharge. Fig. 9 presented spatial patterns of mean annual recharge under baseline conditions, future projections, and their change under the SSP2-4.5 and 5-8.5 for both near- and far-future periods. To enable clearer visual comparison of spatial trends across scenarios, the 90th percentile of the absolute differences was used to define a cutoff threshold, effectively minimizing the influence of outliers. Baseline patterns showed high groundwater recharge rates along the canals and agricultural areas, where those areas are also characterized by high hydraulic conductivity. Under SSP2-4.5 in the near-future scenario, there is a clear increase in recharge magnitude across most parts of the study area. These widespread positive changes could be attributed to projected increases in rainfall under this scenario. Recharge under the far-future projection of SSP2-4.5 remains increased relative to the baseline but shows a slight decrease compared to the near-future period, particularly to the southern part. Under the high-emissions of SSP5-8.5, groundwater recharge dynamics shift notably. The near-future projection under SSP5-8.5 pronounced increase recharge, which coincides with the rainfall increase. Compared to near-future SSP2-4.5, near-future SSP5-8.5

projected less recharge to the system, particularly to the southern part of the study. Under far-future SSP5-8.5, the decrease in recharge becomes across much of the region. Generally, the SSP2-4.5 scenario highlighted the importance of moderate emissions mitigation in supporting sustainable groundwater resources compared to the projected decline in recharge under SSP5-8.5.

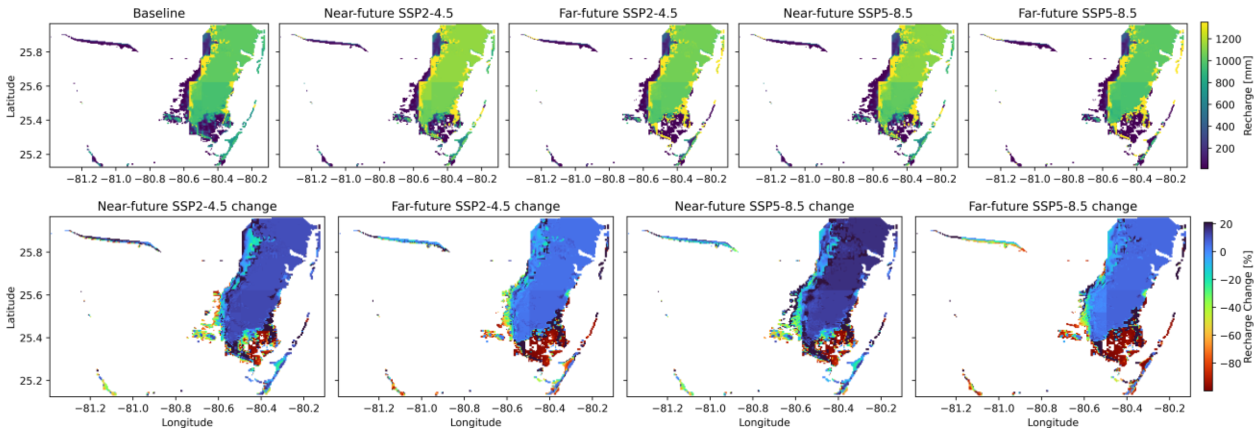

Fig. 9: Simulated spatial groundwater recharge and their projected percentage changes using the Biscayne and Southern Everglades Coastal Transport (BISECT) model under baseline and future climate scenarios.

Understanding groundwater level dynamics is essential for managing freshwater availability, predicting ecosystem responses, and developing climate adaptation strategies in vulnerable coastal regions. The Fig. 10 demonstrated simulated groundwater level distributions and their projected changes under the baseline and future climate scenarios. Under future climate conditions, groundwater levels are projected to increase across much of the study area. A moderate groundwater level rise is demonstrated in the near-future projections for SSP2-4.5 and SSP5-8.5, especially in low-elevated coastal zones. These trends are more pronounced in the far-future projections, particularly under the high-emission SSP5-8.5 scenario, where groundwater levels increase more substantially throughout the study domain. Across all future scenarios, a relatively higher rise is marked within Miami Beach to Bal Harbour. The intensifying red hues in this region across the far-future scenarios highlight the area's high sensitivity to projected climate changes, likely more driven by SLR and slight rainfall increment (Fig. 4). The far-future under SSP5-8.5 indicated the largest increase overall, with groundwater level differences exceeding 0.8 meters in localized areas, showing the highest rise response. Conversely, the spatial change also revealed small groundwater levels decrease compared to the study area, particularly to the north-east part, which are mainly located to the relatively high elevation. The pumping wells are mainly concentrated in this location, which could contribute to lowering the groundwater level. The overall projections suggest that continued climate change will result in widespread groundwater level rises, especially under high-emission scenarios. This could have implications for saltwater intrusion, wetland hydrology, and the sustainability of freshwater resources in the region.

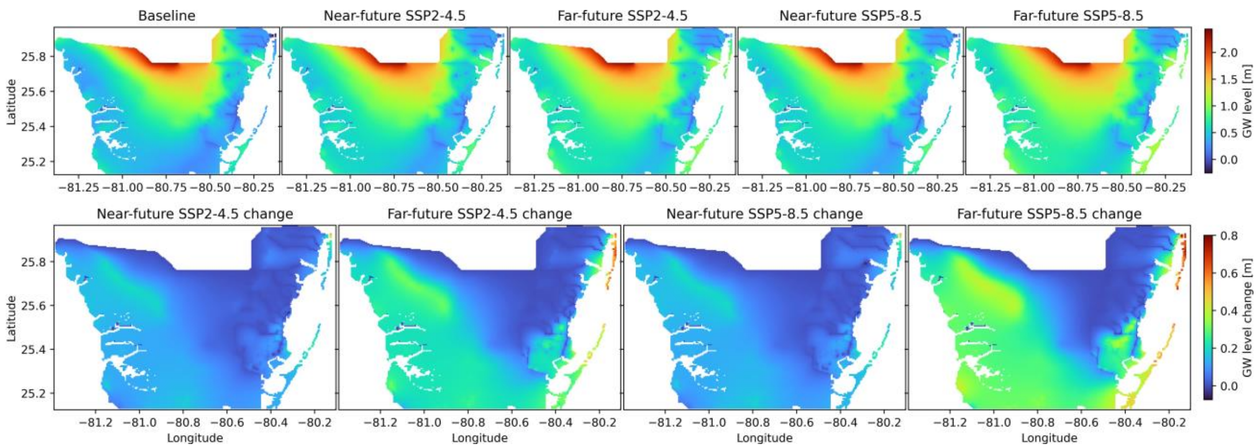

Fig. 10: Simulated spatial groundwater levels and their projected changes using the Biscayne and Southern Everglades Coastal Transport (BISECT) model under baseline and future climate scenarios.

The groundwater evapotranspiration (ET_g) is another flux that is influenced by the GW-SW interaction. The spatial pattern of the ET_g across the study area under current and projected climate scenarios reveals a substantial transformation due to climate-driven hydrological changes, primarily influenced by SLR. The Fig. 11 demonstrated the average ET_g distribution for the baseline, near-future and far-future under SSP2-4.5 and SSP5-8.5. In the baseline scenario, ET_g values are relatively high, especially in the southern and western regions of the domain. This is indicative of shallow water tables, which promote interaction between the surface and groundwater systems. However, the future scenarios indicate a pronounced shrinking in ET_g across these regions of the study area. This decline correlated with model-projected rises in the groundwater table, which reach the land surface. As groundwater levels increase, the zone of evapotranspiration shifts increasingly toward open water or saturated land surfaces. In such settings, evapotranspiration transitions from being largely driven by plant-root uptake of groundwater to a more surface-dominated evaporation regime.

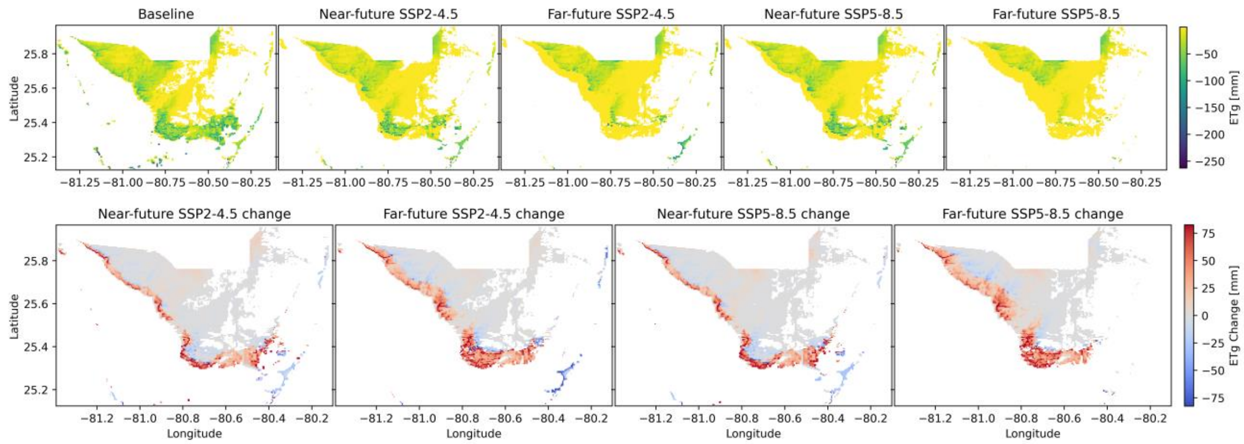

Fig. 11: Simulated spatial groundwater evapotranspiration and their projected changes using the Biscayne and Southern Everglades Coastal Transport (BISECT) model under the baseline and four future climate scenarios.

Coastal salinity in groundwater is substantially affected by SLR. Fig. 12 presented the projected changes in groundwater salinity across four future climate scenarios at layer 4 of the BISECT model. Each map demonstrated salinity change relative to a baseline, reflecting the impact of the SSP2-4.5 (moderate emissions) and SSP5-8.5 (high emissions) over both near-future and far-future periods. The most prominent feature across all four scenarios is the projected increase in salinity, which reaches concentration as high as 34 g/L. This change is spatially concentrated in the eastern part of the study area in the Miami-Dade County, where major wellfields are located. These wellfields are the sources of potable water for urban and agricultural uses. The eastern part proximity to the Atlantic Ocean is mainly vulnerable to saltwater intrusion, especially under SLR and pumping demand conditions.

When comparing the near-future and far-future projections, the magnitude and spatial extent of groundwater salinity increment demonstrated higher under the far-future projections, especially under the SSP5-8.5 scenario. This saline pattern highlighted the increasing risks of aquifer salinization unless substantial mitigation or adaptation strategy is considered. Interestingly, there are scattered patches where groundwater salinity is projected to decrease. These localized declines may be associated with the influence of hydraulic structures and hydrogeologic features benefiting from recharge through canal systems or restoration efforts.

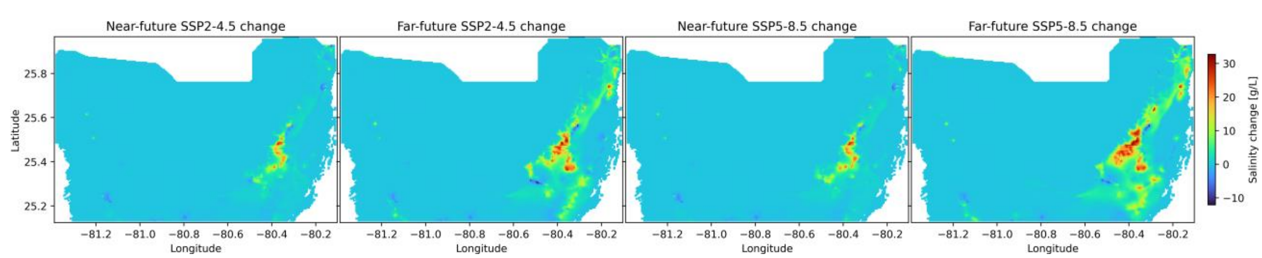

Fig. 12: Simulated spatial groundwater salinity changes the four climate scenarios relative to the baseline distributions at layer 4 of the Biscayne and Southern Everglades Coastal Transport (BISECT) model.

4. Discussion

This study assessed the combined impacts of projected SLR and changing rainfall patterns on surface and groundwater interactions, groundwater recharge, groundwater level and salinity affecting freshwater availability in hydrologically connected systems, applying a density-dependent BISECT model. The BISECT model was validated with independent data and analyzing its future impact. The model simulation results highlighted climate-driven shifts in hydrology, with major implications for groundwater recharge, groundwater levels, surface salinity, and GW-SW interactions in South Florida. The simulations indicated that future climate scenarios, especially the high emissions scenarios, will change the hydrologic variables relative to the baseline period. Such results are important to provide insights for policymakers and water resource managers to develop climate-resilient strategies that ensure sustainable water management in such vulnerable coastal regions.

The BISECT model results demonstrated that projected SLR and shifting rainfall patterns will influence groundwater recharge and water level across South Florida. The groundwater levels under future climate scenarios, especially pronounced in the low-lying coastal zones. This result is consistent with previous studies indicating that SLR can drive significant groundwater increases in coastal aquifers. Guha & Panday (2012) presented that raising sea level by 0.6 - 1.2 m results in water levels increasing by 4-15% in parts of Miami-Dade and Broward Counties. Our study's results align with such projections, indicating that SLR forces a higher hydraulic head by increasing the coastal boundary water levels. Consequently, the recharge zone that drained freely during the baseline may become increasingly saturated in the future. The highest groundwater rise (~ 1 m) occurred in densely developed coastal corridors like Miami Beach (Fig. 10), highlighted that these zones are highly sensitive to climate-driven boundary conditions like the rainfall shift and SLR. This agrees with observations that Florida's flat and low elevation terrain makes its aquifers especially prone to groundwater levels rise as sea levels rise and shifts in precipitation patterns (Haque, 2023). Increased groundwater levels have important implications for recharge processes. Shallow groundwater levels can reduce the soil storage capacity for infiltrating rain, leading to more rejected infiltration converted to surface runoff. Such conditions can severely restrict drainage capacity, particularly in urban areas. This aligns with Davtalab et al. (2020) that even modest groundwater level rise can compromise stormwater retention systems, increasing flood risks. Thus, this study's projection of rising groundwater levels could be challenges for flooding, particularly during events like intensive extreme rainfall and hurricane periods in South Florida's coastal communities.

The GW-SW interactions and freshwater availability is related to the groundwater levels dynamics. When the groundwater level rises to the land surface, as projected in coastal parts of the Everglades and some urban Miami (Fig. 10), the risk of wetland inundation and surface flooding increases. This can enhance GW-SW connectivity, potentially leading to more frequent groundwater seepage which leads to the emergence of groundwater inundation (Davtalab et al., 2020). Moreover, higher groundwater levels reduce the hydraulic gradient toward the coasts, causing the discharge upward into surface wetlands or through seepage into canals. This could sustain surface water in dry periods, but it also indicated that seasonally dry areas could become more persistently wet. The timing and extent of such inundation are crucial for ecosystem functions in the Everglades (Hasan et al., 2023). Hence, climate-driven groundwater level shifts could disrupt the balance between wet and dry seasons that many inhabitants depend on. This study also underscored that climate change could stress the balance of supply and demand, which requires adaptation strategies considering the balance between groundwater withdraws and replenishments. This is consistent with Haque (2023) review, which highlighted that Florida's fresh groundwater withdrawals are already approaching sustainability limits in many coastal regions, including South Florida.

The most critical changes observed in this study's simulations are related to salinity. Both groundwater and surface water salinity are projected to increase under future climate scenarios. The simulated maps of groundwater salinity change (Fig. 12) revealed a clear intensification of saltwater intrusion into the Biscayne Aquifer. In all scenarios, especially under far-future SSP5-8.5, there are large swaths of the eastern part with increased salinity levels relative to the baseline. The simulated groundwater chloride concentrations reach greater than 30 g/L in the Biscayne Aquifer, especially adjacent to the Atlantic coast and near major municipal wellfields. This indicated that migration of the freshwater-saltwater interface within aquifer, driven by the higher sea-level boundary forcing saltwater further inland (Werner et al., 2013). This is also consistent with historical trends and projections for South Florida's aquifers over the past decades, saltwater intrusion has moved inland in the Biscayne Aquifer (Langevin, 2001). Our results indicated this problem will worsen under future SLR. Guha & Panday (2012) similarly projected 100–600% increases in average chloride concentration at some monitoring wells given ~0.6-1.22 m SLR in South Florida. The surface water salinity (Fig. 7) exhibits parallel changes to groundwater salinity, reflecting the interconnected nature of the coastal aquifer and overlying wetland estuary system. The coastal surface waters become saline under future conditions because of SLR pushing saline water inland. While climate scenarios project increases in rainfall, excess water runs off or raises groundwater instead of sustaining low salinity in surface waters. Upstream water management decreased freshwater flow and leads to higher salinity and ecological disturbance in estuarine bays (Lohmann et al., 2012). This is also supported by other coastal wetlands study such as the coastal Louisiana, where SLR have driven saltwater farther inland (Day et al., 2024). The Biscayne Aquifer is highly vulnerable to such saline intrusion due to its high permeability and direct connection to the sea (Langevin, 2001; Langevin, 2003). Such intrusion may become more frequent and severe with climate change during dry periods, as reduced freshwater heads can allow seawater to push further inland.

The changes in evapotranspiration and GW-SW interactions are another notable change in this study. Under baseline conditions, groundwater evapotranspiration (ET_g) is high in the southern Everglades relative to the future, indicating exchange between the aquifer and the wetland root zone. However, under future scenarios, ET_g declines sharply over the western and southern domain, especially in the far-future. This result is explained by the hydrologic shifts that groundwater levels rise to the land surface, where the system transitions to open-water evaporation. This indicated wetlands become more water-logged from higher sea-driven water levels, reducing plant uptake of groundwater as deeply flooded plants may die or stop being the main pathway for water loss. This change is supported by Everglades historical observations showing that landward saline water intrusion degrades ecosystems and alters vegetation distribution and productivity (Obeysekera et al., 2017). Therefore, like groundwater level, reduced ET_g is also indicative of a shift in GW-SW interactions.

There are limitations and uncertainties inherent in modeling approach. The discussion here assumes the model projections are reasonable for future projections. Climate models have uncertainty, the six downscaled GCMs showed variability in their rainfall projections for Florida. While this study sourced the statistical downscaled and bias-corrected rainfall, different downscaling techniques may result different hydrologic impacts (Chen et al., 2012; Kim et al., 2024). Moreover, the real SLR by late century remains uncertain, with recent projections ranging widely depending on emission scenarios and ice sheet dynamics (Siegert et al., 2020; Sweet et al., 2022; Wang et al., 2025). The SSP5-8.5 scenario reflects an upper-end result and if global efforts manage and limit such emissions, SLR might be less severe for the hydrologic disruptions. It should also be noted that extreme values are somewhat averaged over each model cell due to resolution (Swain et al., 2019), where the results might be conservative in terms of extremes. Despite such uncertainties, the overall patterns of this study demonstrated spatially variable recharge in response to more rainfall, rising groundwater levels, accelerated saltwater intrusion, and GW-SW interaction changes in response to SLR. These changes marked substantial shifts of hydrologic patterns in the future in South Florida, signaling challenges for water management and ecosystem conservation in the region.

5. Implications and broader relevance

Beyond numerical analysis, the study also demonstrated broader implications of these hydrological shifts. The projected changes in both surface water and groundwater variables were evaluated in terms of their potential impacts on human communities, water resources, and ecological systems in South Florida. The findings were discussed in the implications of increasing flood risks, saltwater intrusion into freshwater aquifers, changes in wetland hydrology, and potential threats to biodiversity. Given South Florida's reliance on groundwater for drinking water and its extensive wetland ecosystems, understanding these impacts is crucial for developing adaptive water management strategies.

The projected hydrological changes carry wide ranges of implications for the South Florida environment. These include the impacts on the ecology of the Everglades and coastal systems, which are sensitive to water levels, salinity and temperature. Freshwater marshes that currently occupy large areas of the southern Everglades may decline as conditions become more saline and tidally influenced. The future surface water salinity in this area could exceed tolerance thresholds of freshwater plants, leading to vegetation die-off. Common freshwater macrophytes tolerate salinity levels of 5-10 g/L (Moreira et al., 2023), but projections indicate even higher salinity in the Everglades under moderate emission scenarios. Accordingly, other species like mangroves could colonize areas farther inland replacing the freshwater vegetations, which could lead ecological shifts by reducing the biodiversity of the area. This projected transition is following the observed trend that SLR driven salinity has been resulting shifts in vegetation like mangrove encroachment (Ogurcak et al., 2019; Ross et al., 2022).

Another critical implication of increased salinity and changing groundwater levels is the risk of peat soil collapse, which can speed up the wetland loss and increased vulnerability of coastal ecosystems. Salinity driven peat collapse shifts the wetland ecosystem from carbon storage to carbon loss (Chambers et al., 2019; Ishtiaq et al., 2022; Servais et al., 2019). In the Everglades, this collapse has already resulted in the conversion of freshwater marshes to open water environments, experiencing up to 0.5 meters of elevation loss over a few decades (Sklar et al., 2019). Such peat soils collapse also plays a significant role in increasing flood risk, by losing elevation through compaction, which reduces the ability to store water. A study at the Everglades experimented that freshwater peat soils have about three times greater degree of pore dilation when compared to peat soils previously exposed to saltwater conditions (Sirianni et al., 2023). Future increases in salinity will also pose a threat to agriculture by disrupting the soil health in South Florida, including the eastern part where high groundwater salinity intrusion is projected. The region's shallow and highly permeable limestone soils make it especially vulnerable, as saltwater can easily infiltrate both surface and groundwater systems.

Beyond ecological changes, the projected hydrological shifts in this study will have direct implications for human communities, particularly regarding freshwater availability, flood risk and tourism. The Biscayne Aquifer is the primary drinking water source. Worsening saltwater intrusion into this aquifer poses a risk to water-supply security. Wellfields that are currently usable may become too saline, requiring costly interventions such as moving wells further inland or investing in desalination (Haque, 2023; Maliva & Missimer, 2012). Increased groundwater levels also lead to increased inland flooding (Czajkowski et al., 2018), which threatens infrastructures. The groundwater rise can impact building foundations, roads and other infrastructure in low-lying areas. Furthermore, agricultural activities in areas adjacent to the Everglades could be affected with higher water levels, which may require adjustments in irrigation and drainage practices. The economic implications of these changes could be significant, in terms of the costs for damage and mitigation strategies. Tourism and other ecosystem services in South Florida are also closely tied to the sustainable health of the Everglades and coastal environments. These areas are valued with unique natural resources and biodiverse ecosystem habitats, which collectively attract visitors. The future climate driven SLR will degrade these areas into a saltier and less biodiverse system, which will also affect the tourism sector.

The results from this study underlined the importance of integrating climate change projections into water management and conservation planning for South Florida. The Comprehensive Everglades Restoration Plan, which aims to restore more natural flow patterns to the Everglades, should consider SLR and rainfall change patterns in its design management and implementation. Protecting upstream water storage and controlling groundwater pumping near the coast could also be among the possible management actions. Future projection periods indicated that engineering solutions may need to be supplemented by difficult choices, such as moving infrastructure and possibly even allowing some areas to transition to new ecological states. Considering these front challenges, it is very crucial to define a strategy on climate-change mitigation alongside adaptation. This study not only quantifies hydrological changes under future climate scenarios but also highlights the interconnected nature of climate impacts, where changes in hydrology can trigger cascading effects on ecological and human systems.

Beyond South Florida, findings from this study highlighted how density-based integrated hydrological modeling can provide valuable implications for other coastal regions facing similar climate threats. This approach simulates multiple interconnected hydrological processes that together determine system resilience. Traditionally, surface water and groundwater management have been treated separately, which can lead to maladaptation when interventions that reduce one risk worsen another. The Integrated modeling approach instead helps design strategies that balance trade-offs and deliver co-benefits, supported by multiple hydrological outputs. Moreover, spatio-temporal analysis of future climate change impacts allows identification of hotspots, where adaptation measures are most critical.

The relevance of this study extends to other coastal regions impacted by SLR (Magnan et al., 2022), shifting rainfall patterns (Nanditha et al., 2025) and saltwater intrusion into aquifers (Cao et al., 2024). As emphasized for coastal aquifers, sustainability requires integrated evaluation of density-dependent flow along with adaptation measures such as managed aquifer recharge, managed pumping and restoration of infiltration capacity (Elshall et al., 2020). Similar dynamics are presented in the Southern Mediterranean coast, where shoreline retreat, SLR and hydroclimatic changes driven by shifting weather patterns accelerate seawater intrusion, raise groundwater levels and destabilize building foundations (Fouad et al., 2025). Low-lying areas are also increasingly exposed to flooding, which is accelerated by SLR (Hague et al., 2023; Thiéblemont et al., 2024). SLR not only drives the surface inundation but also raises shallow groundwater, compounding flooding and saltwater intrusion challenges for infrastructure and community, which are often overlooked in coastal planning (Bosserelle et al., 2022). These combined dynamics demonstrate that coastal areas are especially sensitive to SLR, given their ecological richness, diverse landscapes, and critical socio-economic importance (Durand et al., 2022). This implies adaptation and mitigation strategies should be grounded in outputs from integrated hydrological approaches, which can capture overlapping risks. Among these, nature-based solutions (NBS) are widely recognized as effective strategies for addressing climate change impacts, but their adequacy depends on spatial context and hydrological interactions. Developing a robust metrics-based framework to evaluate NBS performance before implementation remains an important ongoing research focus. Such integrated evaluations not only identify where NBS provides multiple benefits but also guide decisions on when to integrate gray infrastructure, relocation or limiting costly investment may be the more effective and sustainable options in highly vulnerable areas. Thus, the integrated modeling approach and findings presented here provided a basis for developing frameworks to evaluate NBS, which are highly relevant for building climate resilience in low-lying coastal areas.

6. Conclusion

In this study, a density-dependent BISECT model simulated the combined effects of SLR and changing rainfall patterns on South Florida's hydrology. The model was initially run for the baseline period (2011–2019) to validate its performance, followed by simulations for the near-future (2051–2059) and far-future (2091–2100) periods under the moderate (SSP2-4.5) and high (SSP5-8.5) emissions scenarios. The simulations predicted significant climate-driven changes, including higher groundwater levels, changed recharge patterns, and increased salinity in coastal aquifers and wetlands. Under a moderate scenario, increased rainfall will increase the recharge, while under a high-emissions scenario, a slight decrease in rainfall is projected relative to the moderate scenario. The projected SLR contributes to saturated ground by rising groundwater in low-laying areas, which can cause persistent flooding. The other most critical change is the increase in saltwater intrusion. SLR pushes saltwater farther inland, and the BISECT model projects a pronounced inland shift of the freshwater–saltwater interaction. By the end of this century, parts of the Biscayne Aquifer that are fresh today could become saline, threatening coastal wellfields and drinking water supplies. Likewise, coastal wetlands, particularly the Everglades, become much saltier, causing freshwater vegetation to be impacted. This also supported by the groundwater evapotranspiration shrink from the baseline to the far-future period. These hydrological changes pose serious risks to ecosystems. Saltwater intrusion into the Biscayne Aquifer threatens the region's main drinking water source. These results highlighted the broader relevance of the integrated modeling approach as a basis for effective adaptation strategies that build resilience in vulnerable coastal regions facing SLR and shifting rainfall patterns. Future research should focus on developing frameworks from such integrated modeling approach to evaluate and optimize NBS as adaptation options for coastal resilience.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Open Research

The datasets supporting this study include statistically downscaled rainfall projections from the CMIP6 ensemble (Kao et al., 2022), sea-level rise projections from the NASA IPCC AR6 Sea Level Projection Tool (Garner et al., 2021), and daily observed groundwater levels and surface-water stages from the South Florida Water Management District DBHYDRO database (SFWMD, 2025). The density-dependent integrated hydrological model applied in this study is the U.S. Geological Survey Biscayne and Southern Everglades Coastal Transport (BISECT) model (Swain et al., 2019).

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