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Florida's Groundwater and Surface Water System Reliability in Terms of Climate Change and Sea-Level Rise

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Abstract**—**Florida is one of the most vulnerable states to natural disasters among the 50 states of the USA. The state is exposed to tropical storms, hurricanes, storm surges, landslides, etc. Besides the mentioned natural phenomena, global warming, sea-level rise, and other anthropogenic environmental changes make a very complicated and unpredictable system for decision-makers. In this study, we tried to highlight the effects of climate change and sea-level rise on surface water and groundwater systems for three different geographical locations in Florida; Main Canal of Jacksonville Beach in the northeast of Florida adjacent to the Atlantic Ocean, Grace Lake in central Florida, far away from surrounded coastal line, and Mc Dill in Florida and adjacent to Tampa Bay and Mexican Gulf. An integrated hydrologic and hydraulic model was developed and simulated for all three cases, including surface water, groundwater, or a combination of both. For the case study of Main Canal-Jacksonville Beach, the investigation showed that a 76 cm sea-level rise in time horizon 2060 could increase the flow velocity of the tide cycle for the main canal's outlet and headwater. This case also revealed how the sea level rise could change the tide duration, potentially affecting the coastal ecosystem. As expected, sea-level rise can raise the groundwater level. Therefore, for the Mc Dill case, the effect of groundwater rise on soil storage and the performance of stormwater retention ponds is investigated. The study showed that sea-level rise increased the pond's seasonal high water up to 40 cm by time horizon 2060. The reliability of the retention pond is dropped from 99% for the current condition to 54% for the future. The results also proved that the retention pond could not retain and infiltrate the designed treatment volume within 72 hours, which is a significant indication of increasing pollutants in the future. Grace Lake's case study investigates the effects of climate change on groundwater recharge. This study showed that using the dynamically downscaled data of the groundwater recharge can decline up to 24 % by the mid-21st century.

Keywords**—**Groundwater, surface water, Florida, retention pond, tide, sea level rise.

I.INTRODUCTION

GLOBAL warming has complicated effects on our atmosphere system and consequently on the environment [1]. On one side, temperature increase can cause more evapotranspiration (ET), and on another side, it can decrease/increase precipitation depending on different longitude or latitude [2]. In many areas, regardless of increasing or decreasing precipitation, extreme events like droughts, wildfires, tropical events, hurricanes, and storm surges for coastal areas are projected to have a significant increase [3]. Also, the historical data depicts that the sea level is increased by 1.7 mm/year for the last century. It is projected to rise one more meter by the end of the current century because of global warming and related ocean expansion and ice melting in Greenland and Antarctica [3].

Florida is ranked 3rd in the United States for the number of flood insurance claims for the last four decades [4]. The state is hit by tropical storms every year and threatened by storm surges in low-lying coastal areas [5]. The Sea Level Rise (SLR) is projected 76 cm for time horizon 2060 and 195 cm for time horizon 2100 [5]. The coastal life is very effective to the changes of sea level. Plus, about 10% of Floridians live in an area with a ground elevation less than 150 cm. That is why the SLR should be the core of decision-making on stormwater management of low-lying coastal regions [6]-[8].

Groundwater is the primary source of water supply for different water demands in Florida (e.g., agriculture, industry, and domestic). Also, groundwater is the source of base flow for natural wetlands and swamp spread all over the state, and any significant change may cause damage in wetland and related ecosystems [9]. Precipitation changes and changes in evapotranspiration can change surface water and infiltration and consequently affect the recharge rate [3]. Therefore, Florida is at risk of SLR from coastal areas and challenges of groundwater resources.

Several studies for Florida investigate climate change or global warming effects on surface water, SLR and coastal wildlife, and groundwater [5]-[8], [10]. But limited research studies are investigating the impacts on surface water/ groundwater systems in an integrated approach. This study tried to examine the Climate Circulation Model (GCM) data and SLR on Florida's east coast (Atlantic Ocean) and the Mexican Gulf coast in west Florida, and one of the wetlands in central Florida.

II.STUDY AREA

Three different locations were chosen for this study, including Mc Dill at the east coast of Florida and adjacent to the Gulf of Mexico, Grace Lake almost in central Florida, and Main Canal-Jacksonville Beach (MCJB) in the northeast of Florida and adjacent to the Atlantic Ocean (Fig. 1). MC Dill covers about 49 hectares and discharges to Tampa Bay and

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finally the Gulf of Mexico. This case study evaluates the effects of SLR on the efficiency of stormwater retention ponds. Therefore, the Hydraulic and Hydrologic (H&H) model, including surface water and groundwater, was developed for this case study. This case study is located within Southwest Florida Water Management District (SWFWMD). The case of Grace Lake investigates the effects of climate change on recharge volume and lake hydroperiod. For this case, the H&H model, including surface water and groundwater, was developed for about 500 hectares of the contribution area. Grace Lake is located within the St. Johns River Water Management District (SJRWMD). For the case MCJB, the H&H modeling is considered for about 960 hectares of the contribution area. This case study aimed to evaluate the effects of SLR and tide current on flow velocity and flood stage downstream and upstream of the main Jacksonville Beach outfall. Therefore, for this case, just surface water H&H was developed. Like Grace Lake, this case is within SJRWMD, downstream of St Johns River (See Fig. 1).

III. INPUT DATA

A wide range of input data was used in this study, including but not limited to precipitation, Potential Evapotranspiration (PET), NRCS soil map and related data bank [11], landuse from SJRWMD (for case Mc Dill), and SWFWMD (for case Grace Lake and MCJB), tide and SLR data, LiDAR DEM. The 15-minutes precipitation data from Next Generation Weather Radar (NEXRAD) was used as the source of precipitation. These data are available for a 2-kilometer grid, and the data are ordered and received from SJRWMD and SWFWMD. For Mc Dill and Grace Lake which groundwater and continuous simulation were involved, PET was considered. These data were obtained on a daily time scale from United States Geologic Survey (USGS) website.

The two case studies of MCJB and Mc Dill are affected by the downstream tide near Intercoastal Waterway and Tampa Bay, respectively. The tide data for these two cases are downloaded from the NOAA tide website (station ID 8720218 for MCJB and Station ID 8726520 for Mc Dill). The mentioned tide data was used as boundary data for the current condition, and the tide data plus SLR was used as boundary data for the future. The projected SLR for a time horizon of 2060 is about 76 cm, determined from National Climate Assessment (NCA) to adjust tailwater for the future condition simulation [5]. LiDAR-based digital Elevation Model with spatial resolution 1.5 meters was used as ground base for 2-Dimensional (2D) surface-water/groundwater modeling. Florida Department of Environmental Protection (FDEP) is a reliable source of groundwater surfaces like Florida Aquifer Units (FAU) used as aquifer base, potentiometric surface, and the water table surface. These data were used in the current study for cases of Mc Dill and Grace Lake.

The last major data used just for the case study Grace Lake was future precipitation and PET. The COAPS Land-Atmosphere Regional Ensemble Climate Change Experiment for the Southeast United States at 10-km resolution (CLARREnCE10) was used as future precipitation and temperature [12]. CLARREnCE10 consists of dynamic downscaling of three GCM models of the Geophysical Fluid Dynamics Laboratory GCM (GFDL), the Hadley Centre Coupled Model version 3 (HADCM3), and the Community Climate System Model (CCSM). The data set has precipitation and temperature for time horizon 2060 (2038-2070) on a daily time scale. The future daily temperature from this data set was used to generate PET using the Penman-Monteith method via FAO-Cropwat 8.0.

Fig. 1 The location map of three different case studies

IV. METHODOLOGY

A. Hydrologic and Hydraulic model

In this study, an integrated Hydrologic and Hydraulic (H&H) model was developed for each case study to evaluate the effects of climate change or SLR on surface water and groundwater system. The H&H model for case study MCJB had only the surface water component, while the cases of Mc Dill and Grace Lake had both surface water and groundwater components. The Interconnected Channel and Pond Routing (ICPR) model was applied to simulate the rainfall-runoff, routing of runoff through 1-Dimensional (1D) sub-basins, and 2-Dimensional (2D) surface and routing through 1D hydraulic infrastructures including pipes, channels, control structures [13]. ICPR also simulates the interaction of surface water and groundwater through infiltration and vertical and horizontal water movement in soil columns from the ground surface to surficial aquifer systems.

ICPR can model H&H using the 1D approach, 2D approach, and mix of both. The groundwater component is optional, and it can be inactive for the cases that groundwater effect is not essential or for any reason surface water is the only concern. Fig. 2 represents the main structure and inputs of the ICPR model. 1D component was the only option for the early versions of ICPR. For those cases, the watershed is divided into sub-basins and for each sub-basin, the related parameters like area, impervious percentage, soil properties, and time of concentration were manually estimated and added into the basin table. The 1D model generates run-off and hydrograph for nodes that are representatives of sub-basins. Run-off transfers from one node to another via 1D links like channels, pipes, overland flow, and other hydraulic structures. In ICPR 4, there are different methods for flow routing through the links, and the energy equation was applied in this study:

The energy method was used for flow calculations in this study:

$$H_1 + \frac{c_1 V_1^2}{2g} = H_2 + \frac{c_2 V_2^2}{2g} + h_{en.} + h_{ex.} + h_{fr.} + h_{be.} + h_{ed.} \qquad (1)$$

where subscript 1 and subscript 2 represent conditions at node 1 and node 2, respectively; H represents elevation (m); c_1 and c_2 are energy loss coefficients; V represents velocity (m/s); g is gravitational acceleration (m/s^2); $h_{en.}$ is the entrance loss coefficient; $h_{ex.}$ is the exit loss coefficient; $h_{fr.}$ is the friction loss coefficient; $h_{be.}$ is the bend loss coefficient; and $h_{ed.}$ is the eddy loss coefficient.

For the new versions, in which 2D modeling is involved, GIS map layers including soil, landuse, DEM, Aquifer base potentiometric surface, and … can be added into the model (Fig. 2). The automated triangular mesh, combined with user-defined flexible mesh, specifies the spatial resolution of the 2D model (Fig. 3). The vertices of the triangle mesh generate 2D nodes and surrounded 2D basins equivalent to 1D nodes and 1D basin. The 2D basins intersect with map layers (e.g., soil, landuse, DEM …), and the model using the look-up tables estimates weighted H&H parameters (Manning values, impervious %, elevation, and …) for each 2D basins. Finally, the triangular mesh acts as the 1D link to route flow through 2D basins.

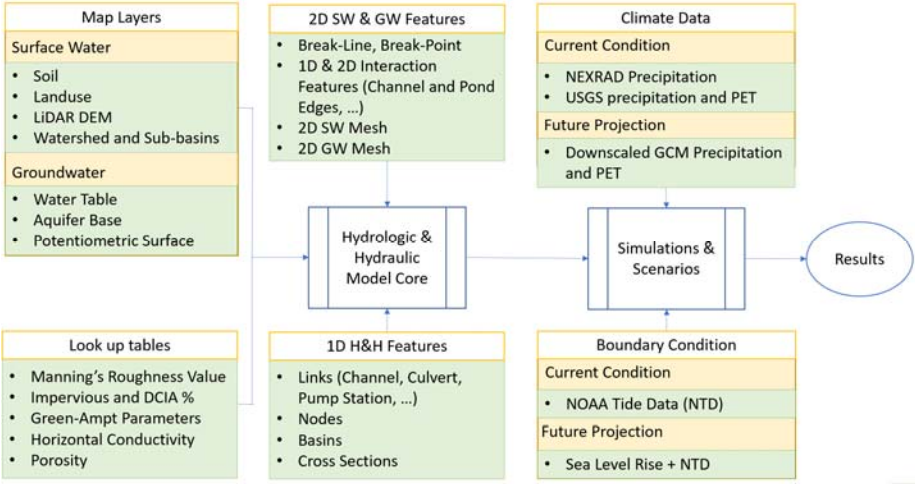

Fig. 2 Structure of ICPR model and developed scenarios

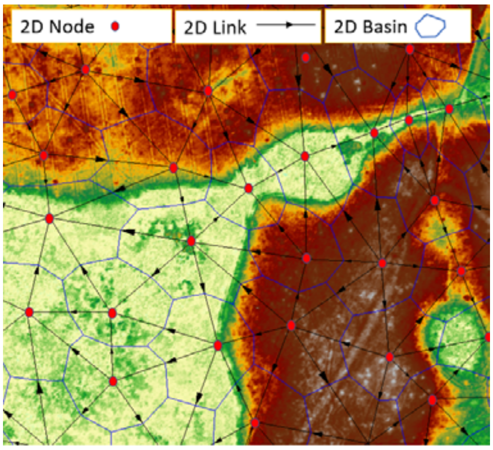

Fig. 3 Example of ICPR 2D features for surface water system

ICPR has different rainfall-runoff methods. In this study, the Green-Ampt method is used [14]. In this method, the excess runoff and vertical water movement in the unsaturated soil column are estimated using a formula derived from Darcy's law [13]. ICPR uses a modified version of Green-Ampt which Evapotranspiration from the surface to the root depth is allowed. ICPR applies horizontal conductivity for water transfer in saturated soil zone. Deep percolation and leakage can be added into ICPR estimation using the potentiometric surfaces.

B. Case Study for MCJB

The Main Canal-Jacksonville Beach (MCJB) is the main outfall for about 10 km^2 of the drainage area. It collects surface water from Neptune Beach and Jacksonville Beach and sends them into the Intercoastal Waterway and the Atlantic Ocean (Fig. 4). The canal is under tide effect, and storm surge and SLR can significantly change its coastal ecosystem and stormwater management capacity. For this case study, no hydrologic and groundwater components were involved. The drainage network for this case includes about 9 km of underground pipe, 7 km channel, 170 overland flow weirs, and nine control structures for the outlet of stormwater ponds. The model was run for two scenarios of tide boundary data and tide plus SLR. As mentioned above, there was no rainfall, and we investigated the

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SLR on the behavior of flow inside the main channel for downstream and upstream (See Fig. 4).

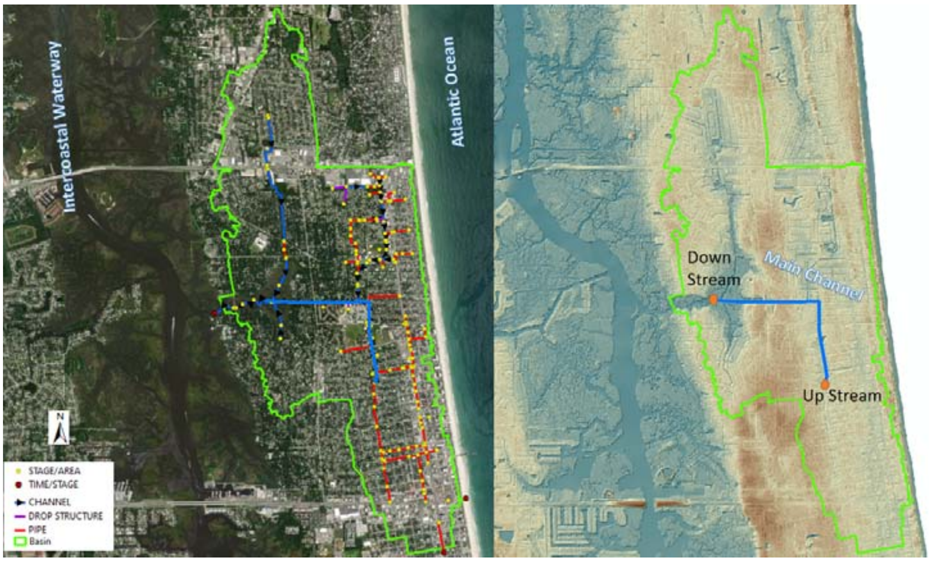

Fig. 4 The MCJB drainage system with aerial map and DEM backgrounds

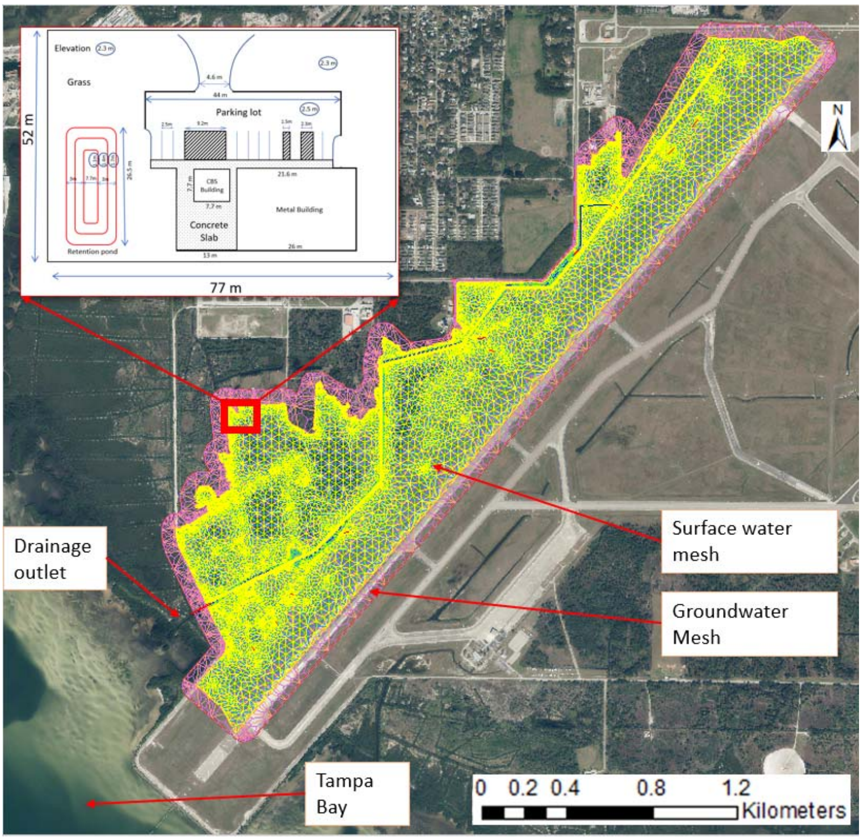

Fig. 5 The Mc Dill Drainage system and simulated 2D surface water groundwater mesh

C. *Scenario for Case Mc Dill*

The Mc Dill drainage system encompasses the main channel and several pipe crossings, which flows from northeast to southwest and the discharges to Tampa Bay and Mexican Gulf (Fig. 1). The most area of this drainage system is affected by tide and storm surge. In this study, a full 2D Surface water/groundwater model was developed for the drainage system and the boundary of the system set to the varied tide from NOAA tide data at Tampa Bay. This study aimed to evaluate the effect of SLR on groundwater rise and consequently on the reliability of the retention pond of a development site (Refer to Fig. 5).

In Florida, all new developments need to get the Environment Resource Permit (ERP) provided by the different water districts. Mc Dill is part of Southwest Florida Water Management District (SWFWMD), and based on the ERP of SWFWMD, the stormwater retention pond for each development site should hold and percolate the first 1" (2.54 cm) of rainfall over the area of the developed site. The study site has a 3966 square meter area; therefore, the total retention pond was estimated 101 cubic meters. The retention ponds are designed to retain about 95% of storm events. Thus, the model was run for the normal year 2012 with two different boundary conditions of the varied tide with and without SLR. The reliability of this stormwater system is defined as the percent of the time that this retention pond can fully capture and the storm runoff without any outflow from the pond berm to the drainage system [15]. Also, the ERP of SWFWMD requires each retention pond to recover the total treatment volume (101 square meters) within 72 hours. So, this study evaluates the reliability of the retention pond for current and future conditions (with and without SLR, respectively). Also, the study tries to evaluate the recovery time for current and future condition.

D. *Scenario for Case Grace Lake*

Unlike the other two case studies, Grace Lake is not close to any gulf or ocean, so the sea level has no significant effect on this drainage system (Figs. 1 and 6). The Grace Lake case study covers a series of interconnected ponds (including Grace Lake and Myrtle Lake) and the drainage system, which covers about 50 km^2 area, and this system drains to the Lake Jesup on the east side of the study area. This case study investigates the effect of climate change on the hydroperiod of Grace Lake and Myrtle Lake and the recharge volume. Except for Grace Lake and Myrtle Lake and a couple of close lakes (the blue mesh in Fig. 6), the rest of the surface water system was modeled using the 1D approach, including the 1D link and 1D basin. For this case, the surface water system includes about 34 km of underground pipe, 29 km channel, 600 overland flow weirs, and 240 control structures for the outlet of stormwater ponds. The groundwater model was developed for about 5.5 km^2 of the focused area and wherever the boundary effects were expected.

For this case, the model was run using 15-minute NEXRAD rainfall and USGS daily PET. The model was calibrated and verified by available lake observed data from the Seminole county Atlas website. Fig. 7 shows the simulated and observed lake stage for the calibrated period (tropical period 2017) and verification period (the whole year 2018). To evaluate the climate change effect, this calibrated model was run using the climate data for the base period 1970-2000 and time horizon 2060 (2040-2070). For both periods of base and future, the dynamically downscaled GCM data of CLARREnCE10 was used. Table I and Fig. 8 show the comparison of average monthly precipitation for base and time horizon 2060. Based on this figure and table, the projected precipitation for all months decreases except February and November. Annual precipitation was projected to decline about 20% in our study area. Also, Table II and Fig. 9 show the comparison of average monthly PET for the period of base and time horizon 2060. Based on this figure and table, the projected PET for all months is decreasing. Annual PET is projected to drop about 15% in our study area.

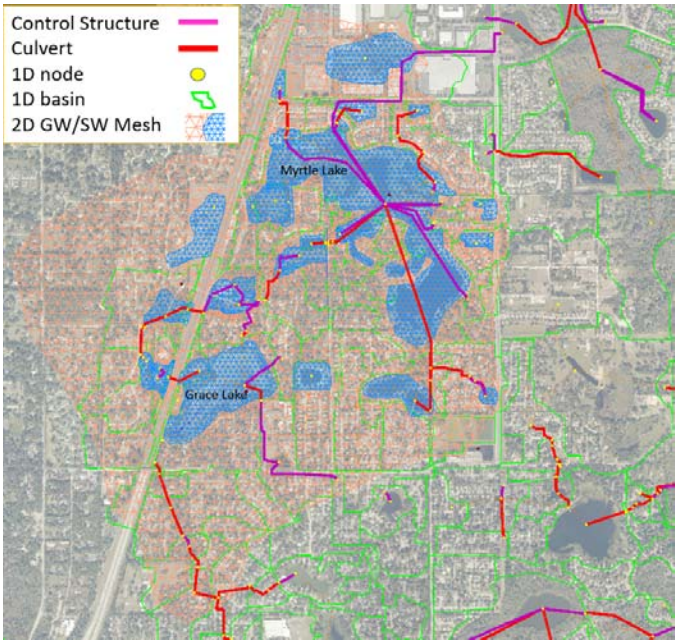

Fig. 6 The surface water and groundwater drainage system for Grace Lake case study

TABLE I
COMPARISON OF AVERAGE MONTHLY PRECIPITATION FOR BASE AND FUTURE PERIOD (PRECIPITATION IN MM)

Month	Base Period (1970-2000)	Future Period (2040-2070)	Percentage of change
Jan.	74	44	-40%
Feb.	73	77	5%
Mar.	98	80	-18%
Apr.	66	43	-35%
May	97	63	-35%
Jun.	173	122	-29%
Jul.	175	128	-27%
Aug.	182	153	-16%
Sep.	153	124	-19%
Oct.	85	71	-16%
Nov.	62	71	14%
Dec.	64	58	-10%
Annual	1301	1035	-20%

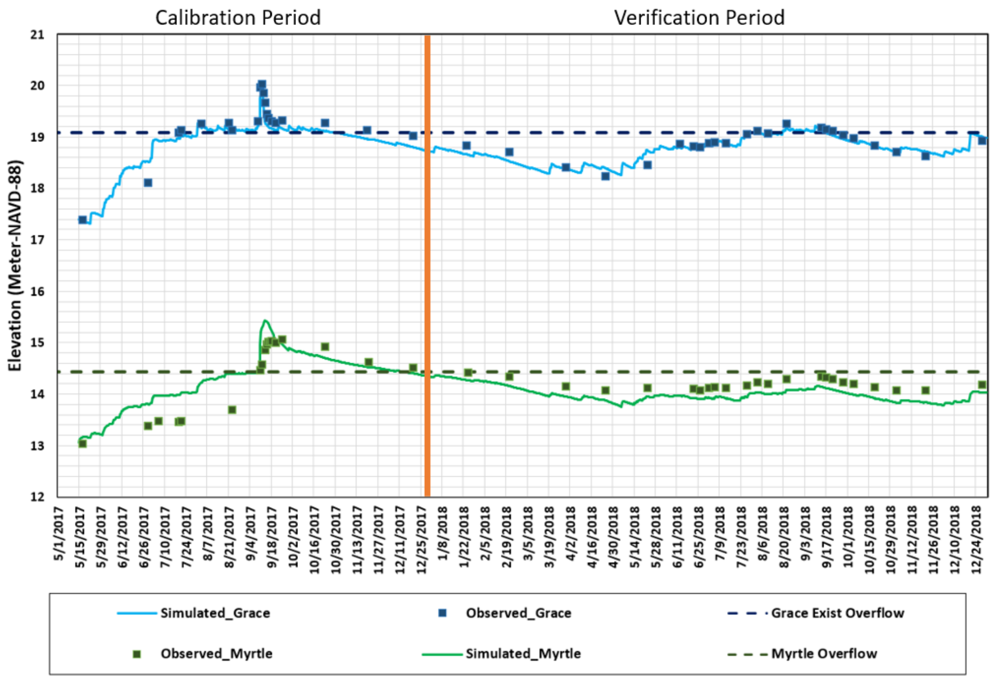

Fig. 7 Comparison of observed and simulated lake stage for Grace Lake case study

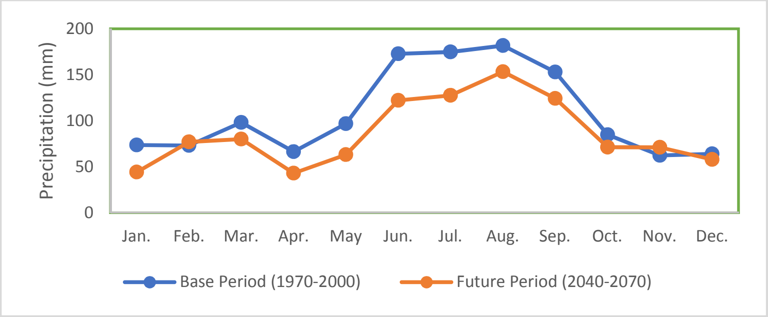

Fig. 8 Projected average monthly precipitation for Grace Lake case study (base and future periods)

TABLE II
COMPARISON OF AVERAGE MONTHLY PET FOR BASE AND FUTURE PERIOD (PET IN MM)

Month	Base Period (1970-2000)	Future Period (2040-2070)	Percentage of changes
Jan.	27.27	30.66	12%
Feb.	33.78	36.72	9%
Mar.	50.77	56.72	12%
Apr.	64.25	72.30	13%
May	79.15	92.33	17%
Jun.	81.30	94.82	17%
Jul.	86.41	100.60	16%
Aug.	84.85	96.45	14%
Sep.	64.38	74.87	16%
Oct.	43.37	51.64	19%
Nov.	31.26	35.57	14%
Dec.	26.06	29.97	15%
Annual	672.84	772.66	15%

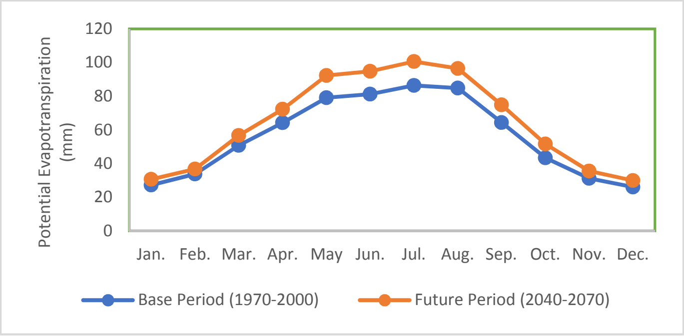

Fig. 9 Projected average monthly PET for Grace Lake case study (base and future periods)

V. RESULTS

Figs. 10(a) to (d) show the tide cycle velocity for outlet and headwater of the MCJC for two scenarios of current tide and future tide, including 76 cm sea-level rise in time horizon 2060. The main canal and location of the outlet and headwater are shown in Fig. 4. Comparison of Figs. 10 (a) and (b) depicts that the future peak velocity is increased about 50% for the outlet. This increase in headwater is not significant. Besides the velocity change, there is a considerable tide flow duration for both outlet and headwater. The figures show that the first peak flow or peak velocity for outlet and headwater for the current condition happens around hour 3 and hour 3.5. While there is more than 2-hour lag for future condition and the peak velocity for outlet and headwater for future happen at hour 5 and hour 6. Based on Alizad et al., the tide cycle change can significantly change the salt marsh productivity in Northeast Florida [16]. Figs. 11(a) to (d) shows the stage change based on current and future tide in the outlet and headwater. The higher stage for downstream can inundate more area for the hightide condition, affecting the life of coastal species like sea turtles [17]. The figures also show that for the current condition between the two peak stages, there are about 5 hours of resting time, and the canal is fully dry for this condition. In contrast, this dry period is wiped for future condition. We did not run the model for Floridian tropical storms, but this can potentially decline the capacity of the canal for the stormwater release.

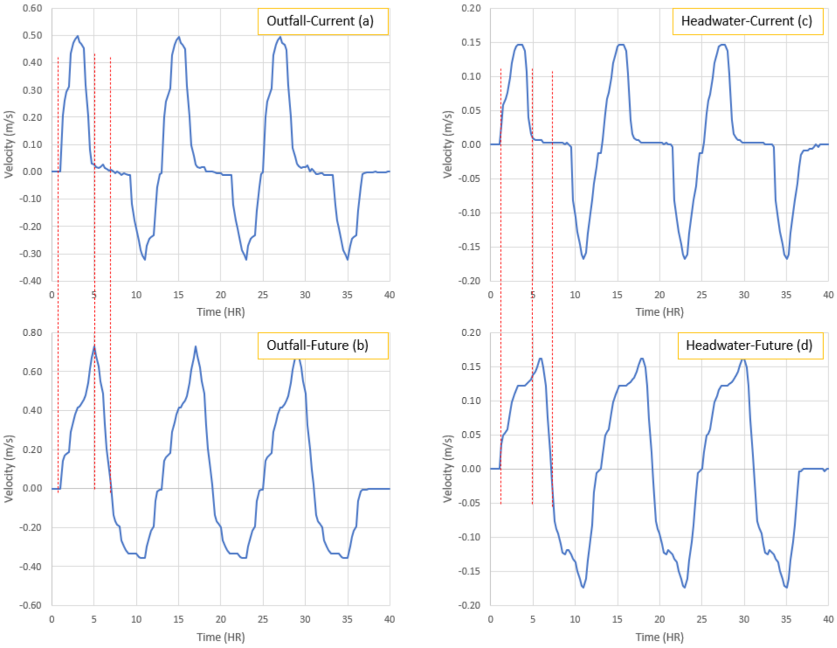

Fig. 10 Comparison of current and future tide cycle velocity-outlet and headwater of MCJB case study

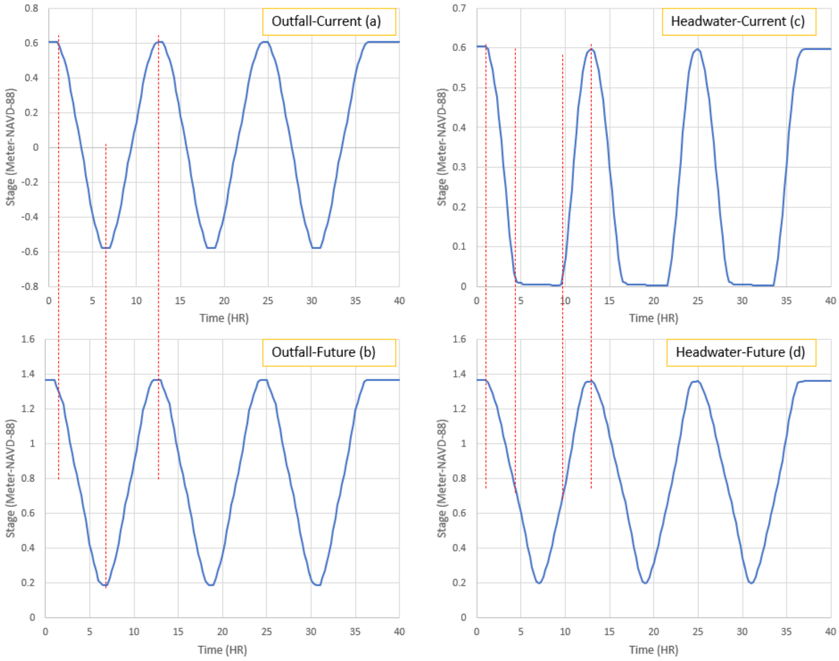

Fig. 11 Comparison of current and future tide cycle stage-outlet and headwater of MCJB case study

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The integrated surface water and groundwater model was run for the Mc Dill case study, and Fig. 12 shows the groundwater elevation for current and future condition. Based on Florida regulation, the Seasonal High Water (SHW) is estimated using the average water elevation for five wet months of June to November. Fig. 12 shows that the SHW for the development site (please see Fig. 5) is changed from 0.8 m to 1.2 m (40 cm increase). The effect of this groundwater elevation increase on the reliability of the stormwater retention pond was evaluated and presented in Fig. 13. The retention pond's outlet is at elevation 1.3 Meter-NAVD-88, and any flood stage higher than this spills from the outlet. As we can see in Fig. 13, during the example normal year 2012, the retention pond can capture and retain about 99% of the storm events, or in other words, there are zero spills from the pond to Tampa Bay. This reliability decreased to 54% for future condition, and there were 168 failure days in which the pond has an outflow of higher than 0 cfs. The ERP of SWFWMD has a regulation of 72 hours for stormwater recovery, which means that the pond with full treatment volume should be able to retain the entire treatment within 72 hours. A draw-down analysis evaluates the treatment recovery. In this analysis, the pond's initial stage was set to the elevation of treatment volume, and the model was run with n rainfall to evaluate the duration of full recovery. Fig. 14 shows the results of the draw-down simulation. Based on this figure, the retention pond retained the full treatment volume (about 101 cubic meters) in 26 hours for the current condition. In comparison, the retention pond infiltrated less than 80 cubic meters in 72 hours in the future condition, which is considered a failure for this stormwater system.

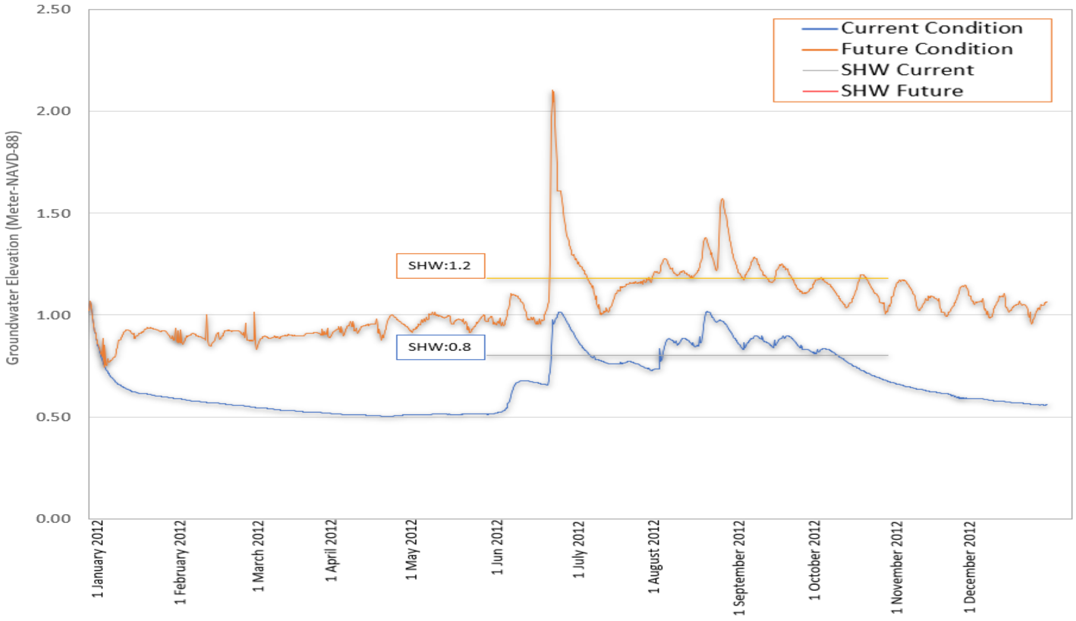

Fig. 12 Comparison of current and future groundwater elevation - Mc Dill case study

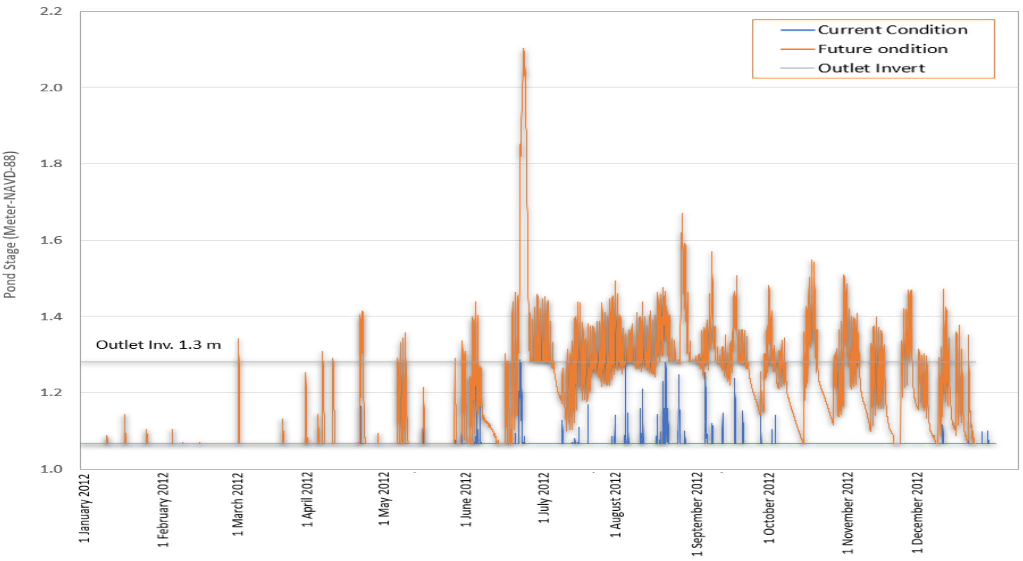

Fig. 13 Comparison of current and future flood stage in retention pond - Mc Dill case study

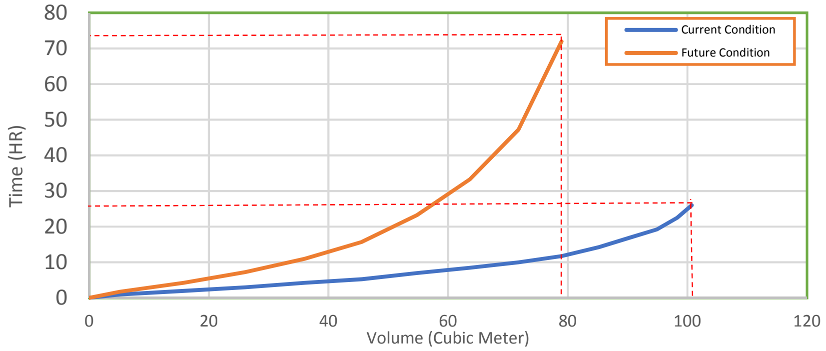

Fig. 14 Recovered treatment volume via retention pond for current and future - Mc Dill case study

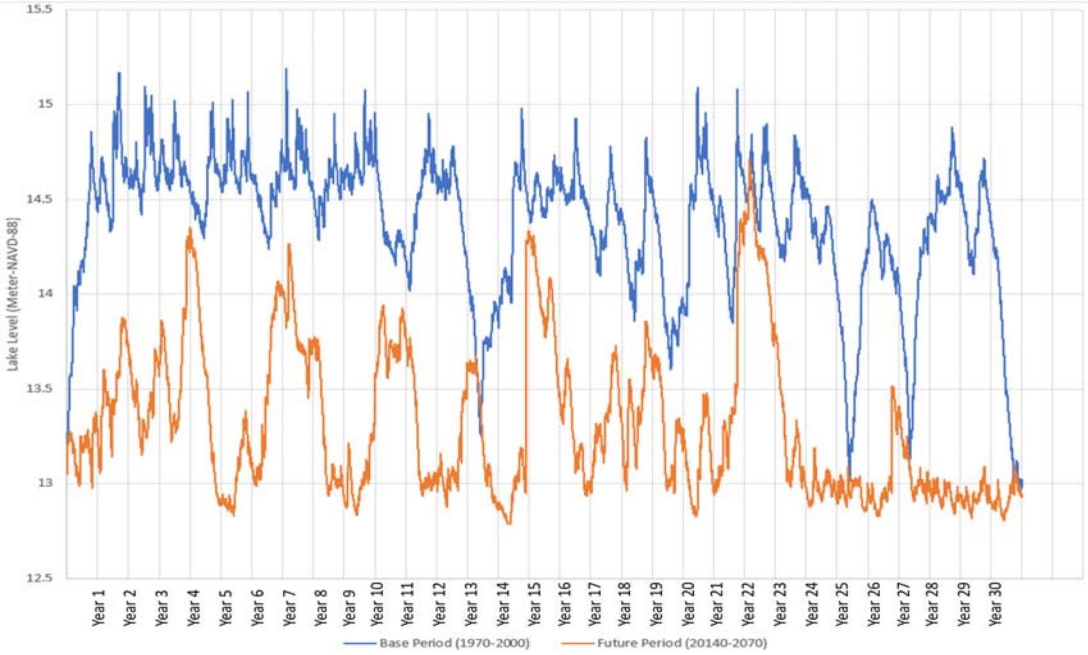

Fig. 15 Comparison of current and future lake level in daily time scale - Myrtle Lake

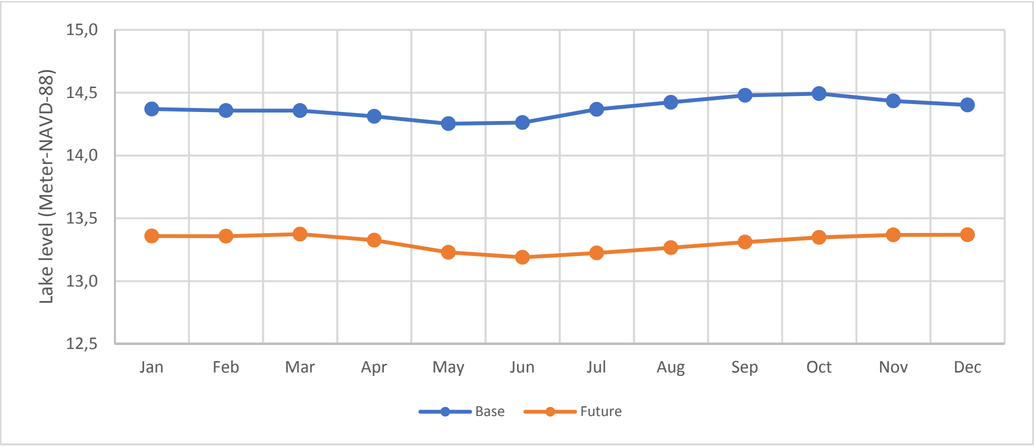

Fig. 16 Comparison of current and future monthly average lake level - Myrtle Lake

An integrated surface water and groundwater model was applied to evaluate the effect of climate change on Grace Lake and Myrtle Lake stormwater systems. Fig. 15 shows the 30 years lake level fluctuation for Myrtle Lake for the base period (1970 to 2000) and future period (2040-2070). Also, Fig. 16 represents the average monthly lake level for Myrtle Lake.

Based on both figures, the lake level has a significant decrease (annual average of 120 cm), which should be because precipitation decreases and PET increases.

Fig. 17 shows the 30 years lake level fluctuation for Grace Lake for the base period (1970 to 2000) and future period (2040-2070). Also, Fig. 18 represents the average monthly lake level for Grace Lake. Based on both figures, the lake level has a significant decrease (annual average of 108 cm) because precipitation decreases and PET increases.

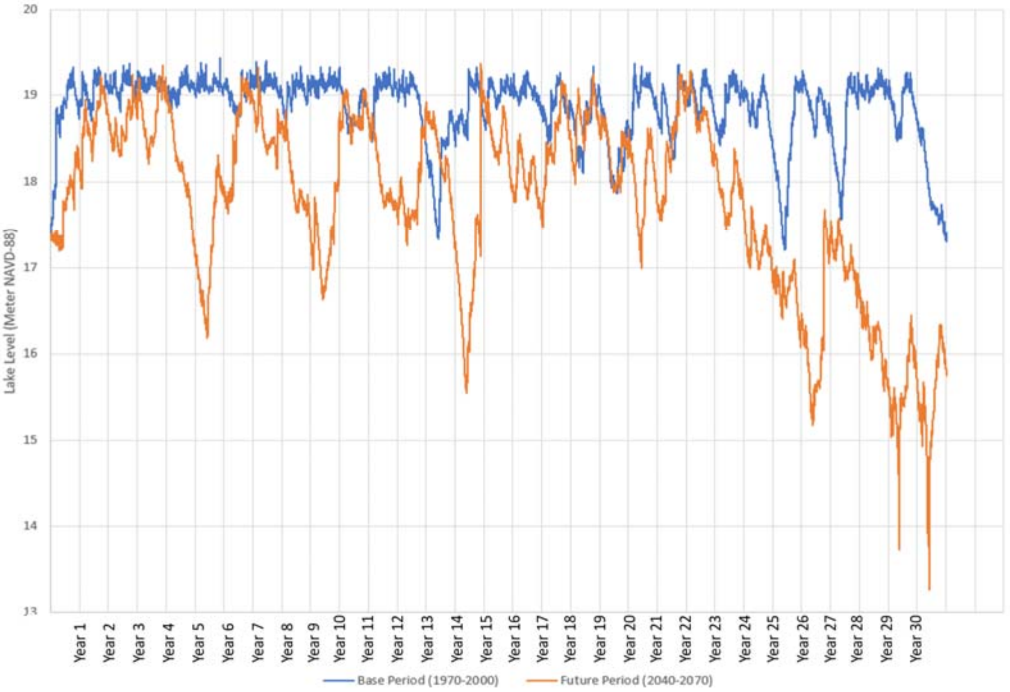

Fig. 17 Comparison of current and future lake level in daily time scale - Grace Lake

Fig. 18 Comparison of current and future monthly average lake level - Grace Lake

Table III and Fig. 19 show the monthly average recharge volume for the entire groundwater system of the Grace Lake case study. The table and figure show the recharge volume for the base period and future period, and the results show that recharge declined for all months except February and November. The average annual recharge decrease is about 13.2 mm or 24%.

TABLE III
COMPARISON OF AVERAGE MONTHLY GROUNDWATER RECHARGE FOR BASE AND FUTURE PERIOD (RECHARGE IN MM)

Month	Base	Future	Percentage of Change
Jan	4.0	3.1	-23%
Feb	3.7	3.6	0%
Mar	4.7	3.7	-21%
Apr	3.3	2.4	-27%
May	3.9	2.3	-40%
Jun	5.4	3.6	-34%
Jul	6.0	3.5	-41%
Aug	5.6	4.0	-28%
Sep	6.0	4.2	-30%
Oct	5.1	4.1	-20%
Nov	3.8	4.1	6%
Dec	3.7	3.3	-12%
Annual	55.1	41.9	-24%

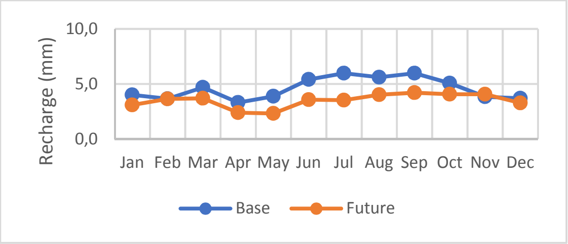

Fig. 19 Comparison of current and future monthly groundwater recharge - Grace Lake case study

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VI. CONCLUSION

The three case studies in this research investigated the effect of climate change and global warming on different aspects of the Floridian environment system. While the MCJB case study evaluates the tide cycle property in outlet and headwater with and without sea-level rise, Grace Lake and Mc Dill investigate climate change and SLR on groundwater and surface water system. The case study of MCJB concluded that SLR could change the velocity and duration of the tide cycle, which can potentially affect the coastal ecosystem. This case can be used as a base for further investigation if we run a couple of tropical storms to see if the upstream stormwater drainage system is reliable under SLR. The Mc Dill case located in the low-lying coastal area of the Mexican Gulf provides a good perspective for the future stormwater management system in those areas. This case draws the attention that SLR and related storm surge can cause direct damage to development close to the coast, but it can also decline the capacity of retention pond by groundwater rise. The retention ponds regulate both the quantity and quality of stormwater. Therefore, the failure of the retention system causes pollution problems for Florida. The example retention pond for this case study showed that the system reliability drops from 99% to 54% under the SLR scenario. Also, the retention system will not recover the full treatment volume in 72 hours based on the SWFWMD-ERP. The case study of Grace Lake depicts that groundwater recharge will substantially decrease for the time horizon 2060 (24%). We need to note that this case is applied just for one set of GCM models. We know that there is significant uncertainty for climate change, especially for the projection of precipitation in Florida. So, there is a need for uncertainty analysis and risk analysis. The other point is that we worked with daily data. Some studies prove that despite a decrease in average precipitation, the fluctuation for future precipitation and the extreme event will increase. So, we may have groundwater level drop, but the surface water runoff and inundation problem can be raised. These three case studies highlighted the complexity of water resources management under future conditions.

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