Resilient MAST@FIU: Adapting the FIU MAST for Living with Coastal Waters Under Extreme Events

Demonstration Category – D27

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ABSTRACT

The Marine Academy of Science and Technology (MAST) is located inside Florida International University's Biscayne Bay Campus (FIU-BBC). MAST is the only university-based magnet high school in Florida specializing in marine and environmental research, blending high school and university life elements. The FIU-BBC campus, with a nearly 200-acres area and 1.4 miles of coastal edge, is at risk due to hurricanes and sea-level rise hazards. Hence, it is imperative to rethink existing campus infrastructure and implement sustainable practices to preserve the site, which benefits students and the North Miami community. Working closely with the FIU-MAST's leadership, students, and FIU-BBC facilities, we identified several problems, including (1) extensive flooding due to projected sea-level rise, (2) lack of freshwater for irrigation of green areas, (3) pollution monitoring of the Biscayne Bay, and (4) lack of public gathering spaces for FIU-MAST and FIU-BBC campus. Based on the 2050 sea-level rise data, our solutions include: (1) elevating a perimeter road of the FIU-MAST to prevent coastal flooding, (2) installing green infrastructures to reduce stormwater runoff and the urban heat island effect (including a green roof on the FIU-MAST building and utilizing permeable pavement for a portion of the existing parking lot), and (3) providing multipurpose smart pavilions for gathering which will communicate water education with its form and interaction. The effectiveness of the proposed solutions has been analyzed using various computational methods and we believe that the effectiveness of the proposed solutions could be adopted by other coastal universities and schools facing similar challenges.

1. INTRODUCTION

Florida International University (FIU) is the largest public university in Florida with multiple campuses. FIU's Biscayne Bay Campus (FIU-BBC) is a unique campus located on the shores of Biscayne Bay in northeast Miami-Dade County with intra-coastal access and is surrounded by Oleta River State Park and a natural preserve. Founded in 2013, The Marine Academy of Science and Technology (MAST) is the only magnet school in Miami-Dade County Public Schools that focuses on marine and environmental science. At FIU-BBC, a new building is being constructed for MAST, providing an environment where students can research local environmental subjects, including mangrove populations, coastal wetlands as habitats, and the diversity of plant and animal species in their backyards. However, sea-level rise has become a concern in Miami-Dade County, ultimately impacting FIU-MAST. In Miami, the sea level has increased by eight inches since 1950 and has increasingly accelerated over the last ten years with the current projection of an increase of one inch every three years (NOAA Tidal Station Data – Virginia Key, 2021). As per the data, it has taken 31 years for the sea level to increase by six inches around Miami. Figure 1 shows the range of NOAA and USACE high and intermediate forecasts for Miami Beach. Many traditional methods to solve sea-level rise and flooding in Florida will not work because water can flow through the porous ground. Therefore, developing a comprehensive resilient plan for the new infrastructure is essential in response to the upcoming sea-level rise. Our project analyzes the potential hazards to FIU-MAST due to coastal and pluvial flooding. In addition, with the help of the Education Outreach & BBC operation department, we conducted a satisfaction survey to identify the other areas of improvement around the new FIU-MAST building; the results of the survey are shown in Figure 2.

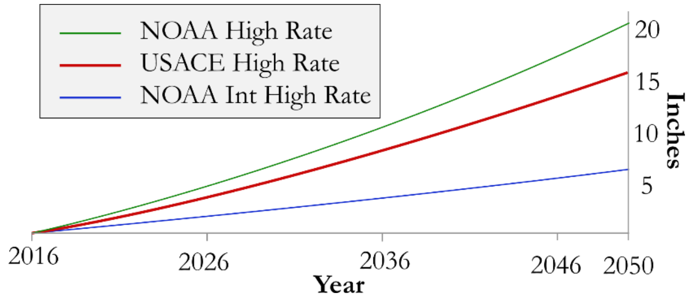


Figure 1. Miami Beach sea level rise forecast (NOAA tidal station data-Miami Beach) tidesandcurrents.noaa.gov

The overall **goals** of this demonstration project, which are related to our proposed solutions, are listed below:

- Investigate and alleviate the potential hazard due to coastal and pluvial flooding for the 24-hour, 25-year return period rainfall and the NOAA 2050 sea-level rise scenario
- Rainwater collection and reuse for the proposed green infrastructure irrigation
- Analyze the uncontrolled release of pollutants discharged to Biscayne Bay and propose solutions to improve the discharged water quality
- Incorporate a real-time and interactive LED-based monitoring system for algae blooms and other contaminants in Biscayne Bay that can inform students on the bay health
- Propose multipurpose smart pavilions for students to gather, study and socialize
- Reduce the urban heat island effect

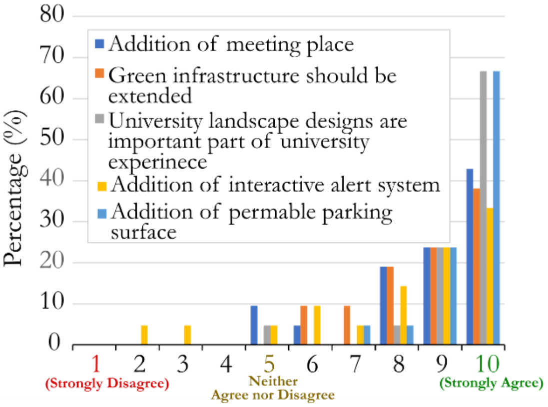


Figure 2. Students and faculty survey results

- Enhance the campus aesthetics with new green spaces
- Provide community learning opportunities using interactive technologies
- Provide a complimentary Augmented Reality (AR) mobile application to communicate the Biscayne Bay water health to the surrounding community

2. SITE DESCRIPTION, EXISTING CONDITIONS & CHALLENGES

2.1 Site Description

Figure 3 shows the implementation area selected for the demonstration project. The 60% footprint of the selected implementation area is impervious. The implementation area encompasses 1.05-acres (45,540 ft^2) of the new FIU-MAST building, 4.9-acres (213,834 ft^2) of the parking lots, and 2.78-acres (120,953 ft^2) of a pervious area including a small pond. Together, the implementation area is slightly under the 15-acres limit established for the Campus RainWorks demonstration category.

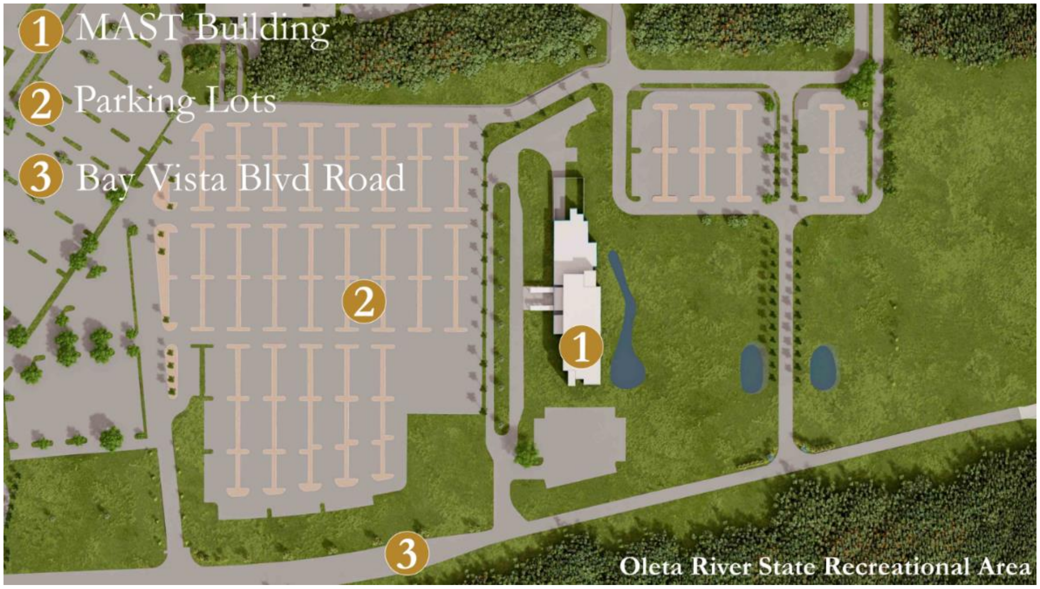


Figure 3: Implementation area for demonstration project at the FIU-MAST (under 15 acres)

North Miami has a tropical monsoon and trade-wind littoral climate with hot and humid summers, short, warm winters, and a distinct drier season in the winter. Its climate is shaped by its sea-level elevation, coastal location, position above the Tropic of Cancer, and proximity to the Gulf Stream. Figure 4 shows the average monthly rainfall data for North Miami (*Average Monthly Rainfall and Snow in Miami, USA*, 2021). On average, September is the wettest month with 250 mm (9.84 in) of precipitation, whereas January is the driest month with 41.0 mm (1.61 in). North Miami receives 1573.8 mm (61.96 in) of rain per year on average, one of the highest among major cities in the U.S. (the U.S. average is 38 in of rain per year). The severe rainstorms and increased rainfall contribute to an increased risk of flooding on site.

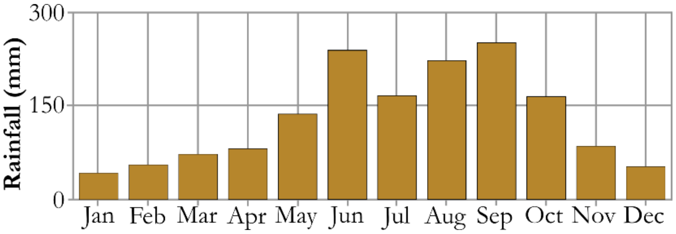


Figure 4. Average monthly rainfall data for North Miami

Of the four types of soils found in FIU-MAST, one was identified as hydric (wetland) soil by the Miami-Dade County Soil Conservation Service at FIU-BBC. The U.S. Department of Agriculture Soil Conservation Service classifies Terra Ceia muck, located to the north and northwest of the campus's central building area, as a tidal hydric soil (USDA, 1991). Terra Ceia muck is tidally inundated and supports mangrove vegetation. Urthodents (excavated limestone material) and Urban land (the built-up portion of campus) are two of the remaining soil types that are well-drained, either due to the nature of the base material or to topography and drainage systems (Florida International University, 2012). After discussion with FIU-MAST schools' leadership and FIU-BBC facility, we were informed that stormwater at FIU-MAST is currently diverted to an existing retention pond, which allows direct infiltration of surface runoff into groundwater via the porous limestone substrate. With the rise of sea level in the future, the capacity of the drainage system will be diminished.

Thus, the combination of extreme rainfall, increase in impermeable surfaces with new infrastructure, and increase in sea-level rise have created several problems. This includes increasing stormwater pollution discharge to Biscayne Bay, diminishing drainage system capacity, and increasing flood inundation due to pluvial and coastal flooding.

2.2 Coastal and Pluvial Flooding

Coastal and pluvial flooding in FIU-MAST is greatly exacerbated due to projected sea-level rise and extreme weather associated with an increase in frequency and intensity of tropical storms, including hurricanes. South Florida sea-level has been steadily increasing in the last few decades and FIU-BBC currently deals with flooding of low-lying areas during periods of sustained heavy rainfall. One of the most prone areas to flooding in FIU-MAST is the region surrounding the Bay Vista Boulevard Road, which is the main access road to the FIU-MAST. FIU provides a freely available storm surge simulator (http://frances-a.cs.fiu.edu/gic/) to visualize storm surge inundation for a selected hurricane category. As per the Florida Climate Center (FCC), category III hurricanes are more frequent in the selected region. As a result, we used hurricane category III data for most of our design calculations. Figure 5 shows the storm surge inundation around the MAST building for a category III hurricane. As shown in this figure, the inundation depth in the FIU-MAST is primarily between 0.6 m (2 ft) and 0.9 m (3 ft).

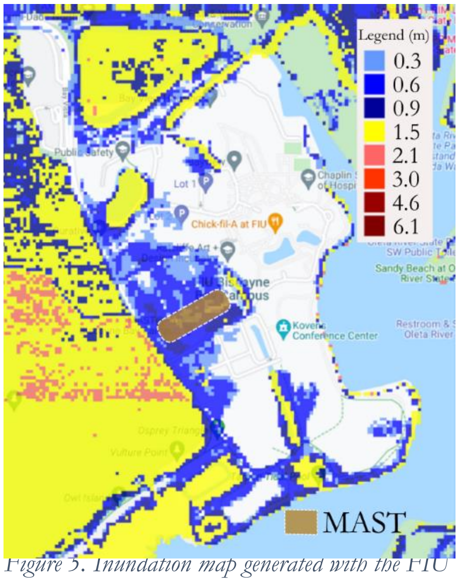


Figure 5. Inundation map generated with the FIU by 'Storm Surge Simulator' for a under category III hurricane (provided by Florida International University: http://frances-a.cs.fiu.edu/gic/)

In addition to the FIU storm surge simulator described above, we used the Hydrologic Engineering Center's River Analysis System (HEC-RAS) hydrology-hydraulics model to estimate pluvial flooding under various sea-level rise scenarios. 24-hr, 25-yr return period rainfall is used in the simulations, which is recommended by the stormwater guidelines of the City of Miami (SFWMD, 2014). A 2D storage area was generated using a 5-m-by-5-m mesh with a friction coefficient of 0.03. The storage area was set up to include the surrounding wetlands and bay area to show the tidal flow. A boundary condition was set up in the southeastern portion of the study area, where the tidal flows come from. A stage hydrograph was used as the input, and the data for this stage hydrograph was sourced from the NOAA Port tidal Water Surface Elevation (WSE) gauge in Biscayne Bay in meters with North American Vertical Datum (NAVD) (*Water Levels - NOAA Tides & Currents*, 2021b). For the current sea-level conditions (2021), the HEC-RAS model showed no flooding. This result was expected because the FIU-BBC does not experience significant pluvial flooding on a day-to-day basis. Three different sea-level rise scenarios [2040 (1 ft.), 2050 (1.5 ft.), and 2060 (2.2 ft.)] were considered to simulate pluvial inundation around the FIU-MAST building. The HEC-RAS model used Water Surface Elevation (WSE) data generated from observations during Hurricane Wilma in October 2005, which directly hit the area, causing a significant storm surge. The models show inundations just south of our specific area of interest for all three sea-level rise scenarios (Figure 6). The Bay Vista Boulevard Road is the main reason why the campus does not flood during extreme tidal events, but conditions will not be similar in the future.

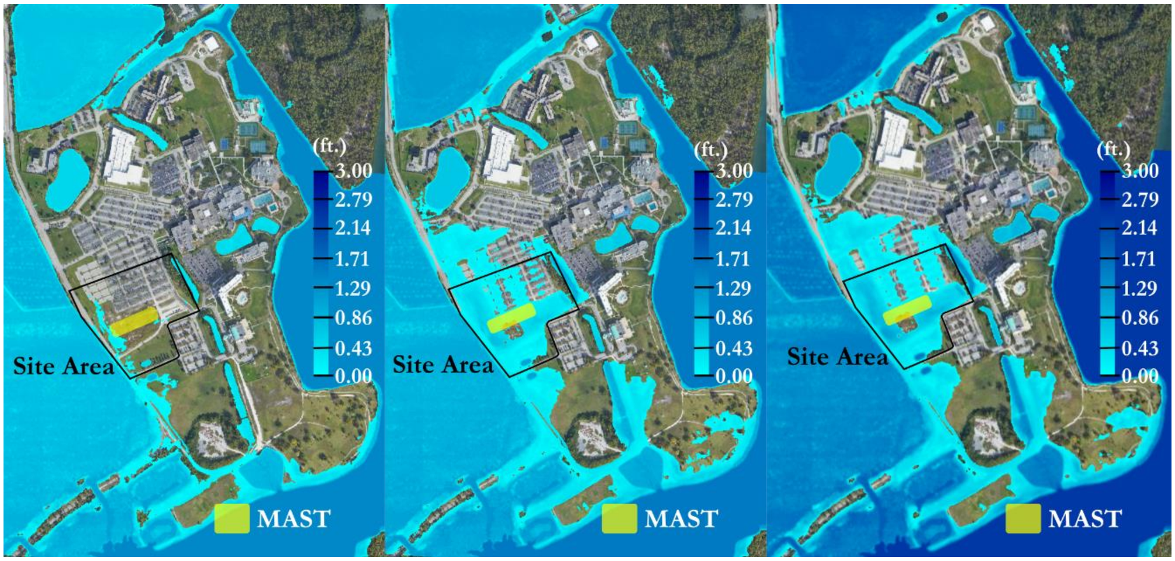


Figure 6. Simulated pluvial inundation around the MAST building for three sea-level rise scenarios: (a) 1ft (2040), (b) 1.5 ft (2050), and (c) 2.2 ft (2060)

After discussing with the FIU-BBC Facility Department, we were informed that the existing storm drain system relies heavily on retention ponds, which allows direct infiltration of surface runoff into groundwater via the porous limestone substrate. The draining (i.e., seepage) and the storage capacity of the retention ponds will be diminished as the sea level rises. To estimate the seepage flow from the retention pond to the ocean and understand the influence of tidal water fluctuations, our team developed a model using GeoStudio SEEP/W, a finite element software for modeling groundwater flow excess pore-water pressure dissipation problems in porous media (*GeoSudio SEEP/W*, 2021). The study was performed for the 25-yr return period rainfall and the 2050 sea-level rise scenario. As mentioned previously, the major portion of the selected implementation area consists of a mixture of porous limestone and sand. Note that the most commonly occurring textures in Florida are those depicted on the lower-left corner of the USDA Textural Triangle (Schuster, 2015). To determine the hydraulic conductivity of such a mixture, we have used the Hazen's Equation [$k \approx C(D_{10})^2$]. Using a mean effective particle size (D_{10}) of 1.15 mm (Hazen, 1892; Heath, 1984; Kresic, 2006; Price et al., 1911), we have determined a hydraulic conductivity (k) value of 1.96×10^{-7} m/s, which was used for the seepage modeling. In addition, GeoStudio has an extensive database compiled from a wide range of literature found across the web to define materials properly. We performed a transient simulation with Head vs. Volume boundary conditions to understand seawater intrusion's tidal water exchange process. The coastal water was simulated using the stage fluctuations in Biscayne Bay recorded by the NOAA (Figure 7).

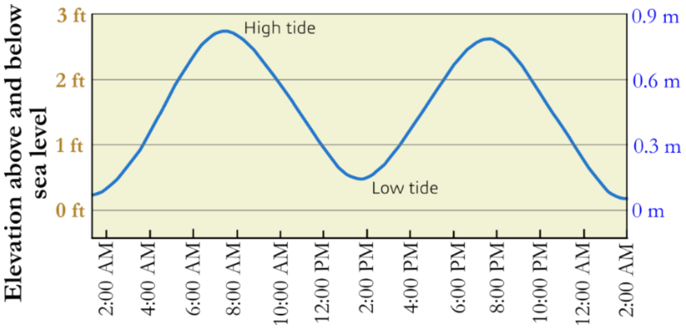


Figure 7. Average hourly seawater levels (National Weather Service, Miami, Miamarina, Biscayne Bay, FL) https://www.weather.gov/mfl/tides_biscayne_bay_miami_marina

The wetlands alternate between filling (exfiltration) and draining cycles (infiltration) depending on the water levels in the wetland and the level of the sea. Figure 8 shows a draining cycle, where the tide has reached approximately 0.25 m, and the water level in the wetland is 0.75 m. As a result, the infiltration rate of 8.6×10^{-8} m^3/s is observed. The flux vectors are reversed when the tide level increases to about 0.58 m, indicating that water flows through the sand embankment and fills the wetland. The maximum exfiltration rate of 9.32×10^{-8} m^3/s is observed (Figure 9). We determined that, with such a seepage rate, pluvial flooding will not be an issue under the 2050 sea-level rise scenario.

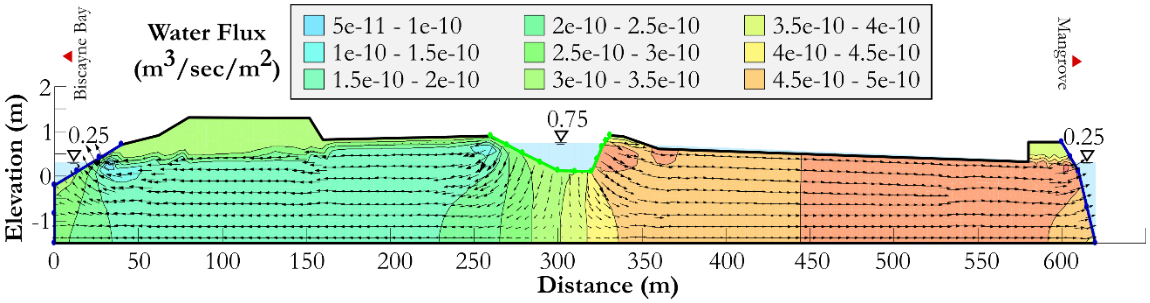


Figure 8: Equipotential and velocity vectors for low tide 'draining' pond (infiltration from wetland to Biscayne Bay)

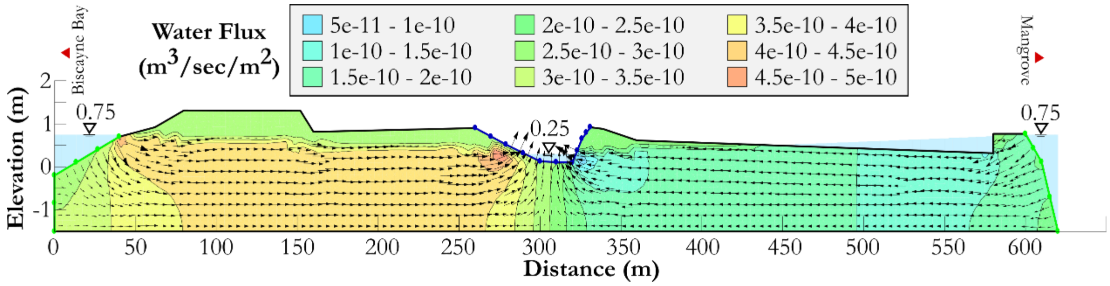


Figure 9: Equipotential and velocity vectors for high tide 'filling' pond (exfiltration from Biscayne Bay to the wetland)

2.3 Stormwater Pollutant Discharge into the Biscayne Bay

The primary source of water pollution in FIU-MAST is stormwater runoff from the Bay Vista Boulevard Road, parking lot, and impervious surfaces. Water pollution is exacerbated by runoff from landscaped and grassed areas. Furthermore, fertilizers and pesticides are used to maintain the campus landscaped areas. In addition, the FIU-BBC campus has several mulch storage areas that contribute some leachate to nearby waters. Monitoring water quality is necessary to assess the effectiveness of implementing green infrastructures, such as rain gardens, permeable pavement, and green roofs. We evaluated the wash off results using the Event Mean Concentration (EMC) from urban non-source pollutants commonly found in FIU-MAST campus stormwater runoff, more specifically Total Suspended Solids (TSS), Total Phosphorus (TP), Total Nitrogen (TN), F. Coli, Copper (Cu), Lead (Pb), and Zinc (Zn). Table 1 presents these typical pollutant concentrations from non-point sources in urban environments.

Table 1: Pollutant Concentrations from Source Areas in urban environments

Constituent	TSS* (mg/L)	TP** (mg/L)	TN*** (mg/L)	F Coli* (1000 col/mL)	Cu* (μg/L)	Pb* (μg/L)	Zn* (μg/L)
Resid. Roof	19	0.11	1.5	0.26	20	21	312
Comm. Roof	9	0.14	2.1	1.1	7	17	256
C/R Parking	27	0.15	1.9	1.8	51	28	139
Res. Street	172	0.55	1.4	37	25	51	173
Lawns	602	2.1	9.1	24	17	17	50

* Claytor & Schueler, 1996
**Average of Steuer (1997), Bannerman et al. (1993), and Waschbusch et al. (1999)
*** Steuer, 1997

3. SOLUTIONS TO ALLEVIATE IDENTIFIED CHALLENGES AND PERFORMANCE ANALYSIS

Working closely with the FIU-BBC facility department and MAST school's leadership, we evaluated a variety of green and conventional infrastructure implementations in order to address key challenges/issues identified for the 2050 NOAA sea-level rise projections. These issues are: (a) coastal flooding for projected sea-level rise, (b) uncontrolled discharge of pollutants to the Biscayne Bay, (c) lack of fresh water for irrigation of green areas, (d) lack of timely alert/monitoring systems for algae blooms and other contaminants in Biscayne Bay, and (e) the lack of common gathering space for the students. We evaluated a wide array of solutions to address these issues, considering the 2050 sea-level rise scenario as our target design. Our solutions include (1) elevating a perimeter road of the FIU-MAST (Bay Vista Blvd road) to prevent coastal flooding, (2) installing green infrastructures for pollutant treatment, runoff reduction, and reducing urban heat island effects, and (3) installing multipurpose smart pavilions for promoting innovative education and student interaction, in addition to serving as rainwater collection system.

3.1 Multipurpose Smart Pavilions

Figure 10. Overview of the proposed pavilion structure

Campus life is inherently richer when learning is integrated with varied spaces and opportunities to allow the campus communities to interact. Currently, FIU-BBC is missing a common gathering space where students from MAST and the FIU-BBC can interact and study comfortably outdoors. Considering the needs, benefits, and positive reviews from student surveys, we propose a common gathering space adjacent to the FIU-MAST building. The strategic placement invites the students of both institutions to study and socialize together. The positioning of the multipurpose smart pavilions is demonstrated in Figure 10. The pavilion's geometry is inspired by biomimetic principles of plant leaves with waterproof doubly curved surfaces that collect and guide rainwater at the base of their roots in order to distribute water throughout the system. Mimicking the geometric language and performance aspects in nature, we are also incorporating various sustainability principles in the construction and structure of the pavilion, of which includes water collection bases constructed from recycled 3D Printed concrete manufactured in the FIU Department of

Architecture's robotics lab (the bases also have built-in planters to plant vegetations which repel mosquitos and other insects). Additionally, the pavilion structure will have an overall shape of four pedals made up of four components. The first component consists of primary frames around the border of each petal which will be made of bent and welded steel rods (5" dia.) and the steel will be painted to avoid rust and degradation over time. On the primary frame, there are 2" diameter steel tube sleeves which are custom cut and welded using industrial robotic arms in FIU's Architecture Department. The second component is the secondary structure made of bamboo culms and uses the advanced characteristics of *Guadua Angustifolia* (Farrelly, 1984), a bamboo species native to South America. The use of *Guadua Angustifolia* is selected for its physical and mechanical properties and potential for industrial use, especially its strength (Luna et al., 2012). The bamboo culms are 1" in diameter and are bent to be placed inside the steel sleeves along with the primary structure. These bamboo culms make up a diagrid pattern and are connected using a 3D Printed Snap-On adjustable sleeve. The third component is the pavilion skin is made of double-layer translucent bioplastic, which covers the entire frame to provide a water collection surface while sheltering the public from rain and sun. This skin system is customized to have continuous pockets within the double layer bioplastic for injecting micro-algae, which carries out the naturally carbon-sequestering process of photosynthesis. The micro-algae is nurtured on daylight and air, capturing carbon dioxide molecules and storing them within the skin system while producing oxygen and releasing it into the surrounding air. The proposed pavilions and the skin system is positioned for optimal sun exposure, and based on the area, it captures approximately four pounds of carbon dioxide per day which is equivalent to that of 40 large trees. The pattern of the pavilion skin is also designed to provide a porous quality to the pavilion and create an aesthetically pleasing environment for the community to gather. The final component is the water quality monitoring system which will act as real-time monitoring indicators of Biscayne Bay's water quality. FIU-BBC houses the FIU Center for Aquatic Chemistry and Environment (CREST) research facility, which uses a number of buoys and surface drones to continuously monitor the health of Biscayne Bay. This data is available for FIU researchers and the public; however, existing web-based visualization does not provide public engagement. Thus, we have incorporated waterproof LED strips along the main steel frames of the pavilions, which in real-time can display levels of different water parameters and indicate the health of the Bay. Showing a warm to cool color range indicates the range from worse to best or displaying specific colors or patterns to indicate when a no-swim advisory is in effect for Biscayne Bay. This continuous lighting will indicate a real-time engagement with the monitoring research of the Bay and increase the visibility of the structures from a distance and invite the community to gather in these structures.

To study the integrity of the proposed structure, wind load was estimated using computational fluid dynamics (CFD) and compared with the ASCE 7-16 building code. The OpenFOAM CFD tool is used to calculate wind load on the structure under the category III hurricane scenario. Moreover, vortex shedding can induce loads that challenge the integrity of the structure (Giosan, 2000). This analysis allowed for an understanding of favorable and unfavorable wind directions and the effectiveness of the shape of the structure. We also performed a separate wind simulation to understand wind comfort and 'venturi effect' for understructure using local daily wind velocity data. In Miami, strong winds are experienced from December to April, whereas slow winds are observed from June to

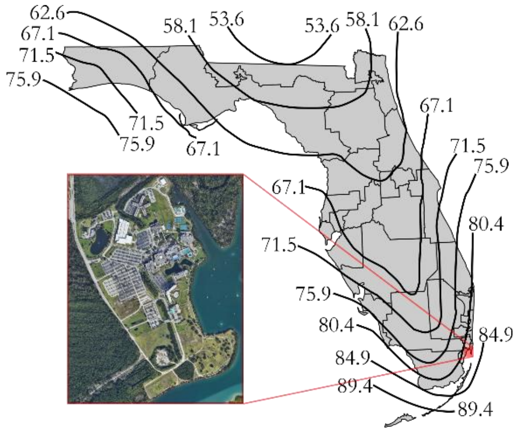


Figure 11. High- velocity hurricane zone depicting ultimate design wind speed for risk category III & IV buildings and structures (FBC 7th Edition, 2020)

October. To determine the wind load on the proposed structure, we have used the wind gust velocity suggested by the Florida Building Code (FBC) 7th edition (ASCE, 2017) for risk III category buildings and structures. As shown in Figure 11, the velocity at the selected area for risk III category buildings and structures is around 83.15 m/s (i.e., 186 mph). Figure 12 shows pressure induced on the proposed structure due to high velocity. Figure 13 and Figure 14 show the average data and wind rose considered to predict local wind velocity and direction, respectively. It is observed that the average velocity of wind is 4.0 m/s at 10-m height from the ground level, and the wind is moving from the E, ENE, and ESE directions for most of the time of the day. As shown in Figure 15, the wind gust velocity surrounding the proposed structure falls under 4 m/s, which is considered suitable for extended sitting (ASCE, 2004). Wind conditions can be further improved by introducing 2 m high dense vegetation and small interventions that can act as windshields (Szűcs, 2013).

Rainwater cisterns collect, store, and filter rainwater from structure roofs for later use. Figure 16 shows a schematic of the water collection and irrigation network for the proposed structure. Our discussion with the FIU-BBC facility department suggested rainwater harvesting and reuse as a viable stormwater management strategy for the MAST building. This recommendation was based on experience with previous projects due to its relatively low cost. For example, a typical 5,000-gallon industrial rainwater cistern can cost between $2,000 and $20,0000. Rainwater harvesting can significantly reduce runoff volume, erosion, and pollution load by reducing the volume of stormwater runoff in the campus stormwater drainage system after a rain event. We used a 2-yr, 24-hr rainfall to design the cistern capacity. A total of 5,400 gallons is estimated to be held temporarily in the cistern over the catchment system, which can be used for the irrigation of the proposed green infrastructure (green roofs, canopies, permeable pavements). The estimated rainwater collection is 169,911 gallons per year (assuming a 60% loss) and can save as much as $13100.13/year.

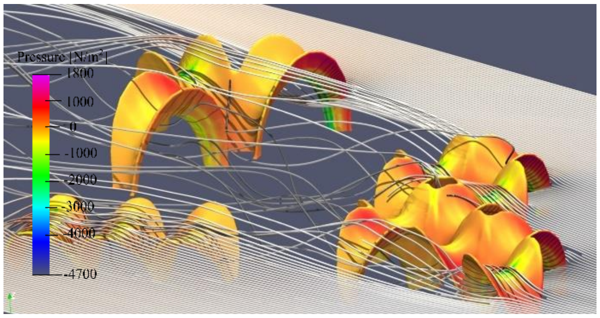


Figure 12. Pressure contour in case of E direction wind under risk of category III wind velocity (186 mph)

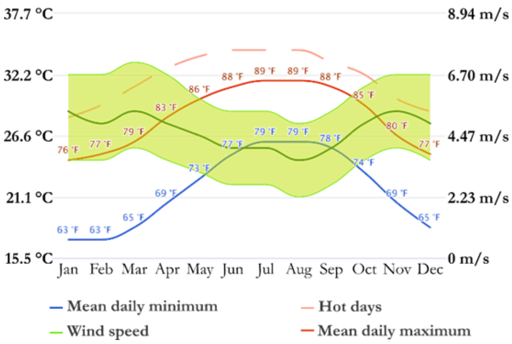


Figure 13. Average weather data for Miami, FL

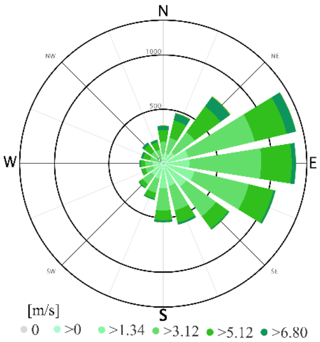


Figure 14. Wind rose for the local wind velocity and its direction

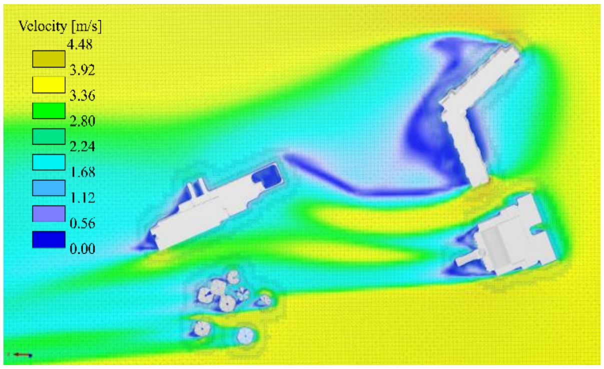


Figure 15. Airflow pattern in case of E direction wind expressed in terms of absolute wind velocity

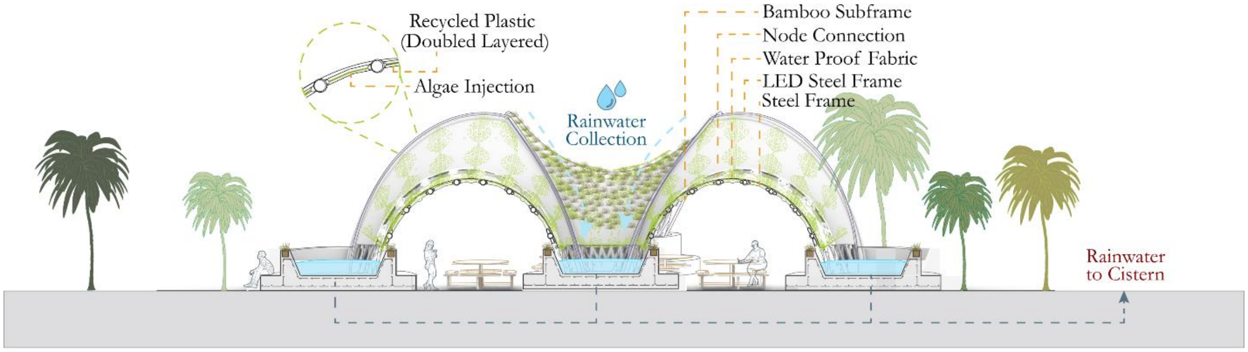


Figure 16. Schematic of water collection and irrigation network for the green infrastructure

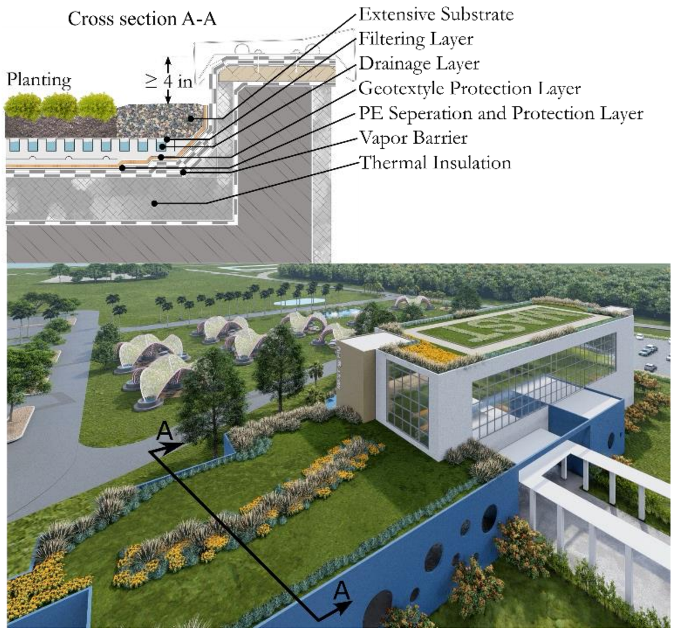


Figure 17. Components of proposed green roof for the MAST building

3.2 Green Roof

This solution aims to reduce stormwater runoff, improve air quality, add aesthetic value, reduce heat island effects, increase building efficiency and reduce energy use for heating and cooling. Figure 17 shows the details of the proposed green roof for the FIU-MAST building. Amorphous poly alpha olefin (APAO) modified bitumen sheet (160 mils) will be used as a base membrane ply. For drainage and filter top ply, engineered geotextile drainage fabric with integrated filtration membrane will be used. To keep the dead weight on the roof within the specified 45 lb/ft^3 limit, a soil depth of 6 inches is suggested. Custom mixed organic components (16%-25%) and coarse aggregate material will be used. Plants and nutrients used in the roofing system are comprised of 60% annuals/perennials, 30% sedums, and 10% native grass, with 70% being grown on transplantable mats and 30% being transplanted individually. We used the Green Roof Energy Calculator (https://sustainability.asu.edu/urbanclimate/green-roof-calculator/) to compare the electricity savings, heat flux, evapotranspiration, and net stormwater runoff of a building with a green roof against the existing FIU-MAST building. Site data selected for the design is shown in Table 2.

Table 2: Site Data for the Green Roof Design

Input	Values
Total surface area of green roofs	20,000 ft^2
Building Type	New Building
Growing media depth (2–11.5 inches)	4
Leaf area index (LAI)	5 (typical for extensive green roofs)
Whether there is irrigation	Irrigation
Percent roof coverage	100%
The albedo of an existing roof	Dark (0.15)

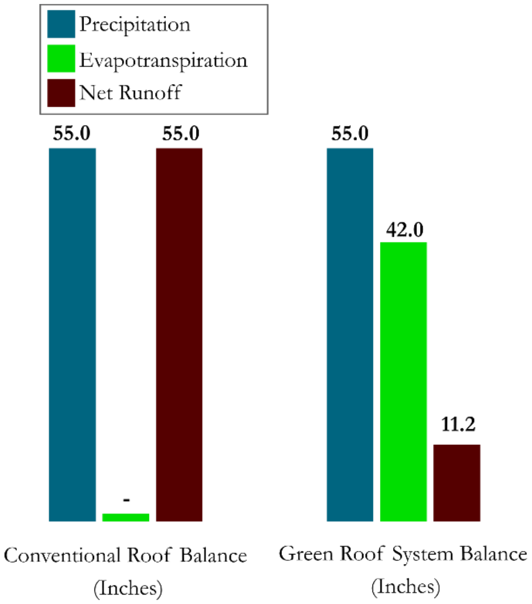


Figure 18: Annual roof water balance for MAST

The results showed that the green roof system could retain up to 42 inches of stormwater runoff per year on average (Figure 18). Instead of draining into storm drains, this water is absorbed by the soil and plants on the roof and eventually returns to the air via evapotranspiration. As a result, the average annual latent heat exchange to the environment for the proposed FIU-MAST roofs increases to 77.2 W/m^2, whereas the summer daily peak average increases to 388.8 W/m^2. Average annual sensible heat exchange to the environment from FIU-MAST roof reduced to 22.6 W/m^2 from 44.7 W/m^2 versus conventional dark roofs, which creates a cooling effect. We analyzed the impact of green roofs for increasing indoor thermal comfort using the ANSYS three-dimensional CFD model. The solar load is applied from morning 6 AM to the following day at 6 AM to visualize two days of simulations. Figure 19 (Right) shows solar heat flux on the FIU-MAST building at 10:00 AM, 01:00 PM, 3:00 PM, and 05:00 PM for July 15th, 2021 (hottest day in Miami). A maximum value of 1000 W/m^2 was achieved at 01:16 PM. Figure 19 (Left) shows the FIU-MAST building interior temperature with and without a green roof from 6:00 AM to midnight. The results showed that the proposed green roof could reduce the indoor room temperature up to 3.5 °C and, achieving better indoor thermal comfort.

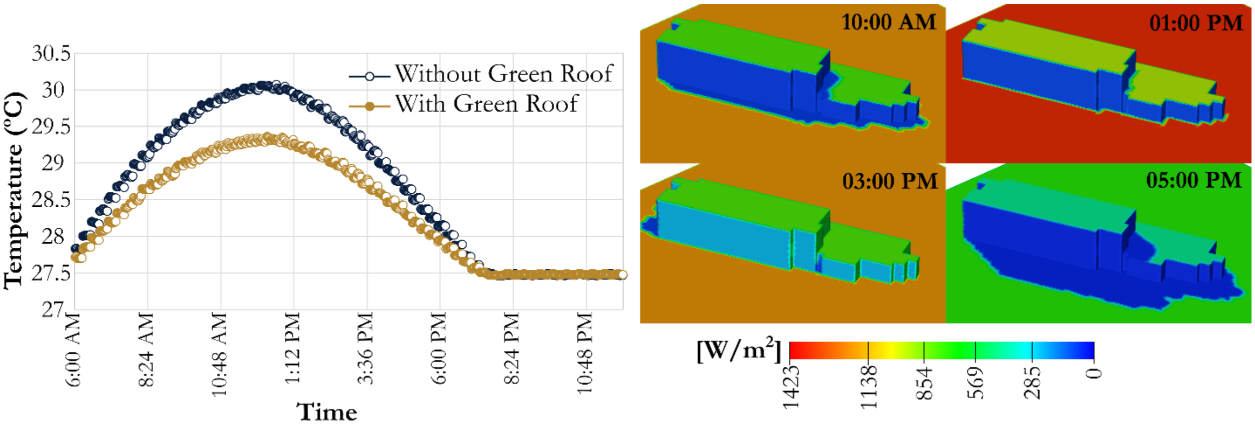


Figure 19: (a) FIU-MAST building's interior temperature Vs. Time (Left), (b) Contour of solar heat flux on the building surfaces at 10:00 AM, 01:00PM, 03:00Pm, and 05:00 PM (Right)

The annual building energy consumption saving due to the green roof system's insulating and cooling effect is 5362.1 kWh, which translates to an energy-saving of $643.47 per year. Knowing the electricity demand savings, we estimated the avoided SO_2, NO_x, $PM_{2.5}$, and CO_2 emissions at the power plants due to lower demand on the electricity grid using AVERT (https://www.epa.gov/avert). Table 3 shows the annual avoided air pollutant emissions across the Miami-Dade County region as a result of the FIU-MAST green roof.

Table 3: Annual avoided air pollutant emissions across the Miami-Dade County region as a result of the FIU-MAST green roof

Air Pollutant	Total Avoided Air Pollutant Emissions (Annual)
SO_2	10 lbs/yr
NO_x	10 lbs/yr
$PM_{2.5}$	5 lbs/yr
CO_2	20 tons/yr

3.3 Permeable Pavement

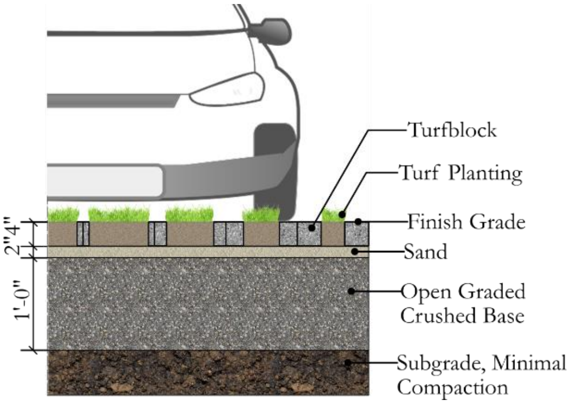


Figure 20: Profile of Turf Block Installation

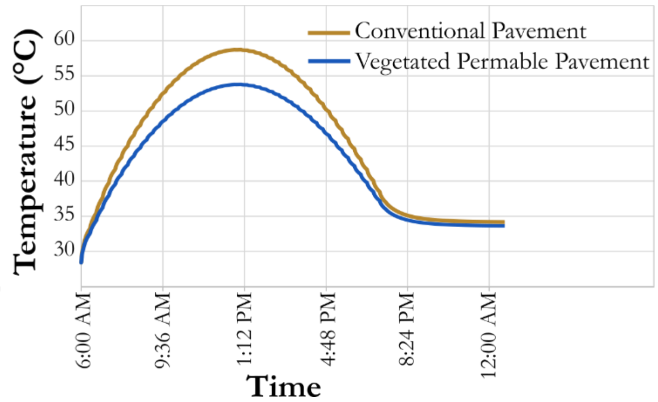
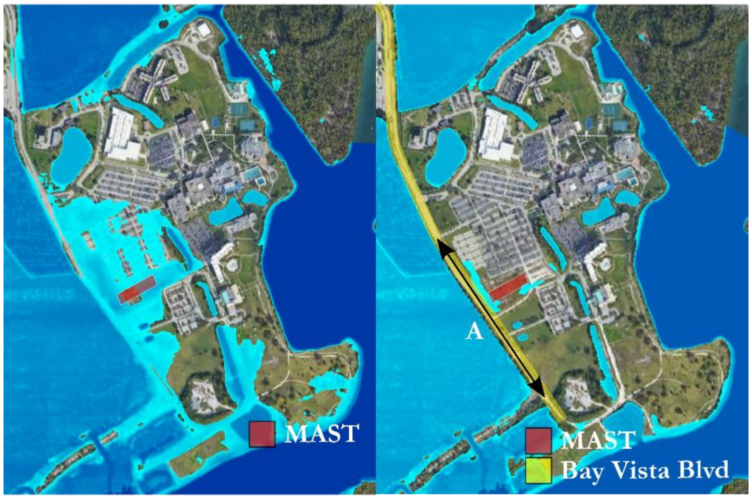


Figure 21: Temperature variation for concrete and permeable pavement

This solution aims to reduce stormwater runoff, add aesthetics, improve water quality and reduce heat island effects. During summer, the surface temperature of conventional pavements (impervious concrete and asphalt) can reach 48°C to 65 °C (Pomerantz et al., 2000b). Therefore, we decided to use vegetated permeable pavements (Grass blocks or Turf Blocks) in the parking lots (Figure 20), considering their suitability and previously proven performance in low-traffic areas/parking lots. Another reason for selecting vegetated permeable pavement was Miami weather, with a moisture content of approximately 60%-80% during summer, which is ideal for vegetated permeable pavements. The pattern designed for the turf blocks is a hexagonal porous concrete block with a hexagonal-shaped insert for the grass. This pattern aims to create more easily walkable surfaces vs. creating more porous areas (where more grass is present proportionally). The blocks consist of an area of about 24 squares inches and 1-1/2 to 5 inches deep. According to laboratory tests, open-celled turf units blocks have runoff coefficients ranging from 0.05 to 0.35 (Richman, 1997). This helps to reduce the stormwater runoff and control the pollutants found in the surface runoff, as it would prevent toxic materials and oils from discharging into the bay or nearby ponds and wetlands. In addition to the above benefits, turf blocks keeps water within the local micro-ecosystem, keeping temperatures cooler than a non-permeable paving system. We used the Ansys Fluent three-dimensional CFD model to perform a conjugate heat transfer study to assess the impact of permeable pavement over conventional pavement (Gao et al., 2019). Figure 21 shows surface temperature variation for concrete and permeable pavement for a period of 18 hours (6 AM to 12 AM). Using the heat index calculator (https://www.weather.gov/epz/wxcalc_heatindex), it was found that the apparent temperature due to permeable pavement is 3°C-4°C lower than the conventional pavement. As the surface temperature of the vegetated pavement is cooler compared to the conventional pavement, the gradient of the temperature inside the pavement will be smaller, which results in less fatigue damage (McAuliffe et al., 1958; Pomerantz et al., 2000a). In addition, the reduced surface temperature of permeable pavement can help reduce the land runoff temperature, thus ameliorating thermal shock to aquatic life in Biscayne Bay.

3.4 Elevating Part of the Perimeter Road of the FIU-MAST



(a) (b)

Figure 22: Flood inundation around the west mangrove channel for the 24-hr, 25-yr return period for 2050 NOAA sea-level rise condition. (a) projected inundation without elevated road, (b) projected inundation with elevated road by 0.25 m (only portion A of the main road is elevated)

Figure 22 (Left) shows the simulated inundation with HEC-RAS for the 24-hr, 25-yr return period for the 2050 NOAA sea-level rise scenario. As shown in this figure, FIU-BBC and FIU-MAST is projected to experience flooding for the 2050 NOAA sea-level rise scenario. In particular, the main access road (Bay Vista Blvd) to FIU-BBC and FIU-MAST is one of the most prone areas to flooding. Working closely with the FIU-BBC facility, we decided to evaluate the elevation of a portion of the Bay Vista Boulevard Road to minimize coastal flooding. After trying several elevation heights and various portions of the road, we determined that the 24-hr, 25-yr return period flooding can be eliminated by elevating portion **A** (400 m length) of the road depicted in Figure 22 (Right) by 0.25 m.

4. REDUCTION OF UNCONTROLLED POLLUTANT DISCHARGE INTO BISCAYNE BAY

To evaluate the effectiveness of the applied green infrastructure, our team has created a SWMM model. This model compares the reduction in total runoff and pollutants under pre- and post-development scenarios. The landscape surrounding the FIU-MAST building, green roofs, and permeable pavement were included in the SWMM model to compare the runoff water quality. The EMC method for buildup and wash-off was used for the analysis. Using the values from Table 1, the wash-off calculations were calculated for the Pre-development and 2050 Post-development using the 24-hour, 25-yr-return-period rainfall (as per the design guidelines established by the South Florida Water Management District). The runoff and TSS results for the Pre-development and 2050 Post-development are shown in Figure

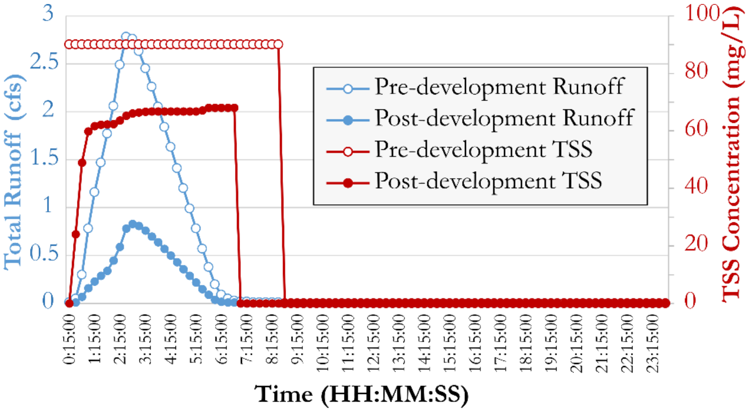


Figure 23: Runoff and TSS reduction through green infrastructure for 24-hour, 25-yr return period rainfall, year 2050 pre-development and post-development scenarios

23. Table 4 summarizes the simulation results from the runoff and infiltration, whereas Table 5 summarizes the results for TSS, TP, and TN for the Pre-development and 2050 Post-development scenarios. The results show that infiltration increased by 68.54% by incorporating green infrastructure, runoff decreased by 72.94%, TSS loading reduced by 75.41%, and loading due to TP and TN reduced by 83.44 and 80.96%, respectively.

Table 4: Runoff for Pre- and Post-Development scenarios using a 24-hour, 25-year return period event

	Total Infiltration (in)	**Impervious Runoff (in)**	**Previous Runoff (in)**	**Total Runoff (in)**	**Total Infiltration Increase (%)**	**Total Runoff Reduction (%)**
2050 Pre-Development	0.28	1.47	0.22	1.7	**68.54**	**72.94**
2050 Post-Development	0.89	1.13	0.17	0.46		

Table 5: Wash-off of Urban Non-Point Sources (TSS, TP, and TN) for Pre- and Post-Development scenarios using a 24-hour, 25-year return period event

	TSS (lbs.)	**TP (lbs.)**	**TN (lbs.)**	**Percent Reduction of Constituent Loading (%)**		
2050 Pre-Development	127.206	0.628	1.534	**75.41**	**83.44**	**80.96**
2050 Post Development	31.281	0.104	0.292			

5. ENGAGEMENT WITH COMMUNITY

To elevate the project impact, the most important goal of this demonstration project has been to involve the FIU and MAST communities in all aspects of the ideation, planning, design, and operation. We will leverage our collaboration with the FIU Facilities Department and MAST leadership to establish an FIU-MAST Project Organization team to host sustainability-focused events for the community. These volunteer events, held on the first Saturday of each month, aim to bring our green infrastructures to the campus and neighboring communities. As aforementioned, a significant component of our design is a multipurpose, flexible, and interactive gathering space which will be used as outdoor classrooms, provide study spaces, and socialization areas designed to raise awareness about the local and overall Biscayne Bay water level and quality issues. Figure 16 shows the pavilions with doubly curved geometry for collecting rainwater and redirecting the water towards its root collection pools. The structure of the pavilions is made of a combination of concrete, steel, and bamboo framing with a recycled plastic skin system that houses algae cultivated from the algae garden within the site's garden area. Another component is the educational gardens surrounding the pavilions, which aim to demonstrate a range of native species for weekly farmer's markets and an area for algae cultivation to reinject into the pavilion's skin system and use in other experimentations.

The pavilions and garden are also interactable using a custom mobile Augmented Reality (AR) application. This app allows the community and visitors to learn more about the specifics of sustainable technologies by walking around the designed area and interacting with digital information overlays over the green infrastructures, including the pavilion structures, species in the gardens, as well as local and global water issues that this project aims to communicate. The app will also highlight existing water monitoring efforts conducted by the FIU Institute of Environment, which uses the Biscayne Bay campus as the leading experimentation site.

The students, faculty, alumni, and community members would work together to conduct routine maintenance activities, such as removing invasive species from gardens and cleaning the rainwater collection pools. In addition, as an educational contribution to the North Miami community, the organization would establish a semi-annual STEM Day, in which local K-12 schools would attend FIU-MAST to learn about green infrastructure practices and water issues in the outdoor classrooms. The STEM Day event would begin with a tour of the rainwater collection system and filtration infrastructure and the native species and algae gardens. The participants in the STEM Day would have the opportunity to interact with FIU researchers and students studying water quality issues and then engage in hands-on activities to design their green solutions for the various stormwater issues faced in South Florida. An event like this would attract stakeholders and allow the Project Organization to establish partnerships and gain financial support. For example, space for informational booths can be offered to stakeholders, such as engineering design firms, construction companies, non-profit organizations, and government agencies, in which they can make a financial donation to the project to secure a spot.

6. PROJECT PHASING

The detailed project phase planning is shown in Figure 24. The construction period was estimated to be 194 working days from 3rd January 2022 to 15th July 2022.

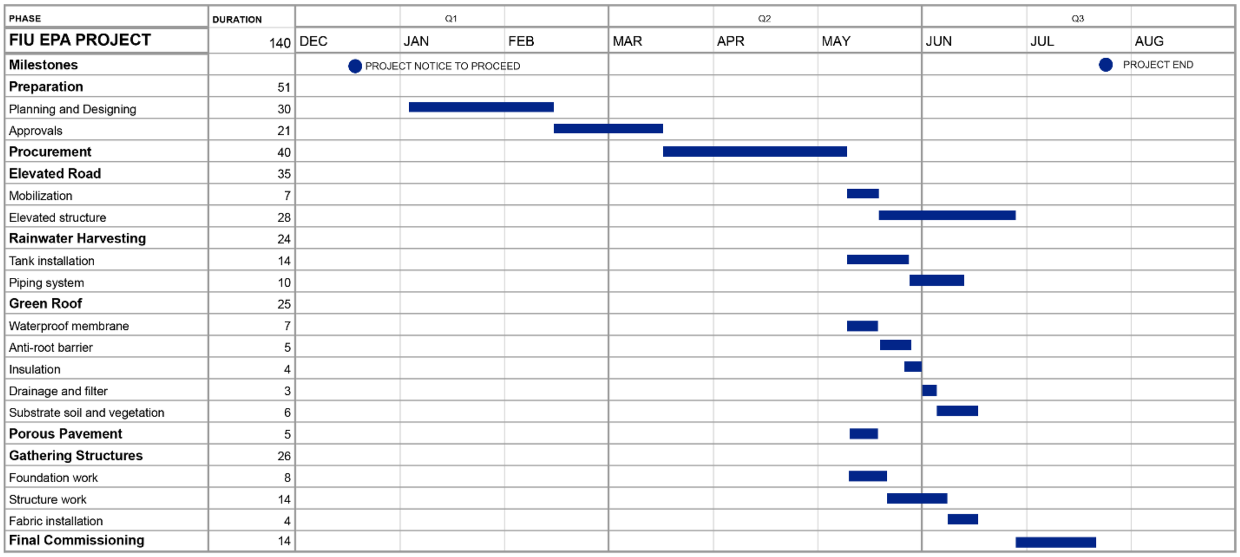


Figure 24: Project phase planning for the proposed infrastructure

7. FINANCING, CONSTRUCTION & MAINTAINANCE COST

7.1 Construction Cost

The total construction cost of our proposed project is $3,430,883. The unit price of the project was obtained from the RS-means platform overall unit pricing and the Florida Department of Transportation (FDOT) website (Table 6 contains detailed construction costs).

7.2 Maintenance Cost

The maintenance cost mainly comprises green roofs, permeable pavement, a rainwater harvesting system, and an elevated road. Typical maintenance activities include debris removal, inspection and repair of components, replacement of filtration materials, pruning, fertilization, and pest and disease management. Please refer to Table 7 for detailed maintenance activities and costs.

7.3 Cost-benefit Analysis and Funding Source

Table 8 summarizes the proposed strategies, the estimated costs for construction and maintenance, the anticipated economic and environmental benefits, and the possibilities for funding. As shown in Table 6 and Table 7, the initial investment for the rain harvesting system and the green infrastructures is $3,430,883 and the annual maintenance cost is about $58,970, respectively. From the perspective of sustainable development, this project brings benefits that are not readily quantifiable, such as reducing the probability of ponding and flooding, increasing carbon sequestration, and reducing the urban heat island effect. Another important benefit is improving campus aesthetics and infrastructure, which many studies have shown to promote recruitment and enhance academic success (Zabihi & Khozaei, 2017; Kuo et al., 2021).

The focus of this project on water reuse, sustainability, and green infrastructure aligns with many funding prospects in the State of Florida. For example, Governor Ron DeSantis and the Florida Legislature approved $40 million in statewide funding for developing water supply and water resource development projects. Each year, the application is opened through the SFWMD Coop Funding. Another viable option is the NRPA Great Urban Parks Campaign, which provided total funding of $2 million in 2018. Another exciting opportunity is the Florida Resilient Coastlines Program, which offered total funding of $2.3 million in 2019. A larger funding source is the Miami Forever Bond, which up to date, has allocated $192 million towards sea level rise mitigation and flood prevention. The Nonpoint Source Funds of the Florida Department of Environmental Protection and FIU are also potential funding providers for the proposed solutions.

Table 6: Construction cost summary

Construction Cost						
No	**Alternatives**	**Unit Cost ($)**		**Quantity**		**Total Cost ($)**
1	**Gathering Structure**					**266,640.00**
1.1	Bamboo structure	7.15	/ft²	33,000	ft²	235,950.00
1.2	Fabric	0.93	/ft²	33,000	ft²	30,690.00
2	**Green Roof**					**234,200.00**
2.1	Waterproof membrane (1/8" thick)	1.77	/ft²	20,000	ft²	35,400.00
2.2	Anti-root Barrier (3/16" plywood)	1.80	/ft²	20,000	ft²	36,000.00
2.3	Insulation (polyurethane form 2")	2.50	/ft²	20,000	ft²	50,000.00
2.4	Root barrier	2.20	/ft²	20,000	ft²	44,000.00
2.5	Drainage layer (1/4")	0.80	/ft²	20,000	ft²	16,000.00
2.6	Filter layer (Polypropylene Roll)	0.30	/ft²	20,000	ft²	6,000.00
2.7	Substrate soil (4")	1.27	/ft²	20,000	ft²	25,400.00
2.8	Vegetation (Asian jasmine)	1.07	/ft²	20,000	ft²	21,400.00
3	**Permeable Pavement**					**1,535,655.00**
3.1	Permeable paver	11.35	/ft²	135,300	ft²	1,535,655.00
4	**Elevated road**					**1,535,655.00**
4.1	Concrete elevated road	15,918,71 to 23,135,38	/km	0.7	km	1,366,893.00
5	**Rainwater Harvesting System**					**58,185.00**
5.1	Tanks (5100 gals)	19,395.00	/tank	3	tank	58,185.00
5.2	Labor cost	35.00	/hr	160	hr	5,600.00
TOTAL COST						**3,430,883.00**

Table 7: Maintenance Schedule

Maintenance Schedule				
No	**Alternative**	**Time**	**Cost/Time**	**Annual Cost ($)**
1	**Gathering Structure**			
1.1	Bamboo structure cleaning	Weekly/As required	$ 150	7,800.00
2	**Green Roof**			
2.1	Weeding	Monthly	$ 480	5,760.00
2.2	Plant replacement	As required	$ 110	110.00
2.3	Irrigation	As required	$ 200	200.00
2.4	Fertilization	As required	$ 660	660.00
2.5	Soil testing	One time per year	$ 300	300.00
2.6	Maintenance	One time per month	$ 70	840.00.00
3	**Permeable Pavement**			
3.1	Paver cleaning	Weekly/As required	$ 200	10,400.00
4	**Elevated Road**			
4.1	Concrete elevated road cleaning	Weekly/As required	$ 100	5,200.00
4.2	Road maintenance	Yearly/As required	$ 25,000	25,000.00
5	**Rainwater Harvesting System**			
5.1	Tank cleaning	Quarterly	$ 300	1,200.00
5.2	Tank inspection	Semi-annually	$ 500	1,000.00
5.3	Replace damaged components	As required	$ 500	500.00
TOTAL COST				**58,970.00**

Table 8: Summary of Costs, Benefits, and Funding Sources

Strategy	**Estimated Cost**		**Anticipated Outcome**			**Funding Options**
	Construction ($)	**Annual Maintenance ($)**	**Direct Economic Benefits**	**Environmental Benefits**	**Social Value**	
Gathering Structure	235,950.00	7,800.00	Increases the property value, decreases water supply demand for irrigation	Hosts green infrastructure	Beautification, Social interaction, alert the community on the Biscayne Bay water health	FIU; SFWMD coop funding
Green Roof	234,200.00	7,870.00	Annual electricity savings of 5362.1 kWh and electricity cost savings of $643.47, increases lifespan of roof	Stormwater reduction (42 in/yr.), reduced heat island effect, improved air quality	Beautification	FIU; Florida Resilient Coastlines Program; SFWMD coop funding
Permeable pavement	1,535,655.00	10,400.00	Low maintenance cost	Enhanced Infiltration, reduced heat island effect, surface runoff reduction, pollutant filtration, CO_2 sequestration	Beautification	FIU; Florida Resilient Coastlines Program; SFWMD; Miami Forever Bond coop funding
Elevated Road	1,366,893.35	30,200.00	Enabling the movement of goods and people during storm surge without causing significant disruption			FIU; FMA grant; Florida Resilient Coastlines Program; Miami Forever Bond
Rainwater Harvesting System	58,185.00	2,700.00	Saves 169,911 gallons of potable water per year (Savings of $13,100/yr).			FIU; SFWMD coop funding
Total	**3,430,883.35**	**58,970.00**				

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