Miami Forever: Stormwater and Coastal Resilience for a Changing Climate

Michael Schmidt, Christopher Bennett, Alan Dodd, Jonathan Goldman, and Thomas Nye

Key Words, Terms, and Acronyms

Adaptation, ARPA grants, aquifer recharge, backflow preventers, B/C analyses, Biscayne Aquifer, Biscayne Bay, CIP, coastal resilience, exfiltration, FEMA BRIC/HMGP/Hazus tool, FDOT, king tides, LOS, OFW, prioritization, recharge wells, resiliency, retrofit, saltwater intrusion barrier, sea level rise, seawalls, SFWMD, SRF loans, stillwater elevation, stormwater management, SWMP, SWMM, sustainability, and tidal surge.

Miami faces challenges with built-out urban conditions being impacted by sea level rise, tidal surge events, and varying precipitation. The stormwater master plan (SWMP) is a comprehensive program to manage stormwater, with changes in sea levels and tidal surge, groundwater, and rainfall patterns, to manage flooding while protecting and enhancing water quality and aquifer recharge. The holistic approach to modeling current and future conditions allows the city to plan for current and future climate stormwater and coastal resilience needs.

This article presents the challenges, opportunities, methodology, and levels of service (LOS) for the stormwater system, benefit-cost (B/C) analyses, and considerations for implementation.

Background

The SWMP for the City of Miami (city) has been developed as a comprehensive effort to define resilient, adaptable, and sustainable stormwater flood mitigation, water quality, and aquifer recharge capital investments—for now and the foreseeable future. The plan includes modeling joint rainfall and tidal flood events, effects of sea level rise and rising groundwater tables, and increased rainfall intensities. The plan also considers anticipated development growth and climate change data, while providing the tools necessary to allow the city to develop an adaptable and resilient capital improvement program (CIP) that anticipates and prioritizes funding and infrastructure needs to help protect public safety, public and environmental health, and Florida's largest urban economy.

Program goals were established to create a vision and metrics for today and for the future, including considerations for:

- Flood mitigation
- Water quality protection
- Aquifer recharge
- Enhanced operation and maintenance
- Community acceptance
- Sea level rise and storm surge
- Stormwater harvesting
- Permitability and constructability
- Long-term financing

Michael Schmidt, P.E., BCEE, D.WRE, is senior vice president with CDM Smith in Jacksonville. Christopher Bennett, P.E., is assistant director/ deputy chief resilience officer, and Alan Dodd, P.E., is chief resilience officer/ director, with City of Miami, Department of Resilience and Public Works. Jonathan Goldman, P.E., is an associate, and Thomas Nye, Ph.D., P.E, is senior water resources engineer, with CDM Smith in Boca Raton.

The city encompasses approximately 56 sq mi (Figure 1); approximately 36 sq mi of this region are located in upland areas, while the remaining 20 sq mi are found within coastal basins and Biscayne Bay, which is an Outstanding Florida Water (OFW) with special water quality protection. The stormwater service area is naturally divided by elevation, topography, and infrastructure into eight major basins that interact with Miami-Dade County, Florida Department of Transportation (FDOT), and South Florida Water Management District (SFWMD) stormwater management systems.

Methodology

Stormwater Models

The hydrologic and hydraulic stormwater models were developed in the public domain of the U.S. Environmental Protection Agency (EPA) stormwater management model (SWMM) for the city's primary stormwater management system (PSMS), which is generally defined by pipes and channels greater than 24 in. in size. The PSMS was defined by a combination of digitized historic

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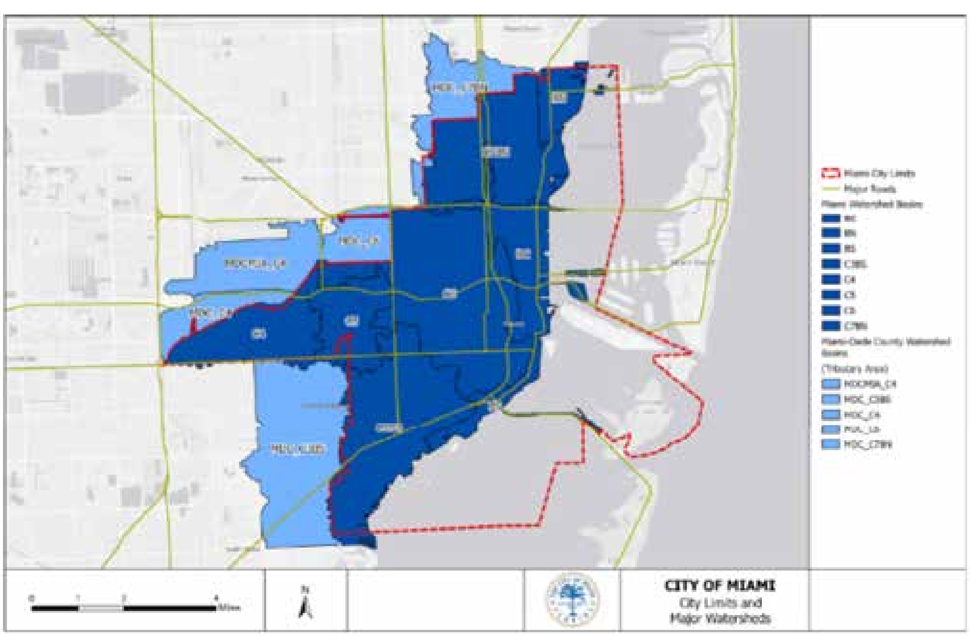

Figure 3. Flood Inundation Map

Continued from page 36
paper records and a field survey. Eight watershed SWMMs were developed and combined to facilitate evaluation of interconnected system LOS performance and alternative mitigative measures to increase LOS to the desired goals.

Problem Areas and Citizen Input

A series of public meetings were conducted across the city, and citizens provided locations of reported problems. This was combined with the Miami-Dade County 311 stormwater complaint system records and the Federal Emergency Management Agency (FEMA) flood insurance rate maps to define flooding problem locations and connectivity between systems (Figure 2).

Stormwater System Inventory and Geodatabase

The data inventory included the digitization of more than 30,000 pages of existing as-built drawings, along with extensive data collection from the field, to update the city's existing stormwater atlas, populate an asset management database, and develop a citywide stormwater model that considers pervious and impervious areas of the urban landscape.

The data collection effort includes a survey of stormwater structures and the development of a digital elevation model based on light detection and ranging (LiDAR) topographic data. The data were validated with the city's existing infrastructure and bathymetric data (and an extensive field survey) to develop a citywide model for the major watersheds that account for varying rainfall events, tidal and groundwater influences, and future sea level rise impacts in coordination with Miami-Dade County and SFWMD stormwater systems.

Modeling inputs and parameters required extensive manipulation and analyses using geographic information system (GIS) tools, such as geographic watershed information system schema and ArcHydro. The modeling provides a comprehensive neighborhood-level and basin-scale analysis of the flood control LOS for both existing and proposed stormwater systems, including the effects of projected climate conditions.

Design Storms and Tidal Boundary Conditions

The five-year 24-hour, and 10-year, 25-year, and 100-year 72-hour design storms were simulated using the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 rainfall estimates and SFWMD rainfall distribution, with a one-year tidal stillwater elevation of 2 ft referenced to the North American Vertical Datum (ft-NAVD) of 1988. The one-year stillwater is approximately equal to a local king tide condition.

The project team used SWMM to estimate flood stages at locations across the city, along with flood inundation maps (Figure 3) to evaluate the flow rates and volumes for storage, conveyance, exfiltration, recharge wells, and potential pumping.

Water Quality and Aquifer Recharge

The city discharges stormwater to the sensitive Biscayne Bay, which is an OFW, so retrofit treatment must be provided and overall discharge volume must be managed. This requires the use of options, such as exfiltration and recharge wells to provide storage, treatment, and infiltration/recharge prior to discharge. These systems provide recharge of the Biscayne Aquifer, which is highly conductive. The recharge also reduces saltwater intrusion for this drinking water supply source.

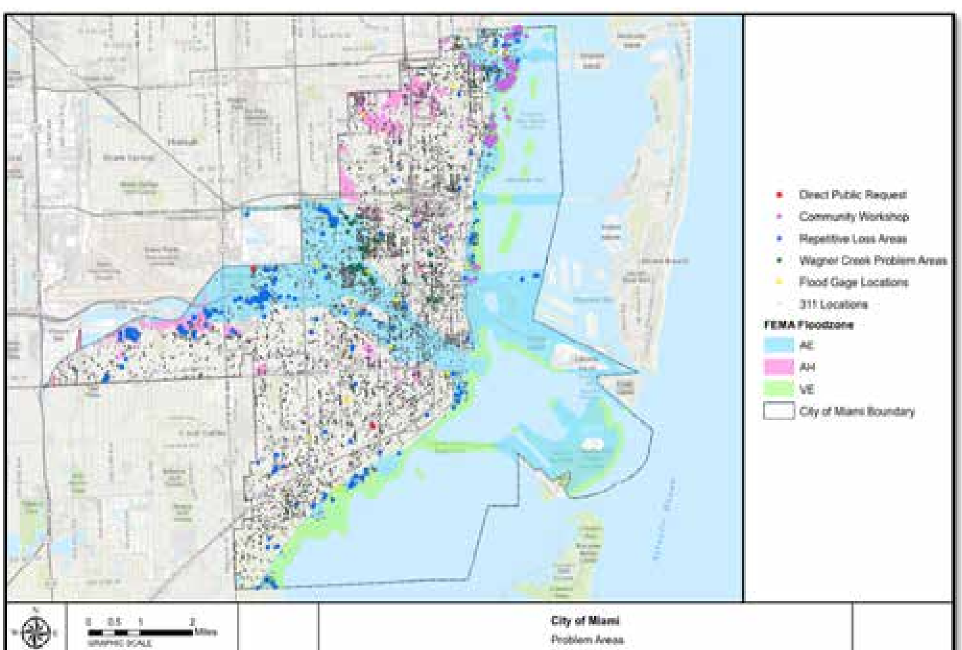

Figure 2. Flooding Problem Areas

Levels of Service

The city's goal for flood control LOS is to manage flooding below road crowns for the 10-year 72-hour event, and below homes and buildings as practicable. For the SWMP analysis, two alternative LOS goals were analyzed to provide a range of potentially achievable LOS and the associated implementation costs:

LOS Alternative 1

The primary LOS goal chosen by the city was zero flooding over the crown of all roads in the 10-year recurrence interval design storm event. This also includes keeping inundation out of buildings for the 100-year design storm where practicable.

LOS Alternative 2

The secondary LOS goal achieves the same roadway and building criteria, but for a smaller five-year recurrence interval design storm event. This allows for temporary flooding of a safe and predictable depth, for short durations of time in known areas, and for a more affordable solution for comparison purposes.

The conceptual solutions for individual neighborhood capital improvement projects were tailored specifically in areas found to be most susceptible to flooding. Several hundred mi of exfiltration systems have been evaluated, along with more than 800 gravity and 1,500 pumped recharge wells to meet flood control LOS, while providing treatment and volume control. Seawall height extensions are also being considered by ordinance for the city's 93 mi of shoreline, along with backflow prevention for the city's 486 outfalls.

Results

The SWMM hydrologic and hydraulic models were validated using reported flooding from the 311 database, public meetings for problem areas, FEMA repetitive loss locations, and photographs of eyewitness accounts at 36 locations across the city.

Using the validated models, predicted flood stage and inundation maps of the city were developed for the five-, 10-, 25-, and 100-year design storms. The maps depict the extent and depth of flooding under the storm conditions for comparison and for the identification of flood-prone areas.

These maps are used as follows:

- The five-year design storm provides information for the secondary LOS goal flood areas for a more-frequently recurring storm. The Alternative 2 CIP is subsequently run with the 10-year storm as well, in order to determine the location, depth, and duration of ponding for this LOS.
- The 10-year design storm provides information for the city's primary LOS goal and for major roadway flooding analyses.
- The 25-year design storm provides the information required for regulatory permitting to the SFWMD for flows and levels in the major canal systems and their impact to Biscayne Bay for pre- and post-CIP implementation.
- The 100-year design storm provides information for the recommended finished floor elevations and for critical structure elevation versus predicted flood stages. It's rerun with sea level rise conditions to demonstrate the future impact to structures.

Figure 3. Flood Inundation Map

For the CIP alternatives analyses, the delineated neighborhood-size sub-basins were combined logically into 78 discrete "CIP areas," which considered common topography and PSMS elements of adjoining neighborhoods. Capital improvements to the stormwater management system were systematically added citywide, and iterative simulations were run to test the proposed infrastructure until the city's desired LOS for each alternative was achieved.

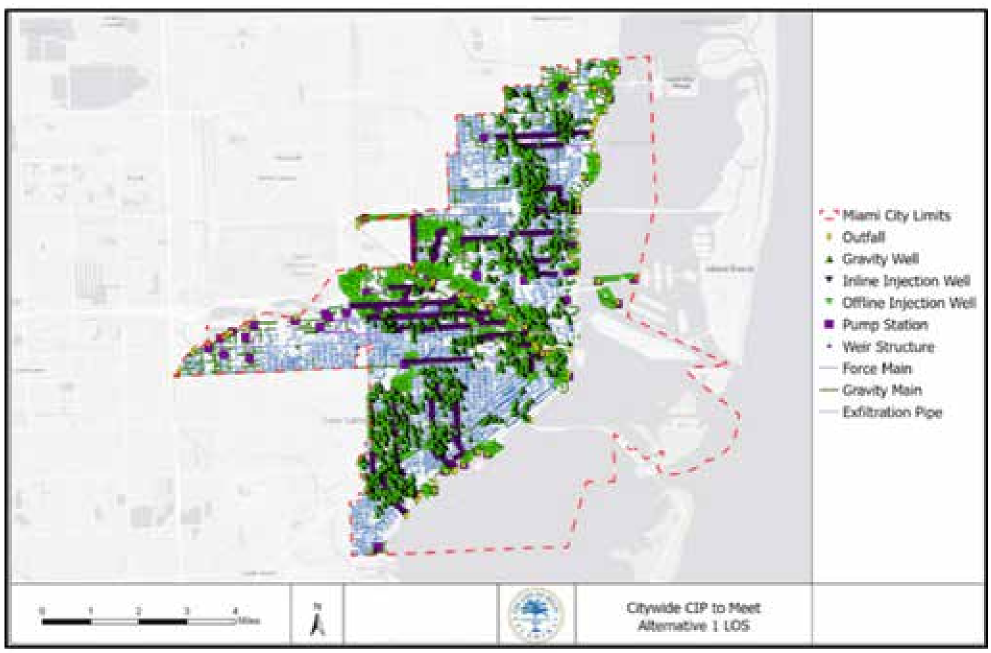

Figure 4. Capital Improvement Program Components

Stormwater Master Plan Capital Improvement Plan Components

Opportunities and considerations for rainfall and tidal flood mitigation components included the following elements that were implemented to improve flood control, water quality, aquifer recharge, and saltwater intrusion reduction.

Exfiltration Systems

The most-cost-effective stormwater management components for the Miami area are exfiltration systems, due to the high flow capacity (conductivity) of the Biscayne Aquifer, their modular implementation flexibility, and delivery of multiple benefits. These systems are perforated pipes in rock trenches wrapped with filter fabric. They collect, store, infiltrate, treat, and convey stormwater in the city's available rights-of-way (ROW) and easements, generally for the lowest cost. They are comparatively straightforward and modular to design, permit, and construct. They can also be phased in as needed or as opportunities arise (i.e., as street, water, sewer, park, and landscape improvements are implemented).

The multiple benefits of these systems include flood mitigation, water quality treatment credits, and aquifer recharge for reduction of saltwater intrusion and protection of groundwater supplies. Exfiltration systems collect, store, treat, infiltrate, and convey stormwater runoff within the city's ROW for the lowest costs and are modular and flexible for implementation as opportunities arise with water, sewer, transportation, parks, and other programs.

These systems rely on the hydraulic grade of the water collected at the land surface to infiltrate stormwater into the porous, surficial aquifer. These systems will not work everywhere due to the variable groundwater table elevation in the city just below the ground surface in many of the lower-lying areas. These systems, therefore, are recommended in areas with topographic elevations greater than 5.5 ft-NAVD. These systems will also be impacted by sea level rise in the future, but will be effective through the 50-year SWMP planning horizon (and beyond) for higher areas.

Continued on page 40

Continued from page 39

Recharge Wells

These wells can be used to discharge stormwater to surficial aquifer zones east of the salinity line, which is generally in the eastern portion of the city. They can be retrofitted into existing stormwater management system manholes to augment the exfiltration systems. Pretreatment is provided for oil, grease, trash, and debris. These systems provide discharge capacity and treatment credits, since dissolved nutrients that would be harmful to Biscayne Bay are discharged into the brackish surficial aquifer. This also assists with creating a saltwater intrusion barrier for current and future sea level conditions. In some cases, these wells can be augmented by pumps to increase the recharge flow rate, as well as reduce flows, volumes, and pollutant loads to the bay, canals, and rivers.

Green Infrastructure

Green infrastructure is the use of natural planted systems to collect, store, treat, and infiltrate stormwater. These systems can be implemented on individual sites or for capital improvement projects along streets and buildings, and in parks. They can include rain gardens and/or landscape planter swales. Additionally, these systems can reduce precious potable water use for irrigation since they are watered by both rainfall and runoff and receive some of their nutrient requirements from the stormwater. The synergistic effect of the installation of many green infrastructure systems spread throughout the city can mitigate chronic flooding areas and allow residents to participate in the flood solutions on their own sites.

Backflow Preventers

The city has more than 480 stormwater outfalls that can backflow during high tides and tidal surge events. Outfalls will require backflow preventers to keep the rising seas out of the system and provisions for the increased head loss to open them, which must be considered in the CIP implementation.

Pump Stations

The SWMP included a focus on the maximum amount of exfiltration and recharge wells possible; however, due to the limitations of these systems and the locations of where they work, the need for new stormwater pump stations still remains to provide flood protection in many low-lying areas. More than 90 systems are proposed.

Seawall

There are approximately 93 mi of bay and river coastline in the city that will need seawall upgrades for current tidal surge, and for future sea level rise and associated tidal surges. The SWMP has included these seawalls along the entire coastal perimeter to demonstrate the extent, benefits, and costs for these systems. These seawalls are largely privately owned and must be upgraded in a consistent manner. The city has drafted an ordinance to address seawall standards. and criteria.

The CIP for Alternative 1 is shown in Figure 4 and ranges from $5.4 to $3.8 billion for Alternatives 1 and 2, respectively. The CIP can be additive by implementing the lower cost of Alternative 2, and then adding more Alternative 1 components as necessary over time, as climate change effects grow and additional funding allows.

Both alternative CIPs include more than:

- 200 mi of exfiltration
- 800 gravity recharge wells
- 1,500 pumped recharge wells
- 90 pump stations
- 80 backflow preventers
- 90 mi of seawalls

Sea Level Rise and Resiliency

The sea level rise and resiliency analysis in the SWMP focused on three primary areas:

- Simulating two future sea level rise conditions of 18 and 30 in., with the associated higher tides and groundwater levels, to predict the impact on effectiveness of the proposed CIP alternatives in the future.
- Simulating coastal armoring and seawall protection at different storm surge heights.
- Resiliency planning simulation for a "worst case" storm (500-year) occurring coincidently with a peak high tide and storm surge event.

The sea level rise predictions used for the analyses were in accordance with the city-adopted 2019 report, "Unified Sea Level Rise Projection and Guidance," produced by the Southeast Florida Regional Climate Change Compact. The results are used to aid in understanding the vulnerabilities of the city and its stormwater management system with relation to surge and sea level rise, and to provide a basis for adaptation strategies, policies, and infrastructure design.

If sea levels and groundwater levels continue to rise as projected, eventually the shallow aquifer disposal and recharge CIP elements, which rely on a minimum hydraulic depth to the water surface elevation, will become less effective over time.

Benefit-Cost Analyses

The B/C analyses were performed using the FEMA Hazus program, which maintains models for estimating the risk of damage from earthquakes, floods, hurricanes, and tsunamis, to establish B/C ratios and documentation for potential grant and loan funding. These were performed for existing base conditions for a 50-year planning horizon and compared to flood damage reduction for the two alternatives and for the two sea level rise conditions. In all cases, B/C ratios ranged from 2.8 to 3.8, indicating

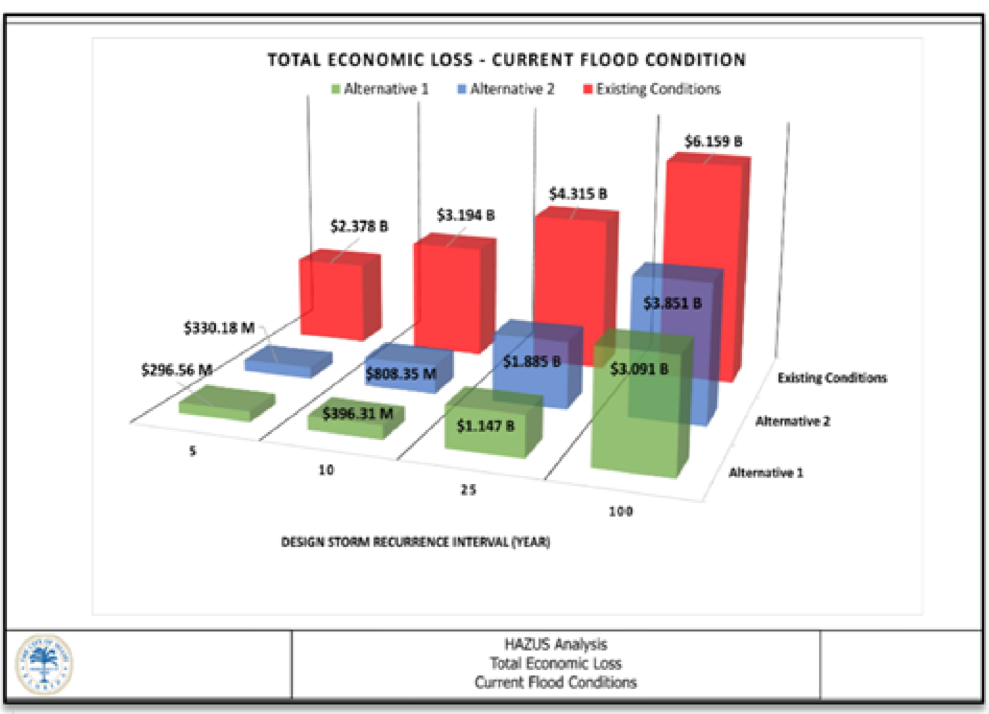

Figure 5. Federal Emerency Management Agency Hazus Benefit-Cost Analysis Results

considerable value for the infrastructure investment. Figure 5 shows a bar-chart representation comparing the flood damages for existing conditions versus the two alternatives, indicting significant flood damage reduction.

Discussion

These opportunities to store, treat, and discharge stormwater underground can reduce costs in a sustainable manner, within city ROW. Exfiltration and recharge wells provide treatment and aquifer recharge to reduce adverse water quality impacts to sensitive receiving waters, while providing aquifer recharge to reduce saltwater intrusion and protect drinking water supplies. More than 1.1 in. of equivalent treatment is provided by CIP. The existing condition discharge volume for the 25-year 72-hour storm is matched in alternative CIP conditions to avoid moving flooding problems downstream, and flood protection is provided across the city. Pump stations are evaluated after collection, treatment, storage, exfiltration, and well recharge to provide the minimum amount of pumping necessary.

The city is currently defining priorities for implementation based on B/C metrics, as well as public and city commission input gathered from a series of public meetings. These will be refined and coordinated with water, sewer, transportation, and parks projects. There will also be coordination with adjacent stakeholders, including Miami-Dade County, FDOT, and SFWMD for joint project and cost-sharing opportunities. Grant and loan programs are being considered to leverage the Miami Forever bond funding, including FEMA Building Resilient Infrastructure and Communities (BRIC) and Hazard Mitigation Grant Program (HMGP) grants, American Rescue Plan Act (ARPA) grants, State Revolving Fund (SRF) loans, and others.

Conclusions

This article presents the results of the comprehensive SWMP for coastal stormwater resilience, an approach for dynamic hydrologic and hydraulic models, tidal surge evaluations for historic storms (e.g., Hurricane Irma, May 2019), LOS evaluations, two sea level rise conditions, alternatives evaluations for cost-effectiveness, CIP, and Hazus B/C analyses, with summary discussion on the coordination with stakeholders and prioritization.

These methods for dynamic SWMM modeling with higher tidal boundary conditions for joint rainfall and tidal events can be used for coastal communities to address existing LOS deficiencies and to plan for and address sea level rise in a phased and adaptable manner for resiliency. The CIP components provide cost-effective grey and green solutions for sustainable and enduring flood mitigation benefits that will provide public safety and health, water quality treatment to protect Biscayne Bay, and Biscayne Aquifer recharge to reduce saltwater intrusion in drinking water supplies. The B/C ratio indicates significant value for the investment and establishes the foundation for successful grant and loan opportunities as the city works to implement the program.

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