# FINAL

# Technical Memorandum

## Adaptation Strategy Analysis for Gandy Blvd.

Hillsborough MPO
Metropolitan Planning for Transportation

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Louisville, CO

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# 1.0 Executive Summary

The Tampa Hillsborough Expressway Authority (THEA) is in the process of developing the request for proposal to design/construct the elevated connector and is interested in including adaptation strategies in the scope of work. The Pilot provided high level estimates of adaptation costs with little detail on physical design and construction. The purpose of this analysis was to analyze the vulnerabilities of the elevated section of the expressway extension at Gandy Boulevard and provide potential adaptation strategies for the three categories of vulnerability. Based on this overall objective, Resilient Analytics utilized both existing information from the Pilot study as well as climate models and analysis from the Infrastructure Planning Support System (IPSS) to determine additional vulnerability and adaptation strategies.

The result of the study indicates that the proposed Gandy Blvd. project is vulnerable in multiple areas including the three overall categories of concern; bridge piers and abutments, road surface and base, and adjoining coastal structures. Of particular concern in the study is the effect of storm surge and sea level rise. The additional height of inundation due to these variables requires the engineering solutions for Gandy Blvd. to consider additional stresses on the project from changing environmental conditions.

For bridge piers, the threat of scour from the increased wave and surge action may require additional strengthening or diversionary design considerations for the elevated section of the roadway. Similarly, the raised profile of the road will create embankments that are vulnerable to increased wave activity and erosion. Additional hardening of the embankments will be essential to minimize damage to the roadway base layers.

The surface of the roadway will not only undergo stress from the storm surge, but climate models indicate additional precipitation may weaken the roadway surface. Although permeable pavement does not appear to be an appropriate option, a cost-benefit analysis for options such as a concrete surface may be appropriate.

In summary, the storm surge and climate models indicate that the greatest threat to the Gandy Blvd. extension is the increased inundation depth that the project will likely experience. Given this vulnerability, a consideration for increasing the profile of the project a minimum of four additional feet will provide a significant benefit in terms of resiliency. When combined with pier strengthening, embankment hardening, and surface strengthening, the resiliency of the Gandy Blvd. project will be significantly enhanced.

## 2.0 Description of Site

The assessed segment commences as Gandy Boulevard makes landfall, continuing east to the site of the planned elevated connector. This segment is a critical link between Hillsborough and Pinellas counties. A map that details the surrounding area can be seen in figure #. The section of road analyzed is highlighted in green.

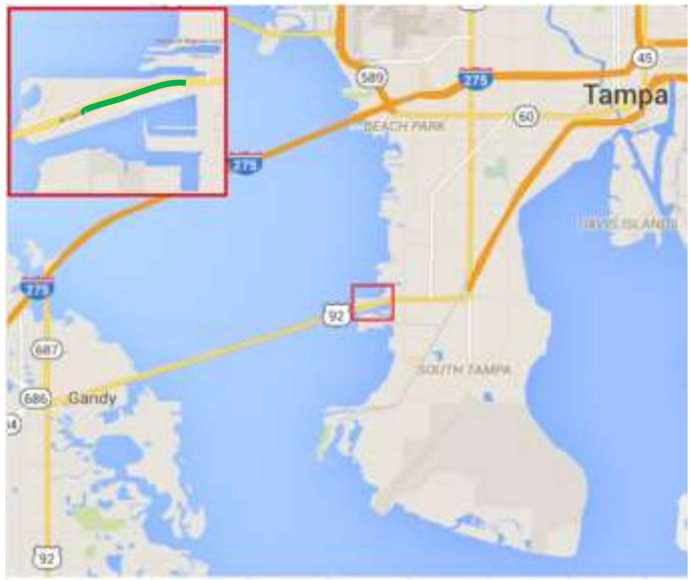


**FIGURE 1: MAP OF SITE**

The area is partially armored with rip rap and a shallow bulkhead (proximate to a commercial/industrial facility on the northern face of the peninsula). Piles (remains of a former pier structure) ring the northwestern tip of the peninsula, providing some wave attenuation benefits (but not systematically so). The eastbound (EB) lane reaches the peninsula at grade, while the westbound (WB) lane rises from grade to an elevated, armored bridge approach. The WB approach is drained on the north side, using a shallow surface channel and grated inlets (flush with channel). The EB lane has no obvious drainage until the median begins (3 inlets near turn lanes).

# 3.0 Climate Data

Three type of inundation were analyzed for the assessment of Gandy Blvd:

- Sea level rise
- Storm Surge (combined with sea level rise), and
- Inland flooding

Sea level rise refers to the gradual increase in ocean elevations relative to land (as measured by tide gages) due to a variety of global and regional factors, such as melting artic ice sheets and glaciers, increasing water temperatures (thermal expansion), increasing salinity, and land subsidence.

For each analysis year and high and low projection was selected (intermediate scenarios were not used), following the methodology adopted by GeoPlan[1]. Mean Higher High Water (MHHW), corresponding to the average highest high water height of each tidal day was selected as the tidal datum for all scenarios. The resulting sea level rise values can be seen in table #1[2].

| **2040 SeaLevel Rise** | | **2060 SeaLevel Rise** | |
|---|---|---|---|
| Scenario | Depth (in) | Scenario | Depth (in) |
| High(MHHW) | 30 | High(MHHW) | 42 |
| Inter(MHHW) | 22 | Inter(MHHW) | 27 |
| Low(MHHW) | 20 | Low(MHHW) | 22 |

**TABLE 1: SEA LEVEL RISE SCENARIOS**

These scenarios were selected collaboratively and reflect the expert judgment and risk tolerance of key partners in the Tampa Bay region (such as the Regional Planning Council).

Storm surge is a coastal phenomenon that occurs when water is forced into the shore by powerful winds—most commonly due to a hurricane, tropical storm, or tropical depression—causing the temporary, sometimes dramatic elevation of sea levels. NOAA models surge using the Sea, Lakes, and Overland Surges from Hurricanes model (SLOSH). The height of the surge is determined based on historical, hypothetical, or predicted hurricanes, accounting for the atmospheric pressure, size, forward speed, tidal phase, and track of the storm event, as well as a set of physics equations that integrate shoreline characteristics, unique bay and river configurations, water depths, bridges, roads, levees and other physical features[3].

SLOSH simulates thousands of storms within a specific ocean basin, producing a record of the maximum recorded result for hundreds of shoreline grid cells, referred to as the Maximum Envelope of Water, or MEOW. By assembling the MEOW for each cell, the Maximum of the MEOWs, or MOM, is produced. There is one MOM for each hurricane velocity tier in the well-known Saffir-Simpson scale (hurricane Categories 1 through 5).

The MOMs, which were used for this study (Category 1 and Category 3), provide a valuable estimate of the greatest depth and extent of coastal flooding associated with the selected hurricane category at

[1] http://sls.geoplan.ufl.edu/

[2] Rise is relative to 1992 Mean Sea Level (midpoint of the current National Tidal Datum Epoch of 1983-2001). Source: Geoplan.

[3] http://www.nhc.noaa.gov/surge/slosh.php

specific locations. However, because the MOMs are the product of a multitude of simulated storms, it is important to note that the surge extents and depths they depict drastically overstate the potential inundation impacts of any single hurricane event within that Saffir-Simpson category[4].

Sea level rise and storm surge were analyzed in combination. SLR was simply added to SLOSH, rather than remodeling surge under SLR scenarios. This technique provides illustrative results, but is valuable for planning. Table #2 shows the inundation depth for all combinations analyzed.

| Inundation Depth (ft) | | Storm Surge Scenario | | | | | |
|---|---|---|---|---|---|---|---|
| | | Cat. 1-Mean | Cat. 1-High | Cat. 2-Mean | Cat. 2-High | Cat. 3-Mean | Cat. 3-High |
| Sea Level Rise Scenario | Present Day-Low | 4.70 | 5.60 | 9.70 | 10.80 | 14.90 | 15.90 |
| | 2040-Low | 6.37 | 7.27 | 11.37 | 12.47 | 16.57 | 17.57 |
| | 2040-High | 7.20 | 8.10 | 12.20 | 13.30 | 17.40 | 18.40 |
| | 2060-Low | 6.53 | 7.43 | 11.53 | 12.63 | 16.73 | 17.73 |
| | 2060-High | 8.20 | 9.10 | 13.20 | 14.30 | 18.40 | 19.40 |

**TABLE 2: INUNDATION DEPTH FROM SEA LEVEL RISE AND STORM SURGE SCENARIOS**

Note that these values may differ slightly when comparing to the pilot report. For this analysis, the SLOSH values were selected from the exact grid where Gandy Blvd is located.

Flooding from intense precipitation can also affect inland transportation assets, in conjunction with or separately from coastal phenomena. The approach to assessing future vulnerabilities to inland flooding leveraged official 100-year (one percent annual chance) floodplain maps. Based on the analysis of FEMA's official Digital Flood Insurance Rate Map (DRIRM), the pilot report defines a FEMA 1% chance flood height of 9 feet.

[4] http://www.nhc.noaa.gov/surge/momOverview.php

# 4.0 Adaptation Strategies

The focus of this effort is to provide adaptation options for three distinct threats to Gandy Blvd; 1) bridge piers and abutments, 2) general road and adjoining area vulnerability, and 3) erosion issues to coastal roads. These three areas combine within a broader group of adaptation strategies that cross the different vulnerability categories. These adaptation categories include; 1) erosion control, 2) drainage, and 3) strengthening and profile adjustment. The following sections delineate options within each of these adaptation categories.

## *4.1 Erosion Control*

Sea level rise is a potential threat to roadways at low lying elevations and to roadways where increased wave height and energies can cause erosion and scour on road embankments. Increases wave heights from sea level rise will require an increase of protection of the coast and roadway embankment. When sea level rise is coupled with storm surge we will see an even greater erosive effects and a greater possibility of overtopping. In order to combat the erosive forces associated with the potential increase in sea level rise and storm surge, adaptation strategies can be put into place to improve the resiliency of Gandy Blvd. This section will discuss a variety of possible strategies.

### 4.1.1 Wave Attenuation Devices

Wave attenuation devices (WADs) can be used to protect on shore infrastructure from increasing forces of erosion. WADs reduce the force of waves striking the coast by dissipating energy when waves encounter them. A field experiment was conducted at the Greenshores Coastal Restoration Inc. (CRI)[5] wave-attenuation-device site in Pensacola Florida in order to quantify the wave-height and wave-energy reduction achieved by a wave attenuation devices. Wave height and wave energy measurements were taken from and offshore area and from various locations in the protected near shore area. The field measurements show that WADs are capable of reducing the wave height and wave energy by over 80%. It is important to note that the effectiveness of the WADs is strongly influenced by the design and configuration of the structures. Results of each site reduction in wave height and waver energy can be seen in figure #2.

[5] http://www.livingshorelinesolutions.com/uploads/Wave_Attenuation_Study_2007.pdf

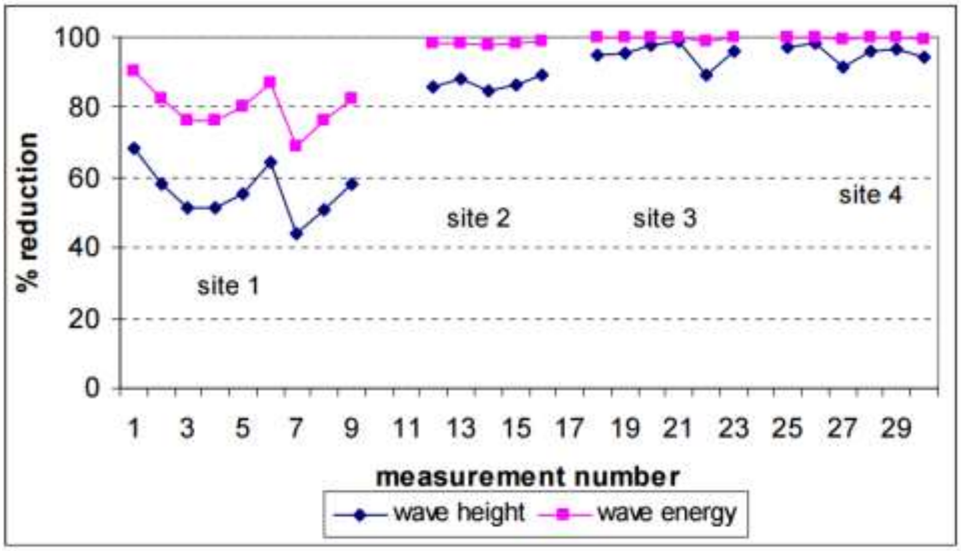


FIGURE 2: SUMMARY OF THE PERCENTAGE OF WAVE HEIGHT AND WAVE ENERGY REDUCTION[6]

For this study one of the 4 sites performed poorly in comparison due to a substantial gap and reflected waves from a seawall. Wave characteristics may also have a significant influence on wave reduction.

There are two main commercial types of WADs. The first type, which was used in the field study, is usually made with concrete and is submerged to the ocean floor and can be seen in figure #3.

FIGURE 3: WAVE ATTENUATION DEVICES[7]

[6] http://www.livingshorelinesolutions.com/uploads/Wave_Attenuation_Study_2007.pdf, Figure 12
[7] http://www.tbo.com/news/business/pyramid-key-to-saving-egmont-key-20140526/

This type of WAD has minimal impact on the live bottom due to its small footprint. They act as an artificial reef and facilitate local fish populations. The second type is a floating WAD. Floating WADs are completely portable and do not require major construction to move.

**FIGURE 4: FLOATING WAVE ATTENUATION DEVICE[8]**

The flexibility provides usefulness for sites that are subject to change. In one case study, a floating Wave Dispersion Technologies, Inc. (WDT)[9] WAD was able to dissipate waves within a marina in Lake Ontario NY by 90%.

The effective use of wave attenuation devices for the Gandy Blvd. project is dependent on the potential increase in wave activity in the more protected, inland area where the project is proposed to be built. As previous studies on wave action in the Tampa Bay region have found, the difference between the outer areas of Tampa Bay and the inner regions is significant in terms of wave impacts[10]. However, sea level rise and the accompanying storm surge could change this dynamic in the future.

#### 4.1.2 Revetments and Sea Walls

Coastal roads can be extremely susceptible to erosion on the seaward side due to increased wave erosion and higher tides. The concept of hardening the seaward side is to provide protection against this increased hydrologic action and specifically to protect the roadbed from direct exposure to the elements. To accomplish this protection, the seaward side of the road embankment will be hardened using a revetment or seawall that is placed along the slope where exposure to water may occur[11].

The distinction between revetments and seawalls is one of functional purpose. Revetments are layers of protection on the top of a sloped surface to protect the underlying soil. Seawalls are walls designed to protect against large wave forces. Seawalls are rigid structures or rubble mound structures specifically designed to withstand large wave forces. Some types of larger seawalls such as the Galveston Seawall

[8] http://www.whisprwave.com/products/wave-attenuators/medium-floating-wave-attenuator/
[9] http://www.whisprwave.com/markets/environmental/wave-protection/

[10] https://tbeptech.org/TBEP_TECH_PUBS/2009/TBEP_03_09_FieldMeasurementsofWaveAction.pdf
[11] FHWA, 2008. Hydraulic Engineering Circular 25

also protect against overtopping. These larger structures are not common in the US because they require extensive marine structural design. Rubble mound seawalls are much more common in the US. Rubble mound seawalls look like revetments, but contain larger stones to withstand larger waves. Thus, the Federal Highway Administration (FHWA) uses the two terms seawall and revetment interchangeably.

For revetments the FHWA recommends a design approach based on determining a design wave and using Hudson's equation to estimate stone size for embankments subject to wave action. The fundamental philosophy is that the revetment will be efficient at absorbing wave energy in that damage is not often catastrophic. Figure #5 shows a typical revetment design cross-section.

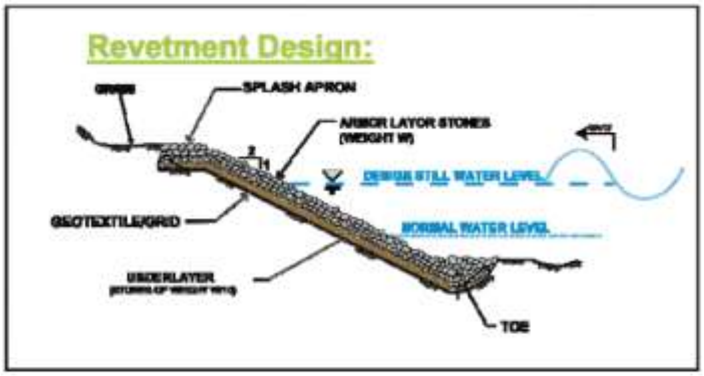


**FIGURE 5: TYPICAL REVETMENT DESIGN CROSS SECTION[12]**

Sea level rise and its impact on sustaining taller waves could present challenges for maintaining the functionality of the roadway or coastal embankments. Therefore, the increase in sea level and wave height should be taken into consideration when designing seawalls and revetments. The current sections of the coast surrounding Gandy Blvd that are already armored with rip rap should be assessed to see if they are appropriately sized for increasing sea level rise and storm velocities.

During a storm surge event, road embankments that are not ordinarily exposed to wave action wave erosion could be due to higher water levels. In order to prevent erosion during these extreme events, this embankment should also be armored according to a revetment design.

[12] FHWA, 2008. Hydraulic Engineering Circular 25

**FIGURE 6: WESTBOUND LANE EMBANKMENT OF GANDY BLVD.**

Figure #6 shows an embankment of the westbound lane of Gandy Blvd. Although the base of this embankment is approximately 7 feet above sea level, under sea level rise and storm surge conditions this slope may be exposed to wave attack. Although the trees will provide some erosion protection, armoring this slope with rip rap or other natural vegetation will help improve the resiliency of the roadway.

### 4.1.3 Vegetation as Erosion Control

Another approach to reducing erosion on the seaward side of a road in scenarios where there is only minor to moderate wave or overtopping actions is to use vegetation as binder on the seaward slopes. Specifically, grassy vegetation and shrubs can be used to combat erosion in slight to moderate conditions. Dune grass and marsh grass have proven to be effective to reduce erosion as well as shrubs appropriate to local conditions[13,14]. Florida has had success with a wide variety of trees and shrubs for erosion control ranging from Live Oak and Buttonwoods to shrubs such as Holly.

However, the most common approach to direct erosion control is seeding with grasses[15]. Grass is effective at covering and protecting soil from wind and water erosion. When seeding grasses it is ideal to use a mixture of creeping and clumping types. Creeping grasses form a continuous root system, or mat. Clumping grasses leave gaps between plants that can be vulnerable to erosion, but grow very deep roots. Seed mixes normally include grasses that germinate quickly, and the optimum seed mic will depend on the soil, site and climatic conditions. To ensure the highest success rate, the surface soil should be scarified and loosened. Grasses can be established by hand seeding, hydro seeding, or with sod.

Another category of grasses that have been used to stabilize structures are deep rooted grasses such as vetiver. Vetiver is a perennial grass that grows in large clumps with a branched and spongy root system. Vetiver has been shown to decrease soil loss by more than 80% compared to stone barriers, other

[13] Western Carolina (2009). Principles of Property Damage Mitigation, Western Carolina University, http://www.wcu.edu/coastalhazards/Libros/, Last reviewed, November 2009.
[14] Williams, M.J. 2007. Native Plants for Coastal Restoration: What, When, and How for Florida. USDA, NRCS, Brooksville Plant Materials Center, Brooksville, FL.
[15] http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_430.pdf

vegetation and bare ground. Vetiver's massive root system generally holds the upper 3-4 meters of soil in place. Vetiver roots have an average tensile strength of 75 MPa, which increase the average strength of the surrounding spoil by 30 to 40%[16]. Furthermore, vetiver grass has not been observed as an invasive species. Vetiver is widely adaptable to adverse growing conditions. It has no major pests or diseases, it is extremely salt tolerant and can grow in many different soil types.

## *4.2 Cost Approach for Coastal Erosion Strategies*

### 4.2.1 Revetments

When determining the appropriate design for the seaward hardening of a road structure, several design guidelines are appropriate. First, the recommended slope of the riprap is important as a slope which is too steep will experience damage from wave action which will result in rocks being removed from the hardening layer. Second, appropriate size armor stones must be used to ensure that the stones are large enough to resist the wave action. And finally, the placement of the riprap must be guided by individuals rather than just dumped by the side of the road to ensure proper interlocking and placement. These guidelines are used to develop the cost approach.

Specifically, the cost of hardening the seaward side of a road is primarily comprised of the cost associated with placing riprap along the seaward side. However, to arrive at an appropriate cost, the recommended design guidelines for the placement are taken into account.

The total cost of riprap is based on the tons of riprap required for a project. Determining this quantity is based on the recommendation that the riprap slope be not more than a 3:1 slope and that the median size of the individual stones in the riprap be 770 pounds[17]. A variable in this analysis is the height of the road above the sea level. Since this will be specific to each case, the DOT recommendation of having at least a 7.5' horizontal run for the slope is used as a baseline. Using this guideline, the actual cost is calculated as follows:

Design height = 7.5' / 3 = 2.5'
Rock weight: 770 pounds
Cost per ton of riprap (RS Means 2008): $40
Weight of rock per cu. Ft. = 150 pounds
Size of design triangle (1 ft wide) = 7.5' * 2.5' * 1' = 18.75 cu. Ft.
Pounds of rock per cu. Ft.: 150 pounds * 18.75 cu. Ft. = 2,812.5 lbs.
Tons of rock per .25 mile: 7,420 tons
Cost of rip rap per .25 mile: $296,775
Cost of geotextile slope protection per .25 mile: $9,920
Total Cost of hardening per .25 mile: $306,695

[16] http://www.vetiver.org/US_California%20Vetiver%20brochure%2009%20v1.pdf

[17] U.S. Department of Transportation. (2003) Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects. Federal Highway Administration Manual. FP-03. U.S. Government Printing Office.

### 4.2.2 Vegetation as Erosion Control

The total cost of vegetation is based on a similar approach to that taken for strengthening the seaward side with riprap. Specifically, the total area of coverage is calculated from the recommended design guidelines for a slope and then the cost of the vegetation is calculated for that area of coverage. Once again, determining this quantity is based on the recommendation that the design slope of the roadside not be more than a 3:1 slope[18]. Since the height of the road is specific to each case, the DOT recommendation of having at least a 7.5' horizontal run for the slope is used as a baseline. Using this guideline, the actual cost can be calculated as follows:

Design height = 7.5' / 3 = 2.5'
Length of slope to cover = 8 Ft. (top to bottom)
Number of rows of vegetation required at 1' intervals: 3
Cost of 3 plants: $3.00 * 3 = $9.00
Total Cost of vegetation per .25 mile installed: $11,871

The variable in this calculation is the specific cost of the vegetation. In the case of Gandy Blvd, several options exist based on experience in Florida including grasses, shrubs, and even trees in some areas. Recent studies have placed installed costs for these different options at $3 per gallon planting for grasses to $5 per gallon for trees[19]. The total cost will then be dependent on amount of coverage required. However, the benefit of vegetation is that it is intended to be self-sustaining in that once it is planted, there should be minimal maintenance cost in the future.

[18] U.S. Department of Transportation. (2003) Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects. Federal Highway Administration Manual. FP-03. U.S. Government Printing Office.

[19] South Florida Coastal Program

## 4.3 Drainage

Sea level rise will effect drainage efficiency in many ways. Lower hydraulic head and higher water tables would reduce natural drainage and storm surges will be higher and may permanently inundate the area. Permanent inundation will render gravity systems useless and will require modifications to prevent seawater from backing up into the system[20]. Increased precipitation may also lead to increases in flood frequencies and therefore will effect drainage systems. Drainage system adaptation strategies should be put into place to expedite flood recovery, and to properly drain larger runoff flows from increased precipitation.

### 4.3.1 Permeable Pavement

Permeable pavements, also referred to as porous pavements, are load-bearing, durable highway surfaces that have an underlying layered structure that temporarily stores water prior to infiltration into soil or drainage to a controlled outlet. The advantage of such a pavement system is that it can help to reduce runoff volume during periods of peak flow and minimize flooding. According to the California Storm Water Quality Association[21], permeable pavements have the following limitations:

- Appropriate only for gentle slopes;
- Can become clogged if improperly installed or maintained; and
- Appropriate only for highways with low traffic volumes, axle loads, and travel speeds (< 30 mph)

Gandy Blvd. does not fall within the limitation of speed limit, however permeable pavements could be an option for the local roads to either side. Limiting the runoff of these surfaces will help to reduce flows into the drainage system for Gandy Blvd. Permeable pavements are up to 25 % cheaper (or at least no more expensive than the traditional forms of pavement construction), when all construction and drainage costs are taken into account[22].

The design elements associated with the construction and maintenance of porous pavements include initial grading, paving, and excavation of up to four feet of soil. Once excavated, a sight well, stone fill, and filter fabric are installed. Finally, the area is seeded and landscaped appropriately. A schematic representation of a porous pavement design, including the major construction elements, is provided below.

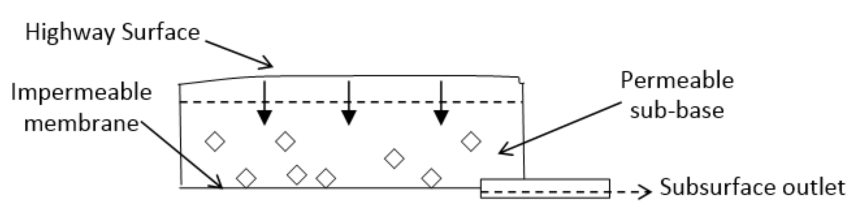


**FIGURE 7: TYPICAL CROSS SECTION OF PERMEABLE PAVEMENT**

The benefit of this form of solution is that permeable pavement will reduce the runoff associated with traditional pavement by allowing greater drainage into the soil. The design lifespan remains the same

[20] Journal of Water Resources Planning and Management, Vol. 113, No. 2., March 1987
[21] https://www.casqa.org/sites/default/files/BMPHandbooks/BMP_NewDevRedev_Section_4.pdf
[22] Niemczynowicz J, Hogland W, 1987.

and typical maintenance remains the same according to existing studies[23]. However, as stated previously, the load capacity of permeable pavements is less than traditional pavements thus making it usable more for side roads than main thoroughfares.

### 4.3.2 Enhance Drainage Structures

Gravity drainage can be enhanced by increasing the size of drainage pipes and inlets. Increasing the size of the pipes or drainage canals will allow the system to drain a greater capacity of water. The number of inlets can also be increased. Inlets should always be located at the low points in the profile. In addition flanking inlets on each side of the low point inlet should be installed to act in relief of the low point inlet when the low point drain gets clogged (common during intense storms) or if the design spread is exceeded[24]. A flanking inlet system can be seen in figure #8.

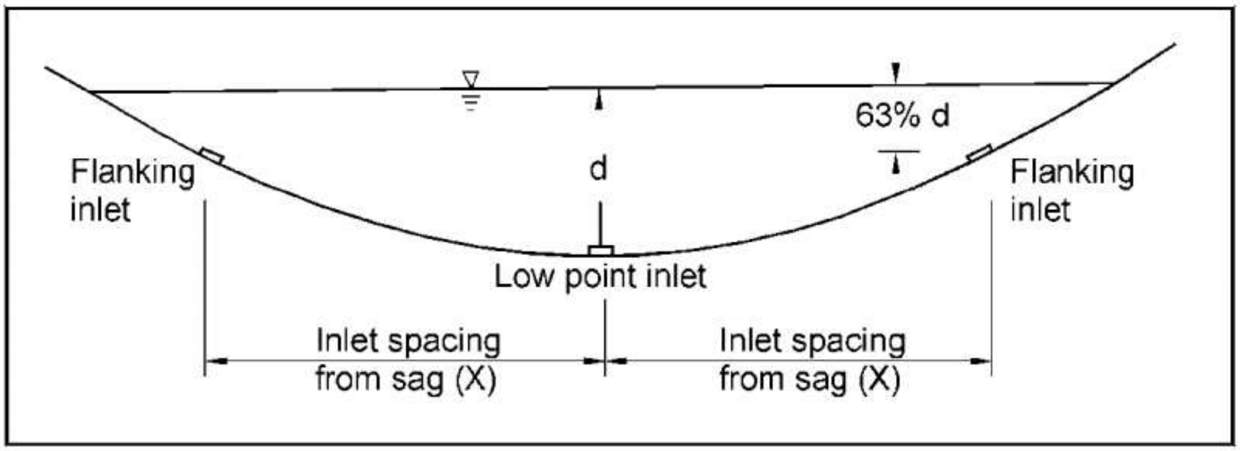


**FIGURE 8: EXAMPLE OF FLANKING INLETS[25]**

This type of system will benefit the roadway under two separate scenarios, increased precipitation and inundation from storm surge. When designing inlets to high volume culvert numerous cross-sectional shapes are available. The most commonly used shapes are circular, pipe-arch and elliptical, box (rectangular), modified box, and arch. Other general drainage design considerations are detailed by the FWHA[26].

Drainage on bridge decks is often less efficient than roadway drainage because slopes are flatter and are easily clogged by debris. Runoff from bridge decks should be collected directly after it flows to the underlying road system. In order to account for this excess water, larger grates and inlet structures should be constructed where the bridge meets the roadway[27].

Another major problem associated with storm water runoff is the stability and durability of the slopes, ditches, and embankments. One identified method for preventing erosion of these earthen structures is to reinforce them with concrete surface treatments. Additionally, during the reinforcement process, the

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[23] Virginia DCR Stormwater Design Specification No 7
http://vwrrc.vt.edu/swc/NonPBMPSpecsMarch11/VASWMBMPSpec7PERMEABLEPAVEMENT.html
[24] FHWA, 2009. Hydraulic Engineering Circular 22
[25] FHWA, 2009. Hydraulic Engineering Circular 22, Figure 4-22.
[26] FHWA, 2009. Hydraulic Engineering Circular 22
[27] Journal of Water Resources Planning and Management, Vol. 113, No. 2., March 1987

ditch capacity can be increased. Such treatment decreases floodwater concentration and promotes flow to designated reservoirs. One should note that ditches are used on many standard highway construction projects as a means to control runoff from the highway surface[28].

Sea level rise is likely to create a higher water table below the road structure. Under this condition the saturation of the sub-base can reach levels that decrease the strength of the aggregate. Impermeable geotextile can be placed between the subbase and the subgrade to avoid such saturation. This should be coupled with a draining layer to let water flow from the subgrade to the lateral drain[29].

[28] Landphair H, McFalls J, Thompson D, 2000.
[29] Climate Change, Energy, Sustainability and Pavements, 2014.

## 4.4 Strengthen and Raise Profile

Sea level rise and storm surges will cause more frequent inundation of Gandy Blvd. This section will detail two of the more direct ways to combat inundation damages. The first is raising the profile of the roadway and the second is strengthening the road to withstand increased flooding forces.

### 4.4.1 Raise Profile

According to the THEA conceptual plans, the elevated connector will run over top of the existing Gandy Blvd. from the Selmon Expressway and begin to decline back to grade approximately .38 miles from the Gandy Blvd Bridge. This will leave approximately .35 miles of Gandy Blvd at grade before the Gandy Blvd. Bridge. The proposed roadway profiles for the eastbound and west bound lane can be seen in figure #9.

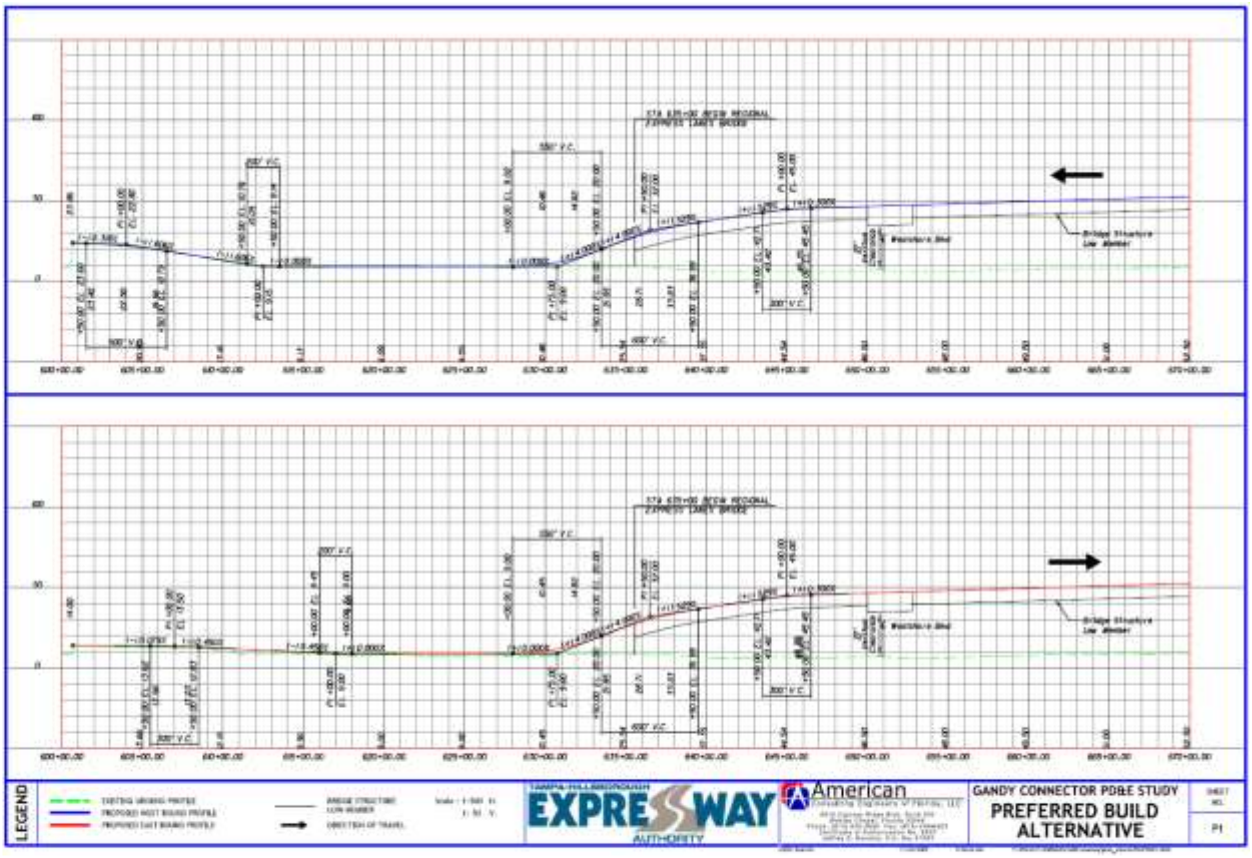


**FIGURE 9: PROPOSED ROAD PROFILE[30]**

Once at grade the westbound lane continues until it eventually rises from grade to an elevated, armored bridge approach, while the eastbound lane reaches the peninsula at grade. According to the plans, the lowest point of the eastbound and westbound lanes are approximately 10 feet above sea level. This section is clearly the most vulnerable to permanent inundation. Raising the profile of these roads using an elevated embankment is one option to alleviate possible inundation. However, the eastbound and westbound lanes have two different limiting elevation assuming that the bridge connectors must be kept at the same elevation. The westbound lane connects with the Gandy Blvd Bridge approximately 24

[30] FTE, 2015

feet above sea level, while the eastbound lane makes landfall at only 14 feet above sea level. Therefore the maximum elevation of the westbound and eastbound lanes are 14 and 4 feet respectively.

In order to analyze the benefits of elevating the roadway, we first have to address the possible storm surge and sea level rise scenarios. All of the possible scenarios analyzed can be seen in table #3.

| Inundation Depth (ft) | | Storm Surge Scenario | | | | | |
|---|---|---|---|---|---|---|---|
| | | Cat. 1-Mean | Cat. 1-High | Cat. 2-Mean | Cat. 2-High | Cat. 3-Mean | Cat. 3-High |
| Sea Level Rise Scenario | Present Day-Low | 4.70 | 5.60 | 9.70 | 10.80 | 14.90 | 15.90 |
| | 2040-Low | 6.37 | 7.27 | 11.37 | 12.47 | 16.57 | 17.57 |
| | 2040-High | 7.20 | 8.10 | 12.20 | 13.30 | 17.40 | 18.40 |
| | 2060-Low | 6.53 | 7.43 | 11.53 | 12.63 | 16.73 | 17.73 |
| | 2060-High | 8.20 | 9.10 | 13.20 | 14.30 | 18.40 | 19.40 |

**TABLE 3: INUNDATION DEPTH FROM SEA LEVEL RISE AND STORM SURGE SCENARIOS**

Based on table # and the FEMA 1% chance flood depth of 9 feet we can begin to see what event the roadway will be vulnerable based on inundation levels and the lowest elevation of the roadway. We can see that if the lowest roadway elevation is 10 feet above sea level, permanent inundation would not occur for any sea level and category 1 storm surge combination. However, we may see overtopping from wave attack if waves are just a few feet in height. For category 2 and 3 storm surges we would see permanent inundation in all but one sea level and storm surge combination if the roadway is 10 feet above sea level.

Based on the limiting elevation of 14 feet for the eastbound lane, both roads could potentially be elevated by 4 feet. This would involve constructing a 4 foot embankment for both lanes to sit on. Furthermore the embankment must be armored with a revetment described in previous sections in order to protect from erosion during storm events. If the roadway is built at 14 feet above sea level it is protected against permanent inundation all category one sea level storm surge and sea level combinations. Furthermore, the roadway would be protected against most category 2 storm surge combinations. Although a 4 foot elevation of the road profile would not protect against a category 3, 4 or 5 storm surge scenario, it would still provide benefits in recovery. When the water levels begin to subside, the elevated road will allow for a quicker recovery effort and allow emergency vehicles to use the roadway again.

Comparing road elevation to categories of storm surge is helpful to understand the level to which the roadway is protected against varying levels of storms. However it is also important to understand how often storm surges will happen. For this we can compare the road elevation to the design peak storm surge heights. Table #4 shows the peak design storm surge heights recommended by the Florida Department of Transportation for Tampa Bay[31].

[31] http://www.dot.state.fl.us/rddesign/Drainage/FCHC/Storm-Surge-Hydrographs-Report.pdf

| | Peak Storm Surge Height |
|---|---|
| 50-Year | 11.00 |
| 100-Year | 12.30 |
| 500-Year | 15.00 |

**TABLE 4: PEAK DESIGN STORM SURGE HEIGHT**

For all sea level and design storm combinations a roadway at 10 feet above sea level would sustain a period of permanent inundation. However, when raising the profile to 14 feet above sea level we avoid permanent inundation for varying design storm and sea level rise combinations. These results are summarized in table # 5.

| Permanent Inundation (14 ft) | | Sea Level Rise Scenario | | | | |
|---|---|---|---|---|---|---|
| | | Present Day | 2040-Low | 2040-High | 2060-Low | 2060-High |
| Design Storm | 50-Year | No | No | No | No | Yes |
| | 100-Year | No | No | Yes | Yes | Yes |
| | 500-Year | Yes | Yes | Yes | Yes | Yes |

**TABLE 5: PERMANENT INUNDATION PROFILE**

Avoiding permanent inundation is extremely valuable for multiple reasons. If the roadway is clear of water, this will allow for emergency vehicles to continue to use the roadway as needed. Furthermore, overtopping can cause significant stresses on the roadway due to weir flow. Furthermore the recovery process is expedited when the road is elevated. Figure #10 shows a time series of surge height for each design storm under present day sea level conditions.

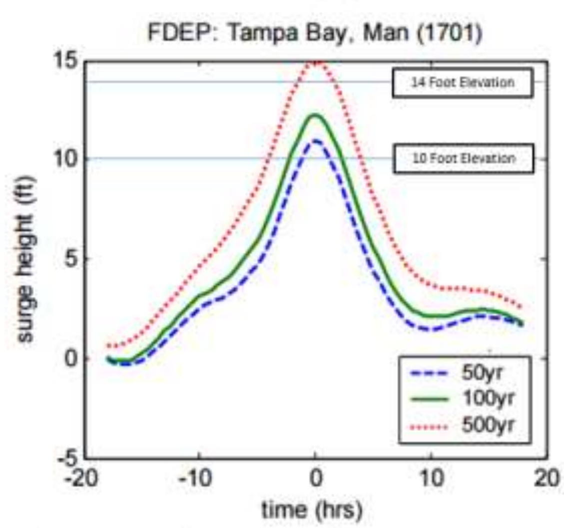


**FIGURE 10: TIME SERIES HYDROGRAPH FOR TAMPA BAY DESIGN STORM SURGE[32]**

[32] http://www.dot.state.fl.us/rddesign/Drainage/FCHC/Storm-Surge-Hydrographs-Report.pdf. Figure IV-27.

Figure #10 shows the time of permanent inundation for each of the road profiles. A 500 year surge height leaves the 10 foot road and 14 foot road permanently inundated for 9 hours and 2 hours respectively. A 100 year surge height leaves the 10 foot road and 14 foot road permanently inundated for 4 hours and 0 hours respectively. A 50 year surge height leaves the 10 foot road and 14 foot road permanently inundated for 2 hours and 0 hours respectively. This illustrates that the raised road profile will decrease the time of inundation significantly, which will allow emergency vehicles to use the roadway once again.

Another option in raising the profile of the road is to only raise the westbound lane to a higher elevation. Only raising the westbound lane would provide economic benefits and still allow the roadway to be utilized in emergency situations. Evacuation traffic or emergency vehicles could still use the raised lane in a storm event in one or both directions, while the lower eastbound lane would remain closed due to inundation. As previously discussed, the westbound lane has a higher limiting elevation and can therefore be raised to a higher elevation. By raising the elevation of the westbound lane to an elevation of 15 feet, 20 feet or 24 feet, inundation could be avoided for a much larger storm surge event. Furthermore, emergency vehicles could use both lanes of the westbound lane to travel east or west. Raising the profile of the road to a higher elevation also provides some additional challenges in embankment construction and protection. The higher elevation would also provide a challenge when connecting Gandy Blvd to the local road on the north side of Gandy Blvd.

It is also important to note that the elevation profile of the route that emergency vehicles will take should be analyzed so that we can verify a limiting elevation. If any elevation under 14 feet exists on the on this route then some benefits of raising the profile on this section are lost until these elevation are also raised.

#### 4.4.2 Bridge Pier and Abutment Protection

The combination of sea level rise and potentially more intense storm surges enhance the threat of potentially damaging coastal bridges. These forces can caused three different modes of failure: (1) the superstructure is uplifted by waves and washes away, (2) the substructure gets uprooted from vertical forces acting on the superstructure, or waves create lateral forces that cause failure, and (3) the substructure fails due to excessive scour[33]. The first two modes of failure generally act on the bridge span, which is not included in the scope of this work, so no further details are provided.

Scour is one of the main failure mechanisms of a bridge pier or abutment. The raising of the Gandy Blvd. profile includes a component of bridge design that introduces the potential of scour for the project. The peak velocities of the storm surge that will cause the most damaging scour will occur during the flood surge and later during the ebb surge[34]. In order to protect the bridge pier or abutment from scour, protection must be put into place. Protection component such as rip rap, bulkheads, and willow mattresses will help to prevent erosion of soil and undermining of the bridge structure.

Determining the appropriate protection for the bridge piers is dependent on the velocity of the water that is determined for the ebb and flow during the storm surge events. The velocities identified to move sand and non-sand particles provide the basis for determining when bridges need to be strengthened. Specifically, if the velocity of the water is fast enough to move particles, then the potential exists for scour

[33] FHWA, 2014, Hydraulic Engineering Circular 25 – volume 2.
[34] FHWA, 2014, Hydraulic Engineering Circular 25 – volume 2.

to occur around the foundation. Therefore, given the establishment of a minimum velocity where strengthening needs to be considered, the next step in the process is to determine what levels of velocity could be absorbed by specific types of strengthening procedures. Once again, the FHWA provides guidance in this matter by establishing the use of riprap as the preferred initial countermeasure against scour (FHWA 2001). In this process, large rocks are placed at the base of bridge piers to protect the foundation footings and piers from the direct impact of water flow (Garcia 2006). The rocks create a diversion around the foundation and protect the bridge from critical scour forces. This recommendation and process are incorporated by the team as the initial countermeasure recommended for increased water flows.

Although riprap provides a strong countermeasure to scour, it is limited in terms of the maximum velocity it can withstand. When flow velocities become too high, there is concern that the riprap will fail and the bridge will once again be subject to scour. When velocities are determined to be above the maximum for the use of riprap, bridge piers need to be strengthened through the use of additional concrete strengthening around the footings.

Once again, the use of additional concrete follows established design guidelines set forth by governing agencies. This process requires the bridge footings to be partially excavated and a new application of concrete to be applied around the footing based on the load that the footing must absorb. This countermeasure will then be sufficient to absorb the increase in flows from climate change.

The east side of the Gandy Blvd. Bridge is already armored with rip rap and a shallow bulkhead. In order to prevent future failure due to scour, the current site should be re-analyzed using future sea level and wave projection scenarios.

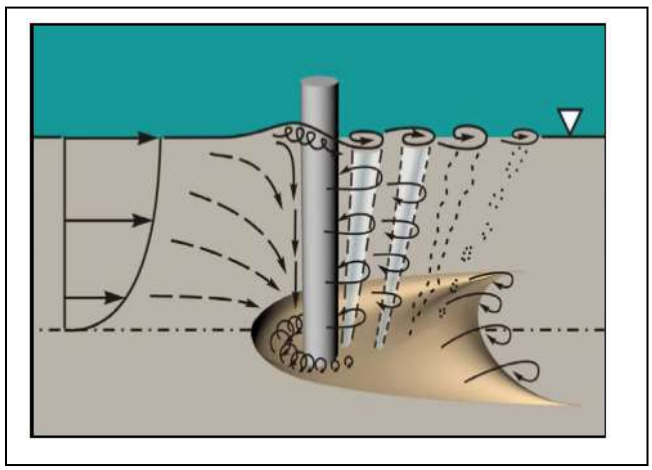

**FIGURE 11 SCOUR MECHANISMS EXAMPLE FROM FHWA HYDRAULIC ENGINEERING CIRCULAR 18**

### 4.4.3 Road Surface

A simple adaptation strategy that can be implemented is the use of rigid pavement over flexible pavements. Rigid pavements are more capable of withstanding erosive flows of water and are not structurally dependent on the sub-grade. Increased flooding and precipitation could cause more deformations in the subgrade which are transferred to the upper layer of flexible pavements and cause surfaces distresses[35]. For rigid pavements, the deformation is not transferred to the subsequent layers and will therefore be more resilient to increase saturation. Overall the strength of the rigid pavements is less dependent on the strength of the subgrade, which limits failures under increased saturated conditions.

[35] AASHTO, 1993.

Although rigid pavements have a higher cost up front, the maintenance frequency and cost is lower. For this particular site, which is less than a half mile, the disadvantage of higher upfront cost would be limited. It also important to note that the use of reinforced concrete in the marine environment typically requires additional engineering considerations[36].

### 4.4.4 Armored Shoulders

There are several ways in which overtopping damages pavements[37]. One is direct wave attack on the seaward side of the road. A second is parallel flow of water to lower spots in the road as a storm surge recedes. The final mechanism is weir flow. Under weir flow conditions the road embankment acts like a broad crested weir to the incoming storm surge. As the surge exceeds the elevation water flows across the road and down the landward side at super critical flows. The super critical flows scour the shoulder material and can create devastating damages. Damages can occur with and without tail water. Figure #11 illustrates weir flow damage.

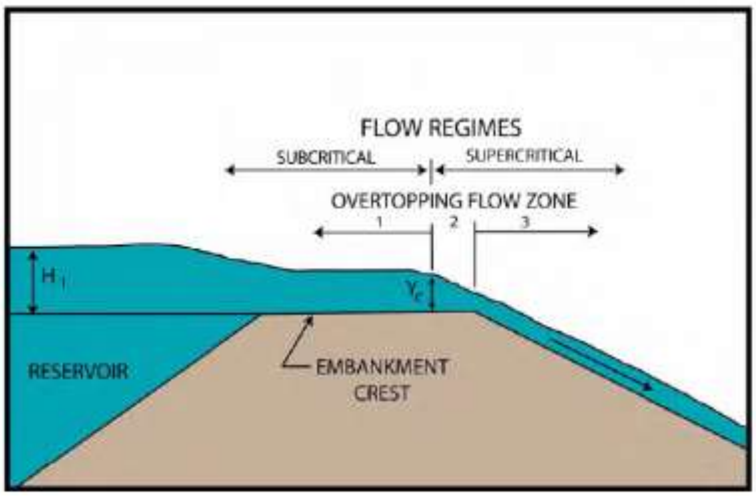


**FIGURE 12: WEIR FLOW LEADING TO FAILURE OF EMBANKMENT[38]**

Roads that experience overtopping can be armored to withstand high velocity flows. The armoring include sheet piling and gabions. The sheet piling should be located on the shoulder where supercritical flows are most likely to occur. Buried gabions are used when overtopping flow may be lower but parallel to the road during a storm event. A concrete revetment system is another option to reduce erosion from overtopping. The system should be comprised of heavy blocks, vertical and horizontal interlocking cables and anchors to resist hydraulic forces from overtopping. Capabilities of interlocking blocks have been confirmed in laboratory tests[39].

[36] Sosa et al, 2011.
[37] FHWA, 2008.
[38] FHWA, 2008. Figure 8.4
[39] FHWA, 2008.

## 5.0 Time Series Analysis

A major decision for adaptation strategies is when they should be implemented. Looking at the general trends of climate stressors can help identify when certain strategies will be needed. This particular study focuses on flooding so the trends for precipitation and sea level rise were analyzed. Storm surge data is adjusted with sea level rise so it will show a similar trend. Figures #12 and #13 summarize the climate stressor trends. Precipitation data was compiled using the Infrastructure Planning Support System (IPSS). IPSS uses 42 IPCC approved CMIP5 climate models for the climate projections and historic Princeton climate data for the historic scenario. Low, intermediate and high scenarios were chosen based on the 5%, median and 95% model respectively from the 42 initial models.

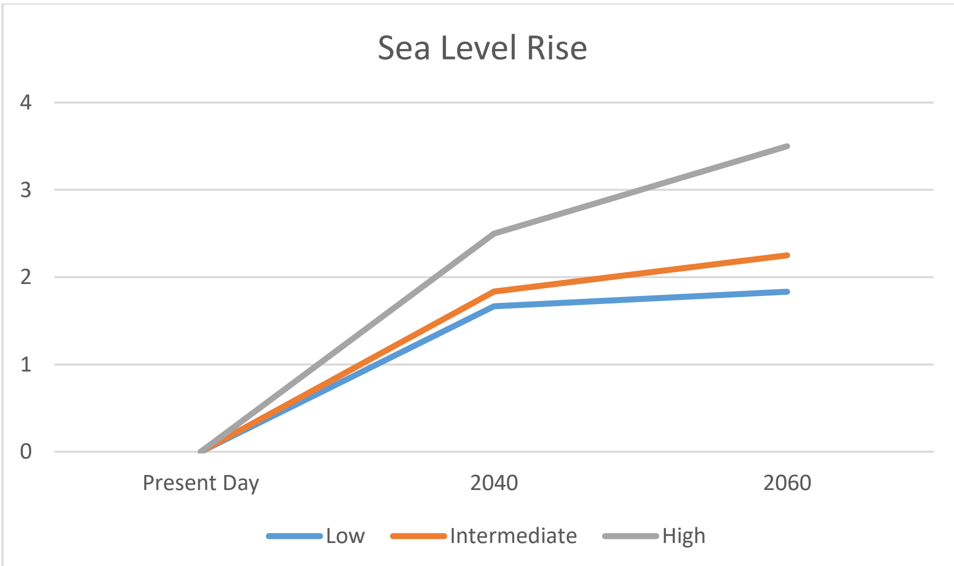


**FIGURE 13: SEA LEVEL RISE TREND**

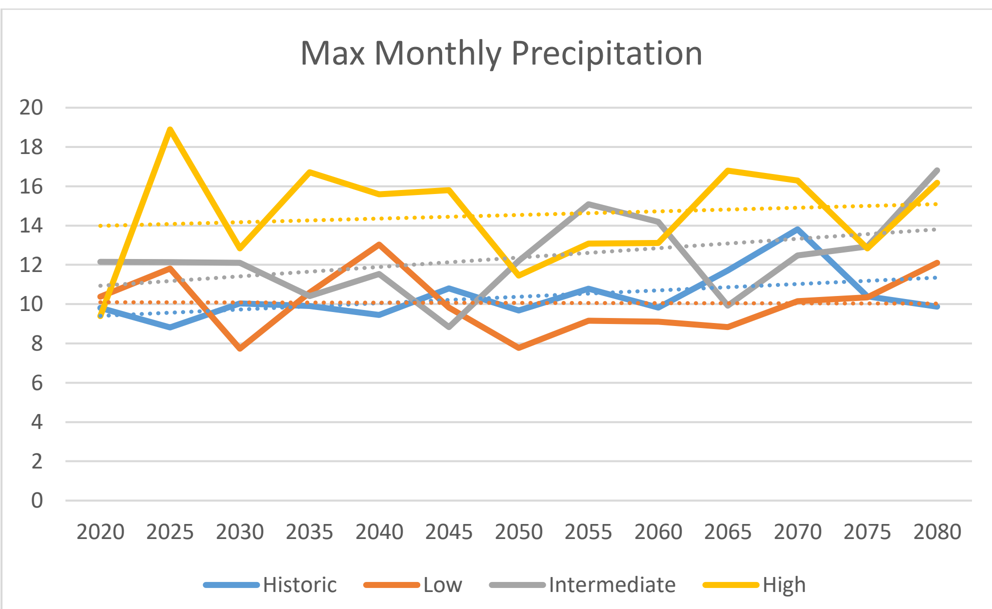


**FIGURE 14: MAXIMUM MONTHLY PRECIPITATION**

The sea level rise trends are very clear. Levels will increase 1.5-2.5 feet by 2040 and 2-3.5 feet by 2060. The precipitation trends are not as clear. The intermediate and high scenario predict that there will be an increase is maximum monthly precipitation compared to historic data. However, the low scenario predicts a decrease. Overall based on the models we can predict that maximum monthly precipitation will increase. The result of this increase is that pavement surfaces and drainage adaptations should be considered as a priority together with the protection from sea level rise and storm surge. Additionally, this increase has an impact on the timing of the adaptation consideration.

Adaptation strategies can be implemented in congruence with planned construction in order to save time and money. The planned elevated connector for this project has a huge influence on the recommended times for implementing many of the adaptation strategies.

Based on climate stressor trends and planned construction projects a recommended time for implementation was chosen for each strategy. A summary of this and each adaptation strategy can be seen in table #6. Near term represents an investment before 2020 which is warranted based on near-term sea level rise predictions together with precipitation projections. Long term represents an investment after 2040 where the climate indicators show that it is appropriate to delay actions. Finally, the congruent actions are adaptations that may make the most sense to implement while constructing the new Gandy Blvd. connector.

| Adaptation Option | Mitigation Effect | Recommended Time of Implementation |
|---|---|---|
| Wave Attenuation Device | Protects against increasing forces of erosion by reducing wave height and energy | Long Term |
| Coastal Revetment | Harden coast and embankment to protect from increasing forces of erosion | Near Term/ Long Term |
| Vegetation as Erosion Control | Reduce erosion of road to minor to moderate wave actions | Near Term |
| Permeable Pavement | Reduce flows into drainage system by limiting runoff of local roads | Congruent with Elevated Connector |
| Enhance Drainage System | Increase capacity and resilience of system to limit damage and increase flood recovery time | Near Term |
| Raise Profile | Prevent or lessen overtopping and permanent inundation | Congruent with Elevated Connector |
| Rigid Pavement | Increases resilience of road surface to erosive flows and subgrade failure | Congruent with Elevated Connector |
| Armored Shoulders | Protects against overtopping damages | Congruent with Elevated Connector |

**TABLE 6: ADAPTATION STRATEGY SUMMARY**

WADs and Coastal Revetments are recommended to be implemented in the long term. Sea level rise is a slow process and will not have dramatic effects on coastal erosion for quite some time. In general the roadway is not very vulnerable to coastal erosion at present day sea levels. The specific stretch of Gandy Blvd. lies 120-300 feet from the coast. As sea levels begin to rise the coast will move closer to the roadway and WADs and revetments may have to be implemented. Erosion of the roadway embankment is still a concern during a storm event. Vegetation as erosion control of the roadway embankment is an easy and cost effective adaptation that can be implemented in the near term. The bridge abutment is vulnerable to storm surge and this vulnerability will increase with rising sea levels. It is recommended that the current site should be re-analyzed using future sea level and wave projection scenarios.

According to the National Oceanic and Atmospheric Administration[40], the frequency and duration of extreme flood events is increasing in the Gulf. Furthermore climate models are predicting an increase in precipitation events in the Tampa Bay area. This makes enhancing the drainage system a top priority and a near term investment. Depending on the construction time of the elevated connector plans, the drainage system could be congruent.

The four remaining adaptation strategies are recommended to be implemented in congruence with the planned elevated connector. The local roads may have to be relocated due to the elevated connector, therefore adapting the local roads to be permeable pavement should wait until the connector construction. Raising the profile of the road will have an effect on the elevated connector, therefore this too should be implemented before for during the elevated connector construction. Raising the profile of the road is recommended to lessen the frequency of permanent inundation and increase recovery time. We recommend the road profile for both lanes be raised to 14 feet above sea level. If raising the profile of both lanes proves to be too costly then we recommend that only the west bound lane be raised. Furthermore the revetment protecting the raised embankment must be designed to withstand storm surge flow forces in order to limit failure. Armored shoulders and embankments are extremely important in protecting the roadway from flood flows. If the road profile is raised, then this strategy should be implemented during construction. If the profile is raised, rigid pavement should also be implemented during the construction process in order to save time and money. However, if the road profile is not raised, then it is recommended that rigid pavement be a long term investment or an investment at the end of the roads life.

[40] http://tidesandcurrents.noaa.gov/publications/NOAA_Technical_Report_NOS_COOPS_073.pdf