

Flood risk management study for Fort Lauderdale and Hollywood,  
Broward County, FL

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# **RMS COASTAL STORM SURGE RISK ASSESSMENT**

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SEPTEMBER 17, 2018



# EXECUTIVE SUMMARY

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Broward County is exposed to flooding from a variety of sources. These range from frequent, comparatively low impact events such as 'sunny day flooding' caused by extreme high tides to large-scale storm surges, which occur infrequently but can have a catastrophic impact on the County, its residents, businesses, infrastructure and ecosystems.

Recent events have particularly highlighted the potential of large storms to cause significant damages, both in terms of financial losses and impacts to communities and business. For Hurricane Irma, which made landfall in Florida on September 10, 2017 as a category 4 storm on the Saffir-Simpson scale, losses to insurable properties in the U.S. are estimated to be as high as \$50bn.<sup>1</sup> Several weeks earlier, Hurricane Harvey had made landfall in Texas, causing losses of up to \$90bn.<sup>2</sup> These estimates only account for damages to building structures and contents, as well as interruptions caused to local business, and can be expected to be further exacerbated by additional losses arising from emergency response activities, damages to infrastructure and wider impacts to local economies.

The County's flood risk can be expected to further increase over the coming decades due to rising sea levels and global temperatures. This applies across key sources severities of flooding and is therefore a critical challenge the County faces. Based on median projections by the Intergovernmental Panel on Climate Change (IPCC) sea levels along the coast of Broward County will rise by 2.6ft until the end of the century, with other projections suggesting even larger rises.<sup>3</sup> These changes significantly increase the risk from flooding due to both high tides and storm surges, in particular across lower-lying areas of the County. In addition, rises in global temperatures could lead to higher frequencies of tropical storms, and therefore the risk posed by severe storm surge events.

Based on the RMS analysis presented in this report, the County currently has a 2% probability of experiencing losses in excess of \$3.9m due to coastal storm surge events alone, on an annual basis. These losses consider damages to building structures and contents, as well as interruptions to local business, but can be expected to be further exacerbated once additional sources of loss, such as damaged infrastructure or emergency response activities, are accounted for. The losses also reflect the relative elevation profiles of the geographical area subjected to a certain surge level with higher areas generally taking lower losses than the lower areas. All elevations values are in terms of height, in feet, above '0 feet' as determined by the North American Datum of 1988 (NAVD88). The study area in Broward County varies, with Fort Lauderdale generally exhibiting a higher elevation profile (10ft-3ft) and Hollywood exhibiting a lower elevation profile (7ft-3ft) (see Appendix 2 for more information on elevation in the region). Average sea level in NAVD88 was a -0.76ft<sup>4</sup> which increases the natural defenses marginally, however the maximum tide was 1.47ft<sup>4</sup> (no hurricanes or tropical storms occurred in the region during the period these calculations were performed). More importantly, the analysis shows that the economic impact of flooding dramatically increases once the impact of rising sea levels is considered. Assuming a sea level rise of 3ft, the corresponding loss from storm surge events rises from \$3.9m to \$574.5m, a nearly 150-fold increase.

In order to address this rapidly rising risk posed by flooding, Broward County requires a holistic flood risk management approach. This approach has to be able to efficiently identify and prioritize mitigation measures which

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<sup>1</sup> Source: RMS; <https://www.rms.com/newsroom/press-releases/press-detail/2017-09-20/rms-estimates-hurricane-irma-insured-losses-from-wind-storm-surge-and-inland-flood-damage-will-be-between-usd-35-and-55-billion> (accessed Jan 12, 2018)

<sup>2</sup> Source: RMS; <https://www.rms.com/newsroom/press-releases/press-detail/2017-09-09/rms-estimates-hurricane-harvey-insured-losses-from-wind-storm-surge-and-inland-flood-damage-will-be-between-usd-25-and-35-billion> (accessed Jan 12, 2018)

<sup>3</sup> Source: <http://www.southeastfloridaclimatecompact.org/wp-content/uploads/2015/10/2015-Compact-Unified-Sea-Level-Rise-Projection.pdf> (accessed Nov 17, 2017)

<sup>4</sup> Source: NOAA; The mean sea level and maximum tide were measured at station South Port Everglades, FL (Station ID: 8722956) averaged over 2018 from January 30, 2018 through August 9, 2018.

provide effective protection to the County and its residents not only today, but also under future sea levels. This study aims to provide a framework to inform such identification and prioritization using state-of-the-art modeling techniques. The approach is illustrated for a mitigation measure the County is currently exploring: the upgrade of seawalls in two key cities in the County, Fort Lauderdale and Hollywood. Specifically, it explores which top elevations are required under this upgrade to ensure effective protection for the two cities under both current and future sea levels. The 'effectiveness' of various top elevation requirements is quantified by the extent to which each elevation is able to reduce the economic (financial) impact of flooding.

The results suggest that upgrading seawalls to a minimum 6ft standard would currently provide effective protection against both frequent, low impact flooding as well as large-scale storm events of up to 0.002% probability<sup>5</sup>. Under current sea levels, a 6ft top elevation could reduce the economic impact of flooding up to 40% compared to the impact which can be expected if no upgrades are implemented. However, the effectiveness of protection – i.e. reduction in economic losses – the 6ft standard provides rapidly decreases once rising sea levels are accounted for in the analysis. Under sea level rise scenarios of 2ft or greater, this standard fails to provide effective protection against even small storm surge events. Increasing the top elevations to 8ft does, however, continue to show significant reductions in losses from flooding even under the most severe (3ft) sea level rise scenario considered in the analysis, and is therefore able to provide effective protection under both current and future sea levels.

Ultimately not only reductions in economic impact, but also economic, environmental and social aspects will need to be considered in the development of a holistic flood risk management strategy. Nevertheless, the ability of different flood risk mitigation measures to effectively reduce the economic impact of flooding will remain a key consideration in the development. This study shows that this economic impact can be objectively quantified and compared, that rising sea levels can – and have to – be considered in the analysis, and that the results provide actionable insights to inform a flood risk management strategy which effectively protects the County both today and over coming decades

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<sup>5</sup> A presence of 6ft seawall means a surge height up to the top elevation of the seawall at selected locations will be blocked. Such a seawall can be seen to be effective at Fort Lauderdale- Islands(North), Hollywood- North lake and South lake for a return period up to 500 years events, assuming no rise in sea level.

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# 1. INTRODUCTION

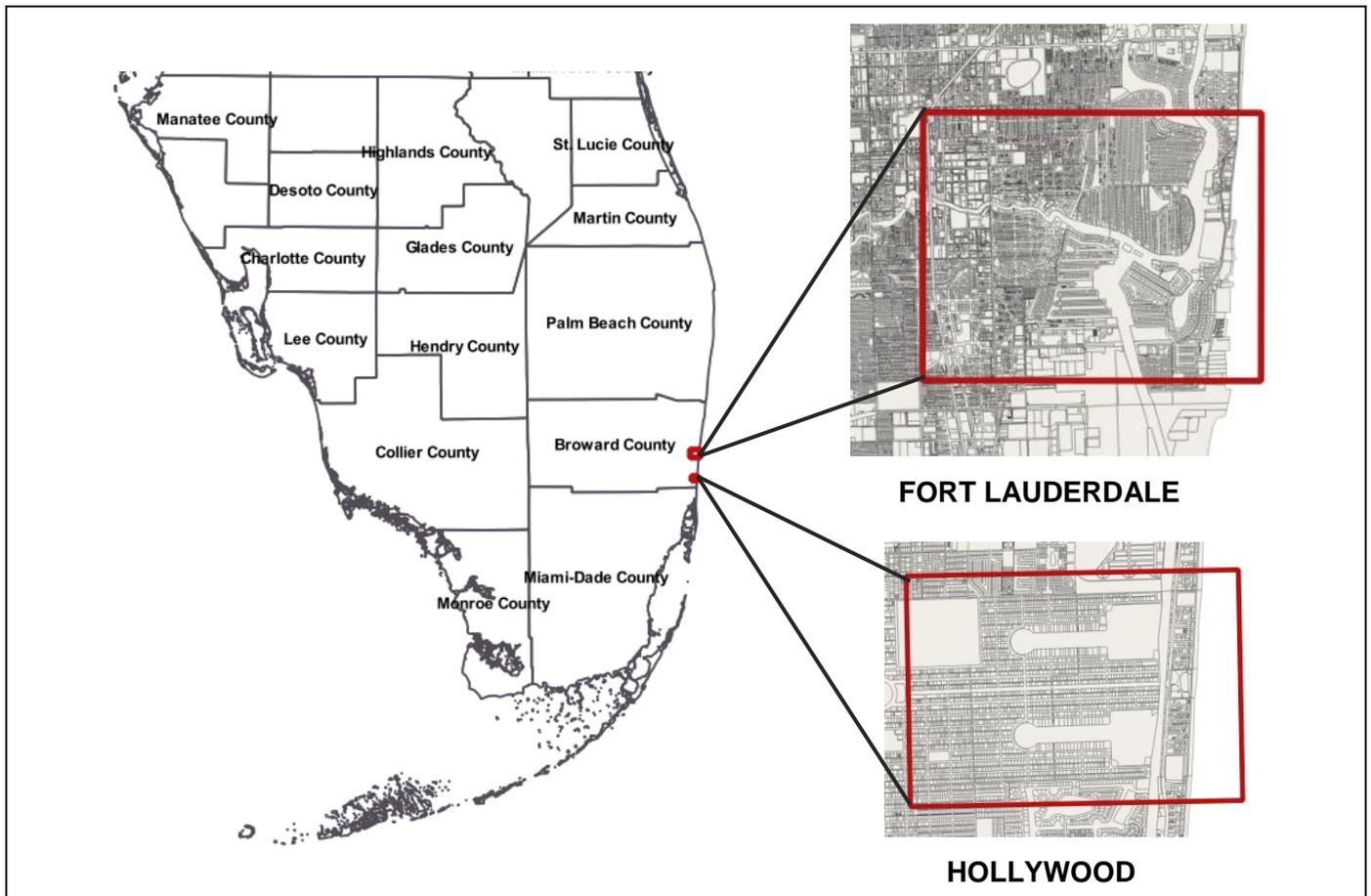
This report is in support of a coastal flood risk assessment conducted as part of the Planning Assistance to States (PAS) program administered by the United States Army Corps of Engineers (USACE). The assessment focuses on two key areas within Broward County, Florida: Hollywood Lakes area in the City of Hollywood and the Las Olas area in the City of Fort Lauderdale.

The study aims to inform the top elevation of potential seawall upgrades the county is considering in these two areas, taking into account both their flood risk today and under a range of sea level rise scenarios which could arise over the coming decades.

The RMS support of this study, as contained in this report, complements the assessment conducted by the USACE through two key additions:

- An independent assessment of the storm surge risk from hurricane events in the study area
- A quantification of the economic impact of flooding events, based on both on the independent storm surge analysis conducted by RMS

The following report provides an overview of the RMS modeling framework and key assumptions used for the project analysis, followed by a detailed account of the analysis results. Finally, the report concludes with recommendations for refinements and extensions to the analysis which could be considered in future assessments.



**FIGURE 1: AREAS OF BROWARD COUNTY CONSIDERED IN THE ANALYSIS**

## 2. RMS MODELING APPROACH

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### **The RMS Modeling Framework**

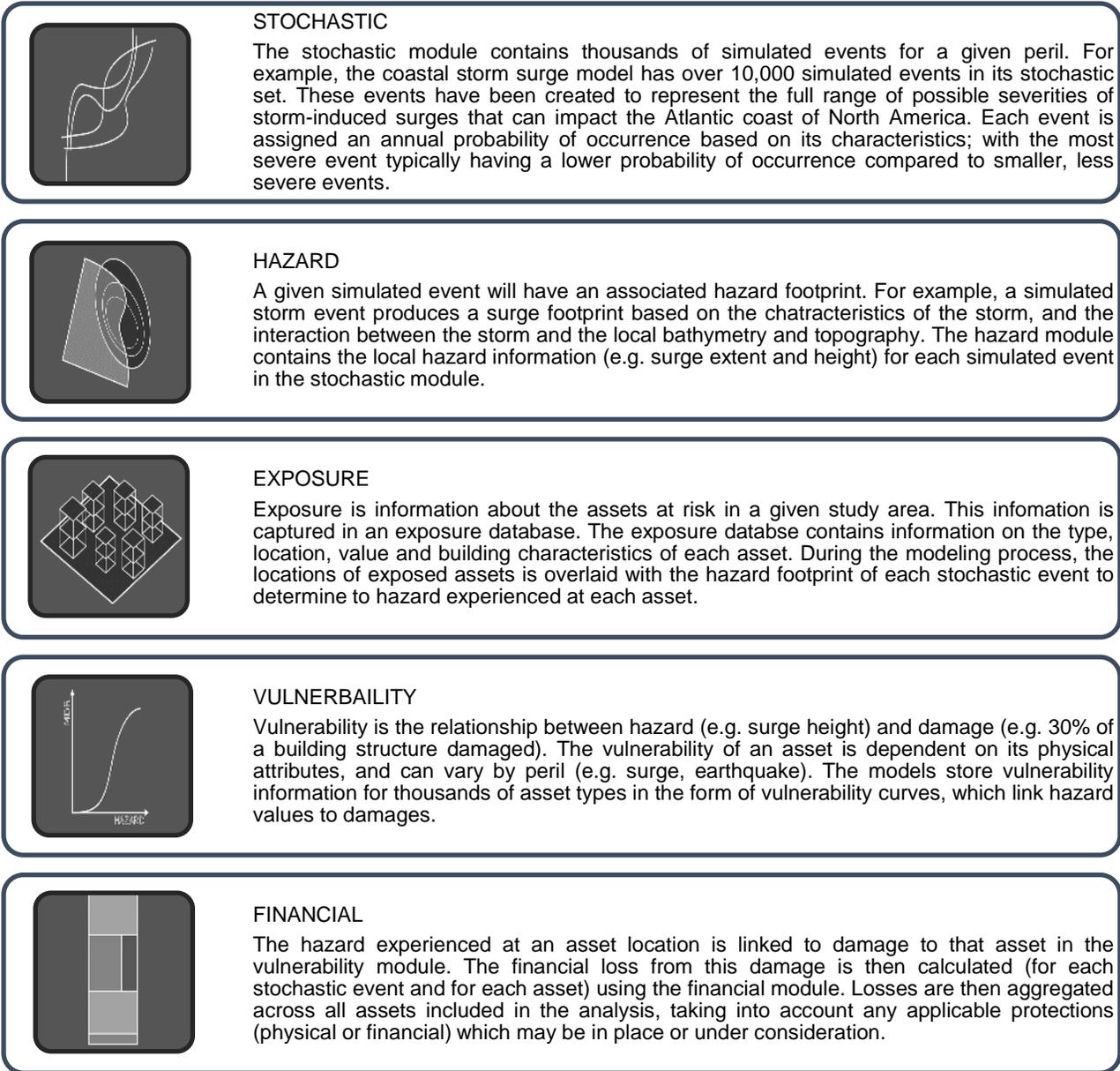
RMS catastrophe risk models are used by governments, financial institutions and their corporate clients globally to quantify and manage their exposure to extreme events. The modeling framework used by all RMS catastrophe models, including the coastal storm surge model used for the analysis presented in this report, consists of five key modules, which are detailed in Figure 2 below.

Particularly key to the modeling framework is the stochastic event set, which distinguishes the catastrophe modeling approach from scenario-based analyses frequently used for engineering studies. This event set has been developed to expand the historical record of coastal storm surges (or other perils under consideration) to a set of events which is representative not only of the type of events which have happened in the past, but also additional events which could occur in the future. The availability of an event set consisting of several thousand individual storms – and their associated surge footprints and expected rates of occurrence – allows for a holistic assessment of hurricane risk. In particular, it eliminates dependencies on single event scenarios, such as historical events specific ‘design scenarios’. While single scenarios are an extremely helpful tool to illustrate the risk faced by a stakeholder based on tangible examples, they are typically unable to capture the full range of potential impacts this stakeholder could face.

Large set of simulated events, such as the event set underlying the RMS model, have been designed to address this problem and to capture the full range of potential impacts the peril under consideration can cause. As each event is associated with an annual rate of occurrence the model also enables users to extract the probability with which any given level of impact can be expected to occur. An analysis based on a large simulated set of events is therefore frequently referred to as a ‘probabilistic’ analysis; whereas analysis based on single scenarios are referred to as ‘deterministic’.

Using only the stochastic module (i.e. the simulated event set) and the hazard module (i.e. the hazard footprint associated with each event), catastrophe models can be used to deliver insights into how frequently a location is to be impacted by different hazard levels. For example, it can be used to determine how frequently a given location can be expected to be impacted by flooding in excess of 6ft, or other thresholds of interest. These insights can then be used to inform decisions such as top elevations for new seawalls, or road elevation standards for new infrastructure developments.

When used in combination with the exposure, vulnerability and financial module, the model can additionally assess the frequency and severity of the economic impact caused a specific peril, such as flooding. This impact is quantified by overlaying the location, vulnerability and financial value of exposed assets with the hazard footprints of each simulated event.



**FIGURE 2: CATASTROPHE RISK MODEL COMPONENTS**

## The RMS Storm Surge Model

The general modeling framework described in the previous section is common to all RMS catastrophe models. The specific model used for the analyses presented in this report is the RMS North Atlantic Hurricane Model version 17.0. This model has last been updated in 2017 and provides an up-to-date view of hurricane risk from both wind and hurricane-induced storm surge along the Atlantic coast of the United States.

The model provides a long-term view of hurricane risk based on the most recently available research, science, and data; most notably the National Oceanic and Atmospheric Administration (NOAA) North Atlantic hurricane database (HURDAT), which contains historical landfall and intensity data through the 2014 season.<sup>6</sup> The model has been validated by over 20,000 storm observations, and extensively reviewed by leading, external, third-party researchers.

For the purposes of this project, only the storm surge risk posed by hurricane events has been considered; no consideration has been given to the impact caused by the hurricane winds.

Using high-resolution coastal data, the surge model simulates surge build up at sea, accounting for changes in a storm's size and intensity prior to landfall, and the dynamic flow of water around coastlines. Utilizing the modeling technology of MIKE21 by the DHI group, the model is fully hydrodynamic, meaning that wind and surge characteristics, tidal state, bathymetry, and onshore topography are tracked throughout the storm's entire lifecycle, not just at landfall. This comprehensive model solution simulates surge build-up at sea, accounting for changes in a storm's size and intensity prior to landfall, and the dynamic flow of water around complex coastlines.

It should be noted that the model, and therefore all results presented in this report exclusively considers the flooding risk due to hurricane-induced coastal storm surge. In particular, it does not consider any rainfall-induced flooding, or flooding caused solely by extreme tidal conditions such as king tides.<sup>7</sup> This distinction is due to fact that the model has been developed to focus on the most severe ('catastrophic') flooding scenarios, which have a low probability of occurring, but have the largest impact on communities when they do occur. These catastrophic flooding events are almost exclusively caused by hurricane-induced coastal storm surges; whereas flooding induced by heavy rainfall or extreme tides are typically the source of more frequent, but less severe flooding. The RMS results are therefore expected to complement the independent analysis conducted by USACE around the risk posed by more frequent, less severe flooding caused by rainfall and extreme tidal conditions, enabling the County to build a complete view of flood risk across all broad range of frequencies and severities.

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<sup>6</sup> It does, therefore not considers storms throughout the 2015-2017 season, including hurricanes Harvey, Irma and Maria in 2017.

<sup>7</sup> The model does, however, consider that coastal storm surge events can coincide with different (including extreme) tidal conditions, and that their impact can vary accordingly.

### 3. RMS STORM SURGE HAZARD ANALYSIS

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RMS analyzed the storm surge height which can be expected in the study area for three different alternatives:

- A base analysis, based on the default elevation assumptions in the RMS model and without explicitly accounting for the presence of seawalls
- An analysis which reflects existing seawalls, as well as potential seawall upgrades the County is considering
- Each of the above in combination with sea level rise of 1ft, 2ft and 3ft

Table 1 shows how the chosen sea level rise scenarios of 1-3ft compare to frequently referenced projections by the Intergovernmental Panel on Climate Change (IPCC), the U.S. Army Corps of Engineers (USACE) and the National Oceanic and Atmospheric Administration (NOAA).

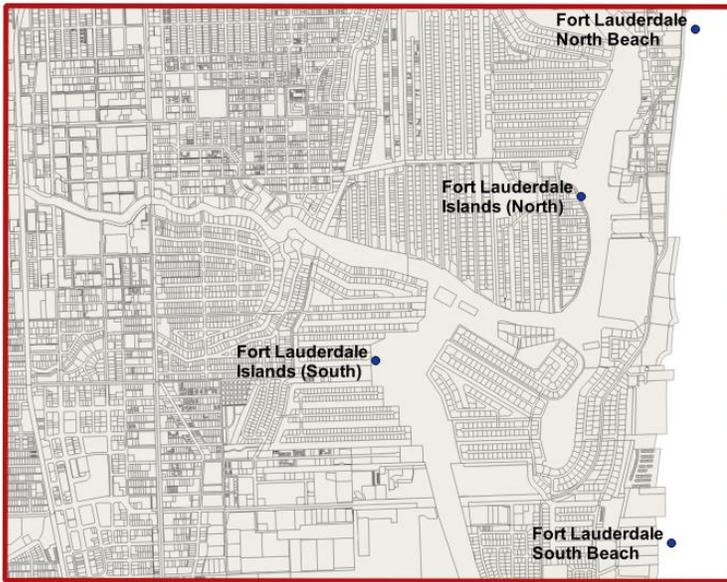
Year	IPCC AR5 Median (ft)	USACE High (ft)	NOAA High (ft)
2030	0.5	0.8	1.0
2060	1.2	2.2	2.8
2100	2.6	5.1	6.8

**TABLE 1: SEA LEVEL RISE NEAR KEY WEST, FL, RELATIVE TO MEAN SEA LEVEL<sup>8</sup>**

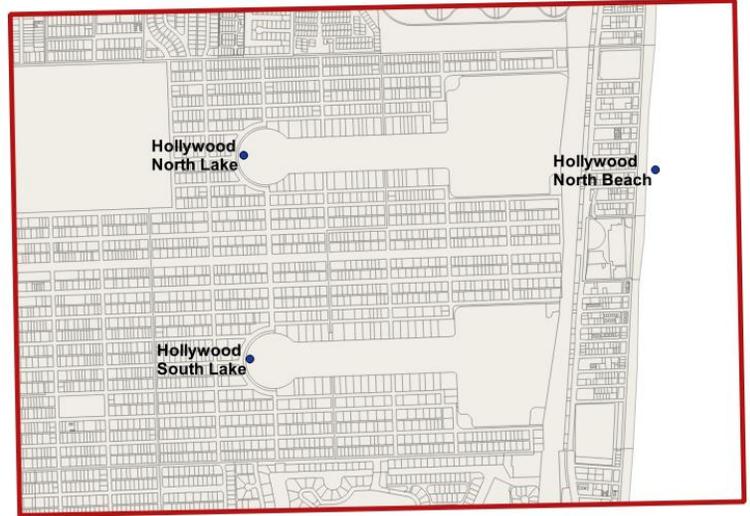
Surge height was analyzed for six different locations in the study area, as shown in Figure 3, which have been selected to illustrate the variations of hazard within the area. At each location, surge heights were determined across different return periods. The concept of return periods is frequently used to illustrate the likelihood with which different level of hazard, such as surge height, are expected to occur: A surge height with a return period of 100 years, for example, can be expected to be exceeded once every 100 years. Conversely, the likelihood of exceeding this surge height within any given year is  $1/100 = 1\%$ . Return period values were derived using the thousands of simulated events in the RMS model. This set of simulated events was derived mainly based on the HURDAT catalogue, as outlined in Section 2, with each event having a surge footprint and an associated rate of occurrence. The hazard values calculated for each return period are a (rate-weighted) average of these simulated events.

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<sup>8</sup> Source: <http://www.southeastfloridaclimatecompact.org/wp-content/uploads/2015/10/2015-Compact-Unified-Sea-Level-Rise-Projection.pdf> (accessed Nov 17, 2017)



**FORT LAUDERDALE**



**HOLLYWOOD**

**FIGURE 3: LOCATIONS SELECTED FOR THE RMS SURGE HAZARD ANALYSIS**

The surge heights derived for the return periods of 50 years, 100 years, 200 years, 250 years and 500 years, based on the RMS model, are summarized in the following sections. All surge heights are reports in feet above the NAVD88 datum for ease of comparison. It should be noted that only the stochastic and hazard components of the RMS modeling framework were required for this analysis, whereas the exposure, vulnerability and financial components were exclusively used for the economic impact analyses described in the following sections.

**Base case analysis**

Assuming current sea levels, and current ground elevations without any explicit modeling of seawalls in the study area, the surge heights for the specified return periods are as presented in Table 2. In both Fort Lauderdale and Hollywood, locations at the very eastern edge of the cities, which are directly exposed to storm surge from the Atlantic Ocean, show the highest surge hazard across all return periods. Hazard levels at these locations along the Atlantic coast (Fort Lauderdale - North Beach, Fort Lauderdale - South Beach, Hollywood - North Beach) generally exhibit comparable return period values; similarly, the hazard to locations further inland (Fort Lauderdale - Islands (North), Fort Lauderdale - Islands (South), Hollywood - North Lake, Hollywood - South Lake) is also comparable across the study area.

Location name	50 Years	100 Years	200 Years	250 Years	500 Years
Fort Lauderdale - North Beach	6.8	7.6	8.0	8.3	9.2
Fort Lauderdale - South Beach	6.2	7.0	7.3	7.6	8.5
Fort Lauderdale - Islands (North)	3.7	4.1	4.4	4.4	4.7
Fort Lauderdale - Islands (South)	4.3	4.9	5.5	5.6	5.8
Hollywood - North Beach	6.3	7.1	7.6	7.8	8.8
Hollywood - North Lake	3.9	4.6	5.3	5.3	6.0
Hollywood - South Lake	4.1	4.6	5.2	5.3	5.9

**TABLE 2: RETURN PERIOD SURGE HAZARD – BASE CASE (FT ABOVE NAVD88)**

**Base case analysis in combination with 1ft – 3ft of sea level rise**

Assuming that sea levels rise up to 3ft above current levels, the surge heights change to the levels summarized in Table 3. It can be seen that for fixed return periods, the surge height associated with each return period increases linearly with sea level rise. This behavior can be expected for the hazard at coastal locations, such as those considered in this analysis, given that only the large-scale storm surge events considered in the analysis. However, the relationship can be expected to be more complex for less severe flooding events, such as those caused extreme high tide conditions, whose footprint extent is typically more sensitive to changes in sea level. Different patterns can also occur for less coastal locations, or locations which are influenced by different, interacting stretches of complex coastlines.

It should be noted that the results for the 0ft sea level rise scenario correspond to the base case analysis presented in Table 2.

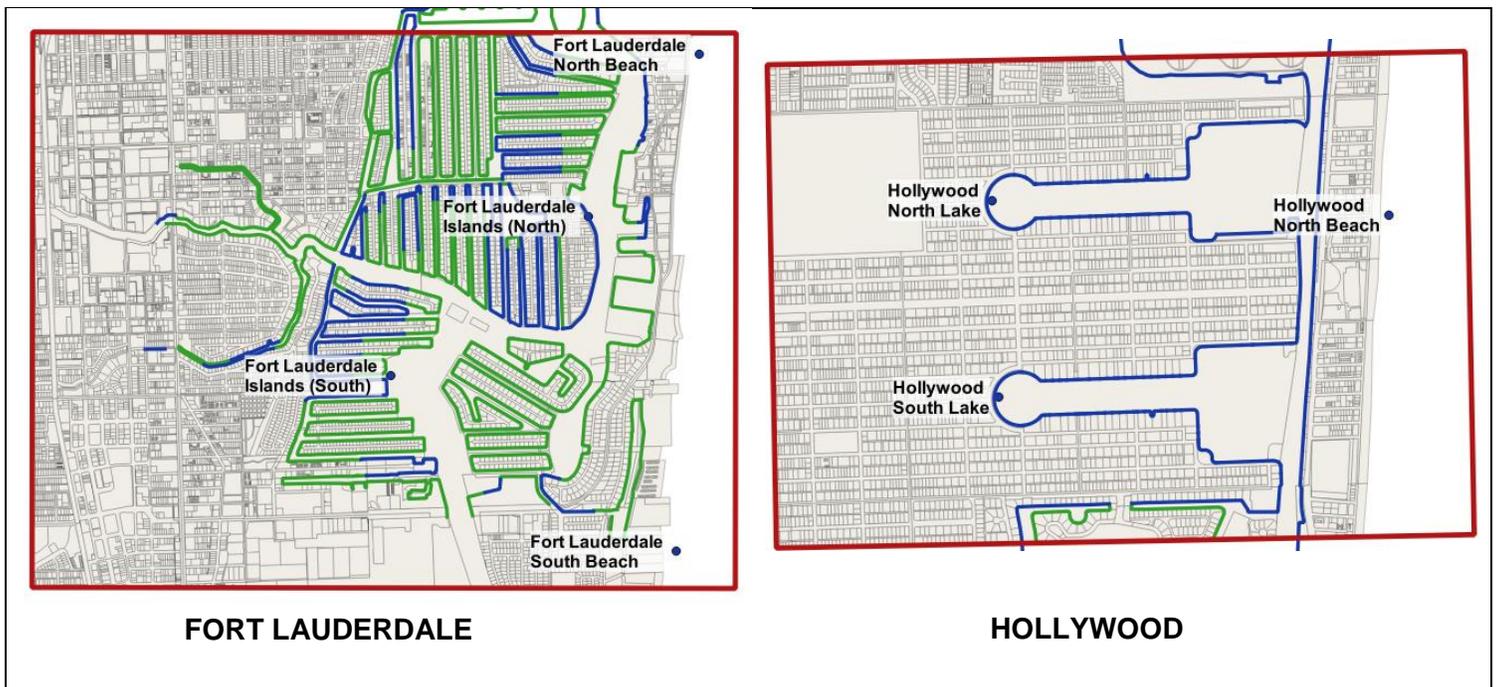
Location	Sea level rise (ft)	50 Years	100 Years	200 Years	250 Years	500 Years
For Lauderdale, North Beach	0	6.8	7.6	8.0	8.3	9.2
	1	7.8	8.6	9.0	9.3	10.2
	2	8.8	9.6	10.0	10.3	11.2
	3	9.8	10.6	11.0	11.3	12.2
For Lauderdale, South Beach	0	6.2	7.0	7.3	7.6	8.5
	1	7.2	8.0	8.3	8.6	9.5
	2	8.2	9.0	9.3	9.6	10.5
	3	9.2	10.0	10.3	10.6	11.5
For Lauderdale, Islands (North)	0	3.7	4.1	4.4	4.4	4.7
	1	4.7	5.1	5.4	5.4	5.7
	2	5.7	6.1	6.4	6.4	6.7
	3	6.7	7.1	7.4	7.4	7.7
For Lauderdale, Islands (South)	0	4.3	4.9	5.5	5.6	5.8
	1	5.3	5.9	6.5	6.6	6.8
	2	6.3	6.9	7.5	7.6	7.8
	3	7.3	7.9	8.5	8.6	8.8
Hollywood, North Beach	0	6.3	7.1	7.6	7.8	8.8
	1	7.3	8.1	8.6	8.8	9.8
	2	8.3	9.1	9.6	9.8	10.8
	3	9.3	10.1	10.6	10.8	11.8
Hollywood, North Lake	0	3.9	4.6	5.3	5.3	6.0
	1	4.9	5.6	6.3	6.3	7.0
	2	5.9	6.6	7.3	7.3	8.0
	3	6.9	7.6	8.3	8.3	9.0
Hollywood, South Lake	0	4.1	4.6	5.2	5.3	5.9
	1	5.1	5.6	6.2	6.3	6.9
	2	6.1	6.6	7.2	7.3	7.9
	3	7.1	7.6	8.2	8.3	8.9

**TABLE 3: RETURN PERIOD SURGE HAZARD – SEA LEVEL RISE SCENARIOS (FT ABOVE NAVD88)**

**Analyses considering current and future seawalls**

RMS received data on seawall heights and locations in the study area by Broward County for the purposes of this project. As illustrated in Figure 4, the set of seawalls considered in the analysis can be split into the following two categories:

- Existing seawalls with no plans for upgrade (marked in green in Figure 4): Based on guidance provided by Broward County, these seawalls currently have a top elevation of 2-4ft high, without any urgent plans for upgrade. For the purposes of this analysis, a uniform seawall height of 4ft was assumed for all seawalls in this category.
- Seawalls which are considered for upgrade (marked in blue in Figure 4): These seawalls are currently considered for upgrade to a 4-6ft standard. For the purposes of this analysis, a uniform seawall height of 6ft was assumed for all seawalls in this category.



**FIGURE 4: SEAWALL HEIGHT AND LOCATIONS IN THE STUDY AREA (GREEN – 4FT, BLUE – 6FT)**

As expected, the same linear increase in surge height with sea level rise, which was already seen in the analysis without seawalls, can be observed for the results of this analysis. However, the presence of the seawalls means that surge heights up to the top elevation of seawalls adjacent to the selected locations would be blocked by the seawalls and be prevented from impacting land. The ‘effective’ (impacting) surge height can therefore be assumed to be zero in these cases (highlighted in Table 4 below).

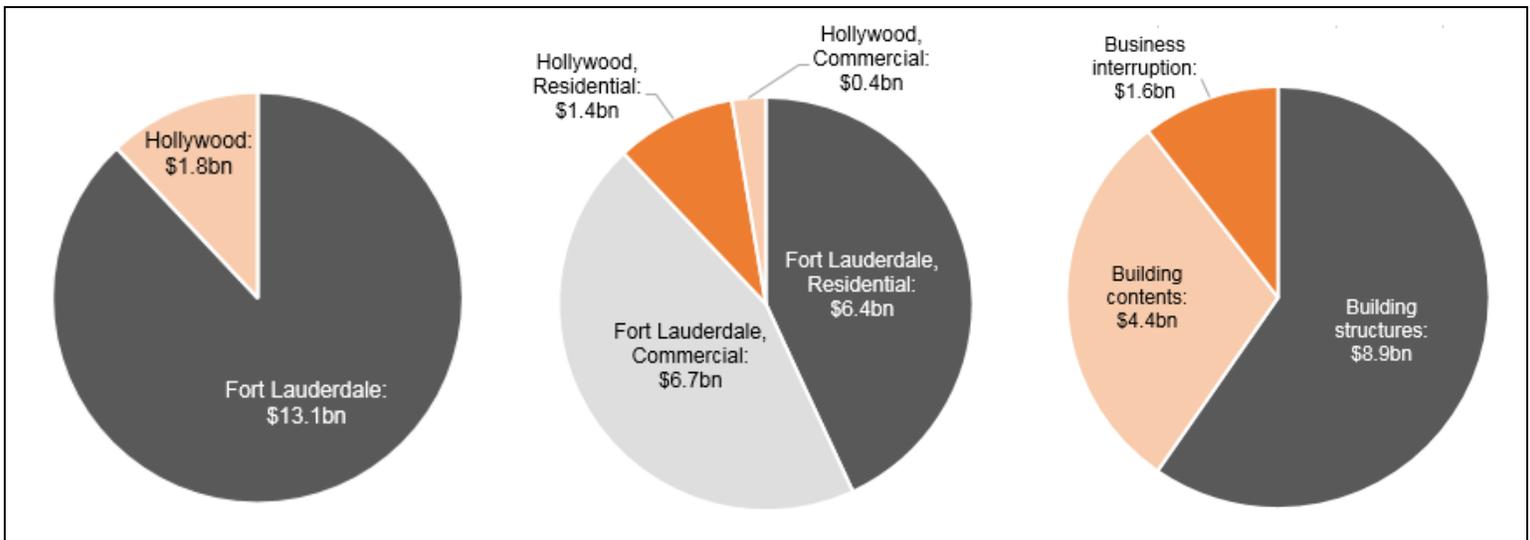
Location	Sea level rise (ft)	50 Years	100 Years	200 Years	250 Years	500 Years	Seawall protection
Fort Lauderdale, North Beach	0	6.8	7.6	8.0	8.3	9.2	No protection
	1	7.8	8.6	9.0	9.3	10.2	No protection
	2	8.8	9.6	10.0	10.3	11.2	No protection
	3	9.8	10.6	11.0	11.3	12.2	No protection
Fort Lauderdale, South Beach	0	6.2	7.0	7.3	7.6	8.5	No protection
	1	7.2	8.0	8.3	8.6	9.5	No protection
	2	8.2	9.0	9.3	9.6	10.5	No protection
	3	9.2	10.0	10.3	10.6	11.5	No protection
Fort Lauderdale, Islands (North)	0	0.0	0.0	0.0	0.0	0.0	6ft protection
	1	0.0	0.0	0.0	0.0	0.0	6ft protection
	2	0.0	6.1	6.4	6.4	6.7	6ft protection
	3	6.7	7.1	7.4	7.4	7.7	6ft protection
Fort Lauderdale, Islands (South)	0	4.3	4.9	5.5	5.6	5.8	4ft protection
	1	5.3	5.9	6.5	6.6	6.8	4ft protection
	2	6.3	6.9	7.5	7.6	7.8	4ft protection
	3	7.3	7.9	8.5	8.6	8.8	4ft protection
Hollywood, North Beach	0	6.3	7.1	7.6	7.8	8.8	No protection
	1	7.3	8.1	8.6	8.8	9.8	No protection
	2	8.3	9.1	9.6	9.8	10.8	No protection
	3	9.3	10.1	10.6	10.8	11.8	No protection
Hollywood, North Lake	0	0.0	0.0	0.0	0.0	0.0	6ft protection
	1	0.0	0.0	6.3	6.3	7.0	6ft protection
	2	0.0	6.6	7.3	7.3	8.0	6ft protection
	3	6.9	7.6	8.3	8.3	9.0	6ft protection
Hollywood, South Lake	0	0.0	0.0	0.0	0.0	0.0	6ft protection
	1	0.0	0.0	6.2	6.3	6.9	6ft protection
	2	6.1	6.6	7.2	7.3	7.9	6ft protection
	3	7.1	7.6	8.2	8.3	8.9	6ft protection

**TABLE 4: RETURN PERIOD SURGE HAZARD – SEA LEVEL RISE & SEAWALL UPGRADE SCENARIOS (FT ABOVE NAVD88)**

## 4. RMS ECONOMIC IMPACT ANALYSIS

The economic impact analysis combines the stochastic and hazard component of the RMS modeling framework, as also used in the preceding surge hazard assessment, with the exposure, vulnerability and financial components of the framework. In order to estimate the economic impact of each simulated event underlying the model, it is important to understand how much value is exposed to the surge footprint of the event, and what percentage of this value is lost due to the event. The exposure, vulnerability and financial components of the model address exactly these two questions.

In order to quantify the exposure which could be impacted by surge events, RMS received detailed data on the building stock in the study area. A detailed description of this data, and any assumptions made in using the data for the modeling can be found in Appendix 1. Overall, the total exposed values in the Fort Lauderdale and Hollywood sections of the study area were estimated at \$13.1bn and \$1.8bn, respectively. These values include the replacement values of building structures and contents, and well as the potential financial impact of business interruption to commercial and industrial companies which are located in the study area. It does, however, not include potential impacts which are commonly referred to as 'contingent business interruption' (i.e., losses incurred to a business which is not directly impacted by flooding itself but experiences a lack of critical supplies from another business, which is directly impacted by flooding), or losses caused by the failure of transport infrastructure, such as roads. It also does not consider potential wider impacts to the County caused by indirect losses such as loss in tax revenue in the aftermath of an event.



**FIGURE 5:** DISTRIBUTION OF EXPOSURE VALUE BY CITY (LEFT), LANDUSE (MIDDLE) AND TYPE (RIGHT)

If a certain exposure asset, such as a specific building, is impacted by a simulated surge event, the vulnerability component of the model determines the percentage of the asset value which is expected to be lost due to the event. This assessment is made based on the modeled surge height (hazard) at the building, as well as key building characteristics such as elevation, construction material, occupancy, building height and age.

Similar to the hazard assessment, the economic impact analysis was conducted for the following three different alternatives:

- A base analysis, based on the default elevation assumptions in the RMS model and without explicitly accounting for the presence of seawalls
- An analysis which reflects existing seawalls, as well as potential seawall upgrades the County is considering
- Each of the above in combination with sea level rise of 1ft, 2ft and 3ft

For each alternative, average annual loss and key return period losses were derived. Average annual loss (AAL) represents the loss that would be expected to occur on average in a year. The figure represents an average over time, and when looking at storm surge losses for individual years it would be expected that no or very little loss occurs during most years, but a very large amount of loss occurs during each of the rare remaining years. Return period losses can be interpreted in a similar way to return period surge height values: The 100-year return period loss is the loss amount which is on average expected to be exceeded once every 100 years; or conversely has a 1% (=1/100) change of occurring in any single given year.

### Base case analysis

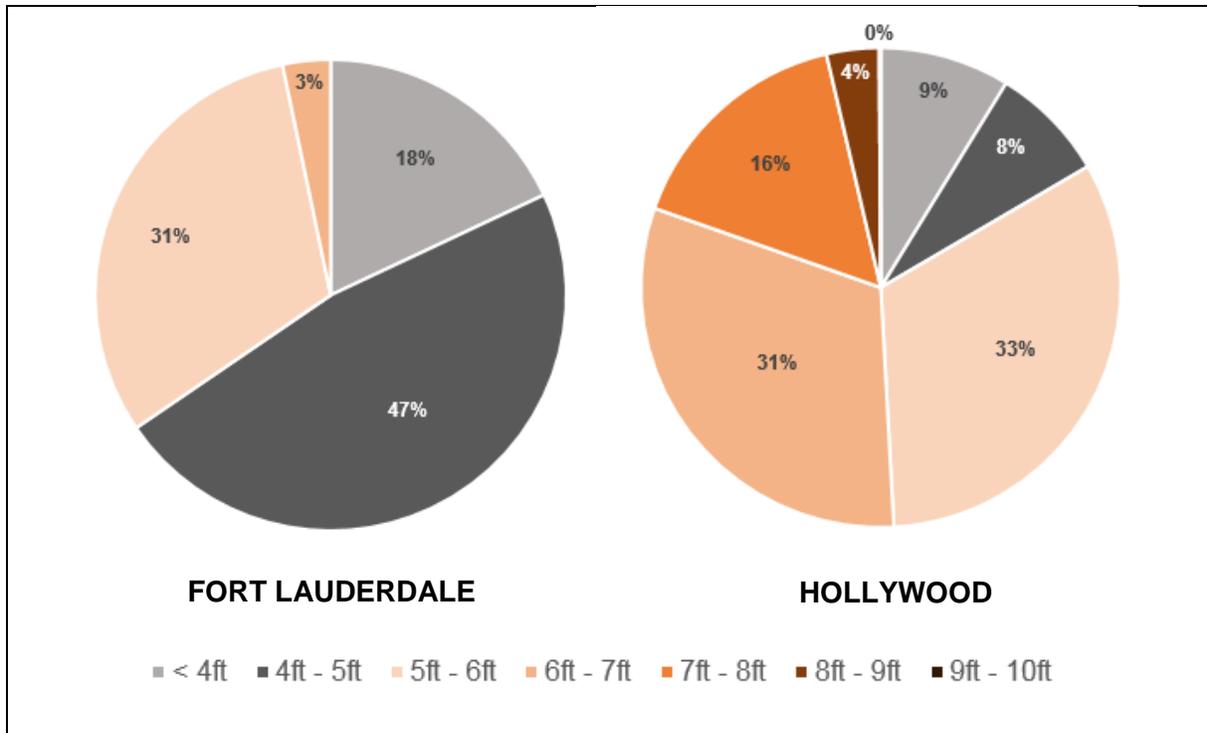
The results for the base analysis are presented in Table 5. The AAL for the entire study area is \$1.2m, with Hollywood contributing roughly two thirds of this amount due to losses in the Fort Lauderdale part of the area. These results contrast the distribution of exposure, which is largely concentrated in the Fort Lauderdale section of the study area. The reason for this contrast is caused by the different elevation profiles across the two parts of the study area, with the Fort Lauderdale area generally exhibiting higher ground level elevations than the Hollywood area (see Appendix 2). The extent and depth of flooding – whether caused by coastal storm surge or other sources - is highly dependent on elevation and can vary greatly across geographically close areas due to differences in elevation profiles.

It should be noted that return period losses are not additive, and as such the total return period loss across the study area can be less than (typically for lower return periods) or larger than (typically for higher return periods) than the sum of the individual return period losses for Hollywood and Fort Lauderdale.

Study Area	AAL	Return Period Losses				
		50 Years	100 Years	200 Years	250 Years	500 Years
Hollywood	\$826,336	\$1,601,406	\$12,126,157	\$37,386,472	\$57,666,914	\$119,921,776
Fort Lauderdale	\$416,222	\$311,337	\$6,204,314	\$21,531,349	\$27,323,870	\$51,976,917
<b>Total</b>	<b>\$1,242,559</b>	<b>\$3,869,857</b>	<b>\$21,876,900</b>	<b>\$64,477,768</b>	<b>\$86,721,337</b>	<b>\$160,688,310</b>

TABLE 5: RMS ECONOMIC IMPACT ANALYSIS – BASE CASE

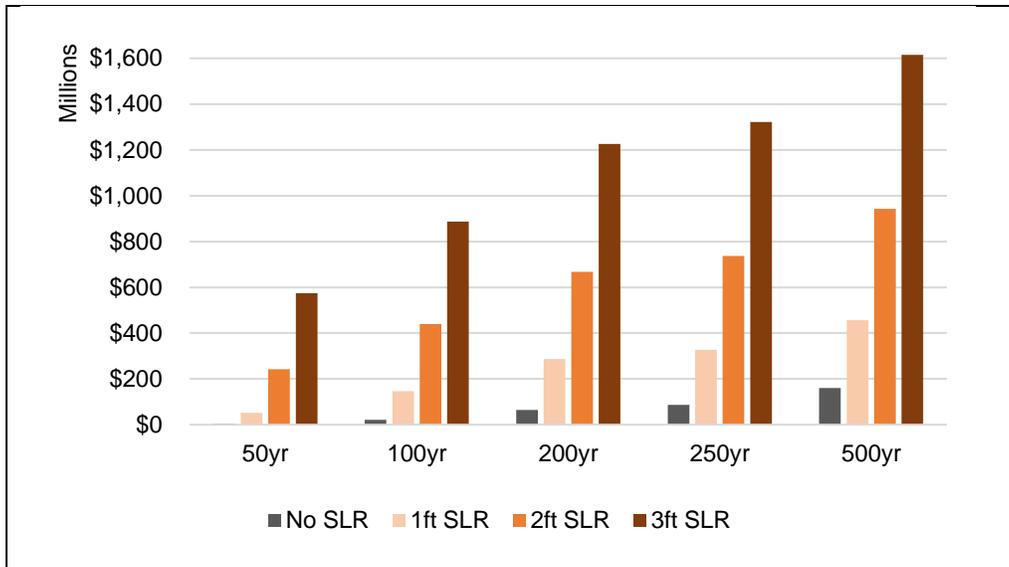
The AAL for each part of the study area is further broken out by surge height at nearby reference points in Figure 6. For Fort Lauderdale, surge heights represent the value as modeled at the ‘Fort Lauderdale - Islands (North)’ reference point; for Hollywood surge heights represent the value as modeled at the ‘Hollywood - North Lake’ reference point, as previously presented in Figure 3. For example, 33% of the modeled average annual loss for Hollywood is caused by events with a surge height of 5-6ft at the ‘Hollywood - North Lake’ reference point, and a further 31% of modeled losses are due to events with surge heights of 6-7ft. Conversely, only 9% of modeled losses in Hollywood and 18% of modeled losses in Fort Lauderdale are caused by events with a surge height of less than 4ft at the chosen reference points, indicating that protection measures up to a 4ft standard are unlikely to provide significant reductions in modeled losses from coastal storm surge events.



**FIGURE 6: RMS ECONOMIC IMPACT ANALYSIS – BASE CASE AVERAGE ANNUAL LOSS BY SURGE HEIGHT AT REFERENCE POINTS**

**Base case analysis in combination with 1ft – 3ft of sea level rise**

Table 6 below shows the changes in average annual loss under different sea level rise scenarios; Figure 7 demonstrates the corresponding changes across different return periods. A detailed table with all results is further included in Appendix 3. Crucially, it can be noted that even though surge hazard at fixed locations increased at the same rate as sea level (as seen in Section 3), the economic impact increases at a much faster rate. For example, the 100yr return period loss across the study area increases roughly 7-fold when 1ft of sea level rise is assumed but increases 20-fold under the assumption of 3ft of sea level rise. This behavior is due to the non-linear relationship between surge height and financial impact on an asset. An increase in surge height of 1ft can result in a difference from a 'slightly wet' floor which can be easily dried and cleaned, to a completely flooded floor which is largely beyond repair.



**FIGURE 7: RMS ECONOMIC IMPACT ANALYSIS – BASE CASE UNDER DIFFERENT SEA LEVEL RISE (SLR) SCENARIOS**

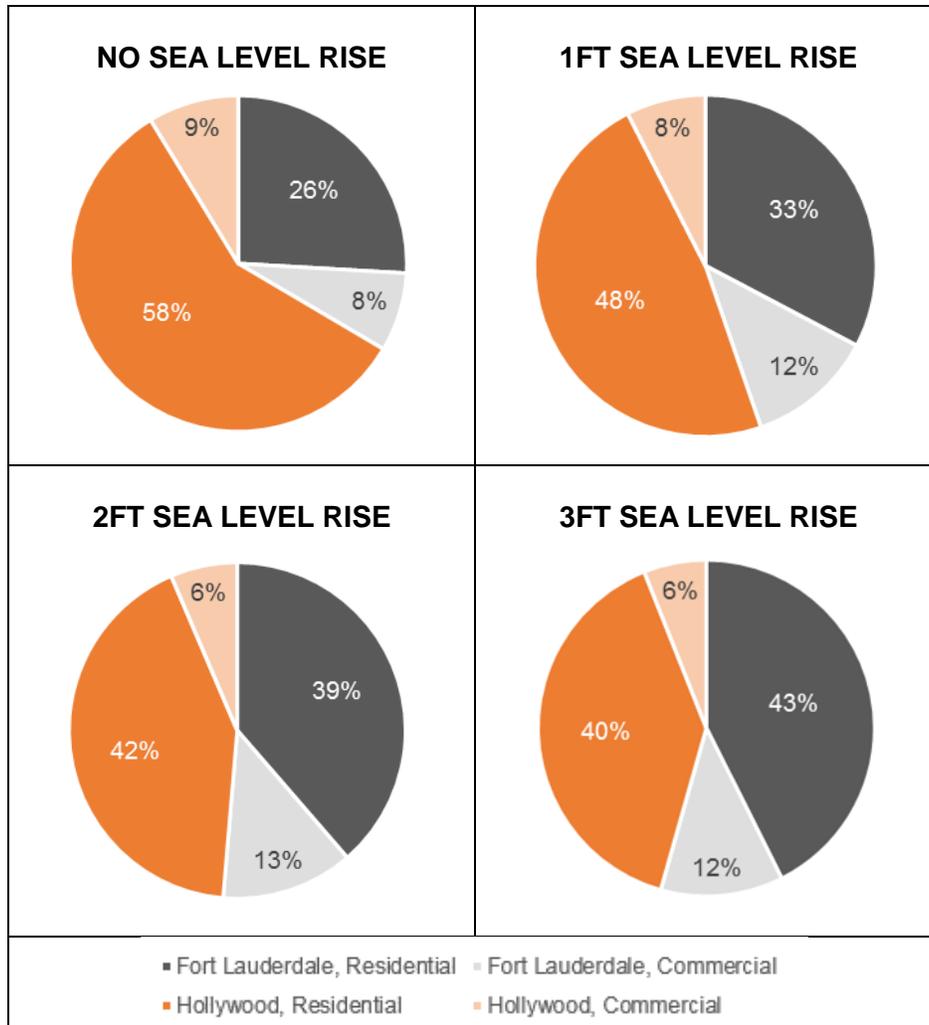
The distribution of losses across the two parts of the study area also changes across different sea level rise scenarios. While Hollywood dominates average annual losses under current sea level rise conditions, the contributions are roughly equal under the 1-2ft sea level rise scenarios, and Fort Lauderdale starts to dominate modeled losses under the 3ft sea level rise scenario. As sea level rises, the amount of protection provided by the higher ground elevations in the Fort Lauderdale area decreases, leading to a faster increase in losses in this part of the study area.

Sea level rise (ft)	Average Annual Loss (AAL)		
	Hollywood	Fort Lauderdale	Total
0	\$826,336	\$416,222	\$1,242,558
1	\$2,883,993	\$2,334,171	\$5,218,165
2	\$9,070,239	\$9,569,965	\$18,640,204
3	\$24,414,896	\$29,095,137	\$53,510,032

**TABLE 6: RMS ECONOMIC IMPACT ANALYSIS – AAL FOR BASE CASE UNDER DIFFERENT SEA LEVEL RISE SCENARIOS**

Figure 8 further breaks out the AAL by commercial and residential assets for each part of the study area. For the Hollywood area, nearly 90% of the modeled losses are due to damages to residential assets. In the Fort Lauderdale area, this contribution is notably lower, with approximately 75% of losses coming from residential exposure. This reflects the larger concentration of commercial business in the Fort Lauderdale area, compared to the largely residential neighborhood of the Hollywood area.

As previously shown in Table 1, the figure also illustrates the changing contributions from both study areas to the total modeled losses: Hollywood clearly dominates losses in the analysis without sea level rise, whereas Fort Lauderdale accounts for the majority of the losses under the 3ft sea level rise scenario.



**FIGURE 8: RMS ECONOMIC IMPACT ANALYSIS – AAL FOR BASE CASE UNDER DIFFERENT SEA LEVEL RISE SCENARIOS BY CITY AND LANDUSE**

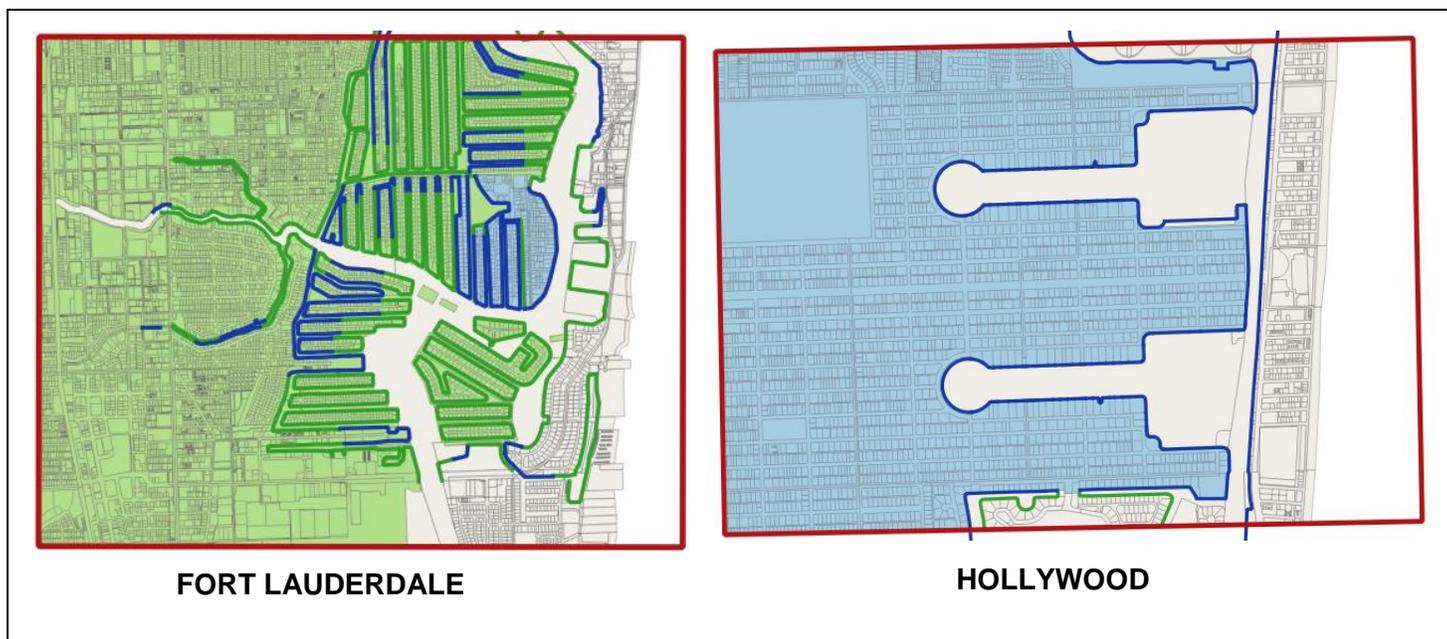
### Analyses considering current and future seawalls

The analysis under current and potential future seawalls in the study area is based on the same seawall data as for the surge hazard assessment, as described in Section 3.

RMS analyzed which assets can be reasonably expected to be protected by these seawalls, and used the following assumptions to assess the reductions in economic impact which can be achieved due to the presence of the seawalls:

- Fort Lauderdale:** Despite the presence of several (largely short) sections of seawalls which are targeted to be updated by the County, only a small area was assumed to be fully protected by upgraded seawalls (shaded in blue in Figure 9). Remaining areas, which are only partly enclosed by upgraded seawalls, are not expected to be comprehensively protected up to the standard of the upgraded seawalls, as they could be penetrated by water from sections of the coastline along which no upgraded seawalls are present. However, large sections of the study area could be assumed to be protected by existing seawalls (shaded in green in Figure 9). Areas which are not coloured (by either green or blue) in Figure 9 were assumed be unprotected by any of the seawalls.

- **Hollywood:** In the Hollywood area, a large part of the study area (shaded in blue in Figure 9) was assumed to be protected by a comprehensive set of upgraded seawalls. A short section of existing seawall was not assumed to provide any additional protection, as the area along this seawall could be impacted by water penetrating from the south of the seawall. Again, areas which are not coloured (by either green or blue) in Figure 9 were assumed to be unprotected by any of the seawalls.



**FIGURE 9:** AREAS ASSUMED TO BE PROTECTED BY EXISTING (GREEN) AND UPGRADED (BLUE) SEAWALLS IN THE STUDY AREA

In order to test to which extent reductions in the economic impact of coastal storm surge events could be achieved if seawalls were upgraded to various elevation standards, the analysis was repeated for the following top elevation assumptions:

- **Option 1:** A base analysis, which uses default elevation assumptions in the RMS model without explicitly accounting for the presence of seawalls beyond those default elevation assumptions, as presented in the preceding section.
- **Option 2:** Both existing seawalls (marked in green in Figure 9) and seawalls which are considered for upgrade (marked in blue in Figure 9) are assumed to have a 4ft top elevation. This assumes that existing seawalls are already built to this standard, and seawall upgrades are completed to the lower end of the targeted 4-6ft standard.
- **Option 3:** Existing seawalls are assumed to have a top elevation of 4ft, and seawalls which are considered for upgrade are assumed to have a top elevation of 6ft. This assumes that existing seawalls are already built to this standard, and seawall upgrades are completed to the higher end of the targeted 4-6ft standard.
- **Option 4:** Both existing seawalls and seawalls which are considered for upgrade are assumed to have a 6ft top elevation. This assumes that all seawalls are upgraded to the higher end of the 4-6ft standard currently targeted for a set of seawalls.
- **Option 5:** Both existing seawalls and seawalls which are considered for upgrade are assumed to have an 8ft top elevation. This assumes that all seawalls are upgraded above the higher end of the 4-6ft standard currently targeted for a set of seawalls.

Each of the above options were analyzed based on the current sea levels, as well as sea level rises of 1ft, 2ft and 3ft. The results of the analysis are illustrated in the remainder of this section; and a detailed table of the full results of the analysis can be found in Table 9 of Appendix 3.

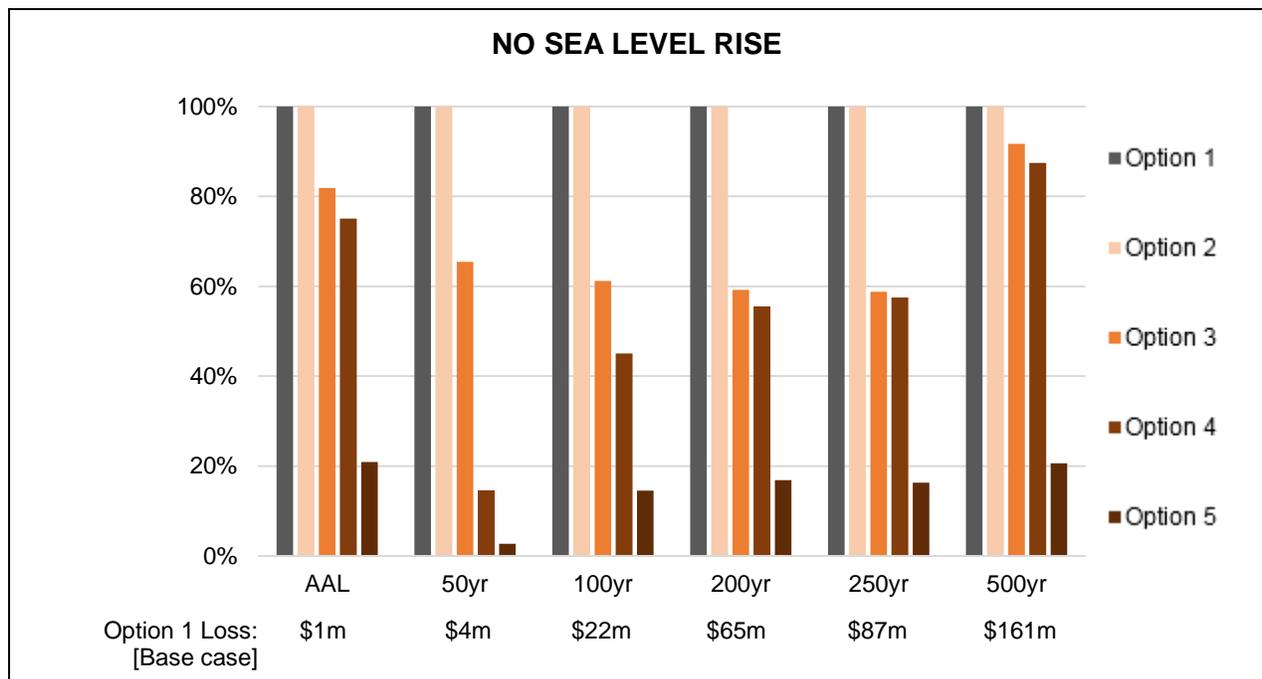
**Results under current sea levels**

As shown in Figure 10, protection up to a 4ft standard (Option 2) does not have a notable impact on losses compared to the base case Option 1 (no explicit seawall protections) and under current sea levels. Damaging, large-scale storm surge events, as those modeled by the RMS analysis, typically exhibit large surge heights above the 4ft level, and therefore cannot be effectively protected against by protection measures around a 4ft standard. Nevertheless, such protection could provide a substantial reduction in losses from smaller, more frequent flooding events, such as those caused by extreme high tides (king tides) or rainfall.

Option 3 (assuming existing seawalls at 4ft and upgraded seawalls at 6ft) starts to produce a notable reduction in losses, in particular for return periods up to 250 years. This reduction is nearly exclusively driven by lower losses in the Hollywood area, which is widely protected by upgraded seawalls. The corresponding impact on the Fort Lauderdale area is less pronounced, as only a small part of the city is fully protected by upgraded seawalls.

Assuming seawalls upgrades to a 6ft standard (Option 4) across both study areas leads to further reductions in modeled losses across both study areas; however, the additional decrease in losses compared to Option 3 is only marginal for return periods above 100 years.

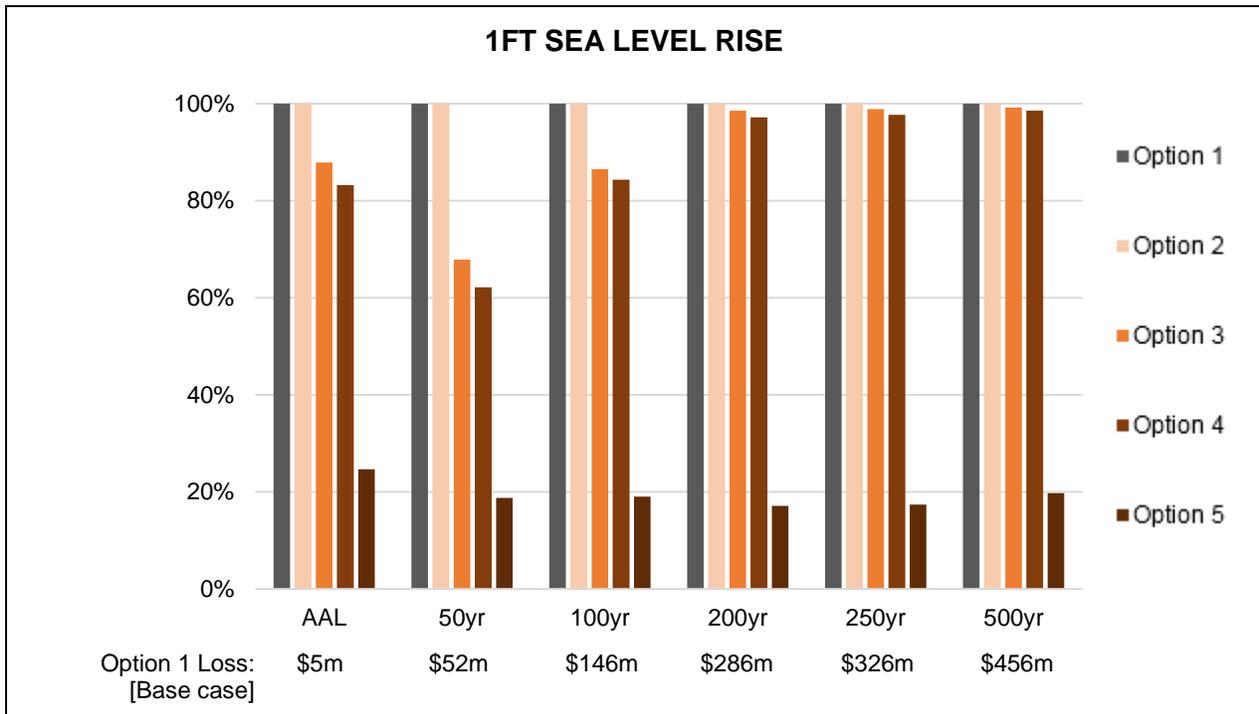
Increasing the seawall upgrade standard to 8ft (Option 5) leads to a significantly larger reduction in modeled losses than all other options, and across all return periods. Even at a 500yr return period, the losses under this option only reach 20% of the base case (Option 1) setting.



**FIGURE 10: AVERAGE ANNUAL LOSS AND RETURN PERIOD LOSSES UNDER VARIOUS SEAWALL OPTIONS, AS PERCENTAGE OF CORRESPONDING OPTION 1 (BASE CASE) LOSS – NO SLR SCENARIO**

### Results under 1-3ft of sea level rise

If sea level rise is additionally considered in the analysis only Option 5 (protection standards of 8ft for all seawalls) provides effective protection from coastal surge events across all return periods, as illustrated in Figure 11. Options 3 and 4 still provide a certain level of protection for return periods up to 100 years under the sea level rise scenarios of 1ft, but do not notably reduce losses from more severe events at larger return periods. Under the sea level rise scenarios of 2-3ft, the 8ft seawall standard assumed in Option 5 is the only protection measure which continues to achieve any notable reduction in losses, whereas all other options show no reduction in losses for any return periods under these sea level rise scenarios (see Appendix 3 for full results).



**FIGURE 11: AVERAGE ANNUAL LOSS AND RETURN PERIOD LOSSES UNDER VARIOUS SEAWALL OPTIONS, AS PERCENTAGE OF CORRESPONDING OPTION 1 (BASE CASE) LOSS – 1FT SLR SCENARIO**

Given current forecasts of sea level rises in the study area over the next decades (see Table 1), it is crucial that the results under potential future sea level rise scenarios are considered in the County's flood risk management approach. Only if the changes in the County's flood risk under these scenarios - and resulting changes in the effectiveness of any protection measures - are carefully considered in the development of a flood risk management approach today, such approach will continue to effectively reduce the impact of storm surge events over the coming decades.

## 5. CONCLUSION

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Broward County is facing significant risk of flooding from coastal storm surges. Over the coming decades, rising sea levels will lead to substantial increases in risk across the County. Even though inundation levels increase linearly with rising sea level at the analyzed locations in the study area, modeled losses resulting from coastal storm surge events increase at a much faster rate under different sea level scenarios, with 3ft of sea level rise leading to a 20-fold increase in the 100-year return period loss for the study area.

The risk is further exacerbated by additional sources of flooding, including extreme high tides and rainfall. Alongside rising financial losses, the increase in frequency and severity across all sources of flooding is likely to also have severe adverse impacts on local communities and businesses which cannot be easily measure in monetary terms, including impacts on quality of life and social security.

The County is actively exploring different strategic options to mitigate the impact of both current and future flooding scenarios. This report analyzed one such mitigation option, the extension and upgrade of seawalls across the two cities of Fort Lauderdale and Hollywood. The analysis highlights the crucial importance of accounting for future sea level rise in the design of any mitigation strategy: The modeled effectiveness of different seawall top elevations varies significantly across different sea level rise assumptions, with certain options providing substantial risk reductions under current sea levels but failing to provide effective protection once expected sea levels rises over the coming decades are accounted for. Furthermore, the effectiveness of mitigation options varies with the type of flooding targeted by the mitigation: While the analysis shows that only seawall top elevations of 8ft are expected to provide effective, lasting relief against the most severe storm surge events, lower top elevations could already be an effective measure to prevent more frequent, less severe instances of flooding.

Regardless of their specific elevation requirements, the seawalls are likely to be only one facet of a larger flood risk mitigation program developed by the County. In order to address the large – and increasing – risk from flooding faced by Broward County, a comprehensive resilience program which combines risk quantification, mitigation and transfer will be required in order to effectively reduce flood risk not only under current sea levels, but also under changes in climatic conditions over the coming years and decades.

## 6. RECOMMENDED FUTURE WORK

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The analysis presented in this project provides an overview of the risk of flooding to selected areas in the cities of Fort Lauderdale and Hollywood. In order to continue to further refine and extent the analysis conducted under this project, RMS has identified the following potential areas of future work which could be conducted by Broward County to continue to build a comprehensive understanding of the flood risk the County is facing and determine the most effective resilience measures to reduce such risk.

- Extension of study area: This initial assessment has focused exclusively on two specific areas in the cities of Fort Lauderdale and Hollywood, in order to inform seawall top elevations in these areas. In order to build a more comprehensive view of the flood risks across the two cities and the entire County, the analysis should be extended to a wider area. A broader analysis could also be used to identify potential ‘hot spots’ of flood risk within the County and guide the prioritization of future risk mitigation initiatives.
- Exposure data: The exposure data provided by Broward County to RMS the purposes of this study contained a significant amount of information to inform the analysis conducted by RMS. While the level of detail already available in this dataset is considerable and has provided a very strong basis for the analysis, further refinements could be made. In particular, adding information on the contents and business interruptions values specific to each parcel could considerably increase the accuracy of the economic impact analysis.
- Consideration of additional sources of loss: The study presented in this report quantifies losses caused by damage to building structures and their contents, as well as business interruption due to flooding damage to commercial properties. In reality, however, however, further sources of loss, which have not been considered in this analysis, are expected to contribute to the total losses experienced by the County during a flooding event. These include (but are not limited to) losses due to damage to infrastructure, such as roads and power distribution networks, reductions in tax income from local residents and businesses, and interruptions to business who have not experienced any flooding themselves but are unable receive crucial goods and services from suppliers affected by flooding (‘contingent business interruption’). Such additional sources of loss are expected to have an additional, significant impact on the scale of total losses the County could experience and should be targeted to be included in further studies wherever possible.
- Elevation data: RMS understands that Broward County is in the process of collecting detailed data on both ground and first floor elevations. High-quality elevation data is critical to an accurate assessment of flood risk; and using detailed, up-to-date data is highly recommended. While the timing of the data collection did not allow the data to be incorporated into the specific analysis presented in this report, the data collected by the County should be incorporated into future risk assessments wherever possible. For the purpose of this study RMS has used its own elevation data, details on which can be found in Appendix 2.
- Assessment of different resilience measures: This analysis considered the impact of seawalls of varying heights and locations on both the surge hazard and associated economic loss which can be expected to occur in the study area. While seawalls are a common, and often effective measure of protection against flooding, other – potentially preferable - options might be available to the County. An assessment of the reductions in hazard and economic impact which different options can achieve could provide valuable information to guide and prioritize future investments into a range of resilience measures.
- Identification of key stakeholders: In order to effectively manage its flood risk, it is important that flood risk management is not only a clear priority on the agenda of the County, but also on the agenda of its residents and businesses. In particular those stakeholders which are most at risk, and likely to be most severely affected by flooding under current and future sea levels, should be aware of, and actively engaged in the County’s flood management efforts. While this study already provides a range of information which can be used for these purposes, the resolution of the results could be further refined to allow for an even more granular identification and prioritization of stakeholders across the County.

# APPENDIX 1 – EXPOSURE DATA

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## Background

RMS models consume exposure data through information on the geographical position, value and key building characteristics, such as occupancy (land-use) and building height, for each asset. This information can be entered in varying levels of detail and completeness; and missing data can be inferred through intelligent assumptions encoded into the model by RMS experts. During the modeling process, the specific hazard values experienced by an asset are determined based on its location and building characteristics. This hazard value is then converted into a monetary loss based on the asset's total value and its susceptibility to damage, commonly referred to as the 'vulnerability' of the asset.

Exposure data has to be captured in an Exposure Database Module ("EDM"), a specific SQL Server database format developed by RMS, in order to be accessible to RMS models. The following sections describe how the EDM for this project was developed, and which data sources and assumptions were used to inform the development.

## Data Sources

RMS used the following data sources, obtained from the County's Property Appraiser's Office, as the basis for key exposure information:

- GIS shapefiles containing parcel boundaries: These shapefiles were used to extract the coordinate location (latitude/longitude) of assets in the Study Area.
- Attribute tables for the GIS shapefiles: The attribute tables were used to extract several key building characteristics for each asset, including land-use and building age, as well as its structural value
- Metadata databases: Additional metadata was provided in the form of several databases. These databases were mapped to the GIS files to extract additional information on building characteristics, including building height, construction material and roof characteristics.

A detailed list of asset-level information extracted from the three data sources listed above is shown in Table 7. In addition, RMS used several of its own proprietary datasets to complement the data received by the County:

- Topographic data: Elevation (ft above NAVD88) was extracted at each asset location in the Study Area from a regional elevation layer developed by RMS from LiDAR data
- Building contents value: Based on RMS research conducted for the property insurance industry, the value of each building's content was assumed to equal 50% of its structural value
- Business interruption losses: Based on RMS research conducted for the property insurance industry, the loss arising from one year of business discontinuity of a non-residential building's content was assumed to equal 40% of its structural value. No business interruption values were captured for residential buildings.

## Additional Assumptions

- Whenever key building characteristics, such as building height, use, construction, and age, were not available in the data received, missing values will be inferred at the point of an RMS model run (see Appendix 1). The selection of missing characteristics is informed by decades of RMS research, and is directly encoded in the RMS model used for the analysis.
- Parcels without structural assets (e.g., with an indicated land use for agriculture or forestry) have been included in the database for completeness but have been assigned a purely nominal monetary value of one US dollar. As such, these parcels will not have a noticeable impact on the economic impact analysis conducted in as part of this project.

## Building Characteristics

The below table details asset-level information extracted from the data sources provided by Broward County. Information from different source databases were linked based on the FOLIO\_NUMBER key present in each database, as well as the BUILDING\_NUM field in the BAS, BUC\_ELEMENTS and BUC\_UNITS databases.

Attribute	Source Database	Source Field
Coordinate location	BrowardParcelForRMS BrowardParcelPoly	N/A
Address	BrowardParcelForRMS BrowardParcelTable	ADDRESS_LINE_1, CITY, ZIP, STATE
Structural value	BrowardParcelForRMS BrowardParcelTable	JUST_BUILDING_VALUE
Construction type	BUC_ELEMENTS	CONSTRUCTION_CLASS
Occupancy / land use	BrowardParcelForRMS BrowardParcelTable	USE_CODE
Number of stories	BUC_UNITS	STORIES_NUM
Year of construction	BrowardParcelForRMS BrowardParcelTable	ACTUAL_YEAR_BUILT
Square footage	BrowardParcelForRMS BrowardParcelTable	BLDG_TOT_SQ_FOOTAGE
Construction quality	BUC_ELEMENTS	CONSTRUCTION_QUALITY
Roof geometry	BUC_UNITS	ROOF_TYPE
Roof material	BUC_UNITS	ROOF_MATERIAL

**TABLE 7: INFORMATION EXTRACTED FROM BROWARD COUNTY DATA SOURCES**

Table 8 illustrates the completeness of key building attributes used in the modeling in the exposure data input for the Study Area. As mentioned above, missing values will be inferred at the point of an RMS model run based on RMS research, which is directly encoded in the model used for the analysis.

Building characteristic	Exposure with missing building characteristic [% of total number of locations / % of total value]
Land use	6.1% / 0.4%
Construction material	29.6% / 5.5%
Number of stories	30.8% / 5.9%
Building age	9.7% / <0.1%

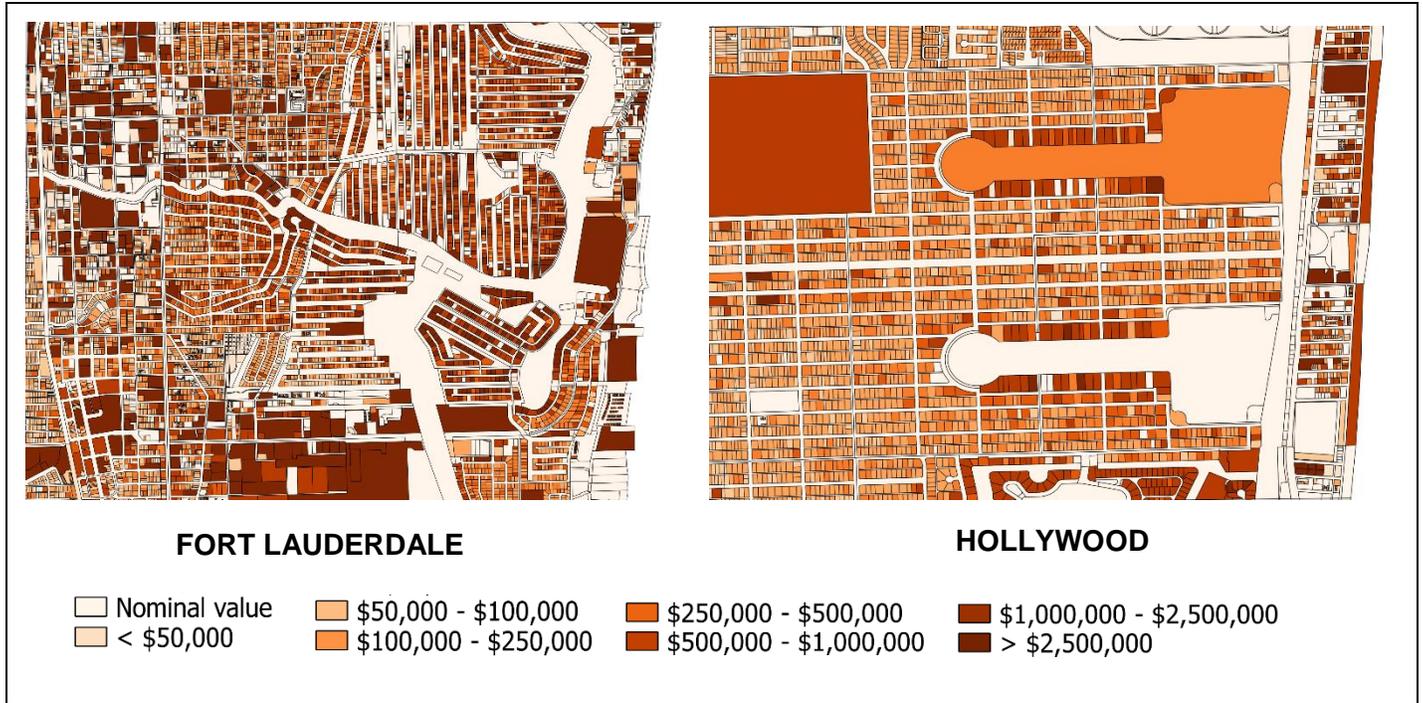
**TABLE 8: COMPLETENESS OF KEY BUILDING ATTRIBUTES IN THE EXPOSURE DATA INPUT FOR THE STUDY AREA**

## Exposure Summary

The exposure dataset developed for the project contains a total of 14,089 locations in the Study Area, with a total value of \$14.9bn.

This value is distributed across building structures (\$8.9bn), contents (\$4.4bn) and business interruption (\$1.6bn) according to the assumptions described in the previous section. The majority of the exposure is located in the Fort Lauderdale region of the Study Area, which contains 73% of all locations (corresponding to a location count of 10,249) and 88% of the total value (\$13.1bn).

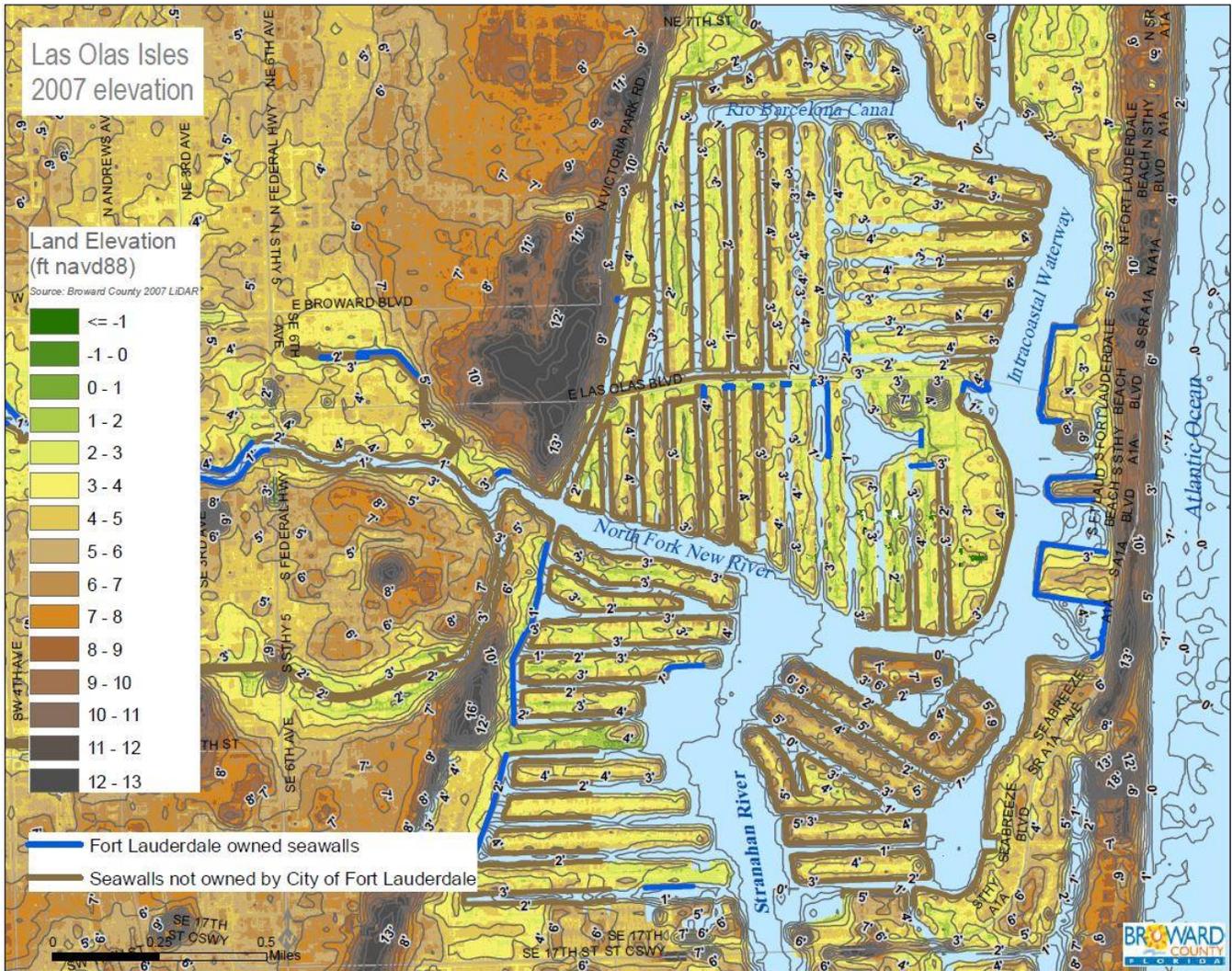
The geographic distribution of locations and their associated values is further illustrated in Figure 12 below.



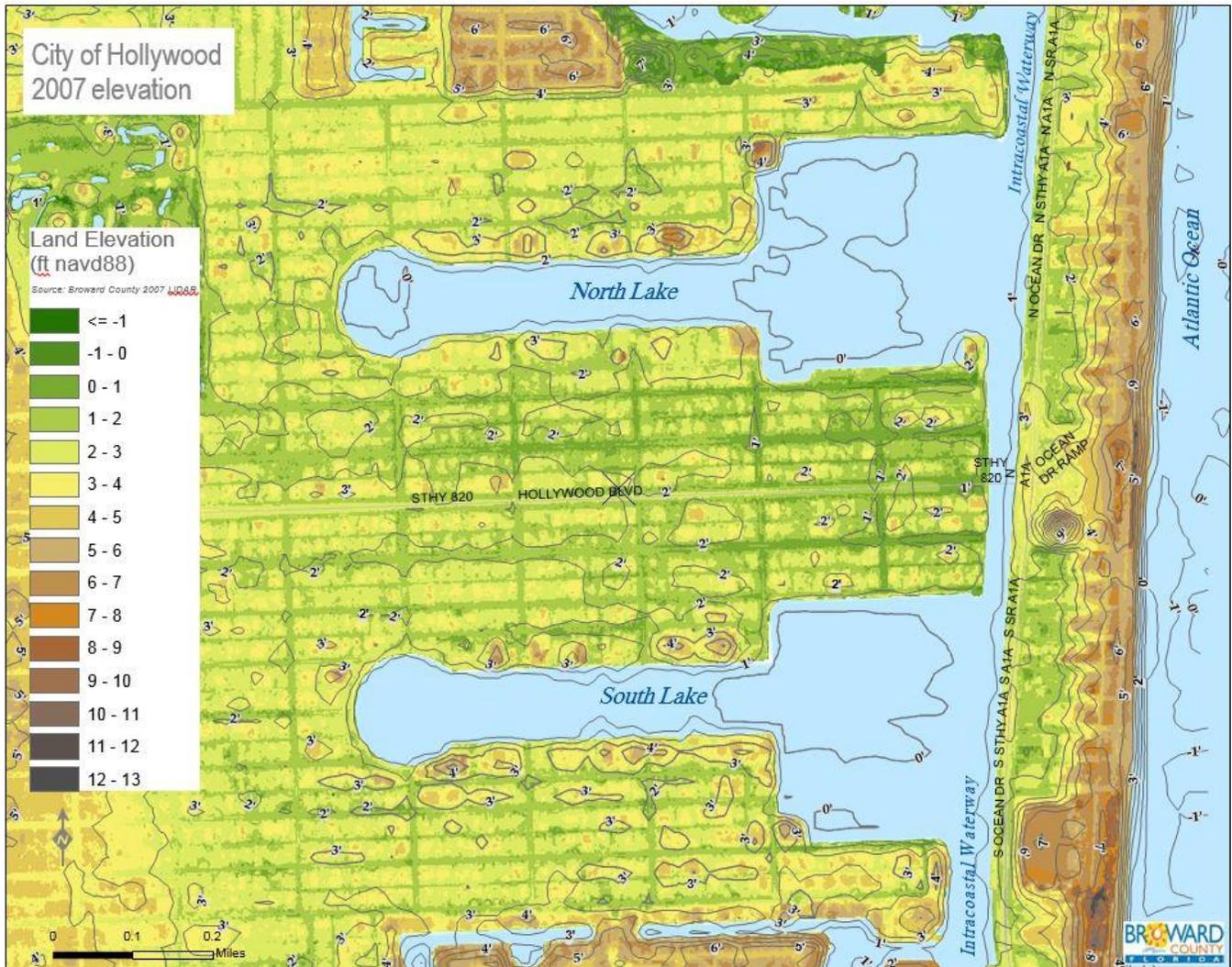
**FIGURE 12: DISTRIBUTION OF EXPOSURE VALUES IN THE STUDY AREA**

# APPENDIX 2 – STUDY AREA ELEVATION PROFILE

The two figures included in this Appendix illustrate the elevation profile across both the Fort Lauderdale and Hollywood section of the study area. It should be noted that the figures are based on 2007 LiDAR data from Broward County; whereas the elevation data used for the analyses presented in this report is based on elevation data developed by RMS. Based on a comparison conducted by RMS, the two data layers compare well, and the figures below therefore give a suitable indication of the elevation profiles used in the analysis across the two sections of the study area.



**FIGURE 13: ELEVATION PROFILE OF FORT LAUDERDALE (SOURCE: BROWARD COUNTY 2007 LiDAR)**



**FIGURE 14: ELEVATION PROFILE OF HOLLYWOOD (SOURCE: BROWARD COUNTY 2007 LIDAR)**

The elevation profile that RMS has developed takes in consideration the FEMA flood zones and the hazard elevation resulting from a flood that has 1 percent chance of equalling or exceeding that level in a given year, known as base flood elevation (BFE). RMS assigns an effective building elevation to U.S. locations by looking at the FEMA flood zones, checking for the availability of BFE and year of construction before or after a reference year (1975). It then assigns the maximum of ground elevation, 4 feet or 0.7 times ground elevation plus 0.3 times BFE for buildings constructed before 1975 and assigns a maximum of ground elevation, 4 feet or BFE for buildings constructed after the reference year 1975 for single family dwellings and low rise multi-family dwellings and commercial buildings falling under most special flood hazard areas. For all other occupancy types under such conditions it assigns a maximum value of ground elevation of 4 feet. BFE are available for most special flood hazard areas. In cases when it is not available, for moderate risk zones, a maximum value of ground elevation or 4 feet is assigned irrespective of year of construction. In special cases when ground elevation is less than 0 feet, 4 feet is added to ground elevation and then a similar approach as mentioned above is followed.

# APPENDIX 3 – DETAILED ANALYSIS RESULTS

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This appendix contains the detailed results of the economic impact analyses based on RMS hazard, considering current and future seawalls in the study area as well as different sea level rise scenarios.

- Option 1: A base analysis, which uses default elevation assumptions in the RMS model without explicitly accounting for the presence of seawalls beyond those default elevation assumptions.
- Option 2: Both existing seawalls (marked in green in Figure 9) and seawalls which are considered for upgrade (marked in blue in Figure 9) are assumed to have a 4ft top elevation. This assumes that existing seawalls are already built to this standard, and seawall upgrades are completed to the lower end of the targeted 4-6ft standard.
- Option 3: Existing seawalls are assumed to have a top elevation of 4ft, and seawalls which are considered for upgrade are assumed to have a top elevation of 6ft. This assumes that existing seawalls are already built to this standard, and seawall upgrades are completed to the higher end of the targeted 4-6ft standard.
- Option 4: Both existing seawalls and seawalls which are considered for upgrade are assumed to have a 6ft top elevation. This assumes that all seawalls are upgraded to the higher end of the 4-6ft standard currently targeted for a set of seawalls.
- Option 5: Both existing seawalls and seawalls which are considered for upgrade are assumed to have an 8ft top elevation. This assumes that all seawalls are upgraded above the higher end of the 4-6ft standard currently targeted for a set of seawalls.

Table 9 presents the full results for each option and sea level rise scenarios analysed. Results are given for both the entire study area, as well as on a city-level.

Figure 15 shows the economic impact of storm surge events under upgrade options 2-5 as a percentage of the impact under the 'base case' option 1, illustrating the reductions in losses achieved by each of the upgrade options. The results are presented both under current sea levels, as well as under the assumption of 1-3ft of sea level rise.

**TOTAL STUDY AREA**

TOTAL STUDY AREA			Return Period Losses				
Seawall Option	Sea level rise (ft)	AAL	50 Years	100 Years	200 Years	250 Years	500 Years
1	0	\$1,242,558	\$3,869,857	\$21,876,900	\$64,477,768	\$86,721,337	\$160,688,310
	1	\$5,218,165	\$51,836,788	\$146,289,927	\$286,325,894	\$326,352,151	\$456,037,978
	2	\$18,640,204	\$242,675,669	\$439,510,317	\$667,295,400	\$736,890,901	\$942,385,311
	3	\$53,510,032	\$574,476,522	\$887,205,277	\$1,225,554,256	\$1,322,160,616	\$1,614,663,198
2	0	\$1,242,531	\$3,869,317	\$21,876,842	\$64,477,695	\$86,721,269	\$160,688,202
	1	\$5,218,164	\$51,836,749	\$146,289,822	\$286,325,697	\$326,351,938	\$456,037,730
	2	\$18,637,760	\$242,674,081	\$439,509,584	\$667,295,023	\$736,890,510	\$942,384,812
	3	\$53,493,992	\$574,474,597	\$887,204,236	\$1,225,553,683	\$1,322,160,022	\$1,614,662,503
3	0	\$1,016,843	\$2,531,921	\$13,390,964	\$38,177,207	\$50,956,134	\$147,349,566
	1	\$4,583,784	\$35,191,730	\$126,543,055	\$282,174,416	\$322,738,087	\$452,360,008
	2	\$17,182,634	\$232,850,249	\$433,731,011	\$665,045,103	\$735,328,974	\$941,250,627
	3	\$51,199,697	\$573,475,614	\$886,708,227	\$1,225,465,910	\$1,322,113,017	\$1,614,652,059
4	0	\$932,311	\$566,003	\$9,859,474	\$35,782,398	\$49,843,836	\$140,505,631
	1	\$4,341,259	\$32,224,461	\$123,353,202	\$278,236,227	\$318,788,157	\$449,594,262
	2	\$16,368,995	\$228,134,279	\$431,314,584	\$664,072,750	\$734,633,394	\$940,863,366
	3	\$50,543,064	\$572,748,855	\$886,673,314	\$1,225,461,618	\$1,322,109,101	\$1,614,649,145
5	0	\$259,554	\$105,933	\$3,185,513	\$10,862,419	\$14,108,294	\$33,186,228
	1	\$1,286,648	\$9,718,363	\$27,841,875	\$49,000,478	\$56,780,510	\$90,104,951
	2	\$6,098,049	\$51,026,986	\$91,043,844	\$286,964,187	\$392,893,048	\$626,058,894
	3	\$21,016,852	\$169,079,990	\$601,057,355	\$1,058,265,740	\$1,190,584,316	\$1,513,754,745

**HOLLYWOOD**

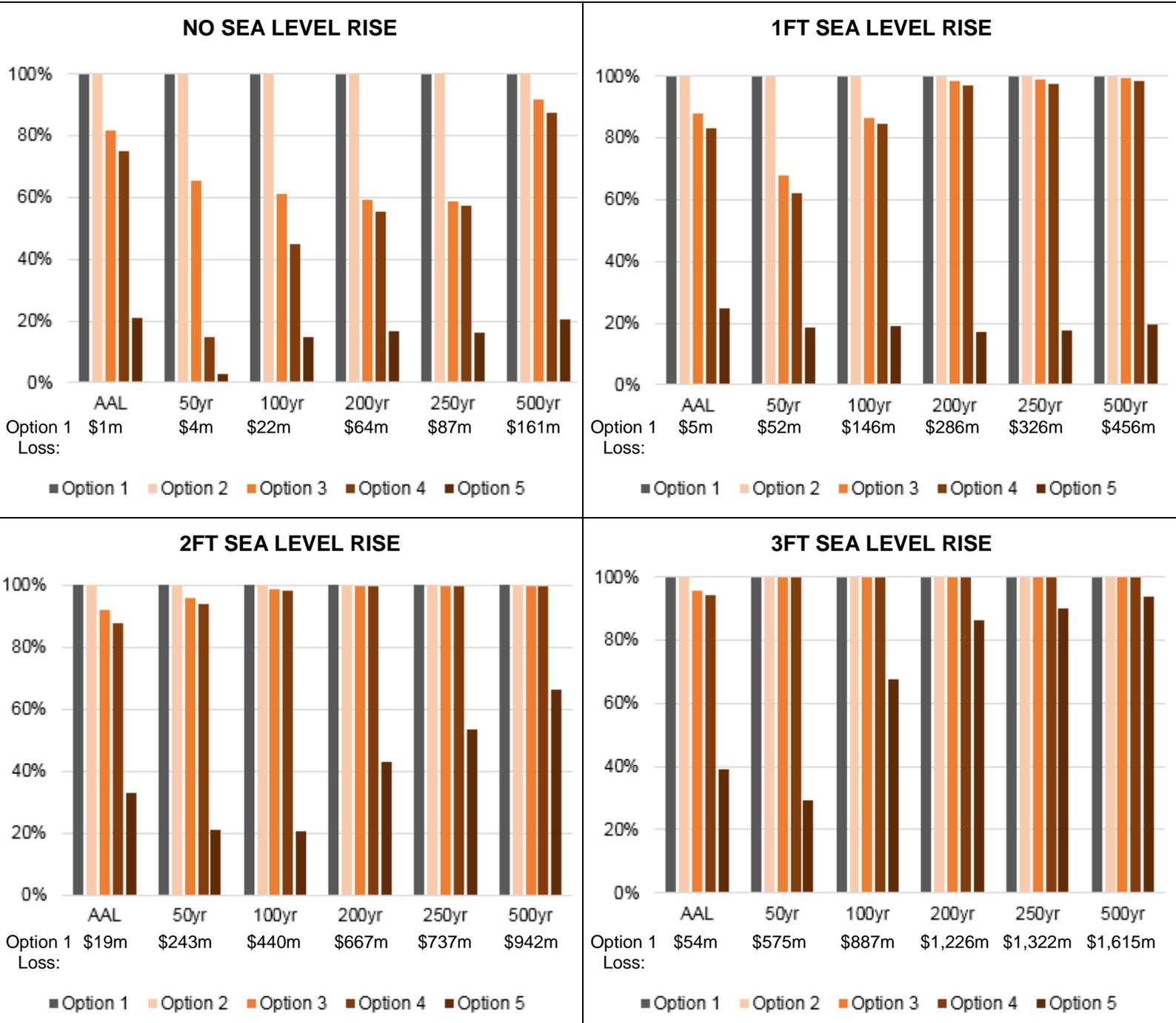
HOLLYWOOD			Return Period Losses				
Seawall Option	Sea level rise (ft)	AAL	50 Years	100 Years	200 Years	250 Years	500 Years
1	0	\$826,336	\$1,601,406	\$12,126,157	\$37,386,472	\$57,666,914	\$119,921,776
	1	\$2,883,993	\$28,295,572	\$83,994,607	\$166,379,928	\$195,315,395	\$277,711,849
	2	\$9,070,239	\$146,944,769	\$232,641,962	\$310,670,029	\$335,198,794	\$409,355,302
	3	\$24,414,896	\$292,626,825	\$366,189,740	\$440,212,496	\$464,821,458	\$542,522,711
2	0	\$826,321	\$1,601,376	\$12,126,157	\$37,386,472	\$57,666,914	\$119,921,776
	1	\$2,883,993	\$28,295,572	\$83,994,607	\$166,379,928	\$195,315,395	\$277,711,849
	2	\$9,070,177	\$146,944,769	\$232,641,962	\$310,670,029	\$335,198,794	\$409,355,302
	3	\$24,412,263	\$292,626,825	\$366,189,740	\$440,212,496	\$464,821,458	\$542,522,711
3	0	\$616,309	\$57,622	\$4,355,749	\$15,721,171	\$23,925,082	\$109,489,749
	1	\$2,309,714	\$13,278,270	\$43,850,366	\$165,591,017	\$195,108,598	\$277,709,329
	2	\$8,105,869	\$146,271,269	\$232,636,125	\$310,669,517	\$335,198,527	\$409,355,282

	3	\$23,189,844	\$292,626,819	\$366,189,740	\$440,212,496	\$464,821,458	\$542,522,711
4	0	\$616,309	\$57,622	\$4,355,749	\$15,721,171	\$23,925,082	\$109,489,749
	1	\$2,309,714	\$13,278,270	\$43,850,366	\$165,591,017	\$195,108,598	\$277,709,329
	2	\$8,105,869	\$146,271,269	\$232,636,125	\$310,669,517	\$335,198,527	\$409,355,282
	3	\$23,189,844	\$292,626,819	\$366,189,740	\$440,212,496	\$464,821,458	\$542,522,711
5	0	\$189,837	\$55,139	\$3,088,340	\$8,865,300	\$11,593,819	\$24,108,588
	1	\$797,766	\$8,536,745	\$19,381,505	\$29,770,978	\$33,234,999	\$45,138,244
	2	\$2,845,859	\$28,092,046	\$39,930,739	\$54,946,459	\$67,637,830	\$383,985,732
	3	\$8,513,250	\$49,934,074	\$159,759,212	\$427,763,334	\$456,295,925	\$539,743,957

#### FORT LAUDERDALE

Seawall Option	Sea level rise (ft)	AAL	Return Period Losses				
			50 Years	100 Years	200 Years	250 Years	500 Years
1	0	\$416,222	\$311,337	\$6,204,314	\$21,531,349	\$27,323,870	\$51,976,917
	1	\$2,334,171	\$18,474,458	\$59,171,962	\$135,920,172	\$159,448,164	\$236,861,524
	2	\$9,569,965	\$107,353,834	\$236,984,381	\$406,117,387	\$453,590,783	\$601,874,069
	3	\$29,095,137	\$304,785,572	\$552,498,528	\$839,589,715	\$914,939,891	\$1,150,934,816
2	0	\$416,210	\$311,336	\$6,204,314	\$21,531,349	\$27,323,870	\$51,976,917
	1	\$2,334,171	\$18,474,458	\$59,171,962	\$135,920,172	\$159,448,164	\$236,861,524
	2	\$9,567,583	\$107,353,492	\$236,984,381	\$406,117,387	\$453,590,783	\$601,874,069
	3	\$29,081,729	\$304,733,338	\$552,498,522	\$839,589,715	\$914,939,891	\$1,150,934,816
3	0	\$400,533	\$311,258	\$6,184,346	\$21,238,348	\$26,599,335	\$48,416,139
	1	\$2,274,070	\$17,949,668	\$54,860,315	\$131,762,950	\$155,628,302	\$234,578,584
	2	\$9,076,765	\$98,421,988	\$235,279,907	\$405,466,981	\$453,136,267	\$601,726,319
	3	\$28,009,853	\$304,680,914	\$552,496,956	\$839,588,564	\$914,938,695	\$1,150,933,579
4	0	\$316,002	\$43,775	\$489,099	\$13,861,276	\$19,974,517	\$45,087,088
	1	\$2,031,545	\$10,988,209	\$49,679,389	\$130,620,974	\$154,825,650	\$233,932,974
	2	\$8,263,126	\$95,741,871	\$233,757,806	\$405,097,009	\$452,878,557	\$601,519,160
	3	\$27,353,220	\$304,482,662	\$552,491,505	\$839,585,795	\$914,936,321	\$1,150,932,190
5	0	\$69,717	\$29,355	\$50,022	\$1,380,864	\$2,463,677	\$8,558,487
	1	\$488,882	\$1,336,768	\$7,079,120	\$18,215,700	\$22,252,972	\$38,399,481
	2	\$3,252,191	\$20,332,924	\$41,748,168	\$102,365,683	\$217,906,771	\$442,027,157
	3	\$12,503,603	\$86,129,498	\$391,412,292	\$766,128,812	\$848,785,978	\$1,095,852,771

**TABLE 9: RMS ECONOMIC IMPACT ANALYSIS – DETAILED RESULTS FOR SEAWALL UPGRADE OPTIONS UNDER DIFFERENT SEA LEVEL RISE (SLR) SCENARIOS**



**FIGURE 15: AVERAGE ANNUAL LOSS AND RETURN PERIOD LOSSES UNDER VARIOUS SEAWALL OPTIONS, AS PERCENTAGE OF CORRESPONDING OPTION 1 (BASE CASE) LOSS – NO SLR (TOP LEFT), 1FT SLR (TOP RIGHT), 2FT SLR (BOTTOM LEFT) AND 3FT SLR (BOTTOM RIGHT)**

# APPENDIX 4 – ECONOMIC IMPACT ANALYSIS FOR USACE HAZARD PROFILES

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The economic impact analysis presented in Section 4 of this report applies the exposure, vulnerability and financial components of the RMS models to its stochastic event set and associated hazard footprints. Similarly, these exposure, vulnerability and financial components can also be utilized to assess the financial impact of specific events for a given hazard footprint (“scenario”) through a so-called scenario-based, or deterministic, analysis. In contrast to a probabilistic analysis based on a stochastic event set, which aims to quantify the full range of potential losses and their associated likelihoods, a deterministic analysis examines the impact for a specific scenario in isolation, without the aim of assessing the likelihood of such scenario, or the possibility of other scenarios to occur.

For the purpose of the analysis presented in this Appendix 4, RMS was provided with a set of such scenarios by the USACE and conducted a deterministic analysis for each scenario in order to model its resulting economic impact in the study area. For each scenario, RMS received the maximum water depths (in ft above NAVD88) at each modeled grid cell in the study area, as derived by the USACE hazard analysis, RMS combined these hazard footprints with the same exposure, vulnerability and financial components as used for the economic impact analysis in Section 2 to model the financial impact of each scenario.

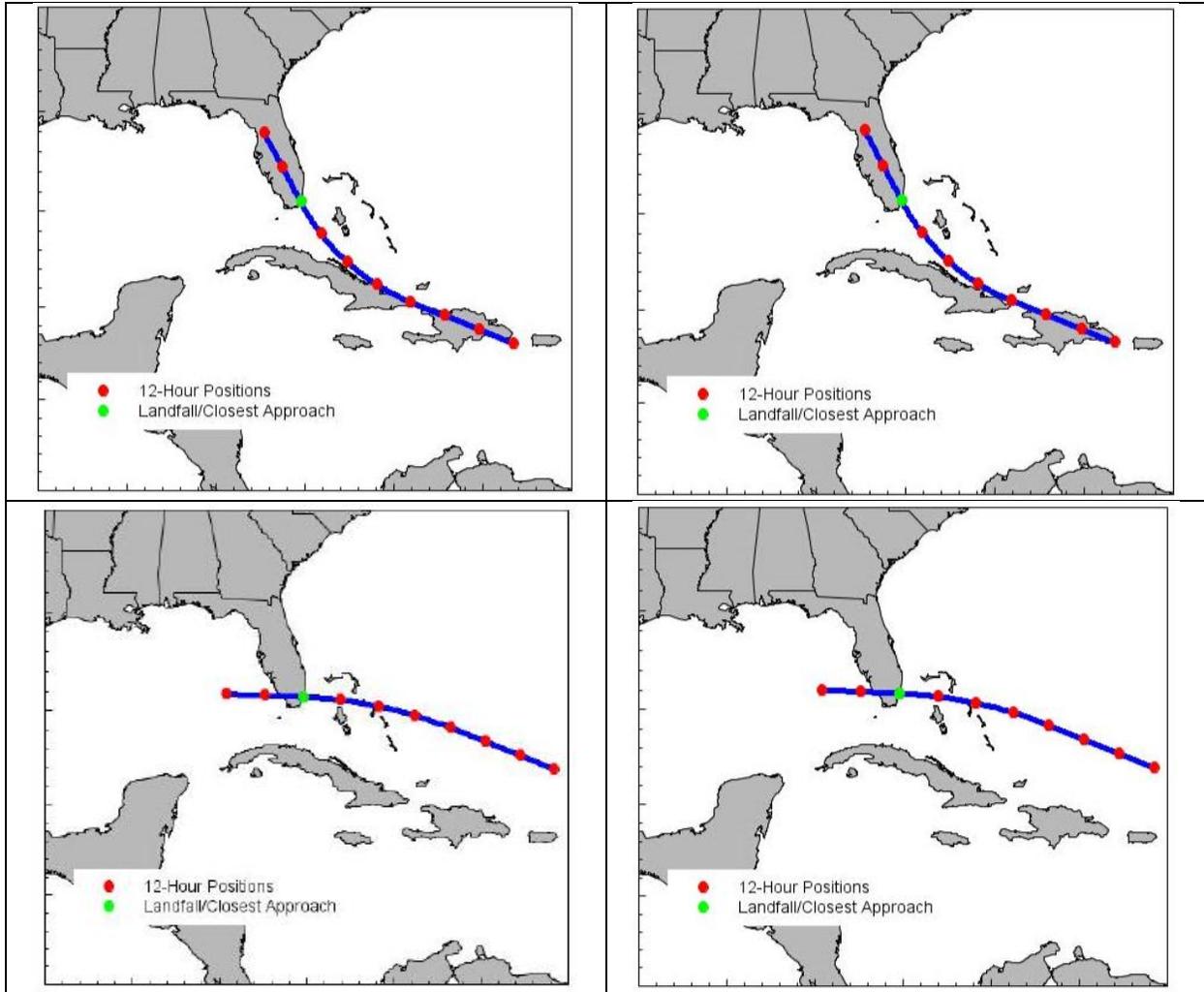
Specifically, RMS received hazard footprints developed by USACE for the four FEMA production storms 60, 61, 122 and 276 (see Figure 16).

Similar to the hazard assessment, the economic impact analysis was conducted for a base case scenario of seawall heights, as well as several alternative seawall assumptions:

- Existing conditions: The base case, which uses the currently existing seawall conditions. The assumption for this option is slightly different to the ‘Option 1 (base case)’ assumption used for the economic analysis in Section 4, which uses default elevation assumptions in the RMS model without explicitly accounting for the presence of seawalls beyond those default elevation assumptions.
- Alternative 1: This alternative assumes a minimum seawall height of 2.5ft for seawalls in the Hollywood area and 4ft for seawalls in the Fort Lauderdale area.
- Alternative 2: This alternative assumes a minimum seawall height of 4ft for seawalls across both parts of the study area. This alternative therefore uses the same seawall assumptions as Option 2 in the analysis presented in Section 4.
- Alternative 3: This alternative assumes a minimum seawall height of 6ft for seawalls across both parts of the study area. This alternative therefore uses the same seawall assumptions as Option 4 in the analysis presented in Section 4.

All hazard footprints received from USACE are based on sea levels during a king tide under sea level conditions in 2060. The water level of 3-4ft above NAVD88 was used for the modeling of this scenario. The hazard footprints are intended to reflect the following storm surge levels on top of the assumed sea level during a king tide in 2060 (3-4ft above NAVD88):

- Storm 276: No surge on top of the assumed sea level during a king tide in 2060
- Storm 60: Surge with a return period of 3 years on top of the assumed sea level during a king tide in 2060
- Storm 122: Surge with a return period of 3 years on top of the assumed sea level during a king tide in 2060, but with a different angle compared to storm 60
- Storm 61: Surge with a return period of 20 years on top of the assumed sea level during a king tide in 2060



**FIGURE 16:** FEMA PRODUCTION STORMS USED FOR THE ANALYSIS: 60 (TOPLEFT), 61 (TOP RIGHT), 122 (BOTTOM LEFT), 276 (BOTTOM RIGHT)

The results from the economic impact analysis for the existing conditions and seawall alternative 2 are presented in Table 10. The table contains the modeled mean loss for each storm, as well as the modeled standard deviation around this mean loss. This standard deviation quantifies the level of variation one could expect to see in the financial impact of the storm due to factors such as uncertainties in the vulnerability of affected buildings and in the exposure data used for the modeling.

The modeled mean losses from different storms are listed in descending order for each storm. Mean losses range from as low as \$17 for storm 122 Alternative 3 to as high as \$340M for storm 61 Alternative 3. The storm 122 in general has lower losses. Storm 276 did not produce any losses. RMS models are built to produce losses for severe hazard levels, which were not met by any of the hazard footprints developed for this storm. Similarly, the results for other storms are likely to underestimate losses from low levels of hazard, which might not be fully captured in the RMS modeling.

Another immediate observation that can be drawn is the directional shift in losses with respect to the seawall heights. It can be seen when run under Alternative 3 the losses decrease with respect to the existing conditions for all storms.

It should be noted that not all combinations of storms and seawall alternatives were included in the set of hazard footprints received by RMS. As such, only results for which hazard footprints were provided are included in this

Appendix 4. In addition, Alternative 2 did not provide significant flood protection compared to the existing conditions based on the hazard modeling conducted by USACE. This alternative is therefore not considered in the RMS results shown in the following exhibits.

Description	Seawall assumption	Modeled mean loss	Modeled standard deviation around the mean loss
Storm 60	Existing conditions	\$187M	\$35M
Storm 61	Existing conditions	\$268M	\$56M
	Alternative 3	\$112M	\$23M
Storm 122	Existing conditions	\$8M	\$2M
	Alternative 3	<\$1M	<\$1M
Storm 276	Existing Conditions	\$0	-
	Alternative 3	\$0	-

TABLE 10: MODELED MEAN LOSS BY STORM

Table 11 breaks out the modeled losses under existing seawall conditions to the two parts of the study area, Hollywood and Fort Lauderdale. Hollywood dominates the contribution towards losses for storm 60, for all other storms Fort Lauderdale dominates the losses. The corresponding breakout of modeled losses for seawall alternative 3 is summarized in Table 12; whereas Figure 17 provides a summary the results for all storms and seawall options.

Storm	Modeled mean loss – Existing conditions		
	Hollywood	Fort Lauderdale	Total
Storm 60	\$103M	\$84M	\$187M
Storm 61	\$39M	\$229M	\$268M
Storm 122	\$0	\$8M	\$8M
Storm 276	\$0	\$0	\$0

TABLE 11: MODELED MEAN LOSS BY STORM AND STUDY AREA UNDER EXISTING CONDITIONS

Storm	Modeled mean loss – Alternative 3		
	Hollywood	Fort Lauderdale	Total
Storm 60	Not analysed	Not analysed	Not analysed
Storm 61	\$2M	\$109M	\$111M
Storm 122	\$0	\$16	\$16
Storm 276	\$0	\$0	\$0

TABLE 12: MODELED MEAN LOSS BY STORM AND STUDY AREA UNDER ALTERNATIVE 3

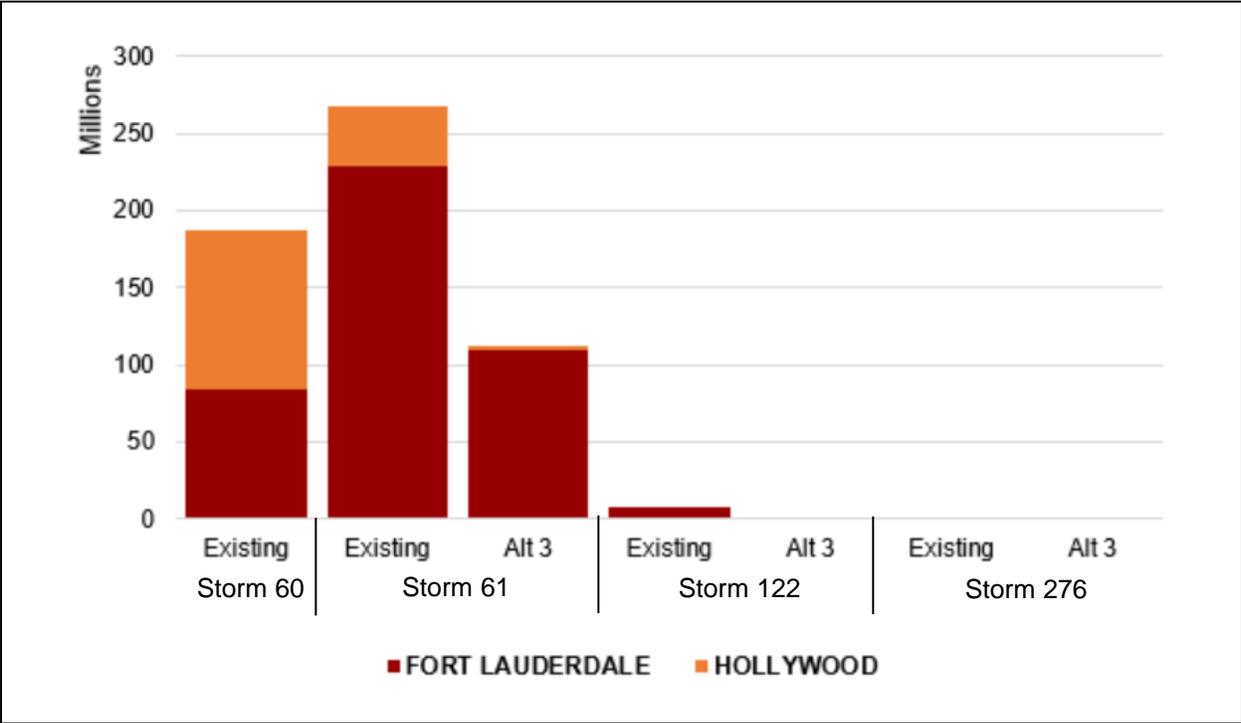


FIGURE 17: SUMMARY OF MODELED LOSSES BY STUDY AREA, SEAWALL ASSUMPTION AND STORM

# APPENDIX 5 – GLOSSARY OF TERMS

Term	Description
Storm Surge	Coastal flooding caused by extreme storms (hurricanes), as the ocean's response to extreme surface winds and low pressure associated with storm systems.
Sunny Day Flooding	Flooding which is not driven by the impact of rainfall or storm surges; typically caused by extreme high tide conditions.
Hazard	Hazard information refers to the peril-specific damage parameter of an event, such as water depth for flood events and wind speed for windstorm events.
Frequency	The rate at which something occurs over a particular period of time or in a given sample.
Exposure	Assets such as buildings and infrastructure that, when impacted by an event, can produce a financial loss for the parties responsible.
Exposure Database	A data set containing information about the location, characteristics and value of assets exposed to the peril of consideration.
Vulnerability	The susceptibility of an asset of risk to physical damage or monetary loss resulting from exposure to a hazard.
Deterministic Model	Model based on a single scenario (hazard footprint) – or a set of independently developed scenarios – of the peril under consideration. Due to being constrained to a small set of independent scenarios, deterministic models do not capture the full range of possible impacts of a given peril, or their associated likelihoods.
Probabilistic Model	A model based on a large set of simulated scenarios for the peril under consideration, which have been developed to capture the full range of potential impacts from that peril. Each simulated scenario is associated with an annual rate of occurrence, enabling the model to quantify the probability with which any given level of impact can be expected to occur.
AAL	Average Annual Loss (AAL) is the expected value of the modelled loss distribution, or the loss one would expect to see in a year on average
Return Period	The return period for a loss is the timeframe over which this loss threshold can be expected to be exceeded at least once
100 Year Return Period Loss	The loss corresponding to an event which has an annual exceedance probability of 1%, i.e. can be expected to be exceeded once in 100 years.