Development of Short- and Long-Term Strategies for Resiliency with respect to Flooding in Miami-Dade County

A quick scan model for assessing the effectiveness of adaptation options

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Executive Summary

Flooding from rainfall events in Miami Dade County is becoming a serious threat as sea levels rise, and the ability to drain water to the bay via gravity drainage is hindered. In the C-7 basin in North Miami, gravity drainage through the S-27 outlet structure is already impossible during high surge levels. Mitigation and adaptation options are needed, but the uncertainty in the rate of sea level rise can hamper the decision-making process about which measures to implement, and when to best implement them. In 2017, Deltares and the South Florida Water Management District (SFWMD) investigated the use of adaptation pathways to support decision-making. In this approach, the effectiveness – in terms of risk-reduction – of flood mitigation and adaptation options is assessed under current and future sea levels. Each option has its own shelf life – the sea level at which it is no longer effective. The adaptation pathways show sequences of measures over time, which identify short-term actions that work well with mid- to longer-term actions that will be needed in the future.

The hydrologic-hydraulic and damage modeling that was carried out in 2017 to support the risk-based assessment in the C-7 basin was time-consuming, and limited the number of drivers (precipitation, sea level rise), mitigation/adaptation options, and tolerable risk thresholds that could be considered.

The current study builds on the 2017 study by developing a fast, simplified model framework that can be used to assess the risk-reduction capacity of mitigation/adaptation options, and their shelf-lives, to support the development of adaptation pathways for a larger region. This fast model framework, referred to here as a quick-scan tool, was developed and calibrated for the C-7 basin using the results of the 2017 study, and then applied to four additional basins: C-2, C-3W, C-4, and C-6. The model can run many combinations of sea level rise, measures, and basins in under 30 seconds, which makes it suitable for use in workshop settings. The quick-scan model serves as a prototype, demonstrating how simplified models can provide a meaningful overview of risk, the effectiveness and shelf-lives of measures in different locations, for use in early-phase adaptation planning.

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1 Introduction

South Florida is one of the most vulnerable areas to climate change. Communities are in urgent need of advice on possible adaptation or mitigation actions in the short-term to combat current flood risk, while also taking a long-term view that accounts for urban development, sea-level rise, and potential increase in intensity and frequency of storms. Because of the high level of uncertainty in rate of sea level rise, and the substantial costs of adaptation, a traditional approach of "predict and act" runs the risk of either over-investing or under-protecting. To address these uncertainties, adaptive approaches have emerged in the last decade. The Dynamic Adaptive Policy Pathways (DAPP[1]) approach was developed for the Dutch Delta Program, a national plan for flood protection and water supply in the Netherlands through 2100. DAPP has since been applied and adopted in national guidelines around the world. DAPP focuses on developing adaptation pathways, which are sequences of adaptation and mitigation actions over time that ensure community objectives (e.g. tolerable flood risk) are met. The pathways enable decision-making on actions that can be taken now, while keeping mid- and longer-term actions open as the future unfolds and we gain more clarity about when those future actions will be needed.

In 2017, South Florida Water Management District (SFWMD) and Deltares USA, together with Miami-Dade County, and involving several city governments, explored the use of DAPP to evaluate the effectiveness of, and prioritize between, several potential adaptation and mitigation actions. With NOAA funding, this study focused on the C-7 Basin[2,3] in Miami-Dade County, and applied an economic/risk-based approach to test the efficiency of measures and develop adaptation pathways, with collaboration from hydraulic engineers, planners, economists, and stakeholders. The 2017 study is hereafter referred to in this report as the 2017 C-7 study. Figure 1-1 gives an overview of the modeling framework that was followed to develop the adaptation pathways in the 2017 C-7 study. The main model components were a hydrodynamic model (XPSWMM) and an economic damage model (Delft-FIAT) which together were used to calculate risk for several adaptation and mitigation options under three sea levels. The risk growth under sea level rise was used to estimate adaptation tipping points - the sea level at which current flood risk was exceeded – for each adaptation/mitigation option. These tipping points were used to develop the adaptation pathways.

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[1] *Haasnoot, M., J.H. Kwakkel. W.E. Walker, J. ter Maat. (2013) Dynamic Adaptive Policy Pathways: A New Method for Crafting Robust Decisions for a Deeply Uncertain World, Global Environmental Change, http://doi.org/10.1016/j.gloenvcha.2012.12.006.*

[2] *Bouwer, L.M. Haasnoot, M., Wagenaar, D., Roscoe, K. (2017). Assessment of alternative flood mitigation strategies for the C-7 Basin in Miami, Florida. Report 1230718-000, Deltares USA.*

[3] *South Florida Water Management District. 2017. Flood Protection Level of Service for the Basins C7, C8 and C9. Identification and Mitigation of Sea Level Rise Impacts. Deliverable 3.4.1. Final Report Flood Protection Level of Service Provided by District Infrastructure for Current (2015) Sea Level Conditions and Future and Three Future (2065) Sea Level Rise Scenarios for the C7 Basin.*

The results of the 2017 C-7 study helped clarify the need for longer-term adaptation options outside drainage infrastructure improvements; it showed that as sea levels rise, those infrastructure improvements will reach their end-date – the tipping point when they cannot keep risk low enough. The study underscored the need for longer-term solutions like elevating roads and structures to meet flood risk targets as sea levels rise.

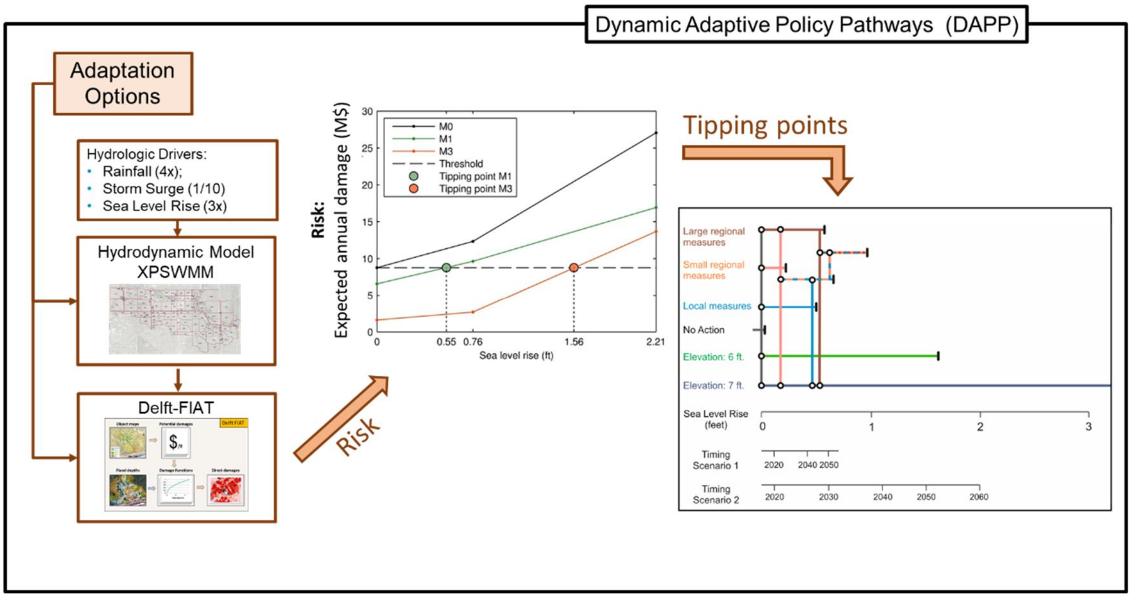


Figure 1-1 Modeling framework used in the 2017 C-7 study to develop adaptation pathways

The current study described in this report, funded by the Florida Department of Environmental Protection, Florida Coastal Management Program, was initiated to expand on the 2017 C-7 study. The objectives are to help support the community in understanding the adaptive DAPP approach, and to gain quick insight into current and future flood risk – with and without adaptation interventions – at a larger spatial scale, under rising sea levels. It focuses on developing a fast hydrologic-hydraulic component that can be combined with Delft-FIAT to rapidly calculate damages, risk, and adaptation tipping points for inputs of climate drivers (precipitation, sea level rise), adaptation options, and risk thresholds.

The quick-scan model was developed first for the C-7 basin and calibrated using information and results from the 2017 C-7 study. Once the quick-scan model was developed for C-7, it was expanded to the C-2, C-3W, C-4, and C-6 basins. Figure 1-2 shows the locations of the basins included in this study.

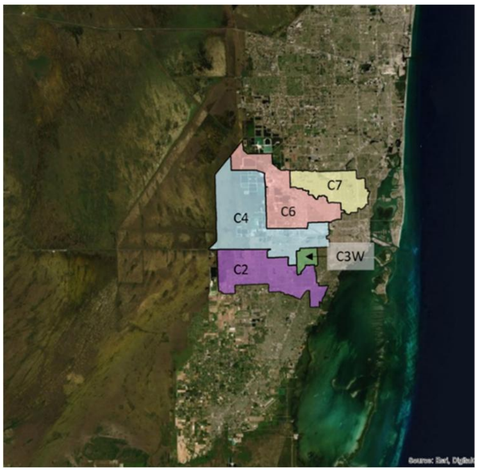


Figure 1-2 Location of the five basins to which the quick-scan model was applied

The content of the report is structured as follows: Chapter 0 describes the development and calibration of the quick-scan model for C-7; Chapter 3 describes the application of the quick-scan model to the additional basins C-2, C-3W, C-4, and C-6; Chapter 0 presents results of the model; and Chapter 5 presents conclusions and recommendations for the use and further development of the model.

The DAPP method and the quick-scan tool developed in this project were presented during a webinar (also referred to as an online workshop) on November 19, 2019, with 146 attendees. The SFWMD, FIU, and Deltares all took an active role in the webinar. The attendees were predominantly Florida-based, with diverse affiliations ranging from government officials to consultants to academics. Appendix A provides a workshop report, including a summary, the presentations given in the webinar, and an overview of the participating institutes (institute and number of participants).

This project consisted of several tasks; Table 1-1 identifies which section of this report documents the results of the individual tasks.

Task	Report Location
Task 1 Identification of measures	Sections 2.5.2 (hydraulic measures) and 2.5.5 (land-use measures)
Task 2: Development, flood impact tool	Chapter 2 & 3 (Model development + Application to other basins)
Task 3: Assess measures	Chapter 4 (Results)
Task 4: Stakeholder workshop	Appendix A (Workshop report)
Task 5: Reporting	Entire report

Table 1-1 Project tasks and associated location in the report where the task is described.

2 Model development

In this project, we developed a prototype of a quick-scan model to assess the effectiveness of hydraulic and land-use measures, in support of developing adaptation pathways. The model is intended to support early-phase exploration of adaptation measures over a regional scale to determine which measures and which locations have the highest potential to achieve adaptation goals. The objective of an early-phase quick-scan model is to help tailor the more expensive, detailed investigations into adaptation options that would follow a quick-scan assessment. The hope is that such a model can weed out ineffective options early on with little investment, and home in on the most promising options.

The model requirements that were considered in the development of the quick-scan model were that it be able to:

- Calculate flood depths for multiple combinations precipitation and sea level rise with a fixed 10-year surge level
- Calculate the economic damages associated with those flood depths
- Simulate both hydraulic measures and land-use measures/changes
- Compute risk with and without measures
- Estimate the tipping points (shelf lives) of measures for various risk thresholds
- Calculate all the above within a few minutes

2.1 Model framework

The model framework, at the highest overview level, is illustrated in Figure 2-1. It highlights the inputs that go into the quick-scan model, and the output from the model. Inputs to the model are: precipitation probabilities and corresponding precipitation depths, sea level rise, land use, hydraulic interventions and land-use interventions. The model outputs economic damages, and by calculating the economic damages for multiple precipitation probabilities, we can combine the probabilities and the damages to estimate the annual expected damage, which is the metric we use for risk.

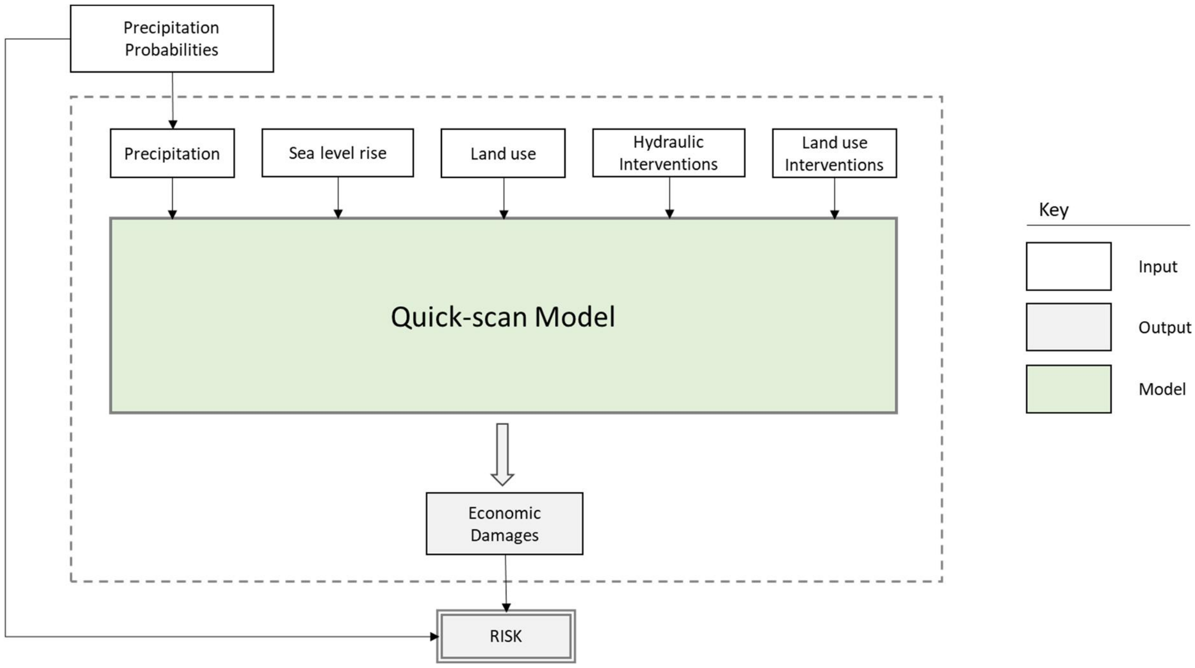


Figure 2-1 The quick-scan model framework at a high abstraction level, highlighting inputs and outputs.

Figure 2-2 shows a little more detail about the internal architecture of the quick-scan model. There are two main modules contained within the model: (1) a hydraulic module that produces flood depth maps and (2) a damage module that calculates economic damages for a given flood depth map. The figure indicates which input is relevant for which module. The following sections describe the hydraulic and damage modules in detail.

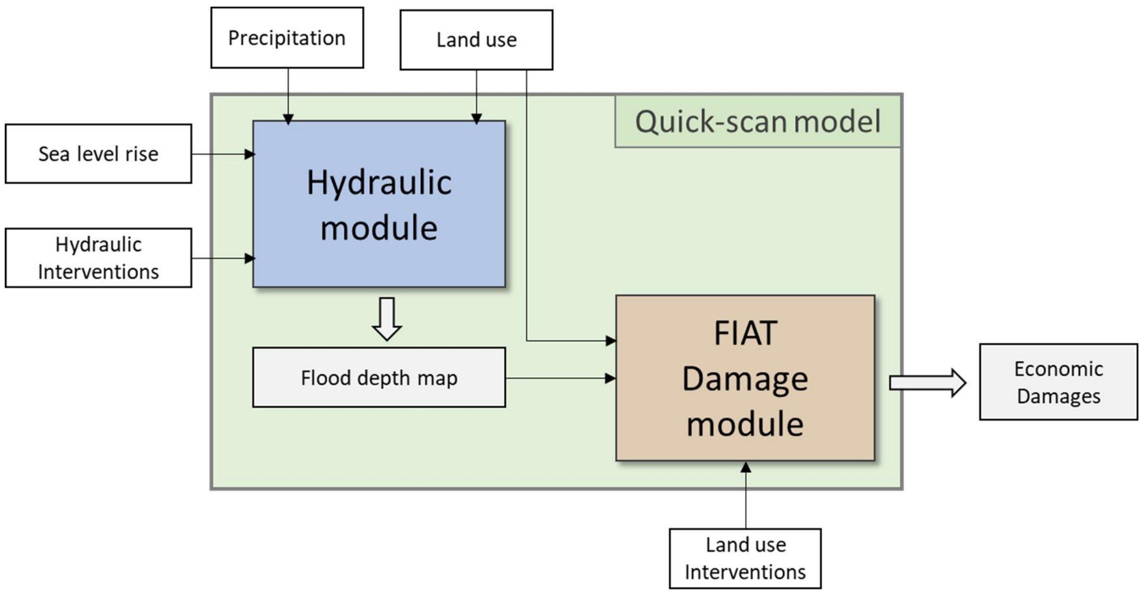


Figure 2-2 The quick-scan model framework showing the internal modules that transform input into flood depth maps and damage estimates.

2.2 Quick-scan hydraulic module

The hydraulic module is elaborated in Figure 2-3. The module contains a hydrologic component and a hydraulic component, but is referred to collectively in this report as the hydraulic component. The curve number method is used to estimate runoff for a given precipitation event and information on land use; this is the hydrologic component. The outflow represents the water that drains out of the basin via the drainage infrastructure, and is calculated using a precipitation-outflow curve that was derived from historic data; this is the hydraulic component. The flood water (or inundation water) is calculated as the runoff minus the outflow. The flood water is then distributed based on elevation data, and the result is a flood depth map. Each of these components of the hydraulic module is described in more detail in the following sections.

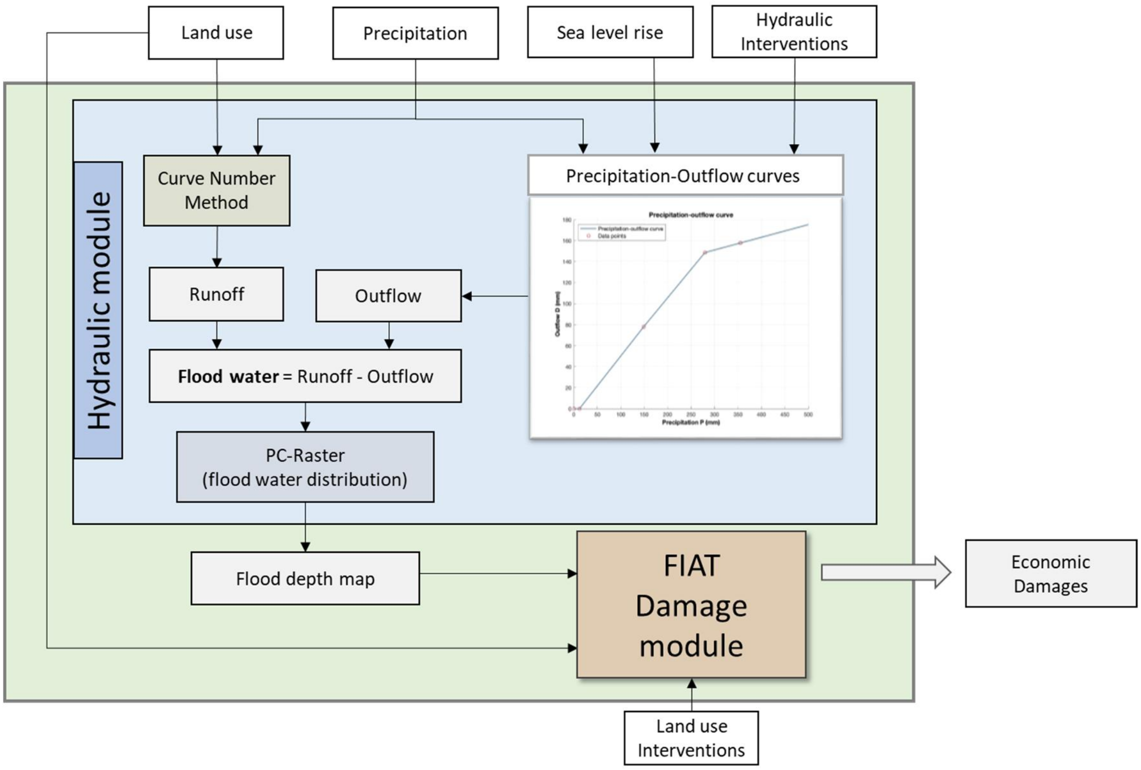


Figure 2-3 The architecture of the hydraulic module within the quick-scan model.

2.2.1 Curve number method

The Curve Number (CN) method[4] was developed by the Soil Conservation Service to estimate the direct runoff Q resulting from a rainfall event and is used in the quick-scan model exactly for this purpose. Based on the hydrologic soil group, cover type, treatment and hydrologic condition of the watershed, the SCS runoff Q is calculated as follows:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{1}$$

[4] *United States Department of Agriculture (1986). Urban hydrology for small watersheds (PDF). Technical Release 55 (TR-55) (Second ed.). Natural Resources Conservation Service, Conservation Engineering Division.*

where Q is the direct runoff, P is the precipitation, S is potential maximum water storage after runoff begins and I_a represents initial abstraction before runoff begins. The initial abstraction I_a refers to the initial status of water losses before runoff occurs. It includes water stored in surface depressions, water intercepted by vegetation, evaporation and infiltration, and is generally assumed to be equal to 0.2 S. The potential maximum water storage S is calculated using the curve number CN which is related to the soil and hydraulic conditions of the watershed. CN (ranging from 0 to 100) directly indicates the infiltration ability and determines S by:

$$S = \frac{1000}{CN} - 10 \qquad (2)$$

The curve number CN is determined by the hydrologic soil group, hydrologic condition, treatment, cover type, impervious area occupancy and antecedent runoff condition of the watershed.

2.2.2 Precipitation-outflow curve

A portion of the runoff Q generated from a precipitation event flows out of the system via drainage infrastructure. To account for this, we introduce two terms, the outflow D, which is the amount of water that flows out via drainage infrastructure, and the flood water F, which is the amount of water that remains on the land surface: $F = Q - D$. The rainfall, runoff, outflow, and flood water are expressed in units of depth (e.g. inches). For the outflow, the volume was first calculated, and was then divided by the area of C-7 to obtain units of depth.

Flood water

The flood water ($F = Q - D$) can be considered an average flood depth over the basin. It is the volume of water remaining in the basin due to a rainfall event, after infiltration and drainage have been accounted for, divided by the area of the basin.

For a given precipitation event, we can calculate the runoff Q using the CN method. To calculate the outflow D through the drainage infrastructure during a given precipitation event, we developed precipitation-outflow curves using historic data.

The SFWMD maintains long-term discharge and water level records at the outfall S-27 in the C-7 basin. Measured precipitation and headwater outflow discharge rates of three historic storms were used to estimate the outflow volumes for these three precipitation events. The three historic storms are: (1) 1998 November Storm, (2) Hurricane Irene (1999), and (3) the No-Name Storm (2000). Details of these events can be found in the sidebar text.

Historic events

Historic Event 1: 1998 Nov Storm

The 1998 Nov Storm began on November 4th in 1998, reaching its highest rainfall of 5.9 inches at around 9:00 on the same day. The period of rainfall and headwater discharge data of this storm was selected from October 25th to November 15th.

Historic Event 2: Hurricane Irene

Hurricane Irene (also known as the 1999 Storm) began at round 9:00 on October 13th in 1999, reaching the peak on the afternoon of the 15th. The rainfall distributed over the C-7 basin varying from 9 inches to 16 inches, with the average of 11 inches. The period of rainfall and headwater discharge data of this storm was selected from October 5th to October 31st.

Historic Event 3: No-Name Storm

The high intensity No-Name Storm began on October 2nd in 2000 at around 07:30 with the peak of the storm occurring on the afternoon of the 3rd. Rainfall of this storm was 15.3 inches at the gauge, 14 inches over the most areas and 13 inches at the inland area. The period of rainfall and headwater discharge data of this storm was selected from September 20th to October 20th.

The total outflow volume for the precipitation event was calculated by multiplying the average outflow discharge rate[5] by the duration of the event. The outflow volume was then divided by the area of the C-7 basin to derive the outflow depth.

The durations of the events were chosen based on outflow time series patterns and expert advice from the SFWMD. We used a 5-day period for the 1998 November Storm and a 7-day period for Hurricane Irene and the No-Name Storm.

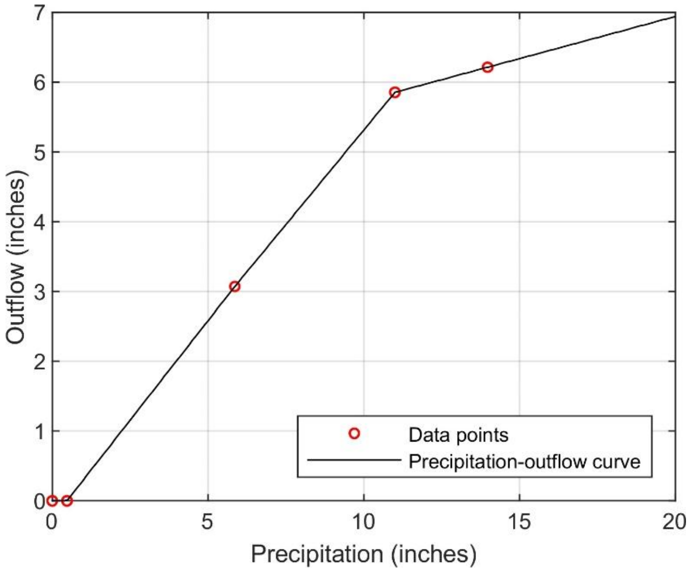


Figure 2-4 Precipitation-outflow curve for C-7

The precipitation-outflow curve shown in Figure 2-4 was constructed using five known data points: zero precipitation (no outflow), precipitation equal to the initial abstraction I_a (no outflow), and the precipitation-outflow data from the three historic storms described in the sidebar. In addition, the outflow is constrained to never exceed the recorded maximum discharge of the control structure S-27 (1992 cfs). This translates to a maximum outflow depth of 11.6 inches.

2.2.3 Inundation mapping

The flood water remaining on the land surface for a given precipitation event is calculated by subtracting the drainage-system outflow from the runoff: $F = Q - D$. Inundation maps were created by distributing the flood water over the basin using information on elevations.

2.3 Quick-scan damage module and risk calculation

Figure 2-5 presents details of the damage module Delft-FIAT. Flood damages were calculated using Delft-FIAT, a set of Python scripts developed by Deltares to calculate detailed damages per land-use category (e.g. residential, industry etc.), based on inundation maps, exposure (object) maps, the vulnerability of each category to flooding (maximum damages), and the damage functions of each category.

[5] *The outflow data was translated into a 12-hour moving average discharge In order to filter out tidal variations*

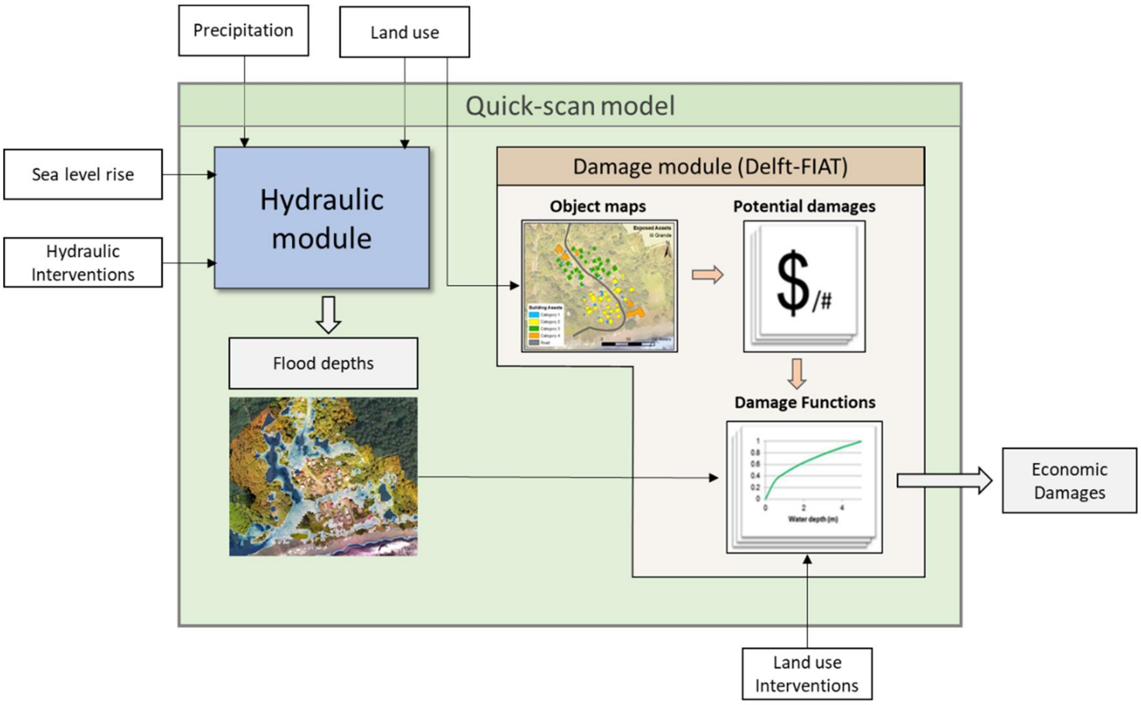


Figure 2-5 The work flow of the flood impact model Delft-FIAT, and how it fits into the quick-scan model.

2.3.1 Object maps

Four GIS shape layers were used to extract geographical inputs for the object (exposure) maps:

- Land-use data
- Small building point data
- Large building polygon data
- Road network polyline data

The small and large building data is used to differentiate buildings according to the size. All single-family houses are indicated by the small building point data with an equal footprint size. Since no building type information is provided by the large building polygon data, the land-use data is therefore used to make detailed classification of the large building data. Seven categories were defined based on the land-use data: Residential, Commercial, Office, Institution, Industry, Airport and Others. ArcGIS was used to separate the large building map into exposures for each land-use category with the number of square meters of buildings. Figure 2-6 shows point and polygon building data for an area within the C-7 basin.

Figure 2-6 Small and large building data within the C-7 basin, shown for an example area within the basin.

The road data from Miami-Dade County is polyline data, which we converted to polygon data by adding buffers to both sides of the lines based on the street width. This allowed us to determine the area of a road that is inundated, and therefore the area of the road which is potentially damaged.

Figure 2-7 An example of road polygon data visualized against satellite image in the C-7 basin. Green polygons refer to the road with buffers and red is the road network.

The road damage function is based on the replacement and reconstruction cost of the damaged roads due to water inundation. The C-7 basin has a conservative recession rate of 0.3 feet per day according to measured data. In the 2017 C-7 study, it was suggested that this recession rate (0.3 feet/day) and a flooding period of 48 hours (roads must be rebuilt when inundated more than 2 days according to County staff) should be applied to the road damage calculation. This results in roads being regarded as damaged with a flooding depth of 0.6 feet or greater in the damage calculation.

In the C-7 study, a $120 replacement cost per lane (8 feet) per foot was applied. This was translated into an equivalent cost of $15 per square foot in our damage estimate to roads.

2.3.2 Damage functions and maximum damages

Damage functions show the relationship between flood depth and damage (as a fraction of a maximum damage value). The US flood damage model HAZUS contains damage functions and maximum damages for numerous building categories (e.g. residential, commercial, etc.). Figure 2-8 shows an example damage function for residential structures.

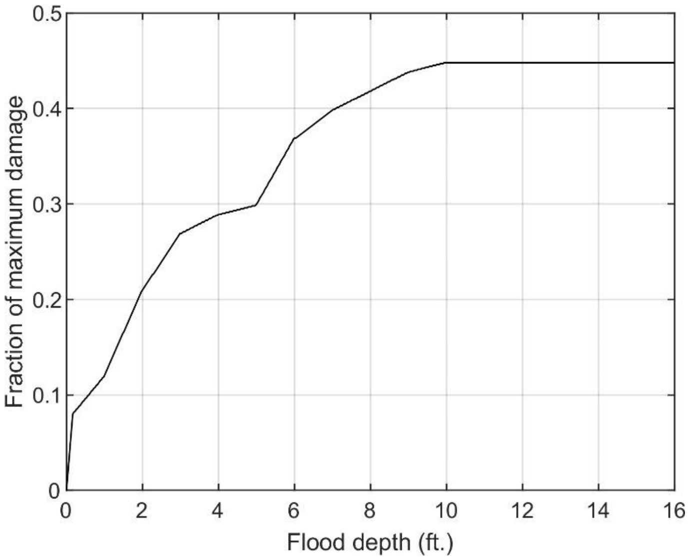


Figure 2-8 Damage function for residential structures in the C-7 basin, showing the fraction of total damage as a function of (flooded) water depth.

The economic damage estimate Dmg (in $) is calculated according to Eq. (3), where d is the flood depth, f is the fraction of the maximum damage, and M is the maximum damage (in $).

$$Dmg = f(d) \cdot M \tag{3}$$

For each building category, there are damage functions for both structural and content damages. For the Airport and the Other category, there are no corresponding HAZUS damage functions, so we used the average of the Commercial and Industry categories. Appendix B provides a table of building categories with associated data types, land-use classes, HAZUS damage functions and applied maximum damages.

2.3.3 Damage verification

In the 2017 C-7 study, damages were verified using flood insurance claims from the No-Name storm from 2000. To verify the quick-scan model damage calculation, the flood depth map for the No-Name Storm from the 2017 C-7 study (calculated using the XPSWMM model) was used as input to the quick-scan damage module for the C-7 basin and then the modeled damages were compared with the 2017 C-7 study. For the damage comparison, flood depth maps were constrained to targeted sub-basins only because the 2017 C-7 study was limited to a sub-set of target sub-basins within C-7.

Table 2-1 Damage comparison between the quick-scan model and the 2017 C-7 study for the 2000 No-Name storm.

	2017 C-7 study	Quick-scan model
Houses Structure (k$)	8,145	13,154
Houses Content (k$)	4,316	6,627
Houses total	12,461	19,781
Offices (k$)	289	46
Industry (k$)	602	7.840
Institutions (k$)	632	732
Commercial (k$)	-	294
Other (k$)	403	2,595
Roads (k$)	50,024	15,678
Total (k$)	64,433	46,966

Table 2-1 shows the damage comparison with the C-7 study for the 2000 No-Name Storm case. In general, the two damage estimates are in the same magnitude, but the quick-scan model damage calculation is around $17 million lower the 2017 C-7 study estimate. The main difference is on the road damage calculation (the quick-scan model estimate is around one-third of the 2017 C-7 study estimate) with our estimate being better aligned with the real road costs.

The county official data tells that the costs of road repairs after the 2000 No-Name storm were totaled to $165 million on the reconstruction and resurfacing work for 355 miles roads during 2002 and 2006. This translates to approximately 0.46 million dollars per mile. From these two modeled damage assessments, an estimated 42.4 miles of two-lane roads had to be repaired/replaced for the selected sub-watersheds (at a cost of about $50 million based on the 2017 C-7 study and about $16 million based on the quick-scan model). The unit cost based on the quick-scan model estimate is around 0.47 M$/mile, and based on the 2017 C-7 study is around 1.17 M$/mile. This indicates the 2017 C-7 study estimate is too high and the quick-scan model is reasonably aligned to the real costs of the road repairs.

For other categories, the damage differences are minor. These differences can be explained by 1) differences in the DEMs (the quick-scan model uses a more recent DEM), 2) construction of new buildings and land-use changes that have taken place in the past two years, and 3) differences in resolutions (quick-scan model uses a resolution of 32x32 ft^2 while the 2017 C-7 study used a resolution of 20x20 ft^2).

2.3.4 Calculating risk

The expected annual damage (EAD) is a metric for risk. As expressed in Equation (4), EAD is the integral over all flood events E of the probability of the event P_E times the consequences (damages) C_E resulting from that event.

$$EAD = \int_{events\ E} P_E \cdot C_E \cdot dE \tag{4}$$

The EAD can be thought of as the area under the probability-damage curve (see the pink area in Figure 2-9). We approximate the area numerically by adding up the area under the probability-damage curve derived for a select number of events. The area under the probability damage curve composed of four events, the 5-, 10-, 25-, and 100-year events, can be calculated by summing up the rectangles and triangles under the curve, as illustrated in Figure 2-9.

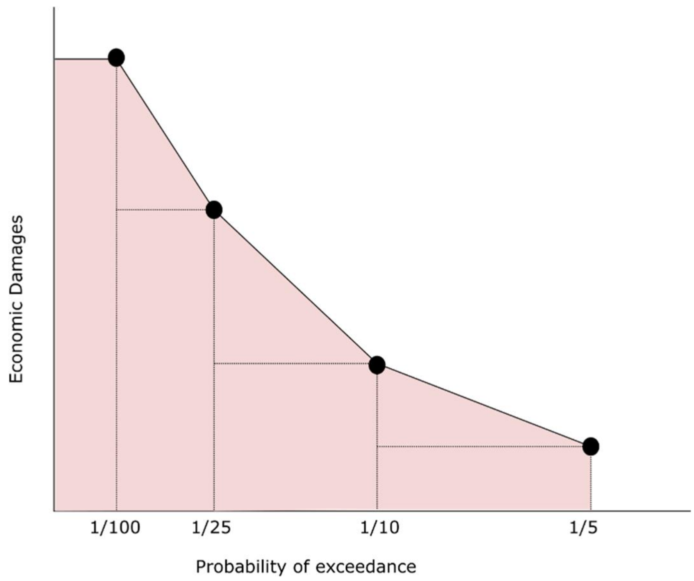


Figure 2-9 Illustration of the risk calculation – the pink area is a numerical approximation of the expected annual damage.

In this study, only the probabilities of the rainfall were considered in calculating the risk, which is a simplification. Each rainfall event is simulated under the assumption of a 10-year storm surge level. This is because the quick-scan model was calibrated to the results of the 2017 C-7 study, which made the same simplification. For a more comprehensive risk assessment, combinations of different surge levels and precipitation should be evaluated, including the joint probability of surge and precipitation.

2.4 Calibration

The quick-scan hydraulic module was calibrated using results from the 2017 C-7 study. The available data used in the calibration were water surface elevations for four precipitation events: the 5-, 10-, 25-, and 100-year precipitation events. The 5- and 10-year precipitation events were simulated in the 2017 C-7 study with a duration of 24 hours and the 25- and 100-year precipitation events were simulated with a 72-hour duration.

Return period	Precipitation
5-year	7 inches
10-year	8 inches
25-year	14 inches
100-year	17 inches

Table 2-2 Return periods and associated precipitation used in this study and in the 2017 C-7 study.

In the 2017 C-7 study, the DEM was subtracted from the water surface elevations to estimate the water depths; these are referred to as the reference flood depths and were used in the calibration. Terminology used to describe the calibration is clarified in Table 2-3.

Terminology	Meaning
Reference flood depths	Flood depths calculated in the 2017 C-7 study
Quick-scan flood depths	Flood depths calculated with the hydraulic module of the quick-scan model
Reference damages	Damages associated with the reference flood depths (damages calculated with the quick-scan FIAT damage module)
Quick-scan damages	Damages associated with the quick-scan flood depths, calculated with the quick-scan FIAT damage module

Table 2-3 Clarification of terminology for the calibration discussion.

The calibration is illustrated in Figure 2-10. The precipitation-outflow curve was adjusted to minimize the differences between the reference damages and quick-scan damages, for the four precipitation events for which reference flood depths were available. The Delft-FIAT damage module developed for the quick-scan model was used both for the reference flood depths and for the quick-scan flood depths. Thus, any differences in damages are solely due to differences in flood depths. Minimizing differences in damages to calibrate the precipitation-outflow curve was preferred over minimizing differences in flood depths, because it is an aggregate metric, and of particular interest in estimating risk.

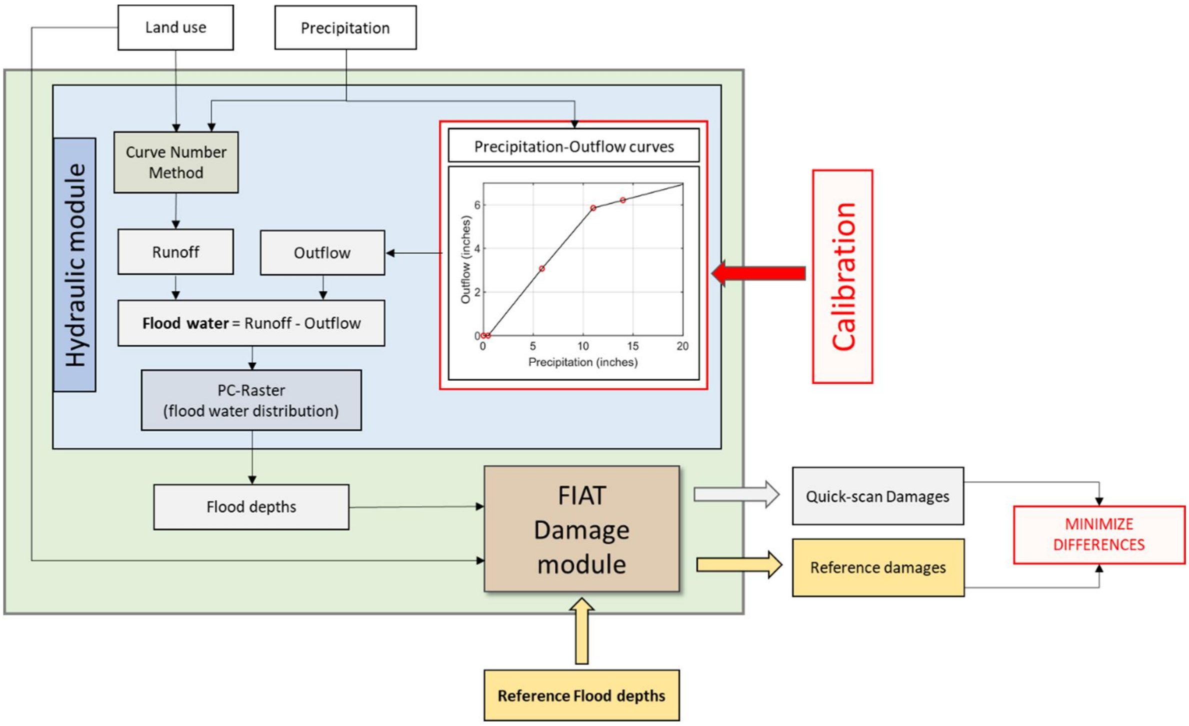


Figure 2-10 Illustration of the calibration of the precipitation-outflow curve to minimize differences between reference damages and quick-scan damages.

Figure 2-11 shows the original precipitation-outflow curve, based on the three historic storms described in Section 2.2.2, and the calibrated precipitation-outflow curve. Figure 2-12 shows the corresponding damages. The *original quick-scan damages* result from flood depths calculated with the original precipitation-outflow curve, and the *calibrated quick-scan damages* result from flood depths calculated with the calibrated precipitation-outflow curve; the reference damages are also shown. With the calibrated precipitation-outflow curve, the quick-scan damages very closely match the reference damages. The calibration compensates for updated drainage infrastructure implemented since the three historic rainfall events that were used in the derivation of the original precipitation-outflow curve.

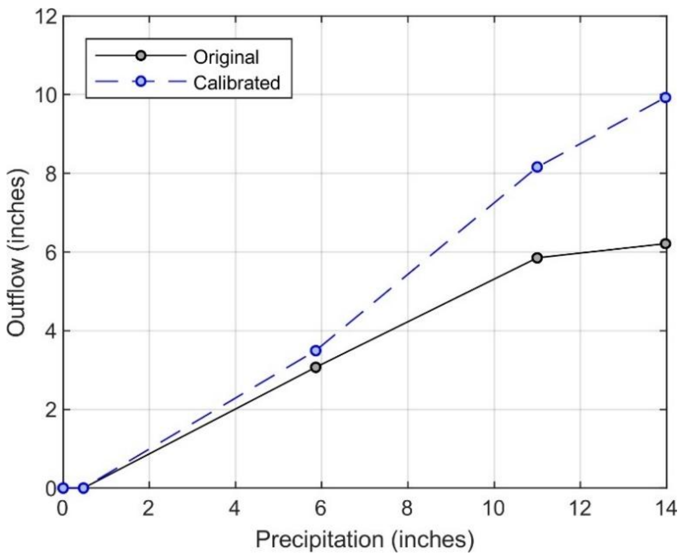


Figure 2-11 Original (based on historic measurements) and calibrated precipitation-outflow curves for C-7

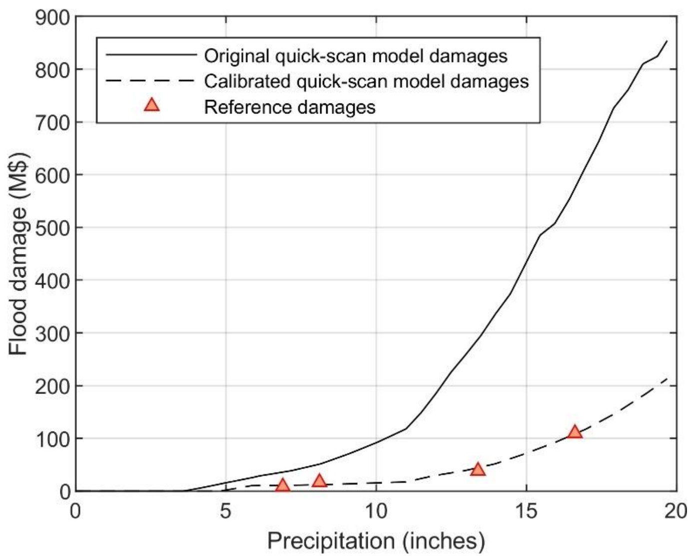


Figure 2-12 Quick-scan damages for targeted sub-basins in C-7 based on original and calibrated precipitation-outflow curves, compared with the reference damages

The XPSWMM model used in the 2017 C-7 study included updated drainage infrastructure, so correcting to the damages obtained with the XPSWMM flood depths implicitly corrects for the missing drainage capacity in the quick-scan model pre-calibrated outflow curve.

2.5 Simulating sea level rise and adaptation measures

Sea-level rise and hydraulic adaptation measures are implemented in the quick-scan model by modifying the precipitation-outflow curve. Sea level rise will reduce the ability to drain water out of the basin to the bay and will therefore reduce the outflow for a given precipitation. This has the effect of a downward shift in the precipitation-outflow curve. Hydraulic adaptation measures have the opposite effect; they improve the ability to drain water from the system and therefore result in an upward shift of the precipitation-outflow curve. To simulate the impact of land-use measures, we modified the damage functions used in the Delft-FIAT model.

For sea level rise and the hydraulic measures, we determined the effect on the precipitation-outflow curve using results from the 2017 C-7 study. The results we used – and sought to replicate – were the changes in risk that resulted from either sea level rise or the implementation of a measure.

2.5.1 Sea level rise

In the 2017 C-7 study, risk was calculated for current sea level (CSL) and two sea level rise scenarios: sea level rise scenario 1 (SLR1), which predicts a sea level rise of 0.76 ft. in 2065, and sea level rise scenario 3 (SLR3), which predicts a sea level rise of 2.21 ft. in 2065. The values associated with these scenarios are shown in Table 2-4. The risk increase calculated in the 2017 C-7 study due to sea level rise is shown in Table 2-5.

Scenario	Sea level rise (ft.)
CSL	0.00
SLR1	0.76
SLR3	2.21

Table 2-4 Sea level rise scenario and associated sea level increase in feet.

Sea level rise scenario	Percentage risk increase
SLR1	40%
SLR3	208%

Table 2-5 Sea level rise scenario and associated increase in risk, based on results of the 2017 C-7 study.

Figure 2-13 shows a schematic of how the quick-scan model is used to calculate risk, at an overview level. The model was run for the four precipitation events shown in Table 2-2, and the associated damages and precipitation probabilities were combined into risk. This was done for CSL, SLR1, and SLR3, using the calibrated precipitation-outflow curve.

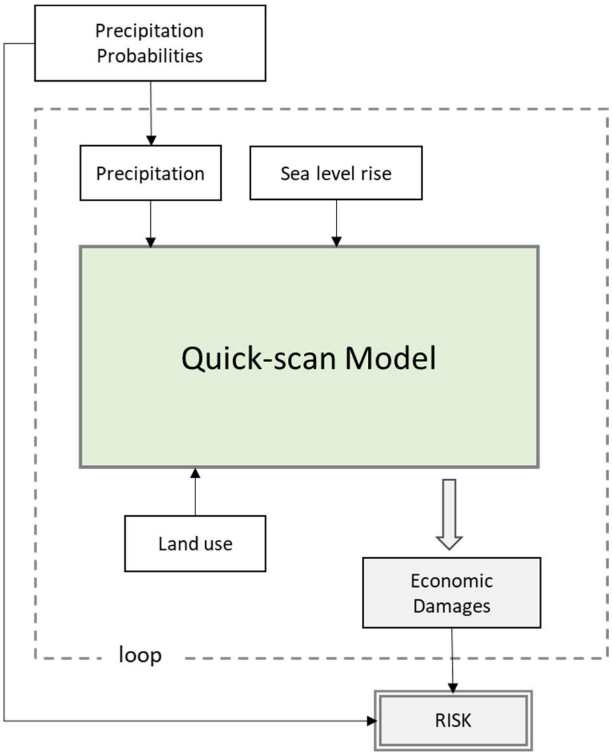


Figure 2-13 Schematic overview of how the risk was calculated for different values of sea level rise inputs.

The precipitation-outflow curve shifts downward under sea level rise (less ability to drain water). A multiplicative shifting factor λ_{SLR} was defined so that the outflow for a precipitation p under sea level rise ($O_{SLR}(p)$) is a fraction $1-\lambda_{SLR}$ of the outflow under current sea level conditions ($O(p)$); Equation (5) shows the relationship between $O(p)$, $O_{SLR}(p)$, and λ_{SLR}.

$$O_{SLR}(p) = \left(1-\lambda_{SLR}\right)\cdot O(p) \tag{5}$$

The value of λ_{SLR} was optimized to best match the risk increases calculated in the 2017 C-7 study (the percentage increases shown in Table 2-5). The resulting factors are presented in Table 2-6.

Sea level rise scenario	Factor λ_{SLR}
SLR1	0.06
SLR3	0.33

Table 2-6 Sea level rise scenario and associated precipitation-outflow curve shifting factor λ_{SLR}.

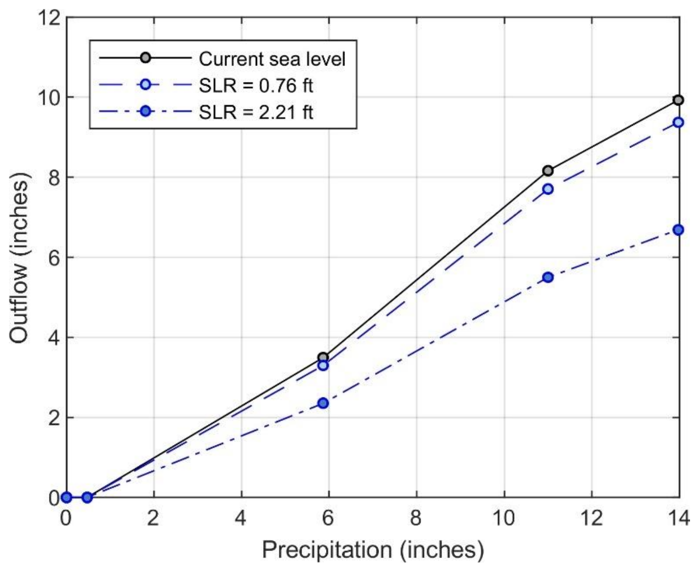


Figure 2-14 Precipitation-outflow curve for current sea level, SLR1 (SLR = 0.76 ft), and SLR3 (SLR = 2.21 ft), using the λ_{SLR} *values in Table 2-6.*

2.5.2 Hydraulic measures

Two sets of hydraulic measures (M1 and M2) were implemented in the quick-scan model; these are the same hydraulic measures considered in the 2017 C-7 study. M1 represents a set of local measures (see below). M2 represents a forward pump at the S27 tidal structure to provide drainage when downstream water levels are too high to allow for gravity drainage; two capacity pumps were considered: 1000 cfs (M2A) and 2800 cfs (M2B).

M1 Suite of local measures

- Flood walls to isolate the watershed from the C7 canal
- A system of pumps to drain flood waters into the C7 canal when gravity drainage fails
- Exfiltration trenches to increase storage in sub-basins
- Backflow preventers (flap gates) to allow discharge from sub-basins to the main canal and prevent reverse flow;
- No seepage barriers.

The cost estimates from the 2017 C-7 study were about $181 million for M1, $28 million for M2 with a 1000-cfs-capacity pump, and $80 million for a 2800-cfs-capacity pump.

The hydraulic measures were implemented in the quick-scan model in a similar way to sea level rise. The hydraulic measures essentially improve the ability to drain water from the system and therefore create an *upward* shift in the precipitation-outflow curve. A multiplicative factor λ_M was also calculated for the hydraulic measures, by optimizing to best match the risk reduction calculated in the 2017 C-7 study. Equation (6) shows how $O_M(p)$ - the outflow for a given precipitation p with the inclusion of a hydraulic measure M - can be calculated once the multiplication factor λ_M is known. Notice for the hydraulic measures λ_M is added to 1 (for increased outflow), whereas for sea level rise it was subtracted from 1 (for decreased outflow).

$$O_M(p) = (1 + \lambda_M) \cdot O(p) \tag{6}$$

The risk reduction calculated in the 2017 C-7 study for each of the measures for CSL, SLR1 and SLR3 are presented in Table 2-7. Because the impact changes as sea level rises, the multiplicative factor λ_M also changes as sea level rises. Table 2-8 presents the values for λ_M that were optimized to best match the risk reduction percentages in Table 2-7.

Measure	CSL	SLR1	SLR3
M1	14%	22%	37%
M2A	4%	16%	35%
M2B	8%	26%	52%

Table 2-7 Percentage risk reduction calculated in the 2017 C-7 study, for measures M1, M2A, and M2B under CSL, SLR1 and SLR3.

Measure	CSL	SLR1	SLR3
M1	0.019	0.04	0.19
M2A	0.006	0.03	0.18
M2B	0.011	0.05	0.26

Table 2-8 Precipitation-outflow curve shifting factor λ_M for M1, M2A, and M2B, under CSL, SLR1, and SLR3

The risk reduction resulting from a combination of M1 and M2 was not specified in the 2017 C-7 study, although the combination was considered in the development of adaptation pathways, and a tipping point (see Section 2.6) was estimated for the combination. We therefore estimated the shifting factor for the combination of M1 and M2 as a weighted combination of the two, with the weights optimized to best match the tipping point found for the combination of M1 and M2B in the 2017 C-7 study. The shifting factor for the combination of M1 and M2 is specified in Eq. (7).

$$\lambda_{M1M2} = \max\left[\lambda_{M1}, \lambda_{M2}\right] + 0.2 \cdot \min\left[\lambda_{M1}, \lambda_{M2}\right] \tag{7}$$

Equation (7) essentially says that the effectiveness of the combination is about 20% increase over the effectiveness of an individual measure.

2.5.3 Combining hydraulic measures and sea level rise

To simulate the risk for a combination of hydraulic measure and sea level rise, we combine the impacts on the precipitation outflow curve, as expressed in Equation (8), where $O_{M,SLR}(p)$ is the outflow for precipitation p, with a measure implemented and under sea level rise. To make it more concrete, Equation (9) shows a numeric example how to calculate the outflow for hydraulic measure M2B with sea level rise SLR1; the values of λ for SLR1 and M2B are found in Table 2-6 and Table 2-8, respectively.

$$O_{M,SLR}(p) = (1 + \lambda_M - \lambda_{SLR}) \cdot O(p) \tag{8}$$

$$O_{M2B,SLR1}(p) = (1 + 0.05 - 0.06) \cdot O(p) \tag{9}$$

2.5.4 Additional scenarios

With the quick-scan model, additional sea level rise scenarios can be considered. In the 2017 C-7 study, two sea level rise scenarios were considered: a rise of 0.76 ft. (SLR1) and a rise of 2.21 ft (SLR3), and for those scenarios we have optimized the outflow curve shifting factor λ. We can interpolate the shifting factor to consider additional sea level rise scenarios, as demonstrated in Figure 2-15. To avoid unrealistic results, λ_{SLR} was not extrapolated for sea level rise beyond SLR3, but rather is constrained to remain at the SLR3 level. Other constraints can be considered in the future to extrapolate beyond the calibration range; for example, expert elicitation may lead to a constraint on the slope of the increase of λ_{SLR}, rather than a constraint on the value of λ_{SLR}.

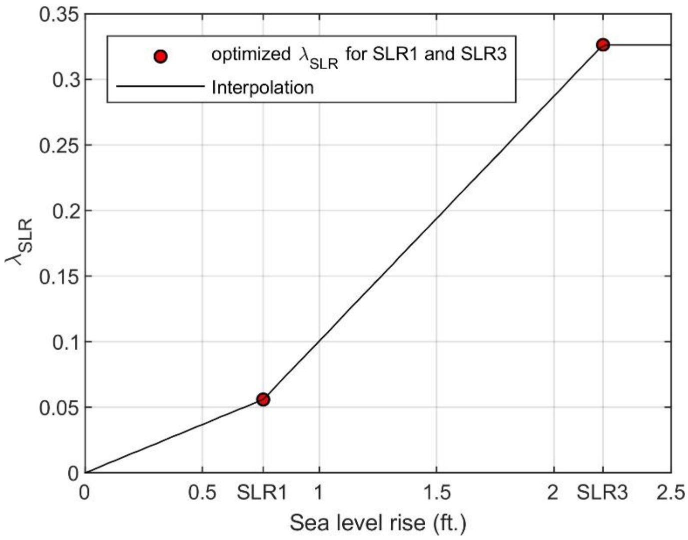


Figure 2-15 Interpolation of the curve-shifting factor λ for sea level rises other than SLR1 and SLR3.

Similarly, we can simulate pump capacities (the M2 regional measure) beyond the two that were simulated in the 2017 C-7 study, by interpolating the factor λ_M between the 1,000 cfs (M2A) and 2,800 cfs (M2B) capacity pumps for which λ_M was optimized.

2.5.5 Land-use measures

The land-use measure we considered (M3) was the elevation of roads and structures. This was implemented in the quick-scan model by modifying the damage function for roads and structures. An example of how this was done for residential structures is illustrated in Figure 2-16; damage that would have occurred at 2 feet (for example) would occur at 8 feet in the modified damage function. The cost associated with raising roads and structures to 6 feet was estimated in the 2017 C-7 study to be $157 million.

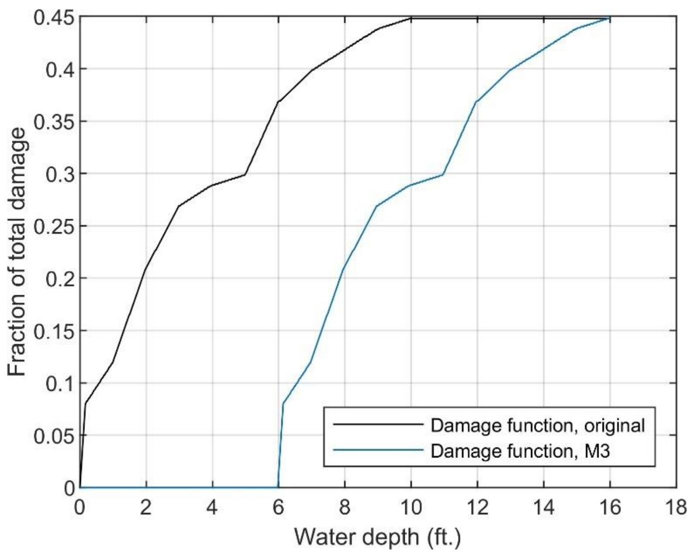


Figure 2-16 Damage curve for residential structures: original, and with the implementation of M3, in which residential structures are elevated 6 feet.

2.6 Adaptation pathways and tipping points

The Dynamic Adaptive Policy Pathways (DAPP) approach is a method for planning under uncertainty[6] that was developed to support flood protection and water supply planning under uncertainty in climate change in the Netherlands through 2100. It has since been applied around the world in situations where uncertainty in the future makes long-term planning challenging.

The essence of DAPP is to plan proactively in the short-term, and respond dynamically in the mid- to long-term as the future unfolds. Adaptation pathways are a key feature of DAPP; they show possible sequences of actions over time which ensure community objectives are continuously met as we move into an uncertain future. The timing when a new or additional action is needed is assessed continuously by monitoring climate and socio-economic trends. Multiple pathways can achieve community objectives, and together these are visualized in a 'Metro-map' infographic. An example metro-map inforgraphic from the 2017 C-7 study is presented in Figure 2-17. In the infographic, sea level rise is shown on the horizontal axis, and the adaptation/mitigation options are shown on the vertical axis. Associated with each measure is a horizontal line, the length of which represents the sea level rise it can handle before objectives (e.g. a risk threshold) are no longer met. The tipping points are specified as 'end terminals' (small black vertical lines) after which no more sea level rise can be accommodated and meet objectives. When a tipping point is approaching, a new or additional action needs to be taken. The transfer from one action to another is indicated with vertical lines between actions.

[6] *Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world, Haasnoot et. Al., Global Environmental Change, 2013*

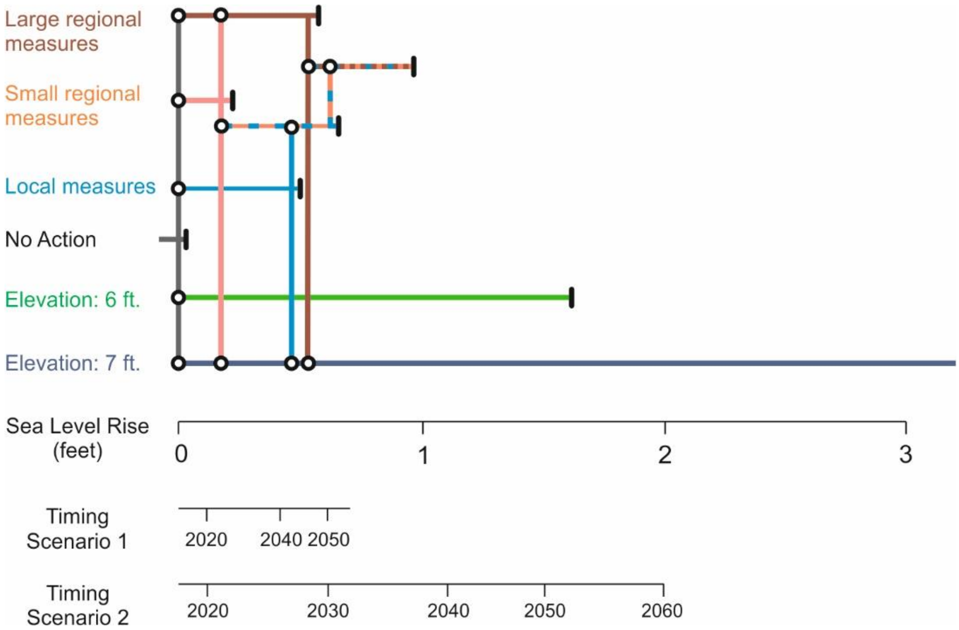


Figure 2-17 Adaptation pathways calculated in the 2017 C-7 study

Figure 2-18 shows an example of a single pathway in the metro-map for the 2017 C-7 study, indicated by red arrows. In this example the short-term action is ‘small regional measures’ (a small-capacity regional pump). When that action approaches its tipping point (around 0.25 ft. of sea level rise), it is replaced with ‘large regional measures’ (installing a larger-capacity regional pump). This is indicated by the vertical line connecting ‘small regional measures’ to ‘large regional measures’. When the large regional measure approaches its tipping point (around 0.6 ft. of sea level rise), it is augmented with ‘local measures’, which meets objectives until about 1 ft. of sea level rise. At that point, one of the land-use measures would be needed to meet objectives after 1 ft. of sea level rise. The timing of the tipping points depends on the sea level rise scenario; two potential time axes are given under the sea level rise axis in the pathways map. As new projections are developed, the timing axis can be revised, but the pathway map would remain unchanged.

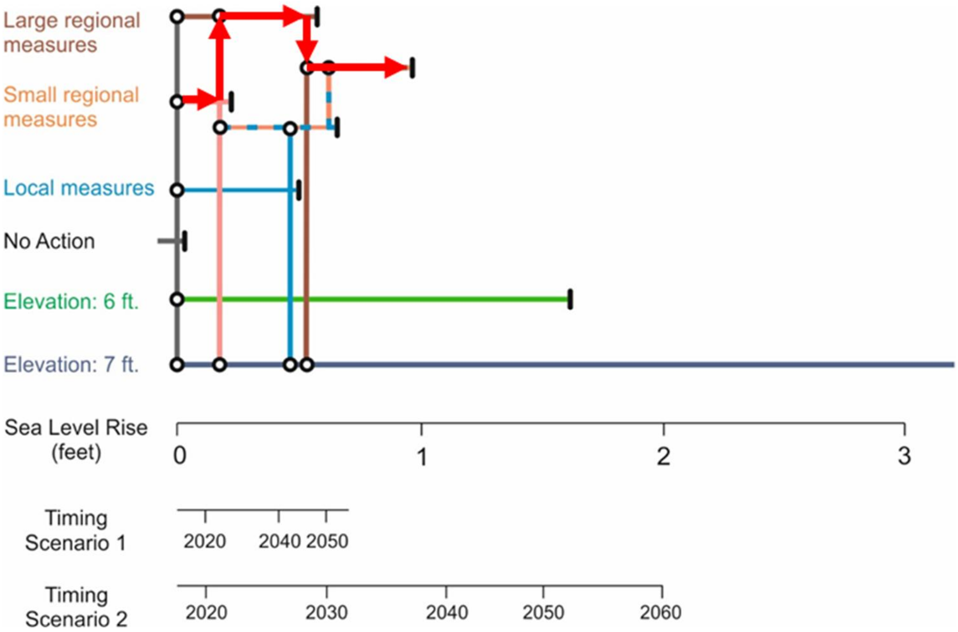


Figure 2-18 Adaptation pathways calculated in the 2017 C-7 study with a specific pathway indicated by red arrows.

For the case of planning under uncertain sea level rise, an adaptive approach like DAPP has considerable advantages over more traditional planning approaches. The most notable one is the inclusion of time; rather than plan for an uncertain snapshot in the future (e.g. the high-projection sea level rise scenario in 2065), the DAPP approach plans sequentially as sea levels rise. One advantage of this is that by looking ahead, it ensures that short-term actions work well with options that will be needed further down the line. Another advantage is that it illuminates short-term low-regret actions that can be taken now, and indicates how long they will remain effective; this buys time for the more complex, more expensive investments that will be needed later. This extra time ensures that these options can be evaluated properly, which may include integrated modeling efforts, financing efforts, and substantial community engagement and permitting processes.

Another advantage of DAPP is that the plan is independent of a scenario. In traditional planning, options would be evaluated for their effectiveness for one or two snapshots of future sea level. But what if those projections are wrong? If they are underestimates, and sea levels rise faster than anticipated, the selected options would be insufficient to project against flooding; if they are overestimates, and sea level rises slower than expected, the selected options may have been an over-investment. The idea of planning adaptively is to accept that the future is unknown, and plan in a step-wise fashion, updating and implementing new measures as the future becomes clearer.

Tipping points are a key element of the DAPP method. Determining tipping points depends on the community's objectives. Figure 2-19 shows an illustrative example, where the objective is specified in terms of a risk threshold. The figure shows sea level on the horizontal axis, and risk on the vertical axis. As sea level rises, the risk is increasing until it hits the threshold (the risk tolerance of the community). The amount of sea level rise that causes risk to reach the threshold is the adaptation tipping point. This is indicated in Figure 2-19 by the red star. To determine the tipping points, risk is often calculated for several values of sea level rise, after which interpolation can be used to identify when the threshold will be reached.

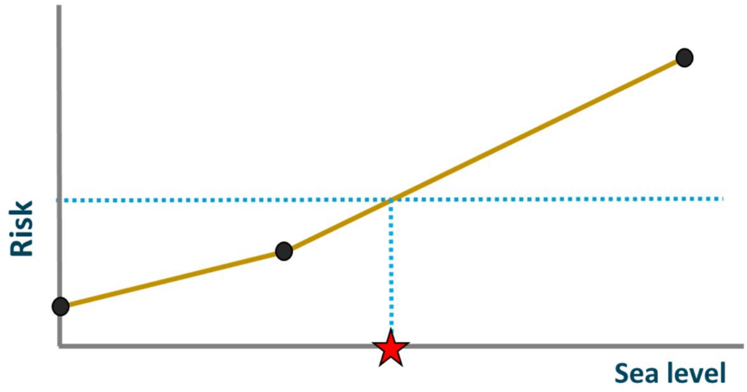


Figure 2-19 Illustration of a tipping point analysis. The risk is increasing as sea level rises; the sea level at which the risk hits the threshold is the tipping point.

2.7 Preprocessing to increase computational speed

To make the quick-scan model very fast, several steps can be done “offline”, before any specific event calculations are carried out. Figure 2-20 illustrates the preprocessing steps. For many values of flood water, the associated economic damages were calculated. Recall that the flood water is the average flood depth over the basin (the flood volume divided by the basin area), which is then distributed over the basin based on elevation to derive flood depth maps. The steps involved in the preprocessing were:

1. Distribute the flood water to derive flood depth maps
2. Input the flood depth maps into Delft-FIAT model, which calculates economic damages

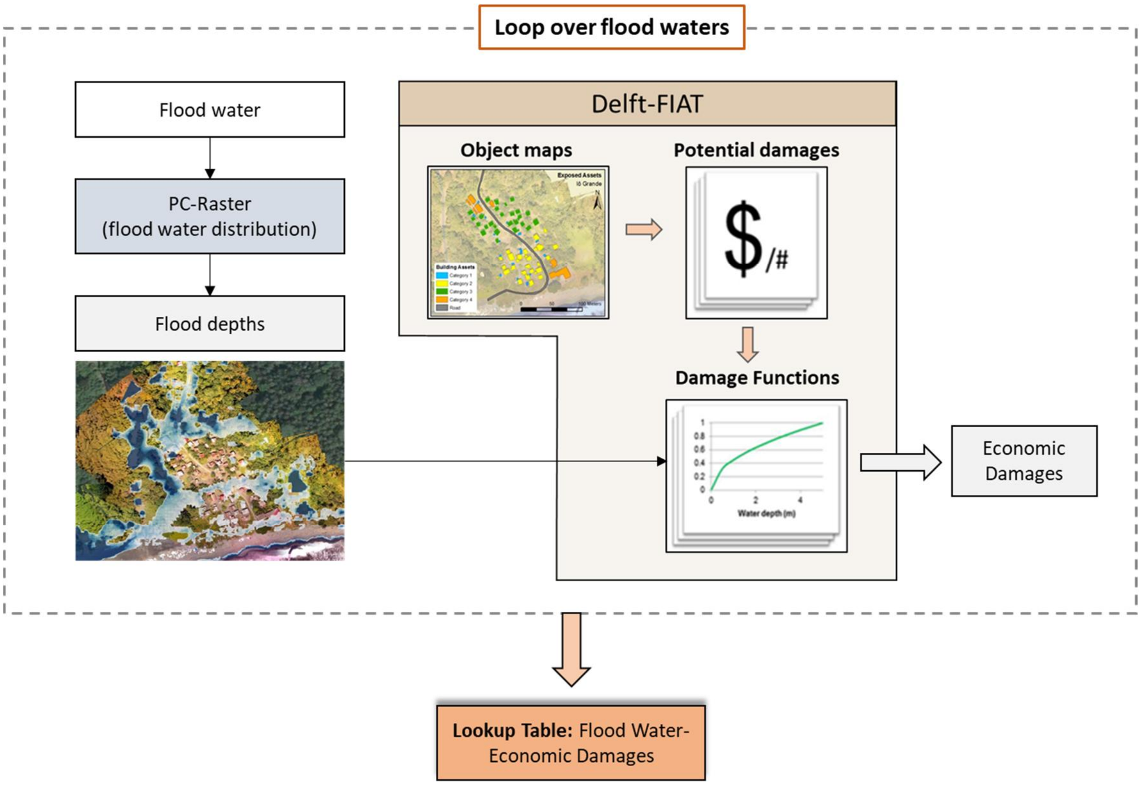


Figure 2-20 Illustration of the preprocessing steps that allow the quick-scan model to be exceptionally fast.

The result is a two-column look-up table with flood water in one column, and economic damages in the second. Figure 2-21 shows the interim relationship between precipitation and flood water. Figure 2-22 shows the look-up table relationship between flood water and damages. Once the look-up table is derived, the quick-scan model is set up as shown in Figure 2-23.

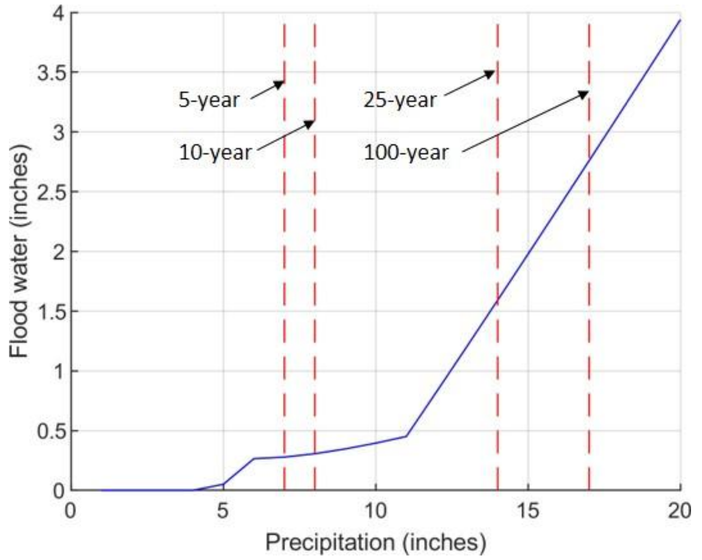


Figure 2-21 Relationship between precipitation and flood water for the C-7 basin; the 5, 10, 25, and 100 year precipitation are indicated by the vertical red dashed lines.

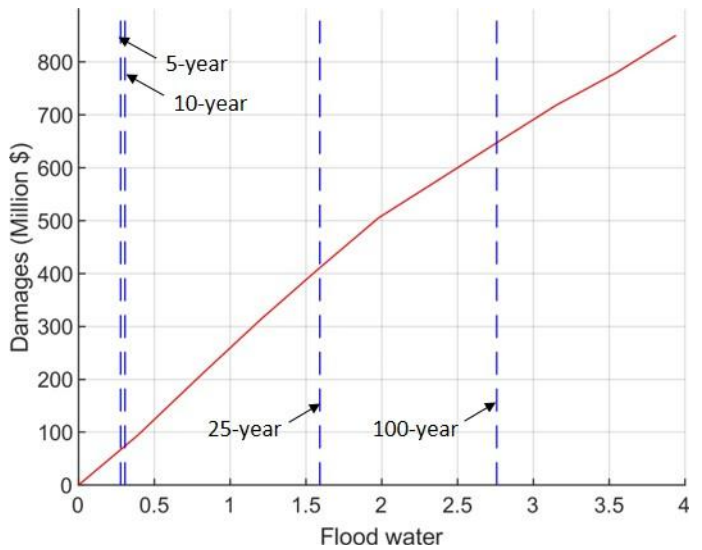


Figure 2-22 Relationship between flood water and damages for the C-7 basin; the flood water associated with the 5, 10, 25, and 100 year precipitation are indicated by the vertical blue dashed lines.

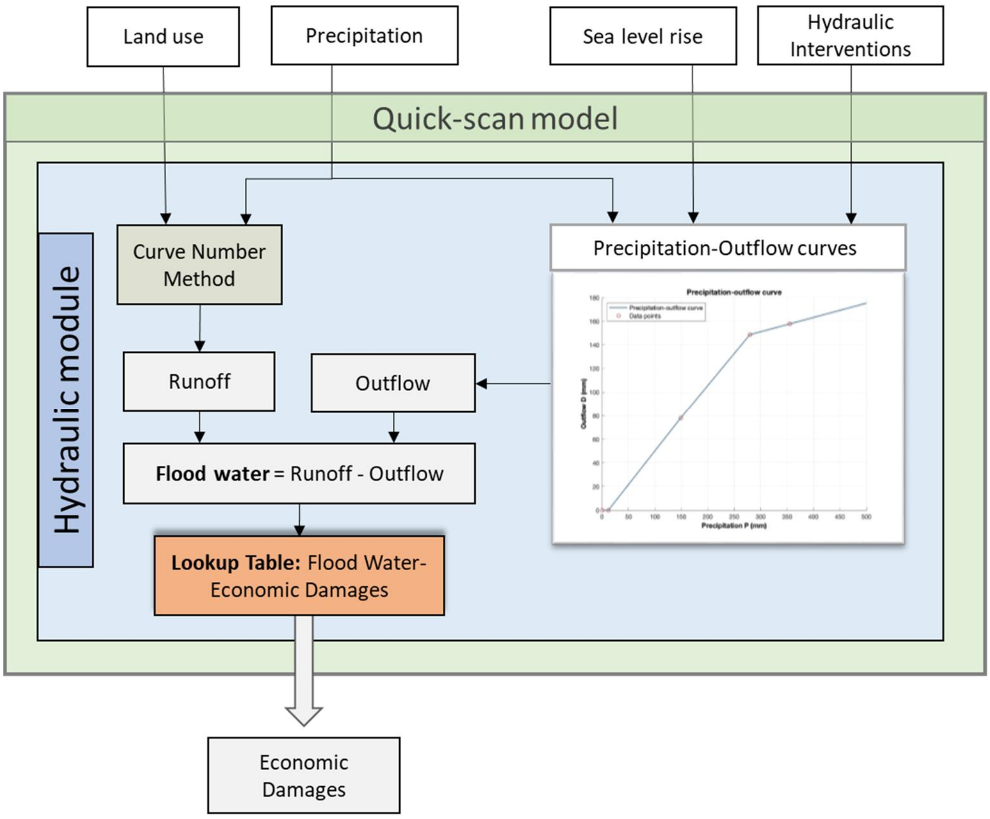


Figure 2-23 Illustration of the quick-scan model using the preprocessed lookup table.

2.7.1 Run time

With the pre-processing implemented, it takes about 13 seconds to calculate the risk and tipping points for five basins, five adaptation/mitigation measures, three sea levels, and four precipitation probabilities on a laptop with an intel core i5-7200U CPU @ 2.50 GHz and 8.0 GB of RAM. The 13 seconds includes generating the figures presented in the Results chapter.

A run time of 13 seconds allows many things to be tested, that wouldn't be feasible with a more traditional model set-up. What-if questions can be rapidly investigated – questions like: 'what if we included a measure that was more effective than M1?', 'what if we chose a higher risk threshold in this basin?', 'what if we added a pump to one basin and not to another?', or 'which basin has the greatest risk reduction with the inclusion of a pump?'

3 Application of the model to other basins

The quick-scan model was calibrated to C-7, and then subsequently applied to four other basins in Miami Dade County: C-2, C-3W, C-4, and C-6, which are shown together with C-7 on the map in Figure 1-2. These basins were chosen because they are similar to C7 in that they are upstream of an outlet structure to the bay.

For each basin, a number of features are unique to the basin: (1) The land-use of each basin was used to determine the curve number for that basin, (2) the exposure data of each basin was used to determine the damages due to flood depths, (3) the outflow curve for each basin was based on historic outflow at the structure of that basin for the three reference storms (described in Section 2.2.2). Appendix C provides the outflow data for the three historic storms, and the derived precipitation-outflow curves, for all the basins.

The features that were transferred from the C-7 calibration were the percentage change in outflow due to the measures and sea level rise (the λ values from Table 2-6 (for sea level rise) and Table 2-8 (for hydraulic measures)). While the transferability of the λ values for C-7 to the other basins is an assumption, we felt that it provides a reasonable estimate without other knowledge of how the measures and sea level rise will affect water levels in those basins. Changes to those factors can be easily implemented in the model in the future once additional information becomes available.

Adjustments to C-4 and C-6 were made to account for the inclusion of pumps which were implemented after the three historic storms used to derive the outflow curve. The average flow volume through the pumps was added to the original outflow curve. The period of record for which outflow data was obtained is shown in Table 3-1 below.

Table 3-1 Start and end date of the period of record used to derive average outflow volume through the pumps of C-4 and C-6

Basin	C-4			C-6
Pump	G422	G423	S25B	S26
Start	Feb 2006	Nov 2010	Aug 2004	Jan 2005
End	Jun 2019	Nov 2018	Aug 2018	Jan 2018

The average outflow was calculated in units of inches by multiplying by the duration (for two durations – 5 days and 7 days) and dividing by the area of the basin. The average outflow in inches is provided in Table 3-2.

Table 3-2 Average outflow, in inches, through the pumps of C-4 and C-6 for a pump duration of 5 days and 7 days.

Basin	C-4			C-6
Pump	G422	G423	S25B	S26
Duration: 5 days	0.4	0.1	1.2	1.6
Duration: 7 days	0.5	0.2	1.6	2.3

4 Results

The quick scan model was applied to C-2, C-3W, C-4, C-6, and C-7 to calculate damages, risk, and adaptation tipping points for the current situation as well as with measures and under sea level rise. In this section we provide some of the model results.

4.1 Flood depths and damages

Figure 4-1 shows the flood depth map and associated damage map for the C-7 basin, for the 25-year precipitation event; Figure 4-2 shows the flood depths and damages together for a zoomed in portion of the C-7 basin. .

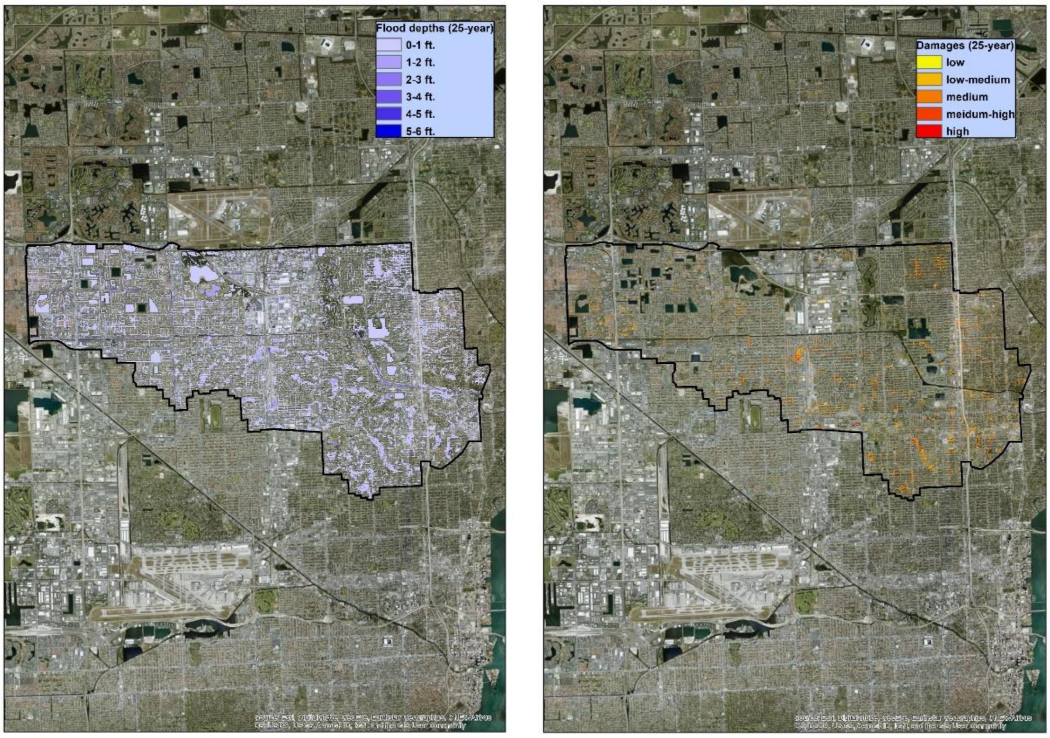


Figure 4-1 Flood depths (left) and damages(right) calculated by the quick-scan model for the 25-year precipitation event for the C-7 basin.

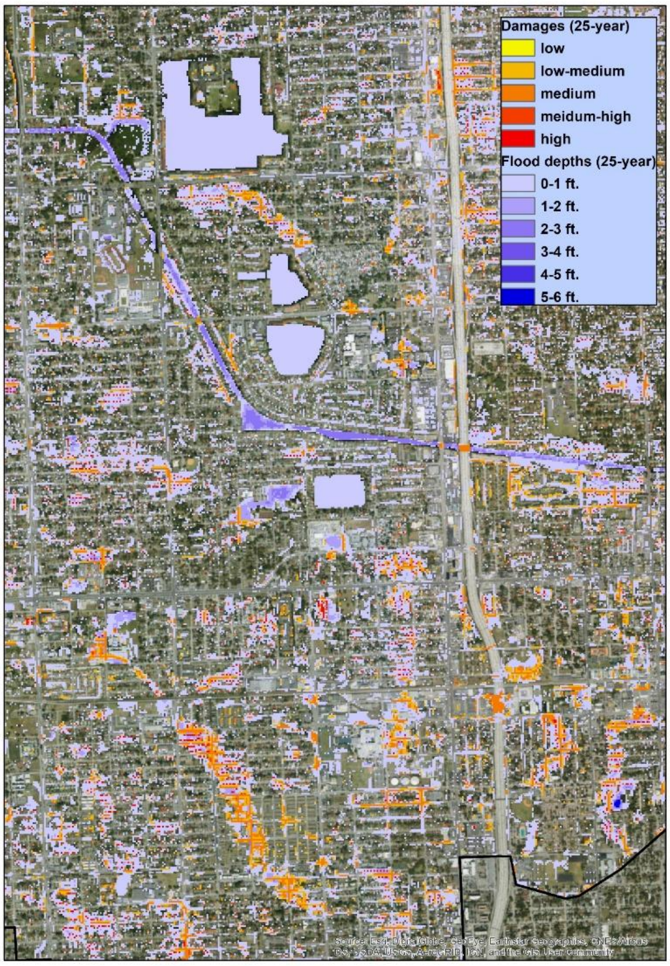


Figure 4-2 Flood depths and damages calculated by the quick-scan model for the 25-year precipitation event, for a zoomed-in portion of the C-7 basin.

Appendix D provides the flood depth and damage maps calculated by the quick-scan model for the 10-, 25-, and 100-year return periods for CSL, SLR1, and SLR3, for the C-7 basin. The 10-, 25-, and 100-year flood depth and damage maps were provided to the SFWMD for current sea level, SLR1, and SLR3, for all five basins.

4.2 Risk

In this section, we present the risk, expressed as expected annual damages, calculated by the quick-scan model for C-7 and compare that with the results from the 2017 C-7 study. We present some results for the other basins, but the complete results are presented in Appendix E.

Table 4-1 presents the risk estimates for C-7 calculated with the quick-scan model, in millions of dollars.

	M0	M1	M2B	M1 + M2B	M3(6)
CSL	37	34	35	33	0
SLR1	48	39	38	36	0
SLR3	103	64	51	43	0

Table 4-1 Expected annual damage (million $) in C-7 for five measures and three sea levels

In the 2017 C-7 study, the risk estimates were lower because they only considered targeted sub-basins within C-7, whereas we estimated risk for the entire basin. To better compare, we present the risk reduction from the 2017 C-7 study in Table 4-2, and the risk reduction estimated in the current study in Table 4-3. Except for M2B under SLR3, and for M3(6) under all SLR scenarios, the results are nearly identical. This is not surprising since we calibrated the implementation of the measures and sea level rise using the risk-reduction from the previous study.

The risk reduction due to M3 (6 feet elevation) was different. In the current study, elevating roads and houses by 6 feet eradicates the risk, even with the highest sea level considered (SLR3 = 2.21 ft.). In the 2017 C-7 study, they found that under the highest sea level, the risk had increased by 56% compared to current risk. The quick-scan model flood depths tend to be lower than the flood depths calculated by the XPSWMM model that was used in the C7 study, but the flooded areas are more extensive. This leads to similar damages under current conditions, but with elevated structures (M3), the differences between the flood maps of the two studies becomes more important.

Table 4-2 Risk increase (+) or decrease (-) compared with current conditions (current sea level + no measures (M0)): results from the 2017 C-7 study

	M0	M1	M2B	M3(6)
CSL	-	-14%	-8%	-82%
SLR1	40%	10%	4%	-70%
SLR3	208%	93%	62%	56%

Table 4-3 Risk increase (+) or decrease (-) compared with current conditions (current sea level + no measures (M0)): results from the quick-scan model

	M0	M1	M2B	M3(6)
CSL	-	-14%	-8%	-100%
SLR1	40%	9%	4%	-100%
SLR3	208%	93%	49%	-99%

The risk was calculated for all five basins, for four measures, and for three sea levels. Figure 4-3 shows the risk over all basins and sea levels, for measure M0, which is the ‘do-nothing’ situation (no measures). Figure 4-4 shows the same for M1 (local mitigation measures), and Figure 4-5 for the M2B measure (2800-cfs-capacity pump at the S-27 structure).

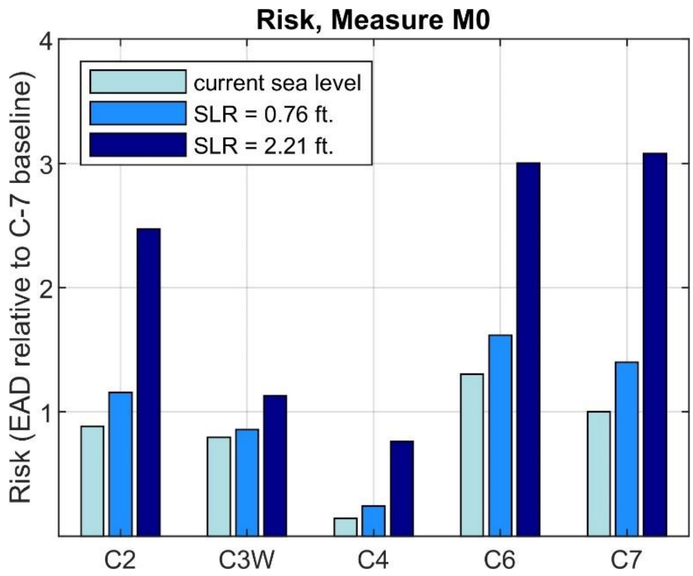


Figure 4-3 Risk for all five basins, for three sea levels, with the do-nothing M0 measure

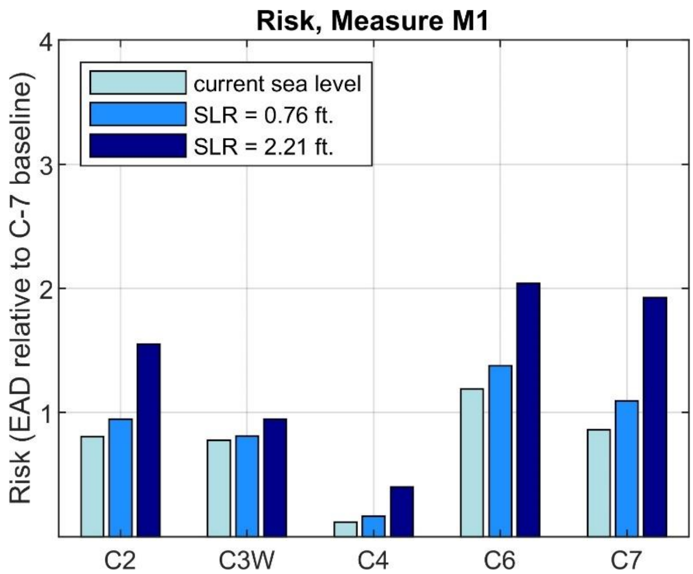


Figure 4-4 Risk for all five basins, for three sea levels, with the implementation of local measures M1

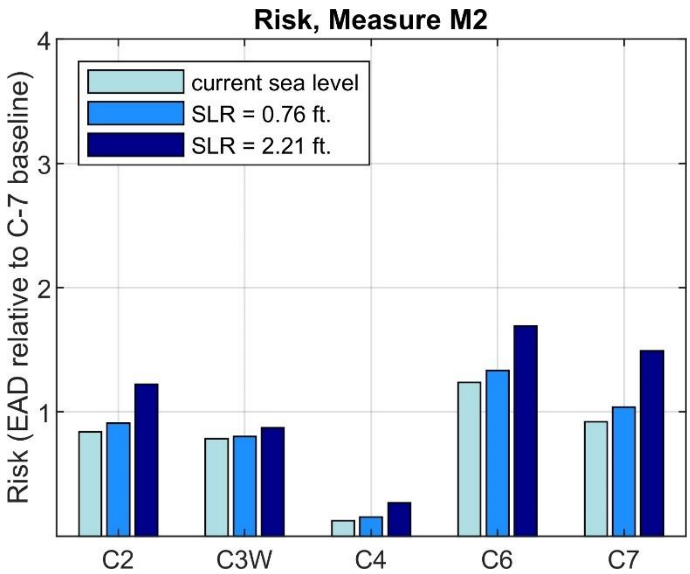


Figure 4-5 Risk for all five basins, for three sea levels, with the implementation of regional measure M2B

Figure 4-6 and Figure 4-7 show the percentage contribution of each basin to the total risk (over the five basins), in the case where the newer C-4 pumps were excluded (Figure 4-6) and included (Figure 4-7). The assumption used in the model is that the pumps operate over the entire duration of the storm event; this is an overestimate, as pumping only occurs when the canal water levels are lower than the tailwater levels. A representative fraction of the storm duration during which the pumps are active should be calibrated based on a combination of historic data and expert opinion. This fell outside the scope of the current project, but is recommended for future development of the quick-scan model.

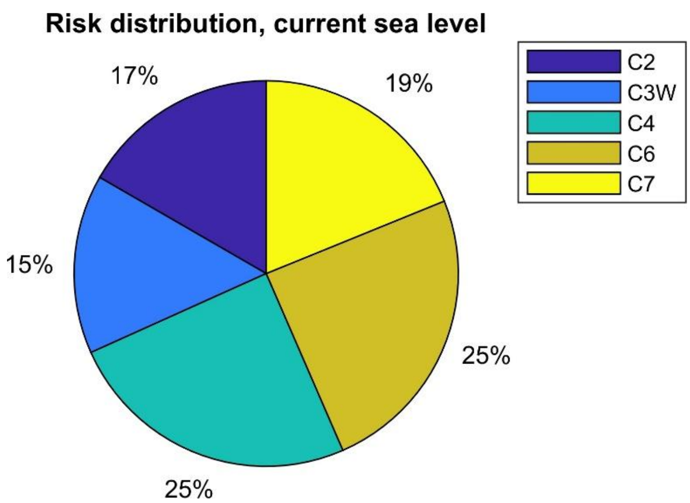


Figure 4-6 Risk distribution over the five basins (percentage contribution of each basin to the total risk), with the newer C-4 pumps excluded

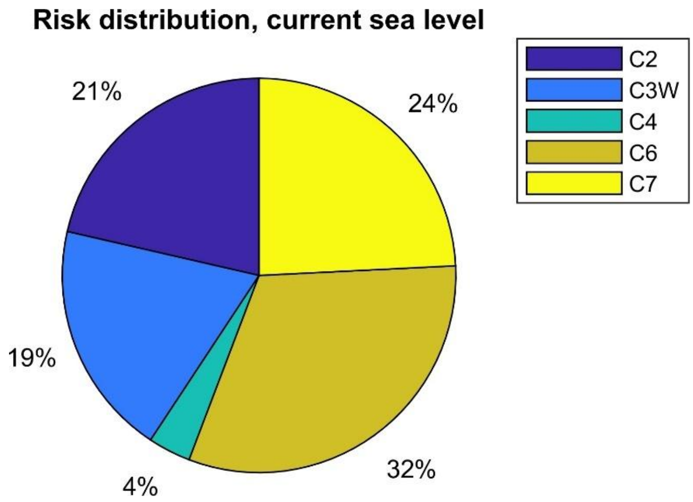


Figure 4-7 Risk distribution over the five basins (percentage contribution of each basin to the total risk), with the newer C-4 pumps included

4.3 Tipping points and adaptation pathways

Tipping points are the conditions – in this case, sea level rise – under which a measure no longer meets a specified objective. In this study we consider the objective to be a tolerable risk threshold. The quick-scan model makes it possible to quickly assess the tipping points for multiple choices of this risk threshold.

Figure 4-8 shows a tipping point analysis for C-7, with a risk threshold equal to present-day risk. For each of the measures, the risk is plotted against sea level rise, and the point at which the risk crosses the threshold (indicated in the figure with a black dashed line) is considered the tipping point for that measure.

Figure 4-9 shows the tipping point analysis for a risk threshold equal to a 5% increase above present-day risk. Increasing the tolerable risk leads to a longer shelf-life of the measures. For example, Figure 4-8 shows that the combination of M1 and M2B has a tipping point just under 1 ft SLR. with a present-day risk threshold; Figure 4-9 shows that the same combination has a tipping point of about 1.2 ft. SLR with a threshold 5% above present-day risk.

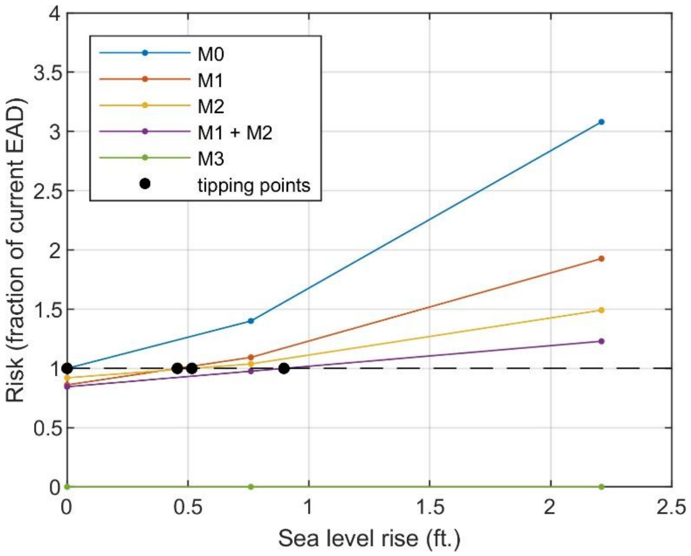


Figure 4-8 Tipping points for C-7, with a threshold of current flood risk

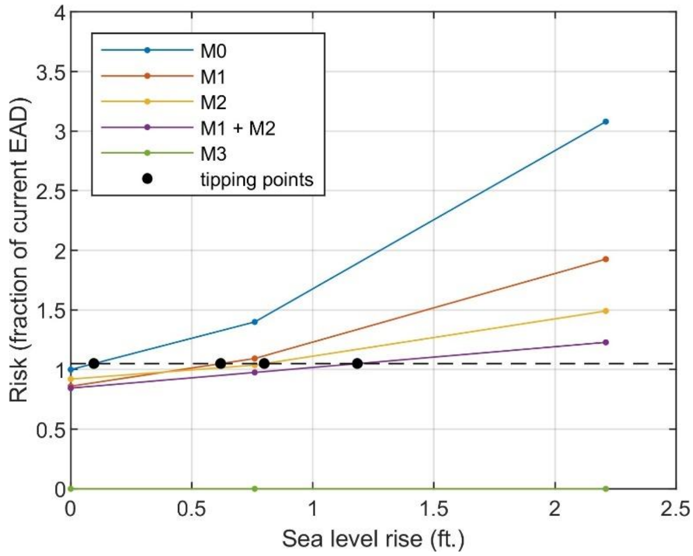


Figure 4-9 Tipping points for C-7, with a threshold of current flood risk + 5%

The tipping points for all measures besides M3 are plotted for all five basins together in Figure 4-10 for a current-risk threshold, and in Figure 4-11 for a 5% increase in threshold above the current risk. M3 is excluded because with this measure, the tipping point was not reached (through the highest analyzed sea level rise of 2.21 ft.). The tipping points are virtually identical for the five basins with the current-risk threshold. This is because the one commonality between the basins is the percentage influence on the outflow due to both the measures and sea level rise. At a certain sea level rise, the percentage increase in outflow caused by a measure is just equal to the percentage decrease in outflow due to sea level rise. That point is the same in all the basins. When the risk threshold is adjusted, the tipping points begin to differ between basins, because the absolute value of the risk is different between the basins.

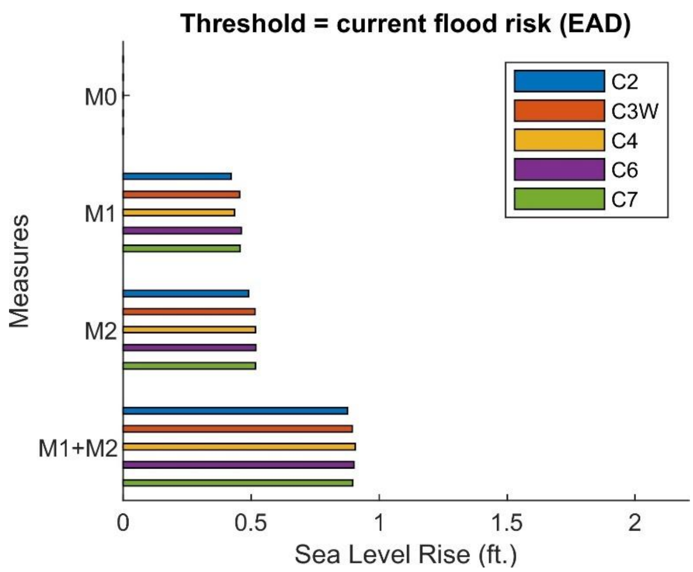


Figure 4-10 Tipping points for all basins, with a threshold of current flood risk

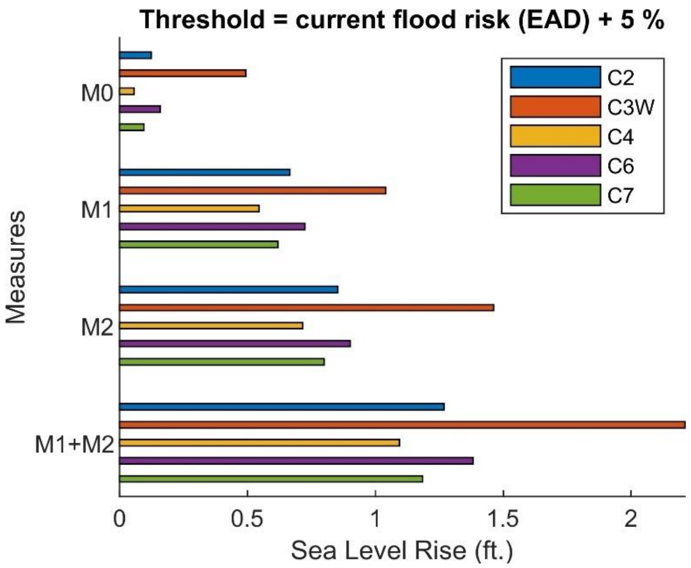


Figure 4-11 Tipping points for all basins, with a threshold of current flood risk + 5%

The tipping points under three thresholds were calculated in the 2017 C-7 study: current flood risk, and an increase above current risk of 5% and 10%. We calculated the tipping points for these three thresholds using the quick-scan model. Table 4-4 shows that the results between the two models are in very close agreement, with the exception of M3, which was discussed above.

Table 4-4 Tipping points: sea level rise (in ft.) at which the measure no longer meets the threshold, for three thresholds: (1) current risk, (2) a 5% increase over current risk, and (3) a 10% increase over current risk. For the quick-scan model, the tipping points for M3(6) were greater than the highest evaluated sea level of 2.21 ft.

	2017 C-7 study			quick-scan model		
	Current Risk	5% in-crease	10% in-crease	Current risk	5% in-crease	10% in-crease
M0	0.00	0.09	0.19	0.00	0.10	0.19
M1	0.55	0.66	0.77	0.46	0.62	0.77
M2B	0.50	0.79	0.95	0.52	0.80	0.96
M3(6)	1.56	1.62	1.68	>>	>>	>>

Appendix F contains the tipping point results for all the basins, for three risk thresholds: current risk, 5% increase above current risk, and 10% increase above current risk.

The tipping points are needed to develop adaptation pathways. An illustrative pathway was developed using the tipping points calculated for a risk threshold of current risk (see Table 4-4). The tipping point for M1 + M2 is not shown in Table 4-4 because it was not quantified in the 2017 C-7 study, but qualitatively estimated. In this study, we calculated a tipping point for M1 + M2 (see Equation (7)) of 0.9 ft. sea level rise for a risk threshold of current risk.

Figure 4-12 shows the starting point for developing pathways. It has sea level rise on the horizontal axis, and the mitigation/adaptation options on the vertical axis, for the C-7 basin. The bars show the shelf lives, in terms of how much sea level rise each measure can accommodate and keep risk below the current risk level.

Figure 4-13 shows the development of a pathway for C-7. In the pathway shown, the local measures (M1) are implemented first. When sea level rise approaches 0.46 feet (the tipping point for M1), a regional high-capacity pump (M2B) is installed. When sea level rise approaches 0.9 feet (the tipping point for M1 + M2B), houses and roads are elevated.

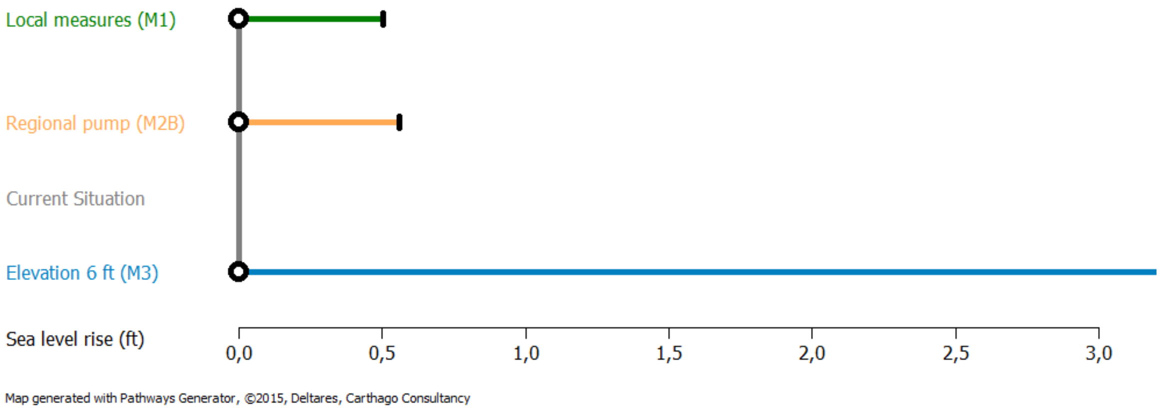


Figure 4-12 Shelf life of each individual measure (the foundation for the development of pathways) for the C-7 basin; sea level rise in ft. on the horizontal axis, and the mitigation/adaptation measures on the vertical axis. Note, the decimal place is indicated with a comma on the horizontal axis.

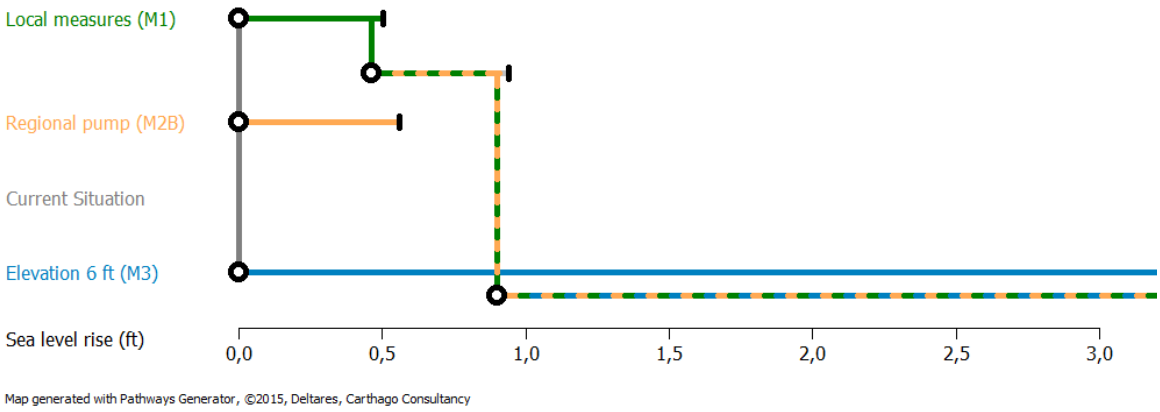


Figure 4-13 Development of a pathway for the C-7 basin: first local measures (M1) are implemented; when they reach their tipping point, a regional pump is installed (M2B); when the combination M1 + M2B reaches a tipping point, houses and roads are elevated. Sea level rise in ft. is on the horizontal axis, and the mitigation/adaptation measures are on the vertical axis. Note, the decimal place is indicated with a comma on the horizontal axis.

5 Conclusions and recommendations

This project has resulted in a powerfully fast prototype of a quick-scan tool that can support the adaptive planning process by rapidly assessing risk, risk-reduction due to measures, and shelf-lives (tipping points) of measures.

The hydraulic component was calibrated using the flood depths from the 2017 C-7 study, and the impact of the hydraulic measures and sea level rise on the outflow (the runoff that leaves the basin via the drainage infrastructure) was calibrated using the change in risk estimates from the 2017 C-7 study. The prototype was used to calculate risk for three sea levels, and adaptation tipping points were calculated for three risk thresholds. These were compared to the 2017 C-7 study and showed very good agreement. The model is able to run a risk assessment for three sea levels, and for five basins, in about 13 seconds. This shows the potential of such a tool for assessing the effectiveness of interventions, together with stakeholders, in a real-time workshop setting. The model is also perfectly suited for educational purposes to help teach about adaptive planning.

The current study investigated the feasibility and architecture of a quick-scan tool for rapidly assessing flood mitigation/adaptation measures. A validation fell outside the scope of the project, so several assumptions still need to be tested and validated before the model is used in practice. Below is a list of our recommendations to move the quick-scan tool from a prototype to a usable tool for Miami-Dade County.

1. Differences in flood depth maps between the C-7 study and the quick-scan model need to be further investigated and understood. The quick-scan flooded areas seem to have a wider extent, but lower inundation depth. This can lead to the same damage in the current situation but not under sea level rise. In the current study, we compensated for this by calibrating the effect of the measures on the outflow per sea level rise. In principal this effect should remain constant as sea levels rise, but to match the risk reduction seen in the 2017 C-7 study, we needed to increase the effect on the outflow for higher sea levels. We recommend investigating in more detail the cause of the differences in the flood depth maps.
2. The use of the lambdas (the impact that the measures have on the outflow) that were calibrated for C-7 in the other basins should be verified, at least qualitatively with stakeholders.
3. Interactions between basins should be taken into account in the model, because there is water transfer between C-2, C-3W, and C-4 during storm events. It needs to be investigated how best to account for these in the quick-scan model and ideally it should be tested against a more detailed model for verification.
4. Pumps in the C-4 and C-6 basins (which were installed after the storms that were used to derive the outflow curves) were assumed to operate over the duration of a rainfall event, which potentially overestimates the volume that is drained from the basin. More investigation should be done to decide on the operable duration, possibly as a function of the precipitation or the runoff.

5. The quick-scan model is calibrated to the results of the 2017 C-7 study, in which they assumed a fixed 1/10-year surge level during each of the precipitation events. Ideally, we would be able to have the surge be a variable in the model; the advantage of the quick-scan model is that multiple combinations of surge and precipitation can be run without any computational burden. This would allow for a more complete quantification of the flood risk, and would allow the consideration of compound events. In order to expand the quick-scan model we would need compound event model results, which are likely available, but may need to be augmented with sea level rise and/or the implementation of measures.
6. A user-interface should be designed and built so that stakeholders can easily modify and operate the quick-scan tool.

With the above recommendations and improvements, the quick-scan tool has the potential to provide strong support to early-phase adaptation planning, and the design of more detailed analyses to assess adaptation options in Miami Dade County.

Appendix A Webinar (Workshop) report

Development of Short- and Long-Term Strategies for Resiliency in Miami-Dade County

Workshop Report

To encourage community awareness of adaptive planning and the use of quick scan tools to support the adaptive planning process, FIU, SFWMD, and Deltares USA hosted an online webinar on November 19, 2019. The webinar provided context about the need for adaptive planning in South Florida, gave an overview of the Dynamic Adaptive Policy Pathways approach to adaptive planning, and introduced the quick-scan tool developed as part of this project.

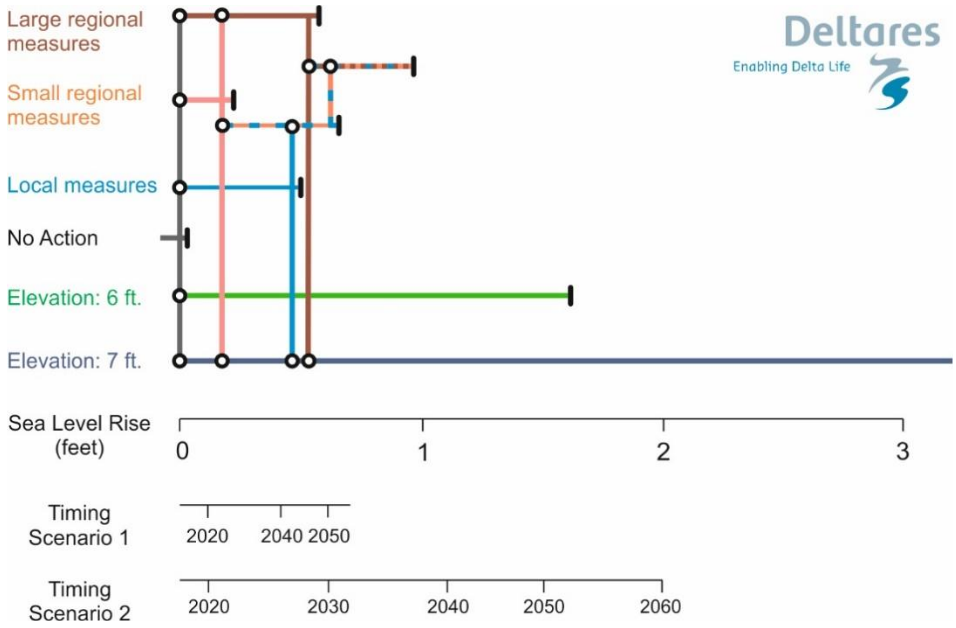
This report provides a summary of the webinar content, the presentations given, and a list of attendees (in numbers by organization). The webinar was recorded and can be viewed online at https://www.deltares.nl/en/webinars/planning-adaptively-rising-sea-levels-supported-quick-scan-tools/.

Workshop Summary

Webinar: Planning adaptively for rising sea levels, supported by quick-scan tools

The South Florida Water Management District, FIU Sea Level Solutions Center, and Deltares USA have been working together on a Florida Department of Environmental Protection research grant to explore the development and use of quick-scan tools to support the adaptive planning process to prepare for rising sea levels.

On November 19, 9:30-11:30 a.m. EST, we invite you to a [webinar](https://attendee.gotowebinar.com/register/7172902000520304139) in which we walk through the adaptive planning method, show adaptive planning outcomes for the Little-River (C-7) basin in Miami from a previously-funded NOAA project, and demonstrate a prototype for a quick-scan model that assesses adaptation options at a multi-basin scale in Miami.



Why adaptive planning?

Uncertainty in sea level rise and extreme rainfall projections makes it challenging to decide on the best investments for adaptation. Selecting options that work best under a specific projection does not give insight into how the community is protected under more rapid sea level rise, or how the community is protected further into the future than the time-stamp of the scenario.

The dynamic adaptive policy pathways (DAPP) is an alternative method of planning for sea level rise that is not dependent on a sea level rise *projection*. Rather, it considers how risk evolves as sea levels rise, both with and without a suite of adaptation options. The ability to reduce risk is considered when evaluating an adaptation option, but also its shelf-life: that is, how long that option will keep risk low as sea levels rise.

Why quick-scan tools?

Assessing the effectiveness of adaptation options is often an expensive and time-consuming endeavor involving complex models. The development and use of quick-scan tools can provide tremendous insight into the relative effectiveness of adaptation options. Less-effective options can be weeded out at this early phase, and the detailed modeling of adaptation options can be reserved for the most promising options.

Webinar registration link: https://attendee.gotowebinar.com/register/7172902000520304139

Attendee List

Organization	Number of attendees
AECOM	4
American Flood Coalition	1
Arcadis	9
Associated Engineering	1
Broward College Environmental Science	1
Broward County	6
Broward MPO	2
CBCL Limited	1
CDM Smith	1
Chen Moore and Associates	2
City of Coral Gables	1
City of Dania Beach	1
City of Delray Beach	2
City of Fort Lauderdale Public Works	1
City of Hallandale Beach	1
City of Hollywood	1
City of Hollywood Florida	1
City of Key West	1
City of Margate	1
City of Miami	4
City of Miami Beach	9
City of Parkland	1
City of Pompano Beach Utilities Department	1
City of Sunny Isles Beach	1
City of Sunrise	2
City of Treasure Island	1
City of Vancouver	1
Colle	1
Consulate-General of the Kingdom of the Netherlands	1
Continuity H2O, LLC	1
Craven Thompson & Associates	1
CUET	1
Curtis & Rogers Design Studio, Inc.	1
Dassault Systemes	1
Delft University of Technology	1
Deltares	9
Deltares USA	1
Duke University	1
E Sciences	1
ecoPreserve - Building Sustainability	1
Edisto Island Community Organization	1
Environmental Hydraulic Institute, IHCantabria	1
Erin L. Deady, PA	1
FAU CES	2
FAU Pine Jog EE Center	1

Organization	Number of attendees
FDOT	1
FDOT District Four	1
FernLeaf Interactive	1
Fernleaf Interactive, LLC	1
FHWA	1
FirstService Residential	1
FIU	10
Florida Advisors for Climate and Energy	1
Florida Atlantic University	1
Florida Department of Transportation - District 6	1
Florida Int Uni	1
Florida International Univ	1
Florida International Univ / City of South Miami	1
Florida International University	7
GAIA Consulting Partners, LLC	1
Geosyntec Consultants	1
Hawaii Philanthropy Forum	1
Hazen and Sawyer	3
HIllsborough County	1
IHCANTABRIA	1
ITS	1
KEMEA	1
Lanier Consulting, LLC	1
LHUMSS	1
MacVicar Consulting, Inc.	1
Miami Dade County	1
Miami Dade County DTPW	1
Miami Herald	1
Miami Shores Village	1
Miami-Dade County	4
Miami-Dade County Office of Emergency Management	1
Miami-Dade County Office of Resilience	1
Miami-Dade County RER	1
Moffatt & Nichol	2
Monroe County BOCC	1
Mott MacDonald	2
National Disaster Preparedness Training Center, University of Hawaii	1
None Organization	1
Nova Consulting	3
Nova Consulting, Inc.	2
Odessa State Environmental University	1
Palm Beach County	1
palm beach county board of county commissioners	1
Palm Beach County Office of Resilience	1

Organization	Number of attendees
Pathman Lewis, LLP	1
Plummer	1
Port Everglades	1
Priscilla Cygielnik	1
Renaissance Planning Group	2
RHDHV	1
Rijkswaterstaat	1
RIKS	1
Royal HaskoningDHV	1
RPM Engineers Sdn Bhd	1
SCALAR CONSULTING GROUP, IN	1
Schwebke-Shiskin & Associates, Inc.	1
Sempergreen / Purple Roof	1
SFWMD	9
SFWMD waater use regulation	1
SIBDP2100, Mott MacDonald	1
SNC-Lavalin	1
South Florida Regional Planning Council (SFRPC)	1
South Florida Water Management District	2
St. Pete Beach	1
suleyman demirel university	1
TECNOCEANO	2
The Nature Conservancy	3
The Water Institute	1
Town of Lauderdale-By-The-Sea, FL	1
Town of Surfside, FL	1
TU Delft	1
UCF	1
UF	1
University of California Berkeley	1
University of Central Florida	2
University of Florida	1
University of Miami	2
University of Minho	1
University of Pennsylvania	1
University of Texas at Arlington	1
UPorto	1
US Army Corps of Engineers	2
USACE	3
USACE (Norfolk District)	1
USGS	3
Village of Key Biscayne Building, Zoning and Planning	1
Walton County	1
WASD	1
Water Institute of the Gulf	1

Organization	Number of attendees
Wetlands International	1
WSP	1
WWF	1
WWF Mexico	1
WWF North Africa	1
WWF-Malaysia	1
Youth Environmental Alliance	1
(unspecified)	6
Grand Total	232

Presentations

Planning adaptively for sea level rise, supported by quick-scan tools

Webinar November 19th, 2019

FIU Institute of Water and Environment
Florida International University

Deltares USA

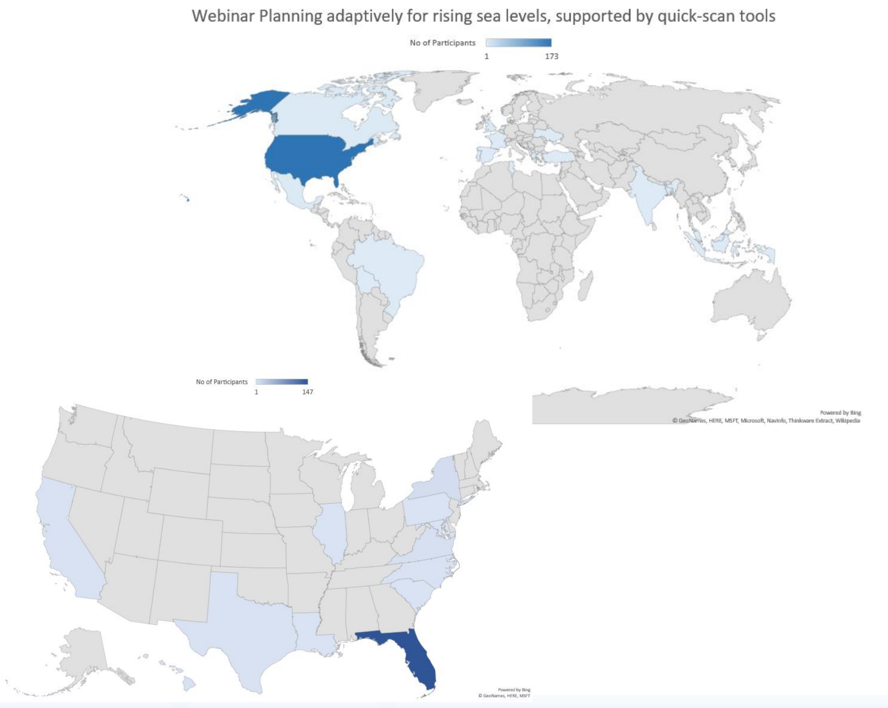
South Florida Water Management District

Deltares
Enabling Delta Life

FIU Sea Level Solutions Center
Florida International University

Introduction | This webinar

- > 200 registrations
- 17 countries
- 173 US, 13 states
- 147 Florida
- Governments, NGO's, consultants, universities, small businesses



Introduction | Speakers

- **Dr. Jayantha Obeysekera**, Research Professor and Director of the Sea Level Solutions Center, Florida International University

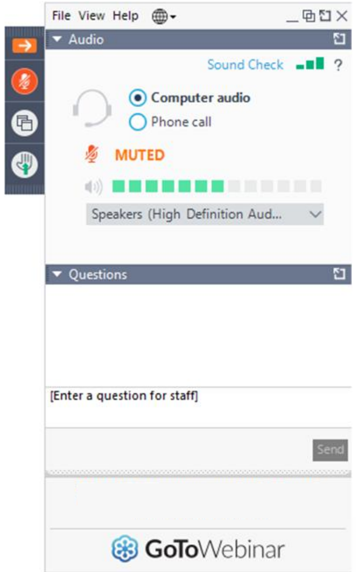
- **Akintunde Owosina**, P.E., Chief Hydrology and Hydraulics Bureau. South Florida Water Management District

- **Dr. Marjolijn Haasnoot**, Adaptive planning and water management specialist, developer of the Dynamic Adaptive Policy Pathways, Deltares

- **Dr. Kathryn Roscoe**, flood risk and adaptation specialist and regional coordinator USA & Canada, Deltares
- **Dr. Claire Jeuken**, nature-based solutions and flood risk adaptation expert, Deltares USA

Introduction | Webinar outline

1. Introduction to adaptive planning
2. Dynamic Adaptive Policy Pathways (DAPP)
3. Tools supporting the DAPP approach
4. Discussion



#daretoask

Webinar outline | next presenter

1. Introduction to adaptive planning
2. Dynamic Adaptive Policy Pathways (DAPP)
3. Tools supporting the DAPP approach
4. Discussion

Introduction to adaptive planning | Background

Project: Development of Short- and Long-Term Strategies for Resiliency with respect to Coastal Flooding in Miami-Dade County

- **Funded by** Florida Department of Environmental Protection (Florida Coastal Management Program)
- **Collaborators:**
  - South Florida Water Management District
  - Deltares USA
  - FIU Sea Level Solutions Center
  - Miami Dade County (Office of Resilience and Emergency Management)
  - City of Miami

Introduction | We need a new paradigm for Resiliency Planning

Five Principles of Resiliency in coping with extremes:

1. Adopt a **system's approach**;
2. Look at **beyond-design** events;
3. Build and prepare infrastructure according to '**remain functioning**'
4. Increase **recovery capacity** by looking at social and financial capital; and
5. Remain **resilient** into the **future**

Implications:

- **Plan for future** and not the present – projections can be deeply uncertain
- **Price tag** can be very high, and financing can be challenging
- **Smart phasing** of adaptation strategies is desirable

De Bruijn et al. (2017)

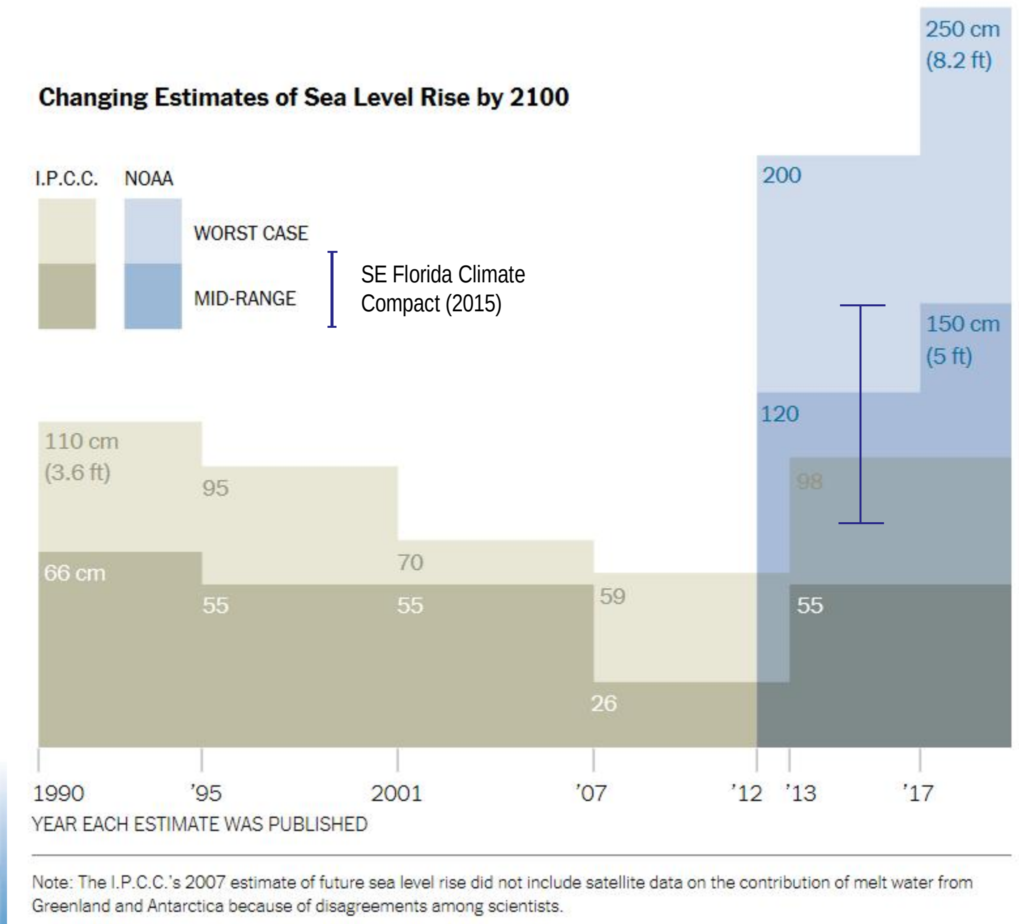
Introduction | Sea level rise projections for 2100

Larger bandwidth
Uncertainty increased
→ Deep uncertainty

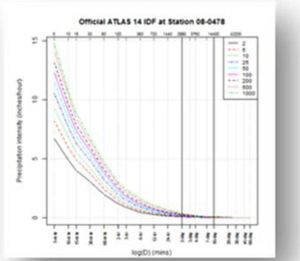
The New York Times

Rising Seas Will Erase More Cities by 2050, New Research Shows

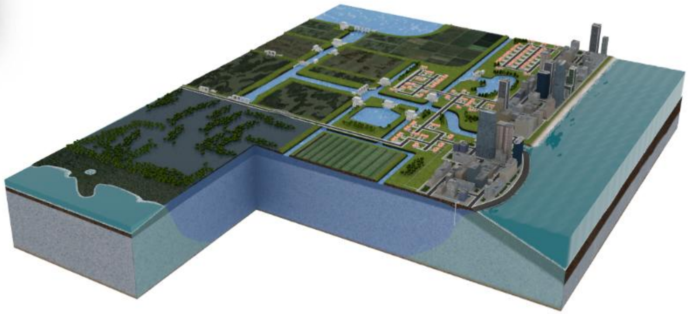
By Denise Lu and Christopher Flavelle Oct. 29, 2019



Introduction | Uncertainties in “Shocks” and “Stresses”



Rainfall Extremes: IDF Curves



Socio-economic trends?

TheBalance.com

Future **Storminess**?

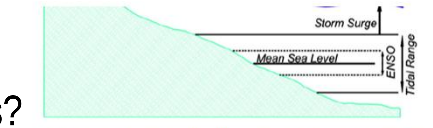
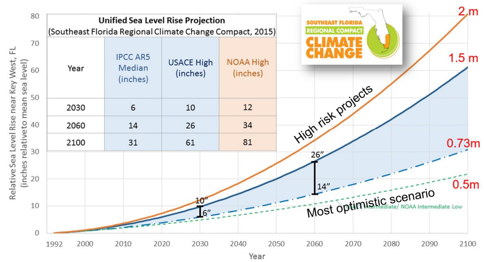


Fig. 2. Diagram illustrating the contributions to sea level due to tides, storm surge and wind-generated waves.

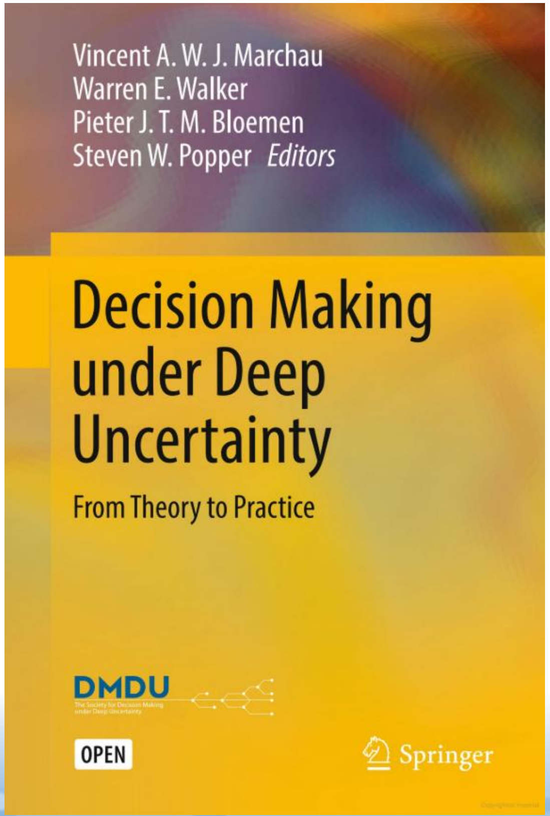
SLR: Which Scenario?



Ocean Dynamics, Gravitational Effects

Selected Methods of DMDU:

- Robust Decision Making (RBM) pioneered by RAND
- Decision Scaling or Stress Test ("bottom-up approach")
- Dynamic Adaptive Policy Pathways (DAPP) developed by Deltares and TU Delft, The Netherlands



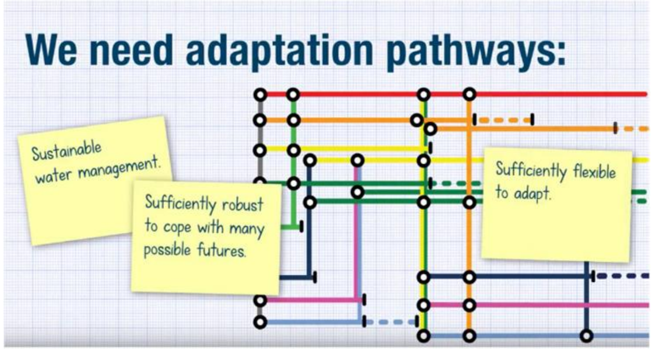
https://link.springer.com/book/10.1007/978-3-030-05252-2

Dynamic Adaptive Policy pathways (DAPP)| Introduction

Decisions are made over time in dynamic interaction with the system and cannot be considered independently

- DAPP explicitly includes decision making over time and sequences of decisions (pathways) under uncertainty.
- Supports planners to design a dynamic adaptive plans: short-term actions, long-term options, adaptation signals.

"Different roads leading to Rome"



Haasnoot et al. (2013) Glob. Env. Change. 10.1016/j.gloenvcha.2012.12.006

Webinar outline| next presenter

1. Introduction to adaptive planning
2. **Dynamic Adaptive Policy Pathways (DAPP)**
3. Tools supporting the DAPP approach
4. Discussion

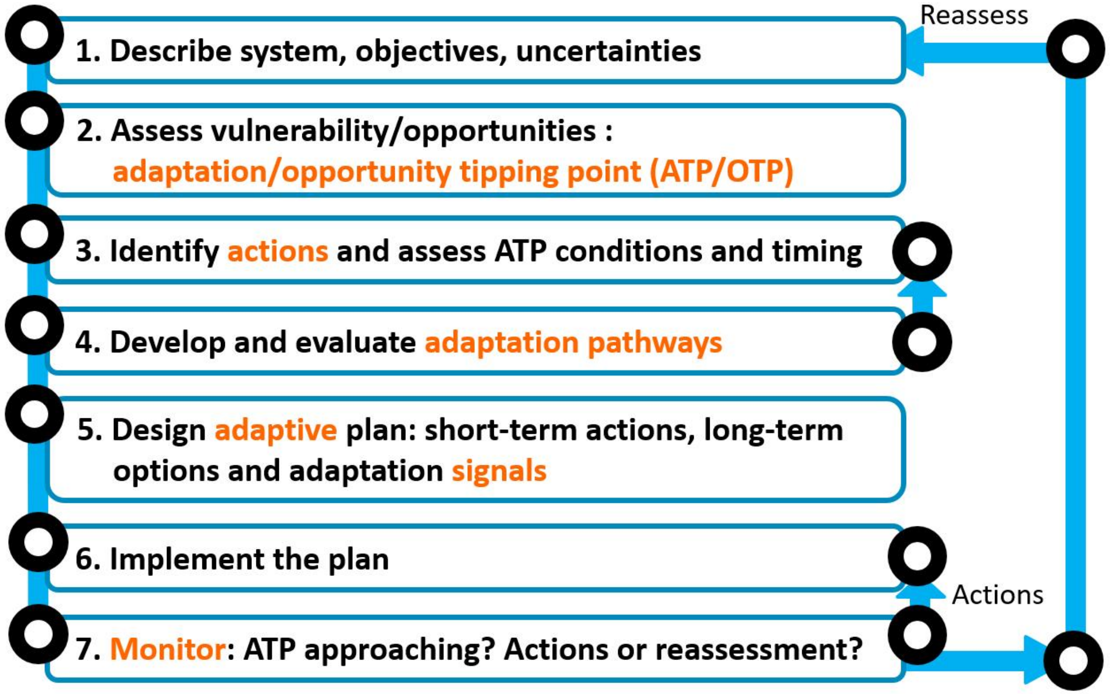
Adaptive pathways planning using DAPP

A **systematic framework** that helps focus on important planning and decision **questions** under deep uncertainty:

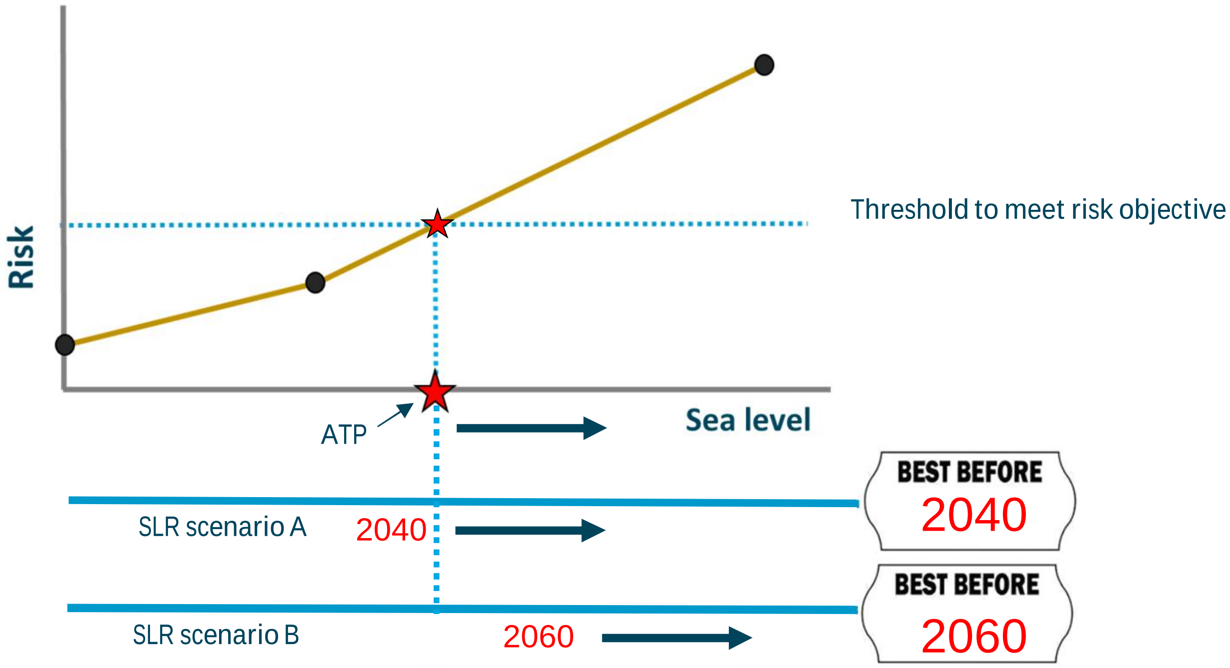
- What low-regret actions can we take now that contribute to future goals?
- What actions can we postpone? How to prioritize?
- What robust and flexible strategies perform well over a wide range of futures?

Systematic framework of DAPP

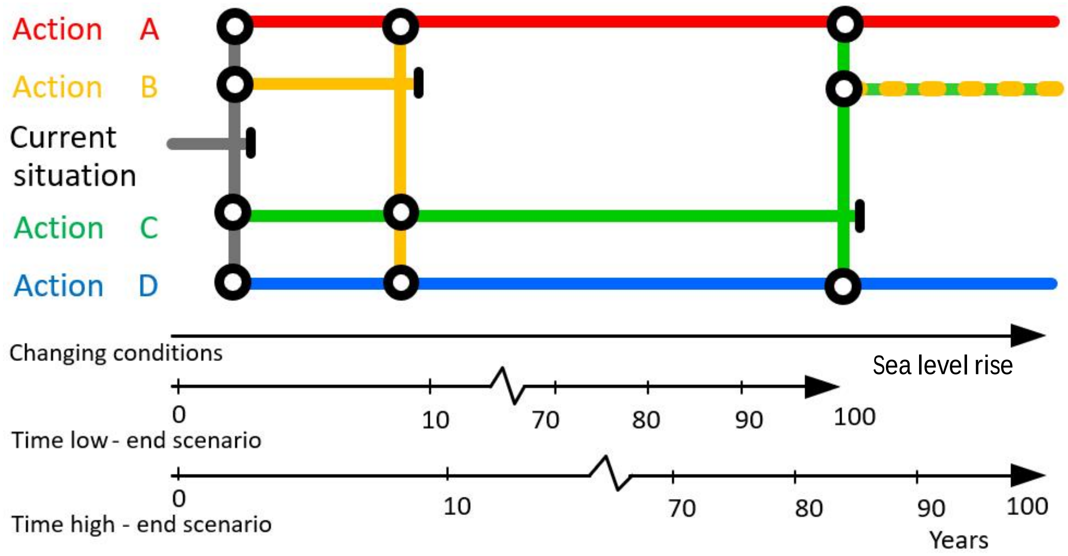
Key features:

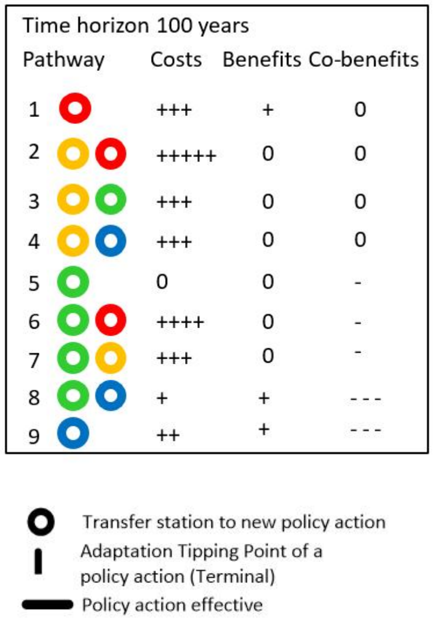


Adaptation Tipping Points (ATP)



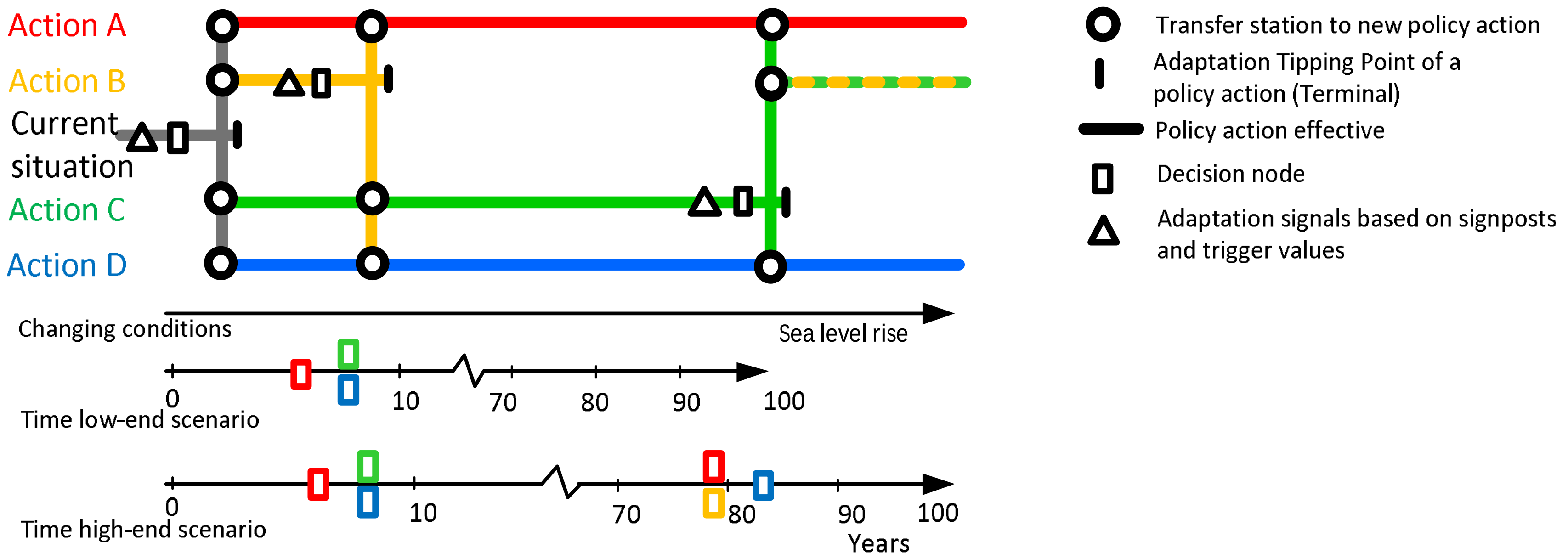
Adaptation pathways maps





The maps (left) show different possible sequences of decisions to achieve objectives. A scorecard (right) helps to evaluate the pathways and decisions.

Adaptation pathways maps

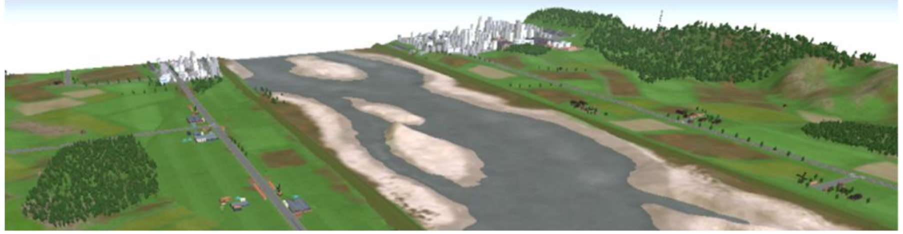


Haasnoot et al. 2013; Haasnoot et al. 2018 Glob. Env. Change, Haasnoot et al. 2019

http://pathways.deltares.nl

A phased approach to pathways

Awareness raising:
- Serious gaming.
- Introduction to adaptive planning method.



http://deltagame.deltares.nl

A phased approach to pathways

Narratives

Level I – Initial qualitative pathways - narratives

Level II – Quantitative design of pathways

Level III – Full assessment of pathways

Requirements for the model and further analysis

A phased approach to pathways

Narratives

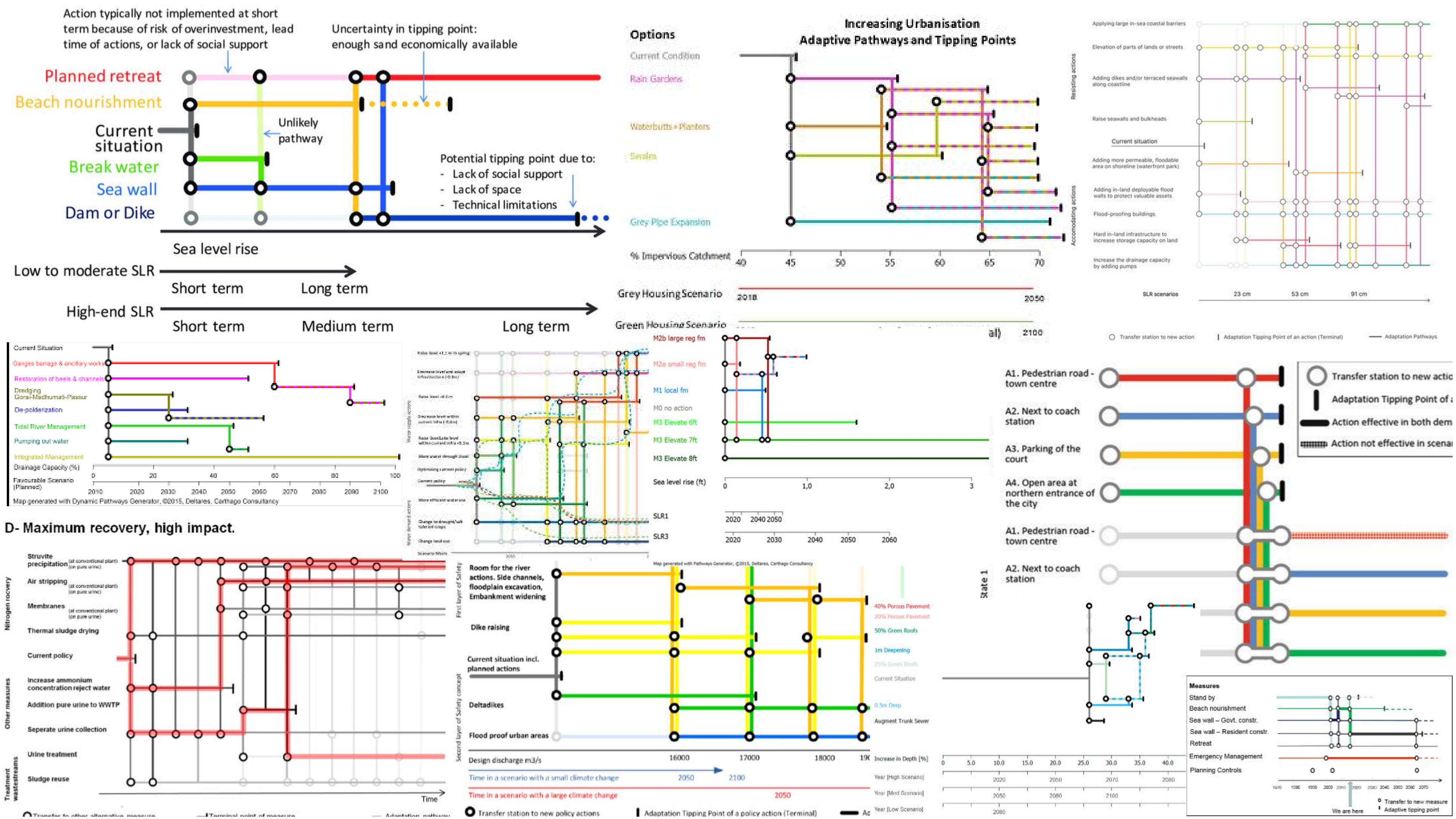
Level I – Initial qualitative pathways - narratives
- Pathways narratives illuminating uncertainties, options and their path-dependencies.

Level II – Quantitative design of pathways
- Preferred portfolio of actions selected for assessment by experts, literature and/or with a (simple) model.

Level III – Full assessment of pathways
- Pathways impact assessment using integrated model Evaluation of trade-offs of pathways.
- Design adaptive plan.

Requirements for the model and further analysis

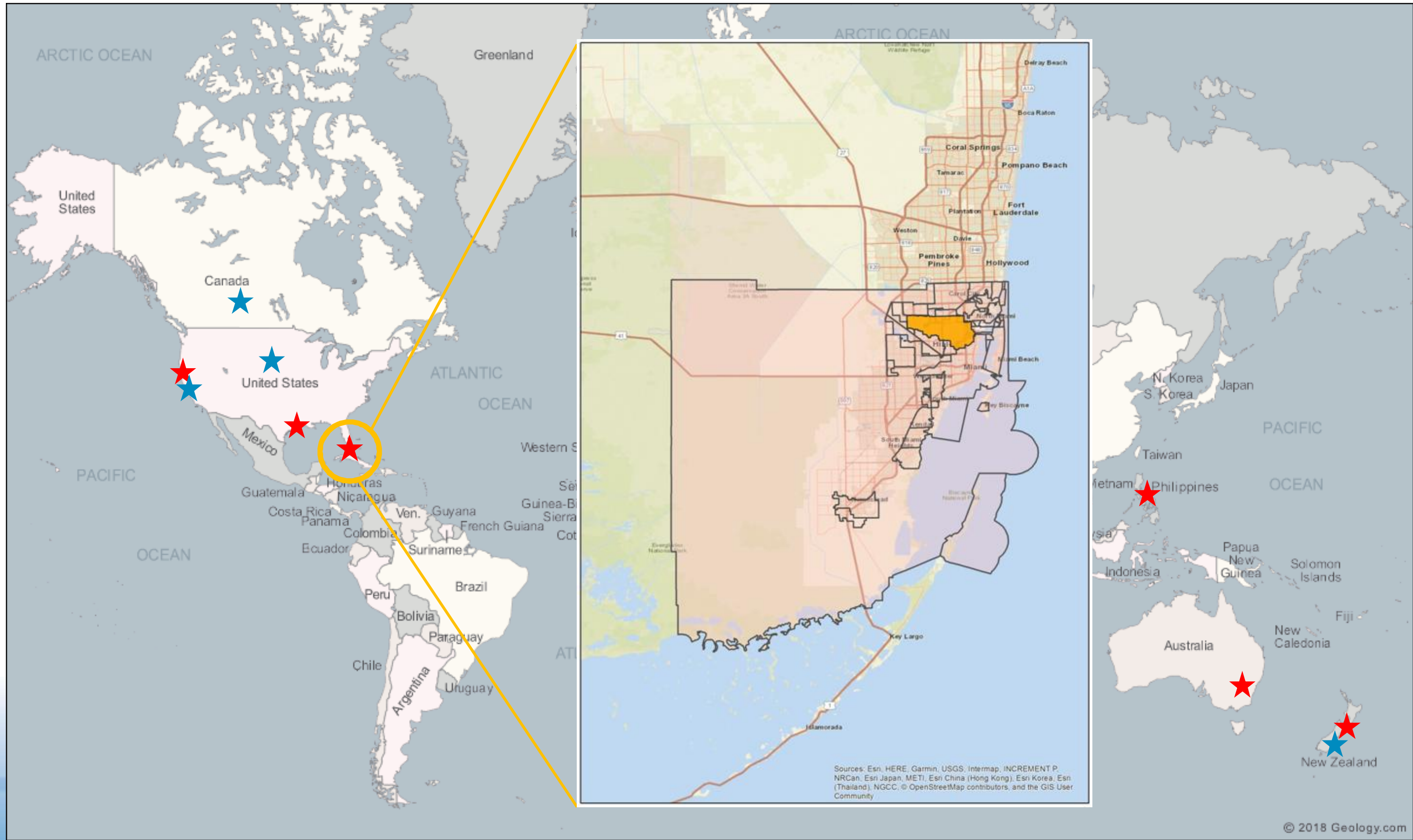
Where have pathways studies been applied?



Action typically not implemented at short term because of risk of overinvestment, lead time of actions, or lack of social support
Uncertainty in tipping point: enough sand economically available
Planned retreat
Beach nourishment
Current situation
Unlikely pathway
Break water
Sea wall
Dam or Dike
Potential tipping point due to:
- Lack of social support
- Lack of space
- Technical limitations
Sea level rise
Low to moderate SLR
Short term
Long term
High-end SLR
Short term
Medium term
Long term
Options
Increasing Urbanisation
Adaptive Pathways and Tipping Points
Current Condition
Rain Gardens
Waterbutts + Planters
Swales
Grey Pipe Expansion
% Impervious Catchment
40
45
50
55
60
65
70
Grey Housing Scenario
2018
2050
Green Housing Scenario
2100
Current situation
SLR scenarios
91 cm
Transfer station to new action
Adaptation Tipping Point of an action (Terminal)
Adaptation Pathways
M2b large reg fm
M2a small reg fm
M1 local fm
M0 no action
M3 Elevate 6ft
M3 Elevate 7ft
M3 Elevate 8ft
Sea level rise (ft)
0
1,0
2,0
3
SLR1
SLR3
A1. Pedestrian road - town centre
A2. Next to coach station
A3. Parking of the court
A4. Open area at northern entrance of the city
A1. Pedestrian road - town centre
A2. Next to coach station
State 1
Transfer station to new actio
Adaptation Tipping Point of a
Action effective in both dem
Action not effective in scenai
Current Situation
Ganges barrage & ancillary works
Restoration of beels & channels
Dredging
De-polderization
Tidal River Management
Pumping out water
Integrated Management
Drainage Capacity (%)
Favourable Scenario (Planned)
Map generated with Dynamic Pathways Generator, ©2015, Deltares, Carthago Consultancy
D- Maximum recovery, high impact.
Struvite precipitation
Air stripping
Membranes
Thermal sludge drying
Current policy
Increase ammonium concentration reject water
Addition pure urine to WWTP
Seperate urine collection
Urine treatment
Sludge reuse
Nitrogen recovery
Other measures
Treatment wastestreams
Time
Room for the river actions. Side channels, floodplain excavation, Embankment widening
Dike raising
Current situation incl. planned actions
Deltadikes
Flood proof urban areas
First layer of Safety
Second layer of Safety concept
Design discharge m3/s
16000
17000
18000
Time in a scenario with a small climate change
2050
2100
Time in a scenario with a large climate change
2050
Transfer station to new policy actions
Adaptation Tipping Point of a policy action (Terminal)
Map generated with Pathways Generator, ©2015, Deltares, Carthago Consultancy
40% Porous Pavement
20% Porous Pavement
50% Green Roofs
1m Deepening
25% Green Roofs
Current Situation
0.5m Deep
Augment Trunk Sewer
Increase in Depth (%)
Measures
Stand by
Beach nourishment
Sea wall – Govt. constr.
Sea wall – Resident constr.
Retreat
Emergency Management
Planning Controls
We are here
Transfer to new measure
Adaptive tipping point

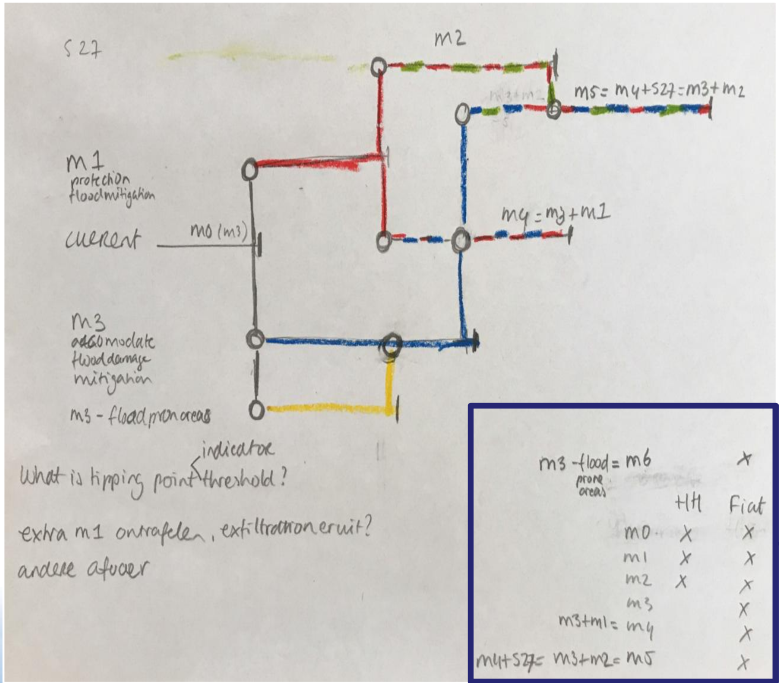
Where have pathways studies been applied?

Application to Miami C7 basin (2017)

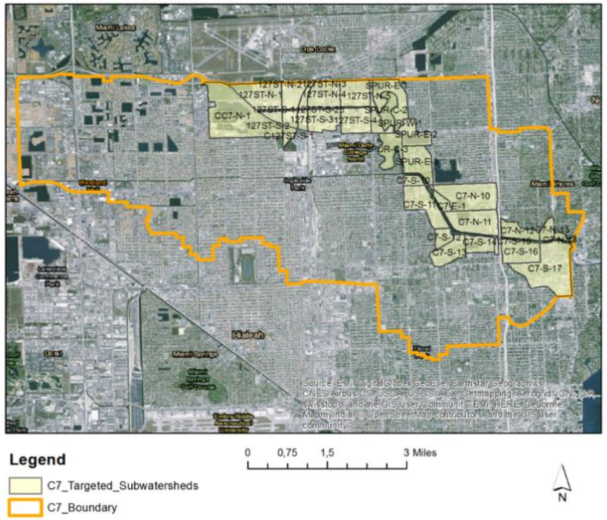


Level I - Workshop to explore pathways

Level I - Initial analysis



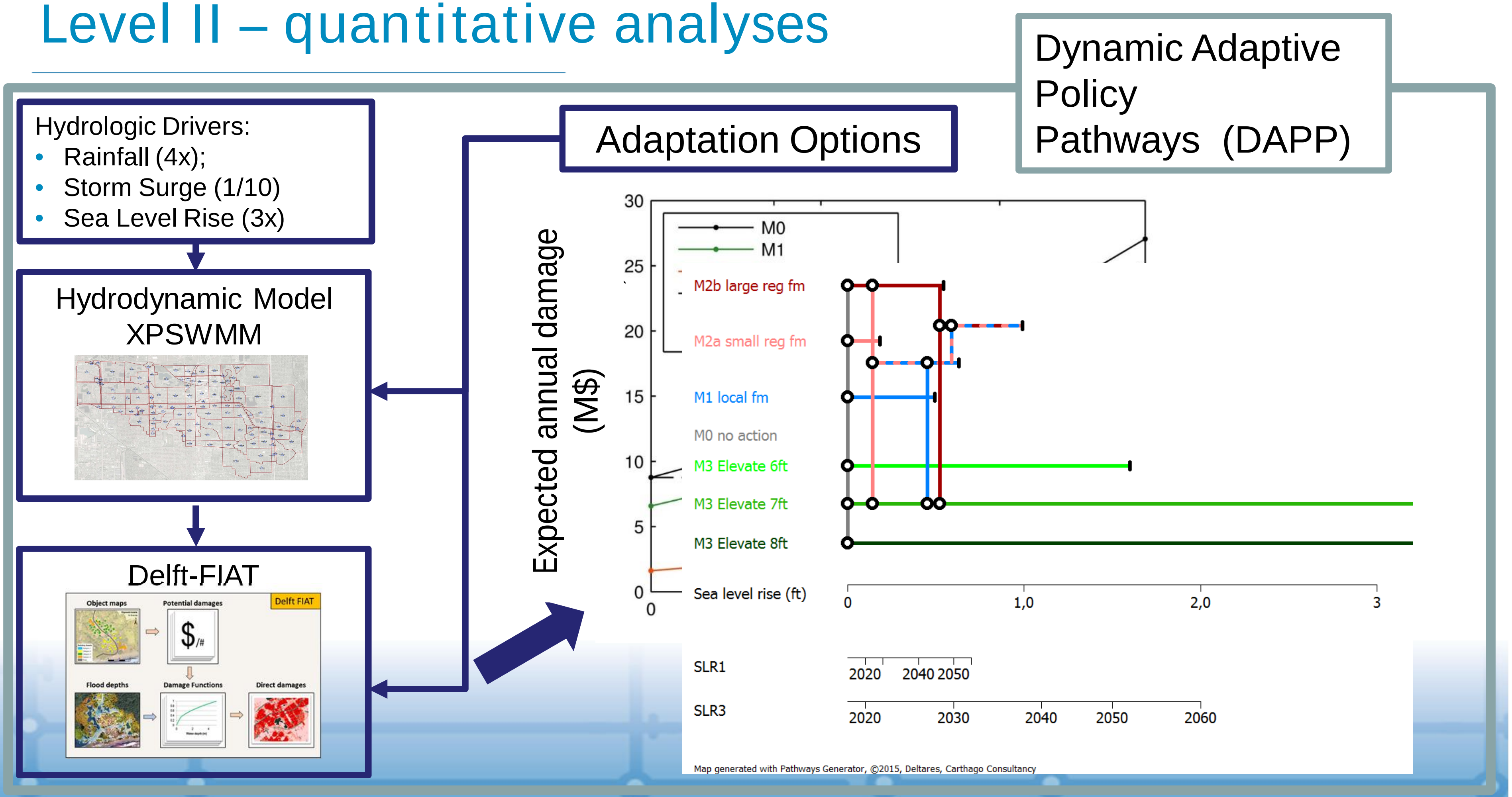
To be modeled



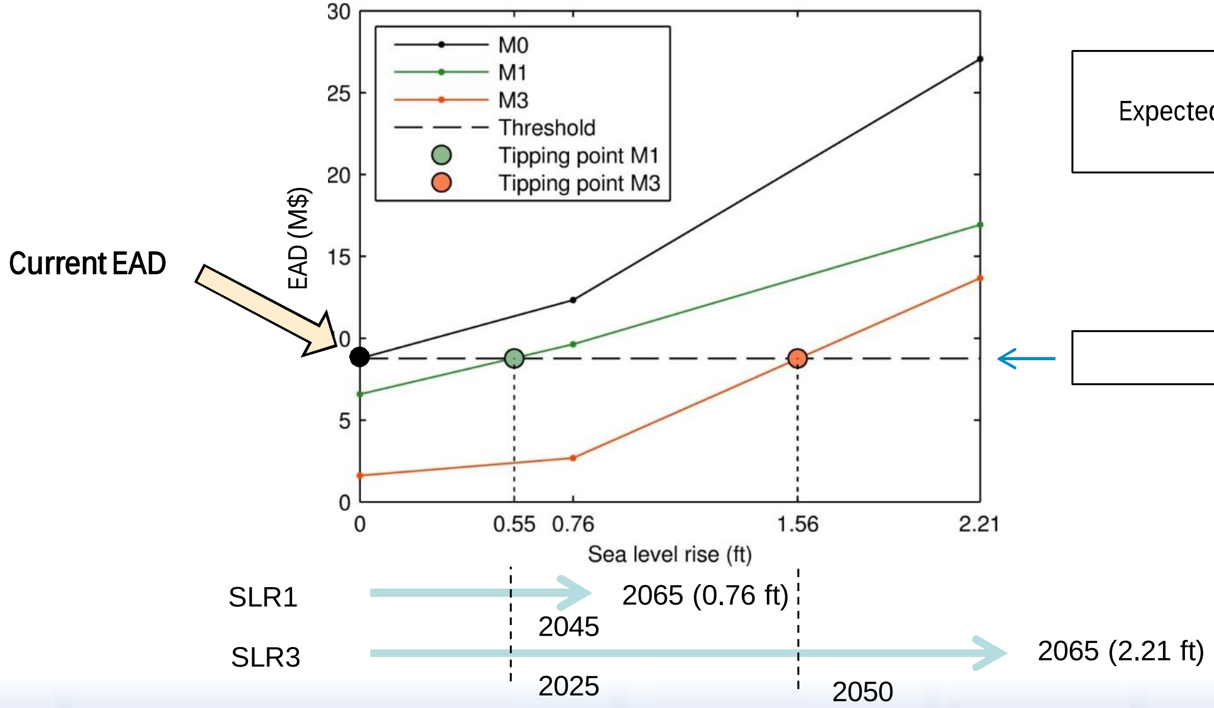
Measures

- **M0 –** No action
- **M1** – Local flood mitigation: flood walls, exfiltration trenches, flap gates, and local pumps
- **M2** – Regional flood mitigation: forward pumps at S-27 coastal structure (small & large pumps)
- **M3** - Land-use mitigation: raise roads and buildings to 6, 7 or 8 feet elevation

Level II – quantitative analyses



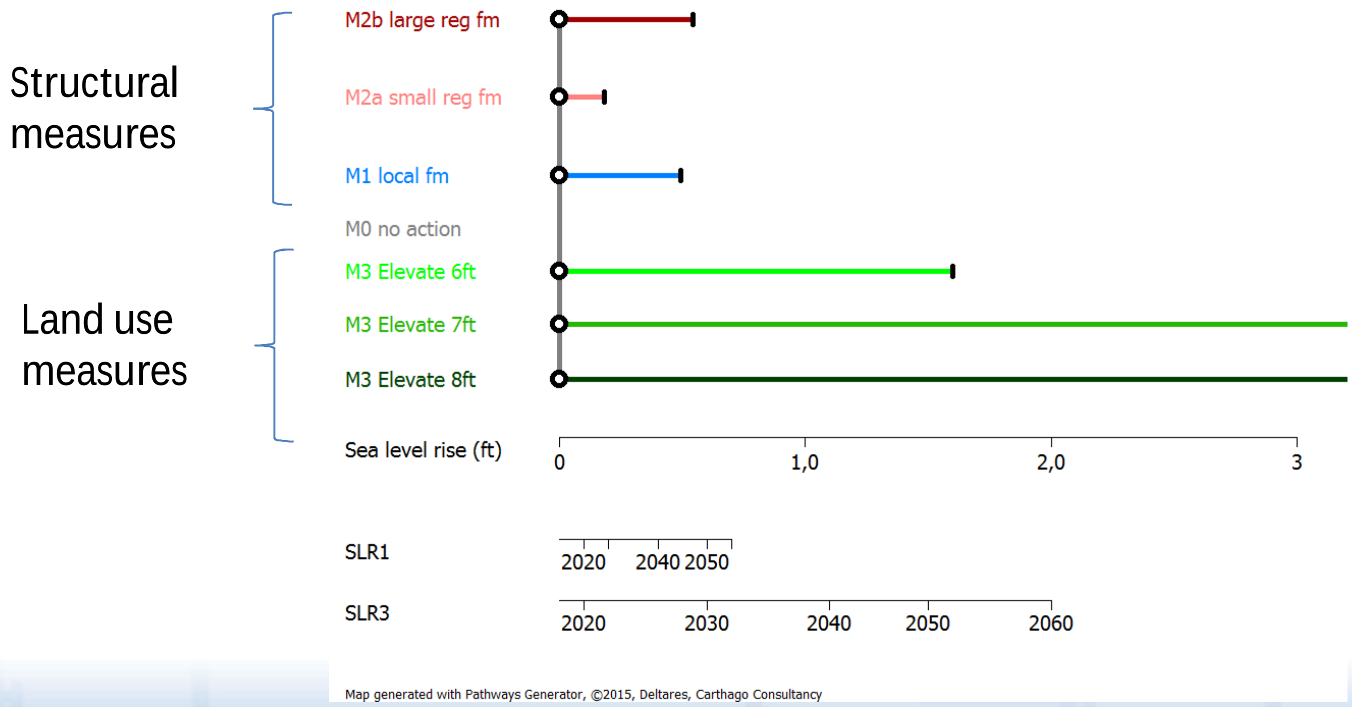
Adaptation tipping points



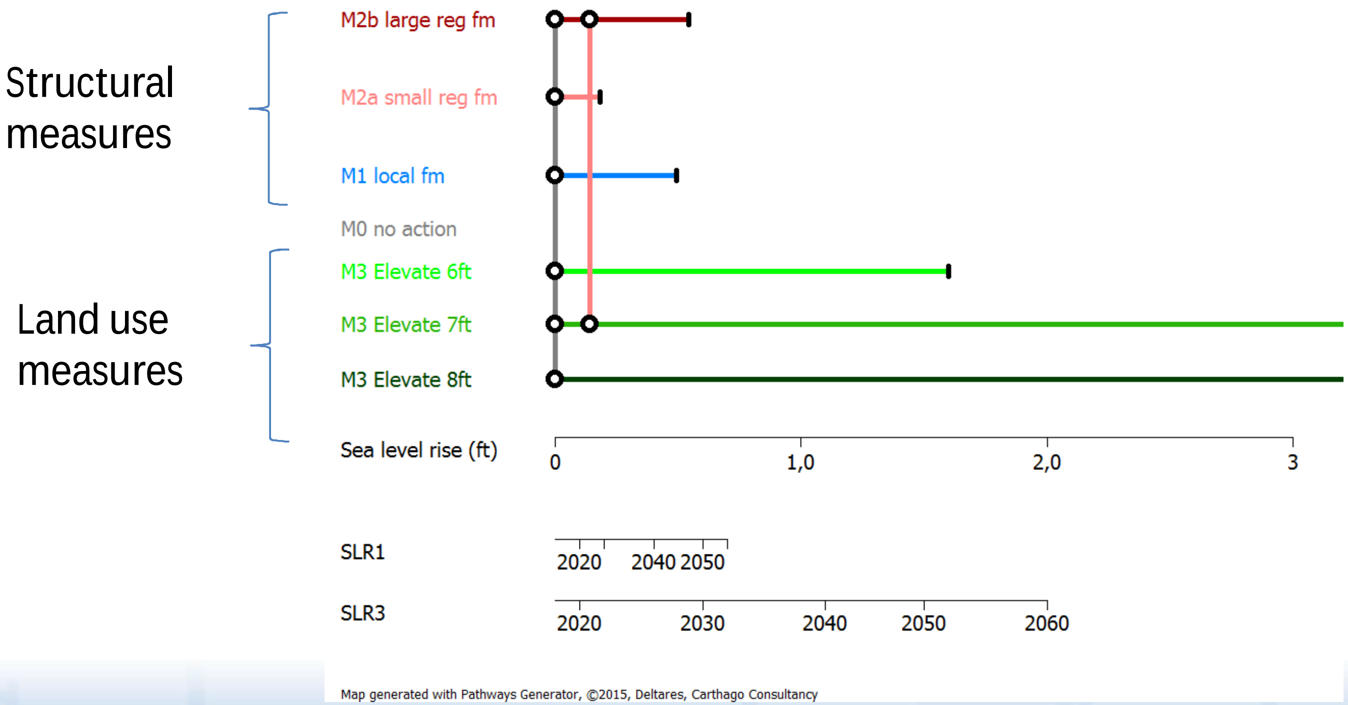
Objective:
Expected annual damage (EAD) should not exceed current levels

Threshold = current EAD

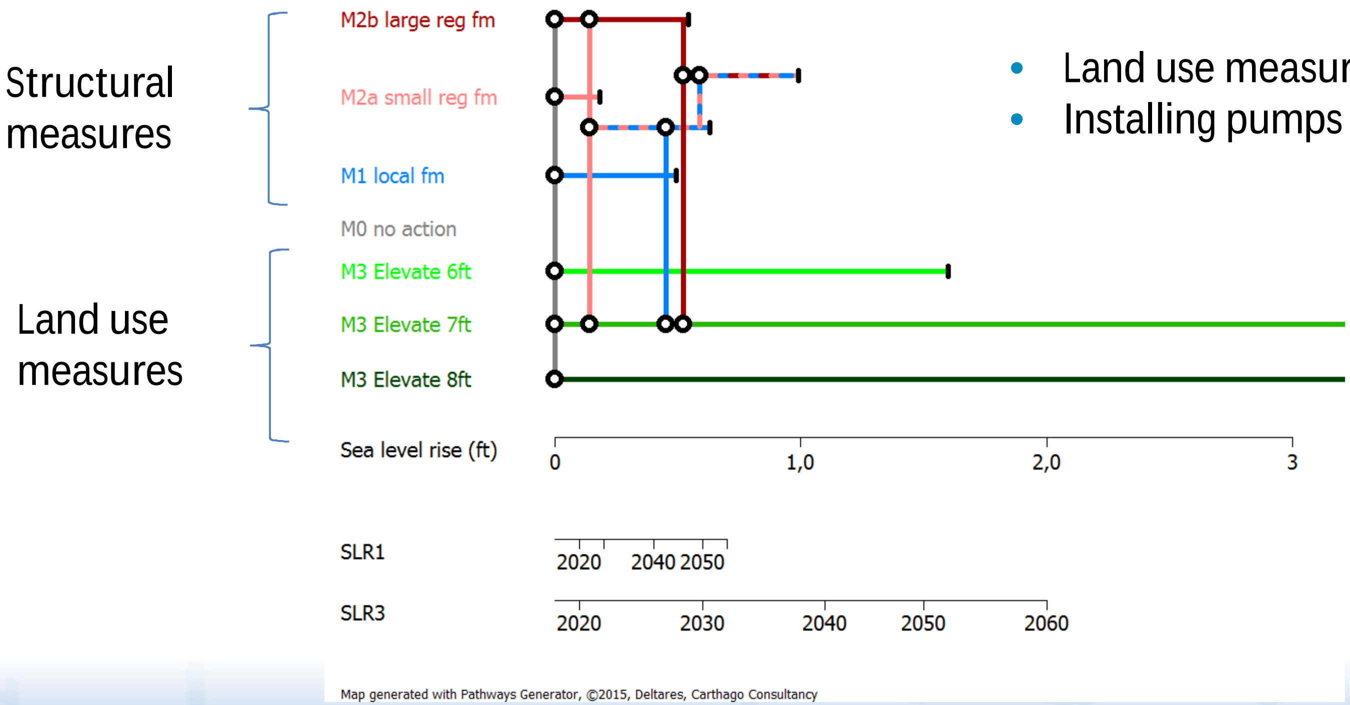
Adaptive pathways



Adaptive pathways



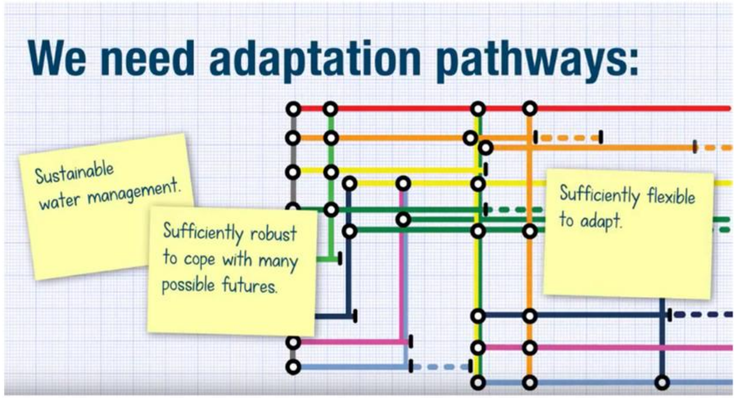
Adaptive pathways

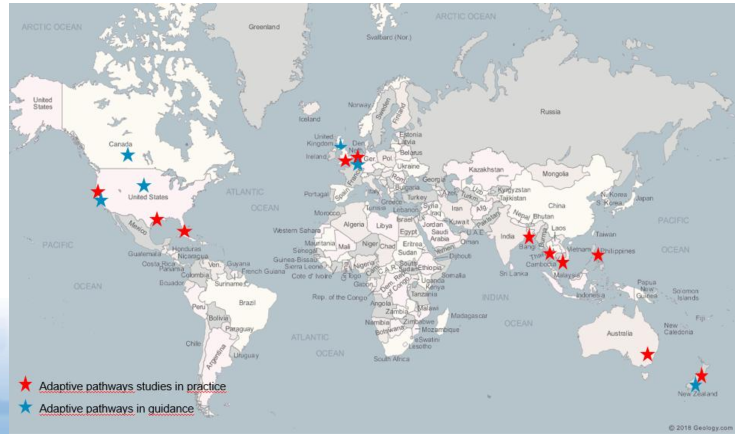


- Land use measures are needed in the end
- Installing pumps can buy some time.

DAPP | a summary

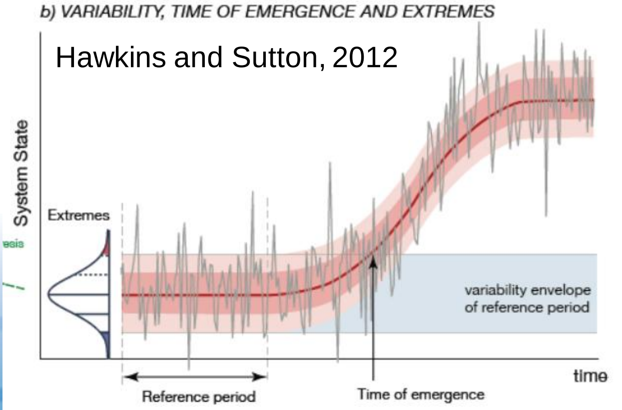
- Decision making under uncertainty
- Adds **adaptiveness** (flexibility, robustness) and **time**
- **Pathways** open **decision space,** identify **path-dependencies** and overcome **policy paralysis**
- **Tipping points** identify **when** to act
- **Monitoring** keeps us on track
- **Assessment modes**: model-based, expert, participatory pathways



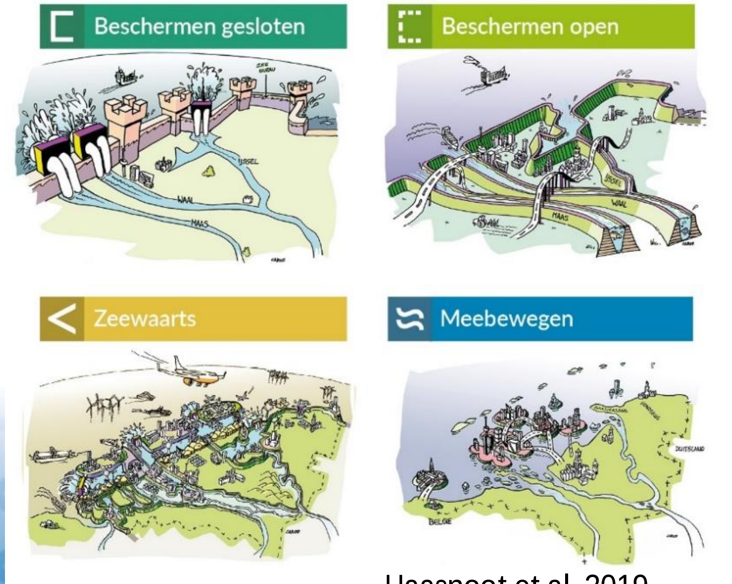


Recent and ongoing developments

- Generic adaptation pathways to sea level rise: https://doi.org/10.1088/2515-7620/ab1871
- Economic evaluation for pathways that considers transfer cost: https://doi.org/10.1007/s10584-019-02409-6
- Detecting timely, reliable and convincing signals of change: https://doi.org/10.1016/j.gloenvcha.2018.08.003
- Compound flooding in Louisiana
- Adaptation to uncertain high-end sea level rise

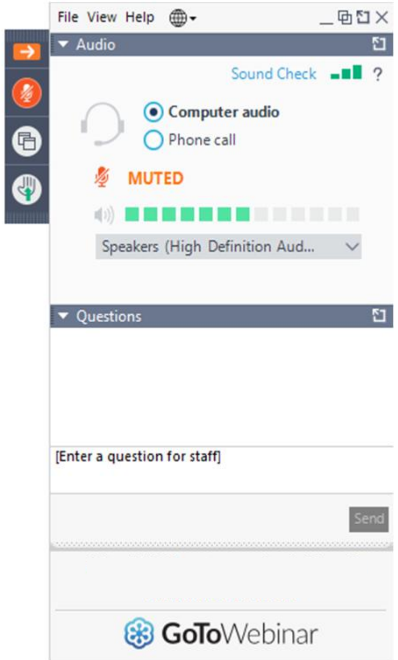


Hawkins and Sutton, 2012



Haasnoot et al. 2019

DAPP | Questions?



#daretoask

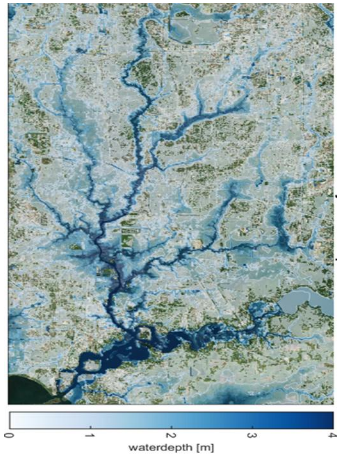
Webinar outline | next presenter

1. Introduction to adaptive planning
2. Dynamic Adaptive Policy Pathways (DAPP)
3. **Tools supporting the DAPP approach**
4. Discussion

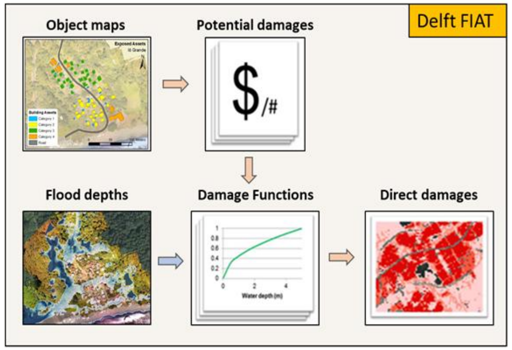
Tools supporting DAPP

Serious Gaming

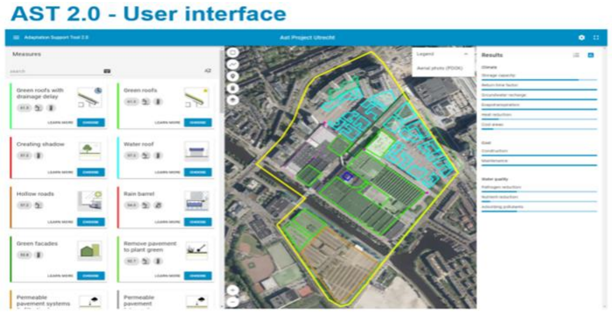
SFINCS



Delft-FIAT



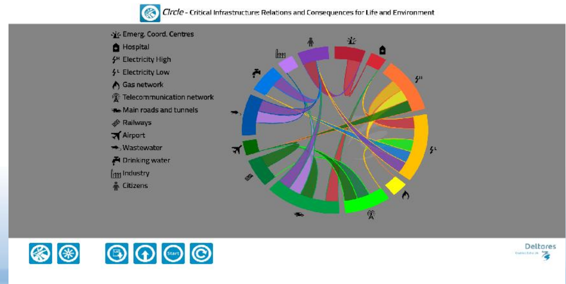
Adaptation Support Tool



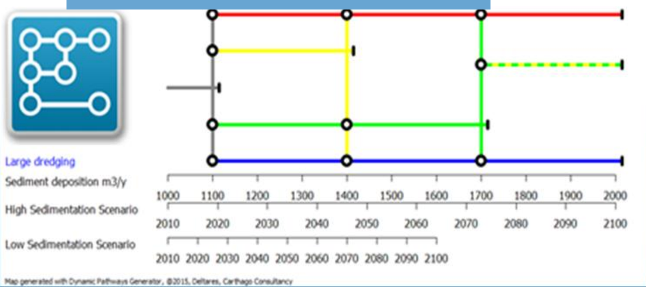
Delft-FIAT Accelerator

1. Input water depth map from anywhere in the world
2. Automatically looks up global exposure data for the area
3. Automatically looks up appropriate damage functions
4. Returns damage map, risk map, and report

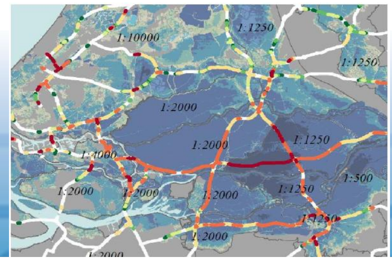
CIRCLE



Pathway generator

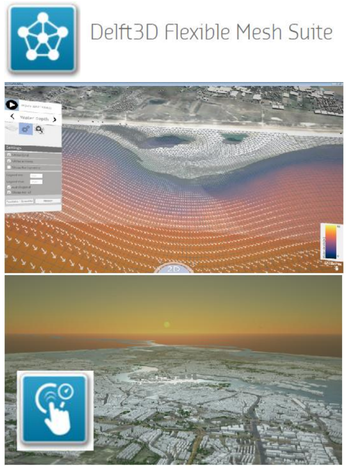


Criticality tool

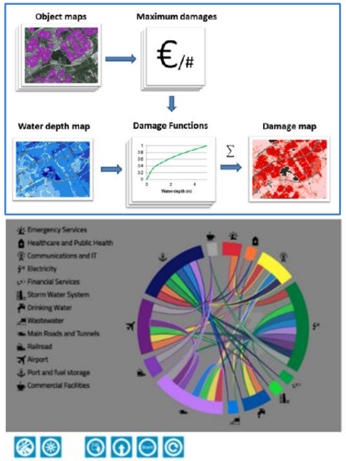


Tools supporting DAPP

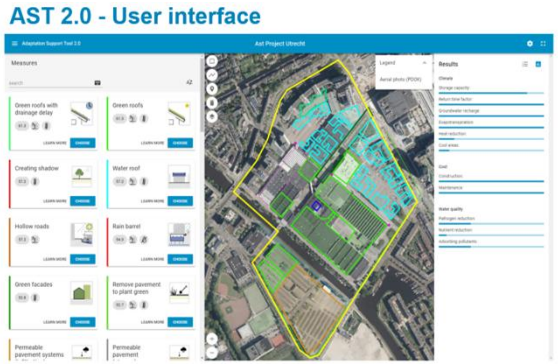
Awareness Raising



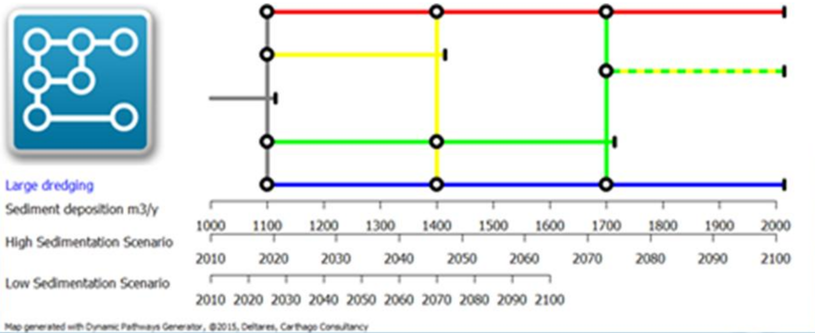
Delft3D-FM

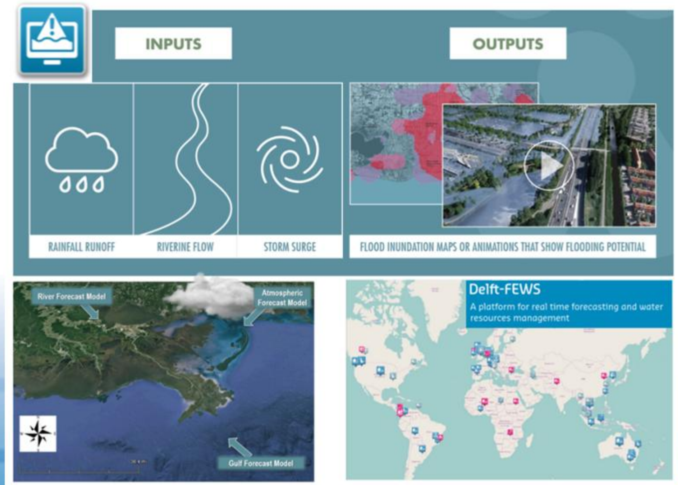


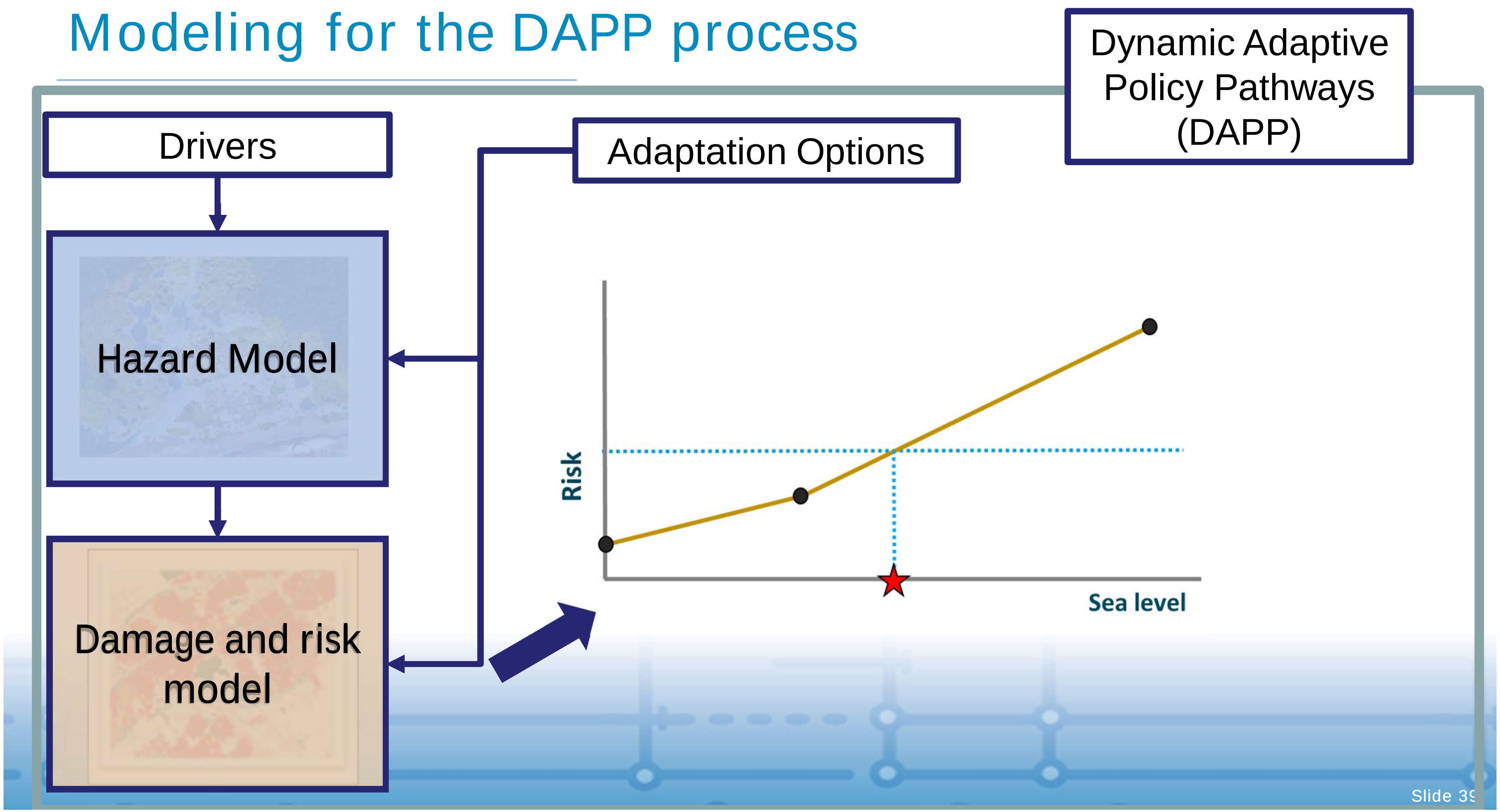
Delft-FIAT and CIrcle



Adaptation support tool

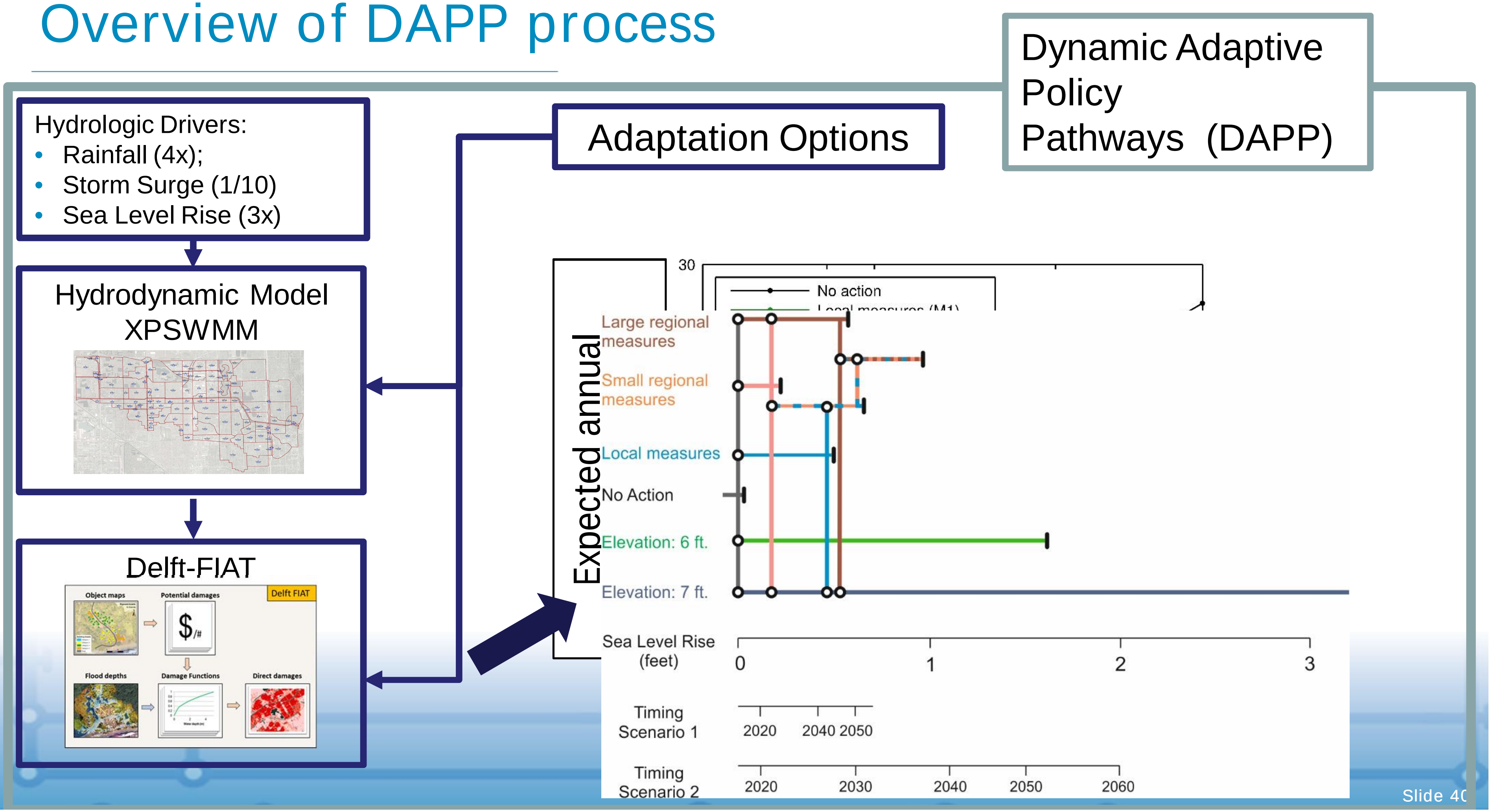




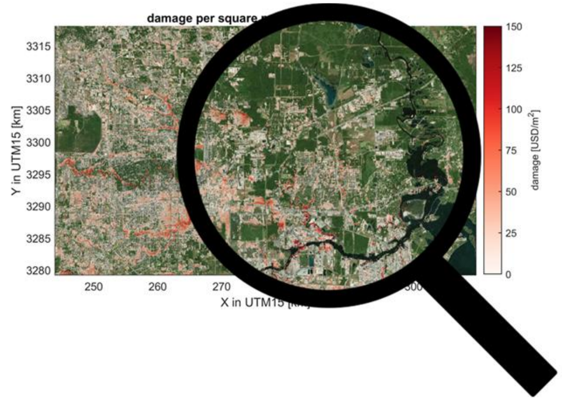


Modeling for the DAPP process
Dynamic Adaptive Policy Pathways (DAPP)
Drivers
Adaptation Options
Hazard Model
Damage and risk model
Risk
Sea level
Slide 39

Overview of DAPP process

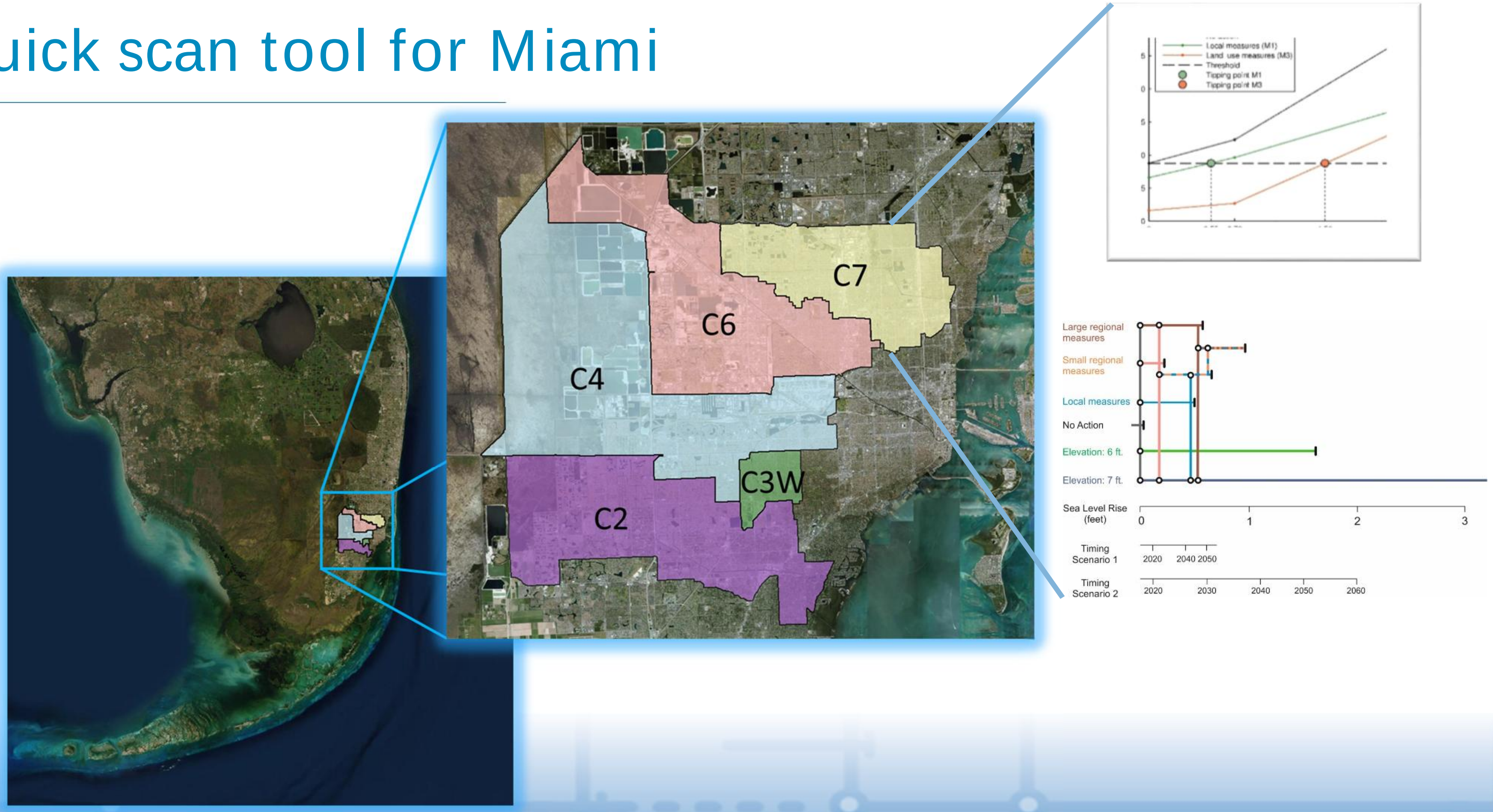


Why a DAPP quick-scan tool

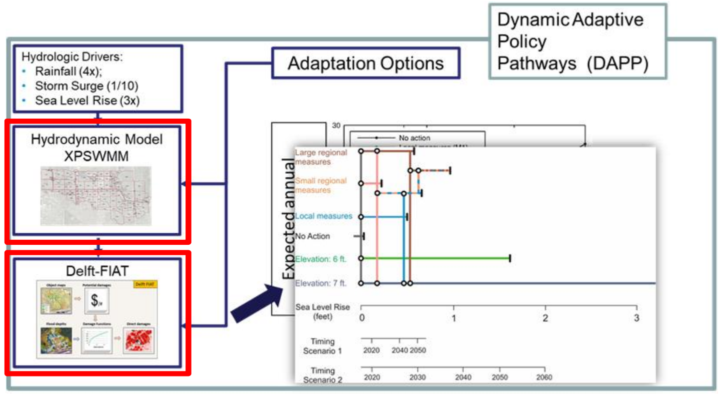


- Quick overview
  - risk --> most at-risk areas
  - system response to climate change
  - risk reduction and shelf-lives of measures
  - influence of risk tolerance on the shelf-life of measures
- Engaging stakeholders in workshops
- Educational tool to understand DAPP process

Quick scan tool for Miami



Recipe for a quick-scan model



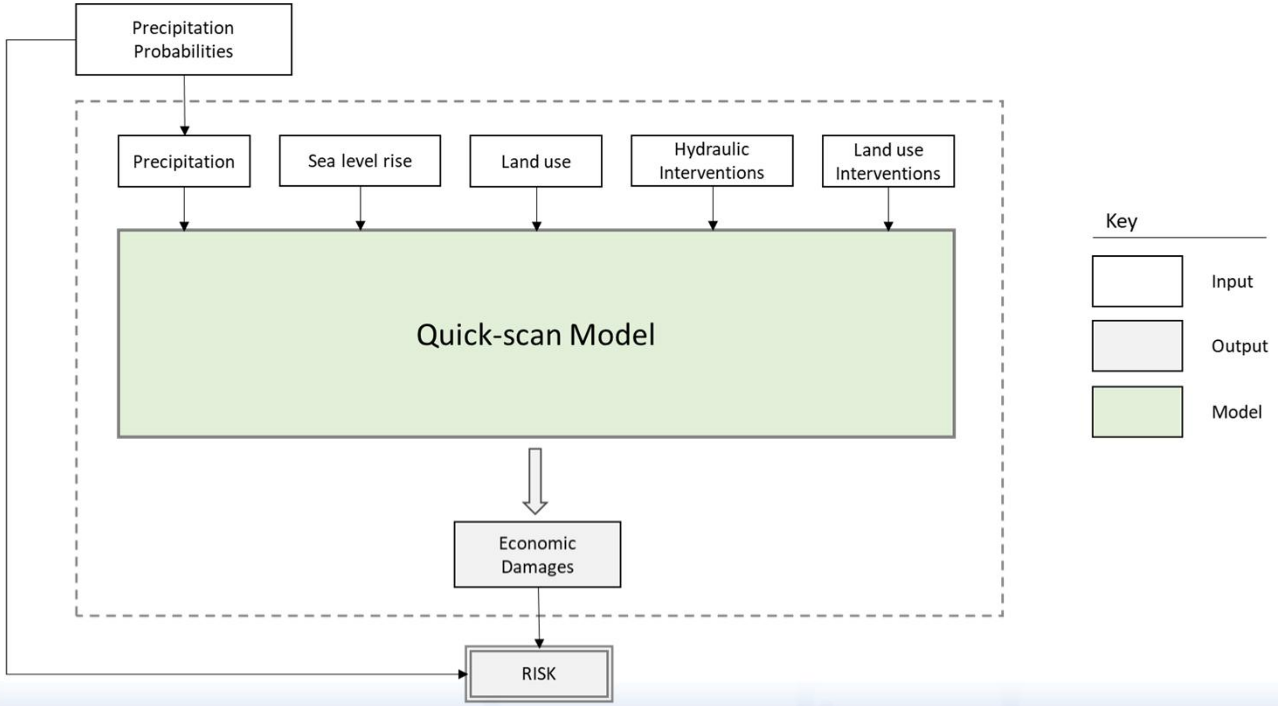
Ingredients:

- Simple hydraulic model
- Fast and automated damage model

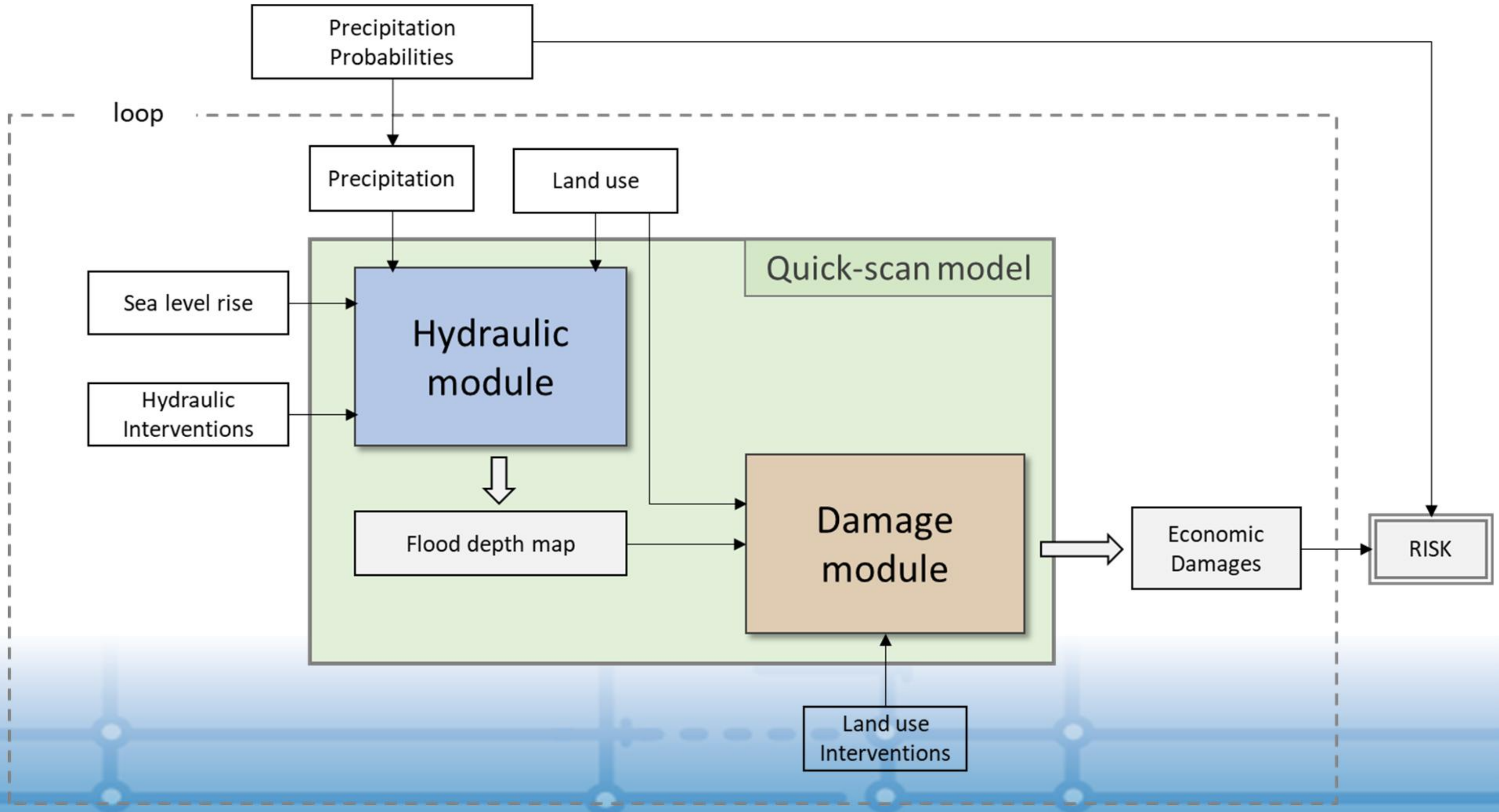
Steps:

- Calibrate the combined hydraulic-damage model
- Implement hydraulic and land-use measures in the model

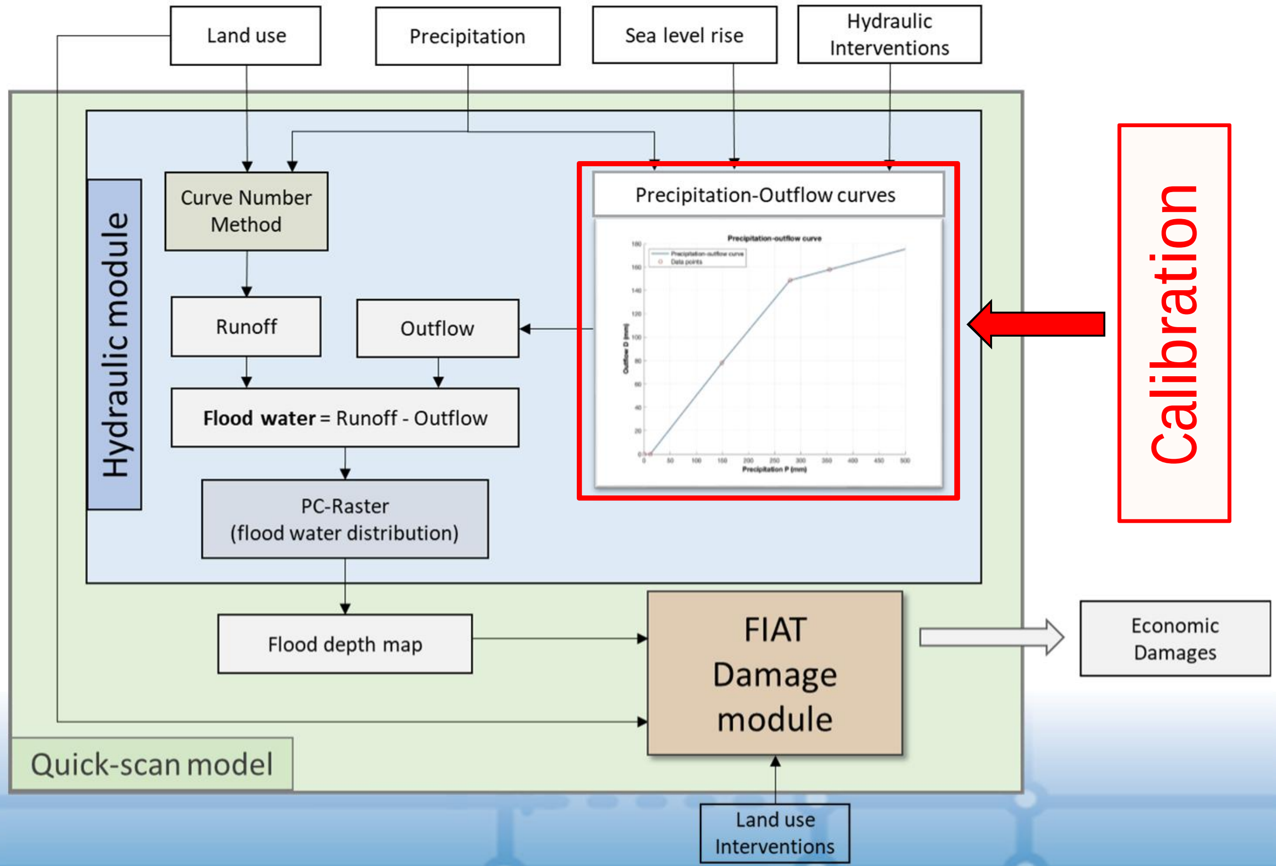
Quick scan tool - overview



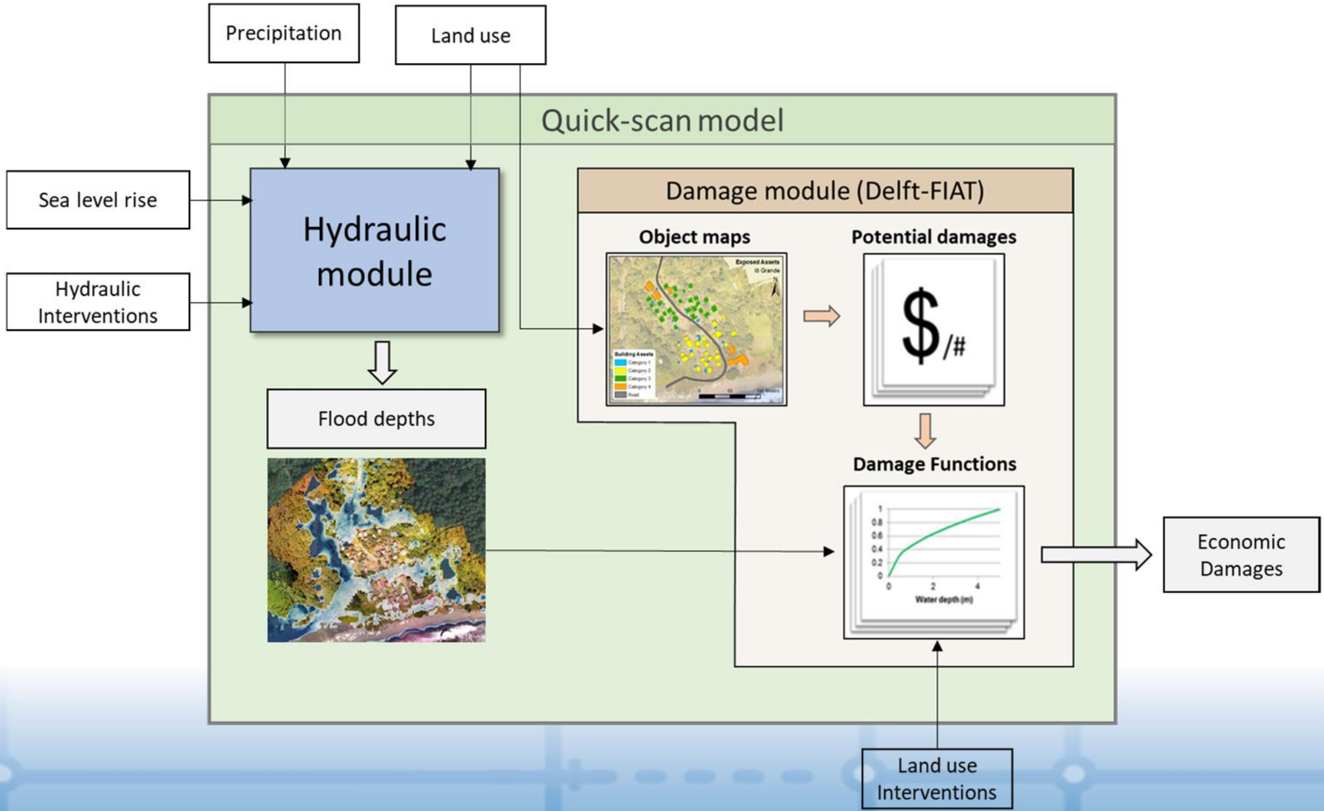
Quick-scan tool model structure



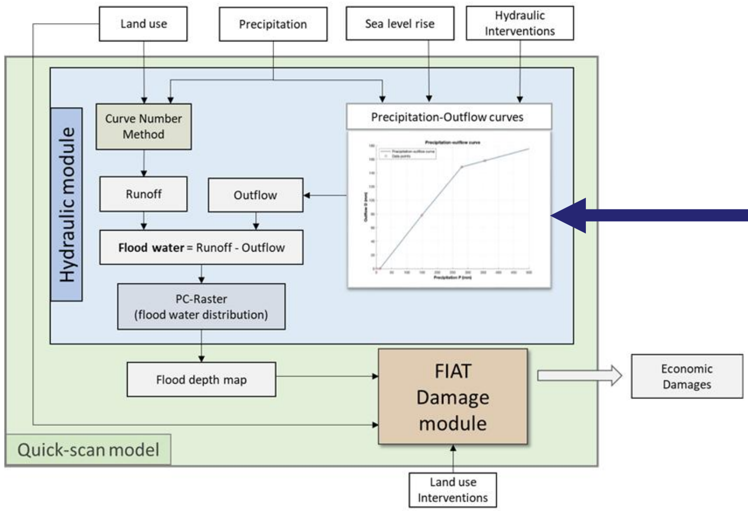
Under the hood: hydraulic module

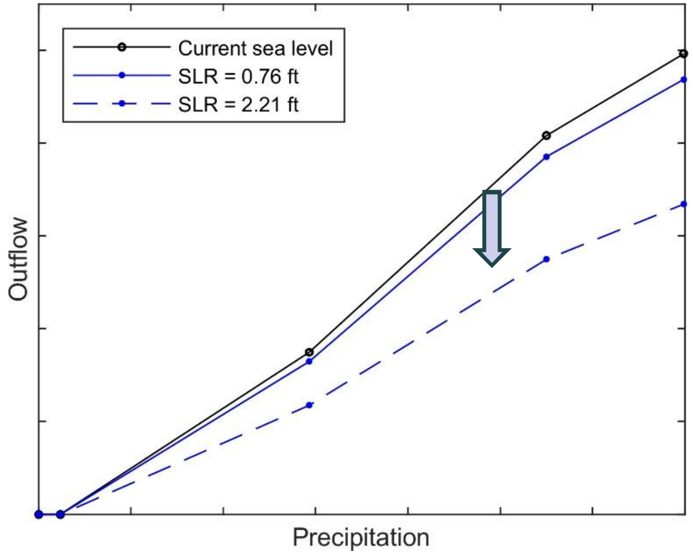


Under the hood: damage module



Sea level rise





Measures (same as C-7 study)

M0 – No action

Hydraulic measures

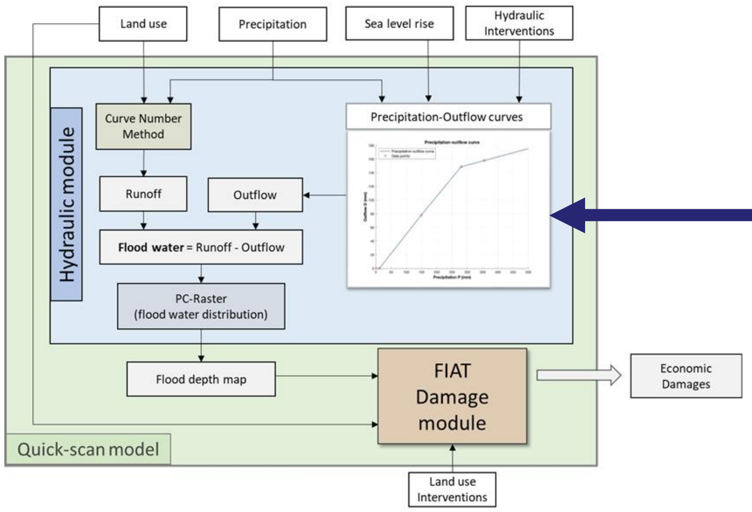
M1 – Local flood mitigation: flood walls, exfiltration trenches, flap gates, and local pumps

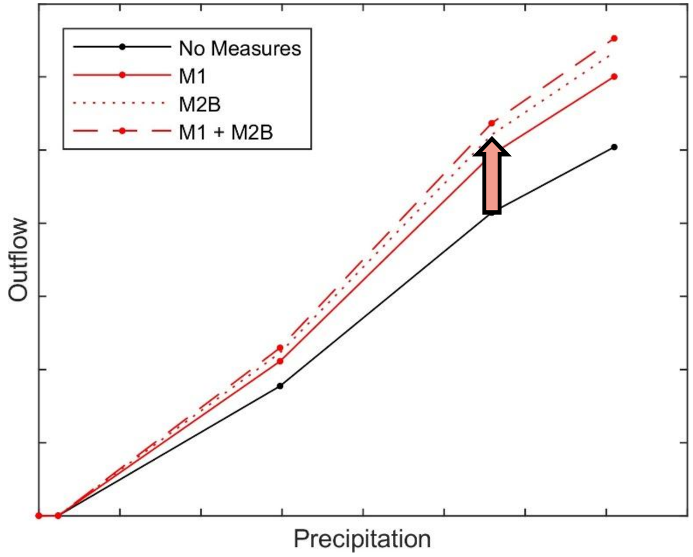
M2 – Regional flood mitigation: forward pumps at S-27 coastal structure (small & large pumps)

Land-use measure

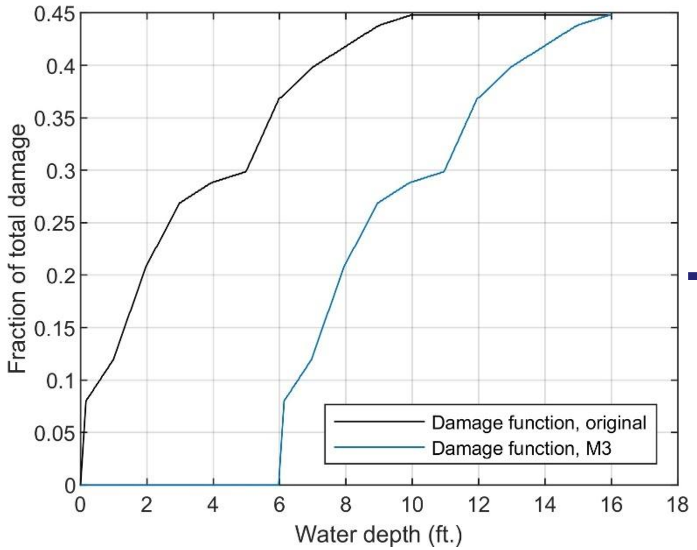
M3 - Land-use mitigation: raise roads and buildings to 6 feet elevation

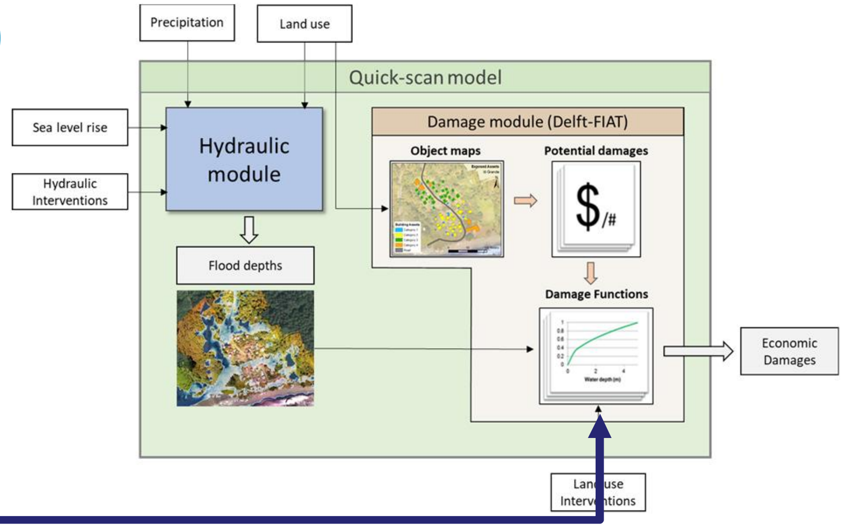
Hydraulic measures (M1 & M2)



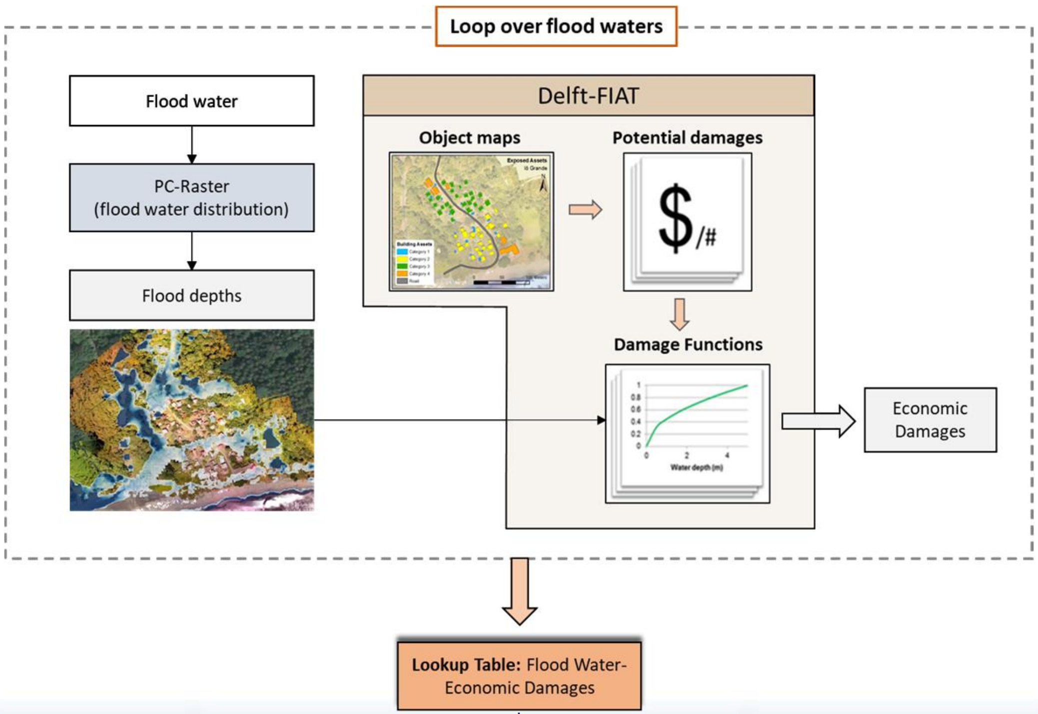


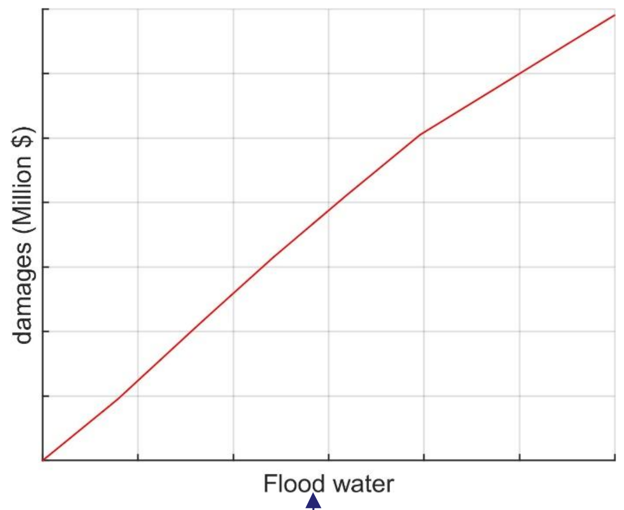
Raising roads and houses (M3)



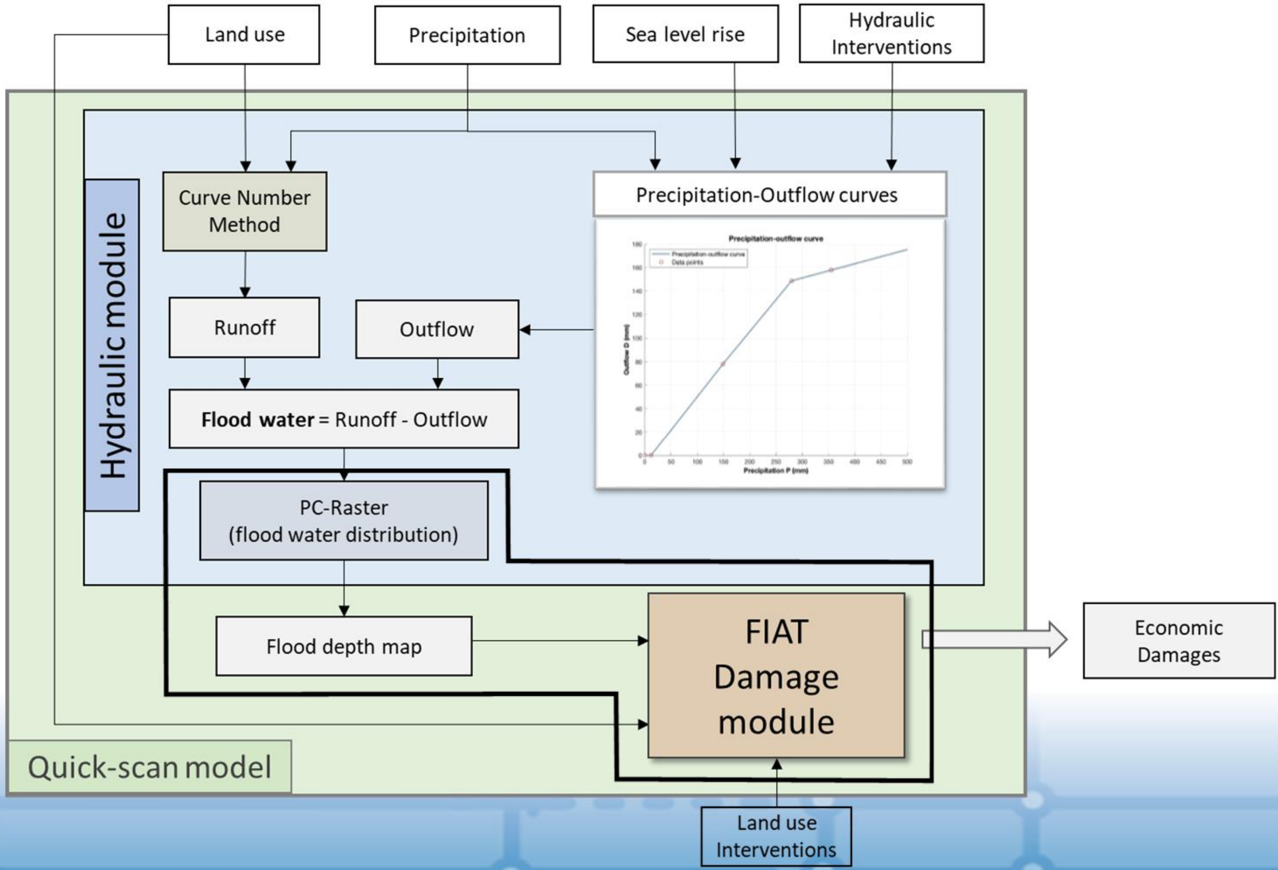


Speeding it up: pre-processing

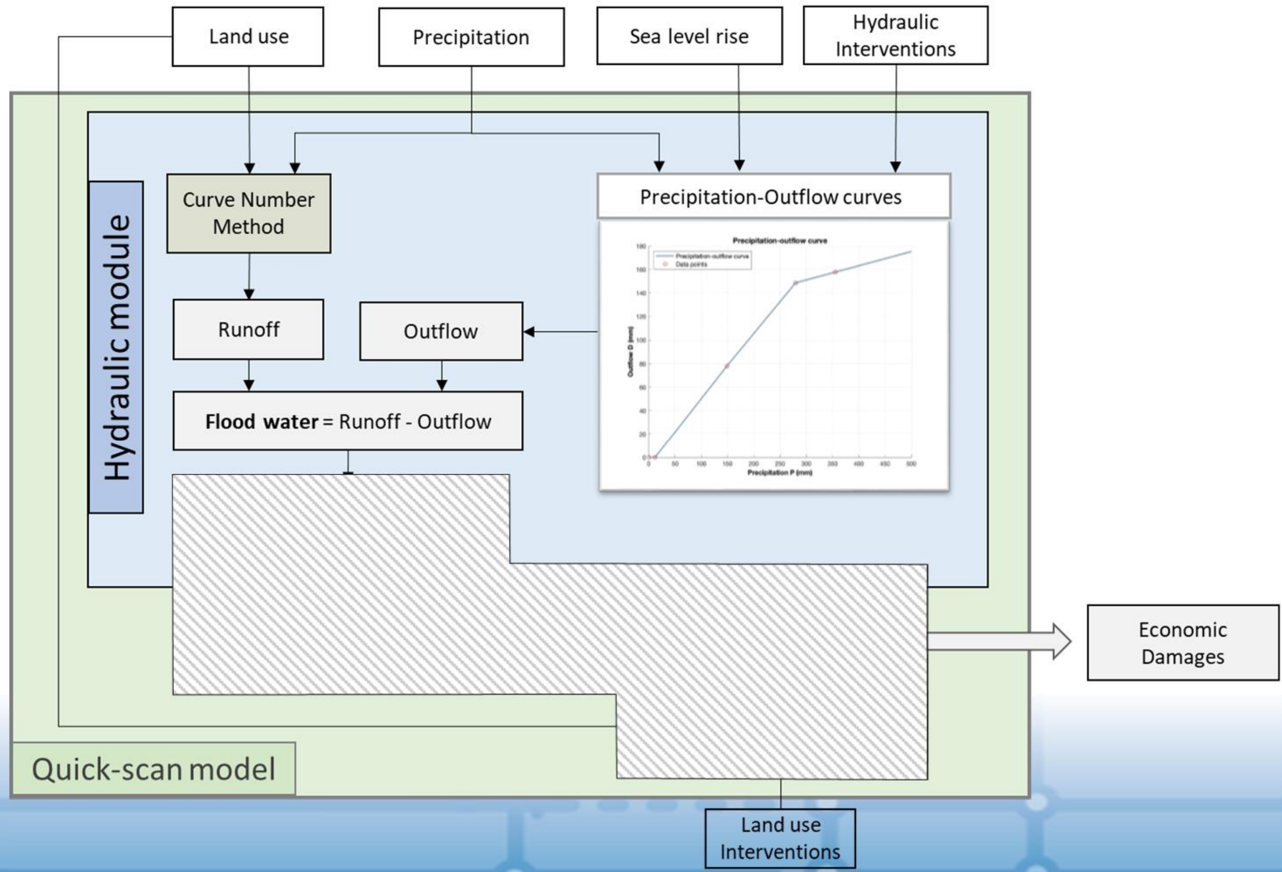




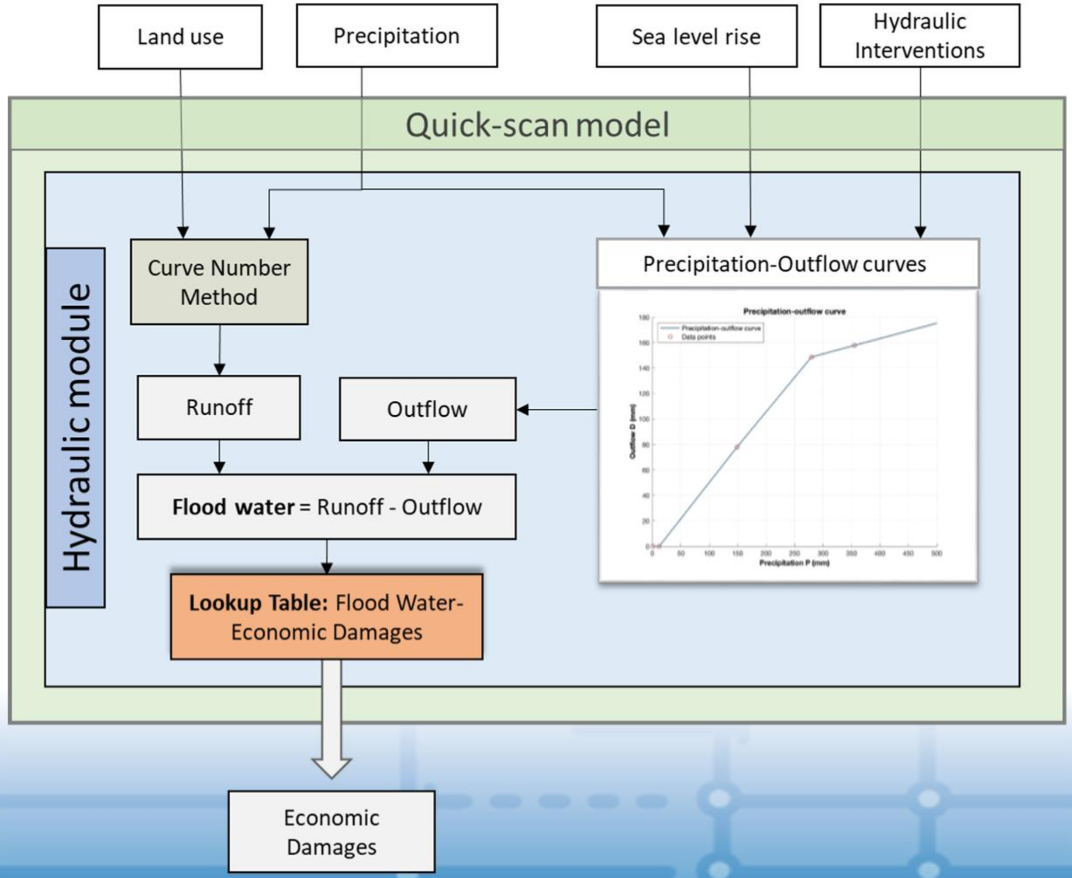
Speeding it up: pre-processing



Speeding it up: pre-processing



Speeding it up: pre-processing

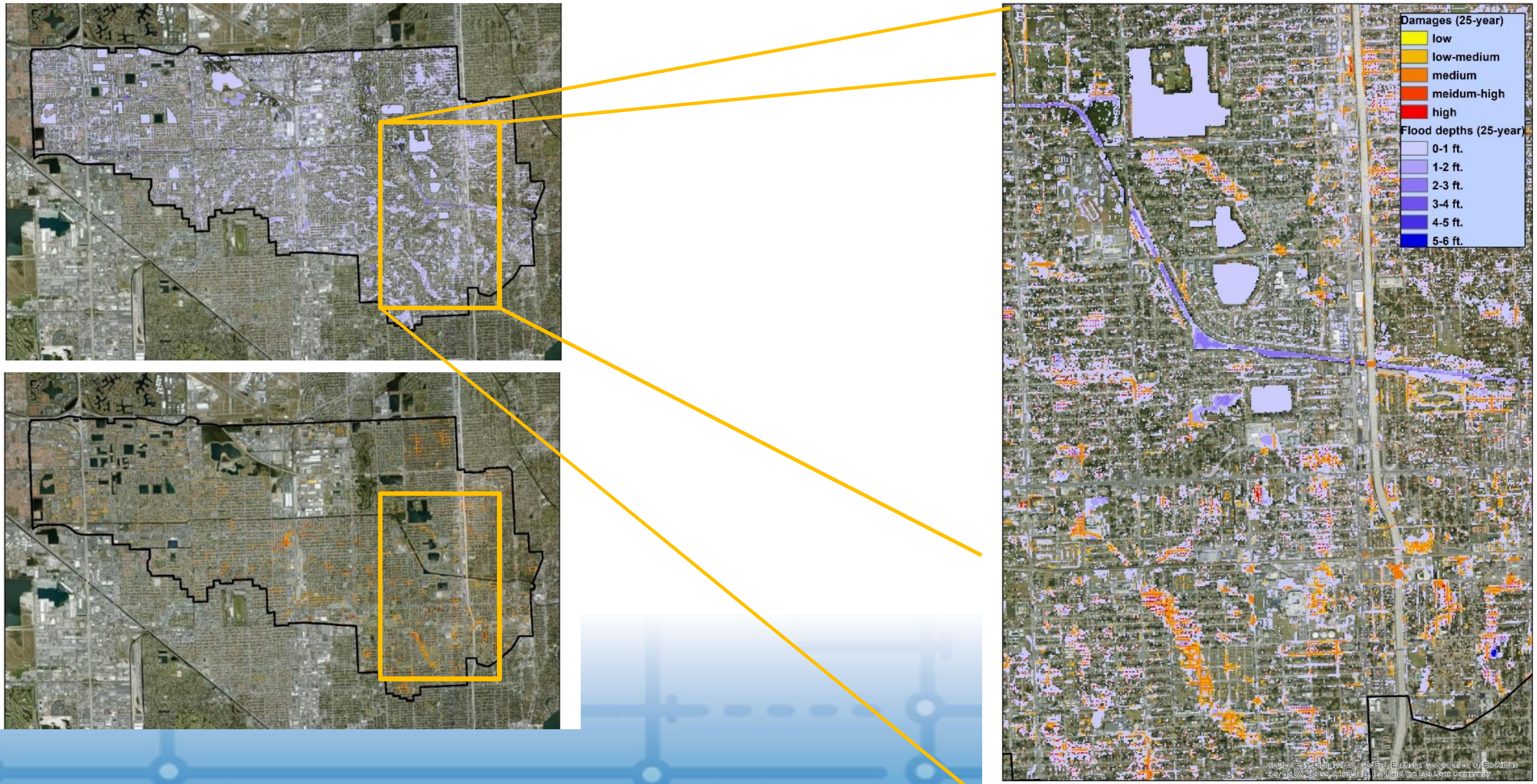


Run time

Single run	⇨	2 seconds
Risk analysis	⇨	30 seconds

Taking it for a test drive

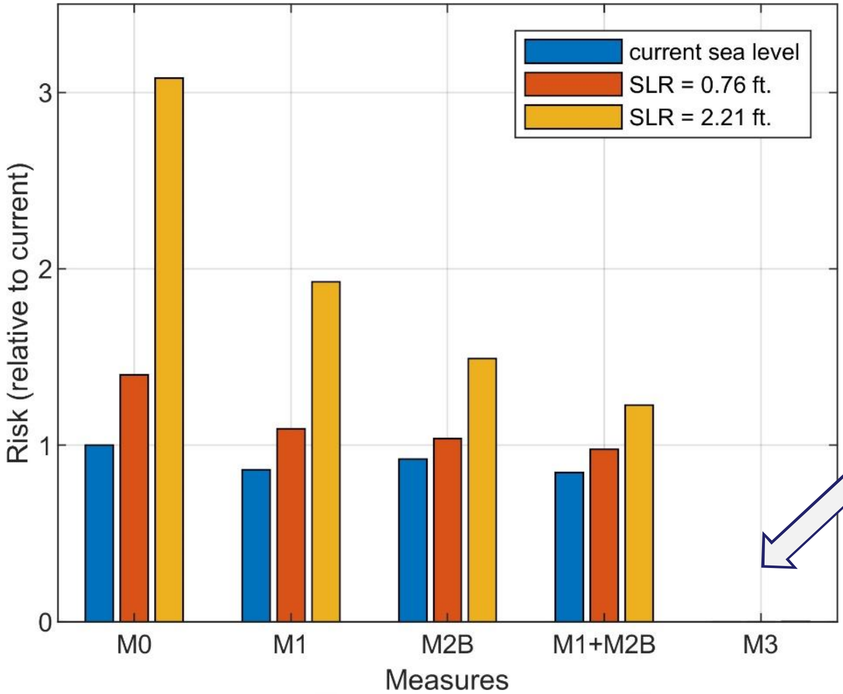
Flood depth and damages



Risk

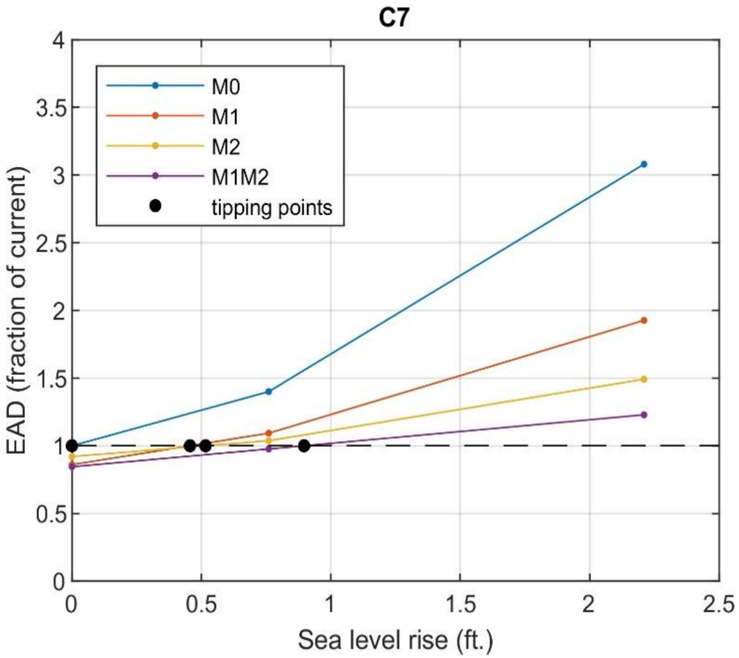
- Three sea levels
  - CSL = 0 SLR
  - SLR1 = 0.76 ft. SLR
  - SLR3 = 2.21 ft. SLR
- Five measures/combinations
  - M0 (no measures)
  - M1 (local flood mitigation measures)
  - M2 (regional pump)
  - M1 + M2 (combination local measures + regional pump)
  - M3 (elevating structures and roads)

Risk analysis, C-7



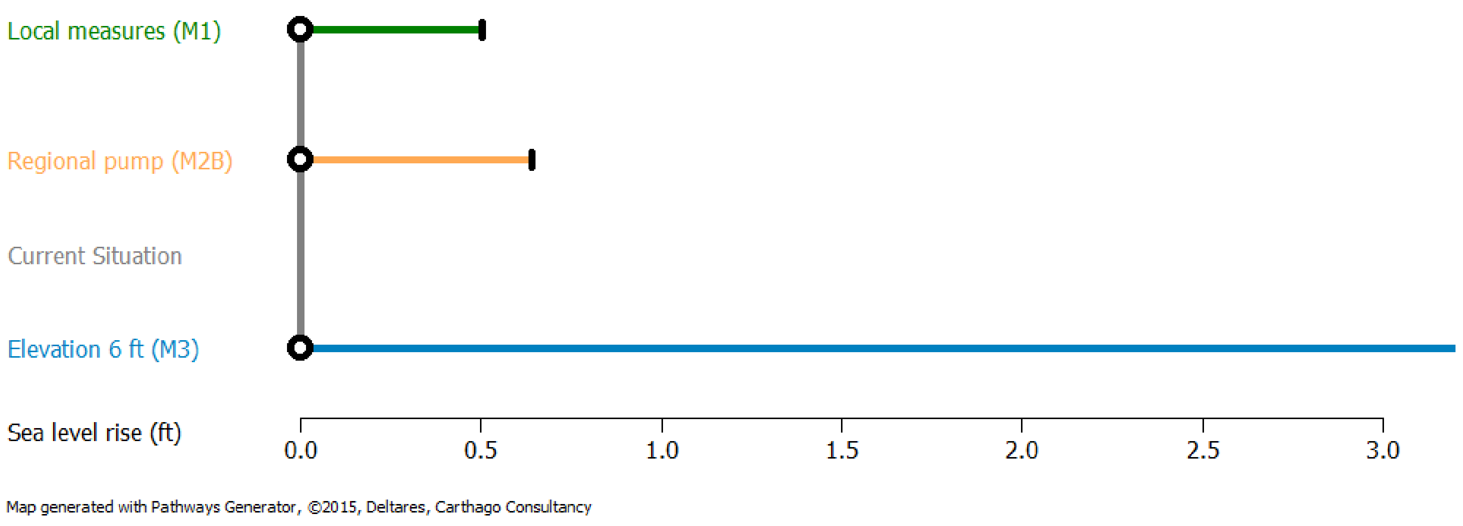
Risk reduced to zero

Tipping points

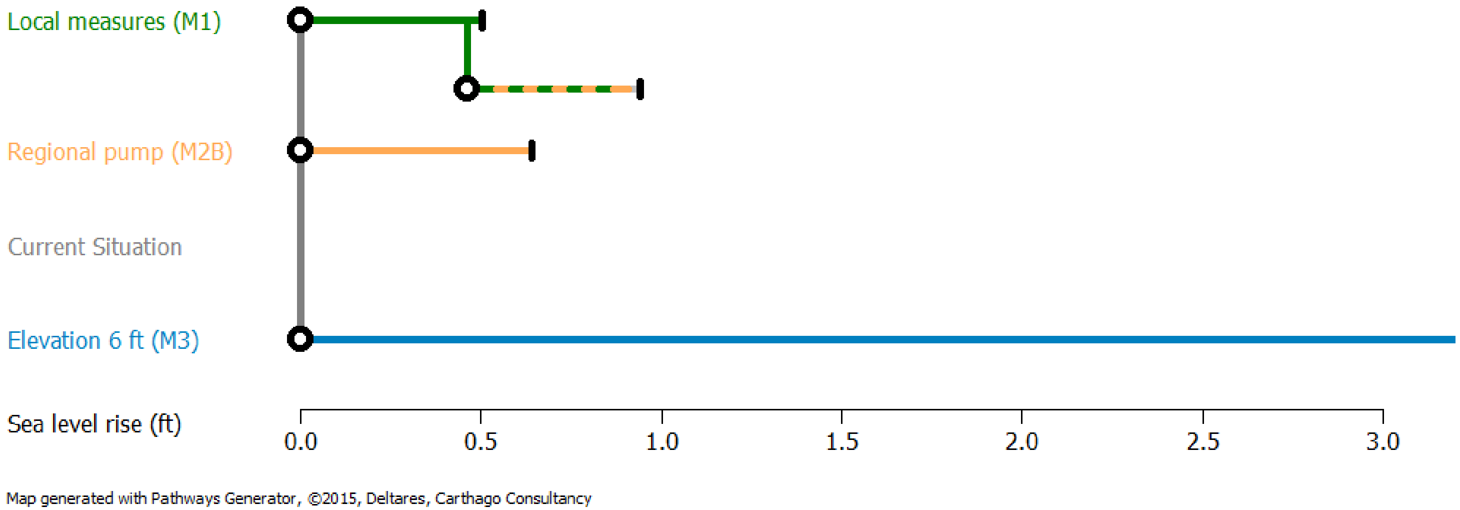


	previous C-7 study			quick-scan model		
	Current Risk	5% increase	10% increase	Current risk	5% increase	10% increase
M0	0.00	0.09	0.19	0.00	0.10	0.19
M1	0.55	0.66	0.77	0.46	0.62	0.77
M2B	0.50	0.79	0.95	0.52	0.80	0.96

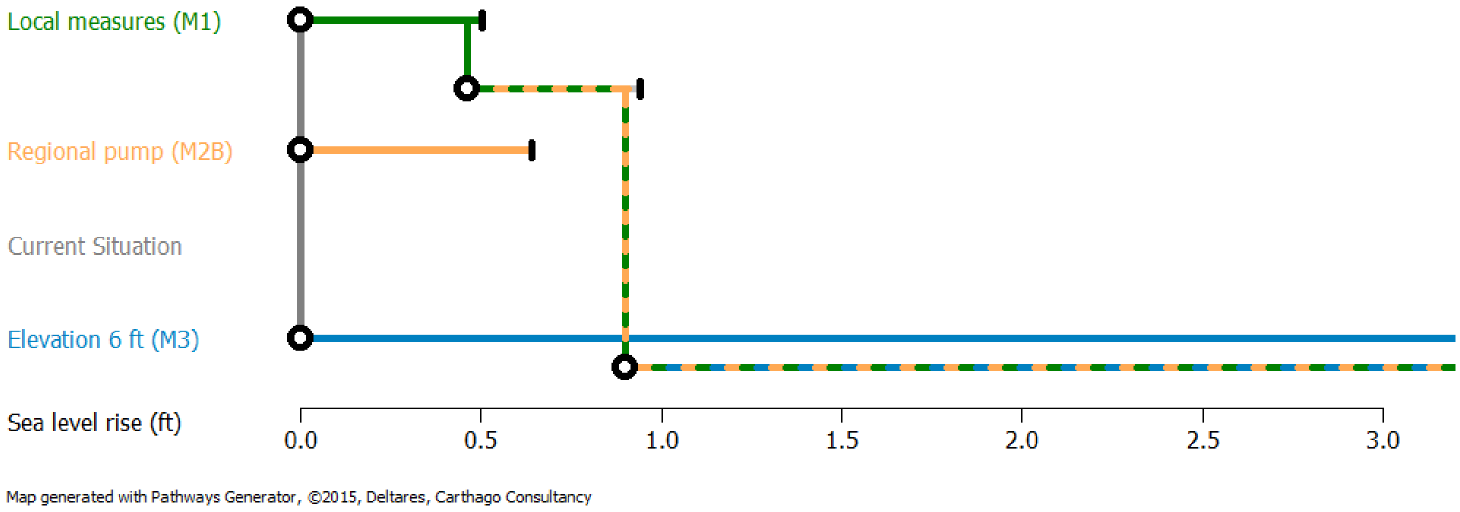
Pathways map



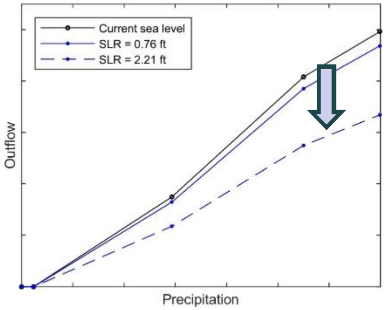
Pathways map

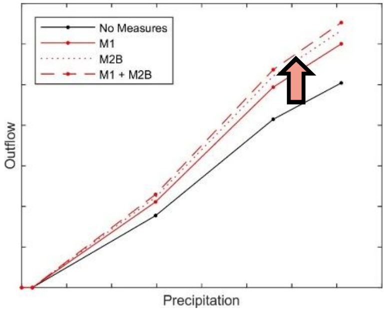


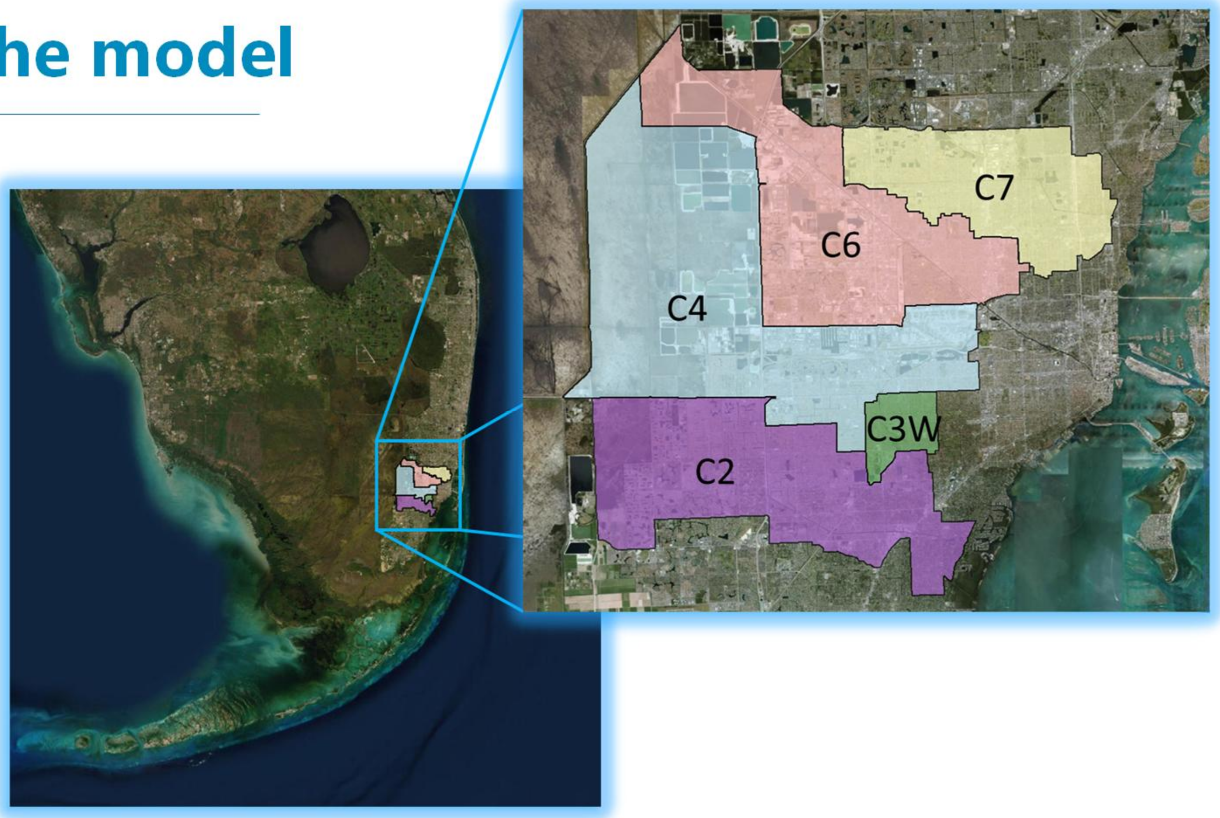
Pathways map



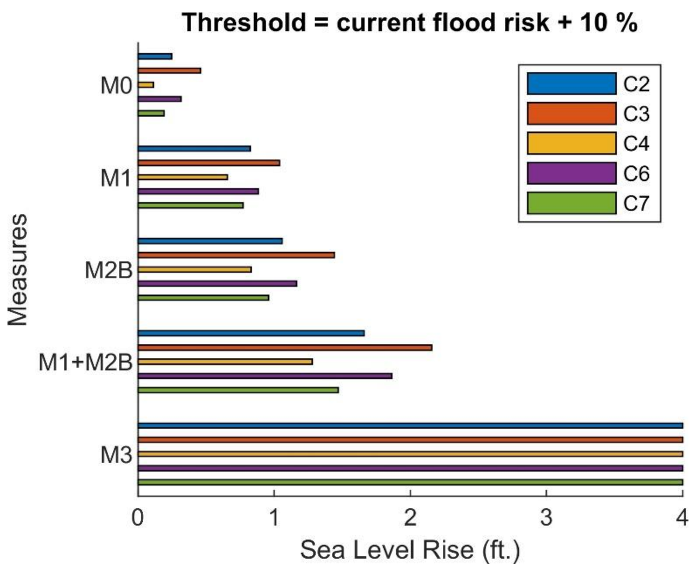
Expanding **the model**

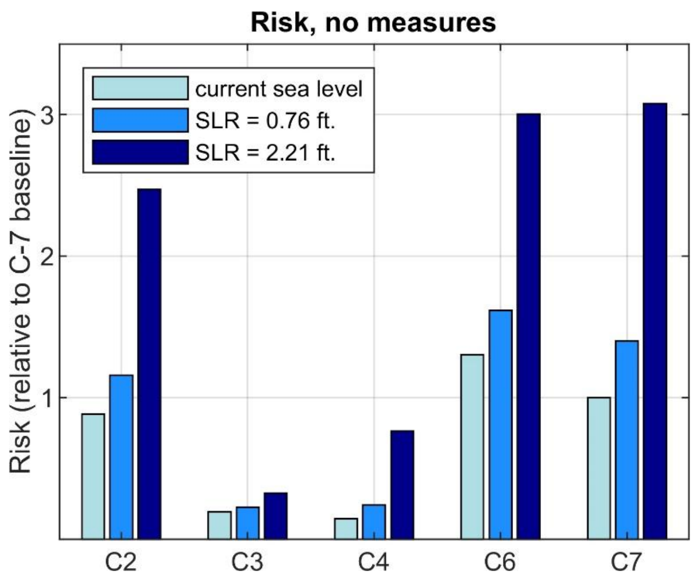






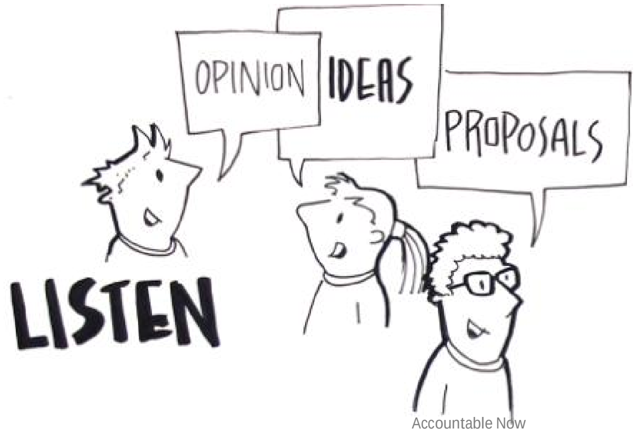
Multi-basin results



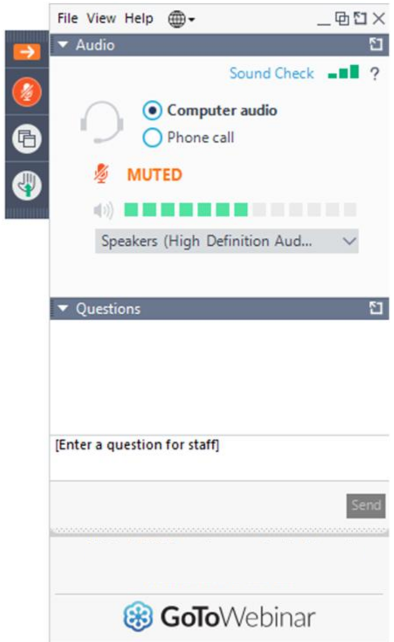


Engaging stakeholders

- Can play with the effectiveness of measures
- Include new measures with expert opinion about relative effectiveness
- Choose different sea level rises
- Change precipitation frequency
- Take future development into account



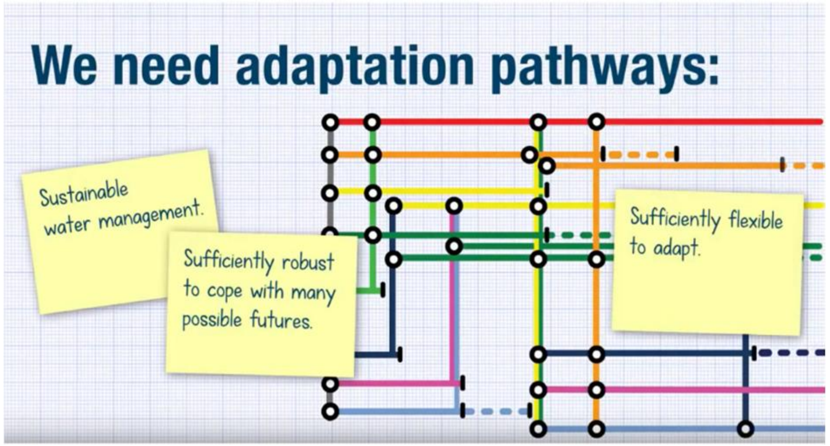
Discussion



#daretoask

Thank you for your attention

Jobeysek@fiu.edu
Claire.Jeuken@deltares-usa.us
Kathryn.roscoe@deltares.nl
www.deltares.nl
www.slsc.fiu.edu



More information:

- https://www.deltares.nl/en/adaptive-pathways/
- https://publicwiki.deltares.nl/display/DFIAT/Delft-FIAT+Home
- https://www.deltares.nl/en/software-solutions/
- Recordings of the webinar.

We hope to see you at the Climate summit!

Appendix B Building categories and associated data

Building category	Building data	Building category description	HAZUS damage function	Maximum damage ($\$/m^2$)-2015 price level
Residential	Houses (point) - Structure	Single-family, two-family, multi-family, townhouse, mobile home parks, permanent mobile home, transient residential, government owned and predominantly residential	RES1 – Single Family Dwelling	286751*
	Houses (area) - Structure		RES1 – Single Family Dwelling	1147
	Houses (point) - Content		RES1 – Single Family Dwelling	86025*
	Houses (area) - Content		RES1 – Single Family Dwelling	574
Commercial	Commercial - Structure	Sales and services (exclude office facilities), shopping centers, rental residential with retail lower floors	COM1 - Retail Trade	1058
	Commercial - Content		COM1 - Retail Trade	1587
Office	Office - Structure	Office building, office and/or business	COM4 - Professional Services	1695
	Office - Content		COM4 - Professional Services	1695
Industry	Industry - Structure	Manufacturing and warehousing-storage type of use, industrial intensive, industrial extensive	IND2- Light Industry	969
	Industry - Content		IND2- Light Industry	969
Institution	Institution - Structure	Public schools, private schools, college and universities, governmental/public administration, cultural, hospitals, house of worship and religious	GOV1 - General Services	1466
	Institution - Content		GOV1 - General Services	1466
Airport	Airport - Structure	Airport	Average of COM1 and IND2	1020
	Airport - Content		Average of COM1 and IND2	1020
Other	Other - Structure	Bus/truck/freight terminals, prisons, parks, electrical power supply infrastructure, communications, parking garages	Average of COM1 and IND2	1020
	Other - Content		Average of COM1 and IND2	1020

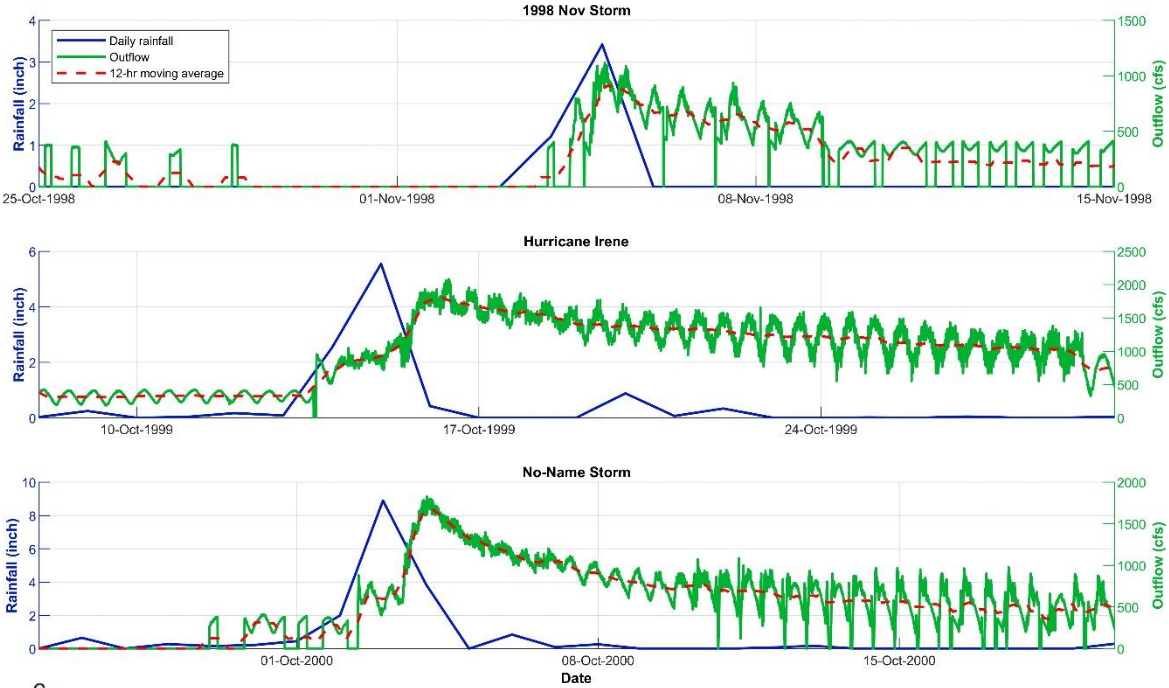
**Per building instead of per m^2 building area*

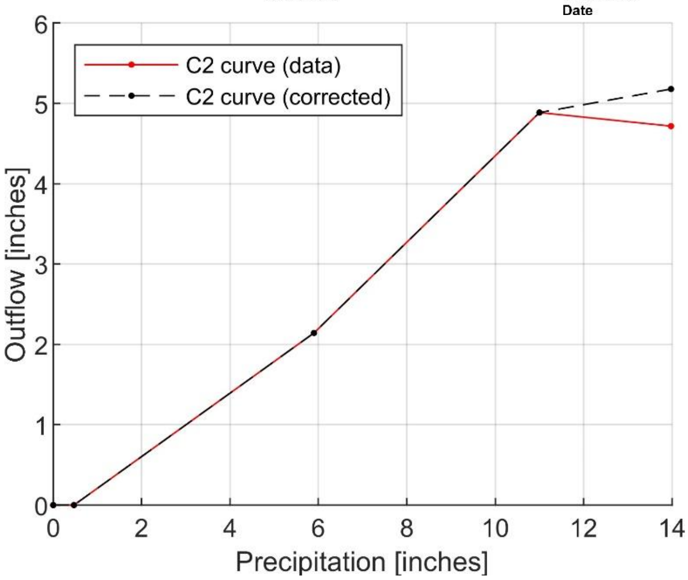
Appendix C Outflow data and precipitation-outflow curves

The outflow data for the three historic storms used to derive the precipitation-outflow curves (see Section 2.2.2), as well as the precipitation-outflow curves, are provided in this appendix. For some basins, the pumps had operation problems during the storm, so that a non-optimal outflow occurred. This can have the effect that for increasing precipitation events, the outflow curve shows decreasing outflow (which is unrealistic). To avoid this, for cases where the pump operated non-optimally, the data point was not used, and interpolation was used instead to derive the 'corrected' precipitation-outflow curve. For the case of C-2 and C-4, where the outflow associated with the highest precipitation needed correcting, we used the slope of the C-7 curve to correct the highest precipitation-outflow point.

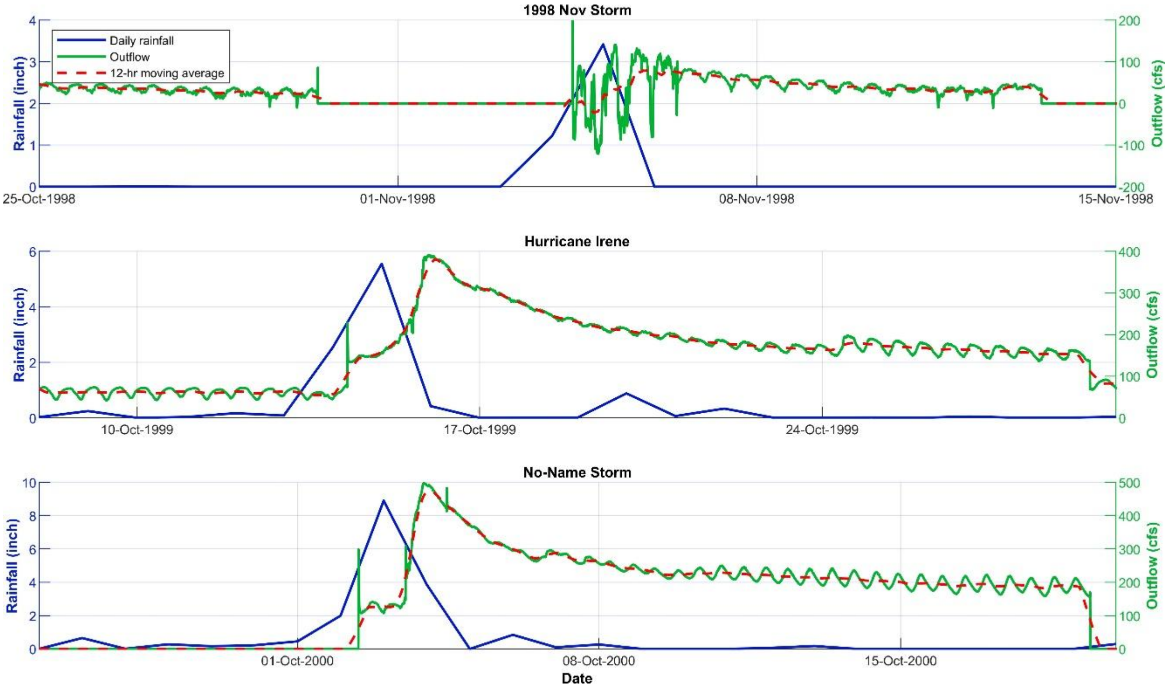
The outflow data figures show rainfall (inches) on the left vertical axis and outflow (cfs) on the right vertical axis. The horizontal axis shows time; there is one plot for each of the three historic storms. The precipitation-outflow curve figures show precipitation (inches) on the horizontal axis, and the outflow (inches) on the vertical axis. The outflow was multiplied by the duration of the storm and divided by the area of the basin to obtain outflow in units of inches.

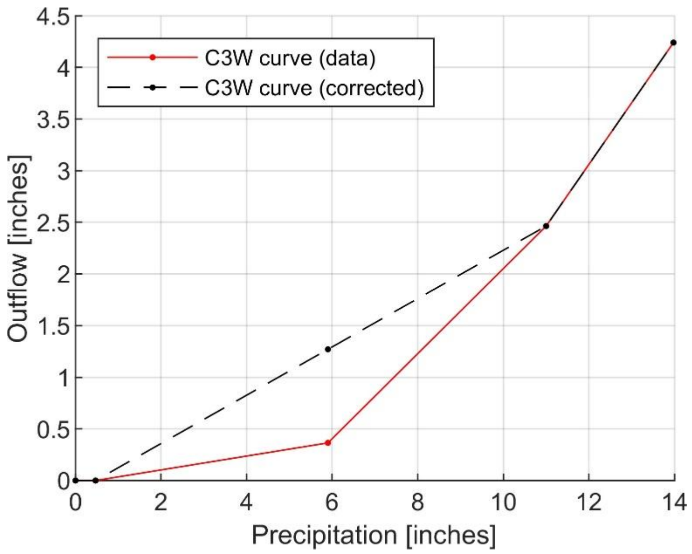
C-2


1998 Nov Storm
Daily rainfall
Outflow
12-hr moving average
Rainfall (inch)
Outflow (cfs)
25-Oct-1998
01-Nov-1998
08-Nov-1998
15-Nov-1998
Hurricane Irene
10-Oct-1999
17-Oct-1999
24-Oct-1999
No-Name Storm
01-Oct-2000
08-Oct-2000
15-Oct-2000
Date

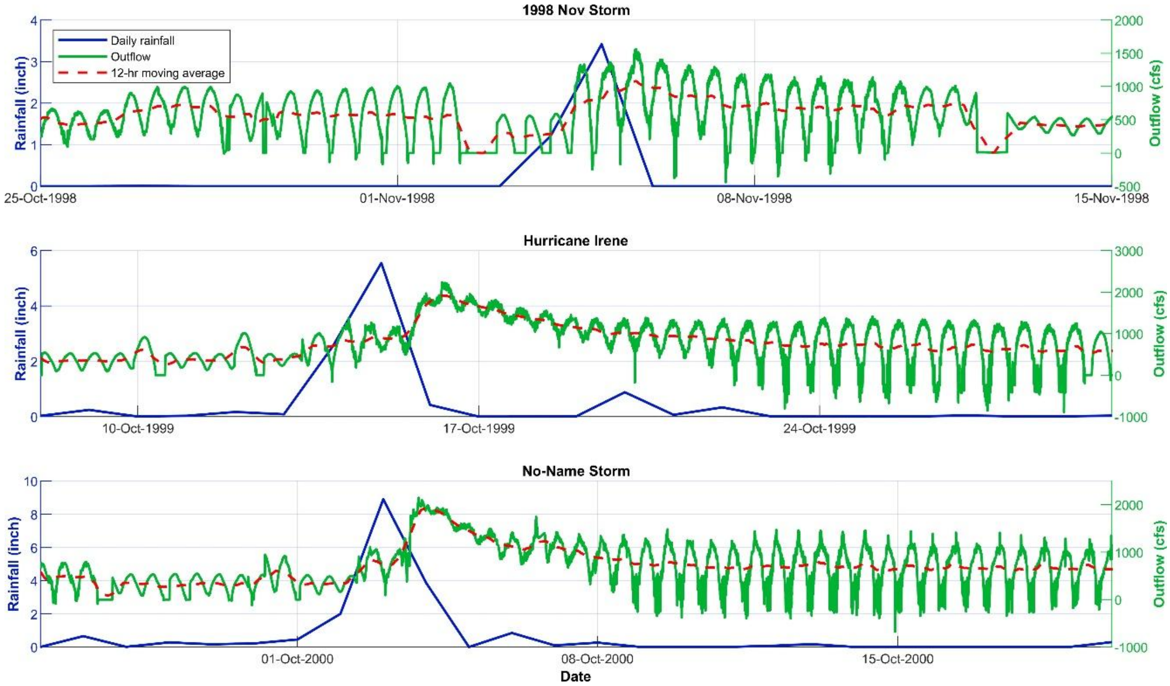

C2 curve (data)
C2 curve (corrected)
Outflow [inches]
Precipitation [inches]

C-3W

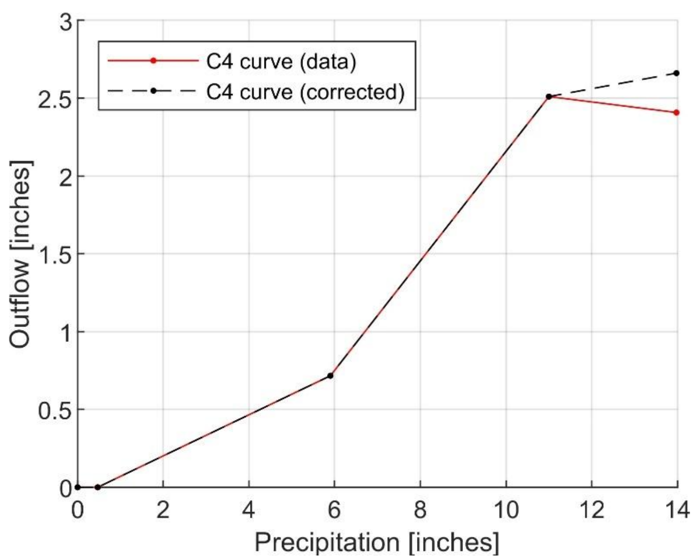

1998 Nov Storm
Daily rainfall
Outflow
12-hr moving average
Rainfall (inch)
Outflow (cfs)
25-Oct-1998
01-Nov-1998
08-Nov-1998
15-Nov-1998
Hurricane Irene
10-Oct-1999
17-Oct-1999
24-Oct-1999
No-Name Storm
01-Oct-2000
08-Oct-2000
15-Oct-2000
Date


C3W curve (data)
C3W curve (corrected)
Outflow [inches]
Precipitation [inches]

C-4

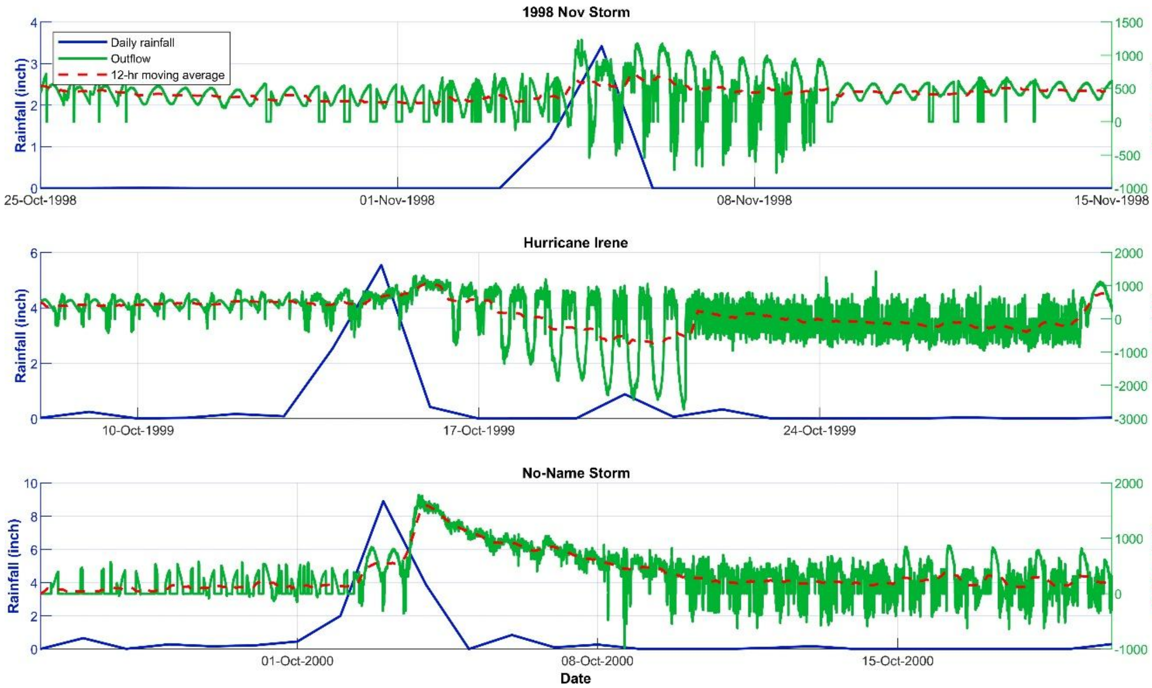


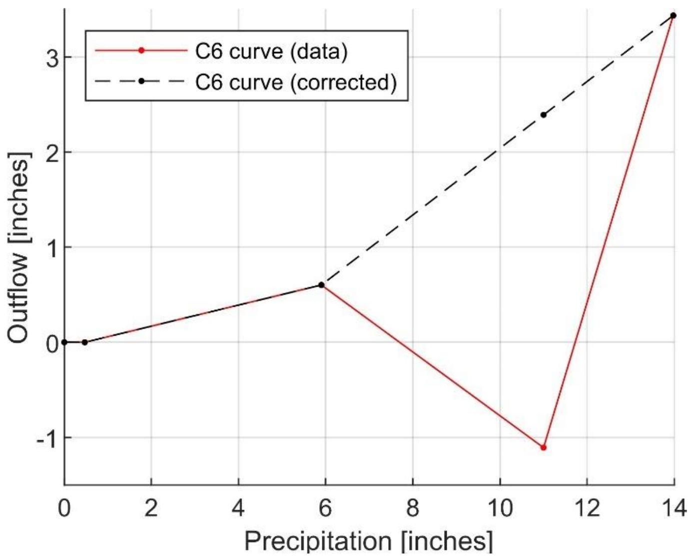
1998 Nov Storm
Daily rainfall
Outflow
12-hr moving average
Rainfall (inch)
Outflow (cfs)
25-Oct-1998
01-Nov-1998
08-Nov-1998
15-Nov-1998
Hurricane Irene
10-Oct-1999
17-Oct-1999
24-Oct-1999
No-Name Storm
01-Oct-2000
08-Oct-2000
15-Oct-2000
Date



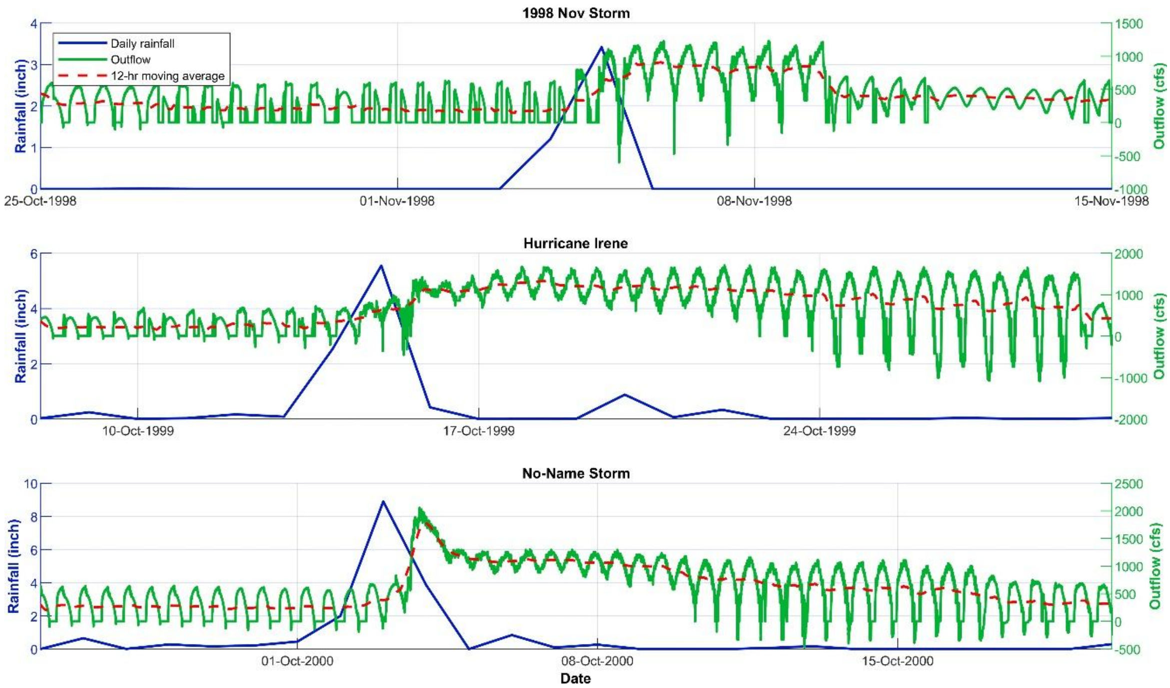
C4 curve (data)
C4 curve (corrected)
Outflow [inches]
Precipitation [inches]

C-6

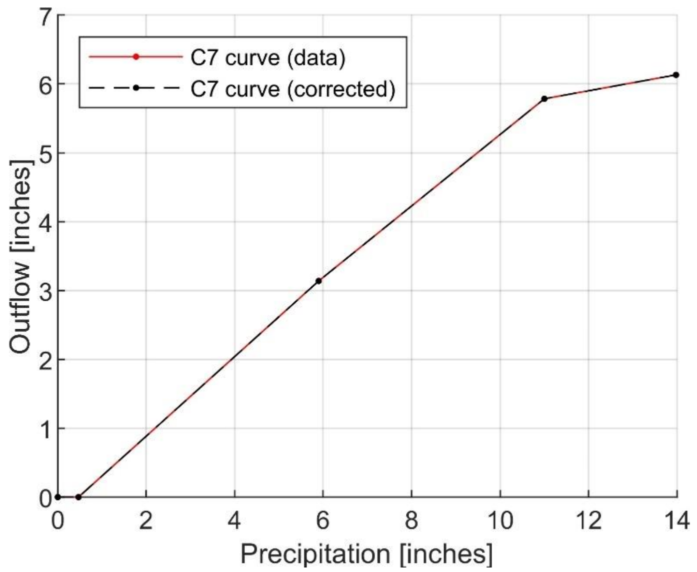

1998 Nov Storm
Daily rainfall
Outflow
12-hr moving average
Rainfall (inch)
Outflow (cfs)
25-Oct-1998
01-Nov-1998
08-Nov-1998
15-Nov-1998
Hurricane Irene
10-Oct-1999
17-Oct-1999
24-Oct-1999
No-Name Storm
01-Oct-2000
08-Oct-2000
15-Oct-2000
Date


C6 curve (data)
C6 curve (corrected)
Outflow [inches]
Precipitation [inches]

C-7



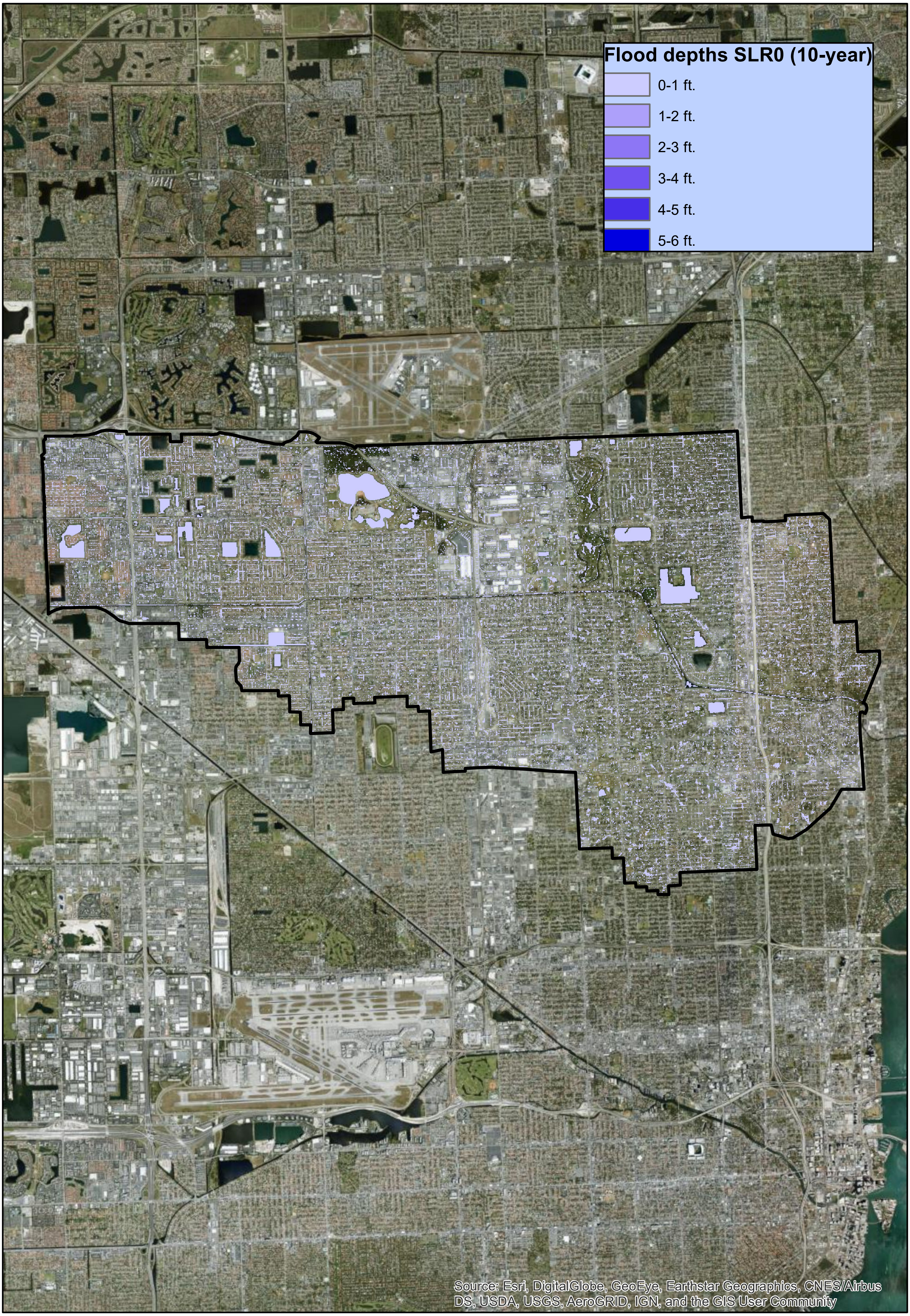
1998 Nov Storm
Daily rainfall
Outflow
12-hr moving average
Rainfall (inch)
Outflow (cfs)
25-Oct-1998
01-Nov-1998
08-Nov-1998
15-Nov-1998
Hurricane Irene
10-Oct-1999
17-Oct-1999
24-Oct-1999
No-Name Storm
01-Oct-2000
08-Oct-2000
15-Oct-2000
Date

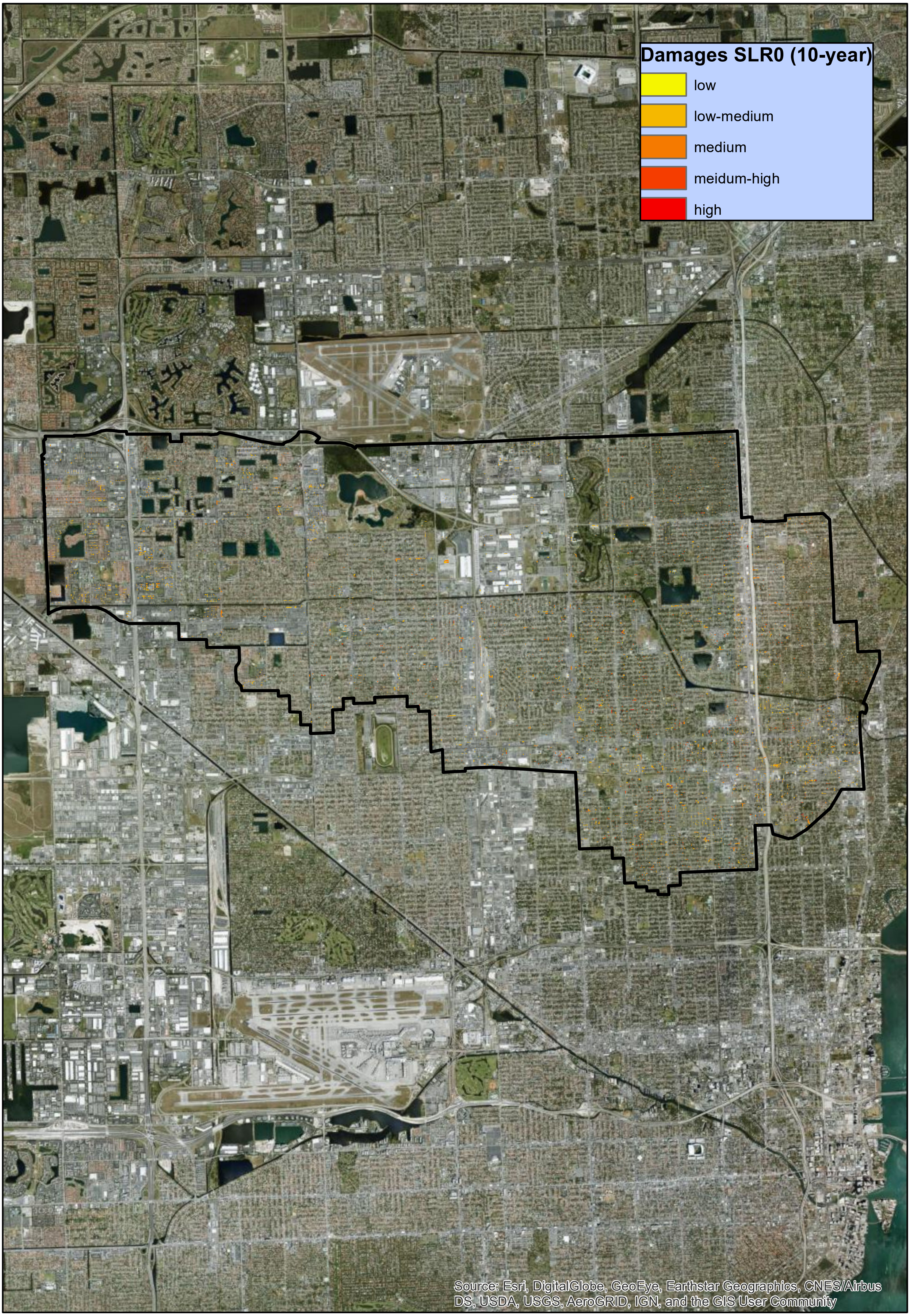


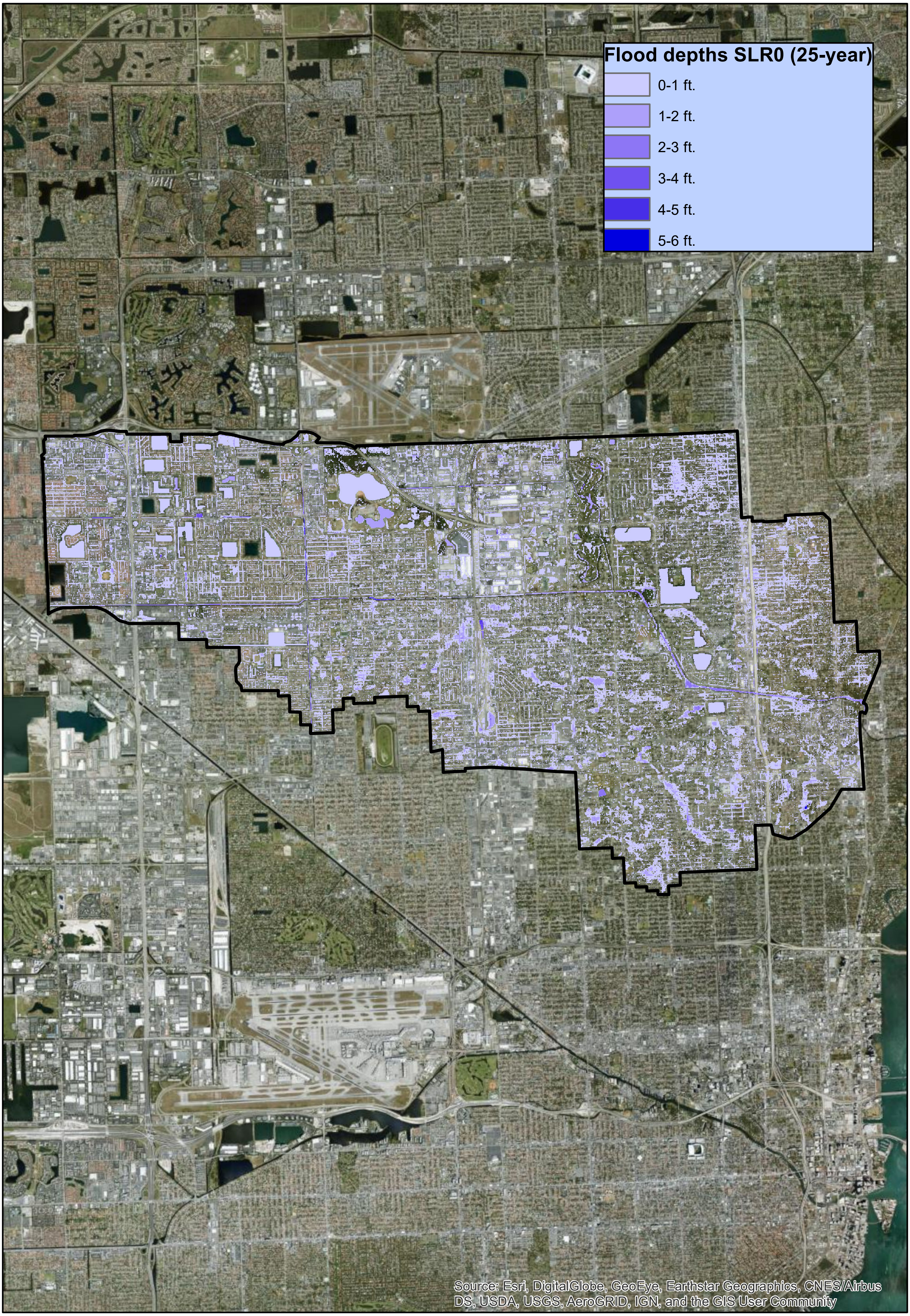
C7 curve (data)
C7 curve (corrected)
Outflow [inches]
Precipitation [inches]

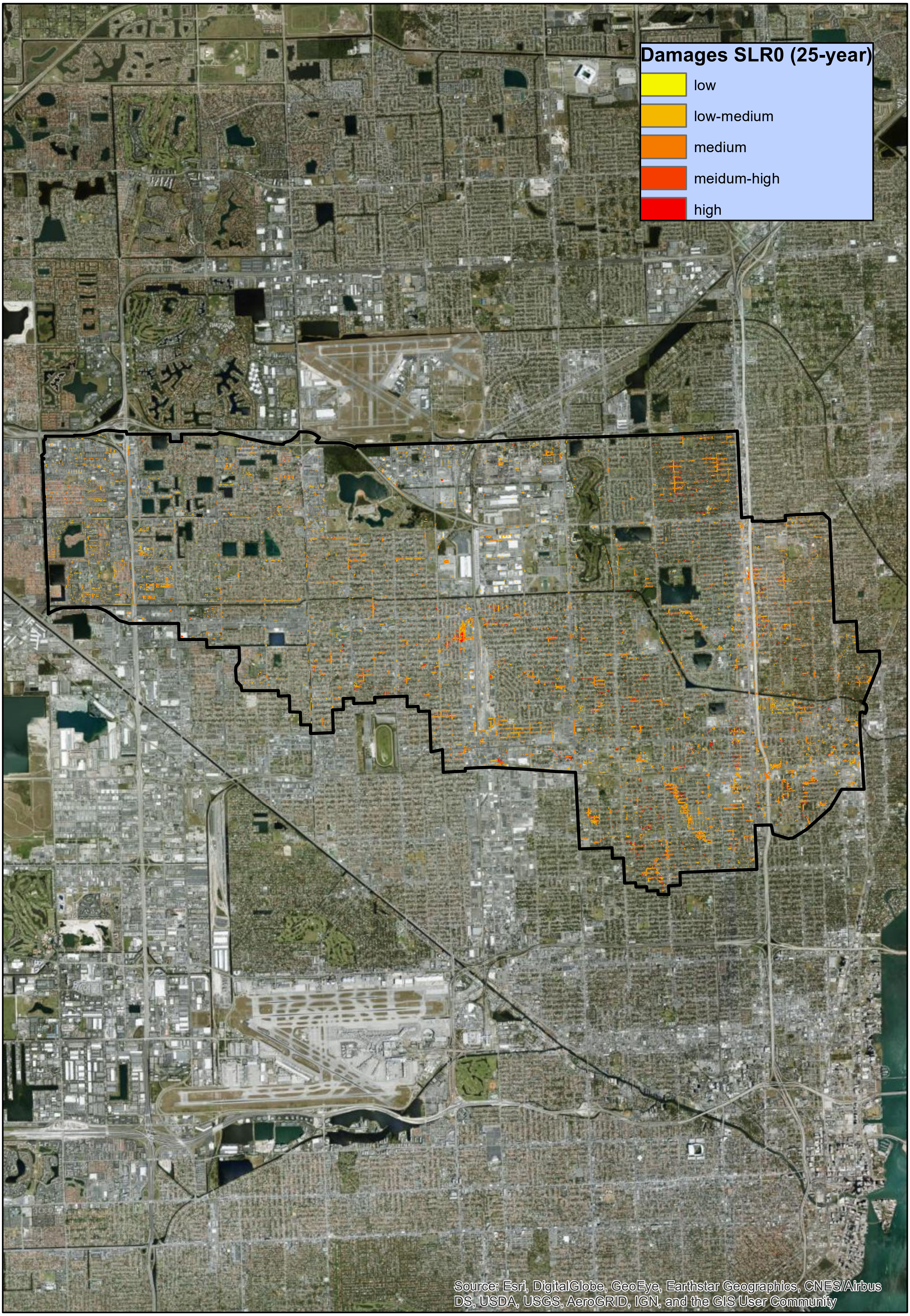
Appendix D Flood Depth and Damage Maps for C-7

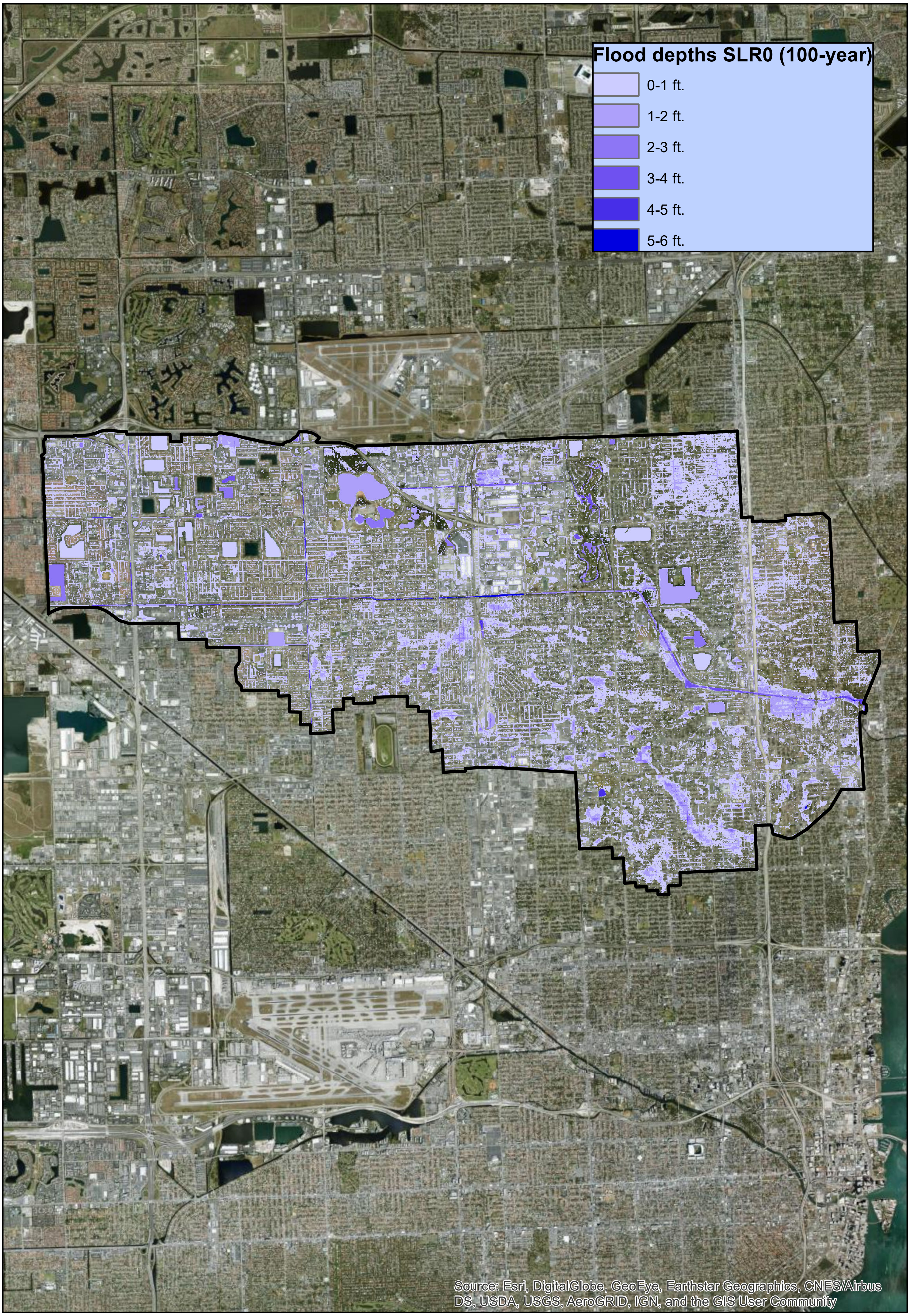
This appendix provides the flood depth and damage maps calculated by the quick-scan model for the 10-, 25-, and 100-year return periods for CSL (referred to as SLR0), SLR1, and SLR3, for the C-7 basin. The 10-, 25-, and 100-year flood depth and damage maps were provided to the SFWMD for current sea level, SLR1, and SLR3, for all five basins.

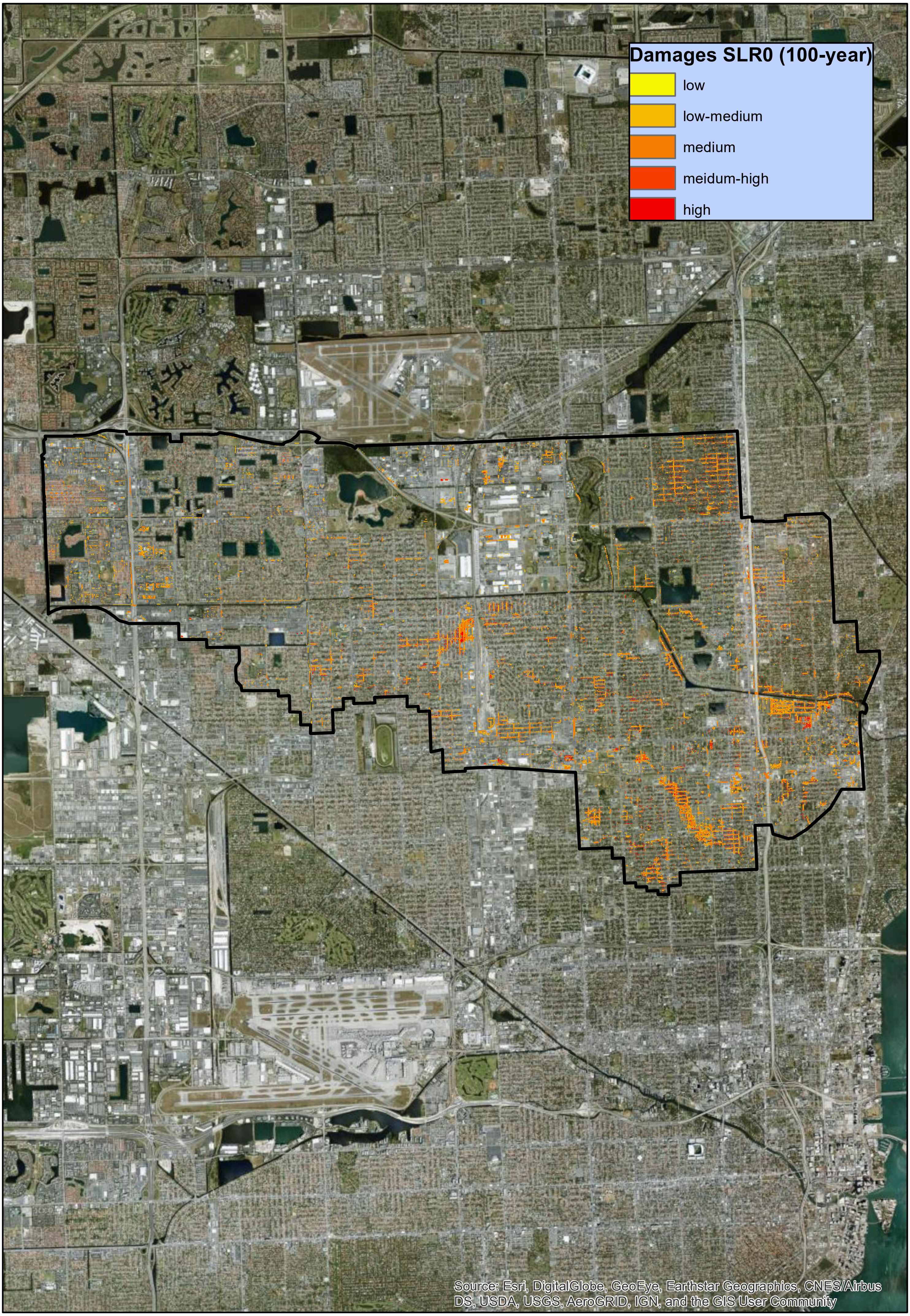

Flood depths SLR0 (10-year)
0-1 ft.
1-2 ft.
2-3 ft.
3-4 ft.
4-5 ft.
5-6 ft.
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

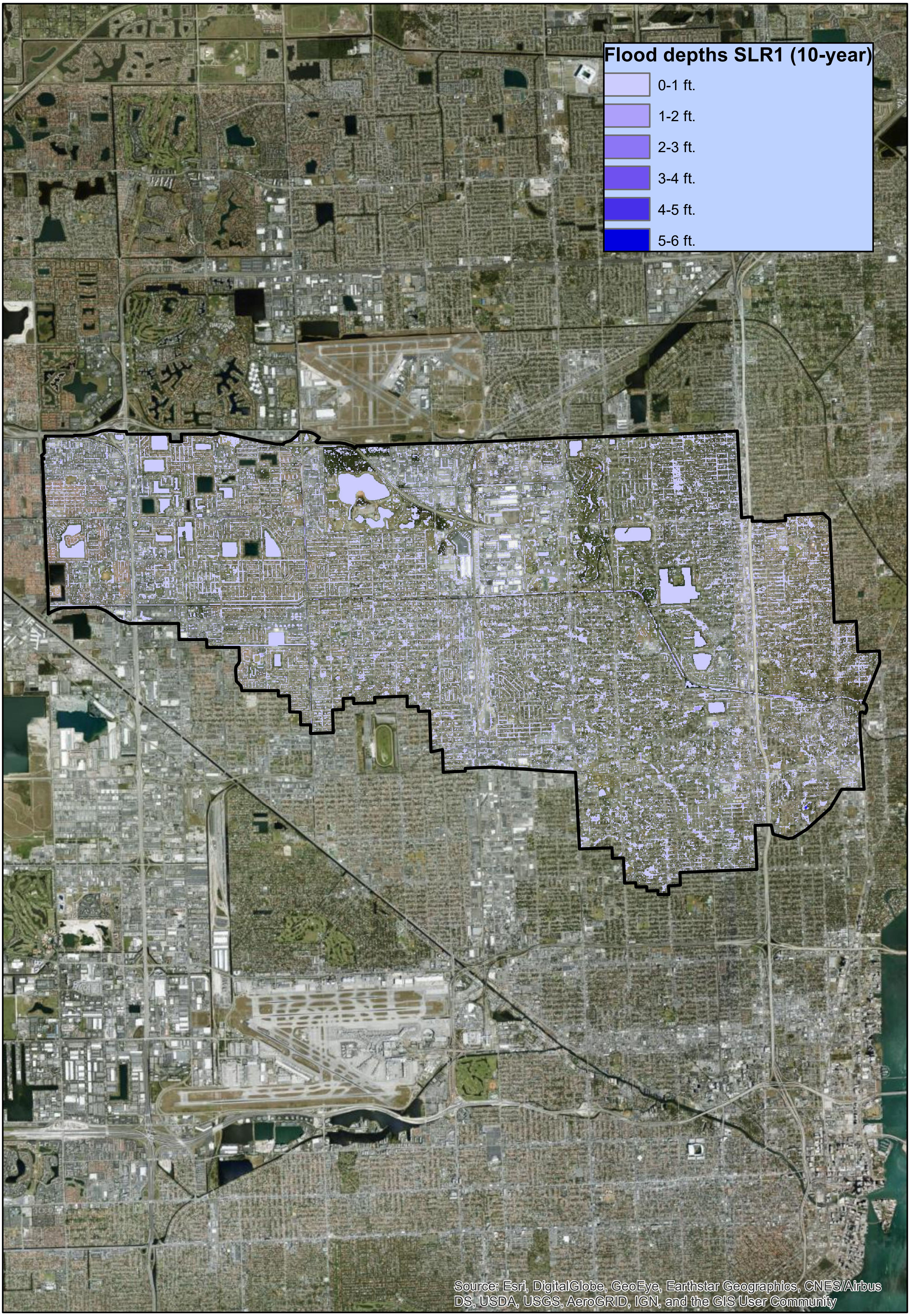

Damages SLR0 (10-year)
low
low-medium
medium
meidum-high
high
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

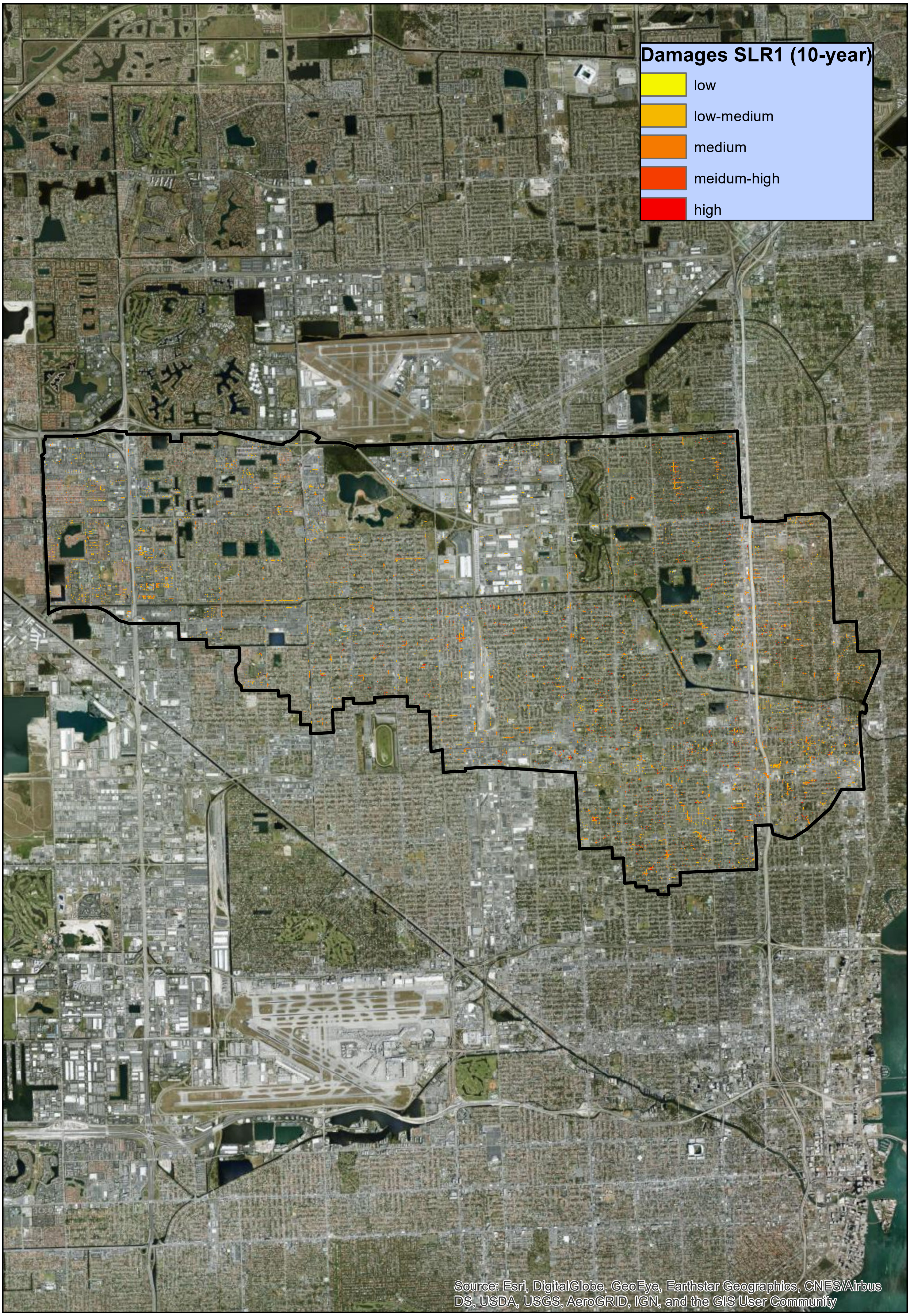

Flood depths SLR0 (25-year)
0-1 ft.
1-2 ft.
2-3 ft.
3-4 ft.
4-5 ft.
5-6 ft.
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

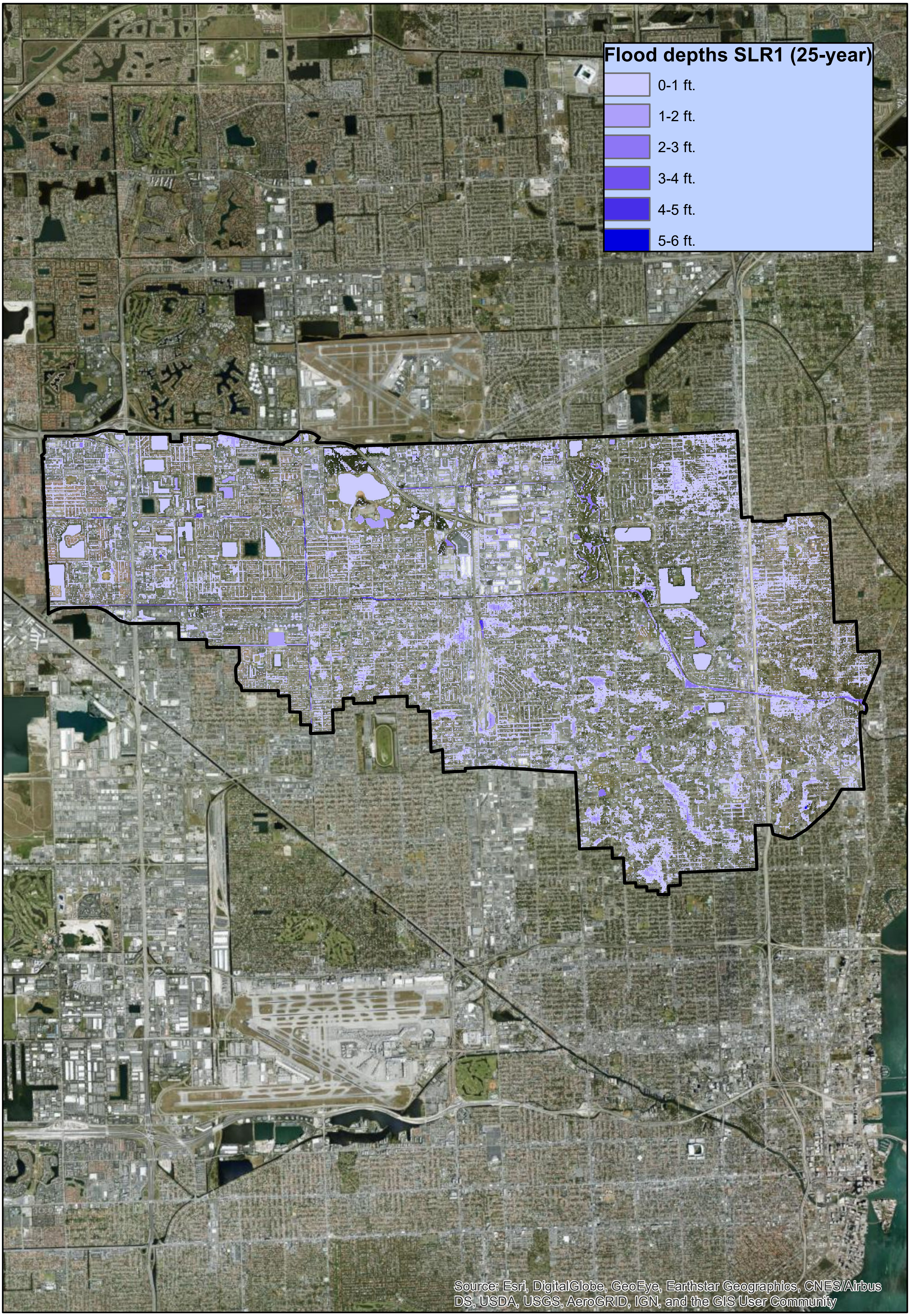

Damages SLR0 (25-year)
low
low-medium
medium
meidum-high
high
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

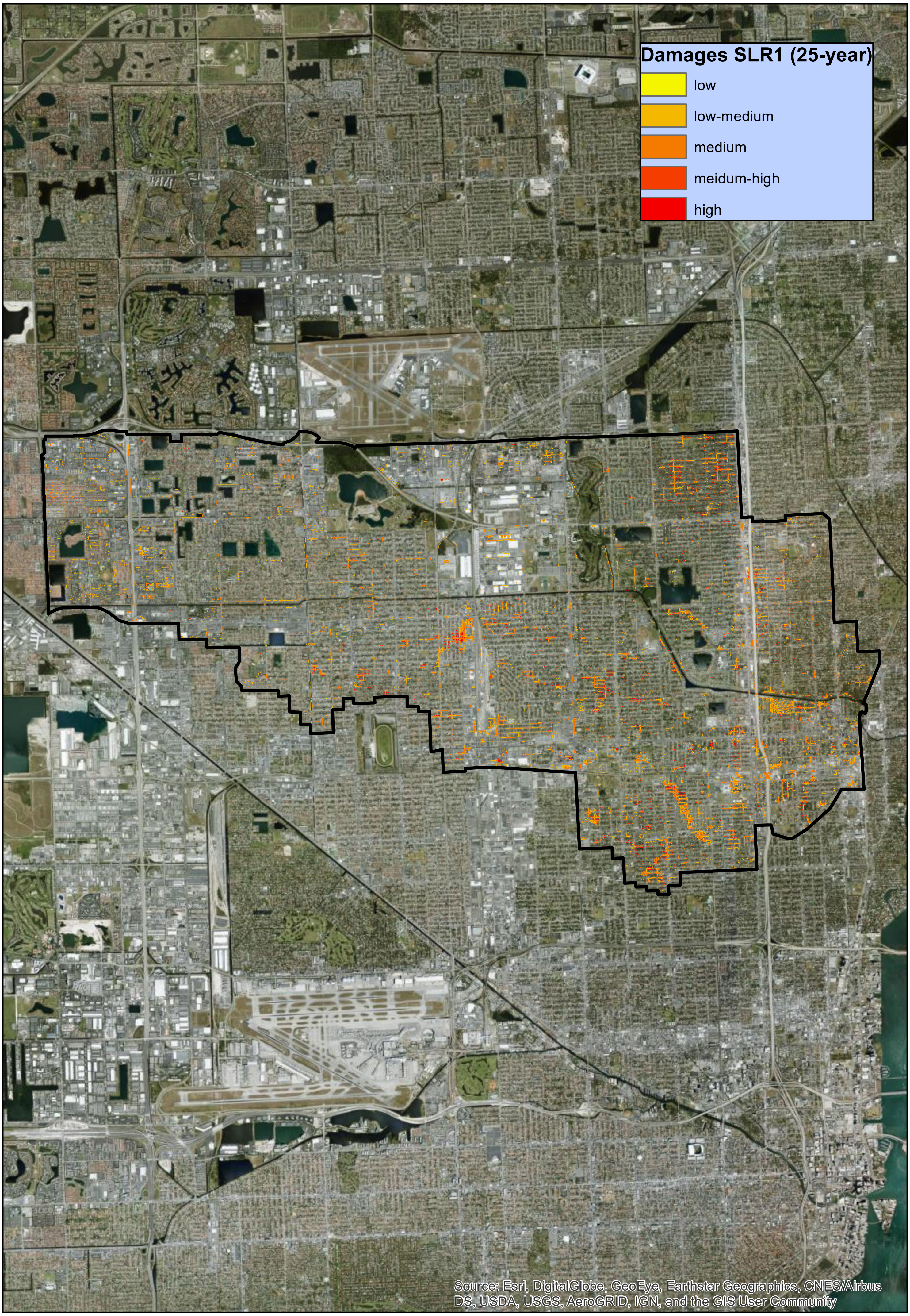

Flood depths SLR0 (100-year)
0-1 ft.
1-2 ft.
2-3 ft.
3-4 ft.
4-5 ft.
5-6 ft.
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

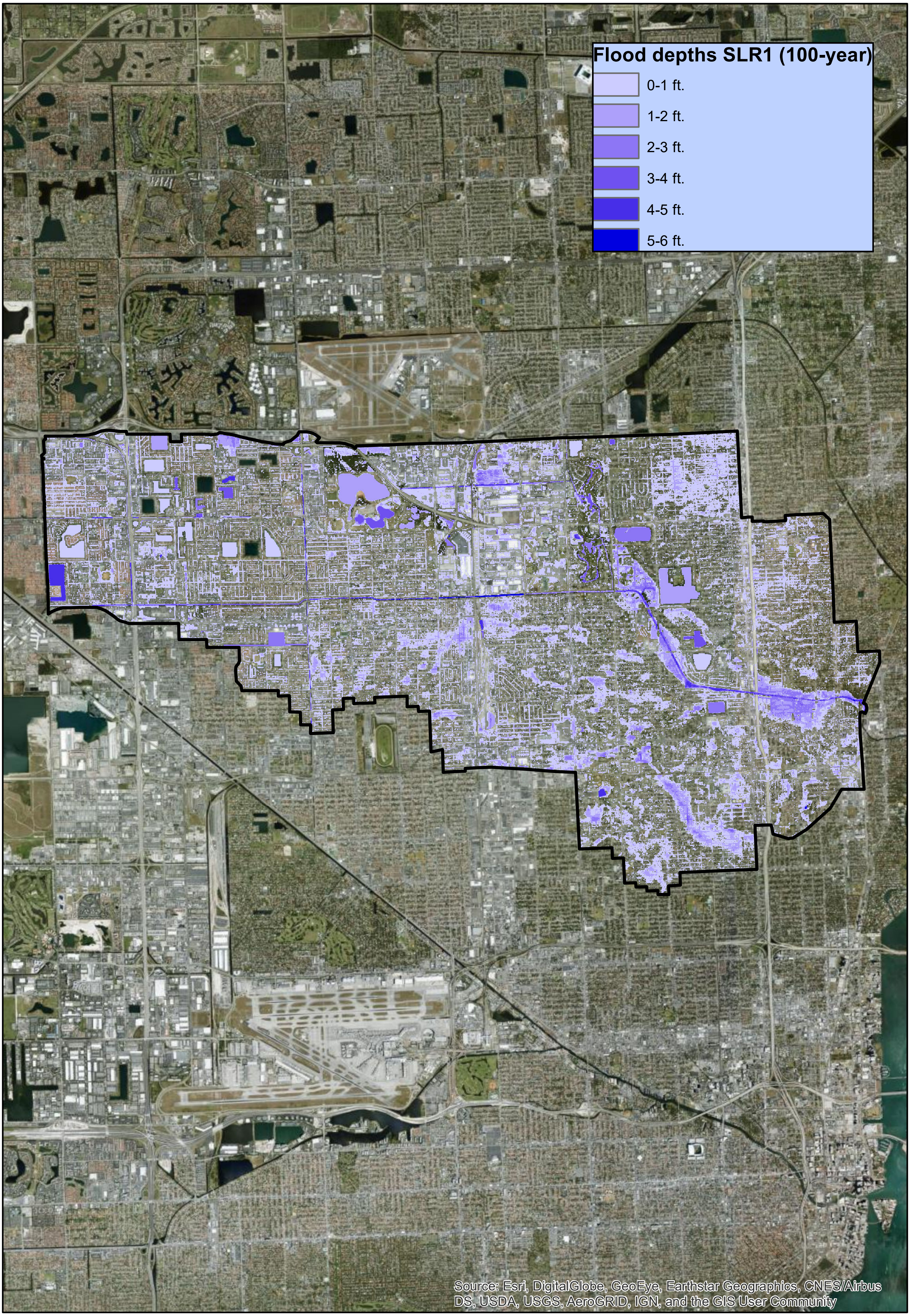

Damages SLR0 (100-year)
low
low-medium
medium
meidum-high
high
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

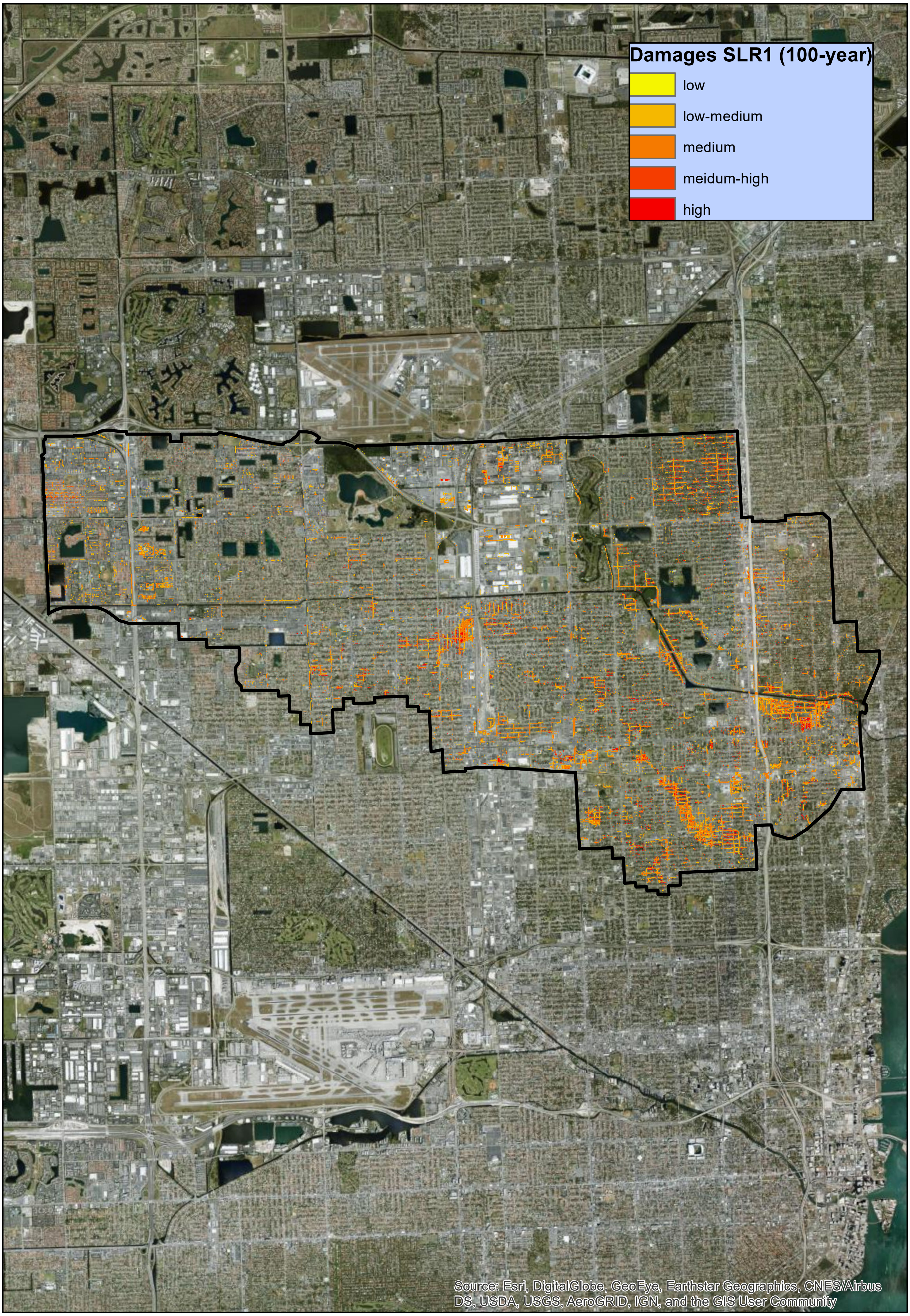

Flood depths SLR1 (10-year)
0-1 ft.
1-2 ft.
2-3 ft.
3-4 ft.
4-5 ft.
5-6 ft.
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

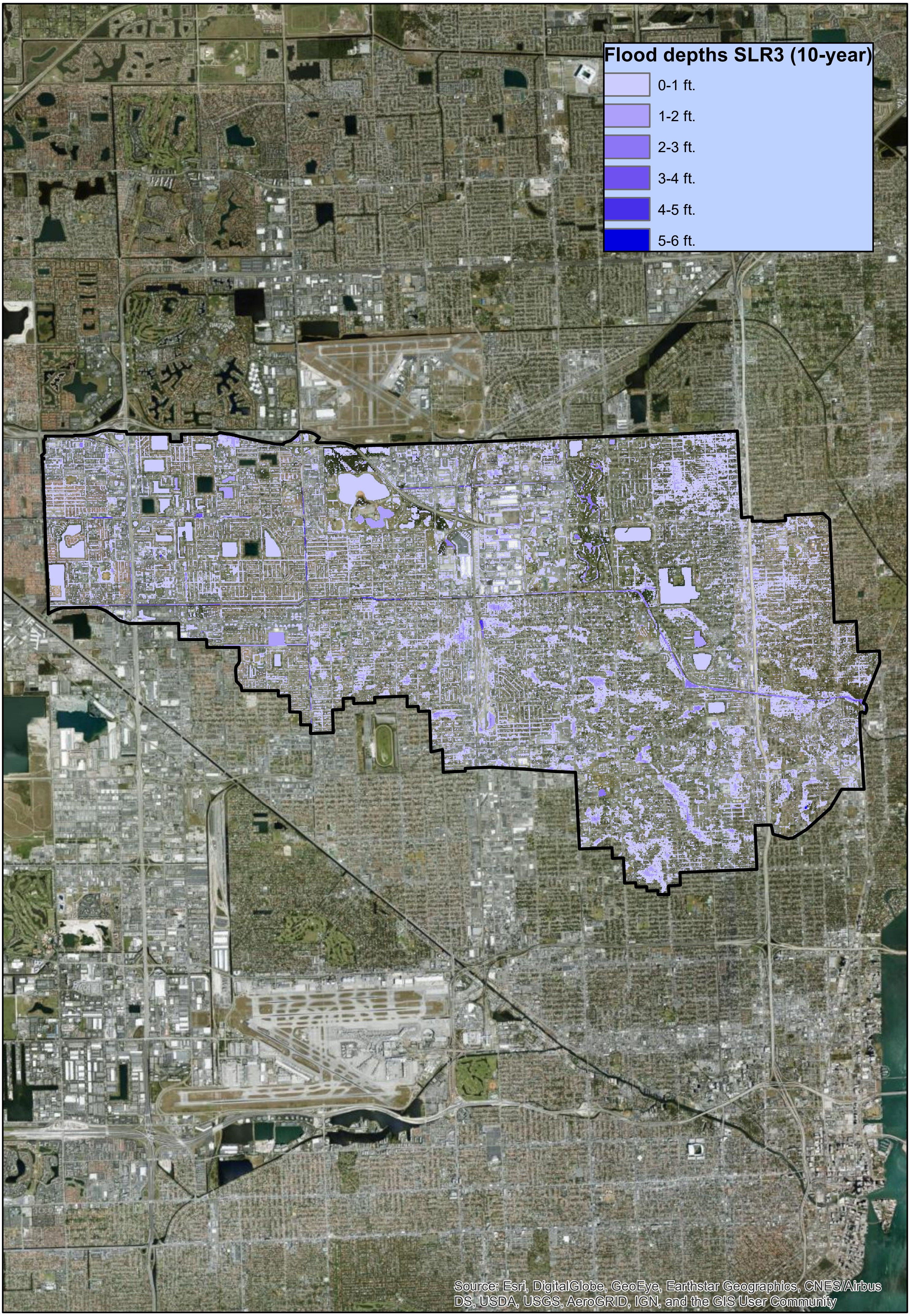

Damages SLR1 (10-year)
low
low-medium
medium
meidum-high
high
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

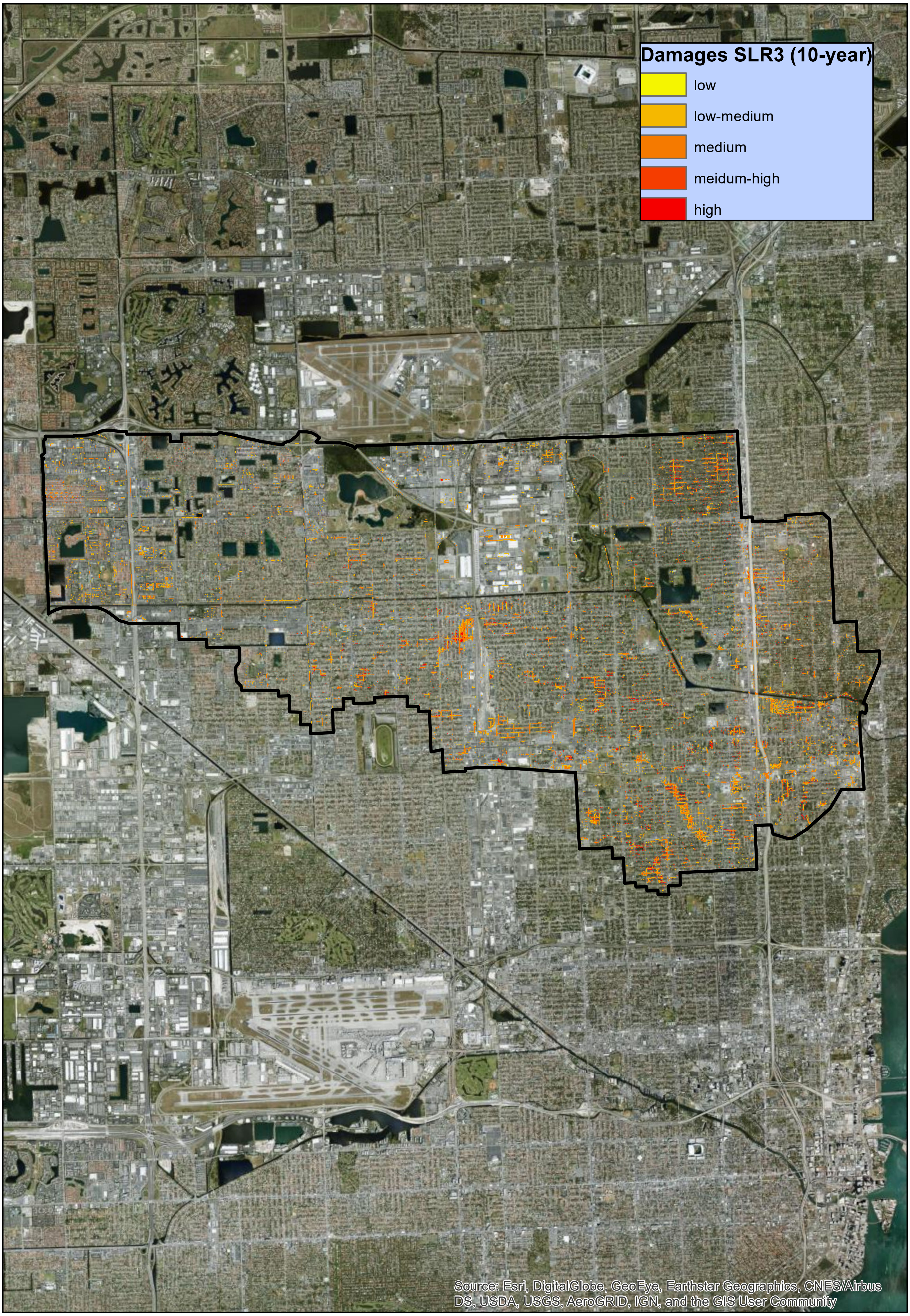

Flood depths SLR1 (25-year)
0-1 ft.
1-2 ft.
2-3 ft.
3-4 ft.
4-5 ft.
5-6 ft.
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

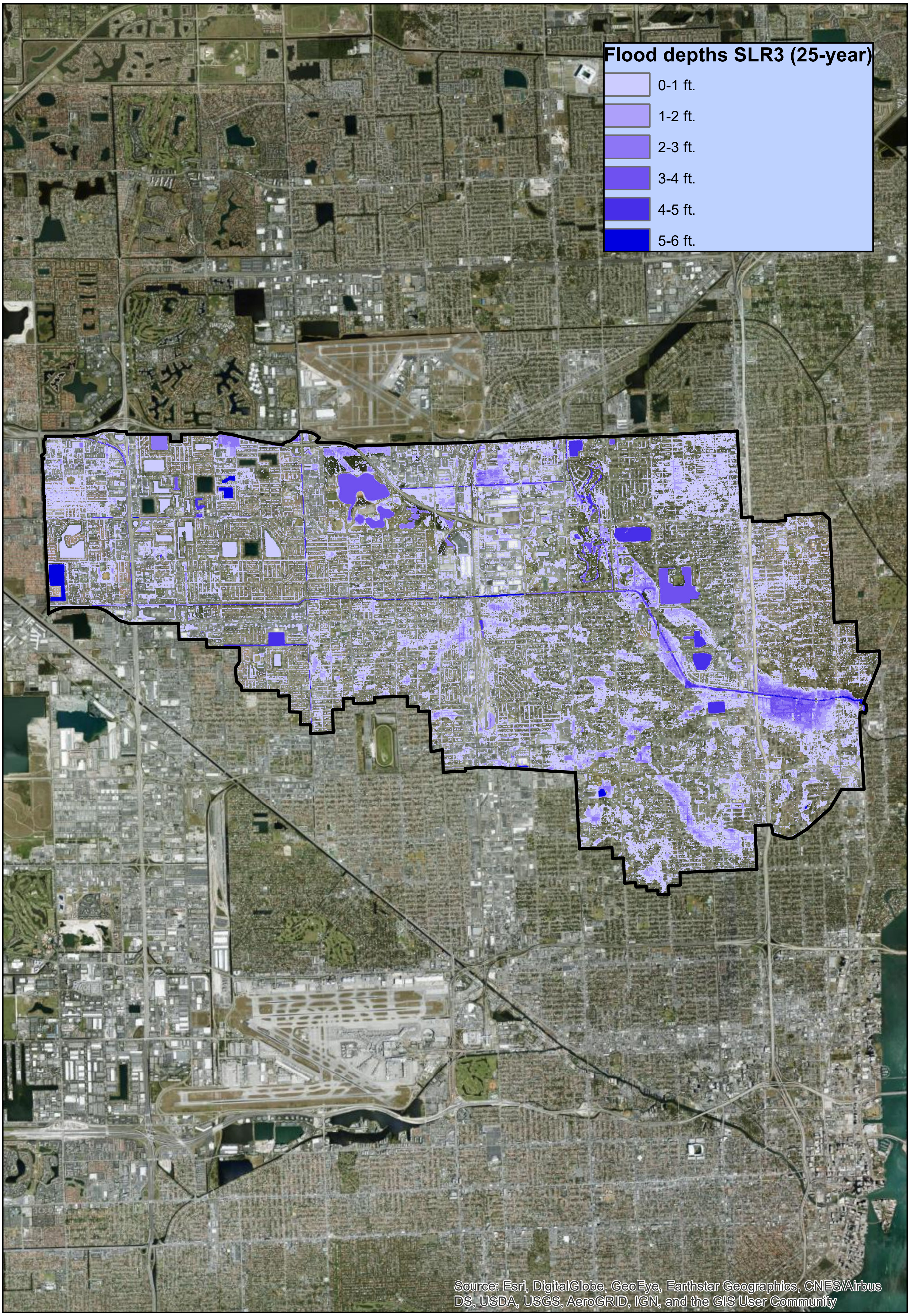

Damages SLR1 (25-year)
low
low-medium
medium
meidum-high
high
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

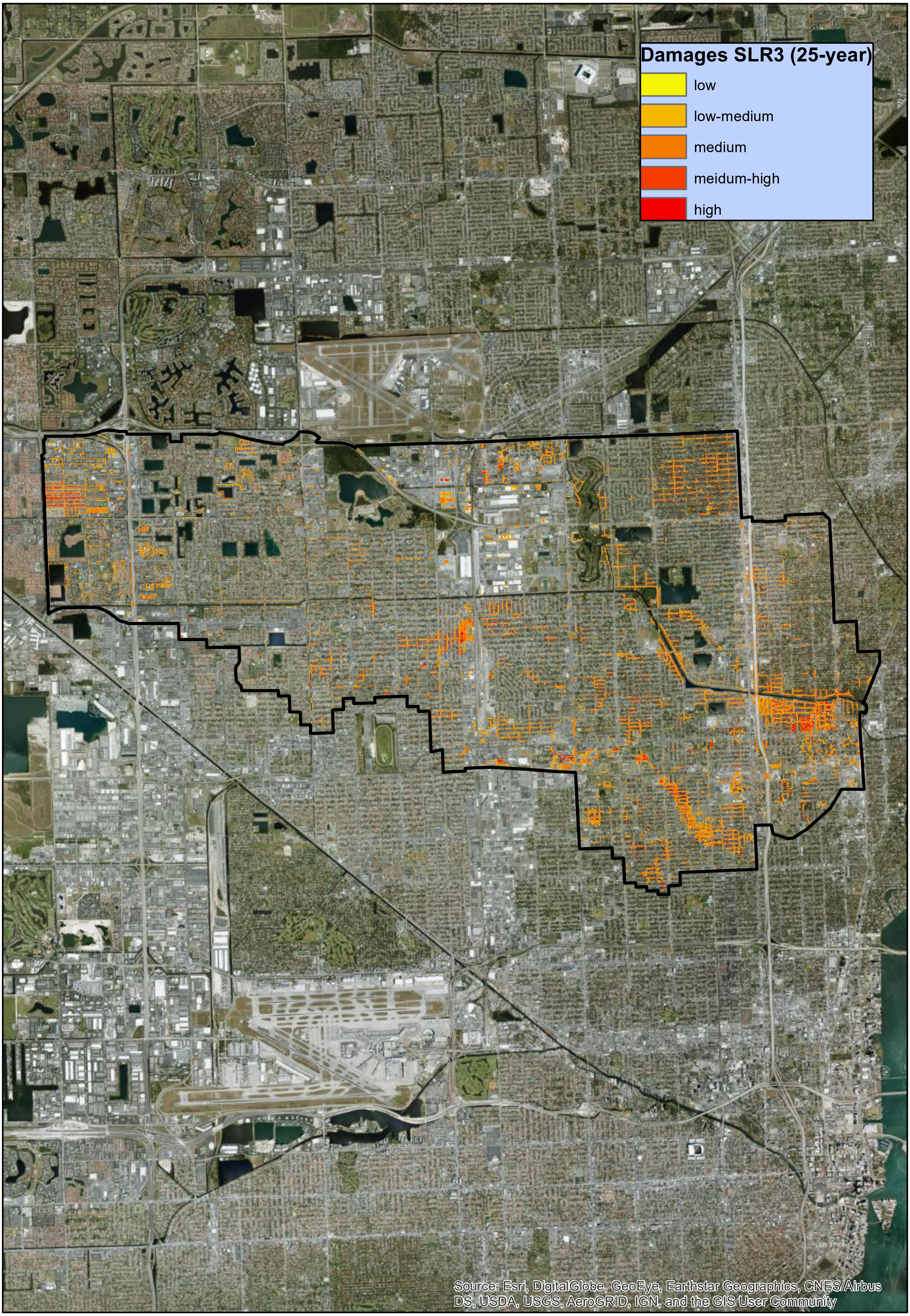

Flood depths SLR1 (100-year)
0-1 ft.
1-2 ft.
2-3 ft.
3-4 ft.
4-5 ft.
5-6 ft.
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

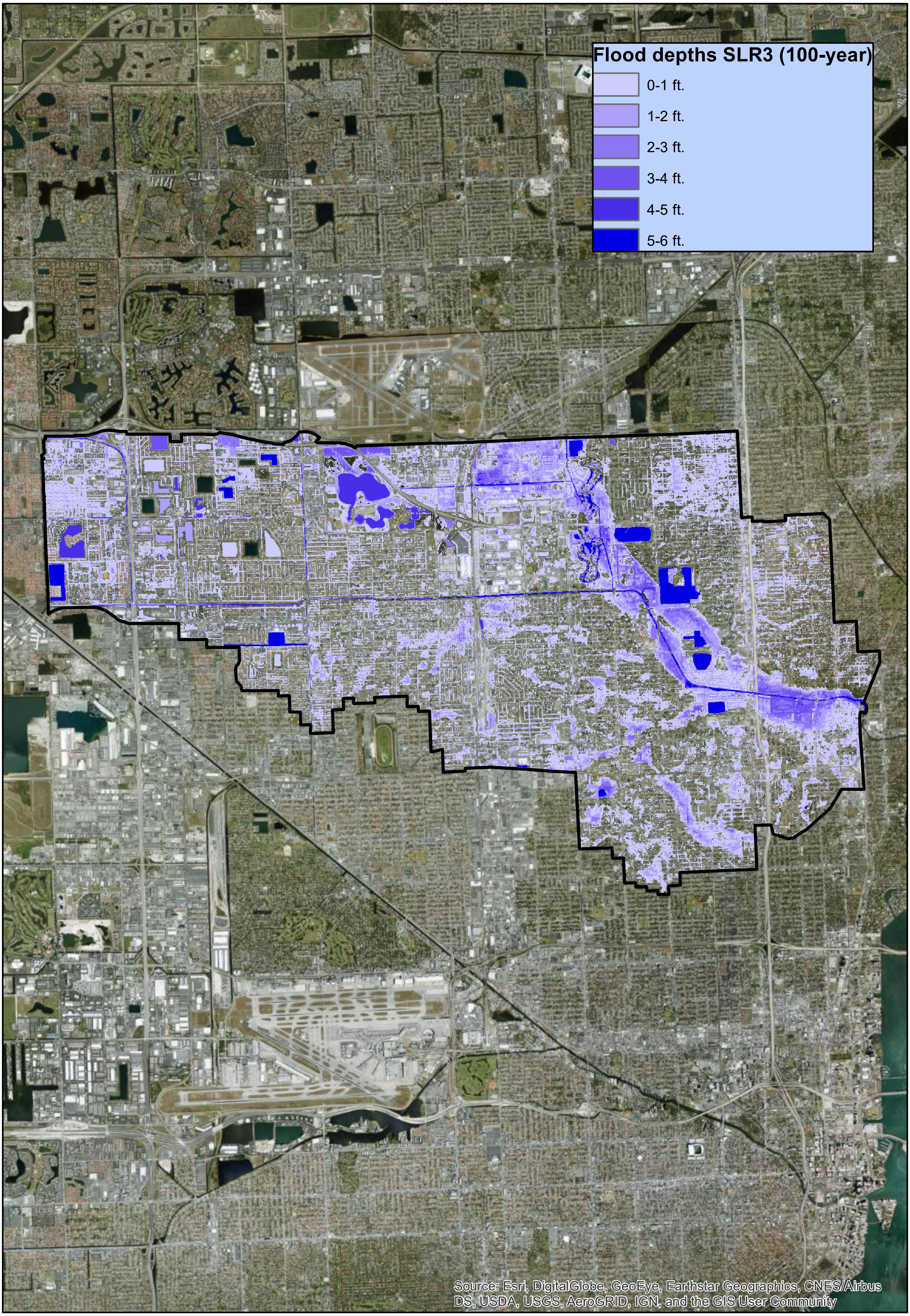

Damages SLR1 (100-year)
low
low-medium
medium
meidum-high
high
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community


Flood depths SLR3 (10-year)
0-1 ft.
1-2 ft.
2-3 ft.
3-4 ft.
4-5 ft.
5-6 ft.
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

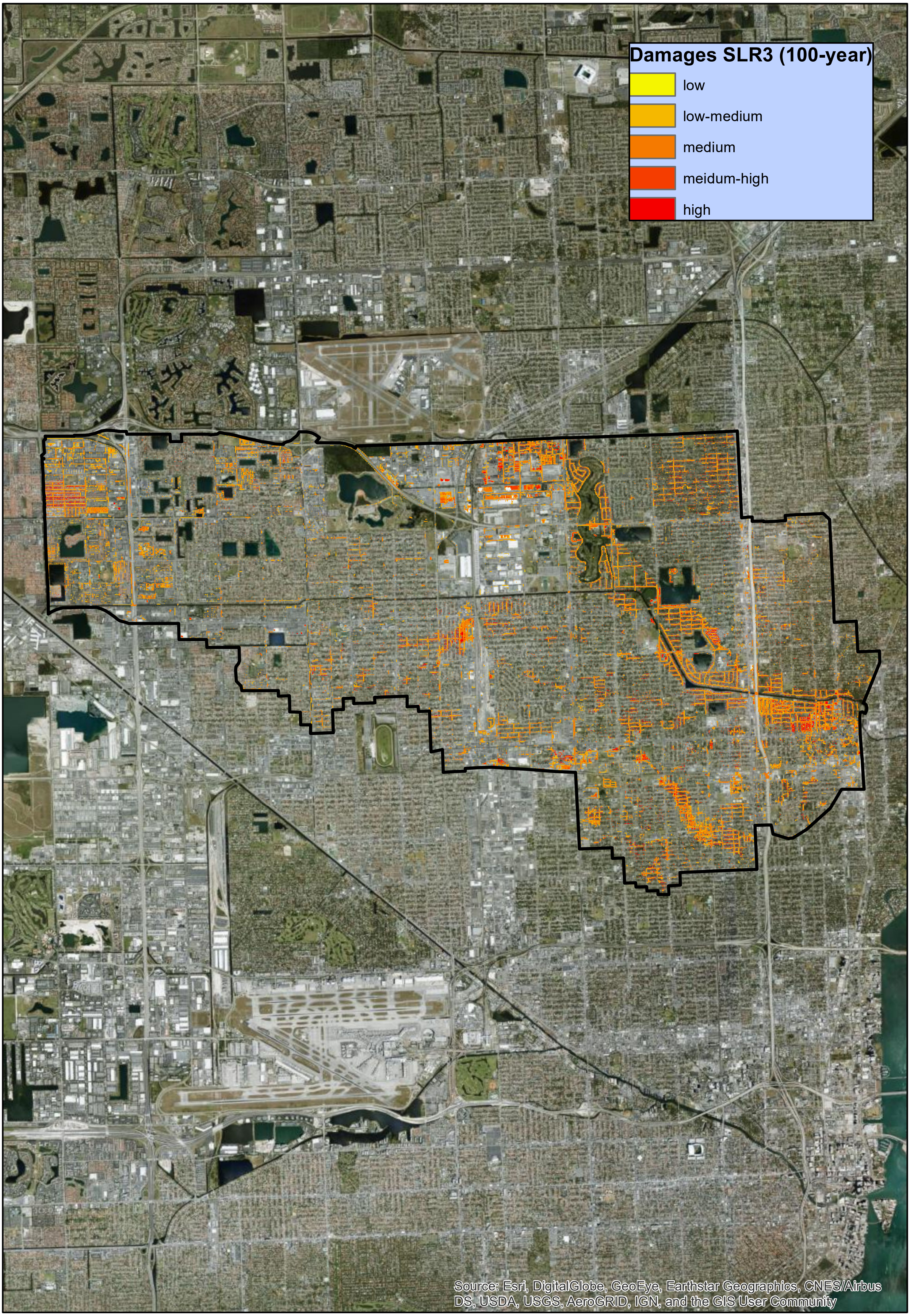

Damages SLR3 (10-year)
low
low-medium
medium
meidum-high
high
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community


Flood depths SLR3 (25-year)
0-1 ft.
1-2 ft.
2-3 ft.
3-4 ft.
4-5 ft.
5-6 ft.
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community


Damages SLR3 (25-year)
low
low-medium
medium
meidum-high
high
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



Flood depths SLR3 (100-year)
0-1 ft.
1-2 ft.
2-3 ft.
3-4 ft.
4-5 ft.
5-6 ft.
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community


Damages SLR3 (100-year)
low
low-medium
medium
meidum-high
high
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Appendix E Risk (EAD) estimates

M0	C2	C3W	C4	C6	C7
CSL	36.8	33.1	6.0	54.2	41.6
SLR1	48.1	35.6	10.1	67.2	58.2
SLR3	102.7	47.0	31.7	124.9	128.0

Table C 1 Risk (EAD) in millions of dollars for M0 (do-nothing situation) for current sea level and two future sea levels, for all five basins.

M1	C2	C3W	C4	C6	C7
CSL	33.6	32.3	4.8	49.4	35.8
SLR1	39.3	33.7	6.9	57.3	45.4
SLR3	64.5	39.3	16.6	84.8	80.1

Table C 2 Risk (EAD) in millions of dollars for M1 (local measures) for current sea level and two future sea levels, for all five basins.

M2	C2	C3W	C4	C6	C7
CSL	35.0	32.6	5.2	51.5	38.3
SLR1	37.8	33.3	6.4	55.4	43.1
SLR3	50.8	36.3	11.2	70.3	62.0

Table C 3 Risk (EAD) in millions of dollars for M2 (regional pump, 2800 cfs capacity) for current sea level and two future sea levels, for all five basins.

M1 + M2	C2	C3W	C4	C6	C7
CSL	33.2	32.2	4.8	48.9	35.1
SLR1	36.2	33.0	5.8	53.4	40.6
SLR3	43.0	34.5	8.1	61.6	51.1

Table C 4 Risk (EAD) in millions of dollars for M1 (local measures) and M2B (regional pump, 2800 cfs capacity) for current sea level and two future sea levels, for all five basins.

M3	C2	C3W	C4	C6	C7
CSL	0.0	0.0	0.0	0.0	0.0
SLR1	0.0	0.0	0.0	0.1	0.0
SLR3	0.0	0.0	0.0	0.1	0.0

Table C 5 Risk (EAD) in millions of dollars for M3 (raising roads and houses 6 feet) for current sea level and two future sea levels, for all five basins.

Appendix F Tipping points

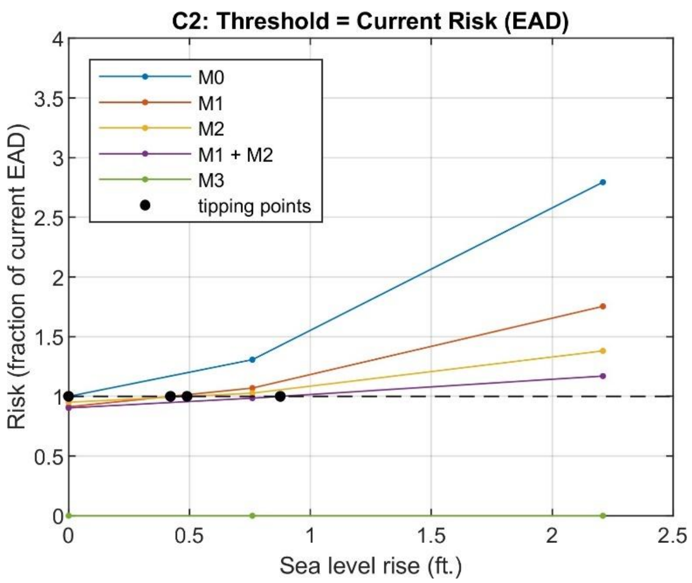
This appendix contains the results of the tipping point analysis.

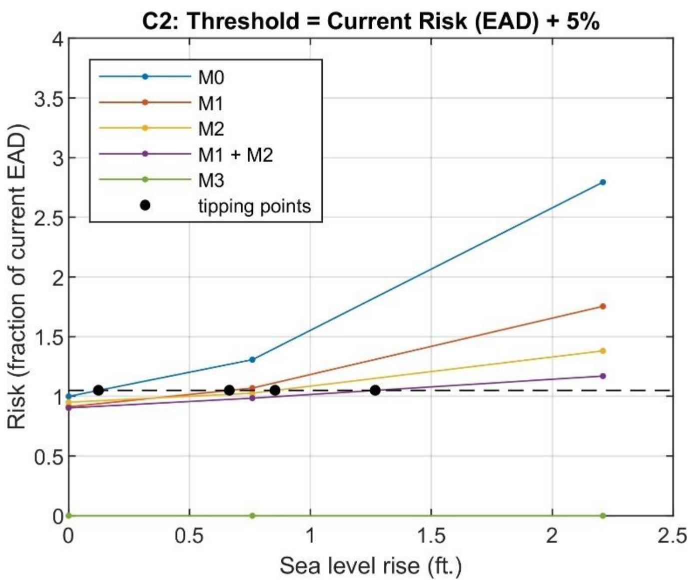
Section 0 shows the tipping point analysis per basin: the increase in risk (relative to current risk) over sea level rise, and the sea level rise at which the threshold is exceeded, for three risk thresholds – current risk (EAD) + 0%, 5%, and 10%.

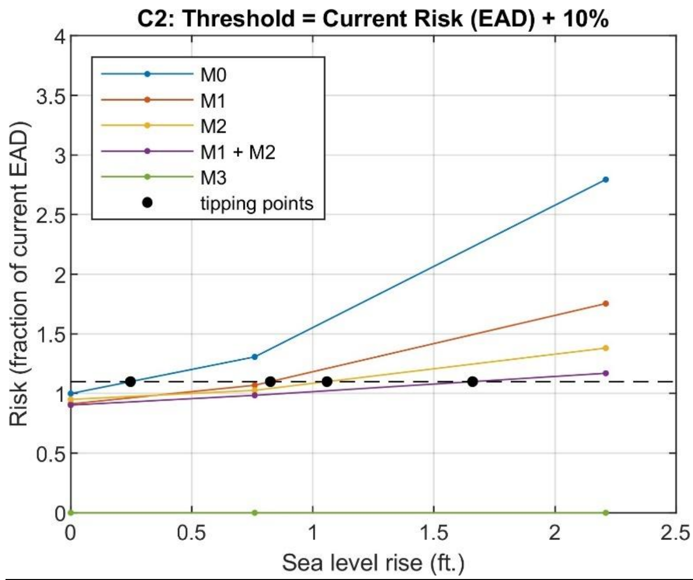
Section F.2 presents the results of the tipping point analysis: the tipping points for each measure, and for each basin, for the three risk thresholds.

F.1 Tipping point analysis

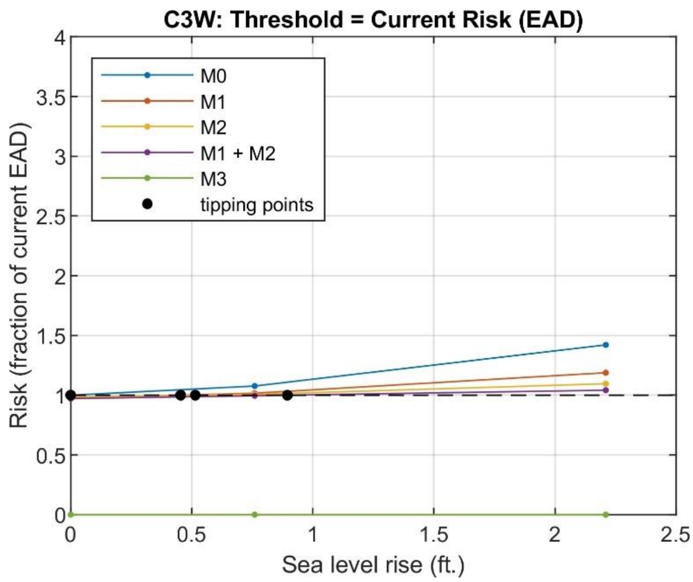
C-2

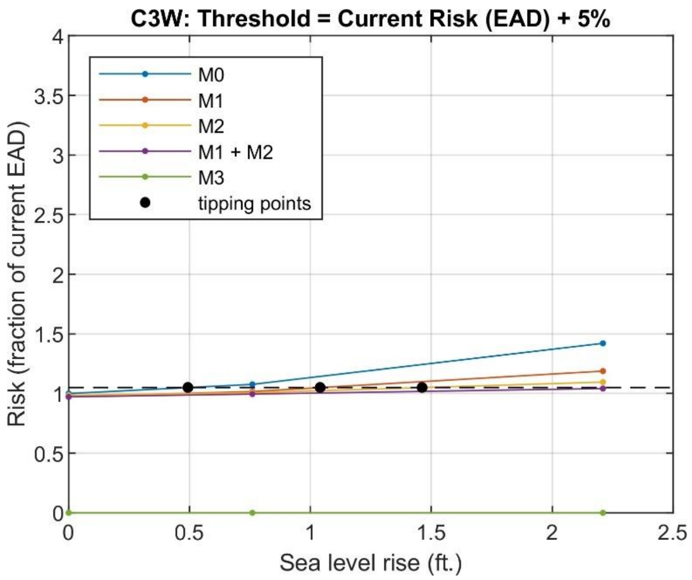


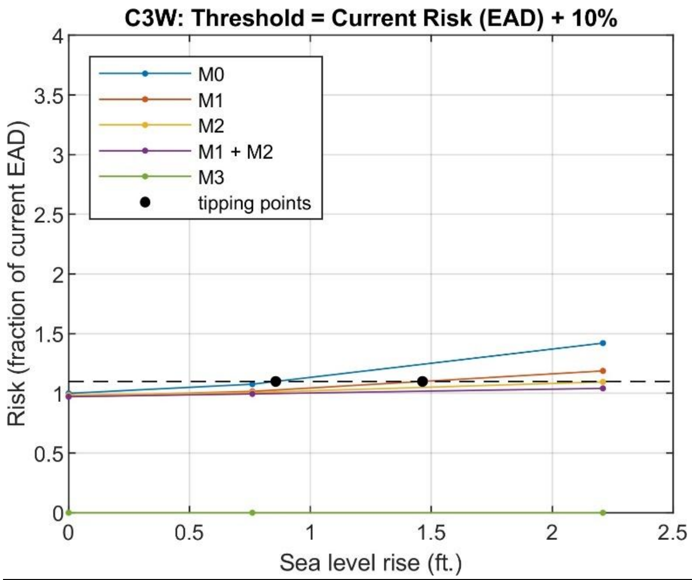



C2: Threshold = Current Risk (EAD) + 10%
Risk (fraction of current EAD)
Sea level rise (ft.)
M0
M1
M2
M1 + M2
M3
tipping points
0
0.5
1
1.5
2
2.5
3
3.5
4
0
0.5
1
1.5
2
2.5

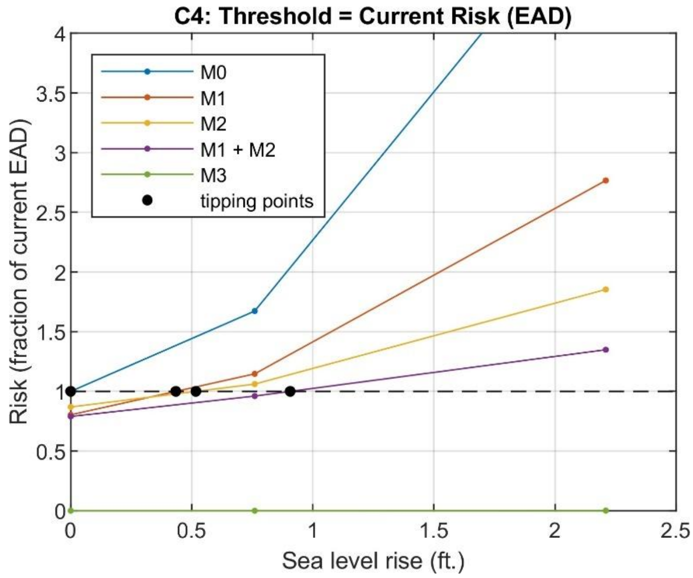
C-3W

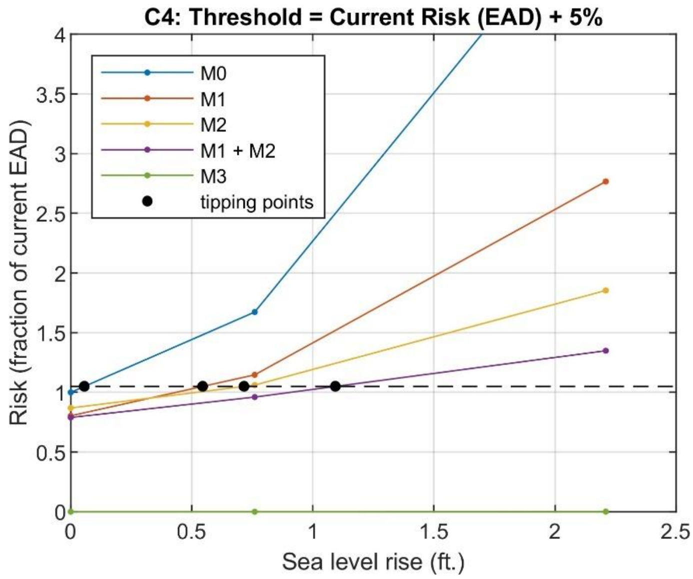

C3W: Threshold = Current Risk (EAD)
Risk (fraction of current EAD)
Sea level rise (ft.)
M0
M1
M2
M1 + M2
M3
tipping points
0
0.5
1
1.5
2
2.5
3
3.5
4
0
0.5
1
1.5
2
2.5

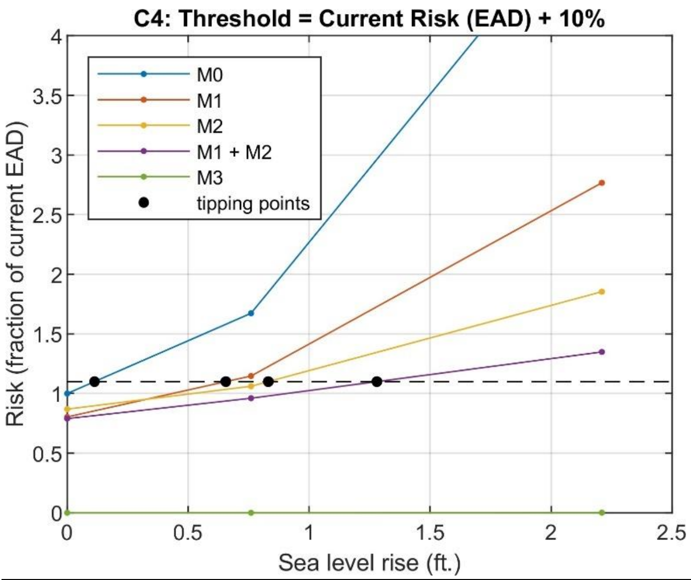

C3W: Threshold = Current Risk (EAD) + 5%
M0
M1
M2
M1 + M2
M3
tipping points
Risk (fraction of current EAD)
Sea level rise (ft.)
0
0.5
1
1.5
2
2.5
3
3.5
4


C3W: Threshold = Current Risk (EAD) + 10%
M0
M1
M2
M1 + M2
M3
tipping points
Risk (fraction of current EAD)
Sea level rise (ft.)
0
0.5
1
1.5
2
2.5
3
3.5
4

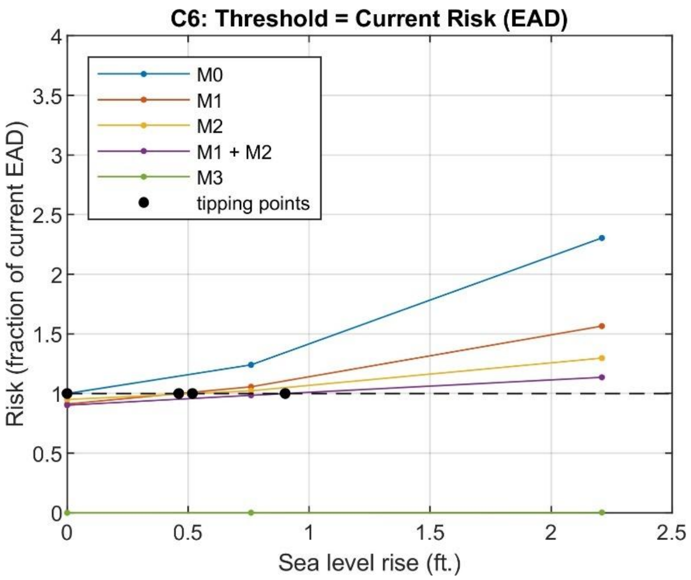
C-4

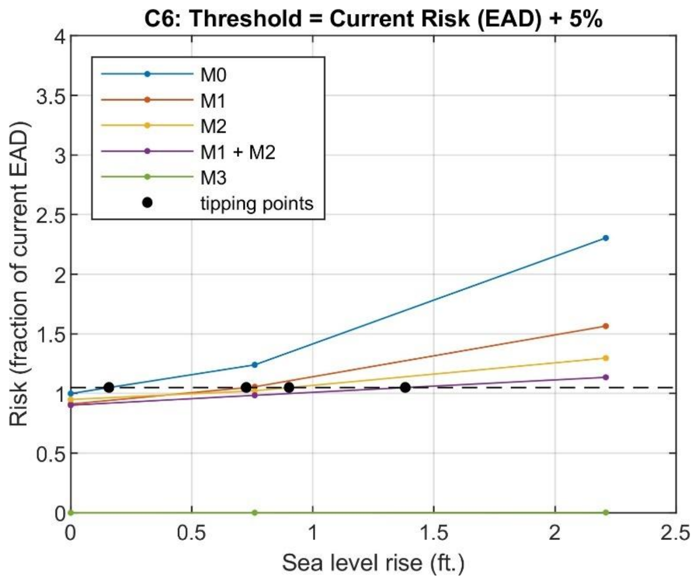

C4: Threshold = Current Risk (EAD)
M0
M1
M2
M1 + M2
M3
tipping points
Risk (fraction of current EAD)
Sea level rise (ft.)
0
0.5
1
1.5
2
2.5
3
3.5
4

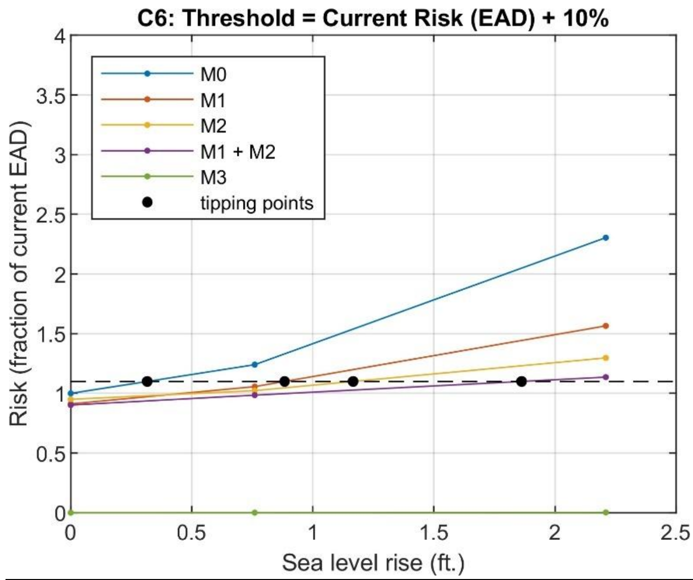

C4: Threshold = Current Risk (EAD) + 5%
M0
M1
M2
M1 + M2
M3
tipping points
Risk (fraction of current EAD)
Sea level rise (ft.)
0
0.5
1
1.5
2
2.5
3
3.5
4


C4: Threshold = Current Risk (EAD) + 10%
M0
M1
M2
M1 + M2
M3
tipping points
Risk (fraction of current EAD)
Sea level rise (ft.)
0
0.5
1
1.5
2
2.5
3
3.5
4

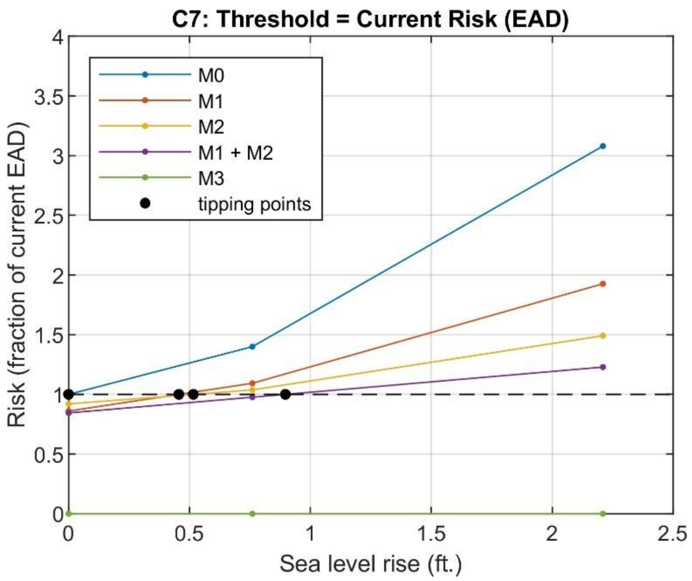
C-6


C6: Threshold = Current Risk (EAD)
M0
M1
M2
M1 + M2
M3
tipping points
Risk (fraction of current EAD)
Sea level rise (ft.)
0
0.5
1
1.5
2
2.5
3
3.5
4

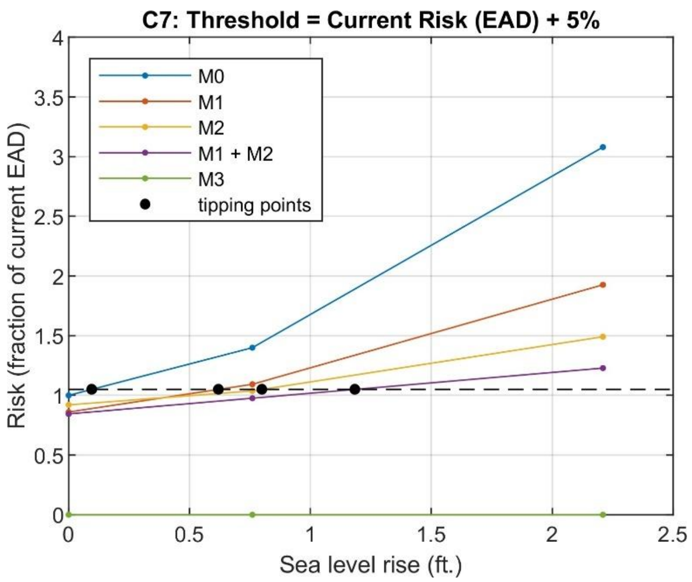

C6: Threshold = Current Risk (EAD) + 5%
Risk (fraction of current EAD)
Sea level rise (ft.)
M0
M1
M2
M1 + M2
M3
tipping points


C6: Threshold = Current Risk (EAD) + 10%
Risk (fraction of current EAD)
Sea level rise (ft.)
M0
M1
M2
M1 + M2
M3
tipping points

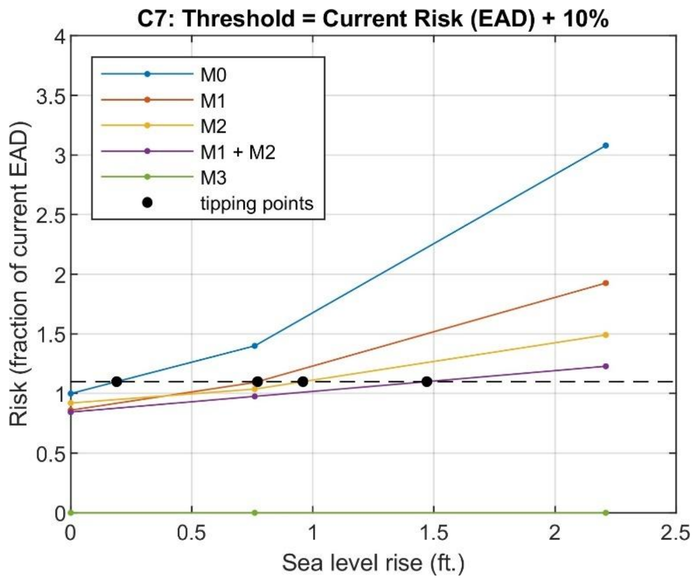
C-7



C7: Threshold = Current Risk (EAD)
M0
M1
M2
M1 + M2
M3
tipping points
Risk (fraction of current EAD)
Sea level rise (ft.)

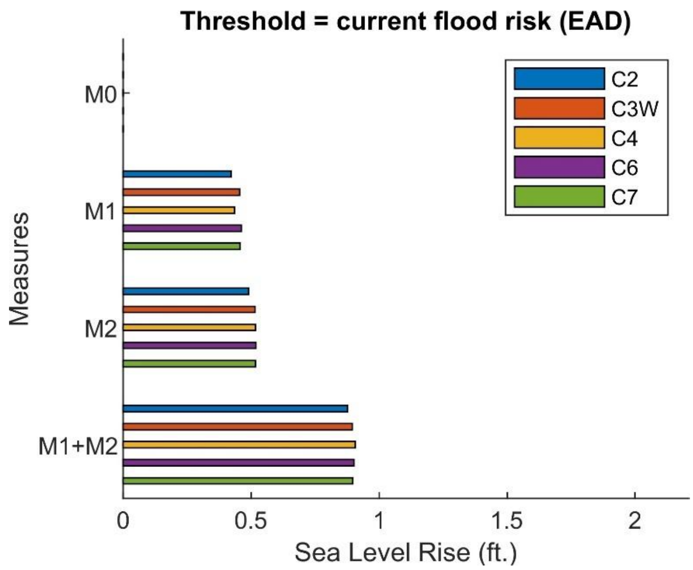


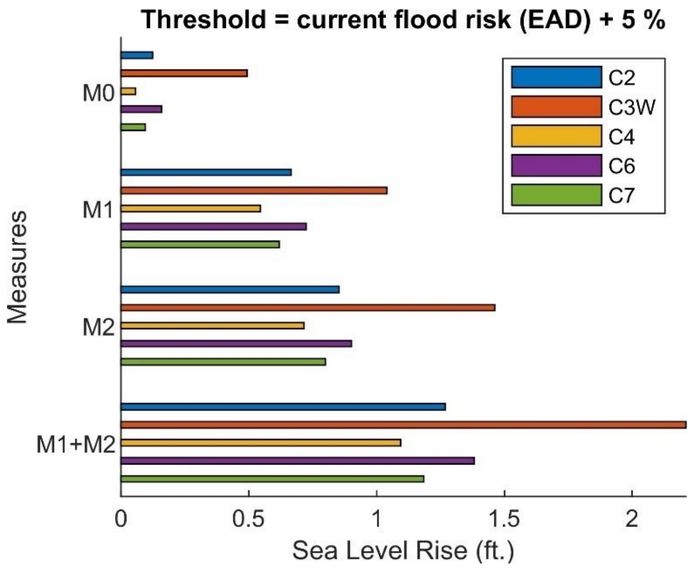
C7: Threshold = Current Risk (EAD) + 5%
M0
M1
M2
M1 + M2
M3
tipping points
Risk (fraction of current EAD)
Sea level rise (ft.)

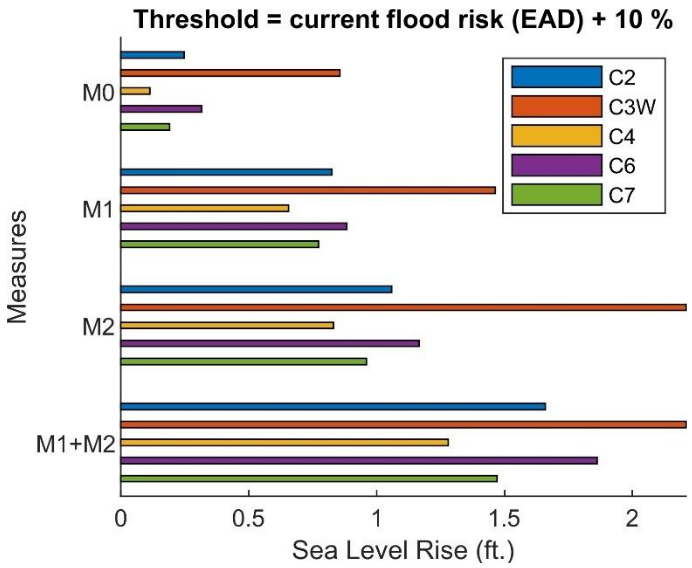


F.2 Tipping point results

This section shows the tipping points as a bar length, showing the sea level rise at which the threshold is exceeded, for M0, M1, M2, and M1+M2. For M3, the tipping points were not reached. The highest analyzed sea level was 2.21 ft (SLR3 scenario in 2065). Thus, if a tipping point is shown to be 2.21 ft., it means that it can tolerate *at least* this sea level rise, but also higher levels (not calculated).




Threshold = current flood risk (EAD) + 5 %
C2
C3W
C4
C6
C7
Measures
M0
M1
M2
M1+M2
0
0.5
1
1.5
2
Sea Level Rise (ft.)


Threshold = current flood risk (EAD) + 10 %
C2
C3W
C4
C6
C7
Measures
M0
M1
M2
M1+M2
0
0.5
1
1.5
2
Sea Level Rise (ft.)