Methods and Approaches for Valuing Mangrove Risk Reduction Benefits in Jamaica

Michael W. Beck

Siddharth Narayan, Antonio Espejo, Sheila A. Herrero, Saul Torres, Ana Fernandez, Iñigo Losada

IH cantabria INSTITUTO DE HIDRÁULICA AMBIENTAL UNIVERSIDAD DE CANTABRIA

The Nature Conservancy

UNIVERSITY OF CALIFORNIA SANTA CRUZ

Outline

- The role of mangroves in coastal protection
- Overall framework and approach
- Offshore dynamics
- Nearshore dynamics and coastal flooding
- Quantifying the role of mangroves in coastal protection using flooding maps
- Assessing exposure and vulnerability
- Quantifying annual expected damages/losses and benefits

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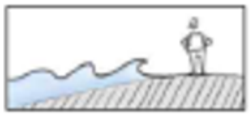
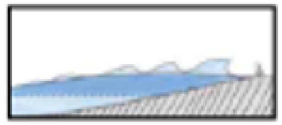
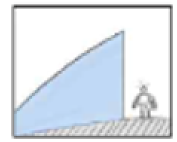
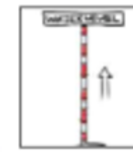
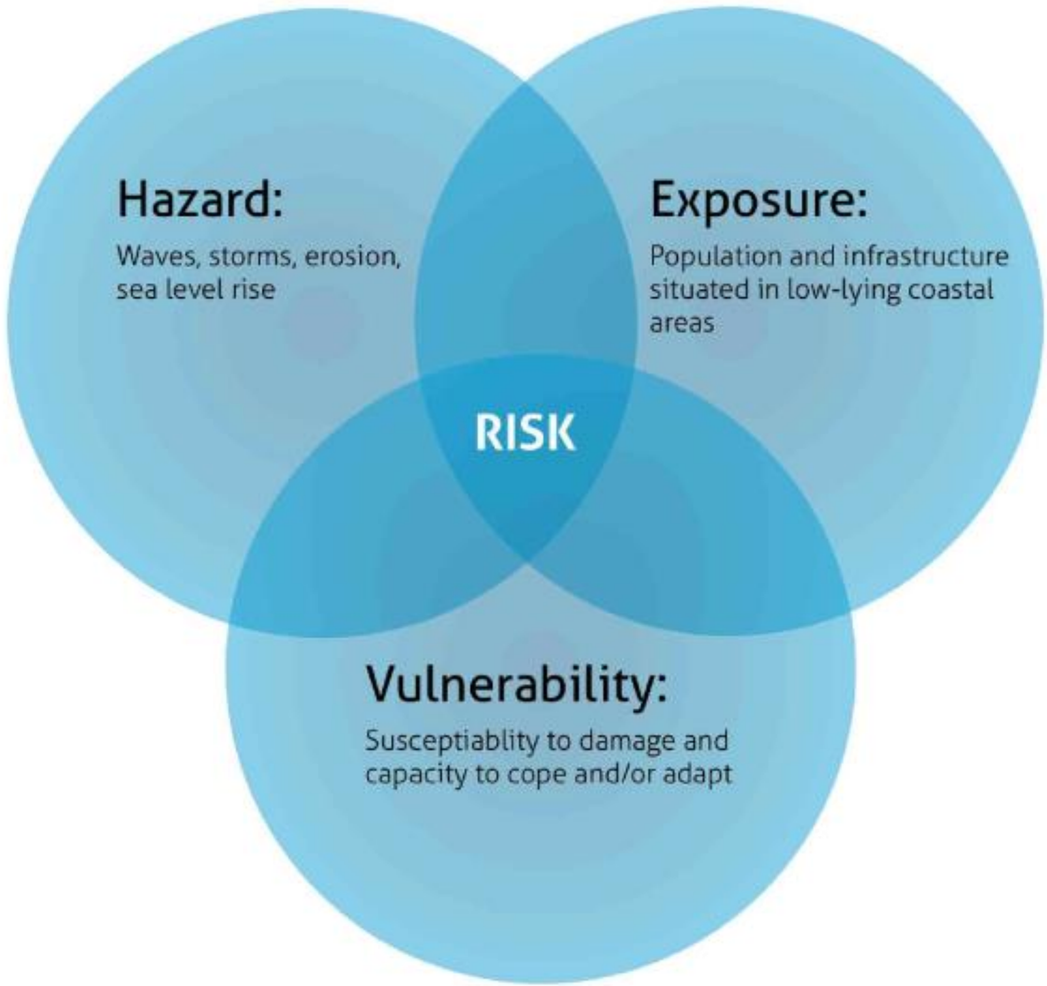
The Role of Mangroves in Protecting Coastlines - Overview

		HAZARD				
		Waves 	Storm surges 	Tsunami 	Erosion 	Sea level rise 
MANGROVE FOREST PROPERTIES	Width	Very effective: 100s of meters for 13-66 % redn	Effective at scale: 1000s of meters for surge redn (5–50cm/km)	Not effective: 1000s of meters for tsunami reduction by 5 – 30%	Effective at specific sites: Wide, healthy mangroves can reduce erosion, trap sediment and build land	
	Struct.	Dense roots and branches	Dense roots, branches and canopies ; no open channels to allow flow		Complex roots slow flow, trap sediments	
	Size	Small trees	Larger trees for surges & tsunamis		Small trees	
	System	Act together with dunes, reefs, seagrasses to reduce flooding				Space
	Factors	Keeping mangroves healthy needs sediment, no subsidence, good levels of salinity, temperature, low pollution, etc.				

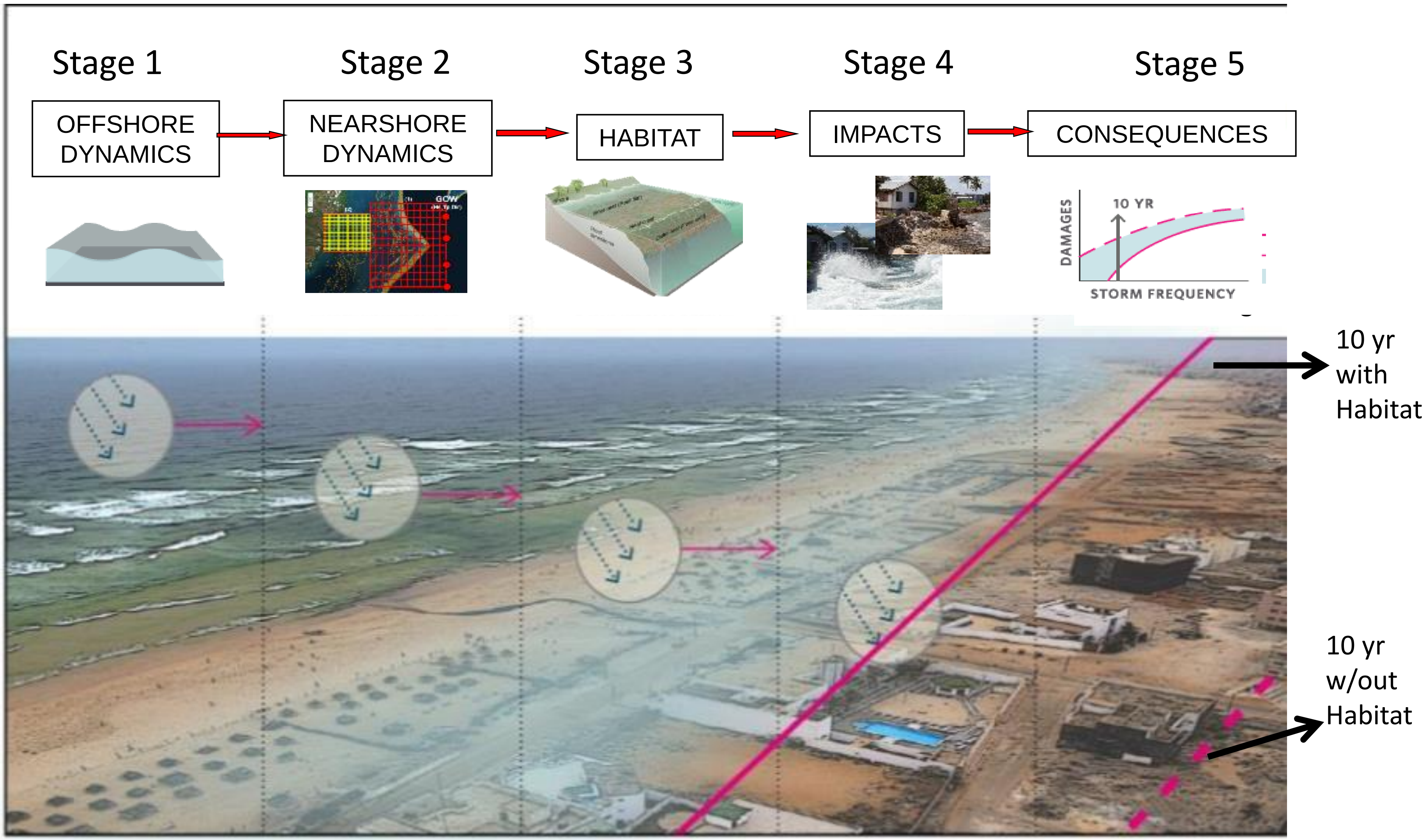
Hazard – Exposure – Vulnerability Framework for Understanding Flood Risks

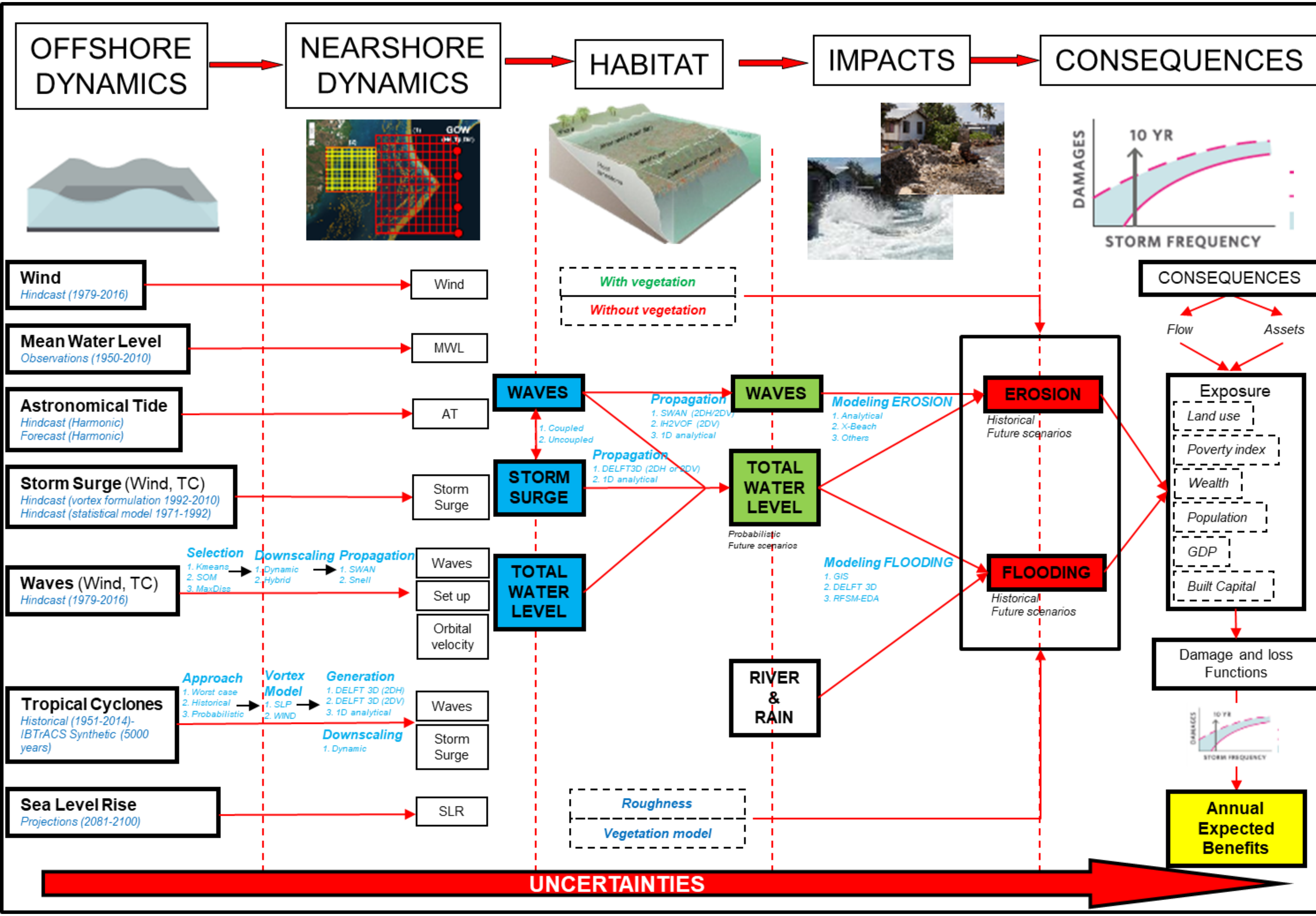


Guidelines for Valuing Coastal Protection Services from Mangroves and Reefs

M W. Beck & G-M Lange (eds)

Recommended Approach: Expected Damage Function





OFFSHORE DYNAMICS
NEARSHORE DYNAMICS
HABITAT
IMPACTS
CONSEQUENCES
DAMAGES
10 YR
STORM FREQUENCY
Wind
Hindcast (1979-2016)
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Astronomical Tide
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Valuing Mangrove Coastal Protection Benefits in Jamaica – Goals and Scope

Obtain the reduction on the expected annual damage caused by hurricanes induced coastal floods in Jamaica

a) Construct a high resolution numerical model able to determine flood heights and extend considering the with and without mangrove scenarios

b) Extend the short aged TC record to thousand of years throughout a synthetic TC database in agreement with the historical TC population

c) Construct probabilistic flood maps for the with and without mangrove scenarios

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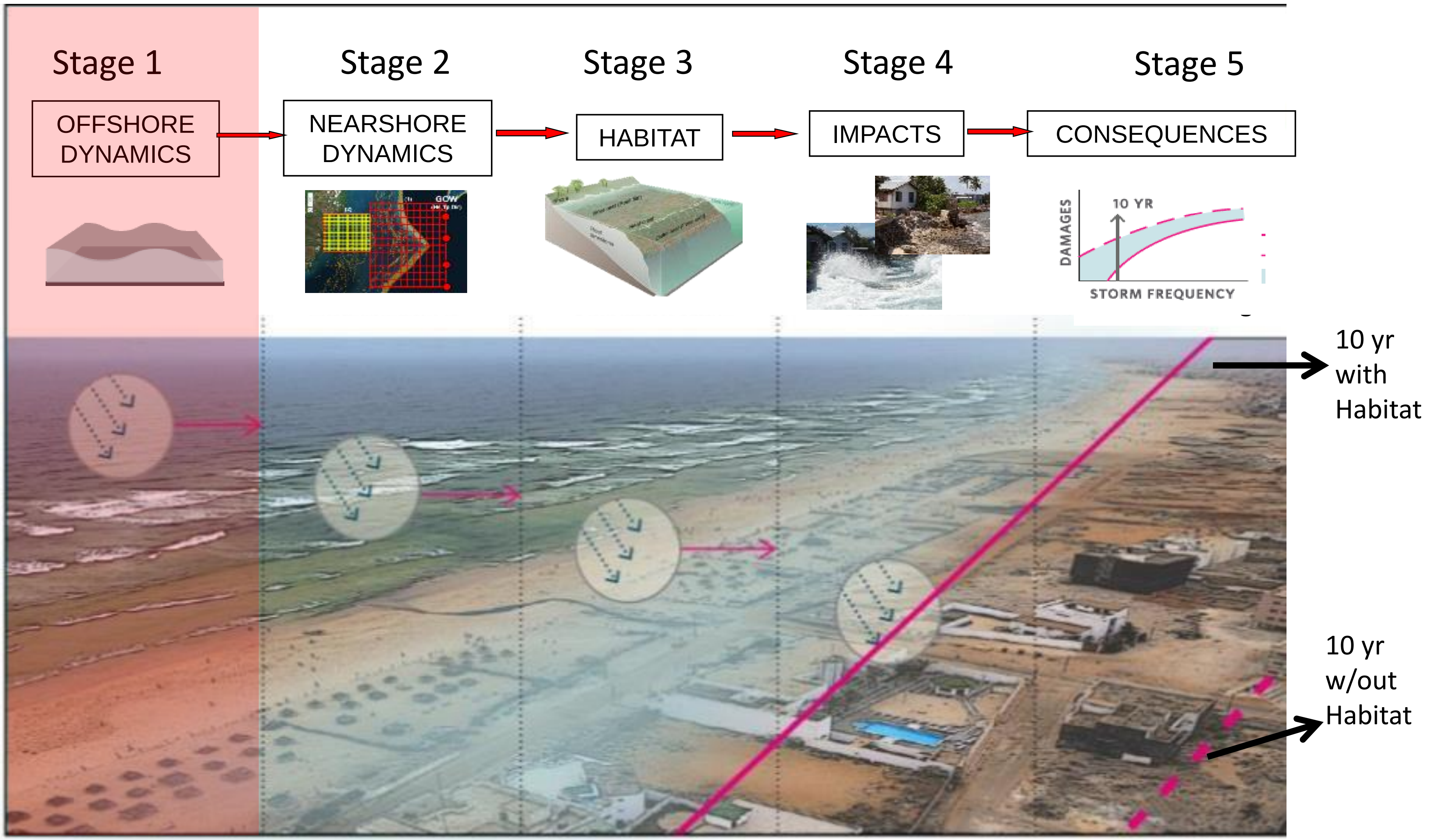
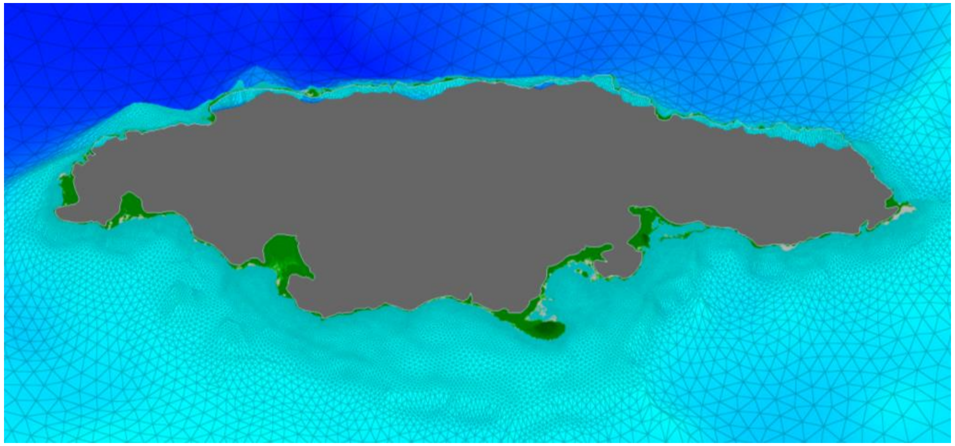


Estimation of Offshore Dynamics for Storm Surges

Global Databases

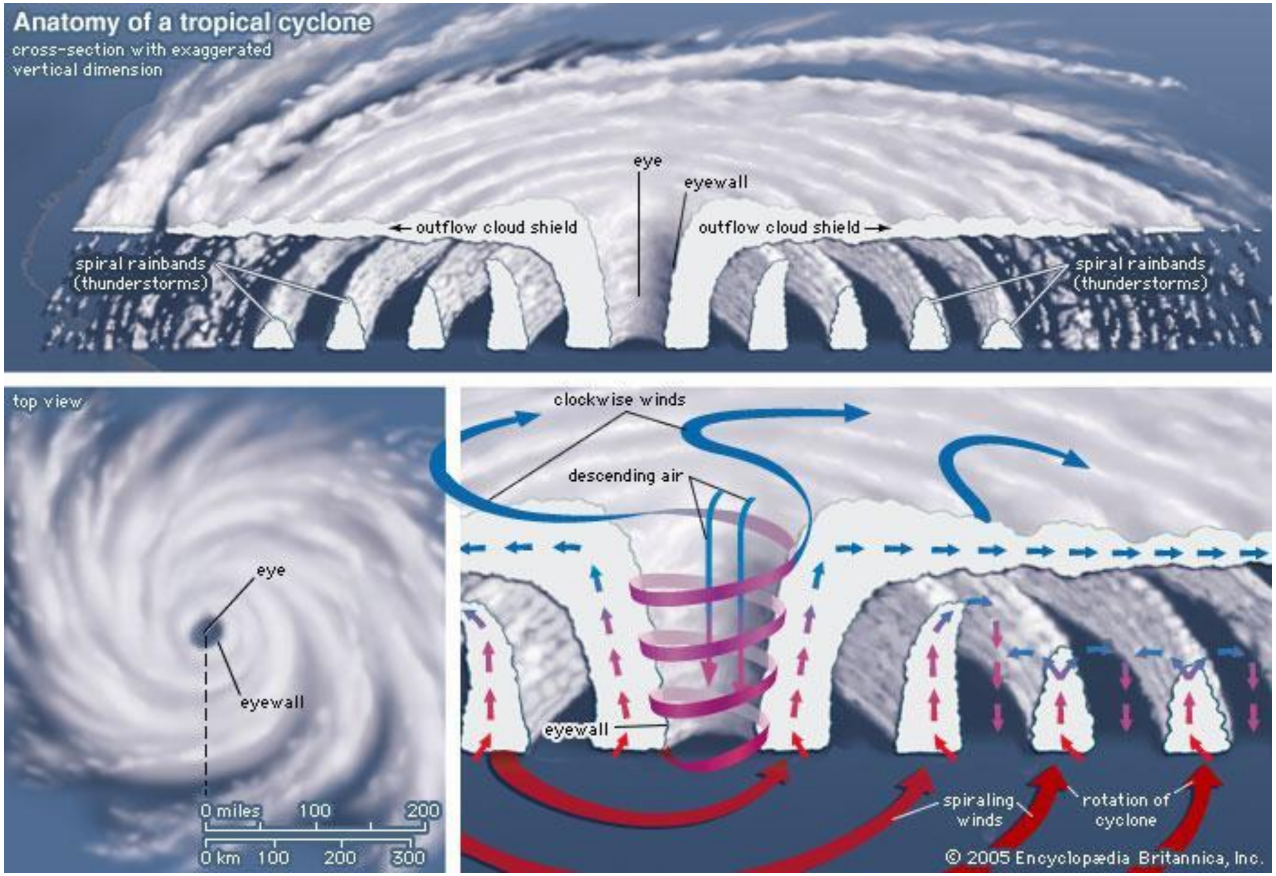
- Mean Sea Level
- Sea Level Rise (Slangen 2014)
- Astronomical tide (GOT)
- Storm Surge (DAC)
- Tropical cyclones (IBTrACS, Global-STM)
- Waves (GOW2)
- Hydrological data (TRMM-3B42)



Metocean Climate in Jamaica

Offshore Dynamics: Tropical Cyclone Parameters

- Motion (track, translation speed)
- Intensity (min pressure, max winds)
- Size (Radius to max winds)



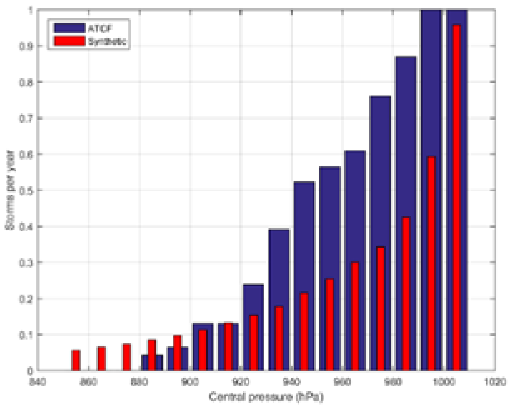
Offshore Dynamics: Historical Tropical Cyclones

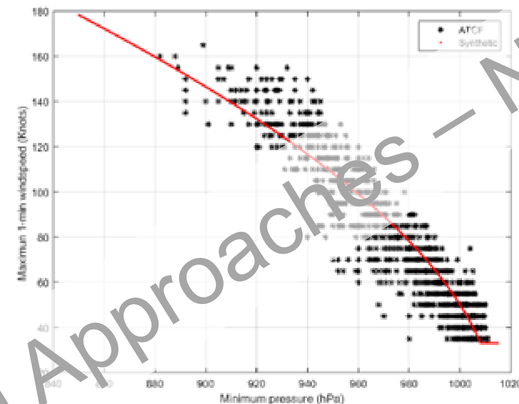
- 9 historical landfalling Tropical Cyclones in Jamaica between 1970 – 2016
- Dataset not long enough for modelling offshore dynamics
- Needs to be extended synthetically using statistical methods

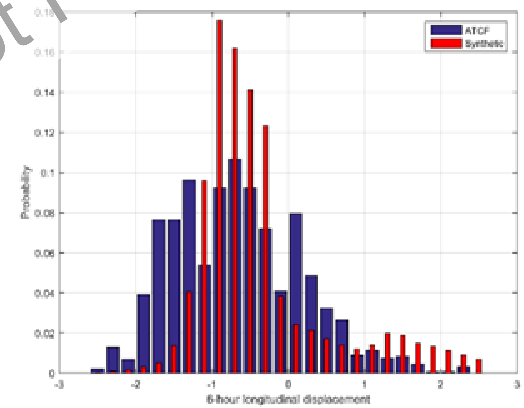
Hurricane	Landfall Date	Wmax (knots)
CARMEN	30-Aug-1974	76.1416
ALLEN	02-Aug-1980	118.2088
GILBERT	09-Sep-1988	117.4809
IRIS	05-Oct-2001	75.0290
CHARLEY	10-Aug-2004	148.3572
IVAN	03-Sep-2004	117.8865
DENNIS	05-Jul-2005	127.5986
DEAN	14-Aug-2007	85.0000
SANDY	22-Oct-2012	85.0000

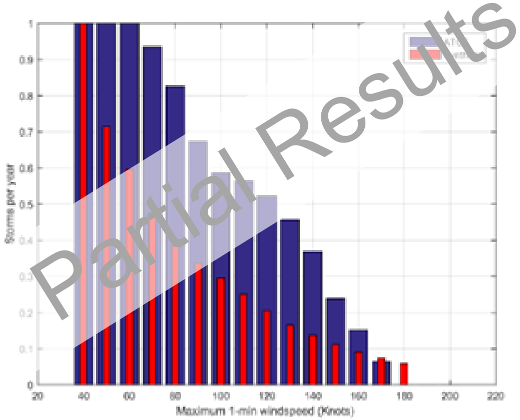
Offshore Dynamics: Selecting Suitable Synthetic TCs

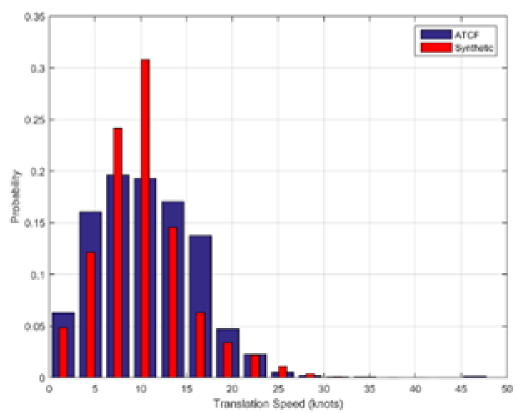
- Using various hurricane parameters (methodology by Knaff et al. 2016)
- Selection based on matching synthetic cyclones to historical observations

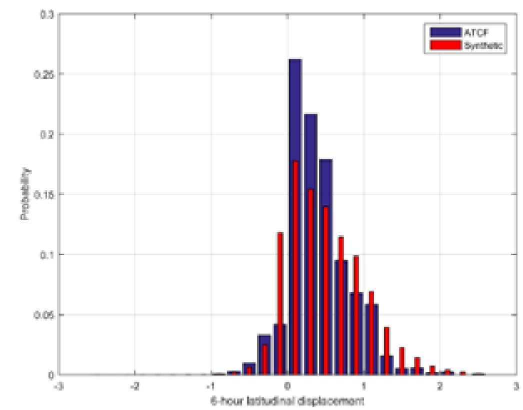










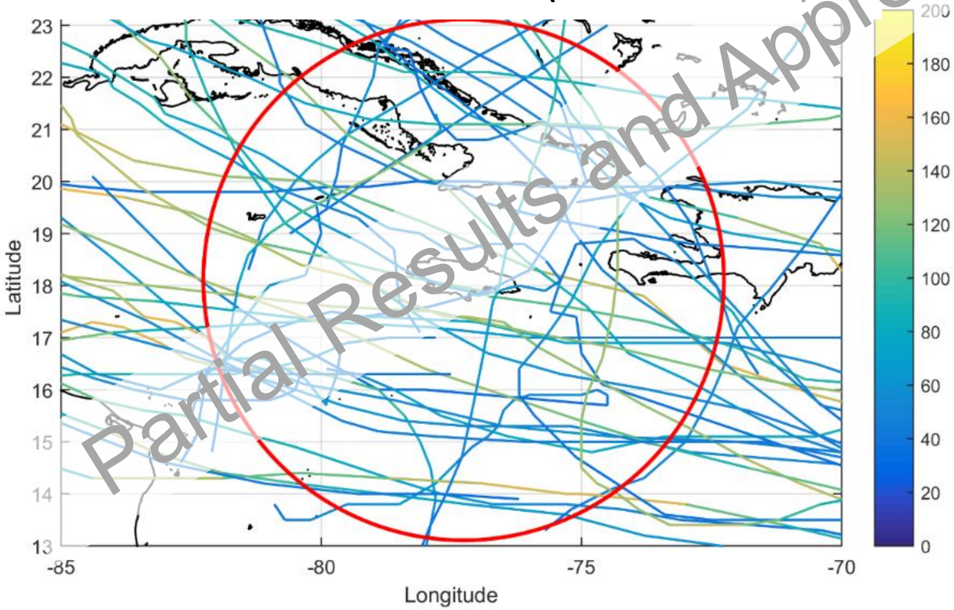


Offshore Dynamics: Combining Historical with Synthetic TCs

- Historical vs. synthetic TCs comparison in a 500 km radius circle around Jamaica
- Historical cyclones from Automated Cyclone Track Forecasting System database
- Synthetic global TC database (5000 years)

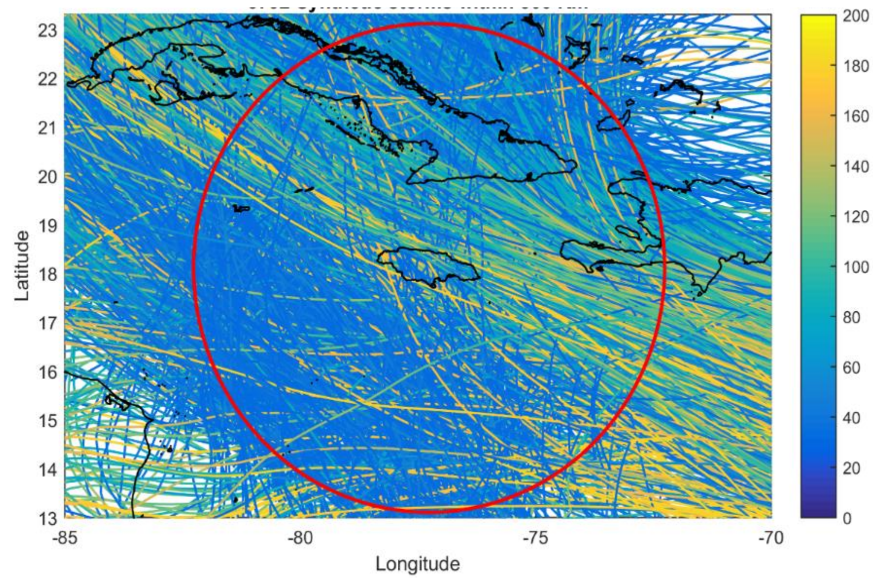
HISTORICAL

46 TCs Within 500 Km (1970 – 2016)



SYNTHETIC

3792 Synthetic Storms Within 500 Km



Offshore Dynamics: Combining Historical with Synthetic TCs

- 462 (9 historical+ 453 synthetic) TCs > Cat 1within 100 Km of coastline selected

9 Historical TCs

Hurricane	Date	Wmax (knots)
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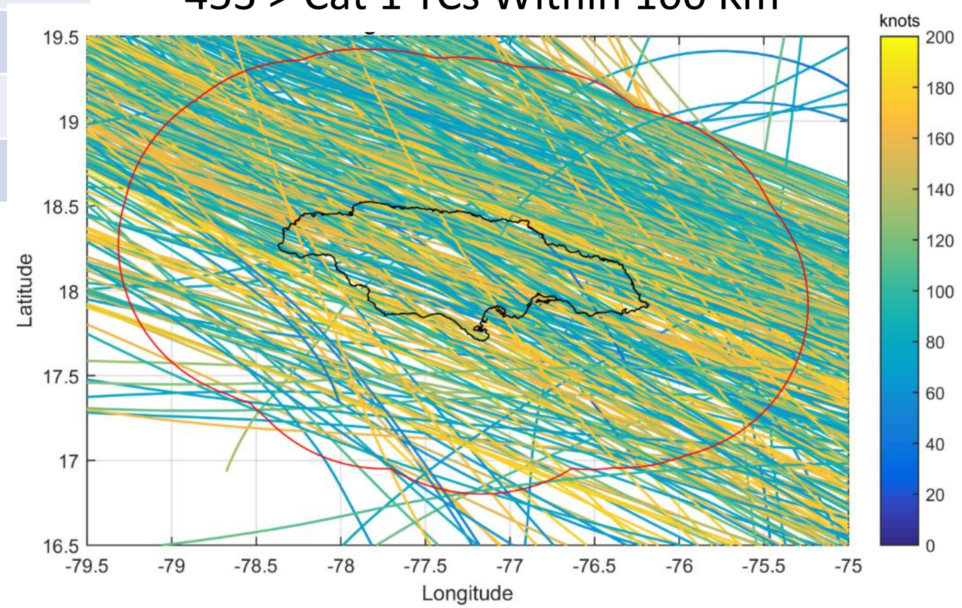
+

453 > Cat 1 TCs Within 100 Km



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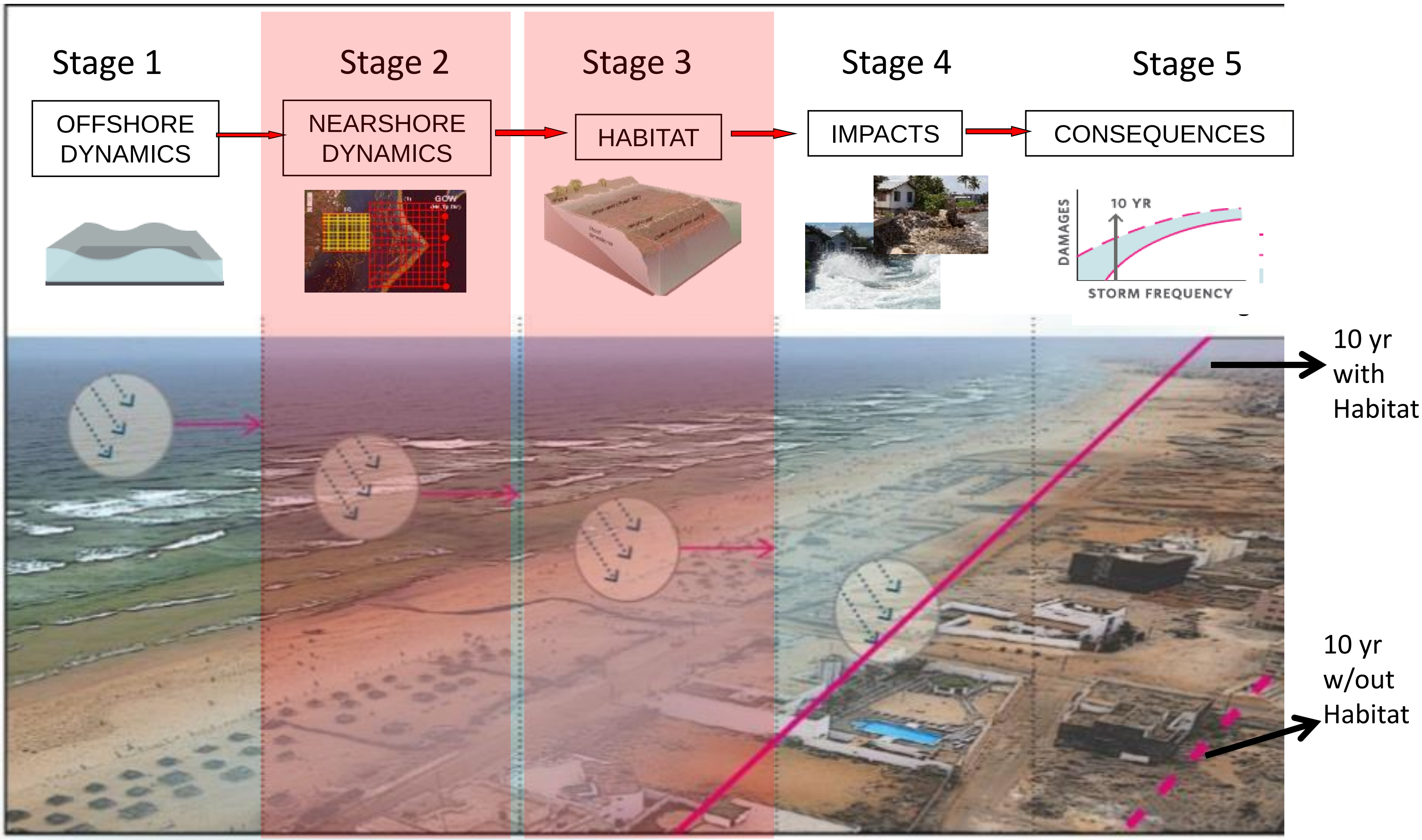

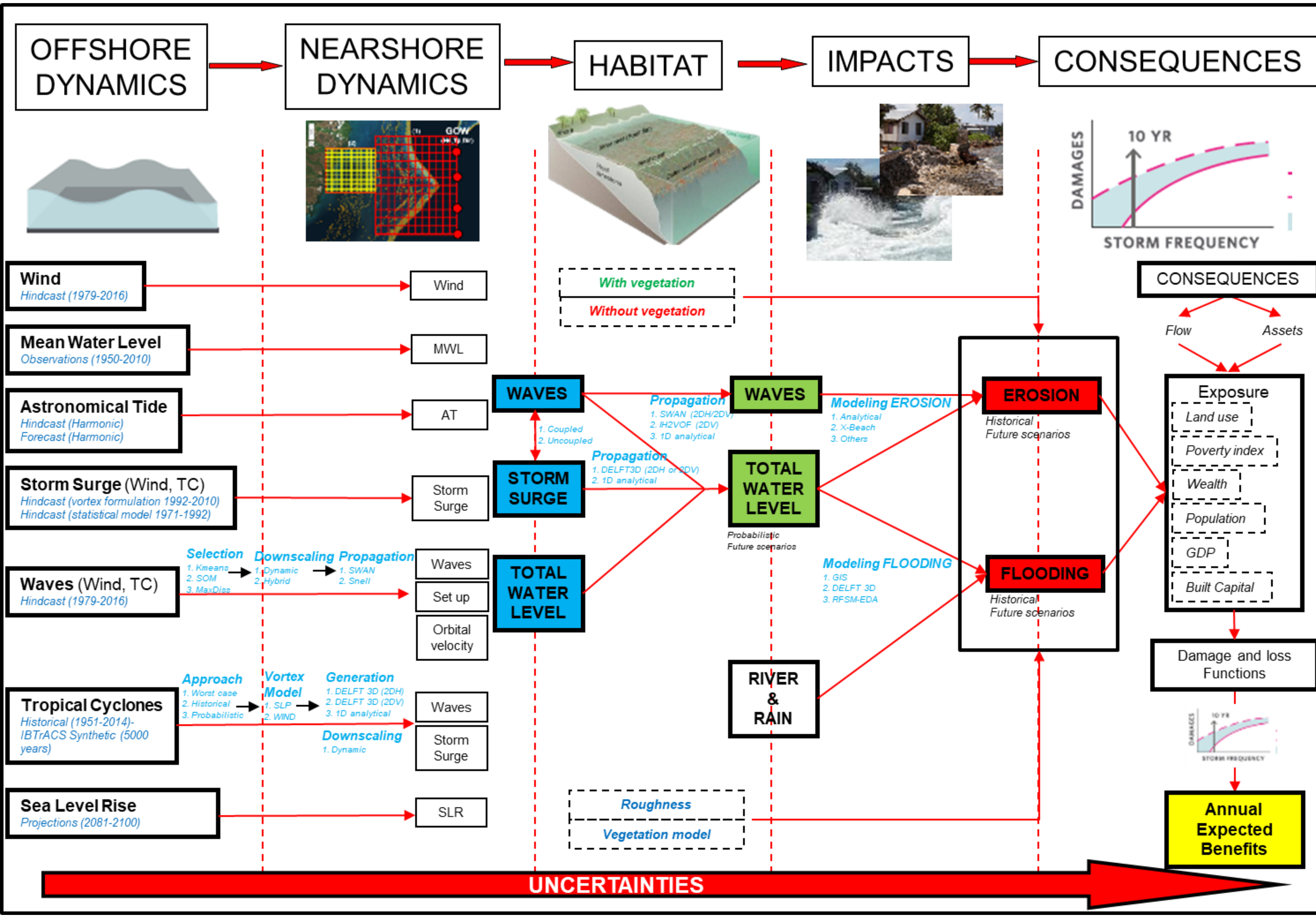

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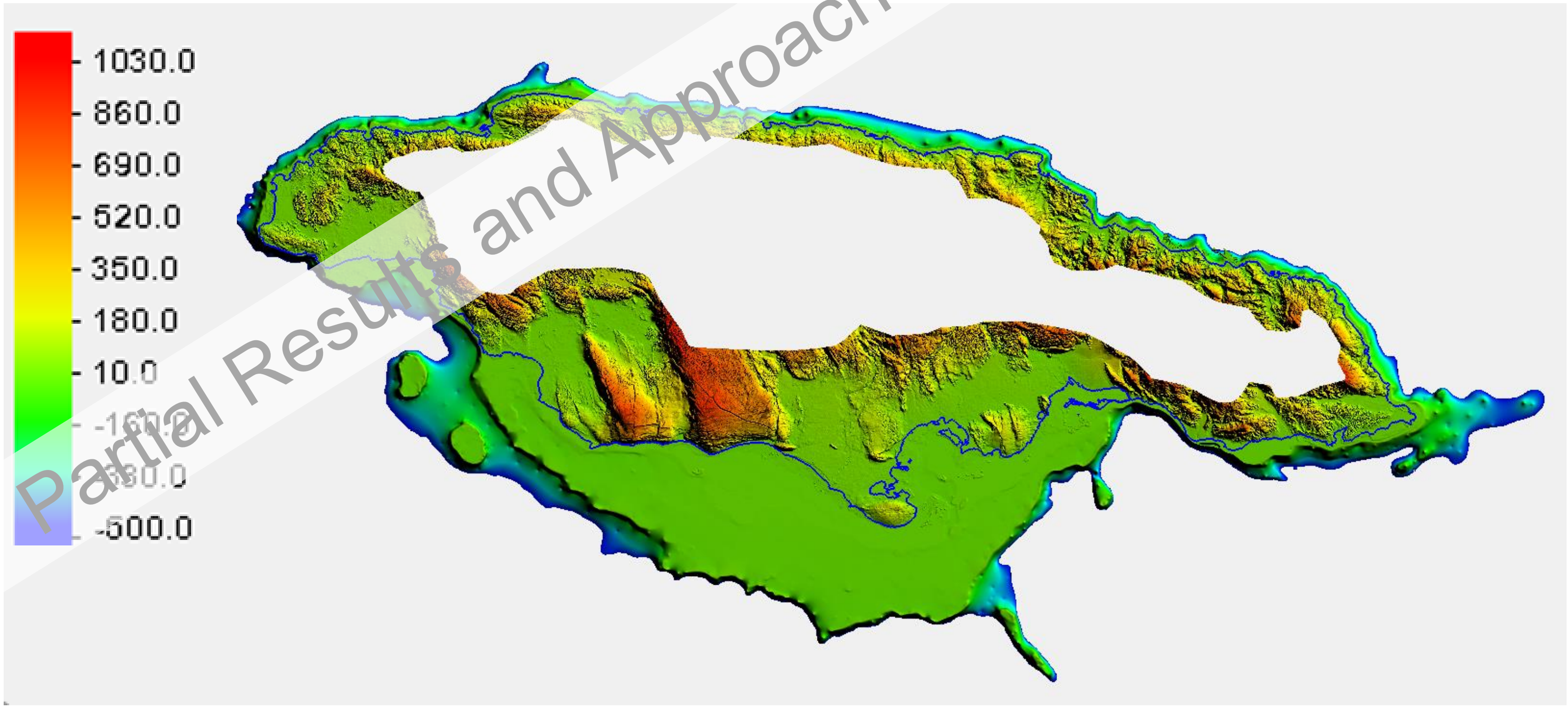
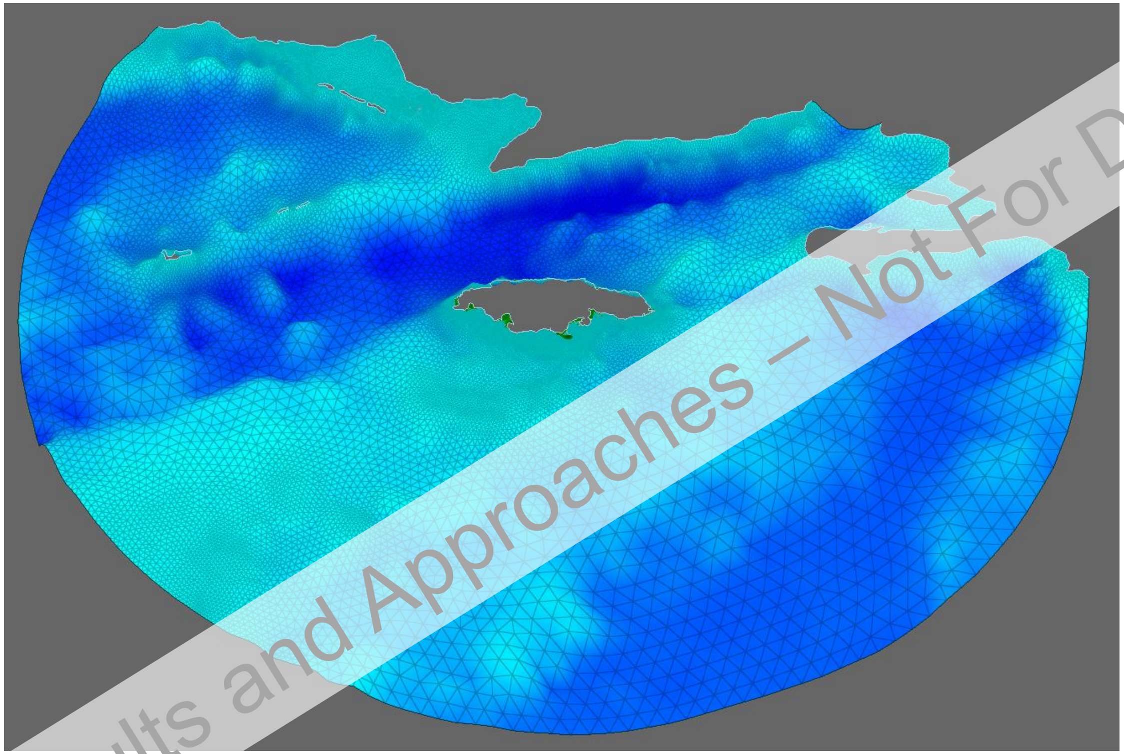
Nearshore Dynamics: Bathymetry and Topography

- Combining Multiple Data Sources for a nested bathy – topo map
  - Bathymetry - ~ 1000 x 1000 m ETOPO (up to 500 m)
  - Bathymetry - 90 x 90 m NAVIONICS nautical chart (25 to 500 m depth)
  - Bathymetry - 10 x 10 m, LANDSAT derived (0 to 25 m depth)
  - Topography - 6 x 6 m, LIDAR



Nearshore Dynamics: ADCIRC Coastal Model



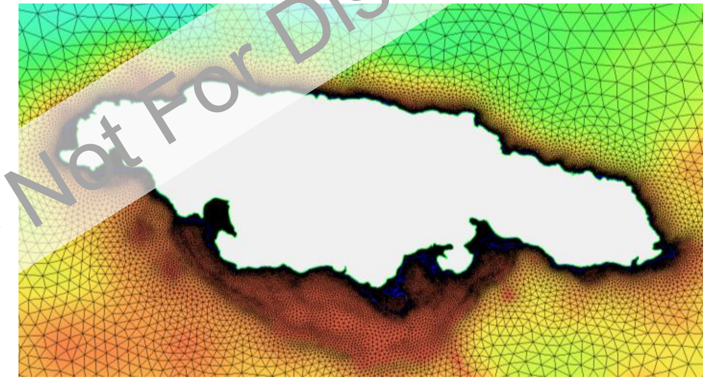
The ADCIRC Model

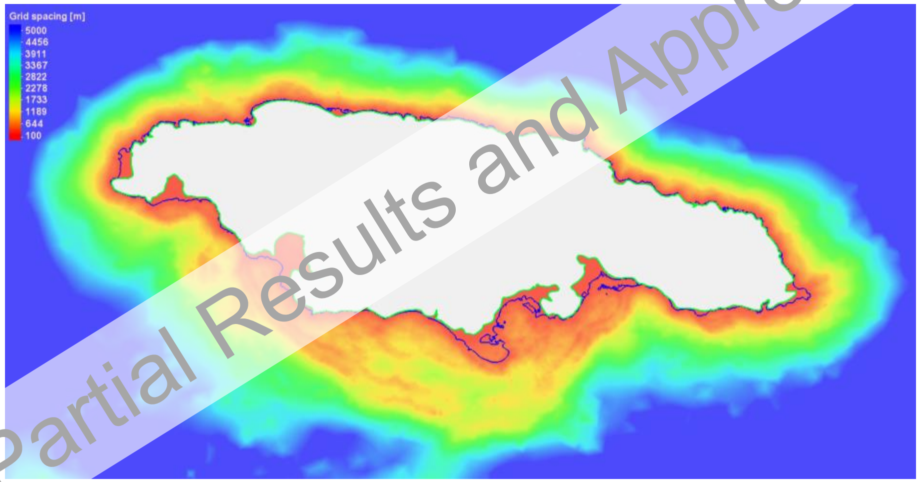
- Built to assess coastal currents and water surface elevations.
- Used by several U.S. agencies for forecasting, operational and risk assessment projects
- Industrial applications from U.S. nuclear power station flood risk assessment required by the NRC to tidal power station design

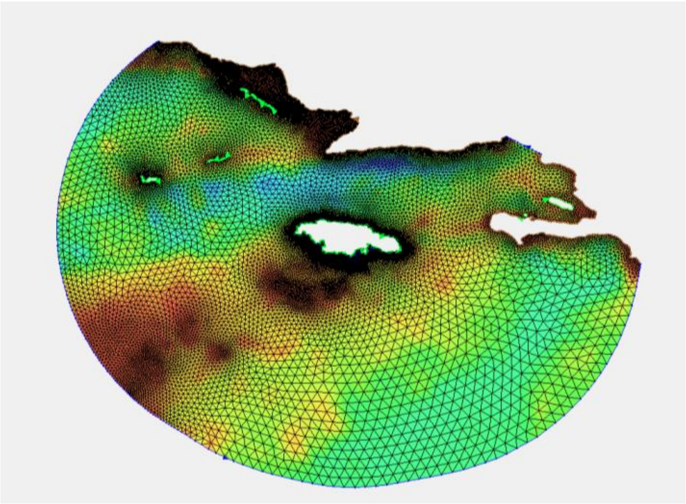
Nearshore Dynamics: ADCIRC + SWAN

- Open boundary at 500 Km from the coastline
- Inland boundary is the smoothed 10 m elevation contour
- Grid spacing from 100 m overland areas to 20 Km in deep water
- Coupled SWAN and ADCIRC models
- 71214 nodes, 136,145 grid elements
- 1 hour of 16 CPUs for 1 day of hurricane

ADCIRC + SWAN mesh

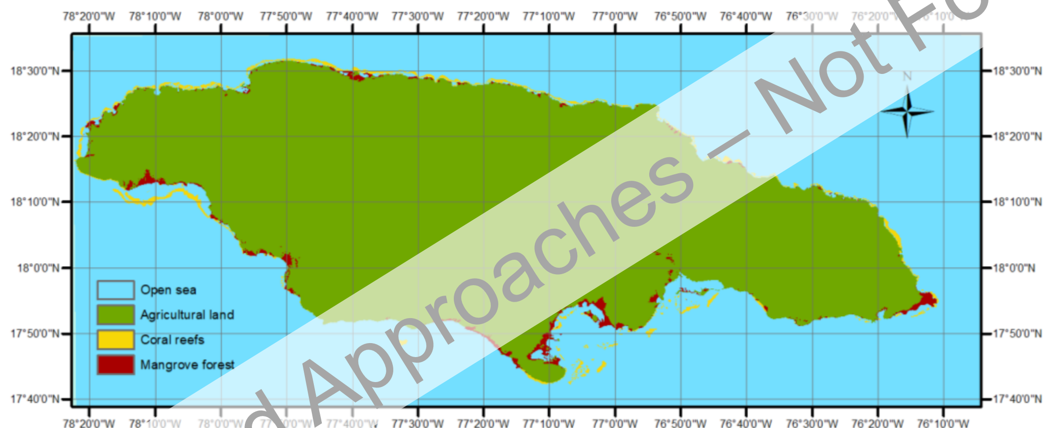






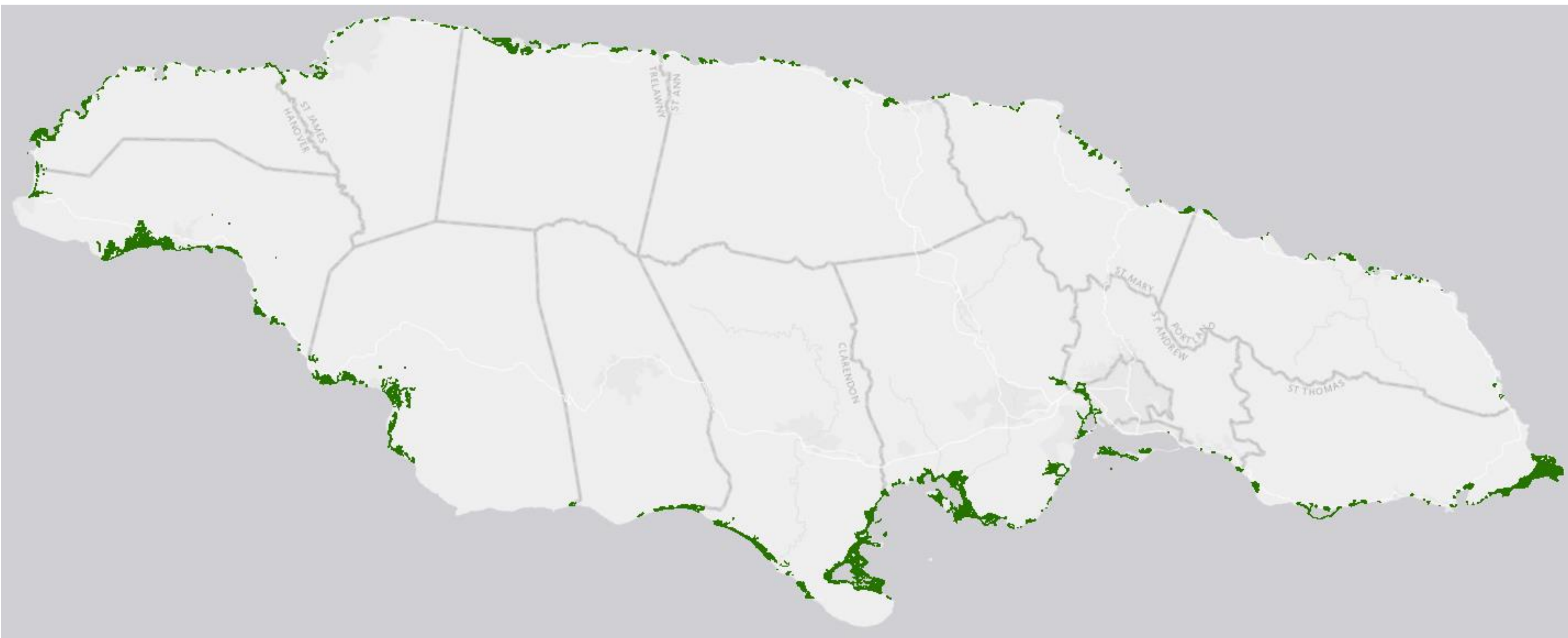
Nearshore Dynamics: Habitats as Bottom Friction

Coral reefs and mangroves included as bottom friction (Dietrich et al., 2012; Zhang et al., 2012)



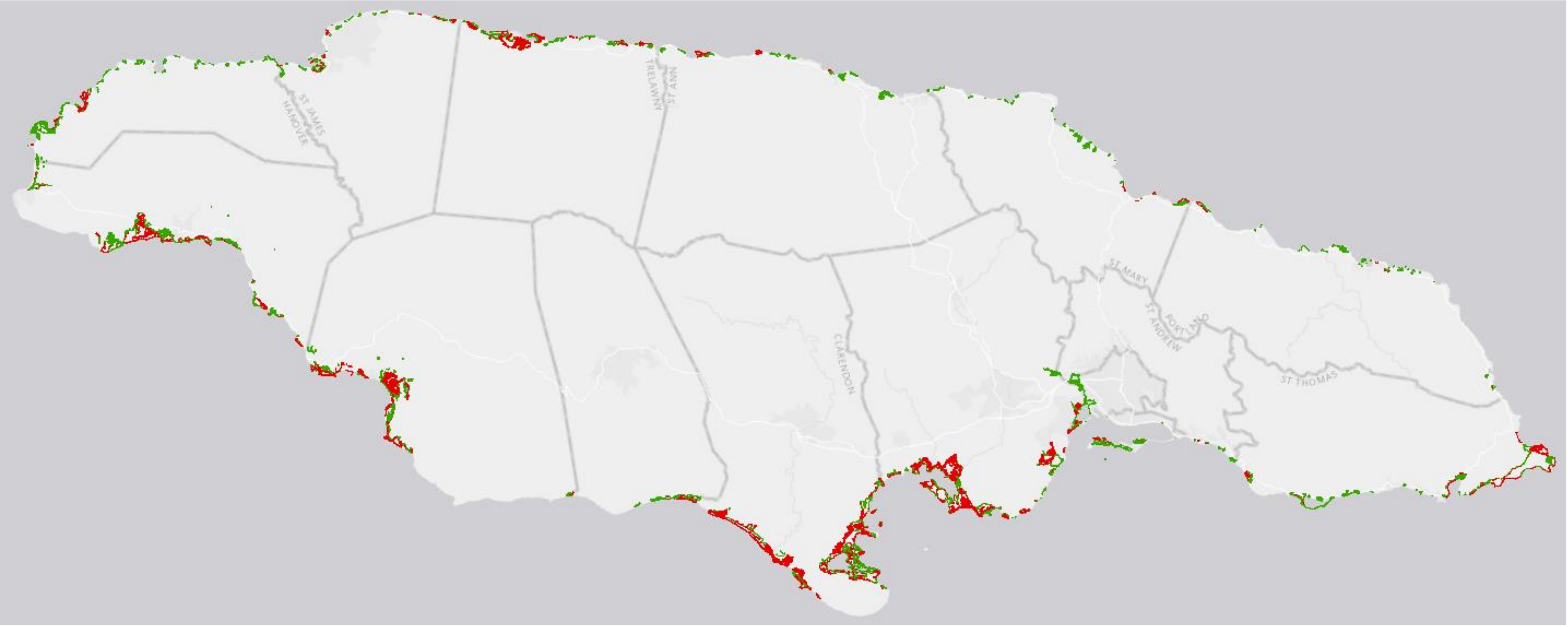
Nearshore Dynamics: Mangrove Extent Data

National Mangrove Distribution - 2013



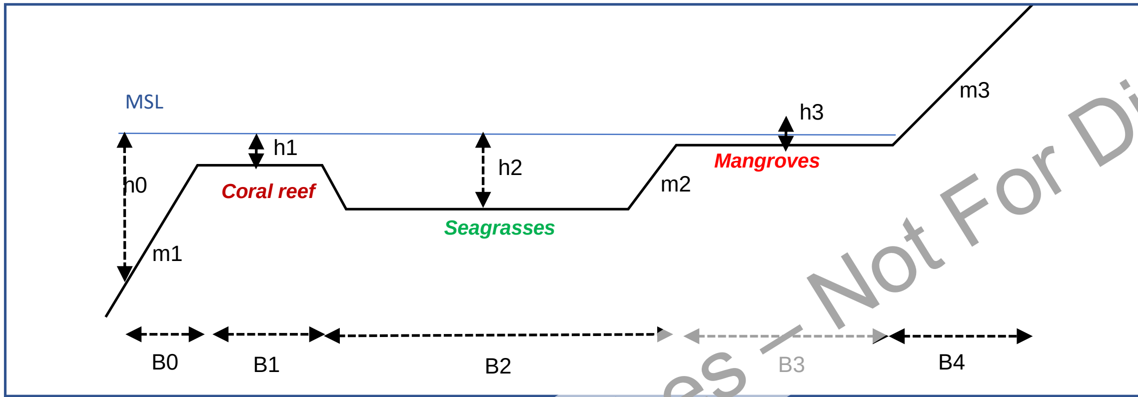
Investigation of Mangrove Change 2005 - 2013

(For Future Work – Assessment of “Restoration” Benefits)

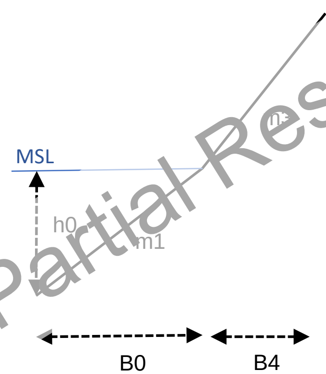


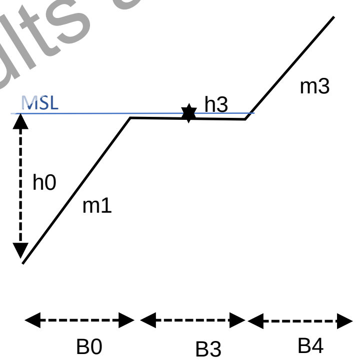
Nearshore Dynamics: Cross-shore Profiles

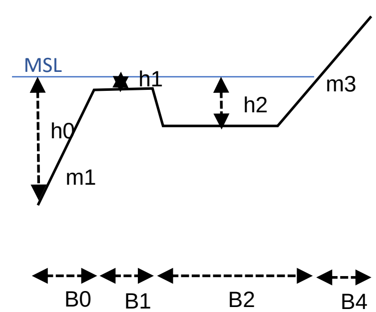
GENERAL PROFILE

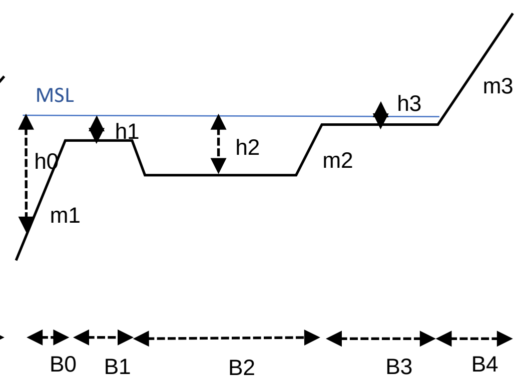


PROFILE 1	PROFILE 2	PROFILE 3	PROFILE 4
Without coral	*Without coral*	*With coral*	*With coral*
Without mangrove	*With mangrove*	*Without mangrove*	*With mangrove*

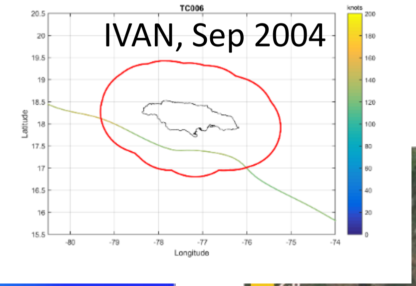




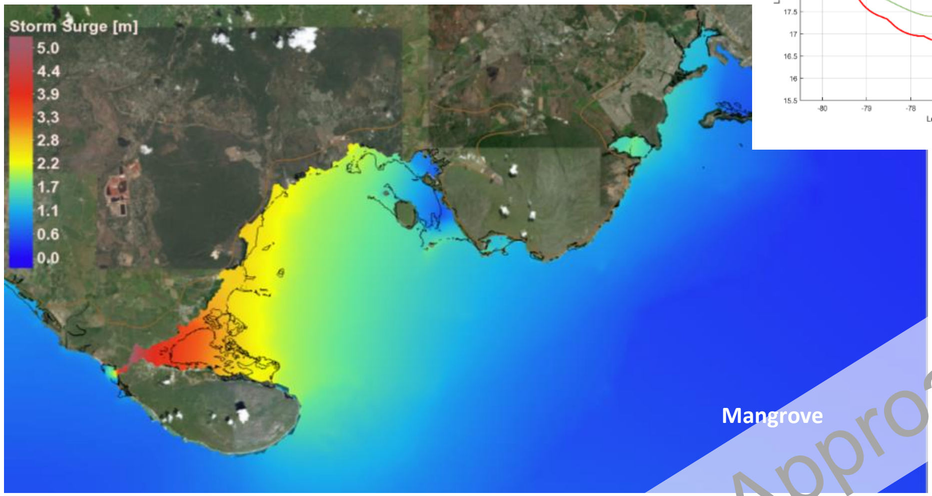




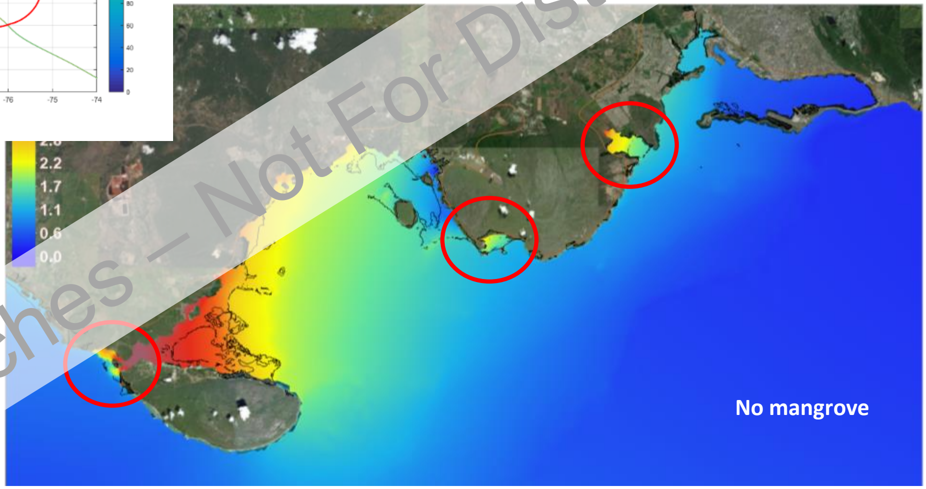
Preliminary Results: Nearshore Dynamics



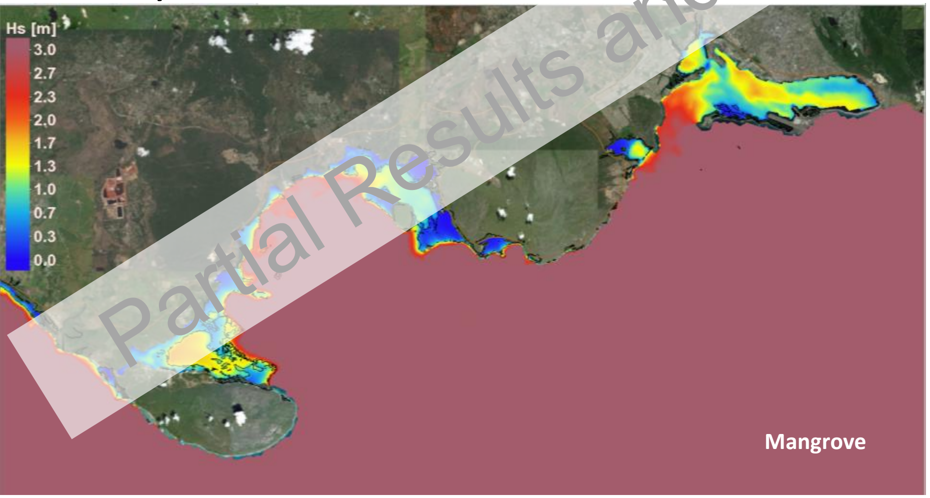
Storm Surge – With Mangrove



Storm Surge – No Mangrove



Cyclone Waves – With Mangrove



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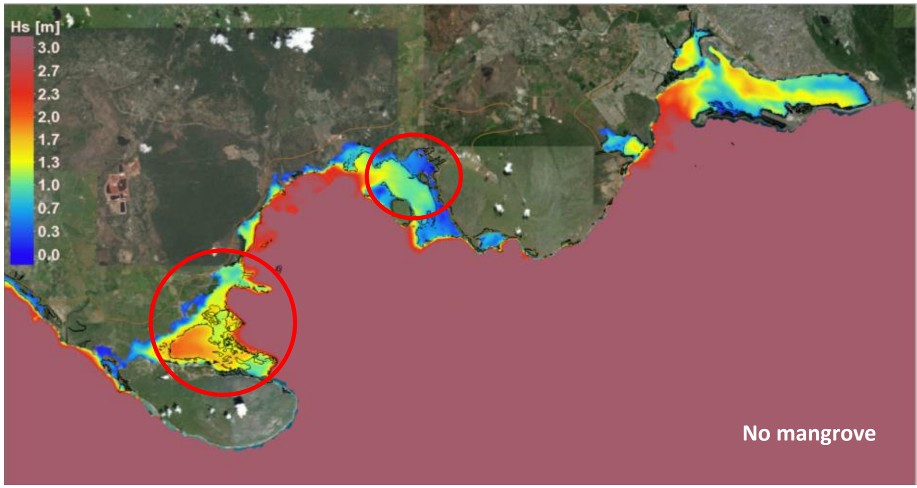

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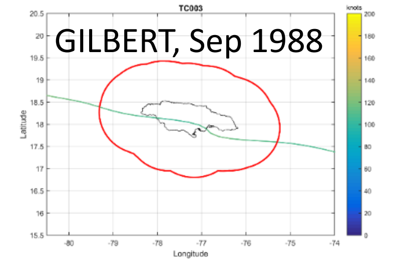

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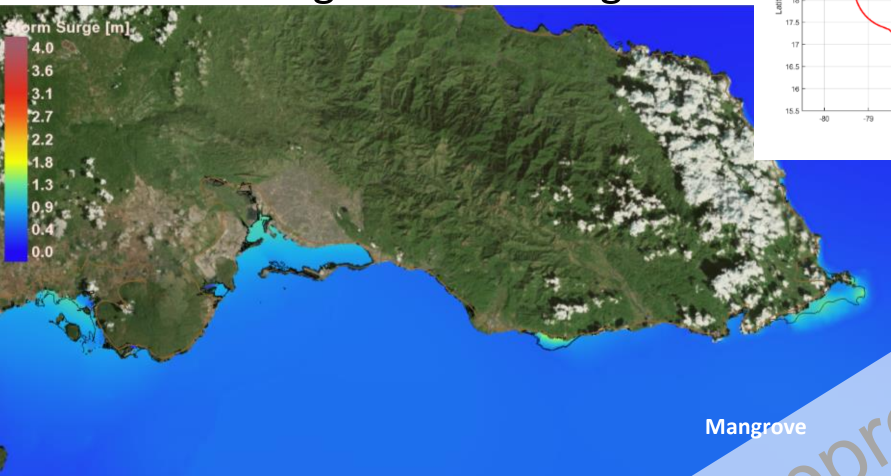

Storm Surge – No Mangrove

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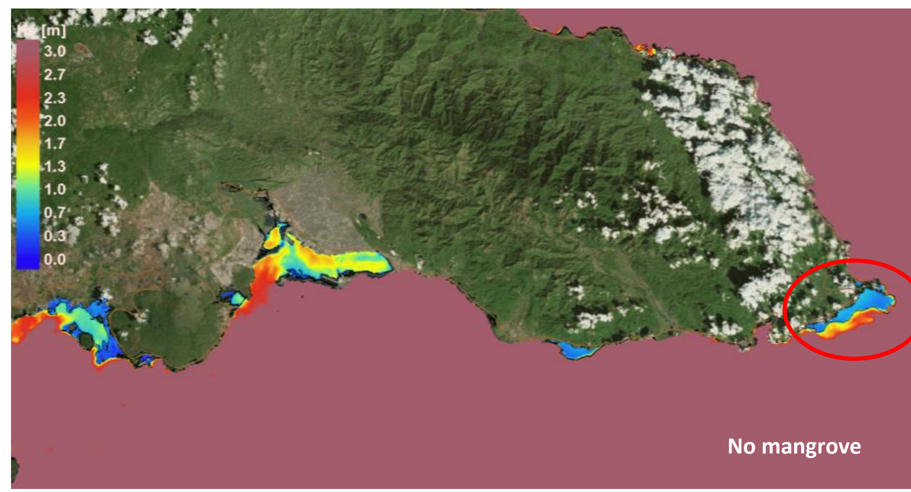

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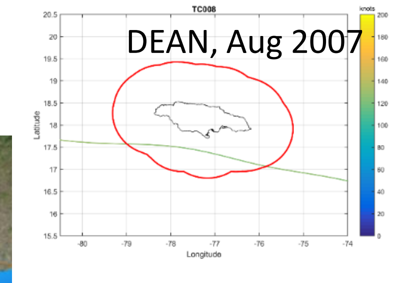

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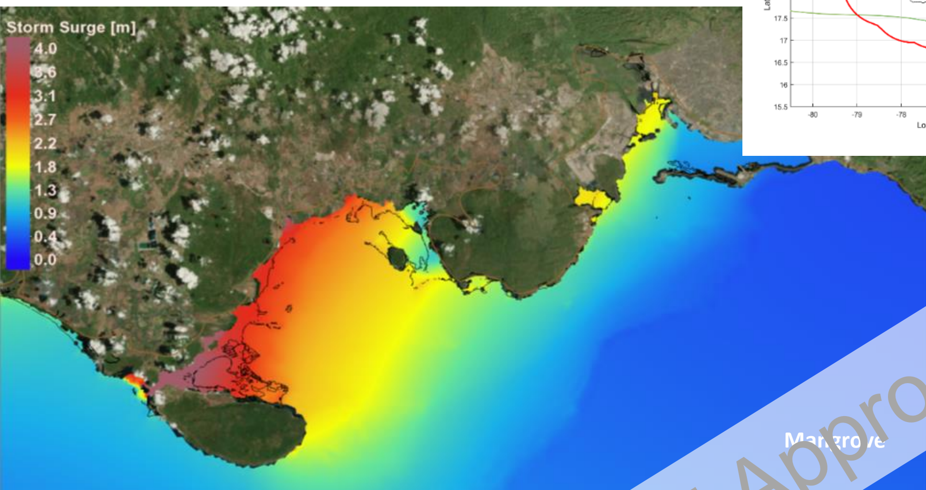
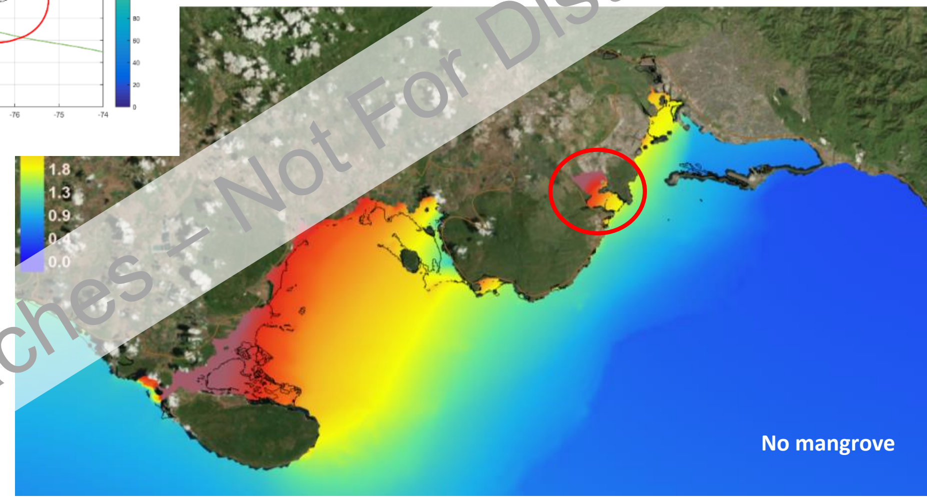
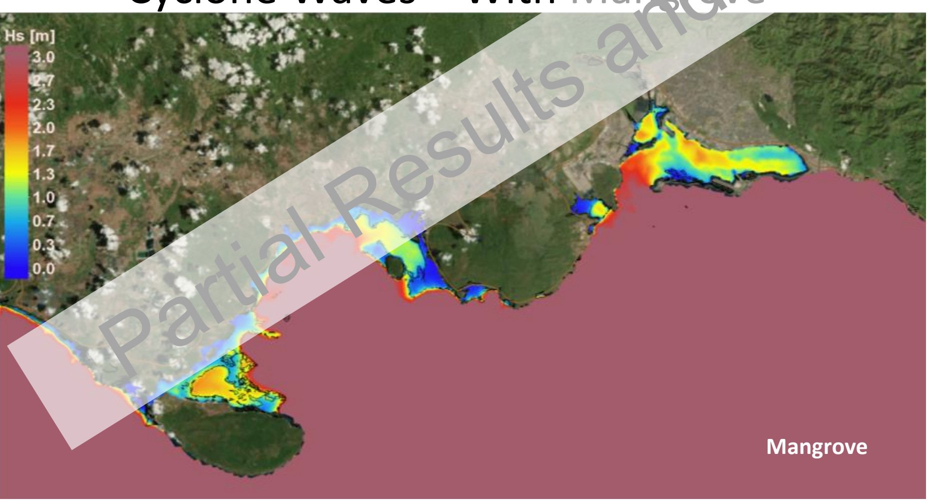


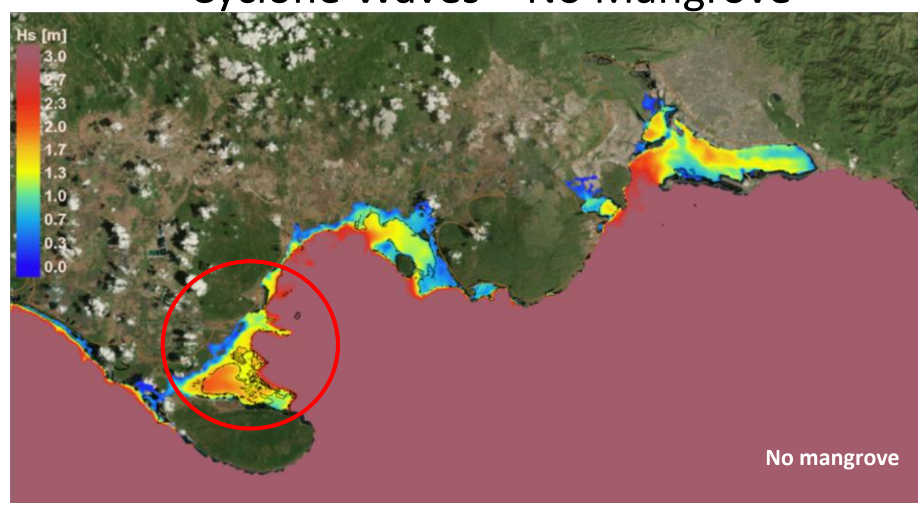
Storm Surge – No Mangrove



Cyclone Waves – With Mangrove



Cyclone Waves – No Mangrove



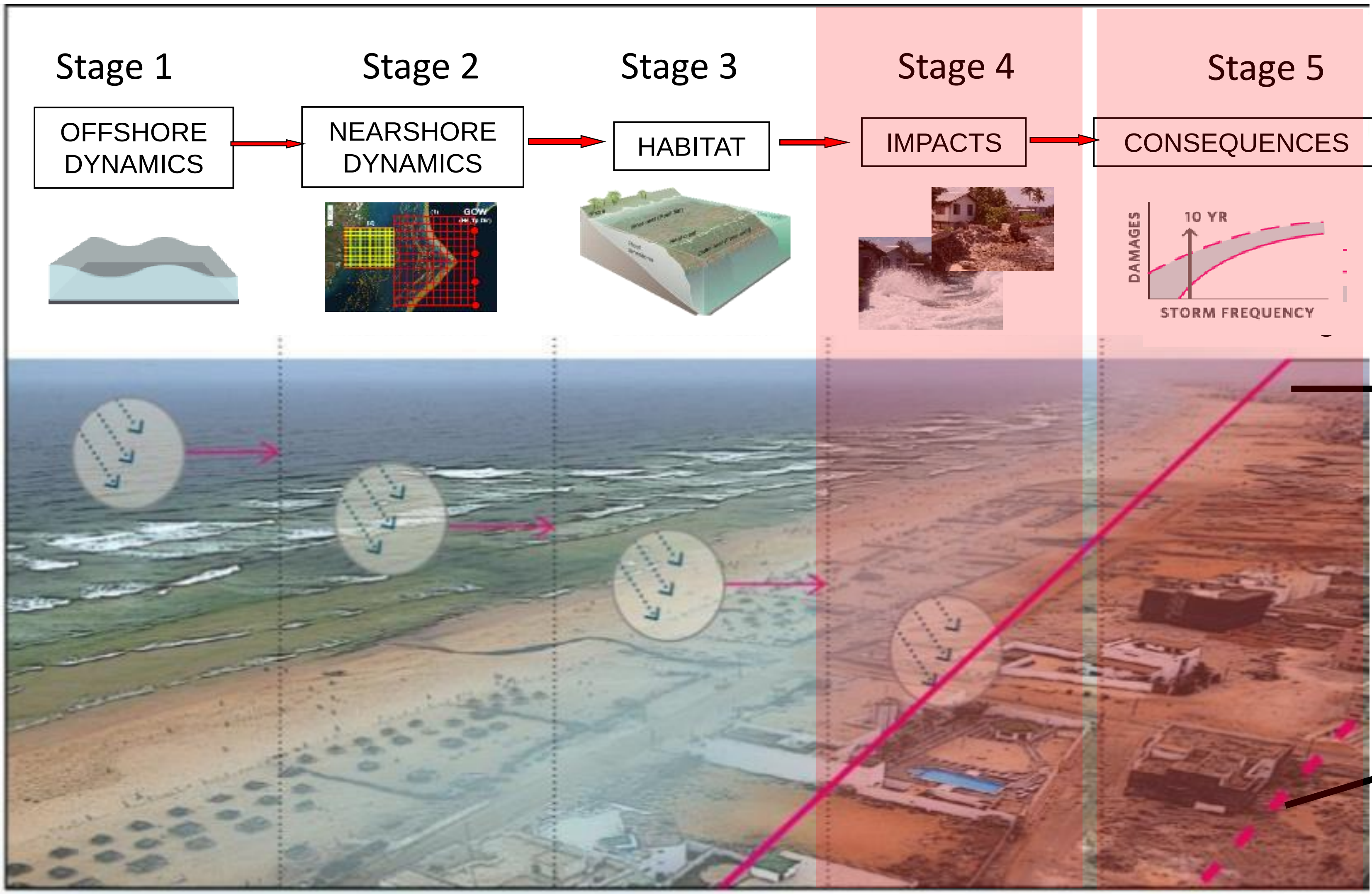
Outline

- The role of mangroves in coastal protection
- Overall framework and approach
- Offshore dynamics
- Nearshore dynamics and coastal flooding
- Quantifying the role of mangroves in coastal protection using flooding maps
- Assessing exposure and vulnerability
- Quantifying annual expected damages/losses and benefits

Guidelines for Valuing Coastal Protection Services from Mangroves and Reefs

M W. Beck & G-M Lange (eds)

Recommended Approach: Expected Damage Function



10 yr with Habitat

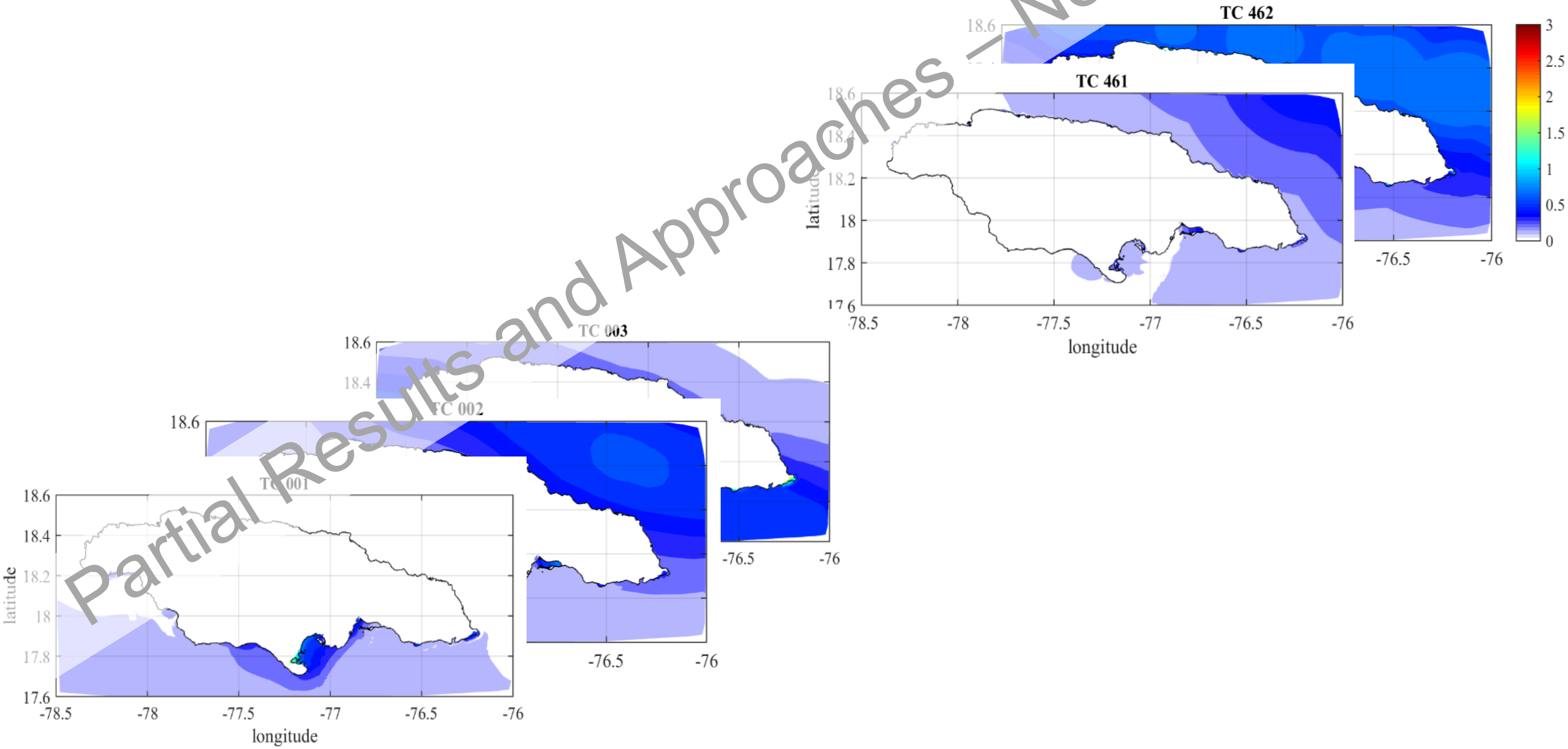
10 yr w/out Habitat

Flood Maps: Identifying Exposure of People and Stock

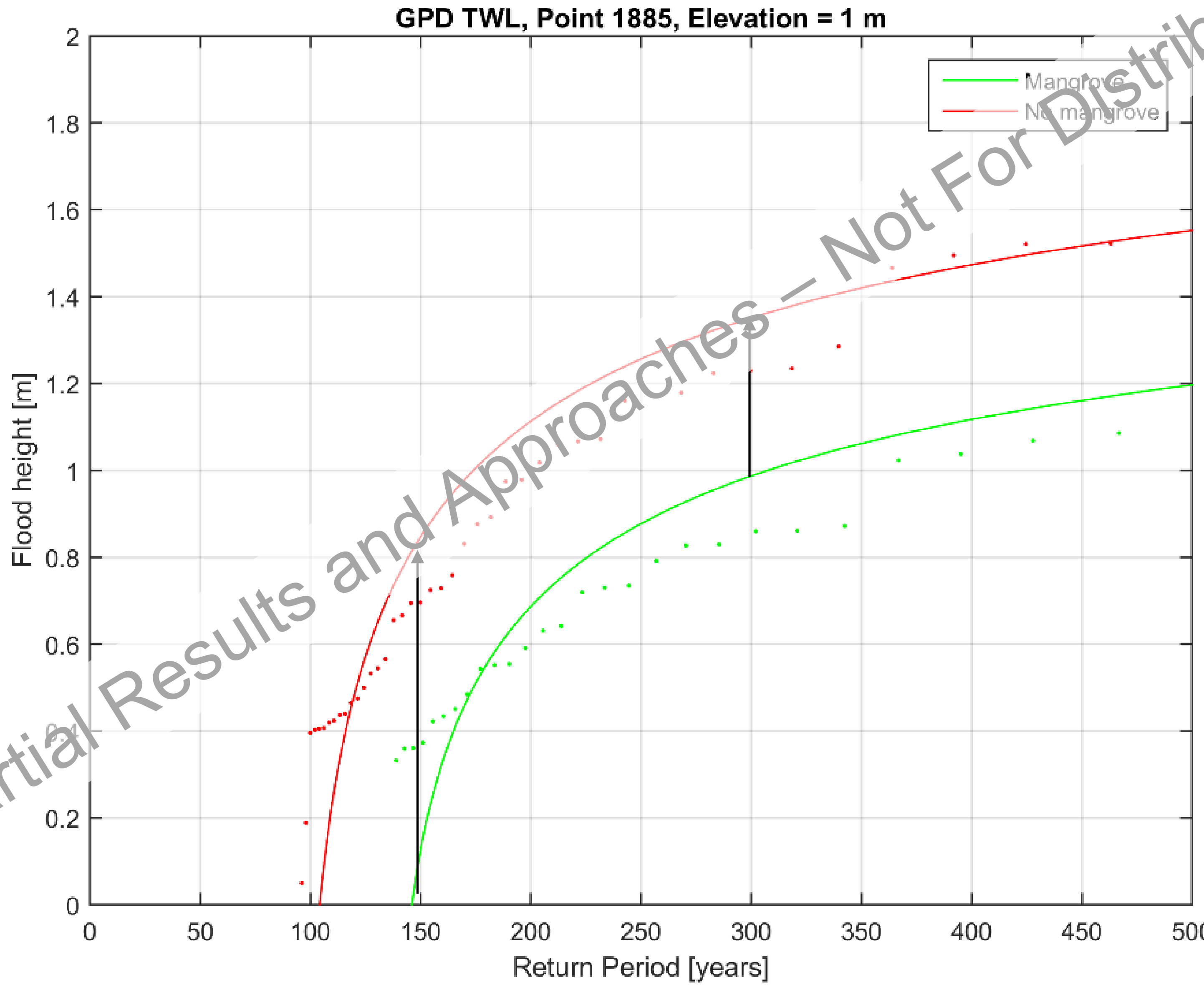
- **Defining Exposure**:
  - Using the Global Human Settlement layer (JRC) at 250 m resolution
  - 4755 points defined with population below 10m above mean sea level

Flood Maps: Mapping Flood Heights to Exposure

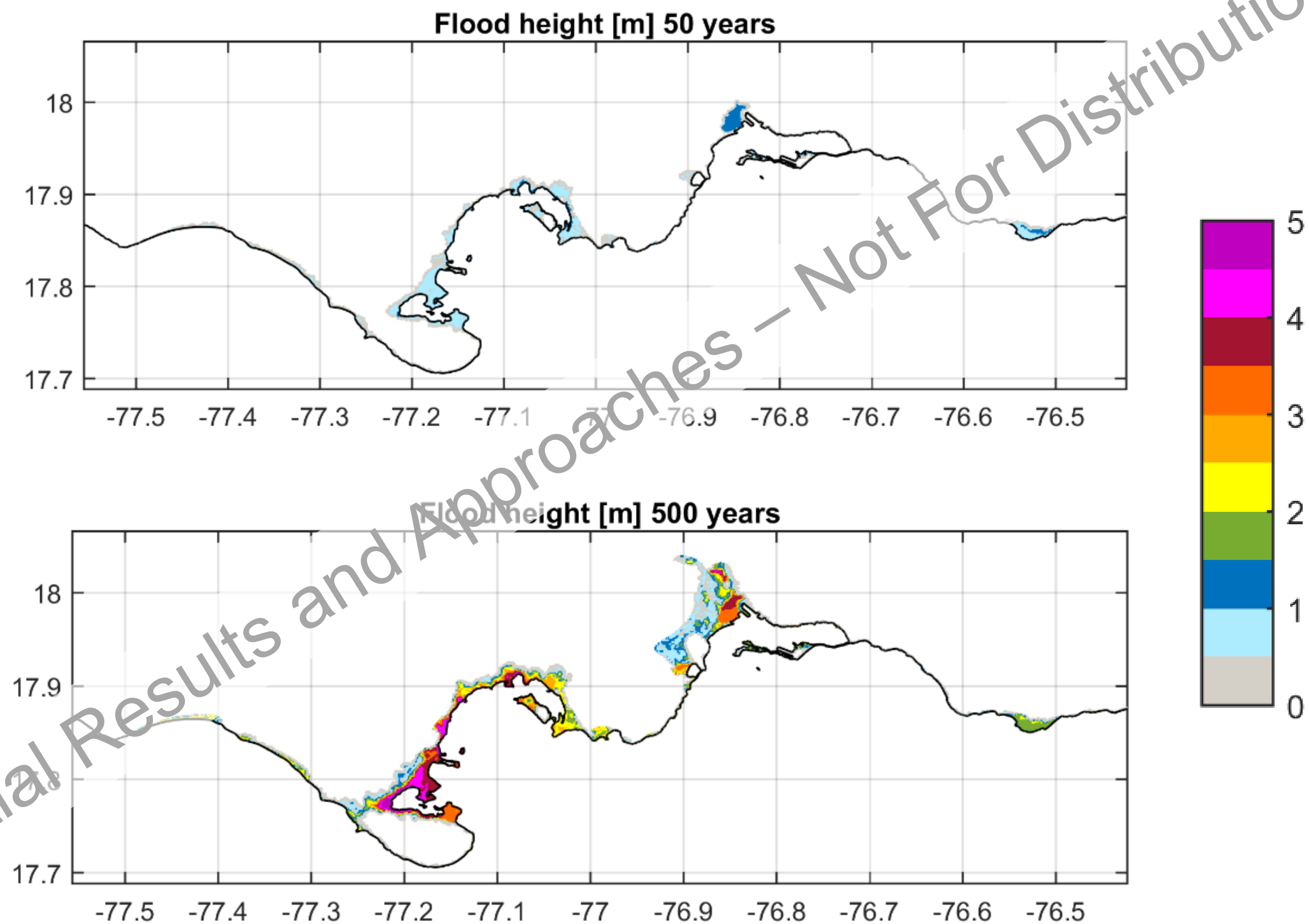
- Flood height distributions for all 4755 points for mangrove and no – mangrove scenarios
- 462 TCs for each scenario - total 924 simulated TC events
- ~ 16 weeks runtime of 16 CPUs



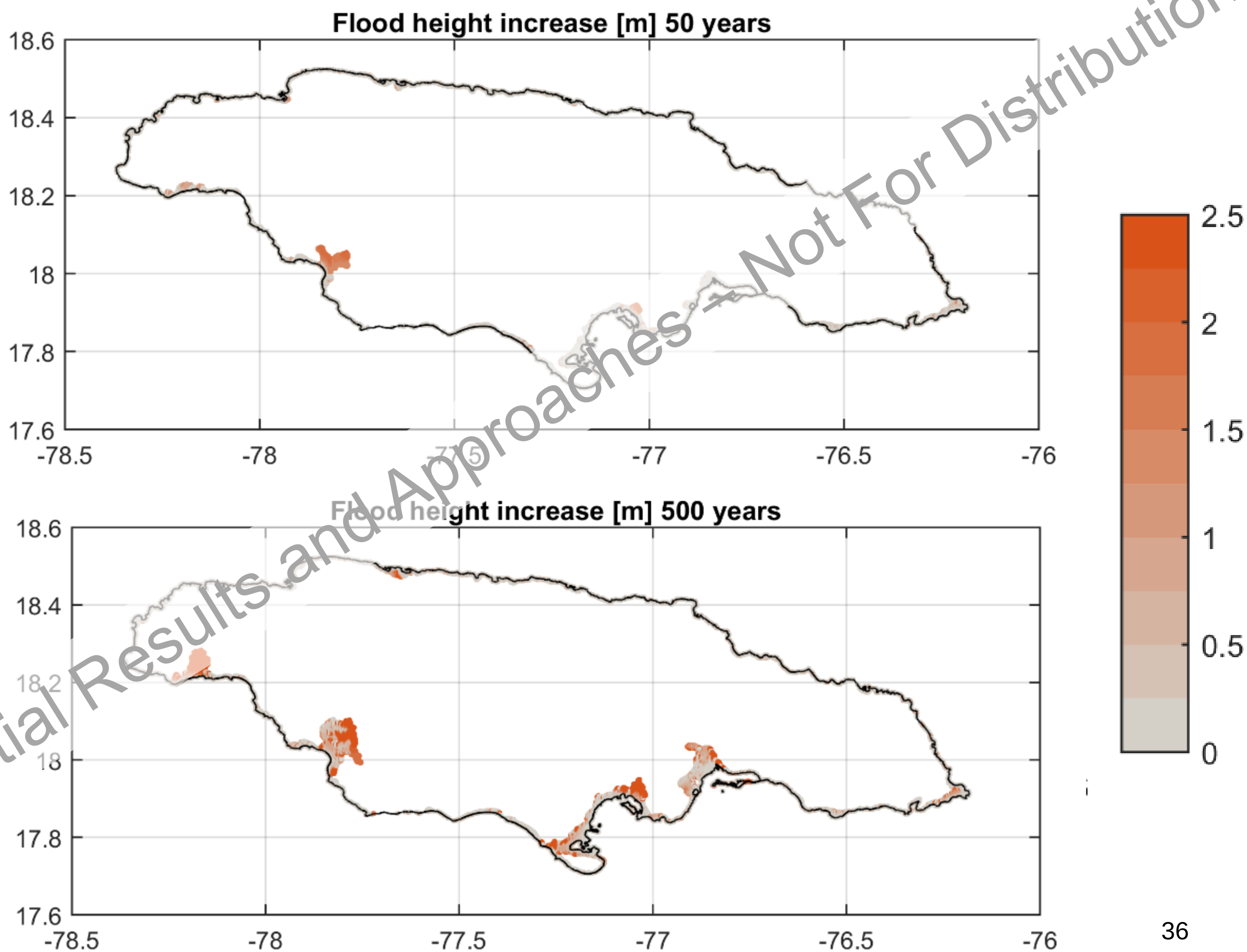
Flood Maps: Example of Flood Heights at Point



Flood Maps: Flood Heights for Different Return Periods



Flood Maps: Flood Height Increase for No Mangroves

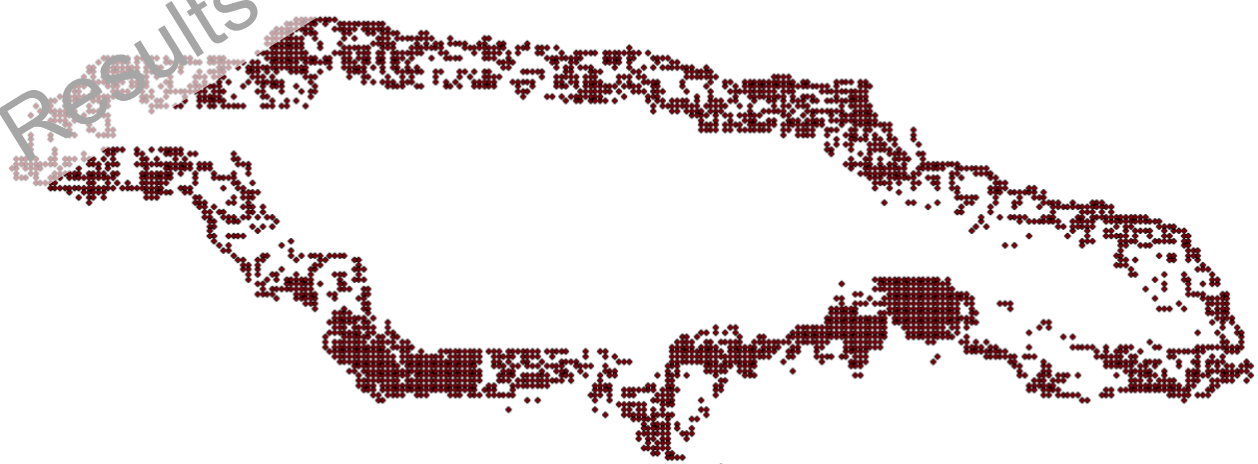


Assessing Impacts: Defining and Assessing Exposure

Data sources:

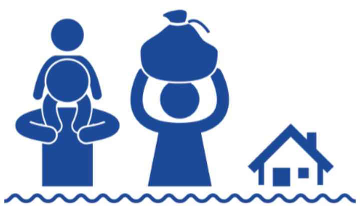
- Global Human Settlement Layer (European Commission, Joint Research Centre (JRC); Columbia University, Center for International Earth Science Information Network – CIESIN, 2015)
    - Number of person
    - 250 m resolution

- Global Assessment Report (United Nations Office for Disaster Risk Reduction (UNISDR), 2017)
    - Number of persons
    - Capital stock (residential, industrial, services)
    - 1 km resolution on coastal areas



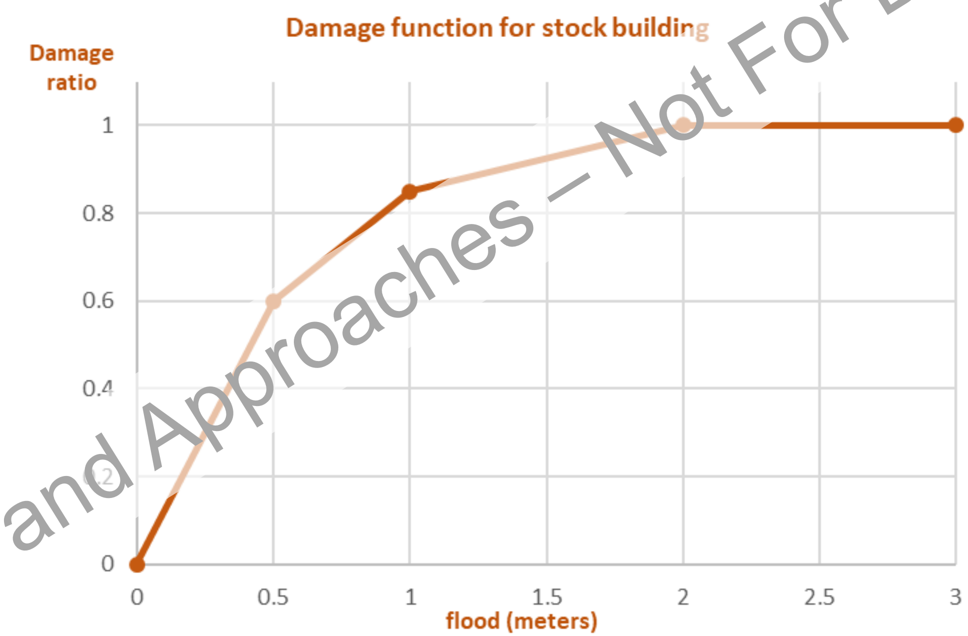
Assessing Impacts: Defining and Assessing Vulnerability

- Damage to structures based on Flood Heights
- Using EU Joint Research Commission Functions (Huizinga et al., 2017)

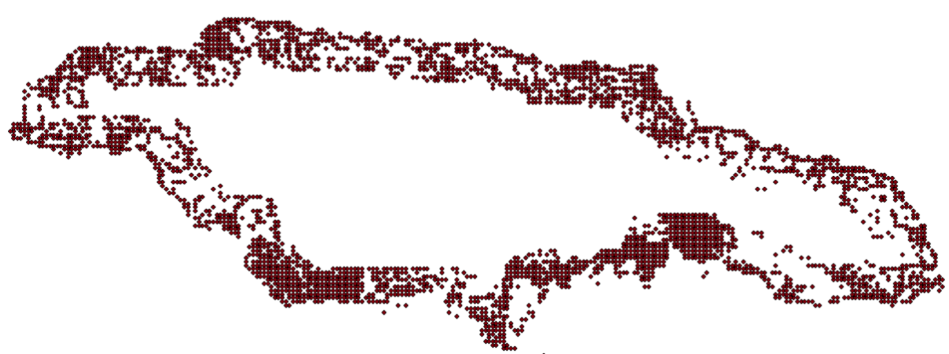


POPULATION

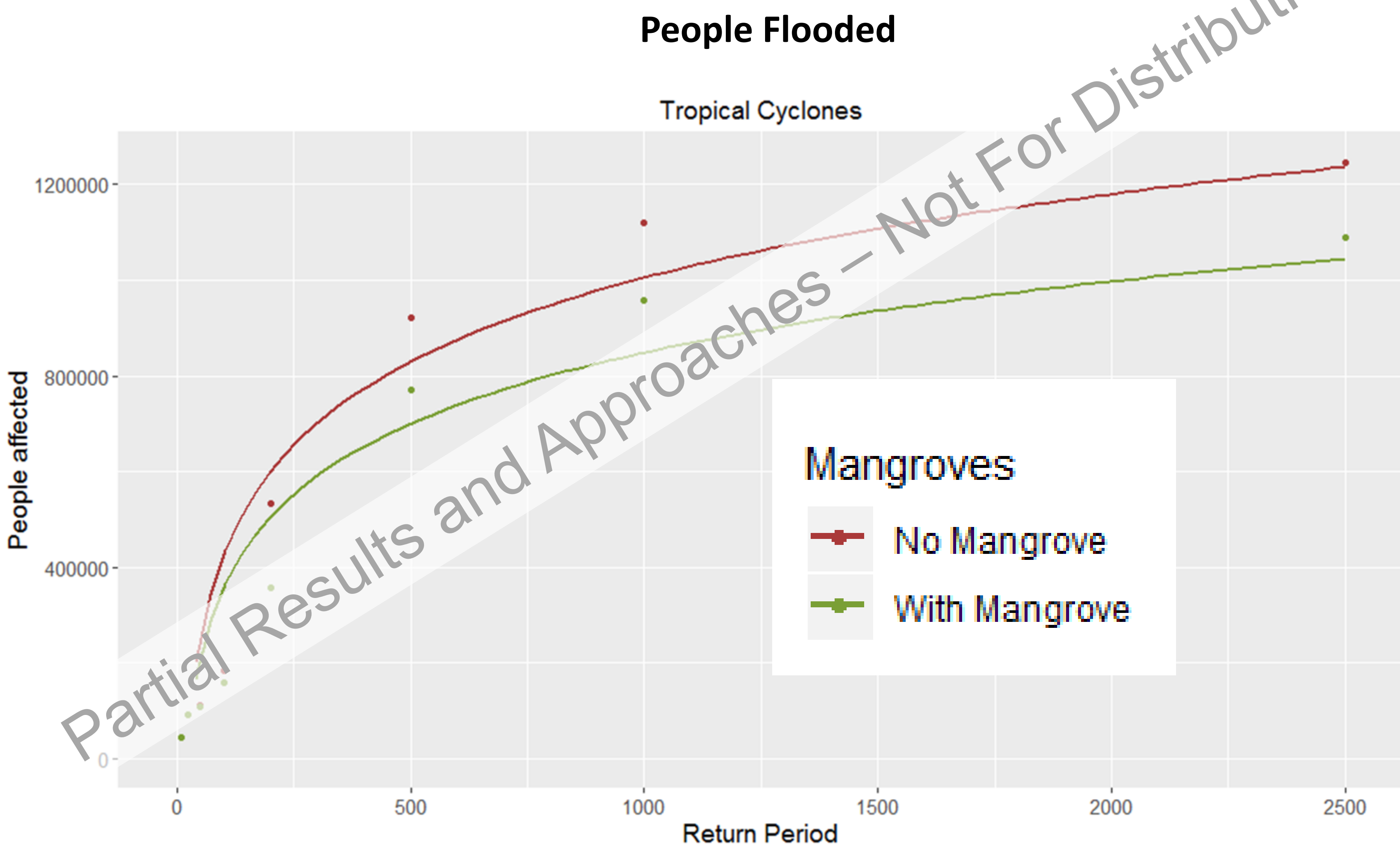
0.5m flood



STOCK

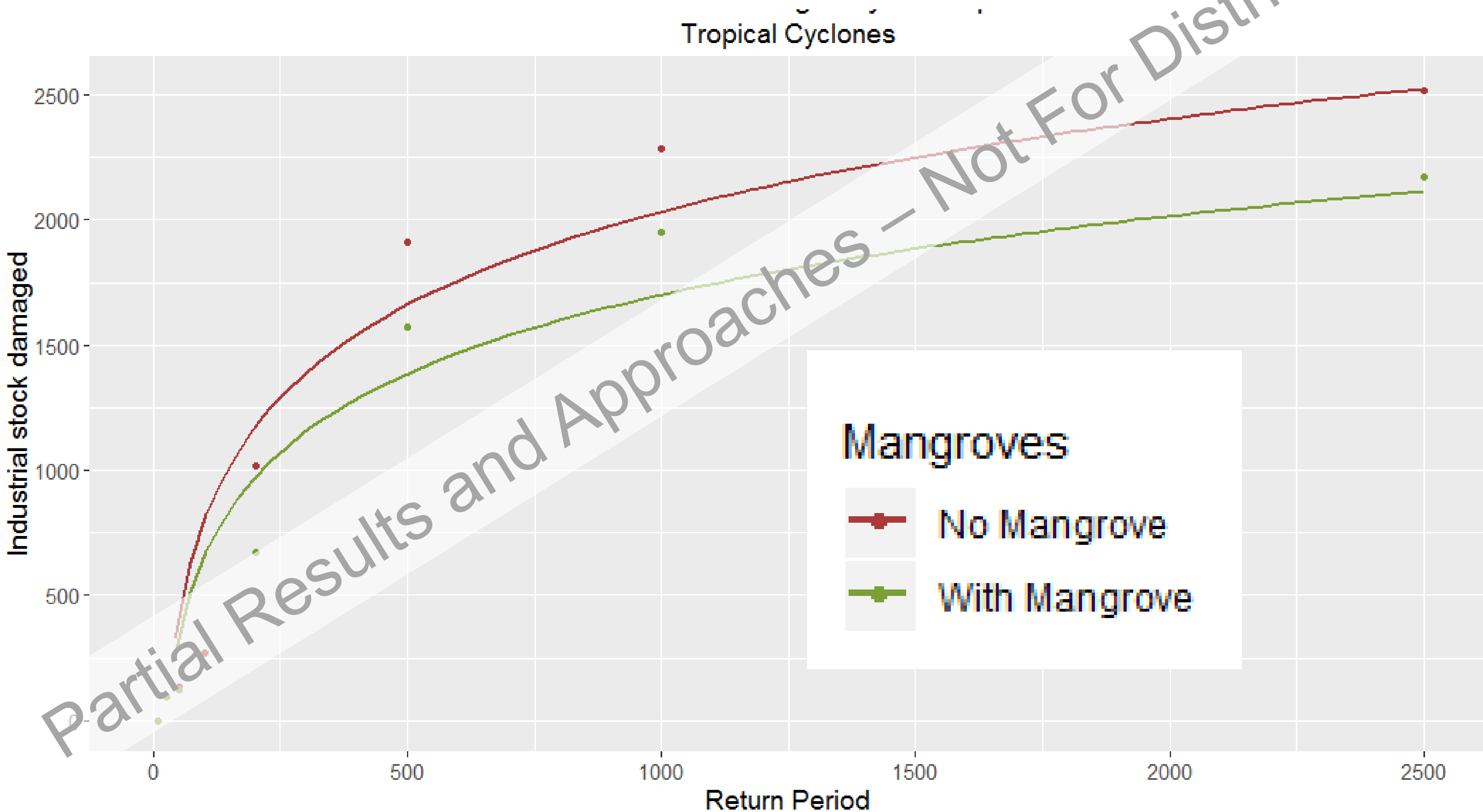


Preliminary Results: Flood Risk Consequences of Mangrove Loss

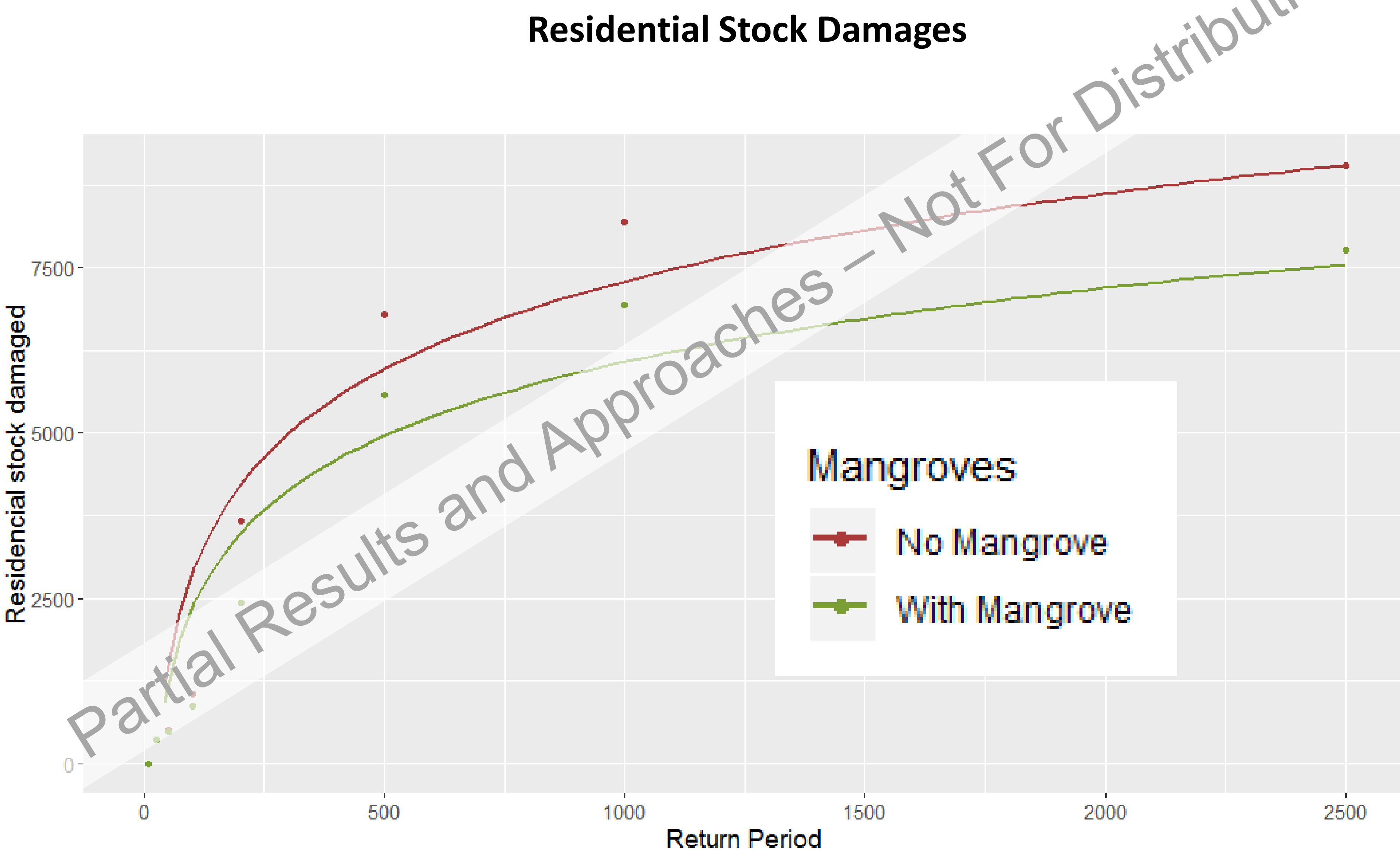


Preliminary Results: Flood Risk Consequences of Mangrove Loss

Industrial Stock Damages



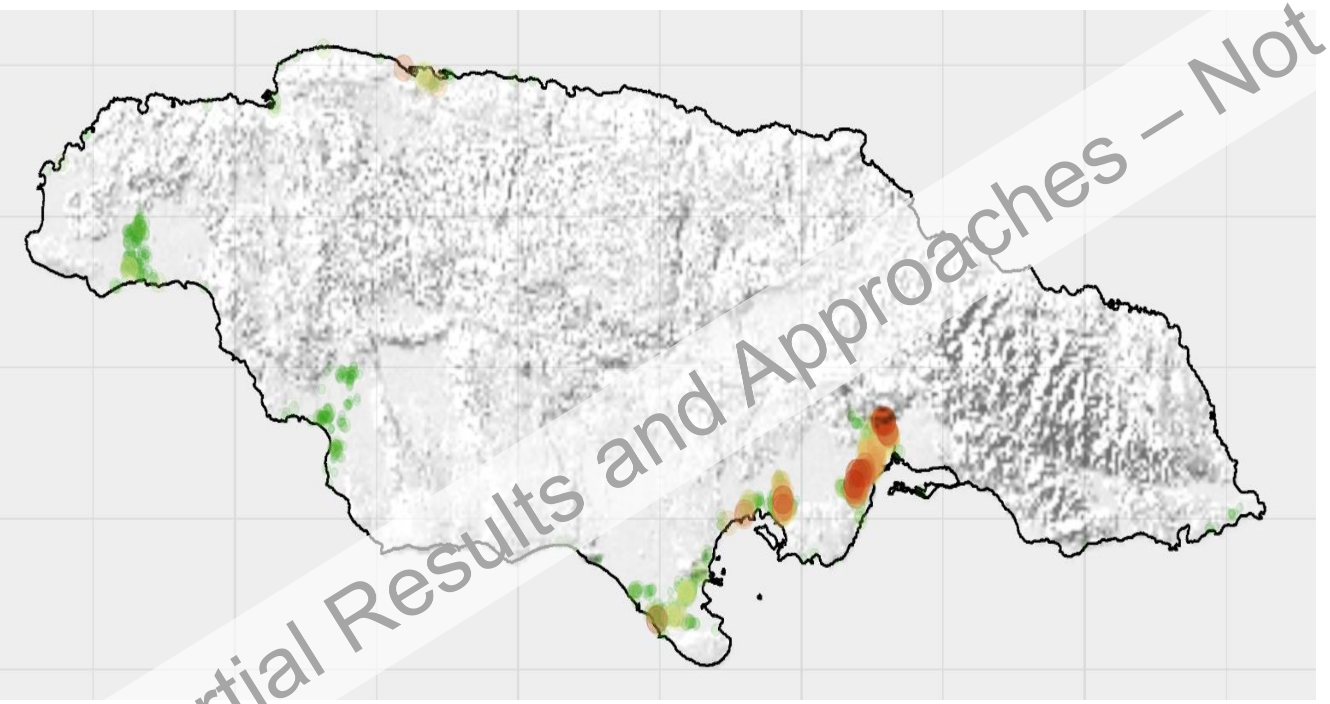
Preliminary Results: Flood Risk Consequences of Mangrove Loss



Annual Expected Benefit (Industrial, Residential, Services) = $US 32.5M

Preliminary Results: Flood Risk Consequences of Mangrove Loss

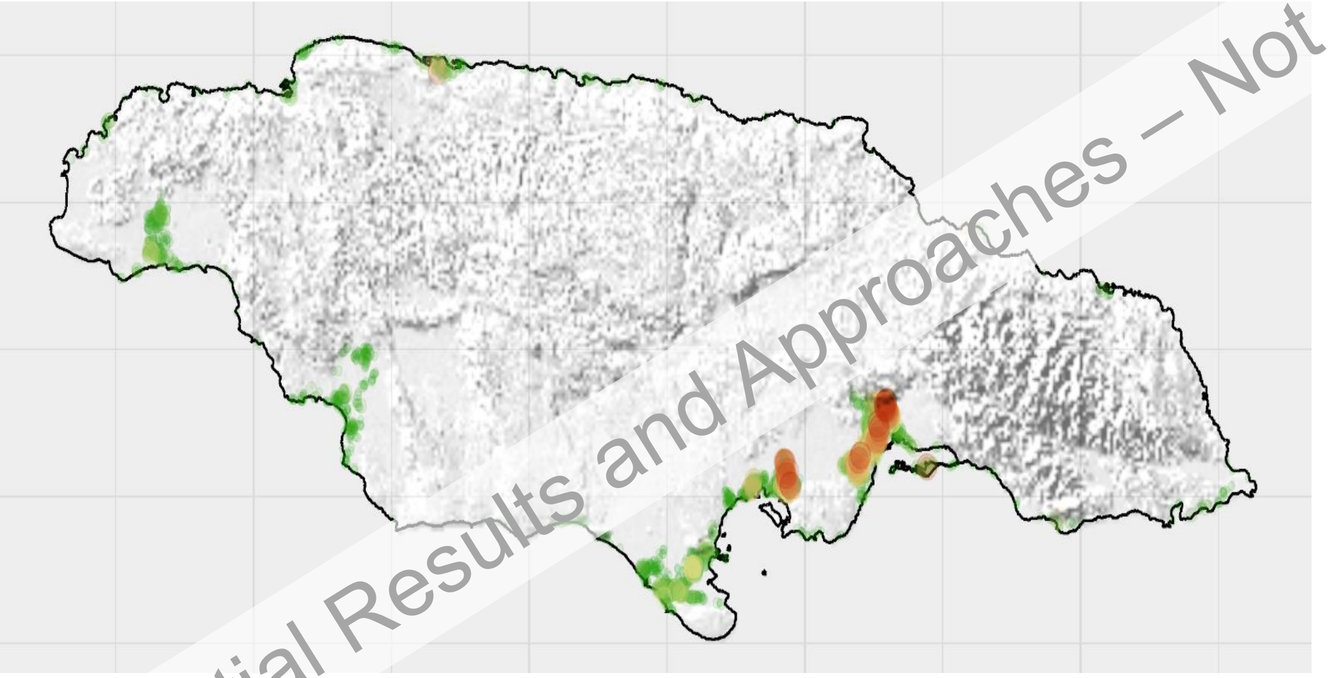
People Protected by Mangroves



20% annual reduction in people flooded

Preliminary Results: Flood Risk Consequences of Mangrove Loss

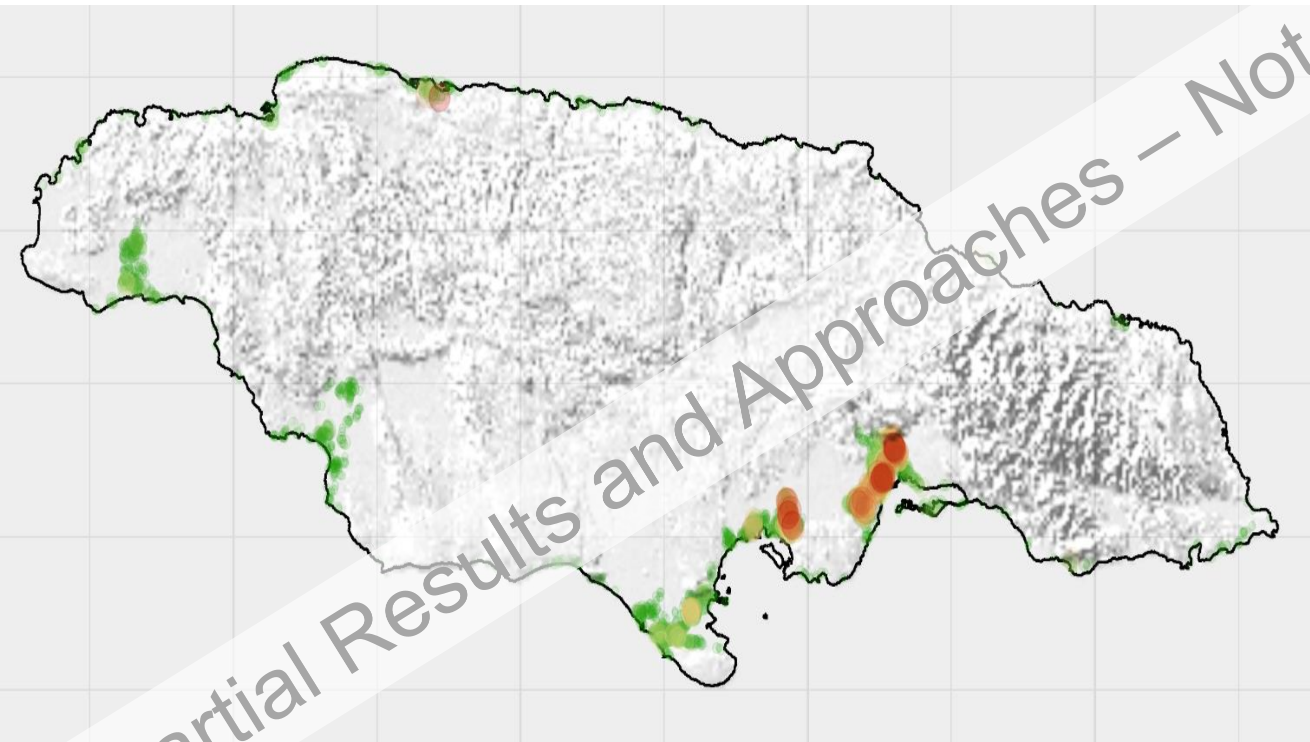
Residential Stock Protected by Mangroves



24% annual reduction in residential stock damaged

Preliminary Results: Flood Risk Consequences of Mangrove Loss

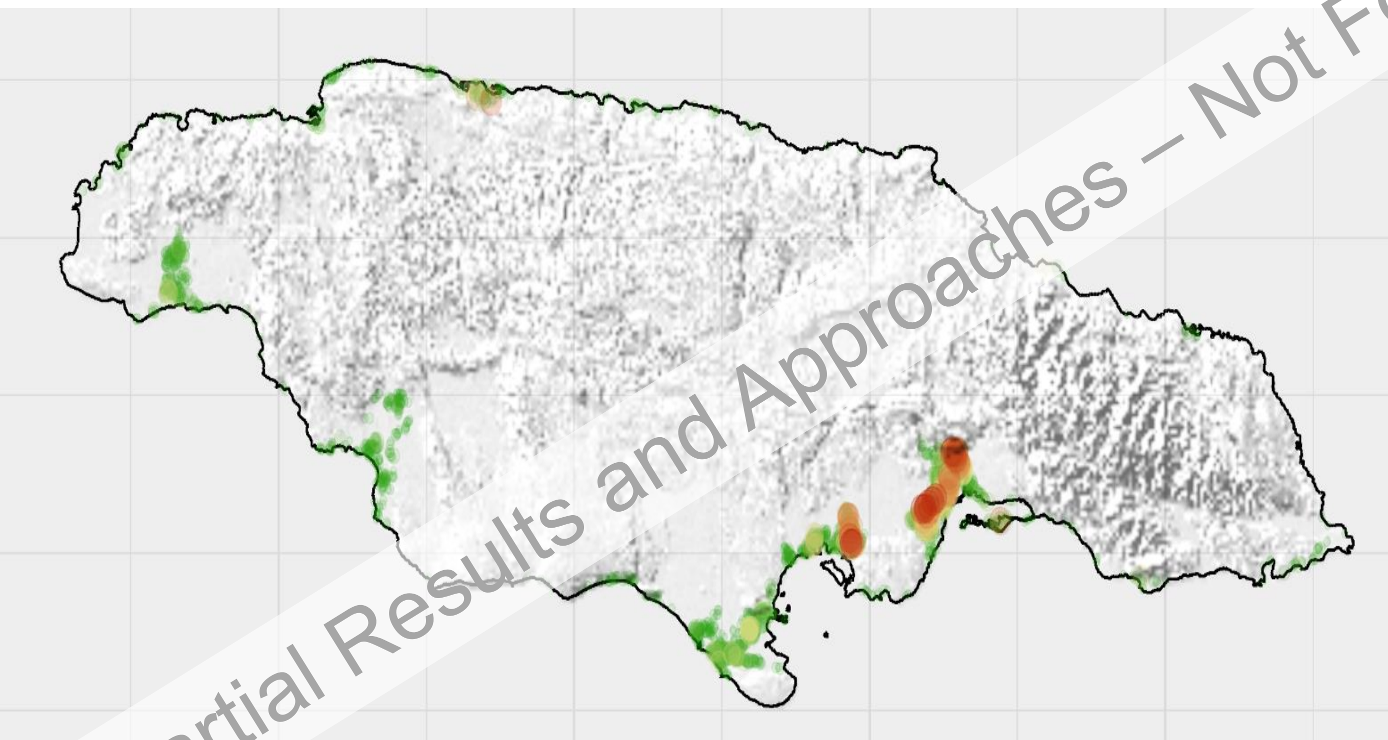
Industrial Stock Protected by Mangroves



24% annual reduction in industrial stock damaged

Preliminary Results: Flood Risk Consequences of Mangrove Loss

Service Stock Protected by Mangroves

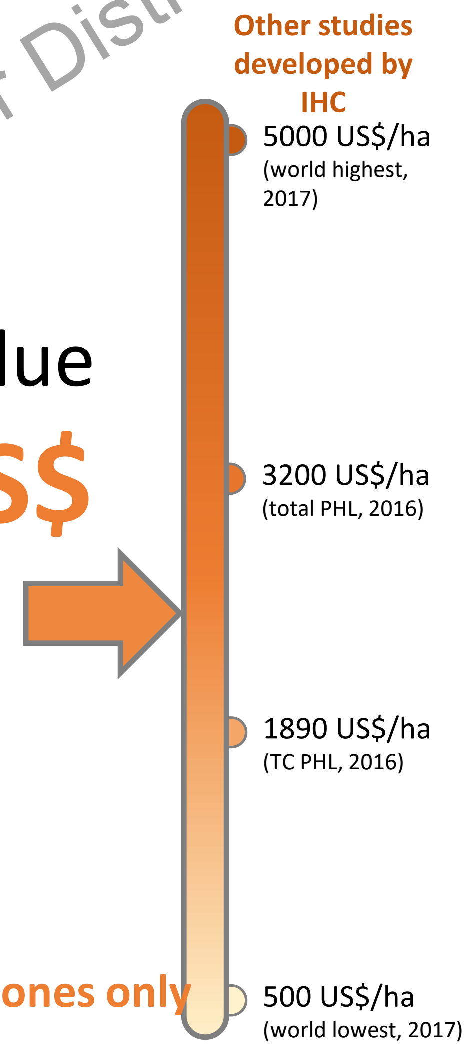


24% annual reduction in services stock damaged

Preliminary Results: Flood Risk Consequences of Mangrove Loss

Considering the 32.49 US$ million per year benefits provided, and 12879 ha of mangroves in Jamaica in 2015,

Mangroves estimated protection value is **2522 US$ per ha (*)**



(*) against tropical cyclones only

Further Work on Wave and Water level Attenuation

Guidelines for Valuing Coastal Protection Services from Mangroves and Reefs

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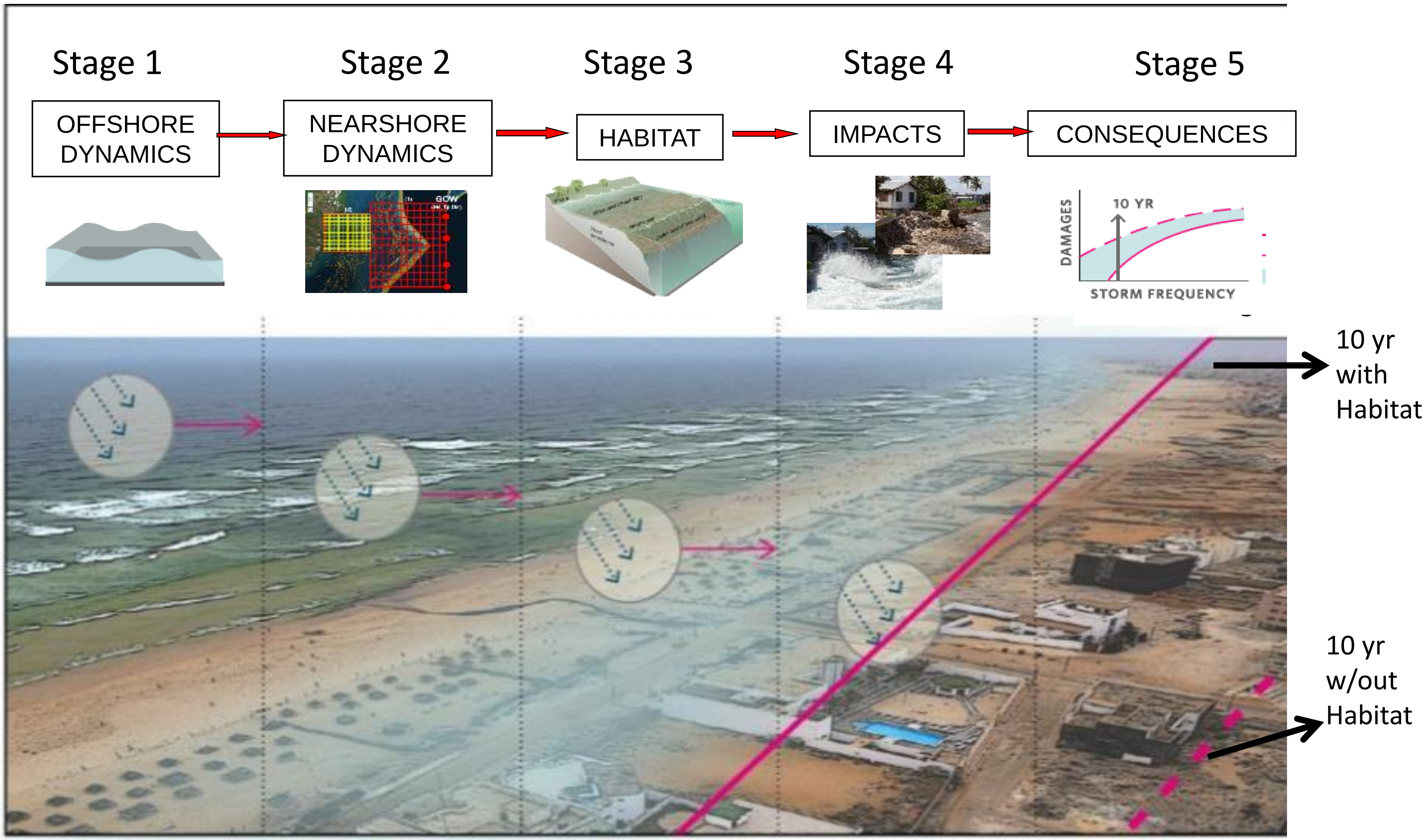
Recommended Approach: Expected Damage Function

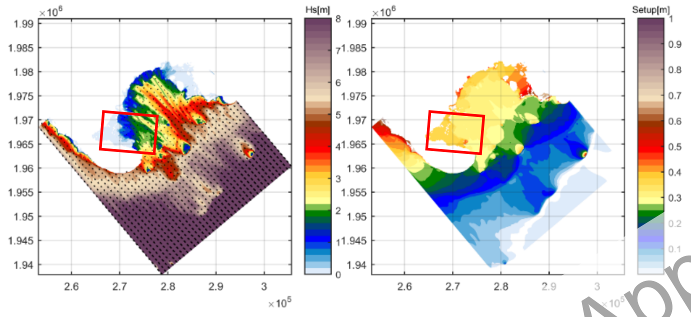


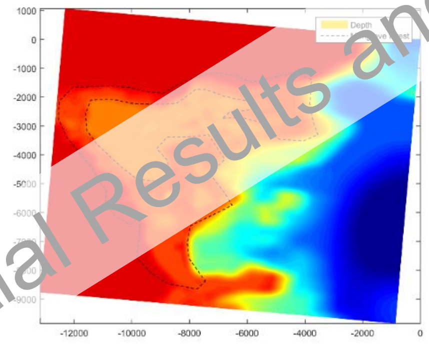
Further Work: Assessing Risk Reduction for non-Cyclone Climate

Xbeach 2D, Mangrove

Hs=10 m Tm=12 s Dir=135° W=0 m/s DirW=°

Waves only





Regular conditions

- 2D Xbeach has been nested to SWAN to solve sea-swell waves, infra-gravity waves and wave setup
- The phase-averaged (surfbeat) mode with wave shape model
- captures effect of nonlinear wave vegetation interaction processes on wave setup.

Integrating Field Data: Mangrove Conditions within Numerical Models

Xbeach 2D, Mangrove

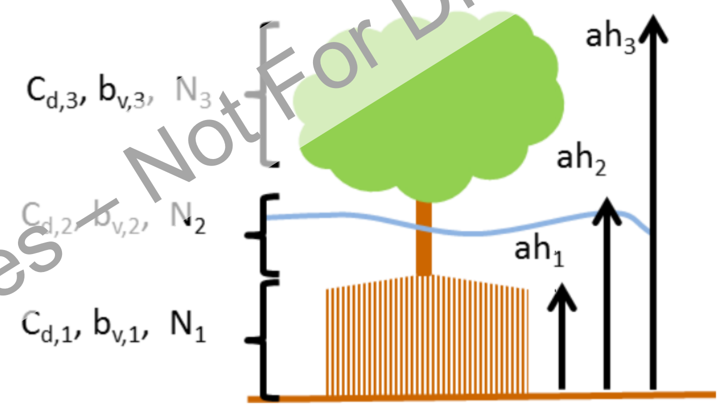
Short-wave attenuation, Mendez and Losada (2004)

$$D_v = \frac{1}{2\sqrt{\pi}}\rho C_D b_v N_v \left(\frac{k}{2\sigma}\right)^3 \frac{\sinh^3 k\alpha h + 3\sinh k\alpha h}{3k\cosh^3 kh} H_{rms}^3$$

Long-wave attenuation, Morrison type equation

$$F_v = 0.5 C_D b_v N_v \frac{\alpha h}{h} u|u|$$

Regular conditions



Somnertia sp.

nsec = 3 % number of vertical sections
ah = 0.5 1 0.5 % section height
bv = 0.01 0.2 0.02 % plant area per unit of height
N = 100 5 50 % number of plants per unit of area
Cd = 1 1 1 % drag coefficient

Key Take-Aways and Implications

1. Highly rigorous assessment of annual avoided damages by mangroves using 2 flood risk scenarios: With Mangroves and No Mangroves – and later, “restoration potential” with historic mangrove extents

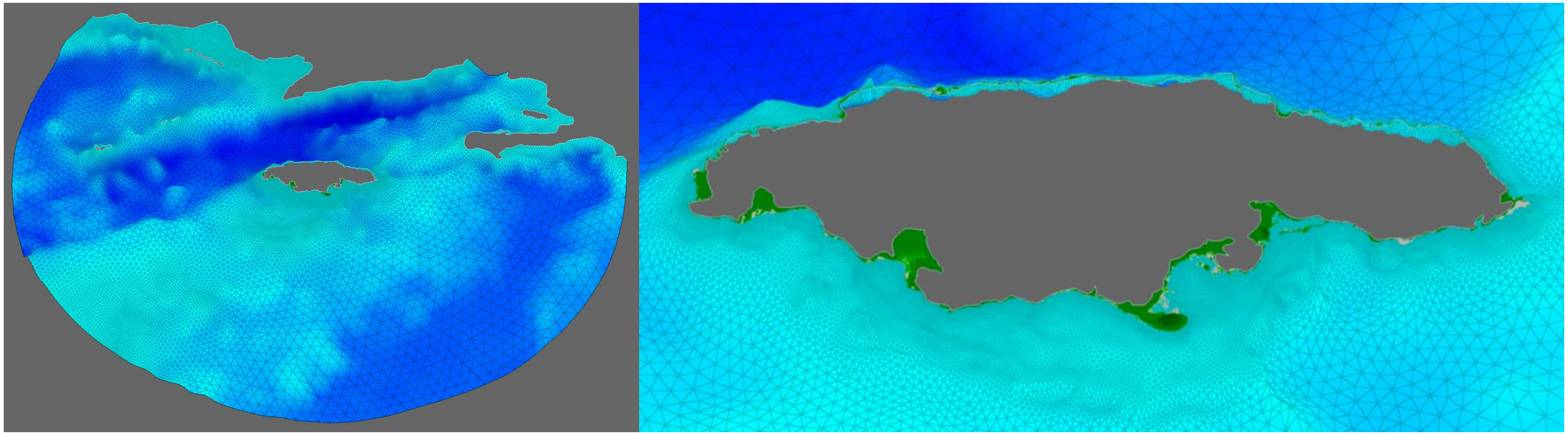
2. Preliminary results (for tropical cyclones only):
   - US$ 32.5 Million annual flood damages avoided
   - US$ ~2500 per Ha in avoided damages
   - National hotspots for protection for people and for stock

3. State-of-art modelling of national flood risk in the process

4. Consideration of probabilistic distributions of hurricane return periods and translation to coastal flooding extents and maps

5. Consideration of different exposure and mangrove condition parameters in next steps

Probabilistic assessment of the storm surge attenuation by mangroves in Jamaica



Marine Climate and Climate Change Group. IH Cantabria

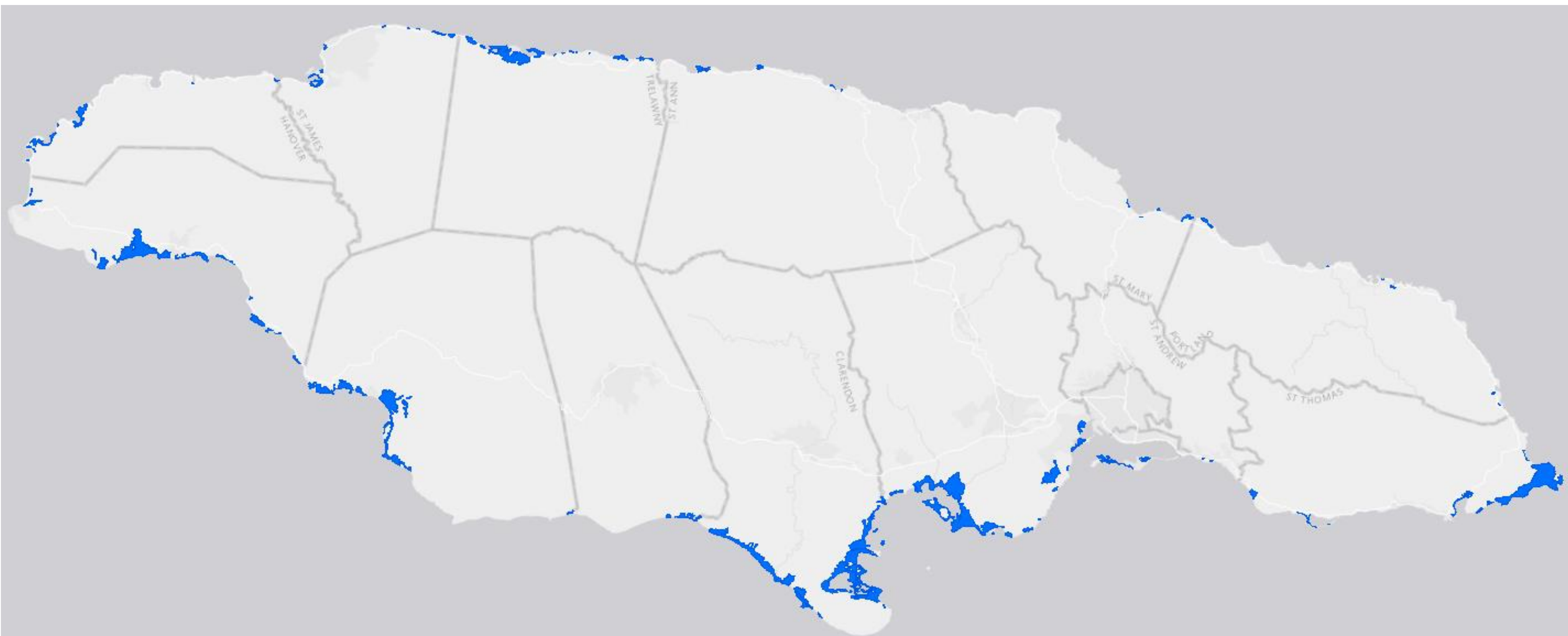
IH cantabria
INSTITUTO DE HIDRÁULICA AMBIENTAL
UNIVERSIDAD DE CANTABRIA

The Nature Conservancy

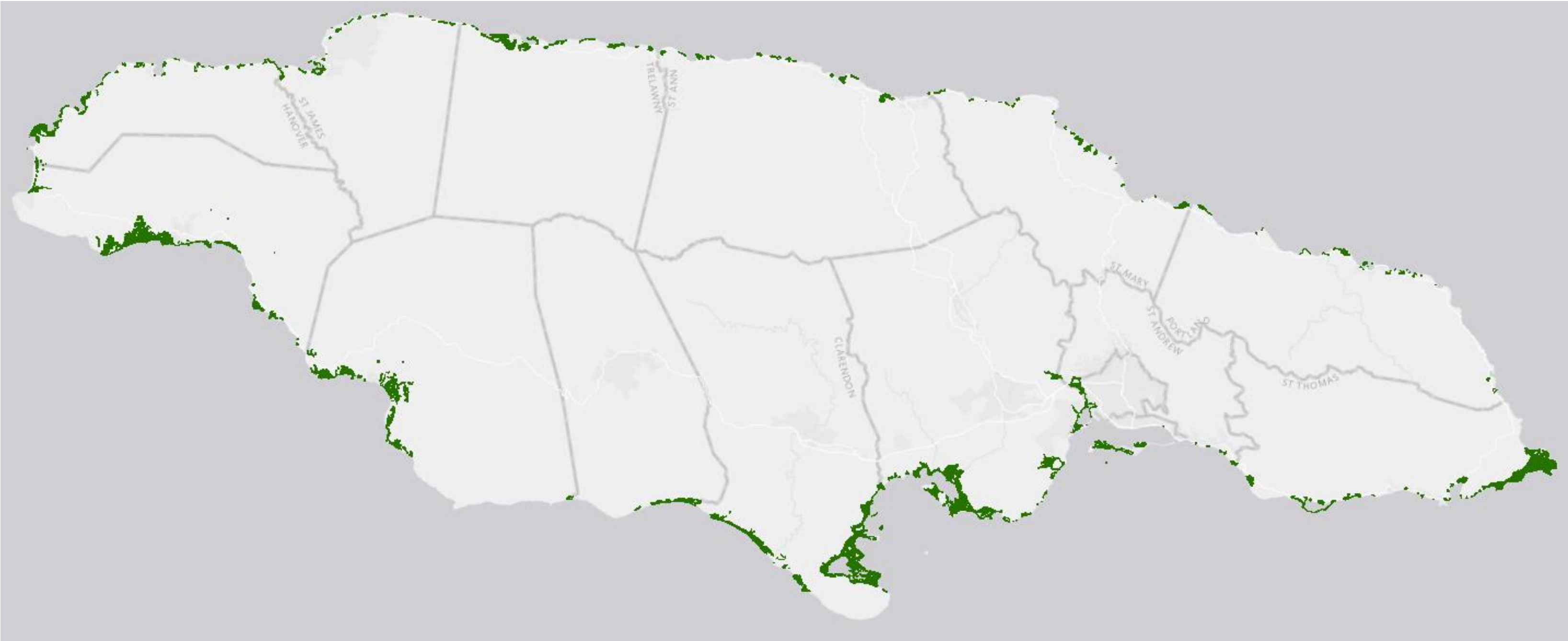
UNIVERSITY OF CALIFORNIA
SANTA CRUZ

Nearshore Dynamics: Mangrove Extent Data

National Mangrove Distribution - 2005



Jamaica Mangroves 2013: TNC



Coastal Protection Model: Critical Data Requirements

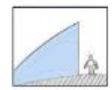
- Study Domain/Extent
- Bathymetry
  - Offshore
  - Nearshore
- Hydrodynamics
  - Offshore wave heights and water levels – *may be computed using global metocean datasets*
  - Storm tracks, intensities – *available from global datasets*
  - Wind speeds, fetch distance – *for every-day waves, e.g. INVEST*
  - Nearshore wave heights and water levels – *may be computed using offshore and bathy data*
- Ecosystem Characteristics
  - Extent
  - Width
  - Density and Fragmentation
  - Species (Primary or Distribution)
  - Age
- Inland Floodplain
  - Topography (i.e. for elevation, slope, distance to coast)
  - Land-use/Land-cover
  - Known coastal defenses – *may be assumed as captured in Topo*
- Flood Damages
  - Population
  - Built Capital (Assets)

Coastal Protection Model: Special Considerations for Ecosystems

- Study Domain/Extent
  - Ecosystem extent may be difficult to define/relate to modelling or accounting unit
- Bathymetry
  - Crucial for all ecosystems; may be difficult to measure within inter-tidal habitats
- Hydrodynamics
  - Storm properties (duration, forward speed,…) will influence variations in ecosystem impacts
- Ecosystem Characteristics
  - Should assess/ measure parameters like relative height, relative width, standing biomass, etc.
  - Should assess uncertainties in ecosystem health (relevant to coastal protection)
- Inland Floodplain
  - Ecosystem presence (esp inter-tidal) can help reduce overall exposure to flood risk
- Flood Damages
  - Ecosystems can occasionally increase flood damages depending on relative location of hazard and assets

Section 2. The role of mangroves in coastal risk reduction

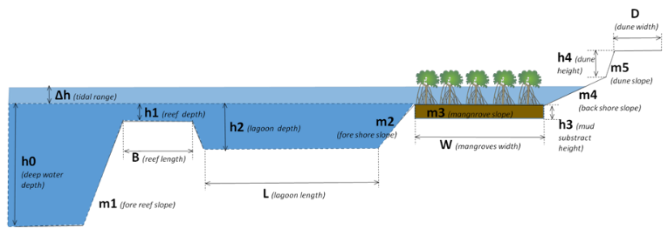
This section summarizes our current understanding of how and to what extent mangroves reduce coastal hazards that put us at risk. It provides practical guidance for coastal zone managers in terms of the mangrove characteristics that are needed to optimize protection against these hazards. A mangrove greenbelt should always be part of a wider risk reduction approach (see section 3).

		HAZARD				
		Waves 	Storm surges 	Tsunami 	Erosion 	Sea level rise 
MANGROVE FOREST PROPERTIES	Width	Hundreds of meters needed to significantly reduce waves (wave height is reduced by 13-66% per 100m of mangroves)	Hundreds of meters needed to significantly reduce wind and waves on top of surge Thousands of meters needed to reduce flooding impact (storm surge height is reduced 5 - 50 cm/km)	Hundreds of meters needed to reduce tsunami flood depth by 5 to 30% Mangroves do not provide a secure defence (nor do many engineered defences)	Sufficient mangrove forest width needs to be present to maintain sediment balance. This can help to prevent erosion and may encourage active soil build-up.	
	Structure	The more obstacles the better: dense aerial root systems and branches help attenuate waves	Open channels and lagoons allow free passage, while dense aerial root systems and canopies obstruct flow		Complex aerial root systems help slow water flows, allowing sediment to settle and causing sediment to accrete rather than erode.	
	Tree Size	Young & small mangroves can already be effective	Smaller trees and shrubs may be overtopped by tsunamis and the very largest storm surges		Young trees already enable soils to build up. The more biomass input into the soil the better.	
	Link to other ecosystems	Sand dunes, barrier islands, saltmarshes, seagrasses and coral reefs can all play an additional role in reducing waves				Allow room for landward retreat of the mangrove
	Underpinning factors	Healthy mangroves are a prerequisite for all aspects of coastal protection. Healthy mangroves require: sufficient sediment and fresh water supply and connections with other ecosystems. Conversely, pollution, subsidence (due to deep groundwater/oil extraction or oxidation upon conversion) and unsustainable use jeopardizes mangroves.				

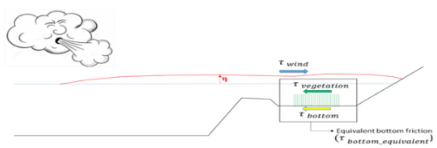
Nearshore Dynamics: Mangrove Effects on Wind-driven Waves

Canopy = 0, no wind stress is applied

1D MODEL



STORM SURGE



$$\frac{\partial \eta}{\partial x} = \frac{1}{g\rho_{water}(h+\eta)}\left[\tau_{wind} - \tau_{bottom\_equiv}\right]$$

$$\tau_{bottom\_equiv} = \rho_{water} \cdot C_b \cdot U_{flow}{}^2 \Rightarrow C_b = \frac{g \cdot n^2}{(h+\eta)^{1/3}}$$

$$\tau_{wind} = \rho_{water} \cdot k \cdot (U_{wind} - U_{flow})^2$$

Manning coefficient
(Zhang et al 2012)

Table 1
Manning coefficients for various categories of land cover (modified from Mattocks and Forbes, 2008).

NLCD Class number	NLCD Class name	Manning coefficient
11	Open water	0.020
12	Perennial ice/Snow	0.010
21	Developed open space	0.020
22	Developed low intensity	0.050
23	Developed medium intensity	0.100
24	Developed high intensity	0.130
31	Barren land (Rock/Sand/Clay)	0.090
32	Unconsolidated shore	0.040
41	Deciduous forest	0.100
42	Evergreen forest	0.110
43	Mixed forest	0.100
51	Dwarf scrub	0.040
52	Shrub/Scrub	0.050
71	Grassland/Herbaceous	0.034
72	Sedge/Herbaceous	0.030
73	Lichens	0.027
74	Moss	0.025
81	Pasture/Hay	0.033
82	Cultivated crops	0.037
90	Woody wetlands	0.140
91	Palustrine forested wetland	0.100
92	Palustrine scrub/Shrub wetland	0.048
93	Estuarine forested wetland	0.100
94	Estuarine scrub/Shrub wetland	0.048
95	Emergent herbaceous wetlands	0.045
96	Palustrine emergent wetland (Persistent)	0.045
97	Estuarine emergent wetland	0.045
98	Palustrine aquatic bed	0.015
99	Estuarine aquatic bed	0.015

WAVES

$$\frac{\partial F_e}{\partial x} = -(D_b + D_f + D_v)$$

$$D_b = \frac{3\sqrt{\pi}}{16}\rho g \frac{B^3 f_p}{\gamma h^5} H^7$$

Thornton and Guza 1983

$$D_f = \frac{C_f}{16\sqrt{\pi}}\left(\frac{\sigma}{\sinh kh}\right)^3 H^3$$

Thornton and Guza 1983

$$D_{veg} = \frac{1}{2\sqrt{\pi}}\rho C_d \left(\frac{kg}{2\sigma}\right)^3 \frac{(D_r + D_t + D_c)}{3k\cosh^3 kh} H^3$$

$$N_v b_v (\sinh^3 k\alpha_v h + 3\sinh k\alpha_v h)$$

Dalrymple et al. 1984, Mendez and Losada 2004

SWAN model

Based on action balance equation (Action $N = N(x, y, \sigma, \theta) = E / \sigma$):

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(c_x N\right) + \frac{\partial}{\partial y}\left(c_y N\right) + \frac{\partial}{\partial \sigma}\left(c_\sigma N\right) + \frac{\partial}{\partial \theta}\left(c_\theta N\right) = \frac{S}{\sigma}$$

shoaling (depth)

frequency shift (current)

refraction (depth, current), diffraction (depth, obstacles)

Action *N* is conserved in presence of current, energy is NOT !

Wave propagation based on linear wave theory

Dispersion relation $\sigma^2 = gk \tanh kh, \quad \sigma = \omega - \mathbf{k} \bullet \mathbf{U}$

- **Mangrove and coral reefs** enter into the computations via two coefficients. Two spatial variable parameters are applied in the bottom and surface stress terms in the depth averaged momentum equations (ADCIRC) and in the action balance equation in SWAN

Bottom stress

ADCIRC

Manning's n

Quadratic bottom friction formulation

$$\frac{\tau_{bx}}{\rho H} = g\frac{n^2}{H^{\frac{1}{3}}}\frac{\sqrt{u^2+v^2}}{H}u$$

$$\frac{\tau_{by}}{\rho H} = g\frac{n^2}{H^{\frac{1}{3}}}\frac{\sqrt{u^2+v^2}}{H}v$$

SWAN

Source terms in SWAN

$$S = S_{in} + S_{nl4} + S_{wcap} + S_{nl3} + S_{br} + S_{bot}$$

deep: $S_{in} + S_{nl4} + S_{wcap}$

shallow: $S_{nl3} + S_{br} + S_{bot}$

$$S_{bot}(\sigma,\theta) = -C_{bottom}\frac{\sigma^2}{g^2\sinh^2(kd)}E(\sigma,\theta)$$

- Madsen et al. (1988): $C_{bottom} = f_w \frac{g}{\sqrt{2}}U_{rms}$

  eddy-viscosity type

  $f_w = f_w(a_{bot}, K_N) \quad (K_N = 0.05 \text{ default})$

Canopy: The effect of forested vegetative canopies is included by reducing W_{land} to zero in the presence of mangroves

Surface stress

ADCIRC

$$\frac{\tau_{sx}}{\rho H} = \frac{C_d}{H}\frac{\rho_{air}}{\rho}|W_{10}|W_{10x}$$

$$\frac{\tau_{sy}}{\rho H} = \frac{C_d}{H}\frac{\rho_{air}}{\rho}|W_{10}|W_{10y}$$

SWAN

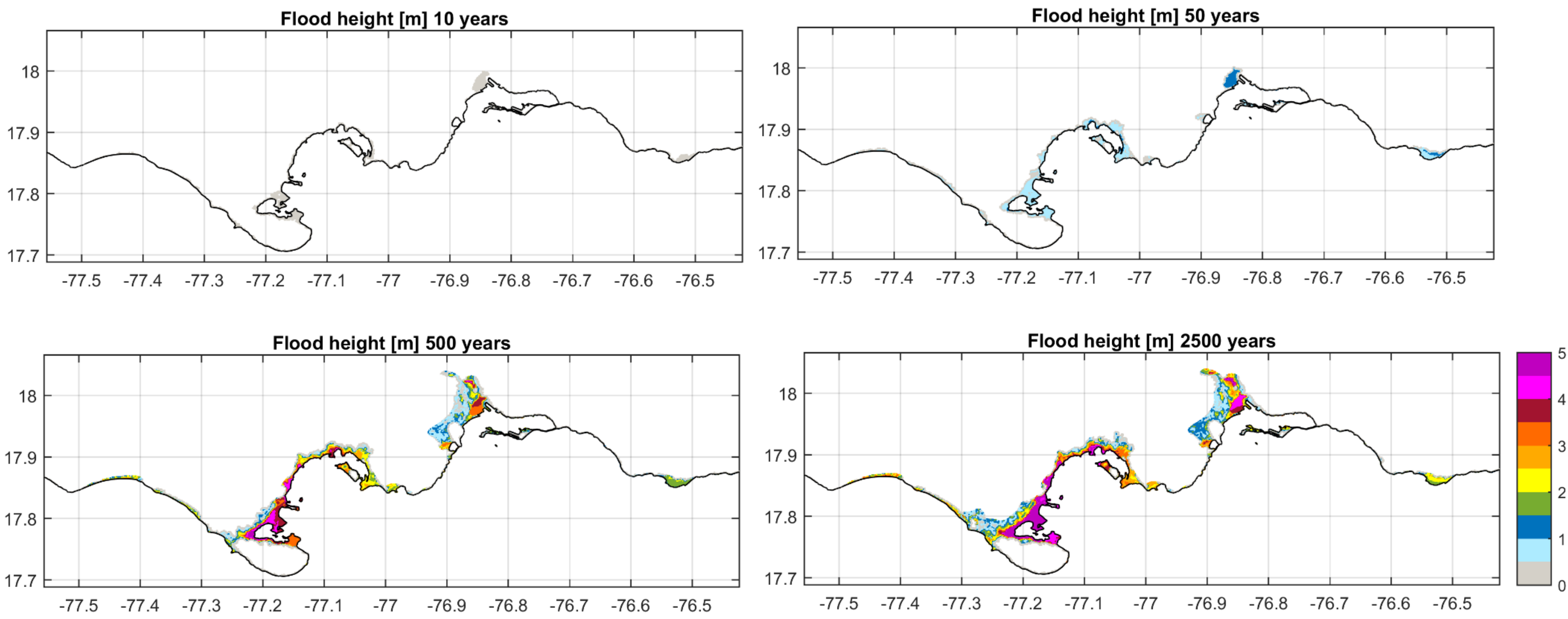
$$S_{in}(\sigma,\theta) = A + B\,E(\sigma,\theta)$$

$$U_*^2 = C_D U_{10}^2$$

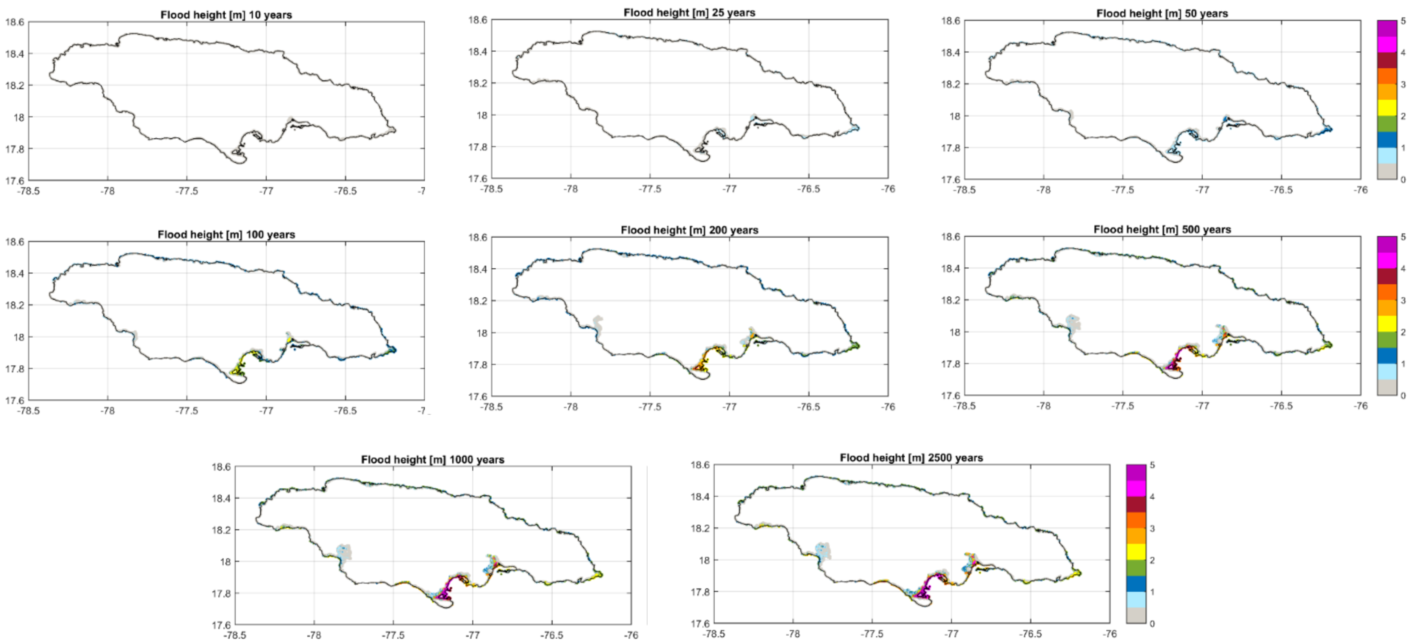
Zijlema et al. (CE 2012):

$$C_D = \left(0.55 + 2.97\,\tilde{U} - 1.49\,\tilde{U}^2\right)\cdot 10^{-3}$$

$$\tilde{U} = U_{10}/U_{ref}\,,\quad U_{ref} = 31.5\,\mathrm{m/s}$$

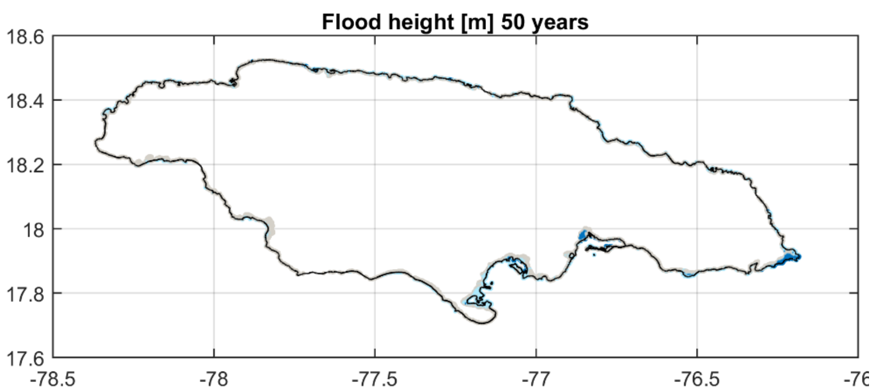

Flood height [m] 10 years
Flood height [m] 50 years
Flood height [m] 500 years
Flood height [m] 2500 years
18
17.9
17.8
17.7
-77.5
-77.4
-77.3
-77.2
-77.1
-77
-76.9
-76.8
-76.7
-76.6
-76.5
5
4
3
2
1
0

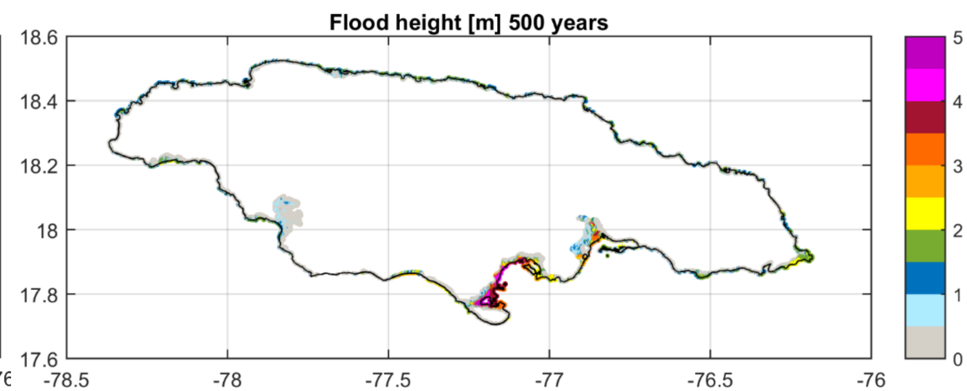
Flood maps

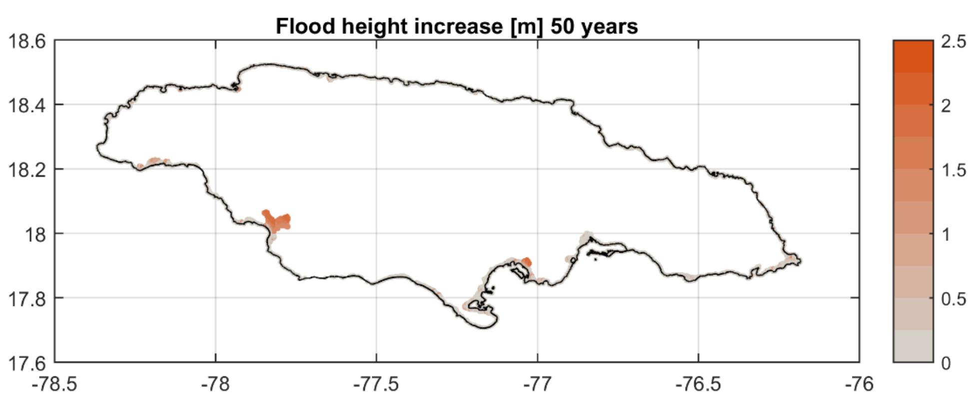


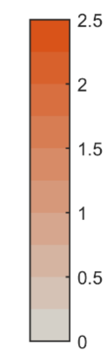
Flood height [m] 10 years
Flood height [m] 25 years
Flood height [m] 50 years
Flood height [m] 100 years
Flood height [m] 200 years
Flood height [m] 500 years
Flood height [m] 1000 years
Flood height [m] 2500 years
18.6
18.4
18.2
18
17.8
17.6
-78.5
-78
-77.5
-77
-76.5
-76
5
4
3
2
1
0

Flood height increase

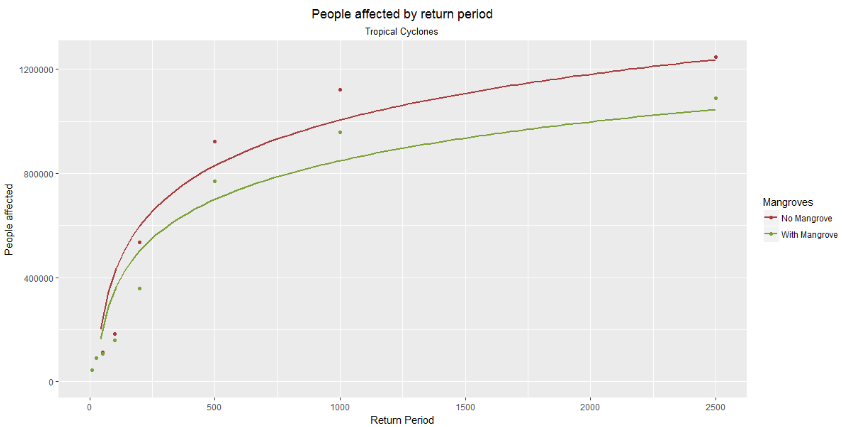


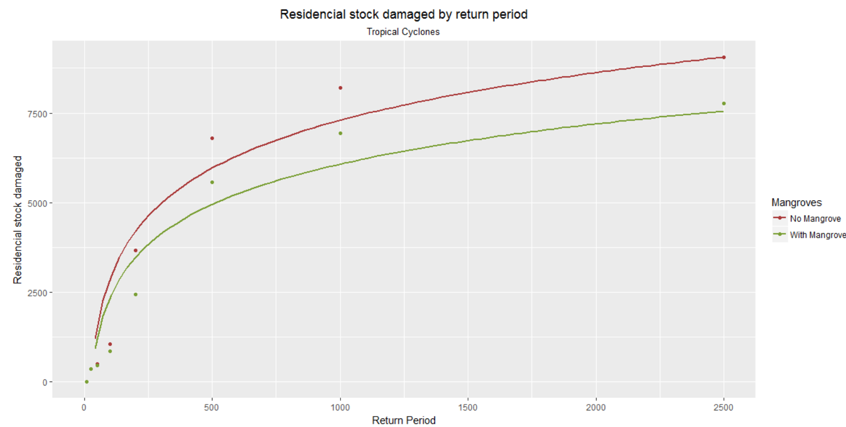


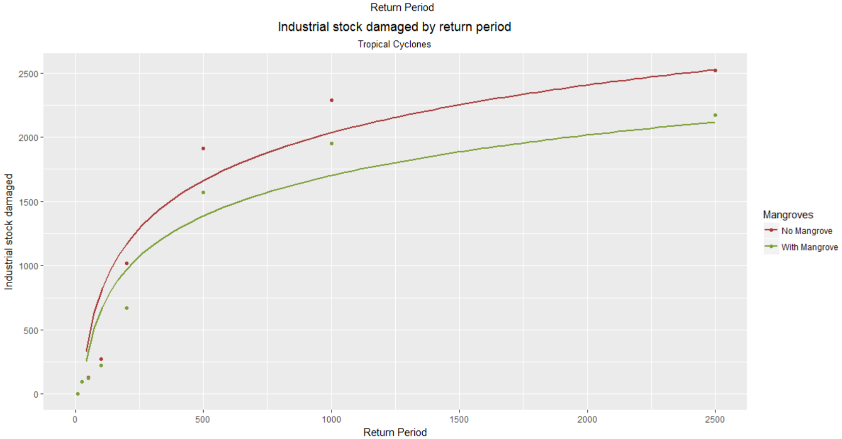


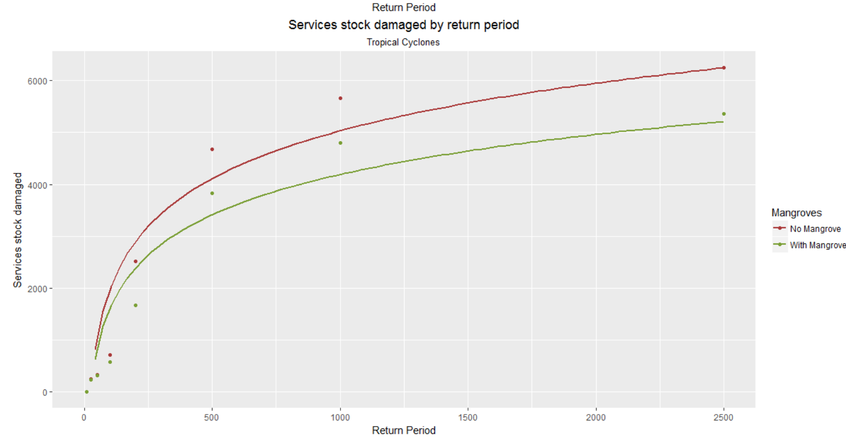


Preliminary Results: Flood Risk Consequences of Mangrove Loss



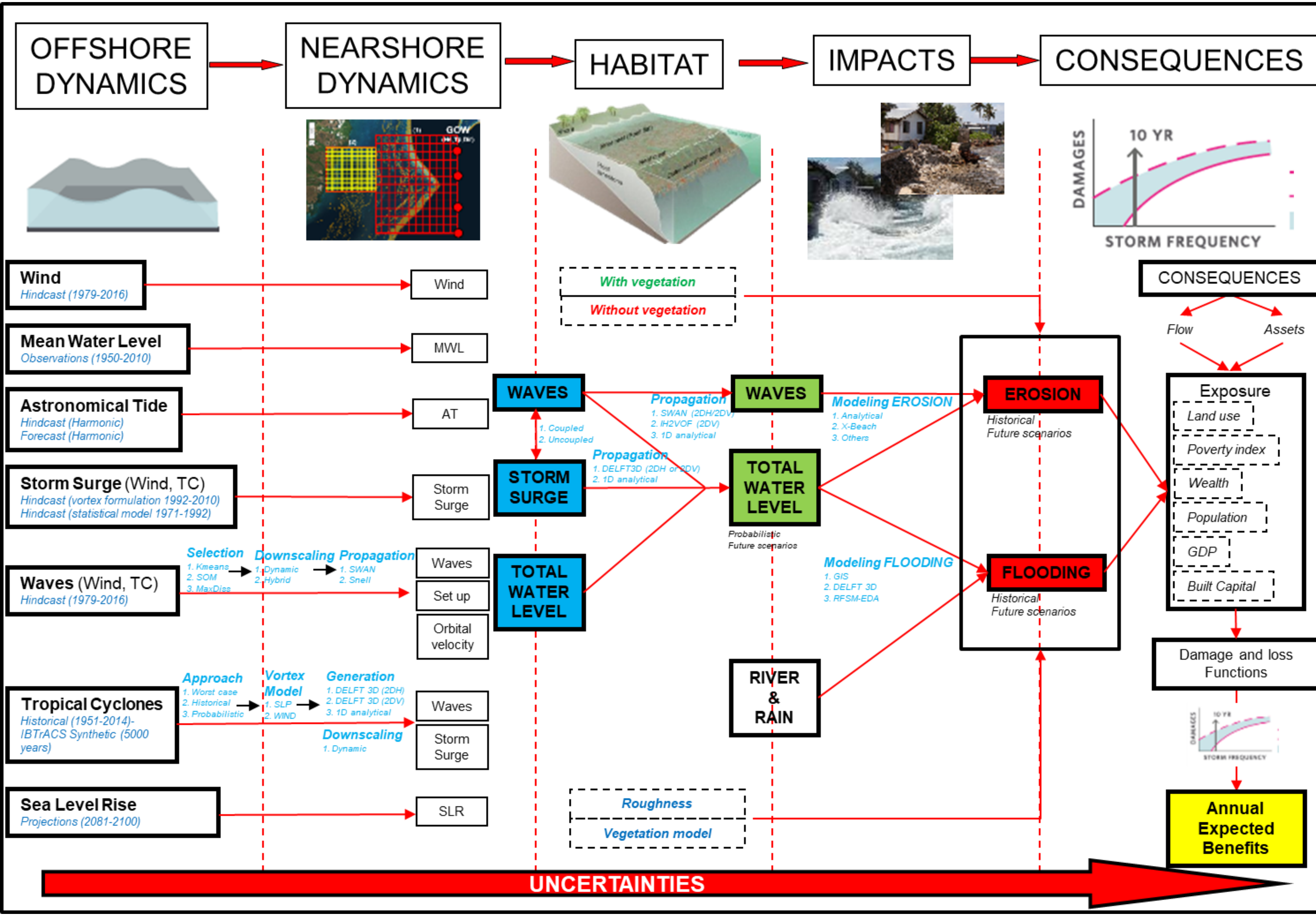






Preliminary Results: Flood Risk Consequences of Mangrove Loss

	Damages Without Mangroves	Damages With Mangroves	*Difference*	*Reduction*
Population	13463	11202	2261	20.18%
Pop below poverty	---	---	---	---
Stock (US$ mill.)				
Residential	86.0319	69.4562	16.5757	23.86%
Services	59.0603	47.6834	11.3769	23.86%
Industrial	23.779	19.2416	4.5374	23.58%



OFFSHORE DYNAMICS
NEARSHORE DYNAMICS
HABITAT
IMPACTS
CONSEQUENCES
DAMAGES
10 YR
STORM FREQUENCY
Wind
Hindcast (1979-2016)
Mean Water Level
Observations (1950-2010)
Astronomical Tide
Hindcast (Harmonic)
Forecast (Harmonic)
Storm Surge (Wind, TC)
Hindcast (vortex formulation 1992-2010)
Hindcast (statistical model 1971-1992)
Waves (Wind, TC)
Hindcast (1979-2016)
Tropical Cyclones
Historical (1951-2014)-
IBTrACS Synthetic (5000 years)
Sea Level Rise
Projections (2081-2100)
Selection
1. Kmeans
2. SOM
3. MaxDiss
Downscaling
1. Dynamic
2. Hybrid
Propagation
1. SWAN
2. Snell
Approach
1. Worst case
2. Historical
3. Probabilistic
Vortex Model
1. SLP
2. WIND
Generation
1. DELFT 3D (2DH)
2. DELFT 3D (2DV)
3. 1D analytical
Downscaling
1. Dynamic
Wind
MWL
AT
Storm Surge
Waves
Set up
Orbital velocity
Waves
Storm Surge
SLR
With vegetation
Without vegetation
WAVES
1. Coupled
2. Uncoupled
STORM SURGE
TOTAL WATER LEVEL
Propagation
1. SWAN (2DH/2DV)
2. IH2VOF (2DV)
3. 1D analytical
Propagation
1. DELFT3D (2DH or 2DV)
2. 1D analytical
WAVES
TOTAL WATER LEVEL
Probabilistic
Future scenarios
RIVER & RAIN
Roughness
Vegetation model
Modeling EROSION
1. Analytical
2. X-Beach
3. Others
EROSION
Historical
Future scenarios
Modeling FLOODING
1. GIS
2. DELFT 3D
3. RFSM-EDA
FLOODING
Historical
Future scenarios
CONSEQUENCES
Flow
Assets
Exposure
Land use
Poverty index
Wealth
Population
GDP
Built Capital
Damage and loss Functions
Annual Expected Benefits
UNCERTAINTIES

Further Work: Assessing Risk Reduction for non-Cyclone Climate

SWAN-SETUP (50x50 m)

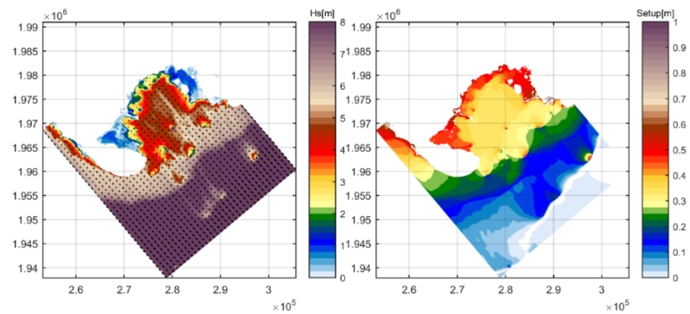
Understanding wave setup

- SWAN solves the wave setup but does not wet and dry, artificial setup very close to the land boundaries. SWAN is not the model to asses the role of the mangroves in mitigating coastal floods
- 3 cases: waves+wind, only waves, only wind
- Locally generated wind waves important contribution to the wave setup
- Mangrove reduction not evident due to the small waves (depth limited)
- Regular waves expected under calm wind conditions

Regular conditions

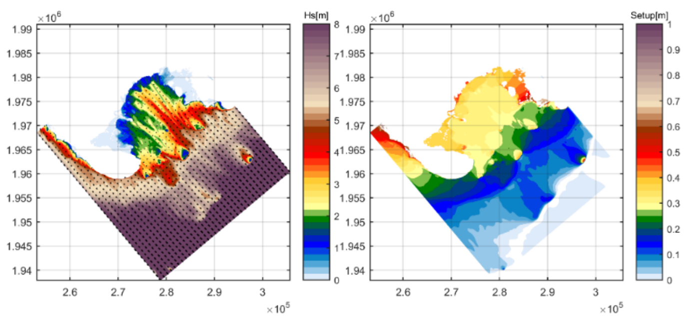
Hs=10 m Tm=12 s Dir=135º W=40 m/s DirW=135º

Waves +Wind



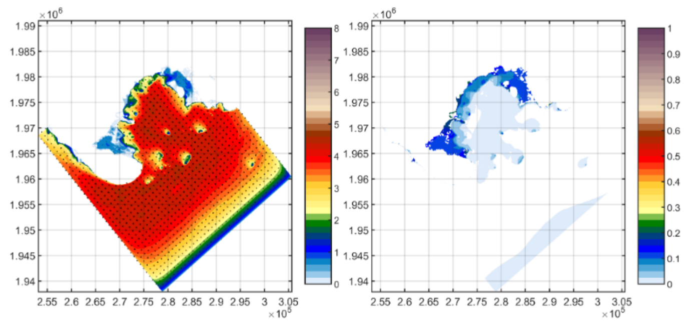
Hs=10 m Tm=12 s Dir=135º W=0 m/s DirW=º

Waves only



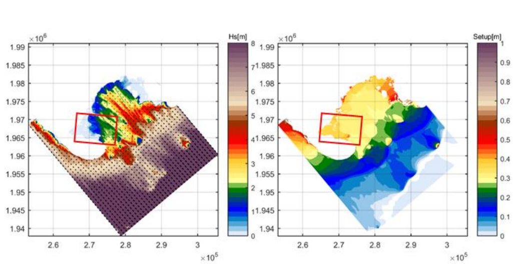
Hs=0 m Tm=0 s Dir=º W=40 m/s DirW=1.35º

Wind only

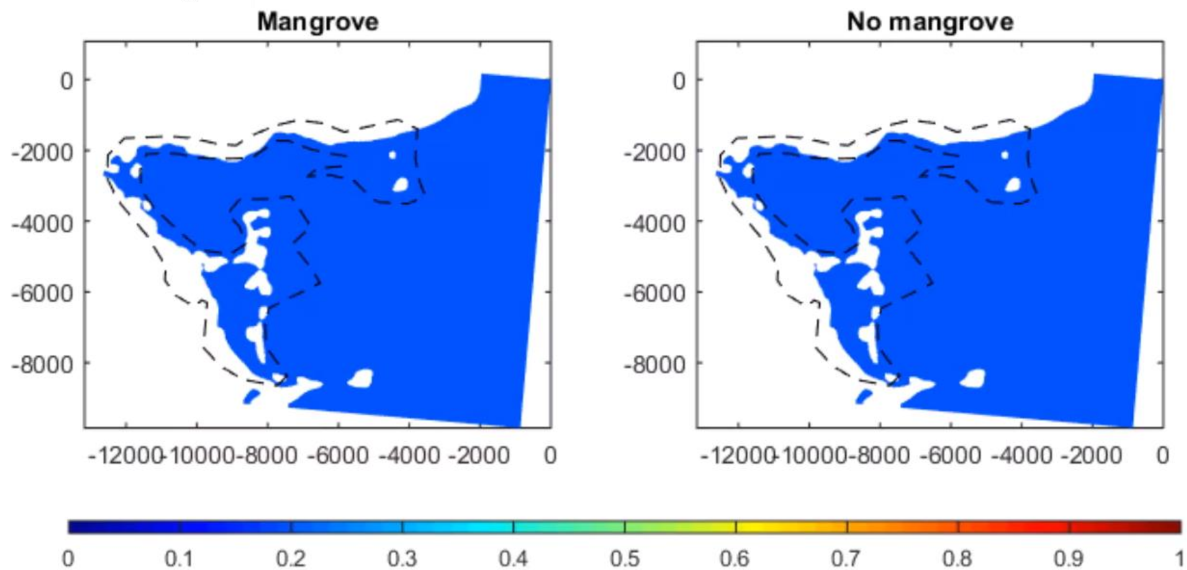


Regular conditions

Xbeach 2D, Mangrove



Hm0 = 4.0000 m
fp = 0.1000 s-1
mainang = 270.0000 º
gammajsp = 3.3000
s = 10.0000
level= 0.3 m



Xbeach 2D, Mangrove

Regular conditions