Quantifying Beach and Dune Resilience Using the Coastal Resilience Index

Zhifei Dong PhD, APTIM, zhifei.dong@aptim.com
Quin Robertson PhD, APTIM, william.robertson@aptim.com
Nicole Elko PhD, ASPBA, nicole.elko@asbpa.org
Julie Rosati PhD, PE, USACE, julie.d.rosati@usace.army.mil

11/10/2018

MOTIVATIONS

- USACE Coastal Storm Risk Management (CSRM) projects have been reducing vulnerability, helping communities anticipate and adapt toward improved resilience.
- To which extent have these restoration projects reduced the vulnerability, in other words, increased the resilience of coastal communities?
- How to quantify coastal vulnerability or resilience?

COASTAL VULNERABILITY INDEX

The USGS Coastal Vulnerability Index (CVI) is based on **six** parameters:

a. Geomorphology
b. Coastal slope
c. Relative sea-level rise rate
d. Shoreline erosion/accretion rate
e. Mean tide range
f. Mean wave height

Each parameter is ranked from 1 (very low) to 5 (very high). CVI is calculated based on the ranked values.

	Ranking of coastal vulnerability index				
	Very low	Low	Moderate	High	Very high
VARIABLE	1	2	3	4	5
Geomorphology	Rocky, cliffed coasts Fiords Fiards	Medium cliffs Indented coasts	Low cliffs Glacial drift Alluvial plains	Cobble beaches Estuary Lagoon	Barrier beaches Sand Beaches Salt marsh Mud flats Deltas Mangrove Coral reefs
Coastal Slope (%)	> .2	.2 – .07	.07 – .04	.04 – .025	< .025
Relative sea-level change (mm/yr)	< 1.8	1.8 – 2.5	2.5 – 2.95	2.95 – 3.16	> 3.16
Shoreline erosion/ accretion (m/yr)	>2.0 Accretion	1.0 – 2.0	-1.0 – +1.0 Stable	-1.1 – -2.0	< - 2.0 Erosion
Mean tide range (m)	> 6.0	4.1 – 6.0	2.0 – 4.0	1.0 – 1.9	< 1.0
Mean wave height (m)	<.55	.55 – .85	.85 – 1.05	1.05 – 1.25	>1.25

$$\text{CVI} = \sqrt{(a * b * c * d * e * f)/6}$$

DISCUSSION ON COASTAL VULNERABILITY INDEX

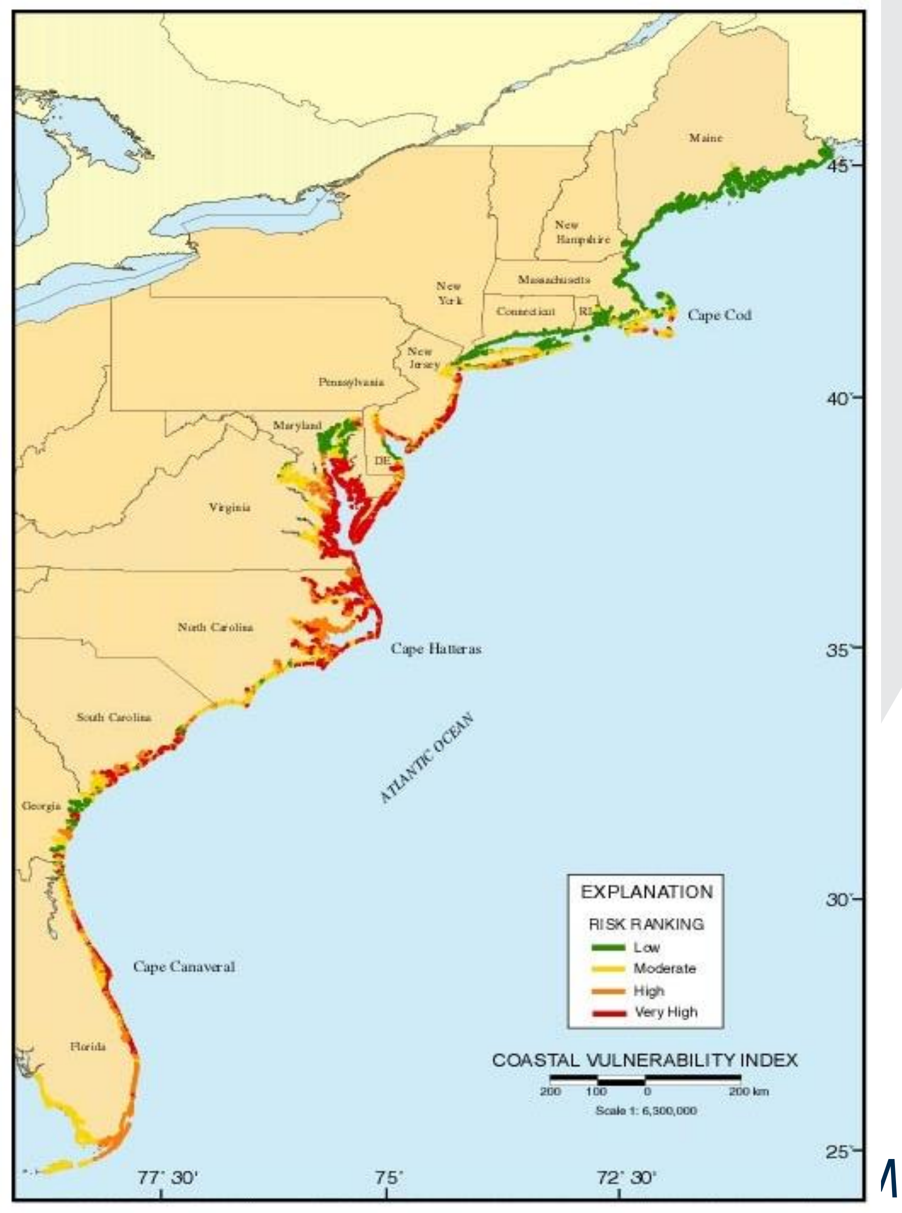
Coastal Vulnerability Index focuses on:

- Disturbances from inter-annual to decadal
- Sea level rise

Coastal resiliency considers:

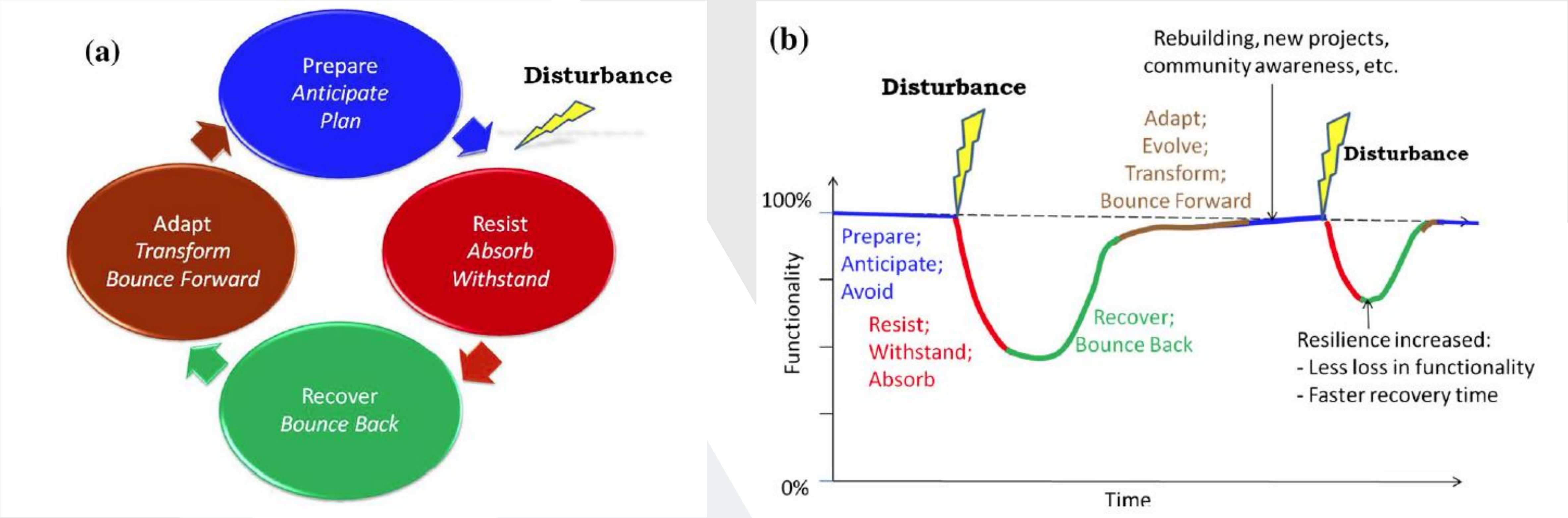
- Seasonal storms
- Storm reduction projects

Need an index that focuses on the beach/dune response to seasonal storms.



COASTAL RESILIENCE

In 2013, the Coastal Engineering Research Board (CERB) utilized work of the National Research Council (2012) to summarize the definition of resilience into four general concepts: **Prepare, Resist, Recover** and **Adapt**.



Rosati, J.D. et al., (2015)

APTIM

COASTAL RESILIENCE INDEX

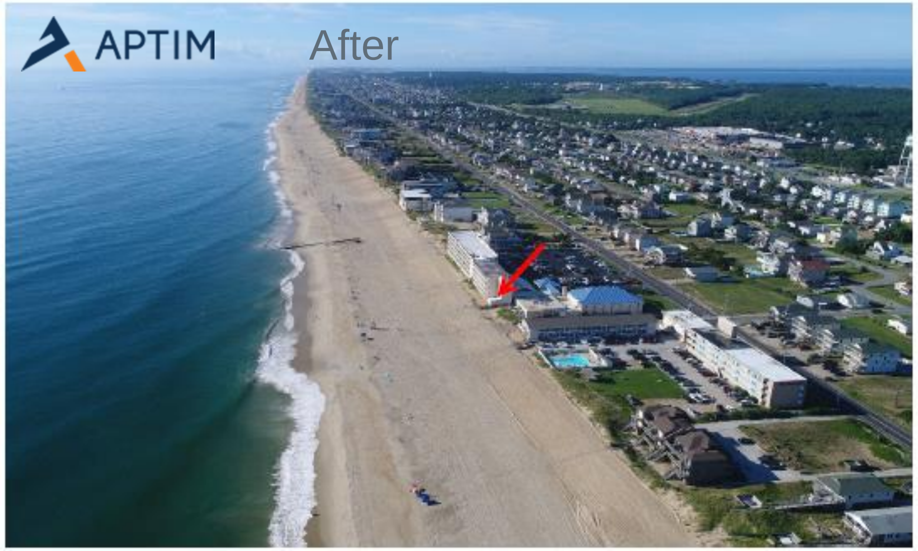
The calculation of **Coastal Resilience Index** will consider three parts of contribution:

- Beach and dune system (representing the concept of Prepare, Resist, Recover and Adapt)
- Storm surge (representing the concept of Resist)
- Waves (representing the concept of Resist)

“Wide beaches and high dunes” help reduce storm damages.

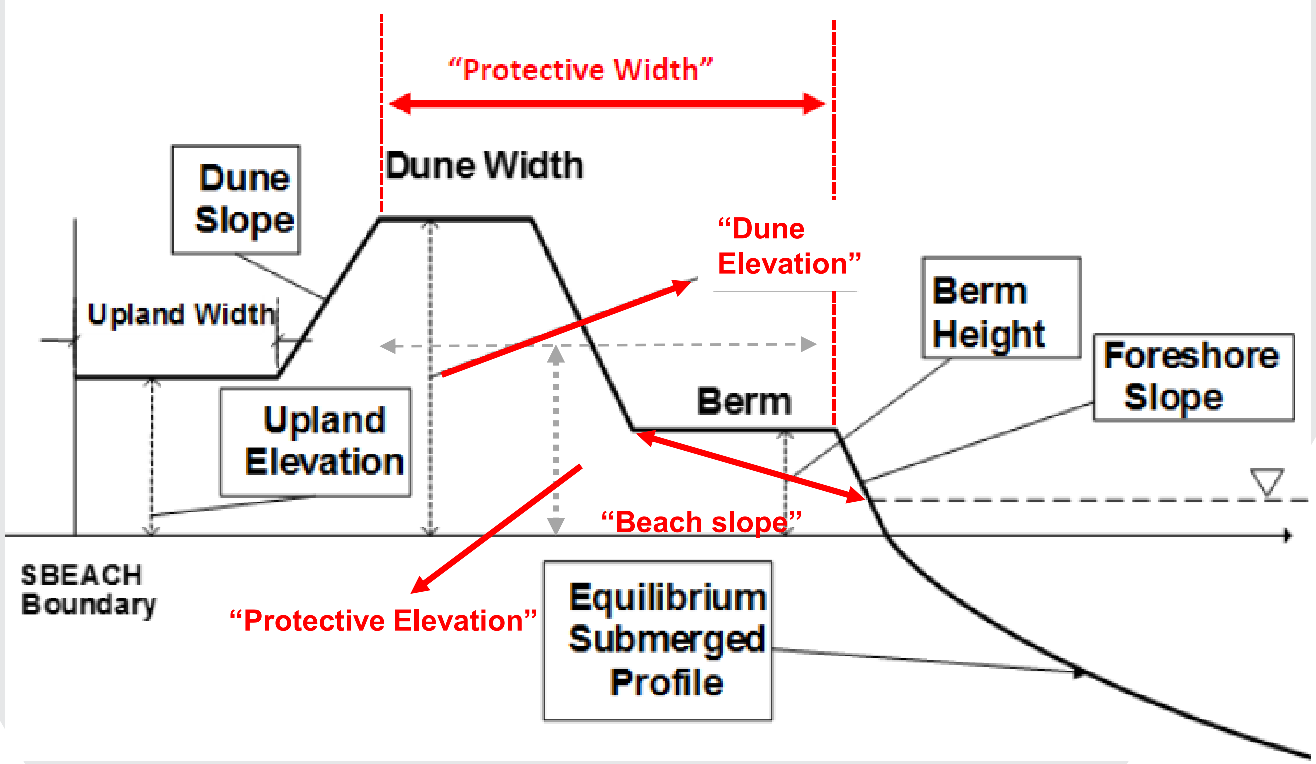
- Qualitative statement by ASBPA

2017 Beach Restoration at Dare County, NC



BEACH AND DUNE PARAMETERS

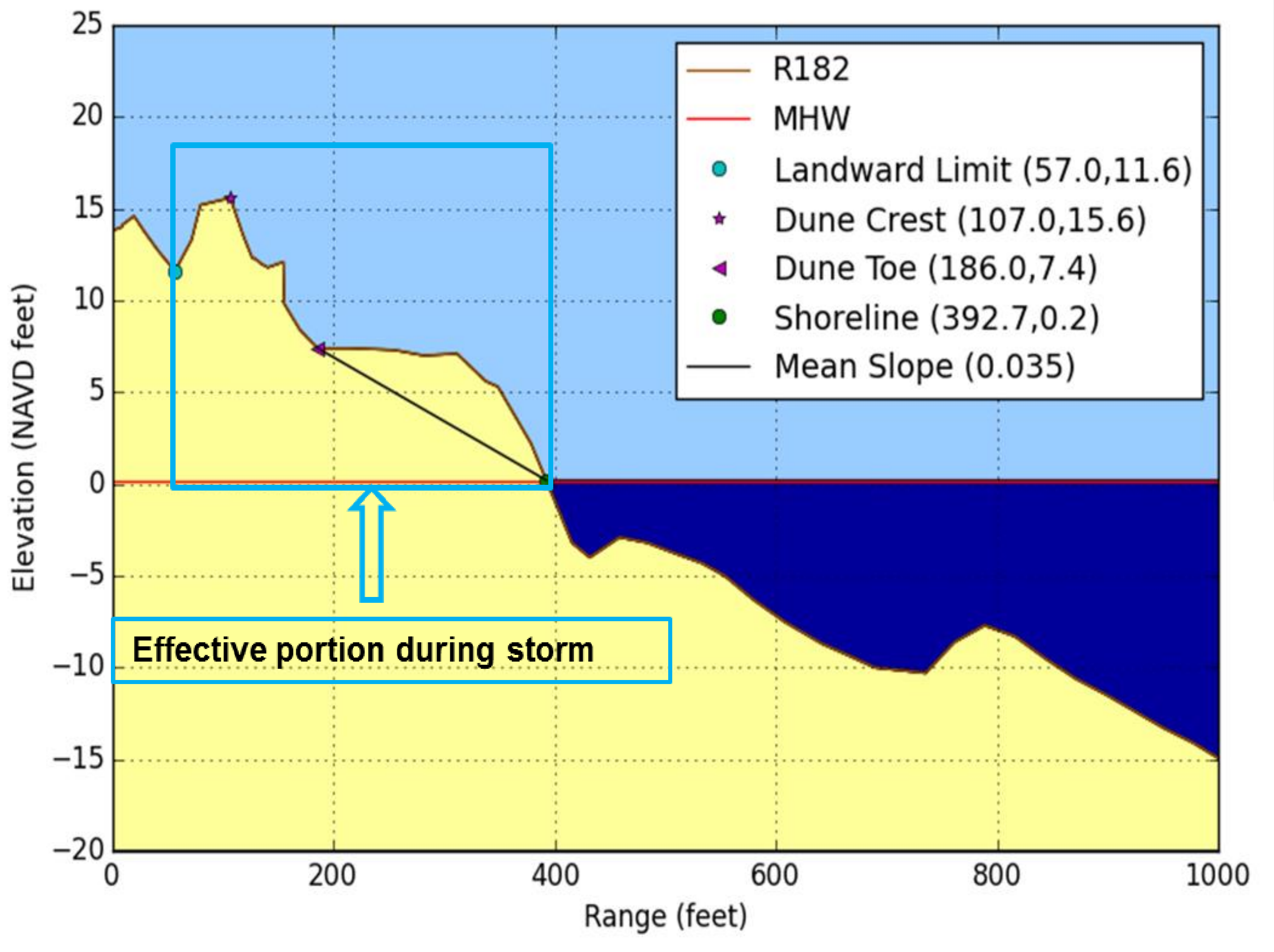
- Protective Width (**PW**): resist shoreline erosion by surge and waves
- Protective Elevation (**PE**): average elevation within the PW portion of profile, indicates the height of berm and dune system
- Volume Density (**VD=PE*PW**): wide berms and higher dunes indicate relatively higher resilience and the availability of sand to recover after storm
- Percentage of fine sediment (***s***): indicates volume loss of the beach system
- Dune Elevation (**DE**): prevent storm surge and wave overtopping
- Beach Slope (***β***): flatter beach reduces wave run-up height



USACE Beach-fx profile summarized by Marty Durkin, SAJ

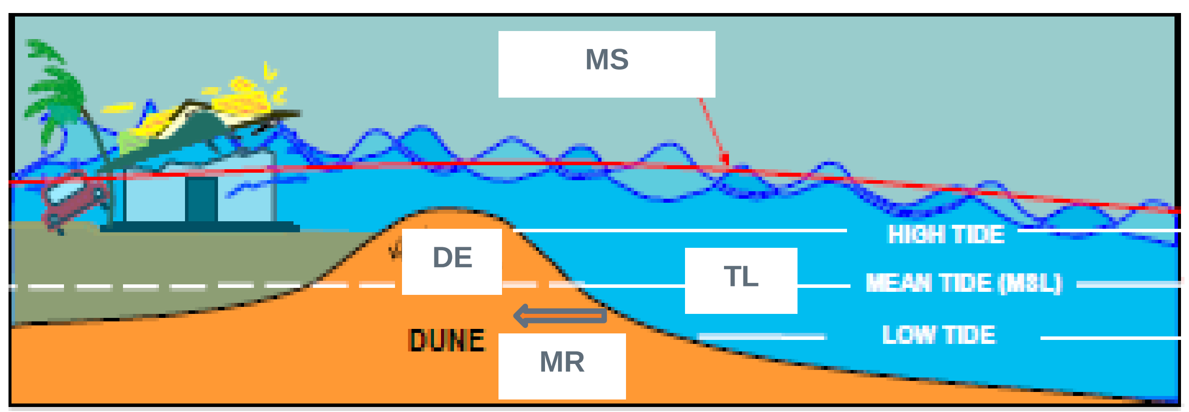
EXTRACTION OF BEACH MORPHOLOGIC FEATURES

- 2004 beach survey of Delray Beach as an example
- Definition of Protective Width (**PW**) is slightly revised for real beach profiles
- Develop ArcGIS Python scripts to process LIDAR data or beach surveys
- Identify beach morphologic features such as dune crest, dune toe and shoreline following Stockton et al. (2012)
- Generate plots of each profile as showing on the right



STORM SURGE PARAMETERS

- Maximum Storm-Surge (**MS**): in addition to tide level (**TL**)
- Maximum Storm-induced Recession (**MR**): beach erosion during storm



Extreme cases:

- **MS**+**TL** > **DE** or **PW** < **MR**: dune submerged or eroded, indicating minimum resilience, referred to as "Inundation Regime" by Sallenger (2000)
- **MS**+**TL** << **DE** and **PW** >> **MR**: safe behind the dune, indicating maximum resilience, referred to as "Swash Regime"

Intermediate cases (most frequent):

- **MS**+**TL**<**DE**: vulnerable to storm wave-induced overwash, referred to as "Collision Regime" and "Overwash Regime"

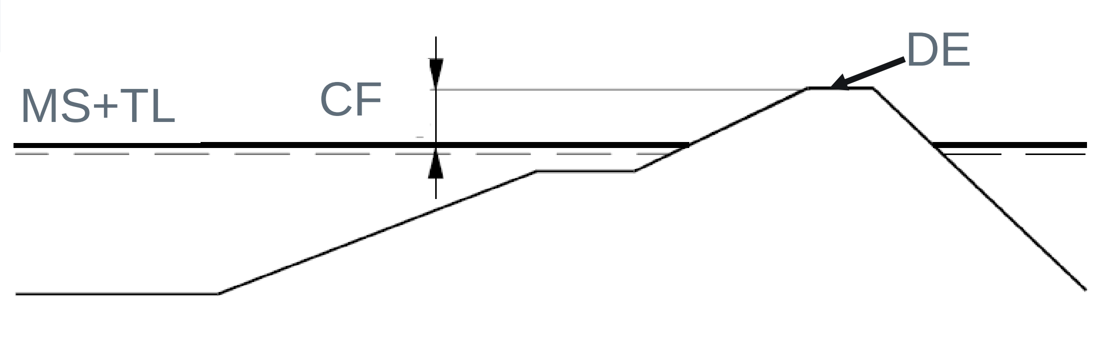
MS and **MR** can be obtained from historical observations or numerical models

WAVE PARAMETERS

- Wave run-up (**WR**) during storms is a primary driver of shoreline recession, dune erosion and sand overwash.
- Wave run-up can be predicted from empirical models based on offshore wave height, wave length, and local beach slope (Stockdon et al, 2006).

$$WR = 1.1\left(0.35\beta_f (H_0 L_0)^{1/2} + \frac{[H_0 L_0 (0.563\beta_f^{\,2} + 0.004)]^{1/2}}{2}\right)$$

- H_0 is offshore wave height. L_0 is offshore wave length.
- β_f is the mean beach slope measured from shoreline to dune toe.
- In wave overtopping models for bermed slope, crest freeboard **CF=DE** – (**MS**+**TL**) is crucial variable in prediction of overtopping.



COASTAL RESILIENCE INDEX (CRI)

Five non-dimensional factors based on beach, storm and wave parameters:

$$\boldsymbol{a} = \frac{PE}{PE_0}; \boldsymbol{b} = \frac{PE * PW * (1-s)}{PE_0 * PW_0}; \boldsymbol{c} = \frac{PW - MR}{PW_0};$$

$$\boldsymbol{d} = \frac{DE - (MS + MHW)}{CF_0}; \boldsymbol{e} = \frac{WR_0}{WR}$$

$$\boldsymbol{CRI = a + b + c + d + e}$$

where :

$\boldsymbol{PE_0}$: Characteristic Protective Elevation

$\boldsymbol{PW_0}$: Characteristic Protective Width

$\boldsymbol{CF_0}$: Characteristic Crest Freeboard

$\boldsymbol{WR_0}$: Characteristic Wave Run-up

1. Control contribution of each factor
2. Calibration parameters
3. Site to site comparison

WR: Wave Run-up

MHW: Mean High Water

PE: Protective Elevation

PW: Protective Width

s: percentage of fine sediment

DE: Dune Crest Elevation

MR: Maximum Shoreline Recession

MS: Maximum Storm Surge

APPLICATION OF COASTAL RESILIENCE INDEX

Delray Beach, FL

- 32 public survey dataset between 1973 and 2016
- 6 major beach nourishment projects and 2 storm repair projects by USACE

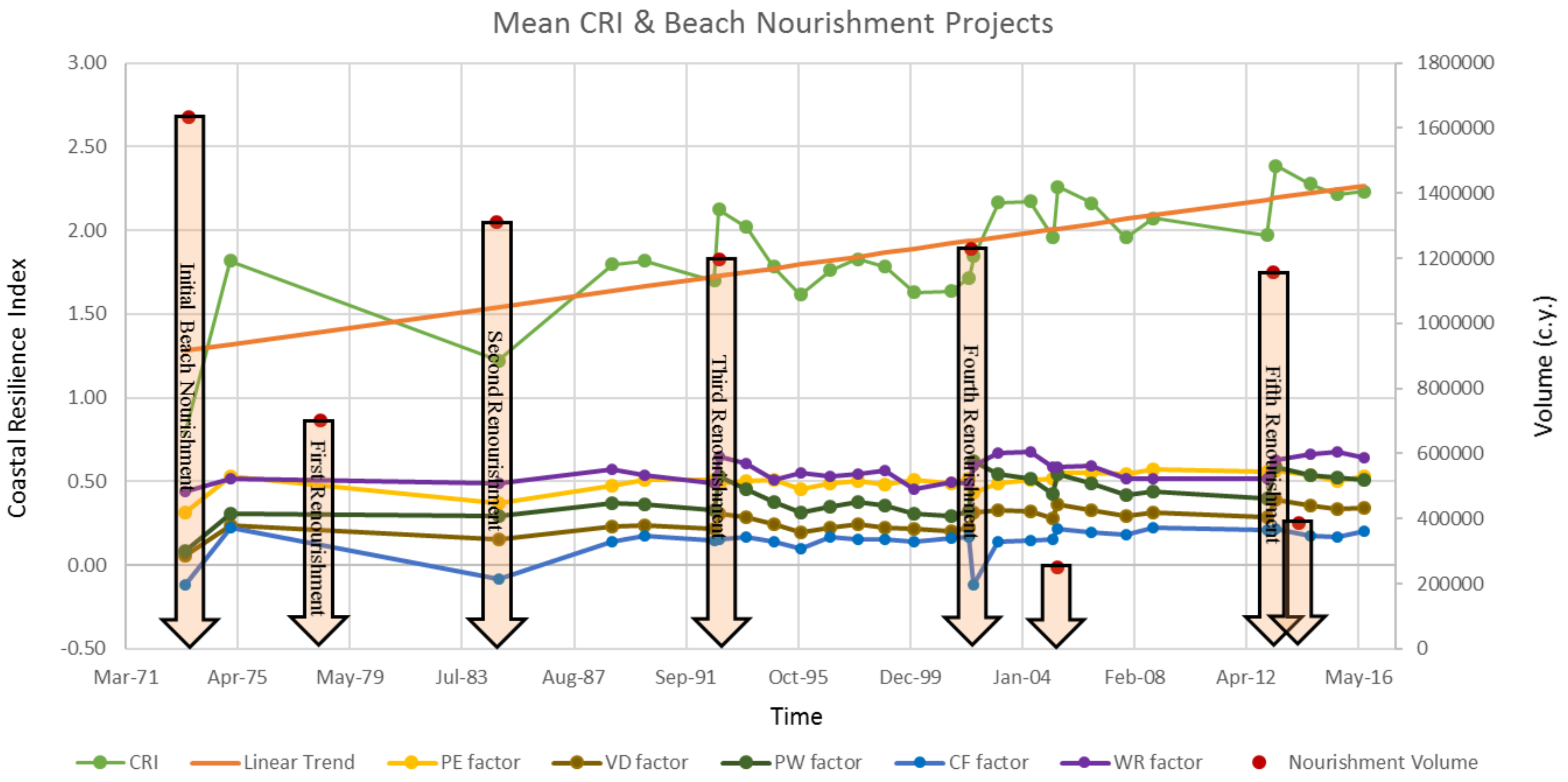
Storm and wave parameters are set as constant during calculation

- Maximum storm surge (MS): 10 feet
- Maximum shore recession (MR): 50 feet
- Deep water wave height for run-up calculation: 5 feet
- Deepwater wave length for run-up calculation: 500 feet

DELRAY BEACH, FL

Delray Beach mean Coastal Resilience Index and historical nourishment projects

- 6 major beach nourishment projects and 2 storm repair projects
- Beach nourishment projects increased mean CRI from 0.75 (pre-project, 1973) to 2.25 (May 2016)



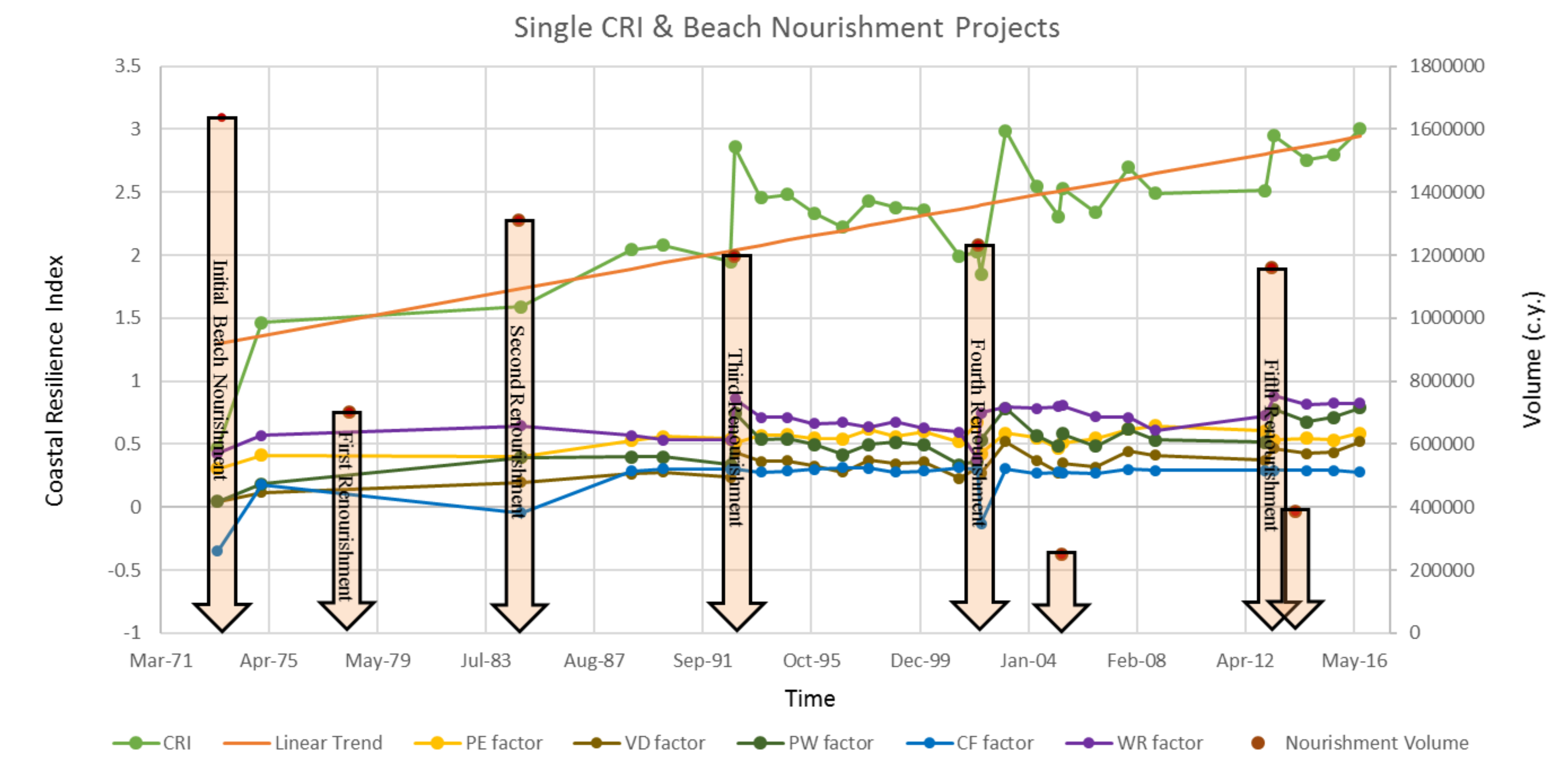
APTIM

DELRAY BEACH, FL

Delray Beach single profile Coastal Resilience Index at R182

- Beach nourishment projects increased CRI from 0.48 (pre-project, 1973) to 3.0 (May 2016)

- PE factor (0.31 to 0.59)
- VD factor (0.04 to 0.52)
- PW factor (0.04 to 0.79)
- CF factor (-0.35 to 0.28)
- WR factor (0.43 to 0.83)

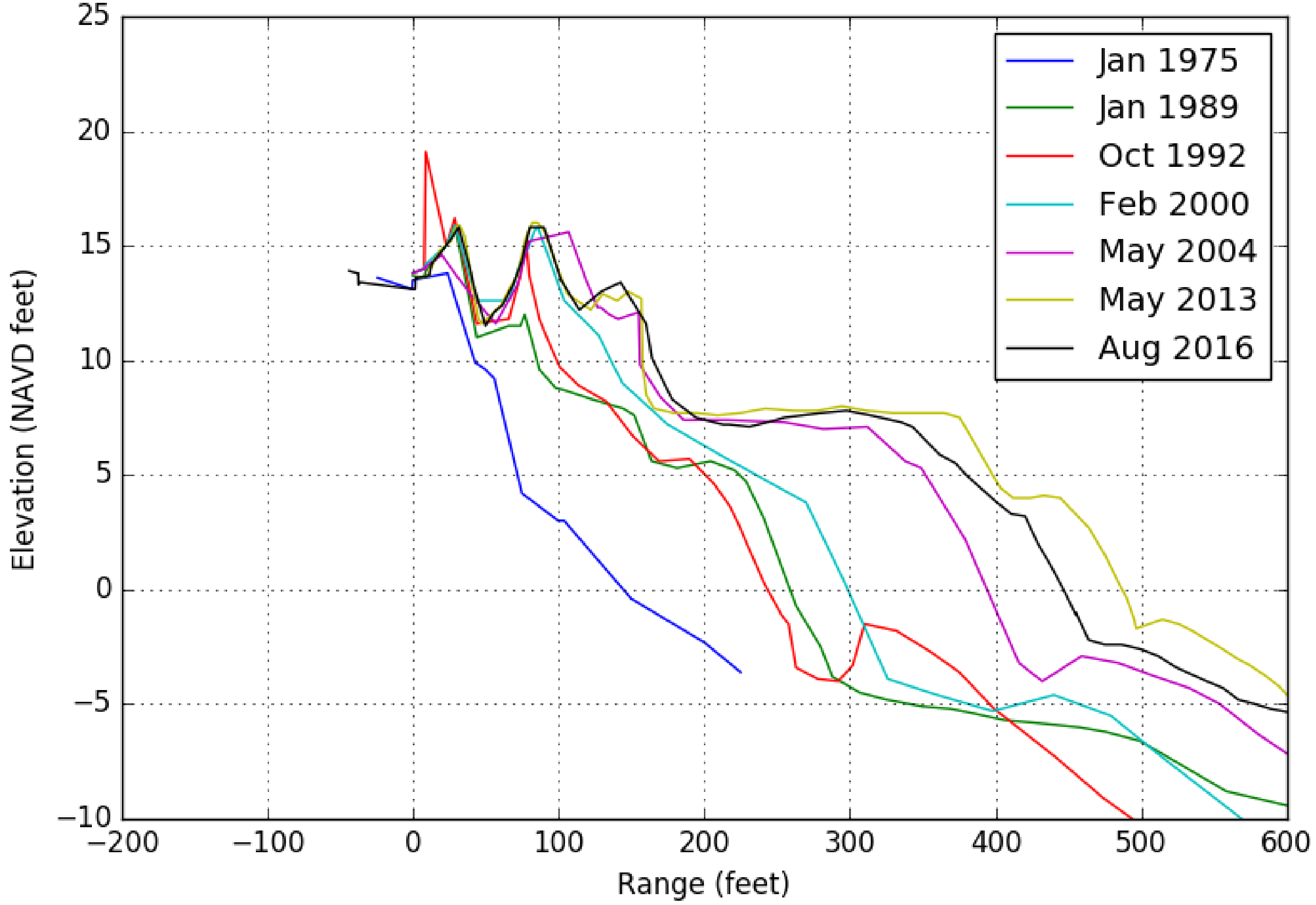


APTIM

DELRAY BEACH, FL

- PE factor (0.31 to 0.59): average elevation is stable
- VD factor (0.04 to 0.52): volume gradually increases
- PW factor (0.04 to 0.79): beach and dune were significantly widened
- CF factor (-0.35 to 0.28): dune elevation was increased
- WR factor (0.43 to 0.83): beach slope was flattened

R182 historical profiles



DELRAY BEACH, FL

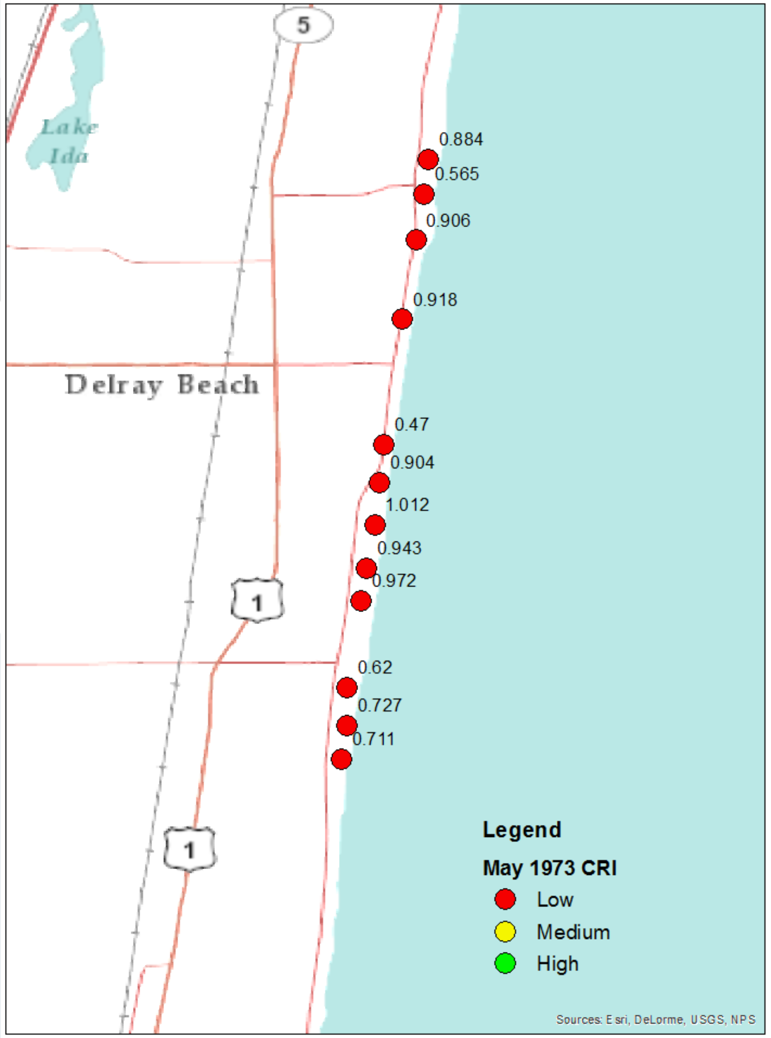
CRI map of Delray Beach:

- Calculated at available monument
- May 1973 pre-project CRI indicates relatively low resilience.
- Aug 2016 CRI indicates relatively high resilience.

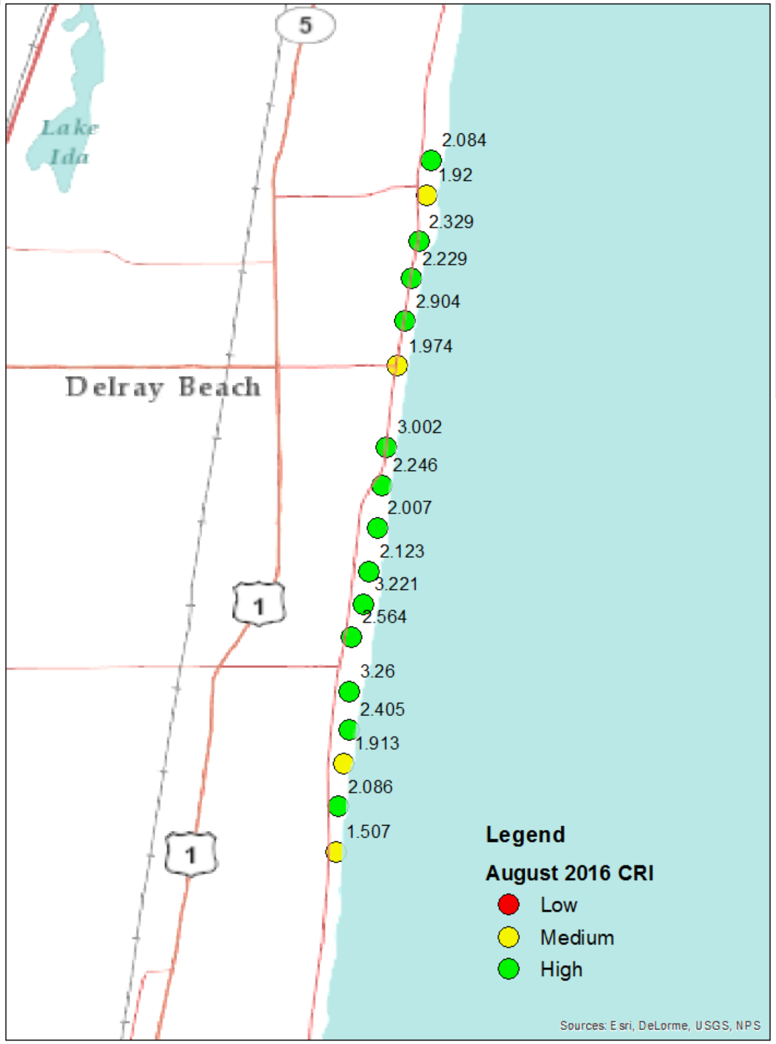
How to interpret CRI?

- CRI<1.5 : Low Resilience
- 1.5<CRI<2.0 : Medium Resilience
- CRI>2.0: High Resilience

May 1973 (pre-project)



August 2016



APTIM

DELRAY BEACH, FL

1972 aerial image indicates:

- Shoreline very close to the road
- Revetment built to prevent further landward erosion

2001 aerial image indicates:

- Shoreline about 350 feet away from the road
- Vegetation on the dunes

Aerial image 1972 vs. 2001

DISCUSSION AND FUTURE WORK

Summary

- Coastal Resilience Index (CRI) aims to quantify the resilience of beach restoration projects to seasonal storms.
- The calculation of CRI considers three aspects: beach and dune system, storm surge and waves.
- CRI consists of five factors: PE, VD, PW, CF, WR which stands for protective elevation, volume density, protective width, crest freeboard and wave run-up.
- CRI was applied to Delray Beach, FL with multiple years of beach profile surveys.

Future Work

- Include other coastal structures such as seawalls, breakwaters, etc.
- Calibrate and adjust the contribution of each parameter using numerical models.
- Scale the storm surge and wave parameters for different sites.
- Analyze LiDAR data nationwide.
- Compare the CRI from site to site, and create nationwide CRI map.

Questions ?

APTIM

COASTAL RESILIENCE INDEX

1. The first factor is the protective elevation (PE). The protective elevation is calculated above Mean High Water. The protective elevation stands for the volume of sand placed on the unit length within the portion of protective width. This factor indicates how high the dune and berm system is.

2. The second factor is the volume density (VD). If the protective width is very short, even high protective elevation does not necessarily indicate high resilience. The volume density is the total volume that considers both protective elevation and protective width. It represents the beach resistance to the storm as well as the ability to recover after the storm. Therefore, we need to consider the volume density as a factor.

3. The third factor is the storm-induced shoreline recession (MR). The shoreline is eroded and retreats during the storm. As a result, the protective width becomes shorter. Therefore we have to consider the actual protective width ($PW - MR$) during the storm.

COASTAL RESILIENCE INDEX

4. The fourth factor is the coastal vulnerability to storm surge and wave-induced overtopping. We consider the concept of the crest freeboard (CF), which is defined as the vertical distance from dune crest elevation to the still water level. In this study, we treat the still water level as the summation of maximum storm surge (MS) and Mean High Water (MHW). According to the coastal engineering manual, the crest freeboard is crucial for the prediction of overtopping.

5. The fifth factor is about wave run-up (WR). The wave overtopping is decided by both crest freeboard and wave run-up height. In this factor, we emphasize the impact of waves. The wave run-up is calculated using the model developed by Stockdon et al. (2006).