

Impact of Climate Change in the Highway and Transportation Infrastructure Adjacent to the Coast in Urban Settings of Caribbean Countries



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Lessons Learned and Best Practices – Resilience of Coastal Infrastructure
Headquarters of the College of Engineers and Surveyors of Puerto Rico
San Juan, Puerto Rico • March 9, 2017



Good Morning!





“The benefit of this research is for the whole population. At the end of the day, the biggest issue isn’t going to be us, it’s going to be the public.”

**Mr. José E. Sánchez, Director
U.S. Army Engineer Research and Development Center
Coastal and Hydraulic Laboratory**

Coastal Transportation Infrastructure



a., b. y d. <https://www.panoramio.com>
c. <https://blog.masslive.com>
e. <https://s-media-cache-ak0.pinimg.com>

Characteristics of Puerto Rico's Highway Network



- 28,862 km, of which 454 km are freeways concentrated along the coast (200 km)
- Uniform density throughout territorial extension

Sources: **CIA World Factbook** <https://www.cia.gov/library/publications/the-world-factbook/geos/rq.html>

Autoridad de Carreteras y Transportación de Puerto Rico

http://geoserver.gis.pr.gov/geoserver/wfs?request=GetFeature&typeName=pr_geodata:g35_viales_carreteras_estatales_julio_2015&outputFormat=SHAPE-ZIP

Condition of bridges and pavements in Puerto Rico



- Condition of network pavements:
 - 80.4% “poor”
 - 16.7% “fair”
 - 2.9 % “good”

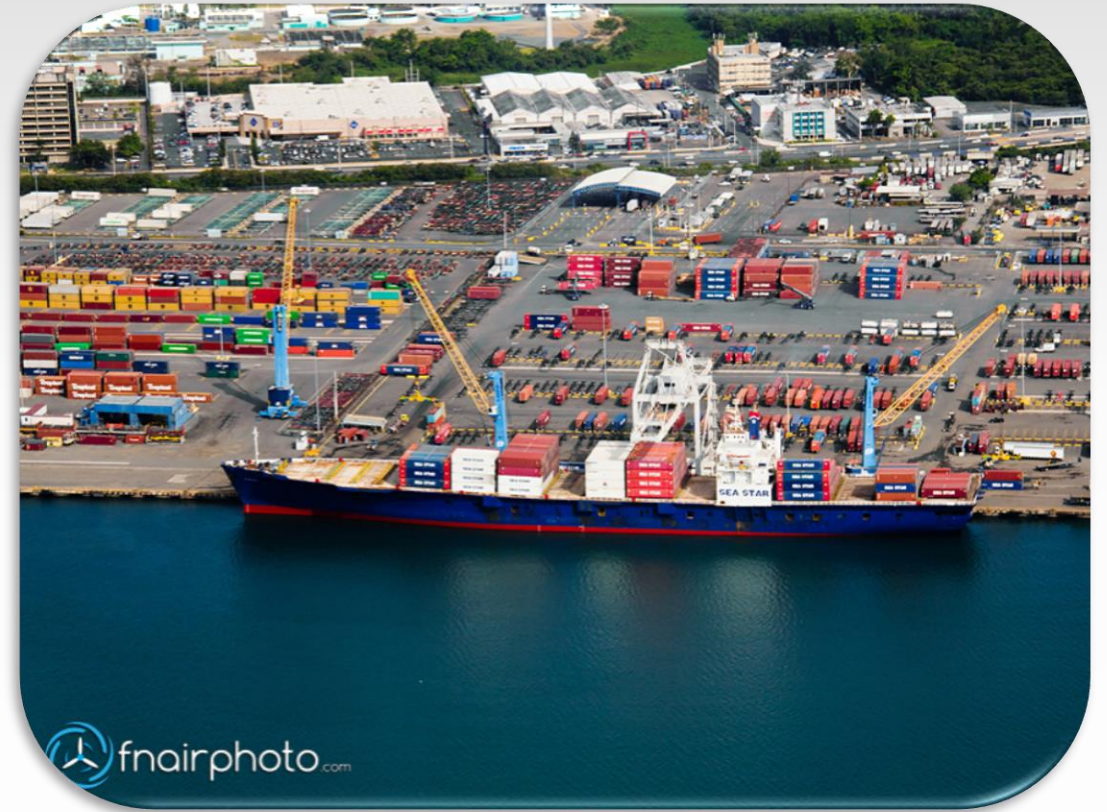
Source: Eng. Carlos Arroyo and Eng. Cándido Ayala, PRHTA, 2015



- Inventory: 2,304 bridges
 - Federal National Highway System: 780
 - Classed as deficient: 1,269
 - Functionally obsolete: 968
 - Structurally deficient: 301

Port Infrastructure of Puerto Rico

- Total foreign trade of Puerto Rico in 2015
 - **Exports:** \$ 69,391 million
 - **Imports:** \$ 43,233 million
 - **Net Balance:** \$ 26,158 million
- ***Port of San Juan*** among ***top 10 container seaports in the USA and territories*** based on trade volume: 1,319,961 TEU (2014, +3.9% growth from previous year)



Sources: Apéndice Estadístico del Informe Económico al Gobernador y a la Asamblea Legislativa, Junta de Planificación
<http://www.inboundlogistics.com/cms/article/top-10-us-container-ports/>

Characteristics of Dominican Republic's Highway Network



- 9,872 km and undergoing rapid expansion
- Greatest density towards interior and south coast

Source: <http://www.godominicanrepublic.com/wp-content/uploads/2014/02/national-map-english-spanish-roads-02.pdf>

Zona marítima in DR Ley 305, May 29, 1968

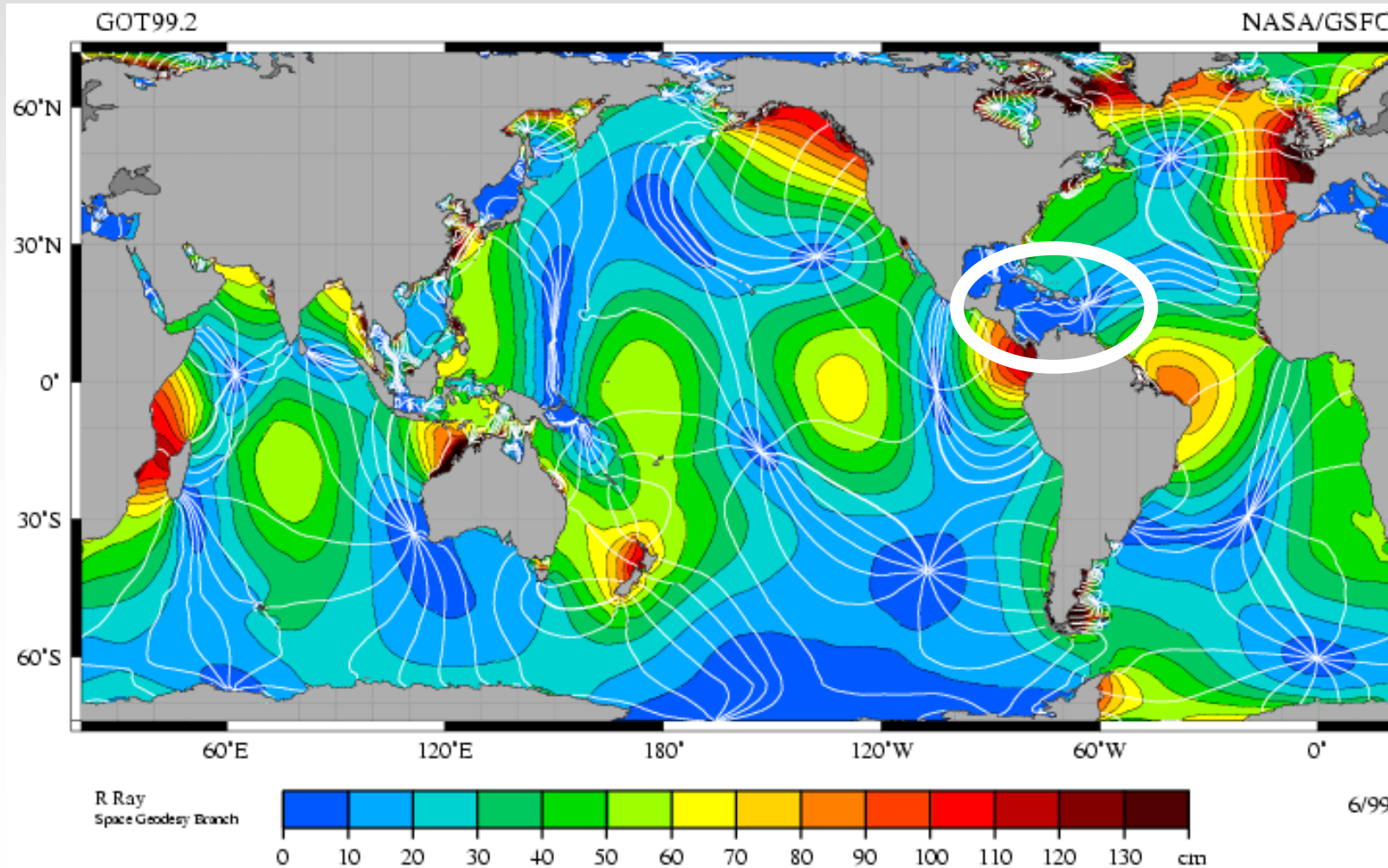
- **Sesenta (60) metros tierra adentro desde línea de pleamar** (marea alta) ordinaria, incluyendo humedales costeros
Excepciones: turístico, utilidad pública
- Extensión lineal: 1612 km

Zona marítimo-terrestre in PR, 1886

- Espacio costanero de Puerto Rico
 - Definida por reflujo de olas donde sean sensibles (significativa) las mareas
 - Definida por mayores olas de los temporales (tormentas y huracanes) donde no sean sensibles las mareas
- Origen: Ley de Puertos de España, 1880
- Extensión lineal: 1,286 km
- Reglamento 4860, DRNA

Sources: <https://web.archive.org/web/20120419075053/http://earthtrends.wri.org/text/coastal-marine/variable-61.html>
<http://www.jmarcano.com/mipais/geografia/costa.html>
<http://ojd.org.do/Normativas/INMOBILIARIA/Leyes/Ley%20Nv%20305,%20que%20modifica%20el%20articulo%2049%20de%20la%20Ley%20No%201474,%20sobre%20Vias%20de%20Comunicación,%20de%20fecha%2022%20de%20febrero%20de%201938.pdf>

Tidal Range in the Caribbean and its Relationship to Global Tidal Ranges



- Caribbean: 10 cm
- West Atlantic Ocean: 30 cm
- Context of Puerto Rico and Dominican Republic

Source: NASA http://svs.gsfc.nasa.gov/stories/topex/images/TidalPatterns_hires.tif

Coastal Zone of Puerto Rico



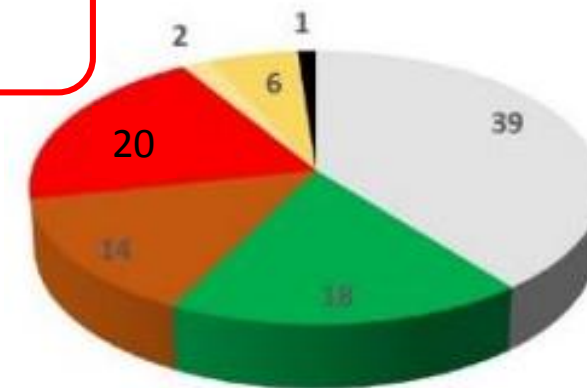
- Strip located along the land-sea interface
- Definition: land strip located up to 1,000 meters inland and the sea strip located up to 3 leagues (16.66 km or 9 miles) from the high tide coastline
- Legal basis: Coastal Zone Management Act

Source: DRNA, http://geoserver.gis.pr.gov/geoserver/pr_geodata/wms/kml?layers=pr_geodata:g27_conserv_zona_costanera

Relevant Data of the Coast of Puerto Rico



- Zona costanera (superficie terrestre): **953.9Km² (1 Km)** = 10.5% of Puerto Rico land area
- Aguas territoriales: **13,154.5 Km² (9 mn)**
- Línea de costa: **1286 kilómetros**
- Número de playas: ~**1,220**
- Frente marino ocupado: **24%**
- Municipios costeros: **44**
- Población municipios costeros: **2,317,189 (61%)**
- Aeropuertos: **10**
- Puertos: **12**
- **200** kilómetros de carreteras primarias
- **1,738** kilómetros de infraestructura sanitaria
- Complejos de generación eléctrica: **7**
- Plantas de tratamiento de aguas usadas: **13**
- Parques industriales: **81**
- Áreas terrestres protegidas: **16 % (CLCC)**
- Áreas marinas protegidas: **27.19%**



Credits: Ernesto Díaz, Department of Natural and Environmental Resources
Maritza Barreto, University of Puerto Rico at Río Piedras

Comparison of Coastal Demographics (0-10 m above sea level) of PR and DR at the Latin America and Caribbean Region

Puerto Rico

- 0.70M / 3.57 M inhabitants (7th)
- 726.7 inh/km² (7th)
- 17.2% of population (14th)



Dominican Republic

- 0.45M / 10.6 M inhabitants (9th)
- 253.5 inh/km² (9th)
- 6.1% of population (29th)



Source: GRUMP-CIESIN

Economic Activities Dependent on Coastal Transportation Infrastructure

- Import and Export of Merchandise → PR and DR are in islands
- Tourism
 - Cruise ships
 - International passengers
 - Sports and aquatic recreation
- Military defense
- Communication with adjacent islands
- Food (imports, fishing)
- **Everyday land-based transportation → coastal roads and highways**



Source: <http://www.fortaleza.pr.gov/sites/default/files/CRUCEROS%206.jpg>

Natural Threats Associated to Climate Change Impacting Coastal Zones of PR and RD



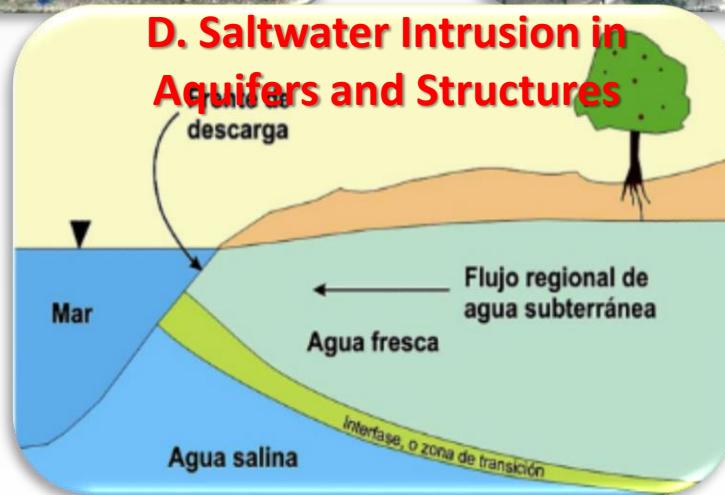
A. Sea Level Rise



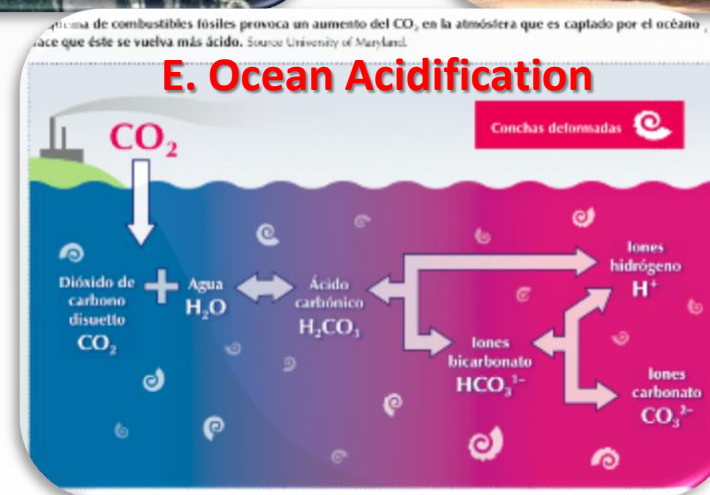
B. Storm Surge and waves



C. Lower River Flooding



**D. Saltwater Intrusion in
Aquifers and Structures**

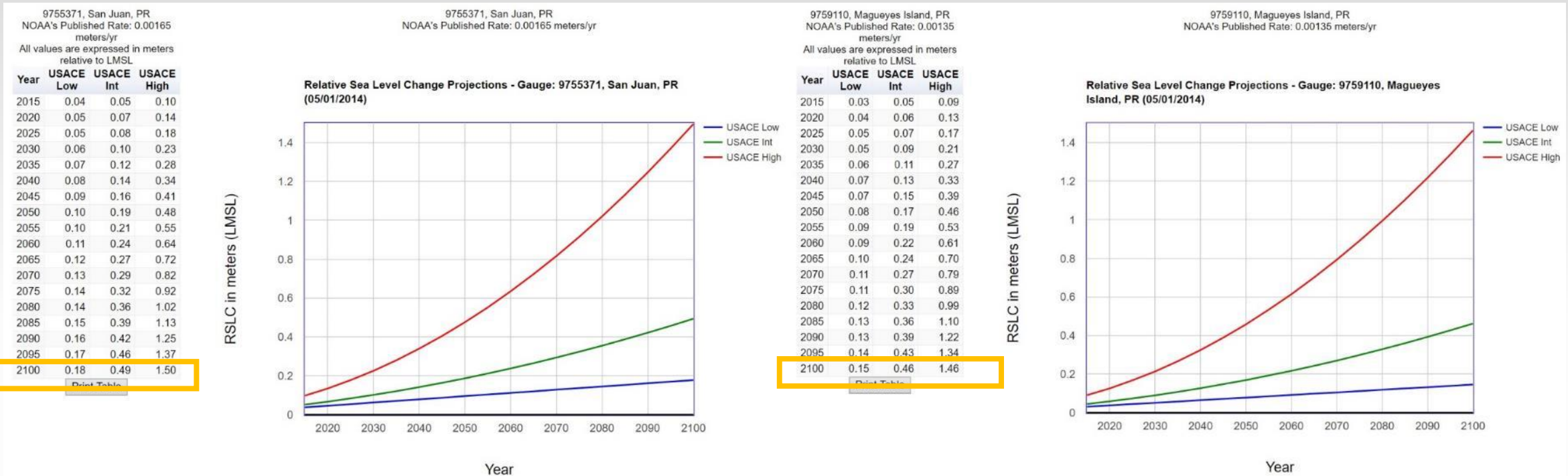


E. Ocean Acidification

- A. Credits: Dr. Aurelio Mercado, Sea Grant Puerto Rico
- B. <http://ecoexploratorio.org>
- C. <http://rec-end.gfrcdn.net>

- D. <http://www.recursosaguapuertorico.com>
- E. <https://cdn.shopify.com>

Probable Sea Level Rise Scenarios for 2100 at La Puntilla (San Juan) and Isla Magueyes (Lajas)



Likely scenarios for La Puntilla:

- Low: 0.18 m
- Medium: 0.49 m
- High: 1.50 m

Likely scenarios for Isla Magüeyes:

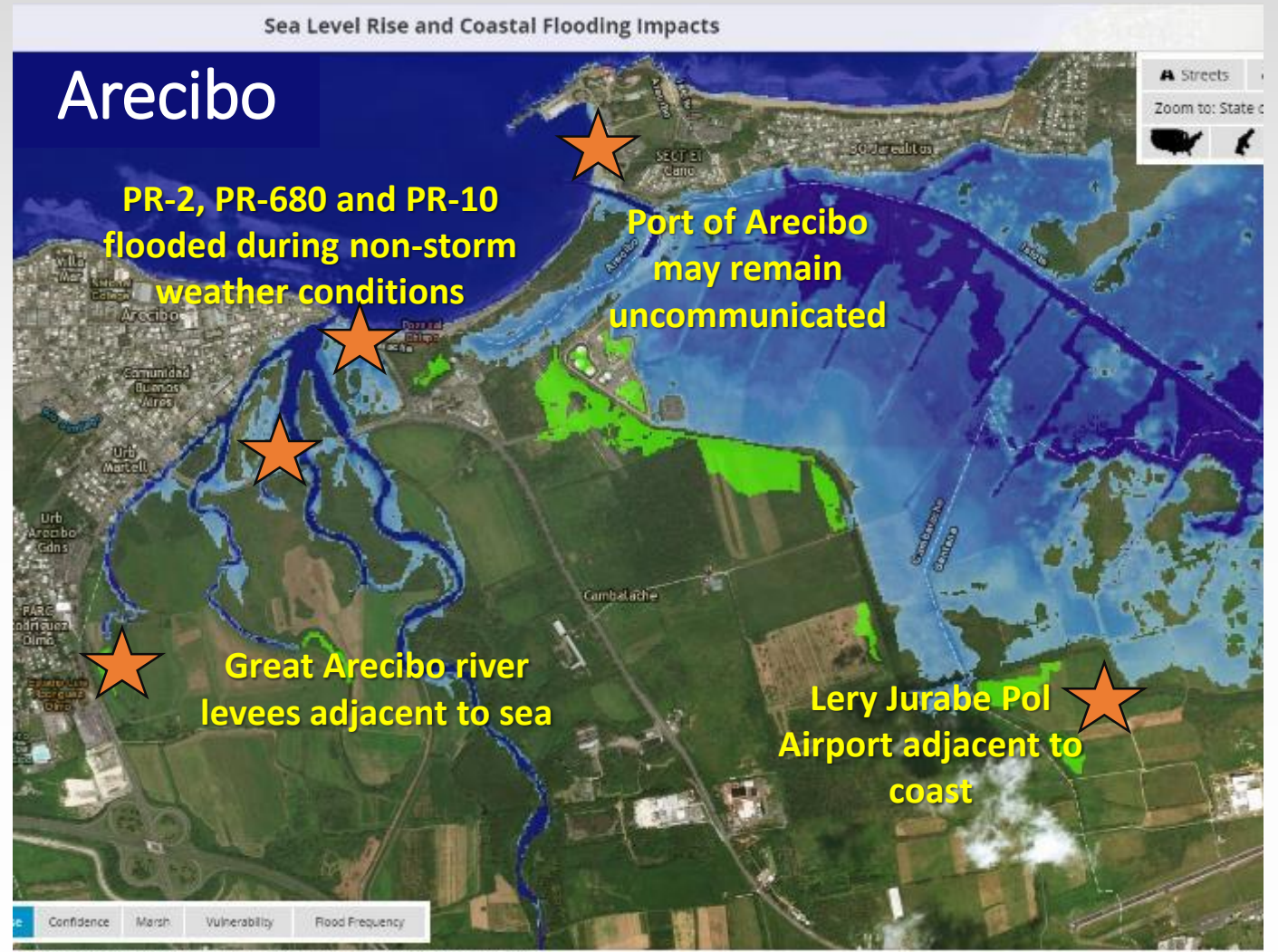
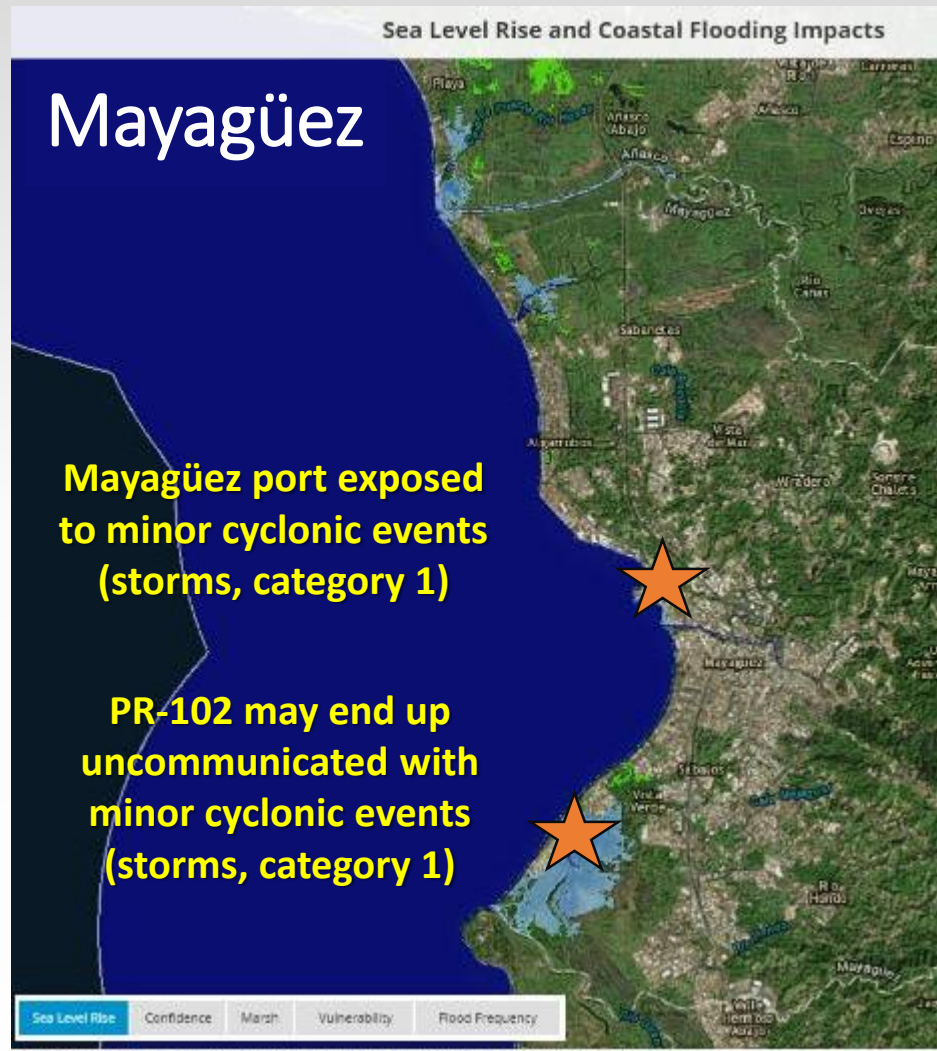
- Low: 0.15 m
- Medium: 0.46m
- High: 1.46 m

Source: Puerto Rico's State of the Climate 2010-2013, United States Army Corp of Engineers

Sea Level Rise Scenario of 1.5m at San Juan and Ponce



Sea Level Rise Scenario of 1.5m at Mayagüez and Arecibo



Source: <https://coast.noaa.gov/slr/>

Storm Surge Effects at Vega Baja, Puerto Rico



Note: direct cause was not a hurricane

Source: Google Earth

Exposure of Puerto Rico Port Infrastructure to Storm Surge

- 45% (5/11) of airports located at 1 km coastal zone
- Total of 12 seaports at **coastal zone**
- Considering category 5 hurricane **storm surge** adds
 - Nery Jurabe Pol Airport (Arecibo)
 - Mercedita Airport (Ponce)



Sources: Autoridad de Puertos, Junta de Planificación, CARICOOS,

“Innovación en la Infraestructura Civil en Transportación y Transporte Público en el Siglo 21” (B. Colucci)

Exposure of Airport and Seaport Infrastructure of the Dominican Republic



71% of 14 airports of Dominican Republic are within 1 km of coastal zone

Sources: <http://www.godominicanrepublic.com/wp-content/uploads/2014/02/mapa.pdf>

Google Earth



69% (9/13) of Dominican Republic seaports located along Caribbean Sea coast

Sources:
<http://www.apordom.gob.do/sistema-portuario.html>
<http://www.caribetrans.com/app/do/maritimo.aspx>

Infrastructure Prone to Corrosion Damage

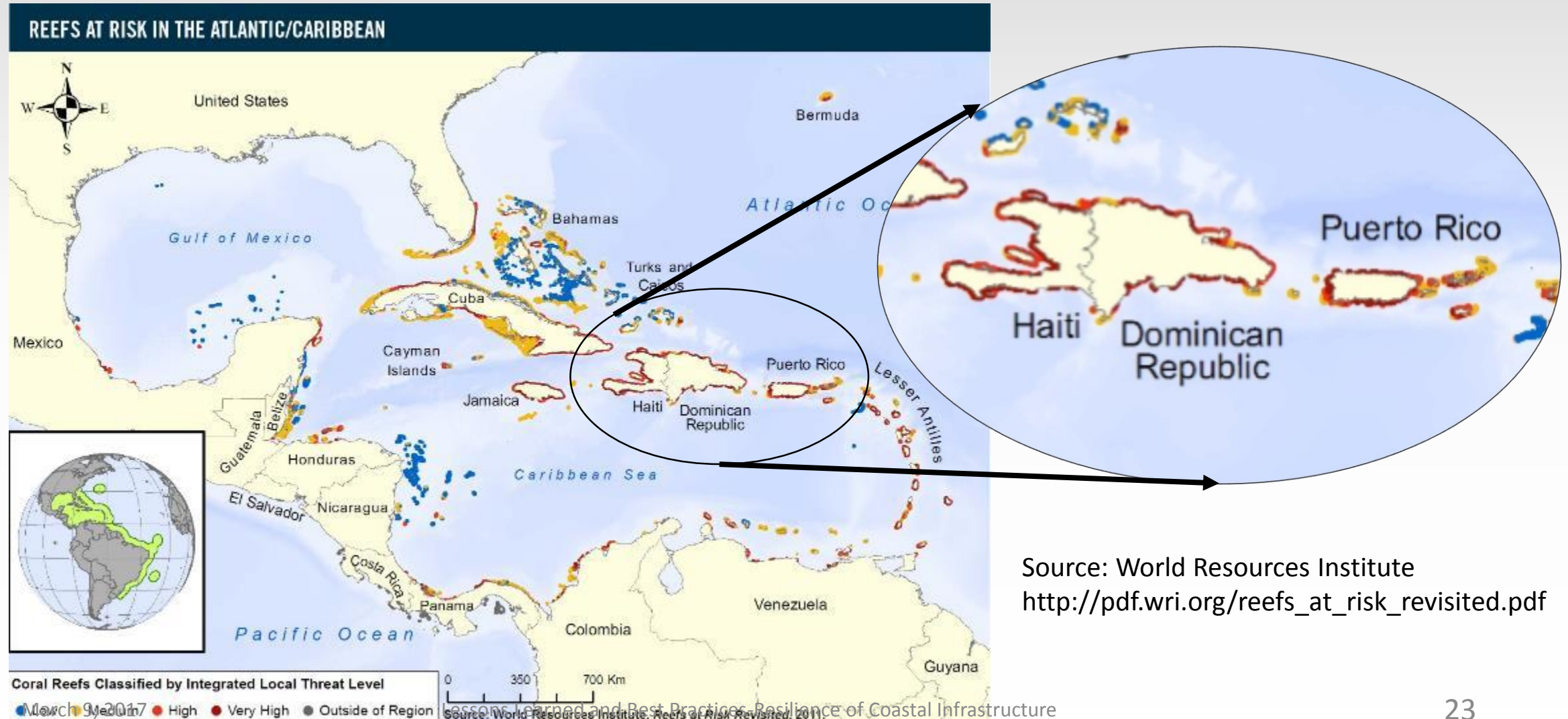


- Vulnerable transportation infrastructure
 - Docks
 - Highway bridges
 - Rigid pavements in highways and runways
 - Navigation aid buildings (lighthouses, air traffic control towers)
- Other vulnerable components
 - Retaining walls
 - Levees
 - Storm drain grates and channels

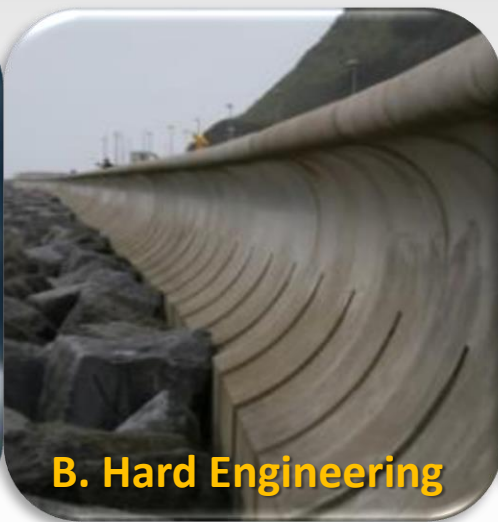
Sources: <http://www.panoramio.com/photo/10101327?source=wapi&referrer=kh.google.com>
https://c6.staticflickr.com/9/8226/8590114813_cbc64abc37_b.jpg

“Challenges of Electrical Tests for Chloride Permeability in Concrete”, A. Molano

Ocean Acidification is a Driver of Coral Reef Damage



Adaptation Strategies



Supported by information and efficient resource use

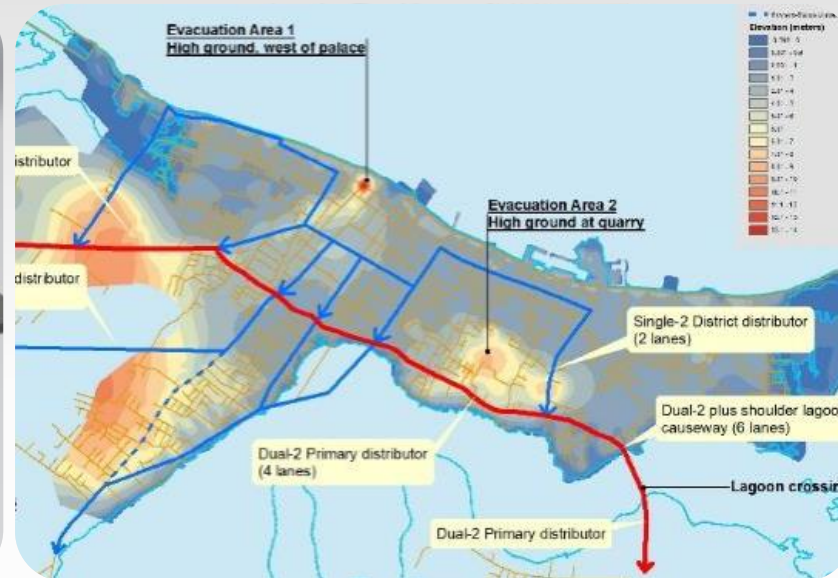
- A. <http://uconn-today.universityofconn.netdna-cdn.com>
- B. <https://classconnection.s3.amazonaws.com>
- C. <https://sites.google.com>

- D. <http://www.climatechwiki.org>
- E. <http://www.ssesb.com>

A. Alternative Emergency Management Practices



A. Unmanned Aerial Vehicles (UAVs or 'drones')



B. Evacuation Route Access Management



C. Multimodal Evacuation Plans

TRR 2532:

“Unmanned Aircraft Systems used for Disaster Management”

“Multimodal Evacuation Simulation and Scenario Analysis in Dense Urban Area: Philadelphia, Pennsylvania, Case Study”

“Selecting Four-Leg Intersections for Crossing Eliminations in Evacuations”

“Hurricane Evacuation Route Choice of Major Bridges in Miami, Florida”

Images:

A. John Fischer in LinkedIn

B. FastAnswers.com

C. The Decatur Daily

B. Hard Engineering



A. Permanent barriers



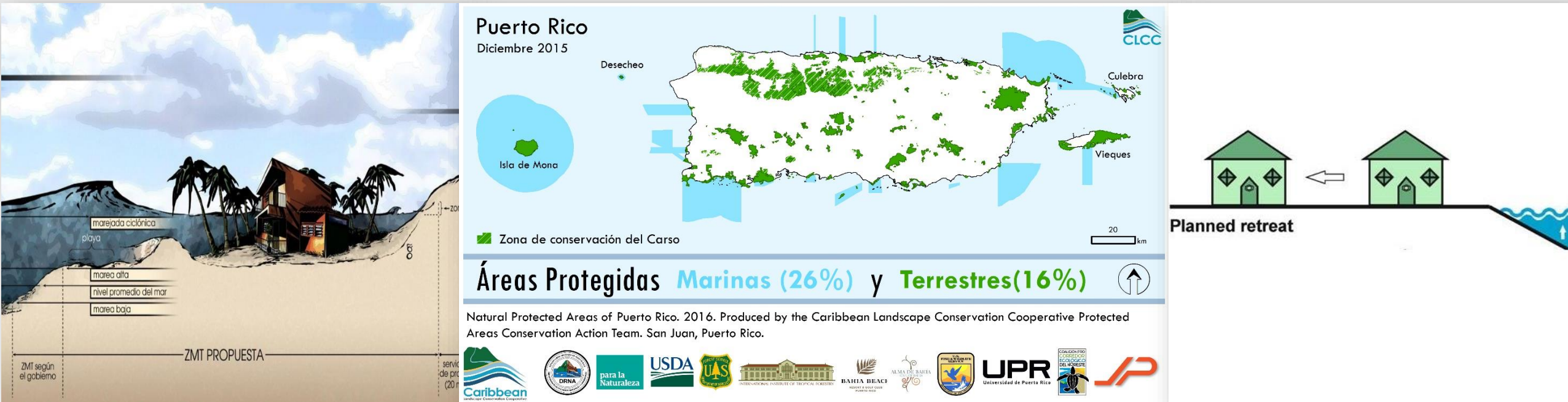
B. Deployable barriers



C. Structure retrofitting
and/or re-design

Credits: A. <http://blog.ucsusa.org>; B. <http://images.dailyhive.com> C. <http://www.asbi-assoc.org>

C. Planned Relocation



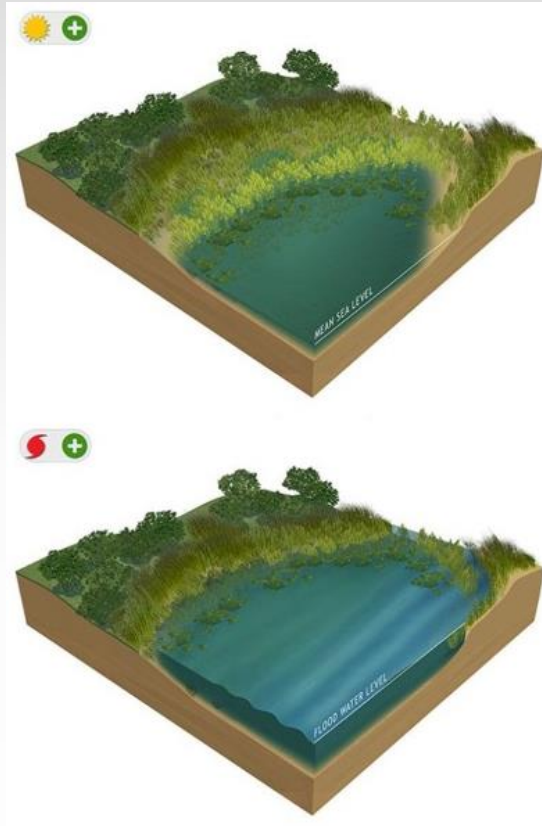
A. Redefined coastal zone

B. Formation of protected coastal areas

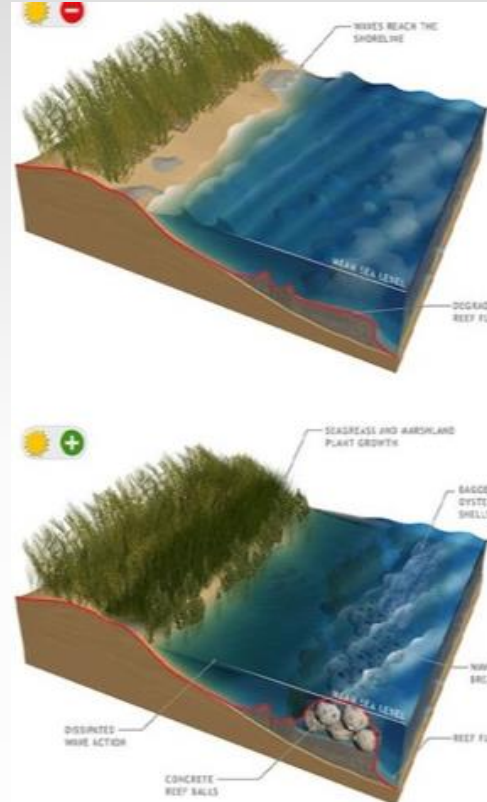
C. Inland relocation

Credits: A. Ruperto Chaparro, Sea Grant B. cienciapr.org C. Ernesto Arroyo, DRNA

D. Green Engineering



A. Wetland Restoration



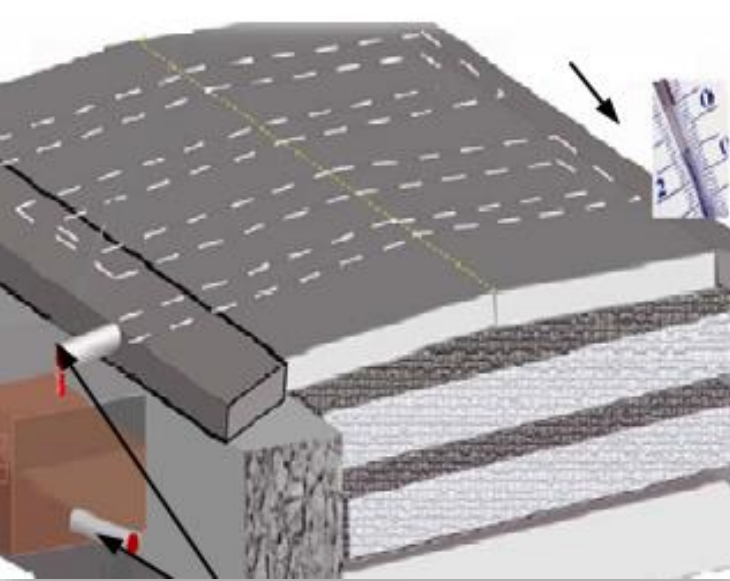
B. Artificial Reefs



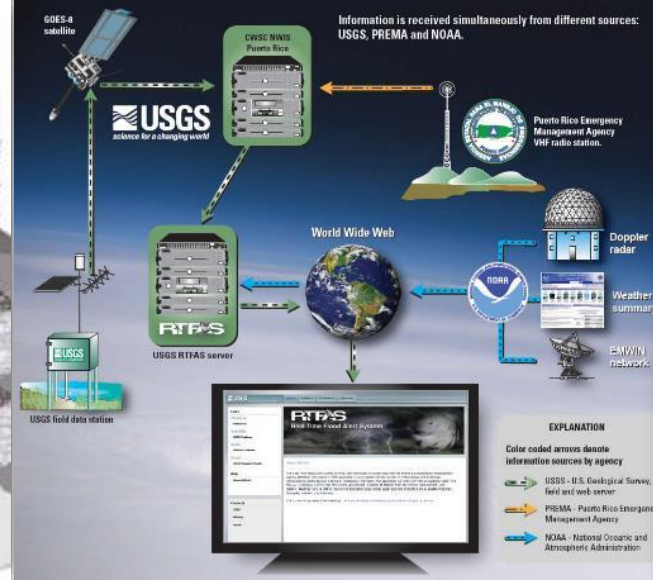
C. Beach Nourishment

Credits: (A, B) Ernesto Díaz, Department of Natural and Environmental Resources; C. Ruperto Chaparro, Sea Grant

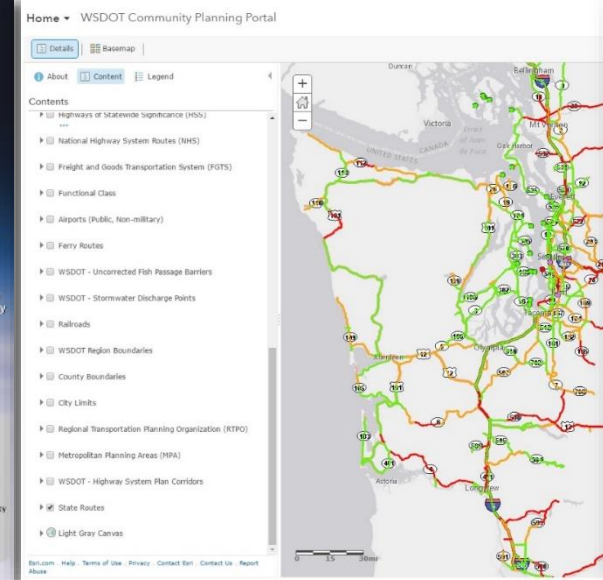
E. Use of Technology



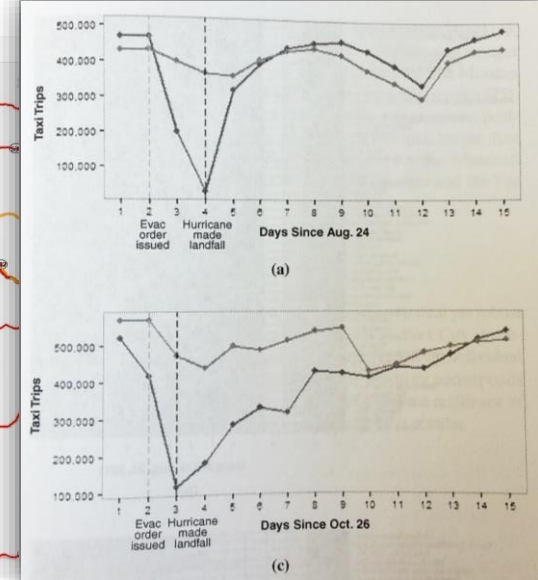
A. Instrumented pavements



B. Real Time Alert Systems



C. Geographic Information Systems (GIS)



D. Data mining for evacuation response

Credits:

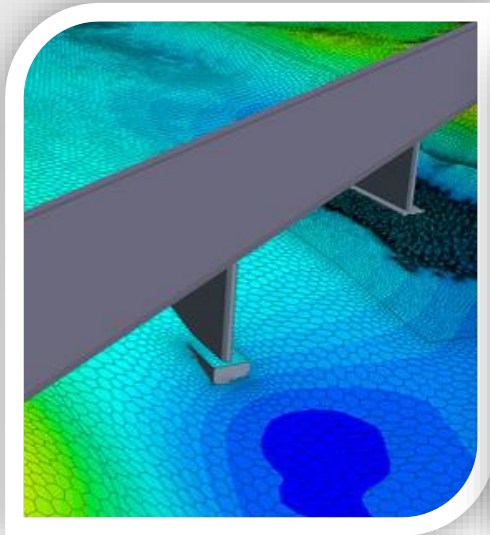
A. "Remote Pavement Weather Sensing and applications for the Transportation Industry" Surface Systems Inc., Research Gate;

B. "Revisión de inundaciones históricas en Puerto Rico", José M. Rodríguez, PE, USGS.

C. Washington DOT <http://wsdot.maps.arcgis.com/>

D. TRR 2599 "Using Big Data to Study Resilience of Taxi and Subway Trips for Hurricanes Sandy and Irene"

EDC-4 Initiatives Related to Resilience and Climate Change



Collaborative
Hydraulics



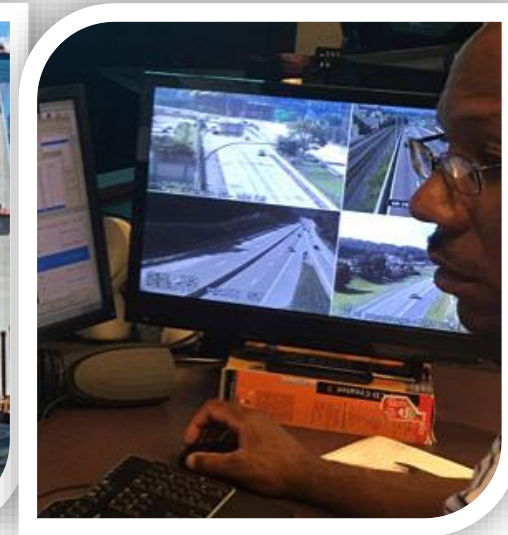
Road Weather
Management



Advanced Traffic
Signal Performance
Measures



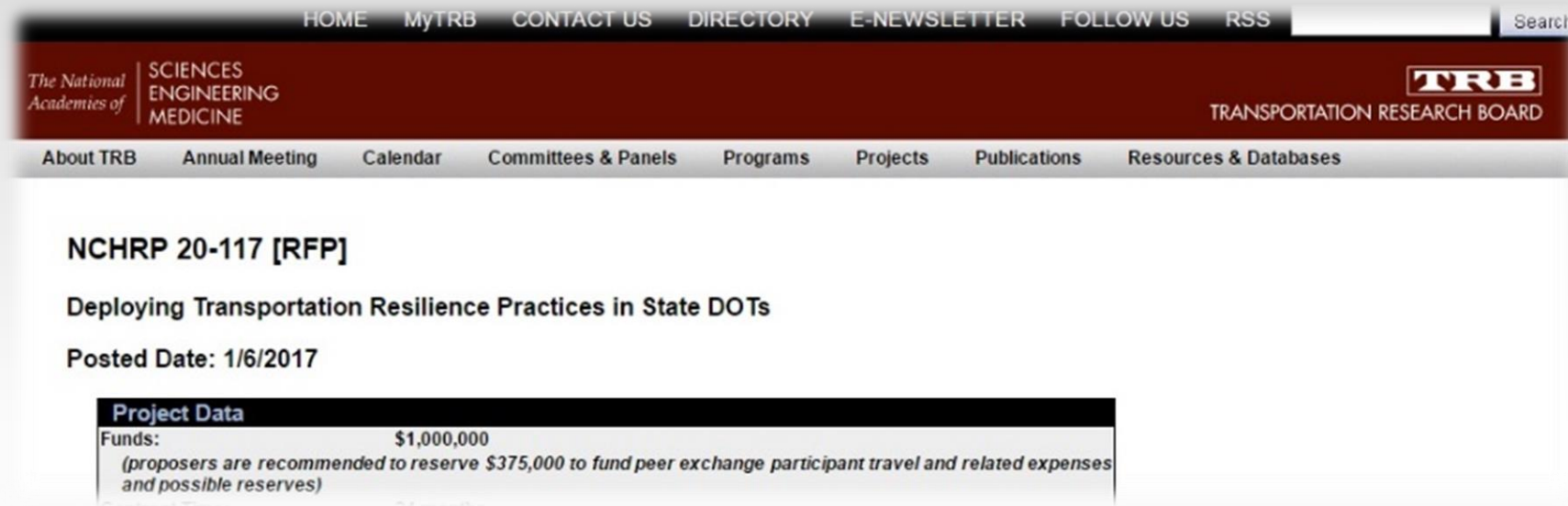
Integration of NEPA
and Permitting



Using data to
improve Traffic
Incident
Management

Sources: https://www.fhwa.dot.gov/innovation/everydaycounts/edc_4/, El Nuevo Día

Deployment of Resilience Practices at State DOTs



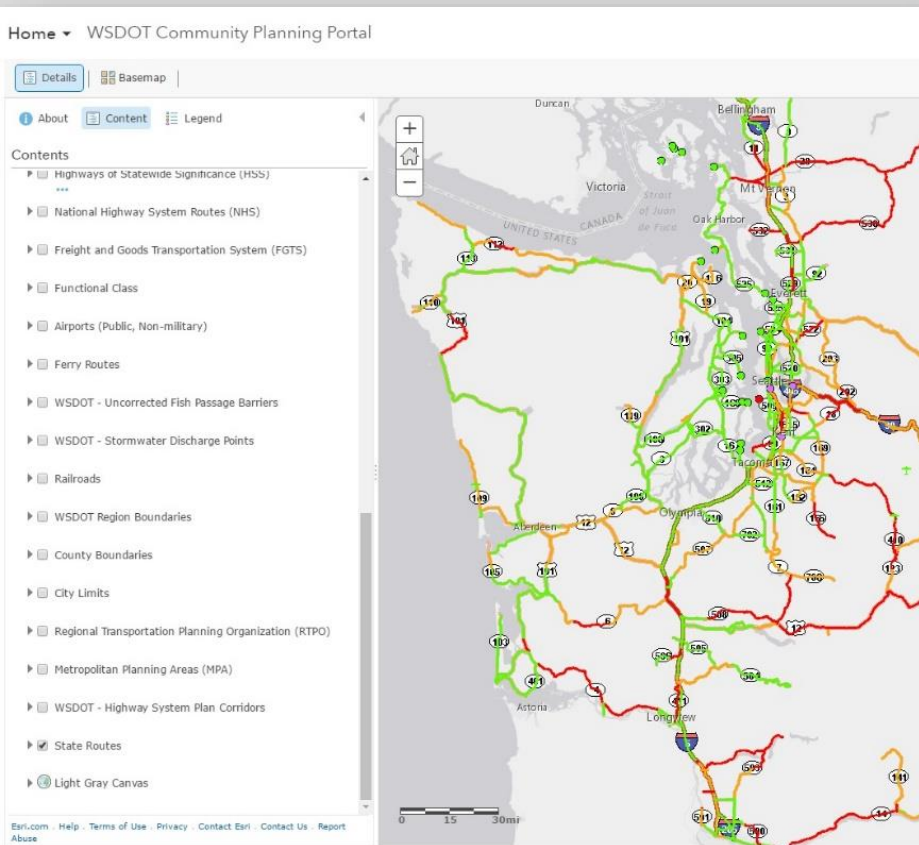
NCHRP Project 20-117: Joint Project of NCHRP, AASHTO, USDOT and National Research Council

Intended outcomes

- Tools and guidelines for transportation resilience
- National Summit and peer Exchange for transportation resilience

Source: <http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4208>

Examples of State DOT initiatives



A. Washington DOT Community Planning Portal

A. <http://wsdot.maps.arcgis.com/home/webmap/viewer.html?webmap=927b5daaa7f4434db4b312364489544d>

B. : GIS For Decision Support and Public Policy Making (book)

C. http://www.dot.ca.gov/newtech/researchreports/preliminary_investigations/docs/resiliency_metrics_preliminary_investigation.pdf



Figure 4.3 Map shows the areas in Miami-Dade County flooded in several severe tropical storms, including Irene and Gordon.

B. GIS for Flood Impact Mitigation, Florida

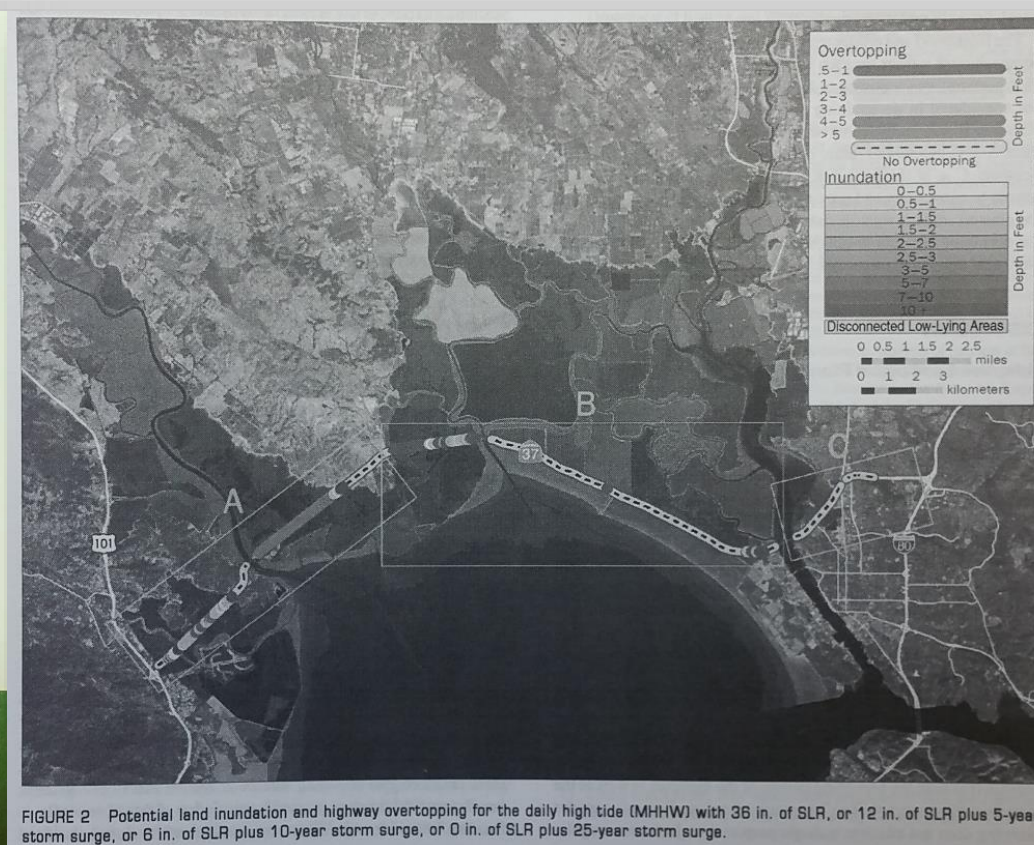


FIGURE 2 Potential land inundation and highway overtopping for the daily high tide (MHW) with 36 in. of SLR, or 12 in. of SLR plus 5-year storm surge, or 6 in. of SLR plus 10-year storm surge, or 0 in. of SLR plus 25-year storm surge.

C. Caltrans Resilience Metrics for Transportation Planning