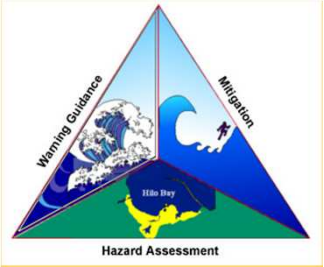
Tsunami Flood Map Development for Puerto Rico

National Tsunami Hazard/Risk Analysis Workshop

July 25-26, 2012

Pacific Marine Environmental Laboratories
NOAA
Seattle, WA



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Marine Sciences, UPRM

• Model: NOAA/Method Of Splitting Tsunamis (MOST) v 2.5 rev.912 (obtained from PMEL; hydrostatic non-linear shallow water equations)

• Topographic/bathymetry data (National Geophysical Data Center PR DEM, 2007) (10x10 meters resolution)

• Sources: For **local** tsunamis see : http://poseidon.uprm.edu/public/Final-Reports/huerfano/PRTWMP-Final%20Report-Task_1-Mode-of-Faulting-in-the-Local-Zone-of-Puerto-Rico.pdf by Dr. Victor Huerfano, Director, Puerto Rico Seismic Network/Department of Geology/Univ. of Puerto Rico. A total of 269 faults all around the island (see below). These are supplemented by 6 faults representing "historical" events, and suggested by different experts (published as a USGS Open File Report).

• Sources: For **regional** tsunamis: under discussion. For **far-field** tsunamis we will include the 1755 Lisbon event (several scenarios).

• Methodology: Each of the fault scenarios is modeled. Inundation outer grid has 60 arc sec resolution. Inundation intermediate grid has 9 arc sec resolution. For the inundation inner grids the island was broken down into three parts: West, Central, and East (see below). Each with a computational cell size of 1 arc second (approximately 30x30 meters). Results (see below) are output for each part, and then a mosaic is created based on joining the three parts.

OUTPUT/RESULTS

For the propagation modeling:

- Bottom deformation
- Maximum Sea Surface Elevation relative to MSL all over the propagation grid.
- Movie showing the propagation in the propagation grid.

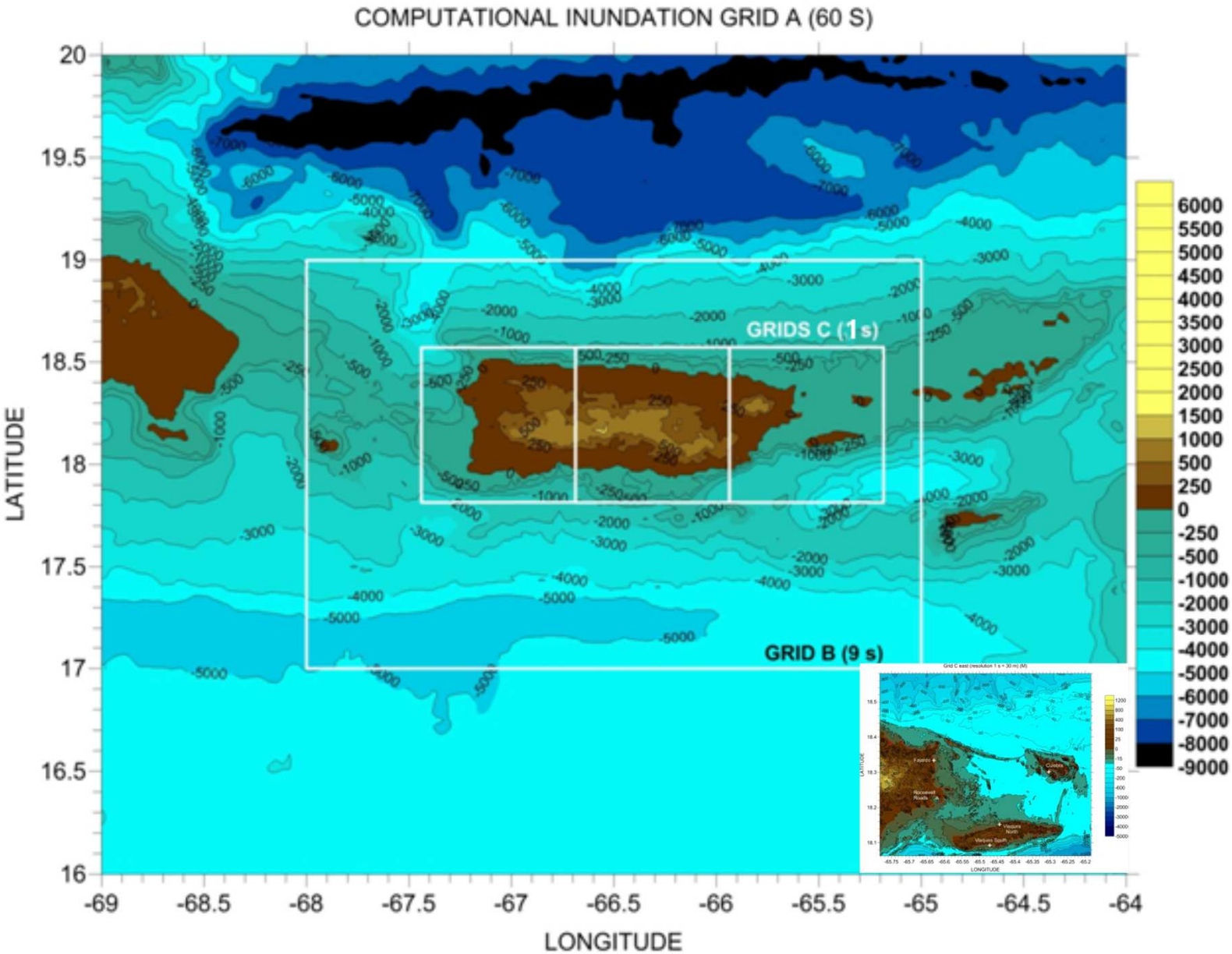
For each island part (West, Central, and East) the following is output in each inundation grid:

- Figure showing Maximum Envelope Of Highest Waters relative to MSL (MEOHW).
- Figure showing the same as above but relative to terrain elevation (called Local Water Depth (LWD) – shown only inland of MSL shoreline.
- Maximum water particle velocity all over the computational grid
- Same as above, but just inland of MSL shoreline.
- Google Earth KMZ of LWD and Particle Velocity (just inland of MSL shoreline)
- Movie of wave propagation.

For the mosaic based on all three parts put together:

- Figure showing Maximum Sea Surface Elevation relative to MSL
- Figure showing the same as above but relative to terrain elevation (called Local Water Depth (LWD) – shown only inland of MSL shoreline.
- Same as above but with streets overlaid on top.
- Maximum water particle velocity all over the computational grid
- Same as above, but just inland of MSL shoreline.

- Google Earth KMZ of LWD
- For each mosaic we also produce a figure showing the sea surface elevation in the surrounding areas stratified into three elevations: 0 to 0.3 m (blue), 0.3 – 1.0 m (gold - ADVISORY), and > 1 m (red - WARNING).
- Same as above (ADVISORY AND WARNING) but just for inland flooding (Local Water Depth).
- Same as above (ADVISORY AND WARNING) but in KMZ format.
- Next we go through all of the output MEOHW's and we get the Maximum of the Maximums (MOM) to get one final map showing the inland extension, and elevations, of the tsunamis. This will be presented as KMZ and shapefiles.
- The databank of modeled tsunamis can serve as the starting set of more scenarios that can be used to make more specific real-time Advisories and Warnings.


COMPUTATIONAL INUNDATION GRID A (60 S)
GRIDS C (1 s)
GRID B (9 s)
LATITUDE
LONGITUDE
20
19.5
19
18.5
18
17.5
17
16.5
16
-69
-68.5
-68
-67.5
-67
-66.5
-66
-65.5
-65
-64.5
-64
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
250
0
-250
-500
-1000
-2000
-3000
-4000
-5000
-6000
-7000
-8000
-9000

SOURCES

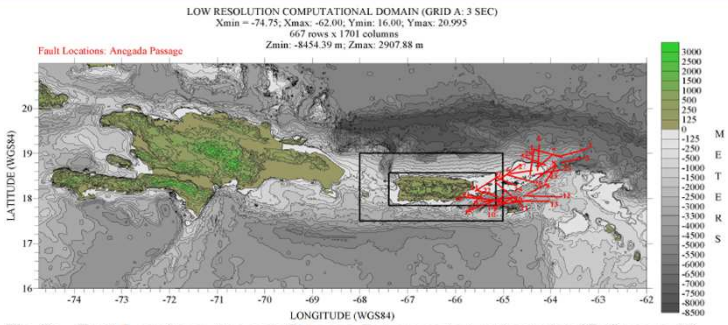


Fig. 2a - Fault Locations: Anegada Passage. Return period estimated at 3762 years. 28 faults.

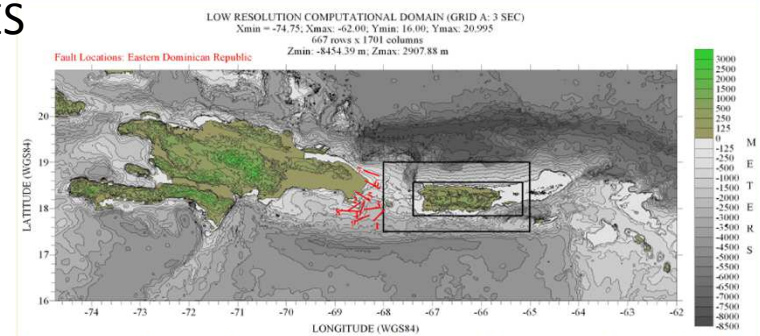


Fig. 3a - Fault Locations: Eastern Dominican Republic. Return period estimated at 807 years. 9 faults.

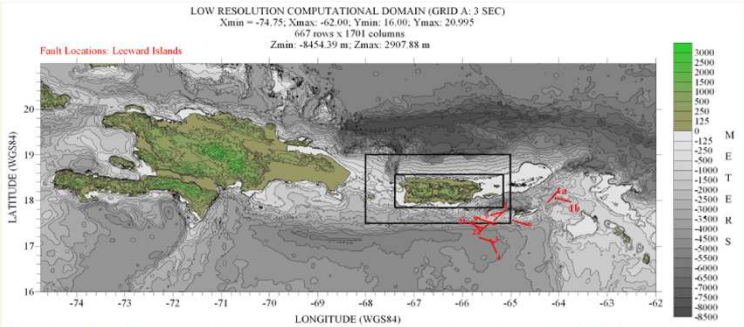


Fig. 4a - Fault Locations: Leeward Islands. Return period estimated at 3053 years. 11 faults.

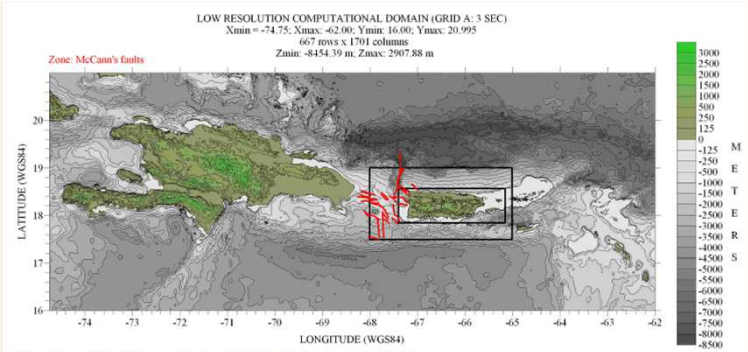


Fig. 5a - Fault Locations: McCann faults. 31 faults.

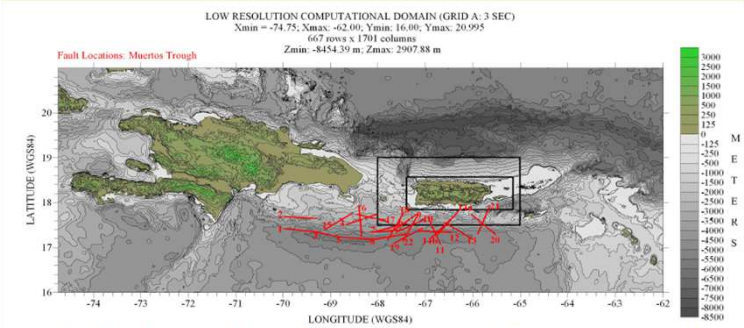


Fig. 7a - Fault Locations: Muertos Trough. Return period estimated at 3092 years. 23 faults.

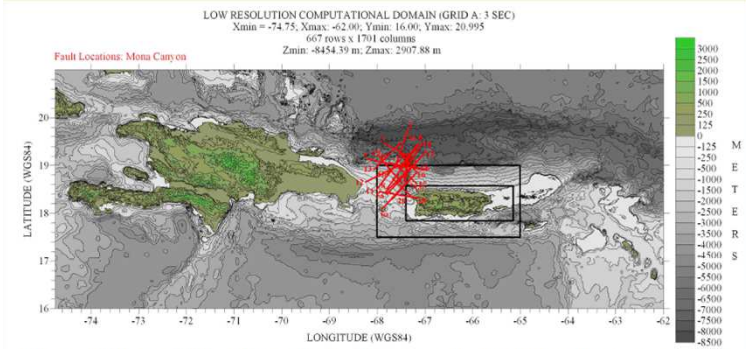


Fig. 6a - Fault Locations: Mona Canyon. Return period estimated at 2083 years. 24 faults.

SOURCES

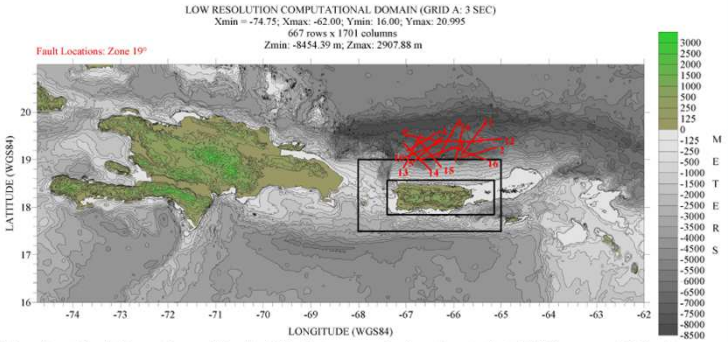


Fig. 8a - Fault Locations: North 19°. Return period estimated at 3382 years. 16 faults.

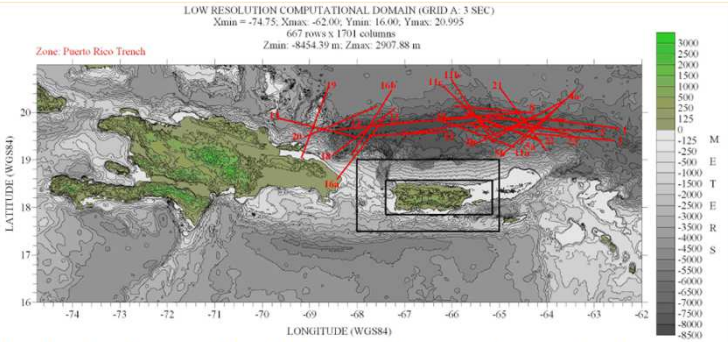


Fig. 10a - Fault Locations: Puerto Rico Trench. Return period estimated at 3841 years. 28 faults.

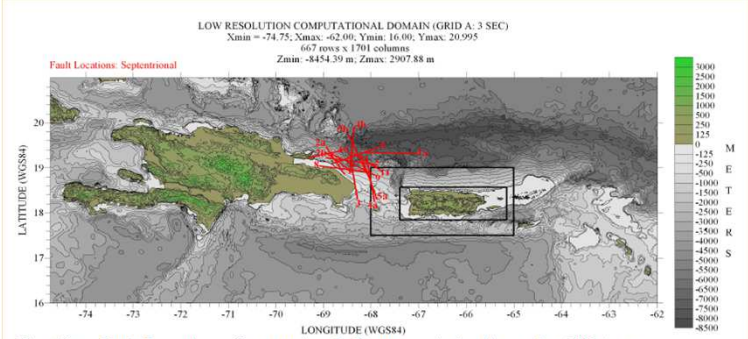


Fig. 12a - Fault Locations: Septentrional. Return period estimated at 795 (von Hillebrandt), or 450 (McCann) years. 14 faults.

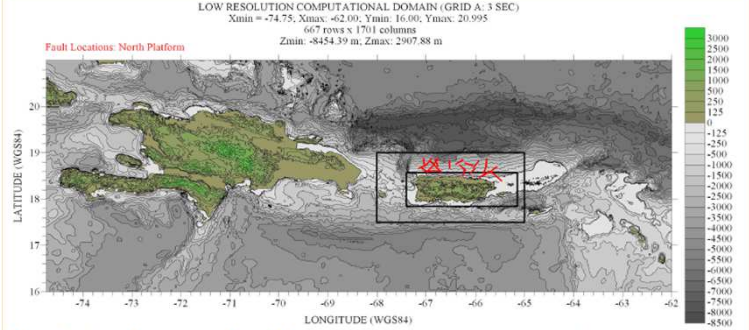


Fig. 9a - Fault Locations: North Platform. Return period estimated at 2506 years. 25 faults.

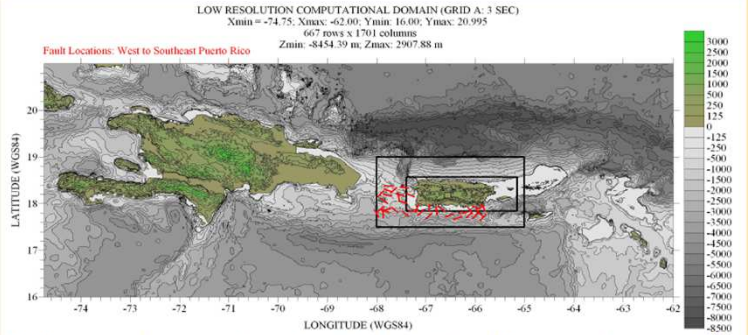


Fig. 11a - Fault Locations: Puerto Rico West to Southeast. Return period estimated at 1823 years. 36 faults.

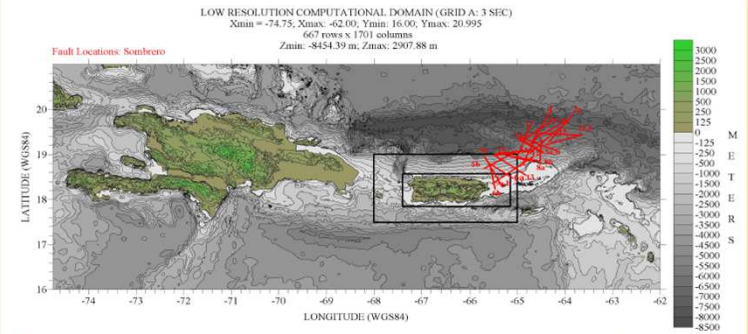
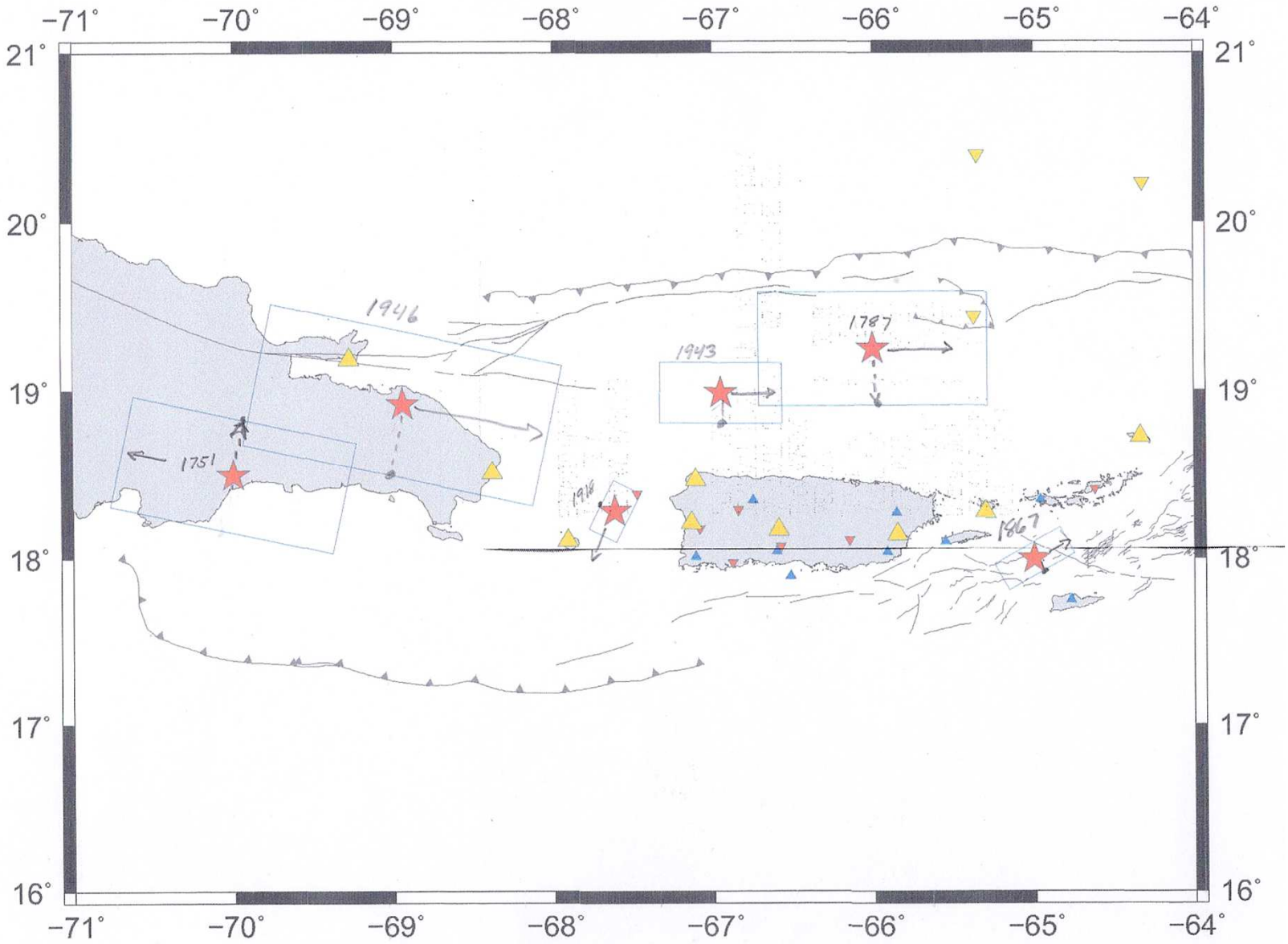


Fig. 13a - Fault Locations: Sombrero region. Return period estimated at 1241 years. 24 faults.

Ali_etalSources



GMT 2011 Mar 15 12:17:12 generated by script PRVleqplotter.gmt

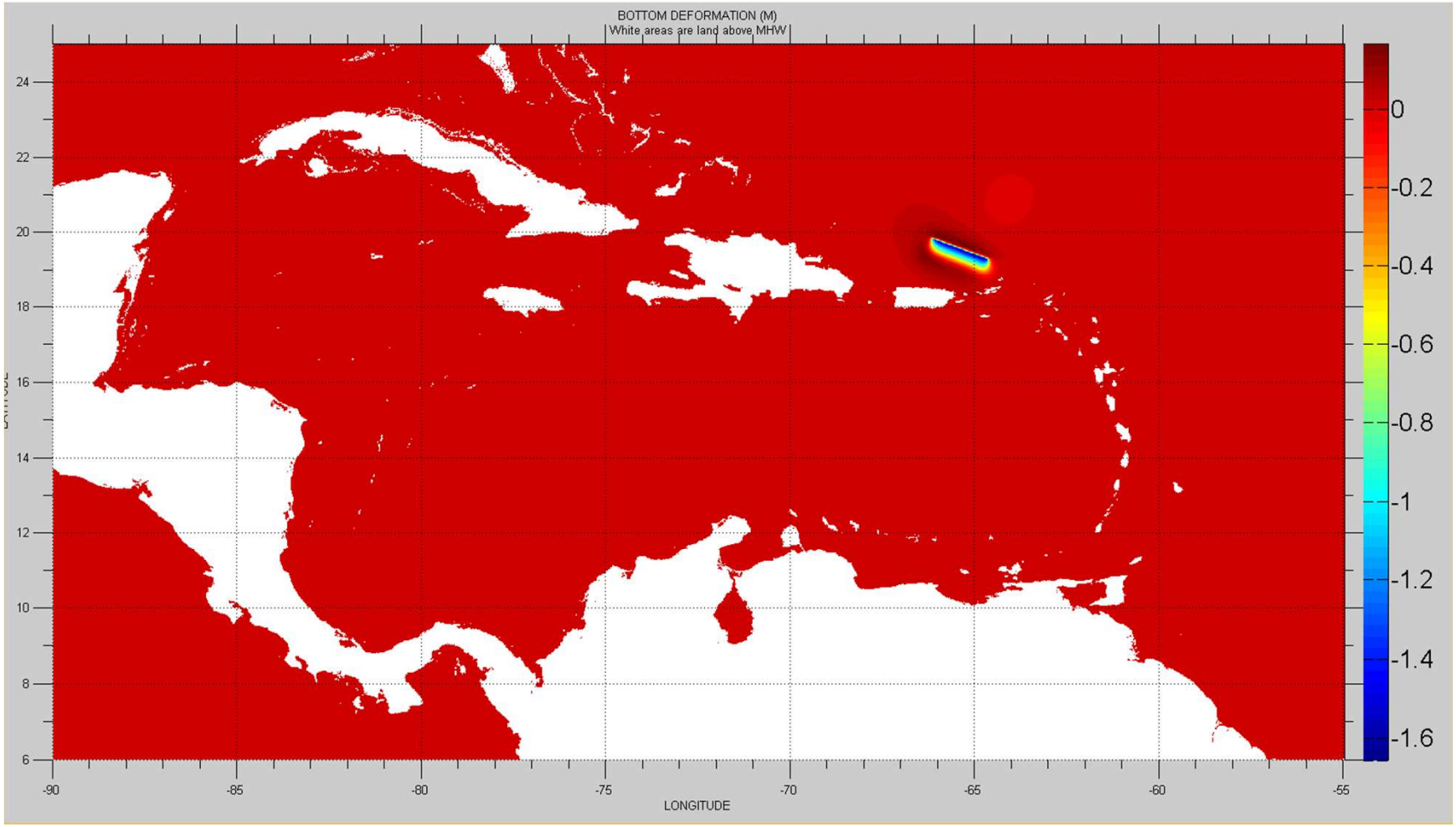
Example: Mw 8.1 at the Puerto Rico Trench (Local fault: /V/PRT/f13)

Length = 174 km, Width = 50.69 km, Dip = 40, Rake = -120, Strike = 111, Slip = 3.2 m, Depth = 4 km

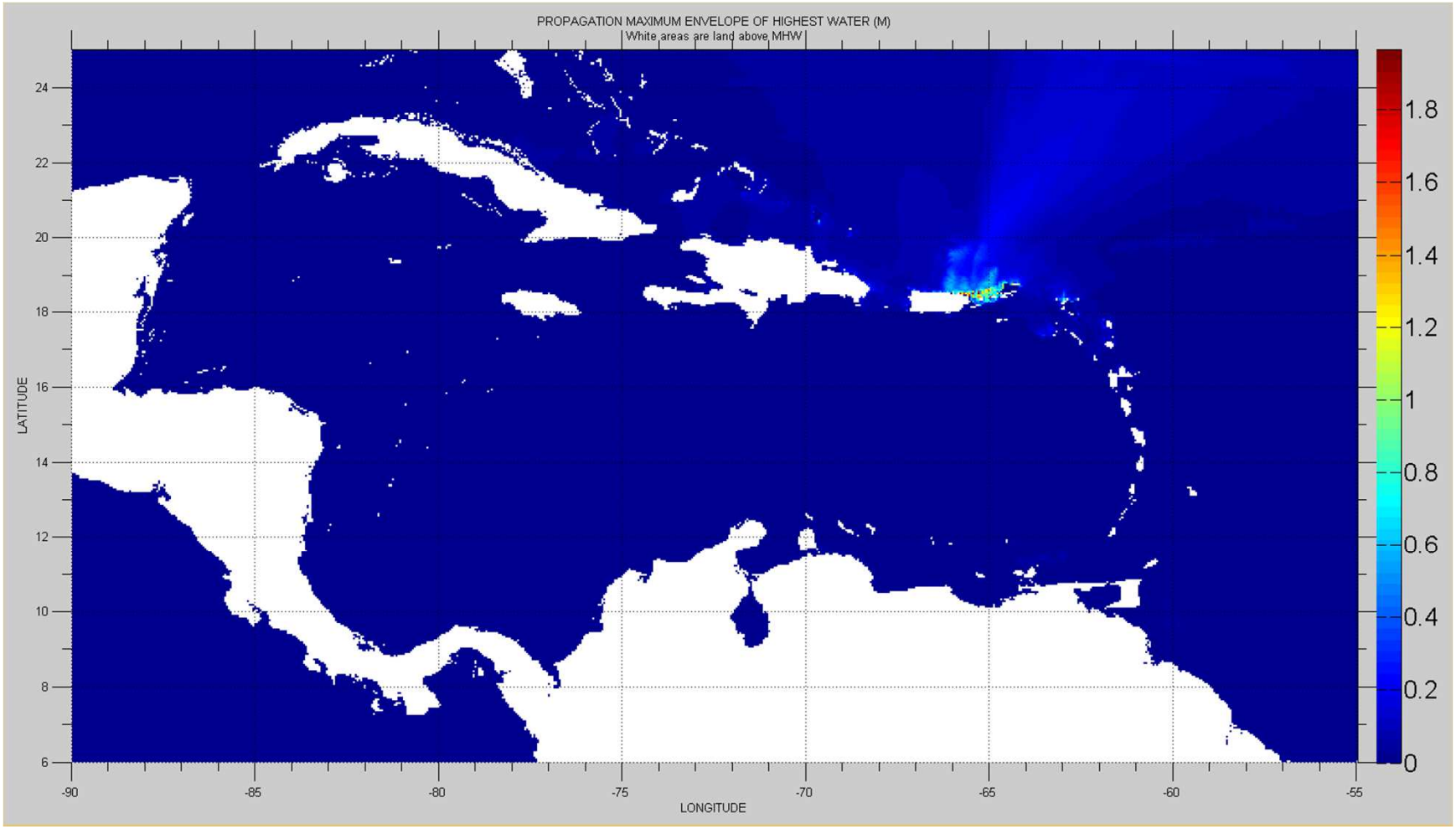
Ref: http://poseidon.uprm.edu/public/Final-Reports/huerfano/PRTWMP-Final%20Report-Task_1-Mode-of-Faulting-in-the-Local-Zone-of-Puerto-Rico.pdf

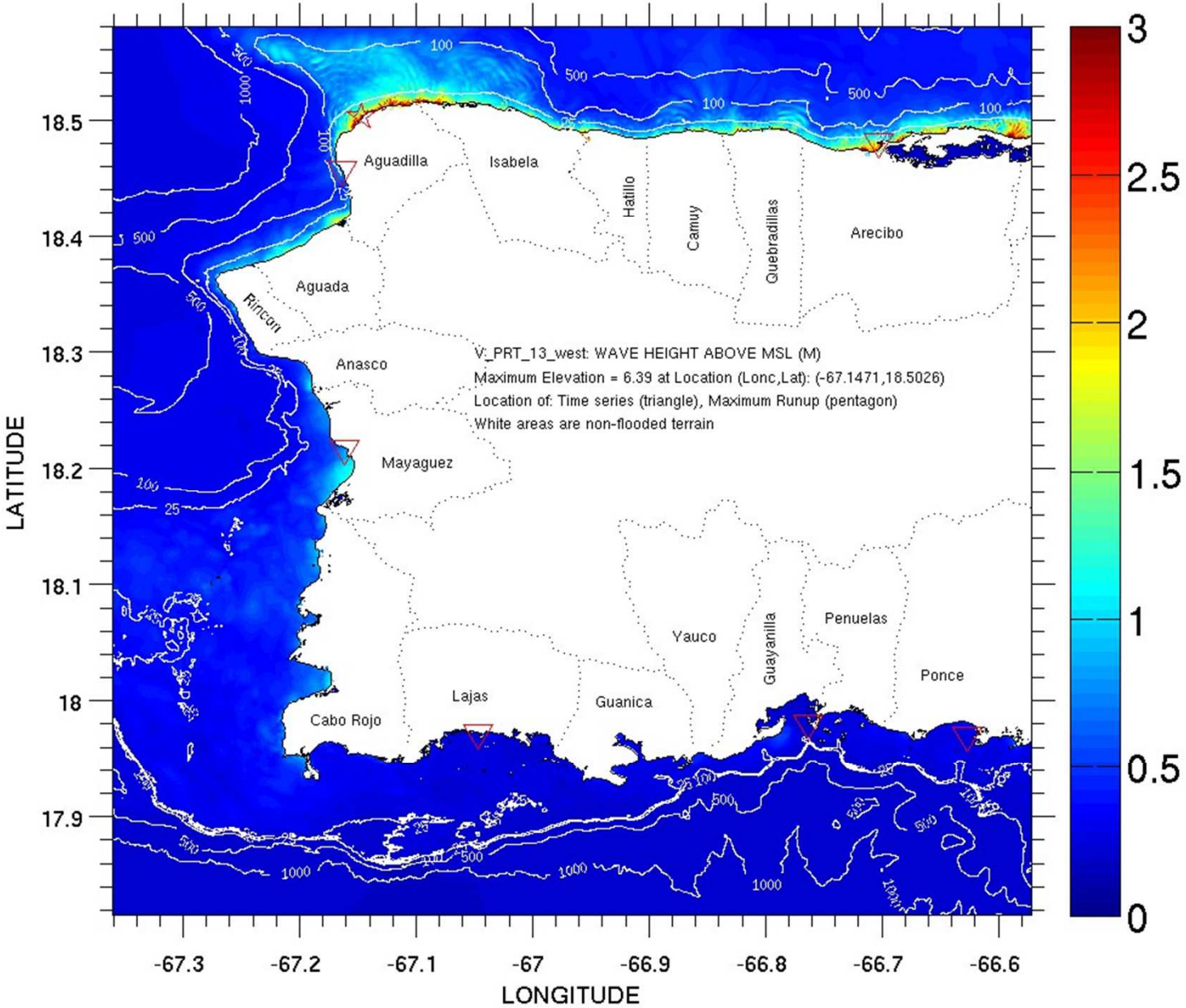
by

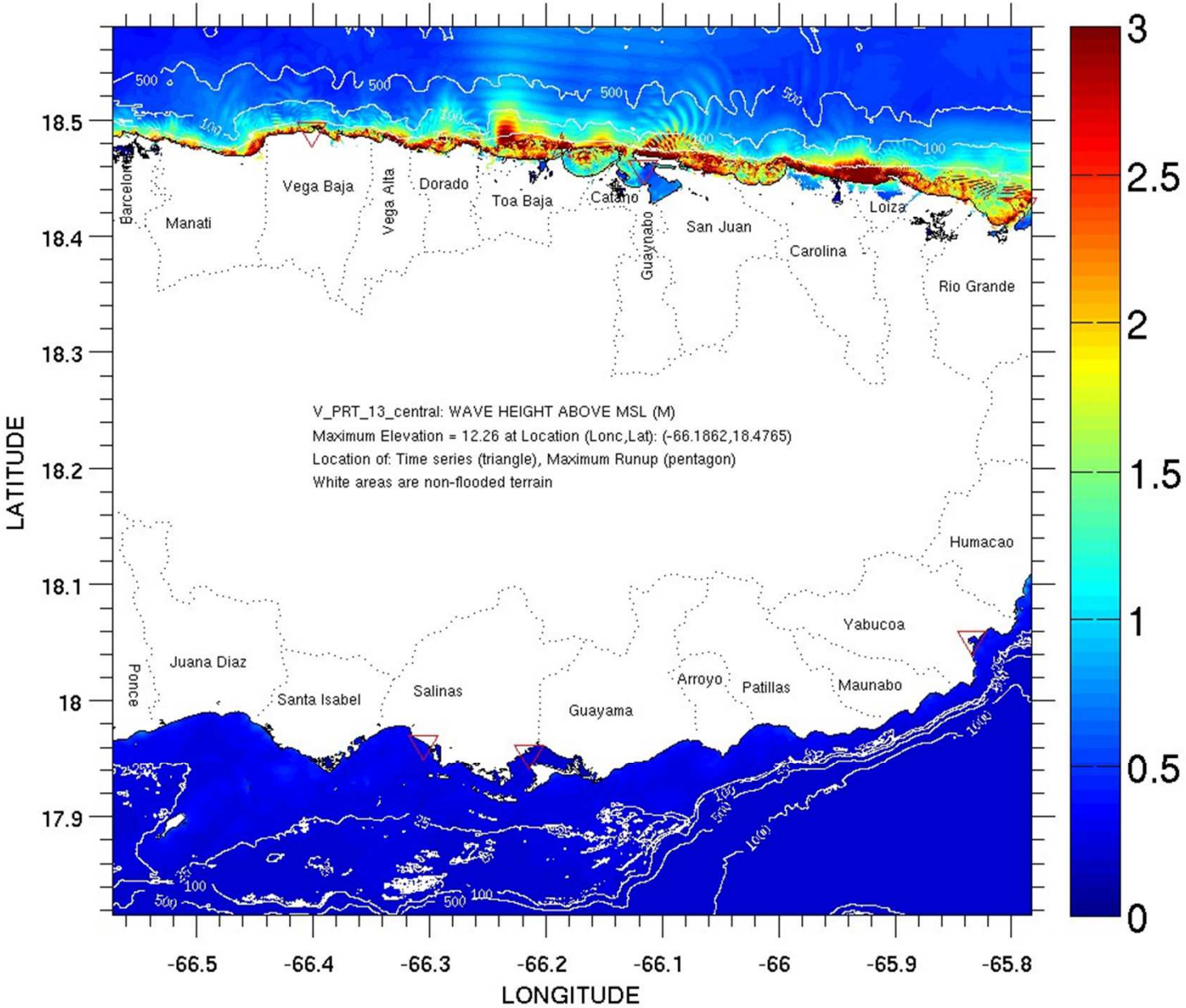
Dr. Victor Huerfano, Director, Puerto Rico Seismic Network/Department of Geology/Univ. of Puerto Rico

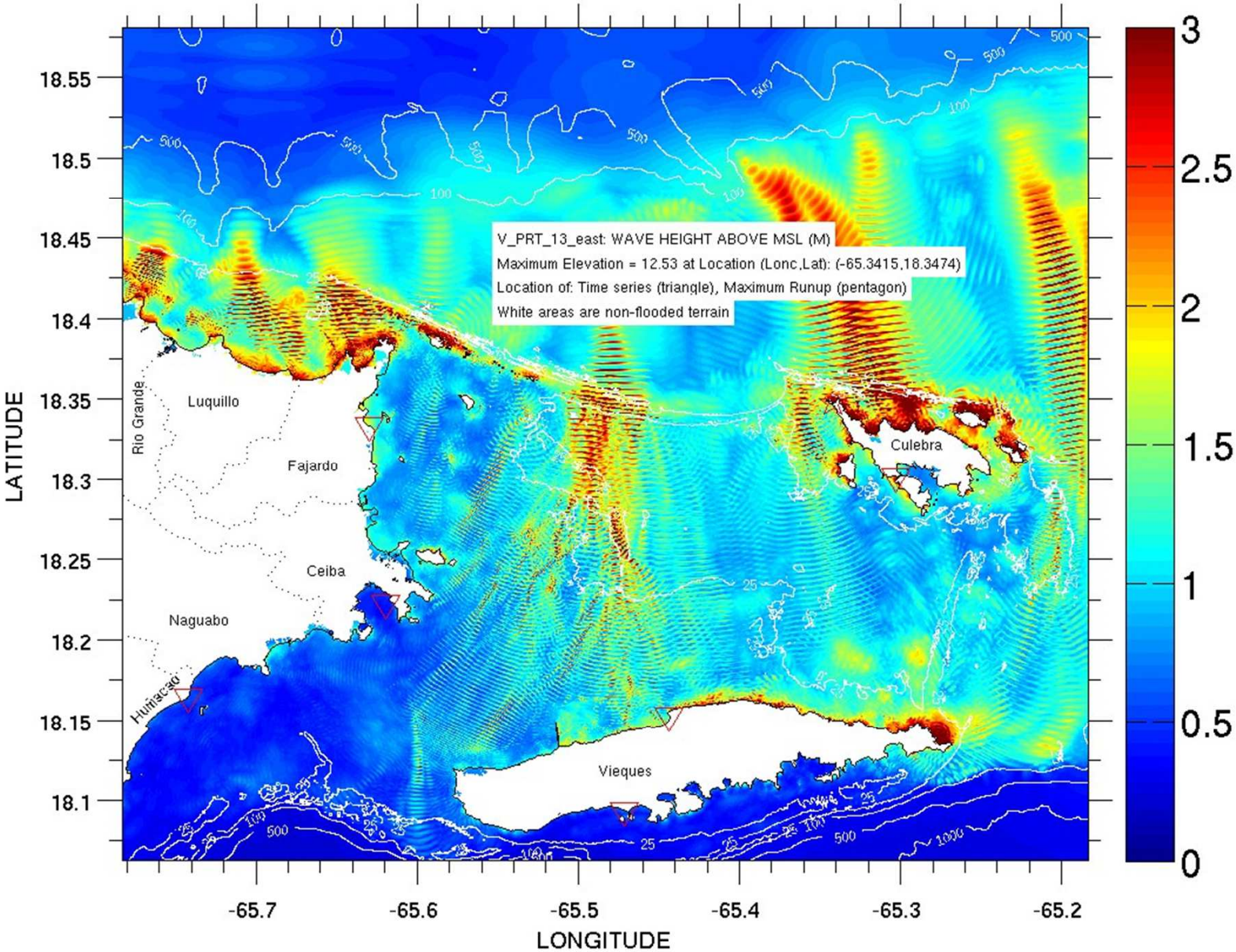


Local and regional propagation grid


PROPAGATION MAXIMUM ENVELOPE OF HIGHEST WATER (M)
White areas are land above MHW
LATITUDE
24
22
20
18
16
14
12
10
8
6
LONGITUDE
-90
-85
-80
-75
-70
-65
-60
-55
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0


V:_PRT_13_west: WAVE HEIGHT ABOVE MSL (M)
Maximum Elevation = 6.39 at Location (Lonc,Lat): (-67.1471,18.5026)
Location of: Time series (triangle), Maximum Runup (pentagon)
White areas are non-flooded terrain
Aguadilla
Isabela
Hatillo
Camuy
Quebradillas
Arecibo
Aguada
Rincon
Anasco
Mayaguez
Cabo Rojo
Lajas
Guanica
Yauco
Guayanilla
Penuelas
Ponce
LATITUDE
LONGITUDE
18.5
18.4
18.3
18.2
18.1
18
17.9
-67.3
-67.2
-67.1
-67
-66.9
-66.8
-66.7
-66.6
3
2.5
2
1.5
1
0.5
0


V_PRT_13_central: WAVE HEIGHT ABOVE MSL (M)
Maximum Elevation = 12.26 at Location (Lonc,Lat): (-66.1862,18.4765)
Location of: Time series (triangle), Maximum Runup (pentagon)
White areas are non-flooded terrain
Barcelo
Manati
Vega Baja
Vega Alta
Dorado
Toa Baja
Catano
Guaynabo
San Juan
Carolina
Loiza
Rio Grande
Humacao
Yabucoa
Maunabo
Patillas
Arroyo
Guayama
Salinas
Santa Isabel
Juana Diaz
Ponce
LATITUDE
LONGITUDE
18.5
18.4
18.3
18.2
18.1
18
17.9
-66.5
-66.4
-66.3
-66.2
-66.1
-66
-65.9
-65.8
3
2.5
2
1.5
1
0.5
0


V_PRT_13_east: WAVE HEIGHT ABOVE MSL (M)
Maximum Elevation = 12.53 at Location (Lonc,Lat): (-65.3415,18.3474)
Location of: Time series (triangle), Maximum Runup (pentagon)
White areas are non-flooded terrain
Luquillo
Rio Grande
Fajardo
Ceiba
Naguabo
Humacao
Culebra
Vieques
LATITUDE
LONGITUDE
18.55
18.5
18.45
18.4
18.35
18.3
18.25
18.2
18.15
18.1
-65.7
-65.6
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-65.4
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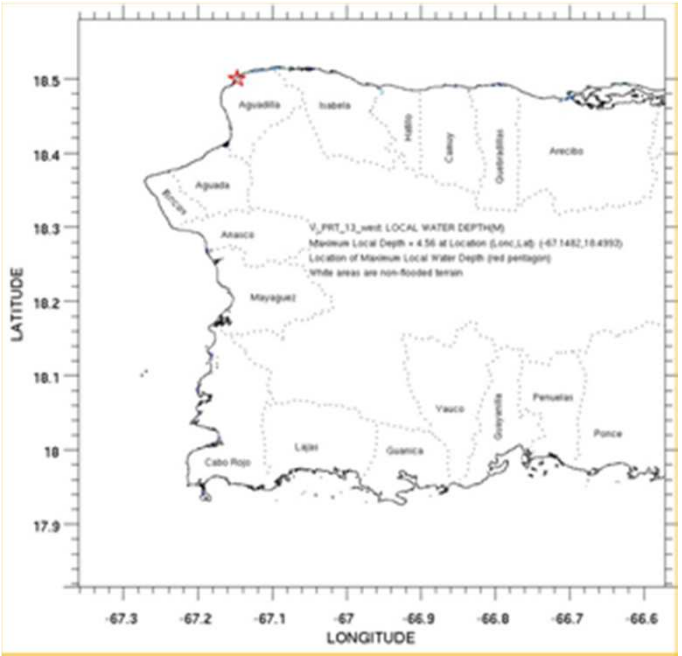
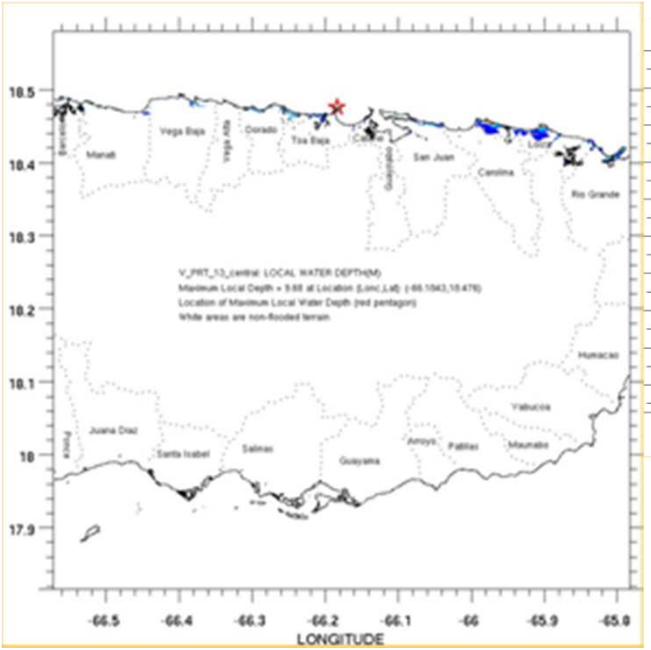
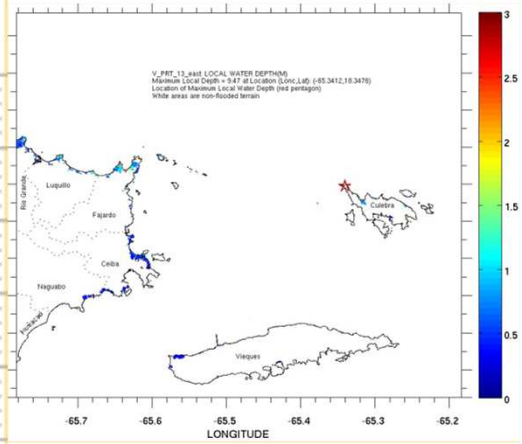
-65.2
3
2.5
2
1.5
1
0.5
0

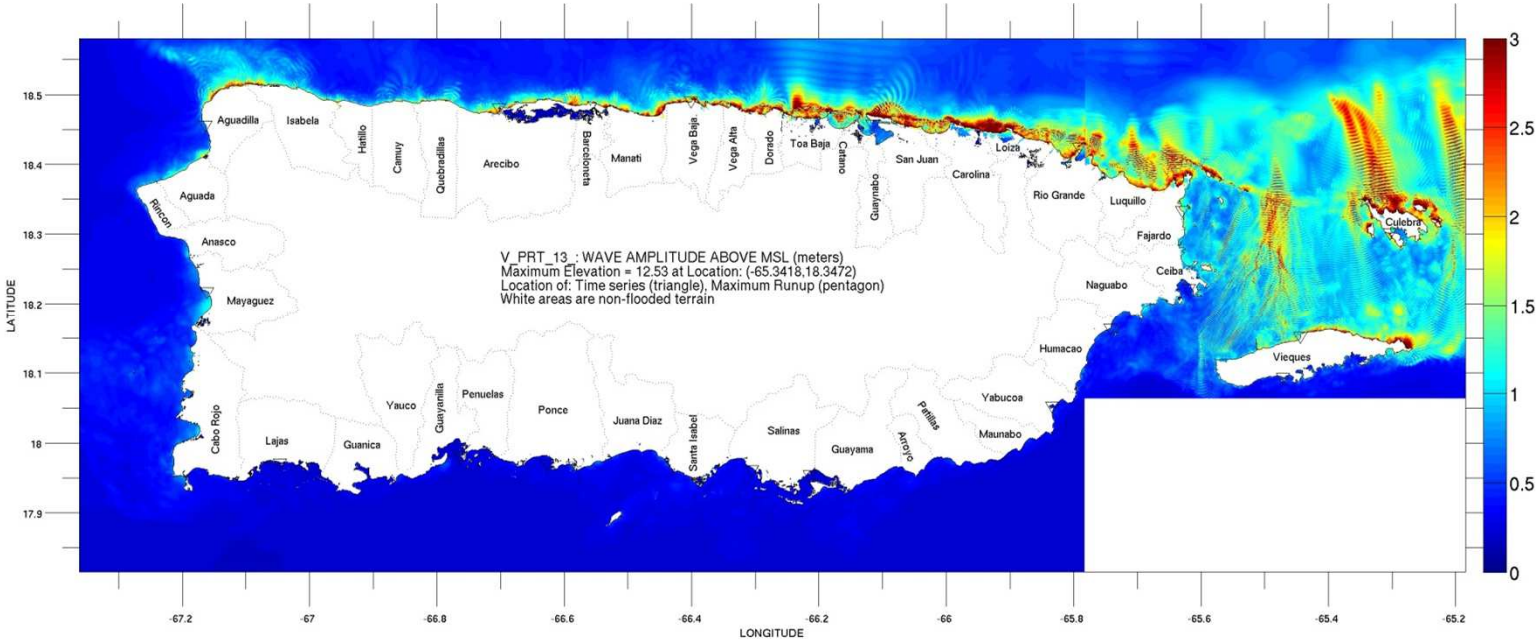

V_PRT_13_west: LOCAL WATER DEPTH(M)
Maximum Local Depth = 4.56 at Location (Lonc,Lat): (-67.1482,18.4393)
Location of Maximum Local Water Depth (red pentagon)
White areas are non-flooded terrain
Aguadilla
Isabela
Hatillo
Camuy
Quebradillas
Arecibo
Aguada
Moca
Anasco
Mayaguez
Yauco
Guayanilla
Penuelas
Ponce
Lajas
Guanica
Cabo Rojo
LATITUDE
LONGITUDE


V_PRT_13_central: LOCAL WATER DEPTH(M)
Maximum Local Depth = 9.88 at Location (Lonc,Lat): (-66.1043,18.476)
Location of Maximum Local Water Depth (red pentagon)
White areas are non-flooded terrain
Barceloneta
Manati
Vega Baja
Vega Alta
Dorado
Toa Baja
Cataño
Guaynabo
San Juan
Loiza
Carolina
Rio Grande
Humacao
Yabucoa
Maunabo
Patillas
Arroyo
Guayama
Salinas
Santa Isabel
Juana Diaz
Ponce
LONGITUDE

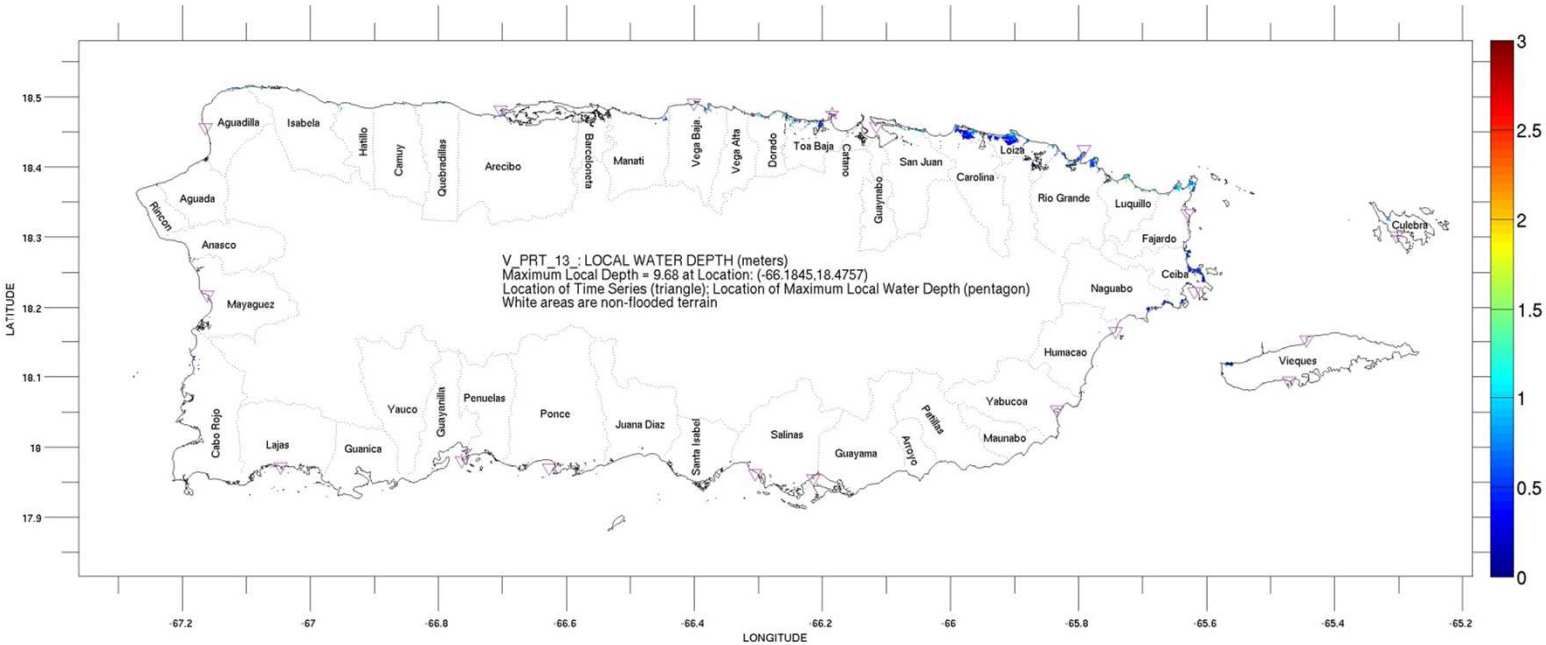

V_PRT_13_east: LOCAL WATER DEPTH(M)
Maximum Local Depth = 9.47 at Location (Lonc,Lat): (-65.3412,18.3476)
Location of Maximum Local Water Depth (red pentagon)
White areas are non-flooded terrain
Rio Grande
Luquillo
Fajardo
Ceiba
Naguabo
Culebra
Vieques
LONGITUDE

MOSAIC

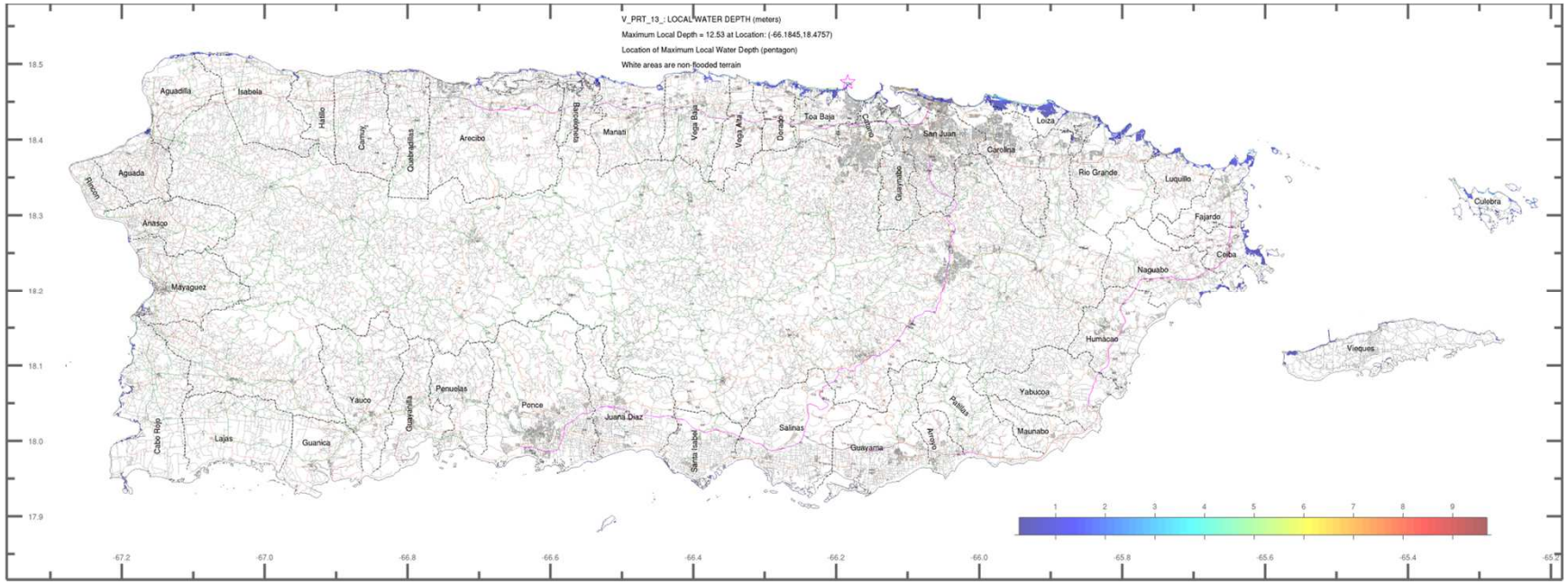
MEOHW

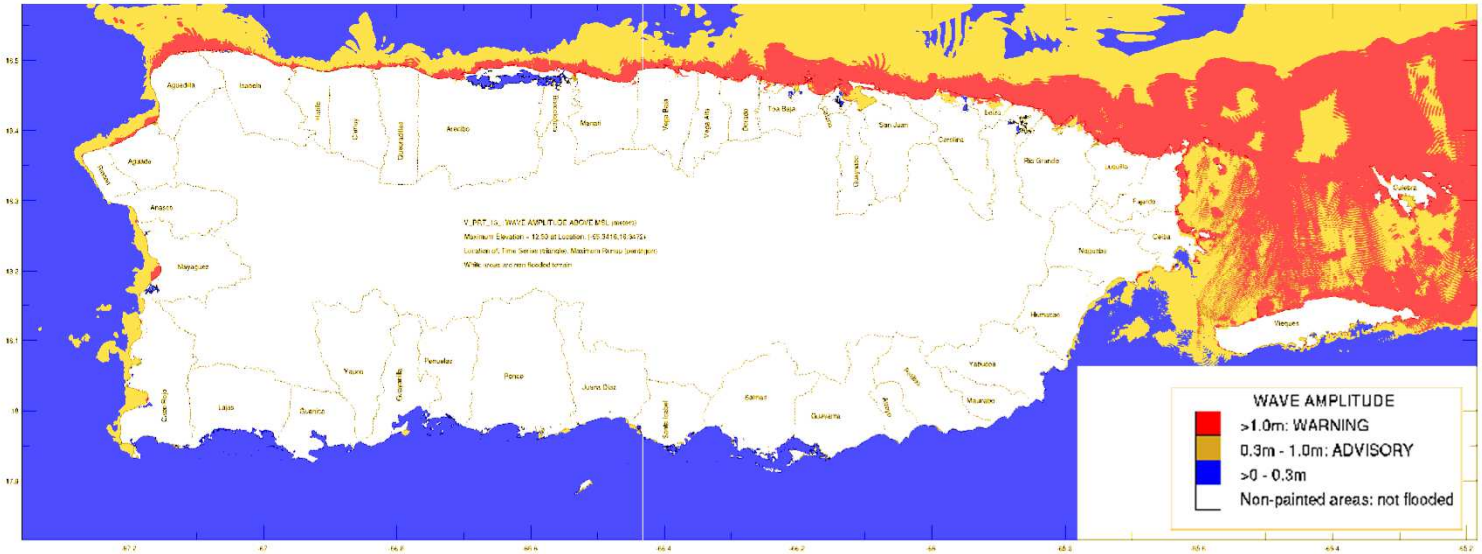


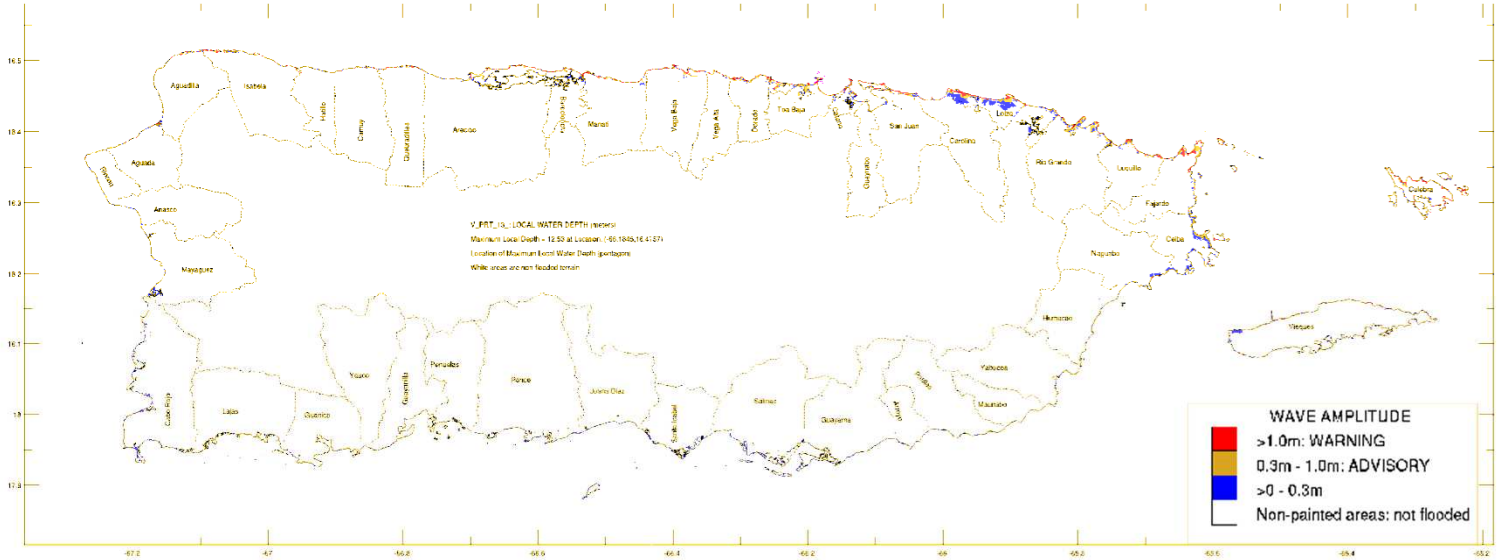
LWD



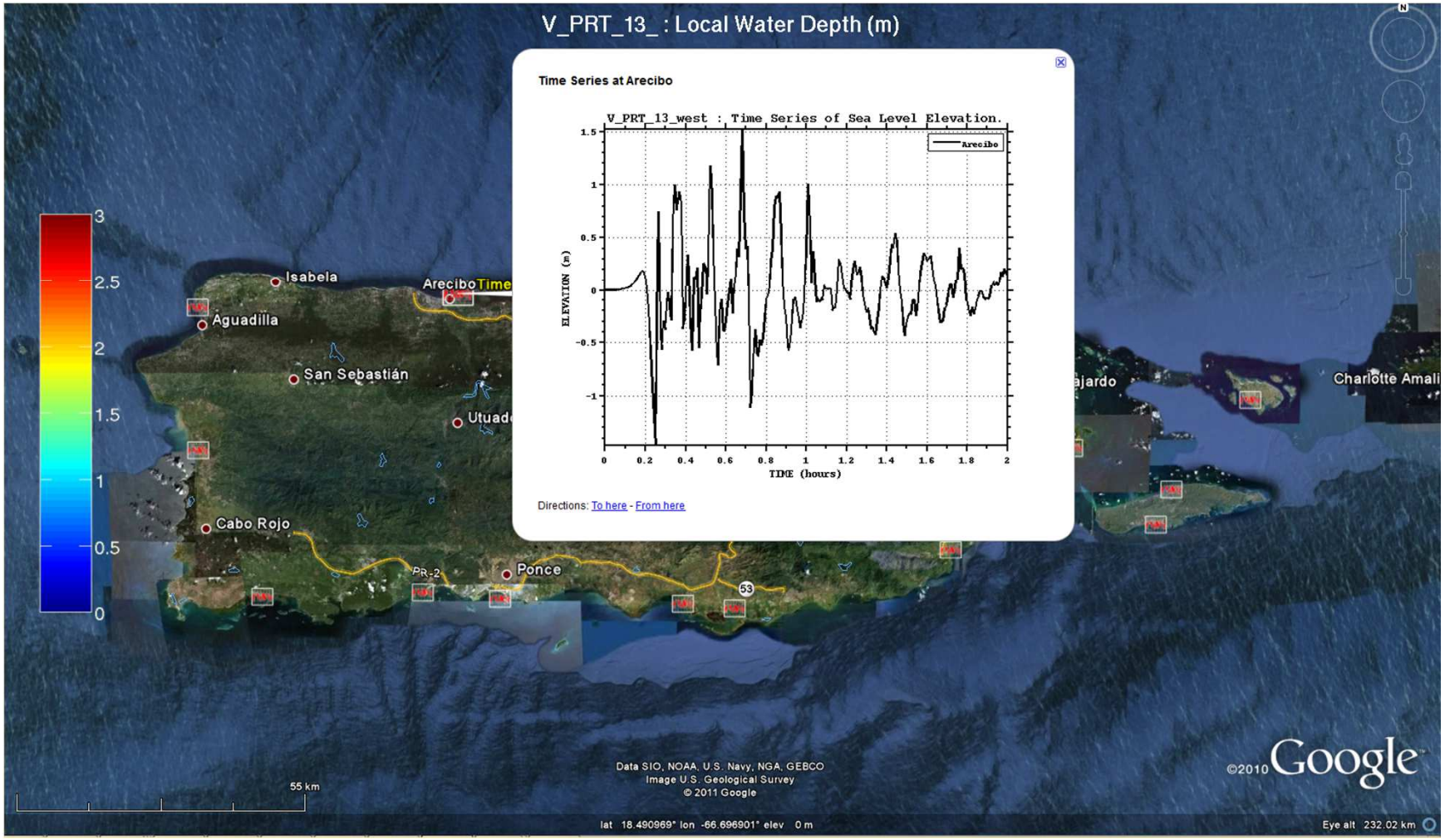
MOSAIC LWD WITH STREETS



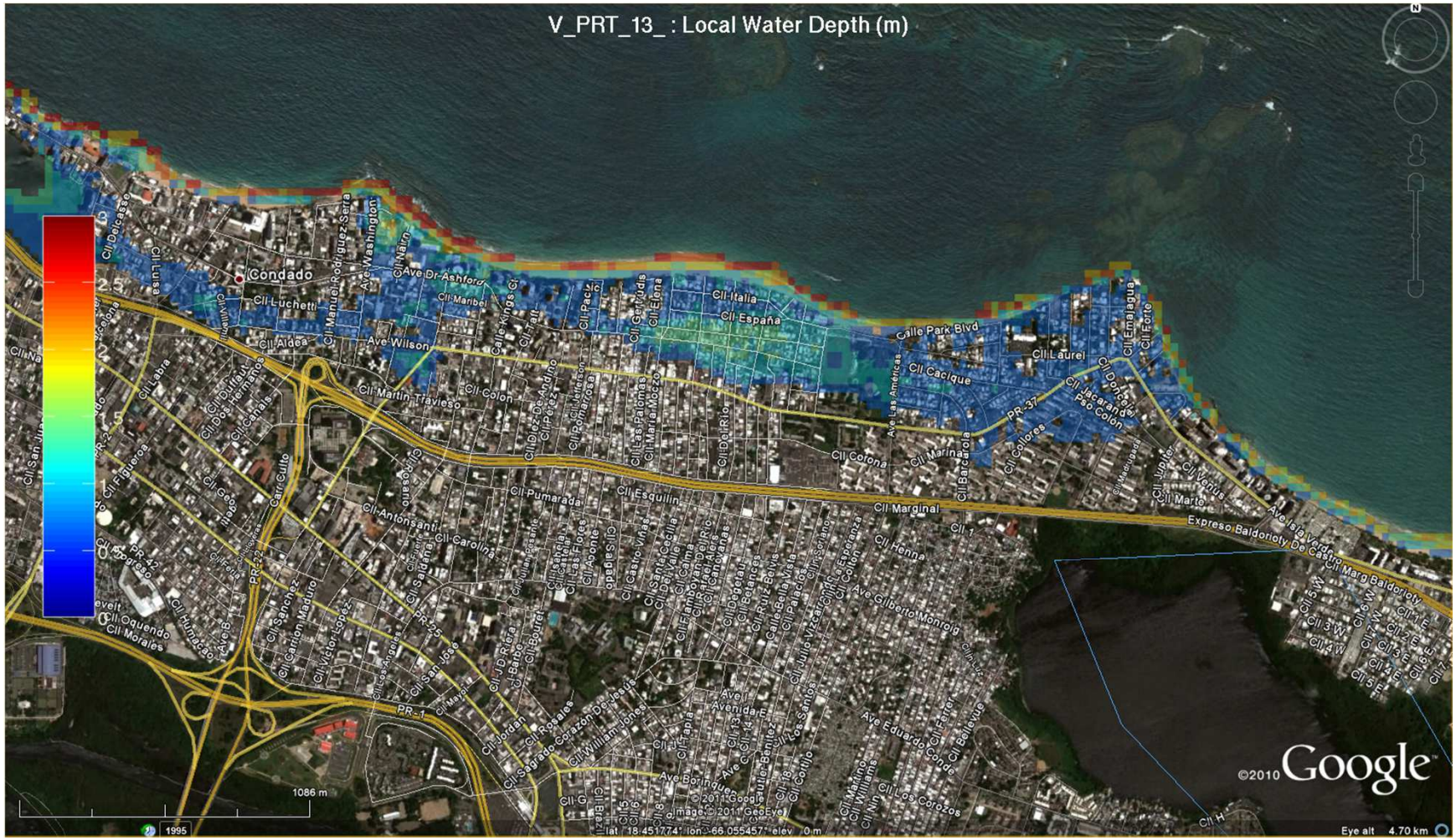

WAVE AMPLITUDE
>1.0m: WARNING
0.3m - 1.0m: ADVISORY
>0 - 0.3m
Non-painted areas: not flooded


WAVE AMPLITUDE
>1.0m: WARNING
0.3m - 1.0m: ADVISORY
>0 - 0.3m
Non-painted areas: not flooded

V_PRT_13_ : Local Water Depth (m)
Maximum Local Water Depth
Maximum elevation: 9.6831 m
Directions: To here - From here
Maximum Local Water Depth
Isabela
Arecibo
Aguadilla
Vega Baja
San Juan
Carolina
San Sebastián
Fajardo
Utuado
Caguas
Cabo Rojo
Ponce
PR-2
PR-22
53
3
2.5
2
1.5
1
0.5
0
52 km
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image U.S. Geological Survey
© 2011 Google
©2010 Google
lat 18.465163° lon -66.177845° elev 0 m
Eye alt 218.15 km

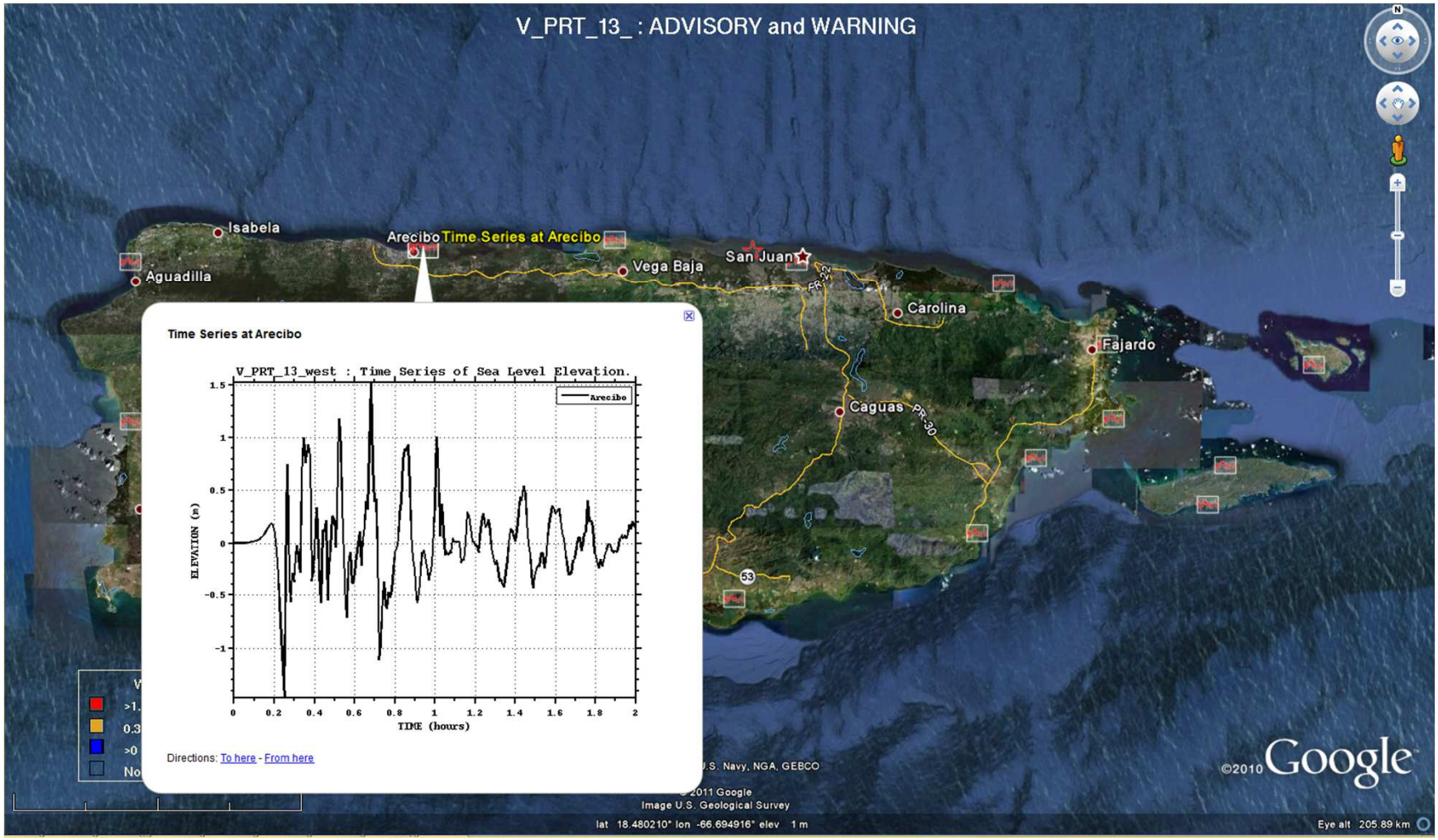

V_PRT_13_ : Local Water Depth (m)
Time Series at Arecibo
V_PRT_13_west : Time Series of Sea Level Elevation.
Arecibo
ELEVATION (m)
TIME (hours)
Directions: To here - From here
Isabela
Arecibo
Aguadilla
San Sebastián
Utuado
Cabo Rojo
Ponce
PR-2
53
Charlotte Amali
3
2.5
2
1.5
1
0.5
0
55 km
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image U.S. Geological Survey
© 2011 Google
©2010 Google
lat 18.490969° lon -66.696901° elev 0 m
Eye alt 232.02 km

V_PRT_13_ : Local Water Depth (m)
3
2.5
2
1.5
1
0.5
0
San Juan
Palo Seco
Levittown
Cataño
Sabana Seca
Ave Del Lago
Ave Sabana Seca
Cll 18
Cll 2
PR-5
PR-869
PR-24
PR-2
PR-1
PR-25
Ave Fernandez Juncos
Ave Borinquen
Expreso Roman Baldorioty De Castro
Expreso Baldorioty De Castro
Ave Luis Muñoz Rivera
Expreso Las Americas
Ave Franklin Delano Roosevelt
PR-22
PR-23
Ave Jesús T Piñero
PR-27
PR-17
Carr 5
Cll San Jose
Cll Principal 4.03 km
Carr 864
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image U.S. Geological Survey
© 2011 Google
Image © 2011 GeoEye
lat 18.451776° lon -66.110169° elev 0 m
©2010 Google
Eye alt 17.55 km

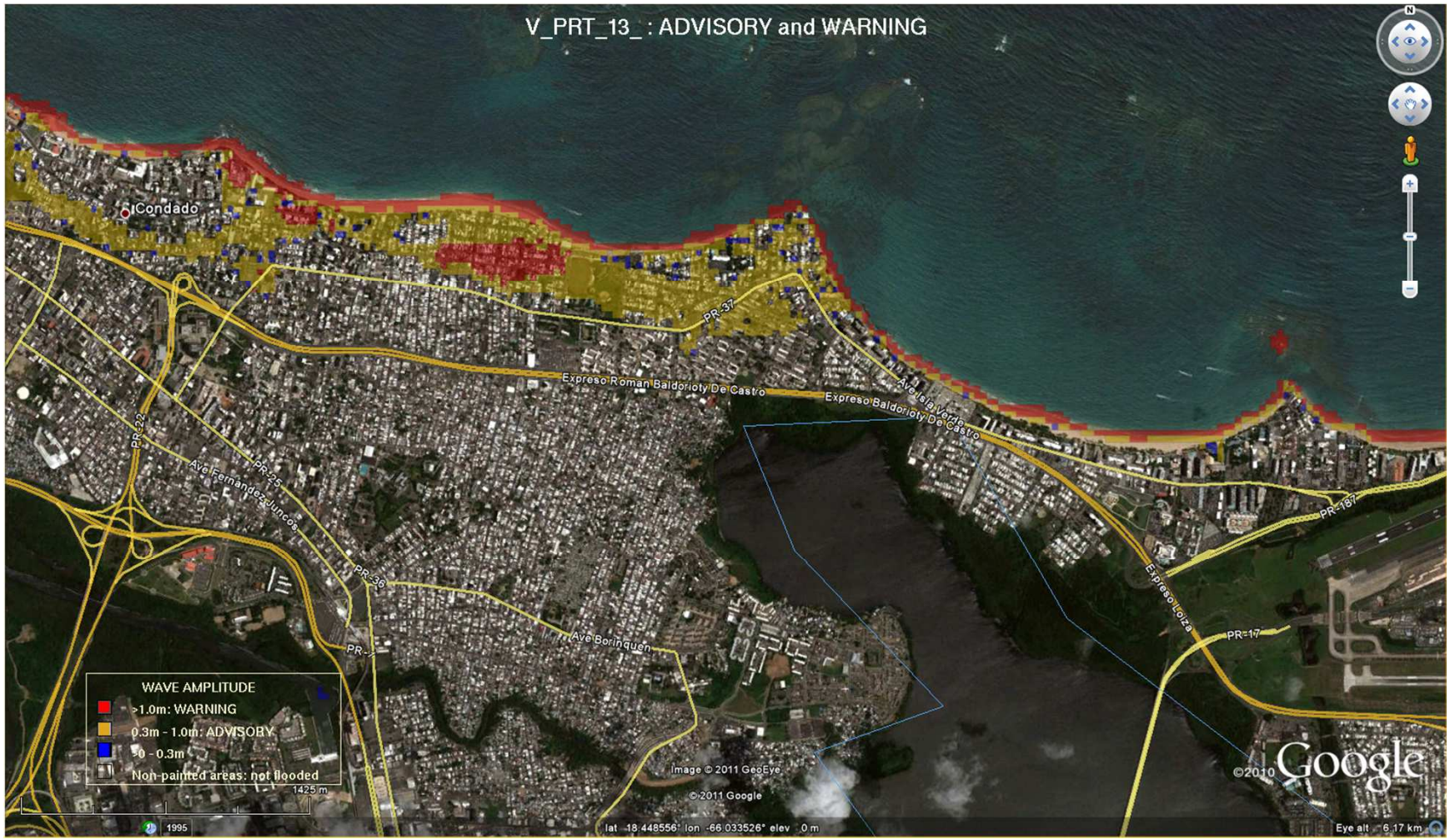

V_PRT_13_ : Local Water Depth (m)
Condado
Cll Luchetti
Ave Wilson
Cll Aldea
Cll Martin Travieso
Cll Colon
Cll Pumarada
Cll Esquilin
Cll Antonsanti
Cll Carolina
Cll Marginal
Cll Corona
Cll Cacique
Calle Park Blvd
Cll Laurel
Cll Italia
Cll España
Cll Henna
Ave Gilberto Monroig
Ave Eduardo Conde
Expreso Baldorioty De Castro
Carr Cuito
PR-1
PR-22
PR-25
PR-37
1086 m
©2010 Google
Eye alt 4.70 km

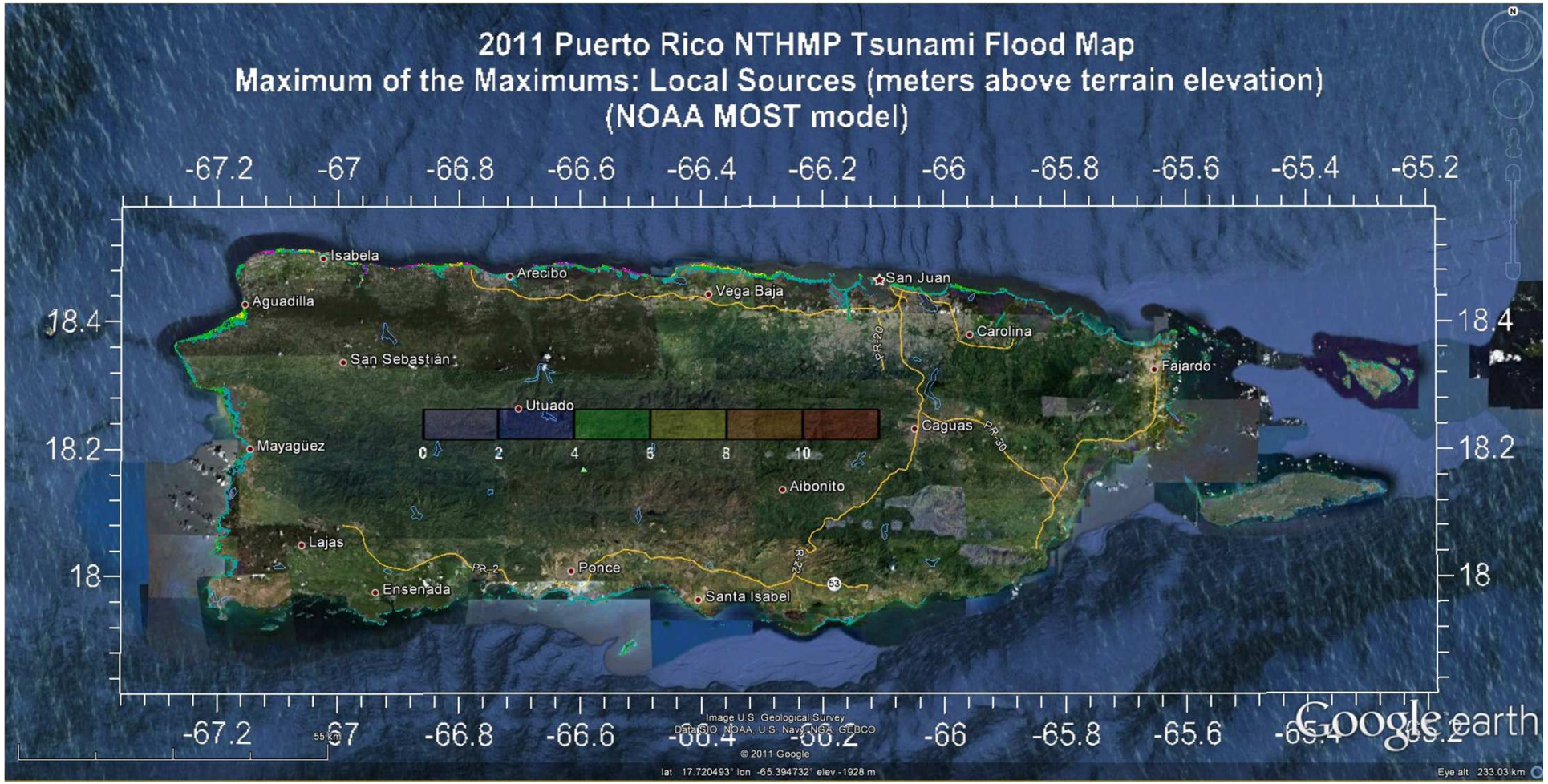
V_PRT_13_ : ADVISORY and WARNING
Isabela
Aguadilla
Arecibo
Vega Baja
San Juan
Carolina
Fajardo
San Sebastián
Utuado
Caguas
Cabo Rojo
Ponce
PR-2
PR-52
53
WAVE AMPLITUDE
>1.0m: WARNING
0.3m - 1.0m: ADVISORY
>0 - 0.3m
Non-painted areas: not flooded
52 km
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2011 Google
Image U.S. Geological Survey
lat 18.115532° lon -66.653561° elev 453 m
©2010 Google
Eye alt 218.15 km

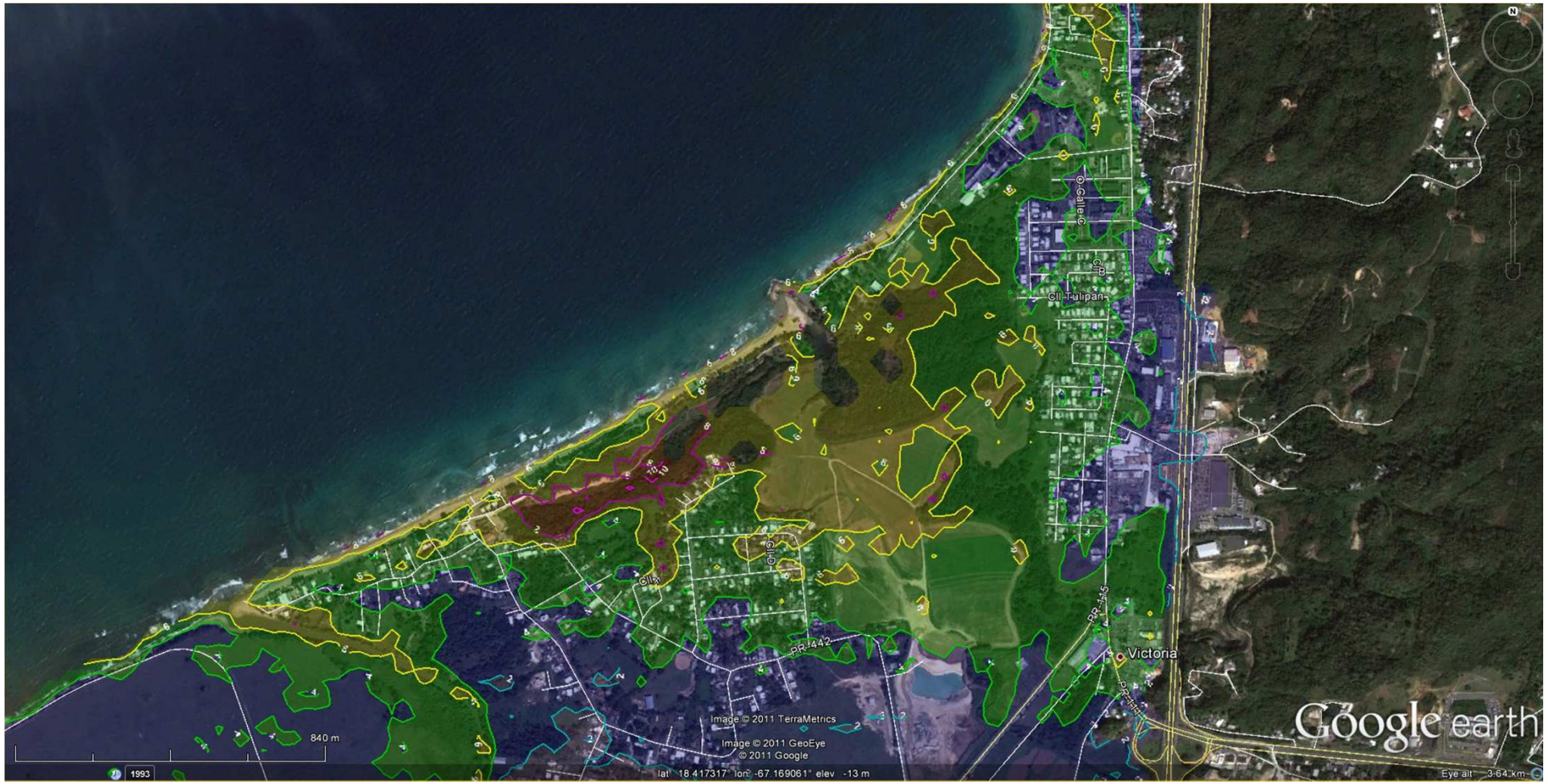
V_PRT_13_ : ADVISORY and WARNING
Maximum Local Water Depth
Maximum elevation: 9.6831 m
Directions: To here - From here
Maximum Local Water Depth
Isabela
Arecibo
Aguadilla
Vega Baja
San Juan
Carolina
San Sebastián
Fajardo
Utuado
Caguas
Cabo Rojo
Ponce
PR-2
PR-30
53
WAVE AMPLITUDE
>1.0m: WARNING
0.3m - 1.0m: ADVISORY
>0 - 0.3m
Non-painted areas: not flooded
49 km
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2011 Google
Image U.S. Geological Survey
lat 18.476666° lon -66.183204° elev 0 m
©2010 Google
Eye alt 205.89 km


V_PRT_13_ : ADVISORY and WARNING
Isabela
Aguadilla
Arecibo
Time Series at Arecibo
Vega Baja
San Juan
Carolina
Fajardo
Caguas
PR-30
PR-52
53
Time Series at Arecibo
V_PRT_13_west : Time Series of Sea Level Elevation.
Arecibo
ELEVATION (m)
TIME (hours)
1.5
1
0.5
0
-0.5
-1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Directions: To here - From here
U.S. Navy, NGA, GEBCO
© 2011 Google
Image U.S. Geological Survey
©2010 Google
lat 18.480210° lon -66.694916° elev 1 m
Eye alt 205.89 km

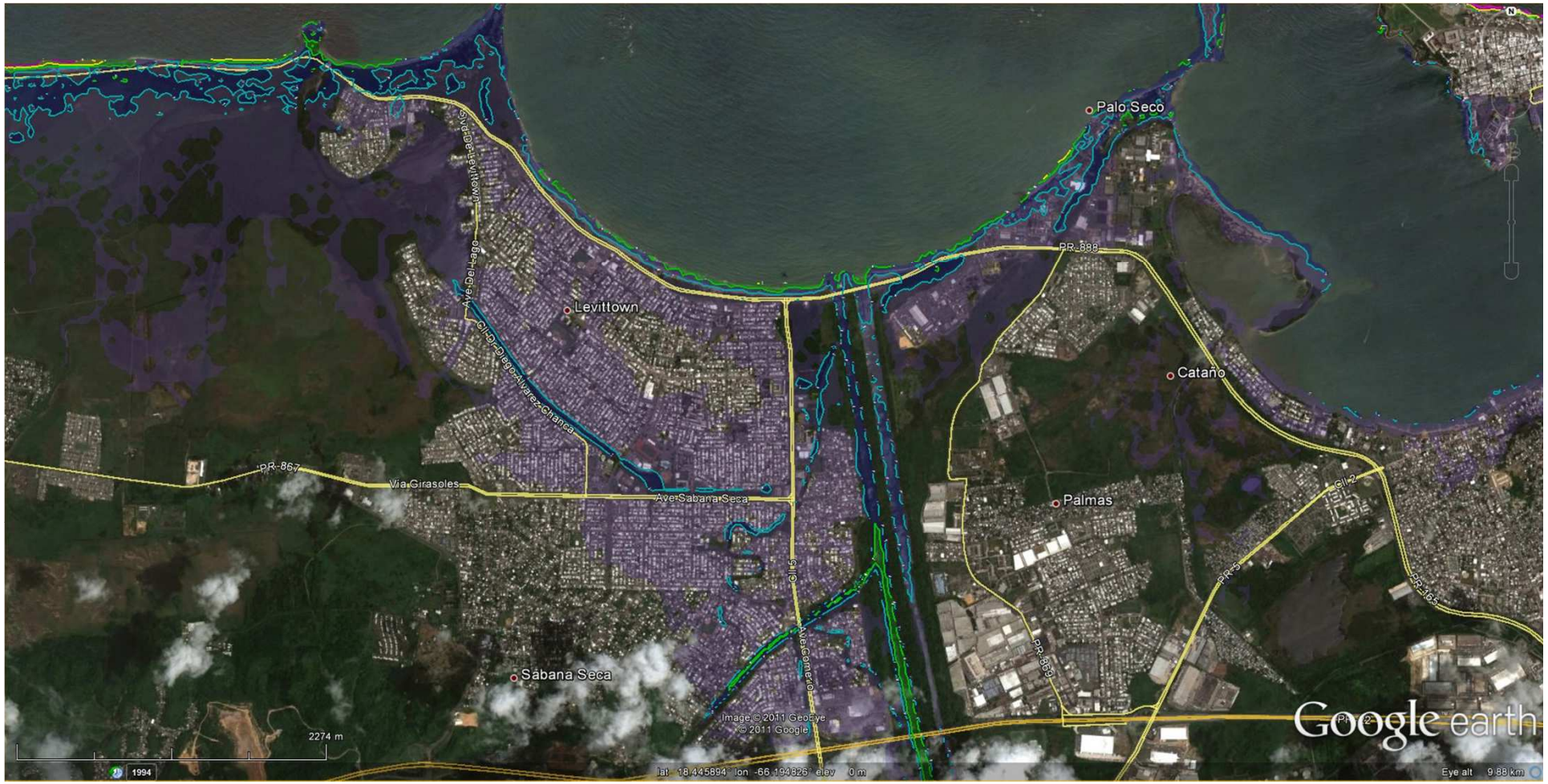
V_PRT_13_ : ADVISORY and WARNING
San Juan
Palo Seco
Dorado
San Antonio
Toa Baja
Ingenio
Levittown
Cataño
Sabana Seca
Campanilla
Candelaria
Toa Alta
Bayamón
Expreso Roman Baldorioty De Castro
PR-2
PR-22
Expreso Las Americas
Expreso MPR-202 Nadal
PR-52
WAVE AMPLITUDE
>1.0m: WARNING
0.3m - 1.0m: ADVISORY
>0 - 0.3m
Non-painted areas: not flooded
5.77 km
Image © 2011 GeoEye
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2011 Google
Image U.S. Geological Survey
lat 18.435822° lon -66.192940° elev 3 m
©2010 Google
Eye alt 25.22 km


V_PRT_13_ : ADVISORY and WARNING
Condado
Expreso Roman Baldorioty De Castro
Expreso Baldorioty De Castro
Ave Isla Verde
Ave Fernandez Juncos
Ave Borinquen
Expreso Loiza
PR-37
PR-22
PR-25
PR-36
PR-187
PR-17
WAVE AMPLITUDE
>1.0m: WARNING
0.3m - 1.0m: ADVISORY
0 - 0.3m
Non-painted areas: not flooded
1425 m
1995
Image © 2011 GeoEye
© 2011 Google
©2010 Google
lat 18.448556° lon -66.033526° elev 0 m
Eye alt 6.17 km


2011 Puerto Rico NTHMP Tsunami Flood Map
Maximum of the Maximums: Local Sources (meters above terrain elevation)
(NOAA MOST model)
-67.2
-67
-66.8
-66.6
-66.4
-66.2
-66
-65.8
-65.6
-65.4
-65.2
18.4
18.2
18
Isabela
Arecibo
Vega Baja
San Juan
Aguadilla
Carolina
San Sebastián
Fajardo
Utuado
Caguas
Mayagüez
0
2
4
6
8
10
Aibonito
Lajas
Ponce
Ensenada
Santa Isabel
PR-20
PR-30
PR-2
PR-22
53
Image U.S. Geological Survey
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2011 Google
lat 17.720493° lon -65.394732° elev -1928 m
Eye alt 233.03 km
Google earth



Cll Tulipan
Victoria
PR-442
PR-115
840 m
1993
Image © 2011 TerraMetrics
Image © 2011 GeoEye
© 2011 Google
lat 18.417317° lon -67.169061° elev -13 m
Google earth
Eye alt 3.64 km


Palo Seco
PR-888
Levittown
Cataño
Palmas
PR-867
Via Girasoles
Ave Sabana Seca
Sabana Seca
Ave Del Lago
Cll Dr Diego Alvarez Chanca
Cll 5
Ave Comerio
PR-869
PR-5
Cll 2
PR-165
Image © 2011 GeoEye
© 2011 Google
2274 m
1994
lat 18.445894° lon -66.194826° elev 0 m
Eye alt 9.88 km
Google earth

Ballajá
Mercado
San Cristóbal
San Francisco
San Juan
Puerta de Tierra
Marina
Cll Del Morro
Cll Tiburcio Reyes
Cll Norzagaray
Cll Beneficencia
Cll Sol
Cll Luna
Cll Las Monjas
Cll San Francisco
Cll Fortaleza
Cll Tetuan
Cll Recinto Sur
Cll Comercio
Pso De La Princesa
Cll Presidio
PR-38
Cll Valdes
Cll Esteves
Cll San Andres
Cll Pelayo
Cll Matias Ledesma
Cll Sur
Cll San Agustin
Cll Del Tren
Cll Rosales
Cll Lindbergh
Image © 2011 GeoEye
© 2011 Google
886 m
1995
lat 18.462425° lon -66.111422° elev 0 m
Eye alt 3.83 km
Google earth

ADDITIONAL WORK AS PART OF NTHMP:

• We have already had two weeks of training by Dr. Juan Horrillo on the use of the coupled models TSUNAMI-3D and NEOWAVE for modeling landslide tsunamis. Tested with what could be a submarine landslide that occurred as a consequence of the 1918 Puerto Rico earthquake. The USGS has identified additional slides along the Puerto Rico Trench, and also along the south coast (in cooperation with Spanish scientists). This is the next phase of work.

FUTURE WORK:

• Must include variable roughness, especially along coastlines protected by fringing reefs, mangrove forests, and very dense vegetation.

• Include the built infrastructure

• Improve bathymetry and topography once the geoid in Puerto Rico is upgraded

• Include dispersive effects