ASSESSMENT OF THE TSUNAMI-INDUCED TSUNAMI HAZARD FOR SAN JUAN BAY, PUERTO RICO

Report Submitted to

Puerto Rico Component of the USA National Tsunami Hazard Mitigation Program

and the

Puerto Rico Seismic Network

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by

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OBJECTIVE

Carry out a tsunami currents hazard analysis for San Juan Bay using the MOST tsunami model. Figure 1 shows a Google Earth view of the Bay and the locations where current velocities time series were collected. Table 1 shows the coordinates of the locations. A total of 4 hours were simulated.

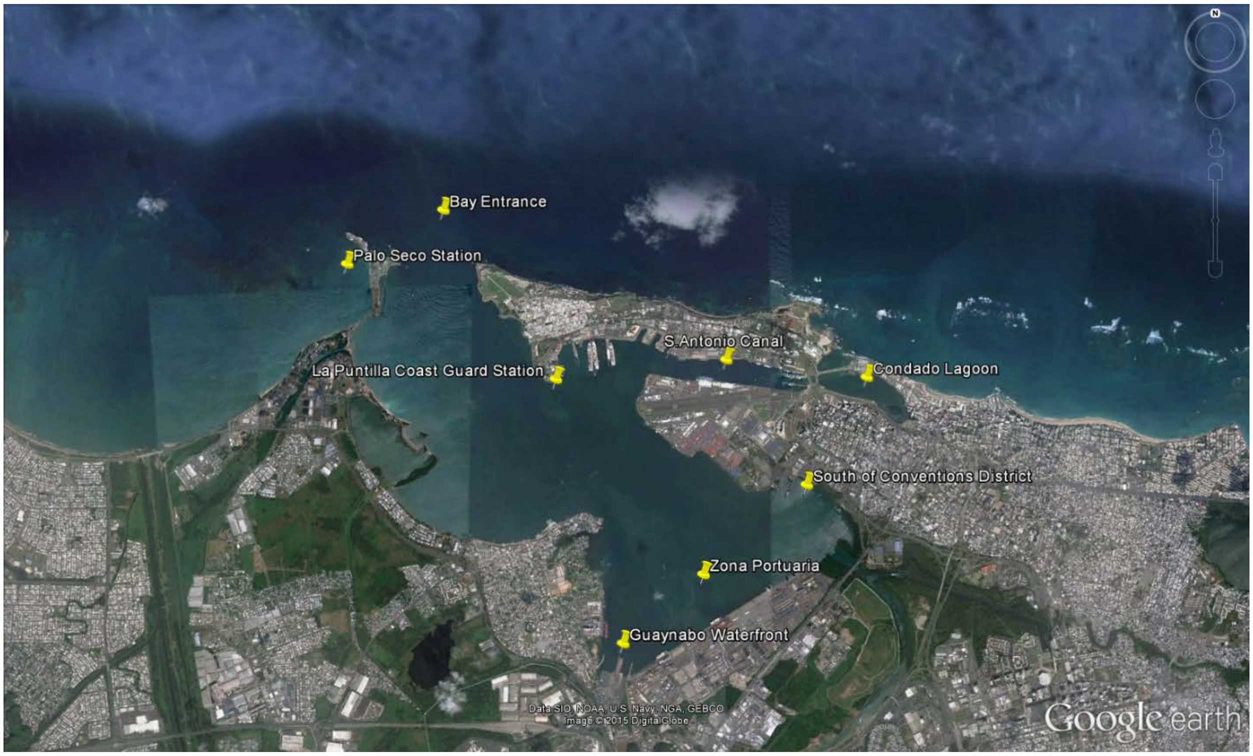

Figure 1 – Google Earth view of San Juan Bay. The locations where time series were measured are shown by the yellow pins. Geographical coordinates are given in Table 1.

Table 1: Geographical coordinates of the locations where time series were collected.

Sta Number	Stations	Longitude(°)	Latitude (°)
1	San Juan Bay Entrance	-66.129244	18.476676
2	San Antonio Canal	-66.096944	18.460315
3	La Puntilla Coast Guard Station	-66.116249	18.458194
4	South of Convention District	-66.087977	18.446885
5	Palo Seco	-66.099628	18.437409
6	Condado Lagoon	-66.108610	18.430171
7	Zona Portuaria	-66.140148	18.470722
8	Guaynabo Waterfront	-66.081033	18.458437

BATHYMETRY

The bathymetry (and topography) is based on the 10 meters resolution DEM for San Juan prepared by NGDC. Figures 2 and 3 show painted contour plots of the bathymetry and topography. The entrance bay channel has a nominal depth varying between 10 and 13 m. In the DEM the narrow channel connecting San Antonio canal with the Condado Lagoon doesn't appear because the Muñoz Rivera and Fernandez Juncos bridges obstructed the LiDAR signal. For this study that narrow channel was manually constructed, thus allowing the passage of water between San Antonio and the Condado Lagoon. This can be observed in Figure 20 as a region of high shear vorticity.

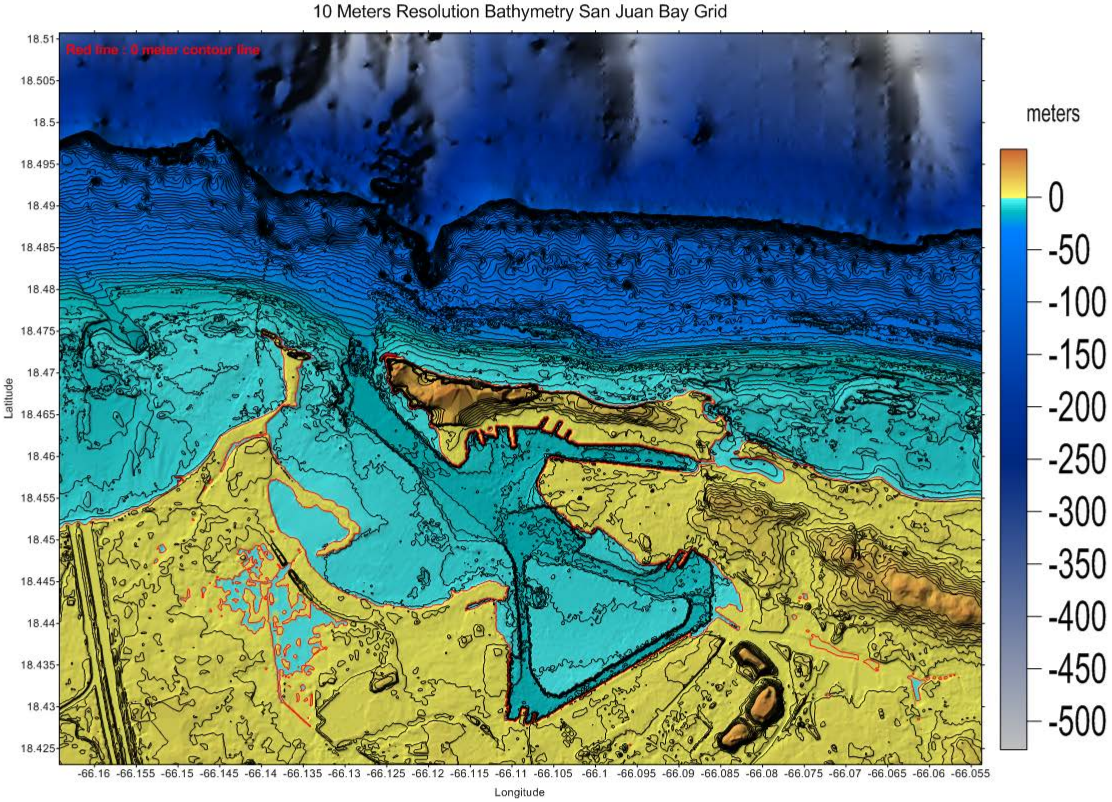

Figure 2 – Contour plot of the bathymetry and topography of the study site.

One of the tests that will be carried out is to evaluate the sensitivity of current speed to the computational grid resolution. Figure 4 shows the area north of the western tip of Isleta de San Juan at 10 m resolution, while Figure 5 shows the same area at 30 m resolution. Thirty meters (30) is the resolution used in the computation of the inundation flood maps prepared for NTHMP and the Puerto Rico Seismic Network. The ruggedness of the sea bottom is evident at 10 m resolution, while at 30 m resolution the bathymetry looks much smoother. Later we will compare current speeds for these two resolutions.

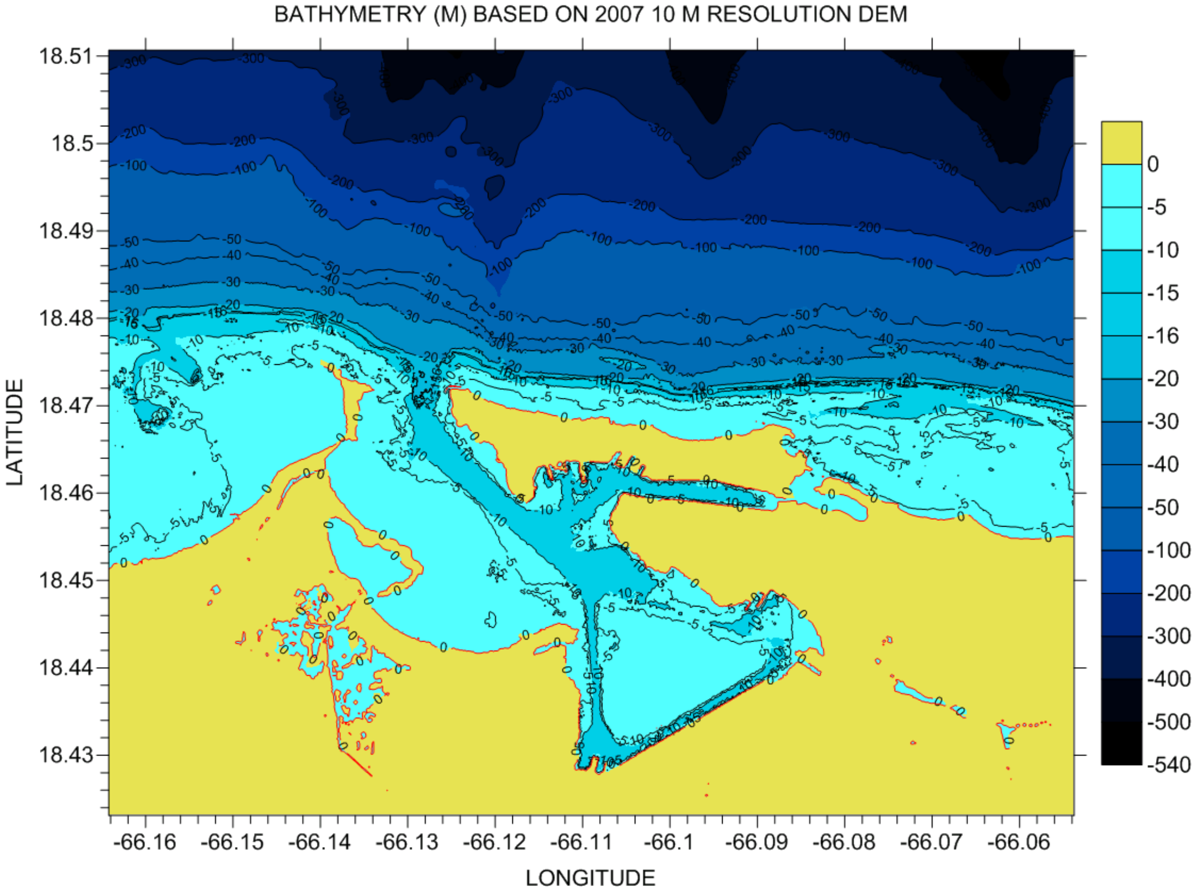

Figure 3 - Contour plot of the bathymetry of the study site, with contour labels showing the depths in meters.

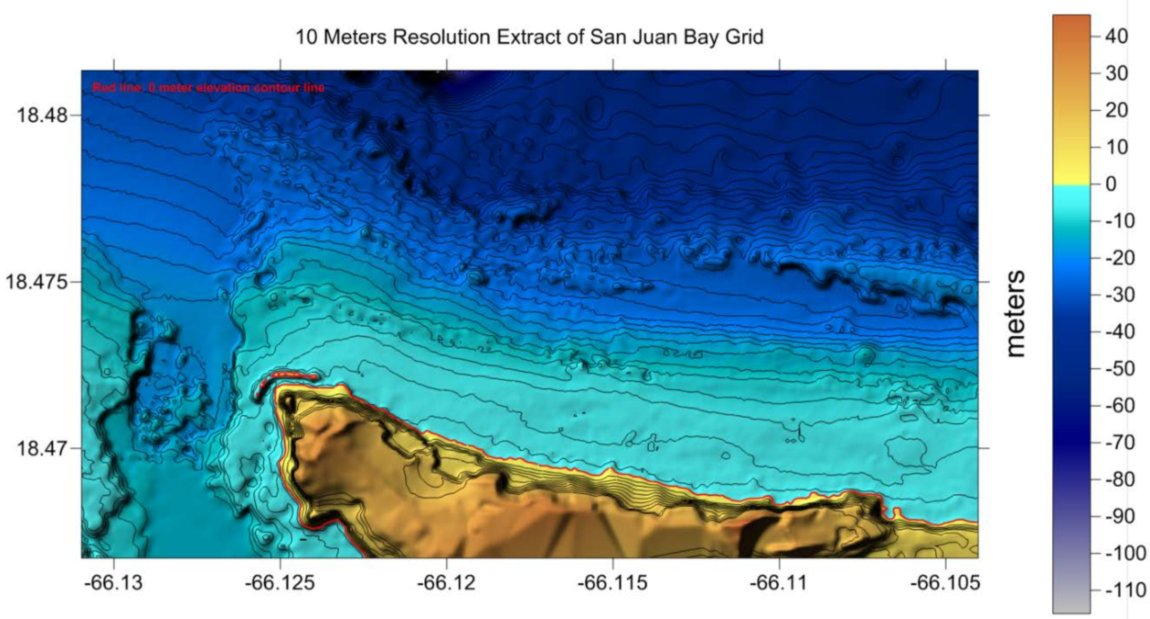

Figure 4 – 10 meters resolution figure showing the complexity of the bathymetry offshore of Isleta de San Juan. One should notice the presence of fosilized sand dunes which presents a challenge for speed estimates.

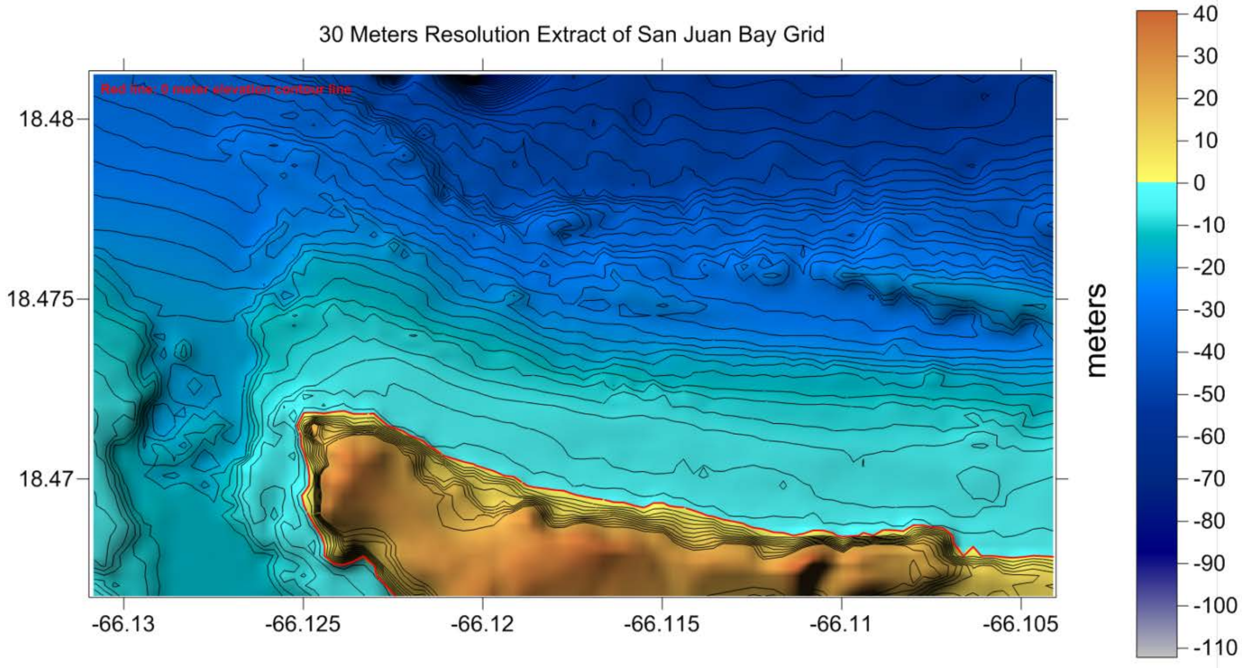

Figure 5 – 30 meters resolution figure showing a smoother version of the bathymetry shown in Figuere 4. The smoothness is due to the decreased resolution, not to the application of a smoothing algorithm.

PREVIOUS WORK

As part of a previous study, a total of 320 local faults were simulated with MOST at a grid resolution of 30 m. With these results the tsunami flood maps for the island were prepared. One of the additional outputs (in addition to the water surface elevation), was the current speed induced by each of the tsunamis. This current speed was output in a netcdf file as the maximum values at each computational cell, irrespective of the time during the event when it occurred. Figure 6 shows the collection of all maximum current speeds for all 320 simulations. The color scale is based on the Mapping & Modeling report publication "Guidelines and Best Practices for Tsunami Hazard Analysis, Planning, and Preparedness for Maritime Communities – Maritime Planning and Preparedness Guidelines", draft June 2015.

The Guidelines provide four current speed ranges which should be used for damage assessment:

1. Blue: 0 to 2.9 knots – no observed damage
2. Green: 3 to 5.9 knots – minor to moderate damage
3. Orange: 6 to 8.9 knots – damage observable, transition to major damage
4. Red: larger than, or equal to, 9 knots – major to complete damage

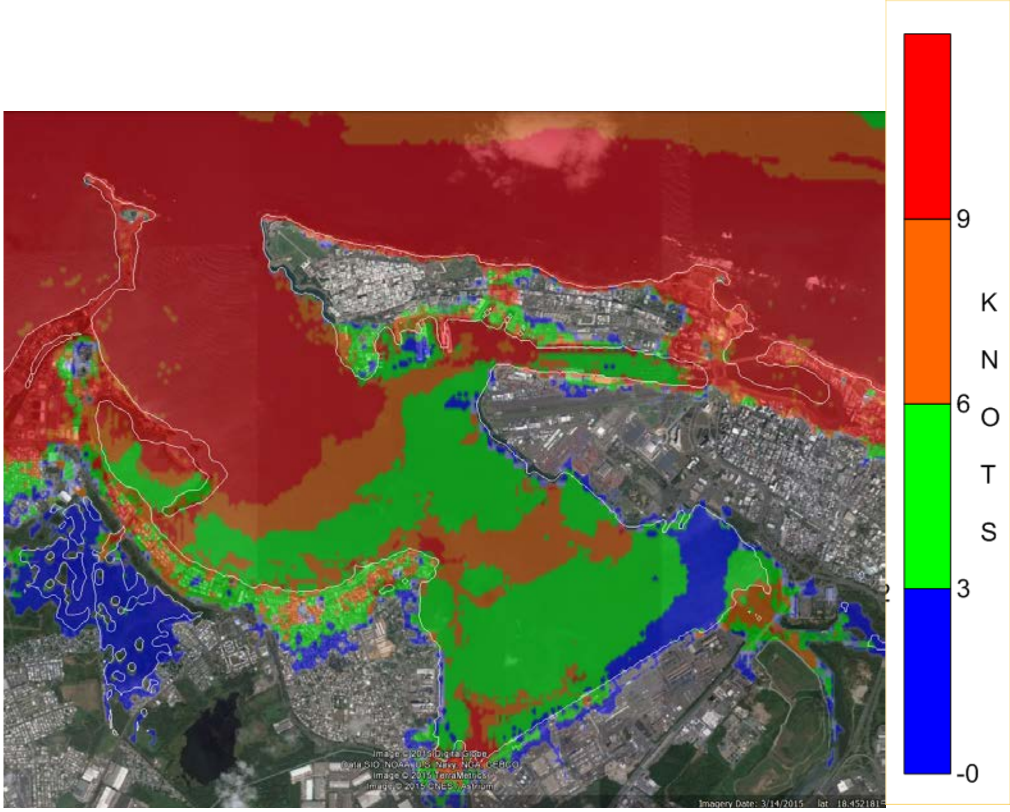

Figure 6 – Maximum tsunami current speed zones for the composite of 320 tsunami simulations.

TSUNAMI SCENARIO

In what follows the assessment of the tsunami induced hazard will be based on the so-called FEMA worst case scenario, an Mw 8.4 generated along the Puerto Rico Trench (see Figure 7). Figure 8 shows the maximum elevation above MSL in the San Juan Bay area for the FEMA event, and at 10 m resolution (later on we will present the same figures but at 30m resolution). Figure 9 shows the flood depths (difference between the elevations relative to MSL and the terrain elevation). This will be denominated the Local Water Depth. Figure 10 shows the maximum current speeds for the FEMA event. **It should be emphasized that the figures could be show a different scenario if another tsunami were to be used as a forcing factor**.

Figure 11 shows elevation and speed time series at the locations shown in Figure 1. Figure 12 to 15 show stick plots of the current vectors at the same locations.
A useful information, especially for cruise and cargo ships is the minimum water depth reached during the tsunami event. Figure 16 shows such information. This is computed by subtracting the maximum sea surface depression from the water depth at each computational cell (see Figure 17).
Figure 18 shows the Minimum Envelope Of Waters (anti-MEOW), which is the maximum sea surface depressions (relative to MSL – see Figure 17) computed irrespective of the time when it occurred. This is the opposite of the MEOWs.

Another one is the Peak-to-Trough water level fluctuation, and shown in Figure 19. This is computed by subtracting the maximum sea surface depression (irrespective of time) from the maximum sea surface elevation (irrespective of time – MEOW minus anti-MEOW).

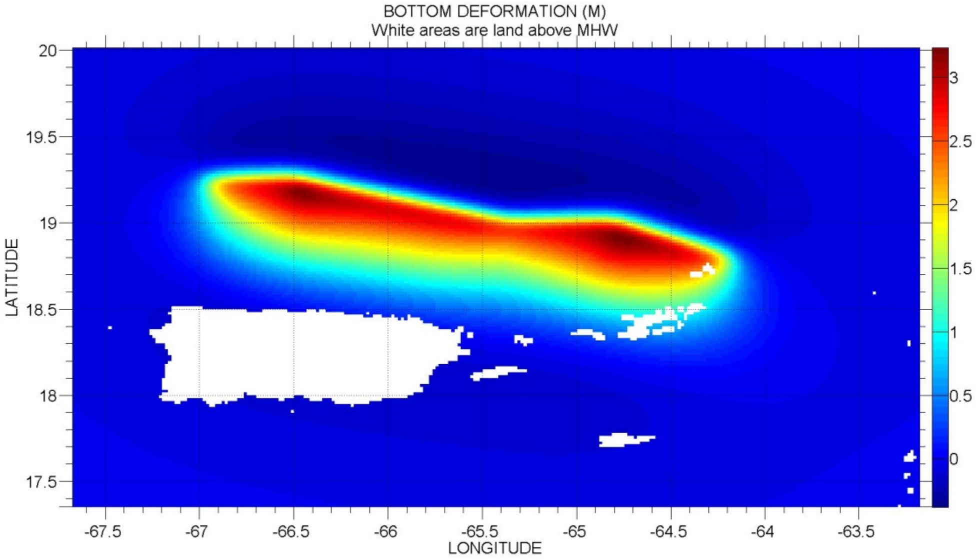

Figure 7 – Initial sea surface deformation for the FEMA Catastrophic Scenario. Elevations in meters.

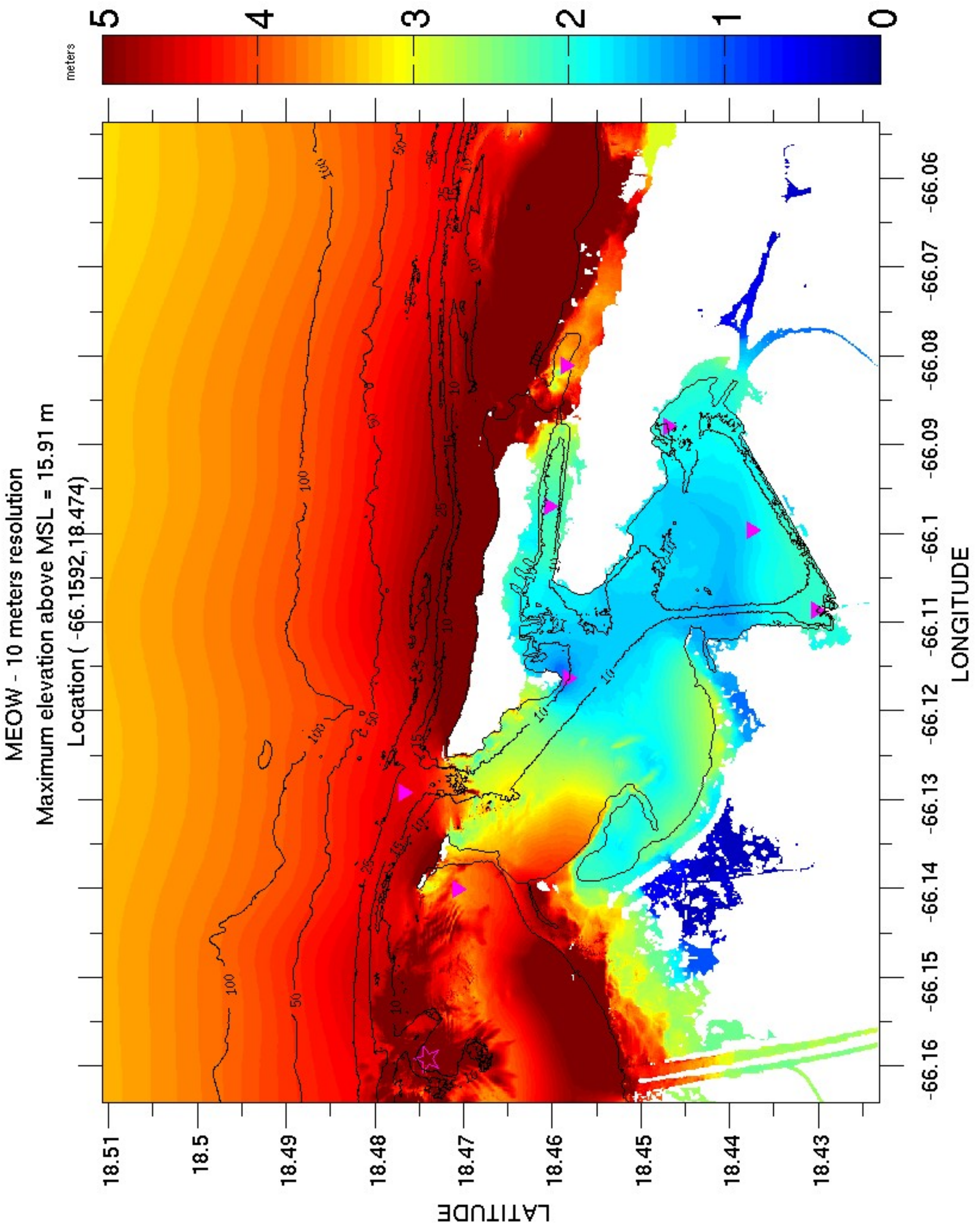

Figure 8 – Maximum sea surface elevation for the FEMA Catastrophic Scenario. Elevations in meters. Grid resolution is 10 m.

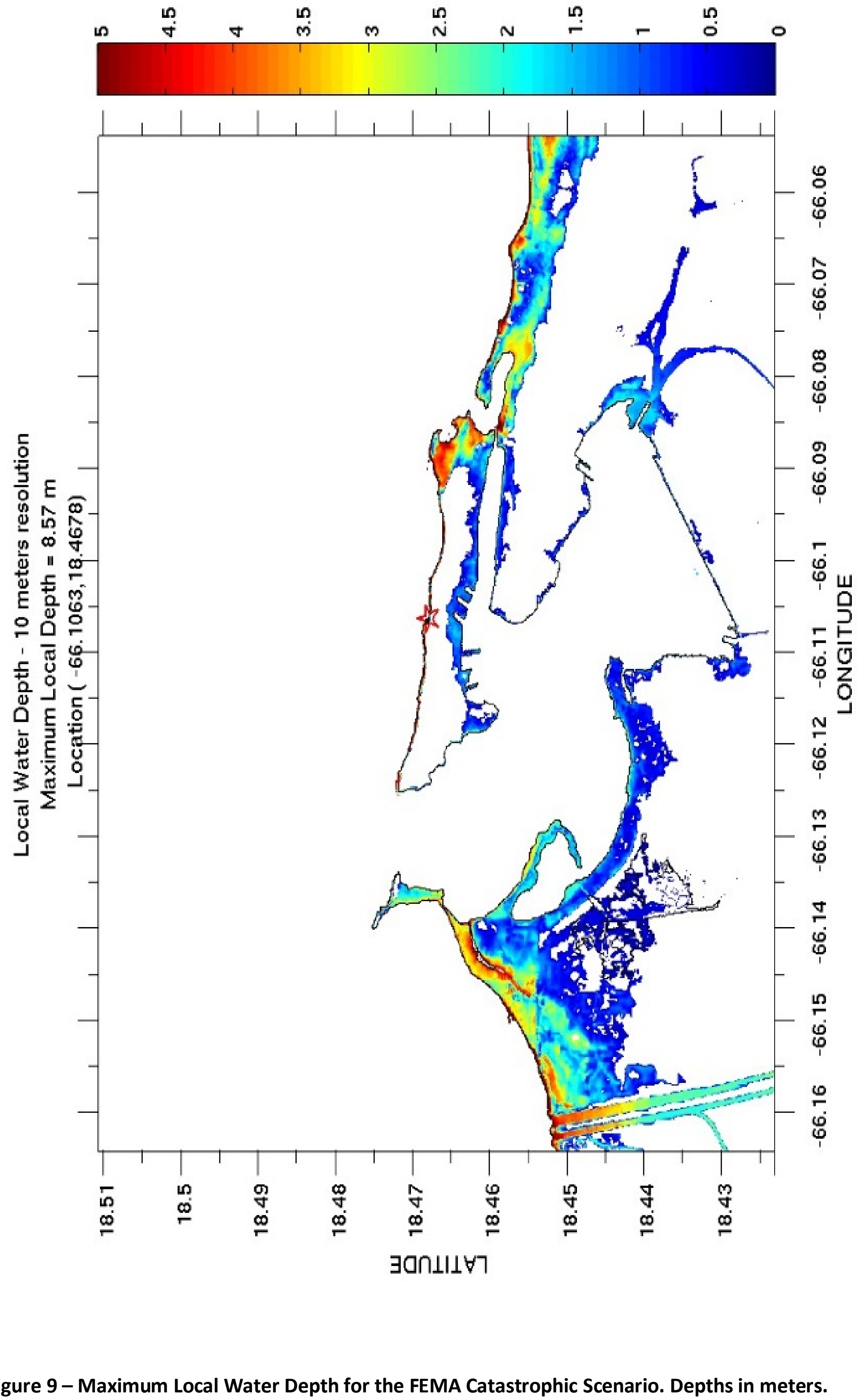

Figure 9 – Maximum Local Water Depth for the FEMA Catastrophic Scenario. Depths in meters.

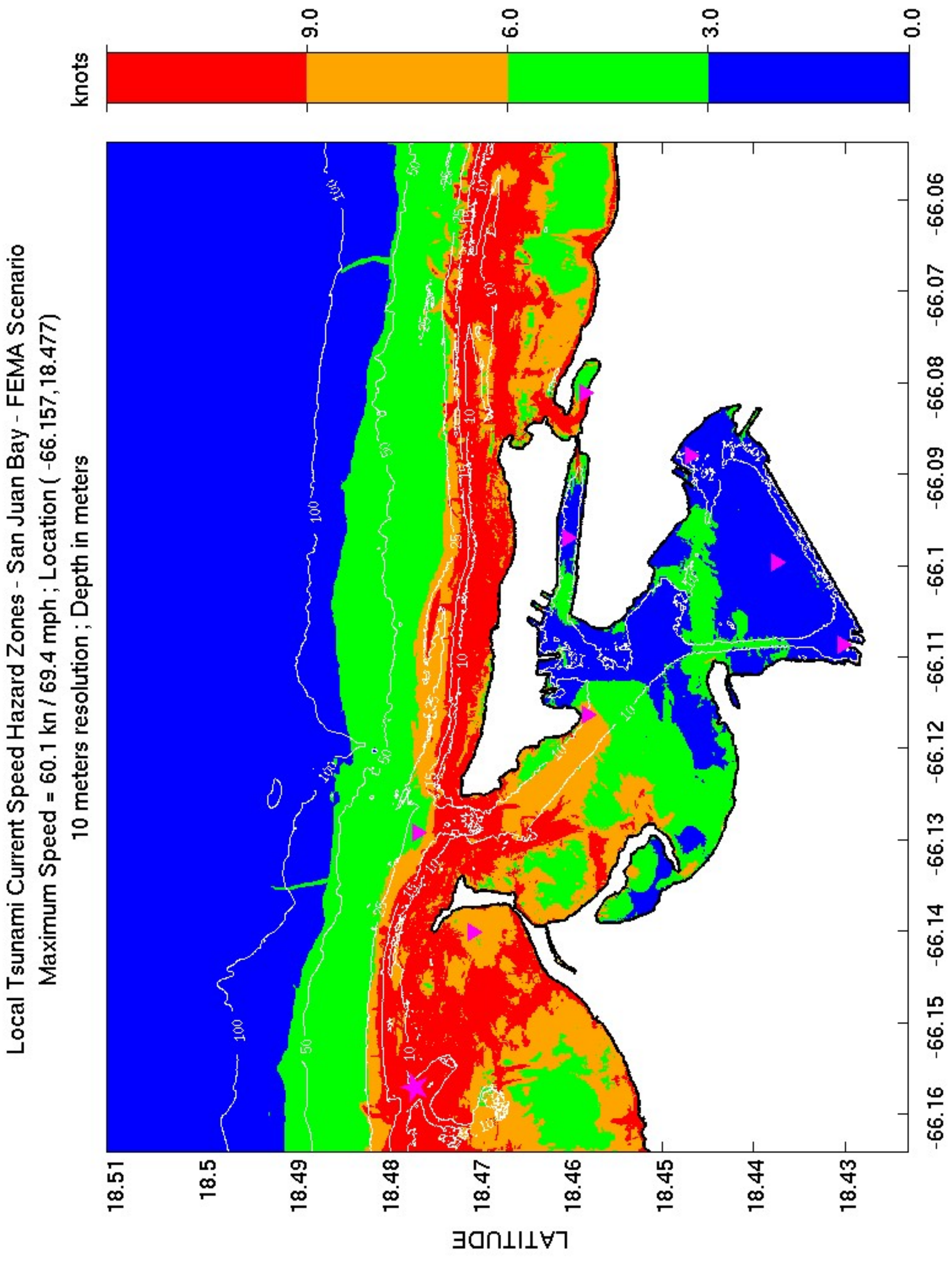

Figure 10 – Tsunami current speed hazards zones for the FEMA Catastrophic Scenario. Being this single scenario the one chosen for the tsunami currents hazards analysis for San Juan Bay, a kmz file showing the same information has also been prepared. A plot of the kmz image is given in Appendix I.

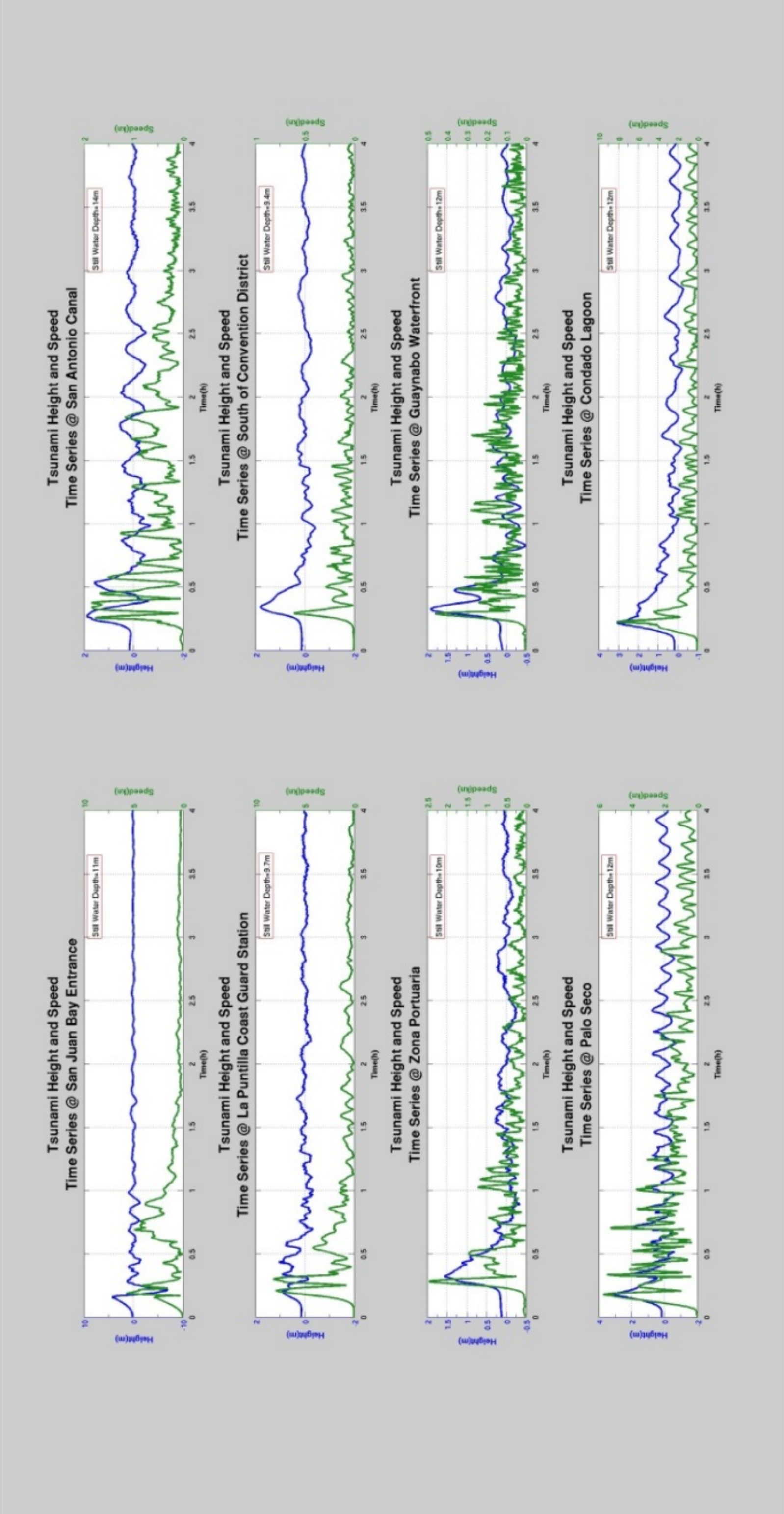

Figure 11 – Tsunami wave height relative to MSL (blue) and tsunami current speeds (green), at stations shown in Figure 1. Grid resolution is 10 m.

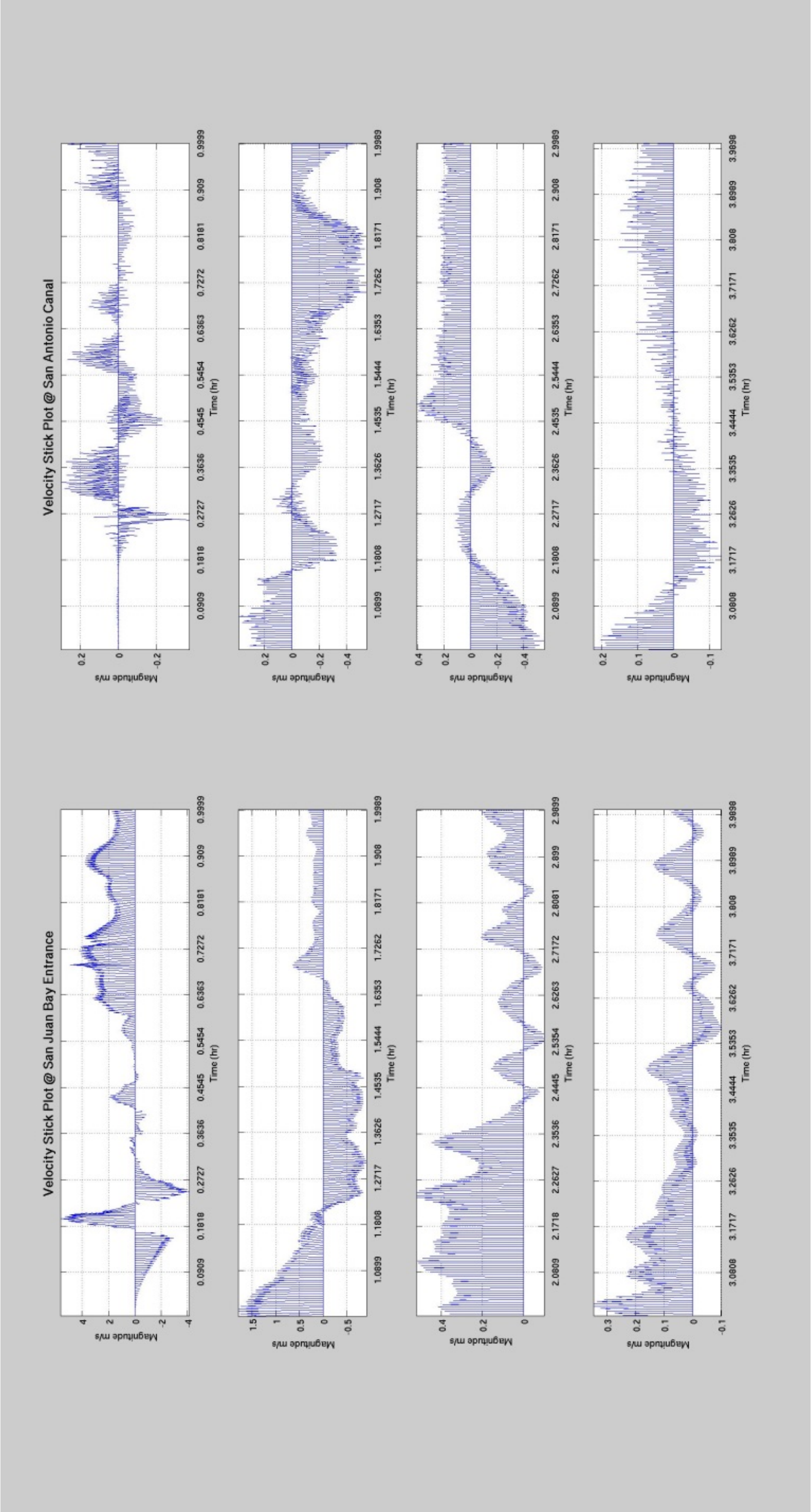

Figure 12 - Stick plots of tsunami current speeds at Stations 1 - San Juan Bay Entrance (left column) and 2 – San Antonio Canal (right column).

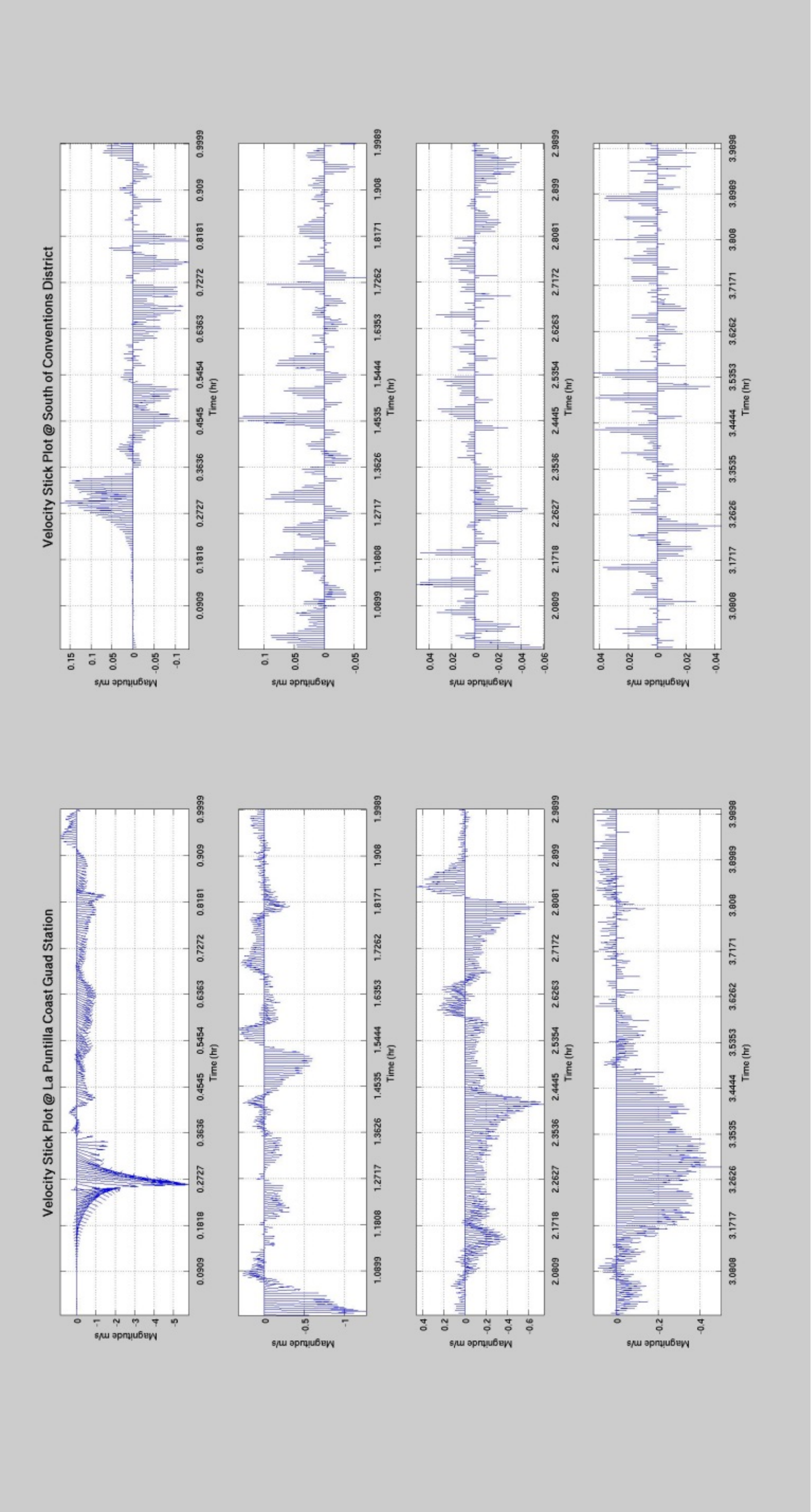

Figure 13 – Stick plots of tsunami current speeds at Stations 3 - La Puntilla Coast Guard Station (left column) and 4 – South of Convention District (right column). Grid resolution is 10 m.

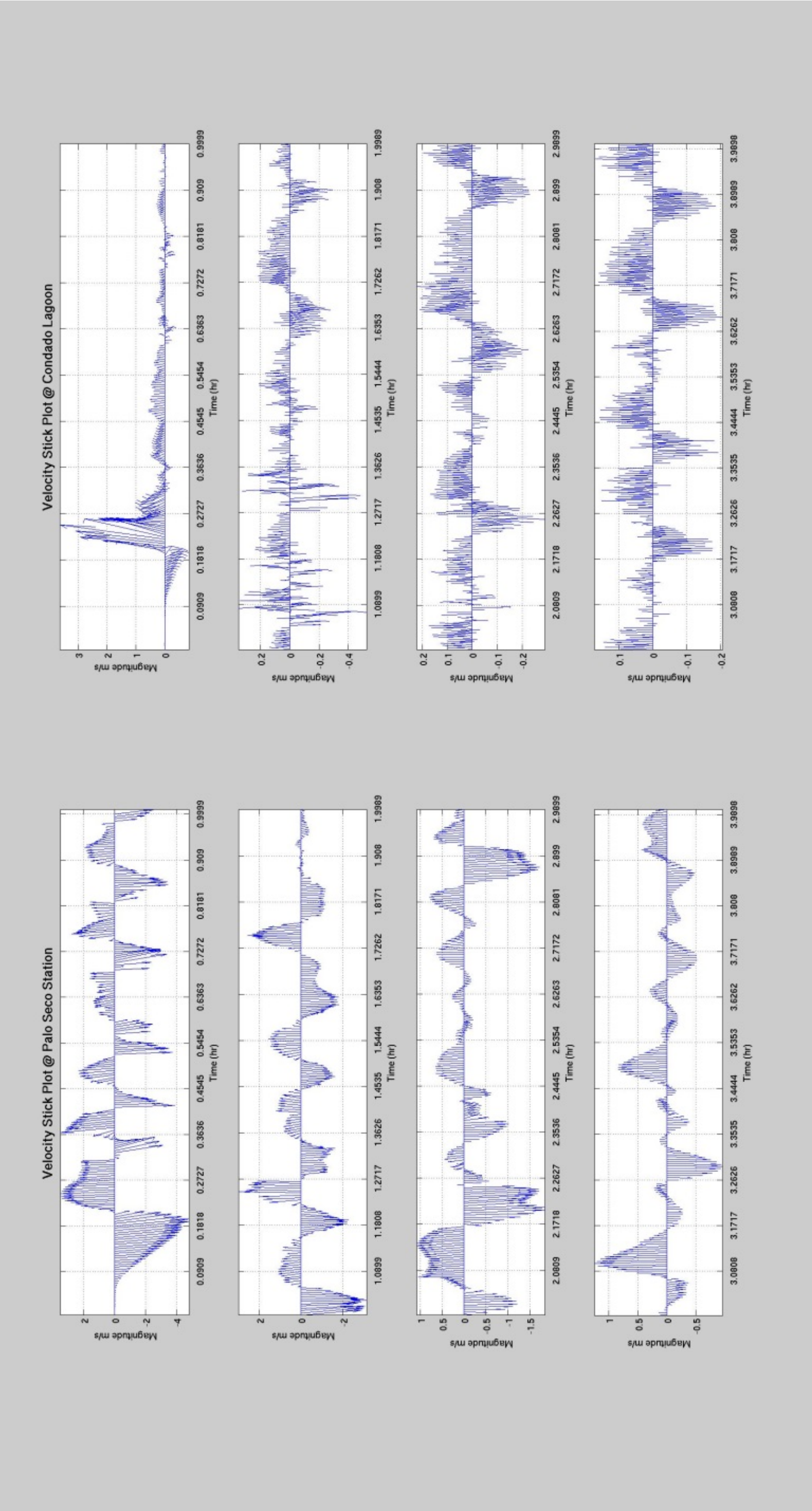

Figure 14 – Stick plots of tsunami current speeds at Stations 5 - Palo Seco (left column) and 6 – Condado Lagoon (right column). Grid resolution is 10 m.

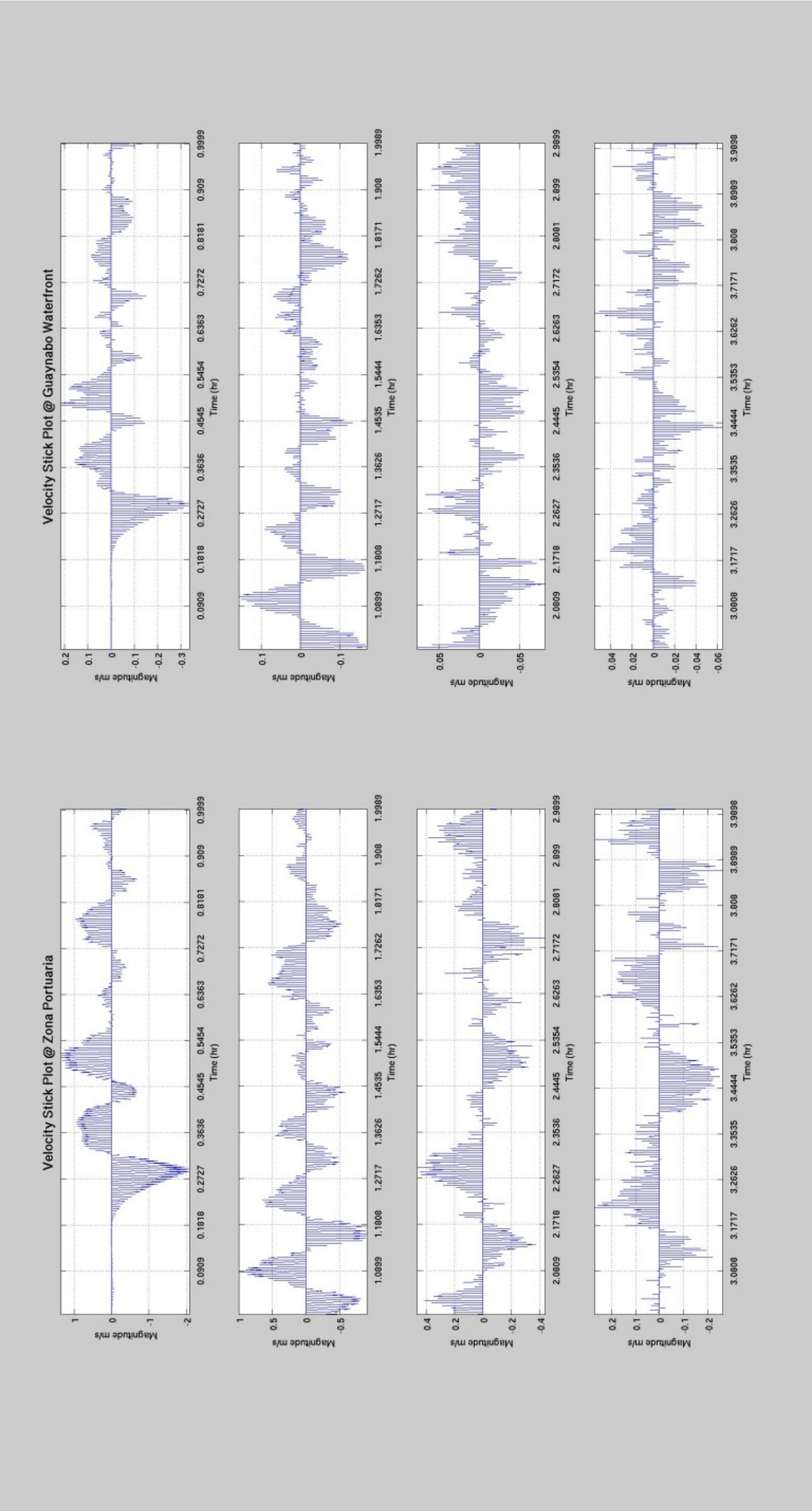

Figure 15 – Stick plots of tsunami current speeds at Stations 7 - Zona Portuaria (left column) and 8 – Guaynabo Waterfront (right column). Grid resolution is 10 m.

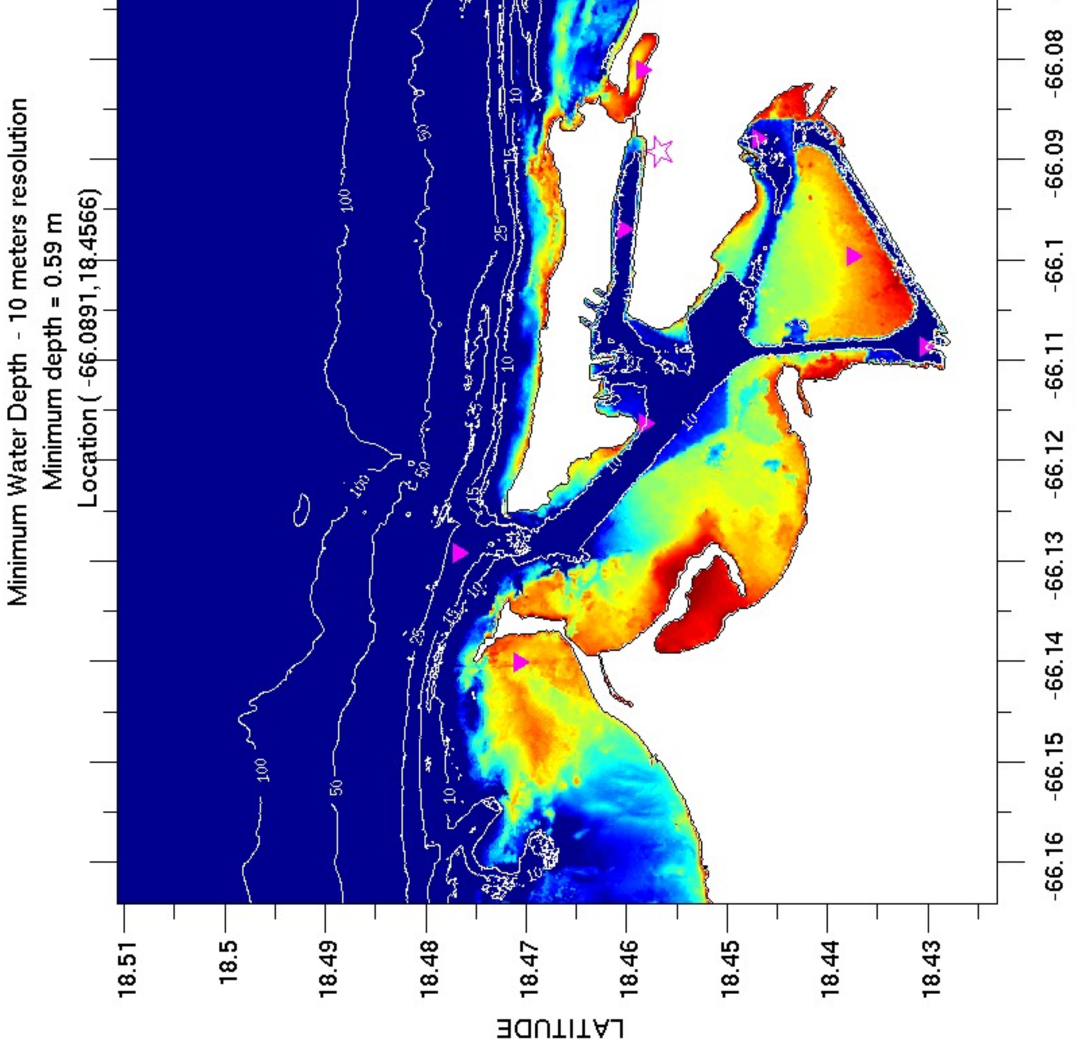

Figure 16 – Minimum remaining water depth. See Figure 17 for a schematic of how it is computed. Grid resolution is 10 m.

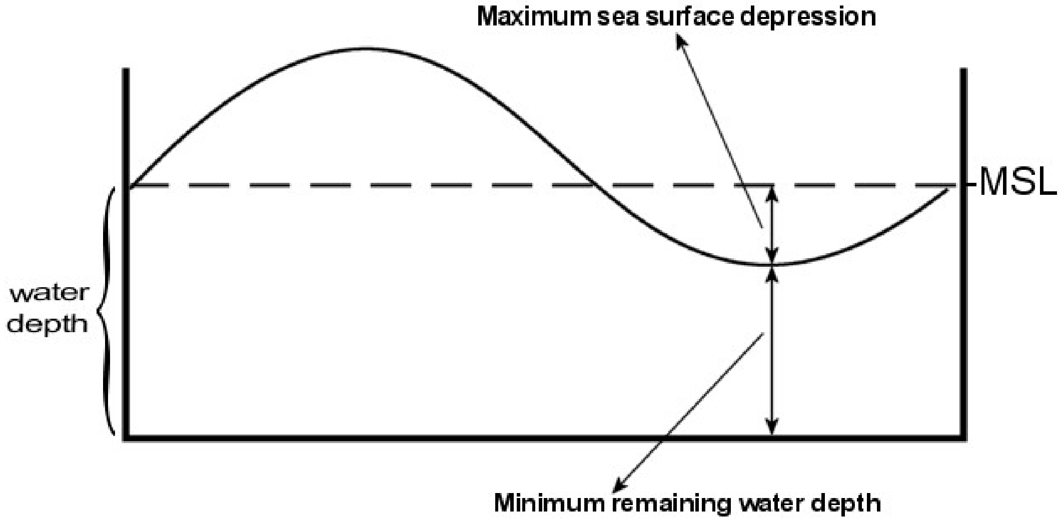

Figure 17 - Schematic of how to evaluate the minimum remaining water depth at each computational node. Minimum remaining water depth = MSL water depth – maximum sea surface depression.

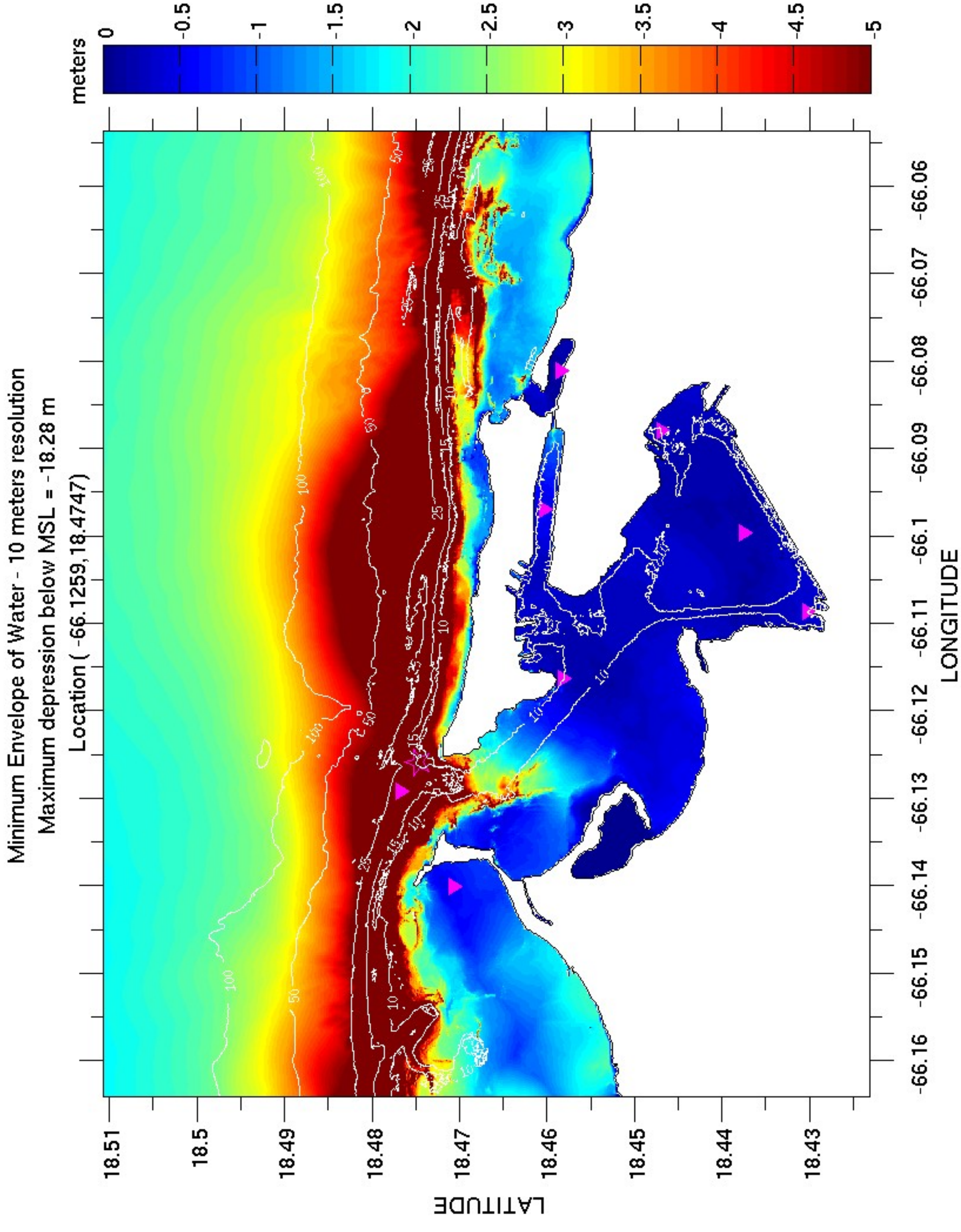

Figure 18 – Minimum envelope of waters (anti-MEOW).

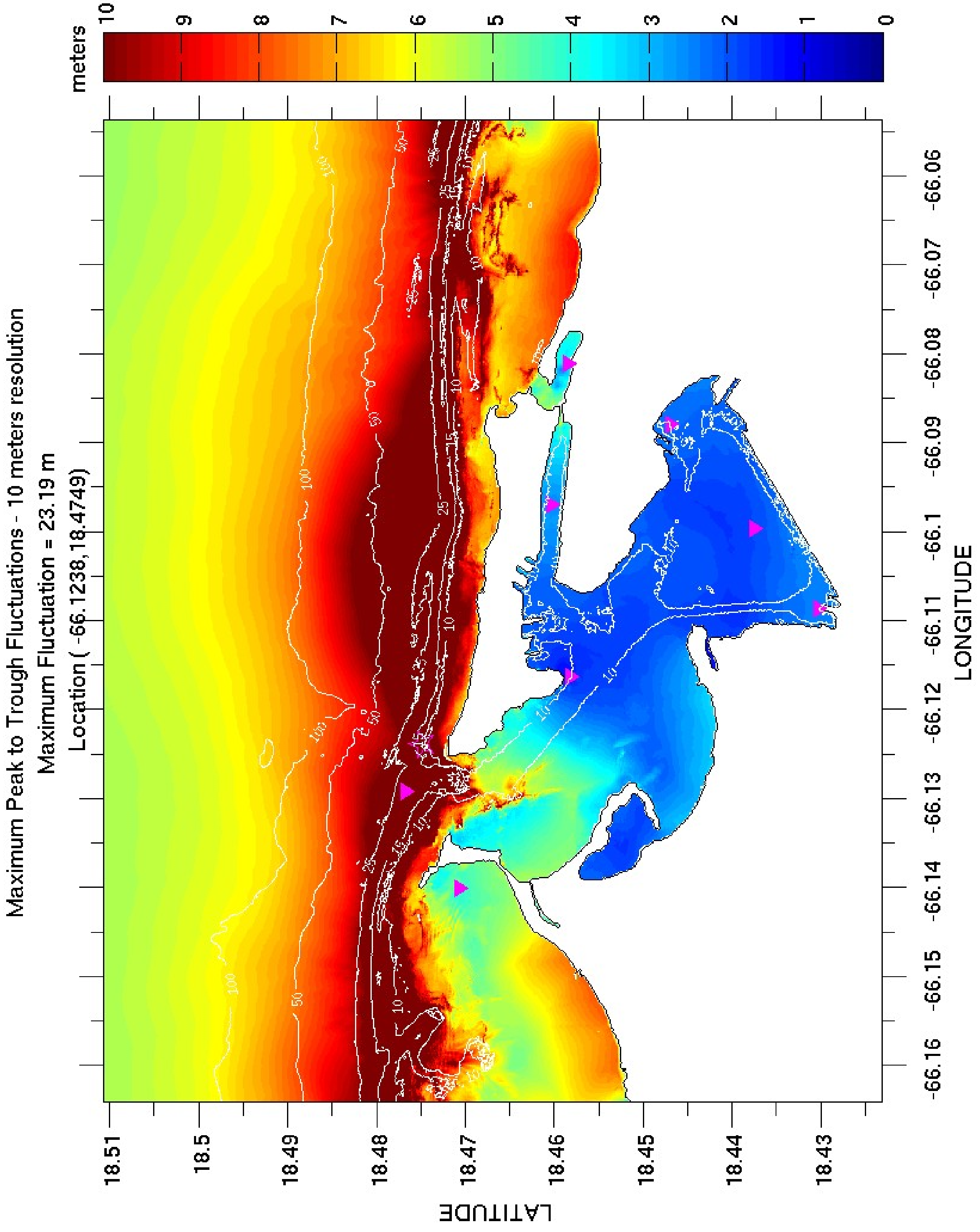

Figure 19 - Peak-to-Trough water level fluctuation. See text for an explanation. Grid resolution is 10 m.

Gyres/eddies within the bay, and near its entrance, have been shown to be a hazard. Figure 20 shows the magnitude of the maximum angular frequency of the eddies (what is actually computed is the flow vorticity, in radians/sec; this is changed to angular velocity by dividing by 2 and changing from radians/sec to degrees/sec). A movie was prepared that shows the eddies and as they spin off from the generation area.

A petition of the Mapping and Modeling sub-committee of NTHMP is to present the so-called Time Threshold Maps (TTM). Quoting from the M&M document titled "Guidelines and Best Practices for Tsunami Hazard Analysis, Planning, and Preparedness for Maritime Communities", developed by NTHMP Mapping and Modeling Subcommittee, Mitigation and Education Subcommittee, and Warning Coordination Subcommittee, Maritime Planning and Preparedness Guidelines – Version 3 (07-22-15), Draft June 2015,

To show the duration of damaging currents, "time-threshold" maps can be generated. For a specified current velocity level, these maps will show the time duration during which the velocity is exceeded based on numerical modeling results run for a 60 hour tsunami scenario. It is recommended that the duration represent the time period between the first and last time a particular velocity is exceeded, not the sum of times the threshold is exceeded. While this type of information should be very useful for harbor personnel to estimate the duration of dangerous conditions, the estimates will be highly source dependent and scenario specific.

The following steps can be taken to produce time-threshold maps:

1) Use the modeled time-history data for various scenarios to determine the length of time specific current thresholds (3/6/9 knots for well-maintained harbors; 2/5/8 knots for older, poorly maintained harbors) are active.

2) Maps can be created that show the same time-threshold for multiple scenarios, or multiple time-thresholds for the same scenario.

3) When displaying multiple time-thresholds on a maps, the colors used for the times should have a consistent scale for the best comparison.

In our case, we only present the TTM for just 4 hours of simulation. Figures 21to 23 show the TTMs using a colorbar cap of 0.5 hours, and a current threshold $\geq$3, 6, and 9 knots, respectively.

For example, Figure 21 shows that the entrance to San Juan Bay is capable of experimenting tsunami-induced currents $\geq$ 3 knots for at least 0.5 hours after tsunami arrival. While currents $\geq$6 knots can be expected for about 0.15 to 0.2 hours.

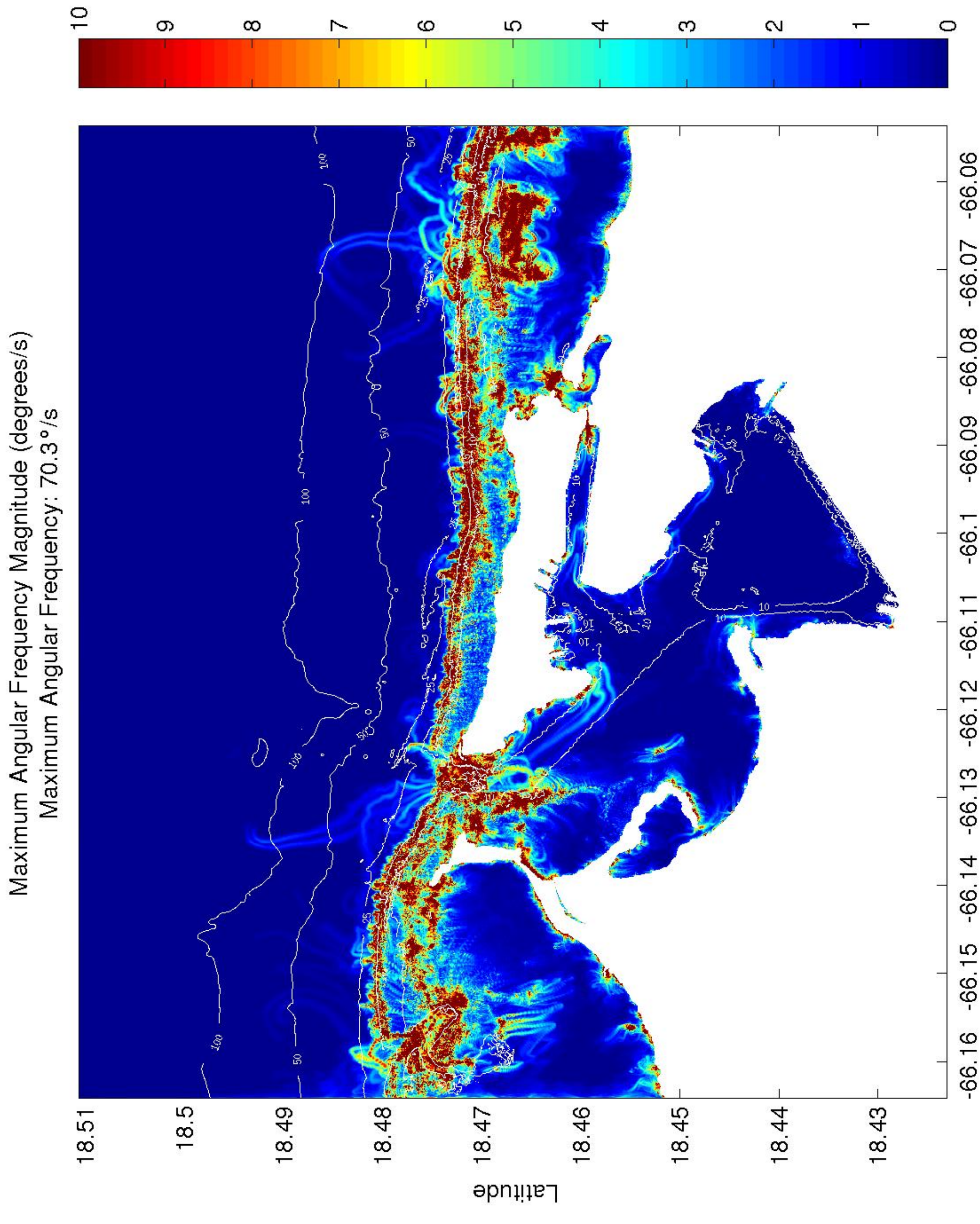

Figure 20 – Figure showing the magnitude of the maximum angular frequency of the eddies induced by the tsunami. Grid resolution is 10 meters.

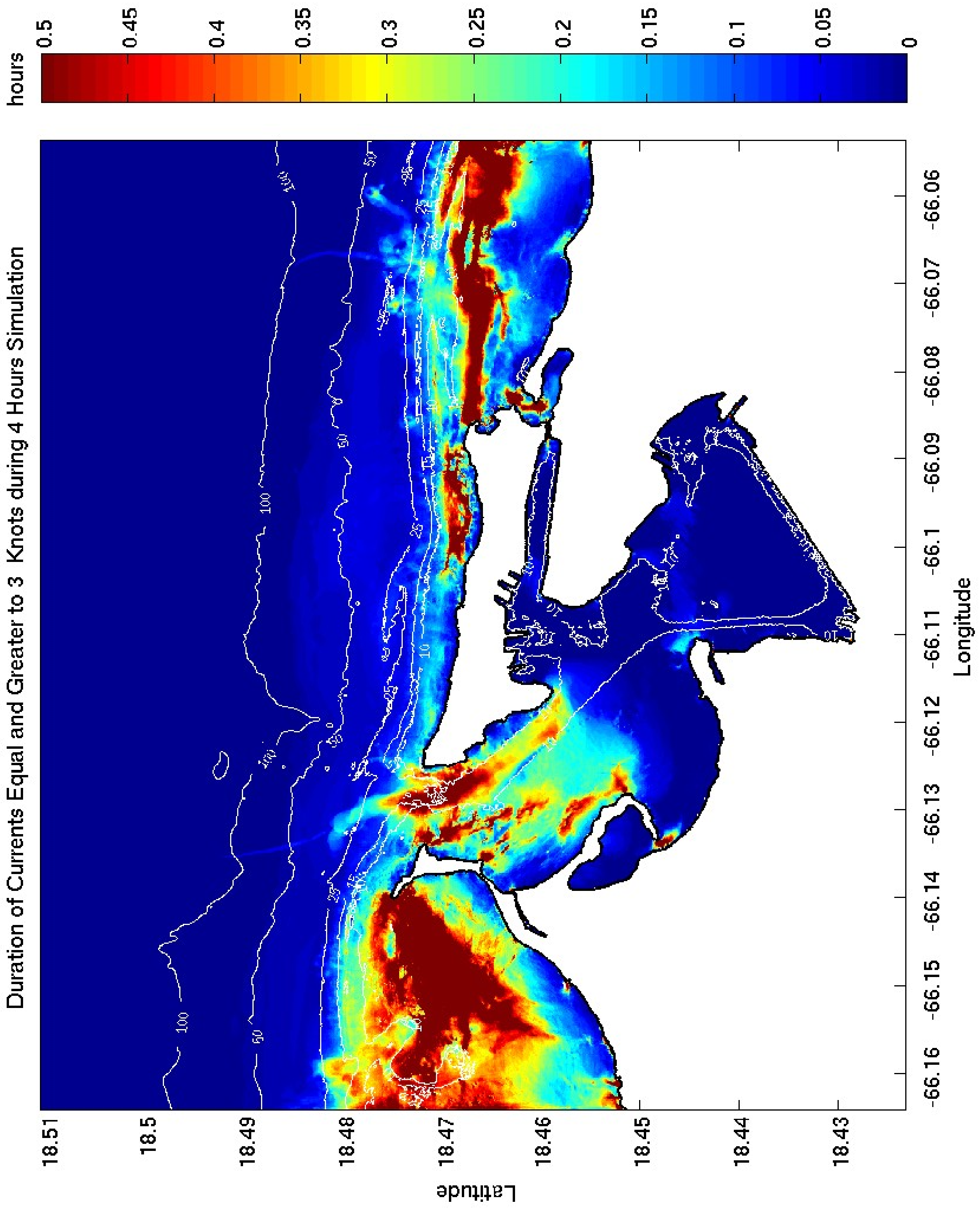

Figure 21 – Duration of tsunami-induced currents ≥ 3 knots during the 4 hours of simulation with a colorbar cap of 0.5 hours. Grid resolution is 10 m.

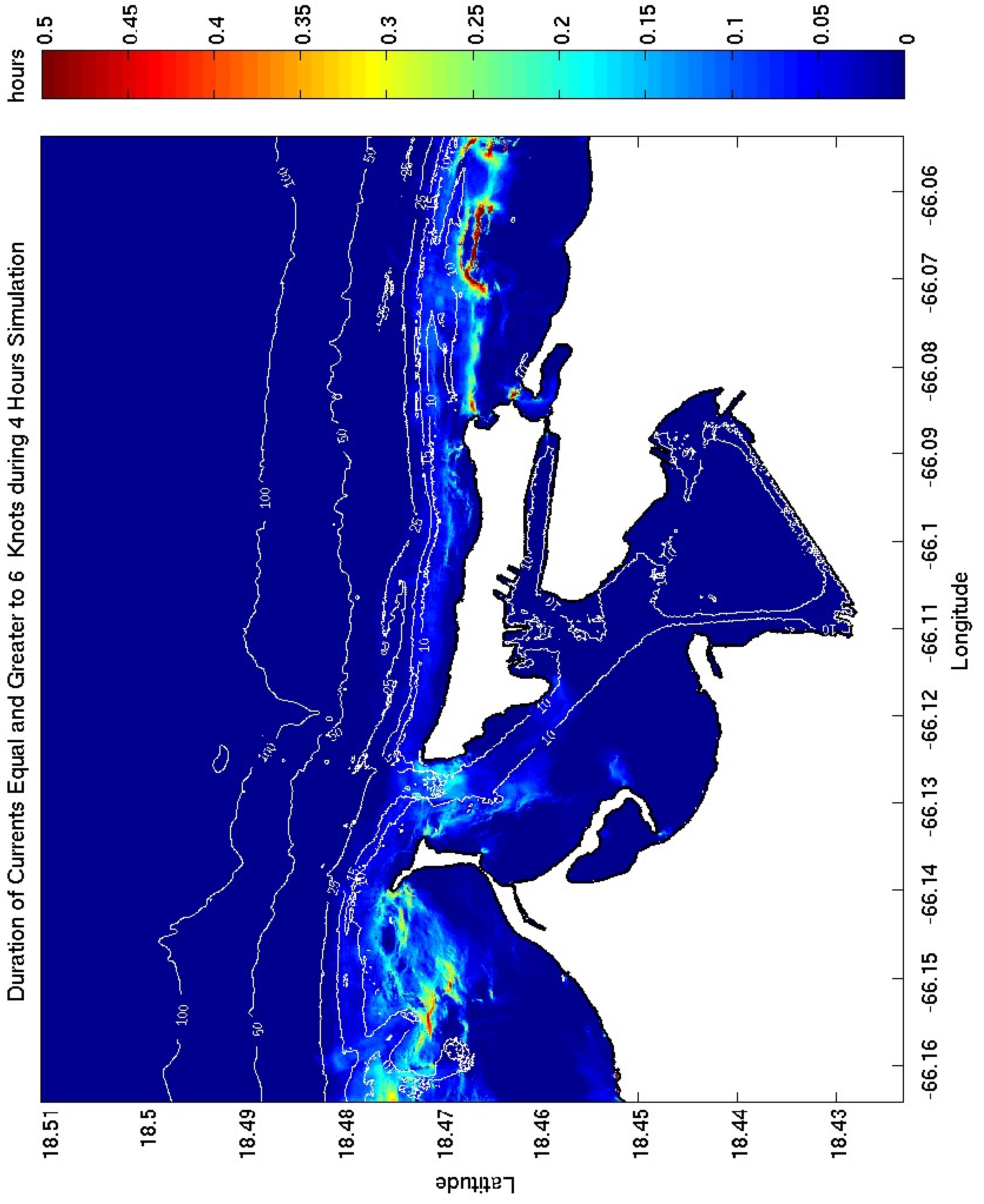

Figure 22 – Duration of tsunami-induced currents ≥ 6 knots during the 4 hours of simulation with a colorbar cap of 0.5 hours. Grid resolution is 10 m.

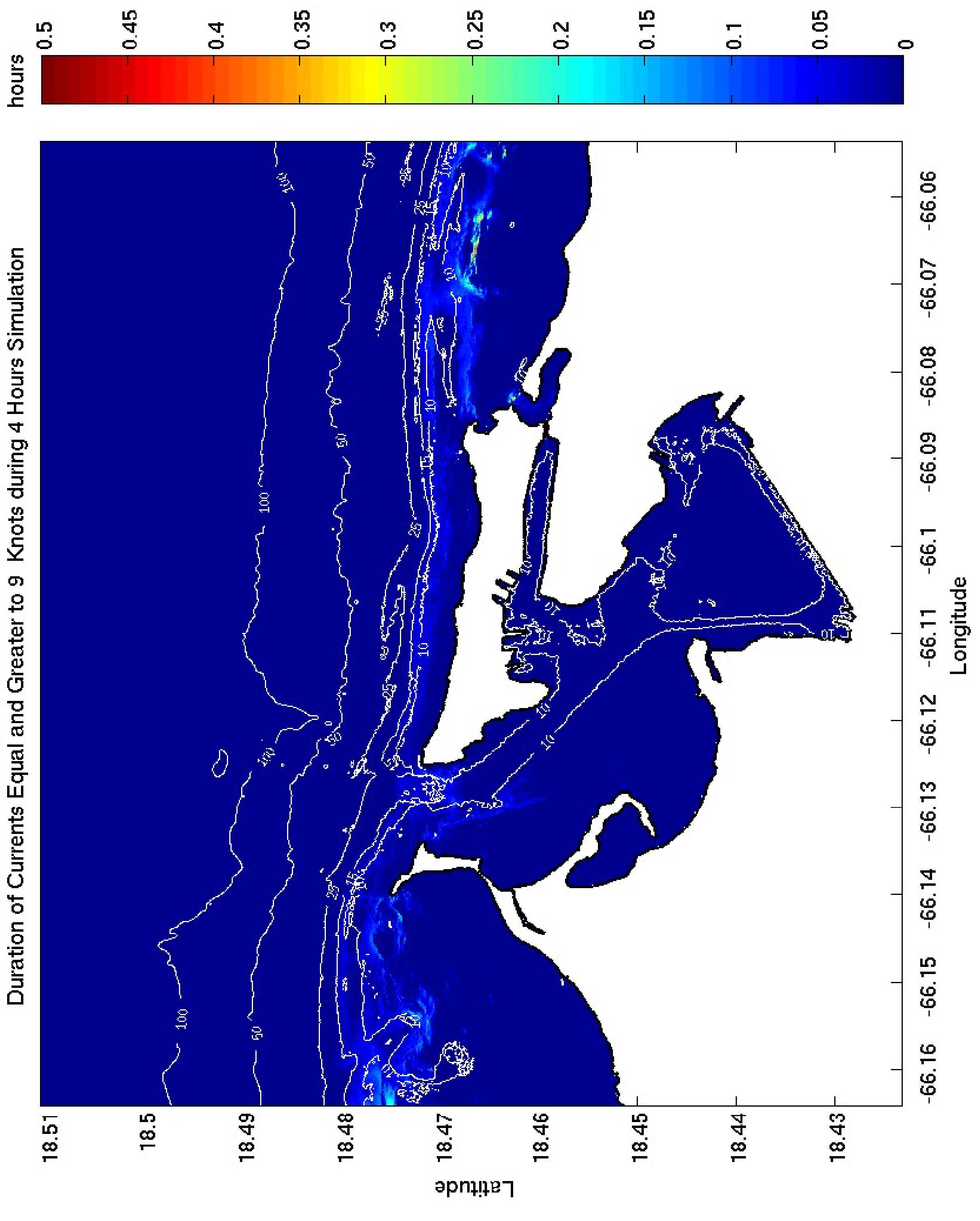

Figure 23 – Duration of tsunami-induced currents ≥ 9 knots during the 4 hours of simulation with a colorbar cap of 0.5 hours. Grid resolution is 10 m.

SENSITIVITY TEST OF COMPUTATIONAL GRID RESOLUTION

As part of this study for San Juan Bay it was decided to compare results computed with different grid resolutions. The present tsunami inundation maps were prepared at 30 m resolution, while for this San Juan Bay study we used 10 m resolution. In general, in numerical models that output current speeds the higher the computational mesh resolution, the more accurate the results. In what follows we will show some of the same figures as above but at a grid resolution of 30 meters.

Figure 24 should be compared with Figure 8. Figure 25 should be compared with Figure 9. Figure 26 should be compared with Figure 10. Figure 27 with Figure 11. Finally, Figure 28 with Figure 20. Overall, the most striking differences are seen between the current speed (Figures 26 and 10) and vorticity (Figures 28 and 20) estimates. One can obviously see much higher velocities in the higher resolution grid (10 m), coming from the more complex parts of the bathymetries just offshore of Isleta de San Juan and in the entrance to the Bay. Unfortunately, there is no field data to compare with.

Finally, in Figure 31 we compute the differences in velocities. It was done in the following way. The MOST results at 10 m resolution were re-gridded to 30 m resolution. Next we subtracted the MOST results obtained at 30 m resolution from the re-gridded 10 m results. The results were then contoured and are shown in Figure 31. Again, it can be seen that the largest differences are in the more complex bathymetry.

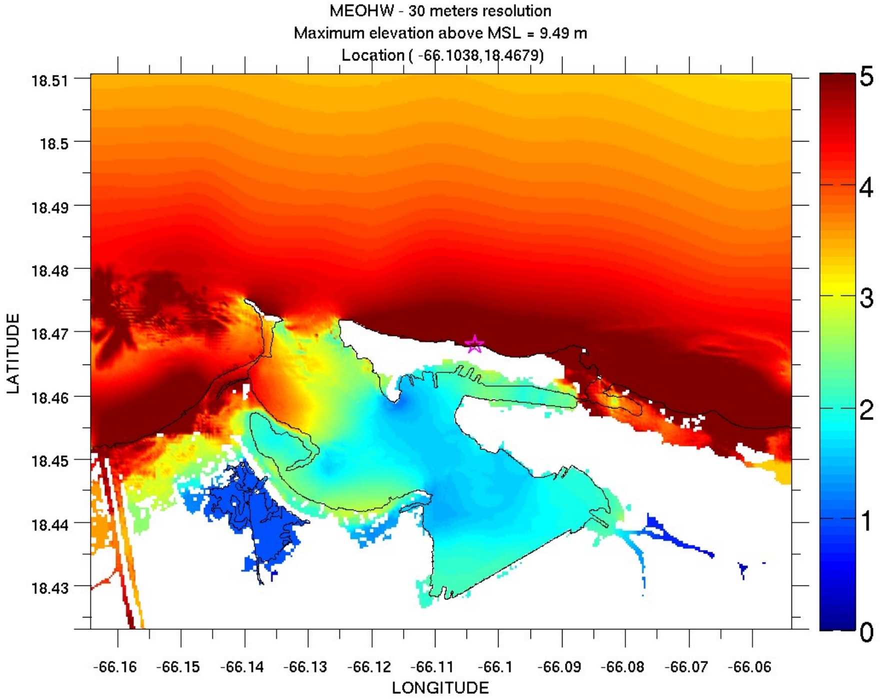

Figure 24 - Maximum sea surface elevation for the FEMA Catastrophic Scenario. Elevations in meters. Grid resolution is 30 m.

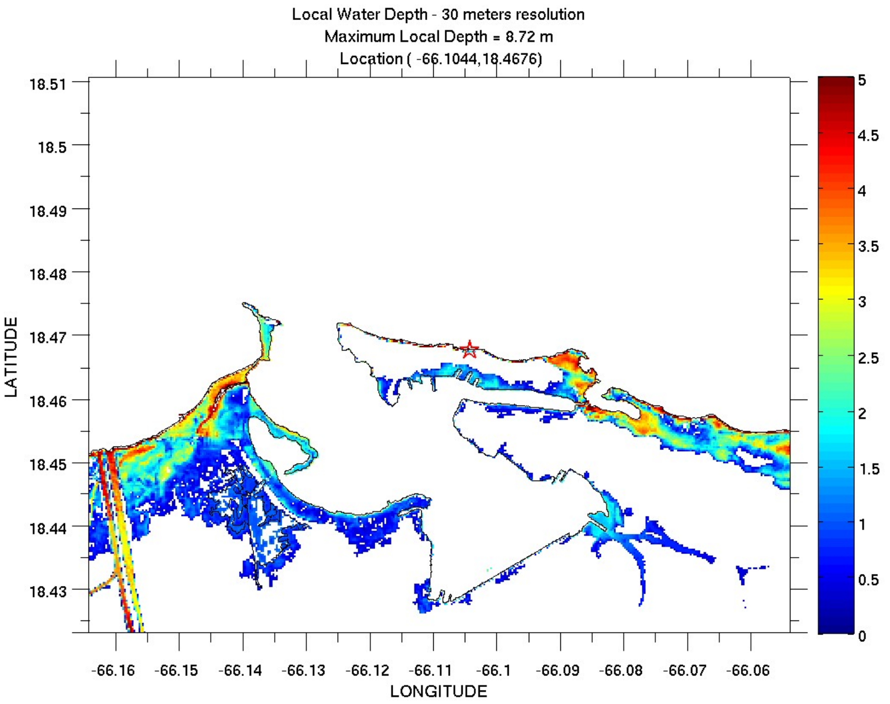

Figure 25 - Maximum Local Water Depth for the FEMA Catastrophic Scenario. Depths in meters. Grid resolution is 30 m.

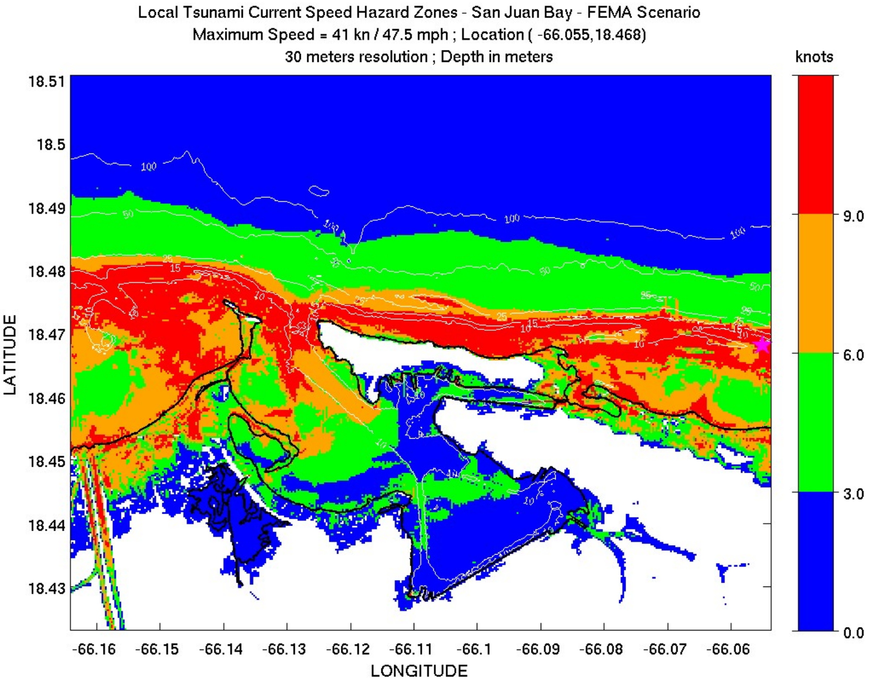

Figure 2625 - Tsunami current speed hazards zones for the FEMA Catastrophic Scenario. Grid resolution is 30 m.

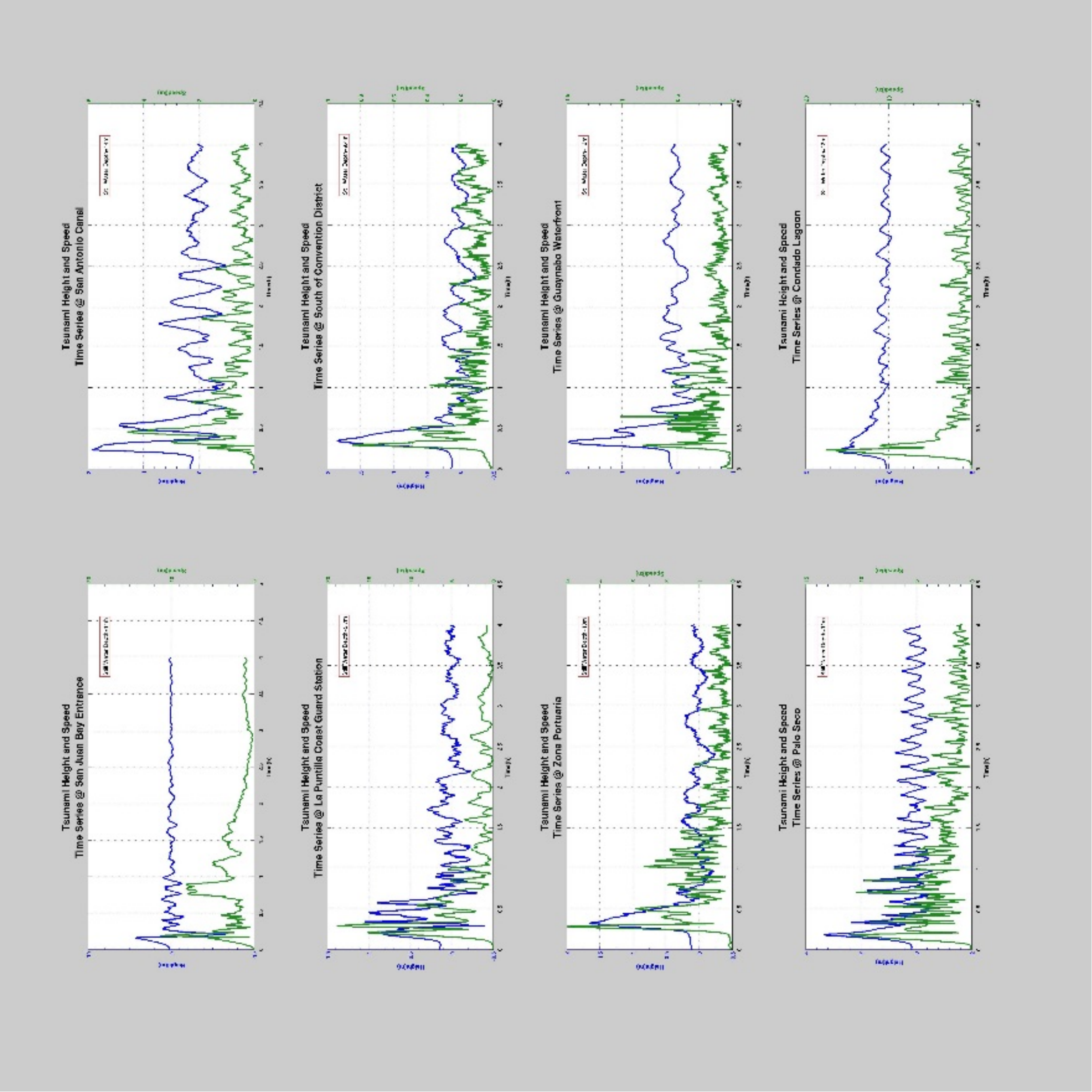

Figure 27 - Tsunami wave height relative to MSL (blue) and tsunami current speeds (green), at stations shown in Figure 1. Grid resolution is 30 m.

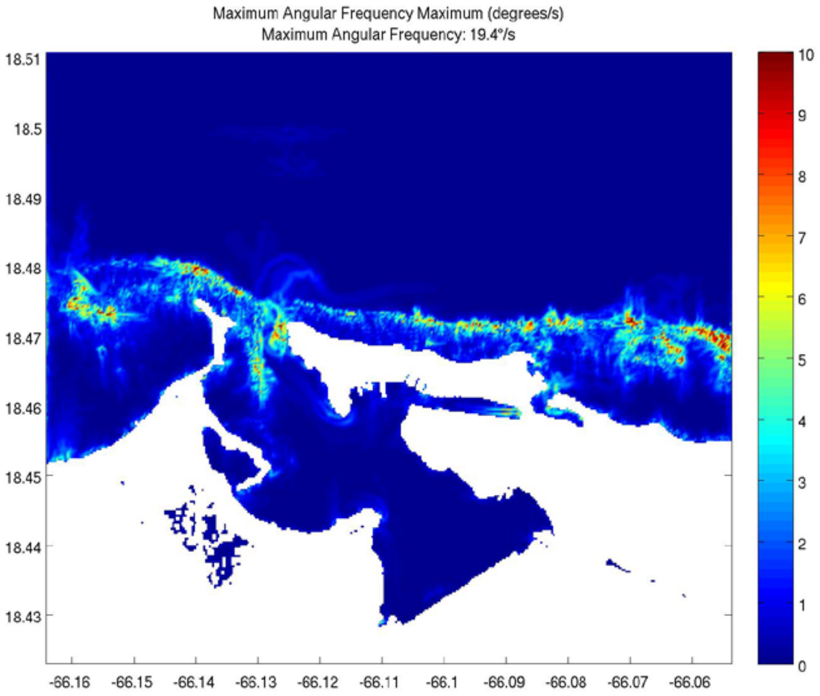

Figure 28 - Figure showing the magnitude of the maximum angular frequency of the eddies induced by the tsunami. Grid resolution is 30 meters.

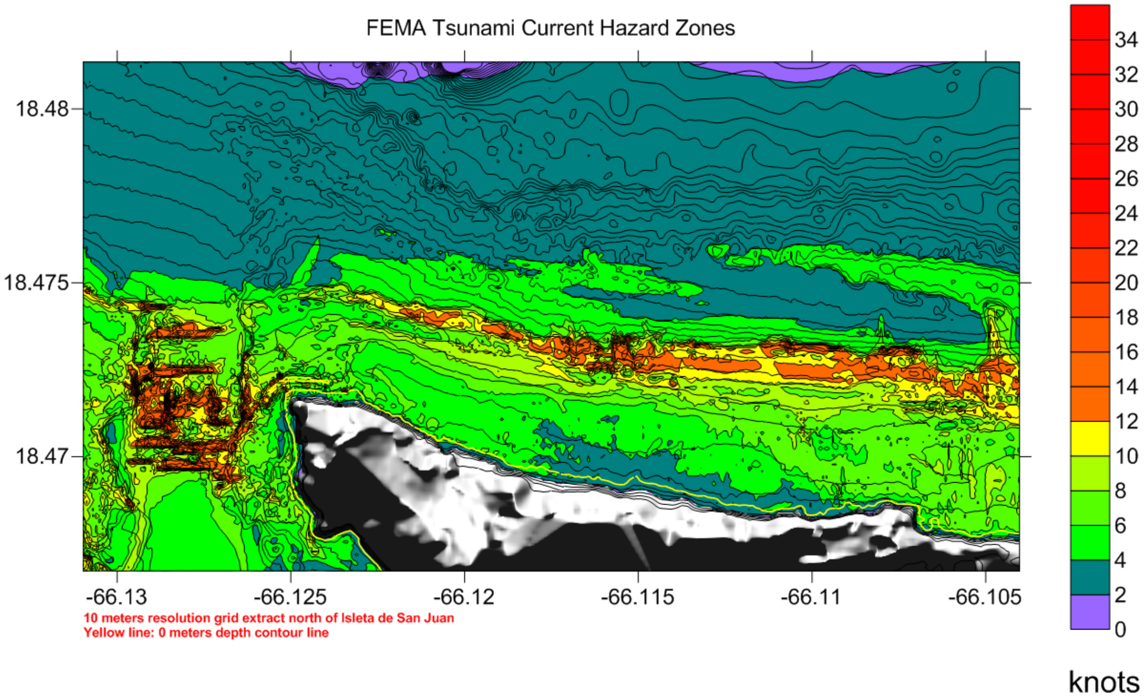

Figure 29 – Tsunami currents hazard zone based on the 10 m resolution grid. Black lines are depth contours (not labelled), and the colors are based on the current speed values.

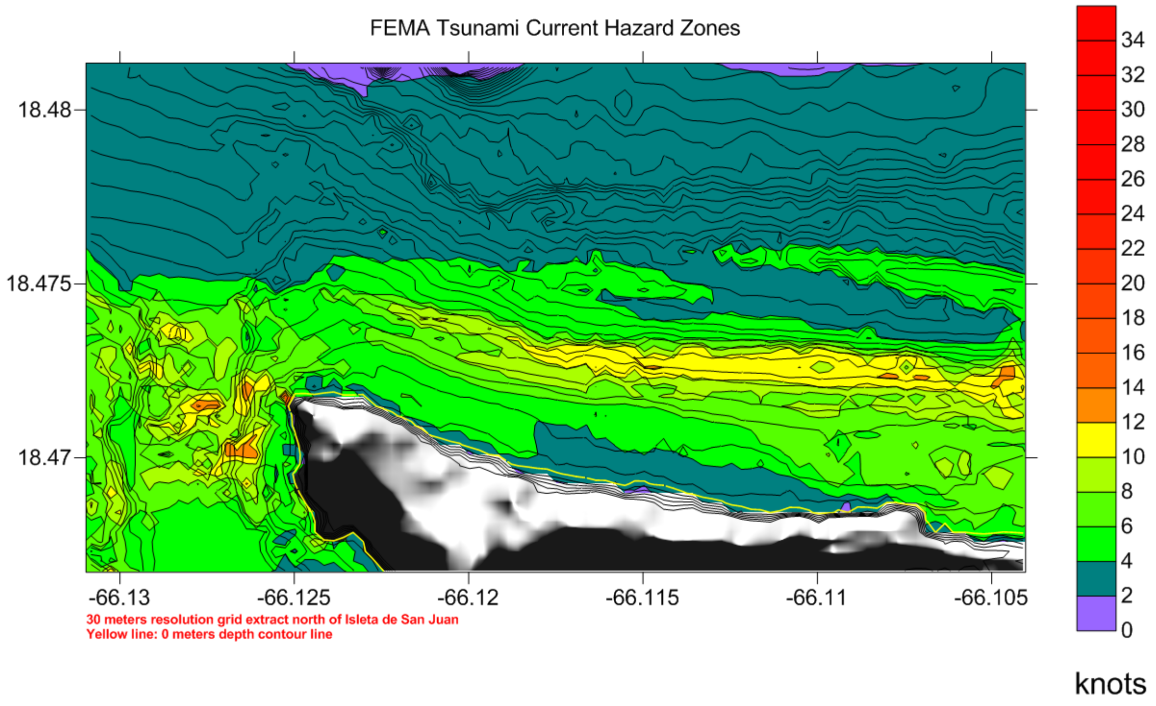

Figure 30 – Tsunami currents hazard zone based on the 30 m resolution grid. Black lines are depth contours (not labelled), and the colors are based on the current speed values.

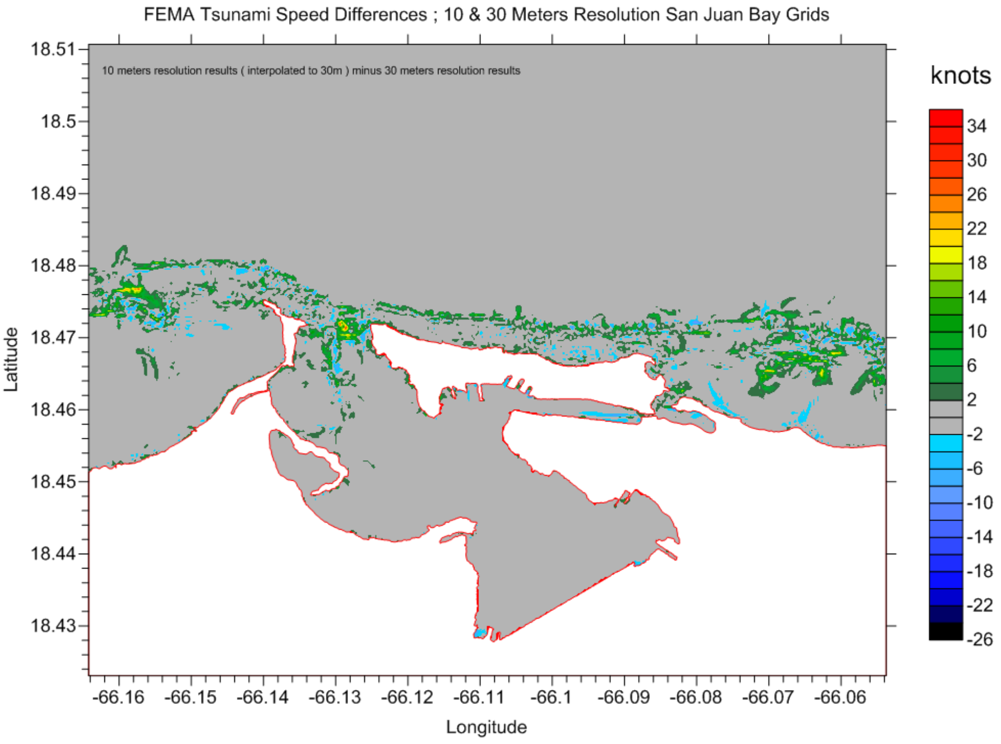

Figure 31 - Tsunami current speed differences between 10 and 30 meters resolutions. See text for explanation.

We would like to point out certain aspects of this study that differ from the original assessment of tsunami-induced current hazards (P. Lynett et al., 2014). The assessment done here is based on a local source tsunami with a magnitude of Mw 8.4 while the original NTHMP currents assessment referred to transoceanic tsunami events. Also, we modeled the tsunami for a total of 4 hours since the original deformation, while the original assessment modeled the tsunami for up to 60 hours. The combination of the complex bathymetry around Puerto Rico and the fact that we used a local and very strong tsunami event shows drastic results in terms of magnitude of current speeds and sea surface elevations. The duration of the tsunami induced currents is much lower in our case possibly due to the fact the transoceanic events have a longer period which helps maintain steady currents for longer time, and could induce resonance effects inside the bays. The constant in and out-flux of tsunami waves due to our local event results in unsteady currents that do not last long periods of time. As part of future work, we should assess the effects of far-field sources.

There is also the concern of whether a model like MOST has all of the Physics required to simulate the extremely high currents reaching San Juan Bay.

For a better understanding of the behavior of tsunami-induced currents inside San Juan Bay, please see the currents and vorticity movies. Finally, these images – with the exception of Figure 6 - were based on just one event, which for San Juan is an extreme event. If it is desired to explore the consequences for all scenarios, use Figure 6, which is based on a composite of 320 events.

ACKNOWLEDGEMENTS

We would like to acknowledge the technical help and support of Mr. Harry Justiniano. Also, the support of Dr. Victor Huerfano, of the Puerto Rico Seismic Network, is greatly appreciated. And also of NOAA’s Center for Tsunami Research, especially Dr. Diego Arcas and Dr. Chris Moore.

APPENDIX I

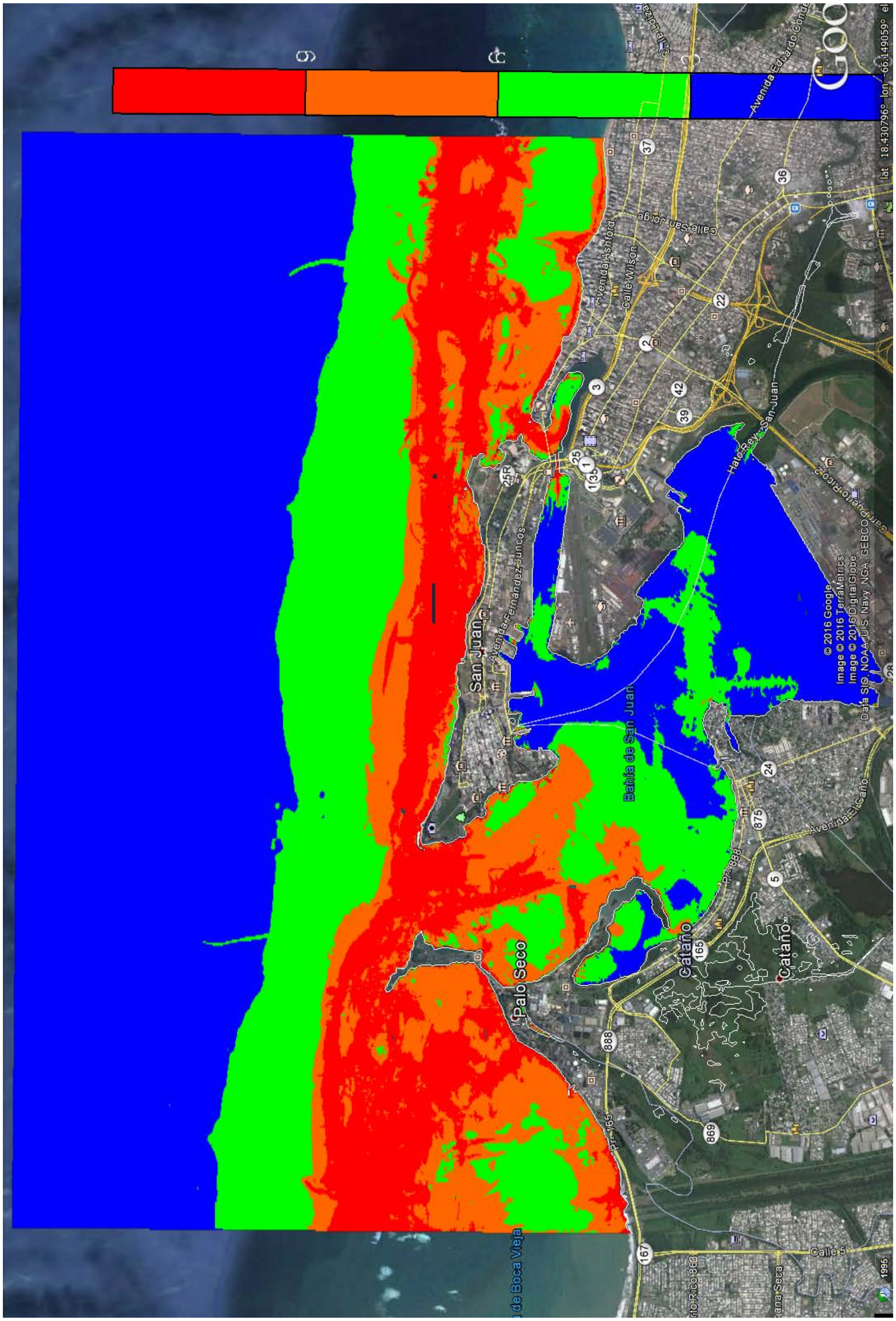

Figure 32 – Screen shot of kmz image of Figure 10 above. Note that the Condado Lagoon is not completely represented in the 10-m DEM used.

When this kmz file was shown using Google Earth it was noticed that the Condado Lagoon is not completely represented in the 10-m DEM used in the modeling. But when the 30-m DEM Lagoon outline was superimposed on the figure, it was noticed that the same problem exists in the 30-m DEM. Figure 33 shows a close up of the area illustrating in a much better way the problem.

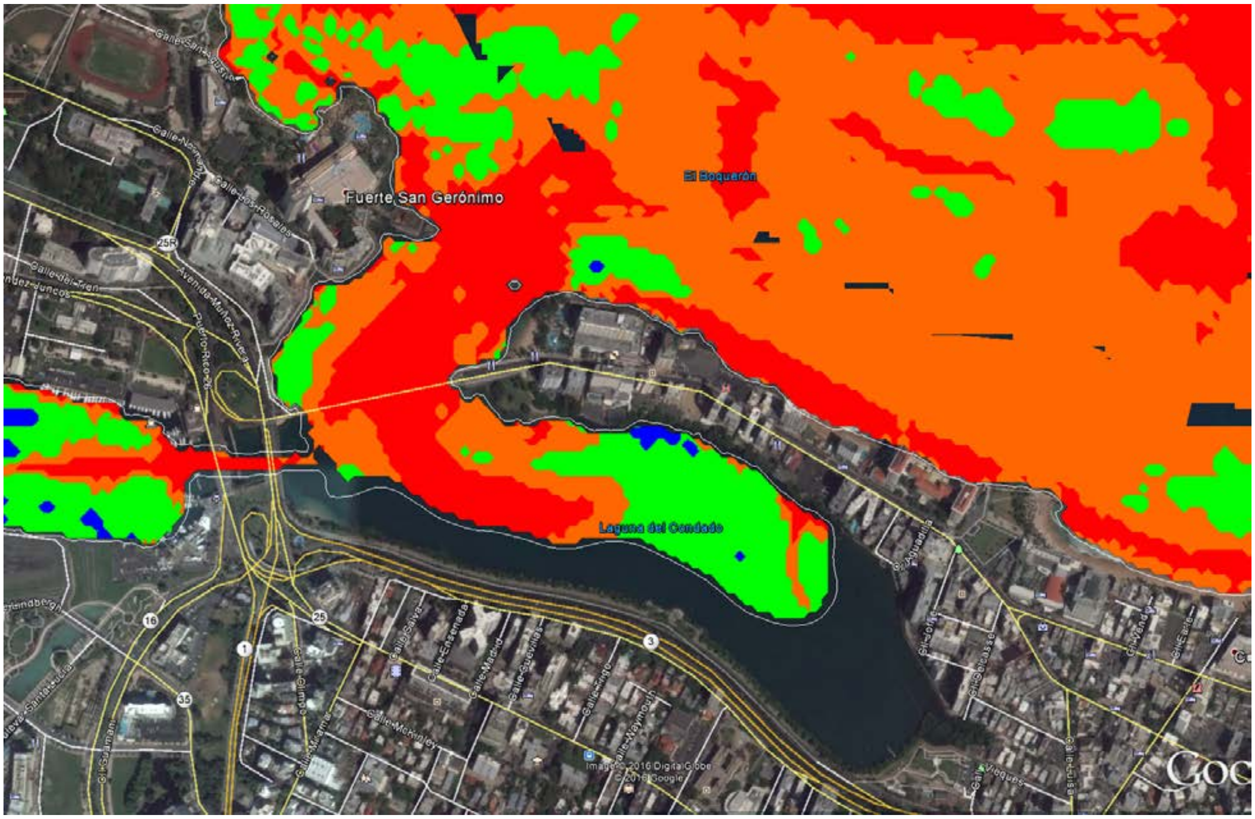

Figure 33 – Close up of the Condado Lagoon.