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Wave and Storm Surge Flooding in a Small Marsh System

James O'Donnell

Department of Marine Sciences

and

Connecticut Institute for Resilience and Climate Adaptation

University of Connecticut

1. Introduction

The coastline of Connecticut is incised by numerous inlets where the streams and rivers carrying runoff from land towards the ocean and the saline tidal waters of Long Island Sound intrude into the channels. Salt marshes have formed in many of these inlets and have become critical habitat for numerous species of insects, birds and fish. Coastal settlements, and the routes between them, have general skirted the inland limits of the salt marshes and many bridges and culverts have been constructed to allow the water and transportation network to co-exists. Rising sea levels will cause segments of roadways to become more vulnerable to flooding in the future. Assessing the most cost effective and appropriate adaptation strategy to reduce the frequency of flooding to an acceptable level requires analysis of the flow of water through the inlets. In this report we develop an approach to the assessment of the current flood risk and the estimation of the future risk as sea level rises. The study site is Sybil Marsh in Branford, CT. This area provides a good example of several issues that are important in the region. It is densely developed with residential housing, it is surrounded by roads, and the flow into the marsh has been controlled by a tide gate for many decades. During "Super Storm Sandy" much of the area was flooded and some data on water levels and flow paths was acquired. Residents reported that water was flowing over the bridge at Linden Avenue and into the marsh. Other reported that breaking waves were overtopping the road at Limewood Avenue that the splashover was flowing northward along Waverly Avenue and into the marsh as well.

In the following sections we first address the flow through the tide gates using observations and a model. We describe the geometry of the region, the observation program and the use of models we have developed to assess flood risk and the effects of sea level rise. Since it is unlikely that we could acquire data on severe events during the contract period, we then address the wave overtopping and flow into the marsh at Limewood Avenue with just model simulations. We conclude with a discussion of the likely effects of sea level rise.

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2. The Geography of the Sybil Creek

The Sybil Creek area of the Town of Branford, CT, is shown in the GoogleEarth Image in Figure 1. It is an affluent town with a mixture of year round residences and some large vacation homes along the shoreline of the Sound. The promontory that extends into Long Island Sound has some rocky high ground and it connected to the mainland by a sandy spit at the area shown by the yellow arrow. The main coastal state highway (RT 146) runs parallel to the shore in the spit and is named Limewood Avenue there. It turns north and crosses Sybil Creek on a bridge-tide gate structure near the junction with Linden Avenue.

Figure 1. The coastline of Branford is shown using a GoogleEarth image with some locations of flooding on RT 146 indicated by the blue and yellow arrows. To understand how the water level in the Sound drives flooding we deployed instruments to measure sea level at the 3 locations shown by the red diamonds. We also deployed a wave sensor at approximately the location of the yellow *.

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A bridge and tide gate carry RT 146 across the Sybil Creek in Branford. Figure 2 shows the topography and bathymetry in the area of the bridge and the location of 4 moored instruments that were deployed to observe water level fluctuations. Flooding have been reported on both Sybil and Linden Avenue to the east of the bridge. The magenta square in Figure 2 includes BR1 and BR2 and surrounds the area prone to flooding. A high resolution map of the area is shown in Figure 3 where the elevation range displayed is restricted to -0.5 m to 2m to reveal the subtle variations in topography around the level of the top of the bridge. The red dots in Figure 3 indicate the locations of measurements of elevation by RTK GPS on the road surface of the tide gate-bridge structure.

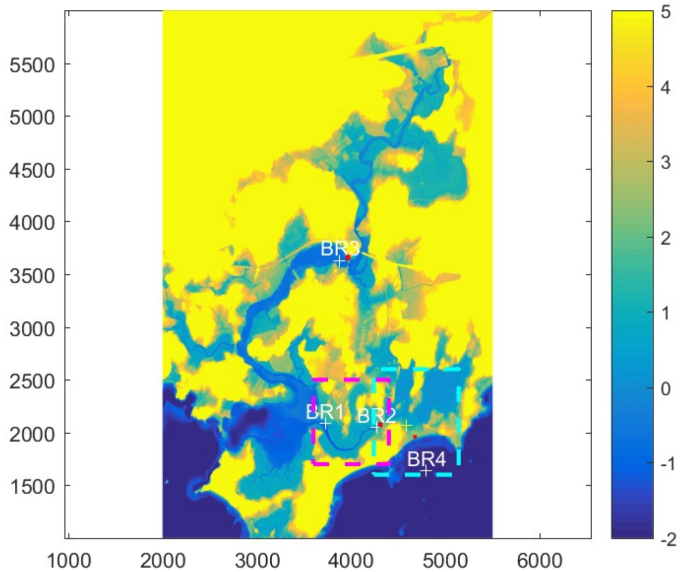

Figure 2. The topography and bathymetry of Branford, CT. The color codes are shown on the right. The square defined by the dashed magenta line surrounds the junction of Sybil and Linden Avenue and defines the area shown in higher resolution in Figure 45. The white + symbols show the location of moored instruments. The area surrounded by the cyan square is discussed in the next section.

The black line in Figure 4 displays the elevation along a north-south line through the red points in Figure 3 using both LIDAR estimates and the direct RTKGPS measurements. The data show that the top of the tide gate is at 1.9 m NAVD88 and the level of the bottom of the channel near the structure is 0.7 m. These measurements are clearly consistent with each other. It is worthy of note that the bridge is scheduled for replacement and the design (90% final) shows it to be at the level 1.96 m (NAVD88).

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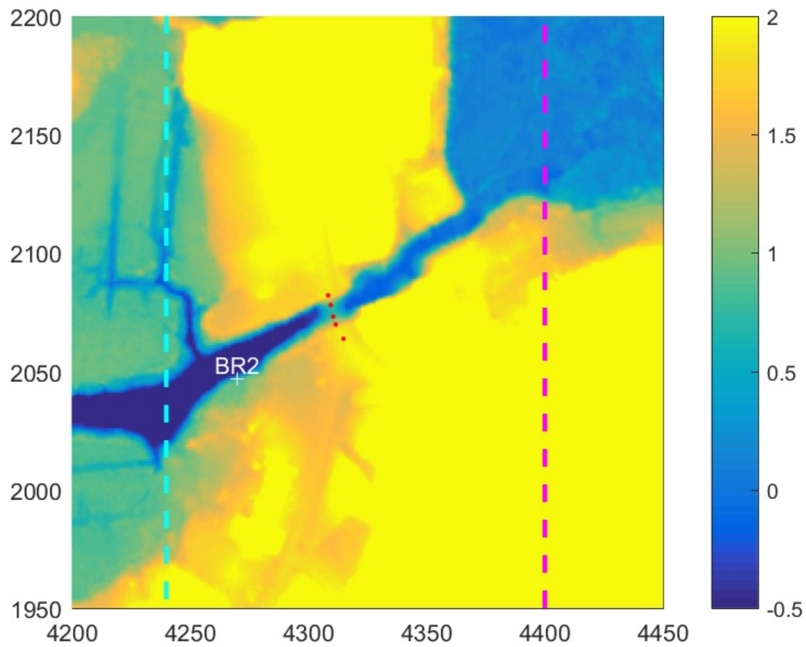

Figure 3. A high resolution map of the elevation in the area of Linden and Sybil Avenue. The color range is set to vary from -0.5 to 2.0 m NAVD to highlight the variation in the elevation in this range. The red dots show the locations where elevation on the road surface at the tide-gate and bridge structure at Linden Avenue was measured with an RTK GPS system.

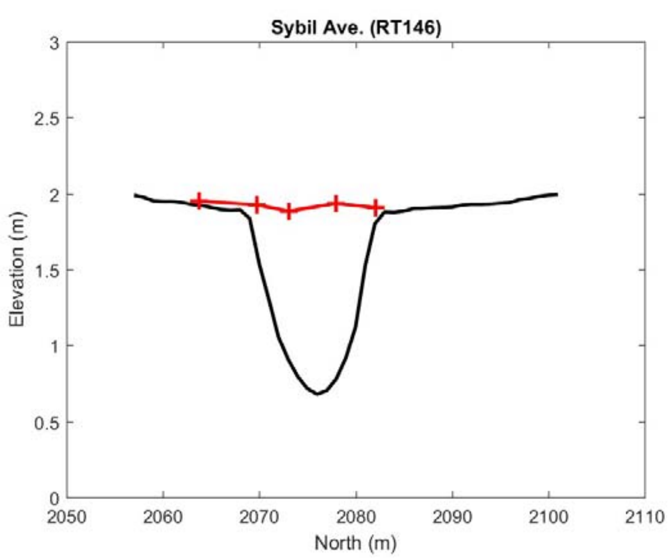

Figure 4. The black line shows elevation estimates along Sybil Avenue from the LIDAR shown in Figure 45, and the red + symbols and line shows measurements by RTK GPS at the locations shown by the red points in Figure 3.

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2 The Observations

The observations from sites BR1, BR2 and the sea level measurements from the NOAA tide gage at New Haven are shown in Figure 5. The mean over the common period of observation of the New Haven and BR1 series was set to -0.08 NAVD, which is the mean sea level reported by NOAA when they maintained a station in Branford (8465233). This was necessary because the NOAA gage in New Haven is not referenced to NAVD directly, and because measuring the water level at the sensors during the deployment was difficult and the consequent uncertainties were too large for the datum to be useful. In Figure 5 (a) we show the evolution of the total water level for all three series. The magnitude of the tidal oscillations, the spring-neap cycle, and the irregular meteorologically forced motions are all evident. but since the differences between the records are so small, the different lines are difficult to distinguish. In Figure 5 (b) we show the same series after the semidiurnal tidal oscillations have been removed by a 5th order Butterworth filter with a 48 hour cut-off period. The New Haven (cyan) and the BR1 (red) series are again almost coincident demonstrating that the low frequency variations propagate from the Sound into Branford harbor with little variation. The dark blue line shows the BR2 record. This record has been adjusted to the NAVD88 datum (approximately) by minimizing the difference between the peaks in the low-pass filtered series at BR1 and BR2. This allows the tidal

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frequency variations, see Figure 5 (c), to be influenced by the bathymetry, but not the low frequencies.

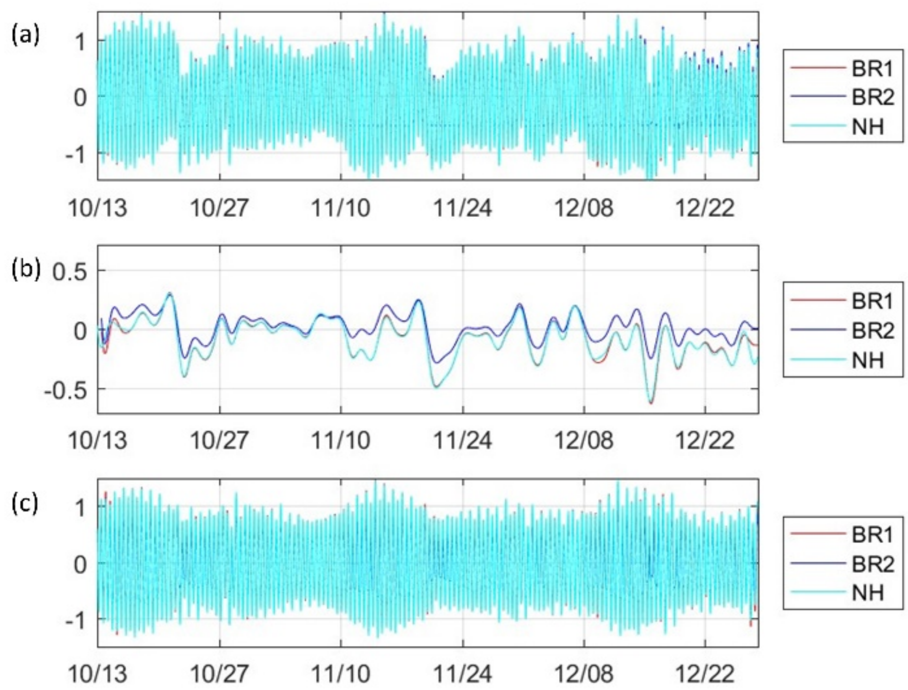

Figure 1. (a) Time evolution of the water level observed at BR1 (red), BR2 (blue) and New Haven (cyan) in the fall of 2016. (b) The low pass filtered series and (s) show the high frequency signal.

To compare the observations more clearly we show in Figure 6 a seven day segment of the same data as in Figure 5. The only noticeable difference in the raw series shown in Figure 6 (a) is that the BR2 series (blue lines) doesn't fall below -0.6 m which is the elevation of the bottom a at the station location. The low frequency variation shown in Figure 6 (b) also shows that the BR2 series (blue) varies from the others, it usually higher, largely as a consequence of the higher minimum value that it can reach.

The maxima in the total water level records from BR2 and New Haven during the observation period are compared in Figure 7. The root mean square difference in the maxima is 0.05 m and the correlation coefficient is 0.98. This demonstrates that there is little difference between the two levels and there is, therefore, no need for a model of the flow in the lower Branford River to link the two levels.

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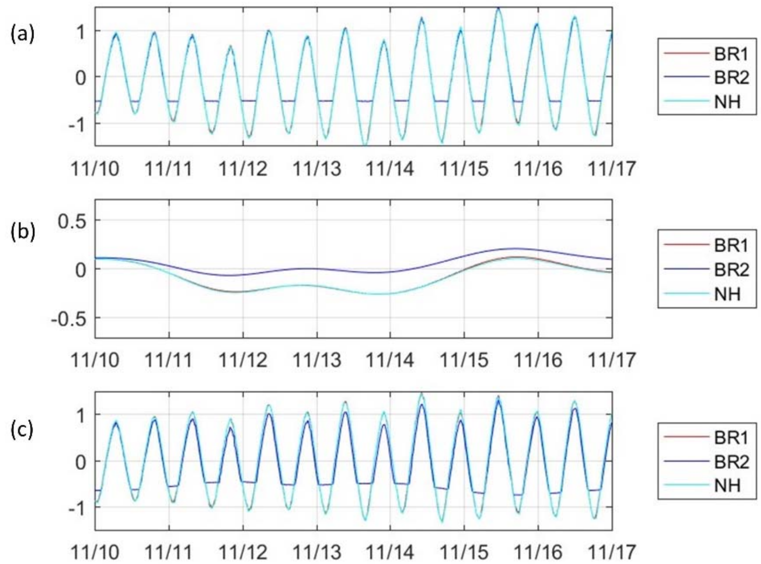

Figure 2. The same data as in Figure 4 but for a 7 day interval in November 2016.

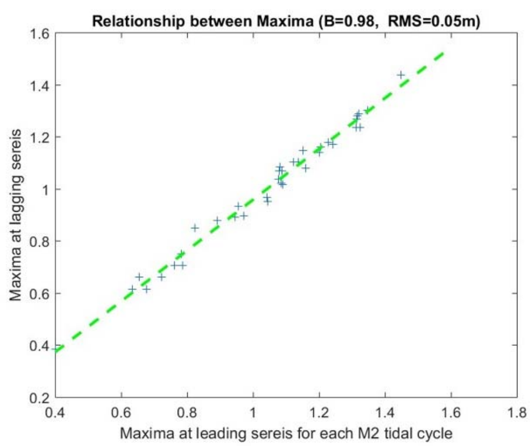

Figure 7. The correlation between the magnitude of the peaks observed in the New Haven (horizontal axis) and BR2 (vertical axis) series shown in Figure 4 (a).

3. Analysis of Observations

The measurements described in the preceding section demonstrate the water level at BR2 and the junction of Linden and Sybil Avenues can be accurately represented by the NOAA water level at New Haven. The analysis of the LIDAR and RTK GPS elevation measurements indicate that the roads are subject to flooding by seawater when the water level exceeds 1.9 m NAVD88. Figure 14 shows the record of sea level reported by NOAA at New Haven in the seventeen years since January, 1999, with the 20 highest levels (separated by at least 48 hours) highlighted by the red

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circles. These values are shown in descending rank order by the red squares in Figure 8. Note that these level assume that the mean sea level at New Haven (and BR1) is -0.08 m NAVD and this may introduce an error of approximately $\pm$ 0.1 m. The largest two values exceed 2 m and occurred during Hurricane Irene in August, 2011, and super-storm Sandy in October 2012. The rest of the peaks were due to the much more frequent extra-tropical storms. The dashed black line shows the level of the roadway at Linden and Sybil Avenues where it crosses Sybil Creek. This graphic suggests that the roadway was flooded during the hurricanes and perhaps the next two largest water level peaks. The levels reached by the peaks ranked 5 and higher lie below the road level in a narrow range between 1.7 and 1.9 m. That the level of the roadway was reached or exceed four times in seventeen years confirms that the area is at risk from coastal flooding. The red dashed line shows the levels that the water level peaks would have reached if mean sea level had been 0.25 m higher, a level that could plausibly occur by 2050. Comparison of the red and the black dashed lines demonstrates that all 20 storm could cause road flooding in the future.

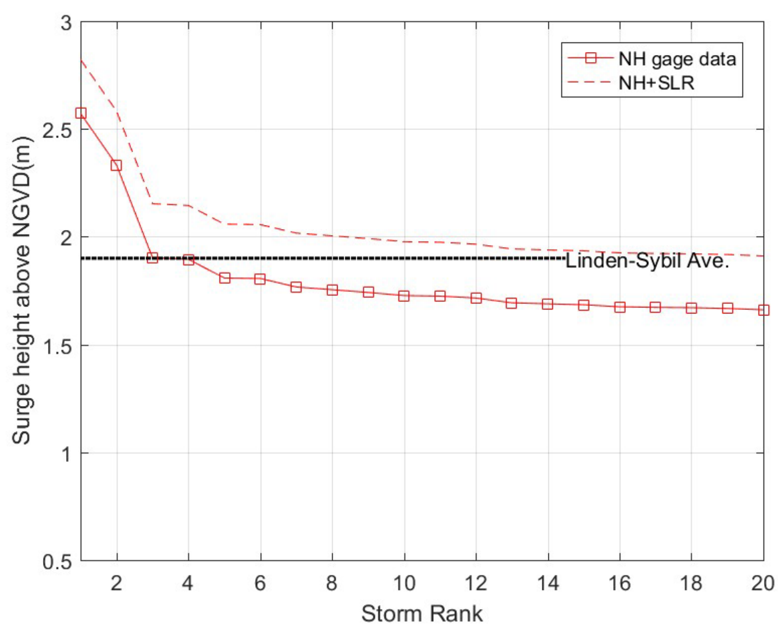

Figure 3. The red squares show the levels of the 20 highest water levels observed at New Haven since January 1999. The dashed black line shows the level 1.9 m, which is the elevation of the road surface at the bridge across Sybil Creek. The dashed line is the levels that the water levels would have reached of the means sea level was 0.25 m higher.

To more clearly show the extent of the area vulnerable to flooding now and in the future, at water levels of 1.9 m we show in Figure 9 (a) the topography of the study area again but with the 1.9 m contour indicated by the black line. The same line is shown in cyan in Figure 9 (b) on a GoogleEarth geo-rectified aerial photograph. It is evident that there are few buildings below the 1.9 m elevation in the area near the junction of Linden and Sybil Avenues. If the mean sea level was to increase by 0.25 m then the same risk of flooding would occur at the 2.15 m contour. This elevation is shown by the green lines in Figure 9 (a) and (b). The separation of the two contours is remarkably small and so the area subject to an increased risk of flooding is small.

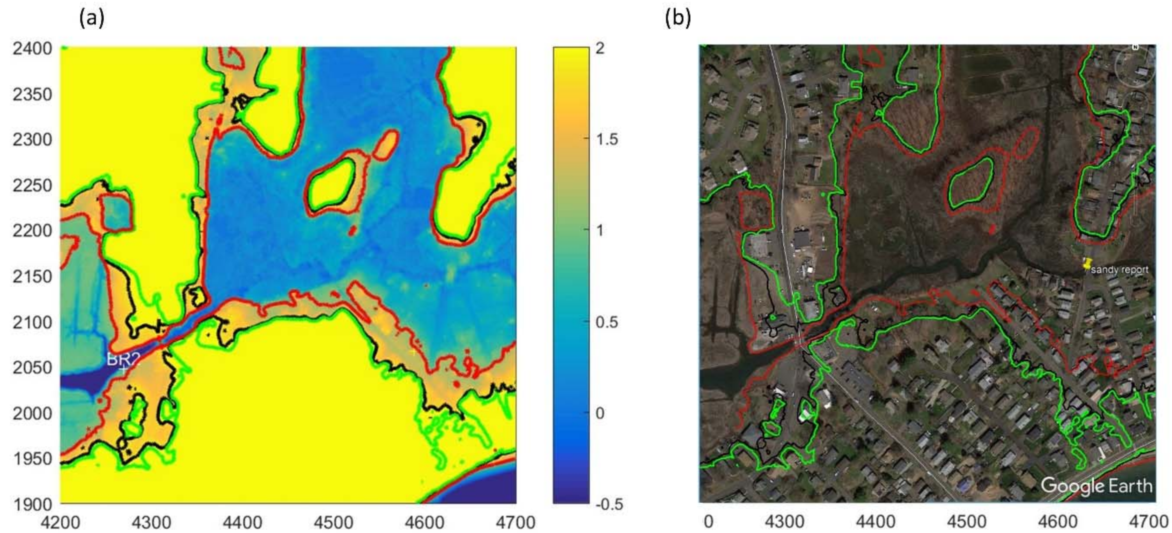

Figure 4 (a) Topography of the study area shown by the colors using the key on the right. The black line shows the 1.9 m contour and the green line shows the 2.15 m contour. (b) GoogleEarth display of the 1.9 m (black) and 2.15 m (green) contours in the study area overlaid on aerial photography. The red line shows the 1.1 m contour which was the maximum level reported during super storm Sandy at the location shown by the yellow pin.

When the water level exceeds 1.9 m at BR2, as it did during the two largest events shown in Figure 8, flow over Sybil Avenue into the large marsh complex to the east can occur. The volume transport into the marsh is largely determined by the elevation above the road, which determines both the vertical cross section and wetted perimeter of the flow. Since the surface extent of the marsh is large, the water level in the marsh and the flooding of the neighborhood in the low lying areas in the vicinity of Waverly Road, will be impacted by the duration of the high water level.

The latter show that the water levels at the bridge are almost equal to those reported at the NOAA tide gage at New Haven. The longer data record available there allows us to characterize the longer term variability of the water levels and to describe the vulnerability of the area to flooding by water from Long Island Sound. We show that in the last 17 years only two major hurricanes raised the water level above the road and two other storms were very close to the 1.9 m road level. However, the next biggest 16 peaks all caused water levels above 1.7 m so that an increase in mean sea level of just 0.25 m would lead to the road being flooded much more frequently. Since the slope of the topography at the 1.9 m level is relatively large in most of the study area, the 1.9 and 2.15 m contours are very close together. Consequently, the area of the study that is subject to an increase flooding risk is small. In addition to the increased frequency of closures of the Sybil Avenue Bridge, the main increase in flooding vulnerability will occur in the low lying areas near Waverly Road, when flow across the Sybil Avenue Bridge into the marsh to the east will occur more often.

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4. Wave Effects at Limewood Avenue (RT 146)

RT 146 in Branford has a short section, Limewood Avenue, that follows the shoreline of Long Island Sound before turning north where it changes name to Sybil Avenue. During super-storm Sandy, the waves that impacted the shoreline from Long Island Sound overtopped the road. The water on Limewood Avenue then flowed down Waverly Road into the marsh surrounding Sybil Creek. The water in the marsh largely is isolated form the Branford River, and Long Island Sound, by the tide-gate at the Sybil Avenue Bridge. Unfortunately there were no direct measurements of the wave characteristics during the storm or of the water levels in the marsh. However, the USGS post storm high water mark surveys did locate a station in the marsh, see (https://stn.wim.usgs.gov/STNPublicInfo/#/HWMPage?Site=19322&HWM=18220). This will be used as an assessment of the effectiveness of the model predictions.

Figure 10 shows the elevation and bathymetry of the region derived from the USGS (2017) digital elevation model. The dotted magenta line along the shore in Figure 10 show the location of RTK GPS elevation measurement along the Limewood Avenue and the solid white line shows the location of Waverly Road. The dashed line from Limewood Road to BR4 shows the location of the water depth section in Figure 11.

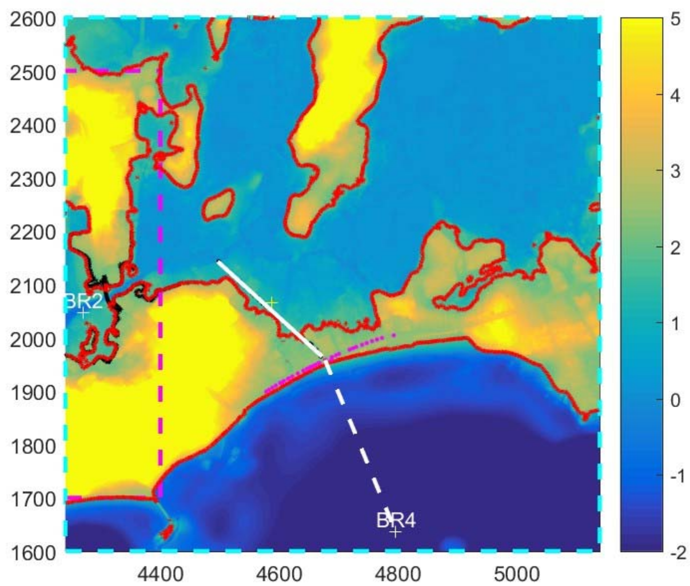

Figure 5. Topography of the Limewood Avenue –Waverly Road area. The color scale show the elevation in the range -2 to 5 m using the color scale on the right. The location of the water level and wave sensors at BR 4 is shown by the white + symbol. The magenta points lie on Limewood Avenue and the solid white line shows Waverly Road.

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In Figure 11 (a) we show the water depth and land elevation along a line from BR4 to Limewood Avenue and then along Waverly Avenue. The black line shows the LIDAR estimates and the red + symbols show the RTK GPS measurements along Waverly Road. From the crest of the road to the -1 m level the topographic slope is steep (approximately 10%). Further from shore the slope reduces to 1%. Figure 10 (b) shows the elevation of the roadway at Limewood. The difference between the LIDAR and the RTK GPS estimates is approximately 0.1 m. This is likely due to the spatial averaging employed in the LIDAR processing and the slope of the road surface. The measurements agree that the road is at approximately 2.3 m elevation though slightly lower to the west of Waverly. This alongshore slope likely funneled the water that reaches the road from splash-over towards the junction of Waverly Road and Limewood Avenue.

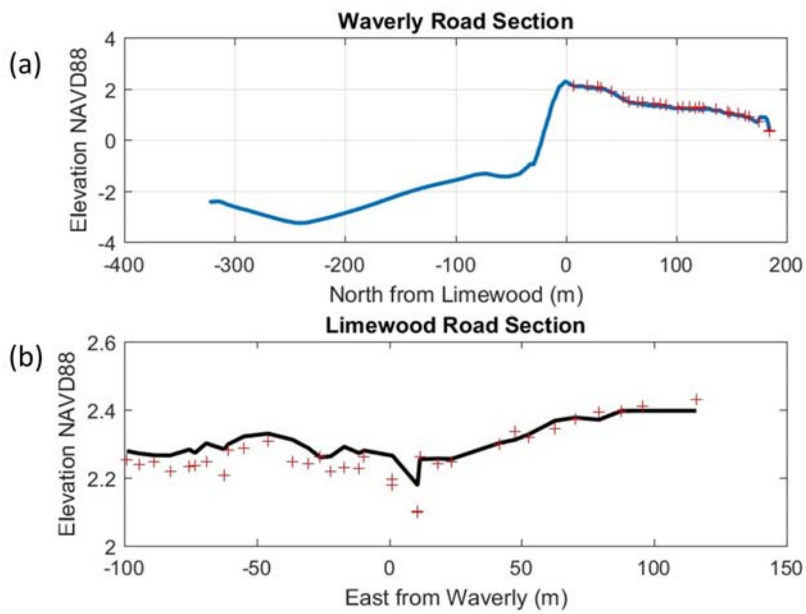

Figure 6. (a) The variation of water depth and land elevation along the dashed white line from BR4 to Limewood Avenue, and along the solid while line that shows Waverly Road in Figure 10. (b) The variation of elevation along Limewood Avenue. The zero of both graphs is at the junction of Limewood and Waverly. The red + symbols show measurements by RTKGPS

4. Wave Observations

We showed in Section 5, using measurements of water level, that the sea level at BR4 was almost the same as at the NOAA tide gage at New Haven. We also measured the amplitude, period and direction of high frequency surface gravity waves at BR4 which was located approximately 300 from the shore in water of 3 m depth. The observations are summarized in Figure 12 where (a) shows the significant wave height, (b) the period at the peak of the spectrum, and the direction of the peak period is shown in (c). The maximum significant wave height during the observation period was 0.6 m. During intervals when the wave heights were in excess of 0.3 m the period was between 4 and 5 seconds and the waves were propagating from the southwest (225 deg). Note that when wave heights were small, the direction was unstable.

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5. Wave Model Performance

Whether or not coastal flooding occurs on Limewood Avenue and Waverly Road is determined by the mean water level and the height and period of the storm driven waves. We have demonstrated in Section 5 that the water levels at Branford and New Haven are effectively the same. However, wave measurements close to shore in the area are limited and long records are only available at two buoys in the center of the Sound. To estimate the wave conditions during major storms we developed a mathematical model of the generation and propagation of waves in Long Island Sound and evaluated it with measurements at a variety of location. A summary of the project and results can be found at http://circa.uconn.edu/crest/wave-research/. The fundamental goal was to establish that the model adequately reproduced observations during major storm events at the buoy locations where data was available for 12 years. We then evaluated how well the model performed at several coastal sites where data had been acquired for several months. When the model was performing well in both tests we used it to generate statistics for waves that occurred at near shore location and published the results on the circa.uconn.edu web site. For this project we also tested the model at the BR4 site using the data shown in Figure 12.

A comparison of the model predictions to the observations at BR4 is provided in Figure 13. The black lines in Figure 13 (a) and (b) show the model significant wave height and the peak period, respectively, and the blue points show the observations. The root mean square error for the December 2016 simulation was 0.87 s for the dominant period, and 0.21 m for the significant wave height. The correlations were both very high as is evident in the figures. The significant wave height was biased low as we have found to be the case at other sites when the wind and waves were in the moderate range, however, at higher wind speeds the bias is less.

To summarize the wave amplitudes and periods that may be expected during severe storms, we simulated 20 storms with the high winds speeds. We used the wind speed data to rank the storms and constructed the return interval diagram shown in Figure 14 using the rank of the wind speed used in the model forcing for the return interval. Table 2 lists the maximum significant wave heights dominant periods in the simulations. The largest significant wave height occurred during Hurricane Carol in 1954 which produced a significant wave height of 3.84 m. Since the waves generated in Long Island Sound are generally fetch limited, the amplitude and period are correlated. Our simulation of super storm Sandy in 2012 was produced maximum significant wave heights near BR4 of 1.89 m with a dominant period of 7.4 s. Figure 14 suggests that the probability of exceeding this significant wave height value in any year is approximately 1/7.

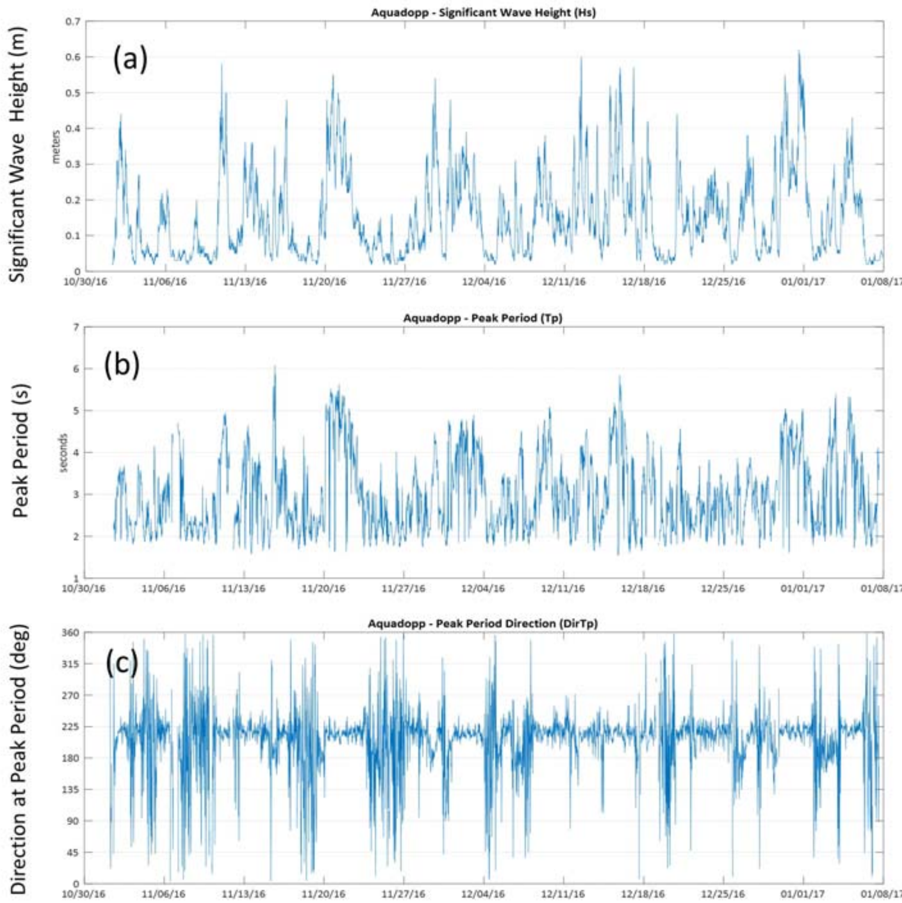

Figure 7. Wave observations at BR4 from October 30, 2016 to January 8th, 2017. (a) shows the significant wave height (m), (b) the peak wave periods (s) and (c) shows the direction (degs.) the waves at the peak period were traveling from.

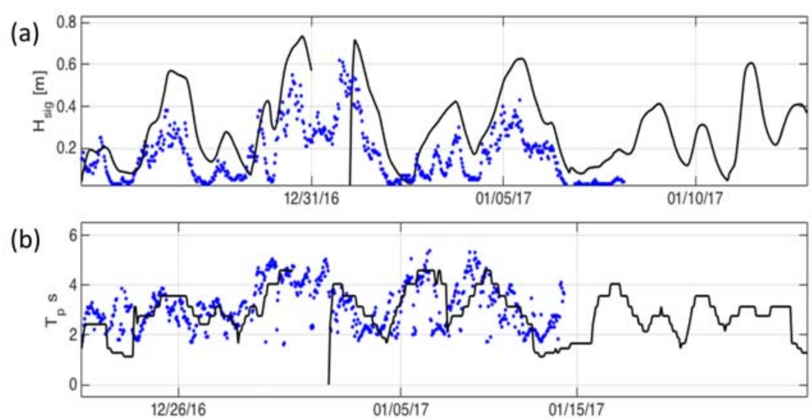

Figure 13. Results of the simulation of the (a) significant wave height at BR4 and (b) the peak wave period.

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Table 2. Results of the simulations of significant wave height, H_s and dominant period T_p near Branford, CT.

Year	[m]	T_p [s]
1985	3.84	8.83
1954	2.38	9.67
2012	1.89	7.37
2011	1.45	6.73
2017	1.41	6.75
2008	1.31	4.68
2014	1.21	5.92
2006	1.06	5.12
1991	0.93	4.61
2015	0.76	5.61
1978	0.75	5.61
2013	0.62	4.27
2007	0.61	4.05
2005	0.59	4.05
2016	0.51	2.26
2003	0.48	4.05
2009	0.41	3.56
2011	0.37	4.68

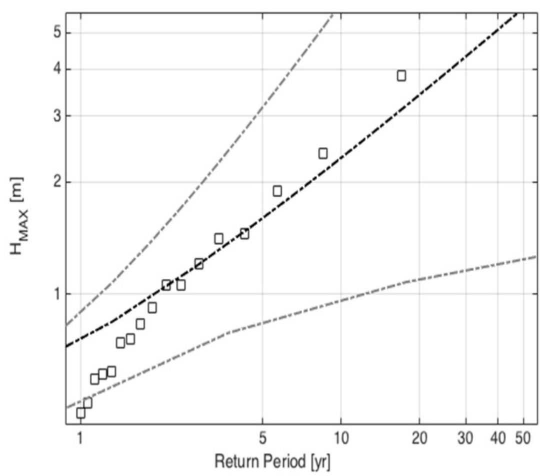

Figure 8. Return period of significant wave heights Branford, CT. The dashed black line corresponds to the best-fit GEV function and the grey dashed lines mark the 95% confidence interval. The black squares show the maximum significant wave height (m) in the simulations at the site.

6. Overtopping

To link the water level and wave predictions to road flooding, a model must be formulated. The EurOtop II report (Van der Meer et al., 2016) provides a comprehensive summary of the empirical relationships that have been established to quantitatively estimate the volume flow rate over a coastal embankment due to both splash-over from waves (Q_{SO}), and the over-bank flow (Q_{OF}) that occurs when the mean water level exceeds the level of the crest of the structure. Figure 10 (a) shows the water depth and elevation profile offshore of Limewood Avenue. To

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apply the results of the EurOtop II approach we approximate this geometry as shown in Figure 15. Using the data shown in Figure 10 (a) we take the slope of the bottom near the road as $s = tan\,\alpha = 0.1$. We also define the elevation of the road surface relative to the mean water level, R_c in the schematic, as the difference between the water level measured at New Haven and the elevation of the low region of Limewood Avenue which Figure 10 (b) shows is 2.3 m.

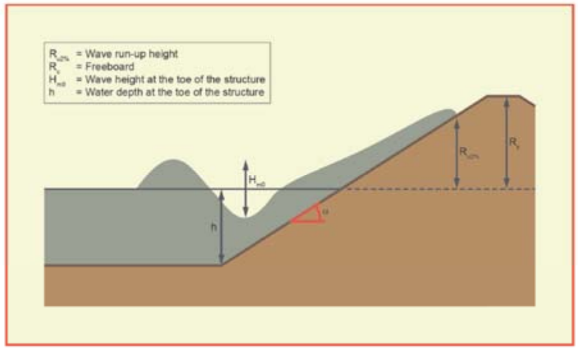

Figure 9. Schematic of an idealized coastal dyke or embankment defined in the EurOtop II report (Van der Meer et al., 2016). The

During super storm Sandy the mean water level exceeded the level of the Limewood Avenue, implying $R_c < 0$, and when that happened seawater flowed directly from the Sound across the road and then down Waverly Road. Following the empirical work of Hughes and Nadal (2009), the EurOtop II report recommends the volume flux per meter of shorefront of the over-bank flow be estimated by a version of the weir formula (White, 2003)

$$Q_{OF} = 0.54\sqrt{g|R_c^3|}$$

where $g = 9.81$ m/s^2 is the acceleration of gravity. Before, during, and after the peak water level, wave splash-over was likely delivering sea water onto the road as well. The volume flux per meter of shorefront can be estimated by the EurOtop II over-topping formula

$$Q_{SO} = \sqrt{gH_0^3}\; a\, exp\left\{-\left\{b\frac{R_c}{H_0}\right\}^c\right\}$$

where H_0 is the spectral significant wave height and the empirical constants are: $c = 1.3$, $a = \frac{0.023}{s}\gamma_b\zeta_p$, and $b = 2.7/\zeta_p\,\gamma_b\gamma_f\gamma_\beta\gamma_V$ where s represents the bottom slope at the coast, $\zeta_p = s/\sqrt{H_0/\frac{gT_0^2}{2\pi}}$ is *the Iribarren Number*, T_0 is the spectral peak period, and the four parameters $\gamma_{f,b,\beta,V} \cong 1$, are factors that can be used to account for the effects of rough bottom, the presence of a berm, wave propagation direction, and vertical sea walls at the road. Note the upper bound on the splash-over flux uses $a = 0.09$ and $b = 1.5/\gamma_f\gamma_\beta\gamma^*$ where γ^* is used to account for additional geometric effects. We assume the γ coefficients are 1 at the moment to estimate the upper bound on the flux.

Figure 16 (a) shows the water level measurements from the tide gage at New Haven during super storm Sandy with the level of the Limewood Avenue road surface near the Waverly Road

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intersection shown by the thick dashed black line. It is clear from comparison of the levels of the water and road that the mean (averaged over many wave periods) water level was above the road for several hours. There is uncertainty inherent in this analysis since the water levels at Limewood Road and New Haven are not exactly the same. Wave conditions are likely to be different and, consequently, the wave induced mean set-up is different. The magnitude of the error is likely to be 10 to 20% of the difference in the significant wave heights at the two locations and in the range of 0.1 to 0.2 m. The green and red lines in Figure 16 (A) show the water level $\pm$ 0.15 m to illustrate our estimate of the uncertainty in the water level.

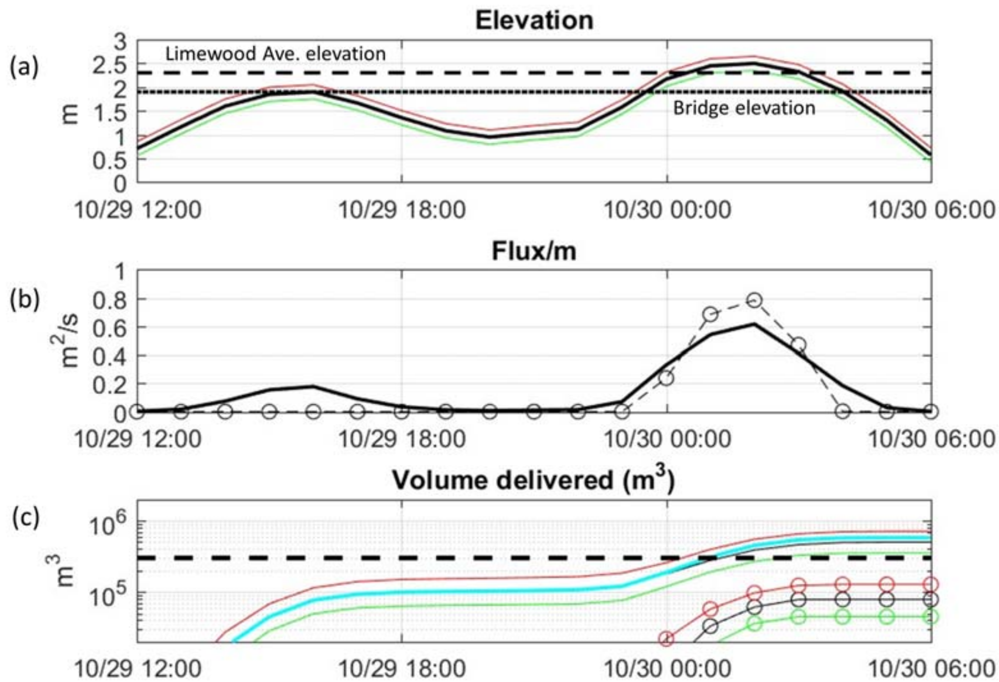

Figure 10. (a) The evolution of the water level at New Haven during super storm Sandy is shown by the solid black line and the level of Limewood Avenue is shown by the thick black dashed line. The red and green lines show the 0.3 m interval surrounding the measured value to represent the uncertainty interval. The dotted black line show the level of the top of the bridge at Sybil Avenue. (b) The thick black line show the estimate of the water flux per meter of shore front (m^2/s) due to both splash over and over-bank flow at Limewood Avenue. The dashed line with circles shows the estimate of the flow over the road at Sybil Avenue. (c) The thin black line and the line with black circles show the accumulated volume (m^3) of seawater delivered into the marsh surrounding Sybil Creek by the flow over Limewood Avenue and Sybil Avenue respectively. The red and green lines show the volumes computed with the higher and lower water level bounds. The thick cyan lines shows the sum of the volume from both sources. The thick dashed line shows our estimate of the volume accumulated in the marsh based on the USGS water level report.

The fluxes on to the road computed using the EurOtop II over-topping formula during super storm Sandy are shown in Figure 16 (b) by the solid black line. During the first high tide the peak flux per meter of shore front was 0.2 m^2/s and at the second peak was 0.6 m^2/s. These are very large fluxes. Van der Meer et al. (2010) suggested upper bounds on allowable limits for low speed vehicles on a road along a well-drained dike of 0.05 m^2/s.

Roads are generally capable of draining with rain rates of several inches per hour. If the extent of Limewood Avenue where the flooding was occurring was 200 m, then the volume flux would

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be 120 m^3/s. For this to be delivered to a 5 m wide road by rainfall, then the rate would 17,000 inches per hour. Even flux values as small as 3.5×10^{-4} m^2/s (10 inches/hour in the example) would lead to significant road flooding.

There are no direct water level measurements with which we can test the accuracy of these estimates. However, the U.S. Geological Survey (2017) surveyed the levels of high water marks in the area impacted by super storm Sandy and one site was located in the marsh drained by Sybil Creek. The location is shown by the yellow push-pin symbol in Figure 17 (a). The elevation recorded was 1.1 m relative to the NAVD88 datum. To estimate the volume of sea water required to fill the marsh complex to that level, we assumed that the surface was uniform across the marsh complex and processed the USGS LIDAR data in the same manner as in Section 2. The results are shown in Figure 19 (b).

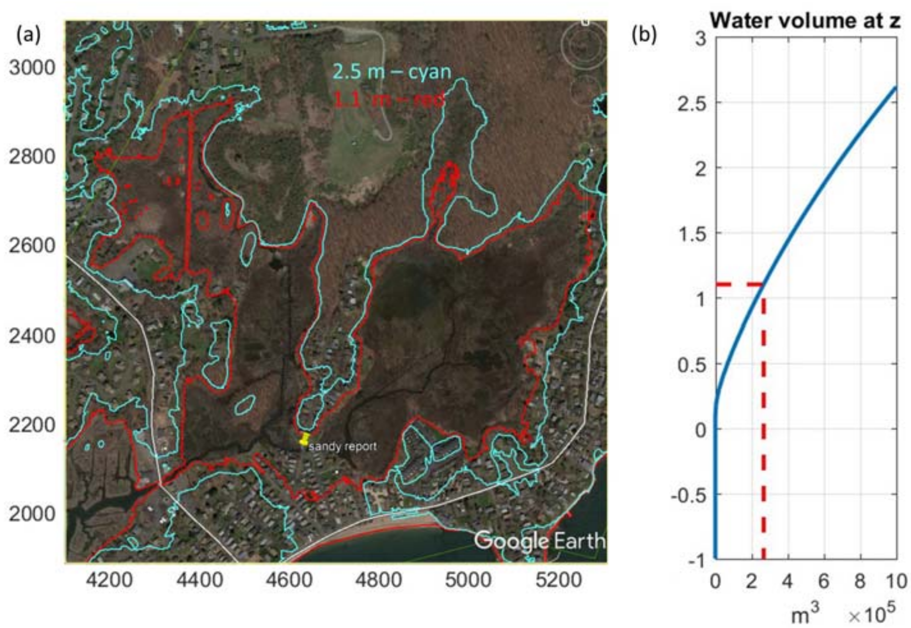

Figure 17. (a) A GoogleEarth map with the location of the USGS high water mark (site CTNEW19322) shown by the yellow push-pin. The 1.1 and 2.5 m elevation contours are shown by the red and cyan lines respectively. The volume required to fill the basin to the 1.1 m elevation is shown in (b).

Figure 16 (c) shows the total volume that would be accumulated in the marsh (horizontal axis) as a function of the water depth. To fill the marsh to 1.1 m would require 2.7×10^5 m^3 of sea water. This water may have come over the tide-gate and bridge at Sybil Avenue as well as over Limewood Avenue. The level of the road surface at the bridge (1.9 m) is shown in Figure 16 (a) by the black dotted line. In Figure 16 (b) we show an estimate of the volume flux per meter to bridge width using the same weir formula as at Limewood Avenue using the water elevation minus 1.9 m as water layer thickness. We neglect splash over since the waves in the Branford River are unlikely to be significant. Since the water level didn't exceed the bridge level in the first high tide during the storm the flow was zero. However, during the second high water the flow per unit width into the marsh from the Branford River was comparable to that at the beach.

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To compare the contributions to the volume in the marsh we integrated the fluxes from both sources, the curves in Figure 16 (b), in time and assumed the flow across the beach occurred in a 50m wide swath and that the width for the flow across the bridge was 10m. In Figure 16 (c) we show the sum of the two volumes as the broad cyan line and the black line, and the black line with circles show the contributions form Limewood Avenue and the Sybil Avenue bridge. The latter is 16% of the flow over the beach.

The sum of the two fluxes is greater than the volume accumulated in the marsh as estimated from the USGS water level measurement. The ratio of the two values is 1.77. The red and the green lines in the Figure 16 (c) show the estimates of the volume transported into the marsh using the EurOtop II formulae but with $\pm$0.15 m added to the sea level observations. The lower value is 30 % larger than the estimate based on the high water mark and marsh geometry. Since we have assumed that the waves were approaching the beach from a normal angle, that the dissipation factors in the overtopping formula were unity, and that the wave height was at the maximum value for the entire storm, a high bias in our estimate is to be expected. Laudier et al. (2011) used a similar approach to calibrating the splash-over formula at a natural beach and found that the product of the γ coefficients in the range 0.64 to 0.72 produced estimates consistent with their observations. It is possible to refine this model further by carefully assessing the geometry and using the time evolution of the wave height from out model, however, the conclusions that a principle factor in the flooding of Sybil Creek marsh was the splash-over at Limewood Avenue, and that the risk of road flooding there can be usefully estimated by a simple model, are unlikely to change.

7. Analysis.

Using the link we have established between the water levels at Limewood and New Haven, then Figure 50 suggests that the mean water level has only exceeded the level of the road (2.3 m) once, during super storm Sandy, which created the highest storm surge in the available 18 year record. At the New London tide gage where the data record spans 80 years, super storm Sandy created the third highest water level. This suggest that at current mean sea level, flooding like that experienced in super storm Sandy has an annual probability in the range of 4% to 6%, or equivalently, a return interval in the range 18 to 26 years.

The risk of flooding on Limewood Avenue is much higher because of wave driven splash-over. The magnitude of the splash-over sea water volume flux is determined by the vertical distance between the mean water surface and the road level, the slope of the beach, and the significant wave height and period. Since the mean water level and significant wave height jointly determine the extent of flooding at Limewood Road, and around the Sybil Creek marsh, quantifying the risk requires estimation of the joint probability distribution. Since both waves and sea level are largely driven by wind the fluctuations are not independent. Estimation of the most appropriate probability distribution function requires further study.

The EurOtop II model can provide guidance on the range of conditions that will lead to significant flooding at Limewood Road. In Figure 18 we plot the estimated flux to Limewood Road per meter of shore front as a function of the sea level (the average over many waves) for a

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range of wave conditions. For these illustrative examples we use $\gamma_f = 0.65$ in the EurOtop II formula, a value in the range suggested by the results of Laudier et al. (2011). Example peak wave periods between 4 and 9 seconds were prescribed and the results of the model simulations listed in Table 2 were used to estimate the significant wave height associated with each period. The values are listed in the left of Figure 18. Three flux thresholds are indicated by the horizontal red lines. The lower (dotted) line shows 3.5×10^{-4} m^2/s which is the equivalent water flux to a 5m wide road at a rainfall rate of 10 inches per hour. This would overwhelm the drainage capacity on most roads and result in water accumulation. An over-topping flux that is one tenth smaller (3.5×10^{-5}) would be equivalent to a one inch per hour rainfall rate, a high, but not uncommon, rate in Connecticut. Van der Meer et al. (2010) suggested that vehicles on a highway along a coastal dyke with effective drainage would be in jeopardy for overtopping fluxes in the range 10 to 50×10^{-3} m^3/s. The upper end of the range is shown by the red dashed line in Figure 18. The maximum value that is estimated to have occurred at Limewood Road during super storm Sandy is shown by the red dot-dashed line.

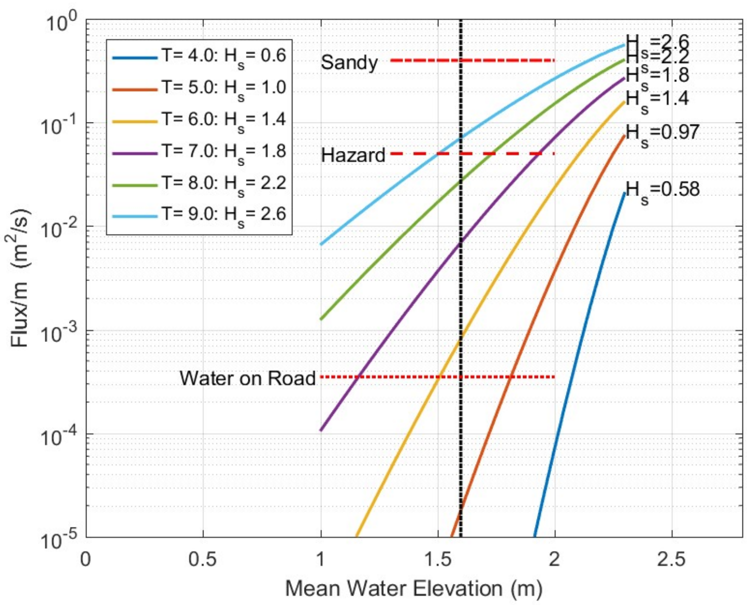

Figure 11. The over-topping flux predicted at Limewood Road as a function on water elevation for 6 different wave conditions that span the range predicted in Figure 7. The red horizontal lines show values that result in significant impacts. The red dotted line is the rate that would be equivalent to equivalent to a 10 inch/hour rainfall rate on a 5 m wide road. The red dashed line shows 0.05 m^2/s which would pose difficulty for vehicles according to Van der Meer et al. (2010), and the red dot-dash line show the level that is estimated during super storm Sandy.

High tide at Branford is approximately 1 m and the purple line in Figure 18 shows that we should expect substantial road flooding at high tide when the significant wave height is between 1.8 and 2.2 m (the purple and green curves). Figure 14 suggests that the probability of waves exceeding the higher range is only 1/7 per year but the lower level is more likely with an annual probability of 1/2. The black dotted vertical line shows the 1.6 m water elevation which, as Figure 8 shows, is characteristic of the highest water level at Branford each year. The orange line in Figure 18 show that when the water level is at 1.6 m, a significant wave height in excess of 1.4 m will

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result in significant water on the road surface. The figure also shows that a significant wave height of 1 m would produce a water flux comparable to a 1 inch per hour rain storm. The green and cyan lines show that the waves would need to be in excess of the conditions during super storm Sandy (1.9 m) for the vehicle hazard level to be exceeded during a “normal” storm.

The dependence of the overtopping fluxes on the wave conditions near high tide and in typical storm (one that should be expected each year) is demonstrated in Figure 19 (a) and (b), respectively. The intersection of the solid black curve and the red dotted line shows again that at high tide a 1.845 m significant wave height will result in severe road flooding. The intersections of the red dotted line with the black dashed, and dot-dashed lines are to the left indicating that at higher water levels, lower wave elevations (1.57 and 1.37 m) are required for splash-over to result in severe flooding. Figure 14 shows that the probability of waves in excess of 2 m is approximately 1/6.5 and that for 1.73 and 1.37 m are 1/4.8 and 1/38. It is plausible that by 2050 or 2100, the mean sea level could increase by 0.25 or 0.5 m. Assuming storm and wave statistics don’t change much over that time, then these relatively small changes in level would increase the risk of severe road flooding at high tide by approximately 134% to 172%.

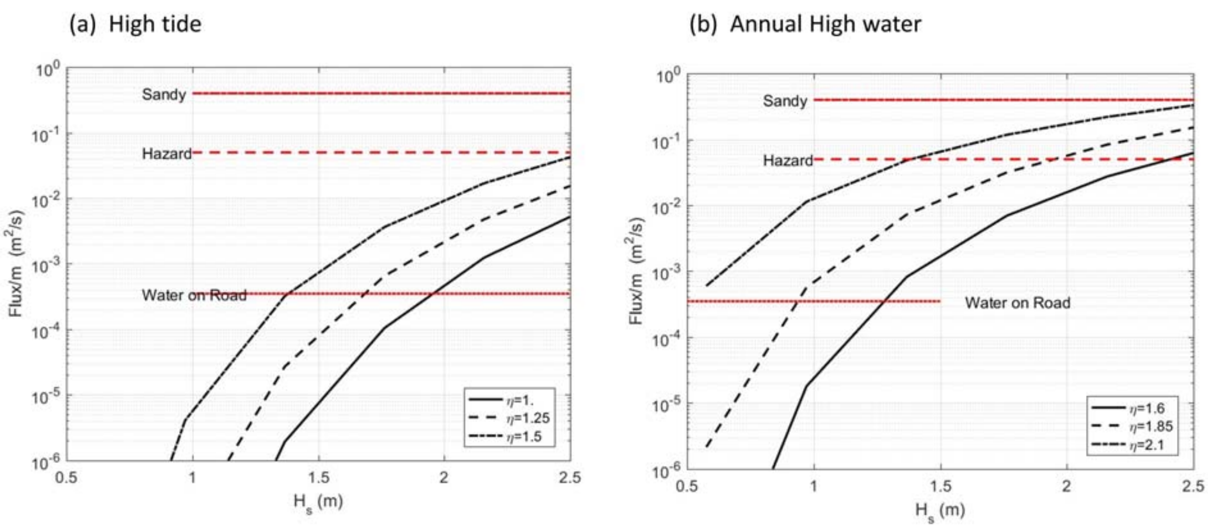

Figure 12. (a) The dependence of the over-topping flux on the significant wave height (and period) at a typical high tide ($\eta = 1$ m) is shown by the solid black line. The variation at .25 and 0.5 m higher levels are shown by the dashed and dot-dashed lines respectively. The variation during high tide in a storm ($\eta = 1.6$) is shown in (b), where again the 0.25 and 0.5 m higher levels are shown by the dashed lines.

A similar analysis for the potential for severe flooding during high tide during normal storms can be developed using Figure 19 (b). At a sea level of 1.6 m (solid black curve) a significant wave height of 2.36 m leads to hazard level (red dashed line) flooding, however at 1.85 m and 2.1 m, significant wave heights of 1.90 and 1.38 m will have the same consequences. Note that the effect of the 0.25 and 0.5 m sea level change has a large impact on the change in wave height required to have the same flooding consequences at higher water levels because the first derivatives of the curves decrease at higher water levels and higher wave heights (they are flatter

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on the right side of the graphs). The wave statistics in Figure 56 imply that the 2.36 m significant wave height has a probability of exceedance of 1/10.2 and that the smaller wave heights have probabilities of 1/6.9 and 1/2.7 respectively. Consequently, the increase in risk of hazard level flooding for .25 m and 0.5 m increases in sea level are 148% and 267%.

It is worthy of note that the substantial increase in risk predicted by the analysis is mainly due to two factors: the dependence of the over-topping flux on the water to road elevation separation, and the exponential shape of the wave exceedance diagram (Figure 56). Though the values reported above are estimates that are based on available data and models have uncertainty associated with them, the most important result (the substantial increase in the risk of flooding associated with small changes in mean sea level) are robust.

To evaluate the consequences of the combined effects of mean sea level changes on the flooding of the area around the Sybil Creek marsh, see Figure 19 (a), we repeated the calculations that led to Figure 15 but incrementally increased the mean sea level from 0 to 0.5 m in 0.05 m increments. We assumed that the sea level at New Haven was 0.15 m higher that Branford during the storm, and used a value of $\gamma_f = 0.65$ in the EurOtop II formula in to make the model predictions more consistent with observations. We did not allow the significant wave height to evolve through the storm. We converted the predicted volume in the marsh using the relationship between volume and elevation computed from the LIDAR based topography and shown in Figure 17 (b). The black solid line in Figure 20 (b) shows the elevation in the marsh at the end of the simulated storm or when the elevation reached 2.5 m. At that catastrophic level the model of the flow into the marsh is not as reliable.

In Figure 20 (a) the green contour shows the 1.1 m contour which is the level of the high water mark surveyed and reported by the USGS (2017) in the Sybil Creek marsh to the east of the Sybil Avenue (RT 146) bridge and tide-gate. The blue line shows the 2.5 m level. This is a good estimate of the high water level during super storm Sandy. The area between the blue contour (2.5 m) and the red contour (1.1 m) were protected from flooding during super storm Sandy by the presence of the Sybil Creek marsh, the berm carrying Limewood Avenue (RT 146) and the tide-gate. The black line in Figure 20 (b) shows how a rise in the mean sea level will influence the maximum water level in in the area surrounding the marsh. A 0.28 m increase in the sea level is predicted to increase the high water level from 1.1 to 1.9 m and reduce the range of the elevations protected from flooding. The 1.9 m contour is shown in green in Figure 19 (a). Note that the .28 m increase in mean sea level leads to the high water level in the marsh areas increasing by 0.8m, a factor of 2.85 larger. This is rapid erosion of the flood protection value by rising sea level continues until at 0.42 m the high water level would reach 2.5 m. Worse still, areas that are between 2.5 and 2.92 m elevation would then be vulnerable to flooding.

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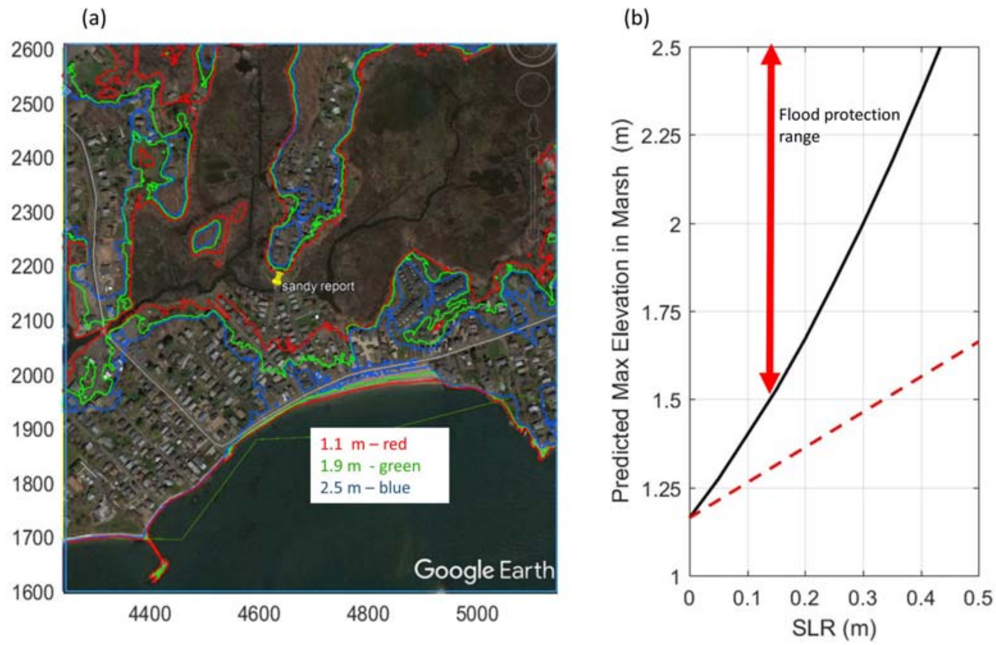

Figure 13. (a) A GoogleEarth map of the coastal area near Limewood Avenue. The white line show the location of RT 146 and the red, green and blue lines show the 1.1 m 1.9, and 2.5 m elevation contours. (b) The black solid line shows the elevation in the marsh that corresponds to the maximum predicted volume transported into the marsh. The red dashed line shows the change in sea level in the marsh if it was just do to sea level rise.

8. Summary

We have described the geography of the area of Branford between Limewood Avenue and the marsh surrounding Sybil Creek that is susceptible to coastal flooding. Using a combination of simple models of wave driven transport over the beach at Limewood, and the bridge at Sybil Avenue, we conclude that most of the flooding around the marsh during super storm Sandy was due to flow over the beach. Without an estimate of the joint probability of wave heights and sea level it is not possible to estimate the risk of future flooding adequately. This should be addressed in the future. However, the model allows us to assess what conditions would likely lead to flooding. At normal high tide levels, significant wave heights in the range of 1.37 to 1.57 m will lead to significant flooding on Limewood Avenue. During severe storm the high tide level increases to 1.6 m and significant wave heights in the range 1.0 to 1.5m will lead to substantial road flooding.

The models we developed also allow us to estimate the effects of sea level rise on the change in the risk of flooding in the area surrounding the Sybil Creek Marsh. It is clear that the land and properties are protected from high water by the tide gate and bridge at Sybil Creek, and by the berm that carries Limewood Avenue along the coast. When the water level in the Sound was 2.5 m during super storm Sandy, the water level in the marsh was only 1.1 m. Our model results show that an increase in sea level of 0.25 m allows flooding to 1.9 m, an increase of 0.8 m, and

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shrinks the width of the flood protection zone from 1.4 m to 0.6 m. This rapid loss of flood risk protection is a robust characteristic of the model, especially at low sea level change values where the model is most reliable. The same analysis has the more positive result that small increases in the elevation of Limewood Avenue would reduce the flood risk considerably.

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