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Coastal and Hydraulics Laboratory

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Short-Wave Modeling for South San Francisco Bay Shoreline Study

Jane McKee Smith

Draft

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Short-Wave Modeling for South San Francisco Bay Shoreline Study

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Draft report

Approved for review

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Under South San Francisco Bay Shoreline Study

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Abstract: This report describes wave modeling in South San Francisco Bay to support water level, levee breaching, and sediment transport components of the South San Francisco Bay Shoreline Study. The full-plane STWAVE model was applied to generate and transform waves in the bay using a nested approach. The model was validated with field measurements in south bay collected in December 2006. The entire bay was modeling with a resolution of 656 ft. Boundary conditions form this grid were fed into a finer resolution grid (164 ft) of the south bay. Simulations were performed for the south bay Year 0 and Year 50 bathymetries. A total of 130 wind conditions were modeled for both bathymetries (10 to 100 mph wind speeds and wind directions of 250 deg clockwise through 10 deg relative to north). Six water levels were simulated for Year 0 (7 to 12 ft NAVD 88) and eight water levels were simulated for Year 50 (7 to 14 ft NAVD 88). Winds and water levels were assumed to be constant throughout the bay for these simulations. Modeled wave parameters (zero-moment wave height, peak period, and mean direction) were provided to circulation, levee breach, and sediment transport modeling efforts within the project.

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Preface

The South San Francisco Bay Shoreline Study wave modeling was performed in support of the San Francisco District, U.S. Army Corps of Engineers. The purpose was to generate wave information to support water level, levee breaching, and sediment transport components of the shoreline study. This report summarizes the wave modeling component of the study.

This report was prepared by Jane McKee Smith, Coastal Processes Branch of ERDC-CHL, under the supervision of Ty Wamsley, Chief of Coastal Processes Branch, Bruce Ebersole, Chief of Flood and Storm Protection Division, Rose Kress, Deputy Director of CHL, and William Martin, Director of CHL. COL Gary E. Johnston was Commander and Executive Director of ERDC, and Dr. James R. Houston was ERDC Director.

Unit Conversion Factors, Non-SI to SI Units of Measurement

Multiply	By	To Obtain
cubic feet	0.02831	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
inches	0.0254	meters
miles (nautical)	1,852	meters
miles (U.S. statute)	1,609.347	meters
square miles (U.S. statute)	2.59	square kilometers
mbar	1.00	hPa

1 Introduction

The South San Francisco Bay Shoreline Study required wave information in South San Francisco Bay to evaluate the processes of wave setup, wave runup and overtopping on the levees, and sediment transport. The Steady-State Spectra Wave model STWAVE was selected for the study. STWAVE was applied in full-plane mode, meaning that it calculated wave generation, propagation, and transformation in all directions (full 360-deg plane). Waves are generated by winds, and the important factors are wind speed, wind direction, water level, and bathymetry. Chapter 2 describes the STWAVE model and the modeling procedure for San Francisco Bay. Chapter 3 provides the wave model validation with field data collected in the bay and a sensitivity analysis. Chapter 4 describes the wave model simulations for the project Year 0 bathymetry. A total of 780 model simulations were made to represent 130 wind conditions (wind speeds of 10 to 100 mph, and direction of 250 deg clockwise to 10 deg relative to north) and six water levels (7 to 12 ft NAVD 88). Chapter 5 describes the 1040 simulations for the project Year 50 bathymetry (with the addition of 13 and 14 ft NAVD 88 water levels). Chapter 6 is a brief summary.

2 Nearshore Wave Model STWAVE

STWAVE Description

The full-plane version of the numerical model STWAVE (Smith 2000; Smith, Sherlock, and Resio 2001; Smith and Smith 2001; Thompson, Smith, and Miller 2004, Smith 2007) was used to generate and transform waves for the study. STWAVE numerically solves the steady-state conservation of spectral action balance along backward-traced wave rays:

$$(C_{ga})_x \frac{\partial}{\partial x} \frac{C_a C_{ga} \cos(\mu - \alpha) E(f,\alpha)}{\omega_r} + (C_{ga})_y \frac{\partial}{\partial y} \frac{C_a C_{ga} \cos(\mu - \alpha) E(f,\alpha)}{\omega_r} = \sum \frac{S}{\omega_r} \quad (1)$$

where

C_{ga} = absolute wave group celerity

x,y = spatial coordinates, subscripts indicate x and y components

C_a = absolute wave celerity

μ = current direction

α = propagation direction of spectral component

E = spectral energy density

f = frequency of spectral component

ω_r = relative angular frequency (frequency relative to the current)

S = energy source/sink terms

The source terms include wind input, nonlinear wave-wave interactions, dissipation within the wave field, and surf-zone breaking. The terms on the left-hand side of Equation 1 represent wave propagation (refraction and shoaling), and the source terms on the right-hand side of the equation represent energy growth and decay in the spectrum.

The assumptions made in STWAVE are as follows:

a. Mild bottom slope and negligible wave reflection.

b. Steady waves, currents, and winds.

c. Linear refraction and shoaling.

d. Depth-uniform current.

STWAVE can be implemented as either a half-plane model, meaning that only waves propagating toward the coast are represented, or a full-plane model, allowing generation and propagation in all directions. The full-plane model was used in this study. Wave breaking in the surf zone limits the maximum wave height based on the local water depth was used in this application:

$$H_{mo_{\max}} = 0.64d \tag{2}$$

where

H_{mo} = zero-moment wave height

d =water depth

STWAVE is a finite-difference model and calculates wave spectra on a rectangular grid. The model outputs zero-moment wave height, peak wave period (T_p), and mean wave direction (α_m) at all grid points and two-dimensional spectra at selected grid points. STWAVE allows input of spatially variable wind and surge fields. Spatially constant surge fields were used in this analysis, and both spatially constant and spatially variable winds were explored. Bottom friction and currents were neglected in this application.

Wave Model Inputs

The inputs required to execute STWAVE include:

a. Bathymetry grid (including shoreline position and grid size and resolution).

b. Incident frequency-direction wave spectra on the offshore grid boundary.

c. Current field (optional).

d. Surge and/or tide fields, wind speed, and wind direction (optional).

e. Bottom friction coefficients (optional).

Wave Model Outputs

The outputs generated by STWAVE include:

a. Fields of energy-based, zero-moment wave height, peak spectral wave period, and mean direction.

b. Wave spectra at selected locations.

c. Fields of radiation stress gradients to use as input to a circulation model (to calculate wave setup).

Wave Modeling Methodology

STWAVE was applied on two grids for San Francisco Bay. The coarse grid encompasses nearly the entire bay (truncates a small portion of the northeast corner of the bay), covering an area of 55.1 miles (88.6 km) by 16.0 miles (25.8 km). The spatial resolution is 656 ft (200) m. The coarse grid bathymetry is shown in Figure 1. Depths exceed 300 ft (90 m) in the channels, but the scale is scale is set to 50 ft to show the detail in the south bay. The fine grid is nested into the larger grid and covers from just north of Dumbarton Bridge to the south bay shoreline, covering an area of 7.6 miles (12.25 km) by 5.3 miles (8.5 km). The resolution is 164-ft (50-m) (Figure 2). The grid specifications are given in Table 1. Grid depths are relative to NAVD 88 and are interpolated from the circulation model grid.

The full-plane version of STWAVE was run with 72 direction bins (5 deg resolutions) and 30 frequency bins (starting at 0.1 Hz with resolution of 0.015 Hz, covering a range of 10 sec to 1.9 sec). The model was run with five iterations. Spectra from the coarse grid were linearly interpolated to the boundary of the fine grid

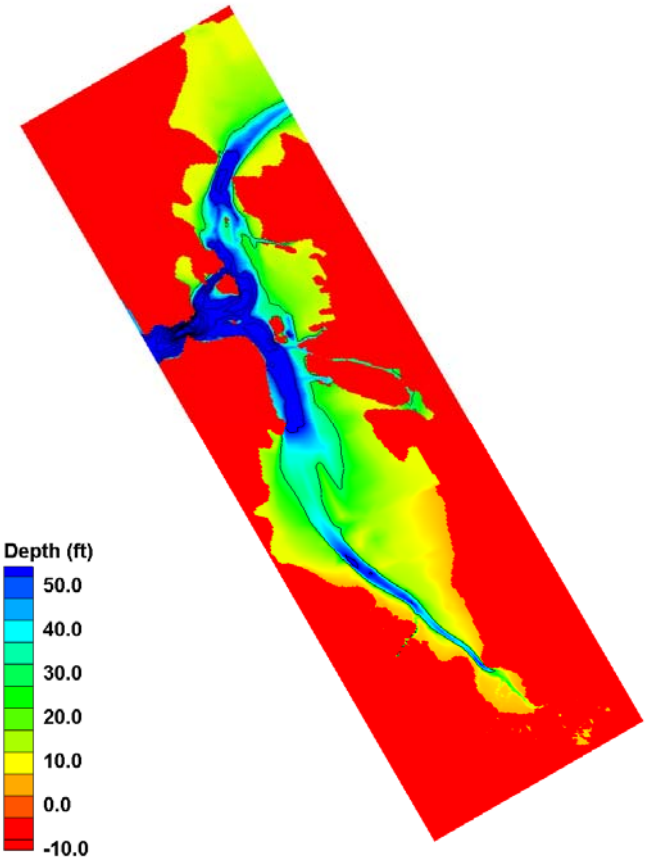

Figure 1. STWAVE Coarse Grid coverage and bathymetry for Year 0.

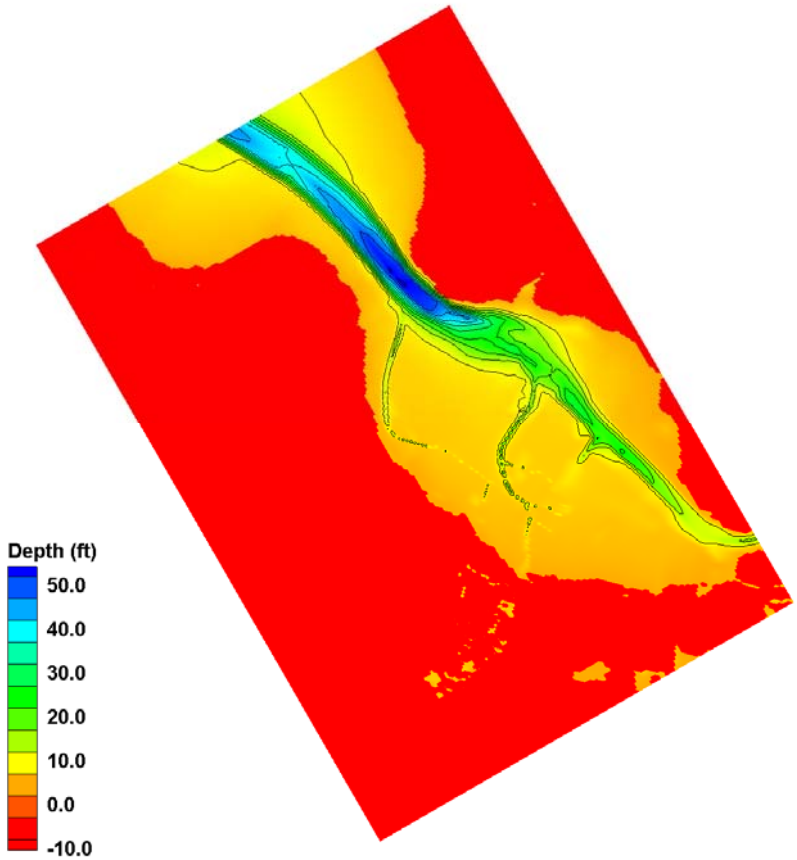

Figure 2. STWAVE Fine Grid coverage and bathymetry for Year 0.

Table 1
STWAVE Grid Specifications

Grid	State Plane	X origin ft	Y origin ft	Δx ft	Δy ft	Orient Deg	X cells	Y cells
Coarse Grid	California Zone 3	5931824.1	2198097.1	656	656	300	443	129
Fine Grid	California Zone 3	6071817.6	2010908.8	164	164	300	245	170

3 Validation and Sensitivity Analysis

Field Measurements

To verify the wave model for South San Francisco Bay, three pressure gauges were deployed in the south bay in December 2006 through January 2007 (Figure 3). The gauge locations and mean water depths are given in Table 2. The gauges sampled the pressure at 4 Hz for 17 min (1024 sec) every hour. The pressure was converted to a relative water depth and a spectral analysis was performed on the time series of water surface elevations. The data were analyzed at 1 Hz and produced hourly zero-moment wave height (H_{mo}), peak period (T_p), and wave spectra.

Table 2
Wave Gauge Locations

Gauge	Water Depth ft	Latitude deg	Longitude deg	Dates
DB	19.0 ft	37.498183333333	-122.109513722222	12/9/2006 -- 1/8/2007
MG	10.2 ft	37.478869305555	-122.077193111111	12/9/2006 -- 1/30/2007
CM8	5.9 ft	37.457499694444	-122.050177388889	12/9/2006 – 1/30/2007

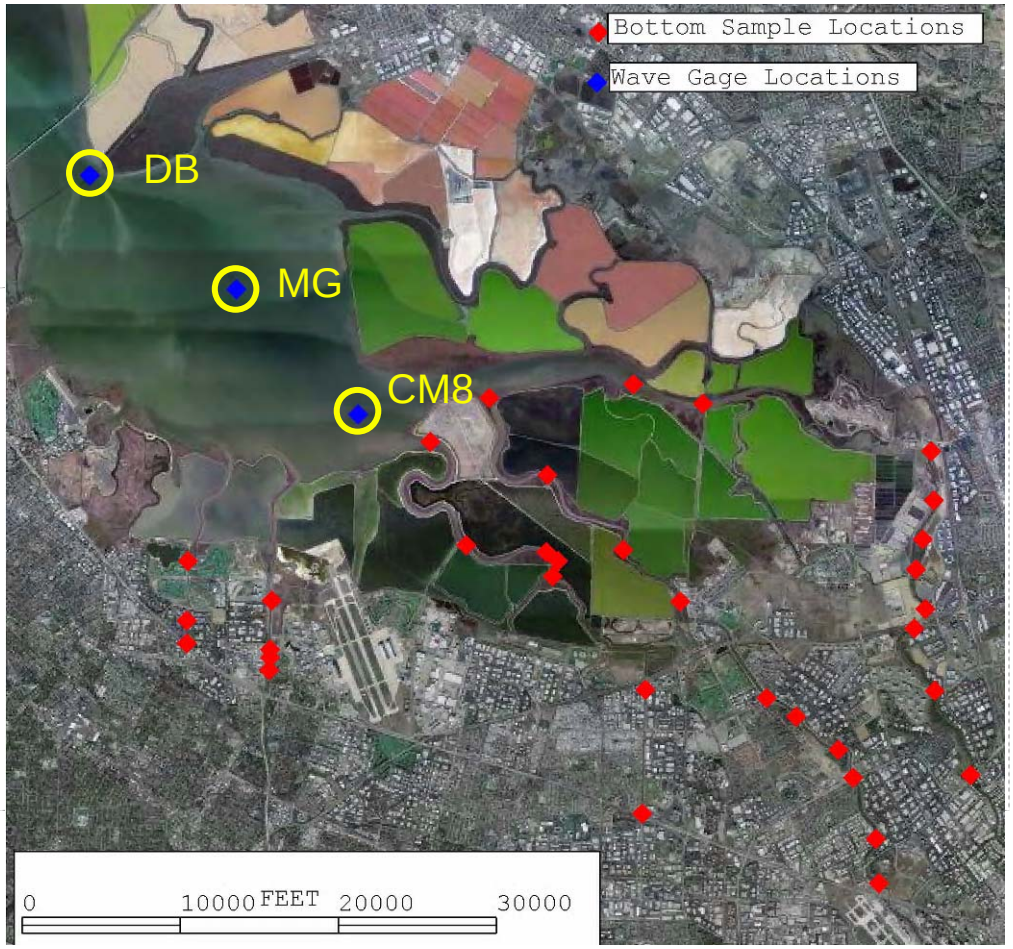

Figure 3. South San Francisco Bay wave gauge locations.

The largest event during the data collection period was on 27 December 2006. Winds recorded at the San Francisco Airport (SFO) exceeded 30 knots for 9 hours (directions of 270 to 300 deg) and the peak winds were 34 knots. Moffett Field in the south bay recorded winds up to 24 knots during this time. Figure 4 shows the initial wave parameters (wave height and peak period) and the relative water depth based on the DB gauge. The initial features seen in the data include a correlation between the tide and the wave height, a lag in peak wave height between the northernmost gauge (DB) and the southern gauges, and a trend of decreasing wave height from the north to the south. Figures 5 and 6 show wave spectra at the MG gauge for this same time period. Wave spectra represent the distribution of wave energy with frequency (or 1/period), and provide insight to the reliability of the data. The spectrum in Figure 5 is typical of wind waves, except that above 0.4 Hz (2.5 sec), the spectral energy is increasing. This is a sign of amplified noise (the pressure correction factor increases exponentially with frequency due to the attenuation of short-period waves over depth, and at high frequencies, noise is amplified and

overwhelms the wave signal). The initial analysis cutoff the spectra at approximately 0.5 Hz, which is why the minimum peak period in Figure 4 is 2 sec. In Figure 6, 12 hrs earlier, the spectrum appears to be all noise. Based on review of the spectra, the data were reanalyzed with a cutoff of 0.4 Hz and any times with peak periods of 2.5 sec or less were disregarded. Figure 7 shows the initial and reanalyzed wave parameters. Note that the wave heights are slightly reduced due to truncating the energy above 0.4 Hz. The largest changes were at the DB gauge because this gauge was the deepest, and thus had the largest amplification at high frequencies. The reanalyzed data from 27 December are used for model validation.

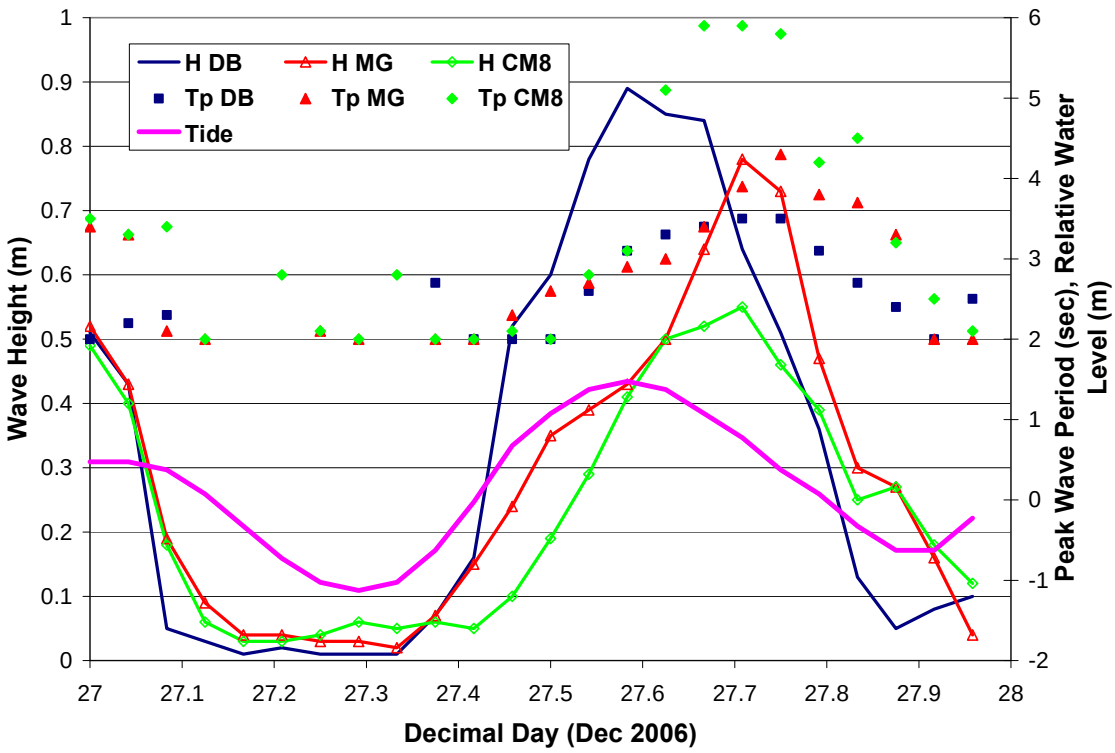

Figure 4. Initial wave parameters for 27 December 2006, UTC.

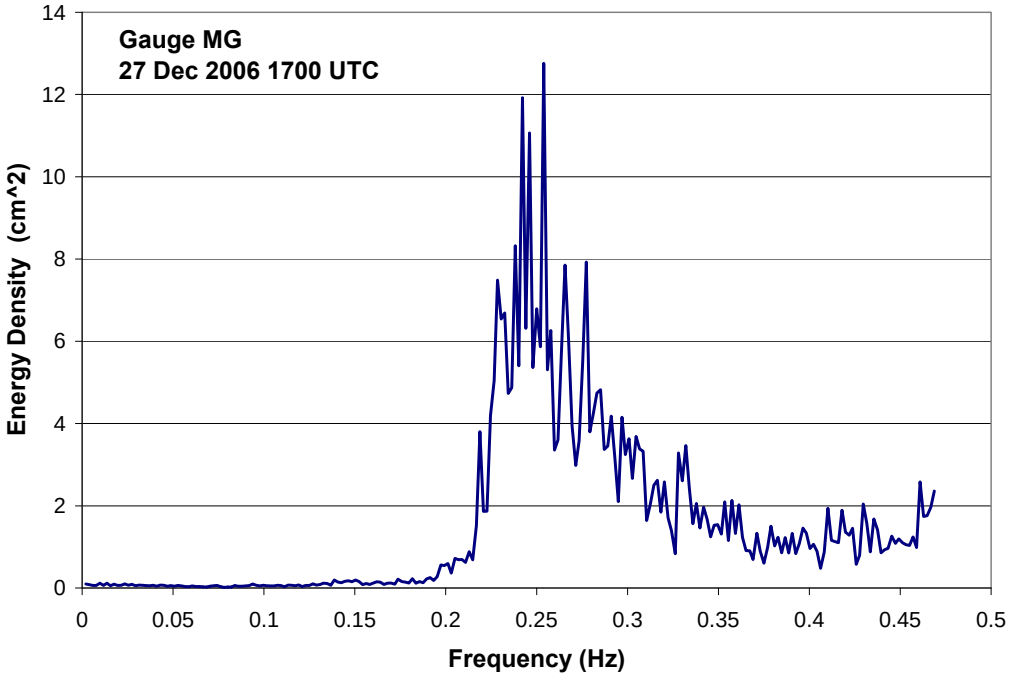

Figure 5. Gauge MG wave spectum at 1700 UTC on 27 December 2006.

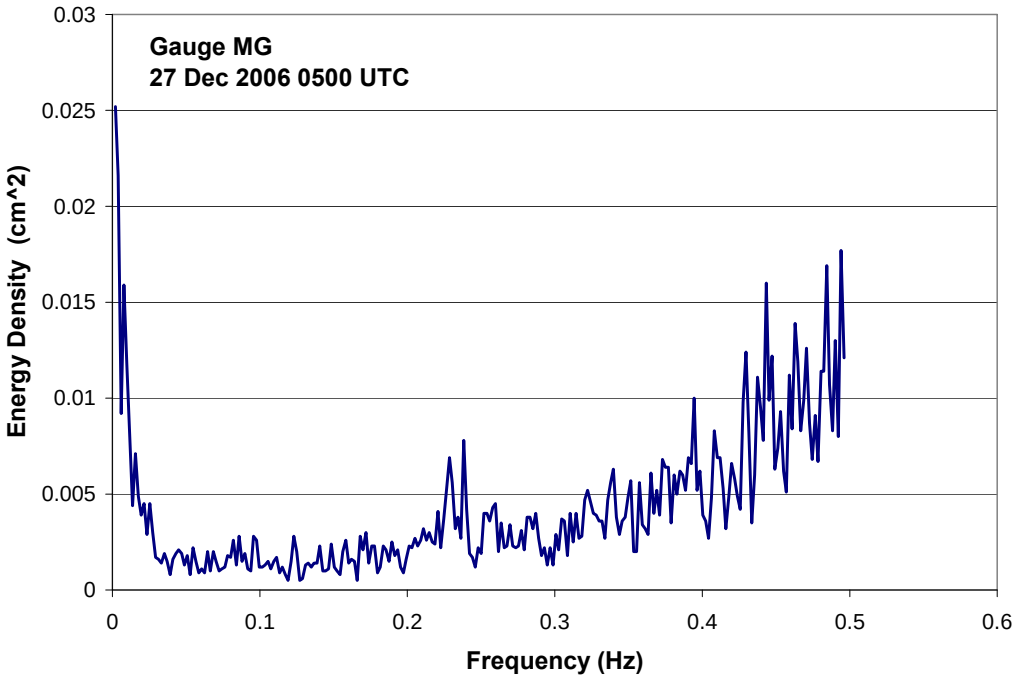

Figure 6. Gauge MG wave spectum at 0500 UTC on 27 December 2006.

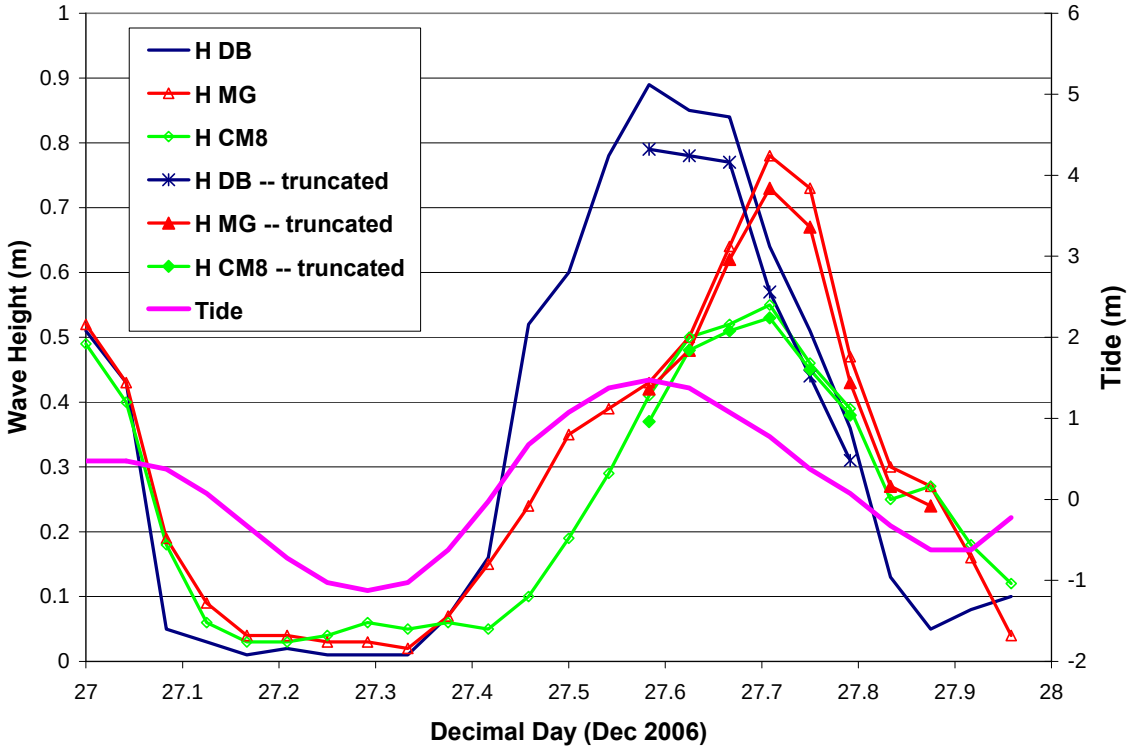

Figure 7. Reanalyzed wave heights for 27 December 2006 (UTC).

STWAVE Validation

STWAVE estimates wave growth as a function of wind speed and fetch (distance the wind blows over the water). The fetch for any location is a function of the wind direction and the bathymetry/topography. The bathymetry also enters into the model by limiting wave growth, inducing depth-limited wave breaking, and refracting and shoaling the waves. The critical input for these simulations is the wind speed and direction, the bathymetry, and the water level variation.

Wind Input

Wind analysis revealed difficulties in specifying winds in San Francisco Bay (spatial variability due to orographic effects). From a wave modeling perspective, applying a constant wind field over the entire bay produces a poor match during the validation period. This is expected due to the phase lag between the peak waves at the DB gauge and the MG and CM8 gauges. Figure 8 illustrates this phase lag in the wave heights and the corresponding phase lag in winds between SFO and Moffett Field. The south gauges and Moffett Field are shown in red to highlight their

correspondence (SFO winds and DB gauge are in blue). For the validation, two wind specification approaches were investigated: 1) specifying a spatially variable wind based on the SFO and Moffett Field winds and 2) using a nested grid approach with the coarse grid run with the SFO winds and the fine (south bay) grid run with the Moffett Field winds. In the validation, SFO winds were adjusted to 10-m elevation (1.108), from over land to over water winds (1.2 factor), and for unknown air-sea temperature difference (1.1 factor) (Resio et al. 2002) for a total adjustment factor of approximately 1.5. The Moffett Field winds were at approximately 10-m elevation, but a larger adjustment factor of 2.0 was applied based on greater sheltering at Moffett Field and preliminary model results. Winds were averaged over a 3-hr period for use in the model.

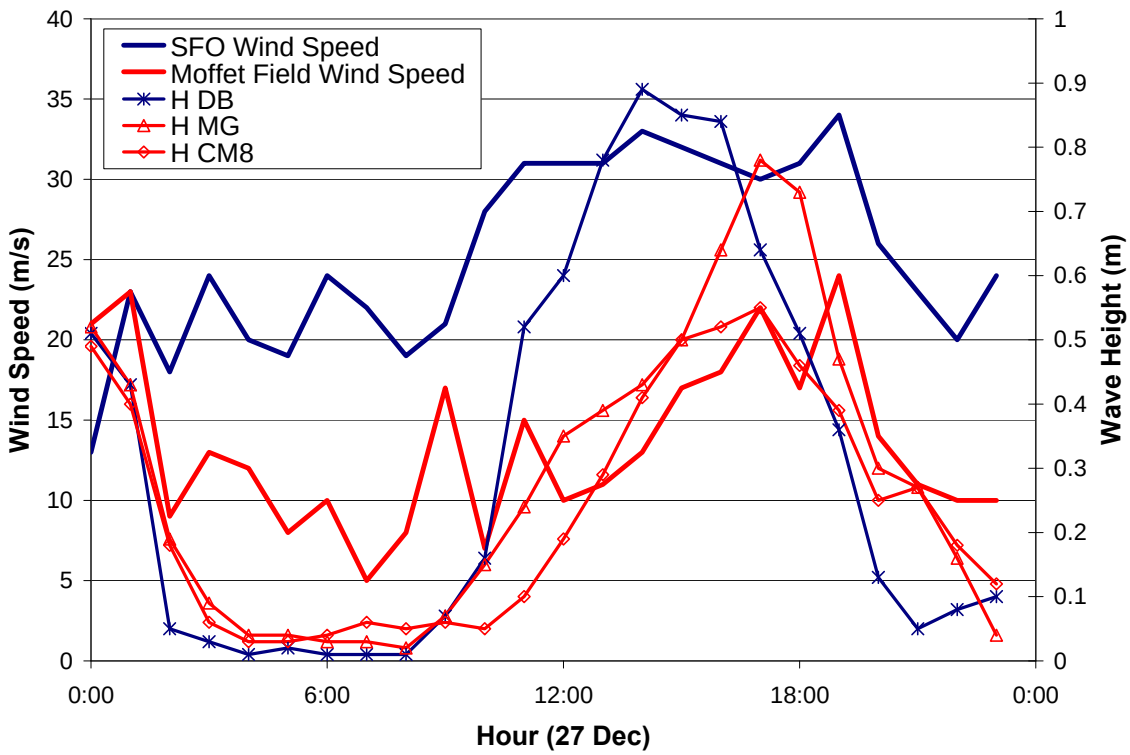

Figure 8. Wind speeds and wave height for 27 December 2006 (UTC).

Spatially Variable Wind Simulations

The wind modeling results from Francis Ludwig's wind model as applied by the USGS were investigated. For wind patterns similar to the 27 December 2006 event, the model produced winds over the middle bay consistent with SFO, wind directions near the Dumbarton Bridge aligned with the axis of the bay, and winds in the south bay consistent the Moffett

Field winds. These are the basic constraints that were applied to develop a spatially variable wind field. The winds in the north and middle bay were specified at the speed and direction at SFO. Between 3.7 miles (6 km) north of Dumbarton Bridge and the bridge, the wind direction was linearly interpolated from the SFO wind direction to 330 deg and the SFO wind speed was used. In a 1.2-mile (2-km) reach at the bridge, the wind direction was specified at 330 deg and the SFO wind speed was used. South of the bridge over 1.2 miles (2 km), wind speed was linearly interpolated from SFO to Moffett Field, and wind direction was interpolated from 330 deg to the Moffett Field directions. In the remainder of the south bay, Moffett Field winds were used. This approach created a smooth transition between the two wind stations. Winds changed only along the long axis of the bay and were constant across the width of the bay.

Figure 9 shows the wave model results and measurements for 27 December 2006 from the coarse grid for the spatially variable winds. The estimated water levels from the pressure gauges were applied to the entire bay (varying in time) for this simulation. The peak wave heights were well represented in the model for all three gauges, but the width of the peaks is somewhat too broad. Figure 10 shows the peak wave periods. The measured periods are between 3 and 5 sec (the lower limit is governed by the analysis) and the modeled periods are between 2.5 and 6 sec. The model periods are more variable, likely due to the discrete nature of the measured wind directions (10-min averages every hour with 10-deg resolution) and from the coarseness of the computational grid.

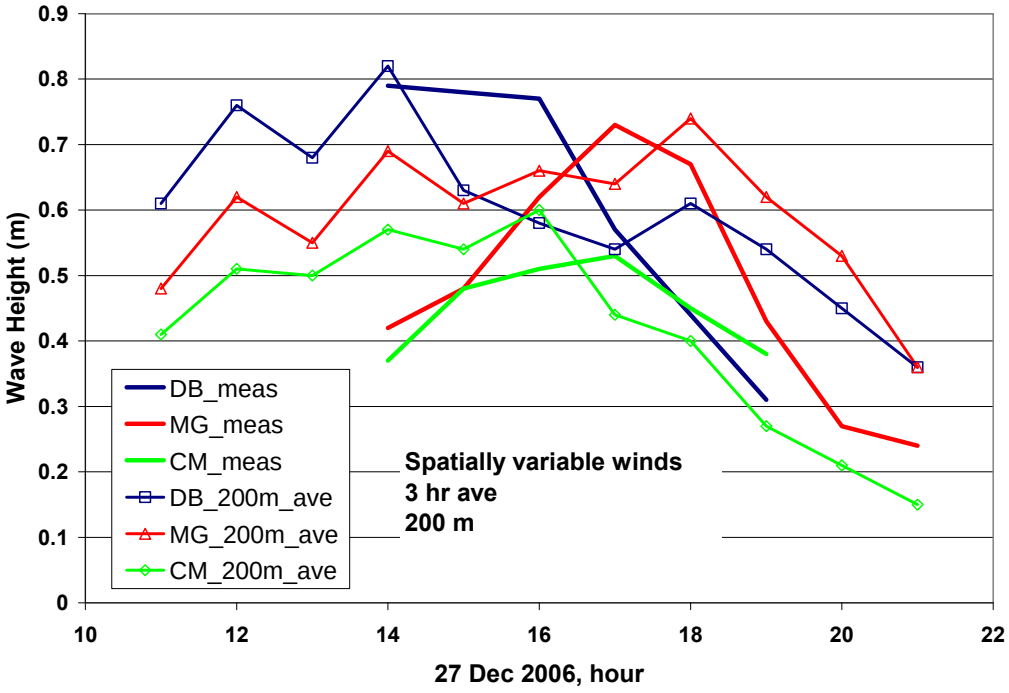

Figure 9. Measured and modeled wave height for 27 December 2006 (UTC) for spatially variable winds.

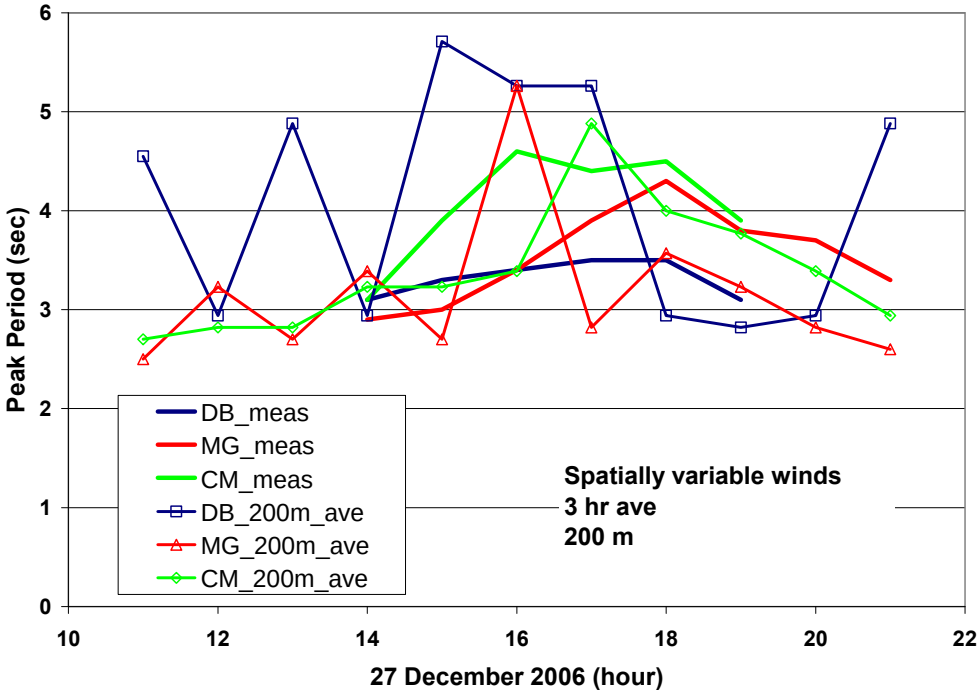

Figure 10. Measured and modeled wave height for 27 December 2006 (UTC) for spatially variable winds.

Nested Simulations

Early wave simulations (the short peak periods in the field measurements) and some anecdotal evidence suggest that the waves in the south bay are predominately generated locally in the south bay. This led to a second modeling approach where the coarse grid is driven by the SFO winds and the nested south bay grid is driven with the Moffett Fields and spatially varying boundary conditions on the north edge of the grid taken from the coarse grid simulation.

Figures 11 and 12 show the wave model results and measurements for 27 December 2006 from the nested grid simulation (both 200 m and 50 m). The estimated water levels from the pressure gauges were applied to the entire bay (varying in time) for this simulation. The wave heights from the 200-m grid are shown to be too high and peak too early (dashed lines), as alluded to earlier. The peak wave heights for the 50-m nested grid are well represented in the model for all three gauges, and the width of the peaks is again somewhat too broad (as in the spatially variable wind simulation). The modeled periods are smoother and shorter than the spatially variable wind simulation. The periods at gauge DB are much improved, but the periods at the other two gauges are underestimated by 0.5 to 1.0 sec at the peak (within measurement accuracy). A summary of the validation statistics (mean and root-mean-square (rms) errors) for the three gauges is given in Table 3. Negative mean error indicates that the model is overestimating the parameter, relative to the measurement.

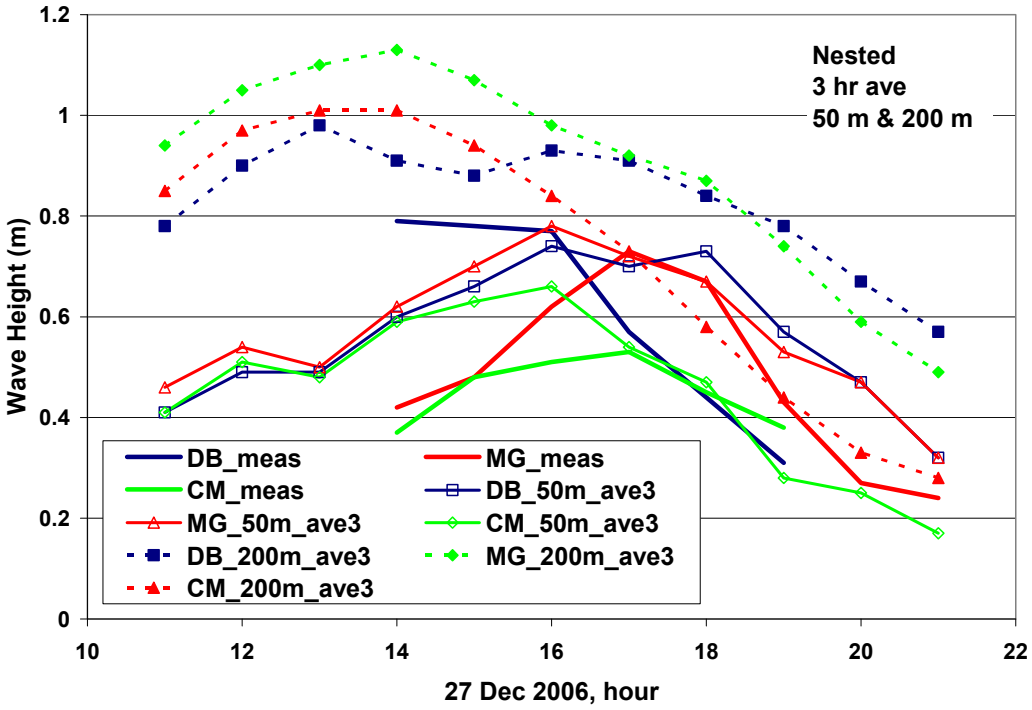

Figure 11. Measured and modeled wave height for 27 December 2006 (UTC) for nested grids.

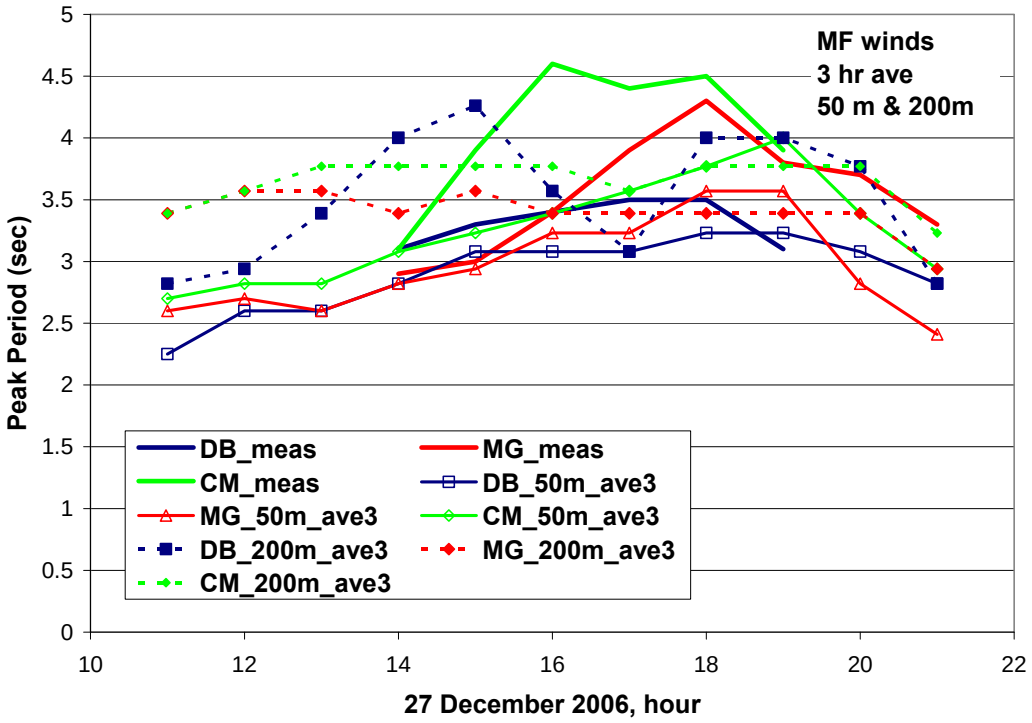

Figure 12. Measured and modeled peak wave period for 27 December 2006 (UTC) for nested grids.

Table 3
STWAVE Validation Statistics

Gauge	H mean error, m		H rms error, m		T_p mean error, sec		T_p rms error, sec	
	200 m	50 m	200 m	50 m	200 m	50 m	200 m	50 m
DB	-0.27	-0.06	0.30	0.19	-0.50	0.23	0.71	0.29
MG	-0.39	-0.11	0.44	0.14	0.13	0.32	0.55	0.42
CM	-0.30	-0.08	0.36	0.13	0.33	0.56	0.63	0.72

The conclusion from the validation effort is that the full-plane STWAVE model can produce realistic simulations of waves in the south bay when driven by representative winds. Validation focused on a single event due to limitations of the field data. Both the spatially variable and nested approaches produced reasonable comparisons to the field data. The results suggest that waves in the south bay are predominantly locally generated in the south bay.

Sensitivity Analysis

The approach to modeling waves in the south bay is to run ranges of wind and water level conditions and develop a lookup table of results along the south shoreline. A sensitivity analysis was performed to look at the range of parameters and the linearity of wave response. For this analysis, the nested grid approach was used with the same, spatially constant wind speed and direction and water level on both grids. A total of 108 sensitivity runs were made. The runs included a full matrix of four wind speeds (38.9, 58.3, 77.8 and 97.2 kts (20, 30, 40, and 50 m/sec)), four wind directions (260, 280, 300, and 330 deg, relative to north), and five water levels (6.6, 9.8, 13.1, 16.4, and 19.7 ft (2, 3, 4, 5, and 6 m)) for a total of 80 runs. Additional runs including finer discretization of each parameter: water levels of 0 to 19.7 ft (0 to 6 m) incremented by 1.6 ft (0.5 m) with wind speed of 77.8 kts (40 m/sec) and wind direction of 330 deg; wind speeds of 38.9 to 116.6 kts (20 to 60 m/sec) incremented by 9.7 kts (5 m/sec) with wind direction of 330 deg and water level of 13.1 ft (3 m); and wind directions of 260 to 350 deg incremented by 5 deg with wind speed of 77.8 kts (40 m/sec) and water level of 13.1 ft (3 m).

Ten points were chosen for investigating the sensitivity of the wave model to winds and water levels. These points include the three gauge locations

in the south bay and seven points along the southern shoreline, which are a subset of the points identified for the wave runup and overtopping analysis. The locations of the points are shown in Figure 13 and summarized in Table 4. Note that the depths in Figure 13 are relative to NAVD 88, and most of the points are at elevations above NAVD 88 (these are reported as negative depths in Table 3). Figures 14 and 15 show examples of the sensitivity runs (wind speed = 77.8 kts (40 m/sec), wind direction = 330 deg, and water level = 9.8 ft (3 m)). Note that the scale changes between plots. Figure 14 illustrates how the constriction at Dumbarton Bridge (combination of the narrowing of the fetch and complex bathymetry) limits the wave heights in the south bay.

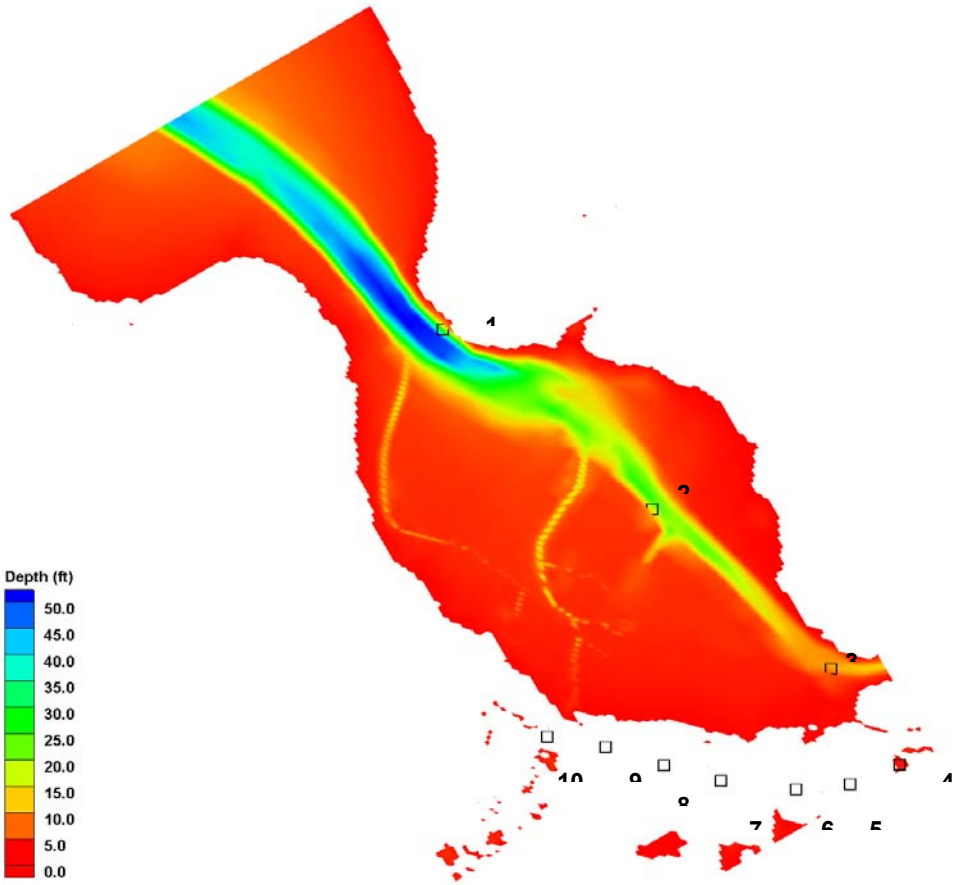

Figure 13. Locations of points used for sensitivity analysis (depths in ft, NAVD 88).

Table 4
Locations of points for sensitivity analysis

Point Number	Depth ft	STWAVE 50-m i cell	STWAVE 50-m j cell
1	22.0	84	114
2	14.0	153	138
3	7.5	213	158
4	-1.1	244	161
5	-2.3	242	147
6	-2.3	236	134
7	-0.2	224	118
8	-0.8	213	107
9	-7.7	201	96
10	-0.9	191	84

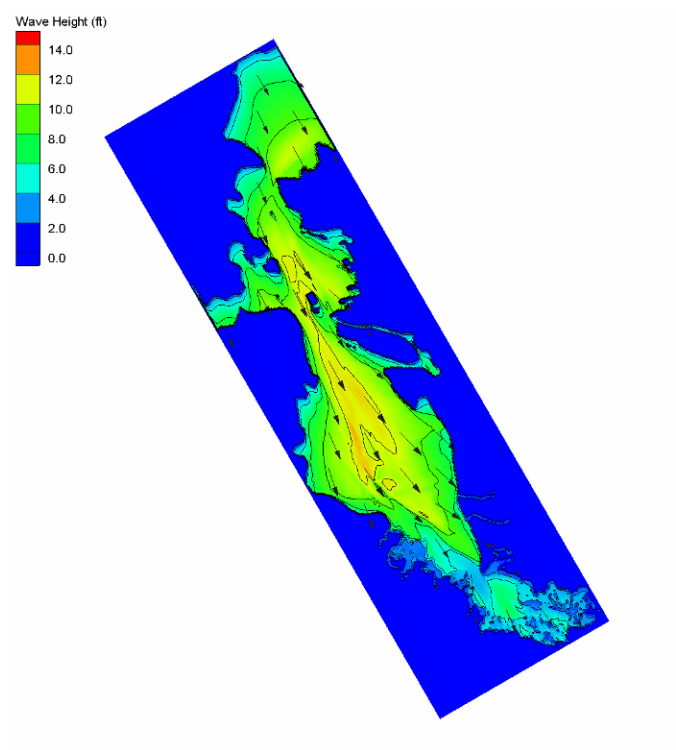

Figure 14. Wave heights from STWAVE on the coarse grid for wind speed = 77.8 kts (40 m/sec), wind direction = 330 deg, and water level = 9.8 ft (3 m).

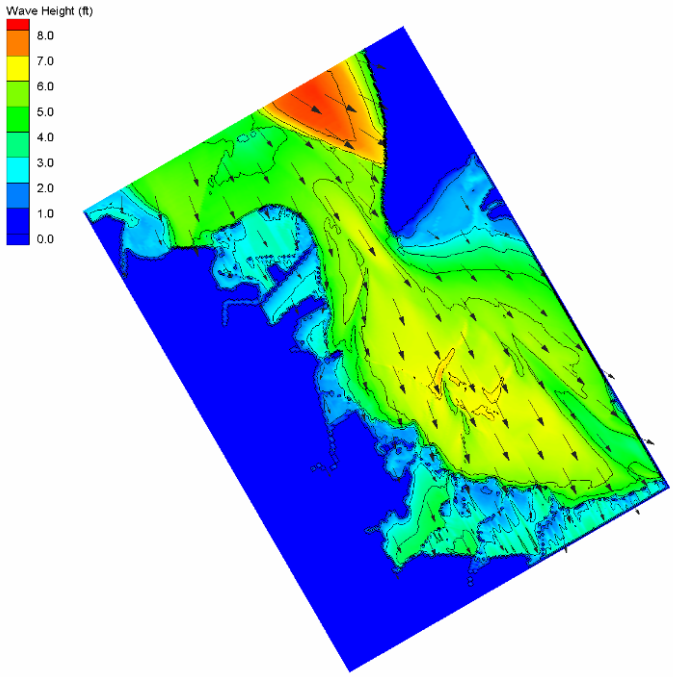

Figure 15. Wave heights from STWAVE on the nested fine grid for wind speed = 77.8 kts (40 m/sec), wind direction = 330 deg, and water level = 9.8 ft (3 m).

Figure 16 shows the sensitivity of the wave heights to wind speeds at the ten locations shown in Figure 13 (H_1 is point 1 and H_10 is point 10). The wind speed is varied between 38.9 and 116.6 kts (20 and 60 m/sec) and the wind direction is 300 deg and the water level is 3 m. The response is linear at all locations. At some locations the response is quite flat. This is due to water depth limits on the wave height (either local or bayward of the point). Figure 17 shows the peak wave period response to the same range of wind speeds. The period response is also fairly linear. The peak period values are limited to the inverse of the discrete frequency bins in the model, so values show some pixilation. Also, there is an anomaly at point 5 where the period drops at larger wind speed. The wave height at point 5 is small (1.6 ft (0.5 m)), and limited by bathymetry between the point and the open bay. The dropping of the peak period is likely due to some regeneration in this shallow area. Mean periods may show a more consistent trend. Figures 18 and 19 show the sensitivity of wave height and period to wind direction, respectively. As the wind direction changes, the fetch lengths change and thus the amount of local generation is effected (also the energy coming through the gap at Dumbarton Bridge). The wave height varies by as much as 2 ft (0.6 m) and the peak wave period by as much as 3 sec over the range of wind directions, although at some the locations the variation is smaller. Figures 20 and 21 show the

sensitivity of wave height and period to water level, respectively. The response is again fairly linear. At the lower water levels, several of the points show zero wave height or flat response, due to depth limitation either locally or at bathymetry bayward of the point. The period response is relatively flat for points in the open water, but for the more protected points, there is jump at water levels between 6.6 and 9.8 ft (2 and 3 m). These are critical water levels for inundating the lower reaches of the grid.

Uncertainty in Wave Model Results

The uncertainty in the wave model results come from the model input (bathymetry and wind), model resolution, and the model itself. The combination of these factors can be estimated based on the validation statistics (Table 3). The mean wave height error for 50-m resolution simulations is approximately 0.1 m and the rms error is 0.15 m. The mean and rms errors in peak period are 0.4 sec and 0.5 sec, respectively. The SFO measured wind speeds have a resolution of 1 kt (0.5 m/sec) and the directions have a resolution of 10 deg. The sensitivity results indicate for the three measurement locations, the resolution of the wind input could result in model errors on the order of 0.03 m and 0.05 sec based on wind speed discritization and 0.15 m and 0.5 sec based on the coarse wind direction discritization. Finally, the field measurements themselves contain errors due to the measurement device, the sampling scheme, and noise (both in the measure system and geophysical system). Accepted measurement error is on the order of 10 to 15 percent in wave height (~0.1 m for this case) and 0.5 to 1 sec in wave period. The uncertainty in the wave model results based on the validation statistics and the wind discritization is approximately 0.15 m in wave height and 0.5 sec in peak wave period.

Validation Summary

STWAVE was set up and run for San Francisco Bay using a nested approach with a coarse resolution grid over the entire bay and a nested fine resolution grid in the south bay. Limited field data (27 December 2006) were used to verify the model. Good agreement was found when the model was run with spatially varying winds with the SFO wind applied north of Dumbarton Bridge and Moffett Field winds applied south of the bridge. The spatial variability was achieved through either an interpolation scheme that also modified the wind direction to align with

the gap at the bridge or through application of SFO wind on the coarse grid and Moffett Field winds on the fine grid. The modeling results showed that the gap at Dumbarton Bridge limits energy transfer to the south bay. The sensitivity analysis showed a strong, linear response of the wave height to wind speed and water level. A water level threshold in the range 7 to 10 ft is important to wave heights along the south bay shoreline. Wind direction is also an important parameter because it determines the fetch for wave generation. Wave height varies by as much as 2 ft (0.6 m) and the peak period by as much as 3 sec over the range of wind directions investigated.

For the wave model production runs, two decisions were required. First, the relationship between winds over the upper bay and south bay for the production runs needed to be set. For the sensitivity analysis, the same winds were used on both grids. The validation showed that the approach this will likely overestimate waves in the south bay (a conservative approach). Mean relationships between SFO and Moffett Field (or San Jose) wind speeds and directions for storm events could also be applied. The conservative choice was made to use the same winds over the upper bay and south bay. Second, in the analysis shown here, a constant water level is applied throughout the bay. The same approach was applied in the production runs.

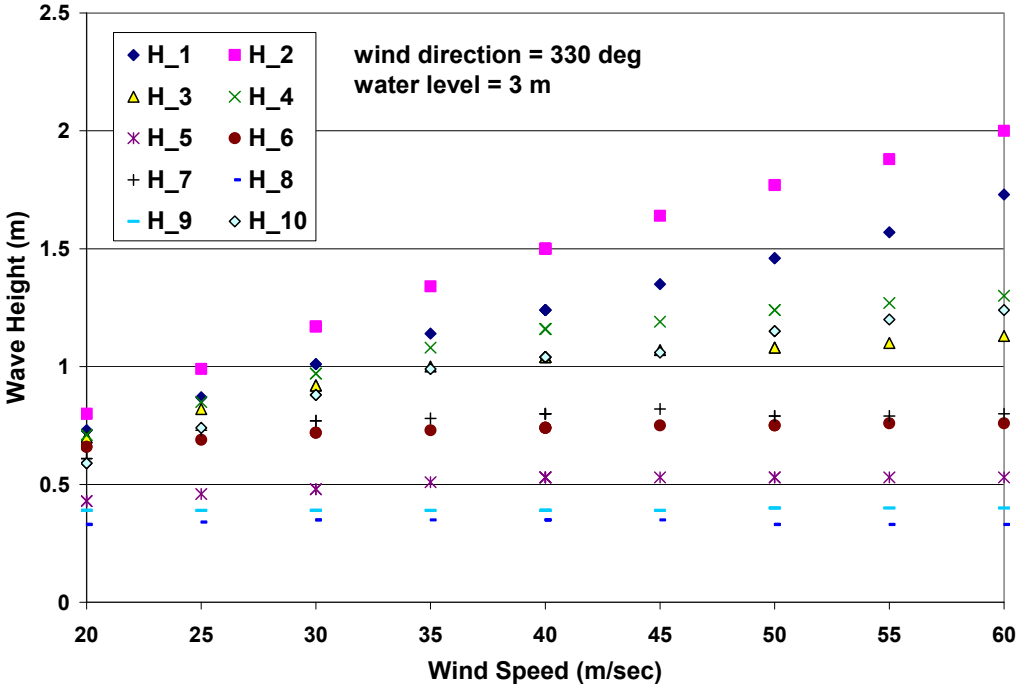

Figure 16. Wave height sensitivity to wind speed at ten south bay locations (wind direction = 330 deg, and water level = 9.8 ft (3 m)).

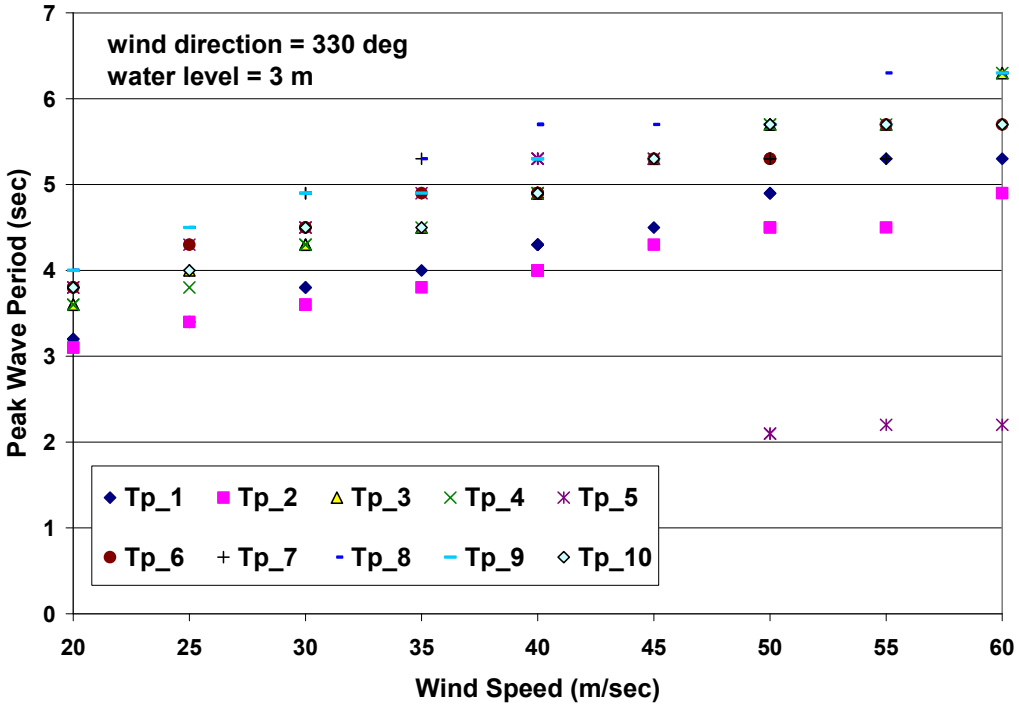

Figure 17. Peak wave period sensitivity to wind speed at ten south bay locations (wind direction = 330 deg, and water level = 9.8 ft (3 m)).

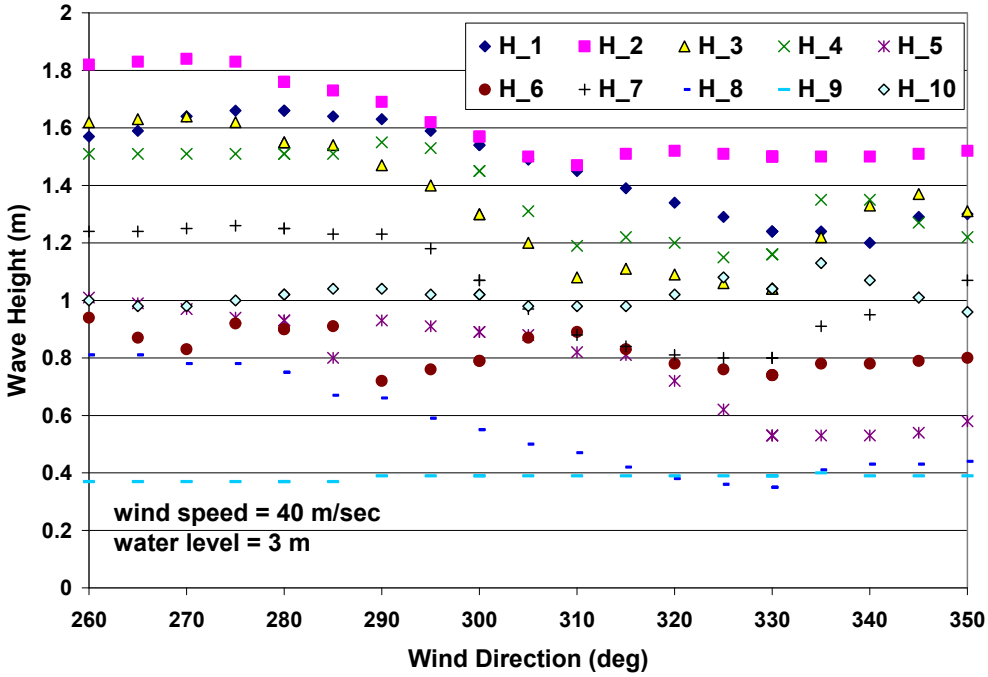

Figure 18. Wave height sensitivity to wind direction at ten south bay locations (wind speed = 77.8 kts (40 m/sec), and water level = 9.8 ft (3 m)).

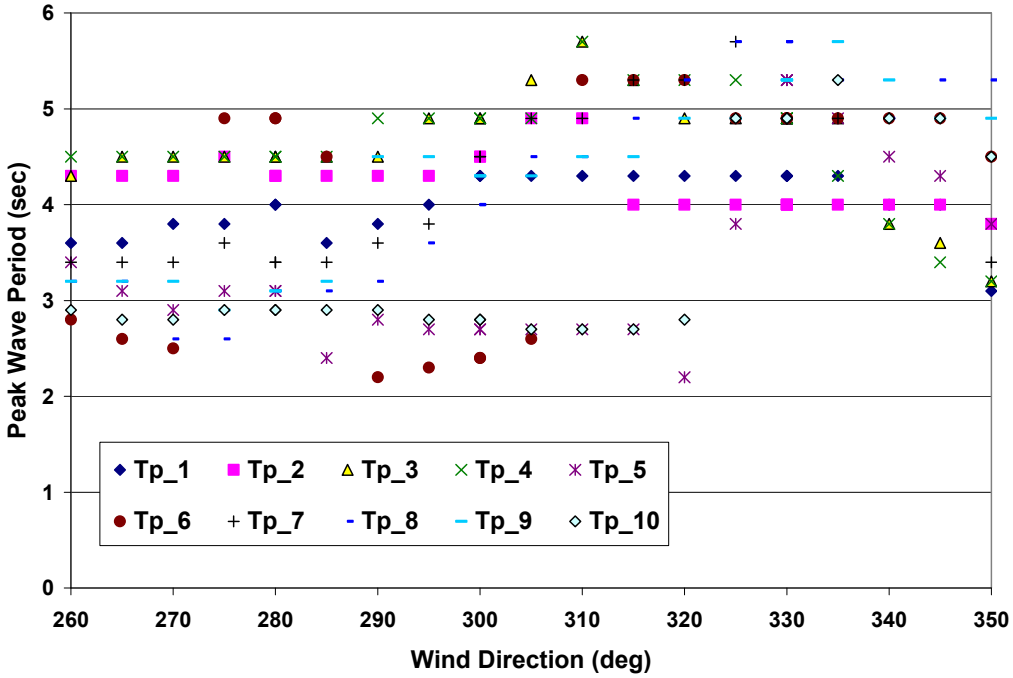

Figure 19. Peak wave period sensitivity to wind direction at ten south bay locations (wind speed = 77.8 kts (40 m/sec), and water level = 9.8 ft (3 m)).

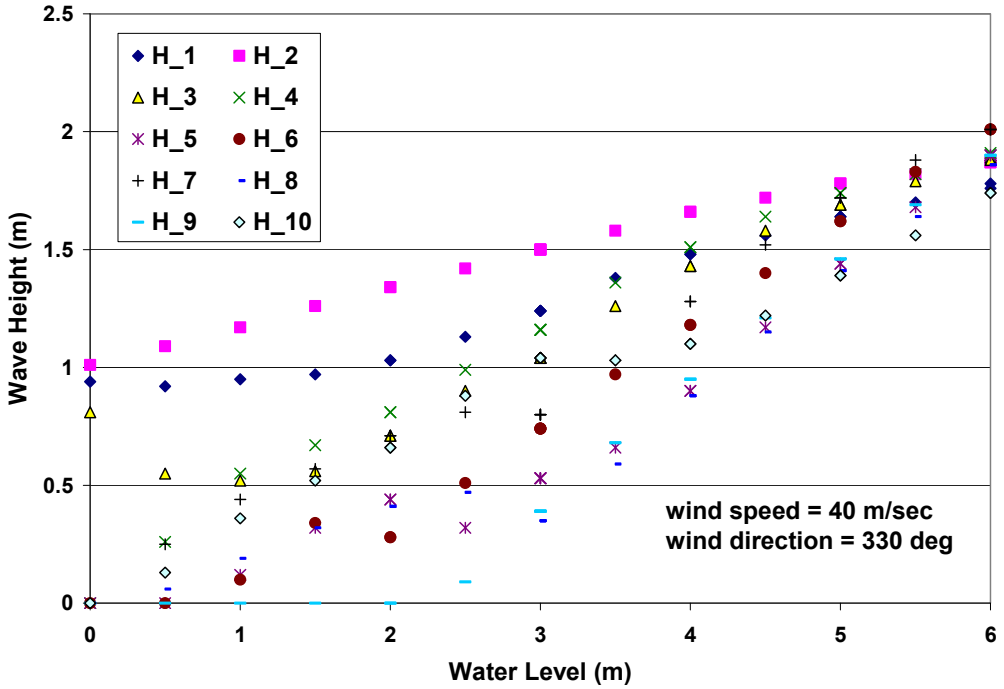

Figure 20. Wave height sensitivity to water level at ten south bay locations (wind speed = 77.8 kts (40 m/sec), and wind direction = 330 deg).

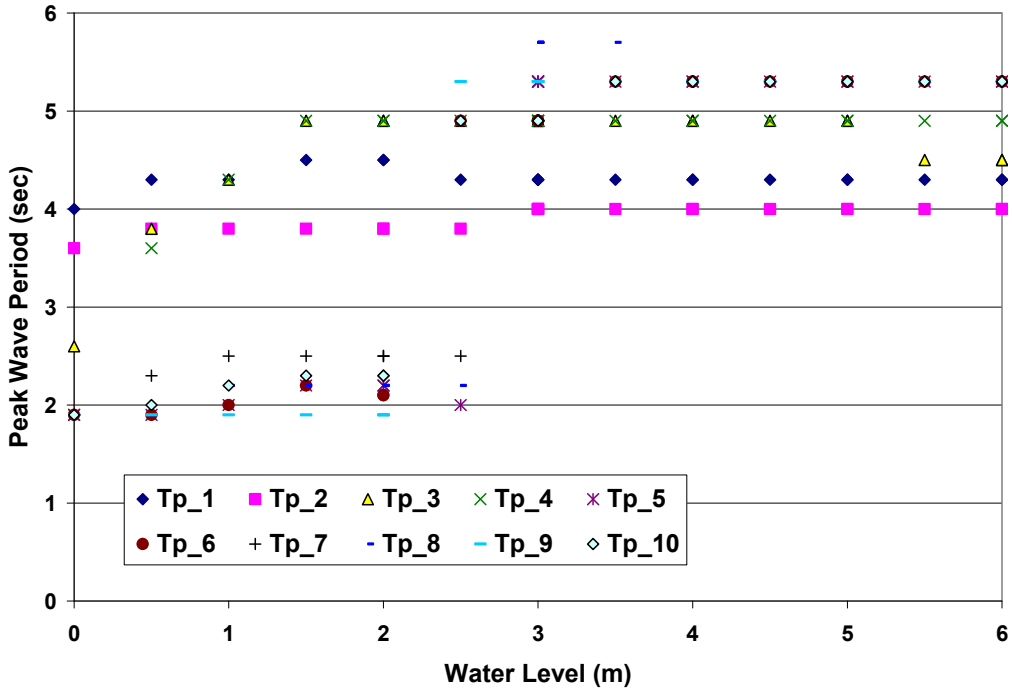

Figure 19. Peak wave period sensitivity to water level at ten south bay locations (wind speed = 77.8 kts (40 m/sec), and wind direction = 330 deg).

4 Year 0 Simulations

A total 780 STWAVE full-plane model runs were made for the Year 0 simulations, representing 130 wind conditions and six water levels. The simulations were made on both the coarse grid and nested, fine grid defined in Table 5. The six water levels simulated were 7, 8, 9, 10, 11, and 12 ft NAVD 88. The water levels were assumed to be constant throughout the bay. The wind speeds simulated were 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 mph. The wind directions simulated were winds from 250, 260, 270, 280, 290, 300, 310, 320, 330, 340, 350, 0, and 10 deg measured clockwise relative to North. Winds were assumed to be constant throughout the bay. The wind and water levels are summarized in Table 5 (all combinations of parameters were simulated). Simulated wave heights, peak periods, and mean directions at 35 south bay locations were extracted from the fine-grid results and passed to surge and sediment modeling efforts (Table 6).

Table 5
Water Level and Wind Input for Year 0

Water Levels ft, NAVD 88	Wind Speed mph	Wind Direction deg, from North
7.0	10	250
8.0	20	260
9.0	30	270 (from West)
10.0	40	280
11.0	50	290
12.0	60	300
	70	310
	80	320
	90	330
	100	340
		350
		0 (from North)
		10

Table 6
Output Point Locations

Point Number	x ft, UTM NAD83	y ft, UTM NAD83	STWAVE i	STWAVE j
1	1897365.12	13605117.91	145	67
2	1898472.08	13604110.66	154	70
3	1902252.33	13602050.89	176	83
4	1902908.79	13602404.86	177	88
5	1903868.77	13601233.6	186	89
6	1904833.66	13600606.96	192	92
7	1905697.51	13600544.62	195	96
8	1906316.60	13600672.57	197	100
9	1907060.04	13600538.06	200	103
10	1907815.62	13599645.67	207	104
11	1908502.95	13599885.17	208	109
12	1909069.55	13599770.34	210	111
13	1909534.12	13599763.78	212	114
14	1910005.58	13599924.54	212	117
15	1910476.71	13599977.03	213	119
16	1911002.62	13599947.51	215	122
17	1911402.89	13599711.29	218	123
18	1911795.28	13599209.32	222	124
19	1912055.77	13598809.06	225	124
20	1912562.01	13598412.07	228	125
21	1912972.11	13598458.01	229	127
22	1913462.27	13598645.01	230	130
23	1913979.66	13598812.34	231	134
24	1914433.07	13599025.59	231	137
25	1914981.30	13599176.51	232	140
26	1915516.08	13599199.48	234	143
27	1915966.21	13599402.89	234	146
28	1916531.17	13599370.08	236	149
29	1917083.66	13599461.94	237	152
30	1917569.55	13599786.75	237	155
31	1918140.42	13600131.23	237	159
32	1918570.54	13600400.26	237	163
33	1919145.01	13600528.22	238	166
34	1919562.99	13600593.83	239	168
35	1919980.97	13600679.13	240	169

Wave heights in the south bay are controlled by the wind speed and direction, the water level, and the bathymetry. Figures 20 and 21 show the wave height for a wind speed of 100 mph, wind direction of 310 deg, and water levels of 7 and 12 ft, respectively. The waves grow in the wind direction, and greater water depths allow more wave growth (1-2 ft for increased water depth from 7 to 12 ft). The waves refract and shoal (increase in height) in the shallow areas. In very shallow depths, waves break and the heights in the breaking region are about 3 ft higher for the 12 ft water depth. Wave periods for these cases are similar in the south bay (5.3 sec for 7 ft water level and 5.7 sec for 12 ft water level). Wave directions are shown by the vectors in Figures 20 and 21.

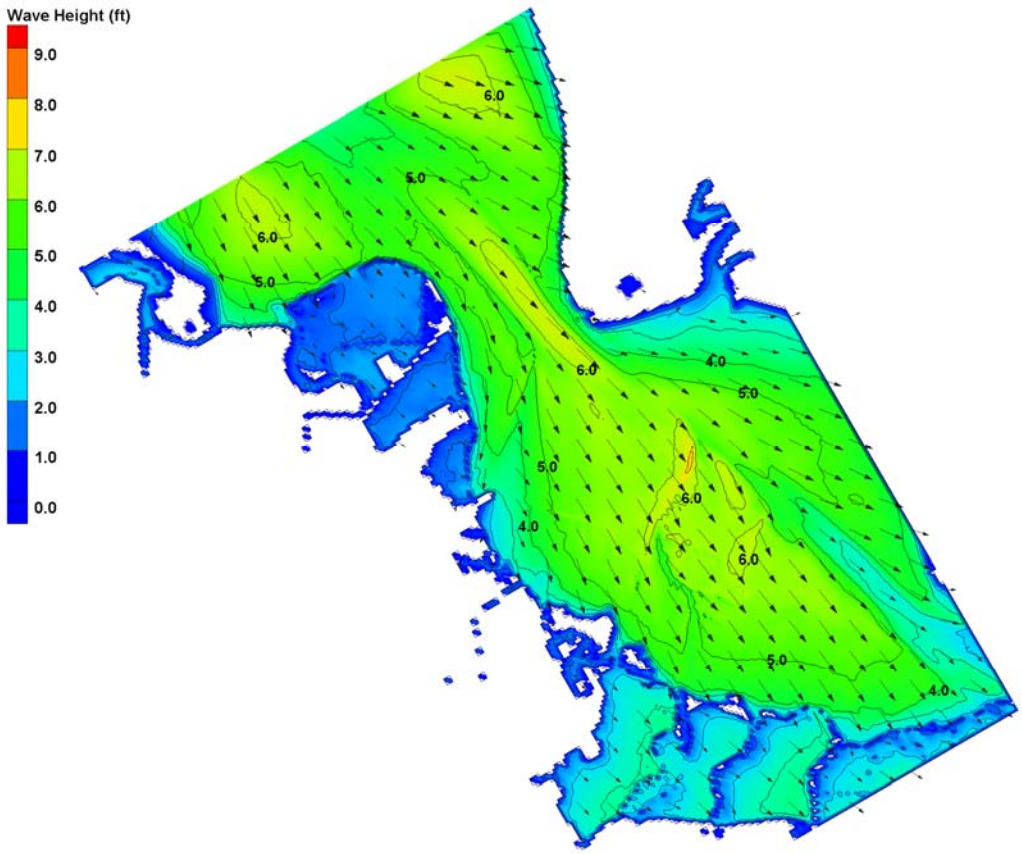

Figure 20. Wave heights in South Bay for wind speed of 100 mph from 310 deg and water level of 7 ft NAVD 88.

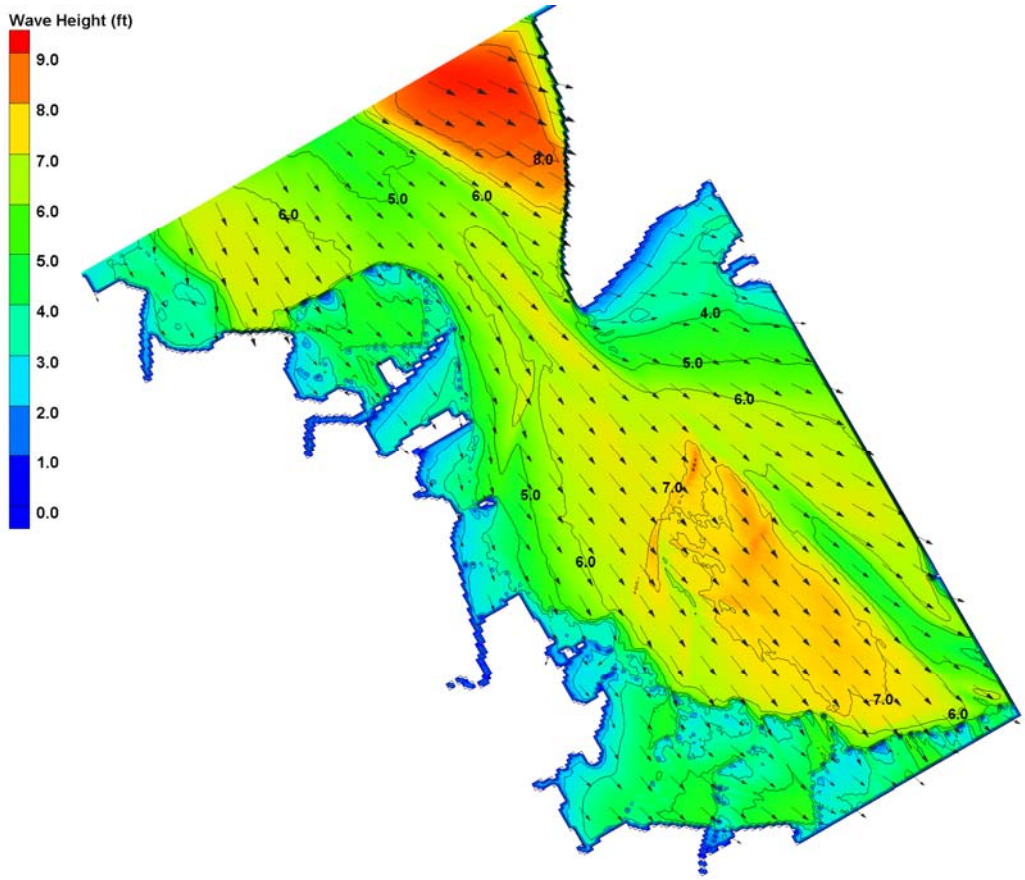

Figure 21. Wave heights in South Bay for wind speed of 100 mph from 310 deg and water level of 12 ft NAVD 88.

Figures 23 and 24 show the wave height for a wind speed of 50 mph, wind direction of 310 deg, and water levels of 7 and 12 ft, respectively (same conditions as Figures 20 and 21, except lower wind speed). For the lower wind speed, the wave heights are approximately half as large, but the patterns are similar. Breaking wave heights in very shallow depths are again approximately 3 ft larger for the 12 ft water depth. Wave periods for lower wind speed are similar in the south bay for water levels of 7 and 12 ft (4-4.3 sec). Wave directions are shown by the vectors in Figures 22 and 23.

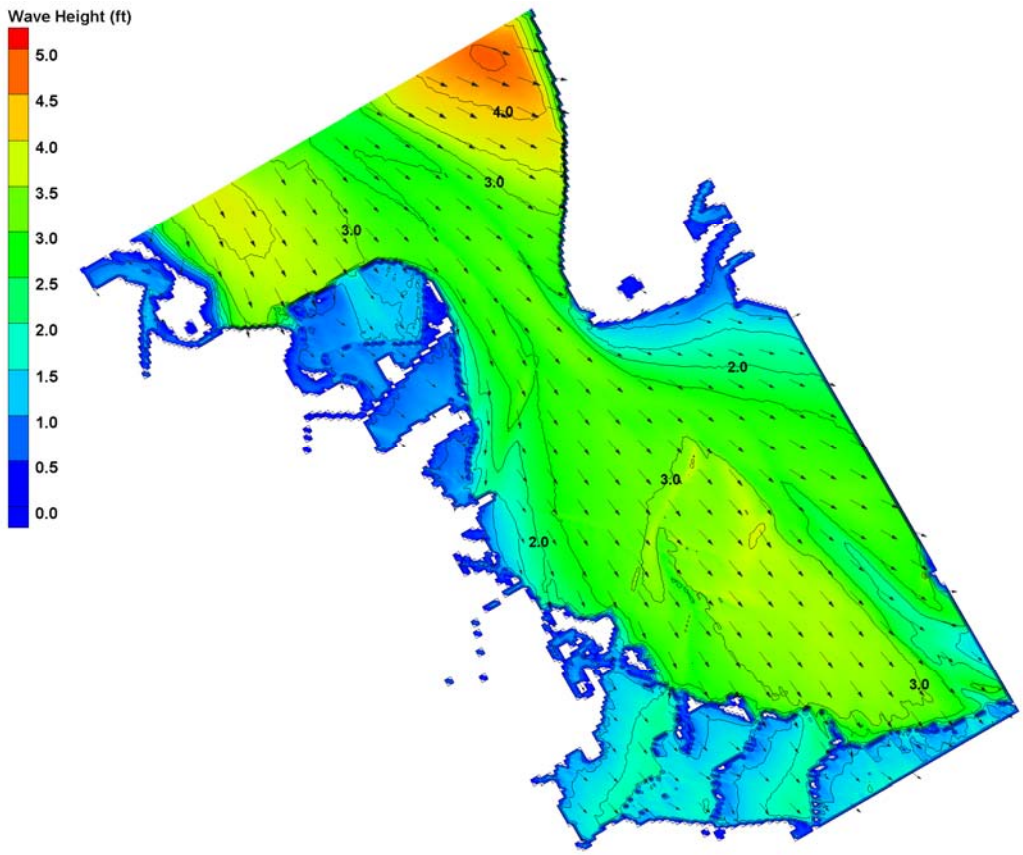

Figure 22. Wave heights in South Bay for wind speed of 50 mph from 310 deg and water level of 7 ft NAVD 88.

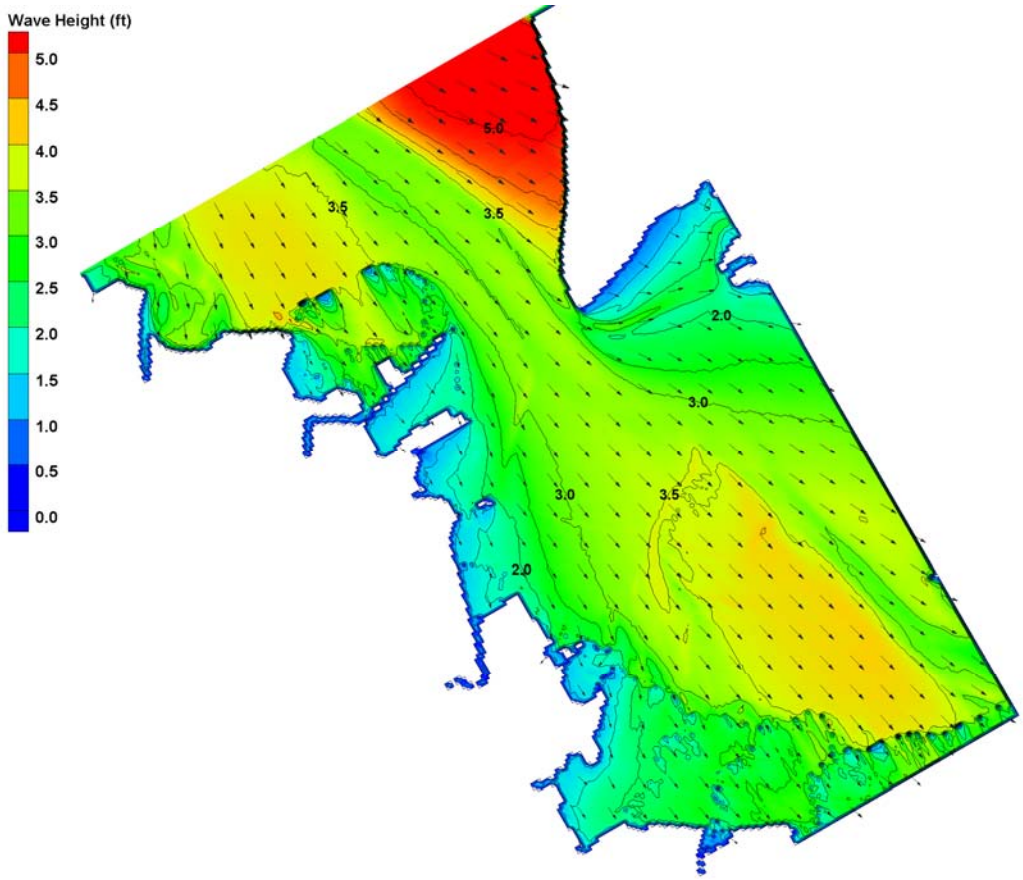

Figure 23. Wave heights in South Bay for wind speed of 50 mph from 310 deg and water level of 12 ft NAVD 88.

Figure 24 shows the location of the 35 save points along the southern bay shoreline (numbered from west to east). Figure 25 shows the wave height at these 35 points for water levels of 7 and 12 ft, wind speeds of 50 and 100 mph, and wind direction of 310 deg. The solid lines in the plot are for the 7-ft water level and the dashed lines are the 12-ft water level. The red lines are 100 mph wind speed and the blue lines are 50 mph wind speed. Note that for the 7-ft water level, the eastern points have the same wave height for the 50 and 100 mph wind speed because the waves are depth limited. For the 12-ft water level, the wave heights are as much as 3 ft higher for the 100 mph wind than the 50 mph wind (average of 2.3 ft). Also, for the 100 mph wind, the wave height is as much a 3.2 ft higher for the 12-ft water level than the 7-ft water level (average of 2.7 ft higher), due to depth-limited wave breaking (waves generated by 50 mph wind with 12 ft water level are not depth limited at these points).

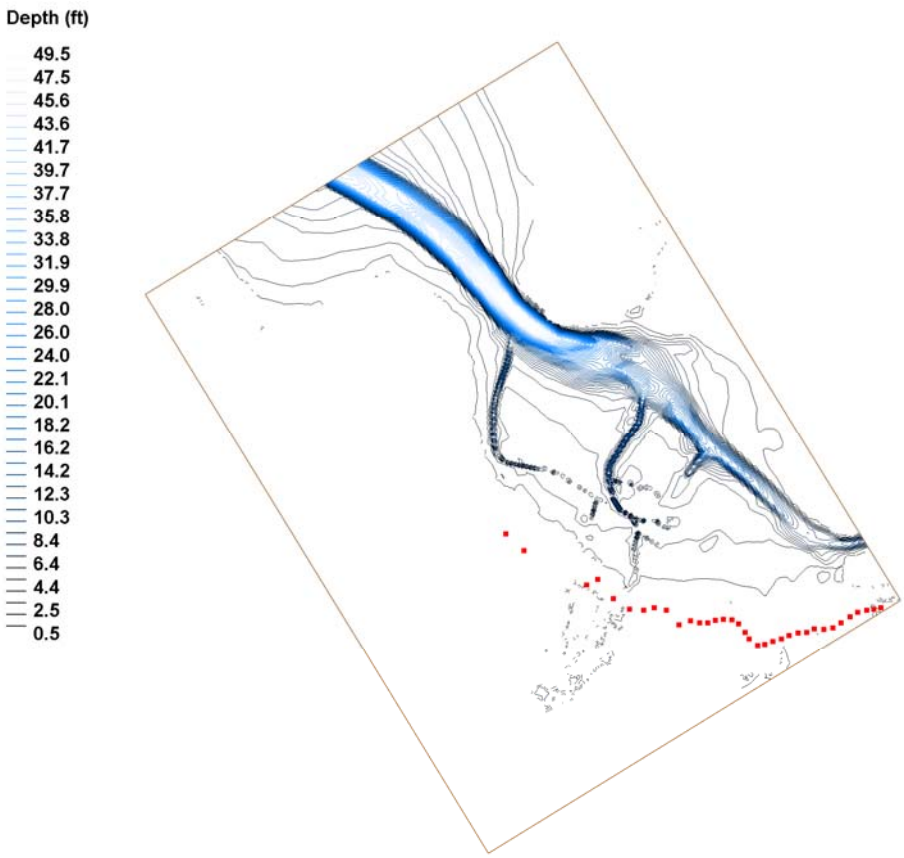

Figure 24. Save point locations, numbered 1 to 35 from west to east.

Figure 25. Save point wave height for 50 and 100 mph winds at 310 deg, 7 and 12 ft water level.

5 Year 50 Simulations

A total 1040 STWAVE full-plane model runs were made for the Year 50 simulations, representing 130 wind conditions and eight water levels. The simulations were made on both the coarse grid and nested, fine grid defined in Table 1. The eight water levels simulated were 7, 8, 9, 10, 11, 12, 13 and 14 ft NAVD 88. The higher water levels for the Year 50 simulations were chosen to represent relative sea level rise. The water levels were assumed to be constant throughout the bay. The wind speeds simulated were the same as for the Year 0 runs. The wind and water levels are summarized in Table 7 (all combinations of parameters were simulated). Simulated wave heights, peak periods, and mean directions at 35 south bay locations were extracted from the fine-grid results and passed to surge and sediment modeling efforts (same points as Year 0 runs, Table 6). The changes made in the bathymetry grid are discussed by Letter (2009). The Year 50 bathymetry is shown in Figure 26. The most significant changes are in the southeast portion of the lower bay (compare to Figure 2).

Table 7
Water Level and Wind Input for Year 50

Water Levels ft, NAVD 88	Wind Speed mph	Wind Direction deg, from North
7.0	10	250
8.0	20	260
9.0	30	270 (from West)
10.0	40	280
11.0	50	290
12.0	60	300
13.0	70	310
14.0	80	320
	90	330
	100	340
		350
		0 (from North)
		10

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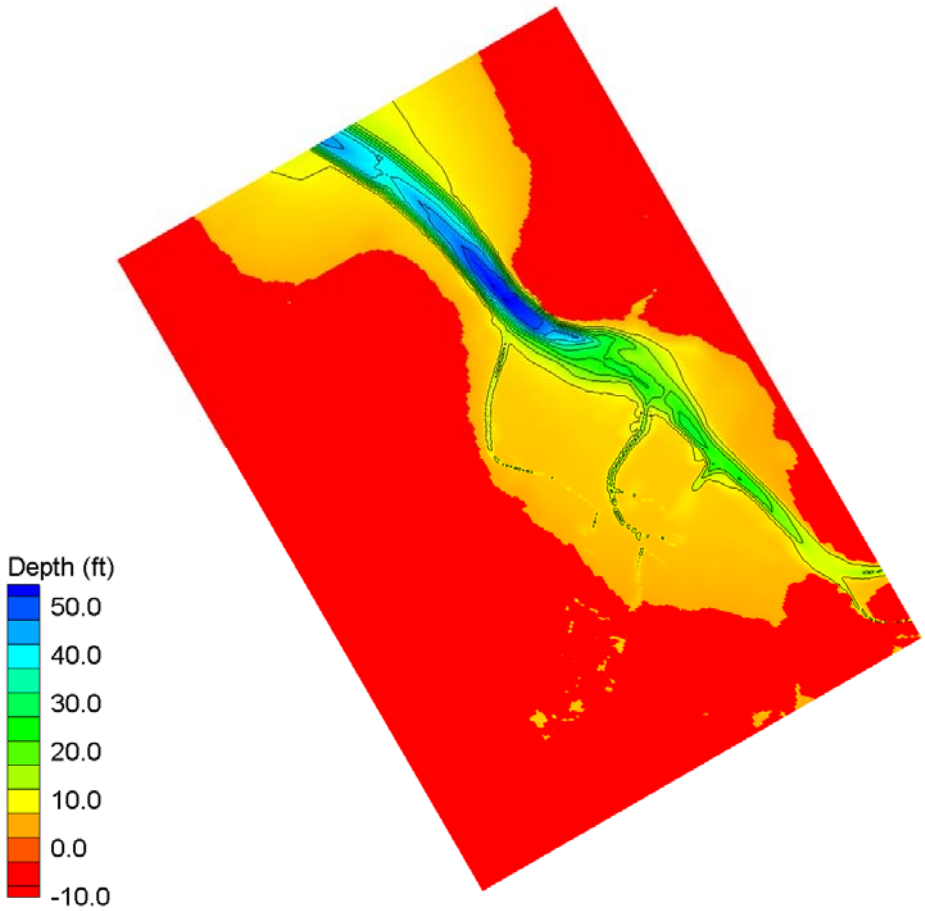

Figure 26. STWAVE Fine Grid coverage and bathymetry for Year 50.

Figures 27 and 28 show the wave height for a wind speed of 100 mph, wind direction of 310 deg, and water levels of 7 and 12 ft, respectively (compare with Figures 20 and 21). The differences between the Year 0 and Year 50 simulations are small, in general. In the southeast corner of the lower bay, wave heights are as much as 2 ft lower for the Year 50 bathymetry for the 100 mph wind and wind direction of 310 deg, 12-ft water level, in the limited area where the Year 50 bathymetry has a deeper channel. For the same simulations, the wave heights are up to 0.5-1.0 ft higher for the Year 50 simulation on some of the south bay tidal flats. Figure 29 shows the wave heights for Year 0 and 50 at the 35 save points (wind speed of 50 and 100 mph, wave level of 7 and 12 ft). Again, the differences in wave height are small, except at points 31 to 35 that are in the area of the most significant bathymetry differences.

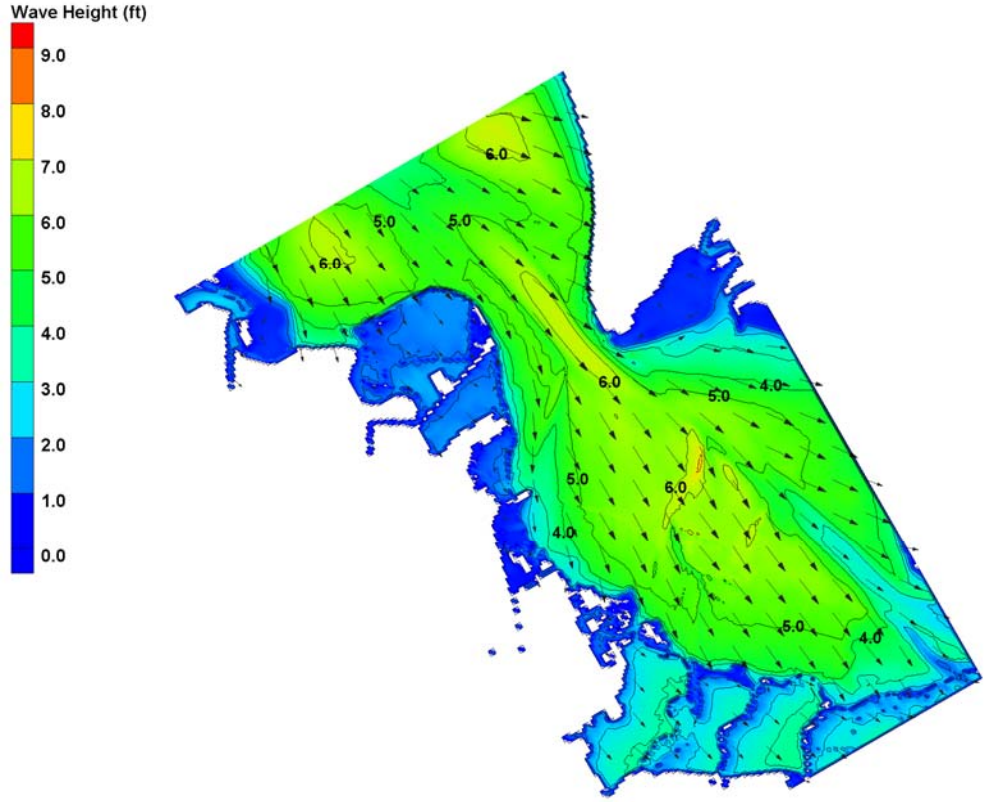

Figure 27. Wave heights in South Bay for wind speed of 100 mph from 310 deg and water level of 7 ft NAVD 88.

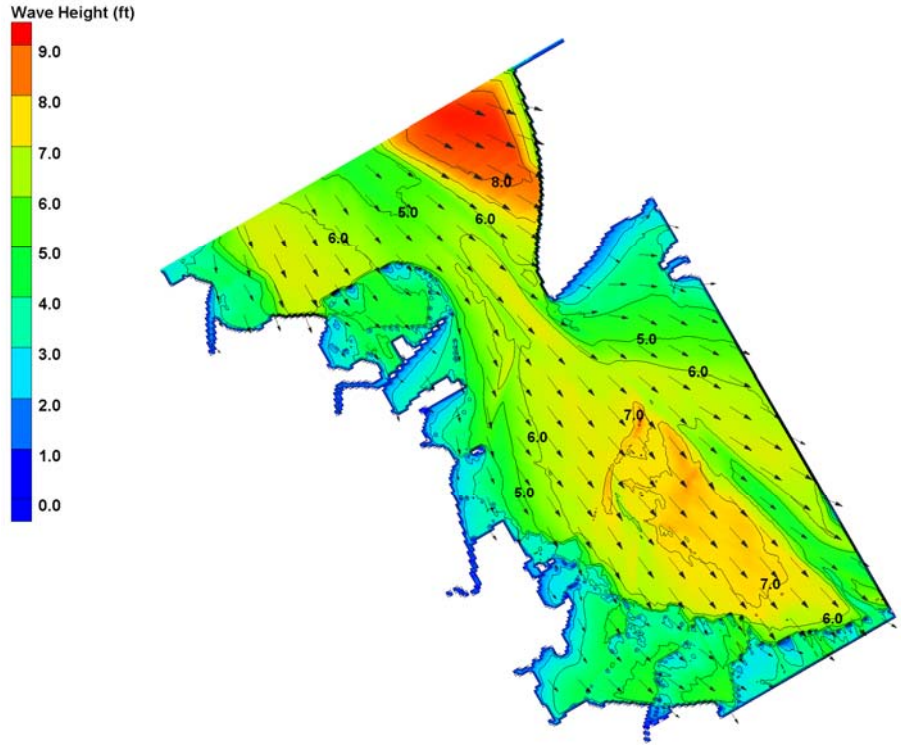

Figure 28. Wave heights in South Bay for wind speed of 100 mph from 310 deg and water level of 12 ft NAVD 88.

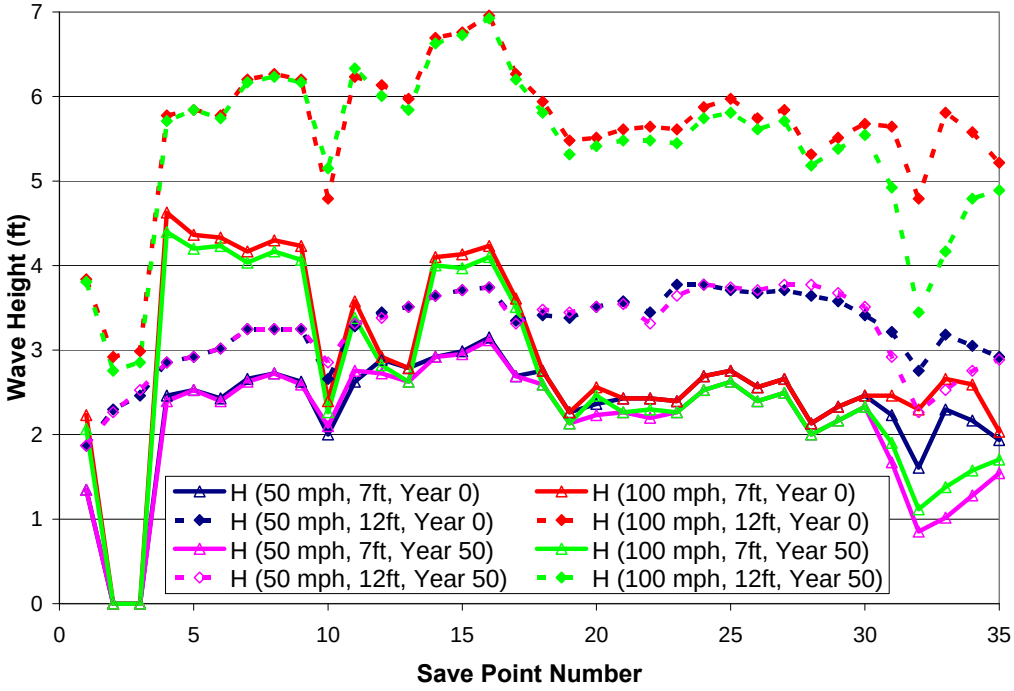

Figure 29. Save point wave height for 50 and 100 mph winds at 310 deg, 7 and 12 ft water level, Year 0 and 50 simulations.

6 Summary

To support the South San Francisco Shoreline Study, wave modeling was performed for San Francisco Bay. The full-plane STWAVE model was applied over the entire bay at a resolution of 656 ft, and a south bay grid of 164 ft resolution was nested into the full-bay grid. The model was validated with field measurements in south bay collected in December 2006. Sensitivity analysis was also performed to select that range of wind and water level conditions to run. Simulations were performed for the Year 0 bathymetry and Year 50 bathymetry. A total of 130 wind conditions were modeled (wind speeds of 10 to 100 mph and wind directions of 250 clockwise through 10 deg, relative to north) together with six water levels (7 to 12 ft NAVD 88, at 1-ft increments) for Year 0 and eight water levels (7 to 14 ft NAVD 88, at 1-ft increments) for Year 50.

Wave heights in the south bay are controlled by the wind speed and direction, the water level, and the bathymetry. The waves grow in the wind direction, and greater water depths allow more wave growth. The waves refract and shoal (increase in height) in the shallow areas. In very shallow depths, waves break and the heights are limited by the local water depth. Maximum wave heights are generated with wind blowing along the bay with the maximum water levels. For the 100 mph wind and 12 ft water level, wave heights in the south bay were approximately 7 ft with peak periods of 5.7 sec. For the 14 ft water level, wave heights increased to 7.5 ft.

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