US Army Corps
of Engineers®

TWAVE Users Guide with Example Application to Oahu, Hawaii

by Justin Goo, Zeki Demirbilek, Jane Smith, and Alejandro Sanchez

PURPOSE: This Coastal and Hydraulic Engineering Technical Note (CHETN) describes the application of the TWAVE (Typhoon Wave) modeling package for the simulation of coastal inundation in island regions due to tropical cyclones. The models within TWAVE, the Microsoft Excel® interface used to run TWAVE, the steps necessary for preparing the input files, running the models within TWAVE, and visualizing the TWAVE outputs are described in this CHETN for the south shore of Oahu, Hawaii.

DESCRIPTION OF TWAVE: TWAVE is a PC-based modeling package that provides nearshore estimates of wave runup and island flooding caused by tropical events (typhoons and hurricanes). Wind, surge, and storm waves during these events transform over reefs that protect island shorelines, and when water level and wave conditions reach a sufficient stage, coastal inundation occurs. TWAVE is a modularized modeling package (Figure 1). Details of the package are described by Sanchez et al. (2007 and 2009). After a brief description of TWAVE in this technical note, we demonstrate its application to Oahu, HI, and provide the steps necessary for preparing input files, running the models, and visualizing the outputs. As shown in the flowchart in Figure 1a, TWAVE consists of regional wind models, astronomical tides, deepwater wave models, deep to shallow-water transformation models and nearshore wave models. TWAVE is a modular system. The numerical models used in each module of TWAVE are shown in Figure 1b. A short description of modules and models follows.

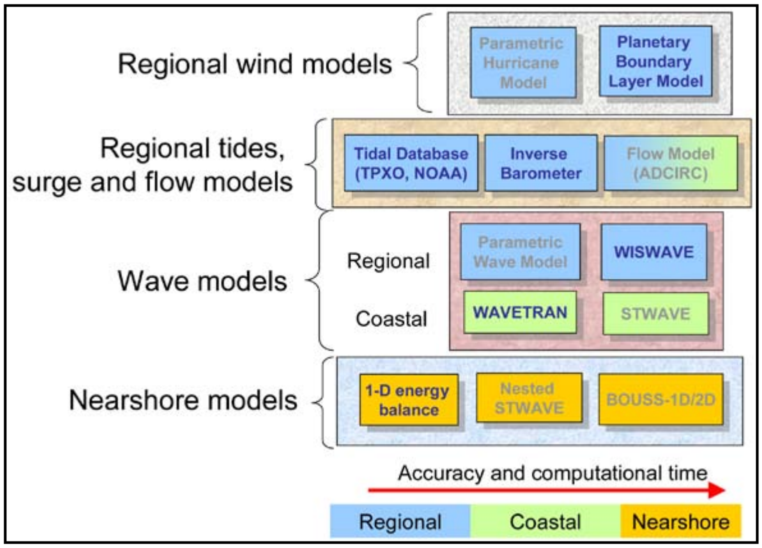


Figure 1a. Modules and numerical models used in the TWAVE modeling system.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUL 2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **TWAVE Users Guide with Example Application to Oahu, Hawaii**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Coastal and Hydraulics Engineering,U.S. Army Engineer Research and Development Center,Vicksburg,MS,39180**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**33**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

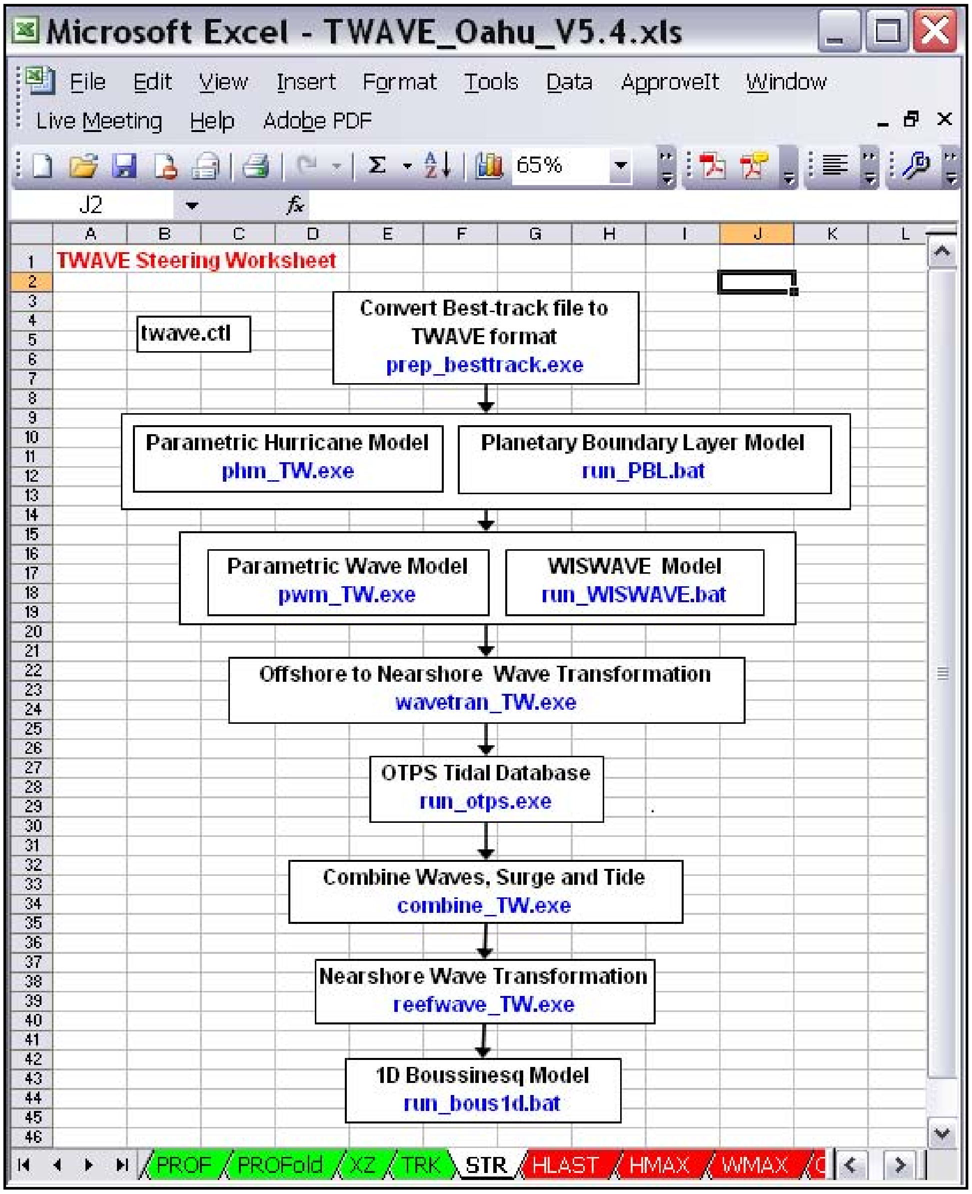


Figure 1b. TWAVE interface (the text in blue represents a hyperlink).

Regional Wind Models: Three methods are available in TWAVE for calculating the time history of wind and atmospheric pressure to drive the wave and storm surge models. The first method uses the Planetary Boundary Layer (PBL) model, while the other two methods use simpler, parametric Holland and Rankin Vortex models. The key features of each model are briefly discussed next.

In the PBL model, the effect of the marine boundary layer is related to surface stress due to the geostrophic flow over the ocean surface. The PBL as used in TWAVE uses a synoptic-scale pressure field to calculate the surface geostrophic flow, and corrects the flow for the curvature effects of isobars. Air-sea temperature differences, surface roughness, and moisture due to wave generation by wind stress have been included in the PBL governing equations to account for the stratification above the sea surface (Cardone et al. 1992; Thompson and Cardone 1996). The simulation time for the PBL model can vary from 5 to 20 minutes. Additionally, PBL requires a fair amount of pre- and post-processing.

When simulating hypothetical storms in planning applications, the parametric Holland and Rankin Vortex hurricane wind models offer a simpler and faster approach to estimate the winds and pressure fields generated by tropical storms. The run time for the parametric models is less than a minute, and no pre- or post-processing is required. The two parametric wind models used in TWAVE have been shown (Phadke et al. 2003) to provide reasonably accurate wind and pressure estimates.

Astronomical Tides: The astronomical tide affects water levels, which in turn influence storm surge and waves that cause flooding of island shorelines. In TWAVE, tidal elevations are computed from the Oregon State Tidal Prediction Software OTPS (*http://www.coas.oregonstate.edu/research/po/research/tide/otis.html*), which operates on a pre-calculated tidal database. Two global and one regional (Hawaiian Islands) tidal database are available. These tidal solutions were calculated using the Oregon State Inversion Software called OTIS (Egbert and Erofeeva 2002). The tidal elevations are calculated with a least-squares fit along track average TOPEX/Poseidon and Jason satellite altimeter data using the Laplace Tidal equations. Eight primary (M2, M4, S2, N2, K1, O1, P1, and Q1) and two minor long-period harmonic constituents (Mf and Mm) are provided as complex amplitudes on a grid with ¼-degree resolution for the global tide database (TPXO7.1) and 1/30 degree for the regional Hawaiian Islands database (Haw). Additional solutions for specific regions may be downloaded from *http://www.coas.oregonstate.edu/research/po/research/tide/region.html*, and placed in the folder called OTIS/DATA/.

The OTPS software has been implemented in TWAVE by adding programs that prepare OTPS input files and convert the output file (Astronomical Tide File) for TWAVE to use. These text files contain hourly tidal predictions at nearshore stations. Other tidal prediction models or databases may be incorporated in TWAVE to generate the astronomical tide files by converting the specific tide data to the TWAVE Astronomical Tide File format. In the future, the 2D circulation model ADCIRC may be incorporated for calculating water levels.

Deepwater Wave Models: Two models are included in TWAVE for calculating the deepwater waves. The first is a spectral wave model and the second is a simpler parametric model.

The spectral model is the second-generation wave model called WISWAVE (Wave Information Studies WAVE model). WISWAVE is implemented in TWAVE to simulate deepwater wave generation, propagation, and dissipation (Hubertz 1992; Resio and Perrie 1989). Wind fields are input at 1-hr intervals. The model output at selected grid points consists of wave parameters (wave height, peak and mean wave period, and mean wave direction) and percent total energy in each frequency band of the wave spectra. The selected grid points for saving model results can be entered in the WISWAVE Options File or in the Offshore Stations File. The Offshore Stations File is used if no stations are specified in the WISWAVE Options File. WISWAVE is setup in TWAVE to use the large PBL model grid, assuming deep water at all grid points. WISWAVE is the most computationally intensive model in the TWAVE package.

A simpler model is adequate for planning studies and hypothetical storms. The parametric hurricane wave model of Bretschneider (1972) is available in TWAVE. Although this parametric wave model is fast, it may not be appropriate for forecasting or hindcasting storms since it approximates many physical processes governing the generation and growth of deepwater waves. Because it does not account for wave propagation, this parametric model underestimates waves that are more than 3 R_{max} (radius of maximum winds of the hurricane) away from the storm center. This model should only be used for stations near the storm eye and for hypothetical events for which the input parameters are estimates.

Deep to Shallow-Water Wave Transformation: The deepwater wave estimates from offshore are transformed to the nearshore region using the Wave Information Study (WIS) Phase3 transformation model called WAVTRAN (Jensen 1983; Gravens et al. 1991). The WIS wave spectra are transformed based on the shoreline orientation with respect to the incident waves, the change in water depth, and sheltering effects. WAVTRAN assumes straight and parallel bathymetric contours and uses an input TMA spectral shape (Bouws et al. 1985). Sheltering is considered by removing the wave energy from sheltered grid points (wave directions that are sheltered by land). The directional spreading function is assumed as a cosine to the 4th power. In the future, the 2D wave model STWAVE may be incorporated for nearshore wave transformation.

Nearshore Wave Models: The term nearshore here refers to the coastal region from intermediate ($0.05 < h/L < 0.25$) to shallow water ($h/L < 0.05$), where h is water depth and L is wavelength, and in which waves interact with the sea bottom (shoal, refract, and break). The nearshore water depths are relative to mean sea level (MSL), and include the still water level (SWL) variation due to astronomical and barometric tide plus wind-driven surge as well as the wave setup (driven by momentum lost from the broken waves). Figure 2 shows a schematic of a fringing reef and typical wave setup distribution across the reef. Wave runup is the elevation of the highest wave excursion relative to the SWL (thus, it includes wave setup). Inundation refers to the horizontal distance landward from the shoreline to the farthest inland reach of the water level with the wave runup. Note that the runup and inundation are defined with respect to the SWL while the maximum water level is equal to the runup level relative to the MSL.

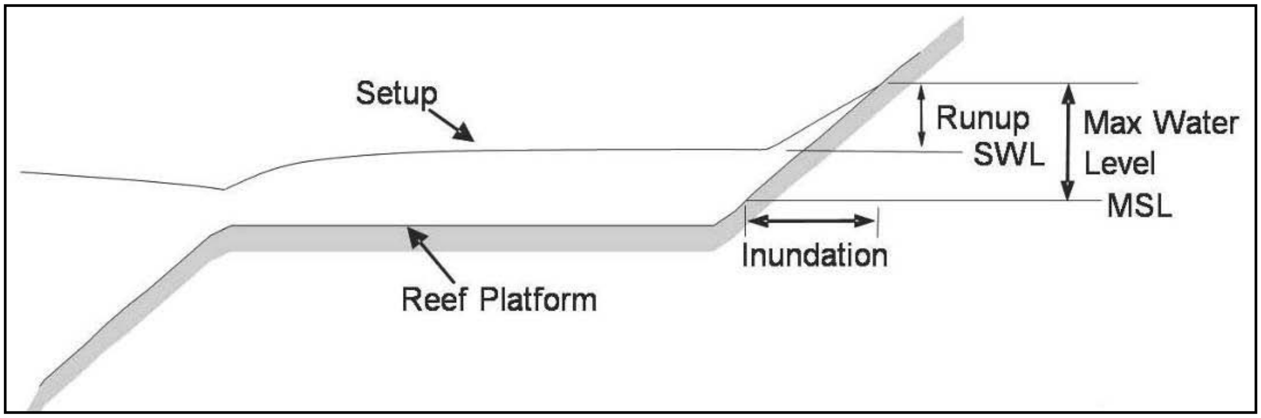


Figure 2. Reef platform and typical cross-shore distribution of water level on a nearshore profile.

Nearshore wave transformation is calculated at hourly intervals on predefined transects that are approximately normal to shore. There are four options for calculating wave heights and water levels over the reef. All methods use the same incident nearshore wave heights and water levels, but vary in their complexity and required input information. The first two methods are used when the bathymetric profile is not available. Method 1 calculates the wave height over the reef by assuming a stable depth-limited wave height on the reef and calculates reef top water levels using simple empirical formulas for wind and wave setup. The second method calculates the cross-shore wave height variation using a simple energy flux method taking into account the width of the reef platform, but also uses the same empirical formulas as Method 1 to calculate reef top water levels. The third method is the WAV1D model which solves the 1-D wave energy and momentum equations. The last method is the phase-resolving (wave by wave) nonlinear wave model BOUSS-1D, based on the Boussinesq equations (Demirbilek and Nwogu 2007, Demirbilek et al. 2009). The nearshore wave methods are calculated within the program reefwave_TW.exe at hourly intervals and BOUSS-1D is run using a separate batch file (run_bouss1d.bat). A brief description of the WAV1D and BOUSS-1D models is provided next.

WAV1D: WAV1D uses the conservation of wave energy flux and momentum to calculate wave transformation and water levels in the nearshore and surf zone. A phase-averaged approach is used to simulate the wave transformation of a representative wave height, period, and direction. Demirbilek et al. (2009) and Sanchez et al. (2009) provide a comprehensive description of the WAV1D model, with four example applications that illustrate the model's performance for wave shoaling, refraction, breaking, and bottom friction. Sánchez et al. (2007) compared WAV1D with two laboratory experiments of wave transformation and wave setup over fringing reef-type profiles. They reported average percent errors (average error divided by offshore wave height) of less than 25 percent for wave heights and setup over the reef platform for both waves with and without strong winds. WAV1D is efficient and robust.

Boussinesq Wave Model: BOUSS-1D (B1D) is a time-dependent, nonlinear, phase-resolving wave model appropriate for estimating nearshore waves, including wave transformation over reefs, wave setup and wave runup. B1D is the one-dimensional version of the Boussinesq model BOUSS-2D (Demirbilek et al. 2009; Demirbilek et al. 2005a and b). The model solves the fully-nonlinear Boussinesq equations using a finite-difference method and implements a one-equation turbulence closure model to simulate wave breaking in the surf zone.

B1D models nearshore wave transformation and can simulate wave shoaling, reflection, bottom friction, nonlinear wave-wave and wave-current interactions, wave breaking, wave setup, wave runup, and overtopping of structures. Within TWAVE, the incident waves in B1D are assumed to be normal to shore. Wind setup is included by adding a constant water level estimated by a parametric equation. B1D is the most accurate of the four methods to calculate nearshore wave transformation and runup. However, it is also the most computationally intensive because it is nonlinear and time-dependent. B1D has two input files, a bathymetry file (*.xy) and a script file (*.gbat) that contains the model input parameters, including wave and water level and the post processing commands.

Because users of TWAVE will most likely be concerned with the maximum coastal inundation rather than its time history, it is unnecessary to run B1D at hourly intervals for each transect as is done in the previous methods. B1D is run only for the time periods of estimated maximum coastal inundation obtained from the previous methods. A typical run time for an 800-m long transect in B1D is approximately 2 minutes.

Calculation of Wave Runup Statistics: Two methods are used to estimate wave runup and inundation statistics in TWAVE. The first method uses empirical formulas embedded within the WAV1D model. The second method applies a zero-crossing analysis of B1D runup time series.

Results in Demirbilek et al. (2009) and Sánchez et al. (2009) indicate that $R_{2\%}$ and R_{max} calculated with empirical runup equations of Mase (1989) provide reasonable agreement with laboratory measurements for fringing reefs. Although these empirical methods are approximate, they are robust means of estimating the maximum wave runup. The time of maximum coastal runup may not necessarily occur during the time of the highest coastal waves because of combined influence of storm surge, tides, wave period, and wave direction. Therefore, the timing may vary for different locations around an island.

The variable *ir2per* defines which empirical equations are used for calculating $R_{2\%}$. The options are:

ir2per = 0 (Mase 1989)
= 1 (HQUSACE 2006)
= 2 (Hedges and Mase 2004).

Similarly, *irmax* defines the equation used for calculating the R_{max} and options include:

irmax = 0 (Mase 1989)
= 1 (Seelig 1983).

Additional guidance on selection of these input variables and options is available in Chapter 5 of Sánchez et al. (2009).

The 2-percent exceedance level runup ($R_{2\%}$) and maximum runup (R_{max}) for each transect can also be calculated from B1D runup time series. This analysis consists of an upward zero-crossing analysis to identify individual runup events. Runup values are sorted in ascending order and percentiles are estimated. R_{max} is calculated directly from the time series, and $R_{2\%}$ is obtained from the 98th percentile. The inundation statistics are calculated by cross-referencing the runup elevation with the transect profile.

TWAVE INTERFACE: The TWAVE modeling system is implemented in a Microsoft Excel® worksheet format, which serves as the user interface to visualize the system's input and output files (Table A1 provides a list of the input/output files for each TWAVE component). The Excel file contains a number of worksheets for different functions. The worksheets, as shown in Figure 3, are color-coded for easy navigation. The first worksheet of the TWAVE package contains the names and descriptions of worksheets.

TWAVE users should become familiar with the Table of Contents and each worksheet before attempting to use it in practical applications. The worksheets are arranged sequentially in the order they are utilized and color-coded based on the worksheet functions. Yellow tabs correspond to worksheets with reference information such as the table of contents and maps. Green tabs represent worksheets used to visualize input. Red tabs are used for worksheets that contain output results in tables and plots. The black tab named *STR* is the steering worksheet that contains the hyperlinks to run executable models of TWAVE.

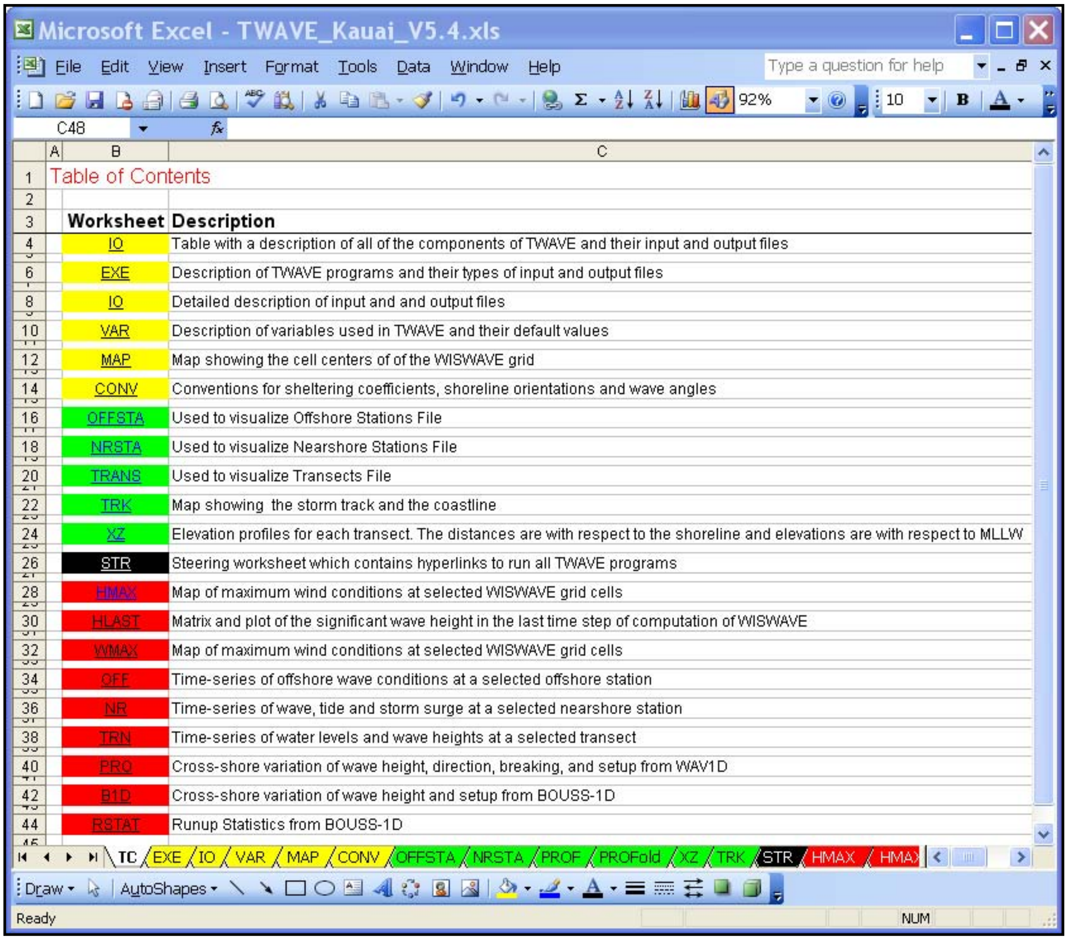


Table of Contents

Worksheet	Description
IO	Table with a description of all of the components of TWAVE and their input and output files
EXE	Description of TWAVE programs and their types of input and output files
IO	Detailed description of input and and output files
VAR	Description of variables used in TWAVE and their default values
MAP	Map showing the cell centers of of the WISWAVE grid
CONV	Conventions for sheltering coefficients, shoreline orientations and wave angles
OFFSTA	Used to visualize Offshore Stations File
NRSTA	Used to visualize Nearshore Stations File
TRANS	Used to visualize Transects File
TRK	Map showing the storm track and the coastline
XZ	Elevation profiles for each transect. The distances are with respect to the shoreline and elevations are with respect to MLLW
STR	Steering worksheet which contains hyperlinks to run all TWAVE programs
HMAX	Map of maximum wind conditions at selected WISWAVE grid cells
HLAST	Matrix and plot of the significant wave height in the last time step of computation of WISWAVE
WMAX	Map of maximum wind conditions at selected WISWAVE grid cells
OFF	Time-series of offshore wave conditions at a selected offshore station
NR	Time-series of wave, tide and storm surge at a selected nearshore station
TRN	Time-series of water levels and wave heights at a selected transect
PRO	Cross-shore variation of wave height, direction, breaking, and setup from WAV1D
B1D	Cross-shore variation of wave height and setup from BOUSS-1D
RSTAT	Runup Statistics from BOUSS-1D

Figure 3. Screen snap shot of the first worksheet in TWAVE.

EXAMPLE APPLICATION: SOUTH SHORE OF OAHU: This section of the CHETN describes the steps for creating the I/O files required for running the numerical models within TWAVE. This example is a TWAVE simulation for estimating wave runup and inundation from a hypothetical hurricane passing directly through downtown Honolulu, Hawaii. Honolulu (Figure 4) is located on the island of Oahu's southern shoreline, and is both the capital and most populated city in the State of Hawaii.

The hypothetical hurricane track in Figure 5 is constructed based on a scenario developed by the National Weather Service (NWS). The Island of Oahu has not been hit directly by a land falling hurricane. Consequently, a hypothetical hurricane track is used in this example application to develop the worst case scenario for hurricane runup and inundation impact on Oahu's south shore, in particular the downtown Honolulu and Waikiki areas. The NWS hypothetical data includes the storms latitude, longitude, central pressure, maximum sustained winds, and radius of maximum winds in three-hour intervals.

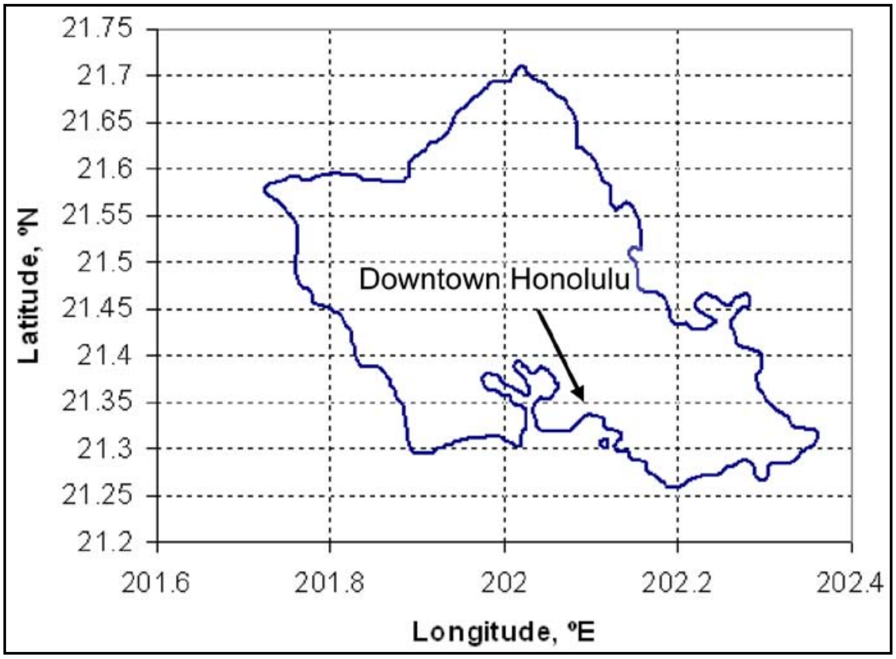


Figure 4. Location of Downtown Honolulu, HI.

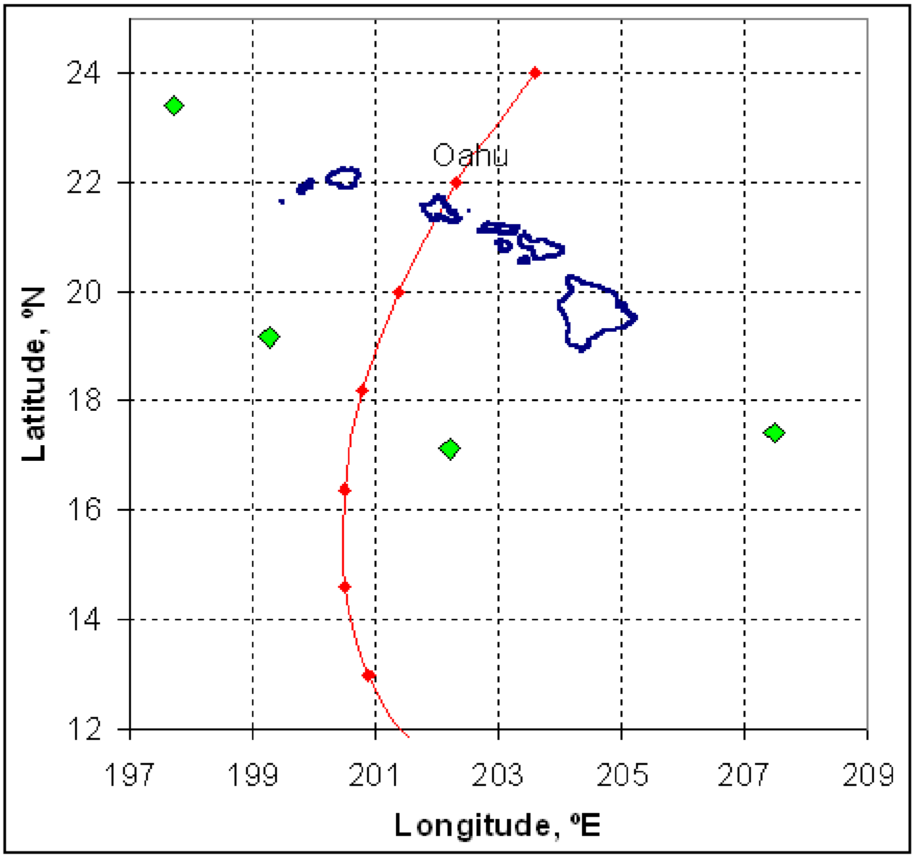
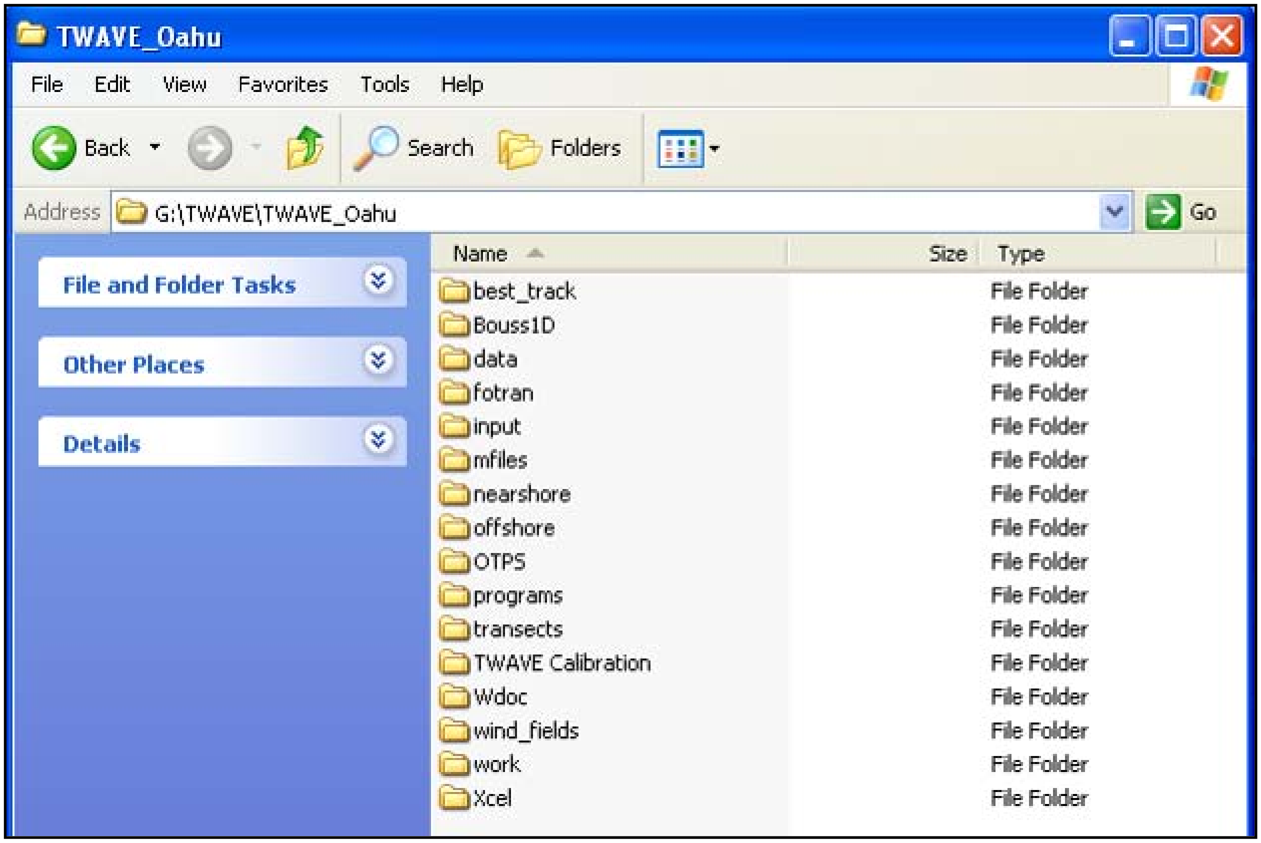


Figure 5. Storm Track for hypothetical Downtown Honolulu hurricane.

These parameters are the forcing conditions for TWAVE to calculate wind, wave, and storm surge associated with a hypothetical hurricane. The 1D transects for runup and inundation calculations are chosen at locations of interest at the study site. In this example, an important section of Oahu's south shore is downtown Honolulu through Waikiki. Multiple transects (Figure 6) are chosen along this stretch of coast to capture the spatial variability and the most critical areas impacted by the selected storm wave runup and inundation.

Figure 6. Offshore stations and nearshore bathymetry transects.

Step 1. TWAVE Data: For a TWAVE simulation, the folder structure shown in Figure 7 is required for the Excel sheet to locate the I/O files. The TWAVE files used in this example include all necessary files to run TWAVE in other applications. These files can be downloaded from *http://chl.erdc.usace.army.mil/swims* and copied to the user's desired directory.



Name	Size	Type
best_track		File Folder
Bouss1D		File Folder
data		File Folder
fotran		File Folder
input		File Folder
mfiles		File Folder
nearshore		File Folder
offshore		File Folder
OTPS		File Folder
programs		File Folder
transects		File Folder
TWAVE Calibration		File Folder
Wdoc		File Folder
wind_fields		File Folder
work		File Folder
Xcel		File Folder

Figure 7. TWAVE Folder Structure.

Step 2. TWAVE Control File: TWAVE requires a Control File (twave.ctl) that contains the input variables, file names, and empirical constants for the various numerical models embedded within TWAVE. This file is located in the input subdirectory and can be edited either with Excel by clicking on its hyperlink in the *STR* worksheet (Figure 3) or by opening the file directly within the input subdirectory with a text editing program (e.g., Notepad or Wordpad). The control file used in this example is shown below. A detailed description of the control file parameters are provided by Sánchez et al. (2009).

In the track file named track_200802.txt, the 1st four digits (2008) in the file name represent the year of the storm and the 5th and 6th digits (02) are the storm identifier number. In this case, the number 02 is the second hypothetical scenario out of the 12 tracks provided by the NWS. The year 2008 was an arbitrary number chosen to represent the storm year because the storm is a hypothetical one and not a historical storm track. The suffix “_oahu” at the end of the input file names refers to location of the study. The user may add a suffix for their project location. All input parameters used for Oahu are the default values. The south shore of Oahu is comprised of coral reefs. The bottom friction for coral reefs is a high value of Nikuradse roughness. The default value of 0.16 was chosen for the Nikuradse roughness in the WAV1D model.

```
TWAVE Control File
Version 5.0

START_CTL

ftrack  track_200802.txt    !Storm Track File
foffsta offsta_oahu.inp     !Offshore Station Information File
fnrsta  nrsta_oahu.inp      !Nearshore Station Information File
ftrans  trans_oahu.inp      !Profile Information File
fwisopt options_oahu.dat    !WISWAVE options file
region hawaii    !specifies which region to run
fwind wind.dat   !Wind File
windmodel 0      !0-Holland, 3-Rankin, default 0
tidemodel haw    !OTIS tidal solution
phm4adcirc 6     !ADCIRC wind input file(s), formats 6 or 12
pa 1010.0        !Atmospheric Pressure, mbar
geostrwind 8.0   !Geostrophic wind speed, m/sec
Bconst 1.3       !Bconst>0 - constant, Bconst<0 - calculate
Rmaxconst -99.0
Ka 0.87          !Conversion factor from 1-min to 10-min wind speeds
centrpres  0     !0-Koba et al. 1990, 1-Atkinson and Holliday 1977
dx 2.5           !Resolution for 1D wave energy balance model
iwave_fric 1     !Toggle for bottom friction, 0-No, 1-Yes
ksr 0.16         !Nikuradse roughness factor
iwave_diss 1     !Toggle for wave dissipation
xRankine 0.5     !Shape factor for Rankine Wind Models
kappa 0.15       !Empirical wave decay coefficient for wave breaking
B 1.0            !Wave breaking intensity factor for wave breaking

END_CTL
```

Step 3. Storm Track File: TWAVE requires a Storm Track File (track_200802.txt). It is used by multiple models within TWAVE and contains the storm positions, wind speeds (10-m elevation, 30-min average), central pressures, and radius of maximum wind speeds at 6-hour intervals. The file is located within the work subdirectory and should be opened and edited with a text editing program. The file should have the naming convention of track_ssssss.txt, where ssssss is a storm identifier number described in the previous section. The Storm Track File used in this example is shown below.

```
yyyymmddhh  LatN  LonE  W_knt Pres_mb  Rmax_km
2008010218  11.2  202.5  140     920   14.816
2008010300  11.9  201.5  150     910   14.816
2008010306  13.0  200.9  150     910   14.816
2008010312  14.6  200.5  140     920   14.816
2008010318  16.4  200.5  135     925   18.520
2008010400  18.2  200.8  135     925   22.224
2008010406  20.0  201.4  130     930   24.076
2008010412  22.0  202.3  125     935   27.780
2008010418  24.0  203.6  105     955   33.336
```

The first column in track_200802.inp contains the date and time in UTC (Coordinated Universal Time) in the format yyyymmddhh where yyyy is the year, mm is the month, dd is the day, and hh is the hour. The latitude is in degrees N (North) and longitude in degrees E (East) and are specified in the 2nd and 3rd columns, respectively. The last three columns are the maximum sustained wind speed in knots, central pressure in mbar, and radius of maximum wind speed in km, respectively. In the event that the central pressure or radius of maximum winds speed are unknown, a negative value should be placed in the respective columns and TWAVE will estimate values of these parameters.

The file may be viewed in Excel using the TRK worksheet. This is done by right-clicking on a cell with external data and clicking on the menu Data | Refresh Data or clicking on the Refresh button!. Refreshing data will also automatically update the associated plots. This technique may be used for any other worksheets that involve visualization of external data. The figure that is displayed in Excel is shown in Figure 5. The eye of the hypothetical hurricane makes land fall at approximately at 10:00 UTC on 4 January 2008.

Step 4. Offshore Stations File: The Offshore Stations File (offsta_oahu.inp) provides TWAVE with the latitude, longitude, and water depth of the user-specified Offshore Stations where deepwater wave estimates from the deepwater wave models are saved. This file is located in the input subdirectory and should be opened and edited with a text editing program. The Offshore Stations File for this example is shown below.

```
StaOff LatOff  LonOff   DepOff
G32    21.250  202.083  -999
G33    21.250  202.167  -999
G99    21.250  202.120  -999
```

The variables LatOff represents the latitude in degrees North, LonOff the longitude in degrees East, and DepOff the water depth at the offshore station, respectively. The value -999 for water depth is used to represent deepwater locations. In this example, the TWAVE Excel sheet has predetermined offshore stations for Kauai and Oahu (Figure 6). G32 is located too far from the selected transects and G33 is located too far to the east of the transect sites because waves from the hurricane will be approaching from the southwest. Station G99 is between G32 and G33 and slightly to the west of the nearshore transects, so that the offshore to nearshore wave transformation will be captured. Station G99 is used for driving the nearshore transects. If predetermined offshore stations are not available, the user will need to choose locations sufficiently offshore to be in deepwater and that are appropriate relative to the nearshore transects.

The offshore stations may be visualized in Excel with the Offsta worksheet. If the user is in an area other than Hawaii, they should obtain the latitude and longitude of the shoreline in their area of interest and input those points into the Map worksheet. They then need to manually update the charts in the *Map* and *Offsta* worksheets by updating the source data for each chart. This allows the user to visualize their specific site of interest.

Google Earth may also be used to visualize the offshore transect locations. Within Google Earth, the user should navigate on the map so that it encompasses their entire site area. To create a marker for an offshore station on the Google Earth map, the user should use the Placemark function and input the station name and the latitude and longitude of the offshore station in degrees North and degrees West. This process allows the user to observe the offshore station positions relative to their project site.

Step 5. Bathymetry Transects: TWAVE requires 1D nearshore bathymetry (bed elevation) transects for inundation and runup calculations. The bathymetry transect files are located in the *Bouss1D* subdirectory and should be opened and edited with a text editing program. Each transect file should be named Pppp.xy, where ppp represents a three digit transect identifier. The file has two data columns, the distances (*x*) are in the first column and elevations (*y*) are specified in the second column. Distances are measured from the MSL-shoreline and elevations are with respect to MSL (bathymetry data referenced to another vertical data, e.g., NAVD88, can be used by applying a tidal offset in the input file for B1D). Water points have negative elevations, and land points have positive elevations in B1D. Points offshore will have negative *x*-values relative to the distance offshore, while points onshore have positive values. It is not necessary for the points to be spaced at regular intervals because the models interpolate the bathymetry from the points specified by the user.

There are a variety of programs that may be used to create bathymetric transects such as SMS or Surfer. In this example Surfer version 8 was used to create the bathymetry transects. In general, when creating a bathymetry transect, the user should first determine the specific locations in which wave runup and inundation calculations will be most important. In this example, transects were spread through the Waikiki and Ala Moana areas of Honolulu to encompass areas of either high tourist traffic or economic importance.

Transects should be aligned perpendicular to the bathymetric contours and should run through the site of interest. If B1D is being run, the offshore end of the transect should not be in deep water (depth should be less than $gT^2/(4\pi)$, where g is acceleration of gravity and T is the peak wave period), should not end on a section with a steep slope, and should have a constant depth wavemaker section (see Figure 8 for an example) of a few wavelengths added past the most seaward data point to improve the B1D stability. The onshore end of the transect should extend, at a minimum, as far onshore as the user thinks inundation will extend. The user should also be aware of any data points below mean sea level that are landward of the shoreline. These data points may cause instabilities within B1D and should be deleted from the bathymetry transects if they are located outside the predicted inundation zone. If LIDAR data or other high resolution datasets are used, it is recommended that the bathymetry be smoothed (e.g., running a mean filter) to improve model stability.

Transect data should be entered into the *XZ* worksheet in Excel. The user may also view the nearshore transects with the offshore stations in Google Earth by adding placemarks for the furthest onshore and offshore data points of each nearshore transect. An aerial view (Figure 6) of the nearshore bathymetry transects can be created through Google Earth and a cross-section view (Figure 8) of the nearshore bathymetry transects is automatically created within the *XZ* worksheet.

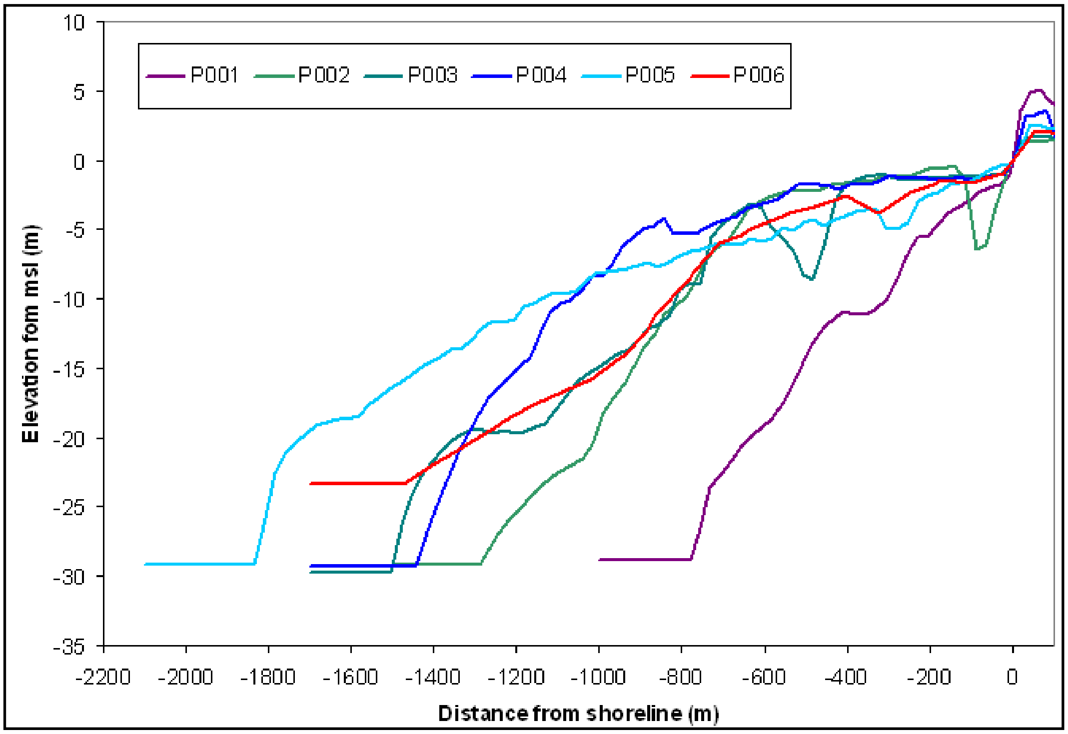


Figure 8. Cross section of the nearshore bathymetry transects.

Step 6. Transects File: The Transects File (trans_oahu.inp) required by TWAVE contains information for the individual transects chosen for the site and is used by B1D and WAV1D. This file should be located within the input subdirectory and should be opened and edited with a text editing program. The Transects File used in this example is shown below.

```
Profile   AngSho   NrSta   WthRf   DepRf   Slope   Diff   Rough   Berm
P001       30        I01   0       0       0       1      1       1
P002       22        I02   0       0       0       1      1       1
P003       40        I03   0       0       0       1      1       1
P004       20        I04   0       0       0       1      1       1
P005       64        I05   0       0       0       1      1       1
P006       69        I06   0       0       0       1      1       1
```

The nearshore models require specification of the shoreline orientation *AngSh*o, the water depth over the reef *DepRf*, the width of the reef *WthRf*, a diffraction coefficient *Diff*, a roughness factor *Rough* for runup calculations, and *Berm*, a factor which accounts for berm effects. The parameters *WthRf*, *Diff*, *Rough*, and *Berm* are used in situations where nearshore bathymetry data is unavailable and the properties of the reef must be estimated. In this event, refer to the TWAVE technical report to choose the appropriate values for each variable. *NrSta* is the nearshore station used to drive hydrodynamics on the profile line. The data in this file should be entered manually into Excel in the *Trans* worksheet for visualization purposes.

Figure 9 offers a visual representation of *AngSho*. It is important to note that *AngSho* is measured clockwise from North. 180°

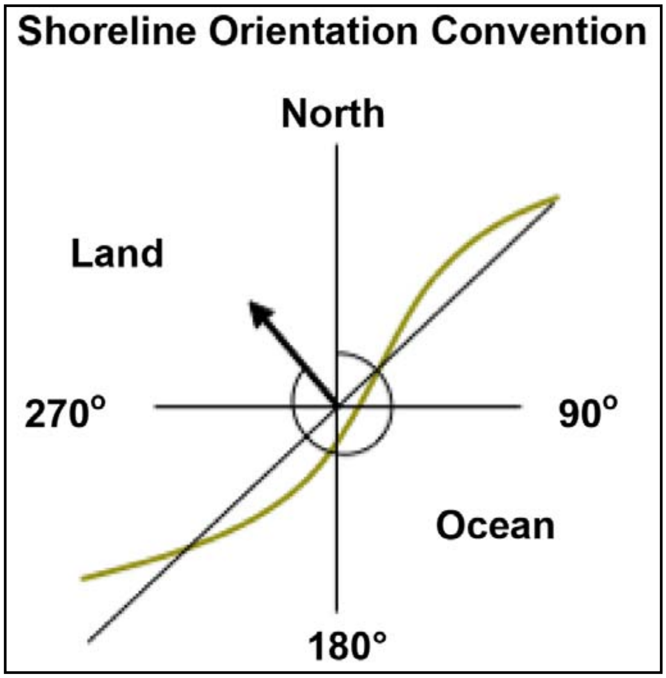


Figure 9. Visualization of AngSho (~315 degrees), AngBath (~315 degrees) parameters.

Google Earth can be used to determine *AngSho* with the Ruler function. The user should first zoom into the shoreline in the area where the nearshore transect intersects the shoreline. Next the user should select the Ruler command, which will calculate the angle between any two points chosen on the map, to determine the angle of the shoreline.

The user should select the first point of the line, by entering a point along the shoreline of interest by left-clicking with the cursor. Next the user should move the cursor in the landward direction (i.e., for a south facing shore, move the cursor northward). This will produce a line on the screen that is extending in the direction from the cursor that is originating from the point selected on the shoreline. The line does not have to be of a particular length, but should be extended long enough to capture the entire reach of the shoreline. The line should then be rotated in the clockwise direction until the line intersects with another point along the shoreline of interest. The user should then select this as the endpoint of the line and now a line should appear on the map that traces the shoreline of interest. This should produce an angle measurement in the Ruler dialogue box that represents the angle of the shoreline. The user should subtract 90 from the angle provided in the dialogue box to determine *AngSho* since *AngSho* is a measure of the line that is perpendicular to the shoreline in the upslope direction and not a direct measure of the angle of the shoreline. The user should refer to Figure 9 for visualization of this concept.

Step 7. Nearshore Stations File: The Nearshore Stations File (nrsta_oahu.inp) in TWAVE provides information on the user specified nearshore stations where hourly estimates of storm surge, tides, wind, wave heights, wave periods and wave directions (wave conditions optional) are output. The file for this example is located in the input subdirectory and should be opened and edited with a text editing program. The Nearshore Stations File for this example is shown below.

```
NrSta  LatNr     LonNr    DepNr OffSta Opt AngBath  KSH  KSH1  KSH2
I01   21.2838   202.1366   29    G99    1     13     0    0     0
I02   21.2797   202.1426   29    G99    1     34     0    0     0
I03   21.2676   202.1576   30    G99    1     21     0    0     0
I04   21.2665   202.1611   30    G99    1     38     0    0     0
I05   21.2634   202.1614   30    G99    1     56     0    0     0
I06   21.2660   202.1605   24    G99    1     55     0    0     0
```

The alphanumeric variable *NrSta* represents the names of the nearshore stations. The physical locations of the nearshore stations are described by the water depth (*DepNr*), the latitude in degrees North (*LatNr*), and the longitude in degrees East (*LonNr*). In this example the depth, latitude, and longitude correspond to the most seaward data point on each nearshore transect. *OffSta* is the name of the offshore station (WISWAVE output grid point) and *Opt* is used to define the input wave parameters for WAVETRAN.

AngBath is also displayed in Figure 9 and represents the angle of the upslope direction of the offshore bathymetry profile measured clockwise from North (if the offshore bathymetry contours are shore parallel, *AngSho* and *AngBath* are equal)**.** Since the 1D transects are chosen to be perpendicular to the offshore bathymetry, the angle of the line that connects the furthest offshore and onshore points of a profile represents *AngBath*.

AngBath can be determined through Google Earth using the ruler function. Placemarks should be added first to the furthest offshore and onshore points of each bathymetry transect on the Google Earth map. The user should use the ruler function next and select the furthest offshore point of the bathymetry transect as the first point of the line. The line should then be extended landward and rotated clockwise until it connects to the furthest onshore point of the bathymetry transect. This point should be selected as the endpoint of the line and the angle that is displayed in the Ruler dialogue box represents the value for *AngBath*.

KSH defines wave directions that are sheltered by islands or protruding land masses. *KSH*, *KSH1*, and *KSH2* were set to zero since there are no areas of wave sheltering. Refer to the TWAVE technical report for further guidance when choosing *Opt* and *KSH* parameters for a different site. The data should be entered manually into Excel in the *NRSTA* worksheet for visualization purposes.

Step 8. WISWAVE Options File: TWAVE requires the WISWAVE Options File (options_wiswave.dat) to provide the input settings for the WISWAVE model. The file includes WISWAVE setup information, including the frequency bins, number of directional bins, and information about grid cells that are land or water. The file should be located in the input subdirectory and should be opened and edited with a text editing program. The default file name is options_wiswave.dat and may be changed using the TWAVE variable *fwisopt*. For additional information about this file, the user is referred to the WISWAVE manual (Hubertz 1992).

Step 9. Set File Path in Excel: Before running TWAVE, the current path in Excel must be set to the TWAVE work directory. First select the Open dialog in Excel by clicking on File | Open or use the Open button. To set the current path go to the directory /TWAVE_Oahu/work and then click on Cancel once the correct path is in the dialog box. If this procedure is repeated, the default path in the Open dialog box will be set to /TWAVE_Oahu/work.

Step 10. Run TWAVE: To run TWAVE, select the *STR* worksheet from the Excel sheet (Figure 1) that contains the hyperlinks to run specific TWAVE applications, which include all the pre- and post-processing routines, numerical models, and batch files (**.bat*) required for each model.

To execute a particular program in TWAVE, click on the corresponding box in the Steering worksheet STR (Figure 1b). This will bring up a DOS window showing the screen output for that program and indicating whether or not the program ran successfully. When the program is finished, review the screen information, check for error messages, and press any key to close the window. The programs are run in a sequential order starting from the top. After running a specific model, the results can be viewed in Excel by refreshing the spreadsheet data (following the same procedure outlined in Step 3).

The first step in running TWAVE for this example is running one of the regional wind models to generate the winds and pressures created by the hypothetical hurricane (Figure 1). The first step in Figure 1b is to run the Convert Best-track file to TWAVE format tab. However, this step is only used if the storm track being used comes from the Joint Typhoon Warning Center (JWTC), Naval Pacific Meteorology database and thus may be skipped in this example.

In this example, the Parametric Hurricane model (phm_TW.exe) was chosen. The model is run by clicking on the Parametric Hurricane Model hyperlink in the STR worksheet. This program creates a Nearshore Wind and Storm Surge file for each nearshore station that contains the hourly nearshore wind speed and direction, storm atmospheric pressure, and storm surge (based on the atmospheric pressure). The output files (i.e., I01_200802.uvs) are located in the nearshore subdirectory. The results may be viewed in the Excel sheet UVS and Figure 11 displays the wind speed and wind direction at nearshore station I01 (Sta I01). The wind speed increases as the storm approaches Sta I01, peaking as the storm approaches landfall. The wind speed then decreases as the storm passes and moves away from Sta I01. The wind direction exhibits a sudden change in direction as the storm passes over Sta I01.

The next step in the flow chart (Figure 1) is choosing one of the deepwater wave models to calculate the offshore waves generated by the hypothetical hurricane. In this example the WISWAVE model package (run_WISWAVE.bat) was chosen and is run by clicking on the WISWAVE Model hyperlink in the *STR* worksheet.

This program creates an Offshore Station Time Series file that contains the wave data generated by the hypothetical hurricane at each offshore point. The output files (i.e., G99_200802.off) are located in the offshore subdirectory and the data can be viewed in the Excel sheet under the *Off* worksheet.

Figure 12 shows the zero-moment wave height (H_{mo}), peak period (T_p), and mean period (T_m), and Figure 13 shows the wind speed estimated at G99. The significant wave height at G99 increases steadily over time peaking as the storm approaches landfall, while the wind speed at offshore station G99 is similar to nearshore station I01.

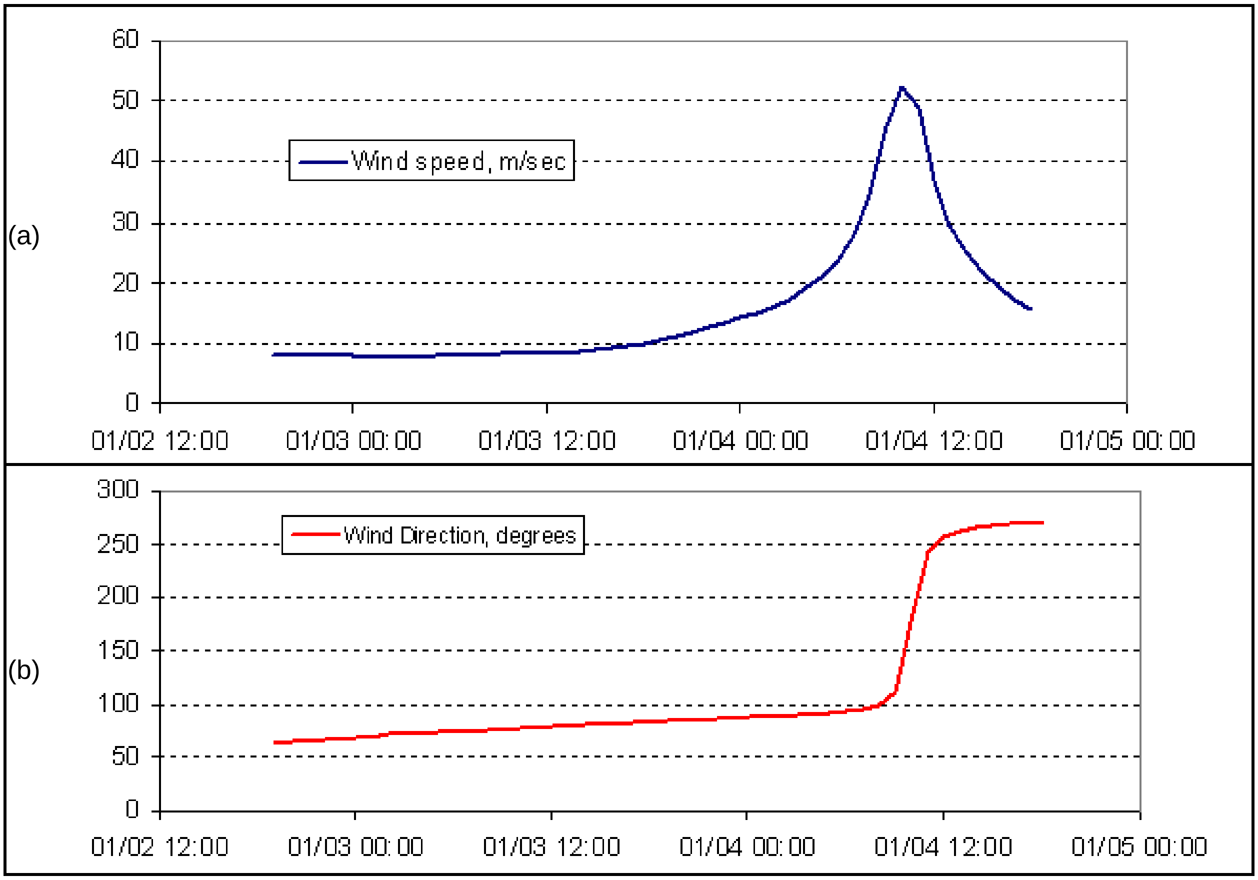


Figure 11. (a) Wind speed and (b) direction at I01 from Parametric Hurricane Model.

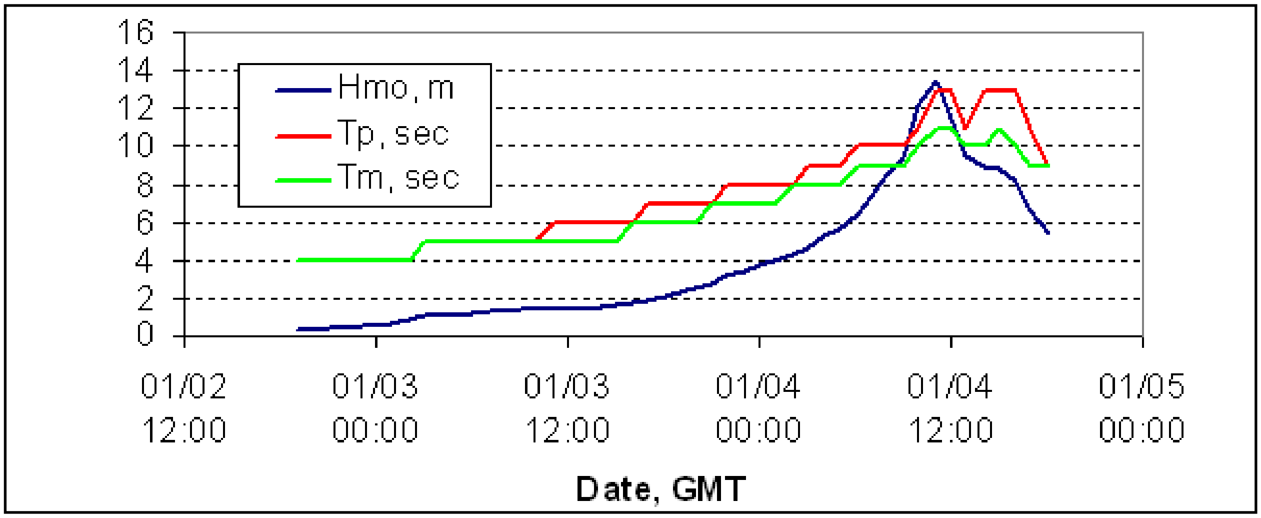


Figure 12. Significant wave height, peak period, and mean period at G99 from WISWAVE.

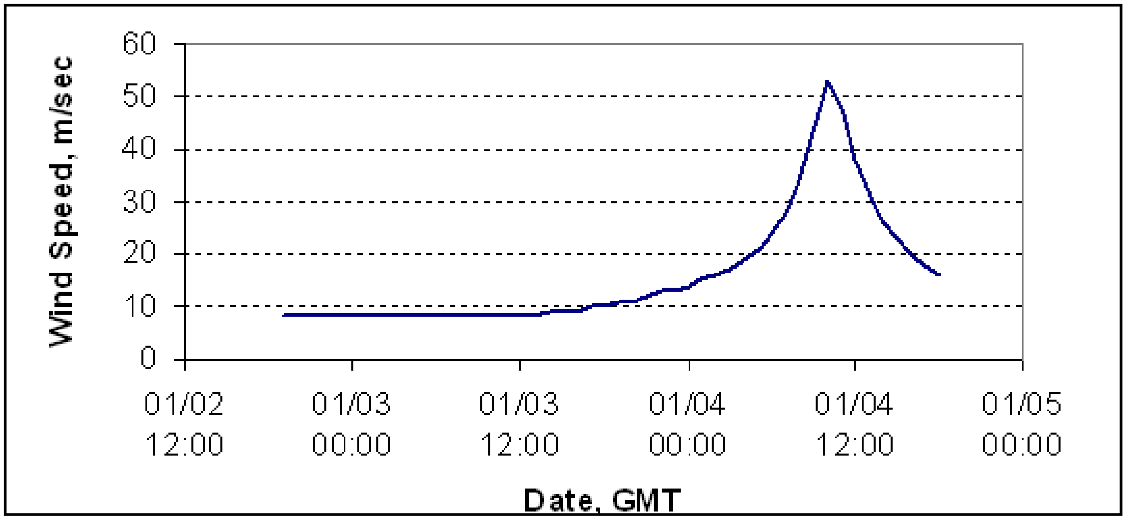


Figure 13. Wind speed at G99 from WISWAVE.

WISWAVE also creates Maximum Significant Wave Height (Hs_max.dat) and Maximum Wind (Wmax.dat) files that are located in the offshore and wind_fields subdirectories, respectively. These files record the maximum significant wave height and wind speed at each grid cell over the entire time history of the storm. The data may be viewed in the *HMAX* and *WMAX* worksheets in the Excel spreadsheet and Figures 14 and 15 show the maximum significant wave height and wind speed generated by the storm at each grid point in the domain, respectively.

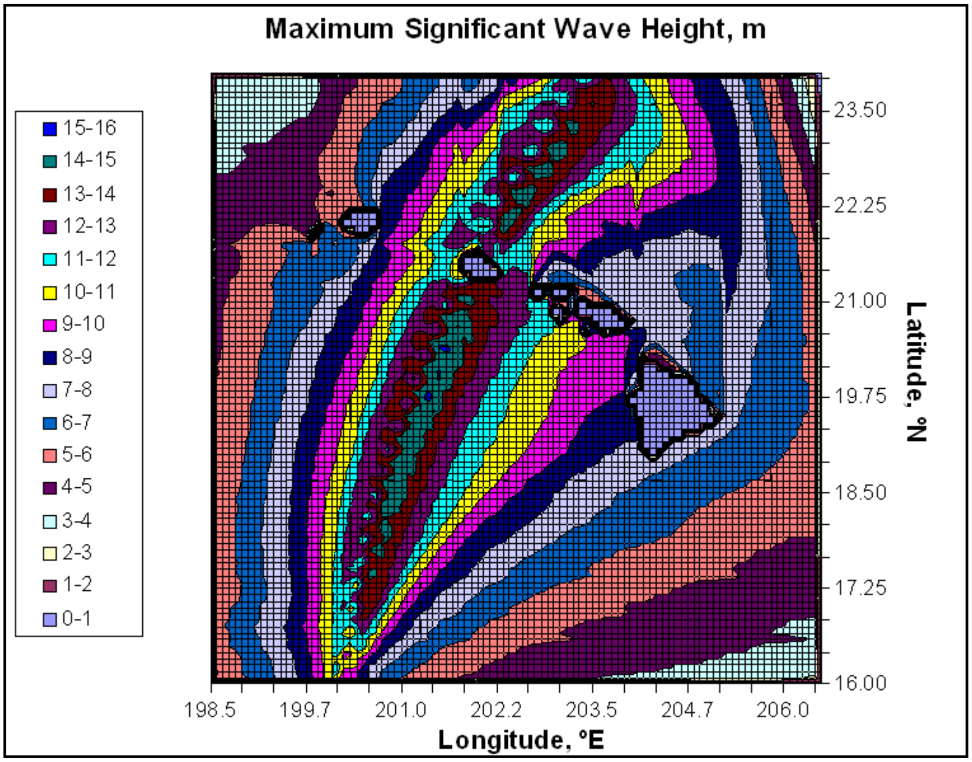


Figure 14. Maximum Hs generated by WISWAVE during hypothetical hurricane.

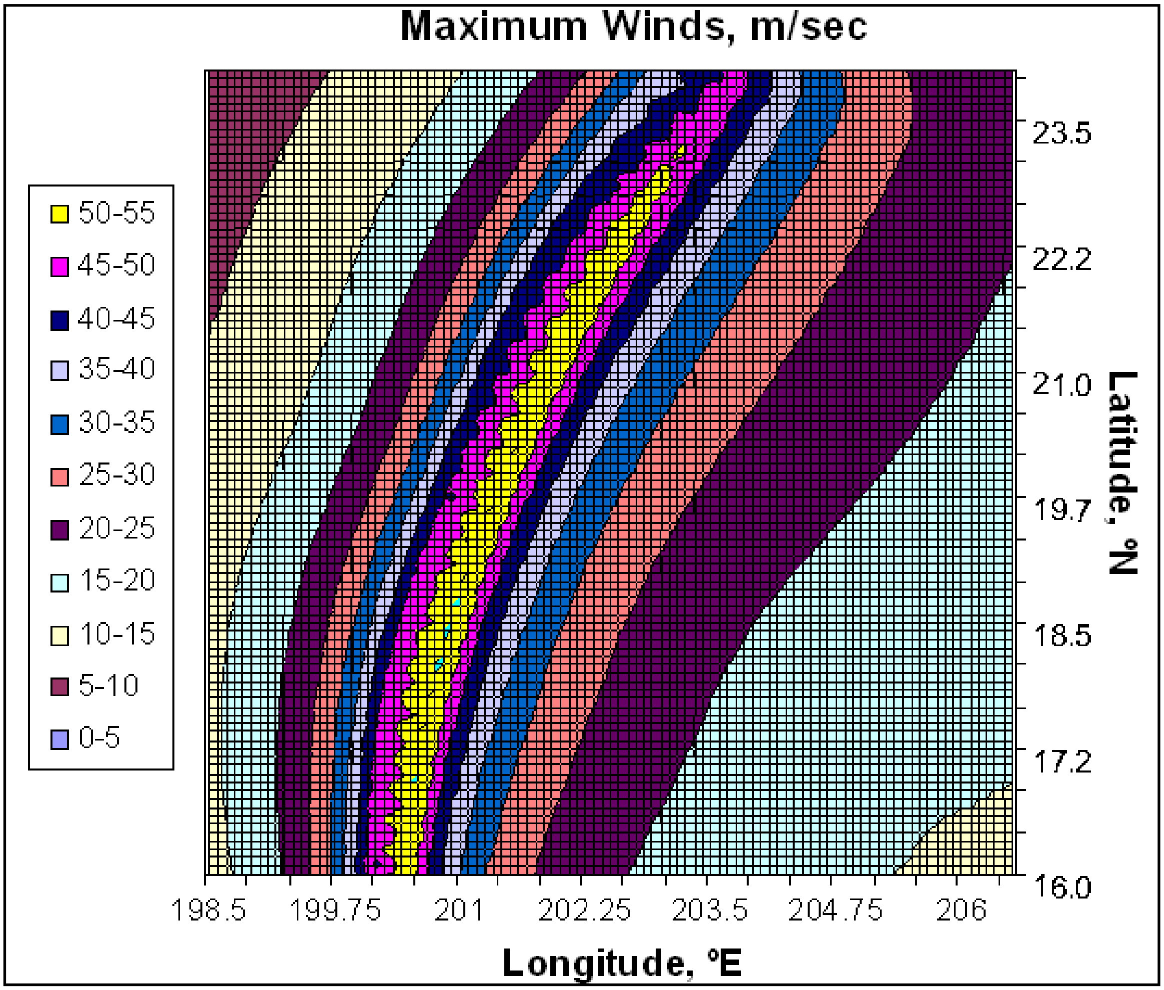


Figure 15. Maximum wind speeds output by WISWAVE during hypothetical hurricane.

The next step in running TWAVE is to estimate the transformation of the storm generated waves from the offshore station to the seaward boundary of the nearshore stations. The transformation model (wavetran_TW.exe) is run by clicking the Offshore to Nearshore Wave Transformation hyperlink in the *STR* worksheet (Figure 1b).

This program creates a Nearshore Waves file for each nearshore transect that contains the hourly significant wave height, peak period, and wave direction data at the most seaward point of each transect. The files (i.e., I01_200802.PH3) are located in the nearshore subdirectory.

Figure 16 shows the significant wave height and peak period estimated at nearshore station I01 during the storm. Figure 17 shows both the nearshore wind and wave direction at nearshore station I01 during the storm. The significant wave height steadily increases over time, peaking as the storm approaches landfall, while the wind and wave directions both exhibit a sudden change in direction as the storm passes over station I01.

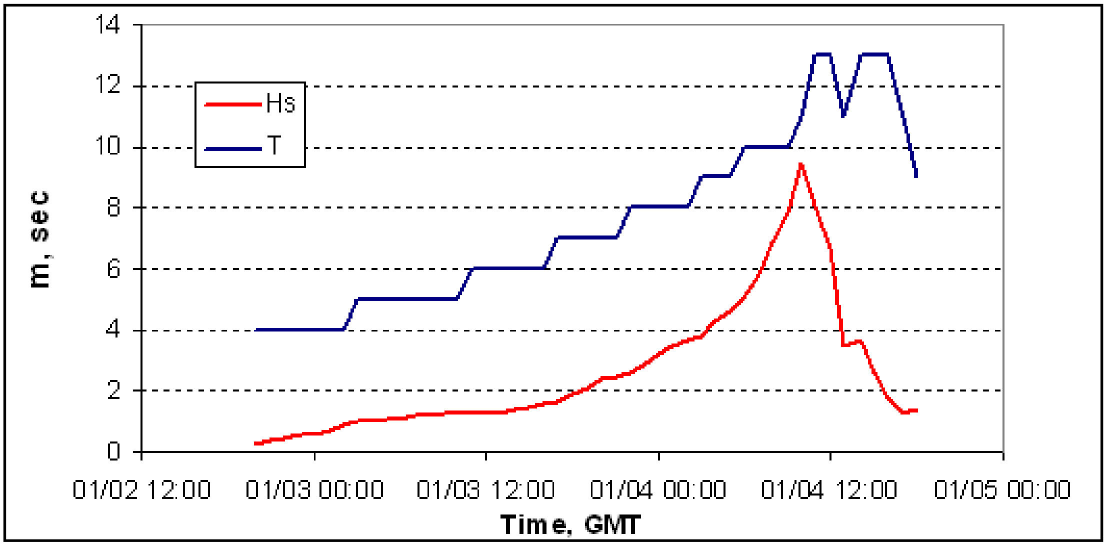


Figure 16. Significant wave height (Hs) and peak period (T) at nearshore station I01.

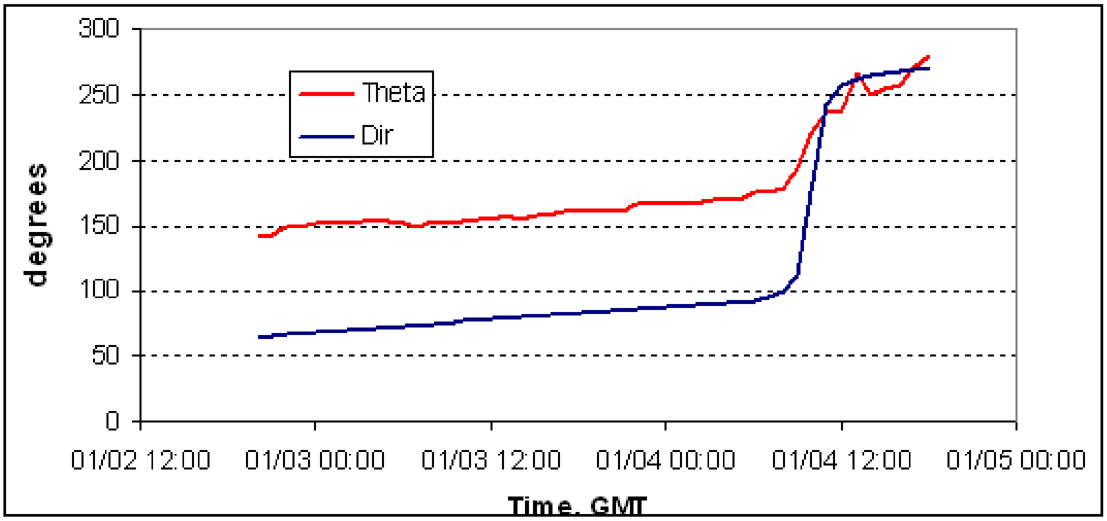


Figure 17. Wind (Dir) and Wave (Theta) direction data at nearshore station I01.

The next step in running TWAVE is to estimate the tide levels during the storm to add as a component of the total water level for inundation and runup estimates in the nearshore wave model. This is accomplished by clicking on the OTPS Tidal Database hyperlink in the *STR* worksheet, which runs the OTPS tide model *(*run_OTPS.exe, Figure 1).

This program creates a Nearshore Astronomical Tide file for each nearshore transect that contains the hourly tide level data at the most seaward points of each nearshore transect. The output files (i.e., I01_200802.ast) are located in the *nearshore* subdirectory.

Figure 18 shows the individual and total water level components at the seaward end of transect I01. The storm surge level at I01 increases and decreases suddenly as the storm approaches and passes station I01. The wave setup generated by the storm waves is calculated in the next steps by WAV1D and B1D.

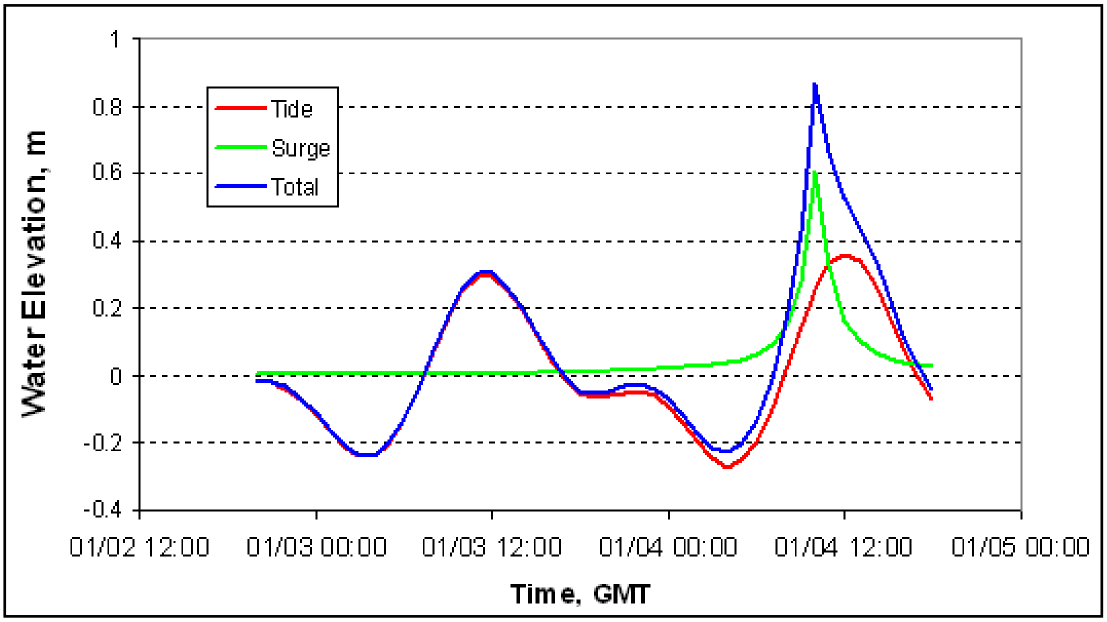


Figure 18. Storm surge, tide level, and combined water level data.

The next step in running TWAVE is to combine the wind, wave, tide, and storm surge data into a singular input file for the WAV1D model. This is done by clicking on the Combine Waves, Surge, and Tide tab in the STR worksheet (Figure 1). This program creates a Nearshore Station Time Series file for each nearshore transect that gathers the hourly wave height, wave period, wave direction, tide level, wind speed, wind direction, and storm surge data from the Nearshore Waves File, Nearshore Wind and Storm Surge File, and the Nearshore Astronomical Tide File for each nearshore transect and combines them into a singular input file for WAV1D. The output files (i.e., I01_200802.wts) are located in the nearshore subdirectory. The data may be viewed in the file *NR_xx* worksheet, where *xx* represents the transect number.

Step 11. WAV1D: The next step in the flow chart is to run the WAV1D model which estimates the inundation and runup for each nearshore transect. This is done by clicking on the Nearshore Wave Transformation tab in the *STR* worksheet, which runs the WAV1D model (reef-wave_TW.exe, Figure 1). The variable parameters available for the WAV1D model are specified in the Control File (Step 2).

This program creates files containing the significant wave height across the nearshore transect for the time step with the greatest water level for each nearshore transect. The output files (i.e., P001_200802_max.dat) are located in the *transects* subdirectory and can be viewed in the Excel sheet under the *PRO_xx* worksheet, where *xx* represents the transect number.

Figure 19 shows the wave transformation across transect I01, where *Hs* represents the significant wave height, *eta* represents the wave setup, and *Qb* represents the percentage of breaking waves in a Rayleigh Distribution. The wave height increases through shoaling as it traverses cross-shore until it reaches its breaking height. The wave height is then quickly reduced through wave breaking until it reaches zero. The waves are able to progress past the mean sea level shoreline demarcation due to wave setup and storm surge.

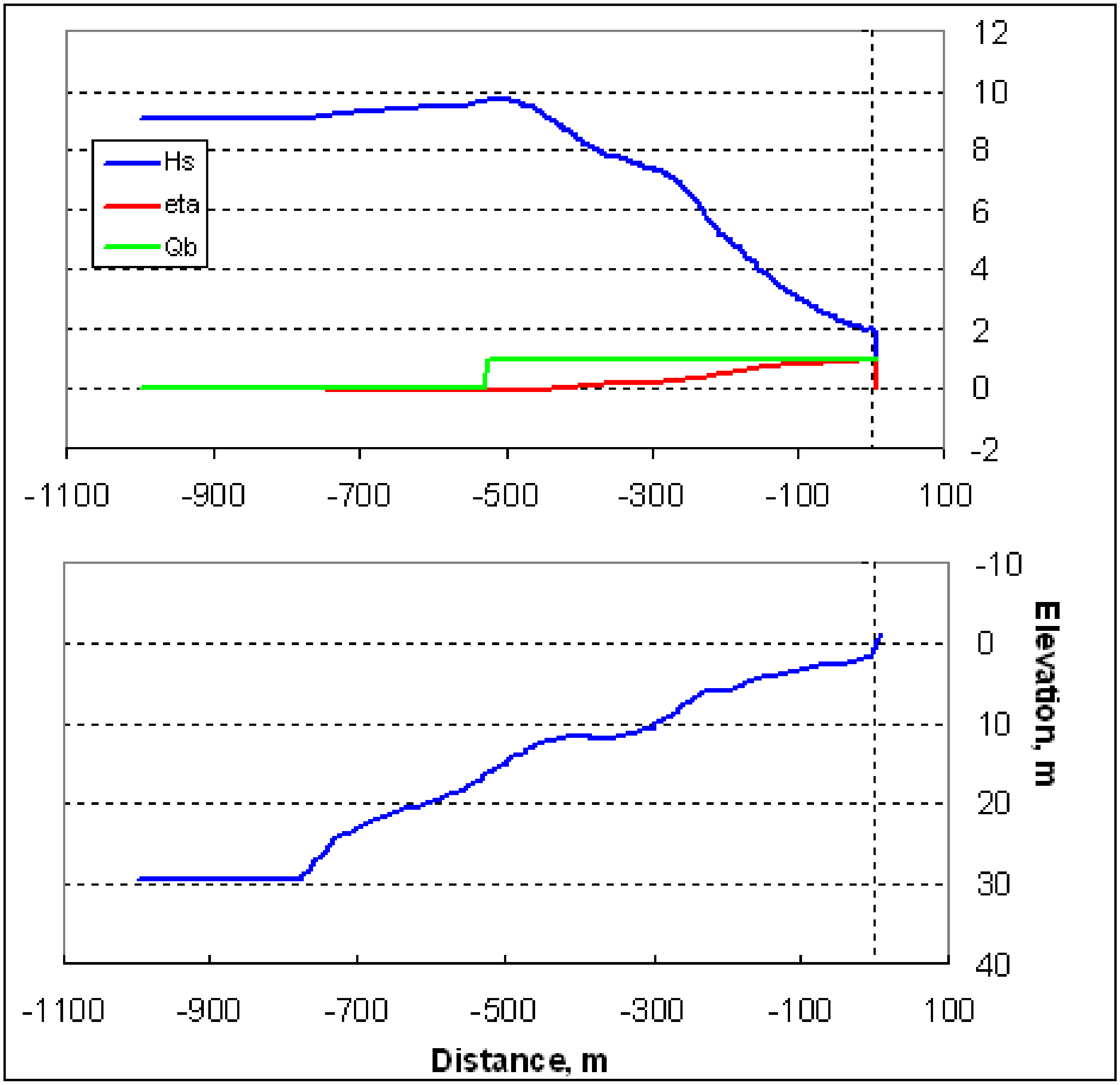


Figure 19. Wave transformation along nearshore transect I01 from WAV1D where Hs is the significant wave height, eta is the wave and wind setup, and Qb is the fraction of breaking waves.

This program also creates a WAV1D Runup Statistics file that contains the inundation and runup levels for each nearshore transect. The output file (Rstat_W1D_200802.dat) is located in the transects subdirectory and can be viewed in the Excel sheet under the *RW1D* worksheet.

Table 1 shows the runup and inundation for each nearshore transect, where $R_{2\%}$ is the runup level exceeded by 2-percent of the waves, *Rmax* is maximum runup level, $\mathrm{WL}_{2\%}$ is the water level exceeded by 2-percent of the waves, *WLmax* is the maximum water level, $I_{2\%}$ is the inundation exceeded by 2-percent of the waves, and *Imax* is the maximum inundation. The data indicate that transect P001 has the highest runup and water levels, while transect P002 has the greatest inundation distance. Runup and inundation are calculated in WAV1D with empirical formulas which may not always be highly accurate.

WAV1D also outputs a batch file (run_Bouss1D.bat) located in the BOUSS1D subdirectory that is used to run B1D from the Excel sheet and contains the wave parameters for each transect corresponding to the time step with the maximum water level. Although the highest runup is expected at the maximum water level, it may occur at other water levels. The next step describes the process for setting up and running the B1D model.

Table 1
Runup and Inundation statistics from WAV1D

Transect	R2% (m)	Rmax (m)	WL2% (m)	WLmax (m)	I2% (m)	Imax (m)
P001	6.41	8.37	8.06	10.03	42.68	53.09
P002	1.14	1.39	2.2	2.45	308.59	317.32
P003	2.07	2.59	3.17	3.69	48.53	56.38
P004	3.49	4.4	5.21	6.13	53.97	63.47
P005	1.65	2.04	3.09	3.48	59.65	67.13
P006	1.66	2.01	2.97	3.32	71.61	79.98

Step 12. B1D: There are two input files for B1D model, a bathymetry file (*.xy) and a batch file (*.gbat). The bathymetry file has been discussed earlier. The batch file contains model run parameters, post-processing utilities for converting model binary output files to text files, and statistical codes for calculating wave runup and inundation statistics. Each transect has its own setup file named as Pppp_setup.gbat, where ppp is the transect ID number as described in Step 4. An example of the B1D script file (P001_setup.gbat) is shown below.

```
(1) #BOUSS1D_v4p0
(2)  2        # bathymetry input option (1-2) [1]
(3)  %2       # name of bathymetry file [.xy]
(4)  %3       # storm surge/tidal offset (m) [0.0]
(5)  2.5      # grid spacing for numerical computations (m)
(6)  -950.0   # x location of wave generation boundary
(7)  2        # type of wave (1-2)
(8)           # time series synthesis option (1-2) [1]
(9)           # incident wave spectra option (1-2) [1]
(10)          # type of wave spectrum (1-5) [1]
(11)          # JONSWAP spectrum option (1-2) [1]
(12) %4       # peak wave period (s)
(13) %5       # significant wave height (m) [0 - 0.22m]
(14)          # spectral peakedness parameter gamma [3.3]
(15) %4*0.6   # minimum wave period [0.69s]
(16) 25.0     # maximum wave period (s) [25.0]
(17)          # Rescale truncated spectrum (y/n)? [Yes]:
(18) 7200     # duration of synthesized time series [150.59s]
(19) 0.04     # time step (s) [0.01]
(20)          # duration of numerical simulation (s) [389.26]
(21) %5       # turbulent length scale (m) [0.09]
(22) 20       # Chezy bottom friction factor (10-1000) [30.73]
(23) 0.2      # Smagorinsky constant [0.2]
(24) 50       # width of left end damping layer (m) [0.91]
(25)          # damping coefficient for  left end damping layer (0-1) [1]
(26)          # width of right end damping layer (m) [0.0]
(27)          # damping value for right end damping layer (0-1) [1]
(28)          # number of instants of time for surface elevation output [0]
(29)          # number of spatial locations for time series output [0]
(30)          # Do you want to create an animation of the surface elevation?
[No]:
(31) %1       # prefix for output files
(32) END
(33) #export2
(34) %2_%1_xHsmwl  # name of ASCII output file [.DAT]
(35) 2          # Implicit Variable Option [1]
```

```
(36) 2          # number of GEDAP input files (1-20) [1]
(37) %1_hs.001  # name of GEDAP input file no. 1 [.001]
(38) %1_mwl.001 # name of GEDAP input file no. 1 [.001]
(39) #END
(40) #Runup_Stats
(41) %1_runup   # name of input file [.001]
(42) %5         # significant wave height (m)
(43) %4         # spectral peak period (s)
(44) runup      # name of output file [.001]
(45) #END
(46) lis2rstat runup.lis Rstat_B1D_%1.dat %2 %3
(47) #shore_stat
(48) %1_xshore  # name of input file [.001]
(49) %2         # transect identifier
(50) %3         # water level
(51) Xmax_B1D_%1.dat # name of output file
(52) #END
```

The first column (with the line numbers in parentheses) is shown here only for describing the lines, but this column does not appear in the setup file used by the model. Values following the percent signs are required wave and water level parameters from the batch file run_bouss1d.bat created by WAV1D. The variables passed to B1D from the batch file are: name of the bathymetry file (line 3), transect label (Pppp, line 31), water level (line 4), peak wave period (line 12), significant wave height (line 13), and storm ID.

Lines 2 through 31 are the input parameters for B1D. The pound sign (#) in front of a program name signifies executing that code. It is important to choose the proper parameters for the B1D model, because choosing improper parameters will cause model instability. The B1D model input parameters specified on each line with a preceding pound sign (#) are user comments or recommended default values. A brief description of input parameters is provided on each line following the pound sign. If no value exists, then the default value in the square brackets is used.

The important parameters for B1D in this example are the grid spacing (line 5), location of the wave generation boundary (line 6), duration of the synthesized time series (line 18), time step (line 19), turbulent length scale (line 21), and the Chezy coefficient (line 22). The nearshore areas around the South Shore of Oahu are comprised of rough reef areas, so the bottom roughness coefficient was applied. A Chezy coefficient of 20 was chosen for the B1D model. A grid spacing of 2.5 m was chosen for model stability. The durations for B1D simulation and synthesized time series were set to 7200 seconds (2 hours) to be comparable to the duration of the storm event. For additional information on choosing B1D parameters, users may consult Demirbilek et al. (2005a and b) and related references.

When B1D is run for the first time, the model should be run interactively. This is done by opening a DOS window, navigating to the B1D folder within DOS, and running the executable code (run_Bouss1D.bat) in the DOS window. This interactive Q/A process allows the user to determine whether the model inputs have been properly defined, if the model runs or if there are instabilities within the model, and if there are errors in the input files. When the model is run directly from the Excel spreadsheet, the DOS window will immediately close when the model either finishes or if an error occurs within the model. This prevents the user from determining if an error has occurred. When the model is run interactively, the DOS window will stay open when the model either finishes or an error occurs, allowing easier debugging.

When B1D finishes all transects without error, a Transect file is output for each transect. The file contains the significant wave height along each nearshore transect. The output files (i.e., P001_200802_xHsmwl.DAT) are located in the Bouss1D subdirectory and can be viewed in the Excel sheet under the *B1D_xx* worksheet, where xx represents the transect number. Figure 20 shows the wave transformation across transect I01 (Tra I01). The cross-shore wave profile computed in B1D is similar to that of WAV1D in Figure 19, where *Hs* is the significant wave height and *eta* is the wave setup.

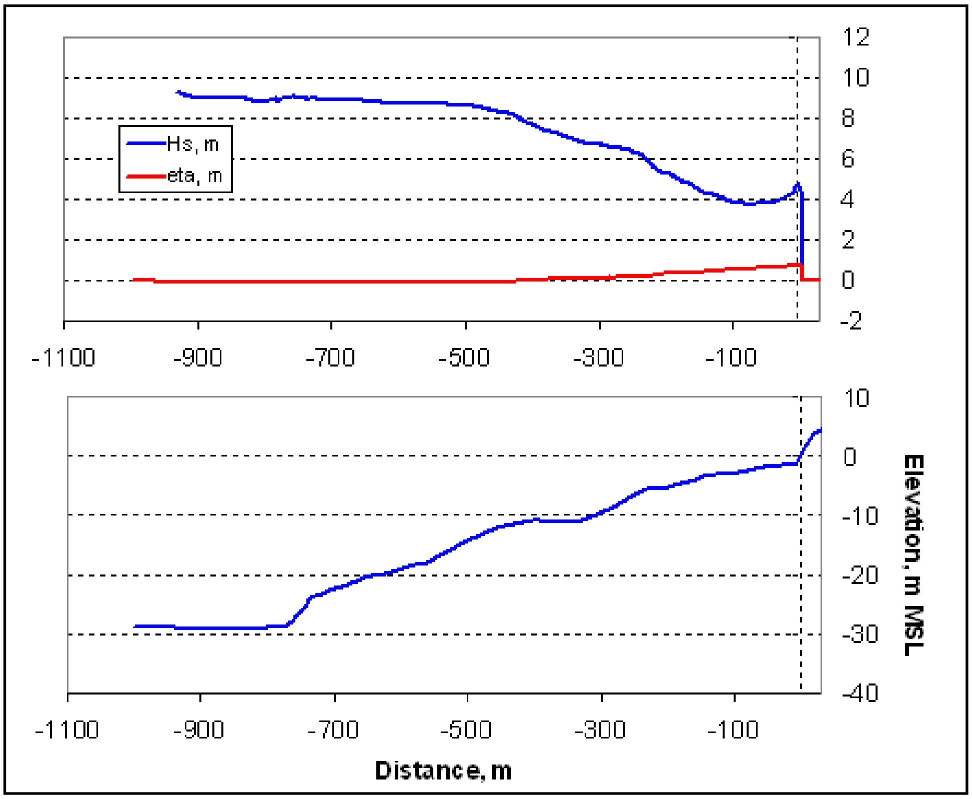


Figure 20. Wave transformation along nearshore transect I01 from B1D.

In addition, B1D creates a Runup Statistics File that contains wave runup statistics for each transect. The output file (Rstat_B1D_200802.dat) is located in the `Bouss1D` subdirectory and can be viewed in the Excel sheet under the *RB1D* worksheet. Table 2 shows the various statistical runup calculations for each transect, where R_{max} is maximum runup level, $R_{2\%}$ is the runup level exceeded by 2-percent of the waves, $R_{10\%}$ is the runup level exceeded by 10-percent of the waves, $R_{33\%}$ is the runup level exceeded by 33-percent of the waves, and $R_{50\%}$ is the runup level exceeded by 50-percent of the waves. For this application, there is little difference in the R_{max} and $R_{2\%}$ values. This is likely due to the bathymetric features of the south shore of Oahu where there are steep nearshore features at the shoreline, and nearly flat ponding areas landward. In this case, inundation is a more significant evaluation metric than is the wave runup.

It is important for users to understand the differences between wave runup, setup and inundation values calculated with B1D versus other models. B1D provides these estimates by solving the depth-integrated mass and momentum equations for the time-dependent evolution of the water surface elevation and velocity field over transect lines. There are no empirical equations used in B1D to calculate these quantities. In simulations where initially-dry computational cells are flooded, B1D keeps track of the horizontal position of the land-water interface, $x_s(t)$, and the elevation of the water level at the land-water interface, $R(t)$. The time histories of the shoreline position and runup height can then be post-processed to obtain the maximum runup height/shoreline position or other statistical quantities of interest. For monotonically increasing beach profiles as shown in Figure 21, there is a one-to-one correspondence between the shoreline position and runup height.

Table 2
Runup statistics from BOUSS-1D

Trans	R_{max}	$R_{2\%}$	$R_{10\%}$	$R_{33\%}$	$R_{50\%}$
P001	5.55	5.51	5.34	4.76	3.07
P002	1.81	1.79	1.77	1.66	1.35
P003	2.02	1.99	1.98	1.86	1.45
P004	3.77	3.61	3.53	2.98	2.21
P005	2.99	2.93	2.91	2.80	2.09
P006	2.61	2.54	2.52	2.42	1.94

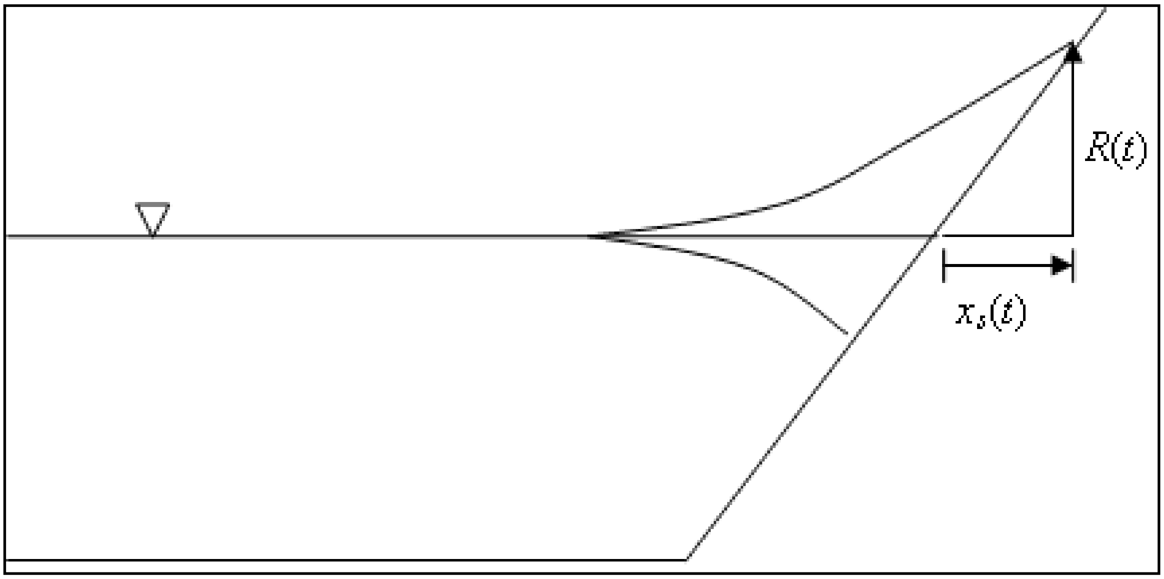


Figure 21. Monotonic beach profile.

However, one has to be careful in analyzing and/or interpreting the runup output/statistics from B1D in cases where the beach profile is not monotonically increasing. Several of the transects for the Island of Oahu had irregular bathymetric profiles similar to Figure 22 with multiple plateaus (reef crests) and/or trenches (ponding areas). Using the profile shown in Figure 22 for illustrative purposes, the runup and shoreline time histories would correspond to the water level and shoreline position on Beach #1 in simulations when the reef crest is not overtopped. When the reef crest is overtopped, the runup height would correspond to water level in the ponding area while the shoreline position would represent the horizontal extent of flooding in the ponding area. Depending on the incident wave conditions and storm surge level, the reef crest may only be occasionally overtopped during groups of large waves, resulting in very little water in the ponding area and no runup on Beach #2 in Figure 22. The runup statistics would not yield any useful information under this scenario. Even if the water front makes it to Beach #2, the runup time history could correspond to water levels on either Beach #1, Beach #2 or the ponding area and the resulting statistics would have to be interpreted in that context. The maximum value of $x_s(t)$ represents the inundation line and is most relevant for coastal flooding studies.

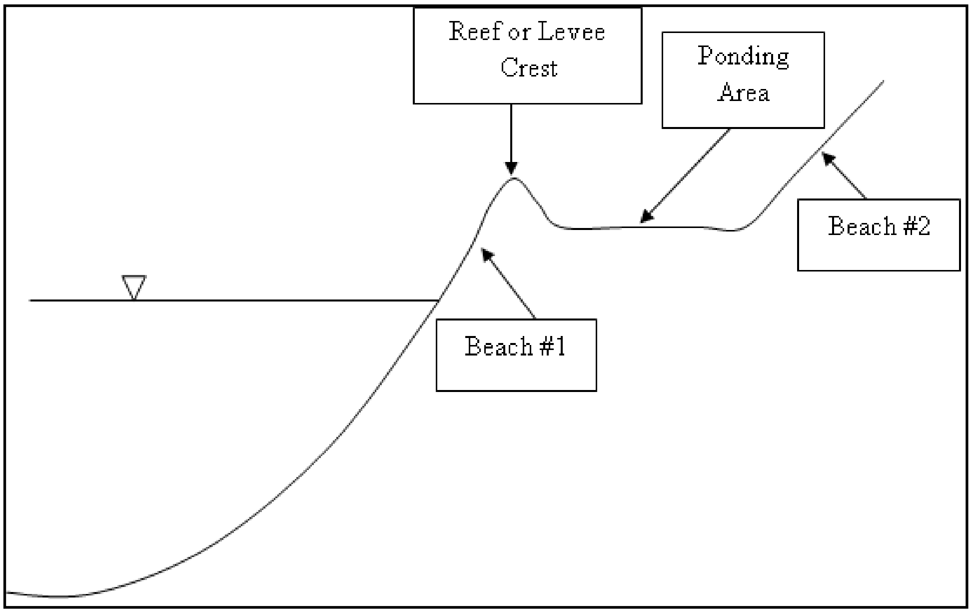


Figure 22. Composite beach profile.

The B1D model creates an Inundation Statistics File that contains the inundation levels for each transect. The output file (Xmax_B1D_200802.dat) is located in the Xmax subdirectory and can be viewed in the Excel sheet under the *XB1D* worksheet. Table 3 shows the extent of the inundation lines for each transect. The data indicates that transect P006 has the furthest inundation reach. B1D includes more detailed calculations of the wave and water level evolution (particularly wave and water level nonlinearities) compared to the empirical formulas. Figure 23 provides a comparison of the inundation estimates from WAV1D and B1D. The results indicate that the inundation estimate from B1D is generally greater than the values from WAV1D. The reason for this difference is that waves over reefs are highly nonlinear. Since wave nonlinearities are included only empirically in WAV1D, wave height and period obtained with the model are different from those values calculated with B1D and do not include detailed long-wave generation. It should also be emphasized that wave runup and inundation estimates obtained with WAV1D are based on empirical formulas which are approximations based on laboratory data with idealized geometry. B1D results can be sensitive to the input parameters, so analysis of computational sensitivity to these parameters is recommended to ensure model estimates are stable.

Table 3
Inundation statistics from BOUSS-1D

Transect	WL (m)	Inundation (m)
P001	0.75	242
P002	0.36	123
P003	0.39	138
P004	0.91	67
P005	1.00	192
P006	0.97	283

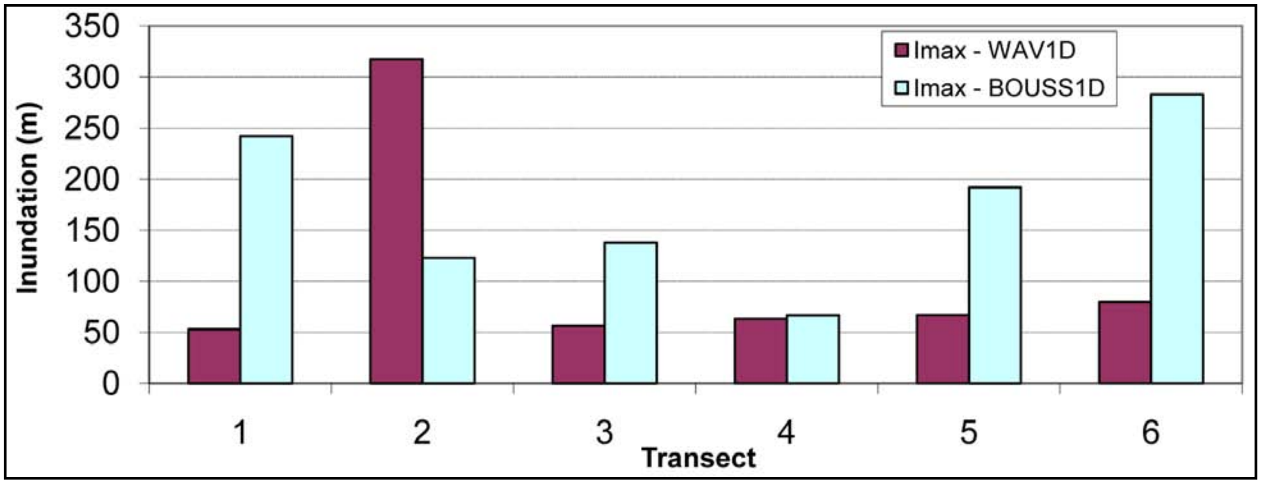


Figure 23. Comparison of WAV1D and BOUSS-1D runup statistics.

CONCLUSIONS: The Oahu example described in this CHETN provides users a detailed step-by-step procedure for preparing required inputs to run the TWAVE modeling package to develop estimates of coastal wave parameters, runup, and inundation caused by tropical storms. Although there was no validation data available for the hypothetical hurricane considered in this example, this storm event is used to demonstrate the overall capabilities of TWAVE for tropical applications.

The TWAVE modeling system is a predictive engineering tool for planning and emergency response management for tropical storms that may affect islands in both the Pacific Ocean and Caribbean Sea. TWAVE has been configured for the U.S. Territory of Guam and the islands of Oahu and Kauai Island in Hawaii, and can also be adapted to other areas of the U.S. coasts. TWAVE may also be used in engineering studies concerned with the protection of shores and wetland systems using barrier islands and levees. The next application of TWAVE will be for a Caribbean island. Please direct inquiries and suggestions to the attention of the authors.

ADDITIONAL INFORMATION: This CHETN was prepared as part of the Surge and Wave Island Modeling Studies (SWIMS) project and was written by Justin Goo (*Justin.A.Goo@usace.army.mil*) of the U.S. Army Corps of Engineers Honolulu District, Dr. Zeki Demirbilek (*Zeki.Demirbilek@usace.army.mil*), Jane Smith (*Jane.M.Smith@usace.army.mil*), and Alejandro Sanchez (*Alejandro.Sanchez@usace.army.mil*), of the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL). The SWIMS Program Manager is William Birkemeier. Files for the examples may be downloaded from *http://chl.erdc.usace.army.mil/swims*. This CHETN should be cited as follows:

> Goo, J., Z. Demirbilek, J. Smith, and A. Sanchez. 2009. TWAVE User's Guide with Example Application to Oahu, Hawaii. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-I-81. Vicksburg, MS: U.S. Army Engineer Research and Development Center. *http://chl.erdc.usace.army.mil.chetn*.

REFERENCES:

Bouws, E., H. Gunther, W. Rosenthal, and C. L. Vincent. 1985. Similarity of the wind wave spectrum in finite depth waves; 1. Spectral form. *Journal of Geophysical Research* 90(C1):975-986.

Bretschneider, C. L. 1972. A non-dimensional stationary hurricane wave model. Offshore Technology Conference, Preprint No. OTC 1517. Houston, Texas.

Cardone, V. J., C. V. Greenwood, and J. A. Greenwood. 1992. Unified program for the specification of hurricane boundary layer winds over surfaces of specified roughness. Contract Report CERC-92-1. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Demirbilek, Z., O. G. Nwogu, D. L. Ward, and A. Sánchez. 2009. Wave transformation over reefs: Evaluation of one-dimensional numerical models. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL TR-09-1. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Demirbilek, Z., and O. G. Nwogu. 2007. Boussinesq modeling of wave propagation and runup over fringing coral reefs, model evaluation report. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-07-12. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Demirbilek, Z., A. Zundel, and O. Nwogu. 2005a. BOUSS-2D wave model in the SMS: I. Graphical interface. Coastal and Hydraulics Laboratory Technical Note CHETN-I-69. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Demirbilek, Z., A. Zundel, and O. Nwogu. 2005b. BOUSS-2D wave model in SMS: II. Tutorial with examples. Coastal and Hydraulics Laboratory Technical Note CHETN-I-70. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Egbert, G., and S. Erofeeva, S. 2002. Efficient inverse modeling of barotropic ocean tides. Journal of Atmospheric and Oceanic Technology 19:183-204.

Gravens, M. B., N. C. Kraus, and H. Hanson. 1991. GENISIS: Generalized model for simulating shoreline change. Coastal and Hydraulics Laboratory Technical Report CERC-89-19. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Headquarters, U.S. Army Corps of Engineers (HQUSACE). 2006. *Coastal Engineering Manual*. EM 1110-2-1100. Washington, DC: U.S. Army Corps of Engineers (in 6 volumes).

Hedges, T. S., and H. Mase. 2004. Modified Hunt's Equation Incorporating Wave Setup. *Journal of Waterway, Port, Coastal and Ocean Engineering* 130:109-113.

Hubertz, J. A. 1992. User's guide to the Wave Information Studies (WIS) wave model, Version 2.0. WIS Report 27. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Jensen, R. E. 1983. Methodology for the calculation of a shallow-water wave climate. Wave Information Study Report 8. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Mase, H. 1989. Random wave runup height on gentle slope. Journal of Waterway, Port, Coastal and Ocean Engineering 115(5):649-661.

Phadke, A. C., C. D. Martino, K. F. Cheung, and S. H. Houston. 2003. Modeling of tropical cyclone winds and waves for emergency management. Ocean Engineering 30(4):553–578.

Resio, D. T., and W. Perrie. 1989. Implications of an F-4 equilibrium range for wind-generated waves. Journal of Physical Oceanography 19:193-204.

Sánchez, A., J. Smith, Z. Demirbilek, and S. Boc. 2007. Combined wind and waves over a reef. Proceedings 10th International Workshop, Wave Hindcasting and Forecasting and Coastal Hazard Symposium. Oahu, HI.

Sánchez, A., Z. Demirbilek, and J. Smith. 2009. TWAVE: A modeling system for flooding and inundation of islands by tropical storms. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL TR-09-2, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Seelig, W. 1983. Laboratory study of reef-lagoon system hydraulics. *Journal of Waterway, Port, Coastal and Ocean Engineering* 109:380-391.

Thompson, E. F., and V. J. Cardone. 1996. Practical modeling of hurricane surface wind fields. Journal of Waterway, Port, Coastal and Ocean Engineering 122(4):195-205.

APPENDIX: Summary of Programs and Associated Input and Output Files

Table A1. Description of TWAVE models and I/O files

Program	Description	Input	Output
phm_TW.exe	Parametric Hurricane Model	TWAVE Control File Storm Track File	Nearshore Wind and Storm Surge Files
pwm_TW.exe	Parametric Wave Model	TWAVE Control File Storm Track File	Offshore Waves Files
pblinput_TW.exe	Prepares the input files for the PBL model Run within the batch file run_PBL.bat	TWAVE Control File Storm Track File	6-hr Storm Parameters File 1-hr Storm Parameters File
pbl_TW.exe	Planetary Boundary Layer (PBL) model as described in Thompson and Cardone (1996) configuered on a WISWAVE grid	TWAVE Control File 6-hr Storm Parameters File 1-hr Storm Parameters File	1-hr Wind and Pressure Fields
wiswave_TW.exe	Spectral wave growth and propagation model as described in Hubertz (1992). The model is run Within the batch file run_WISWAVE.bat	TWAVE Control File 1-hr wind and pressure fields WISWAVE Options File	Offshore Station Spectra File Last Significant Wave Height File Maximum Significant Wave Height File
spec_TW.exe	Extracts time-series of wind and wave parameters for each WISWAVE observation stations (offshore stations). Run within the batch File run_WISWAVE.bat	TWAVE Control File Offshore Station Spectra File WISWAVE Options File	Offshore Station Time-series Files
wavetran_TW.exe	Transforms hourly deep water wave parameters to shallow water to represent near-breaking waves approaching the coast (Jensen, 1983; Gravens eta al. 1991)	TWAVE Control File Storm Track File Nearshore Station File Offshore Station File Offshore Station Time-series Files	Nearshore Wave Files
wind_inv_bar_TW.exe	Extracts the wind and atmospheric pressure from the PBL model output data and computes the storm surge time-series at nearshore stations	TWAVE Control File Storm Track File Nearshore Station Information File 1-hr wind and pressure fields	Nearshore Wind and Storm Surge Files

Key to filename components: *ww* = wis station #, *ssssss* = storm #, *xx* = nearshore station, *ppp* = profile #, *yyyy* = year

Program	Description	Input	Output
prep_tide.exe	Prepares the input files for the TPXO tide model	TWAVE Control File Storm Track File Station Information File	Tide Model Setup File Tide Model Lat/Lon/Time File
OTPS.exe	Computes time-series of astronomical tides at nearshore stations using the Oregon State Tidal Prediction Software (Egbert and Erofeeva, 2002)	Tide Model Setup File Tide Model Lat/Lon/Time File	OTPS Tides File
proc_tide.exe	Converts the OTPS output file to TWAVE format	TWAVE Control File OTPS Tides File	Astronomical Tides File
combine_TW.exe	Prepares the input file for setup_TW.exe by combining the time-series of tides, storm surge and wave conditions at nearshore stations	TWAVE Control File Nearshore Station Information File Tide Model Setup File Nearshore Wave Files Nearshore Wind and Storm Surge Files Nearshore Tide File	Nearshore Time-series Files
WAV1D.exe	Computes time-series of wave levels, wave ponding, wave setup, runup and inundation at transects along the coast	TWAVE Control File Nearshore Station Information File Profile Information File Nearshore Time-series File Transect Bathymetry Files	Transect Time-series Files Transect Profile Files WAV1D Runup Statistics File run_bouss1d.bat
bouss1d_v3p1exe	1D Boussinesq wave model. Run within the batch file run_bouss1d.bat	BOUSS-1D script files Transect Bathymetry Files	BOUSS-1D Transect Files BOUSS-1D Runup time series
proc_ts.exe	Calculates the runup statistics from BOUSS-1D results	BOUSS-1D Runup time series	BOUSS-1D Runup Statistics File

Key to filename components: *ww* = wis station #, *ssssss* = storm #, *xx* = nearshore station, *ppp* = profile #, *yyyy* = year