Modeling Nearshore Wave Transformation with STWAVE

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PURPOSE: The purpose of this Coastal and Hydraulics Engineering Technical Note (CHETN) is to provide guidance for applying the nearshore wave transformation model STWAVE. Background information is provided to give the context for the application of STWAVE relative to other wave modeling technology. The STWAVE model is described, and application of STWAVE within the Surfacewater Modeling System (SMS) interface is discussed. Web sites to download the STWAVE executable and user manual are given.

BACKGROUND: Wind-wave processes can be separated into three scales: generation, transformation, and local (Figure 1). Wave generation typically occurs in relatively deep water and across the continental shelf. The dominant processes for wave generation are atmospheric (wind) input, nonlinear wave-wave interactions, and dissipation (whitecapping). In intermediate to shallow water depths, wave transformation processes become dominant. These processes include wave shoaling, refraction, and breaking. In shallow depths and near coastal structures, local-scale process of diffraction, reflection, and wave nonlinearities govern. Although there is overlap in the wave processes between scales, numerical modeling approaches naturally fit into these three scales.
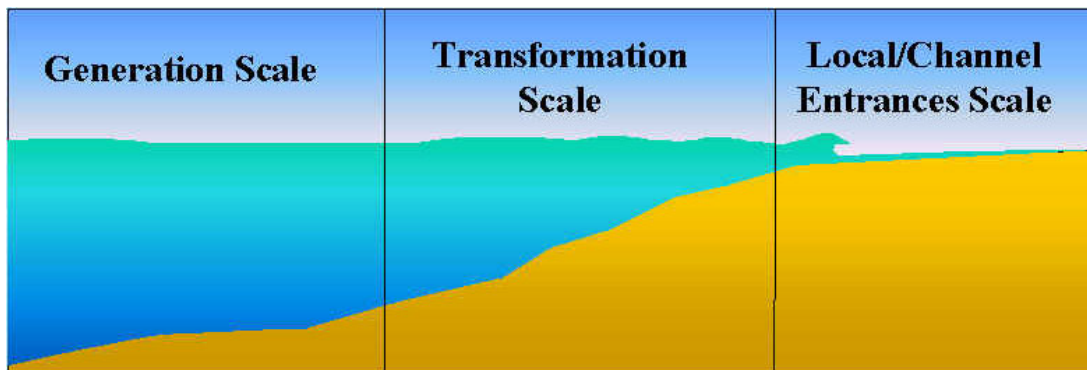

Figure 1. Scales of wave processes

Generation Scale Modeling: Wave generation occurs over tens, hundreds, and thousands of miles, as momentum is transferred into the wave field by the winds. Wave heights and periods increase with wind speed, fetch (distance over which the wind blows), and time, up to fully developed conditions. Modeling of wave generation and propagation requires accurate wind field estimation and specification of the basin geometry. For coastal applications, wave generation modeling is performed at multiple scales, nesting toward the shore. For example, the Wave Information Studies (WIS) hindcast for the U.S. Atlantic coast includes a 1-deg-resolution grid of the north Atlantic basin, nesting into a one-fourth-deg grid approximately 1,000 miles (1,609.34 km) from the coast, which then nests into a one-twelfth-deg grid approximately 300 miles (482.80 km) from the coast. The higher resolution close to the coast provides better

definition of the land-mass sheltering, and bathymetry. Generation models are based on a statistical representation of waves using two-dimensional (frequency-direction) wave spectra. Spectral wave models, also known as phase-averaged models, do not save information about the relative phase of the spectral wave components because the phases are random (i.e., components of the spectrum are not locked together as in cnoidal waves, which reinforce to give consistently higher crest elevations because the wave crests are in phase). Generation-scale modeling has evolved from empirical relationships (based on dimensional analysis) to solutions of the action or energy balance equation. Jensen (1994) describes the evolution of spectral wave generation models. The U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL) presently uses the model WISWAVE (Hubertz 1992) for the WIS hindcast because of the model's efficiency and accuracy. The WAM model (WAMDI Group1988) is also used in some applications.

Transformation Scale Modeling: The wave transformation processes of refraction, shoaling, breaking, and wind input dominate in intermediate water depths (depth less than approximately 50 to 200 ft (15 to 60 m)), which is within a few miles to tens of miles from the coast. Wave heights may increase or decrease in shallower depths due to wave refraction and shoaling and wave directions refract to become more shore normal (wave crests parallel to shore). In very shallow depths, waves break where the wave height is of the same order as the water depth. To represent the bathymetry features that cause refraction, shoaling, and breaking, transformation-scale grid resolution is of the order of 100 to 1,000 ft (30 to 300 m). Accurate nearshore bathymetry is required. The input to calculate wave transformation is the output from a wave generation model (e.g., WIS hindcast) or field wave measurements. CHL presently uses the steady-state spectral wave model STWAVE (Smith, Sherlock, and Resio 2001) for nearshore wave transformation applications.

Local Scale Modeling: In areas where wave properties change on a subwavelength scale, a high-resolution local-scale model is required. These processes include reflection from breakwaters and jetties, diffraction around coastal structures, and phase-dependent wave nonlinearities (generation of harmonics and subharmonics), as well as refraction, shoaling, and breaking. Grid domains on the local scale are generally small (on the order of a few miles or less) because the models are computationally intensive and the processes are localized. Numerical model grids must contain 8-10 grid cells per wavelength (resolution of tens of feet). Input to calculate local-scale waves is typically output from a wave transformation model or field wave measurements. Accurate bathymetry and structure configuration is also required. CHL is presently developing the BOUSS-2D model (based on the Boussinesq equations) for local scale modeling (Nwogu and Demirbilek 2001). The model CGWAVE (Demirbilek and Panchang 1998) is also applied at CHL for local-scale wave modeling and harbor resonance, but it does not include wave nonlinearities.

DESCRIPTION OF STWAVE: The purpose of applying STWAVE is to quantify the change in wave parameters (wave height, period, direction, and spectral shape) between the offshore, where the wave field is fairly homogeneous on the scale of miles, and the nearshore, where waves are strongly influenced by variations in bathymetry, water level, and current. Wave parameters in the nearshore vary significantly on the scale of tens to hundreds of feet. Nearshore wave information is required for the design of almost all coastal engineering projects. Waves

drive sediment transport and nearshore currents, induce wave setup and runup, excite harbor oscillations, influence navigation, and impact coastal structures. The longshore and cross-shore gradients in wave height and direction are often as important as the magnitude of these parameters for sediment transport and nearshore current studies. Present field measurement technology cannot provide such high-resolution nearshore fields of wave parameters. STWAVE simulates depth-induced wave refraction and shoaling, current-induced refraction and shoaling, depth- and steepness-induced wave breaking, wind-wave growth, and wave-wave interaction and whitecapping that redistribute and dissipate energy in a growing wave field.

Model Assumptions: The assumptions made in STWAVE are as follows:

a. *Mild bottom slope and negligible wave reflection.* STWAVE is a half-plane model, meaning that wave energy can propagate only from the offshore toward the nearshore (±87.5 deg from the x-axis of the grid, which is the approximate shore-normal direction). Waves reflected from the shoreline or from steep bottom features travel in directions outside this half plane and thus are neglected. Forward-scattered waves, e.g., waves reflected off a structure but traveling in the +x direction, are also neglected.

b. *Spatially-homogeneous offshore wave conditions.* The spatial variation in the wave spectrum along the offshore boundary of a modeling domain is rarely known, and for domains on the order of tens of miles, is expected to be small. Thus, the input spectrum in STWAVE is constant along the offshore boundary.

c. *Steady-state waves, currents, and winds.* STWAVE is formulated as a steady-state model. A steady-state formulation reduces computation time and is appropriate for wave conditions that vary more slowly than the time it takes for waves to transit the computational grid. For wave generation, the steady-state assumption means that the winds have remained steady sufficiently long for the waves to attain fetch-limited or fully developed conditions (waves are not limited by the duration of the winds). Winds are assumed uniform over the model domain.

d. *Linear refraction and shoaling.* STWAVE incorporates only linear wave refraction and shoaling, thus does not represent wave asymmetry. Model accuracy is therefore reduced (wave heights are underestimated) for large wave heights in shallow water (large Ursell numbers).

e. *Depth-uniform current.* The wave-current interaction in the model is based on the assumption that current is constant through the water column. If strong vertical gradients in current occur, their modification of refraction and shoaling is not represented in the model. For most applications, three-dimensional current fields are not available.

f. *Negligible bottom friction.* The significance of bottom friction on wave dissipation has been a topic of debate in wave modeling literature. Bottom friction has often been applied as a tuning coefficient to bring model results into alignment with measurements. Although bottom friction is easy to apply in a wave model, determining the proper friction coefficients is difficult. Also, propagation distances in a nearshore model are relatively short (tens of miles), so that the cumulative bottom friction dissipation is small. For these reasons, bottom friction is neglected in STWAVE.

g. *Linear radiation stress.* Radiation stress is calculated based on linear wave theory.

STWAVE solves the steady-state conservation of spectral wave action along backward traced wave rays (Jonsson 1990) with the source/sink terms of surf-zone wave breaking, wind input, wave-wave interaction, and whitecapping (Resio 1987, 1988a, 1988b; Smith, Sherlock, and Resio 2001). The STWAVE governing equations are numerically solved using finite-difference methods on a Cartesian grid. Model grid cells are square. STWAVE operates in a local coordinate system, with the x-axis oriented in the cross-shore direction and the y-axis oriented along the shore. Figure 2 shows an example STWAVE bathymetry grid for Grays Harbor, Washington. This grid is approximately 10 miles by 18 miles (16 km by 29 km) with a depth at the offshore boundary of 130 ft (40 m). The y-axis is typically aligned with the bathymetry contours. Wave angles are measured counterclockwise from the x-axis.
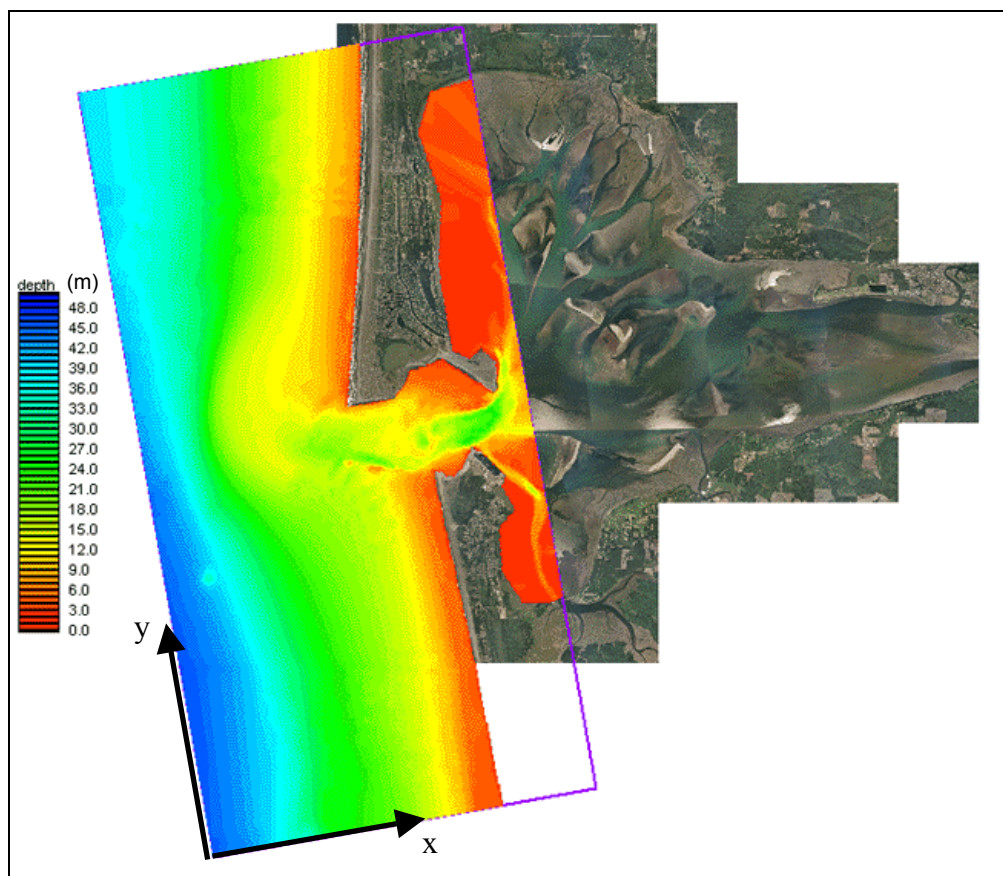

Figure 2. Example STWAVE model domain

STWAVE Input and Output: STWAVE input and output are illustrated in Figure 3. All STWAVE input files can be generated using SMS (Brigham Young University Environmental Modeling Research Laboratory 1997), as discussed in the next section. The model input includes:

a. *Model parameters.* The model parameters tell STWAVE which model options are to be applied for simulation and model output. The input options include wind input (for local wave growth) and wave-current interaction. Activating these options slows model computations, but increases model accuracy if local winds or currents are significant. In

applications where wave propagation distances are short, wind input may not be required. For longer propagation distances, strong winds, or cases where locally generated waves dominate (e.g., bays), the wind input should be included. In typical U.S. East and West Coast applications, peak tidal currents exceeding 3 ft/sec (1 m/sec) may significantly alter wave transformation and should be included. The output options include specifying regions of wave breaking, calculating radiation stresses, and saving wave spectra at selected output locations. Radiation stresses can be used to calculate wave-driven currents and setup within a circulation model, such as ADCIRC (Luettich et al. 1992). The more output options or special output points selected, the more disk space required for model output and computational time to write the output. Two-dimensional fields of significant wave height, peak period, and mean direction are also saved over the entire model domain.
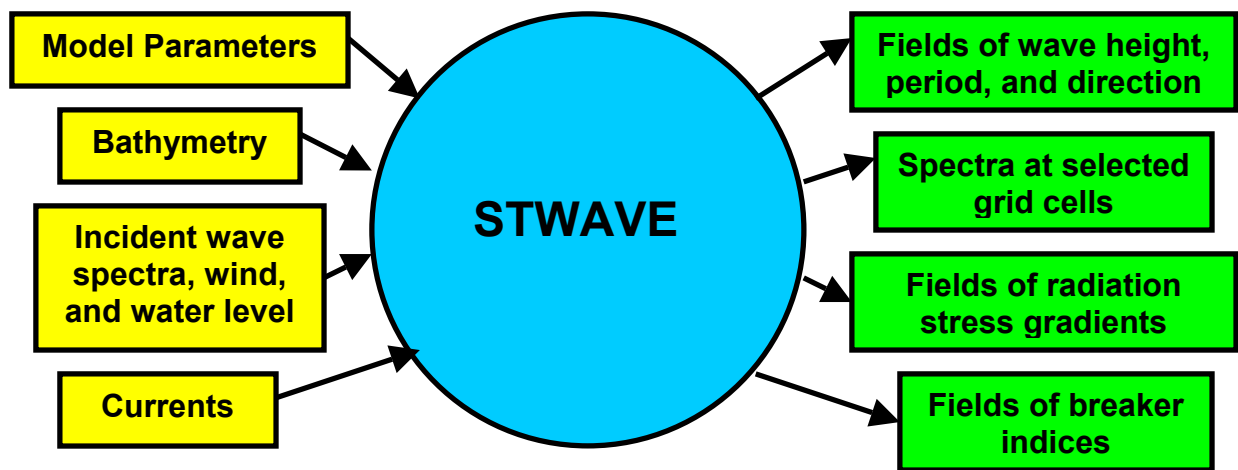

Figure 3. STWAVE input and output file schematic

b. *Bathymetry.* The input bathymetry describes the STWAVE grid dimensions and grid spacing as well as the water depth for each grid cell. The grid must be defined in a flat-earth coordinate system (e.g., state plane). Water cells are denoted with positive depths and land cells with negative depths. Lateral grid boundaries can be specified as land (bay or lake site) or water (open coast site). Water boundaries are assumed to be open and allow wave energy, consistent with neighboring cells to propagate into or out of the domain (zero-gradient type boundary condition). Land boundaries allow no energy to propagate in or out of the domain. The offshore boundary can also be completely or partially land for local generation cases (bays or lakes).

c. *Incident wave spectra, wind, and water levels.* The input waves on the offshore grid boundary are specified as a wave spectrum. Input spectra can be interpolated from the WIS hindcast, results from another numerical model, or field measurements; or spectra can be generated based on wave height, period, and direction using standard spectral shapes. SMS provides tools to generate spectra. The spectral input also includes the number of frequencies and directions given in the input spectra (and used for all calculations). The number of directions is fixed at 35 in STWAVE (5-deg resolution). Smith, Sherlock, and Resio (2001) provide guidance on selecting the number and

distribution of frequencies. For each input spectrum specified, the additional parameters of wind speed, wind direction, and water level are required. The wind information is only used if the wind input option is selected. Winds blowing offshore are neglected because of the half-plane model assumption. Tide information is specified relative to the bathymetry datum used to generate the depth grid. Multiple wave model runs can be executed by inserting multiple spectra in the input file. STWAVE will run multiple cases in a quasi-time stepping mode.

   d. *Current fields*. Current field input is required only if the wave-current interaction option is selected. Current information is specified with x- and y-components of the currents at each grid cell. Currents can be interpolated from output of a circulation model. SMS provides algorithms to interpolate between circulation and wave model grids. A single current field can be used for all input spectra or the number of current fields must equal the number of input spectra.

STWAVE model output includes:

   a. *Fields of wave height, period, and direction.* For each input spectrum, STWAVE outputs fields of significant wave height (defined as the zeroth moment of the spectrum), peak period, and mean direction. The parameters are provided for all grid cells. The mean directions are given in the STWAVE local coordinate system, but can be visualized in global coordinates within SMS.

   b. *Spectra at selected grid cells.* For the grid cells selected in the model parameter input, STWAVE outputs the full two-dimensional (frequency-direction) spectrum. The spectral output may be used for model validation with field measurements or as input to a nested STWAVE run or a local-scale wave model. STWAVE also writes out the significant wave height, peak period, and mean direction for the selected grid cells to a separate output file. This summary output is useful for validation or input to other engineering calculations.

   c. *Fields of radiation stress gradients.* The x- and y-components of radiation stress gradients are provided for all grid cells if the radiation stress option is selected. These stresses can be used as input to a circulation model to calculate wave-driven currents and setup.

   d. *Fields of breaker indices.* For applications to sediment transport, navigation, and structure design, it is useful to know the location of wave breaking. The breaker index output notates grid cells where waves are breaking with an index of 1 and cells without breaking with an index of 0.

All STWAVE input and output are specified in metric units and ASCII format. SMS provides the option to convert input from English units to metric and visualize output in English or metric units. The STWAVE user's guide provides file formats for all input and output files (Smith, Sherlock, and Resio 2001).

SMS USER INTERFACE: The SMS user interface is a powerful tool for generating and visualizing STWAVE input and visualizing STWAVE output. SMS can be used to run STWAVE, but is not required. However, SMS can significantly reduce the time and effort

required to prepare input files and process results. The steps required to run STWAVE in SMS are:

a. *Build Cartesian grid*. Developing an STWAVE grid in SMS requires digital bathymetry data. These data can come from digitized nautical charts or hydrographic surveys. Within SMS, bathymetry data sets can be merged, coordinate systems can be converted (e.g., bathymetry data can be converted from geographic to state plane), and images can be overlaid (e.g., aerial photos, nautical charts, or plots of structure locations). Once bathymetry is imported into SMS, the STWAVE grid is defined either graphically or by specifying the origin, orientation, and size of the grid. Plotting contours of the bathymetry can identify errors in bathymetry data. Corrections to the bathymetry can be easily made within SMS. An example STWAVE bathymetry grid overlaid on an aerial photograph within SMS is shown in Figure 2.

b. *Generate input wave spectra*. SMS can generate STWAVE input spectra based on the parameters of significant wave height, peak period, and mean direction (Bouws et al. 1985). Spectral peakedness and directional spread may be specified or defaults can be applied. One-dimensional and two-dimensional plots of the spectra are provided in SMS.

c. *Select output grid cells*. Grid cells for output of directional spectra can be defined graphically or positioned by geographic coordinates.

d. *Interpolation of current fields*. Current field input for STWAVE can be interpolated from output of a circulation model. The circulation model grid and current fields are required as input. Interpolation is possible in time as well as space.

e. *Specify model parameters*. Model control parameters (input and output options) are specified through a dialog box in SMS.

f. *Run STWAVE*. STWAVE can be executed through SMS or run in a DOS window on a Windows PC. In DOS, the command to run the model is **stwave32.exe project.sim** where stwave32.exe is the executable file name and project.sim is a file that lists the input and output file names. The format for project.sim is given by Smith, Sherlock, and Resio (2001).

g. *Visualize simulation output*. One of the most useful aspects of SMS is the visualization capability. Model outputs should be visualized to verify that the model is running correctly and to identify any problems. SMS can provide color contour plots of significant wave height, period, and direction; current magnitude; and two-dimensional spectra at the selected grid cells. Vector plots of wave direction and current direction can be overlaid on the color contour plots. Another plotting capability is x-y plots of wave parameters along a user-defined arc, e.g., a cross section through a channel or a cross-shore profile.

GETTING STWAVE: The most recent STWAVE executable (Version 3.3, 10/13/2001), sample input files, and example applications are available on the CHL Web page at:

http://chl.wes.army.mil/research/wave/wavesprg/numeric/wtransformation/stwave.htp

The Web site also provides the STWAVE user's manual in PDF format:

http://chl.wes.army.mil/research/wave/wavesprg/numeric/wtransformation/downld/erdc-chl-sr-01-11.pdf

Recent STWAVE applications are documented in Smith and Harkins (1997); Smith and Ebersole (2000); Smith and Smith (2001); and Cialone and Kraus (2001). These applications address wave-current interaction, complex bathymetry, verification with field and lab measurements, and wave climate simulations.

Information about downloading SMS, SMS documentation, system requirements, and software registration are available at:

http://chl.wes.army.mil/software/sms/

U.S. Army Corps of Engineers users can register SMS through CHL, and non-Corps users must register SMS through Environmental Modeling Systems, Inc. (*http://www.ems-i.com/*).

Further information on generation and local scale wave models can be found on the CHL Web site at:

http://chl.wes.army.mil/research/wave/wavesprg/numeric/

FUTURE PLANS FOR STWAVE: Development of STWAVE continues to be a research thrust at CHL. The areas of planned improvement include the following:

a. *Wave breaking*. Improvement to the empirical breaking formulation in STWAVE is planned to provide better representation of surf zone spectra, especially for the case of breaking of multiple waves trains.

b. *Grid nesting*. Regional application of STWAVE as part of the Regional Sediment Management initiative requires nesting of STWAVE to resolve the nearshore. This requires variable input spectra on the offshore boundary and new capabilities in SMS to generate nested grids.

c. *Model efficiency*. Regional model applications also require improved model efficiency. Efforts are underway to increase computational speed. A high-performance version of STWAVE has been developed for parallel computers. This version is available and is being run at CHL. Applications have been run using up to 64 processes at 87 percent efficiency (i.e., a run that takes a week on a serial computer will run in 3 hr on the parallel computer).

d. *Full-plane STWAVE*. Over the next 2 years, a new version of STWAVE will be developed that eliminates the half-plane assumption. This version will include wave propagation and generation over a full 360-deg circle. This version will provide improved results for application in bays and lakes.

Updated STWAVE information and executables will be made available periodically on the CHL Web site.

ADDITIONAL INFORMATION: Questions about this CHETN can be addressed to Dr. Jane McKee Smith (601-634-2079, Fax 601-634-4314, email: *Jane.M.Smith@erdc.usace.army.mil*). This Technical Note should be referenced as follows:

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