The Third Generation Spectral Wave Model, WAVEWATACH-III, Enhanced for use in Nearshore Regions

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Abstract

WAVEWATCH-III is a third generation spectral wave model, developed originally for deep water in Ocean Modeling Branch of NOAA. By adding nearshore processes and removing some restriction from its code, the model can be applied to a full range of water depths from offshore to coastal regions. Depth induced wave breaking, surf zone energy dissipation and Triad wave-wave interactions are the important physical processes considered in shallow waters. The restrictions on time steps and minimum water depth in the original code have been relaxed to make the model applicable to coastal areas with high spatial resolution. The simulation results of the modified model have been compared with another third generation and widely tested spectral model, SWAN, in addition to some laboratory and field data.

Keywords: Spectral Wave Models, WAVEWATCH-III, Wave Breaking, Energy Dissipation, Triad Wave-Wave Interaction, SWAN

Introduction

Wave models can be categorized into phase-resolving (based on mass balance) and phase-averaged (based on energy conservation) models. The former is appropriate for small domains where diffraction and reflection are important (e.g. ports and around structures). They are based on Boussinesq equations (e.g., Madsen and Sorensen (1992), Wei et al. (1995)) or using elliptic mild or steep slope equation (e.g., Chamberlain and Porter (1995)). On the other hand, phase-averaged models are suitable for large scale simulations.

After pioneer model of Gleci et al (1957), many researchers started to parameterize wave processes for phase averaged models. Philips (1957) and Miles (1957) theories for wind-wave interaction and Hasselmann (1962) calculation of wave-wave interaction were significant progress in wave modeling. Due to lack of computational resources and underestimation of the importance of nonlinear wave interactions, there was no interest to solve full energy conservation equation in so called first generation wave models. Instead, those models assumed a saturation level for wave spectrum.

Some experiments done by Snyder (1981) and Hasselmann (1986) showed some deficits in the first generation

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models. Second generation wave models used simple parametric formulations to take nonlinear wave interaction into account. Introducing an approximation for wave interaction by Hasselmann (1985), made it applicable for wave models. Appling realistic relationship for nonlinear wave interaction and replacing explicit wave dissipation term instead of saturate spectrum level assumption resulted in the first third generation wave models called WAM. This model proposed by Komen et al (1996) is still the base of all current wave models.

Third generation models were originally designed for large scale simulation and deep waters but gradually some development has been done to take into account nearshore processes. Abreu (1992) suggested a 1D formulation for shallow water wave interaction. Eldeberky (1996) showed that the result of that model was unrealistic and proposed a successful approximation for triad wave-wave interaction. Simulating depth induced break was another issue for wave models in the coastal zone. Several methods has been suggested so far such as Dally (1985), Liu (1990), Mase and Kirby (1992) and Battjes and Eldeberky (1996). The latter one has spectrum form which is suitable for spectral wave models such as WAVEWATCH-III.

The aim of this study is to enhance the capabilities of the third generation spectral model WAVEWATCH-III so that it could be applied to nearshore and coastal areas. The method of achieving this objective is described as follows.

First, WAVEWATCH-III is briefly introduced and its main capabilities are delineated. The nearshore processes which have been implemented in this model together with the modifications made to its original code to make it work for shallow water regions are described next. The modified model is validated against the results of the simulations of another third generation spectral wave model for shallow waters; the SWAN model. Field observations and laboratory experimental data are also compared with the results of this model.

WAVEWATCH-III

WAVEWATCH-III is a third generation spectral wave model developed by the National Oceanographic and Atmospheric Agency (NOAA) of the United States of America. This model has been well validated and widely used throughout the world for deep water depth (e.g. Chu et al (2004), Hemer et al (2008), Jouana et al (2009), Lahuz and Albiach (2005) and Tolman (2002)). In this model the generation and propagation of waves are governed by the conservation of wave action equation:

$$\frac{DN}{Dt} = \frac{Q}{\sigma} \qquad (1)$$

in which N is the wave action, $\frac{D}{Dt}$ is the total derivative, σ is the relative frequency and Q represents effect of sources and sinks for wave action. Three main sources and sinks are considered; the contribution of wind on wave growth which is a source (Q_{in}), the quadruplet nonlinear wave-wave interactions (Q_{nl}) which can be a source for some frequencies and a sink for others, and the dissipation term (Q_{dis}) due to white capping (Q_{wh}) and bed friction (Q_{bed}).

This model is developed for deep waters with spatial resolution of the order of 1 to 10 km. Different parametric equations can be chosen by the user for wind energy input, energy dissipation and non-linear quadruplet wave-wave interactions. This model uses an explicit third order finite difference scheme for solving spectral action density balance equation for wave number-direction spectra.

Nearshore Processes

There are two main processes in the nearshore region which affect wave generation. Nonlinear triad wave-wave interaction, considered as a source for some frequencies and a sink for others, is one of them and depth induced wave breaking and energy dissipation in the surfzone is the other. These two processes and the methods they are implemented in the model are described below.

Triad Wave-Wave Interaction

Lumped Triad Approximation (LTA), proposed by Eldeberky (1996), is a computationally efficient method to take the effects of triad wave-wave interactions into account. It is based on a deterministic model proposed by Madsen and Sorensen (1993). They used a complex expansion for water surface elevation ζ:

$$\zeta(x,t) = \sum_{p=-\infty}^{+\infty} \mathrm{A_p}(x) e^{i(\omega_p t - \psi_p(x))} \qquad (2)$$

in which p is the rank of harmonic, A_p is spatially varying complex Fourier amplitude and $A_{-p} = A_p^*$, with A_p^* being the complex conjugate of A_p, ω_p is angular frequency and $\omega_{-p} = -\omega_p$, ψ_p is the linear phase and $\psi_{-p} = -\psi_p$ and $\frac{d}{dx}\psi_p = k_p(x)$ in which k_p is wave number. Their final equation represents spatial evolution of A_p over a mild slope bottom. Using higher order spectra, Eldeberky calculated nonlinearity in phase averaged models. Defining complex Fourier amplitude C_p as:

$$C_p = A_p e^{i\psi_p} \quad (3)$$

one may find discrete power spectrum E_p as:

$$E_p = < C_p C_p^* > \quad (4)$$

in which $< \cdot >$ stands for expected value. Similarly, bispectrum $B_{m,p-m}$, which is the third order moment, can be defined as:

$$B_{m,m-p} = < C_m C_{p-m} C_p^* > \quad (5)$$

Bispectrum $B_{m,p-m}$ vanishes in two cases; first, if there is no energy available at frequencies m, p or $p-m$ and second, if there is no phase coherence between those three components. The phase of $B_{m,p-m}$ is called biphase and defined as:

$$\beta_{l,m} = \arctan\left(\frac{\mathrm{Im}\left[B_{l,m}\right]}{\mathrm{Re}\left[B_{l,m}\right]}\right) \quad (6)$$

The triad interaction process in LTA is restricted to self-self interactions to reduce the computational cost. The final source term in the Equation (1) due to triad interactions as derived by Eldeberky (1996) is:

$$Q_{nl3}(f_p,\theta) = Q_{nl3}^{+}(f_p,\theta) + Q_{nl3}^{-}(f_p,\theta)$$
$$Q_{nl3}^{+}(f_p,\theta) = \alpha c_p\, c_{g,p}\left(\frac{R_{\frac{p}{2},\frac{p}{2}}}{S_p}\right)^2 \times \sin\left|\beta_{\frac{p}{2},\frac{p}{2}}\right|\left[E_{\frac{p}{2}}^2 - 2E_{\frac{p}{2}}E_p\right]$$
$$Q_{nl3}^{-}(f_p,\theta) = -2Q_{nl3}^{+}(2f_p,\theta) \quad (7)$$

$Q_{nl3}^{\pm}$ represent the sum and difference triad interaction source terms, c_p and $c_{g,p}$ are the phase and group velocities for the p harmonic and α is a tuning parameter. The coupling coefficient R can be obtained from the Equation (8):

$$R_{m,p-m} = \left(k_m + k_{p-m}\right)^2 \times\left(\frac{1}{2} + \frac{\omega_m\omega_{p-m}}{ghk_m k_{p-m}}\right) \quad (8)$$

and S_p is:

$$S_p = -\frac{2}{g}(ghk_p + 2Bgh^3k_p^3 - (B+\frac{1}{3})h^2\omega_p^2 k_p) \quad (9)$$

in which $B = \frac{1}{15}$. Biphase in Equation (7) is calculated from experimental formula proposed by Eldeberky and Battjes (1995):

$$\beta(f_p, f_p) = -\frac{\pi}{2} + \frac{\pi}{2}\tanh\left(\frac{0.2}{Ur}\right) \quad (10)$$

In which Ur is the Ursell number defined as

$$Ur = \frac{g}{8\sqrt{2}\pi^2}\frac{H_s\, T_m^2}{h^2} \quad (11)$$

where h is water depth, T_m is mean wave period and H_s is significant wave height.

Depth induced Breaking and Dissipation

Depth induced wave breaking is a complex processes. Several models with different assumptions and simplifications have been proposed to describe energy decay due to wave breaking. In an extension to Battjes and Janssen (1978), Eldeberky first calculated the total local rate of random-wave energy dissipation per unit area due to breaking (D_{tot}) from:

$$D_{tot} = \frac{\alpha}{4} f_c Q_b H_m^2 \qquad (12)$$

where α is a parameter of order 1, f_c is a characteristic frequency (usually mean frequency) and Q_b stands for the fraction of broken waves given by:

$$\frac{1-Q_b}{\ln Q_b} = -\left(\frac{H_{rms}}{H_m}\right)^2 \qquad (13)$$

H_{rms} is the root mean square wave height and H_m is the maximum possible wave height:

$$H_m = \gamma h \qquad (14)$$

where h is the local water depth and γ is the breaking coefficient. Equation (13) requires a time consuming trial and error solution algorithm. An approximation can be made for Q_b through following set of equations:

$$\begin{cases} 0 & : \quad \beta \le .2 \\ Q_0 - \beta^2 \dfrac{Q_0 - e^{\frac{Q_0 - 1}{\beta^2}}}{\beta^2 - e^{\frac{Q_0 - 1}{\beta^2}}} & : \quad 0 < \beta \le 1 \\ 1 & : \quad 1 < \beta \end{cases} \qquad (15)$$

where $\beta = H_{rms} / H_m$; $Q_0 = 1$ for $\beta \le 0.5$ and $Q_0 = (2\beta - 1)^2$ for $0.5 < \beta \le 1$. Spectral distribution of energy decay can be found by applying the results obtained from Beji and Battjes (1993) experiments which showed that: (1) the dissipation does not interact with other processes affecting wave evolution and (2) the distribution of dissipation is in such a manner that it does not influence the local rate of evolution of the spectral shape. So depth induced breaking can be incorporated in Equation (1) as Q_{br}:

$$Q_{br}(f_r, \theta) = -\frac{D_{tot}}{E_{tot}} E(f_r, \theta) \qquad (16)$$

in which $E(f_r, \theta)$ is energy density at frequency f_r and direction θ and E_{tot} is the total wave energy.

Structure of WAVEWATCH-III and the process of modifying the source code

The core of WAVEWATCH-III consists of two main subroutines; W3INIT, which takes the input data and produces the initial values. The second subroutine, W3WAVE, performs as the main engine of the program and calls different subroutine to determine wave propagation in spatial and spectral spaces. One of the subroutines called by W3WAVE is W3SRC, which calculates the effects of source and sink terms using WAM semi-implicit integration scheme [Komen et al. 1996].

This subroutine takes the matrixes of values and the derivatives of the source/sink terms with respect to energy. Since wave breaking and triad interaction are considered as source and sink terms, this subroutine has been utilized to take their effects into account. In this part, the procedure of introducing these processes into W3SRC is described.

For triad interaction, the matrix of values can be obtained from Equation (7):

$$\begin{aligned} Q_{nl3}(f_p,\theta) &= Q_{nl3}^{+}(f_p,\theta) + Q_{nl3}^{-}(f_p,\theta) \\ Q_{nl3}^{-}(f_r,\theta) &= -2Q_{nl3}^{+}(2f_r,\theta) \\ Q_{nl3}^{+}(f_r,\theta) &= F_t \cdot E(\frac{f_r}{2},\theta) \\ &\times \left(E(\frac{f_r}{2},\theta) - 2E(f_r,\theta) \right) \end{aligned} \tag{17}$$

Where

$$F_t = \alpha c_p \, c_{g,p} \left(\frac{R_{\frac{p}{2},\frac{p}{2}}}{S_p} \right)^2 \sin \left| \beta_{\frac{p}{2},\frac{p}{2}} \right| \tag{18}$$

In order to calculate the matrix of derivative it is assumed that:

$$\begin{aligned} {Q_{nl3}^{+}}^{n+1}(f_r,\theta) &= F_t \cdot E^{n}(\frac{f_r}{2},\theta) \\ &\times \left(E^{n}(\frac{f_r}{2},\theta) - 2E^{n+1}(f_r,\theta) \right) \\ {Q_{nl3}^{-}}^{n+1}(f_r,\theta) &= -2F_t \cdot E^{n+1}(f_r,\theta) \\ &\times \left(E^{n}(f_r,\theta) - 2E^{n}(2f_r,\theta) \right) \end{aligned} \tag{19}$$

Taking the derivative of Equations (19) is straight forwards and yields:

$$\begin{aligned} \frac{\partial Q_{nl3}^{+}}{\partial E} &= -2F_t \cdot E(\frac{f_r}{2},\theta) \\ \frac{\partial Q_{nl3}^{-}}{\partial E} &= -2F_t \left(E(f_r,\theta) - 2E(2f_r,\theta) \right) \end{aligned} \tag{20}$$

For wave breaking the matrix of values can be obtained similarly from Equation (16):

$$Q_{br}(f_r,\theta) = -\frac{D_{tot}}{E_{tot}} E(f_r,\theta) \tag{21}$$

The derivatives are calculated as follows

$$\begin{aligned} Q_{br} &= -\frac{D_{tot}}{E_{tot}} E = \\ &-\frac{\alpha}{4} f_c Q_b H_m^2 \frac{E}{E_{tot}} = W_t \cdot E \end{aligned} \tag{22}$$

where W_t is:

$$W_t = -\frac{\alpha}{\pi} \frac{\bar{\sigma} Q_b}{BB} \tag{23}$$

Using (13), (22) and (23) BB is obtained as follows:

$$BB = 8\frac{E_{tot}}{H_m^2} = -\frac{1-Q_b}{\ln Q_b} \tag{24}$$

Using chain rule derivatives for Equation (22):

$$\frac{\partial Q_{br}}{\partial E} = \frac{\partial W_t}{\partial E} E + W_t \tag{25}$$

Since BB is proportional to E, the above equation can be rewritten as follows:

$$\frac{\partial Q_{br}}{\partial E} = \frac{\partial W_t}{\partial BB} BB + W_t \tag{26}$$

Considering Equation (23):

$$\frac{\partial Q_{br}}{\partial E} = -\frac{\alpha\bar{\sigma}}{\pi} \frac{\frac{\partial Q_b}{\partial BB} BB - Q_b}{BB} + W_t \tag{27}$$

where:

$$\frac{\partial Q_b}{\partial BB} = \frac{Q_b(1-Q_b)}{BB(BB-Q_b)} \tag{28}$$

Comparison between SWAN, modified WAVEWATCH-III results and field measurements

Results of modified WAVEWATCH-III are compared against SWAN which is another third generation model particularly developed for coastal areas, and field measurements. It should be noted that SWAN uses the same methods mentioned above for nearshore processes.

Station	Distance from P1 (m)	Depth (m)
P1	---	14.5
P6	241.2	10
W1	434.7	5.1
W6	507.3	3.6

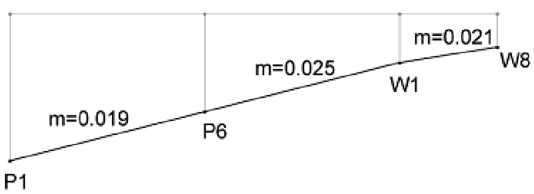

Figure 1: Bathymetry for non-breaking wave test.

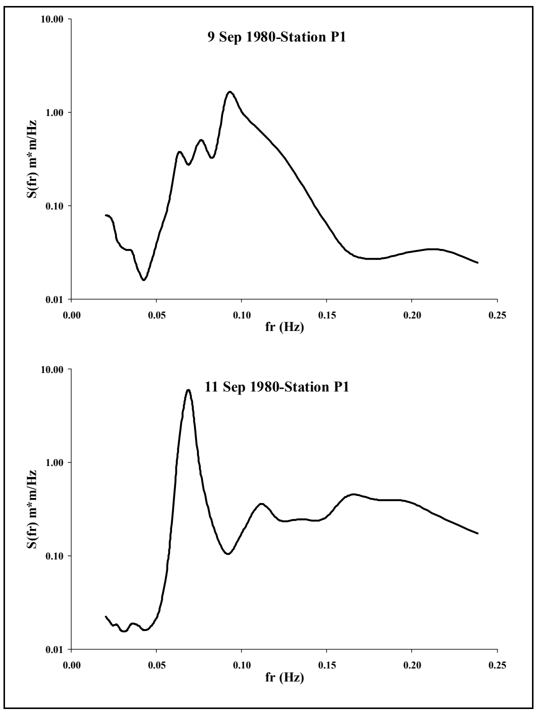

Figure 2: Input frequency spectrums for non-breaking waves tests.

Non-breaking waves (field observations)

Field measurements of Freilich and Guza (1984), at Torrey Pines Beach, California are used for testing the models for non-breaking waves. Their experiments cover the so called "Shoaling Region" of a wave field, defined as the nearshore area excluding breaker zone. Wave propagation was almost normal to the coastline. Bathymetry is semi-linear and in their paper, numerical simulations were made assuming a constant bottom slope of 0.022 instead of the real bathymetry. Water depths were available at 4 stations, so linear approximation is used here between stations shown in Fig. (1).

The measured frequency spectrums in station P1 in Sep 9, 11 in 1980 are shown in Fig. (2). the first spectra (9 Sep 1980) is wide band frequency spectrum while the other (11 Sep 1980) is narrow band one.

These spectrums are used as the boundary conditions for models. There was no information about direction distribution of energy in direction-frequency spectrum in station P1. So a simple cosine type direction function is used. Special resolution was 60 meters in this test. Since the propagation and not generation of wave is important here so no wind-wave interaction and quadruplet wave-wave interaction is considered. Bed dissipation is calculated from JONSWAP method [Tolman (1999)].

The frequency spectrum output of SWAN, modified WAVEWATCH-III and

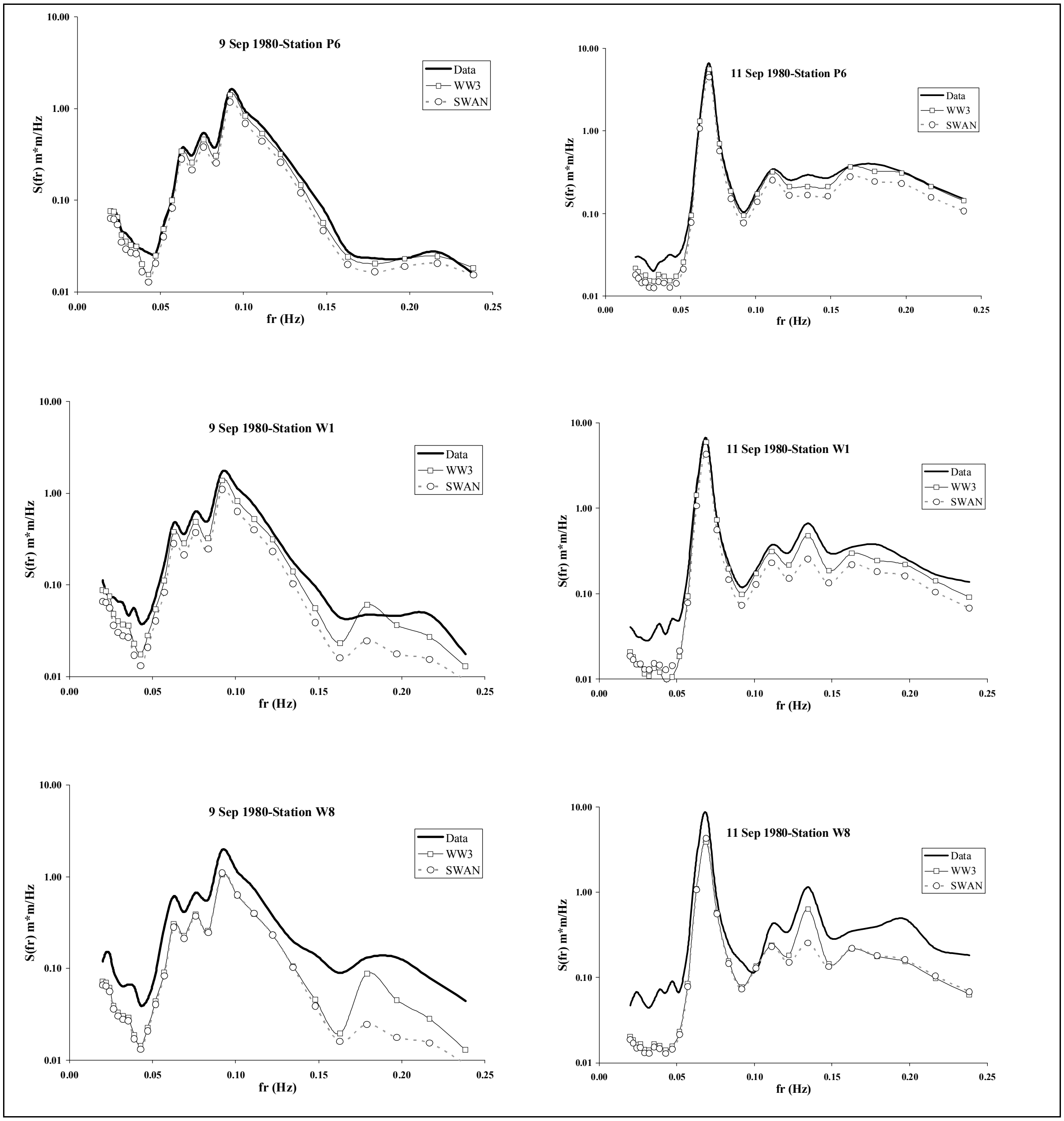

Figure 3: frequency spectrum for 9 Sep 1980 and 11 Sep 1980 in stations: P6, W1 and W8.

field measurements in stations: P6, W1 and W8 are shown in Fig. (3). As in both models, only positive contributions to higher harmonics are considers and no energy is transferred to low frequencies, both models have underestimate energy density function in low frequency part of the spectrum.

It seems both models have some problem for wide band spectrum (9 Sep 1980) between f_p and $2f_p$ and this part of spectrum should get much more energy.

Although good agreement can be seen between model results and measured data but modified WAVEWATCH-III is obviously more successful.

Breaking Waves (laboratory data)

Propagation of waves in shallow water for breaking waves in SWAN and modified WAVEWATCH-III has been verified against laboratory measurements of Arcilla et al. (1994). The bed profile is shown in Fig (4). Frequency spectrum in station (1) is shown in Fig (5). This spectrum is used as a boundary condition for both models. Spatial resolution was 10 meters and again, wind-wave generation and quadruplet wave-wave interactions are disabled in both models.

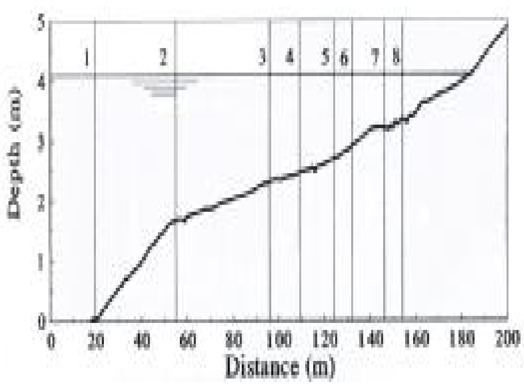

Figure 4 : Bathymetry for breaking waves test.

Breaking coefficient γ in the Equation (14) can be chosen between 0.6 and 0.83 [Booij (2004)]. The energy spectrums in stations 4, 6 and 8 are shown in Fig. (6) using breaking coefficient $\gamma = 0.83$. As shown in Fig. (7) Using lower value for γ makes better agreement in the station 8 but increases the errors in the prediction of spectrums in the station 6 and 4. The least error in these three stations is found by $\gamma = 0.83$.

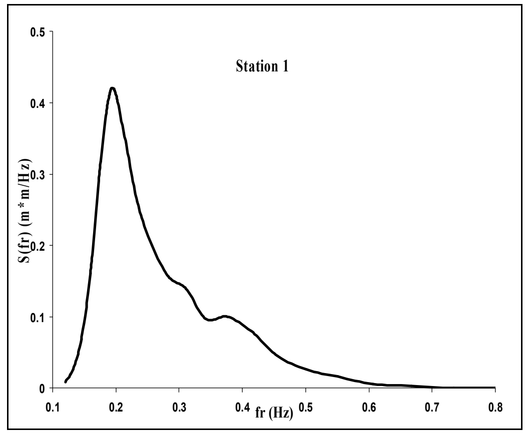

Figure 5 : Input frequency spectrum for breaking waves test.

As shown in Fig. (6), in the stations 4 and 6, both models underestimate the energy density function. Both models have almost the same values in all the frequencies. But in the station 8, which has the least water depth, SWAN output is closer to measured data except in high frequency part of spectrum in which more energy transfer to second harmonic $(3f_p)$ in modified WAVEWATCH-III results to better agreement with field data than swan results.

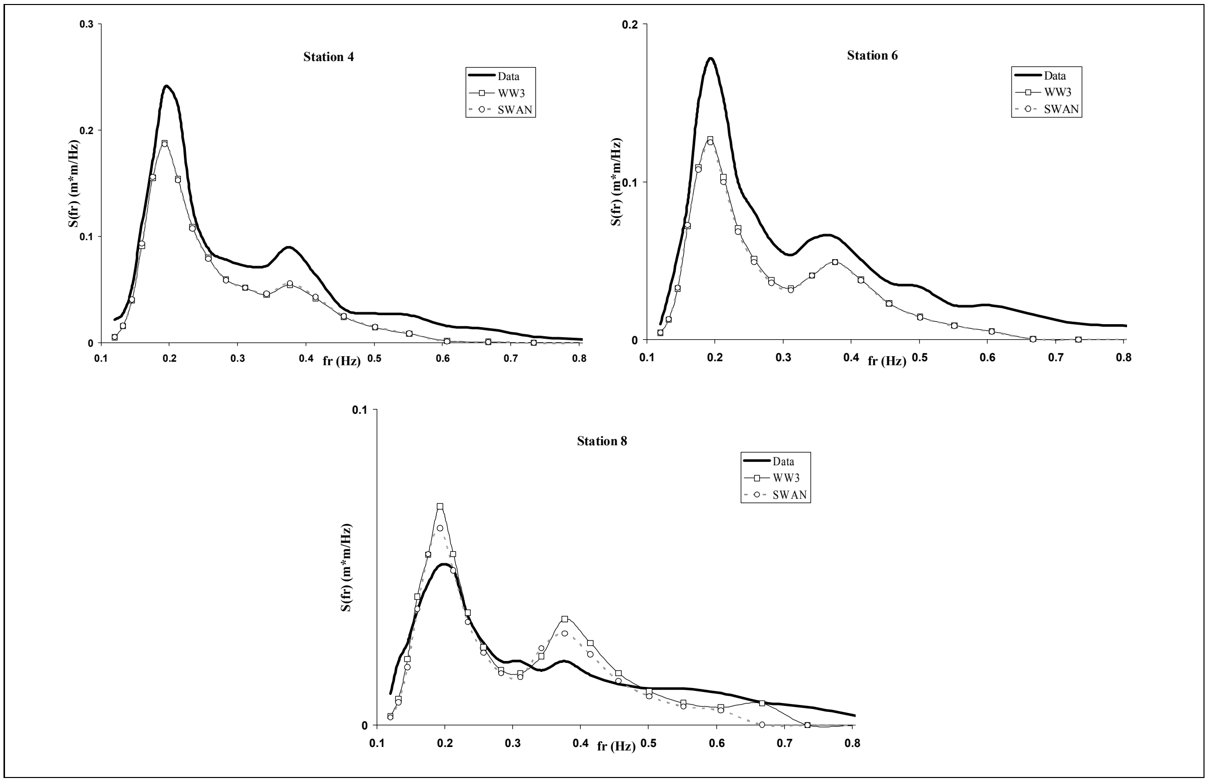

Figure 6 : frequency spectrum for breaking test in stations 4, 6 and 8 using $\gamma = 0.83$.

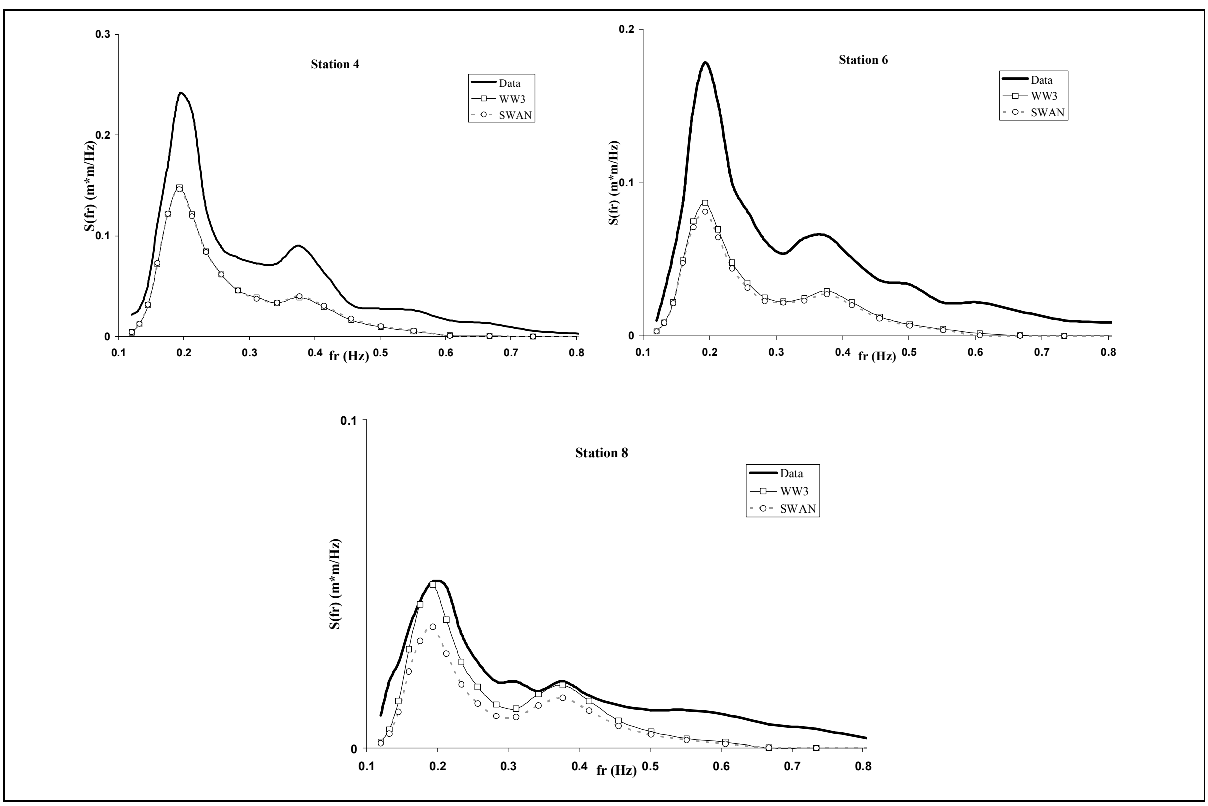

Figure 7: frequency spectrum for breaking test in stations 4, 6 and 8 using $\gamma = 0.6$.

Conclusions and Recommendations

Triad Nonlinear interactions and Depth induced breaking was included as a nearshore processes to WAVEWATCH-III and the result of modified model was compared against field and laboratory measurements.

Comparison against the results of non-breaking field observations revealed that LTA model performs well for narrow banded wave spectrum. However, for the transformation of a wide banded wave spectrum in the non-breaking zone , this method underestimated energy density around $1.5 f_p$.

Breaking waves test showed good agreement between the results of modified model with SWAN. However, SWAN showed slightly better results in comparison with laboratory measurements. The agreement between models and experimental data was highly dependent on the value of breaking coefficient γ. In order to obtain better agreement between models results and laboratory data, a decreasing value of γ from 0.83 to 0.6 is proposed as transformation is carried out into the surfzone. In other words, variable γ (depending on water depth) can improve the results of mathematical models.

Implementation of shallow water processes such as triad wave-wave interaction, wave breaking and dissipation in the surfzone into WAVEWATCH-III made it fairly applicable to shallower waters.

The original numerical scheme of the model is equally applicable for coastal scales.

It should be mentioned that in this paper, models were only verified against measurements in the case of water wave propagation toward coastal areas. Field and numerical experiments including wave generation are required to validate the model for a broader range of applications.

Acknowledgements

The authors acknowledge the grateful help and guidance from Dr. Tolman.

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