Evaluation of SWAN numerical model & SPM method for wave hindcasting

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Abstract
Wave characteristics are one of the most important factors in design of coastal and marine structures. Therefore accurate prediction of wave parameters is very important. The wave hindcasting process is conducted by field measurements, empirical methods or numerical simulations. In this paper the SWAN third-generation spectral model and SPM (Shore Protection Manual) empirical method have been used for prediction of wave parameters. The field data set for Lake Erie of the Great Lakes in year 2002 has been used for evaluation of these methods. The significant wave height (H_s) and the peak wave period (T_p) were the parameters employed in the study. Rectangular grids have been utilized for identification of bathymetry and the SWAN has been executed in nonstationary mode. The exponential growth from wind input, four-wave nonlinear interaction, whitecapping, and bottom friction have been taken in the simulation. The calibration of SWAN was carried out based on wave height because it is more important than wave period. The results of this study show that the average scatter index of SWAN is about 17 percent for significant wave height and 19 percent for peak period, whereas average scatter index of SPM method is about 54 and 36 percent for significant wave height and peak period.

1-INTRODUCTION

In the marine environment the planning of the sustainable development of economic activities requires long term information about environmental conditions such as waves. Accordingly, the knowledge of wind waves statistical characteristics is necessary in a variety of applications including coastal engineering design, studies of sediments transport and coastal erosion and pollution processes. Due to incompleteness of such information in many regions, the wave characteristics should be produced with an appropriate method. Hindcasting process is conducted by numerical models or empirical methods.

Until now different empirical methods have been developed for wave hindcasting such as SMB (Bretschneider, 1970), Wilson (Wilson, 1965), JONSWAP (Hasselmann et al., 1973), Donelan (Donelan, 1980 & Donelan et al., 1985), Shore Protection manual (SPM, 1984) and Coastal Engineering Manual (CEM, 2003). Furthermore in recent years with development of high speed processors several complicated numerical models have been developed for wave prediction. These models are usually phase-averaged spectral wave model that developed in three generations and consist of various physical processes.

SWAN (Booij et al. 1999, Ris et al. 1999) is one of the most widely applied spectral wave models at present in coastal engineering studies and is freely available for both research and consultancy studies. This model specially designed for coastal applications and can be used from laboratory conditions to ocean scale.

Such numerical models are more time consuming than empirical methods and should have more accurate results.

Weiqi Lin. et al (2002) have used the SWAN model for wave simulating in Chesapeake Bay. Their results show that the SWAN model over estimates significant wave height and under estimate peak wave period. In their simulation all of the wave heights have been below than 1 meter. The SWAN model also has been used for simulating typhoon waves in coastal waters of Taiwan (Ou et al., 2002).

The aim of this study is to evaluate the SWAN numerical model and SPM empirical method by comparing their results with field observations. For this purpose the wave records of Lake Erie of the Great Lakes in year 2002 have been used. For evaluation of the model accuracy the significant wave height (H_s) and the peak wave period (T_p) were the parameters employed in the study and BIAS parameter and scatter index were used for comparing with field observations.

2- Field data

In this study the meteorological and wave record information of Lake Erie of the great lakes have been used. Lake Erie has a laterally-prolonged scale of about400 km in the west-east direction between $79^0\ 00'\ W$ and $83^0\ 30'\ W$. Its width is about 100 km in the north-south direction between $41^0\ 30'\ N$ and $44^0\ 00'\ N$. This lake has an average depth about 19 meters and the deepest water depth is only 58 m around the position in lat. 42° north and in long. 80° West. The data recorded of two buoys have been used in this study. The ID numbers of the buoys with their water depth and are; 45005 (14.6 m) and 45132 (22.0 m) respectively. The height of the anemometer equipped to each buoy is 5 m over the lake surface. Figure 1 illustrates Lake Erie contour lines of water depth and location of 2 buoys deployed for wind and wave measurement. The used data consist of hourly measured wind speed and direction and wave height and period. For evaluating of the SWAN model the subset of data recorded in 2002 have been used.

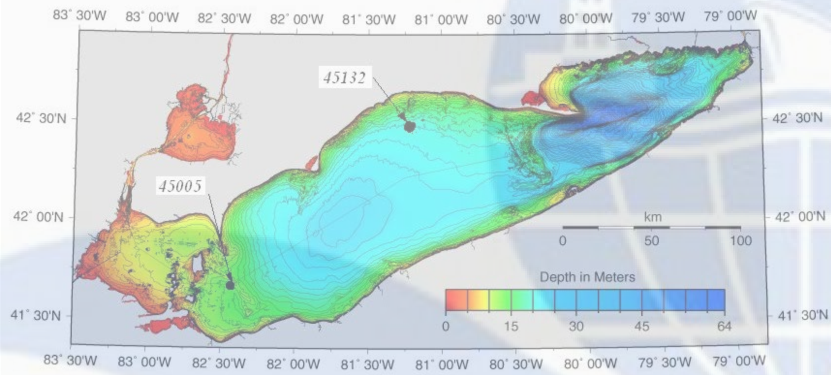

Figure 1. Grid on Lake Erie, contour line of water depth and location of each buoy.

3- Wave prediction methods

3-1 The SWAN model

The SWAN model (Booij et al. 1999, Ris et al. 1999) is a third generation spectral model, suitable for the simulation of wind generated waves from the nearshore to the surf-zone. The spectrum that is considered in SWAN is the action density spectrum rather than the energy density spectrum. The action density is equal to the energy density divided by the relative frequency:

$$N(\sigma,\theta) = E(\sigma,\theta)/\sigma \qquad (1)$$

The independent variables are the relative frequency σ (as observed in a frame of reference moving with current velocity) and the wave direction θ (the direction normal to the wave crest of each spectral component). In the SWAN wave model the evolution of the wave spectrum is described by the spectral action balance equation which for Cartesian coordinates is (Hasselmann et al., 1973):

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}C_x N + \frac{\partial}{\partial y}C_y N + \frac{\partial}{\partial \sigma}C_\sigma N + \frac{\partial}{\partial \theta}C_\theta N = \frac{S}{\sigma} \qquad (2)$$

The first term in the left-hand side of this equation represents the local rate of change of action density in time, the second and third term represent propagation of action in geographical space (with propagation velocities C_x and C_y in x and y space, respectively). The fourth term represents shifting of the relative frequency due to variations in depths and currents (with propagation velocity C_σ in σ space). The fifth term represents depth-induced and current-induced refraction (with propagation velocity C_θ in θ space).

The term $S(=S(\sigma,\theta))$ at the right hand side of the action balance equation is the source term in terms of energy density representing the effects of generation, dissipation and nonlinear wave-wave interactions. This term consists of linear and exponential growth by wind, dissipation due to whitecapping, bottom friction and depth-induced wave breaking and energy transfer due to quadruplet and triad wave-wave interaction.
The integration of the action balance equation has been implemented in SWAN with finite difference schemes in all five dimensions: time, geographic space (x, y) and spectral space (σ,θ). The equations are solved numerically and in a trial and error process.

3-1-1-SWAN simulation

In this study the SWAN cycle III version 40.41 has been used for wave simulation. The model has been run in third generation and in nonstationary mode (the use of time series for wind condition) with Cartesian coordinates. Linear (Cavaleri et al. 1981) and exponential (Komen et al. 1984) growth of wind input have been used. Quadruplet wave interaction activated for nonlinear interaction and has seen that activating of triad interaction has no effect in results because of deep water location of measurements. Dissipation due to whitecapping, bottom friction and depth-induced wave breaking have been considered in the simulation. Since the SWAN model uses the wind velocity in 10-meter elevation and the measured velocities are in 5-meter elevation, the following equation has been used to change the velocities for SWAN input (SPM, 1984):

$$U_{10} = U_Z\left(\frac{10}{z}\right)^{\frac{1}{7}} \tag{3}$$

Wind speed and direction have been given to the model as time and domain variable. The used time step was 10 minutes and spectral space were computed at 36 equally spaced propagation directions in the circle and 40 logarithmically spaced frequencies, between 0.05 Hz and 1 Hz. This means that the lowest period of simulated wave is 1 second and the highest is 20 second covering typical surface waves in Lake Erie. In the simulation a computer with 2.4 GHz processor has been used and the time of running the model for 12 hours simulation, was about 8 minutes.

3-2 The SPM method

SPM semi-empirical method is based on JONSWAP spectral method that presented in shore protection manual (SPM, 1984). This method is appropriate only if the geometry of the waterbody is relatively simple. Under fetch-limited conditions, winds have blown constantly long enough for wave heights at the end of the fetch to reach equilibrium. Under duration-limited conditions, the wave heights are limited by the length of time the wind has blown. These two conditions represent asymptotic approximations to the general problem of wave growth. In most cases the wave growth pattern at a site is a combination of the two cases.
In this method dimensionless wave height and period have been defined using wind-stress factor U_A and dimensionless fetch. In this method some adjustment should be conducted on the wind speed and finally the wind-stress factor U_A must be calculated (SPM, 1984). After calculating of fetch length and U_A, this method can be used for predicting the significant wave height and the peak spectral period in fetch limited; duration limited and fully developed conditions. For fetch limited condition, the wind duration must be greater than t_{min}, which is given as:

$$t_{\min} = 6.88\times10^1\left(\frac{U_A}{g}\right)\left(\frac{gF}{U_A^2}\right)^{2/3} \tag{4}$$

Where F is the fetch length (m) and g is the gravitational acceleration (m/s^2). If the wind duration is smaller than t_{min}, the duration limited condition will occurred and equivalent fetch length should be calculated from equation (4) with substituting wind duration instead of t_{min}.

Then the significant wave height and the peak spectral period can be computed from the following equations:

$$H_{m_o} = 1.6\times10^{-3}\left(\frac{U_A^2}{g}\right)\left(\frac{gF}{U_A^2}\right)^{1/2} \quad (5)$$

$$T_P = 2.857\times10^{-1}\left(\frac{U_A}{g}\right)\left(\frac{gF}{U_A^2}\right)^{1/3} \quad (6)$$

Where H_{mo} is the significant wave height (m) and T_P is the peak spectral period (s); and U_A is the wind-stress factor (m/s).

4- Results and discussion

For wave simulation and analysis of measured and predicted wave characteristics a 270 hours time series from 21 o'clock of third of November of 2002 to 2 o'clock of 15th November of 2002 has been chosen. Figure 2 shows the variation of wind speed and direction for this period in each 2 buoy. Also some statistic information of recorded wind data has been illustrated in table 1.

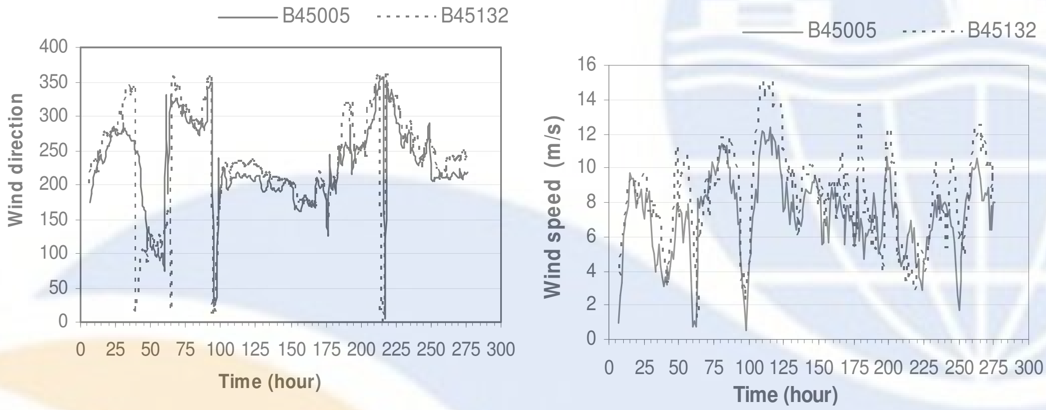

Figure 2. Variation of wind speed and direction in each 2 buoy

Table 1. Statistic specification of recorded wind data in two buoys.

Buoy	Wind speed (m/s)				Wind direction			
	minimum	maximum	average	Standard deviation	minimum	maximum	average	Standard deviation
45005	0.5	12.2	7.2	2.39	5	357	230.4	60.9
45132	1.3	15.1	8.1	2.94	0	360	230.4	77.0

In figure 3 the predicted and measured significant wave height (H_s) and peak spectral period (T_p) of tow buoys has been illustrated. It is necessary to mention that the initial four hours of simulation has been eliminated due to warming up of the model.

As can be seen in figure 2, the wind direction has been variable and hasn't been followed a regular regime. According to this figure can be claimed that most winds have blown from west and north-west of the lake. In addition the wind speed has had many changes. So the sensitivity of the SWAN model to change of wind speed and direction can be evaluated. According to figure 3 the SWAN predict the H_s very well while underestimates the T_p. The SPM method also predicts the maximum of significant wave height and peak wave period very higher than recorded values.

For quantitative evaluation of these methods efficiency the bias parameter and scatter index have been used for comparison of measured and predicted values:

$$Bias = \sum_{i=1}^{N}\frac{1}{N}\left(S_i - O_i\right) \quad (4)$$

$$SI = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - O_i)^2}}{\frac{1}{N}\sum_{i=1}^{N}O_i} \qquad (5)$$

Where: *SI* is scatter index, *N* is total number of data, O_i is measured data and S_i is predicted data from the SWAN model or SPM method. Table 2 and 3 show the summary of statistical analysis of wave prediction error in studied period.

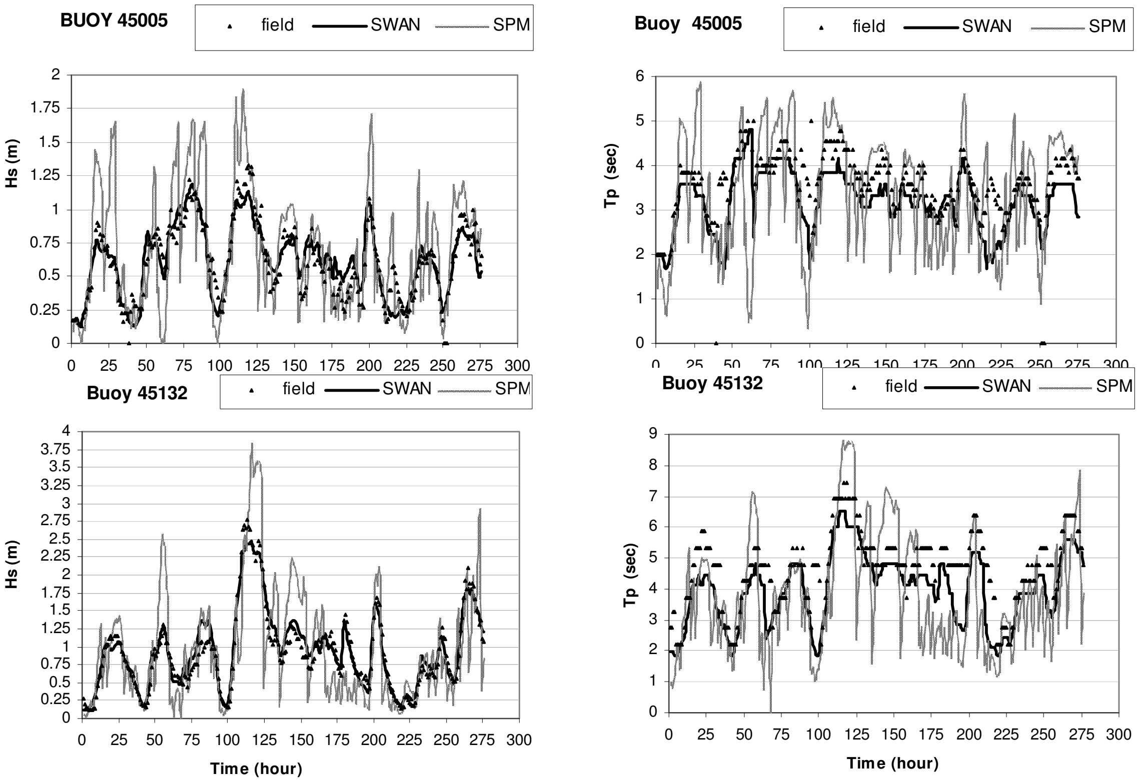

Figure 3. H_S and T_p for measured and predicted data in each buoy

Table 2. The summary of statistical analysis of wave prediction for the SWAN model

Buoy	H_s (m)			T_p (sec)		
	Ave.	**Bias**	**SI**	**Ave.**	**Bias**	**SI**
45005	0.62	0.00	19.74	3.59	-0.38	18.80
45132	0.93	0.02	14.18	4.69	-0.68	19.74
Average	0.78	0.01	16.96	4.14	-0.53	19.27

Table 3. The summary of statistical analysis of wave prediction for the SPM method

Buoy	H_s (m)			T_p (sec)		
	Ave.	**Bias**	**SI**	**Ave.**	**Bias**	**SI**
45005	0.62	0.08	52.39	3.59	-0.21	33.95
45132	0.93	0.02	56.60	4.69	-0.86	38.96
Average	0.78	0.05	54.50	4.14	-0.54	36.46

According to the negative Bias parameter in tables 2 and 3, both methods underpredict the peak spectral period. In addition the maximums of significant wave height that are modeled with SWAN are smaller than the measured value. The reason could be justified by blowing the sudden gusts while in the simulation the 1 hour average of wind speed has been used. The SPM method in general overpredicts the significant wave height and underestimates the peak spectral period. Locally this method predicts the maximum of significant wave height and peak wave period very higher than recorded values that occurs in high durations.

5-conclusions

In this study, wind and wave characteristics on Lake Erie of the Great Lakes were investigated. The obtained results are summarized as follows:

The SWAN model showed a fairly good response in predicting the rate of change of H_s and T_p when wind suddenly changes its direction and speed.

The SWAN model slightly over-predicted significant wave height and under-predicted peak spectral period. The average Bias parameter for H_s was 0.01 meter and for T_p was -0.53 second. While the average of recorded wave height and period were 0.78 meter and 4.14 second respectively. The scatter indexes between modeled and measured data were 16.96 and 19.27 percent for significant wave height and peak spectral period respectively. So the accuracy of the SWAN model in simulating wave height was better than wave period.

The SPM method over-predicted significant wave height and under-predicted peak spectral period. The average Bias parameter for H_s was 0.05 meter and for T_p was -0.54 second. The scatter indexes between modeled and measured data were 54.5 and 36.46 percent for significant wave height and peak spectral period respectively. The accuracy of the SPM method in simulating wave period was better than wave height. Locally this method has predicted the maximum of significant wave height and peak wave period very higher than recorded values that occurs in high durations.

Finally it can be said that using the SWAN numerical model is more accurate than SPM empirical method and leads to better results for both wave height and period. But it should be noticed that using of numerical model is more time consuming than empirical methods and needs some extra information such as calibration data.

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