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# Sensitivity analysis of numerical wave predictions models, considering wind and geometry effects in rectangular lakes

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ABSTRACT

Wave prediction is one of the most important issues in coastal and ocean engineering. This study investigates the wave regime in lakes under different lake geometric parameters and wind speeds and directions. For this purpose several SWAN simulations are carried out to study the wave regime considering different geometry and wind conditions. The model sensitivity to computational grid size is thoroughly investigated to apply the optimum grid size for accurate results in the shortest computation time. SWAN results are compared with different empirical wave prediction methods for different lake geometries and winds. CEM and Krylov methods show the most accurate predictions in shallow water, and SMB and Krylov in deep water. Finally the effects of different parameters like fetch, depth, bed slope, wind direction, and wind speed on prediction of wave are studied. Results show that the increase in fetch length increases the wave height. Wind speed and direction will affect the length for fully developed wave regime. Bed slope increases the water depth and consequently the wave height, and wave reaches its fully developed condition in longer distance. In a lake with 10 m depth wave height has an increasing trend for about 85 km before reaching fully developed situations.



## 1. Introduction

The estimation of wave height is essential for almost any engineering activity in the oceans and lakes. Wave prediction in coastal areas has direct effect on the safety and efficiency of any coastal design. Underprediction of wave height may end up in failure of the coastal and marine structures while overestimation may unnecessarily increase the construction costs. Any numerical model in wave regime prediction needs a complete source of inputs including lake or coastal characteristics, such as size, bed slope, bed friction, and depth as well as wind speed and direction (Nekouee and Hamidi, 2015). In many cases there is no accurate data for lake geometry and wind regime, or it is very expensive and unpractical to collect these data. For this reason it is an important challenge in any coastal design and also for marine navigation to have a good prediction of the wave regime while the input data is sparse. Sensitivity study of wave prediction models (numerical and empirical) gives coastal engineers and researchers a preliminary idea about the accuracy level of their methods and this will help to avoid any overestimation or underprediction of wave heights and consequently any unnecessary costs or failure in coastal engineering and navigation.

Different empirical, numerical and soft computing approaches have been proposed for wave prediction in lakes (Abed-Elmdoust and Kerachian, 2012). In sediment studies, wave prediction has also direct influence on the estimation of sediment transportation. Sediment is one of the leading sources of pollutants in the coastal areas. Sediments in shallow lakes influence physical and chemical processes in the water column. Suspended sediment increases light attenuation along the water column and affect the growth of phytoplankton and photosynthesis (Hamidi et al., 2013). In addition, nutrients may interact with suspended sediment through the processes of adsorption and desorption (Chao et al., 2008). Jin and Sun (2007) studied the flow circulation, wave dynamics and their impacts on sediment resuspension and vertical mixing in Lake Okeechobee and presented that wave action is the dominant factor in sediment resuspension in the lake. Cozar et al. (2005) showed correlations between total turbidity and wind speed observations. Luettich et al. (1990), Hawley and Lesht (1992), and Rebich and Knight (2001) have shown that sediment resuspension in shallow lakes is primarily a result of wave action. Hawley et al. (2014) studied the sediment resuspension in Saginaw Bay and showed that sediment resuspension in both the inner and outer bay is due almost entirely to surface wave action. The knowledge of wave climate is necessary in a variety of applications including design of coastal structures, sediment transport, coastal erosion and pollution transport studies. Due to the lack of measurements in many

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regions of the world, wave characteristics are estimated using different methods. Wave climate hindcasting is mostly conducted by numerical models or empirical methods (Moeini and Etemad-Shahidi, 2007).

Although waves and its occurrence and interaction with coastal structures have been an area of concern for researchers for a long time, but in recent decades our knowledge has been improved by utilizing high capacity computers. The pioneer modeling attempts in wave prediction considered the pressure and the shear tension variation, caused by wind, as a driver of the waves. So having a good knowledge of boundary layer at the interface of water and atmosphere is critical for any wave prediction study (Massel, 1996). Lin et al. (2002) used SWAN model for wave prediction in Chesapeake Bay. They showed that SWAN model overestimates significant wave height and underestimates peak spectral period where all wave heights were less than 1 m. Liu et al. (2002) compared the results of different third generation wave models for Lake Michigan. They showed that all the models they used for wave hindcasting are weak in prediction of wave peak period.

The major goal of this study is to investigate the wave regime in lakes under different lake and coastal geometries and wind regimes. As mentioned above it is a very important task to have an accurate prediction of wave height and frequencies while the input sources are sparse. Having a precise knowledge about the sensitivity of different numerical and empirical wave models to geometric and meteorological inputs is critical for any coastal design, sediment studies, navigation, and coastal management. This study gives necessary knowledge to coastal engineers to makes a rational judgment when there is not complete data on coastal geometry and wind regime. To simplify the problem for all cases the lake is considered rectangular with a constant wind speed and direction. In order to have a proper grid size for each run, the effect of grid size on accuracy of results is studied and the optimum grid is chosen for each condition. SWAN results are compared with different empirical wave prediction methods, including CEM, Donelen, krylov, and SMB, for different lake geometries and wind conditions. Finally, the effects of different parameters like fetch, bed slope, wind direction, and wind speed on prediction of wave are studied.

## 2. Methods

### 2.1. SWAN numerical wind-wave model

In this work, SWAN (Simulation of WAves Nearshore) a third generation wave prediction model specialized for coastal and inland waters (Booij et al., 1999) are applied to predict wave regime in idealized lake geometries. This model has been developed and verified in Delft Research Institute (Ris et al., 1999; Booij et al., 1999; SWAN Group, 2003). Extensive data of field experiments such as those conducted by Lin et al. (2002) and Nekouee and Hamidi (2015) have been used for model verification. The code uses an implicit upwind finite difference scheme to solve the wave action density ($N$) balance equation that is based on radiative energy transfer principle in Cartesian coordinate system (Hasselmann et al., 1973):

$$\frac{\partial}{\partial t}N+\frac{\partial}{\partial x}C_xN+\frac{\partial}{\partial y}C_yN+\frac{\partial}{\partial \sigma}C_\sigma N+\frac{\partial}{\partial \theta}C_\theta N=\frac{S}{\sigma} \tag{1}$$

where $\frac{\partial}{\partial t}N$ represents the local action density temporal variation rate, $\frac{\partial}{\partial x}C_xN$, and $\frac{\partial}{\partial y}C_yN$ show the action propagation in $x$ and $y$ directions, $\frac{\partial}{\partial \sigma}C_\sigma N$, represents shifting of the relative frequency due to depths changes and currents with the propagation velocity $C_\sigma$ in $\sigma$ direction, and $\frac{\partial}{\partial \theta}C_\theta N$ represents depth-induced and current-induced refraction with the propagation velocity $C_\theta$ in $\theta$ direction. The propagating velocities are defined based on linear wave theory (Massel, 1996).

$S=S(\sigma,\theta)$ is the source function represented in terms of energy density that is a combination of the wave growth effects by wind, dissipation, and nonlinear wave–wave interactions as below:

$$S=S_{in}+S_{ds}+S_{nl} \tag{2}$$

$S_{in}$ represents transfer of wind energy to waves with a resonance and a feedback fluctuation mechanism as described in SWAN manual (SWAN Group, 2003). The terms corresponding to these mechanisms are defined as the summation of a linear and exponential growth contribution. The dissipation term$S_{ds}$, is shown by the sum of three energy loss terms due to whitecapping, bottom friction and depth-induced breaking. The last term$S_{nl}$, covers the effect of quadruplet wave interactions in deep water and triad wave–wave interactions in shallow water. These two mechanisms primarily determine the exchange and redistributing of the resonant sets of wave in energy spectrum (SWAN Group, 2003).

Three types of discretization are used in SWAN: spectral, spatial, and temporal for nonstationary computations. Spectral grids are defined by the user that includes two kinds of computational grids: frequency and directional space. For application in coastal areas it is recommended to use $\Delta\theta$ between 10–15° for wind sea and 2–5° for swell conditions; $f_{min}$ and $f_{max}$ is also recommended to be respectively 0.04 and 1.00 Hz. We discretize frequency and directional space respectively into 50 and 36 elements in all executions. The lowest frequency used in the test was 0.05 Hz and the highest discrete frequency was 1 Hz. This meant that the lowest wave period to be modeled was 1 s and the highest period to be modeled was 20 s, covering the period range of surface wind waves in the lakes.

### 2.2. Grid sensitivity study

The proper size of computational grids needs to be determined before any numerical model runs, as using a finer mesh increases the computational time and reduces computational errors. An investigation was carried out on a rectangular lake with different dimensions to obtain an optimum limit of computational mesh size in order not to lose the accuracy of the results up to about 10% and not to take considerable time on each execution. The number of runs is summarized in Table 1.

The spatial grids are categorized in three groups: input, computational and output grids. Input grids (bottom, current field, water level, friction coefficient and wind) are mainly dependent on field data availability and influence on wave regime. To avoid numerical instability it is better to use the same mesh for input and computational grids.

**Table 1**
Summary of grid size, wind, and lake geometry.

| Study cases | No. of runs | Lake size (km) | Depth (m) | Wind vel. (m/s) | Wind dir. (deg) | Slope |
|---|---|---|---|---|---|---|
| Grid size (bed) | 16 | 20 × 100 | 10 | 10 | 90 | 0 |
| Grid size (computational) | 16 | 5 × 5, 10 × 10, 10 × 50, 5 × 100 | 5 | 5, 20, 30 | 30, 60 | 0, 0.0001 |
| Comparison with empirical methods | 4 | 20 × 100 | 2, 20 | 20 | 90 | 0 |
| Lake geometry and wind parameters | 36 | 5, 10, 50, 100 | 2, 20 | 5, 10, 20, 30 | 0, 30, 60, 90 | 0, ±0.0001, ±0.0002 |