

**FIELD MEASUREMENTS AND NUMERICAL MODELING OF WIND-WAVES
IN LAKE BIEL: A BASIC TOOL FOR SHORE PROTECTION PROJECTS**

SAYAH S.M.¹, MAI S.², BOILLAT J-L.³ and SCHLEISS A.J.⁴

¹ Ecole Polytechnique Fédérale de Lausanne (EPFL),
Laboratory of Hydraulic Constructions (LCH), CH-1015 Lausanne, Switzerland,
(Tel: +41-21-693-24-82, Fax: +41-21-693-22-64, e-mail: selim.sayah@epfl.ch)

² University of Hannover, now at German Federal Institute of Hydrology, Koblenz, Germany,
(Tel: +49-261-1306-5322, Fax: +49-261-1306-5369, e-mail: mai@bafg.de)

³ Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Hydraulic Constructions
(LCH), CH-1015 Lausanne, Switzerland,
(Tel: +41-21-693-23-82, Fax: +41-21-693-22-64, e-mail: jean-louis.boillat@epfl.ch)

⁴ Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Hydraulic Constructions
(LCH), CH-1015 Lausanne, Switzerland,
(Tel: +41-21-693-23-82, Fax: +41-21-693-22-64, e-mail: anton.schleiss@epfl.ch)

Abstract

Large lakes in Switzerland, as many other lakes in Europe, suffer from severe beach erosion. In order to thwart the continual regression of shores, systematic analysis of the effect of wind waves on natural shores is undertaken. The analysis allows a better and comprehensive understanding of the impact of waves on the surf zone, generated during mean as well as extreme wind events. It provides a helpful tool for the design of shore protection measures in Swiss lakes. The research is carried out at Lake Biel. It comprises field measurements of wind and waves, and includes furthermore, numerical simulations of wind-waves. In a first stage, a large-scale phase averaging wave model is set-up. This allows predicting the wind generated surface wave climate in Lake Biel and the impact of incident waves on the eroding shores. The simulation is based on in-situ measurements of wind over land and water, in addition to wave characteristics. The results are compiled in a wave atlas relating wind conditions (speed and direction) and wave conditions (significant wave height, mean period, mean wave direction). Using the transfer functions, wave statistics are determined based on wind statistics. For the calibration of the model, a transient calculation of the wave field is carried out using a time-series of winds, measured in December 2003, as the driving force. The quality of the model is proven when comparing its results with wave measurements. They can be used to analyze the effectiveness of different projected shore protection measures, e.g. brushwood fences or breakwaters.

Keywords: In situ measurements; Wind and wave prediction; Numerical wave modelling

1. INTRODUCTION

The present paper investigates the wind generated waves in Lake Biel on the basis of in situ wave measurements, and numerical modeling using the SWAN wind wave model. Such investigation aims at providing an adequate wave prediction tool for shore protection projects. The proposed methodology is applicable, not only for the present case study, but for other confined water surfaces, where fetch limited conditions prevail.

At present, when no in situ measurement is available, wind-wave prediction in lakes for shore protection projects, is commonly based on empirical approaches requiring knowledge of the wind velocity, direction, frequency, and duration on one hand, and the fetch of the project location on the other hand (Sayah et al. 2004a). However, such knowledge does not take into consideration the effect of the changing bathymetry of the lake that may modify significantly wave heights and directions. Furthermore, the waves obtained by before-mentioned calculations are related to deep water region. Additional calculations need thus to be realised in order to define the waves at the project location, making the procedure of wave estimation, long and full of uncertainties.

The proposed new methodology is summarized in Fig. 1. It consists firstly on an appropriate selection of on-land anemometers located in the same region of the lake (step A). In Switzerland, such anemometers are found at significant “hot points” where wind can be measured excluding the influence of the local topography. The instruments are integrated in automatic weather stations network called “ANETZ”. They measure instant wind intensity and direction at 10m above the ground at 72 measurement points. Data are registered on a basis of 10 minutes average values. Since such values are measured on-land, it is crucial to take into consideration the air-sea interaction.

Step B in Fig. 1 allows to correct the measured “over land” wind data according to wind data over the surface of water, where wind velocities tend to be higher, since the friction of wind “over water” is lower. Such correction is made, for the present case study, by using in situ wind measurements. However, when measurements are not provided, an eventual correction based on theoretical background is necessary.

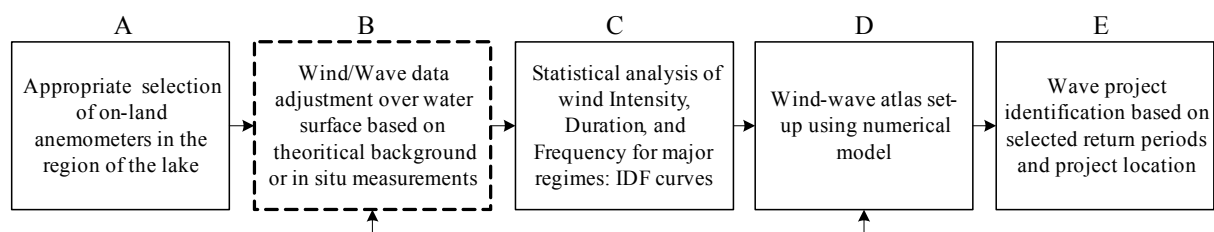


Fig. 1 The proposed methodology for the selection of the design wind-waves for shore protection measures in lakes

In step C, IDF curves (Intensity-Duration-Frequency) are required to define afterwards the design wind velocities for a selected direction and return period. They are determined on the basis of the wind-rose. Over Lake Biel, the wind blows in two main regimes (see Fig. 2a-ba).

The first one, called “La Bise”, is a north-eastern long lasting wind present during an average of 27% of time. The second main regime, called “Le Vent”, is a south-western wind present during an average of 45% of time. Such knowledge allows a good estimate of the main regime to consider according to the location of the protection project in the lake.

Afterwards, a wind-wave atlas is generated numerically using main wind regimes (step D). The atlas contains surface waves over the lake for each wind regime and for fetch-limited conditions. The results should be compared and adjusted according to in-situ measurements, if they are available. Finally, depending on the location of the shore protection structure, and the selected return period, it is possible to identify the nearshore wave characteristics (Step E) by using directly the wave atlas of the lake. Reflection and transmission coefficients of these structures have to be introduced into the numerical model, based on physical model tests (Sayah et al. 2004b).

The wave atlas can be used for risk analysis as well. By studying the major wind events and calculating the corresponding surface waves over the lake, it is possible to identify the shores attacked by high waves. Such analysis allows a risk assessment of the entire nearshore region of the lake.

The proposed methodology for wind wave estimation provides a practical and reliable tool that allows better calculation of wave characteristics in confined water surfaces like lakes. However, in order to have better estimation of over water wind speed, it remains useful to calibrate for each lake wind speed measured over land. For the present case study, such calibration is based on in situ wind measurement.

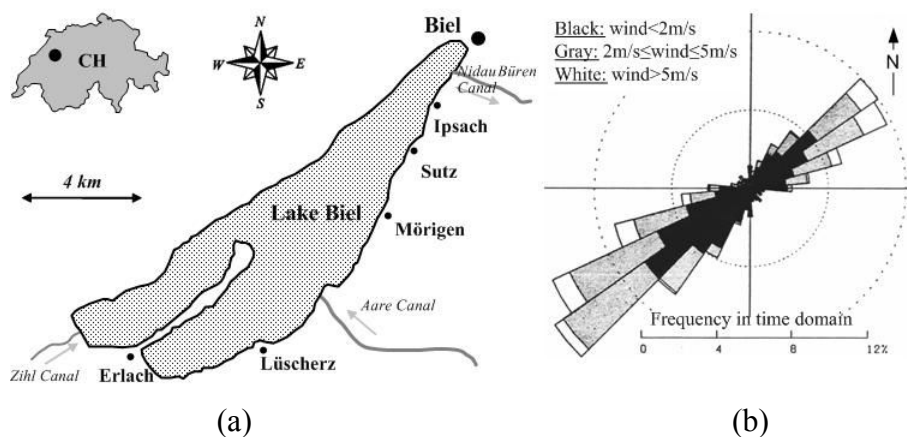


Fig. 2 (a) Lake Biel in Switzerland and localities where in situ measurements are undertaken; (b) Wind rose based on statistical analysis at Payerne wind station situated at 30km south-west of Lake Biel (MeteoSuisse 1990)

2. DESCRIPTION OF IN SITU MEASUREMENTS OF WIND

In situ measurements at Lake Biel are realized on many localities as shown in Fig. 2a. The site of Lüscherz is selected for the present case study, where measurements show substantial results concerning wind velocities for the two major regimes, in addition to the numerous shore protection projects already realized at this location (see Fig. 3a).

Instant over water wind velocities (U_w) and directions are measured during one month period (Dec. 2003) with a Young anemometer (see Fig. 3b). Velocities and directions are averaged on a 10 minutes basis, and presented in Fig. 4a.



Fig. 3 (a) In situ wind and wave measurement platform at Lüscherz; (b) Wind anemometer powered by solar panels

The comparison of over water and over land wind speeds and events (events 1 to 8 in Fig. 4a and b) shows relevant similarities. The events are considered when wind speed is significantly higher than 2.5m/s and lasting at least 1 hour. Fig. 4b shows that events at Payerne (at 30km south of Lake Biel) occur at the same period and almost for the same direction trends as at Lüscherz (Steps A and B). However, the measured wind speeds are not similar for every event.

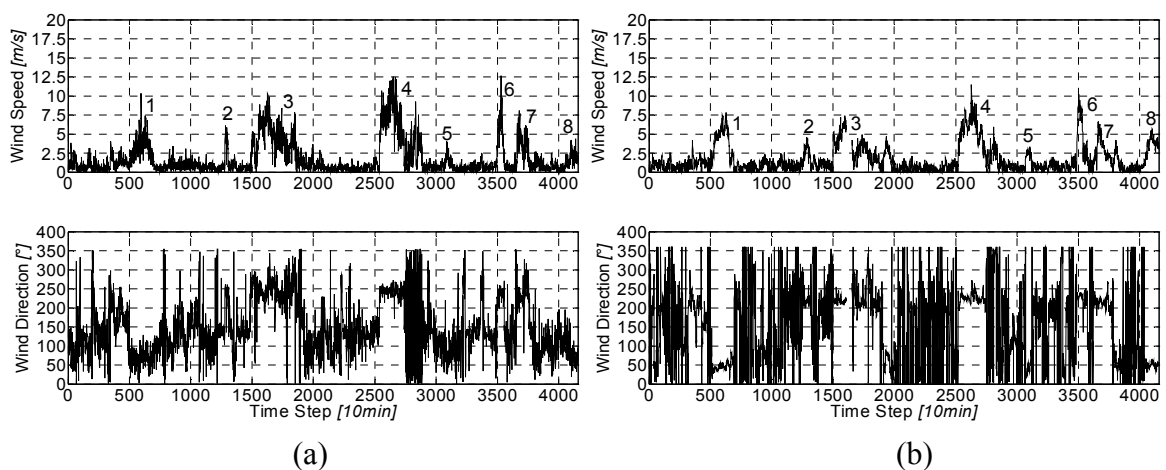


Fig. 4 (a) Over water wind speed and direction at Lüscherz; (b) Over land wind speed and direction at Payerne located at 30km south of Lake Biel

Fig. 5 highlights the effect of wind speed variation due to transition from land to water. The data shown in Fig. 5a corresponds to wind speeds for the south-western wind. It includes

measurement during the 8 wind events as shown in Fig. 4. Thus, wind speed tends to increase after a transition from a land surface.

However, due to the behaviour of water roughness as a function of wind speed, the ratio of over water wind speed at a fixed level to over land wind speeds (U_W/U_L) is not constant, but varies nonlinearly as a function of wind speed. Fig. 5b provides the trend for the form of such variation.

Yet, the exact magnitude and characteristics of the transition depend on the roughness properties of the terrain and vegetation on one hand, and on the stability of the air flow on the other hand. Resio and Vincent (1977) presented a simplistic approximation of this wind speed variation based on a logarithmic fitting curve to the asymptotic over land and over water wind speed values.

Furthermore, trends in Fig. 5b indicate, as expected, that wind speeds over water follows a power-law fitting. The ratio U_W/U_L tends to infinity when U_L tends to zero and to 1 when U_L is higher than 20m/s. The latter fitting depends mostly on the location of on water measurement station and on the wind regime. For “mean” wind speeds (varies between 6 and 8m/s in Switzerland), corresponding to recurrent wind events, such fitting provides a rough ratio of U_W/U_L equal to 1.25. Thus, wind over water is 25% stronger than wind over land for average wind events.

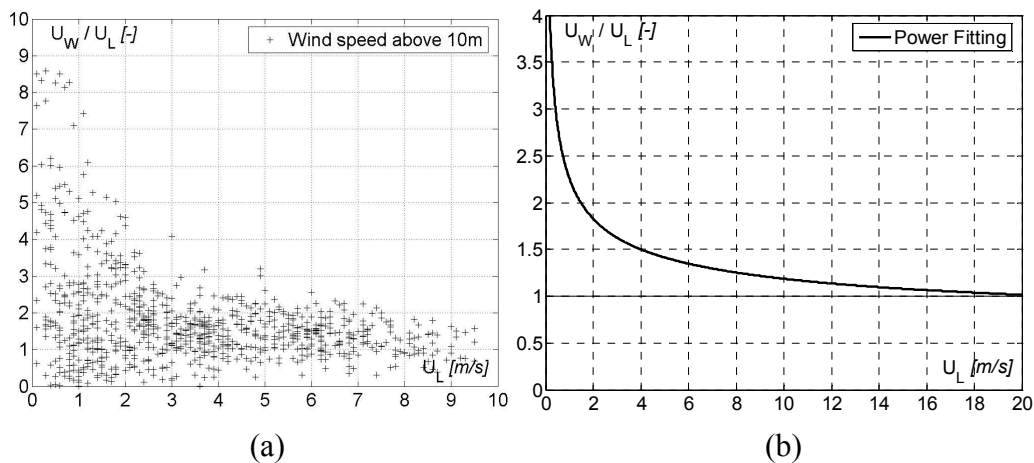


Fig. 5 Ratio of wind speed over water U_W at Lüscherz to wind speed over land U_L at Payerne according to U_L , for a wind sector 180° to 300° ; (a) in situ measurement (b) Curve fitting ($r^2 \sim 0.3$)

The IDF curves, presented in Fig. 6, are based on statistical analysis of 26 years of over land wind measurements at Payerne. A comparison between two different methods for data analysis gives similar results (Wyler 2004) although the simple scaling method (Fig. 6b) seems to be more adequate for this analysis.

For defined wind duration and selected return period (T_r), the curves provide a corresponding wind speed. In reality, by providing wind speed, such curves are relevant for the calculation of wind-waves in lakes for a defined return period (Step C).

The relation between wind speed and wind duration is not linear. By considering for instance the maximum and minimum of wind speeds in Fig.6, it can be seen that when wind speed is multiplied by 1.5, the corresponding duration is multiplied approximately by 50. Therefore, when considering the fetch limited condition, it is crucial to calculate in a first step the wind duration that allows such conditions, and, by referring to IDF curves, it is possible to obtain wind speeds for different return periods.

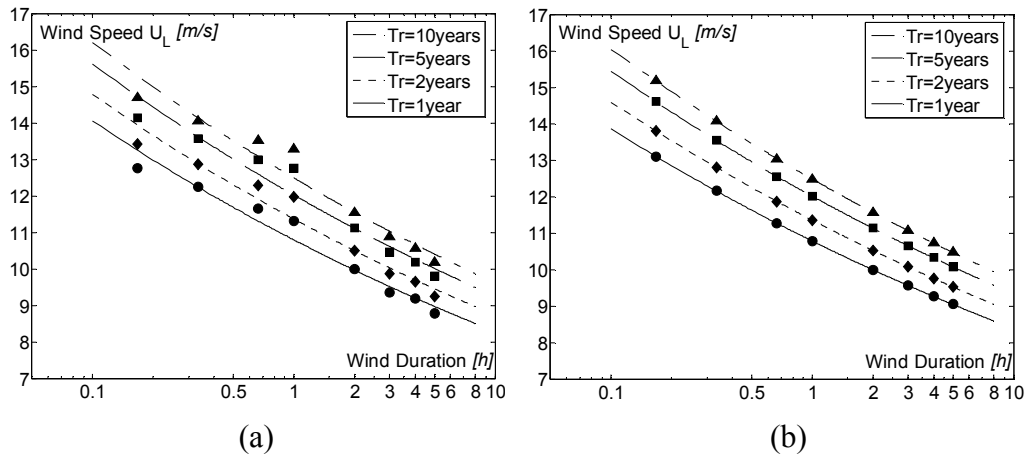


Fig. 6 IDF curves for long term analysis of wind measurement data (year 1978 to 2003 at Payerne wind station) according to the return period (Tr) based on (a) quantile-regression method and (b) simple scaling method

3. THE NUMERICAL MODEL OF LAKE BIEL

The numerical modeling of Lake Biel is based on data provided by the digital height model DHM25 derived from the digitized contour lines and spot heights of the NM25 the Swiss National Map 1:25'000. Since the DHM25 is based on the National Map 1:25'000 it basically corresponds to its accuracy level. Comparisons with photogrammetrically determined control points have shown that the average accuracy is up to 1.5 m for the Swiss Plateau where Lake Biel is situated.

The course of the digitized lake contours is a highly accurate representation of those on the map. Deviations from the original map contours should remain within the cartographic tolerance of 0.1 to 0.3 mm (corresponds to 2.5 to 7.5 m in reality). For technical reasons slight deviations are possible, especially where there is a strong curvature of the contours. In areas where the contours are incomplete, differences to the "true" course of the contours may occur because such gaps have to be completed and closed manually through visual interpretation of the map. The height assignment of the contours is screened by a profile test (a search for unnatural breaks) and a margin test (a continuity test along the edges of the model).

Fig.7 shows the digital elevation model of Lake Biel where the mean water level (MWL) is regulated at 429.4 m above sea level.

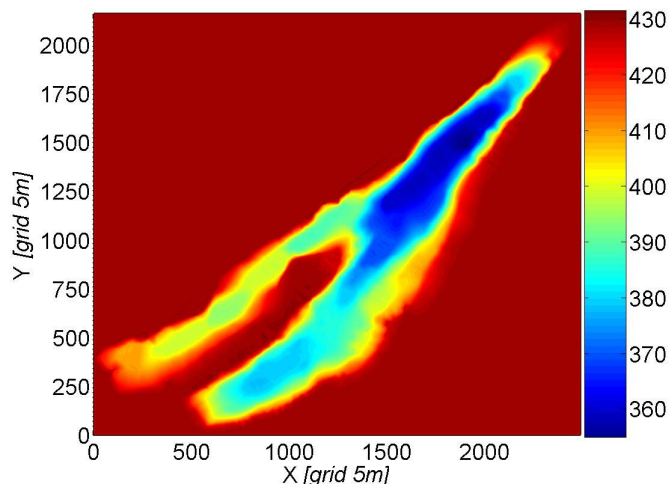


Fig. 7 The digital elevation model of Lake Biel (Switzerland) based on a squared 5m cubic gridding for MWL 429.4 m; The values in the coloured bar indicate altitudes above sea level

4. DESCRIPTION OF THE NUMERICAL MODEL SWAN

The numerical wave simulations for Lake Biel are carried out using the model Simulating Waves Nearshore (SWAN) developed at Delft Technical University (Booij et al. 1999, Ris et al. 1999). SWAN incorporates the physical processes of refraction, shoaling, wave breaking, bottom friction, nonlinear wave-wave interactions and wind set-up. However diffraction is not included in the phase-averaged model SWAN. In the absence of currents SWAN is based on the following non-stationary action balance equation:

$$\frac{\partial}{\partial t} N(\omega, \theta) + \frac{\partial}{\partial x} c_x N(\omega, \theta) + \frac{\partial}{\partial y} c_y N(\omega, \theta) + \frac{\partial}{\partial \omega} c_\omega N(\omega, \theta) + \frac{\partial}{\partial \theta} c_\theta N(\omega, \theta) = \frac{S(\omega, \theta)}{\omega} \quad (1)$$

with the wave action (N), the wave period (ω), and direction (θ). Sources and sinks of wave action (S) are wind growth (S_w), dissipation due to wave breaking (S_{br}) and bottom friction (S_{bo}), as well as the spectral redistribution of wave energy due to triad- and quadruplet wave-wave interactions. S , S_{br} , and S_{bo} are expressed following equations (2), (3), and (4) respectively:

$$S(\sigma, \theta) = S_w(\sigma, \theta) + S_{br}(\sigma, \theta) + S_{bo}(\sigma, \theta) + S_{nl}(\sigma, \theta) \quad (2)$$

$$S_{br}(\sigma, \theta) = -\frac{1}{4} \alpha_{BJ} Q_b \frac{\bar{\sigma}}{2\pi} \rho_w \cdot g \cdot \gamma^2 \cdot d^2 \cdot \frac{E(\sigma, \theta)}{E_{tot}} \quad (3)$$

where

$$S_{bo}(\sigma, \theta) = -C_{fw} \cdot g \cdot U_{rms} \cdot \frac{\sigma^2}{\sinh^2\left(\frac{\sigma}{k|d}\right)} \cdot \frac{E^2(\sigma, \theta)}{\rho_w^2 g^3} \quad (4)$$

and

with the energy density in frequency and directional space (E), the total wave energy (E_{tot}), the wave number (k), the water depth (d), the orbital velocity (U_{rms}), the fraction of breaking waves (Q_b), the water density (ρ_w), the acceleration of gravity (g), and the dimensionless parameters α_{BJ} , γ , or C_{fw} .

The applicability of SWAN in wave forecast is widely proven for coastal waters. Although the default parameterization of the dissipative processes used in SWAN, like α_{BJ} , γ or C_{fw} ,

need some modification by comparisons of model results and wave measurements carried out in-situ and at prototype scale in the large wave flume at the University of Hannover (Mai et al., 1999a-b). For lakes only few validations of the model SWAN can be found. One is given by Booij et al. (1996). Therefore a validation is given for Lake Biel hereafter.

5. EXTREME WIND-WAVES EVENT SIMULATION ON LAKE BIEL

The comparison of the results of non-stationary wave modeling based on the bathymetry (Fig. 7) with wave measurements as shown in Fig. 3, is carried out for the period of the 20th of December to the 21st of December 2003, corresponding to event no. 4 in Fig. 4. An example of the modeled wave field is given in Fig. 8, where the location of the wave measurements near Lüscherz (L2) is indicated (Step D).

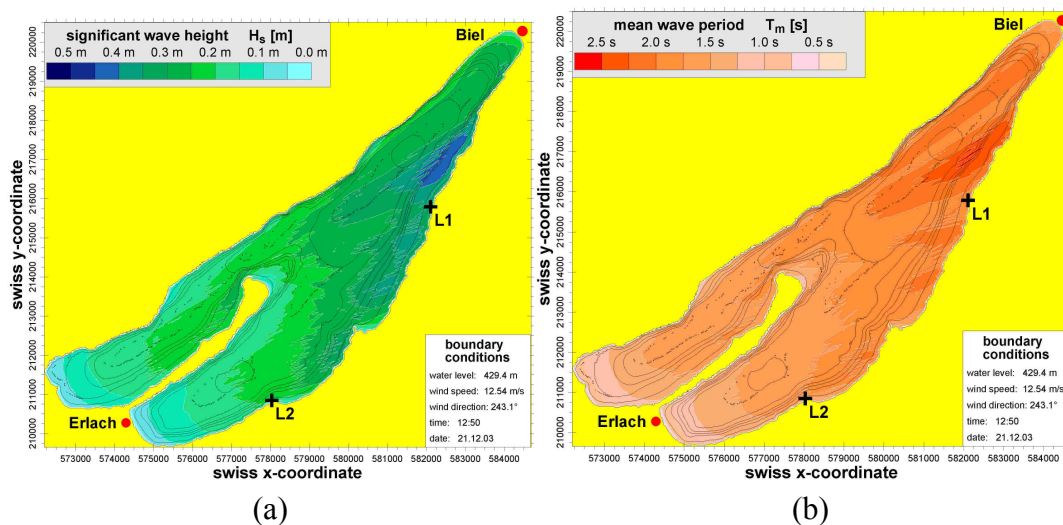


Fig. 8 Wave field in Lake Biel during an event of “Le Vent” (Dec. 20-21.2203) (a) Significant wave height and (b) mean wave period

During the “Le Vent” wind regime, the maximum wave heights and periods amount to 0.5m and 2.5s in Lake Biel. They have to be expected near Mörigen (L1). For Lüscherz the time-series of significant wave height of both – numerical model and measurement – is given in Fig. 9. The model results and measurements are in good agreement. Differences may be attributed to the assumption of a homogeneous wind field all over the lake. The coefficient of correlation amounts to $r^2 = 0.75$ for significant wave height.

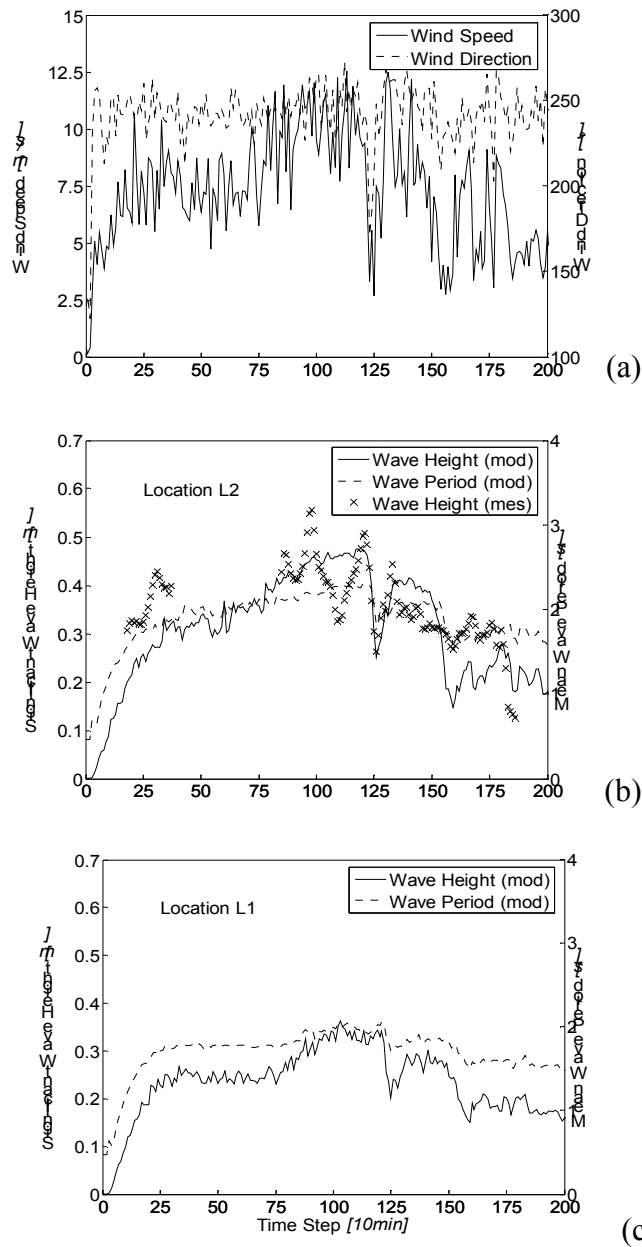


Fig. 9 Time-series of significant wave height and mean wave period derived from (a-b) in-situ wind measurements and numerical modeling at Lüscherz and (c) at Möriegen

Besides the comparison of the frequency averaged wave parameter, the applicability of the wave modeling is also confirmed with respect to the spectral shape. An example of the frequency spectrum at Möriegen (L1) derived from modeling is given in Fig. 10.

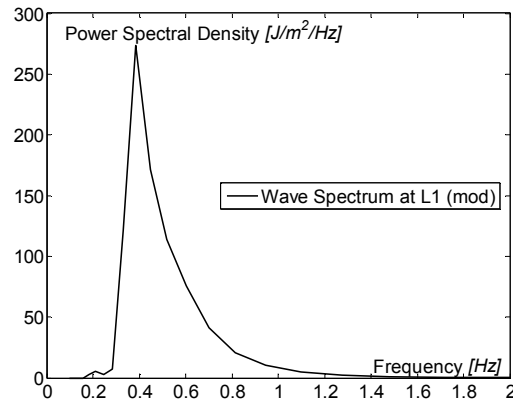


Fig. 10 Wave spectrum at Lüscherz

6. WAVE STATISTICS IN LAKE BIEL

The non-stationary numerical simulations reveal that wind triggers the wave conditions in Lake Biel with a comparably short response time of a few hours. Besides of long-term non stationary modeling, the wave statistics may therefore also be calculated by stationary modeling of characteristic wind conditions (3 hours) with known probability density pdf (u_w , θ_w). The model provides functions f_{H_s} , f_{T_m} for the transfer of the parameter wind speed u_w , and direction θ_w , into wave conditions. Modeling results are collected in an internet-based wave atlas (Mai & Liebermann, 2000). Applying the results of stationary modeling the wave statistics are calculated from the wind statistics using Eq. (5):

$$\int_0^{H_s} pdf(\tilde{H}_s) d\tilde{H}_s = \iint_{H_s > f_{H_s}(u_w, \theta_w)} pdf(u_w, \theta_w) du_w d\theta_w \quad (5)$$

The return period (Tr) of exceeding a certain wave height is calculated by integrating the probability density function using Eq. (6):

$$1/Tr = \int_{H_s}^{\infty} pdf(\tilde{H}_s) d\tilde{H}_s \quad (6)$$

On the basis of the wind statistics shown in Fig. 2, which is transferred to over water conditions using Fig. 5, an example of the wave height statistics at Möringen and Lüscherz is given in Figure 11. At Lüscherz the return period of a wave height of more than 0.35 m amounts to approx. 1 month (Step E).

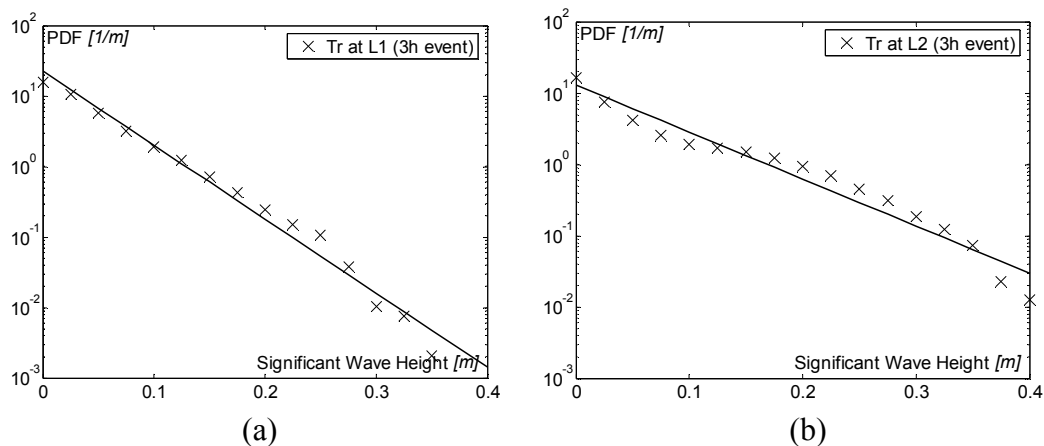


Fig. 11 Statistics of wave height at (a) L1 and (b) L2

7. CONCLUSIONS

The design of shore protection projects in large Swiss lakes, to be built for the control of beach erosion, requires accurate knowledge of wave parameter and wave statistics. While the average wave conditions are easily assessed by measurements, the determination of the design wave conditions is often not possible with measurements due to time limitations. It is possible to fill this gap by the proposed methodology of transferring wind statistics into wave statistics using numerical simulations with the model SWAN. When using the concept of relating wind and wave statistics, focus has to be put on the determination of the over water wind statistics from over land statistics. Since the wind statistics are based on wind data measured over land, the transition ratio to wind over water is therefore to be determined. A rough correlation showed that, during mean wind conditions at Lake Biel, the over water wind speed is approximately 25 % higher than the over land wind speed. Furthermore, the comparison of modeled and measured wave data proved the applicability of SWAN for lakes (with slight changes in the default parameter set). The wave atlas proposed for Lake Biel, could be applicable thus for any shore protection project in this lake. An application of the proposed methodology for building reliable wave atlas could be similarly carried out not only for the remaining lakes in Switzerland, but for any confined water surface where wind-wave conditions prevail.

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