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Wind-wave climate analysis and wave height prediction using neural network for Lake IJssel and Lake Marken

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Master of Science Thesis

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Abstract

Extended measurement of wind and wave conditions were carried out from 1997 on Lake IJssel and from 2010 on Lake Marken by Rijkswaterstaat in the Netherlands. The objective of the current study was the analysis of measured data for different ranges of wind speed, fetches and water depth, verifying parametric formulas of Bretschneider and Breugem-Holthuijsen to predict wave parameters such as significant wave height (H_{m0}), and finally, usage soft computing tools, such as artificial neural network (ANN) for prediction of significant wave height. The study will serve a number of purposes, particularly dike design and flood risk assessment.

The study allowed reducing the gap between the measured wind-wave data and the dike design conditions (about 24 m/s and well over 30 m/s wind respectively, see Bottema, 2007), as 27.3m/s wind speed was observed in October 2013. In addition, notable outcomes of the study are a detailed analysis of monitoring network and data availability; the small differences of wind speed between land and water during strong winds; and quantifying relations between wave height and the wind for different ranges of wind direction, effective fetch and water depth.

The data selection that was used for verification and validation of the models of wave height prediction comprised winds > 9 m/s and the winter seasons November-April.

Verification of Bretschneider and Breugem-Holthuijsen parametric formulas, with all November-April data with more than 9 m/s wind for Lake IJssel and Lake Marken, shows that in general Bretschneider formula performs better than Breugem-Holthuijsen. However, the Breugem-Holthuijsen formula is more accurate for prediction of relatively severe (more than one meter) wave conditions. The Bretschneider formula was locally optimized by calibrating its parameters using existing measured data and the error becomes a factor 1.1-1.3 smaller with calibrated parameters.

Wind speed (U_{10}) measured at 10-meter height, effective fetch (F_{eff}) and water depth (D) as input variables and significant wave height (H_{m0}) as the output variable were used to train, validate and test an artificial neural network (ANN) model, applying Levenberg-Marquardt algorithm. The relative error of predicted wave height is 10-11% (even 8-9% in case of prediction of wave height in strong wind conditions (U_{10}>18m/s)) by ANN, which performs better than parametric formulas (calibrated formula of Bretschneider has 11-13% relative error) for measurement locations on Lake IJssel and Lake Marken.

Keywords: *wave climate; wind climate; Bretschneider formula; Breugem-Holthuijsen formula; artificial neural network modelling; wave height prediction; Lake IJssel, Lake Marken.*

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List of definitions, abbreviations and symbols

Definitions

Direction	Wind and wave directions are indicated as the direction the wind and waves are coming from.
Effective fetch	Fetch parameterization to translate complex coastline situation into an equivalent situation with the straight coast.
Fetch	Distance from which the wind blows over the water to generate waves and/or storm surge. For (small) lakes generally equivalent to the downwind distance from the coastline to the point of interest.
Outlier	Data point outside expected range of scatter
Sample	Individual measuring value
Validation	Integral approach to assure correctness of measured or model results
Wave height	Vertical distance between wave crest and trough
Wavelength	Horizontal distance between successive wave crests
Wave period	Time between passage of successive wave crests
Wave shoaling	Shortening and heightening of the waves due to reduction in wave propagation speed when waves enter shallow water

Abbreviations

KNMI	Royal Netherlands Meteorological Institute
NAP	Dutch reference datum (~mean sea level)
RWS	Rijkswaterstaat organisation (NL)
SWL	Still water level: average water level that remains after filtering out fluctuations by short, wind-induced, waves.

Symbols

D	Water depth, [m]
dir	Wind direction, from which wind is blowing, [degree]
F	Fetch of along-wind distance from upwind coast to the point of interest, [m]
F_{eff}	Effective fetch, [m]
g	Gravitational acceleration, [9.81 m/s^2]
H_{m0}	Spectral significant wave height, [m]
L	Wavelength, [m]
S_{Tm-10}	Wave steepness parameter
$S_{Tm-10,o}$	Wave steepness parameter for deep water
T_{air}	Air temperature, [ºC]
T_{m-10}	Spectral mean wave period (energy period), [s]
T_{m01}	Spectral mean wave period (mean period), [s]
T_p	Peak period, [s]
T_{water}	Water temperature, [ºC]
U_{10}	Wind speed at 10-meter height, [m/s]
U_{pot}	Potential wind speed (as U_{10}, but with partial exposure correction), [m/s]

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1. Introduction

1.1 Background

The Netherlands is a country, where over half of its territory is prone to flooding and a significant part of the country is below sea level. Flooding risk along the Dutch coastline and lakes is one of the major issues for the country. The water levels of some large lakes, such as Lake IJssel and Lake Marken, are higher than the surrounding land. So that the lands must be almost fully protected by dikes. The dikes are prone to wave's attack, which are along the large water bodies, such as the sea and the large lakes in the Netherlands, (Bottema 2007) because waves could be driving force for overtopping failure and revetment failure of dikes (Slomp, Knoeff and Bottema 2016). Hence, the knowledge of wave parameters and especially the wave climate are essential for flood risk assessment, design and maintenance of coastline infrastructures in the Netherlands. This information can come from direct measurement of wave parameters or it can be obtained from meteorological data, using physically based models or data driven models.

The coastline structures (levees and sluices), which are exposed to wave impact and requires flood risk assessment, widely exist around Lake IJssel (area 1140 km^2 and average depth 4.2 m) and Lake Marken (area 696 km^2 and average depth 3.5 m) (Figure 1. 1), as the lakes are almost fully surrounded by dikes. Considering these conditions, systematic measurements of wave parameters started in 1997 (Bottema 2007). However, it is not possible to do the measurement in front of each levee and certainly not during design conditions (which are much more severe than anything measured so far). Therefore, there is a need for wind-wave climate[1] analysis and validation of wave models as a function of the wind, as the wave model is one type of models (amongst others) to do a proper flood risk assessment.

The above-mentioned problem has already had its attention, as there were studies on wave climate of Lake IJssel. The most significant study was carried out by (Bottema, 2007) and (Bottema & van Vledder, 2009). Noteworthy, there is no validated and well-documented wave climate analysis for Lake Marken and this is a crucial problem since Rijkswaterstaat needs to provide updated Hydraulic Boundary Conditions for surrounding levees within a few years.

Figure 1. 2 introduces the structural frame of the generalised flood defence failure graph for the Netherlands, with all possible cases (red boxes), which is a consequence of wave load (Slomp, Knoeff, & Bottema, 2016).

[1] Wave climate is the distribution of wave height, period, and direction averaged over a period for a particular location (Wiegel R. L., 1964).

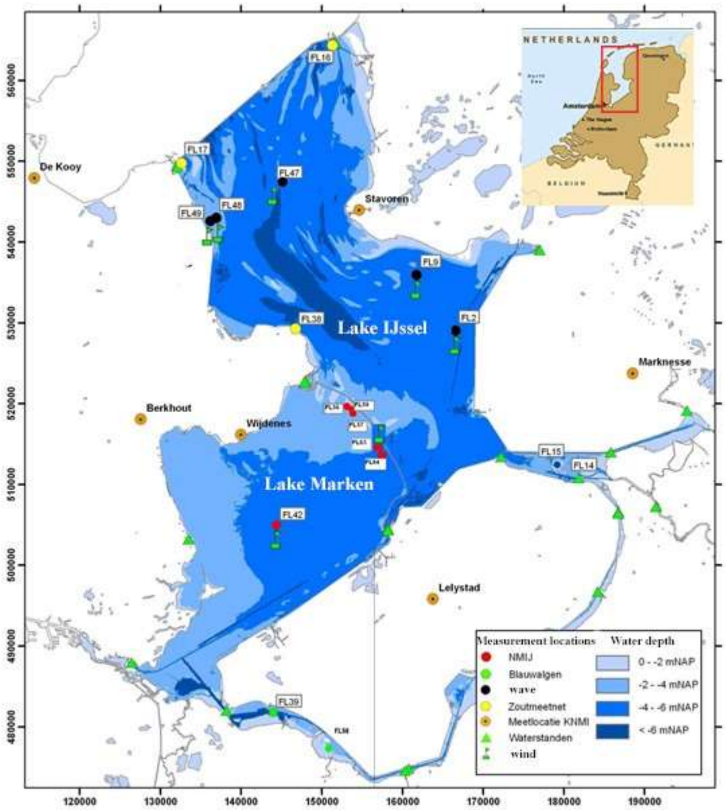


Figure 1. 1 Current map of the study area (Lake IJssel and Lake Marken), with measurement stations. (Hans Miedema, RWS)

The red boxes of Figure 1.2 represent the main failure fault tree for flood defences around Lake IJssel and Lake Marken. The failure refers to the hydraulic structures (sluices) and the dikes (levees). Overtopping and structural failure are the causes of the failure of the hydraulic structure. The erosion of inner and outer slopes and the wave impact can be the cause of failure of dike/levees as well.

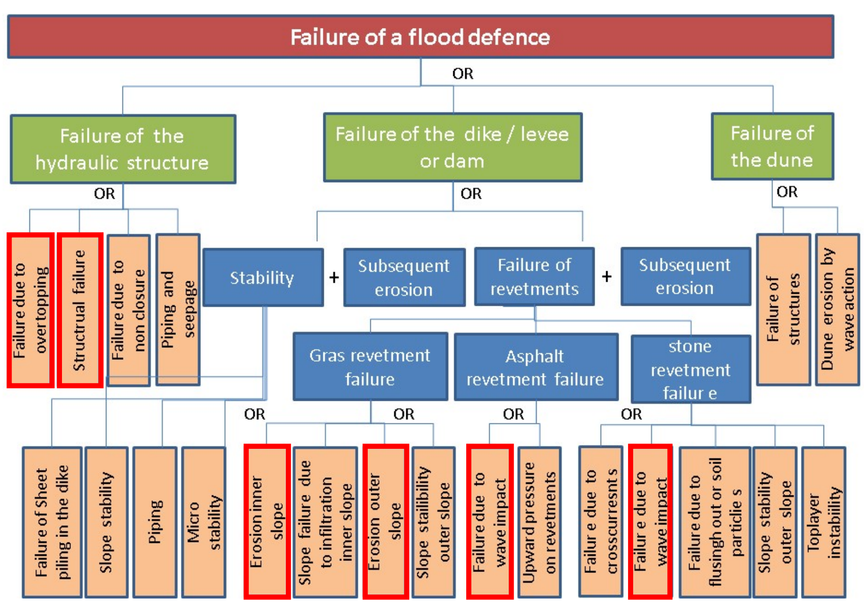


Figure 1. 2 Fault tree for the flood defence (Slomp, Knoeff, & Bottema, 2016)

1.2 General problem statement

The prediction of wave parameters for Lake IJssel and Lake Marken is done by physically based hydraulic models such as SWAN (SWAN user manual, 2016). However, the present models are potentially inaccurate since to simulate extreme conditions they have to be applied far outside their calibrated ranges. In addition, it used to be common practice to calibrate and validate models on just a few cases, disregarding natural scatter and the errors that may result if a particular selected case is not fully representative compared to other data obtained for similar conditions. Therefore, the general problem is having validated wave climate analysis, in order to estimate the extent of inaccuracy of predicted wave conditions by physically based models. Particularly, extensive model validation is required for a wide range of conditions, since models have to be applied beyond the measuring range, as safety standards for flood defenses in the Netherlands, require the use of wave conditions that are far extreme than anything measured so far (Slomp, Knoeff, & Bottema, 2016). Physically based wave growth prediction models are often validated by just few storm cases, the representativeness of the cases of wave model validation is rarely verified, and it is unknown whether such validation cases are along the axis of a scatter cloud of data or outliers (Bottema 2007).

After consulting previous related studies (Bottema, 2007), (Bottema & van Vledder, 2009), the following knowledge gaps were identified in relation to this study:

1. The climatology of directly measured wave parameters of Lake IJssel is not accepted for dike design purposes, as their extrapolation can produce physically unrealistic trends.
2. The wave steepness and dimensionless wave heights agreed reasonably well with parametric growth curves, although there is no single curve to which the present data fit best for all cases (Bottema and van Vledder 2009).
3. The dikes around Lake IJssel were designed for wave overtopping and run-up condition with 2000 to 10000 years return period (Berger, 2007). For these return periods, the deep-water parametric formulas (formulas which are most acceptable for deep-water bodies) in some conditions of wind and fetch, yield significant wave heights as large as the actual water depth, which is not plausible physically. Hence, finite depth effects are expected to play a role.
4. It is not clarified whether a shallow-water wave growth limitation exists on Lake IJssel and Lake Marken. If it exists, the next problem is the depth-limited properties of wave growth.
5. Do the waves scale with the wind speed or with the wind drag (friction force)? A crucial knowledge gap, which unfortunately cannot be dealt with in this study by lack of suitable measurements.

Noteworthy, there is no validated and well-documented measured wind-wave climatology for Lake Marken. This is a crucial problem, since Rijkswaterstaat needs to provide updated Hydraulic Boundary Conditions (HBCs) for surrounding levees within a few years, and these HBCs should include biases and scatter indices. Nowadays, there is twenty years period of systematic measurements for some locations on Lake IJssel (from 1997), and six years (from 2011) of systematic measurements on Lake Marken (locations FL42 and FL44). Therefore, one of the aims of the current study is to do wind-wave climatology analysis with recently measured data of Lake Marken and Lake IJssel, because the last analysis of this type is ten years old (Bottema, 2007).

Since there is a need for predicting significant wave height, especially for extreme wind conditions (which is already done by physically-based models in Rijkswaterstaat), the development of data-driven modelling for wave height prediction has also been set as an aim in this study. Wave period information is equally needed, but by lack of time, this aspect could not be included in the scope of this report.

1.3 Objectives

The main objectives of the study are derived from the stated problems and from data availability.

1. The first objective is to produce verified wave climate for Lake IJssel and Lake Marken, to facilitate further validation of physically based wave models that are going to be used for safety assessments and design of flood defence infrastructures around the lakes. The objective of wave climate analysis consists of the following:
   a. Representation of exploratory analysis of the wind and various wave parameters (height, period and steepness). The statistical analysis (average, standard deviation) and analysis of the spatial behaviour of variability and consistency of wave parameters.
   b. Validation of the relation between effective fetches and wave height.
   c. Clarification of the existence of shallow water conditions for wave growth limitation on Lake IJssel and Lake Marken.
2. The second objective is the verification of parametric wave growth empirical models (Bretschneider formula and Breugem-Holthuijsen formula) for the measurement locations on Lake IJssel and Lake Marken. In addition, the objective is calibration of the parameter of Bretschneider formula.
3. The third objective is a validation of data-driven model (Artificial Neural Networks) for wave height prediction as a function of wind speed, effective fetch and water depth.

The first objective is dealt with in chapter three and four. The second objective is discussed in chapter five, and the third objective is discussed in chapter six.

1.4 Research questions

In order to achieve the objectives, it is necessary to set the research questions that will allow reaching the goals. The following research questions are stated to reach the objectives of the current study:

1. What are the characteristics of averaged wave height (H_{m0}) and period (T_{m01}) for each measurement location on Lake IJssel and Lake Marken?
2. What are the most significant storm conditions for each measuring location?
3. What is the extent of consistency between wave parameters and between different periods? The relationship of wave parameters, like significant wave height, wave period have to be confident, as the wave parameters were obtained from raw data processing.

4. Whether the data of different conditions and different locations are scalable and can be described through one set of parametric wave growth formula?
5. To what extent data-driven modelling, with wind speed (U_{10}), effective fetch (F) and water depth (D) input variables, can predict significant wave height (H_{m0})?

1.5 Significance and practical value

Wave climate analysis has significant and practical value for Rijkswaterstaat since the Dutch law requires regular flood defence safety assessments using safety standards prescribed by law, while the government provides model-based Hydraulic Boundary Conditions (HBCs) for these assessments (Slomp, Knoeff and Bottema 2016). HBCs consist of still water levels (water depth) and wave parameters in extreme conditions. These are evaluated from hydraulic models like WAQUA (water levels) and SWAN (waves). These models need extensive validation using benchmark experimental data. Given the fact that models have to be applied well beyond the range of available, a robust validation is needed, with a wide range of benchmark conditions. The movement from blindly selecting validation cases to more balanced selection for models could be the scientific innovation of this study, where the position of a selected event (storm case) on the scatter cloud is a measure of representativeness of the (storm) case.

The next significance is the application and calibration of parametric formulas. Here calibrated and more accurate Bretschneider formula could perform wave height prediction significantly better for Lake IJssel and Lake Marken, than with initial parameters. The expected significant value will be the same as Breugem-Holthuijsen (Breugem & Holthuijsen, 2007) did a calibration of Young and Verhagen formula (Young & Verhagen, 1996) for Lake George.

Although existing measured dataset is so far from design conditions, validated wave height prediction neural network modelling could be significant alternative of existing physically based models.

1.6 Research methodology

The research methodology is the way to reach the objectives, after knowing and stating the essence of the problem and the objectives.

The first methodology of the current study is a literature review. It helps to identify relevant studies to the current study, to see what kind of knowledge gaps still exist for this case study. This method allows understanding the extent of previews studies related to the current case study, and review the case studies of other locations similar to the current study. The literature review is discussed in chapter 1.7.

Univariate and bivariate analysis methods were used to detect outliers in measured data and to see the level of confidence between wave parameters in chapter 2. The detection of outliers also was done by comparison method, when unreliable wind speed was compared with general meteorological conditions.

As the concept of effective fetch was used in the current study, the bearing distance method was used in geographical information systems to calculate fetch for each measurement of wind direction. However, as it is accepted in wave theory the single fetch cannot represent real effect and features of shoreline. That is why the method of effective fetch (Waal, 2003) calculation was used to describe the influence of fetches. The effective fetch (F) is a distance of the range of fetches (X) on the both sides of the main fetch with specified intervals of angles of wind direction (Bottema & Vledder, 2006). More details on calculation of effective fetch will be in chapter 4.2.1.

Trend analysis method and spatial estimation methods (WMO) were used for wind analysis and wave climate analysis in chapters 3 and 4. These methods apply to show the change of wave height and wind speed over wind directions (to see the trends) and spatial transformation of wind speed and wave height.

The theory (methods) of dimensionless parametric formulas of wave height prediction were used to estimate the extent of inaccuracy of wave height prediction at the measurement locations on Lake IJssel and Lake Marken in chapter 5. Parametric formulas are physically based empirical formulas. Particularly, Bretschneider formula and Breugem-Holthuijsen formula were used for wave height prediction. More explanation on parametric formulas is presented in chapter 5.

The use of dimensionless parametric method had its next step for the Bretschneider formula. Generalized reduced gradient (GRG) nonlinear optimisation method (Leon, Richard, & Margery, 1974) were used to calibrate the parameters of Bretschneider formula based on data of measurement locations on Lake IJssel and Lake Marken.

The methodology of Data-Driven modelling was applied for wave height prediction in chapter 6. Particularly, cross-correlation method was used to observe the relationship between input variables and Artificial Neural Networks (ANN) were used for validation of a model of wave height prediction, with wind speed, effective fetch and water depth input variables. Multi-layer perceptron (MLP) neural network was used in this study (Solomatine, 2016). The architecture of MLP model includes three layers: input, hidden and output layer (Figure 1. 3). Each layer is connected by weights and bias but no weight is assigned to nodes within layers. Levenberg-Marquardt algorithm was chosen as weight updating method.

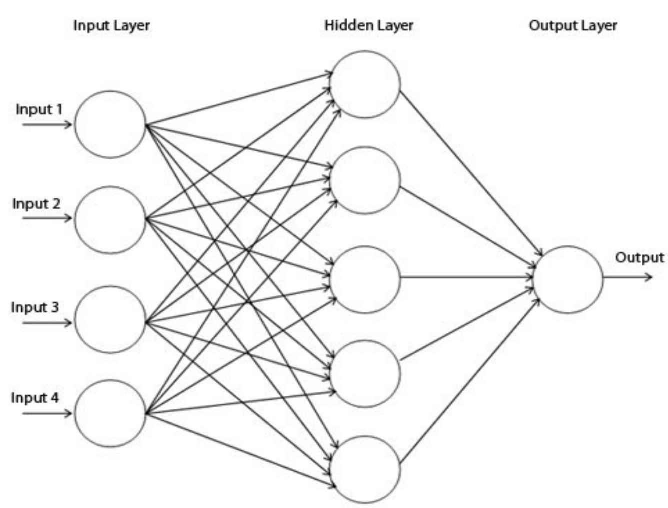


Figure 1. 3 The scheme of Multilayer Neural Network

Software support: Matlab, ArcGIS, MS Excel and MS Word were used to carry out the current study.

1.7 Literature review

The literature review follows the sequence of chapters and stems from three general objectives. The first group of literature refers to data analysis, the second group of reviewed literature about dimensionless parametric formulas of wave height prediction. The third group of reviewed literature refers to wave height prediction by data-driven modelling.

The main literature, which was reviewed for data analysis (Wind analysis in chapter 3 and Wave analysis in Chapter 4) is “Measured wind-wave climatology Lake IJssel” (Bottema, 2007). This study was done in Rijkswaterstaat, based on measured wind and wave parameters on Lake IJssel from 1997 to 2007. Since current study was also carried out in Rijkswaterstaat, so data analysis (chapters 3 and 4) mainly follows and emphasises the steps, methods and presentation given in “Measured wind-wave climatology Lake IJssel” (Bottema, 2007) to keep consistency between the present study and the one of (Bottema, 2007). The aim of (Bottema, 2007) was gathering and analysing wind and wave measurements, for a range of fetches, water depths and wind conditions. In particular, some of the key conclusions and outcomes are following:

- The wind speed differences mainly disappear between land and water surfaces during the storms.
- It was discussed whether the wave should scale with a wind speed parameter (U_{10}) or a wind force parameter (the friction velocity u*), because the difference between approaches may be as large as 25-50%, for typical wind in the Netherlands.
- It was not advised to use directly measured wave climatology of Lake IJssel for dike design purposes, as their extrapolation tends to produce physically unrealistic trends (Bottema, 2007). Main reasons for not directly applying measured data are the large gap between measured and design conditions and the fact that mathematical (linear) extrapolation beyond the measured range does not take into account the physical behavior and more specifically not any changes in physical behavior,.
- SWAN model run for specific storm events. According to the results of (Bottema & van Vledder, 2009), the standard SWAN wave model underestimates the wave periods by about 15%. In windy and strongly depth-limited conditions, wave heights and wave periods may be underestimated by about 20-35%. On the other hand, overestimations are likely during the first few kilometers of fetch.

In addition the above mentioned major report, there are also a number of journal articles that refer to the wave-wind climatology of Lake IJssel, where individual cases were discussed. In particular, Bottema and van Vledder (2009) carried out an analysis on fetch and depth-limited wave growth for Lake IJssel and Lake Sloten. The study was also about the differences of fetch-limited wave growth results of Bretschneider and Young-Verhagen (1996) formulas for depth-limited wave growth, which is not as thoroughly investigated as wave growth in deep water.

The next group of reviewed literature refers dimensionless parametric wave growth formulas (physical based empirical models). The two main studies, which are reviewed and used in this study, are Bretschneider formula and Breugem-Holthuijsen formula.

Bretschneider formula (Bretschneider C. , 1958) is one of the key empirical models with dimensionless parameters, which predict significant wave height for the lakes with depth and fetch limited conditions (Lake Okeechobee, USA). This study adopted that the wind velocity (U_{10}), measured at 10-meter height is the appropriate scaling parameter for wind speed. Bretschneider considered dimensionless parameters as inputs for wave height prediction in his formula, where $\widetilde{H}$ is dimensionless wave height, $\widetilde{F}$ is dimensionless effective fetch, and $\widetilde{D}$ is dimensionless water depth (equation 1.1). Empirical formula of Bretschneider, which was presented in Shore protection manual (1984) is the following:

$$\widetilde{H} = \frac{g*H_{m0}}{U^2} \qquad \widetilde{F} = \frac{g*F}{U^2} \qquad \widetilde{D} = \frac{g*D}{U^2} \quad (1.1)$$

$$\frac{g*H_{m_0}}{U^2} = 0.283 * v * \tanh\left(\frac{0.0125}{v} * \left(\frac{g*F}{U^2}\right)^{0.5}\right); \qquad v = \tanh\left(0.53 * \left(\frac{g*D}{U^2}\right)^{0.75}\right) \quad (1.2)$$

Or

$$H_{m_0} = \frac{0.283*U^2*v}{g} * \tanh\left(\frac{0.0125}{v} * \left(\frac{g*F}{U^2}\right)^{0.5}\right) \quad (1.3)$$

Where, g is an acceleration of gravity [m/s^2], units of wave height (H_{m0}), effective fetch (F) and water depth (D) are meter and U_{10}^2 is [m^2/s^2].

Based on the facts, that the cornerstone JONSWAP concept (Hasselmann, Barnett, Bouws, Carlson, & Cartwright, 1973) of wave growth is well established for deep water, and the significant percentage of coastal engineering application is in the shallow water area, Young and Verhagen (1996) carried out the growth of fetch-limited waves in water of finite depth, which was followed the field investigation stage in Lake Okeechobee, USA (Bretschneider C. , 1958). Lake George (Australia) was selected as a case study, as it has approximately uniform 2m depth and the coast ruggedness is small. Analyzing wave parameters and dimensionless wave parameters, Young and Verhagen present formula to evaluate the fetch-limited waves in finite depth water. Breugem and Holthuijsen (2007) carried out a study on “Generalized shallow water wave growth for Lake George” where the formula of Young and Verhagen was discussed. The main outcome of our interest of this study was the calibration of Young and Verhagen formula, considering wave growth generated by northern winds on Lake George. The parametric formula of Breugem-Holthuijsen was used to verify the extent of accuracy of performance on Lake IJssel and Lake Marken. The formula is presented in equation 1.4, where $\widetilde{H}$, $\widetilde{F}$, and $\widetilde{D}$ are the same dimensionless parameters in equation 1.1.

$$\widetilde{H} = 0.24 * \left(\tanh\left(0.343 * \widetilde{D}^{1.14}\right) * \tanh\left(\frac{0.000441*\widetilde{F}^{0.79}}{\tanh(0.343*\widetilde{D}^{1.14})}\right)\right)^{0.572} \quad (1.4)$$

It is probably noteworthy that the measurement locations have relatively smooth characteristics (uniform water depth and approximate triangular shape of the lake) on Lake George, so it will be interesting to see how the Breugem-Holthuijsen formula will perform for the various conditions of fetches and depths of Lake IJssel and Lake Marken.

The last group of reviewed literature referring to the wave height prediction based on Data-Driven Modelling (DDM). Unfortunately, DDM models of wave height prediction mainly refer to the lakes with deep-water conditions or prediction of ocean wave parameters.

The first reviewed literature was “Learning from data for the wind–wave forecasting” (Zamani, Solomatine, Azimian, & Heemink, 2008), which carried out for two measurement locations on the Caspian Sea. However, only wind speed has been used for wave height forecast in data-driven modelling, since two locations have 15 and 800 meters water depth and located significantly far from the coastline. In this frame, this case study does not correspond to the current study. However, it is worth to mention that artificial neural network (ANN) and instance-based learning (IBL) were used in this study. In addition, the results show that the ANNs yield slightly better agreement with the measured data than IBL, as ANN can also predict extreme wave conditions. This outcome was one of the incentives to use ANN in the current study.

Second reviewed literature of wave height prediction modelling with DDM is the comparison the results of model trees (M5) and ANN models in a measurement location on Lake Superior (Etemad-Shahidi & Mahjoobi, 2009). The input variables were wind speed measured at 10-meter height and wave height at the location, which has two years of the measurement period, 300 meters water depth and located more than 50 km far from the coastline. The results of this study indicate that error statistics of model trees and ANN were similar, while ANN was marginally more accurate. Perhaps this fact reaffirms the use of ANN in the current study.

In conclusion, this is probably the first study into the measured wind-wave climate of Lake Marken and this thesis extends the study into the Lake IJssel wave climate of (Bottema, 2007) by including ten years of more recent data and some new measuring locations.

2. Monitoring network and data availability

2.1 Monitoring network

Systematic measurements of hydrological and meteorological conditions were started since mid-1997 on Lake IJssel and since 2010 on Lake Marken. Wind speed (U_{10}) and wind direction (dir) at 10-meters height, significant wave height (H_{m0}), wave period (T_p, T_{m-10}, T_{m01}), still water level, and the temperature of air and water (T_{air}, T_{water}) have been observed on both lakes. Twelve of these structural measurement locations were used for the current study, which were operational during (parts of the) period 1997 to 2016. Two of them are on the Lake Marken (FL42, FL44); ten of them are on the Lake IJssel (FL2, FL5, FL9, FL25, FL26, FL37, FL46, FL47, FL48, and FL49). Locations FL42, FL46, FL47 are situated in a relatively central part of the lakes, locations FL25, FL26, FL37, FL48 and FL49 are located near western shorelines, and locations FL2, FL5, FL9 and FL44 are located near eastern shorelines (Table 2.2).

The potential wind speed[2] and wind direction data of five meteorological station of KNMI were used as reference land-based monitoring stations. Stavoren meteorological station is located on the northeastern side of Lake IJssel, Houtribdijk is located in the middle of both lakes (on top of the levee separating these lakes), and Berkhout and Wijdenes stations are located on the northwestern side of Lake Marken (Wijdenes is right on the shore of Lake Marken). Schiphol (Amsterdam Airport) meteorological station is located almost 20 km far from Lake Marken and 40 km far from Lake IJssel, on the southwestern side of both lakes (Table 2. 1, Figure 2. 1).

Table 2. 1 Coordinates[3] and operation periods of KNMI meteorological stations

location	x	y	operation period
Berkhout	127337	517216	22.03.1999-31.12.2016
Houtribdijk	155874	517725	09.03.2006-31.12.2016
Schiphol	114236	481086	01.07.1997-31.12.2016
Stavoren	154710	545386	23.12.1999-31.12.2016
Wijdenes	140512	516015	01.07.1997-31.12.2016

Source: www.KNMI.nl

[2] Potential wind: measured wind after nearby exposure correction (converted to 10m height above short grass without obstacles). More details on potential wind speed in (Bottema, 2007)

[3] Geographic Coordinate System: GCS Amersfoort; Spheroid: Bessel 1841 RD New; EPSG: 28992

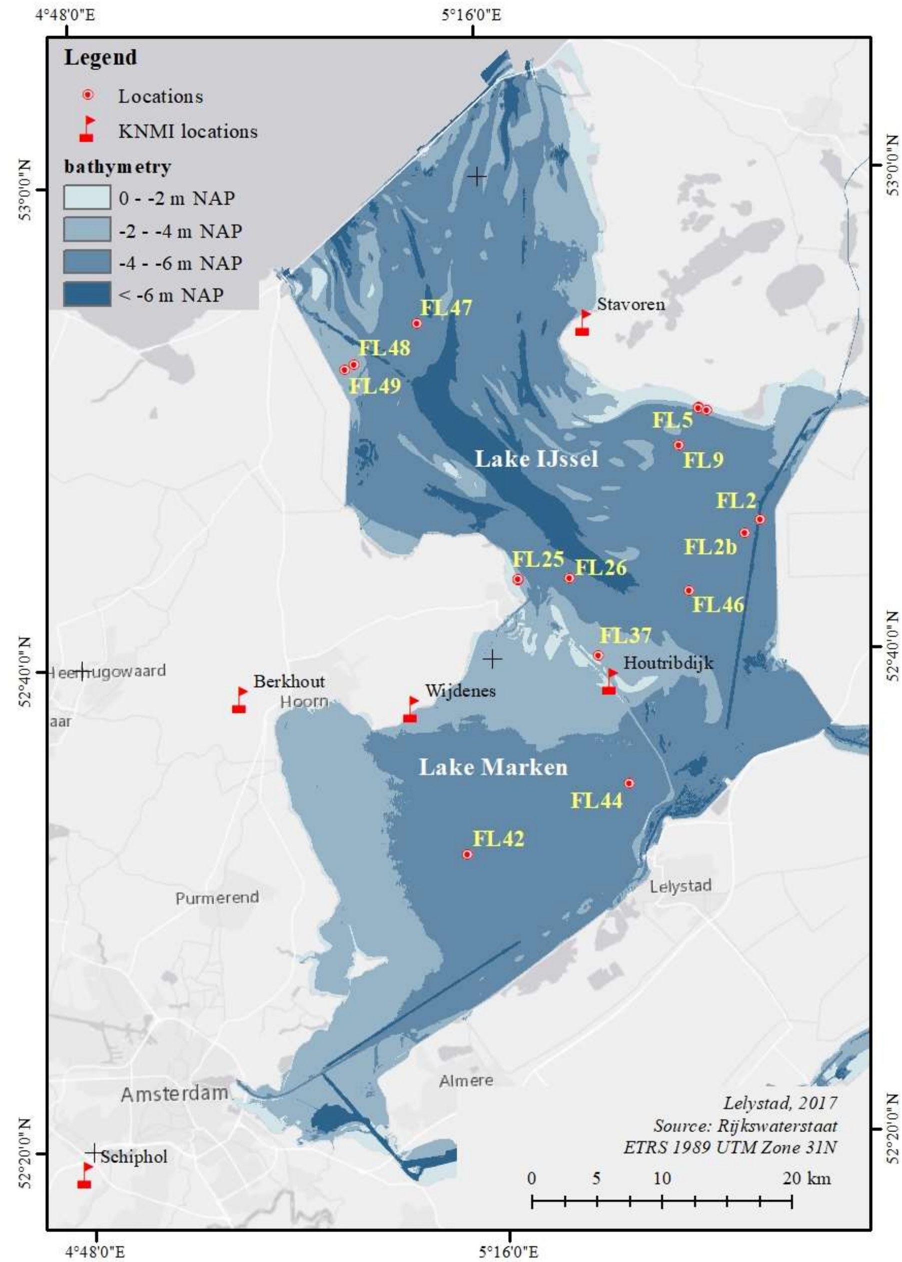


Figure 2. 1 Measurement locations on Lake IJssel and Lake Marken. KNMI meteorological stations

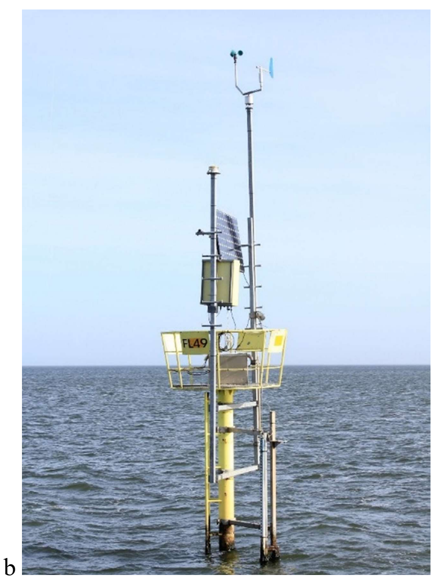
The monitoring network has been subject to changes over time for various reasons, such as unfavourable conditions on the lakes, shortage of the budget or changing research priorities. For example, causes of the relocation of the instruments were ice cover on the lake or digging of the shipping lane, which was in the case of FL2 (Bottema, 2007). Most of the time, the distance of movement does not exceed few hundred meters (sometimes less than one hundred meters), which is usually not significant for the current study. Only location FL2 was moved more than one kilometre. Since the relocation, FL2 has considered as a separate location and conditionally called FL2b (since 02 August 2005). A general overview of the coordinates and operation period of locations are given in Table 2.2.

Table 2. 2 Coordinates, operation period and bathymetry of measurement locations

lake	location	coordinates[4]		operation period	bathymetry
		x	y		
IJssel	FL2	167861	530005	1997-1999	-4.42
IJssel	FL2	167872	530022	1999-2005	-4.43
IJssel	FL2b	166600	529015	2005-present	-4.41
IJssel	FL5	163395	538815	1997-1998	-1.63
IJssel	FL5	163458	538773	1998-2001	-1.69
IJssel	FL5	163391	538780	2001-2003	-1.89
IJssel	FL5	163978	538578	2003-2006	-1.45
IJssel	FL5	163973	538567	2006-2007	-1.50
IJssel	FL9	161775	535920	1997-2001	-4.18
IJssel	FL9	161770	535920	2001- present	-4.18
IJssel	FL25	149000	526000	1997-2001	-2.62
IJssel	FL25	148997	525997	2001-2003	-2.82
IJssel	FL25	149006	526012	2003-2006	-2.91
IJssel	FL26	153000	526000	1998-2001	-5.50
IJssel	FL26	152990	526000	2001-2009	-5.49
IJssel	FL37	155007	519983	2006-2008	-2.69
IJssel	FL46	162152	524752	2009-2014	-5.14
IJssel	FL47	141889	545944	2010- present	-5.08
IJssel	FL48	136935	542957	2010- present	-3.48
IJssel	FL49	136209	542583	2010- present	-3.22
Marken	FL42	144416	504953	2010- present	-4.31
Marken	FL44	157101	510016	2010-2013	-4.32

The main types of measurement locations are shown in Photo 2. 1. Photo 2. 1a shows a location where wave parameters and still water level were measured. Photo 2. 1b shows a location where wind speed and wind direction at 10-meter height, wave parameters, still water level, and the temperature of air and water are measured.

a



b

Photo 2. 1 Measurement location FL25[5] (2000) (a) and FL49 (2017) (b)

Wind speed and direction are measured with “cup anemometer” and “wind vane” instruments (Photo 2. 2a). Wave parameters are measured with “step gauge”, “capacitance probes”

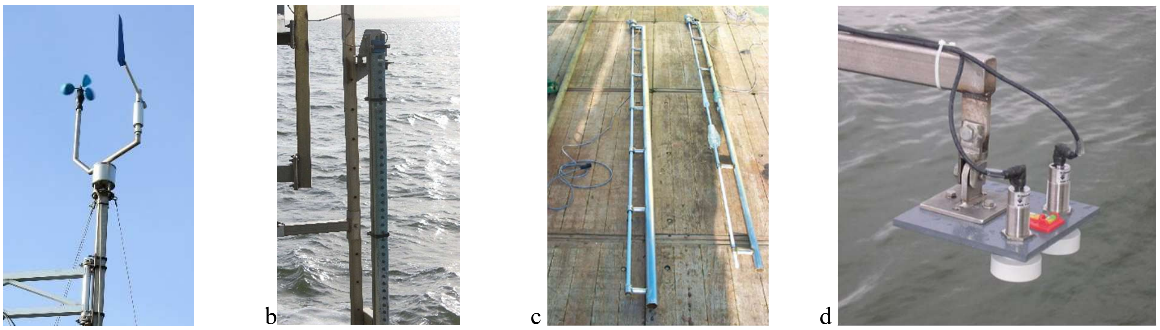
[4] Geographic Coordinate System: GCS Amersfoort; Spheroid: Bessel 1841 RD New; EPSG: 28992

[5] Photo from Rijkswaterstaat

and "log-a-level" instruments (Photo 2. 2b, c, d). Some instrument details are given in (Bottema, 2007).

The wave data for this study were initially obtained from an early step gauge (before 2000) and capacitance probes (until 2000 and 2007 respectively, see (Bottema, 2007)), later on, a newer step gauge was used. Some acoustic log-a-level measurements are also available (FL2, FL26 and FL37), but were deemed unreliable (Bottema, 2007).

The step gauges and capacitance probes were sampled at 4Hz frequency, except FL25, which was sampled at 8 Hz. Further data acquisition details are given in (Bottema, 2007).



a b c d

Photo 2. 2 Anemometer FL48 (a), step gauge FL48 (b), capacitance probes (c)[6], log-a-level FL26 (d)[6],

Table 2. 3 summarises the monitoring network and shows the periods and measured parameters for each location on Lake IJssel and Lake Marken.

Table 2. 3 Chronology of monitoring network on Lake IJssel and Lake Marken for 1997-2016 study period

lake	station	wind speed	wind direction	wave	water level
IJssel	FL2	Sep-1997 - Jul-2005	Sep-1997 - Jul-2005	Jun-1997 - Jul-2005	Jun-1997 - Jul-2005
IJssel	FL2b	Aug-2005 - Dec-2016	Aug-2005 - Dec-2016	Aug-2005 - Dec-2016	Aug-2005 - Dec-2016
IJssel	FL5	-	-	Jul-1997 - May-2007	Jul-1997 - May 2007
IJssel	FL9	Nov-2009 - Dec-2016	Nov-2009 - Dec-2016	Jul-1997 - Dec-2016	Jul-1997 - Dec-2016
IJssel	FL25	Jul-2005 - Sep-2006	-	Aug-1997 - Sep-2006	Jul-1997 - Sep-2006
IJssel	FL26	Apr-1998 - Dec-2009	Apr-1998 - Dec-2009	Apr-1998 - Dec-2009	Mar-1998 - Dec-2009
IJssel	FL37	Sep-2006 - Dec-2008	-	Oct-2006 - Dec-2008	Sep-2006 - Dec-2008
IJssel	FL46	Dec-2009 - Jan-2014	Dec-2009 - Jan-2014	Mar-2010 - Jan-2014	Mar-2010 - Jan-2014
IJssel	FL47	Sep-2010 - Dec-2016	Sep-2010 - Dec-2016	Aug-2010 - Nov-2016	Aug-2010 - Nov-2016
IJssel	FL48	Oct-2010 - Dec-2016	Oct-2010 - Dec-2016	Oct-2010 - Dec-2016	Oct-2010 - Dec-2016
IJssel	FL49	Oct-2010 - Dec-2016	Oct-2010 - Dec-2016	Oct-2010 - Dec-2016	Oct-2010 - Dec-2016
Marken	FL42	Nov-2010 - Dec-2016	Nov-2010 - Dec-2016	Nov-2010 - Dec-2016	Nov-2010 - Dec-2016
Marken	FL44	-	-	Nov-2010 - Jan-2013	Nov-2010 - Jan-2013

[6] Photo from (Bottema, Measured wind-wave climatology Lake IJssel (NL), 2007)

2.2 Data availability

2.2.1 Data sources

The result of the measurements is raw data, which is not readily available for this study. For that reason, and to save significant amounts of time, the data processed by WAVES data processing software of Xi Company (Xi-alles.nl) were made available for this study (Actually data comes from Rijkswaterstaat but is processed by Xi company). The data was provided by Xi Company and freely accessible on www.xi-alles.nl web page. Xi Company provides processed wind data (measured by anemometer), wave parameters (measured by step gauge and log-a-level) and still water level. All parameters are given for 20-minute intervals and represented either hourly averages (wind) or 20-minute-averages (all other parameters). All spectral wave parameters are calculated for a frequency interval of 0.03 to 1.5 Hz as the commonly used interval of 0.03 to 0.5 Hz (for marine applications) was deemed unsuitable for the relatively short waves on Lake IJssel and Marken (Bottema, 2007).

On the www.xi-alles.nl web page, water level data was missing for FL2, FL9, FL25 and FL26, before 2007. Instead, the data-DVD of (Bottema, 2007) was for this period. Wave parameter data of FL5 was compared from both sources, from 1997 to 2007 (Xi web page and aforementioned data-DVD) in order to ensure that data from Rijkswaterstaat is consistent with data provided by Xi (Figure 2. 2). FL5 was chosen because it is the only location with data from both sources for the same period (from July 1997 to May 2007). As it is shown on the graph, the wave height (H_{m0}) has exactly the same value for both datasets and data from Rijkswaterstaat can be used.

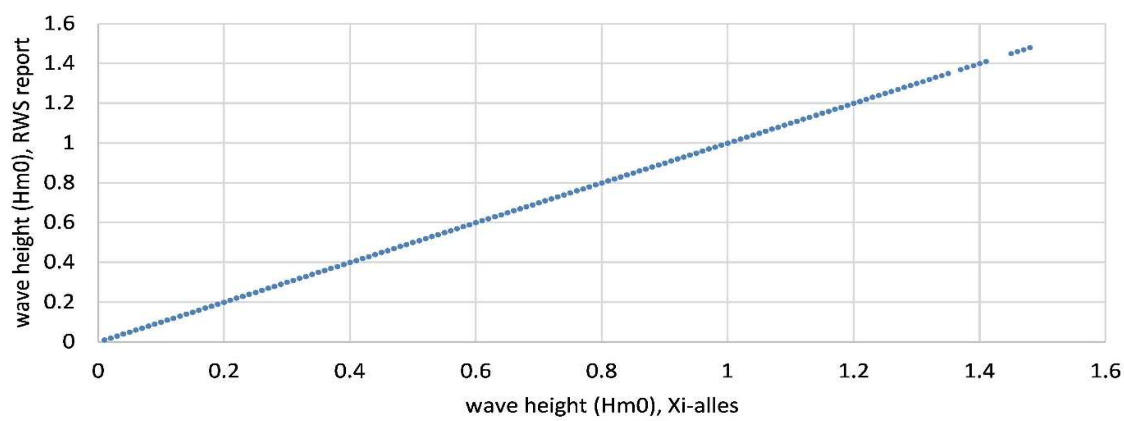


Figure 2. 2 Comparison of wave height (H_{m0}) of Rijkswaterstaat and Xi datasets, at FL5

The wind was measured at various locations at Lake IJssel and Lake Marken, but the dataset is too short and has too many interruptions to allow for reliable extreme-value analysis. The latter is rather done on land-based wind speeds as measured by KNMI. These are expressed as potential wind speed (U_{pot}) which includes nearby exposure corrections and is representative of 10m wind over a standard meteorological site with short grass. Together with the wind direction, these data are provided by KNMI, through their freely accessible www.KNMI.nl web page.

2.2.2 Available data set

As it was already mentioned, data of twelve measurement locations were used for the current study, from 1997 to 2016, on Lake IJssel and Lake Marken. Measurement locations were operational during different periods of 1997-2016, on both lakes. Five of them were operational since 1997-1998, and six of them since 2010; FL37 was only operational during 2006-2008. The chronology of operation period of locations by measured parameters is presented in

Table 2. 3. In addition, the detailed graphical illustration of percentage availability of monthly data is presented in Appendix A, for all locations.

Locations FL43 and FL45 were also operational on Lake Marken in 2010, besides twelve measurement locations. However, their observation lasted only 9 days, and no strong wind speed was measured in the nearby location FL42 for that period of time (Figure 2. 3).

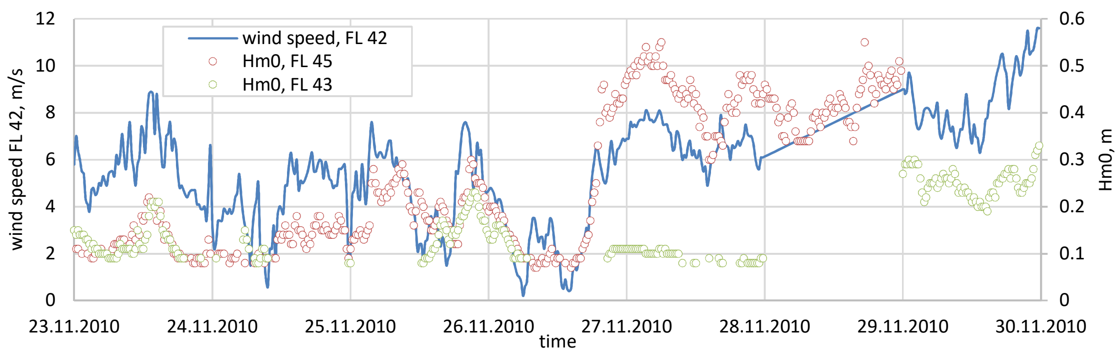


Figure 2. 3 Comparison of wind speed at FL42 with wave height (H_{m0}) at FL43 and FL45

As it is shown on the graph, wind speed at FL42 does not exceed 12 m/s and wave height is less than 0.6 meters. That is why these locations were not considered in the current study, because of a short period of measurement and insignificant wind and wave conditions.

It is noteworthy that the FL5 and FL44 do not have wind observations during their operation periods, FL9 has wind data only since 2009 and has data gap for all parameter from May 2007 to November 2009. FL48 has some missing data (almost 35%) of wave parameters during April-August 2015. The FL25 and FL37 have only wind speed data without wind direction. For some locations, wind direction data is missing with the following proportions: FL2 (1.3%), FL9 (1.5%), FL26 (2.2%), and FL49 (6.6%).

Wind speed and wind direction of FL2 and FL42 were used for FL5 and FL44 respectively, as references. The wind direction of FL26 was used as a reference for locations FL25 and FL37.

Analysis of data availability graphs shows that locations, which were operational since 1997-1998, have significant missing data till 2000-2001 (Figure A- 1, Figure A- 2, Figure A- 3, Figure A- 4, Figure A- 5). The main causes for missing data in early years are discussed in (Bottema, 2007). Locations have relatively confident percentage of data availability after 2000, and especially after 2010.

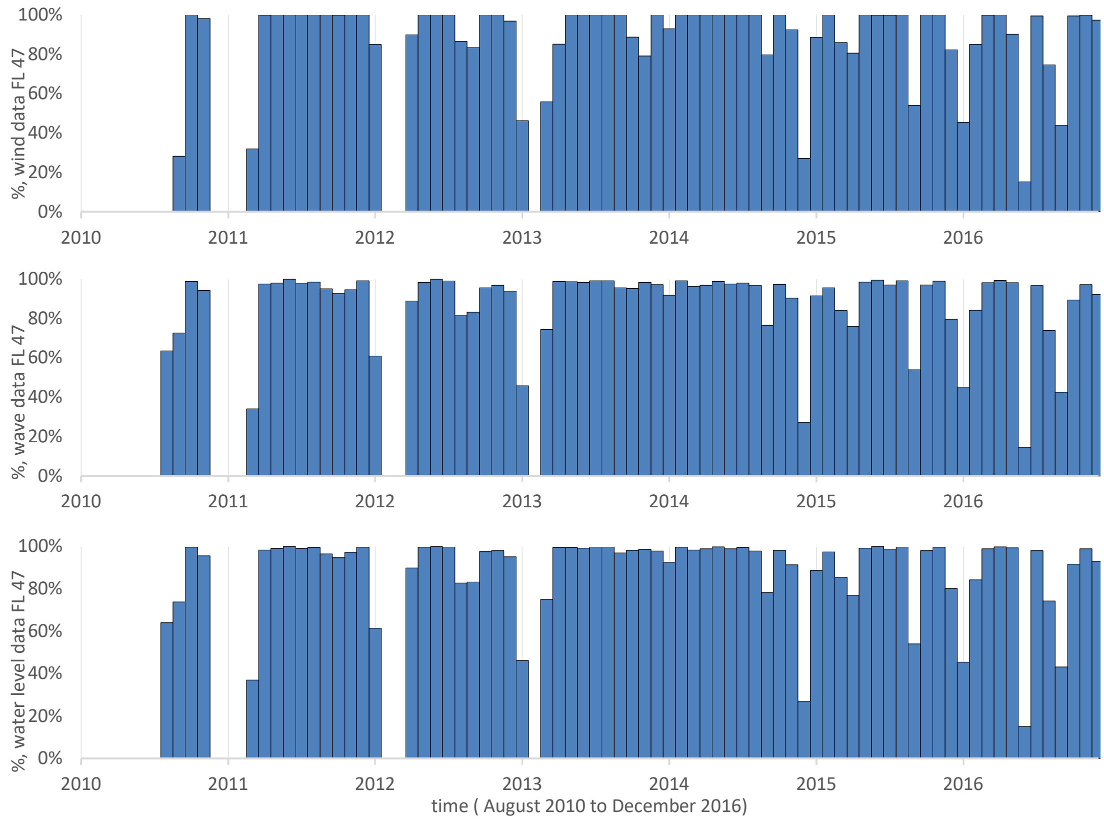


Figure 2. 4 Percentage available data per month, FL47, Lake IJssel

The graphs in Appendix A also show that there are missing data in the winters of several years, especially in 2001, 2003, 2011-2013. These gaps are because of measuring interruptions during and after frosty periods when all installations were removed (Bottema, 2007). Figure 2. 5 shows the hourly air temperature for the most apparent cold winters at Berkhout meteorological station, which could be proof the causes of interruption of measurements.

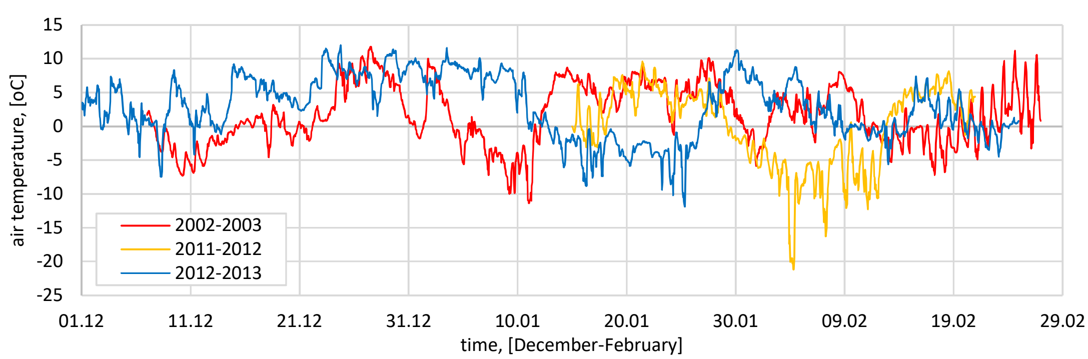


Figure 2. 5 Hourly air temperature for winter period of some years at Berkhout meteorological station (KNMI)

Potential wind speed of KNMI meteorological stations is considered as a land-based reference of wind, as the wind measurements on the lakes are done for too short a period and have too many interruptions, for an accurate extreme-value analysis of wind. Potential wind speed is the transformation of measured wind speed at 10-meter height with corrected exposure effects, as the raw wind is not fully representative of internationally required standard (open grass) meteorological location, because of nearby terrain roughness and obstacles. (Bottema, 2007), (Wieringa, 1986).

Potential wind speed is rounded to 0.1 m/s, with a one-hour averaging time interval and wind direction rounded to 10 degrees. The graph of measurement periods of KNMI stations is presented in Figure 2. 6.

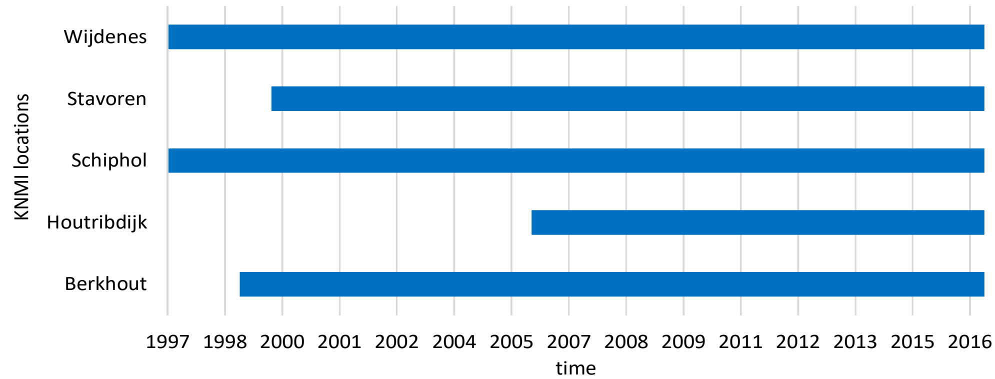


Figure 2. 6 Data availability of KNMI wind speed measurement locations

The KNMI-measurements began before 1997 at Schiphol and Wijdenes station, but the data was taken from July 1997, as wave measurement on the lakes has been started from that period.

2.2.3 Data quality

The obtained data has some shortcomings, and to some extent, this applies to the underlying dataset. Periods of suspected data were specified in (Bottema, 2007) until early 2007 and replaced by dummy values where needed). More recent data were processed by Xi Company, which at least should remove obvious outliers and other signal problems. However, less obvious problems like algae soiling in summer (Bottema, 2007) may not have been detected in recent data (since 2007). In addition, some data issues arise from the fact that the download website www.xi-alles.nl primarily was meant as a graphical presentation website, rather than a real data platform. Some examples of recent data issues (after 2006) are mentioned below.

1. Wind measurement interval is 20 minutes, but in some cases, the interval becomes 10 minutes (Table 2. 4), and even random intervals (Table 2. 5). The extra values were added by Xi Company to facilitate graphical presentation. Also, Xi company added extra wind direction values to enhance graphical presentation for winds crossing through the North (which is 0 or 360 degrees).

Table 2. 4 Measured wind data with 10 minutes interval, FL9

time	wind speed, m/s	wind direction, degree
04:00:00 16-04-2010	5.7	7.30
04:20:00 16-04-2010	5.4	0.98
04:30:00 16-04-2010		0
04:40:00 16-04-2010	5.6	NULL
04:50:00 16-04-2010		360
05:00:00 16-04-2010	5.6	355.7
05:20:00 16-04-2010	5.4	353.9

Table 2. 5 Measured wind data with random intervals, FL9

time	wind speed, m/s	wind direction, degree
23:40:00 31-05-2010	5.1	352.11
23:57:29 31-05-2010		NULL
00:00:00 01-06-2010	5.1	1.26

2. Water level reaches -2.5 m NAP, and then varies from -1.3 m to -1.0 m NAP at location FL2, during 23 - 24 October 2007. This is most probably due to an offset error in the data logger software, or an unstable instrument offset (Figure 2. 7).

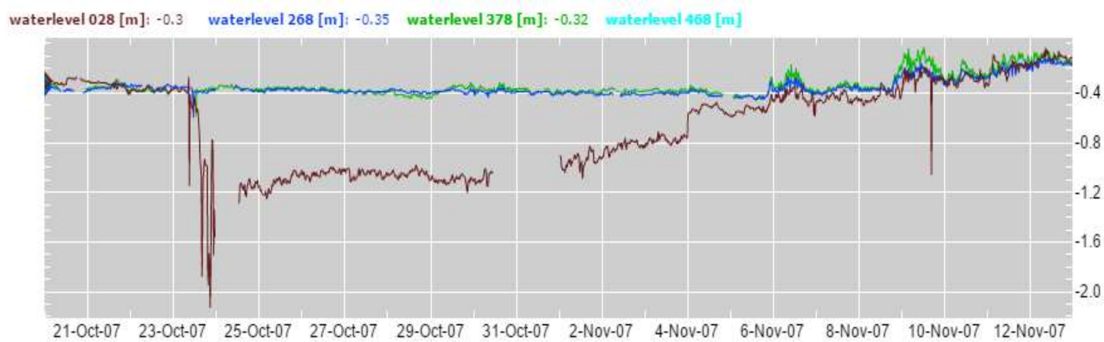


Figure 2. 7 Water level at FL2, October-November 2007

3. Water level data also had inaccuracies at FL47. Particularly, the water level at FL47 is considerably lower than at nearby locations FL 48 and FL 49, but fluctuations are similar for all three locations, from December 2015 to June 2016. In this case, the standard bias of 0.5 meters was adjusted with Xi company and water level data was recovered at FL47 (Figure 2. 8).

Figure 2. 8 Water level at FL47, December 2015 – June 2016

4. In some cases, the wind directions are exactly constant for long period (days, weeks). This kind of error appears at FL2, FL26 from March 2008 to March 2009 (Figure 2. 9). Such periods are most likely an experimental error (damaged instrument or its connection) and therefore excluded from the analysis.

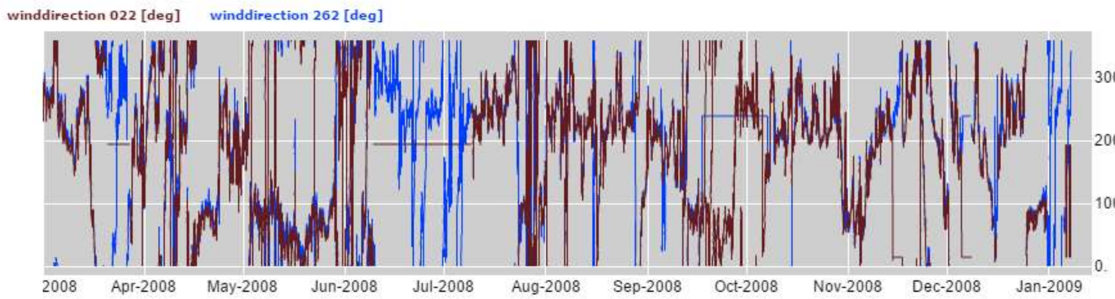


Figure 2. 9 Wind direction at FL 2 and FL26, March 2008 – March 2009

5. The coordinates of some locations (FL37, FL47) have differences in different sources (Rijkswaterstaat, Xi, Donar data service). The coordinates of closed locations were taken from Rijkswaterstaat report (Bottema, 2007). The coordinates of current location were taken from the maintenance group of the locations and taken during the field trip.

2.3 Range of experimental data

The ranges of experimental data were defined for data analysis and modelling, after evaluation of data availability, gaps and errors.

The first and important condition of data sampling is the selection of the experimental data period. The wave parameters measurement could have significant unreliability due to soiling by algae, during the summer season (Bottema, 2007). Therefore, data only from November to April will be used for wave climate analysis and modelling (data of entire year will be used only for wind analysis).

The range of wind data: The maximum wind speed (U_{10}) was measured 27.3 m/s at location FL47 (one-hour averaging interval). In general, the average of maximum wind speed is 24.9 m/s (there is a short period of wind measurement at FL25 that is why it has only 15.6m/s maximum speed). The average wind speed is 6.85 m/s for measurement locations. The average wind speeds are higher at FL37 and FL47, which are located in the middle of lakes and the wind blows through the smooth (water) surface from all sides of the horizon. In total, more than 66% of wind speeds of all locations are within 1σ (Table 2. 6).

Table 2. 6 Range of experimental wind speed (U_{10}) (for whole year)

location	number of samples	range, m/s	average, m/s	standard deviation	percentage of data within 1σ (%)
FL2	372872	0.1-24.1	6.77	3.2	67.7
FL9	135280	0.1-24.8	6.97	3.2	68.0
FL25	19293	0.1-15.6	5.73	2.6	66.6
FL26	172705	0.1-23.3	6.77	3.2	67.8
FL37	53108	0.1-24.4	7.17	3.2	67.7
FL42	138811	0.1-25.1	6.80	3.1	68.2
FL46	82654	0.1-24.3	6.89	3.2	67.1
FL47	136001	0.1-27.3	7.05	3.2	68.1
FL48	142012	0.1-26.8	6.85	3.1	67.9
FL49	136662	0.1-24.5	6.36	3.1	67.8

Note: the measurement period is presented in Table 2. 3

In total, 38 cases with more than 20 m/s wind speed were measured on Lake IJssel and Lake Marken, during 1997-2016. The most of the strong winds (84%) happened during November-April period. Wave parameters are available during strong wind events most of the time, but in some cases, wave data is partly available. The wind directions of strong winds are north-west and south-west, but the most significant part is from the south-west. The overall strong wind events are presented in Table 2. 7, where "½" is the event when wave data is partly available, "v" is the case when wave parameters are fully available, and "No data" is the case when the wave is unavailable. "V" in brackets just mention the cases, which is out of an experimental period of November-April but still can be considered for strong wind analysis.

Table 2. 7 Available wave data for cases with at least 20 m/s hourly-averaged wind

date	FL2	FL2b	FL9	FL26	FL37	FL42	FL46	FL47	FL48	FL49	wind speed [m/s]	wind direction
05.01.1998	½										20.7	248
04.03.1998	V										20.7	270
28.02.1999	V										20.7	270
03.12.1999				½							21.2	270
28.05.2000			V								22.0	225
30.10.2000	(½)										21.5	203
28.12.2001	V										20.4	276
26.02.2002	V			V							21.1	239
09.03.2002	V			V							21.2	294
27.10.2002	(V)										23.4	246
20.03.2004	No data			No data							20.7	237
08.01.2005	V			V							20.3	240
01.11.2006		V			½						20.6	321
30.12.2006				No data	V						20.3	240
11.01.2007				V	V						20.5	228
18.01.2007		½		V	V						24.4	272
31.01.2008		V		V	V						20.6	205
01.03.2008		V									20.3	276
12.03.2008		No data									20.0	256
21.11.2008		V		V	No data						22.3	353
12.09.2011		(V)					(V)				22.2	237
07.12.2011		V									20.4	288
08.12.2011								V	V		20.7	219
24.12.2011		V									20.2	338
03.01.2012		V	V			V	V	No data	V	V	21.9	212
05.01.2012		V	V								21.1	292
22.01.2012		V									20.5	289
24.09.2012		(V)									20.0	209
28.10.2013		(V)	(V)			(V)	(V)	(V)	(V)	(V)	27.3	227
05.12.2013		V	V			V	V	V	V		21.9	278
24.12.2013									V		20.5	196
15.02.2014								V	V	V	21.6	213
10.01.2015						V					20.9	239
31.03.2015		V	V			V		V			21.4	286
25.07.2015		(V)	(V)			(V)		(V)	(V)	(V)	23.9	317
18.11.2015		V	V			V					21.5	262
08.02.2016			V								20.1	226
28.03.2016								V			20.5	207
20.11.2016		V				V		V	V		21.3	204

The experimental range of potential wind of KNMI meteorological stations is up to 22-25 m/s. The maximum and average potential wind speeds are higher at Houtribdijk station, which is located between Lake IJssel and Lake Marken. More than 65% of data is within 1σ (Table 2.8).

Table 2. 8 Range of experimental potential wind speed (U_{pot}) (for whole year)

location	number of samples	range, m/s	average, m/s	standard deviation	percentage of data within 1σ (%)
Berkhout	155864	0-24.2	5.12	2.85	64.9
Houtribdijk	94826	0-25.4	6.58	3.41	67.9
Schiphol	170976	0-24.0	5.21	2.85	65.1
Stavoren	149248	0-24.2	5.68	2.91	72.6
Wijdenes	170976	0-22.6	5.33	2.73	67.0

Note: the measuring period is presented in Table 2. 1

The range of water depth (water level): The average water depth (D) is 3.64 meter for the locations of Lake IJssel and it is 4.04 meter for the locations of Lake Marken (the average water depths are not the general average depths of both lakes). Besides location FL5, the standard deviation of the water depth is almost 0.16 meter (location FL5 was relocated several times (Table 2.2), in the transitional area of lake bottom).

Table 2. 9 Range of experimental water depth (D) data

location	size of dataset	range, m	average, m	standard deviation	percentage of data within 1σ (%)
FL2	60613	3.76-5.08	4.20	0.19	78.6
FL2b	105953	3.84-5.10	4.20	0.15	71.3
FL5	72265	1.08-2.98	1.68	0.38	61.8
FL9	143591	3.61-4.74	3.94	0.16	71.4
FL25	67908	1.81-3.03	2.27	0.15	72.5
FL26	96639	4.82-6.19	5.38	0.17	77.7
FL37	25898	2.13-3.27	2.48	0.15	68.8
FL42	63974	3.88-4.30	4.05	0.09	64.4
FL44	15449	3.79-4.50	4.03	0.12	66.0
FL46	31634	4.57-5.56	4.91	0.15	68.8
FL47	59854	4.44-5.39	4.83	0.14	68.8
FL48	62489	2.68-3.81	3.23	0.14	70.7
FL49	63113	2.40-3.50	2.96	0.14	69.3

The range of wave parameters: The significant wave height (H_{m0}) was reached 1.85 meters at location FL2b. In general, the average of maximum wave height is 1.39 meter for all locations of Lake IJssel and it is 1.32 meter for the locations on the Lake Marken.

Table 2. 10 Range of experimental significant wave height (H_{m0}) data

location	size of dataset	range, m	average, m	standard deviation	percentage of data within 1σ (%)
FL2	53673	0.01-1.52	0.37	0.23	66.8
FL2b	107147	0.01-1.85	0.39	0.23	67.3
FL5	27345	0.01-1.48	0.35	0.24	67.0
FL9	132515	0.01-1.79	0.39	0.23	67.9
FL25	57212	0.01-0.97	0.21	0.15	70.4
FL26	87555	0.01-1.64	0.40	0.22	67.9
FL37	25595	0.01-1.19	0.26	0.16	68.0
FL42	63124	0.05-1.29	0.37	0.20	65.8
FL44	15411	0.05-1.35	0.37	0.22	68.6
FL46	31382	0.05-1.34	0.39	0.21	67.5
FL47	59246	0.05-1.51	0.41	0.22	67.6
FL48	61331	0.05-1.09	0.31	0.16	66.2
FL49	61562	0.05-1.00	0.27	0.15	66.7

The range of spectral mean wave period (T_{m01}) is almost 0.9-3.7 seconds for locations FL42, FL44, FL46, FL47, FL48, and FL49, and almost 0.9-5.0 seconds for locations FL2, FL2b, FL5, FL9, FL25, FL26 and FL37. The average of mean wave period (T_{m01}) is 1.92 seconds.

Table 2. 11 Range of experimental spectral mean wave period (T_{m01}) data

location	size of dataset	range, m	average, m	standard deviation	percentage of data within 1σ (%)
FL2	53673	0.8-4.8	2.02	0.49	68.0
FL2b	107147	0.9-4.9	2.03	0.47	64.0
FL5	27345	0.8-5.0	1.90	0.51	66.9
FL9	132515	0.8-4.1	2.01	0.47	63.7
FL25	57212	0.8-5.0	1.68	0.42	65.1
FL26	87555	0.8-5.0	2.01	0.45	65.6
FL37	25595	1.0-4.9	1.70	0.37	65.7
FL42	63124	1.0-3.5	1.98	0.42	66.8
FL44	15411	1.0-3.7	1.93	0.49	65.6
FL46	31382	1.0-3.7	2.01	0.44	67.2
FL47	59246	0.9-3.8	2.08	0.48	67.5
FL48	61331	0.9-3.6	1.83	0.42	62.0
FL49	61562	0.9-3.6	1.75	0.42	62.5

Summarizing, the data were selected as an experimental range from November to April, where the wind speed at 10 meter height (U_{10}) is up to 27.3 m/s, the water depth (D) is from 1.08 to 6.19 meter, the significant wave height (H_{m0}) is up to 1.85 meters and mean wave period (T_{m01}) varies from 0.9 to 5 seconds.

2.4 Summary of Chapter 2

Summarizing the results of Chapter 2, the following general conclusions could be stated:

1. Processed raw measured data of Xi Company are consistent with the processed data by Rijkswaterstaat as provided on the DVD with (Bottema, 2007).
2. The measurements of the late 1990s and early 2000s are often interrupted and less reliable for locations FL2, FL5, FL9, FL25 and FL26. This does not influence the analysis since unreliable data were labelled and/or replaced by exception values in the source data.
3. There is an interruption of measurement for some winters due to ice cover on the lakes.
4. In some relatively recent cases, biases in the still-water levels and unreliable wind direction data had to be corrected for, since these were overlooked in the analyses by Xi. In addition, some peculiarities of the Xi data sets (such as adding extra time steps on just a few of the variables in order to facilitate graphical presentation) had to be dealt with.

3. Wind analysis

The main force of gravity wave growth is the wind in Lake IJssel and Lake Marken. Therefore, the analysis of wind speed on the lakes has significant importance. Characteristics of wind speed will be discussed in chapter 3.1. Qualitative wind climate analysis will be discussed in chapter 3.2. Spatial transformation of wind speed will be analysed in chapters 3.3 and 3.4, as the wind is transforming spatially over the lakes and from land to the water body.

3.1 Characteristics of wind speed and wind direction on Lake IJssel and Lake Marken

As it was already mentioned in chapter 2.3, (Table 2. 6) the maximum wind speed was measured 27.3 m/s at location FL47. In general, the average of maximum wind speeds is 24.9 m/s (location FL25 has a short period of measurement of wind speed (Figure A- 4), that is why it has 15.6 m/s of maximum wind speed). The average wind speed is 6.85 m/s for all locations. More than 66% of wind speed data of all locations are within 1σ and 99% of the data is with 3σ (Table 2. 6).

The graphs of the wind speed distributions show that wind speeds are not fully distributed according to a normal distribution for all locations, but rather a little bit skewed to the right (Figure 3. 1). This is also illustrated by the fact that average wind speeds are about 7 m/s, whereas the mode (most occurring) wind speed is about 6 m/s, while the measured extreme range up to order 25 m/s (exact value depending on location and length of measuring record).

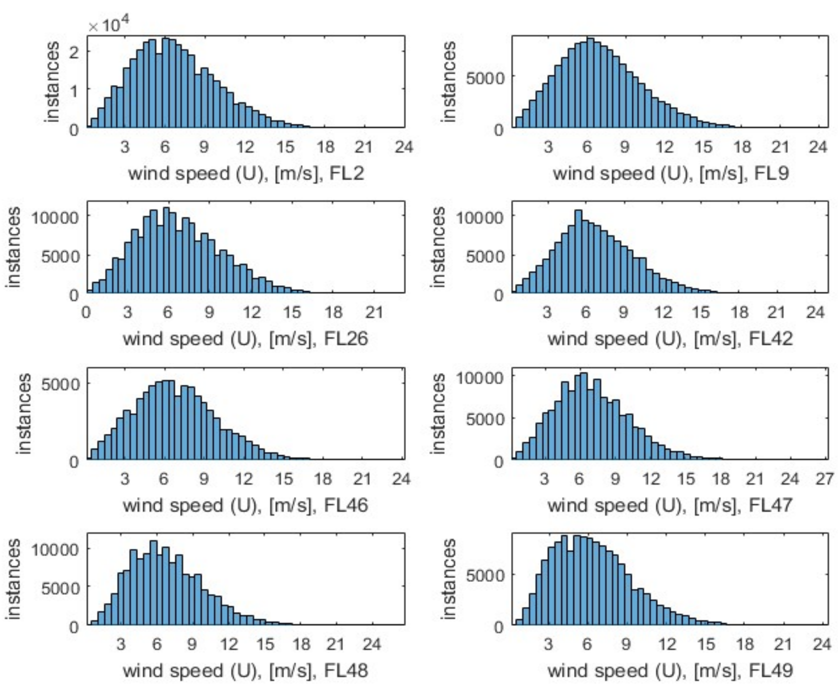


Figure 3. 1 Distribution of wind speed (U_{10}) for eight measurement locations on Lake IJssel and Lake Marken

The relatively extreme winds (more than 15m/s) are mainly dominating from southwestern and western directions in all locations. The example of scatter graph of location FL2 shows the general overview of wind conditions on the lakes (Figure 3. 2). Wind speed and direction conditions will be discussed more detailed in chapter 3.2.

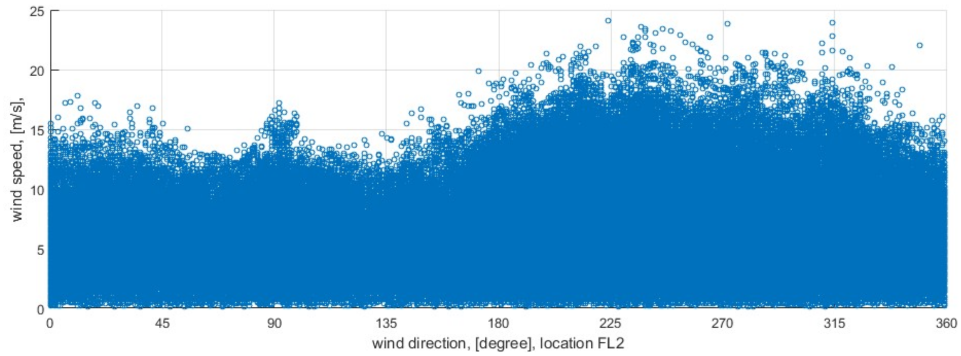


Figure 3. 2 Wind conditions at FL2, from 1997 to 2016

Regarding the maximum wind speed, there were 39 cases of storm events with more than 20 m/s wind speed on Lake IJssel and Lake Marken, during 1997-2016 (2010-2016 for Lake Marken). The most of the strong winds (84%) happened during November-April. The significant portion of storm events have wind directions of the south-west and the minority is from the north-west.

Table 3. 1 The dates of strong wind events, with more than 20m/s hourly-averaged wind speed

date	FL2	FL9	FL26	FL42	FL46	FL47	FL48	FL49	wind speed [m/s]	wind direction
05.01.1998	V								20.7	248
04.03.1998	V								20.7	270
28.02.1999	V								20.7	270
03.12.1999			V						21.2	270
28.05.2000		V							22.0	225
30.10.2000	V								21.5	203
28.12.2001	V								20.4	276
26.02.2002	V		V						21.1	239
09.03.2002	V		V						21.2	294
27.10.2002	V								23.4	246
20.03.2004	V		V						20.7	237
08.01.2005	V		V						20.3	240
01.11.2006	V								20.6	321
30.12.2006			V						20.3	240
11.01.2007			V						20.5	228
18.01.2007	V		V						24.4	272
31.01.2008	V		V						20.6	205
01.03.2008	V								20.3	276
12.03.2008	V								20.0	256
21.11.2008	V		V						22.3	353
12.09.2011	V				V				22.2	237
07.12.2011	V								20.4	288
08.12.2011						V	V		20.7	219
24.12.2011	V								20.2	338
03.01.2012	V	V		V	V	V	V	V	21.9	212
05.01.2012	V	V							21.1	292
22.01.2012	V								20.5	289
24.09.2012	V								20.0	209
28.10.2013	V	V		V	V	V	V	V	27.3	227
05.12.2013	V	V		V	V	V	V		21.9	278
24.12.2013							V		20.5	196
15.02.2014						V	V	V	21.6	213
10.01.2015				V					20.9	239
31.03.2015	V	V		V		V			21.4	286
25.07.2015	V	V		V		V	V	V	23.9	317
18.11.2015	V	V		V					21.5	262
08.02.2016		V							20.1	226
28.03.2016						V			20.5	207
20.11.2016	V			V		V	V		21.3	204

Table 3. 1 shows the dates of the cases with the storms (wind speed > 20m/s) and the maximum wind speed and direction during the storm. According to the available data, two storm events are happening per three years on average, with more than 20m/s wind speed, except locations FL9 and FL26, where it happens two times per two years. These numbers are approximate since the locations each have different periods of measurement and interruptions during measurements.

3.2 Qualitative wind climate analysis

The wind data is classified and averaged by wind directions and wind speeds, so that the prevailing wind analysis and trends can be seen more clearly, for the overall analysis of wind climate. The wind speed was classified (and averaged) in 0-5m/s, 5-10m/s, 10-15m/s and 15-25m/s ranges. Here, the last group of wind speed (15-25m/s) was taken with a large range, because an extra class starting at 20 m/s would not have enough data for a useful analysis. The wind direction was averaged by 15^{O} intervals and the percentage of wind was calculated for each range of wind speed. Figure 3. 3 shows the results of the analysis of the percentage of wind data for given ranges of wind speeds at locations FL42 and FL47. The main results of this analysis are presented in Appendix B.

According to the analysis, the wind speed of 0-5m/s range is distributed almost equally (almost 5%) for all directions of most locations. However, FL48 and FL49 are exceptions (Figure B- 7 and Figure B- 8), because they are located next to the western shoreline of Lake IJssel and the 195^{o}-225^{o} range of wind directions coincides with the side of nearby land and the local winds (like breezes) could have an influence on small wind speeds. In addition, offshore winds are more likely to be small because of shelter effects, for these short fetches, so that the low-wind-speed classes in the Appendix B graphs have a somewhat greater preference for offshore winds. This can also be seen for FL2 (at easterly winds).

The distribution of the wind speed by the directions is not clearly expressed (there is slight preference) for the range of 5-10 m/s winds also. However, the winds from 195^{o}-255^{o} directions begin to dominate slightly, amounting up to 40-50% of the total wind data, for all locations.

The difference of wind distribution by direction is becoming significant, for the range of 10-15 m/s wind speeds. The wind, which is blowing from 180^{o}-270^{o} directions, are significantly dominated. Their share in the whole range of the wind data is up to 70%.

The prevalence of western and southwestern winds increases even to 80%, for the range of strong winds (15-25 m/s). The fluctuation of the line of strong wind speeds (red line on the graphs in Appendix B) is high, as the strong winds are not happening frequently so that a few of these events could already influence the plotted distributions. For example, the percentage of the strong wind from 90^{o} direction is 10% of all cases, at location FL46 (Figure B- 6). This is because the cases with more than 15-25m/s of wind speed are few at this location and even one single event can have a high percentage in all dataset. Such cases also happen at locations FL9, FL48 and FL49, but with small percentages (Figure B- 2, Figure B- 7 and Figure B- 8).

In the majority of locations, the strong wind blow from 195^{o}-270^{o} directions. Only FL48 and FL49 have emphasised peaks (225^{o}), which could be because of their location and few strong wind cases.

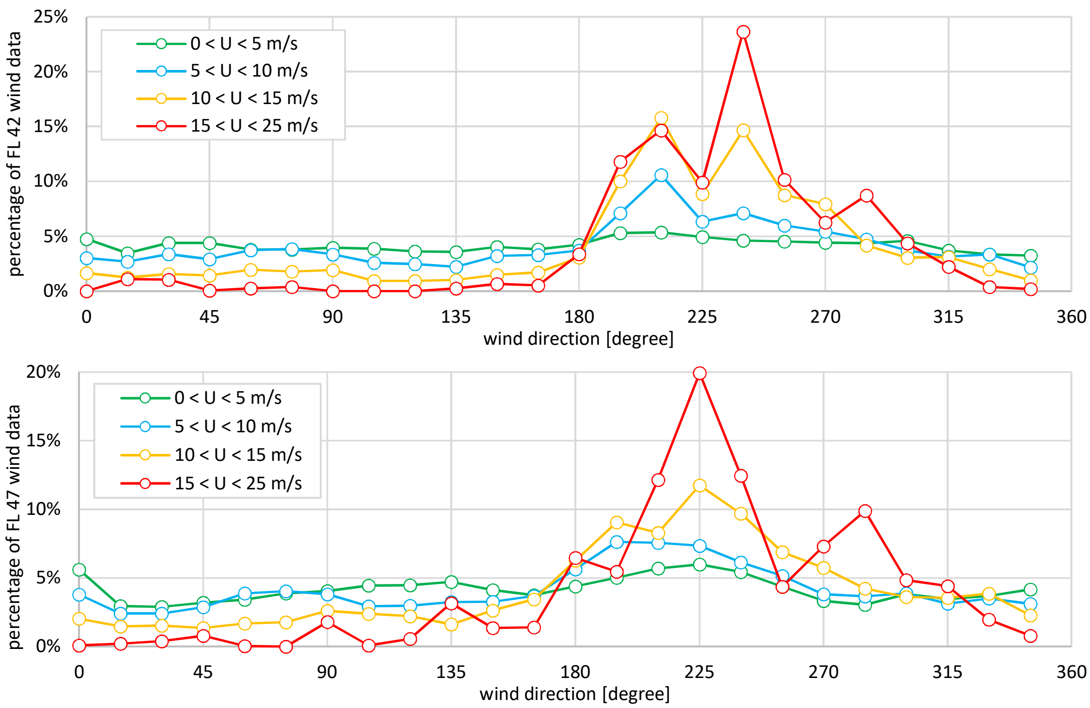
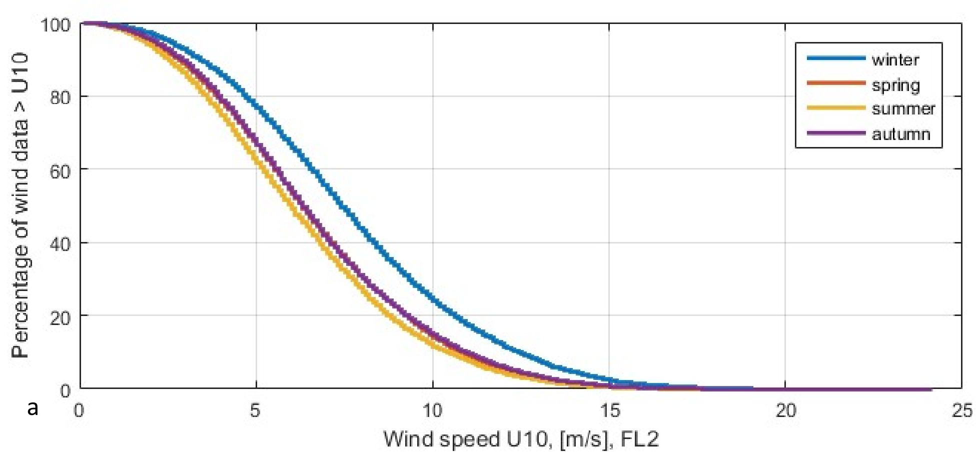


Figure 3. 3 Percentage of wind data in a given wind direction for different ranges of wind speeds, FL42 and FL47

Figure 3. 4 shows the percentage of wind speed above a threshold U_{10}, by seasons. The graphs of all locations are presented in Appendix B. According to the results of the analysis, the percentage of wind speed during winter (Dec-Feb) exceeds almost 20% other seasons, for the wind speed range 5-15m/s.

The percentage of wind speed more than 10m/s almost makes up 25-30% of all measured wind data in winter and 12-18% in summer, for all locations. The wind speed more than 15m/s is 5-7% of all measured data, for almost all locations.



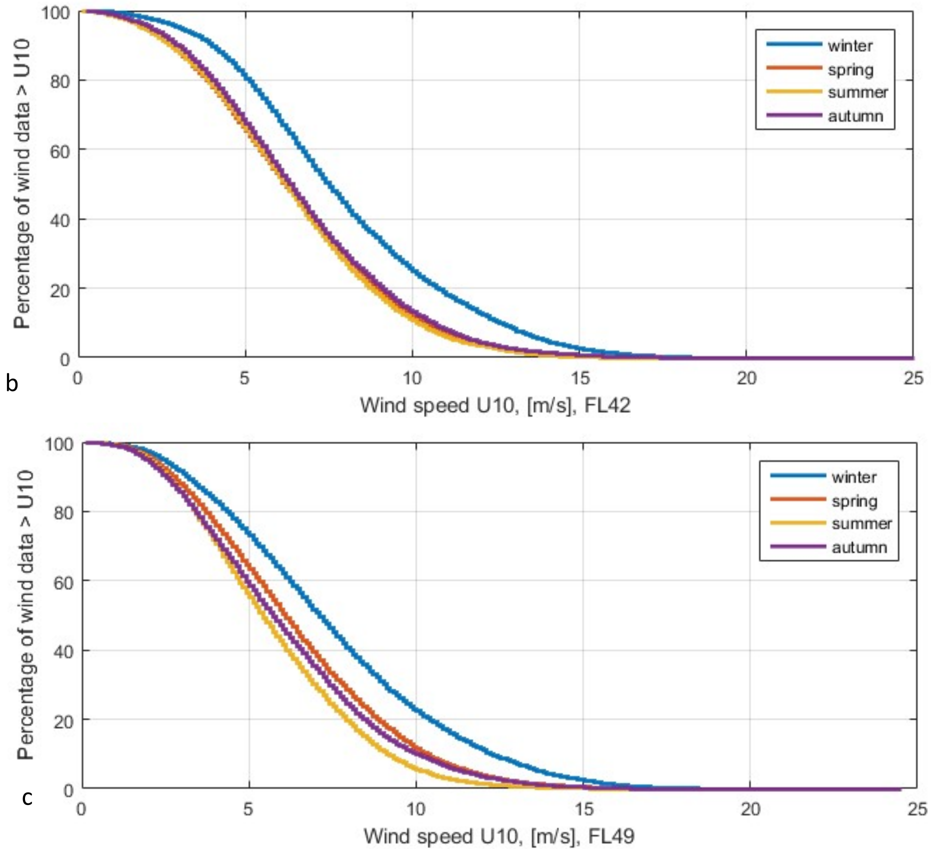


Figure 3. 4 Percentage of FL2 (a), FL42 (b) and FL49 (c) data with U_{10} wind speeds above a threshold U_{10}, for winter (Dec-Feb), spring, summer and autumn.

The seasonal variation of wind also has distinctly separated phases, especially for high wind speeds (wind speed more than 15m/s). According to the graph on Figure 3. 5, the strongest winds are mostly observed in winter months and then in autumn. In addition, the seasonal distribution of winds is related to the position of measurement locations on the lakes (Table 3.2). Particularly, the percentage of strong wind during winter seems to be slightly decreasing from the western to the east. Here the percentage of strong winds (more than 15m/s) is more than 50% (of winter data compared to data for the full year) at locations FL26, FL48 and FL49, it is 46% at locations FL46 and FL47, and the percentage is 42% at location FL2 and FL9.

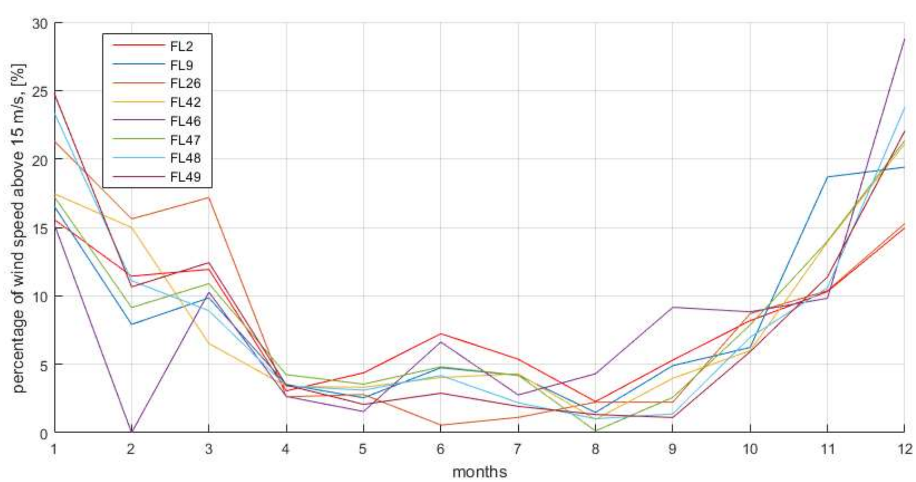


Figure 3. 5 Percentage of wind data with more than 15 m/s wind speed, by months

Table 3. 2 also presents the distribution of high wind speeds (more than 15m/s) by November-April and May-October periods. The reason for such a division of periods was that reliability of wave data could not be guaranteed from May-Oct (risk of soiling, see Section 2.3 and Chapter 5-6). In addition, it is essential to know the percentage of high wind speeds in the range of experimental dataset. Thus, more than 67% observed high wind speeds (more than 15m/s) occur within the months considered for wave analysis so that most of the relevant strong-wind events will be included (unless they occur during or just after an ice period, when most or all instruments are removed).

Table 3. 2 Percentage of the wind with more than 15m/s wind speed by seasons, and for November-April and May-October periods

periods	**locations**							
	FL2	**FL9**	**FL26**	**FL42**	**FL46**	**FL47**	**FL48**	**FL49**
Winter (Dec-Feb)	42%	44%	52%	54%	44%	48%	58%	57%
Spring (Mar-May)	19%	16%	23%	13%	14%	19%	15%	18%
Summer (June-Aug)	15%	10%	4%	9%	14%	9%	7%	6%
Autumn (Sep-Nov)	24%	30%	21%	24%	28%	24%	19%	18%
November-April	67%	76%	82%	77%	67%	77%	81%	85%
May -October	33%	24%	18%	23%	33%	23%	19%	15%

In conclusion, the result of qualitative wind climate analysis shows the following:

1. There is no significant change of wind by wind directions for small wind speeds,
2. Southwestern (almost 60-70%) and Northwestern (20-30%) winds are considerably dominating in case of strong wind speeds (more than 18m/s),
3. According to the seasonal variation, strong winds predominantly (but not only) occur during the winter half of year,
4. The selected November-April period represents the majority of strong wind speed cases, and could be used for further analysis.

3.3 Spatial transformation of wind speed on Lake IJssel and Lake Marken

The investigation of change of wind speed over the lakes has two attributes. The first attribute is the discovering specifications and trends of the spatial transformation of wind speed over the lake, and the second, it could be a method to check the consistency of wind speed at the measurement location, comparing with other locations.

The Wind with more than 6m/s speed was taken for the current study of wind transformation because the small winds could be due to local phenomena and reasons. Wind speed ratio was averaged by 15^{o} wind direction interval, between two measurement locations. The overall graphs of analysis of wind speed ratio are presented in Appendix C.

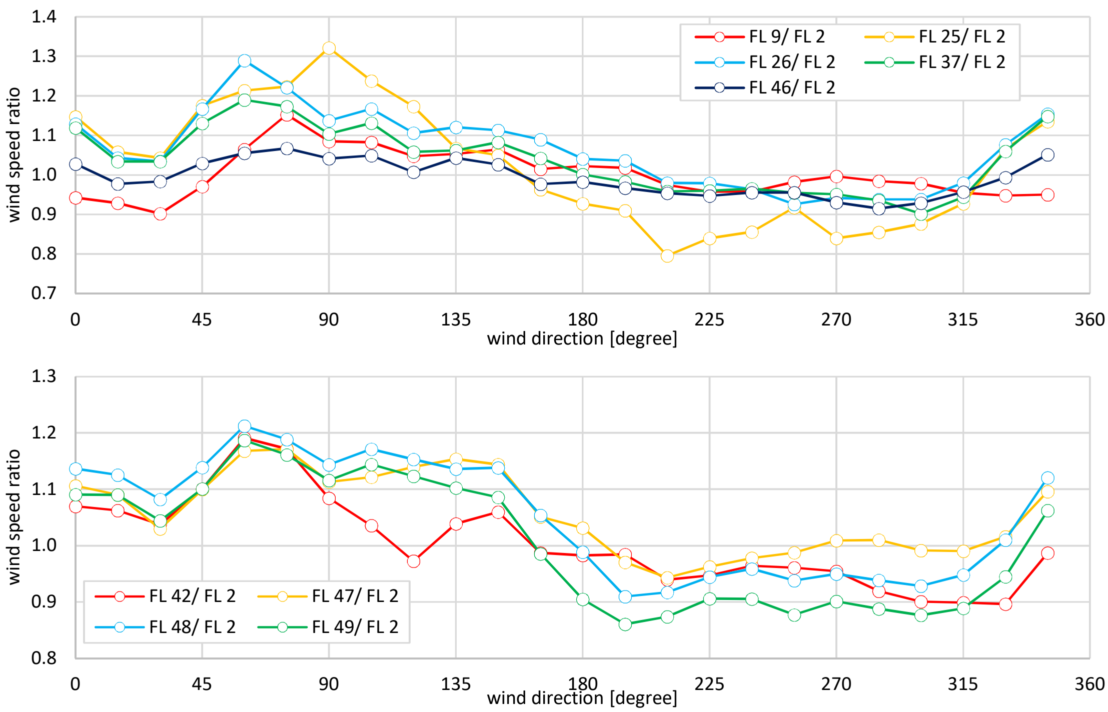


Figure 3. 6 Wind speed ratio as a function of wind direction, at location FL2

The analysis of the graphs in Figure 3. 6 and Appendix B, shows that the wind ratio is almost one in case of almost equal fetches. The particular cases are the ratio of FL9/FL2 (direction 180°-315°), FL26/FL2 (180°-225°), FL37/FL2 (180°-240°), FL46/FL2 (165o-195° and 300o-330°), FL46/FL9 (75°-210°), FL47/FL9 (180°-225°), FL26/FL25 (30°-120°) and FL49/FL47 (0°-105°), where it is almost one.

The effect of shelter makes the ratio of wind speed almost 0.8-0.9 western, southwestern winds, for example, FL25/FL2 (210°-270°), FL48/FL2 (195°-210°) and FL49/FL2 (195°-285°). The shelter effect on the opposite wind directions has 1.2-1.3 wind speed ratio, for example, FL25/FL2 (45°-120°), FL48/FL2 (60°-120°) and FL49/FL2 (60°-120°). The ratio of central locations, such an FL46/FL42 (0°-285°), is almost one for most of the directions.

To examine the change of wind speed ratio for increasing fetch, the ray of locations FL49-FL48-FL47 direction (215°) was considered, where the ratios of FL49/FL48 and FL48/47 are 1.05 and 1.08 respectively.

Table 3. 3 Wind speed ratio of between measurement locations for some range of wind directions (white color indicates ratio one, red and blue colors indicate less than one and more than one ratios respectively)

the ratio of	directions											
locations	0	30	60	90	120	150	180	210	240	270	300	330
FL9/ FL2	0.94	0.90	1.06	1.08	1.05	1.06	1.02	0.97	0.96	1.00	0.98	0.95
FL25/ FL2	1.15	1.04	1.21	1.32	1.17	1.05	0.93	0.80	0.86	0.84	0.88	1.07
FL26/ FL2	1.13	1.03	1.29	1.14	1.11	1.11	1.04	0.98	0.96	0.94	0.94	1.08
FL37/ FL2	1.12	1.03	1.19	1.10	1.06	1.08	1.00	0.96	0.97	0.95	0.90	1.06
FL46/ FL2	1.03	0.98	1.06	1.04	1.01	1.03	0.98	0.95	0.96	0.93	0.93	0.99
FL42/ FL2	1.07	1.04	1.19	1.08	0.97	1.06	0.98	0.94	0.96	0.95	0.90	0.90
FL47/ FL2	1.11	1.03	1.17	1.11	1.14	1.14	1.03	0.94	0.98	1.01	0.99	1.02
FL48/ FL2	1.14	1.08	1.21	1.14	1.15	1.14	0.99	0.92	0.96	0.95	0.93	1.01
FL49/ FL2	1.09	1.04	1.19	1.12	1.12	1.09	0.90	0.87	0.91	0.90	0.88	0.95
FL42/ FL9	1.13	1.17	1.10	1.01	0.94	1.00	0.97	0.96	1.00	0.96	0.92	0.95
FL46/ FL9	1.11	1.15	1.03	0.98	0.99	0.99	0.98	1.00	1.03	0.97	0.97	1.05
FL47/ FL9	1.17	1.18	1.08	1.02	1.10	1.07	1.01	0.96	1.01	1.02	1.01	1.06
FL48/ FL9	1.22	1.24	1.13	1.06	1.11	1.06	0.98	0.93	0.98	0.97	0.94	1.06
FL49/ FL9	1.16	1.18	1.09	1.02	1.09	1.01	0.89	0.89	0.92	0.91	0.88	0.99

the ratio of locations	directions											
	0	30	60	90	120	150	180	210	240	270	300	330
FL46/ FL42	1.01	0.97	0.96	0.98	1.01	1.04	1.03	1.04	1.03	1.02	1.06	1.13
FL47/ FL42	1.04	1.00	0.98	1.04	1.16	1.13	1.09	1.00	1.01	1.07	1.10	1.14
FL48/ FL42	1.07	1.04	1.01	1.06	1.18	1.11	1.06	0.97	0.97	0.99	1.03	1.14
FL49/ FL42	1.03	1.00	0.98	1.03	1.15	1.07	0.97	0.92	0.91	0.94	0.97	1.07
FL47/ FL46	1.10	1.04	1.06	1.05	1.10	1.12	1.04	0.95	1.00	1.09	1.04	1.01
FL48/ FL46	1.12	1.09	1.10	1.08	1.13	1.10	0.98	0.92	0.98	0.98	0.97	1.01
FL49/ FL46	1.07	1.05	1.09	1.05	1.11	1.05	0.90	0.87	0.93	0.92	0.91	0.95
FL26/ FL25	0.96	0.98	1.02	0.99	0.99	1.04	1.13	1.25	1.17	1.08	1.02	1.01
FL37/ FL26	0.98	1.01	0.98	0.99	1.00	0.98	0.98	0.98	1.00	1.01	0.97	0.94
FL48/ FL47	1.04	1.06	1.03	1.04	1.02	0.99	0.96	0.93	0.96	0.92	0.92	1.01
FL49/ FL47	0.99	1.01	1.00	1.01	0.99	0.95	0.88	0.88	0.90	0.87	0.87	0.95
FL49/ FL48	0.95	0.96	0.97	0.97	0.97	0.95	0.90	0.94	0.93	0.94	0.93	0.94

Table 3. 3 shows the coloured representation of wind speed ratio between locations by wind directions. The dark red and dark blue colours are the ratios, which are far from one. It is clearly shown on the table that ratio of FL25 and FL2 varies by direction, and the ratio of FL37 and FL26 is relatively smooth over wind direction.

In addition, wind speed ratio as a function of reference wind speed has been observed. This analysis will show the extent of change of wind transformation by the change of wind speed itself. The scatter of that relationship will represent the specific range of wind direction to exclude the influence of wind direction. The selected locations have a relatively constant ratio over a specific range of wind direction on the graphs in Appendix C.

Table 3. 4 shows the ratio of locations and a selected range of wind direction. The priority of the selection of these measurement locations also comes from their positions (FL2 represents eastern shore of the lake, FL42 and FL47 are central, and FL49 is located near western shore).

Table 3. 4 Selected range of wind direction for comparison of wind speed ratio with the wind speed of reference location

locations	selected range of wind direction
FL42 / FL2	210-270
FL47 / FL2	240-300
FL49 / FL47	255-315

The ratio of FL42 and FL2 is almost constantly 0.95, the ratio of FL47 and FL2 is 1.0, and the ratio of FL49 and FL47 is almost 0.85 for the given ranges, that is why these locations were selected (Table 3. 4).

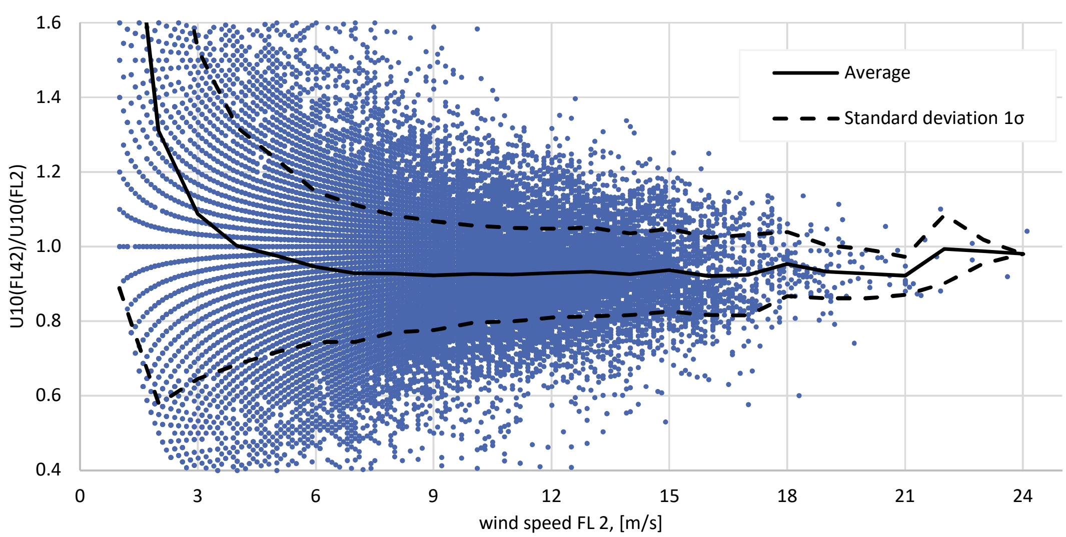


Figure 3. 7 Wind speed ratio FL42/FL2 as a function of wind speed at FL2 (U) for 210°-270° wind direction

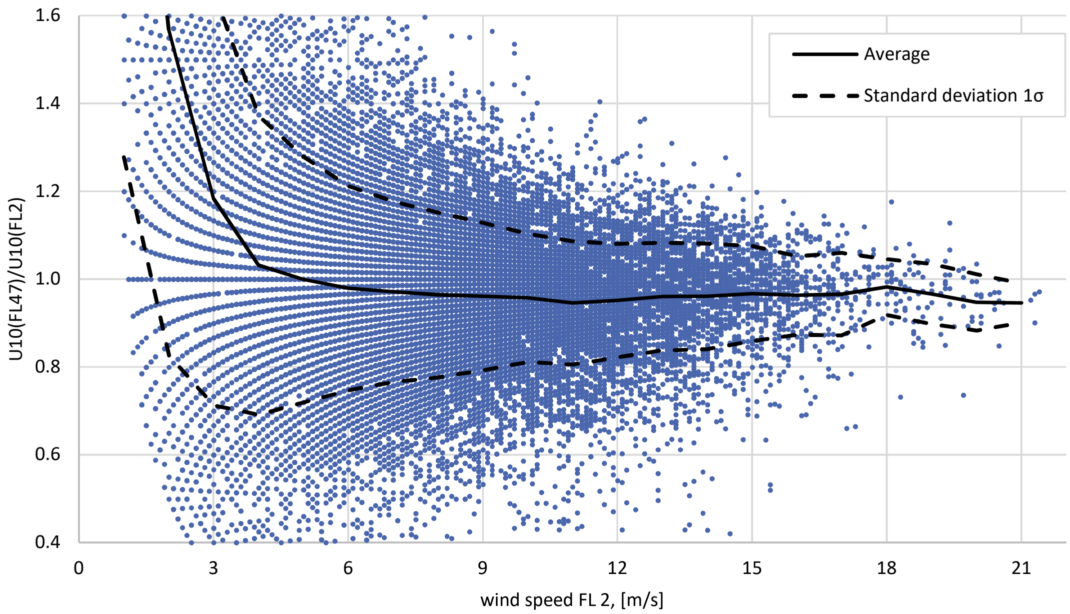


Figure 3. 8 Wind speed ratio FL47)/FL2 as a function of wind speed at FL2 for 240°-300° wind direction

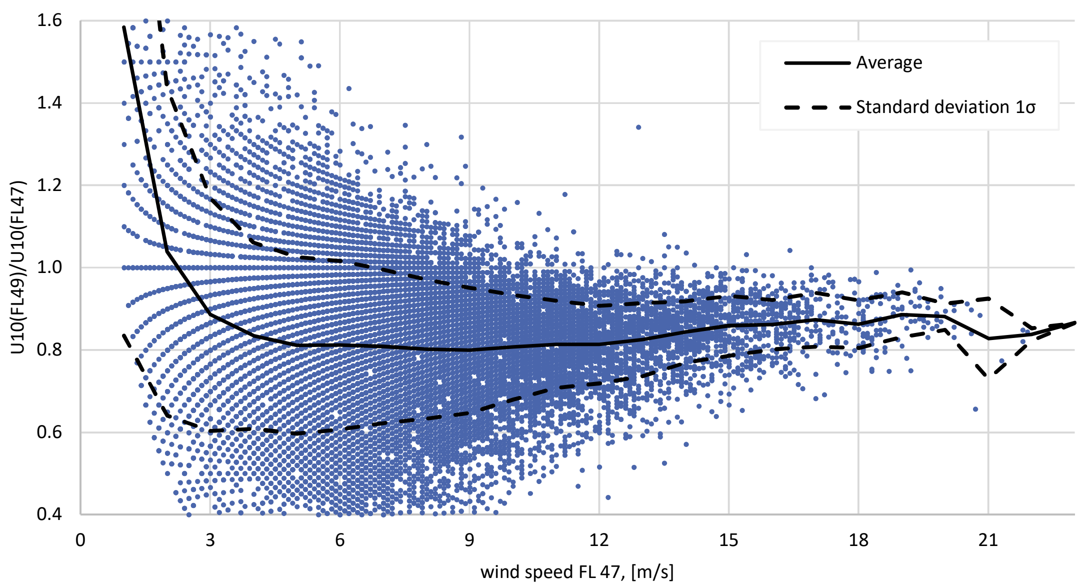


Figure 3. 9 Wind speed ratio FL49/FL47 as a function of wind speed at FL47 (U) for 255°-315° wind direction

The result of this analysis shows that in all cases the scatter has a wide range in the case of small wind speeds and it gradually becoming narrow for high wind speeds (Figure 3. 7, Figure 3. 8, Figure 3. 9). The standard deviation also becoming narrow in the same way. The results suggest that the wind has a local character and transformation rules are random for small wind speeds.

Coming to some general conclusions, wind speed is higher for the locations, which have long fetch from the side of strong wind directions. The ratio of the wind speed between central locations and the location on the western or eastern side of the lakes is significantly varying by wind direction (Table 3. 3). The wind ratio varies between 0.8-1.3 on Lake IJssel and Lake Marken. The wind speed ratios are almost constant and could be the base to transfer wind data from one location to another, for high wind speeds.

3.4 Spatial transformation of wind speed – land and water measurement locations

Since the wind speed data on the lakes is not sufficient for probabilistic calculation, there is a need to shift the wind speed from the land to the water surface. This section will not discuss the data and their trends in detail, as it is not the main objective of the study. The main KNMI land-based reference station to be considered here is Schiphol (Amsterdam Airport). As wind speed at 10 meters on the land includes the influence of obstacles, the potential wind speed of the stations of KNMI was considered for the current study. See (Bottema, 2007) for explanations of the topic.

For strong winds (around 12 m/s and 18 m/s), the ratio U_{10} (FL2)/U_{pot} (Schiphol) agrees quite well with the data in (Bottema, 2007), which has a range of 0.97-1.12. However, the present 12m/s data are higher, for easterly winds. For 6 m/s, the present ratios appear to be over 20% higher than those in (Bottema, 2007) for all wind directions. No explanation could readily be found for the fact that the present 6 m/s data (not the other data) differ so much from the (cross-validated) data of (Bottema, 2007), and the scope of this study did not allow for in-depth analysis here.

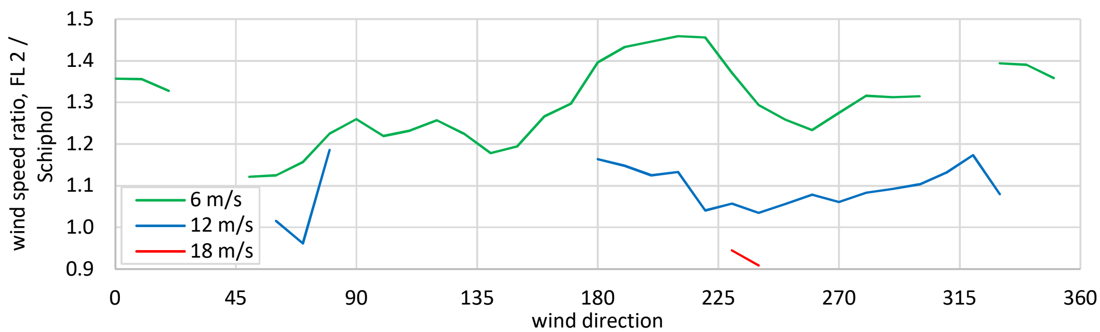


Figure 3. 10 Wind speed ratio U_{10}(FL2/)U_{pot}(Schiphol), as a function of wind direction, for 6m/s, 12m/s and 18m/s wind speeds

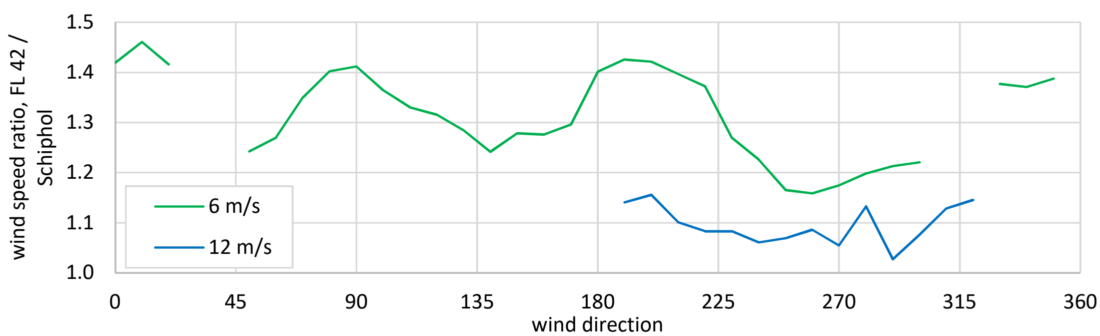


Figure 3. 11 Wind speed ratio U_{10}(FL42/)U_{pot}(Schiphol), as a function of wind direction, for 6m/s, 12m/s and 18m/s wind speeds

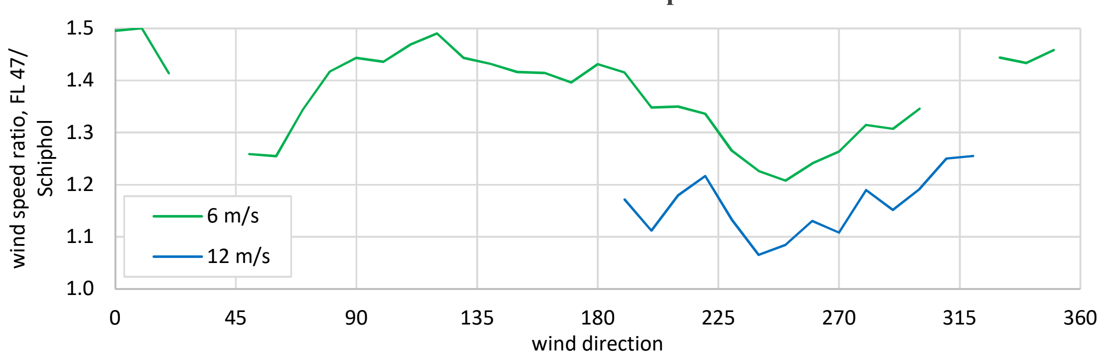


Figure 3. 12 Wind speed ratio U_{10}(FL47/)U_{pot}(Schiphol), as a function of wind direction, for 6m/s, 12m/s and 18m/s wind speeds

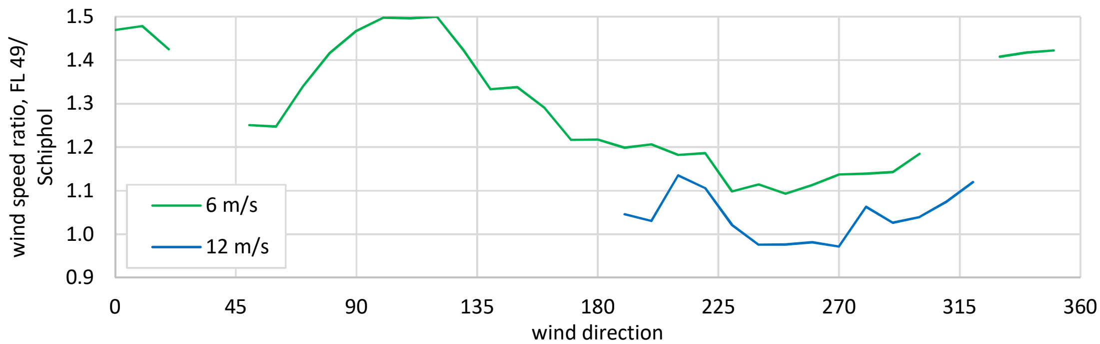


Figure 3. 13 Wind speed ratio U_{10} (FL49/)U_{pot} (Schiphol), as a function of wind direction, for 6m/s, 12m/s and 18m/s wind speeds

The graphs show that wind speed ratio has strong variation from 1.1 to 1.5, in the case of 6m/s wind, but one should realize these data are not consistent with those of Bottema (2007). In the case of 12m/s wind speed, the ratio was calculated for 180°-330° wind directions (because of available data) and the variation is 0.2 (approximately 1.0-1.2). The ratio is almost clearly expressed 1.1 for 150°-345° wind directions, at FL2 (Figure 3. 10). In the case of 18m/s wind, the ratio is calculated for the small ranges of wind directions (225°-270°). Here it is almost one, but insufficient data do not allow coming to general conclusions for 18m/s wind speed.

Table 3. 5 Wind speed ratio U_{10}/U_{pot} (Schiphol), for three different wind speeds, by measurement locations

locations	the ratio of U_{10}/U_{pot}(Schiphol)		
	6 m/s	12 m/s	18 m/s
FL2	1.1-1.5	1.0-1.2	0.9-1.0
FL42	1.2-1.5	1.0-1.2	-
FL47	1.2-1.5	1.1-1.3	-
FL49	1.1-1.5	1.0-1.1	-

Table 3. 5 shows a numerical representation of wind speed ratio between locations FL2, FL42, FL47, FL49 and Schiphol, where the variation of ratio becoming small and ratio approaching one as wind speed increases, which means the transformation of wind speed from land to water surface could be done in high accuracy in case of high wind speeds.

3.5 Summary of Chapter 3

Summarizing the results of Chapter 3, the following general conclusions could be stated:

1. The frequency distribution of wind speed (U_{10}) is not strongly different from a Gaussian distribution, but rather a little bit skewed to the right for all locations.
2. The majority of the storms (more than 20m/s wind speed) happens during the November-April period (84%).
3. On average, two of storm events (more than 20m/s wind speed) are happening roughly per two or three years in all locations.
4. The strongest (U_{10}>15m/s) wind speeds are from southwestern direction and then from southern and western directions for all locations. The average wind speeds (5m/s<U_{10}<15m/s) have the same pattern but do not dominate from above-mentioned

directions as much as strong winds. Weak winds (U_{10}<5m/s) are distributed equally along all directions of the horizon.

5. The ratio of wind speed in the case of almost equal fetches is almost one. In addition, it seems that during offshore winds, wind speed at near shore locations is lower by a factor of 0.8-0.9 due to the shelter effect of nearby land.
6. The accuracy of the transformation of wind speed over the lakes improves significantly with increasing wind speed and is quite poor (>20% uncertainty) for winds < 6 m/s.
7. The ratio of wind speed of measurement locations and Schiphol meteorological station varies from 1.1 to 1.5 for weak winds (less than 9m/s wind speed). It is almost 1.1 for average wind speed (12m/s). As far as the limit amount of data allows to draw conclusions, the ratio is in the range 0.9-1.1 for strong winds (more than 18m/s) which implies that most of the land-water wind speed differences than seem to vanish (in accordance with findings of (Bottema, 2007).

4. Wave climate analysis

This chapter discusses the key elements of the wave climate. In particular, the wave height and wave period as a function of wind direction and wind speed were analysed in Chapter 4.1. Chapter 4.2 presents the wave height as a function of effective fetch. The wave steepness is analyzed in Chapter 4.3. In addition, the wave height as a function of water depth is analysed in Chapter 4.4.

4.1 Wave and wind analysis

4.1.1 Significant wave height and wind analysis

Wave and wind analysis as a part of overall wave climate has its important application for dike design and flood protection in general (Bottema, 2007). With a continuous measurement of wave parameters on Lake IJssel and Lake Marken wave climate could have been calculated directly, but this is not the case. Instead, one has to rely on wind statistics as a benchmark, together with knowledge of the functional relationship between waves and the wind (forcing). As it was already mentioned, the wave climatology will focus on the months November to April, because of data reliability.

To get the first impression, Table 4.1 shows the general statistics of significant wave height (H_{m0}) and wave period (T_{m01}) for all locations, during the months when no error due to algae soiling are expected (November to April).

Table 4. 1 Long-term mean and standard deviation of H_{m0} and T_{m01}

locations	size of dataset	mean H_{m0}	standard deviation H_{m0}	mean T_{m01}	standard deviation T_{m01}
FL2	53673	0.37	0.23	2.02	0.49
FL2b	107147	0.39	0.23	2.03	0.47
FL5	66026	0.33	0.24	1.88	0.50
FL9	125178	0.39	0.23	2.00	0.47
FL25	57212	0.21	0.15	1.68	0.42
FL26	87555	0.40	0.22	2.01	0.45
FL37	25595	0.27	0.16	1.70	0.37
FL46	31382	0.39	0.21	2.01	0.44
FL47	59246	0.41	0.22	2.08	0.48
FL48	61331	0.31	0.16	1.83	0.41
FL49	61562	0.27	0.15	1.75	0.42
FL42	63124	0.37	0.20	1.98	0.43
FL44	15411	0.37	0.22	1.93	0.49

The (roughly) average wave height is 0.32 meter in the nearshore locations and it is 0.39 meter in central locations. Locations FL25, FL37, FL48 and FL49 have the low average wave height and wave period, which is reasonable, as they are located near the western coastline from where main strong winds are blowing.

The wave height was considered as a function of wind direction for a range of wind speeds, to analyse the wind-wave climatology. The graphical results of the analysis are presented in the Appendix E. The numerical results are in Appendix G. Wave heights were averaged by 15^o wind direction interval (in accordance with (Bottema, 2007)). In addition, the wind speed interval is 1 m/s for 6m/s, 9m/s and 12m/s winds, the interval is 2m/s for 15m/s and 18m/s winds. More than 20 m/s wind speeds are presented as a 21m/s. The analysis represents the data from November-April period.

Since the strongest winds tend to blow from the southern, southwestern and northwestern directions, the high wave heights are mostly happening in case of these directions. In addition, the number of strong wind speeds is small and wave height data are either not presented or presented by interrupted lines (graphs in Appendix E).

Wave height corresponding to 6m/s is smoother than strong winds, such as 18m/s, along with wind directions (Figure 4. 1-Figure 4. 3 and Appendix E). The standard deviation of wave height varies 0.02-0.09 meter for 6m/s wind speed and all wind directions at all locations. The standard deviation of wave height varies 0.05-0.18 meter for 18m/s wind speed and all wind directions at all locations.

Table 4. 2 Size of dataset and standard deviation of wave height (H_{m0}) for given wind speeds and wind directions, location FL2

wind dir. [deg.]	Wind speed, [m/s]					
	6		12		18	
	Size of dataset	H_{m0}	Size of dataset	H_{m0}	Size of dataset	H_{m0}
0	139	0.06	24	0.09	-	-
30	170	0.06	-	-	-	-
60	181	0.04	-	-	-	-
90	300	0.02	64	0.04	-	-
120	269	0.04	5	-	-	-
150	276	0.06	14	0.12	-	-
180	390	0.07	75	0.05	-	-
210	449	0.06	357	0.07	38	0.10
240	522	0.07	252	0.09	74	0.12
270	273	0.06	182	0.08	44	0.11
300	276	0.05	65	0.05	10	0.05
330	207	0.05	58	0.07	1	-

All locations on the eastern coast of the lakes, such as FL2, FL2b, FL5, FL9 and FL44 have a clearly expressed low wave height for 0^o-150^o range of wind direction, and the wave height for those directions varies from 0.2 to 0.6 meters for 6m/s-15m/s wind speeds respectively. In the 150^o-360^o range of wind direction, the wave has 0.4-1.0 meter height for 6m/s-15m/s wind speeds respectively and more than 1-meter height for wind speeds more than 18m/s, at these locations. In addition, it reaches its peak (1.4-1.7 meter) when the wind has 225^o-240^o direction (Figure 4. 1). It is important to note, that the differences in wave height between two general ranges (0^o-150^o and 150^o-360^o) are high, because of the cumulative effect of strong wind and long fetches.

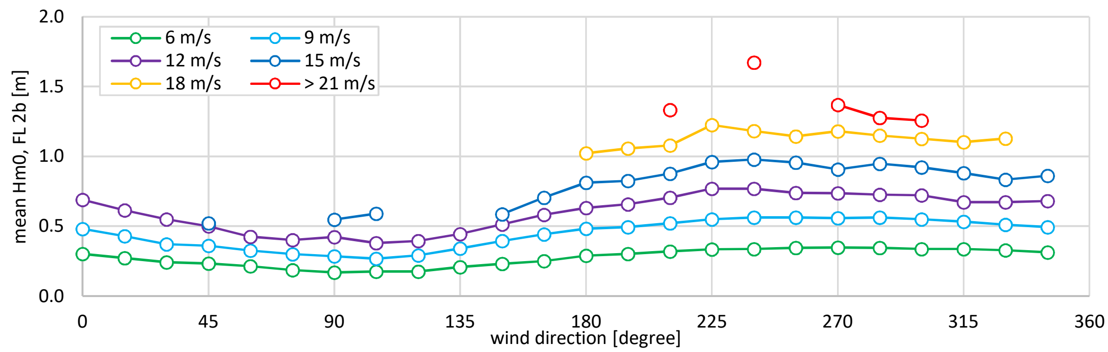


Figure 4. 1 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL2b

For the locations near the western shoreline of the lakes, such as FL25, FL37, FL48 and FL49, the lowest wave height for each range of wind speed is within 180°-315° wind directions and the highest wave height is in the range of 45°-135° wind directions. However, the strong winds and fetches balance each other and the difference in maximum observed wave height for the two main ranges of wind directions are small. Typical wave heights for offshore winds are 0.10 meter for 6m/s wind speed and it is about 0.6 meters for 18 m/s wind (Figure 4. 2).

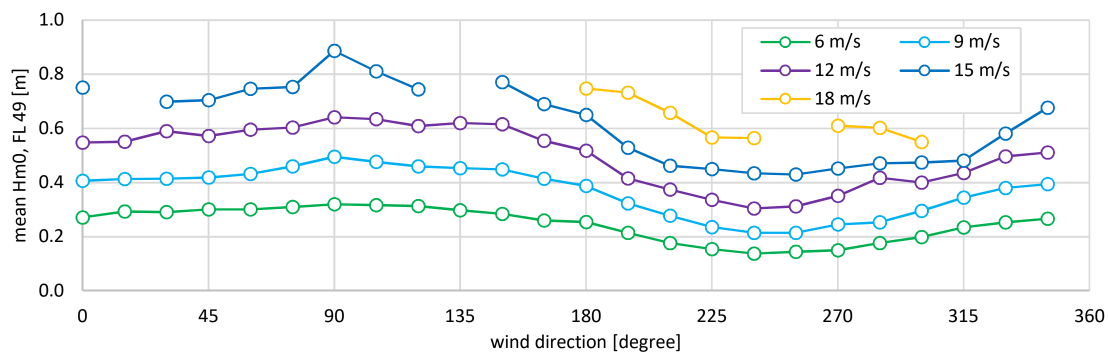


Figure 4. 2 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL48

For the central locations, such as FL42, FL46 and FL47, there is no change of wave height depending on wind directions for all ranges of wind speeds. Here, the average wave height is almost 0.3m for 6m/s wind speed and it is about 1.0m for 18m/s wind speed (Figure 4. 3).

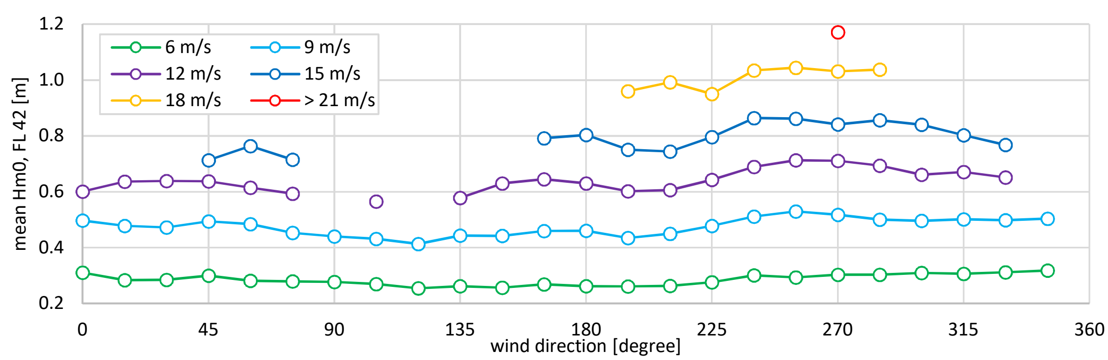


Figure 4. 3 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL42

As it was already mentioned, Appendix G represents numerical results of the wind-wave analysis. It is important to know that individual 20-minute samples may deviate from the data points in the above graphs, which represent (class averages). These deviations can be expressed as standard deviations. According to Table G. 1 - Table G. 13 (b), the standard deviations of wave height are 0.06m for 6m/s wind speed. It is 0.07m for 12m/s wind, and 0.1m for 18m/s.

In general, the wave height is not significant (up to 0.3 m) in the case of wind speed up to 6 m/s. This circumstance is important for further modelling also (Chapter 6), to define the range of experimental dataset. The average wave height exceeds 0.6m only after about 12m/s wind speed and it is higher than 1 meter after 18 m/s wind speed. The wave heights for each range of wind speed are more balanced along wind direction in the locations near the western shoreline than on the eastern shoreline of the lakes.

4.1.2 Wave period and wind analysis

In general, wave period (T_{m01}) behaves roughly the same way as wave height (H_{m0}), because the significant wave height and wave period are fairly well correlated (Whalin, Camfield, & Parker, 1984). The graphs in Figure 4.4 shows the relationship between wave height and wave period for all locations. Two parameters are well correlated, except the cases of wave height less than 0.5-meter at locations FL2b and FL9, and wave height less than 0.2meter at locations FL2, FL25, FL26 and FL37. Although overall correlations coefficient is high, western locations have 0.80-0.92 and the rest of locations has 0.95-0.98 correlation coefficient.

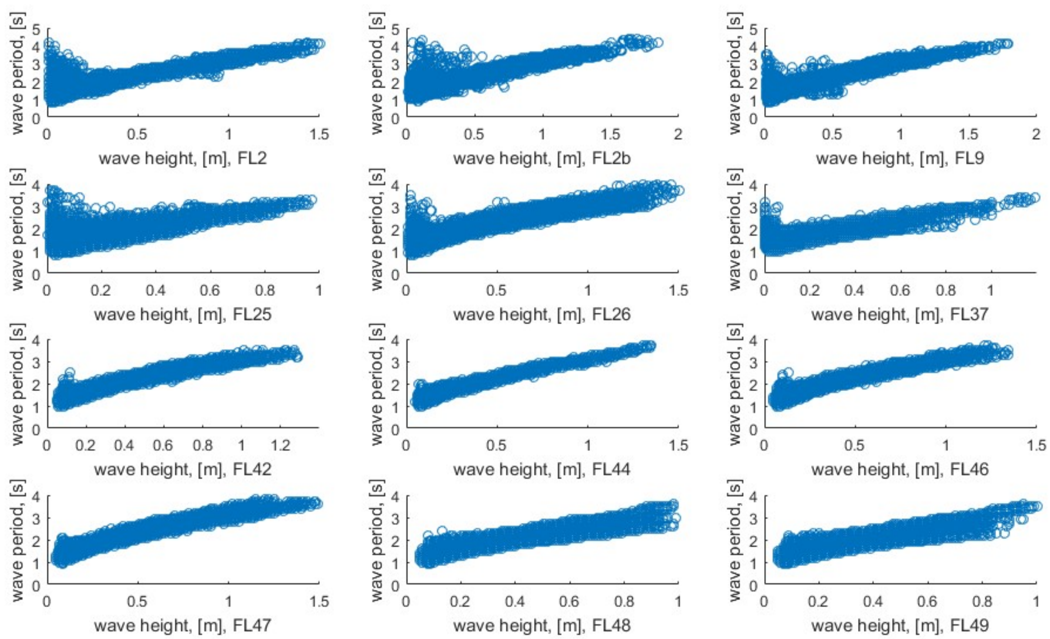


Figure 4.4 Wave period (T_{m01}) as a function of wave height (H_{m0}), location FL47

The wave periods were considered as a function of wind direction for a range of wind speeds, to analyse the wind-wave climatology. The graphical results of the analysis are presented in the Appendixes F. The numerical results are in Appendix G. The wave period analysis has the same data treatment (wind range, wind speed, experimental period) as for H_{m0} in previews section.

Here also, all locations on the eastern coast of the lakes, such as FL2, FL2b, FL5, FL9 and FL44 have a clearly expressed low wave period for 0^o-135^o wind direction, and the wave period varies from 1.0 to 2.5 seconds. The wave period increases up to 2.5 seconds for 9m/s wind speed and it more than 3 seconds for wind speed more than 18m/s, at these locations, in the 135^o-360^o range of wind directions. It is important to note, that the differences of wave period between two general ranges (0º-135º and 135º-360º) are again high, because of the cumulative effect of strong wind and long fetches (Figure 4. 5).

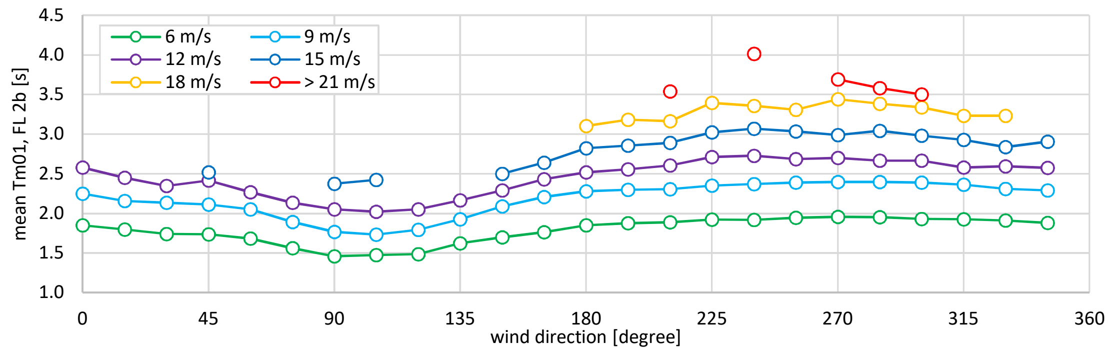


Figure 4. 5 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL2b

For the locations near the western shoreline of the lakes, such as FL25, FL37, FL48 and FL49, the lowest wave period for each range of wind speed is within 195º-315º wind direction and the highest wave period is in the range of 15º-135º wind directions. However, the strong winds and short fetches balance each other and the wave period differences in maximum observed wave periods for the two main ranges of wind directions are small. The directional variation of wave period is 0.7 seconds for 6m/s wind speed, and it is 1.3 seconds for 18m/s wind speed (Figure 4. 6).

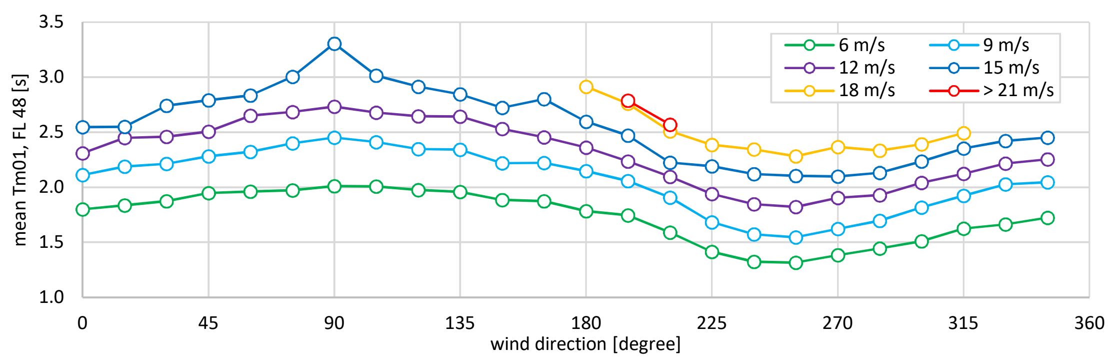


Figure 4. 6 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL48

There is no significant change of wave period depending on wind directions for all ranges of wind speeds, for the central locations, such as FL42, FL46 and FL47. Compared to the wave height, wave period is varying more slightly along wind directions (Figure 4. 7).

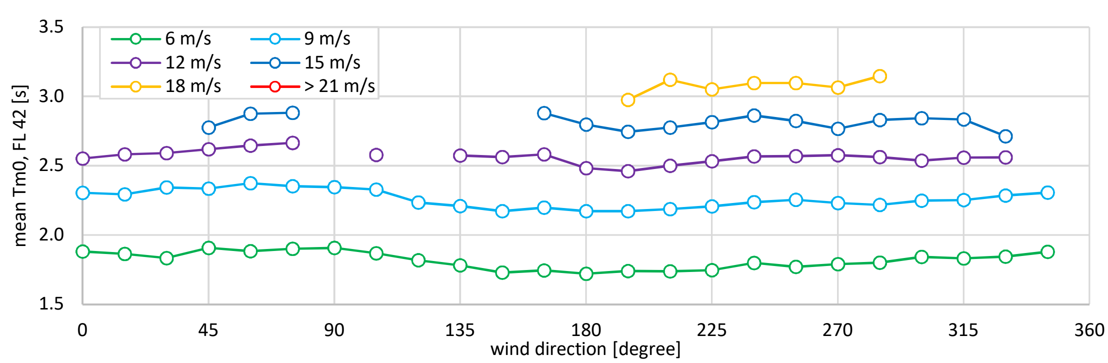


Figure 4. 7 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL42

As it was already mentioned, Appendix G represents numerical results of the wind-wave analysis. It is important to know the standard deviation of average wave period for different ranges of wind speeds and directions, as the wave period was averaged for graphical analysis. According to Table G. 1 - Table G. 13 (b), the standard deviation of wave period is 0.18 seconds for 6m/s wind speed. It is 0.12 seconds for 12m/s wind, and 0.13 seconds for 18m/s wind.

In general, the wave period is quite small (up to two seconds) in the case of wind speed up to 6 m/s. The average wave period exceeds 2.5 seconds only after 12m/s wind speed and it can be more than 3 seconds (for fetches greater than about 10km), after 18 m/s wind speed.

4.2 Wave height and effective fetch analysis

4.2.1 Brief description and calculation of effective fetch

In addition to the wind impact, the distance from the coastline of any location from the direction of blowing the wind has an influence on wave height and wave period, on the lakes with limited dimensions. This distance over water body is called fetch (F).

Figure 4.8 shows fetch of location FL49 for different wind directions. As it is shown on the map the fetch from southwest direction is small (875 meters) and the fetch from southeastern direction is long (43 km).

However, the impact of the wind on wave formation cannot be described by the fetch from only one direction, as the shape of coastline along the lakes is complex. In addition, the wave itself does not grow in one narrow path; it takes a range of massive water body.

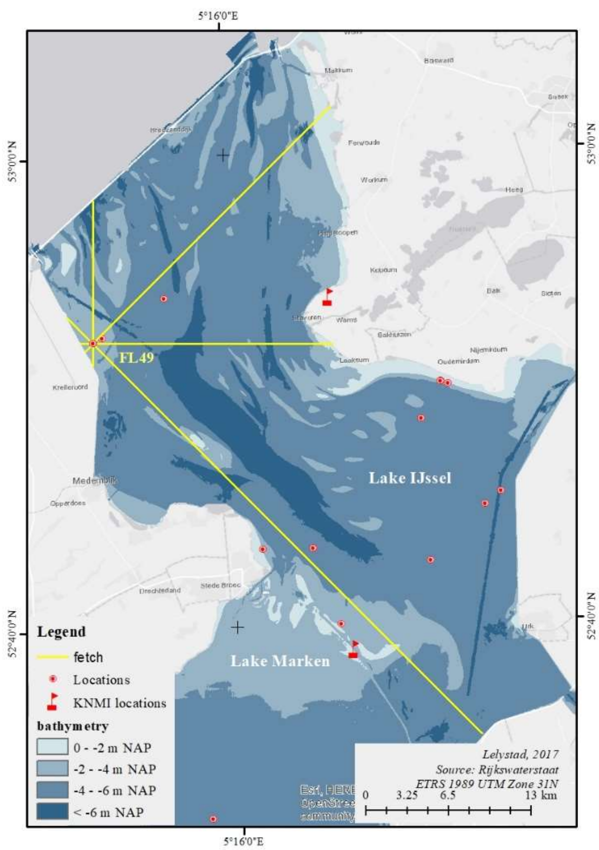


Figure 4. 8 Fetches for different direction of the wind at FL49

For this reason, the effective fetch was calculated and used in current study. The effective fetch was calculated using the concept of JP Waal (2003). As an example of calculation of effective fetch is shown at location FL47 (Figure 4.9). The red line is the fetch (southeastern direction) and the green lines are distances (X_i) along directions φ. The range of angle is [-45° - +45°] with 5° intervals (φ), where the main fetch directions correspond to 0°, as a central line.

The formula of effective fetch is the following:

$$F_{eff} = \frac{\sum_{i=1}^{n} X_i * \cos^2 \varphi}{\sum_{i=1}^{n} \cos \varphi} \quad (4.1)$$

Where F_{eff} is effective fetch, φ is the fixed step size angle; X_i is the distance along the direction of φ.

Hydra-B software (Geerse, Slomp, & Waal, 2011) (Duits, 2007) is used to calculate the effective fetch in Rijkswaterstaat, but Hydra-B calculates effective fetch only for specific directions of the horizon (Figure 4. 10), which is not sufficient for current study.

In addition, executable software (provided by Waal) was used to calculate effective fetch in "Measured wind-wave climatology Lake IJssel (NL)" report (Bottema, 2007), which was impossible to run on latest Windows operation systems.

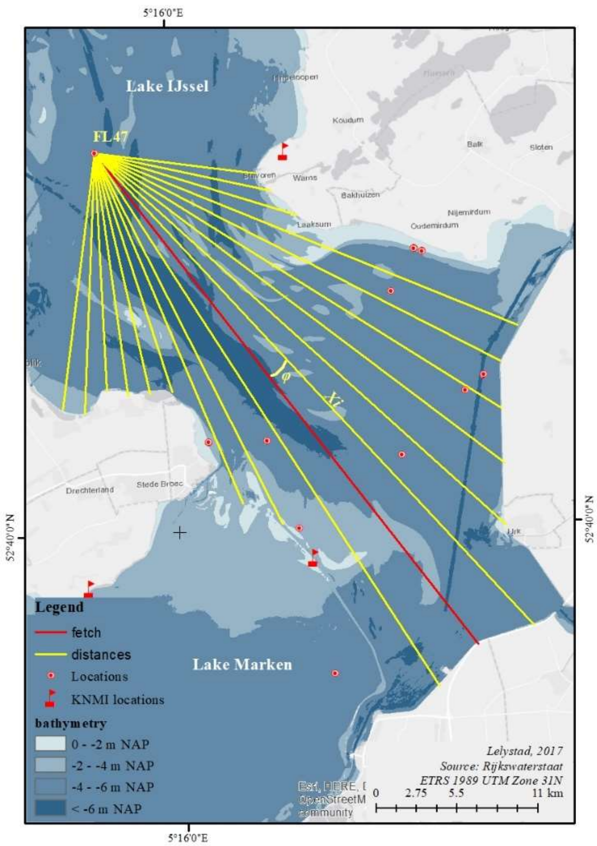


Figure 4. 9 Illustration for the calculation of the effective fetch for wind direction

Regarding unclarified points in the literature relating to the correct effective fetch definition and software, there have been some discussions with the mentors of this study. After consultation with experts involved in an ongoing effective fetch study Equation 4.1 is indeed correct, and reflects the fact that one should not calculate a weighted average of fetches from various directions, but rather a weighted average of fetch projections along the wind direction axis (personal communication JP de Waal and G Van Vledder, 2017).

For this reason, the fetches were calculated using bearing distance method in ArcGIS, for each location on the Lake IJssel and Lake Marken, and then the effective fetch was calculated using the Waal's formula (eq. 4.1). Calculated results were compared with the results in RWS report (Bottema, 2007), to check the confidence. The effective fetch of locations FL2, FL2b and FL26 were compared for specific ranges (with 15° interval) of wind directions (Table 4. 3). The maximum difference does not exceed 3% and even 3% of difference happens rarely. This proves that current calculation method is acceptable and can be used in further analysis. However, some short fetches from FL25 and FL37 may need further consideration as the difference between present and previous fetches can be well above 3% for these cases (compare Table 4.4 of this report with Figure 6.19 and 6.20 of Bottema, 2007). The difference fetches is probably due to the difference in land contour definitions (schematized shoreline in old calculations versus actual shoreline in ArcGIS, which is -0.4m NAP).

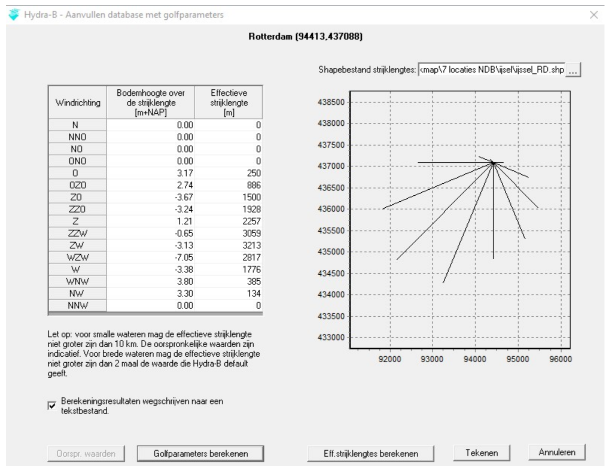


Figure 4. 10 The screenshot of the result of calculated effective fetch with Hydra-B software

Thus, the effective fetch was calculated for locations FL2, FL2b, FL9, FL26, FL46, FL47 and FL49 on Lake IJssel and for FL42 on Lake Marken. Effective fetches were also calculated for locations FL5, FL25, FL37 and FL44 (based on the standard directions of wind speed by 1-degree interval and the geometry of the lakes), however, they were not used in the next chapter, as there are not measurement of wind directions in these locations.

Table 4. 3 Comparison of effective fetch of RWS report and current study

direction	effective fetch [m], FL2			effective fetch [m], FL2b			effective fetch [m], FL26		
	RWS report	calculated	%	RWS report	calculated	%	RWS report	calculated	%
0	9240	9174	0.7%	10514	10693	-1.7%	22600	22165	1.9%
15	8000	7820	2.3%	9360	9142	2.3%	19950	20234	-1.4%
30	6555	6462	1.4%	8032	7794	3.0%	17874	18158	-1.6%
45	4850	4981	-2.7%	6062	6219	-2.6%	16630	16250	2.3%
60	3093	3134	-1.3%	4714	4831	-2.5%	16775	16303	2.8%
75	1700	1747	-2.7%	3200	3256	-1.7%	16770	16552	1.3%
90	1194	1200	-0.5%	2450	2482	-1.3%	16992	16825	1.0%
105	1235	1232	0.2%	2450	2509	-2.4%	16900	16772	0.8%
120	1460	1479	-1.3%	3016	3089	-2.4%	16734	16521	1.3%
135	2400	2471	-3.0%	4770	4840	-1.5%	15500	15343	1.0%
150	4890	4986	-2.0%	7472	7474	-0.0%	13246	12848	3.0%
165	8400	8621	-2.6%	10600	10519	0.8%	10200	10310	-1.1%
180	11890	11613	2.3%	13330	12998	2.5%	7276	7376	-1.4%
195	14700	14255	3.0%	15100	14785	2.1%	5300	5399	-1.9%
210	16710	16394	1.9%	16060	15576	3.0%	4497	4388	2.4%
225	17600	17451	0.8%	16010	15835	1.1%	4400	4339	1.4%
240	18850	18935	-0.5%	16900	16982	-0.5%	4417	4333	1.9%
255	21400	21338	0.3%	19380	19281	0.5%	4700	4654	1.0%
270	24600	24261	1.4%	23262	22856	1.7%	6528	6665	-2.1%
285	24460	24575	-0.5%	25060	24831	0.9%	10300	10539	-2.3%
300	24030	23364	2.8%	24700	24118	2.4%	15475	15343	0.9%
315	20400	20506	-0.5%	22070	21735	1.5%	21000	20651	1.7%
330	15690	16057	-2.3%	17720	18238	-2.9%	24203	23710	2.0%
345	11750	12003	-2.2%	13600	14002	-3.0%	24600	23906	2.8%

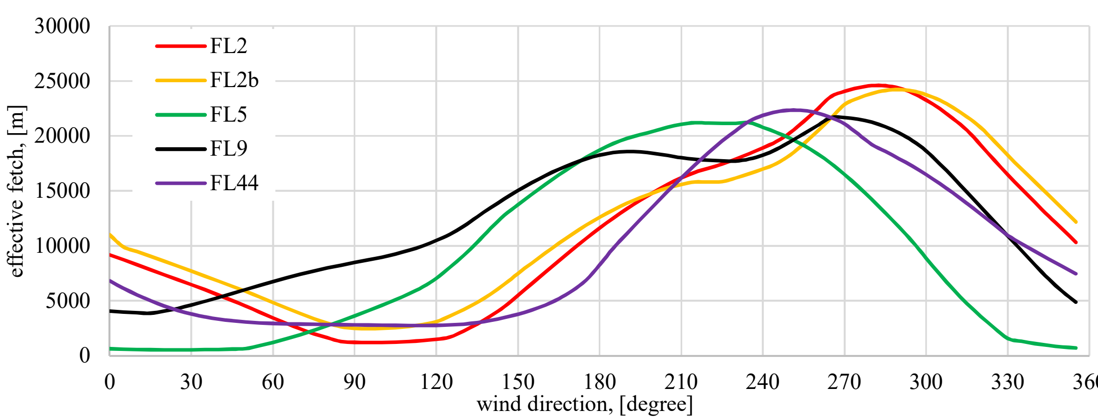
Since the effective fetch has smoothing nature, the difference of real fetch and effective fetch can be big (almost 20 km). In particular, the real fetch can vary from 0.85 km (FL49) to 45 km (FL47, FL48 and FL49). However, the effective fetch starts from 7-10 km for central locations (FL46 and FL47) and from 1km for locations near the coastline. The maximum effective fetch is 27 km at locations FL47, FL48 and FL49. Only location FL42 has effective fetch from 10km to 15km, due to its central location and the shape of Lake Marken (Figure 2. 1).

The numerical and graphical representation of effective fetch for the locations on Lake IJssel and Lake Marken are in Table 4. 4 and Figure 4. 11.

Table 4. 4 Effective fetches by the directions of horizon for the locations on Lake IJssel and Lake Marken, [meter]

wind direction	FL2	FL2b	FL5	FL9	FL25	FL26	FL37	FL42	FL44	FL46	FL47	FL48	FL49
N	9174	10693	630	4054	21148	22165	25605	13485	6803	18020	12826	12566	12105
NNE	7066	8486	530	4065	22546	19697	22235	14498	4364	13067	14866	16337	16479
NE	4981	6219	596	5655	20119	16250	17847	14950	3170	11023	15726	18780	19057
ENE	2512	4027	1893	7225	19173	16442	16106	13934	2889	8676	15019	21127	22069
E	1200	2482	3622	8476	20056	16825	14842	12410	2800	7147	16981	24404	25069
ESE	1333	2758	6126	10012	17835	16497	12997	10772	2747	8335	22597	25844	26886
SE	2471	4840	10303	12638	12587	15343	10202	9844	3006	10437	24850	25119	24610
SSE	6997	9104	15245	16298	7753	11629	6275	10355	4333	12095	24322	18004	16254
S	11613	12998	18712	18260	2502	7376	2603	12919	8249	12236	18602	10235	7897
SSW	15233	15174	20669	18341	996	4623	929	14441	14008	10867	11946	4701	2484
SW	17451	15835	21151	17735	854	4339	786	14588	19529	10017	9303	2311	901
WSW	19596	18118	20416	19227	789	4188	873	13182	22227	11037	7752	1658	844
W	24261	22856	16492	21670	801	6665	1953	12113	21094	15780	7789	2014	1022
WNW	23337	23996	11735	19394	1795	12610	8364	12331	17901	22666	8317	3333	2112
NW	20506	21735	4739	14874	8997	20651	17411	12641	13853	24036	8952	5291	4147
NNW	14064	15869	1227	8318	15385	23720	23269	13131	9940	22966	10302	8074	7193

The graphs in Figure 4. 11 give an indication that groups of locations have approximate specific positions on the lakes. Particularly, the first graph shows that FL2, FL2b, FL5, FL9 and FL44 have small effective fetches for 30°-120° wind direction. The second graph shows that FL25, FL26, FL37, FL48 and FL49 have small effective fetch on 210°-270° wind direction. Moreover, FL42, FL46 and FL47 have almost smoothed fetches from all directions (besides the highest effective fetch from 315° direction in FL46 and from 150° direction in FL47).



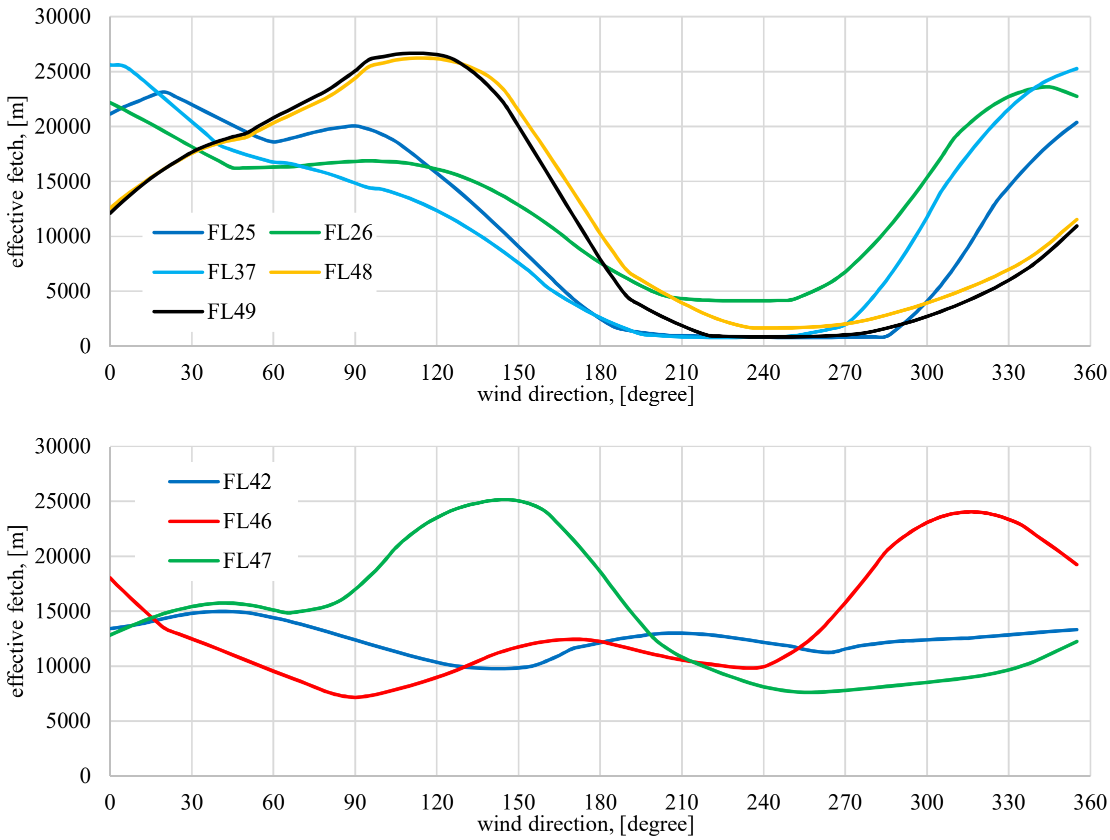


Figure 4. 11 Effective fetch as a function of wind direction for the measurement locations on Lake IJssel and Lake Marken

Thus, locations FL2, FL2b, FL5, FL9 and FL44 were conditionally considered as eastern locations. FL25, FL26, FL37, FL48 and FL49 were considered western locations and FL42, FL46 and FL47 were central locations. This categorization will mostly be used in chapters 5 and 6 for verification of formulas and validation of models respectively.

4.2.2 Qualitative analysis of wave height as a function of effective fetch

Theoretically, the fetch can have its influence on the formation of wave growth (Bretschneider C. , 1958). So that, the wave height was considered as a function of the effective fetch in certain wind speeds, in order to investigate effective fetch-wave height relationship on Lake IJssel and Lake Marken.

The wave height was averaged by 1km effective fetch range and 6m/s, 9m/s, 12m/s, 15m/s and 18m/s wind speed ranges for the wave-fetch analysis. The division of wind speed in five groups was done to assure the plotted trends were not contaminated by hidden wind speed dependencies. Figure 4. 12-Figure 4. 14 present the graphs of average significant wave height (H_{m0}) as a function of effective fetches for locations FL42, FL47 and FL49 (entire graphs for all locations are presented in Appendix H).

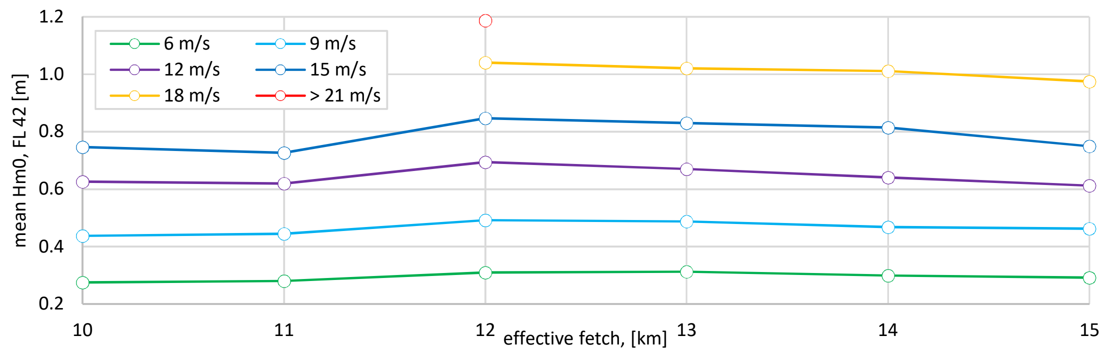


Figure 4. 12 Average significant wave height (H_{m0}) as a function of fetch, for given ranges of wind speeds, FL42

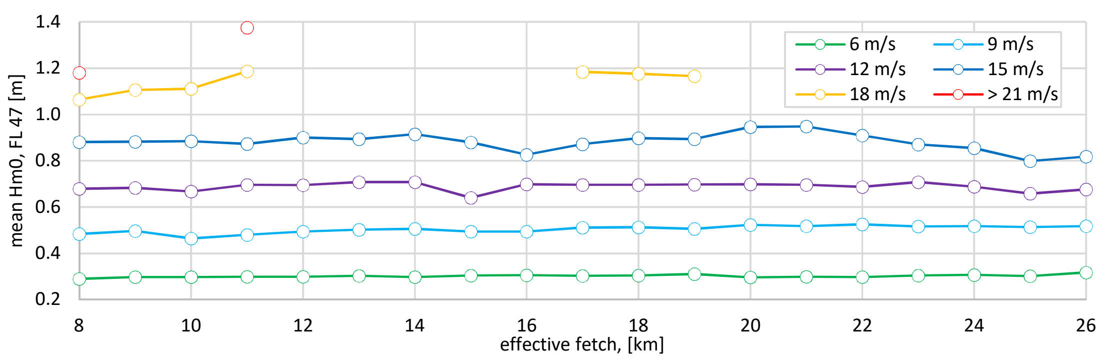


Figure 4. 13 Average significant wave height (H_{m0}) as a function of fetch, for given ranges of wind speeds, FL47

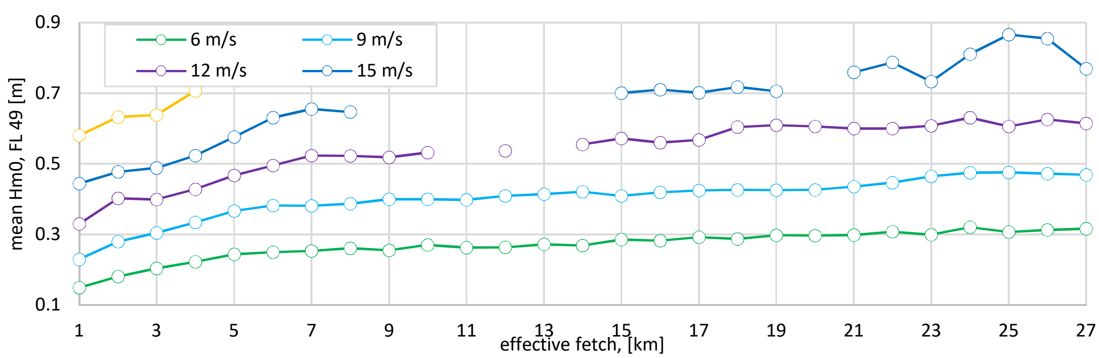


Figure 4. 14 Average significant wave height (H_{m0}) as a function of fetch, for given ranges of wind speeds, FL49

According to the analysis, in the case of 6m/s wind speed, wave height increases with 0.01m/km gradient until 13-15km effective fetch in eastern and western locations. In particular, the change of wave height faster up to 8km effective fetch, at FL48 and FL49. It seems that starting from 13-15km, the impact of fetch on wave formation is weakening (Appendix H). There is almost no change in central locations with the increase of effective fetch.

In the case of 9m/s wind speed, the conditions of the change of wave height are the same as 6m/s. However, the change of wave height depending on fetch stabilizes slightly later, after 16-18km. The gradient of the wave height is high in western locations (Figure H- 8, Figure H- 9).

In the case of a 15 m/s wind, the average wave height increases with the increase of fetch in all measurement locations. However, there is an exception in locations FL42 and FL47, where the wave height reduces after 12km at FL42 and it reduces after 21 km at FL47. It is speculated (although not verified by analyses of similar cases for other locations) that those cases could be due to the shape of the lakes (Figure 2. 1). In particular, 21km fetch corresponds to the 110° and 170° wind directions, and 26km correspond to 145° wind direction at location FL47. Considering these wind directions, it will be clear from the map in Figure 2. 1 that the wind with 21km and 26km fetches blows from the similar conditions, and the small fetch value (21km) is just due to a side effect of Lakeshore.

In the case of wind speeds more than 18 m/s, there is few data and no firm conclusions can be drawn. Nevertheless, in some cases (locations FL2b, FL9, FL48 and FL49), it seems that the increase of the effective fetch brings the increase of average wave height (Figure H- 2, Figure H- 3, Figure H- 8, Figure H- 9).

4.3 Brief analysis of wave steepness

Although the analysis of wave steepness is not the main objective of this study, it was briefly analysed as a part of wave climate. The wave steepness can be useful for validation of both (wave height and wave period) experimental data, and it is important auxiliary information should one consider statistical extrapolation to estimate dike or platform design conditions from given wave data set (Bottema, 2007).

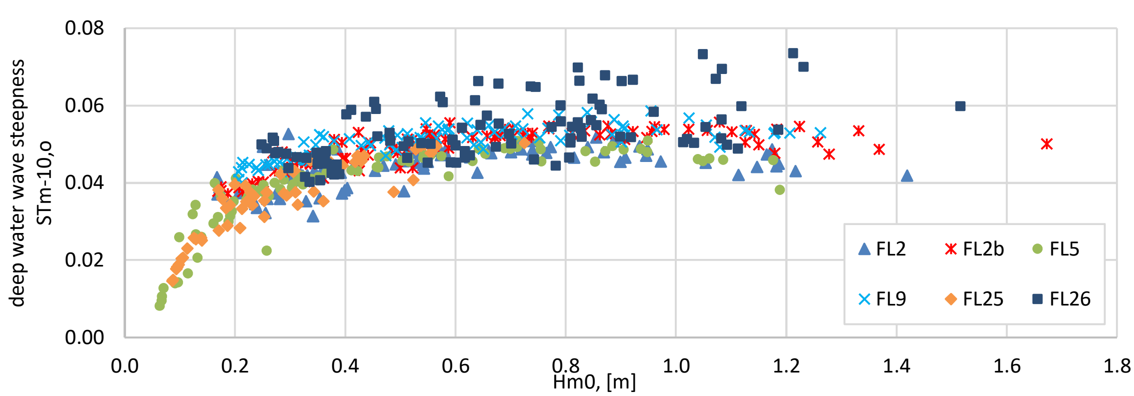
The wave steepness defined as a ratio of significant wave height (H_{m0}) and wavelength (L). The real wave steepness (S_{Tm-10}) and deep-water steepness ($S_{Tm-10,o}$) parameters were considered in the current study, which is calculated by equation 4.2 and 4.3 (Dean & Dalrymple, 1991) (Wiegel R. L., 1964).

$$S_{T_{m-10}} = \frac{H_{m0}}{L(T_{m-10})} \quad \text{where } L(T_{m-10}) = \frac{g*T^2}{2*\pi} * \tanh(\frac{2*\pi*D}{L(T_{m-10})}) \quad (4.2)$$

$$S_{T_{m-10,o}} = \frac{2*\pi*H_{m0}}{g*T_{m-10}^2} \quad (4.3)$$

Where g is acceleration due to gravity (9.81 m/s^2), D is water depth. The wavelength calculated as a function of wave period T_{m-10}.

The real wave steepness and deep-water steepness were calculated based on averaged wave height and wave period data in Appendix G. Then wave steepness has been plotted as a function of wave height (Figure 4. 15, Figure 4. 16).



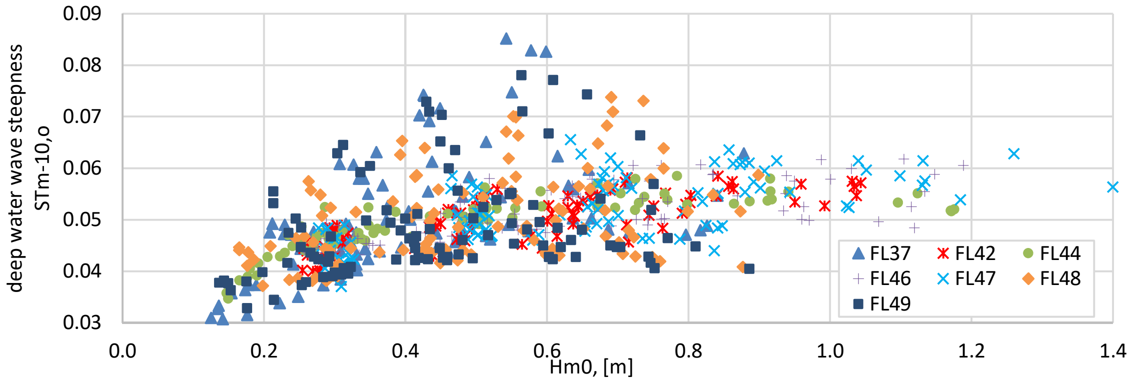


Figure 4. 15 Deep-water wave steepness (S_{Tm-10}) as a function of wave height (H_{m0}) for the averaged data in Appendix G

Deep-water steepness greatly increases up to 0.05, while wave height reaches 0.35 meter in all locations. Then it is remaining almost constant around 0.05 along the increase of wave height, besides for locations FL26, FL37, FL48 and FL49. The deep-water steepness reaches up to 0.09, for those four locations, which are located near the western coastline of Lake IJssel. The reason for this phenomenon could be the southwesterly strong winds with short fetches, which forms high wave height with high steepness.

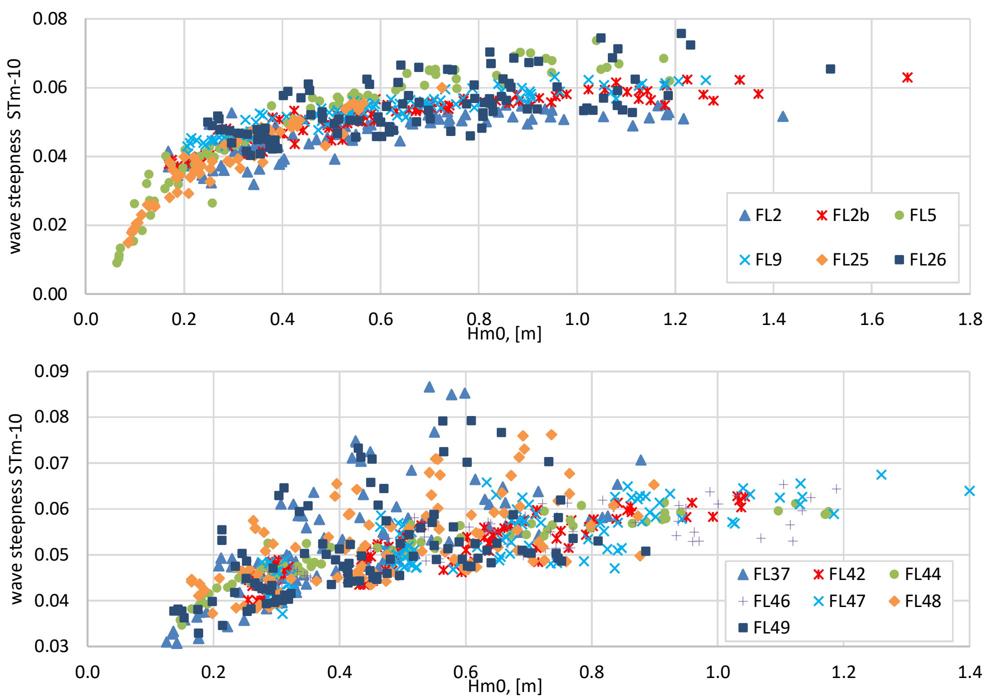


Figure 4. 16 Wave steepness (S_{Tm-10}) as a function of wave height (H_{m0}) for the averaged data in Appendix G

Real wave steepness almost completely repeats the pattern of deep-water steepness. Here, the steepness again has increased up to 0.05 and then it becomes almost constant around 0.05, after 0.4m wave height. In this case, the steepness is also continuing increasing up to 0.09, for locations FL26, FL37, FL48 and FL49 (Figure 4. 16).

4.4 Wave height and water depth analysis

Theoretically, depth limited wave could be formed in the water bodies, in conditions where the height (or length) of the wave is comparable with water depth. In this context, there were studies on Lake George (average depth is 1m) (Breugem & Holthuijsen, 2007), Lake Okeechobee (average depth is 2.7m) (Whalin, Camfield, & Parker, 1984), also by Bottema and van Vledder (2009) and Young and Verhagen (1996). The depth limited wave height also was analysed for Lake Marken and Lake IJssel, as the average depths of the lakes are respectively 3.5m and 4.2m (Bottema, 2007).

The classification of deep and shallow water depth from "Shore protection manual" (1984) was used to analyse the shallow water depth conditions in Lake IJssel and Lake Marken. As it is shown in Table 4. 5, shallow water conditions are defined by wavelength (L) and water depth (D) ratio. The wavelength was calculated by Equation 4.2 (Chapter 4.3).

Table 4. 5 Classifications of water depth conditions by L/D magnitude

deep water conditions	shallow water conditions	intermediate depth conditions
D > 0.5*L	D < 0.05*L	All L and D
Or		
1 > 0.5*L/D	1 < 0.05*L/D	All L and D

The calculation of wavelength (L), then the calculation of L/D ratio were done based on averaged wave height (H_{m0}) and wave period (T_{m-10}) in Appendix G. the results of 0.5*L/D and 0.05*L/D were presented as a function of significant wave height (H_{m0}) for all location on both lakes.

According to Table 4. 5 and Figure 4. 17, the wave formation is in intermediate depth condition starting from 0.7m of wave height for all locations, as the ratio is more than one. Only locations FL5 and FL25 are completely in intermediate depth conditions, as the depth of those locations starts from 1.08m and 1.81m respectively (Table 2. 9).

The maximum value of the ratio is up to 2.3 at locations FL26, FL42, FL46 and FL47, as these are the deepest locations on the list (the minimum depth is 4 meters, see Table 2. 9).

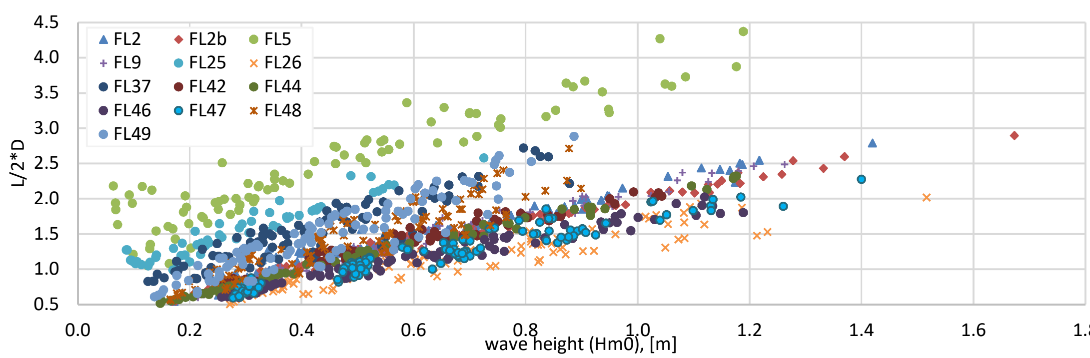


Figure 4. 17 The ratio L/2*D as a function of wave height (H_{m0})

The graph of Figure 4. 17 shows, whether the wave is formed in deep-water conditions or not, however the graph of Figure 4. 18 shows, if wave formation in shallow water condition. As it is shown in Table 4. 5, the wave could be in shallow water conditions, when the L/20*D ratio is more than one. However, according to analysis results, the ratio is far from shallow conditions as the maximum value is 0.44 at location FL5.

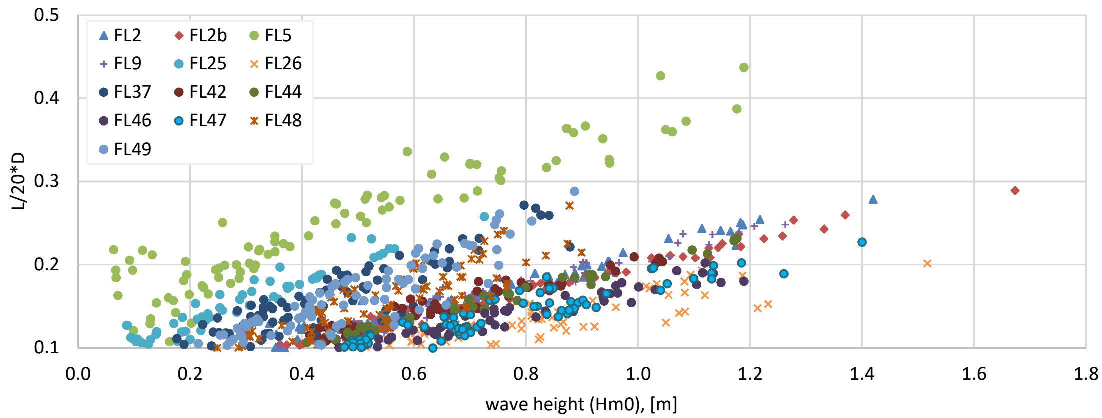


Figure 4. 18 The ratio L/20*D as a function of wave height (H_{m0})

An alternative way of investigating depth limitation is to explore the trends in H_{m0}/D as a function of the dimensionless depth parameter gD/U_{10}^2, as is done by (Wall, 2002), (Bottema, 2007). Figure 4. 19 shows a selection of FL2b, FL9, FL42 and FL47 data. As much wind speed increases (which means a decrease of dimensionless water depth), as the ratio of wave height and water depth increases. However, the ratio is up to 0.3 at locations FL42 and FL47 (central locations) and up to 0.4 at locations FL2b and FL9 (eastern locations). This means that wave height reaching 30-40% of the water depth cannot be excluded. It is somewhat remarkable that the maximum observed Hm0/d ratios for FL47 and FL42 (0.31) are so much smaller than those for FL2b and FL9 (0.4), this difference would merit further investigation in another study.

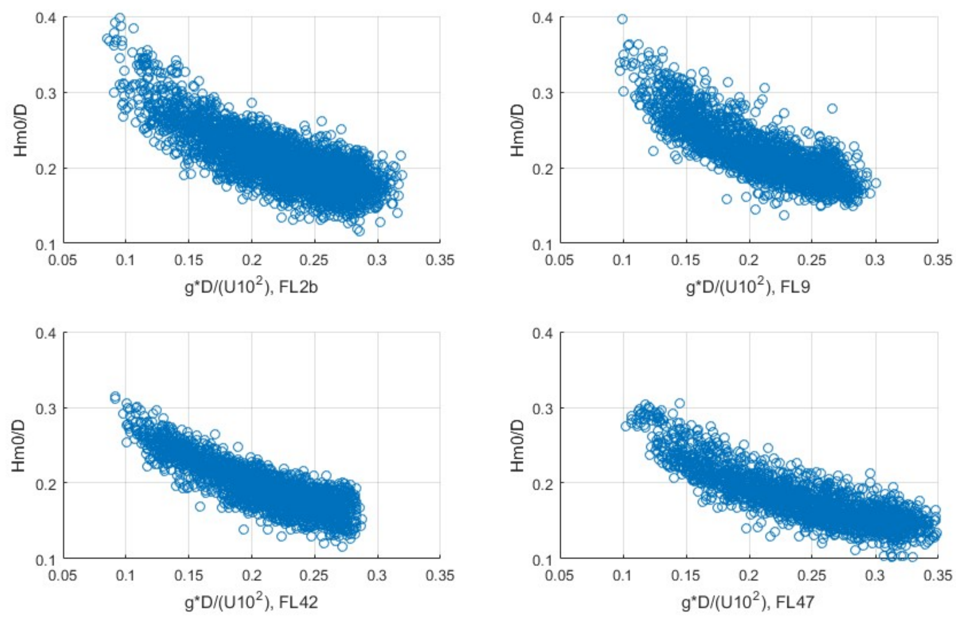


Figure 4. 19 Wave-height-over depth ratio Hm0/D as a function of dimensionless wind-and-depth parameter gD/U_{10}^2. Experimental results for FL2b, FL9, FL42 and FL47 are shown, for WSW winds (210°-260°) of at least 12m/s wind speed

Based on the above results, the average wave height was analysed as a function of water depth for a range of wind speeds, on locations FL5 and FL37 (Figure 4. 20). Although conclusions could be too approximate, the graphs show that the wave height is decreasing as water depth decreases, especially for strong wind (18m/s).

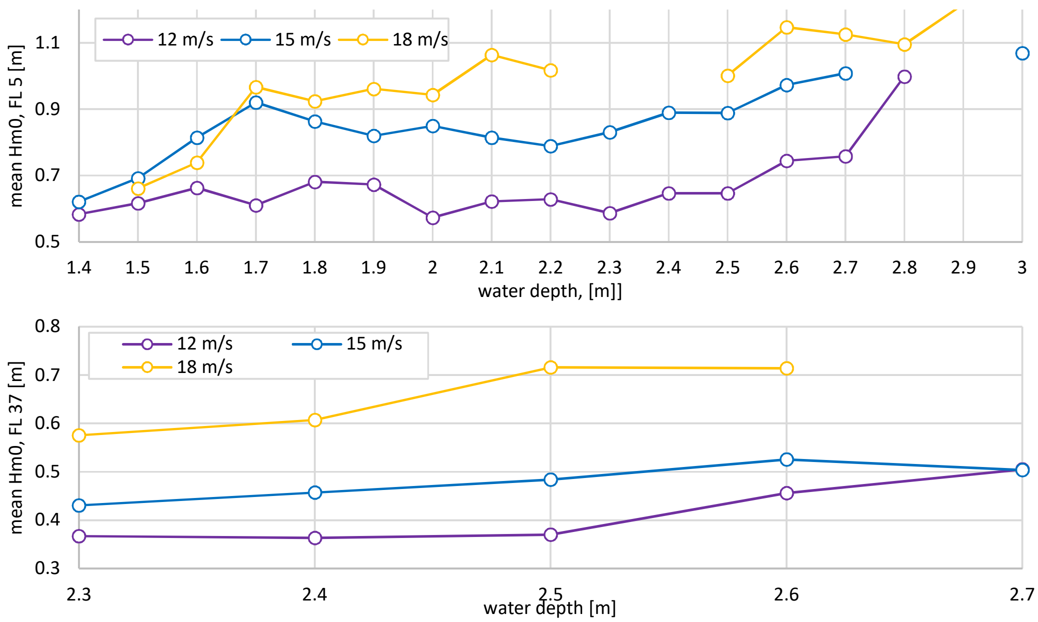


Figure 4. 20 Average wave height (H_{m0}) as a function of water depth (D), for 12m/s, 15m/s and 18m/s wind speeds, at locations FL5 and FL37

Thus, according to measured wave parameters in locations and classification in Table 4. 5, the deep-water conditions exist on Lake IJssel and Lake Marken in small cases, when the wave height is less than 0.7m. In addition, there are no shallow water conditions during wave formation at the measurement locations. The wave growth happens mostly in intermediate (transitional) depth conditions.

4.5 Summary of Chapter 4

Summarizing the results of Chapter 4, the following general conclusions could be stated:

1. Average H_{m0} during a November-April period is 0.29m, 0.37m and 0.39m for western, eastern and central locations respectively. Average T_{m01} during a November-April period is 1.79s, 1.97s and 2.02s for western, eastern and central locations respectively.
2. Relations between wind and H_{m0} and T_{m01} were explored in a qualitative sense. They are for H_{m0} roughly proportional to wind speed U_{10}. For near shore locations, there is a marked difference between onshore and offshore winds, for the central locations FL42/46/47 directional trends are quite small.
3. Wave period (T_{m01}) is largely consistent with wave height (H_{m0}). The correlation coefficient between H_{m0} and T_{m01} is 0.80-0.92 for western locations, and 0.95-0.98 for the rest of locations.
4. The effective fetch, calculated during this study, corresponds to the one in (Bottema, 2007) within 3% accuracy (based on locations FL2, FL2b and FL26).
5. H_{m0} increases quite systematically with effective fetch. Particularly, H_{m0} increases highly with the increase of effective fetch up to 8 km. The wave height is almost invariable after this point, especially for small wind speeds. Hereby, the effective fetch concept of Eq. 4.1 is largely valid.

6. The steepness greatly increases up to 0.05, while wave height reaches 0.35 meter in all locations. Then it is almost constantly remaining around 0.05 along the wave height increase, besides western locations, where steepness reaches up to 0.09.
7. Waves often behave as transitional rather than deep water waves when H_{m0} more than 0.7m. However, only the shallow-foreshore location FL5 shows clear finite depth effects. Significant wave heights at FL42/FL47 and FL2b/FL9 can become as high as 31% and 40% of the water depth without clear signs (without flattening trend) that would indicate these numbers would be a physical upper limit. Yet it is worthwhile to investigate (in a future study), why the wave-height-depth ratio for FL42/FL47 seems to remain lower than for FL2b/FL9.

5. Verification of wave height prediction parametric formulas for Lake IJssel and Lake Marken

5.1 Preparation of experimental data

Not all observation locations and periods have been selected for wave height prediction modelling. The locations with simultaneous observation of the wind and wave data were chosen for study (see Appendix A for observation locations and periods). FL2, FL2b, FL9, FL26, FL42, FL46, FL47, FL48 and FL49 were considered for verification and validation of wave height prediction. FL5 and FL44 are not taken because of missing wind data, FL25 and FL37 are not included because of missing wind direction data, and FL9 is involved since November 2009 (Figure A- 3).

As it is already mentioned in Section 2.2, data is not fully reliable from May to October, because of soiling by algae (Bottema, 2007), that is why data of winter period (November-April) is selected for modelling. The specified period is not for all the initial data, as it was suggested in chapter 2.3. The data with more than 9m/s wind speed was selected for model verification and validation, as the analysis in chapter 3 and 4 show that wave height has high instability, uncertainty and local effects in case of small wind speeds. In addition, waves during less than 9m/s wind are not highly significant for model validation and safety assessment. A comprehensive description of the selected data is presented in Table 5. 1.

Table 5. 1 The size and the ranges of parameters of the experimental data for wave height prediction modelling

location	size of dataset	H_{m0}			wind speed range [m/s]	fetch range [m]	water depth range [m]
		range	mean	stand dev.			
FL2	12850	0.12 – 1.52	0.66	0.19	9.0 - 20.6	1188 - 24758	3.81 – 5.08
FL2b	29666	0.18 – 1.85	0.65	0.19	9.0 – 23.8	2447 - 24956	3.84 – 5.09
FL9	17498	0.17 – 1.58	0.67	0.18	9.0 – 21.2	3858 - 21670	3.61 – 4.56
FL26	21509	0.14 – 1.64	0.65	0.16	9.0 – 23.3	4107 - 24646	4.91 – 6.16
FL42	17232	0.25 – 1.29	0.62	0.14	9.0 – 21.5	9777 - 15027	3.88 – 4.30
FL46	8317	0.25 – 1.34	0.66	0.16	9.0 – 20.4	7099 - 24932	4.57 – 5.56
FL47	17954	0.22 – 1.51	0.67	0.17	9.0 – 21.9	7580 - 25879	4.44 - 5.36
FL48	18927	0.17 – 1.09	0.47	0.13	9.0 – 21.6	1647 - 26515	2.68 – 3.77
FL49	14102	0.13 – 1.00	0.43	0.14	9.0 – 20.6	838 - 26906	2.42 – 3.43

Since there are limitations for experimental data, the number of samples within the proposed data selection is significantly less than initial data. The resulting wave height range varies from 0.13 to 1.85, the wind speed range is from 9 to 24 m/s, the effective fetch range is from 840 m to 27000 m, and the water depth is from 2.4 to 6.2 m for experimental data.

The percentages of wave height (H_{m0}) data within 1σ and 3σ are almost 70-75% and 99% respectively (Table 5. 2).

Table 5. 2 Percentage of wave height (H_{m0}) within standard deviation

location	percentage of wave height within a standard deviation		
	1 σ	2 σ	3 σ
FL2	74.6 %	93.6 %	99.1 %
FL2b	72.4 %	95.6 %	99.1 %
FL9	73.1 %	95.5 %	99.0 %
FL26	72.3 %	95.4 %	98.9 %
FL42	70.7 %	95.3 %	98.9 %
FL46	72.3 %	95.4 %	98.9 %
FL47	72.9 %	95.0 %	98.6 %
FL48	70.6 %	95.6 %	98.8 %
FL49	69.1 %	95.7 %	99.0 %

This factor indicates that the frequency distribution of H_{m0} is not strongly different from a Gaussian distribution. In particular, the frequency distribution of wave height at location FL2 is shown in Figure 5. 1. Appendix I presents the distribution of experimental wave height for all locations.

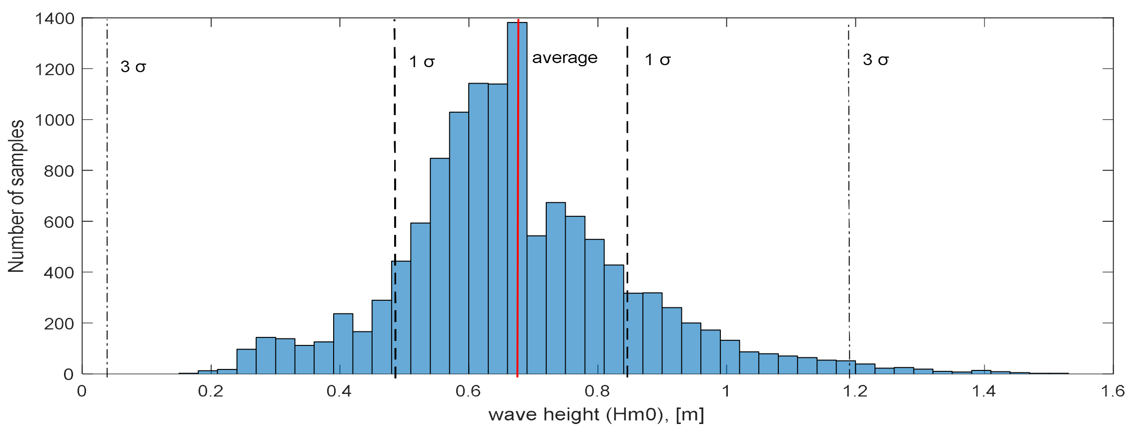


Figure 5. 1 Distribution of significant wave height (H_{m0}) of experimental data (for wind speed more than 9m/s), location FL2

5.2 Bretschneider formula

5.2.1 Verification of Bretschneider formula

One of the basic approaches of significant wave height (H_{m0}) prediction is Bretschneider formula, which is an empirical model considering dimensionless parameters (Bretschneider C. , 1958), (Whalin, Camfield, & Parker, 1984). The inputs of the formula are wind speed (U_{10}), effective fetch (F_{eff}) and water depth (D) and the output is wave height (H_{m0}) (Eq. 5.1).

$$\frac{g*H_{m_0}}{U^2} = 0.283 * v * \tanh\left(\frac{0.0125}{v} * \left(\frac{g*F}{U^2}\right)^{0.5}\right); \qquad v = \tanh\left(0.53 * \left(\frac{g*D}{U^2}\right)^{0.75}\right) \quad (5.1)$$

Or

$$H_{m_0} = \frac{0.283*U^2*v}{g} * \tanh\left(\frac{0.0125}{v} * \left(\frac{g*F}{U^2}\right)^{0.42}\right) \quad (5.2)$$

Input and output variables are dimensionless wave height ($\widetilde{H}$), dimensionless fetch ($\tilde{F}$), and dimensionless water depth ($\widetilde{D}$) (Eq. 5.3).

$$\widetilde{H} = \frac{g*H_{m0}}{U^2} \qquad \tilde{F} = \frac{g*F}{U^2} \qquad \widetilde{D} = \frac{g*D}{U^2} \quad (5.3)$$

Here, g is an acceleration of gravity [m/s^2], units of wave height (H_{m0}), effective fetch (F) and water depth (D) are meter and U^2 is [m^2/s^2], therefore the results of (5.3) are dimensionless parameters.

Bretschneider formula was used for nine measurement locations. The specification of the use of formula is the variety of the locations on the lakes in the current study (variety of fetches, water depths and positions of the locations).

The results of predicted wave height are presented in Table 5. 3 and Figure 5. 2. The most common and basic estimation of predicted wave height is the indicator of correlation, according to which measured and predicted wave heights have 0.78-0.91 correlation coefficient (Table 5. 3). The correlation coefficients for high-winds only (>18m/s) are typically smaller and more variable, since all data are in a rather narrow range.

Table 5. 3 Statistical indicators of predicted significant wave height (H_{m0}) by Bretschneider formula

location	complete data				data with more than 18m/s wind speed			
	correlation coefficient	RMSE	RMSE/ mean H_{m0}	Average relative bias	correlation coefficient	RMSE	RMSE/ mean H_{m0}	Average relative bias
FL2	0.88	0.091	0.14	-1.0%	0.19	0.216	0.20	-18.0%
FL2b	0.91	0.087	0.13	-0.8%	0.59	0.265	0.25	-22.6%
FL9	0.90	0.090	0.14	-1.1%	0.42	0.289	0.29	-26.3%
FL26	0.83	0.107	0.17	-6.0%	0.55	0.273	0.30	-23.9%
FL42	0.87	0.077	0.12	-1.3%	0.57	0.167	0.18	-14.9%
FL46	0.87	0.081	0.12	-0.4%	0.04	0.173	0.17	-13.2%
FL47	0.78	0.107	0.15	-0.6%	0.60	0.260	0.27	-23.8%
FL48	0.85	0.068	0.14	-0.3%	0.61	0.181	0.28	-16.3%
FL49	0.90	0.067	0.16	-1.7%	0.09	0.190	0.35	-15.2%

Root-mean-square-error (RMSE) statistical measure was used to estimate the accuracy of the result of predicted wave height by Bretschneider formula for all locations (Table 5. 3). According to the results, the lowest RMSE value has western locations FL48 and FL49 (up to 0.068) and the highest values have FL26 and FL47 (0.107). The overall RMSE value shows that the accuracy of the predicted wave height has not a dependence on the position of the locations. Since one of the main interests of this study is extreme wave conditions, the RMSE has also been considered for the strong wind events (U_{10}>18m/s). Here, RMSE is more than 0.21 meter for eastern locations and FL47. In addition, it is more than 0.16 for the rest of locations (Table 5. 3).

The relative error of Bretschneider formula is 12-17% (12% for central locations FL42 and FL46 and 16-17% for western locations FL26 and FL49). The relative error for strong wind conditions is generally higher and varies from 17% (FL46) to 35% (FL49) (Table 5. 3).

The relative bias (model output minus experimental data, divided by experimental data) of prediction shows that formula underestimates significant wave height for all locations. In additions, the underestimations are quite large in case of strong wind events (-13- -26%) (Table 5. 3).

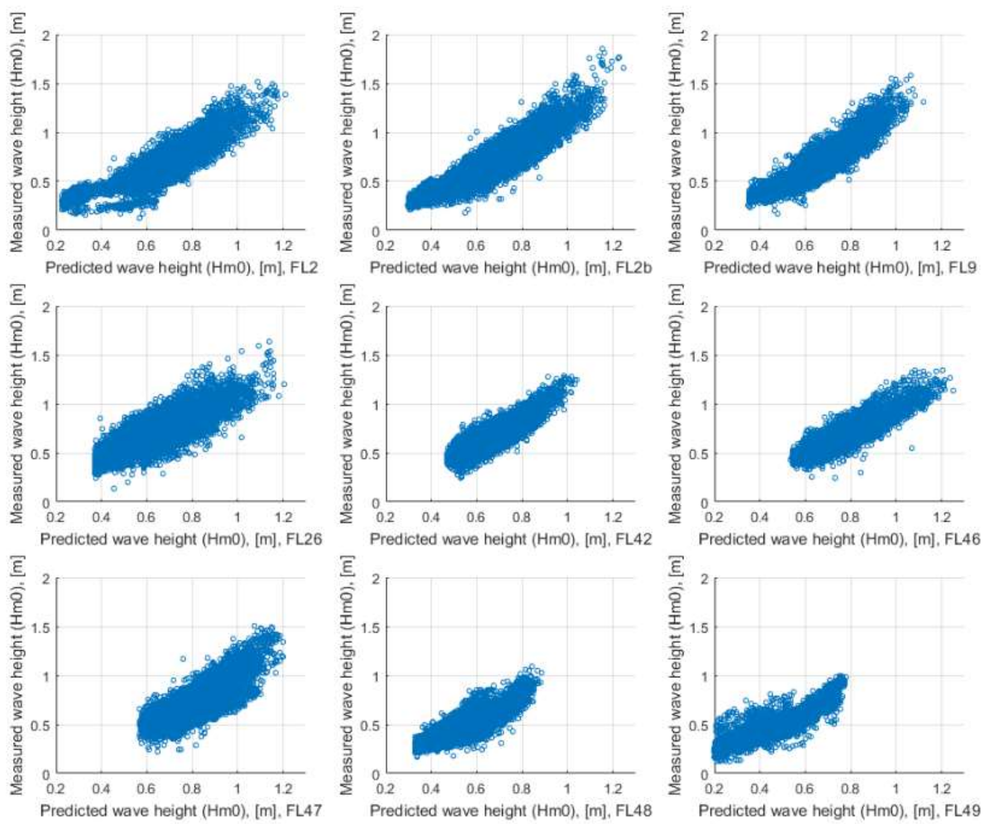


Figure 5. 2 Scatter of Measured and predicted (with Bretschneider formula) wave heights

In addition, mean absolute percentage error (MAPE) was used for the more thorough study of the precision of the results of predicted wave height.

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{y_i - y_i'}{y_i}\right| \quad (5.4)$$

Where Y_i is a measured value (H_{m0}), Y_i' is predicted value. MAPE allows understanding the percentage meaning of RMSE.

MAPE was calculated for different ranges of wind speed and effective fetches. The fetches were rounded with 5km interval and the wind speed was rounded with 3m/s interval. The results of MAPE is presented in Figure 5. 3, where green color indicates low error and red is a high error.

FL2		Effective fetch, [km]					
		0	5	10	15	20	25
wind speed, [m/s]	9	14%	15%	19%	10%	10%	12%
	12	19%		17%	8%	10%	8%
	15			7%	9%	11%	8%
	18				15%	17%	11%
	21					20%	

FL2b		Effective fetch, [km]					
		0	5	10	15	20	25
wind speed, [m/s]	9	9%	14%	12%	10%	9%	9%
	12	9%	14%	10%	10%	8%	8%
	15	10%	19%	10%	11%	9%	8%
	18				17%	14%	11%
	21				21%	19%	13%

FL9		Effective fetch, [km]					
		0	5	10	15	20	25
wind speed, [m/s]	9		16%	18%	13%	9%	
	12		13%	12%	11%	8%	
	15			10%	8%	10%	
	18				9%	17%	
	21					21%	

26		Effective fetch, [km]					
		0	5	10	15	20	25
wind speed, [m/s]	9		14%	8%	9%	10%	8%
	12		16%	8%	9%	9%	8%
	15		19%	10%	13%	11%	8%
	18		21%	11%	9%		6%
	21		25%				

42		Effective fetch, [km]					
		0	5	10	15	20	25
wind speed, [m/s]	9			10%	13%		
	12			9%	10%		
	15			10%	9%		
	18			14%	11%		
	21			17%	13%		

46		Effective fetch, [km]					
		0	5	10	15	20	25
wind speed, [m/s]	9		8%	11%	10%	12%	11%
	12		9%	9%	8%	8%	10%
	15		15%	11%	9%	5%	6%
	18			13%		7%	5%
	21			13%			

47		Effective fetch, [km]					
		0	5	10	15	20	25
wind speed, [m/s]	9			11%	14%	14%	20%
	12			10%	12%	10%	18%
	15			14%	11%	9%	14%
	18			18%	18%	12%	20%
	21			22%			

48		Effective fetch, [km]					
		0	5	10	15	20	25
wind speed, [m/s]	9	9%	9%	12%	15%	14%	14%
	12	12%	8%	9%	12%	11%	9%
	15	19%	8%	6%	7%	5%	9%
	18	23%	13%	12%			
	21		19%				

49		Effective fetch, [km]					
		0	5	10	15	20	25
wind speed, [m/s]	9	12%	9%	10%	13%	14%	7%
	12	14%	8%	8%	10%	8%	6%
	15	20%	8%	10%	7%	7%	13%
	18	27%	13%	20%			
	21						

Figure 5. 3 Mean absolute percentage error (MAPE) of predicted wave height (Bretschneider formula), for different ranges of wind speeds and fetches. The green indicates small errors, and the red is big errors. (Note: effective fetch 0km is the rounded effective fetch of 0-2.5km)

According to the results, the highest error is 27% at location FL49, when the wind is in 18m/s range and fetch is up to 5km. In general, the cases with more than 20% error are few and most of the time occurs during strong winds (which happen to be the most relevant cases in a context of flood risk management). Particularly there is clearly expressed increase of MAPE along wind speed for 5km fetch at FL26. This fetch (5km) coincides with south-southwesterly winds, where the wind does not have fetch limitation (it blows from water surface), but the wave has fetch limitation because of Houtribdijk (Figure 2. 1).

Thus, according to Table 5.3, Bretschneider formula has 12-17% inaccuracy for prediction of wave height on locations in Lake IJssel and Lake Marken. It has 17-35% inaccuracy for prediction of wave height in strong wind conditions, where the average underestimation by the model is 13-26%.

Finally, Figure 5. 4 shows the prediction of wave height by Bretschneider formula for the particular storm event on 28th of October 2013. Locations FL2b, FL42 and FL49 were selected, as they are the representatives of western, central and eastern positions. It is just an example of one particular storm case, so one should not draw hasty conclusions based on Figure 5.4, other than that it confirms the strong-wind underestimations mentioned in the previous paragraph.

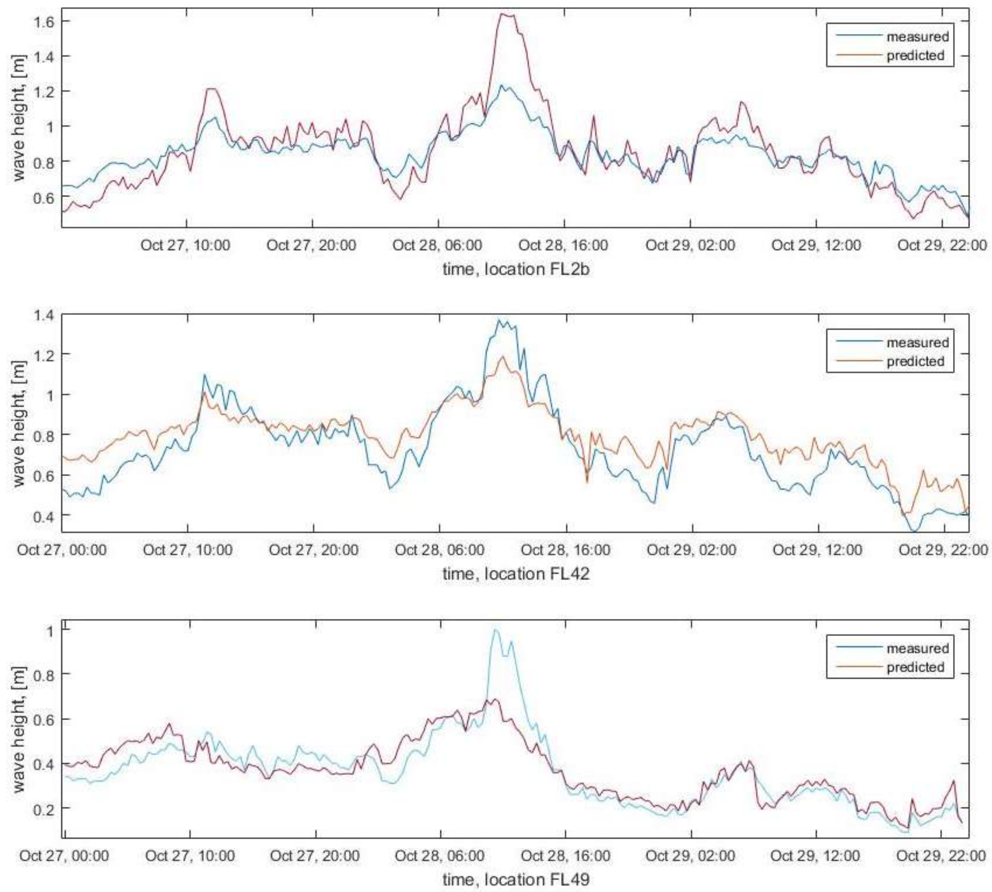


Figure 5. 4 Measured and predicted wave height for 28.10.2013 storm event, locations FL2b, FL42 and FL49

5.2.2 Calibration of parameters of Bretschneider formula

An attempt was done to optimize Bretschneider formula for Lake IJssel and Lake Marken, calibrating the parameters of the formula. Equation 5.5 represents Bretschneider formula but with the assigned parameters a_1, a_2, a_3, a_4 and a_5 instead of existing parameters.

Parameters of Bretschneider formula were calibrated using the experimental data (see Chapter 5.1) and generalized reduced gradient (GRG) nonlinear optimization method (Leon, Richard, & Margery, 1974). It is worth to notice, that ±30% constraint of existing parameters were defined for optimization, to avoid unrealistic results of parameters, as Bretschneider formula is a physical-based, empirical model.

$$H_{m0} = \frac{a_1 * U^2 * v}{g} * \tanh\left(\frac{a_4}{v} * \left(\frac{g * F}{U^2}\right)^{a_5}\right); \quad \text{where } v = \tanh\left(a_2 * \left(\frac{g * d}{U^2}\right)^{a_3}\right) \quad (5.5)$$

The calibration was done based on minimization of RMSE. At first, calibration was done for individual locations. Then the calibration was done for the group of measurement locations (data was merged) based on their position. FL2, FL2b and FL9 were grouped together as eastern locations, FL42, FL46 and FL47 were grouped as central locations, and FL26, FL48 and FL49 were grouped as western locations. In addition, calibration was also done for all locations together. The result of calibration are presented in Table 5. 4.

Table 5. 4 Initial and calibrated parameters and RMSE of Bretschneider formula

locations	parameters of Bretschneider formula					RMSE for new coefficients	RMSE for initial coefficients
	a_1	a_2	a_3	a_4	a_5		
Initial	0.283	0.53	0.75	0.0125	0.50		
FL2	0.314	0.37	0.53	0.0163	0.37	0.082	0.092
FL2b	0.198	0.63	0.53	0.0163	0.43	0.077	0.087
FL9	0.368	0.39	0.53	0.0093	0.40	0.075	0.090
FL26	0.269	0.37	0.53	0.0163	0.44	0.072	0.107
FL42	0.198	0.45	0.53	0.0163	0.55	0.067	0.076
FL46	0.270	0.37	0.53	0.0163	0.41	0.072	0.081
FL47	0.217	0.40	0.53	0.0163	0.55	0.077	0.107
FL48	0.368	0.37	0.67	0.0163	0.33	0.051	0.068
FL49	0.368	0.37	0.64	0.0163	0.33	0.049	0.067
FL2, FL2b, FL9	0.235	0.53	0.53	0.0162	0.40	0.078	0.089
FL26, FL48, FL49	0.270	0.37	0.55	0.0163	0.43	0.065	0.086
FL42, FL46, FL47	0.198	0.45	0.53	0.0163	0.55	0.073	0.091
All locations	0.277	0.37	0.53	0.0163	0.41	0.076	0.088

According to the results, a_1 has a big variety. Particularly, it is 0.198 for FL2b, FL42 and the group of "FL42, FL46, and FL47", it is 0.368 for FL9, FL48 and FL49 and the value of a_1 is 0.277 for the group of all locations. In most of the cases, the parameter a_2 is 0.37, which is quite far from initial value. Parameter a_3 is stable most of the time and has a value of 0.53. Parameter a_4 constantly has 0.0163 value, except location FL9, where it is 0.093. Parameter a_5 has 0.33-0.55 range of values and particularly, the calibration of "all locations" is almost the same as an initial value (0.42). In addition, the fact that the calibrated 'a1' is over 50% higher for FL2 than for the highly similar location FL2b does not imply the calculated Hm0 is also 50% higher for FL2. This is because high values for some other parameters (a2 and a5 in the case of FL2b) can compensate the effect of a low a1-value, see Eq. 5.5.

It is logical that the calibrated parameters of each location will improve the RMSE of wave height prediction of their own data. However, the calibrated formula of one location not always could be acceptable for other locations. That is why Bretschneider formula with all calibrated parameters in Table 5. 4 was applied to nine locations (Figure 5. 5).

locations	Initial	FL2	FL2b	FL9	FL26	FL42	FL46	FL47	FL48	FL49	FL2, FL2b, FL9	FL26, FL48, FL49	FL42, FL46, FL47	All locations
FL2	0.092		0.084	0.086	0.086	0.106	0.090	0.114	0.095	0.090	0.084	0.089	0.106	0.085
FL2b	0.087	0.079		0.079	0.087	0.107	0.086	0.114	0.091	0.086	0.078	0.088	0.107	0.083
FL9	0.090	0.077	0.076		0.085	0.108	0.087	0.117	0.091	0.084	0.076	0.089	0.108	0.082
FL26	0.107	0.088	0.113	0.129		0.086	0.088	0.090	0.109	0.106	0.114	0.075	0.086	0.080
FL42	0.076	0.074	0.074	0.071	0.077		0.068	0.070	0.071	0.069	0.071	0.070	0.068	0.070
FL46	0.081	0.073	0.078	0.090	0.080	0.077		0.077	0.083	0.080	0.078	0.074	0.077	0.072
FL47	0.107	0.089	0.101	0.113	0.086	0.077	0.086		0.099	0.096	0.099	0.084	0.077	0.085
FL48	0.068	0.064	0.076	0.083	0.069	0.077	0.053	0.080		0.053	0.070	0.059	0.077	0.058
FL49	0.067	0.057	0.074	0.081	0.060	0.073	0.052	0.080	0.049		0.067	0.055	0.077	0.053

Figure 5. 5 RMSE of predicted wave height by calibrated Bretschneider formula, for nine measurement locations

The results show that Bretschneider formula performs better for all locations when it was calibrated by FL2 dataset. Formula obviously has low accuracy for eastern locations (FL2, FL2b and FL9), when it is calibrated by FL42 and FL47 (which are central locations). Bretschneider formula, calibrated by a merged group of locations FL26, FL48 and FL49 (western locations), performs better than individual locations and another group of locations, but still with high RMSE at locations FL2, FL2b and FL9. Bretschneider formula applies almost equally accurate for all locations when it is calibrated by merged data of all locations. RMSE value varies from 0.053 to 0.085.

Thus adopting the last case of calibrated parameters (calibration by merged data of all locations, last column of Figure 5.5) results in a modified Bretschneider formula that applies well for all nine-measurement locations.

The results of predicted wave height by the calibrated formula of Bretschneider are presented in Table 5. 5. The correlation coefficient between measured and predicted wave heights is 0.88-0.93 for complete dataset, which was improved by the factor of 1.04 in average (particularly 1.12 for FL47). The coefficient is again less than 0.64 in case of prediction of wave height in strong wind conditions, however, it was improved by the factor of 1.3 (particularly 2.75 for location FL46).

Table 5. 5 Statistical indicators of predicted significant wave height (H_{m0}) by calibrated formula of Bretschneider

location	complete data				data with more than 18m/s wind speed			
	correlation coefficient	RMSE	RMSE/ mean H_{m0}	Average relative bias	correlation coefficient	RMSE	RMSE/ mean H_{m0}	Average relative bias
FL2	0.90	0.085	0.13	-1.2%	0.27	0.138	0.12	-7.2%
FL2b	0.91	0.083	0.13	-0.4%	0.64	0.166	0.14	-10.2%
FL9	0.90	0.082	0.12	-1.0%	0.43	0.182	0.16	-13.9%
FL26	0.89	0.080	0.12	-3.1%	0.63	0.162	0.16	-10.6%
FL42	0.88	0.071	0.11	2.0%	0.56	0.076	0.07	-2.1%
FL46	0.90	0.072	0.11	0.8%	0.12	0.107	0.09	-1.7%
FL47	0.87	0.085	0.13	0.6%	0.62	0.154	0.14	-11.6%
FL48	0.92	0.058	0.12	2.7%	0.61	0.088	0.11	-3.1%
FL49	0.93	0.053	0.12	1.2%	0.11	0.128	0.19	-3.6%

The lowest RMSE value has western locations FL48 and FL49 (up to 0.058 meters) and the highest values have eastern locations and FL47 (0.082-0.085 meters). The RMSE value of predicted wave height by calibrated formula was improved by a factor 0.86 (it is 0.74 in case of FL26). Since one of the main interests of this study is extreme wave conditions, the RMSE has also been considered for the strong wind events (U_{10}>18m/s). Here, RMSE is less than 0.182 meter for all locations. The RMSE of predicted wave height in strong wind conditions was reduced by a factor 0.59.

The relative error of predicted wave height by the calibrated formula of Bretschneider is 11-13% (11% for central locations FL42 and FL46 and 12-13% for eastern and western locations). The relative error of predicted wave height in strong wind conditions is 7-9% for central locations FL42 and FL46, and 11-19% for the rest of locations (19% has location FL49). Relative error was reduced after calibration by a factor 0.52 (0.4 for locations FL42 and FL48).

The bias of prediction wave height shows that formula underestimates wave height in eastern locations and FL26 and overestimates for central and western locations (which were underestimated before calibration of Bretschneider formula Table 5. 3). For the strong wind conditions, the bias of predicted wave height significantly decreased and became more than -14%. However, the formula continues to underestimate wave height after calibrations.

Thus, the application of the calibrated formula of Bretschneider has 11-13% relative error (and 7-19% for strong wind conditions). Both, initial and calibrated formulas mainly have underestimation of predicted wave height on Lake IJssel and Lake Marken.

Figure 5. 6 shows a particular example of the performance of calibrated formula of Bretschneider for the same cases as in Figure 5. 4, to illustrate the aforementioned model underestimation for strong winds.

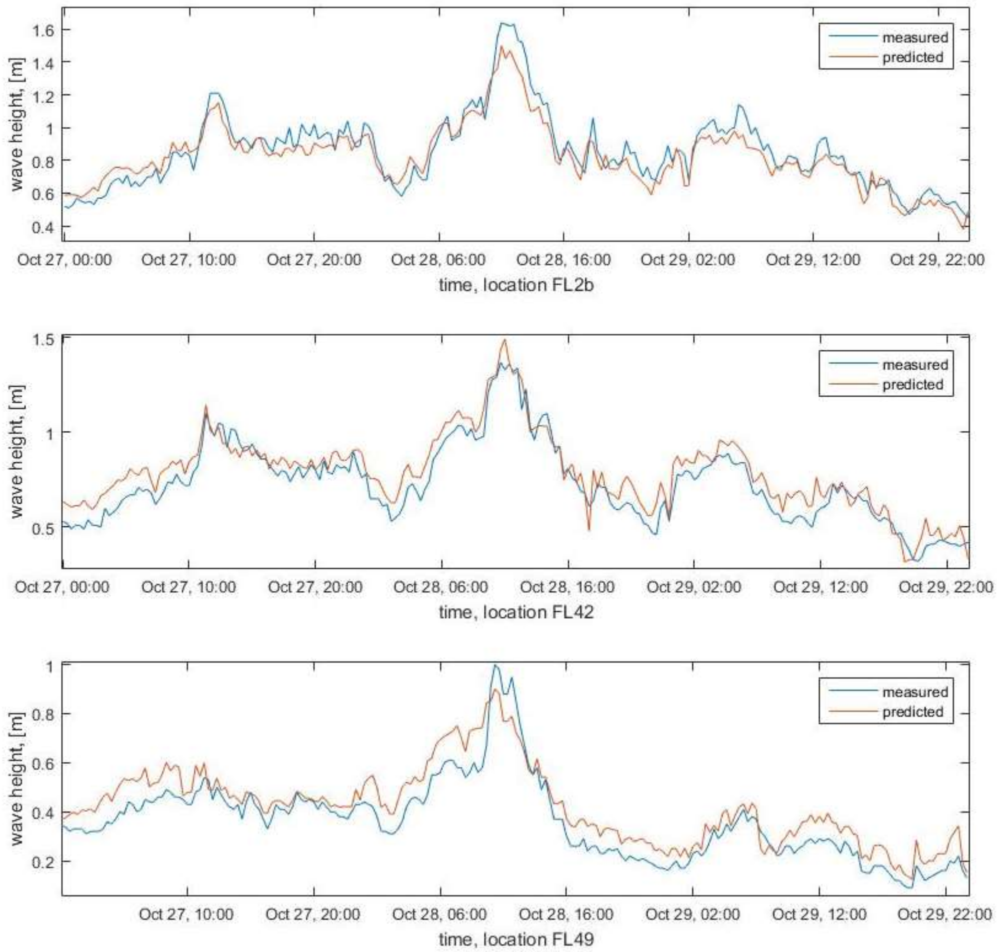


Figure 5. 6 Measured and predicted wave height by calibrated formula of Bretschneider (calibrated with data from all locations), for 28.10.2013 storm event, locations FL2b, FL42 and FL49

5.3 Breugem-Holthuijsen formula

The next parametric formula is Breugem-Holthuijsen, which was verified for Lake IJssel and Lake Marken.

According to Breugem and Holthuijsen, the best set of observations of wave growth in shallow water has been acquired by Young and Verhagen (1996) in Lake George, Australia. The study of Young and Verhagen were based on wind observed from all directions. However, Breugem and Holthuijsen found a north-south stratification that Young and Verhagen ignored in their data, and did a calibration of Young and Verhagen formula, based on that fact (Breugem & Holthuijsen, 2007). In that way, they developed a sort of unified formula, which is expected to be applicable in a wider range of fetch conditions (both narrow, wide, narrowing and widening lakes). Their parametric formula is the following:

$$\tilde{H} = 0.24 * \left(\tanh\left(0.343 * \tilde{D}^{1.14}\right) * \tanh\left(\frac{0.000441 * \tilde{F}^{0.79}}{\tanh(0.343 * \tilde{D}^{1.14})}\right)\right)^{0.572} \quad (5.6)$$

Or

$$H_{m0} = \frac{0.24 * U_{10}^{2}}{g} * \left(\tanh\left(0.343 * \tilde{D}^{1.14}\right) * \tanh\left(\frac{0.000441 * \tilde{F}^{0.79}}{\tanh(0.343 * \tilde{D}^{1.14})}\right)\right)^{0.572} \quad (5.7)$$

Here, $\tilde{H}$, $\tilde{F}$ and $\tilde{D}$ are dimensionless wave height, fetch and water depth from equation 5.3. Breugem-Holthuijsen formula was used for the group of locations described in chapter 5.1.

The results of predicted wave heights by Breugem-Holthuijsen formula are presented in Table 5. 6 and Figure 5. 7. The correlation coefficient as a first indicator is 0.78-0.91 in case of the complete dataset for all locations. However, the correlation is lower in case of prediction of wave height in strong wind conditions. Particularly, FL46 and FL49 has 0.06 correlation coefficient, which could be because of the small size of the dataset.

The RMSE of predicted wave height is more than 0.1 meter for most of the cases (except FL48 and FL49), which is less accurate than the performance of Bretschneider formula. In contrast of the Bretschneider formula, RMSE of predicted wave height by Breugem-Holthuijsen formula is less than 0.2 meter for strong wind conditions. In fact, Breugem-Holthuijsen seems to be a factor 1.6 more accurate than Bretschneider for the data subset with more than 18m/s wind speed (compare Table 5.3 with Table 5. 6).

Table 5. 6 Statistical indicators of predicted significant wave height (H_{m0}) by Breugem-Holthuijsen formula

location	complete dataset				data with more than 18m/s wind speed			
	correlation coefficient	RMSE	RMSE/ mean H_{m0}	average bias	correlation coefficient	RMSE	RMSE/ mean H_{m0}	average bias
FL2	0.88	0.111	0.17	6.5%	0.24	0.124	0.10	-3.5%
FL2b	0.91	0.104	0.16	6.7%	0.64	0.155	0.13	-8.0%
FL9	0.90	0.104	0.16	6.5%	0.43	0.173	0.15	-12.7%
FL26	0.80	0.103	0.16	0.7%	0.50	0.199	0.22	-15.8%
FL42	0.87	0.116	0.19	9.2%	0.58	0.073	0.07	-0.3%
FL46	0.87	0.108	0.16	7.3%	0.06	0.113	0.10	-1.3%
FL47	0.78	0.128	0.19	7.1%	0.61	0.144	0.13	-10.2%
FL48	0.84	0.088	0.18	3.7%	0.56	0.127	0.17	-8.2%
FL49	0.88	0.080	0.19	1.0%	0.06	0.180	0.30	-10.6%

The relative error of the performance of Breugem-Holthuijsen is 16-19% for all location. The relative error is somewhat smaller (7-15%) for all locations in case of strong wind conditions, besides FL42 (22%), FL48 (17%) and FL49 (30%) (Table 5. 6).

The bias of predicted wave height shows that Breugem-Holthuijsen formula overestimates the wave height for all locations by 1.0- 9.0%. However, formula underestimates wave height in case of strong wind conditions up to -16%.

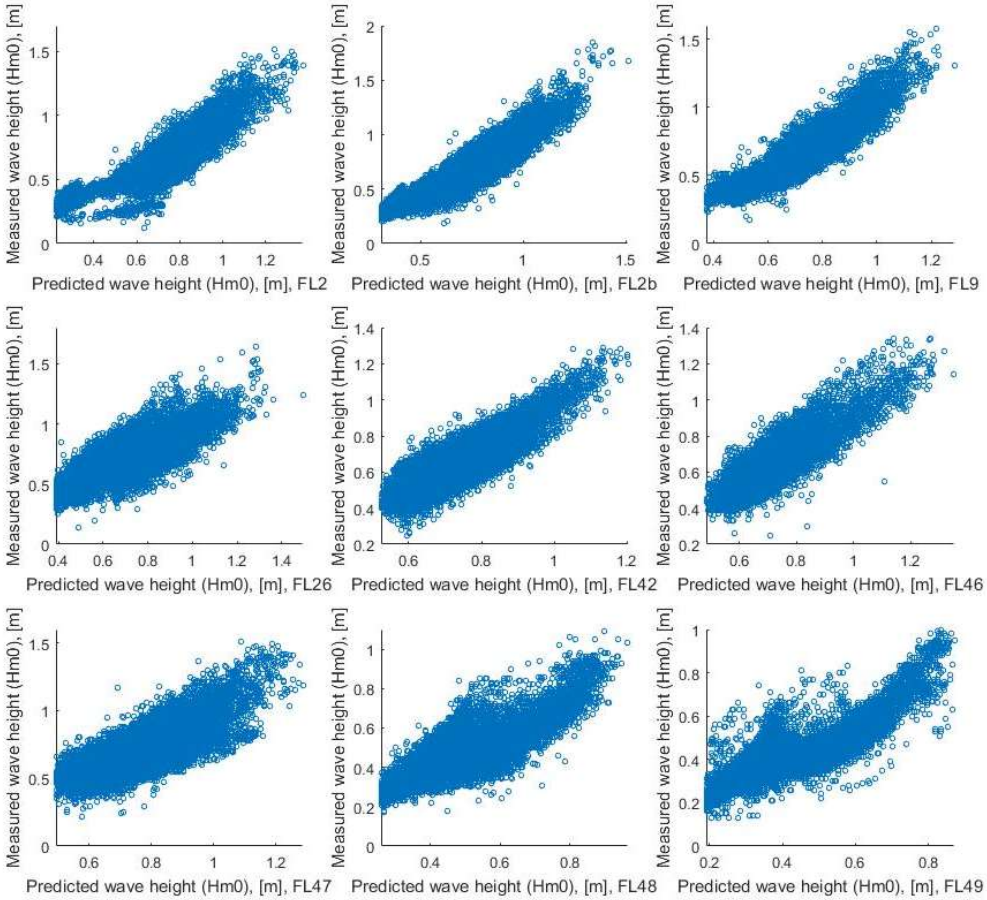


Figure 5. 7 Scatter plot of measured and predicted wave heights (Breugem-Holthuijsen formula)

MAPE was calculated for different ranges of wind speed and effective fetches for Breugem-Holthuijsen formula as well. The fetch was rounded with 5 km interval and the wind speed was rounded with 3 m/s interval. The results of MAPE is presented in Figure 5. 8.

The interesting fact of MAPE analysis is the proportional increase of accuracy of wave height prediction, with the increase of wind speed (Figure 5. 8). It is clearly expressed in locations FL2, FL2b, FL9, FL42 and FL47. This same pattern also exists in FL26, FL48 and FL49, except the cases with up to 5km fetches. The accuracy of wave height prediction is low, when wind speed and fetch are smaller (mainly northeastern wind direction), in eastern locations (FL2, FL2b, FL9). The accuracy is high, when wind speed and fetch are high (mainly southwestern wind direction), in the eastern locations (FL2, FL2b, FL9). The central locations (FL42, FL46 and FL47) have low accuracy in case of small wind and long fetches, and have high accuracy, in the case of high wind speed and short fetches. The locations near the western coast (FL26, FL48 and FL49) have high accuracy in case of long fetches and high wind speeds (Figure 5. 8).

FL2	Effective fetch, [km]					
wind speed, [m/s]	0	5	10	15	20	25
9	14%	16%	26%	17%	14%	22%
12	20%	31%	24%	15%	13%	16%
15			11%	9%	9%	11%
18				10%	9%	10%
21						

FL2b	Effective fetch, [km]					
wind speed, [m/s]	0	5	10	15	20	25
9	11%	20%	22%	16%	16%	18%
12	10%	20%	18%	14%	14%	16%
15	7%	27%	16%	10%	9%	9%
18				9%	8%	6%
21				12%	9%	7%

FL9	Effective fetch, [km]					
wind speed, [m/s]	0	5	10	15	20	25
9		24%	29%	25%	15%	
12		20%	22%	21%	12%	
15			21%	15%	9%	
18				6%	9%	
21						

26	Effective fetch, [km]					
wind speed, [m/s]	0	5	10	15	20	25
9		11%	13%	15%	18%	17%
12		12%	10%	12%	15%	15%
15		14%	8%	13%	11%	10%
18		17%	8%			12%
21		20%				

42	Effective fetch, [km]					
wind speed, [m/s]	0	5	10	15	20	25
9			17%	24%		
12			11%	20%		
15			6%	13%		
18			5%	6%		
21			5%	7%		

46	Effective fetch, [km]					
wind speed, [m/s]	0	5	10	15	20	25
9		10%	18%	17%	23%	22%
12		6%	13%	12%	18%	21%
15		6%	10%	7%	12%	13%
18			9%		7%	12%
21						

47	Effective fetch, [km]					
wind speed, [m/s]	0	5	10	15	20	25
9			13%	26%	27%	33%
12			10%	21%	22%	30%
15			8%	15%	14%	26%
18			9%	9%	8%	
21			11%			

48	Effective fetch, [km]					
wind speed, [m/s]	0	5	10	15	20	25
9	9%	15%	24%	28%	24%	22%
12	10%	14%	20%	23%	19%	17%
15	16%	10%	14%	12%	13%	8%
18	19%	8%	5%			
21		10%				

49	Effective fetch, [km]					
wind speed, [m/s]	0	5	10	15	20	25
9	13%	13%	21%	24%	24%	13%
12	15%	14%	18%	20%	15%	9%
15	21%	13%	11%	10%	9%	8%
18	26%	10%				
21						

Figure 5. 8 Mean absolute percentage error (MAPE) of predicted wave height (Breugem-Holthuijsen formula), for different ranges of wind speeds and fetches. The green indicates small errors, and the red is big errors. (Note: effective fetch 0km is the rounded effective fetch of 0-2.5km)

Figure 5. 9 shows a particular example of the performance of Breugem-Holthuijsen formula for the storm event on 3rd of January 2012. October 2013. Locations FL9, FL46 and FL48 were selected, as they are the representatives of eastern, central and western positions on Lake IJssel.

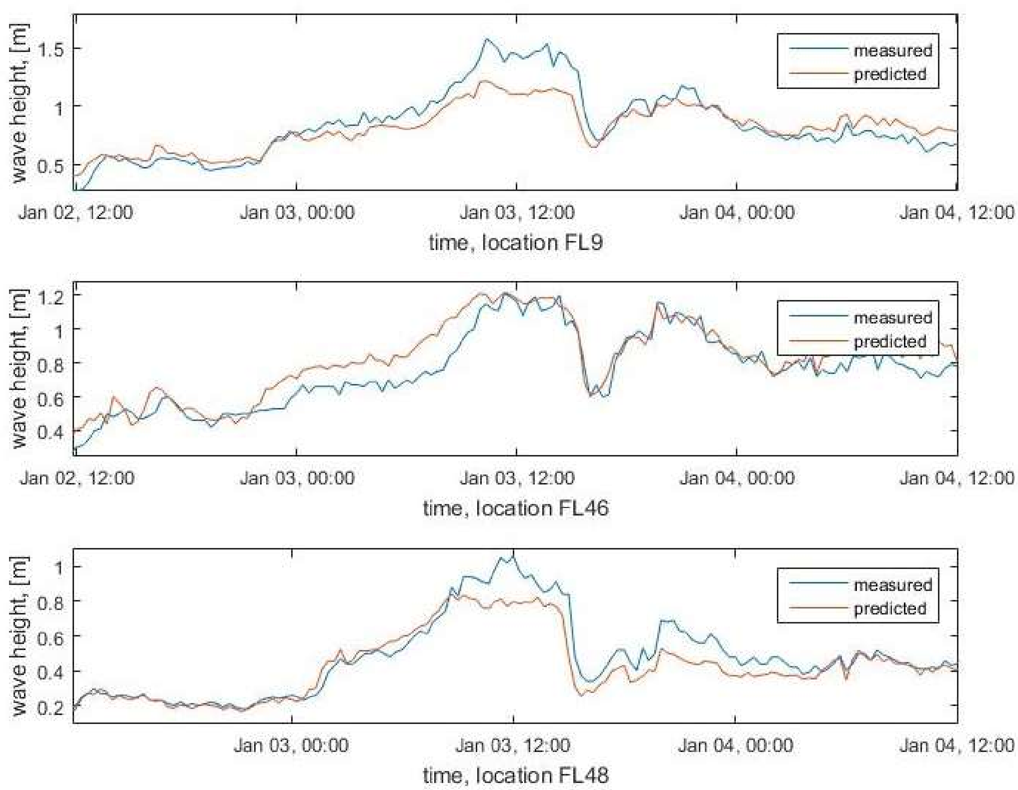


Figure 5. 9 Measured and predicted wave height for 03.01.2012 storm event, locations FL9, FL46 and FL48

5.4 Summary of Chapter 5

Summarizing the results of Chapter 5, the following general conclusions could be stated:

1. The original parametric formula of Bretschneider has 12-17% relative error of wave height prediction on Lake IJssel and Lake Marken, particularly; the error is higher in western locations. In addition, the relative error is 17-35% in case of strong wind conditions (> 18 m/s). In general, the formula underestimates wave height (overall by a few percent, for winds > 18 m/s by 15-26%) in all locations.
2. In this study, the Bretschneider formula was calibrated to the present data set. The calibrated formula of Bretschneider (calibrated with merged data of all locations) performs overall a factor 1.2-1.3 better RMSE than initial formula.
3. The calibrated formula of Bretschneider has 11-13% relative error of wave height prediction on Lake IJssel and Lake Marken. For strong wind, the relative error is 7-19% while the model underestimates wave height by 2-14% in all locations.
4. Overall, the parametric formula of Breugem-Holthuijsen has 16-19% relative error of wave height prediction on Lake IJssel and Lake Marken and overestimates predicted wave height by up to 9%. For strong winds (>18 m/s), the relative error is 7-30% and the model then underestimates wave heights by 0.3-16% in all locations.

6. Wave height prediction modelling (Artificial Neural Network)

6.1 Analysis of the input variables used in ANN modelling

The experimental dataset, which was discussed in Chapter 5.1, will be used for Neural Network modelling as well.

The first step in data-driven modelling is to explore the relationship between the proposed input variables and the output variable. Initially, the wind speed (U_{10}), effective fetch (F) and water depth (D) were selected as input variables and significant wave height (H_{m0}) was chosen as the target variable for ANN model training. This preliminary selection is based on the parametric formulas, discussed in Chapter 5.

The scatters between wind speed and significant wave height, presented in Figure 6. 1 and Table 6. 1, show a high correlation between them.

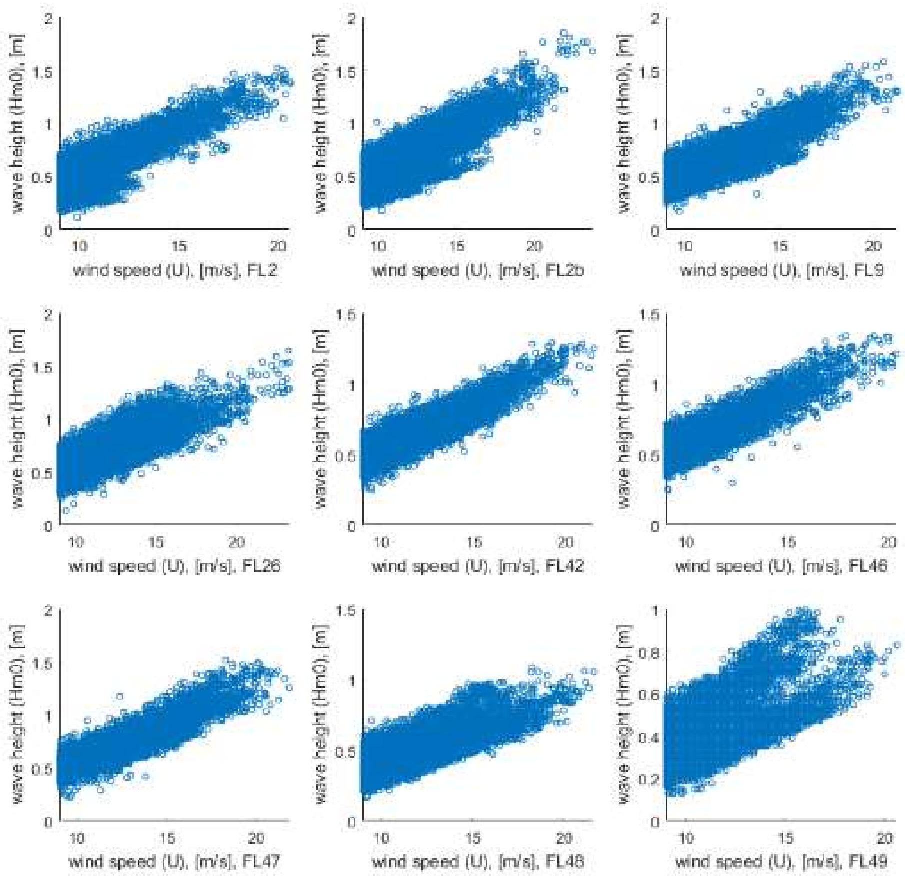


Figure 6. 1 Scatter plots of wind speed (U_{10}) and significant wave height (H_{m0}) for measurement locations FL2, FL2b, FL9, FL26, FL42, FL46, FL47, FL48 and FL49 on Lake IJssel and Lake Marken

The graphical representation of correlation shows the clearly expressed dependence of wave height on wind speed. Correlation is the highest for the central locations such as FL42 (Lake Marken), FL46 and FL47 (Lake IJssel), where the influence of fetches is low. The correlation is low for the locations, which are located near the shorelines of lakes from which the strong winds blow (locations FL26, FL48, FL49). In particular, FL49 has two quite clearly separated scatter clouds, which is due to sharp change of the fetch influence (see chapter 4.2.2). All in all the correlation between wind speed and wave height is high and varies from 0.5 to 0.9 (Table 6. 1).

Table 6. 1 Correlation coefficients of input variables for nine locations on Lake IJssel and Lake Marken

locations	wind speed (U_{10}) and wave height (H_{m0})	effective fetch (F) and wave height (H_{m0})	effective fetch (F) – ratio of wave height (H_{m0}) and wind speed (U_{10})	water depth (D) and wave height (H_{m0})
FL49	0.50	0.68	0.87	0.15
FL48	0.71	0.46	0.82	0.06
FL26	0.76	0.37	0.71	0.20
FL2b	0.81	0.56	0.71	0.45
FL2	0.82	0.56	0.65	0.39
FL9	0.85	0.46	0.65	0.29
FL46	0.88	0.25	0.40	0.23
FL42	0.89	-0.04	-0.14	0.21
FL47	0.90	-0.13	0.03	0.12

The maximum of the correlation coefficient of effective fetch (F_{eff}) and significant wave height (H_{m0}) is 0.68 (FL49) and there is no well-established correlation between both parameters for all locations, as it is shown in Figure 6. 2 and Table 6. 1. The low correlation could be conditioned by two circumstances. The first is the shape of the lakes, because of which the same fetch could have a different impact on wave generation. For example, FL37 and FL49 have almost the same fetches for southwestern winds, but impact of the fetches are different for those locations as it is shown on the map of Figure 2. 1. However, one mentor for this study provided an alternative explanation based on curve-fitting experience: if an independent variable (such as fetch) on a given location has hardly any variation, then it will be hard to obtain any good or stable correlation with the dependent variable (personal communication Bottema, 2017).

The second circumstance is the non-direct influence of wind speed on the relationship of effective fetch and wave height. The simple ratio of wave height and wind speed is here proposed to capture more clearly the relationship of effective fetch and wave height. (It is worth to mention that the ratio of wave height and wind speed is not an input variable for modelling). The graphs in Figure 6. 3, shows the scatter of H_{m0}/U_{10} as a function of fetch for nine locations on Lake IJssel and Lake Marken.

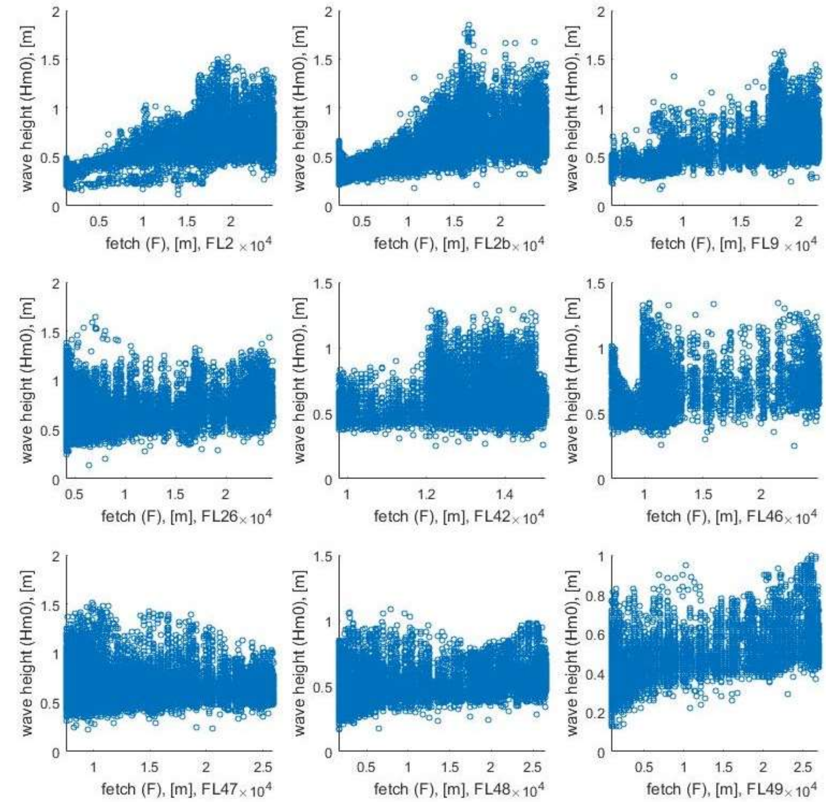


Figure 6. 2 Scatter plots of effective fetch (F) and significant wave height (H_{m0}), for measurement locations FL2, FL2b, FL9, FL26, FL42, FL46, FL47, FL48 and FL49 on Lake IJssel and Lake Marken

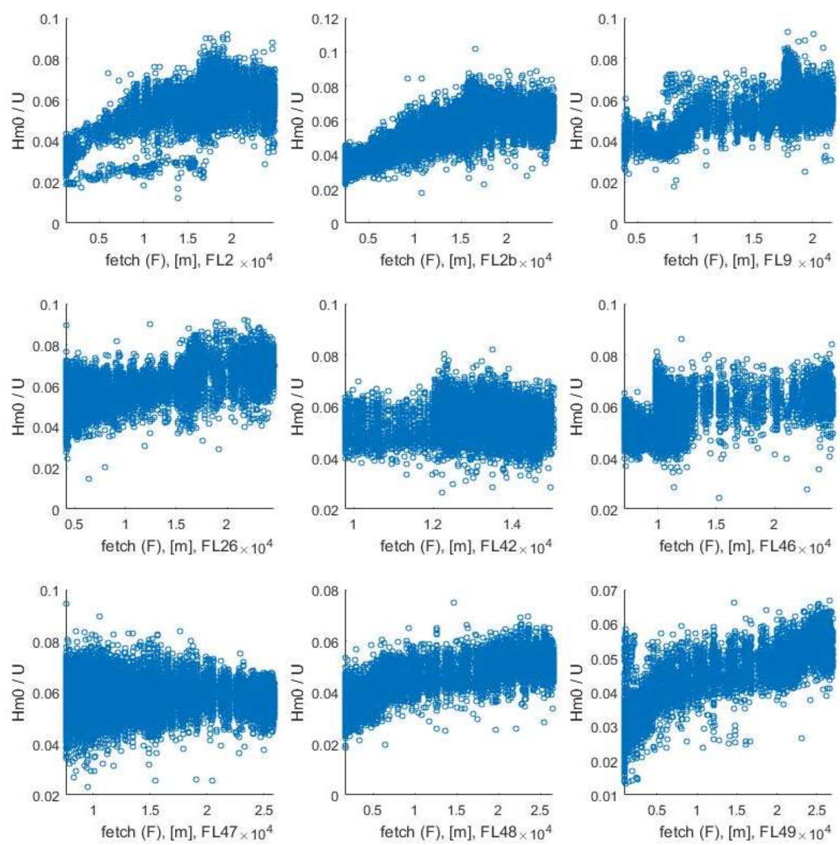


Figure 6. 3 Scatter plots of effective fetch (F) and the H_{m0}/U_{10} parameters, for nine measurement locations FL2, FL2b, FL9, FL26, FL42, FL46, FL47, FL48 and FL49 on Lake IJssel and Lake Marken

Correlations in Figure 6.3 become higher than 0.65 for locations FL2, FL2b, FL9, FL26, FL48 and FL49 as it also shown in the fourth column of Table 6. 1. For the central locations (FL42, FL46 and FL47), the correlations remain low, as explained in previous paragraphs.

Here, the expected and interesting regularity is the increase of correlation coefficient in the second column coincides with the decrease of the coefficient in the fourth column in Table 6. 1 (Figure 6. 4). Therefore, we can conclude that as much the influence of fetch decreases on wave formation more the influence of wind speed increases on wave formation.

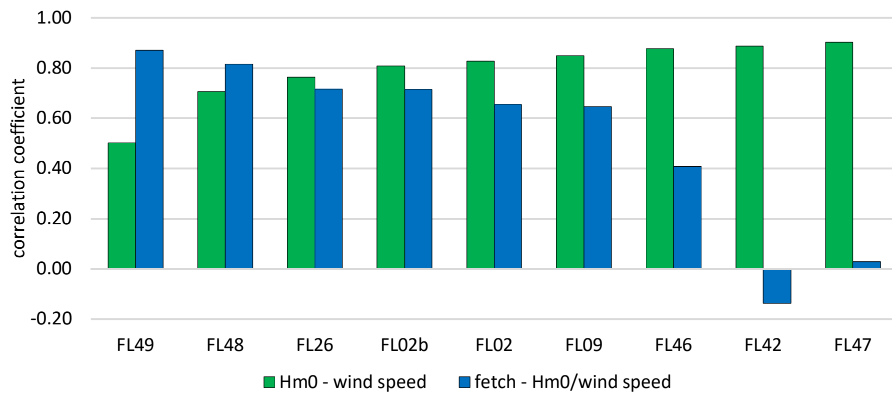


Figure 6. 4 Correlation coefficients of wave height-wind speed and fetch and wave height and wind speed ratio by locations

The dependence of wave height on the water depth is low and the correlation coefficient hardly reaches to 0.45 (Table 6. 1, Figure 6.5). However, consideration of water depth as an input variable could be wrong if the only correlation coefficient is considered, since, in many cases, waves on Lake IJssel and Lake Marken are neither strictly deep-water waves nor shallow-water waves, as it shows the analysis in Chapter 4.4. This means that validation of model will be based on data in transitional depth conditions, whereas the aim of the study to have validated a model to predict extreme wave height (which could happen in shallow water conditions).

The graphs in Figure 6.5 shows that the wave height as a function of water depth is scattered, which is expected as the minimum water depth of 2.5 meters has location FL49. However, the rough approximation of the graph in Figure 4. 20 show that the wave height increases as water depth increase especially at locations FL5, which has 1.4m water depth.

Nevertheless, the water depth was considered as an input variable for modelling, for the following reasons:

- The transitional condition of water depth during wave formation in both lakes, which can turn into shallow water condition during storm events,
- There is expressed dependence of wave height on water depth in relatively shallow water locations, such an FL5,
- Small depth of water near shorelines.

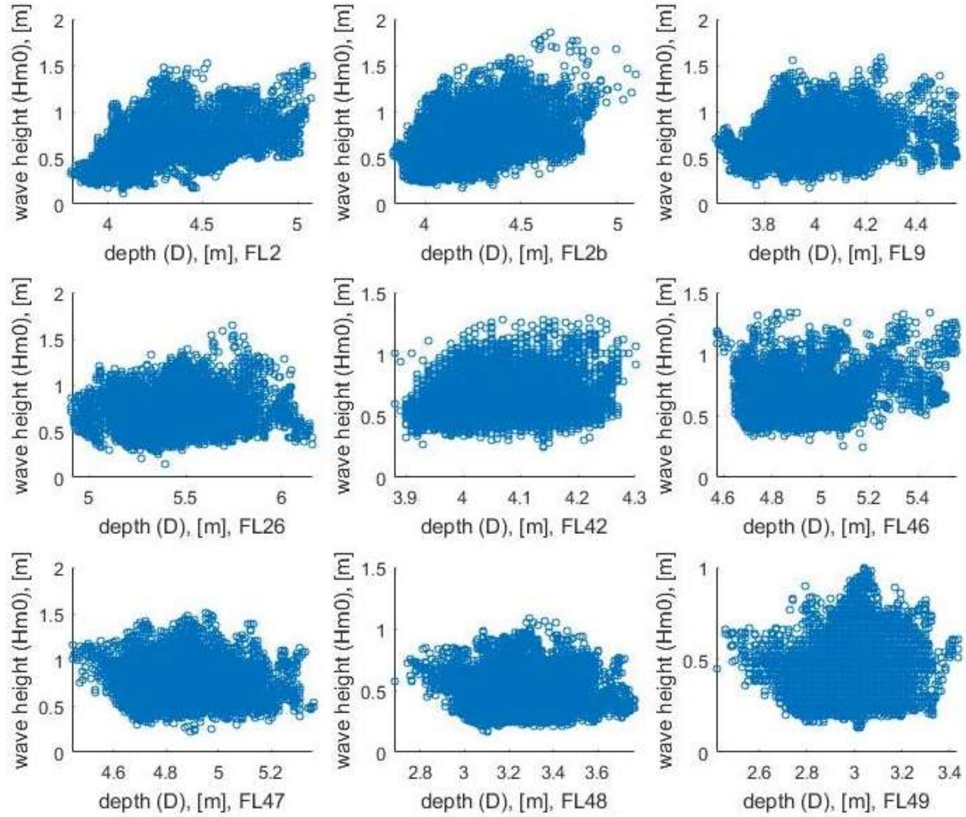


Figure 6.5 Scatter plots of water depth (D) and significant wave height (H_{m0}), for measurement locations FL2, FL2b, FL9, FL26, FL42, FL46, FL47, FL48 and FL49 on Lake IJssel and Lake Marken

Thus, based on the results, measured wind speed at 10-meter height (U_{10}), calculated effective fetch (F_{eff}) and water depth (D) could be used as input variables for prediction of significant wave height (H_{m0}) in nine measurement locations on Lake IJssel and Lake Marken.

6.2 Set up of Artificial Neural Network (ANN) model for wave height prediction

As it was already mentioned, nine measurement locations have been taken for validation of artificial neural network (ANN) modelling of significant wave height prediction, one of which is on Lake Marken. The following cases were discussed for validation and training of ANN model of wave height prediction:

1. The complete data of measured wind speed at 10-meter height (U_{10}), calculated effective fetch (F_{eff}) and water depth (D) were chosen as input variables and significant wave height (H_{m0}) as an output variable.
2. The above-mentioned input variables, but with more than 18m /s wind speed rule, were chosen for model training and validation.
3. Input variables mentioned in the first bullet, with less than 18m/s wind speed was chosen for model training and with more than 18m/s wind speed was chosen for the testing of ANN model, to check the robustness of ANN model.

Apart from ANN modelling of significant wave height prediction for individual locations, ANN modelling was performed for the groups of measurement locations. Particularly, the data of eastern (FL2, FL2b, FL9), western (FL26, FL48, FL49) and central (FL42, FL46, FL47) locations were considered as groups of input variables. In addition, ANN model was validated for a merged data set of all locations as well. The size and type of the data set of input variables are presented in Table 6. 2.

Table 6. 2 The size and types of input variables for ANN modelling

name of the input	type of input	size of complete data set	size of dataset with more than 18m/s wind speed	size of dataset with less than 18m/s wind speed
FL2	Individual locations	12850	119	12731
FL2b		29666	333	29333
FL9		17498	142	17356
FL26		21509	214	21295
FL42		17232	154	17078
FL46		8317	64	8253
FL47		17954	258	17696
FL48		18927	199	18728
FL49		14102	81	14021
FL2, FL2b, FL9	Group of locations	60014	594	59420
FL26, FL48, FL49		43503	476	43027
FL42, FL46, FL47		54538	494	54044
All locations	All locations	158055	1564	156491

Levenberg-Marquardt algorithm was used for the training with multi-layer perceptron (MLP) neural network (Hagan & Menhaj, 1994). The algorithm minimizes a combination of squared errors and weights, and then determines the correct combination to produce a network that generalizes well (Marquardt, 1963). This algorithm appears to be the fastest method for training moderate-sized feed forward neural networks (Hagan, Demuth, & Beale, 1996).

The data was split up in the following way: 70% for model training, 15% for model validation and 15% for the model test, which was done on the principle that each group represents the full picture of the significant wave height (Figure 6.6).

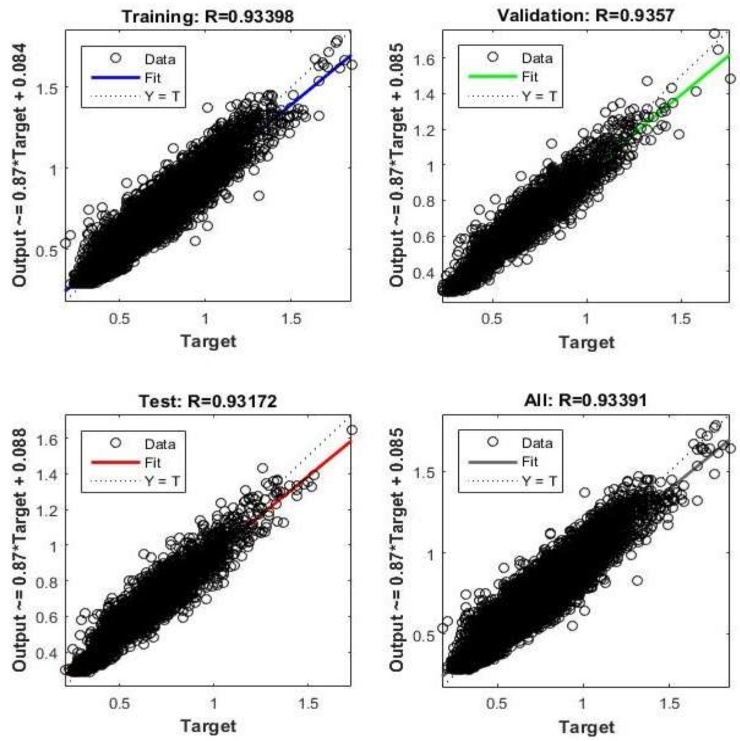


Figure 6.6 Distribution of data according to training, validation and test, at FL2b

The number of hidden layers (nodes) were chosen 10, which was obtained by a trial-and-error approach. The general scheme of modelling is presented in Figure 6.7, which includes data processing and neural network modelling.

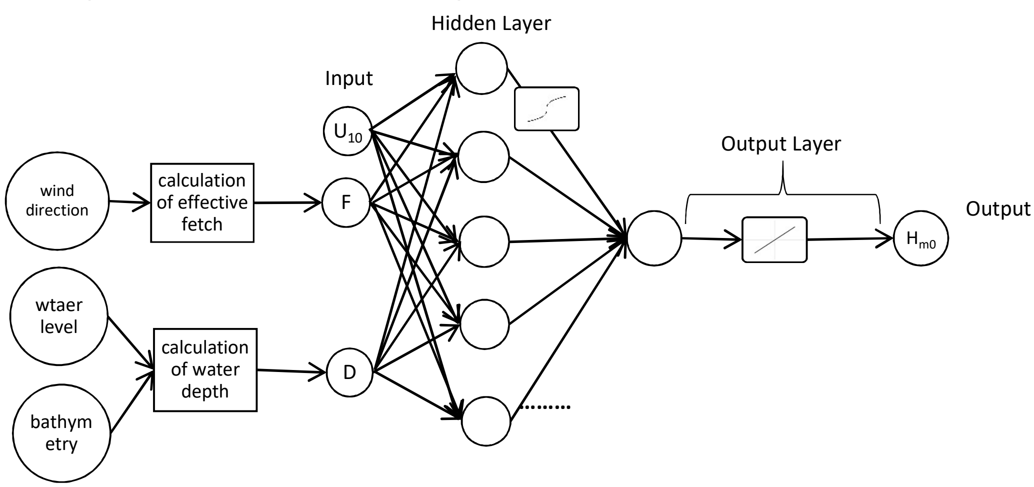


Figure 6.7 The scheme of data processing and multilayer feedforward Neural Network modelling

The each result of ANN modelling has also been tested for other locations to see if there is a universal model, which can be applied to all locations. The modelling results are presented in the next chapter 6.3.

6.3 Validation of neural network model for wave height prediction

6.3.1 The results of validated neural network models

The results of the correlation coefficient, RMSE relative error (RMSE/mean H_{m0}) and relative bias were considered to estimate the accuracy and the performance of artificial neural network (ANN) model for wave height prediction at experimental locations on Lake IJssel and Lake Marken. Those results are presented in Table 6. 3.

Table 6. 3 Correlation coefficients and RMSE of predicted wave height by neural networks, for the measurement locations and the groups of measurement locations (the green-yellow-red color bar indicates from high to low correlation coefficient and from low to high RMSE, RMSE/mean H_{m0}, bias)

name of model	location	correlation coefficient				RMSE, [meter]			RMSE/ mean H_{m0}	average bias	rules
		general	training	validation	test	training	validation	test			
ANN1	FL2	0.92	0.92	0.93	0.93	0.072	0.073	0.070	0.105	5.1%	
ANN2	FL2b	0.93	0.93	0.93	0.93	0.068	0.068	0.070	0.108	-2.8%	
ANN3	FL9	0.93	0.93	0.93	0.93	0.065	0.067	0.065	0.098	-5.6%	
ANN4	FL26	0.92	0.92	0.91	0.92	0.063	0.064	0.063	0.097	2.8%	
ANN5	FL42	0.91	0.91	0.91	0.90	0.058	0.058	0.060	0.097	4.1%	all data
ANN6	FL46	0.92	0.92	0.93	0.93	0.062	0.061	0.060	0.090	8.8%	
ANN7	FL47	0.92	0.92	0.92	0.92	0.066	0.068	0.069	0.103	-2.2%	
ANN8	FL48	0.95	0.95	0.95	0.95	0.041	0.041	0.041	0.086	2.8%	
ANN9	FL49	0.95	0.95	0.96	0.95	0.042	0.040	0.042	0.098	-2.7%	
ANN10	FL2	0.92	0.92	0.93	0.92	0.070	0.070	0.070	0.106	5.2%	
ANN11	FL2b	0.93	0.93	0.92	0.93	0.068	0.069	0.068	0.105	-3.3%	
ANN12	FL9	0.93	0.93	0.92	0.93	0.065	0.064	0.065	0.098	-4.6%	
ANN13	FL26	0.91	0.91	0.91	0.91	0.063	0.063	0.063	0.097	0.9%	
ANN14	FL42	0.90	0.89	0.90	0.90	0.059	0.060	0.061	0.099	4.3%	U<18m/s
ANN15	FL46	0.92	0.92	0.91	0.92	0.061	0.063	0.060	0.091	7.3%	
ANN16	FL47	0.91	0.91	0.91	0.90	0.066	0.066	0.068	0.102	-2.3%	
ANN17	FL48	0.94	0.94	0.94	0.94	0.042	0.041	0.041	0.087	3.5%	
ANN18	FL49	0.95	0.95	0.95	0.95	0.042	0.040	0.042	0.099	-3.6%	
ANN19	FL2	0.85	0.93	0.72	0.48	0.048	0.081	0.089	0.071	0.5%	
ANN20	FL2b	0.83	0.84	0.89	0.65	0.086	0.091	0.041	0.032	-4.4%	
ANN21	FL9	0.65	0.71	0.53	0.46	0.092	0.106	0.118	0.094	0.2%	
ANN22	FL26	0.87	0.92	0.86	0.74	0.060	0.077	0.131	0.115	10.6%	U>18m/s
ANN23	FL42	0.86	0.90	0.75	0.64	0.041	0.055	0.048	0.044	1.3%	
ANN24	FL47	0.81	0.85	0.79	0.70	0.068	0.092	0.091	0.075	-4.6%	
ANN25	FL48	0.88	0.91	0.85	0.82	0.040	0.049	0.062	0.076	-1.2%	
ANN26	FL2, FL2b, FL9	0.92	0.92	0.92	0.92	0.071	0.072	0.072	0.110	-1.5%	
ANN27	FL42, FL46, FL47	0.91	0.91	0.91	0.91	0.065	0.065	0.065	0.101	-0.3%	all data
ANN28	FL26, FL48, FL49	0.95	0.95	0.95	0.95	0.053	0.054	0.053	0.100	2.0%	
ANN29	All locations	0.93	0.93	0.93	0.93	0.066	0.066	0.067	0.109	-0.5%	
ANN30	FL2, FL2b, FL9	0.92	0.92	0.92	0.92	0.071	0.070	0.071	0.109	-1.9%	
ANN31	FL42, FL46, FL47	0.90	0.90	0.90	0.90	0.065	0.065	0.065	0.102	-0.8%	U<18m/s
ANN32	FL26, FL48, FL49	0.95	0.95	0.95	0.95	0.053	0.054	0.053	0.101	1.5%	
ANN33	All locations	0.93	0.93	0.93	0.93	0.066	0.066	0.066	0.109	-1.5%	
ANN34	FL2, FL2b, FL9	0.73	0.74	0.67	0.74	0.105	0.094	0.103	0.082	-2.6%	
ANN35	FL42, FL46, FL47	0.77	0.81	0.74	0.69	0.068	0.087	0.100	0.086	1.9%	U>18m/s
ANN36	FL26, FL48, FL49	0.95	0.95	0.95	0.93	0.067	0.069	0.086	0.092	-4.0%	
ANN37	All locations	0.91	0.91	0.91	0.90	0.089	0.085	0.098	0.087	4.6%	

The modelling results were conditionally named ANN with a regular number in Table 6. 3, where

- Models ANN1-ANN9 and ANN26-ANN29 were developed (trained) based on complete data (the third column of Table 6. 2) of each location (or group of locations).
- Models ANN10-ANN18 and ANN30-ANN33 were developed (trained) based on data with less than 18m/s wind speed (the sixth column of Table 6. 2).

- Models ANN19-25 and ANN34-37 were trained based on data with more than 18m/s wind speed (the fifth column of Table 6. 2).

The results of ANN1-ANN9 and ANN26-ANN29 models: According to the results, ANN1-ANN9 and ANN26-ANN29 models have more than 0.9 correlation coefficient, which is quite a high indicator. Particularly, it is more than 0.95 for locations FL48 and FL49 (an example of FL48 is given in Figure 6.8). Relatively small correlation coefficients (0.9-0.92) have ANN models developed by data from central locations (or the group of central locations).

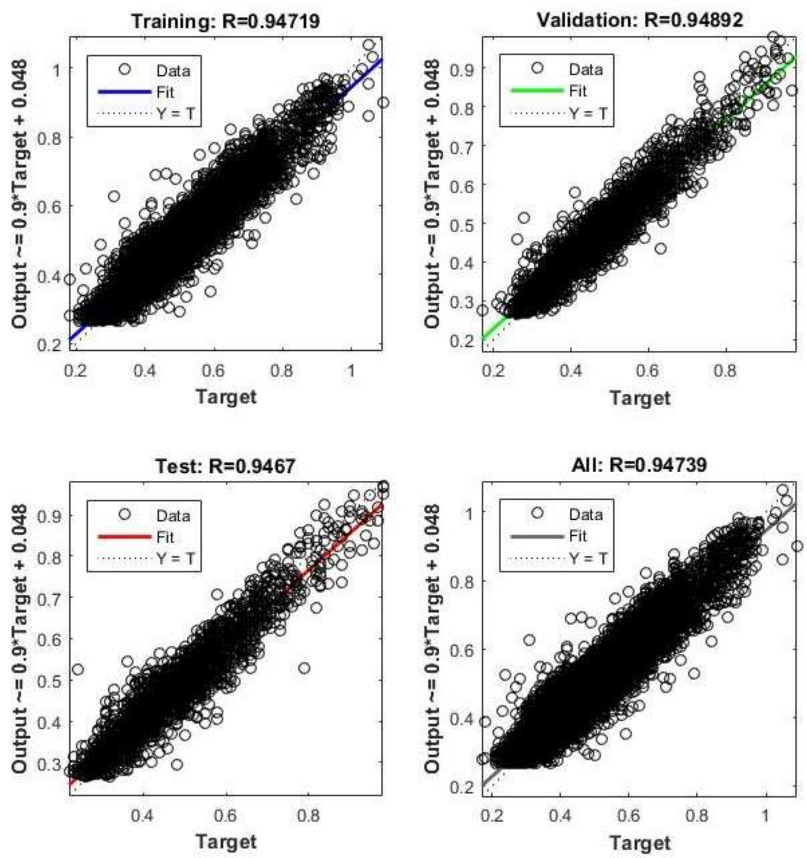


Figure 6.8 Training, validation, test and overall correlation coefficients and scatter of wave height prediction neural network model, location FL48 (ANN8)

RMSE has been considered in order to assess the accuracy of the modelling results. The maximum value of RMSE is 0.07 meter for location FL2 and the minimum is 0.049 meter at FL49. In general, RMSE decreases from east to the west on Lake IJssel. Particularly, the RMSE of ANN26 (eastern locations), ANN27 (central locations) and ANN28 (western location) models are respectively 0.072, 0.065 and 0.053 (Table 6. 3). RMSE of ANN29 (model based on merged data from all locations) is 0.067, which is quite higher than individual models, such as FL2, FL2b, FL9 and FL47.

The ratios of RMSE and the mean value of H_{m0} allow revealing the relative error of the models (Table 6. 3). The ratio varies from 0.086-0.11 (8.6-11%). Particularly models ANN1 (trained on data of FL2), ANN2 (FL2b), ANN7 (FL47) and ANN26-ANN29 have more than 10% of relative error.

The biases of individual modelling cases (ANN1-ANN9) can be up to +/- 9%, but show no systematic trend. However, the models of grouped locations (ANN26-ANN28) show that ANN model underestimates predicted wave height in central and eastern locations (average bias is -0.3%

- -1.5%) and overestimates in western locations (average bias is 2.0%). The overall model ANN29 underestimates predicted wave height by 0.5%.

The results of ANN10-ANN18 and ANN30-ANN33 models (U_{10}<18m/s): The performance of these models has almost the same pattern of correlation coefficient, RMSE and the relative error as those were discussed in the previews paragraph. However, there is slight increase of average biases in case of models ANN30, ANN31 and ANN33. The aim of validation neural network models with the subset data less than 18m/s wind speed is to check the robustness of the ANN model by performing test on subset of data with more than 18m/s wind speed (this will be discussed in chapter 6.3.3).

The results of ANN19-ANN25 and ANN34-ANN37 models: The performance of these groups of neural network models has lower correlation coefficients and higher RMSE. (Table 6. 3). The reason of such a low indicators could be the small size of the dataset (Table 6. 2). The behaviour of correlation coefficients and RMSE are random and strongly different in training or test phases. Particularly, the overall correlation coefficient is 0.85 for the ANN19 model, whereas it is 0.46 for testing (Figure 6. 9). As it is presented on the graph, there are few data for validation and testing, and it is strongly scattered. Neural network modelling with the data of central (ANN35) and eastern (ANN34) locations have 0.73-0.77 correlation coefficient. In the case of ANN37, the correlation coefficient is 0.91 and stable in training, validating and testing modes.

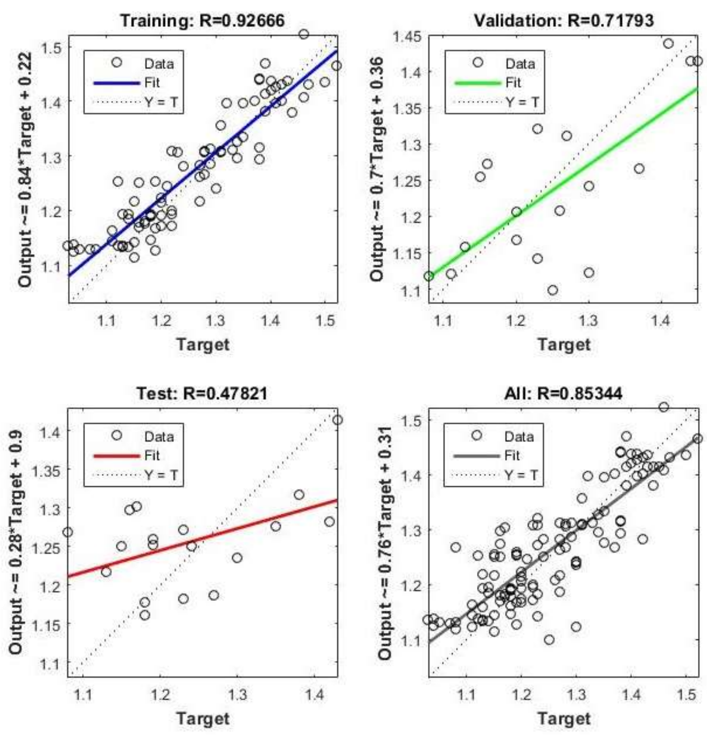


Figure 6. 9 Training, validation, test and overall correlation coefficients and the scatter of wave height prediction neural network model, location FL2 (ANN19)

RMSE of the models show less systematic trend in the case of strong wind conditions (U_{10}>18m/s). It is 0.131 meter for FL26 and less than 0.05 meter for locations FL2b and FL48. This distortion is expected because data has a small size for validation and test. RMSE is slightly more stable, in the case of models based on data of grouped locations (ANN34-ANN36). Here also, the accuracy of models increasing in an east-west direction, from 0.103 meters (ANN34) to 0.096 meters (ANN36). RMSE of ANN37 is 0.098 meter and does not have a big variation in training, validation and testing (Table 6. 3).

The relative error is from 0.032 to 0.115 (or 3.2-11.5%) for the models ANN19-ANN25 and from 0.082 to 0.092 (or 8.2-9.2%) for the models developed with the data of grouped locations (Table 6. 3).

According to the results of average relative biases, the highest overestimation (10.6%) has ANN22 model. In general, ANN models of strong wind conditions underestimates predicted wave height near shorelines by -2.6% - -4.0% (ANN34, ANN36) and overestimates on central locations by 1.9% (ANN35).

In conclusions, ANN models perform quite well when they are developed (trained) based on complete data or subset of data with less than 18m/s wind speed.

6.3.2 Testing of the universal application of the validated models

The special interest of current study is to establish a generalized ANN model, which will be acceptable for prediction of wave height at all locations on Lake IJssel and Lake Marken and to see whether ANN model developed in one location could be acceptable for others. For this reason, ANN26-ANN29 were applied to predict wave height at individual locations, as these models have relatively high accuracy, which was discussed in previews chapter.

Table 6.4 Correlation coefficient and RMSE of wave height prediction by ANN26-ANN29 neural network models, for nine measurement locations (the green-yellow-red color bar indicates from high to low correlation coefficient and from low to high RMSE)

location	Correlation coefficient				RMSE, [meter]			
	ANN26	**ANN27**	**ANN28**	**ANN29**	**ANN26**	**ANN27**	**ANN28**	**ANN29**
FL2	0.91	0.86	0.86	0.93	0.076	0.115	0.113	0.066
FL2b	0.93	0.87	0.89	0.93	0.071	0.114	0.102	0.072
FL9	0.92	0.81	0.89	0.92	0.068	0.170	0.100	0.070
FL26	0.72	0.88	0.91	0.91	0.137	0.083	0.065	0.068
FL42	0.77	0.91	0.84	0.89	0.094	0.061	0.082	0.065
FL46	0.81	0.90	0.88	0.90	0.097	0.069	0.079	0.072
FL47	0.71	0.91	0.83	0.90	0.123	0.069	0.096	0.073
FL48	0.90	0.57	0.94	0.94	0.092	0.191	0.043	0.045
FL49	0.88	0.55	0.95	0.95	0.103	0.175	0.044	0.045

Table 6.4 and Table 6. 5 show the results of the correlation coefficient, RMSE, relative error (RMSE/mean H_{m0}) and average relative bias of application of ANN26-ANN29 models in nine locations. The models validated with data of a group of western locations (ANN28) and all locations (ANN29 or global model) have the highest correlations.

Table 6. 5 RMSE/Hm0mean and average bias of wave height prediction by ANN26-ANN29 neural network models, for nine measurement locations (the green-yellow-red color bar indicates from low to high RMSE/mean H_{m0}, and green-white-red color bar indicates high (green and red) and low (white) biases)

location	RMSE/H_{m0}mean				average relative bias			
	ANN26	**ANN27**	**ANN28**	**ANN29**	**ANN26**	**ANN 27**	**ANN 28**	**ANN29**
FL2	0.12	0.17	0.17	0.10	0.1%	-22.5%	0.3%	-0.4%
FL2b	0.11	0.17	0.16	0.11	-0.2%	-19.5%	0.4%	-0.3%
FL9	0.10	0.26	0.15	0.11	0.3%	-27.5%	-1.0%	0.4%
FL26	0.21	0.13	0.10	0.10	5.7%	8.0%	0.0%	0.1%
FL42	0.15	0.10	0.13	0.10	-0.1%	0.1%	0.8%	0.0%
FL46	0.15	0.11	0.12	0.11	3.7%	0.3%	2.0%	0.0%
FL47	0.18	0.10	0.14	0.11	1.1%	-0.1%	2.4%	0.2%
FL48	0.19	0.40	0.09	0.10	-7.5%	-36.9%	0.2%	-0.1%
FL49	0.24	0.41	0.10	0.11	-7.7%	-20.3%	-0.2%	0.0%

RMSE of predicted wave height shows that the models of grouped locations perform well for their own locations. For instance, ANN26, which is validated based on a group of FL2, FL2b and FL9 data, has the smallest RMSE for these individual locations. Such performances are common for other models with grouped locations as well (ANN27 and ANN28). However, the best performance for all locations has ANN29, where RMSE is less than 0.073 meter (Table 6.4).

The indicator of relative error makes possible to compare the extent of model performance in deferent locations. Particularly, the model of eastern locations (ANN26) is quite well applicable for the central locations (small relative error). Moreover, the model of western locations (ANN28) is less acceptable for eastern locations. Here also, the performance of ANN29 model has equally low value relative error for all locations, which is 10-11% (Table 6. 5).

The results of bias show not only the extent of the performance of the models but also evaluate whether it overestimates or underestimates the predicted wave height. Model ANN27 has quite high underestimation for western and eastern locations (Table 6. 5). The bias is within ±0.4% for all location in case of ANN29, which again suggest that this model is well accepted for all locations.

The results of analysis show the ANN29 has relatively high accuracy of prediction of wave height for all locations on the Lake IJssel and Lake Marken.

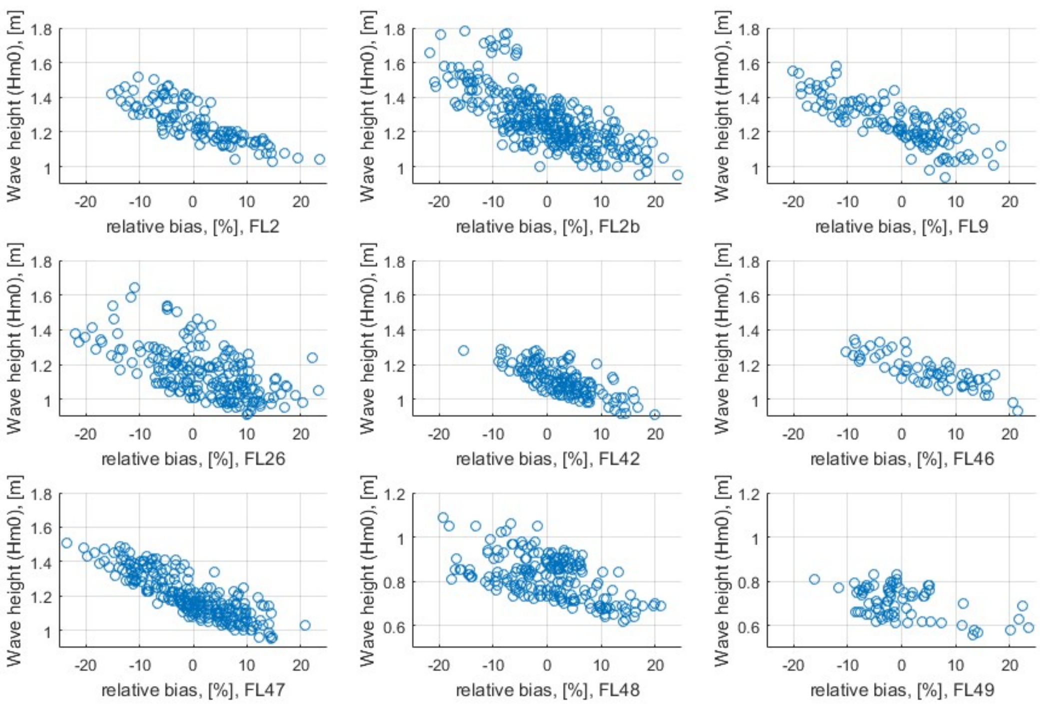


Figure 6. 10 Relative bias of predicted subset of wave height (U_{10}>18m/s) by ANN29 model, for nine locations on Lake IJssel and Lake Marken

The ANN29 model was also applied to predict subset of wave height in strong wind conditions (U_{10}>18m/s). Figure 6. 10 shows the results of the ANN29 model with graphs of scatter plots of measured wave height and relative bias of predicted wave heights. According to the graphs in Figure 6. 10, the prediction does not exceed 20% of relative bias for all locations. What the results of Figure 6.10 seem to suggest is that the ANN29 model (meant to cover all data) has a tendency for model underestimation for the largest measured wave heights in the data set, and a tendency for model overestimation for somewhat smaller wave heights. This could be just the result of natural data scatter, but it could also be a warning that the model may underestimate severe wave conditions. Hence, careful testing seems advisable before applying the ANN29 model in practice.

Table 6. 6 Statistical parameters of wave height prediction by the ANN29 model based on all data, when tested for strong wind conditions only (U_{10}>18m/s)

location	size of dataset	correlation coefficient	RMSE, [meter]	RMSE/ mean Hm0	Average relative bias
FL2	119	0.46	0.104	0.08	0.90%
FL2b	333	0.70	0.120	0.09	-0.01%
FL9	142	0.46	0.118	0.09	-0.69%
FL26	214	0.74	0.106	0.09	3.11%
FL42	154	0.60	0.084	0.08	3.11%
FL46	64	0.41	0.126	0.11	5.47%
FL47	258	0.65	0.098	0.08	-0.44%
FL48	199	0.71	0.075	0.09	0.40%
FL49	81	0.38	0.091	0.13	2.63%

The indicators of predicted subset of wave height in strong wind conditions (U_{10}>18) by ANN29 model, shows that the correlation is small for locations FL46 and FL49, which could be due to the small size of the dataset. RMSE is high in eastern location (also in FL26 and FL46), but the relative error is 8-9% for all locations, besides FL46 (11%) and FL49 (13%) (Table 6. 6). Thus, the general conclusion could be drawn, as:

- The models (ANN26-ANN28), which are validated based on data of grouped locations, are only well acceptable for their own locations.
- ANN29, which was validated based on merged data from all locations, is well applicable for all locations. Particularly, the relative error is 10-11%; in addition, it is 8-9% in cases of prediction of wave height in strong wind conditions. However, the model underestimations for conditions with severe/high waves are a warning against using the model in practice without thorough testing.

Figure 6. 11 is a visual example of wave height prediction by ANN29 for the particular storm event on 28th of October 2013. Locations FL2b, FL42 and FL49 were selected, as they are the representatives of western, central and eastern positions.

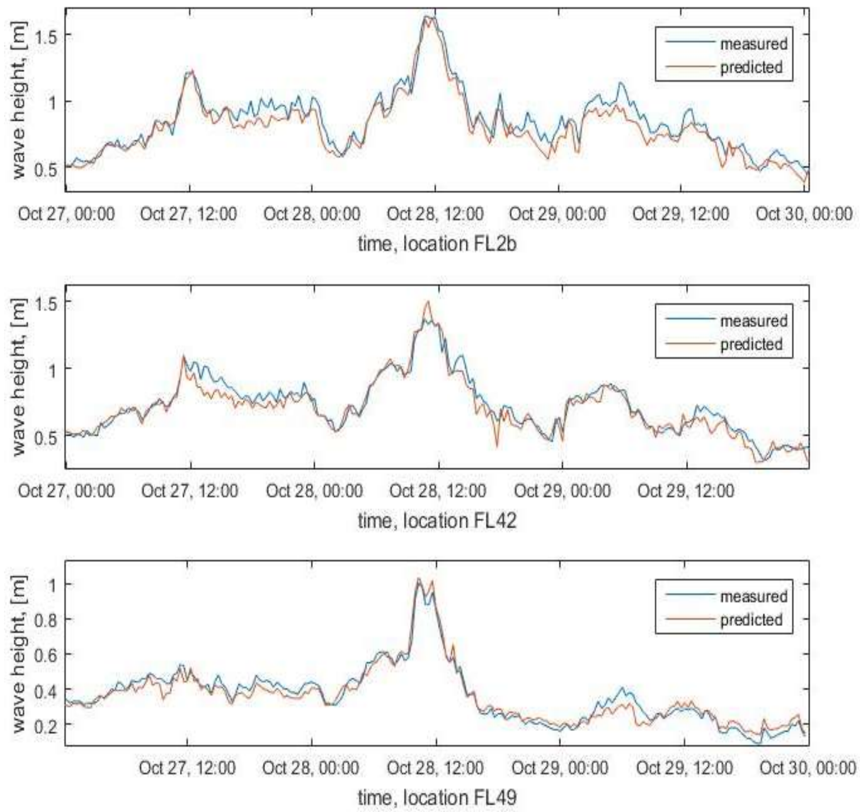


Figure 6. 11 Measured and predicted wave height for 28.10.2013 storm event by ANN29 model, locations FL2b, FL42 and FL49

6.3.3 Verification of the robustness of neural network modelling

There is need to check the robustness of ANN model validated in chapter 6.3.1, since one of the aims of the current study is to develop wave height prediction model, which will be applicable outside of its range of training, which is not measured so far. That is why model ANN33 (Table 6. 3 in chapter 6.3.1), which was trained and validated with subset of data less than 18m/s will be tested on data out of its range, particularly for subset of data with more than 18m/s wind speed.

Table 6. 7 Statistical parameters of wave height prediction in strong wind conditions (U_{10}>18m/s) by the model ANN33 (developed with data less than 18m/s wind speed)

location	size of dataset	correlation coefficient	RMSE	RMSE/ mean Hm0	Average relative bias
FL2	119	0.66	0.089	0.07	1.07%
FL2b	333	0.67	0.127	0.10	-6.92%
FL9	142	0.60	0.115	0.09	-5.44%
FL26	214	0.71	0.109	0.10	-0.69%
FL42	154	0.66	0.076	0.07	4.21%
FL46	64	0.32	0.115	0.10	5.30%
FL47	258	0.65	0.099	0.08	-4.24%
FL48	199	0.70	0.070	0.09	-1.12%
FL49	81	0.32	0.098	0.14	9.67%

According to the results in Table 6. 7, the model ANN33 has a quite high correlation (more than 0.6) in most of the locations (besides FL46 and FL49, where the size of the dataset is small). The relative error is 0.07-0.10 (or 7-10%), besides FL49, where not only the size of the dataset is small but also the measured wave height is not so high (less than one meter).

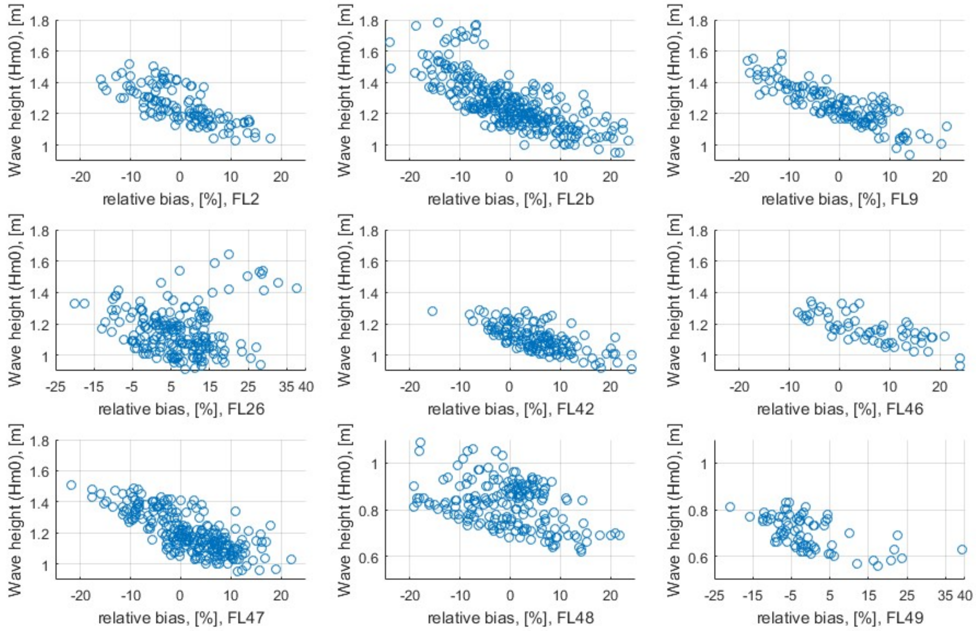


Figure 6. 12 Relative bias of predicted subset data of wave height (U_{10} >18m/s) by ANN33 model, for nine locations on Lake IJssel and Lake Marken

The average bias is ±10% and ANN33 model underestimates wave height at locations FL2b, FL9, FL26, FL47 and FL48, and overestimates at locations FL2, FL42, FL46 and FL49.

According to the graphs in Figure 6. 12, the maximum underestimation predicted wave height does not exceed 23% at locations FL2b, FL47 and FL49 and less than 15% for FL2, FL9, FL26, FL42, FL46 and FL48. The results of Figure 6.12 suggest that the ANN33 model (meant to cover all data) has a tendency for model underestimation for the largest measured wave heights in the data set, and a tendency for model overestimation for somewhat smaller wave heights. This could be just the result of natural data scatter, but it could also be a warning that the model may underestimate severe wave conditions. Hence, careful testing seems advisable before applying the ANN33 model in practice.

Thus, we can say that the robustness of the neural network model, outside of its range of trained data, has 7-10% relative error for all locations (besides FL49).

7. Discussion of the results

In general, the results of the reviewed literature showed that there was already a lot of work done for the lake IJssel regarding wind-wave climate analysis (Bottema, 2007), and there were no studies found on measured wind-wave climate on Lake Marken. The reviewed literature of wave height prediction modelling of the shallow-water condition in lakes was mostly referring parametric formulas (mainly developed in 1950-1990's). The literature of wave height prediction by neural network modelling was primarily for the lakes with deep-water conditions and long fetches.

This thesis compares measurements with results of three parametric formulas (one with calibration) and a set of neural network models for wave height prediction on Lake IJssel and Lake Marken in chapters 5 and 6. Table 7. 1 represents the relative error (RMSE/mean H_{m0}) (also in Figure 7.2) and the relative bias (bias divided by experimental mean, bias being model minus experimental result) of Bretschneider formula, calibrated formula of Bretschneider, Breugem-Holthuijsen formula and neural network modelling (ANN29 or global model and ANN33) to evaluate the performance of the models on Lake IJssel and Lake Marken. Here, global ANN model was presented, as it was developed based on merged data of all locations and it well applicable for all locations. In addition, ANN33 was presented, as it was developed by the subset of merged data of all locations with less than 18m/s wind speed and gives possibility to check the robustness of ANN model.

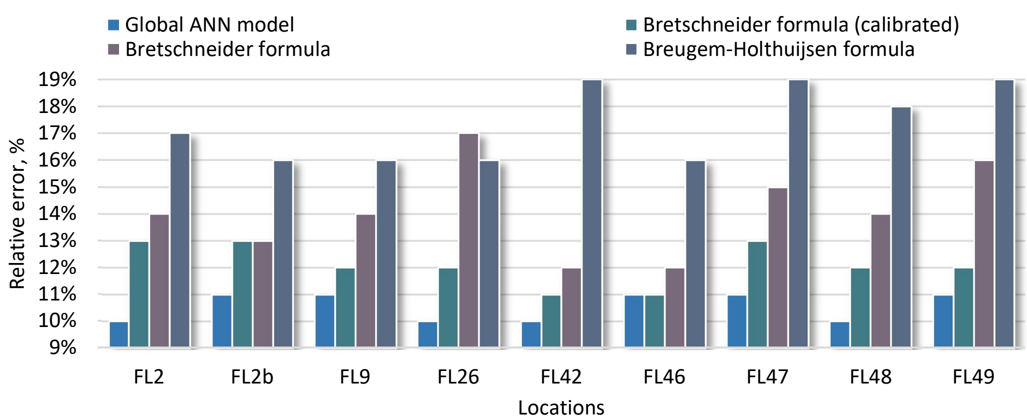


Figure 7. 1 Comparison of average relative error (%) of predicted wave height by parametric formulas and global ANN model

In addition, the same indicators were presented for prediction of wave height in strong wind conditions (U_{10}>18m/s) in Table 7.2 and Figure 7.2.

According to the comparison of the results in Table 7. 1, the most accurate performance has global ANN model, with 10-11% relative error, then calibrated formula of Bretschneider, with 11-13% relative error. On average, global ANN performs better than Bretschneider formula, the calibrated formula of Bretschneider and Breugem-Holthuijsen formula by factors 1.3, 1.1 and 1.6 respectively (Figure 7.1).

Regarding biases, Bretschneider formula has underestimation (besides FL49) and Breugem-Holthuijsen formula has overestimation for all locations. Although global ANN model has underestimation of predicted wave height for most of the cases, it is ±0.4% for all locations.

Table 7. 1 Relative error (RMSE/mean H_{m0}) and relative bias of predicted wave height by verified and validated models on Lake IJssel and Lake Marken

Locations	Bretschneider formula		Bretschneider formula (calibrated)		Breugem-Holthuijsen formula		Global ANN model	
	RMSE/ meanH_{m0}	bias	RMSE/ meanH_{m0}	bias	RMSE/ meanH_{m0}	bias	RMSE/ meanH_{m0}	bias
FL2	0.14	-1.0%	0.13	-1.2%	0.17	6.5%	0.10	-0.4%
FL2b	0.13	-0.8%	0.13	-0.4%	0.16	6.7%	0.11	-0.3%
FL9	0.14	-1.1%	0.12	-1.0%	0.16	6.5%	0.11	0.4%
FL26	0.17	-6.0%	0.12	-3.1%	0.16	0.7%	0.10	0.1%
FL42	0.12	-1.3%	0.11	2.0%	0.19	9.2%	0.10	0.0%
FL46	0.12	-0.4%	0.11	0.8%	0.16	7.3%	0.11	0.0%
FL47	0.15	-0.6%	0.13	0.6%	0.19	7.1%	0.11	0.2%
FL48	0.14	-0.3%	0.12	2.7%	0.18	3.7%	0.10	-0.1%
FL49	0.16	1.7%	0.12	1.2%	0.19	1.0%	0.11	0.0%

Table 7.2 compares the indicators of prediction of subset of wave height with more than 18m/s wind speed. According to this comparison, the predictions of wave height in strong wind conditions was performed better by global ANN model and ANN33 on Lake IJssel and Lake Marken. The relative errors for global ANN model and ANN33 are 8-13% and 7-14% respectively. The less accurate performance has Bretschneider formula. On average relative error of ANN models are lower than Bretschneider formula, the calibrated formula of Bretschneider and Breugem-Holthuijsen formula respectively 2.75, 1.4 and 1.6 times (Figure 7.2).

Table 7. 2 Relative error (RMSE/mean H_{m0}) and relative bias of predicted wave height by verified and validated models on Lake IJssel and Lake Marken, for the subset of data $U_{10} > 18$m/s

locations	Bretschneider formula		Bretschneider formula (calibrated)		Breugem-Holthuijsen formula		Global ANN model		neural network model (ANN33)	
	RMSE/ meanH_{m0}	bias	RMSE/ meanH_{m0}	bias	RMSE/ meanH_{m0}	bias	RMSE/ meanH_{m0}	bias	RMSE/ meanH_{m0}	bias
FL2	0.20	-18.0%	0.12	-7.2%	0.10	-3.5%	0.08	0.90%	0.07	1.07%
FL2b	0.25	-22.6%	0.14	-10.2%	0.13	-8.0%	0.09	-0.01%	0.10	-6.92%
FL9	0.29	-26.3%	0.16	-13.9%	0.15	-12.7%	0.09	-0.69%	0.09	-5.44%
FL26	0.30	-23.9%	0.16	-10.6%	0.22	-15.8%	0.09	3.11%	0.10	-0.69%
FL42	0.18	-14.9%	0.07	-2.1%	0.07	-0.3%	0.08	3.11%	0.07	4.21%
FL46	0.17	-13.2%	0.09	-1.7%	0.10	-1.3%	0.11	5.47%	0.10	5.30%
FL47	0.27	-23.8%	0.14	-11.6%	0.13	-10.2%	0.08	-0.44%	0.08	-4.24%
FL48	0.28	-16.3%	0.11	-3.1%	0.17	-8.2%	0.09	0.40%	0.09	-1.12%
FL49	0.35	-15.2%	0.19	-3.6%	0.30	-10.6%	0.13	2.63%	0.14	9.67%

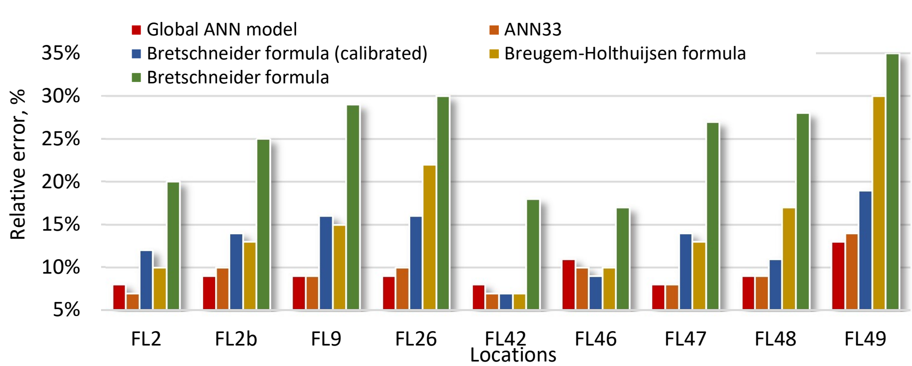


Figure 7. 2 Comparison of average relative error (%) of predicted wave height in strong wind conditions by parametric formulas and ANN models

8. Conclusions and limitations

8.1 Conclusions

One of the main aims of this study was collection and analysis of wind and wave measurement for measurement locations on Lake IJssel and Lake Marken (Chapters 2, 3 and 4), particularly, exploratory analysis of wind and wave parameters, relation between waves and effective fetch, clarification of shallow water conditions on Lake IJssel and Lake Marken. The second aim was verification of parametric formulas of wave height prediction for the measurement locations on Lake IJssel and Lake Marken (Chapter 5). Moreover, the last objective was the validation of data-driven model for prediction of wave height at measurement locations on Lake IJssel and Lake Marken.

The objectives have mostly been reached. However, current study does not produce the desired result for dike design purposes, as there were no extreme wind speeds more than 27.3m/s during the period of the study and there yet no proof that the models used in this thesis are sufficiently robust for the prediction of wave conditions beyond the measured range, models for dike design conditions.

Thus, the results of the study allow coming to the following conclusions:

Data analysis:

1. The analyses of this thesis are based on preprocessed data of Rijkswaterstaat, provided by Xi Company. No clear inconsistencies were found between either data.
2. It is important to note that the Lake IJssel and Lake Marken data set is not without interruptions. In cold winters, many data were missing due to ice.The measurements of the late 1990s and early 2000s are often interrupted and less reliable for locations FL2, FL5, FL9, FL25 and FL26. This does not influence the analysis since unreliable data were labelled and/or replaced by exception values in the source data.
3. The strongest wind speeds (U_{10}>15m/s) are from southwestern direction and then from southern and western directions for all locations. The average wind speeds (5m/s<U_{10}<15m/s) have the same pattern but do not dominate from above-mentioned directions as much as strong winds. Weak winds (U_{10}<5m/s) are distributed equally along all directions of the horizon.
4. Over 80% of the stormy events (with more than 20 m/s, typically occurring about once per year) wind occurred in the winter half year November-April, which is also the period which is least sensitive to soiling (algae) problems.
5. The ratio of wind speed in the case of almost equally fetches is almost one. For near shore locations, it seems offshore wind speed is lower by the factor of 0.8-0.9 due to the shelter effect of the upwind land. The accuracy of the transformation of wind speed over the lakes improves significantly with increasing wind speed and is quite poor (>20% uncertainty) for winds < 6 m/s.
6. Relations between wind and significant wave height (H_{m0}) and mean wave period (T_{m01}) were explored in a qualitative sense. Wave heights are roughly proportional to wind speed

U_{10}. For near shore locations, there is a marked difference between onshore and offshore winds, for the central locations FL42/46/47 directional trends are quite small.

7. Mean wave period (T_{m01}) is quite consistent with significant wave height (H_{m0}). The correlation coefficient between H_{m0} and T_{m01} is 0.80-0.92 for western locations, and 0.95-0.98 for the rest of locations.
8. H_{m0} increases quite systematically with effective fetch. Particularly, H_{m0} increases highly with the increase of effective fetch up to 8 km. The wave height only slow increases after this point, especially for small wind speeds. The largely monotonic increase of wave height with fetch is qualitatively in accordance with the effective fetch concept of Eq. 4.1.
9. The steepness greatly increases up to 0.05, while wave height reaches 0.35 meter in all locations. Then it is almost constantly remaining around 0.05 along the wave height increase, besides western locations, where steepness reaches up to 0.09.
10. Waves often behave as transitional rather than deep water waves when H_{m0} is more than 0.7m. However, only the shallow-foreshore location FL5 shows clear finite depth effects. Significant wave heights at FL42/FL47 and FL2b/FL9 can become as high as 31% and 40% of the water depth without clear signs (without flattening trend) that would indicate these numbers would be a physical upper limit. Yet it is worthwhile to investigate (in a future study), why the wave-height-depth ratio for FL42/FL47 seems to remain lower than for FL2b/FL9.

Verification of parametric formulas and validation of artificial neural network modelling.

11. The parametric formula of Bretschneider underestimates wave height prediction in all locations on Lake IJssel and Lake Marken.
12. The calibrated formula of Bretschneider (calibrated with merged data of all locations) performs with 1.2-1.3 better RMSE than initial formula.
13. Breugem-Holthuijsen formula performs with 1.2-2.5 better relative error than Bretschneider formula, for strong wind conditions.
14. For the neural networks, the input variable wind speed (U_{10}) is highly correlated with output wave height (H_{m0}). In addition, the correlation between wind speed and wave height is inversely proportional to the correlation between effective fetch and wave height.
15. Validated artificial neural networks model in one location and group of locations is not acceptable for other locations, due to the increasing error.
16. In general, ANN modelling has a smaller relative error than parametric formulas by the factor of 1.4-2.8 in case of strong wind conditions, for all locations on Lake IJssel and Lake Marken.

8.2 Limitations

Time limitation had great importance for current study. Data collection and wind-wave climate analysis and wave height prediction modelling have been done in seven months in the current study.

The absence or partly availability of wind measurement in some locations makes it complicated to do detailed analysis and modelling for those locations.

The only height (10 meters) of wind speed measurement does not allow concluding whether this wind speed is the most efficient for wave height scaling or not.

Although effective fetch gives more idea about the effect of coastline on the wave formation than the single fetch, sometimes there was impression that the shape of the lakes does not allow effective fetch to describe real conditions. Thus, the absence of numerical representation of the shape of the lakes could be the limitation of current study.

As the ANN modelling was done based on transitional conditions where water depth was not (yet) the dominant parameter. There is a limitation to evaluate the robustness of model for shallow water conditions.

Although the global performance of the ANN models was promising, it is not advised to use them in practice without thorough testing before. This is because there are some doubts about the models performance near the high end of the data range (the most extreme conditions in terms of wind and wave).

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Appendix A. Data availability

Appendix A refers to Chapter 2.2. It represents the percentage of available wind, wave and water level data per month, for all monitoring locations on Lake IJssel and Lake Marken.

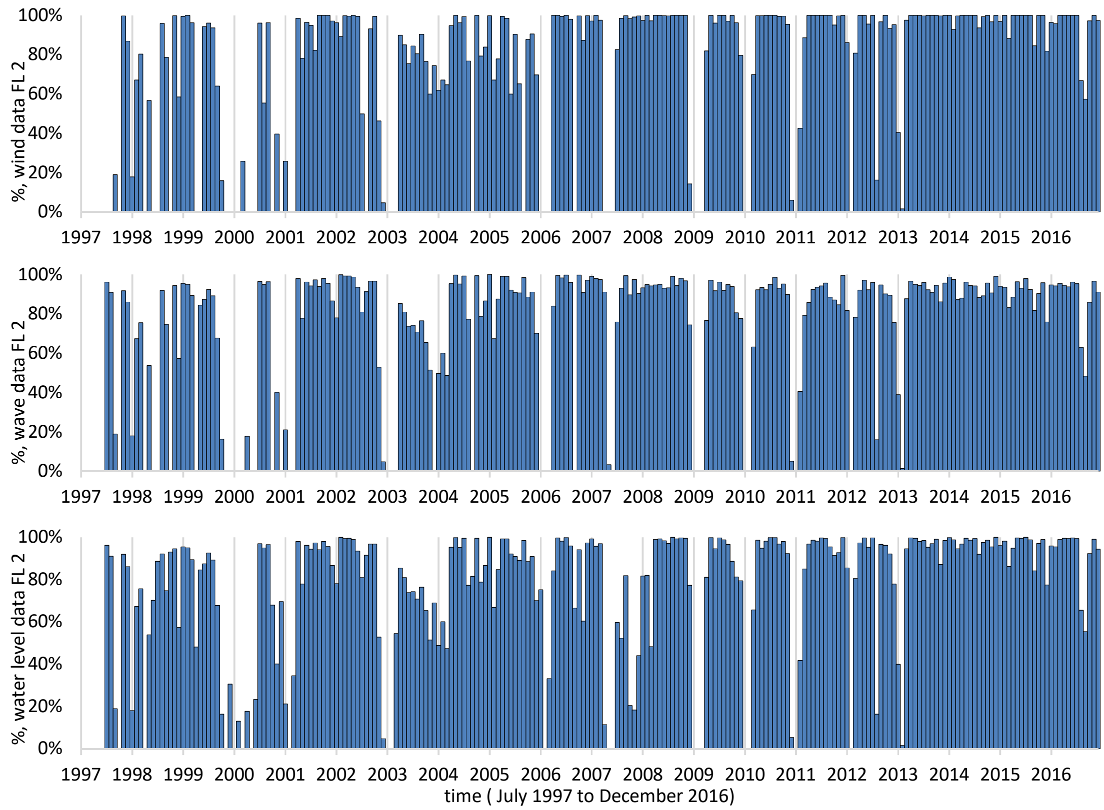

Figure A- 1 Percentage available data per month, FL2

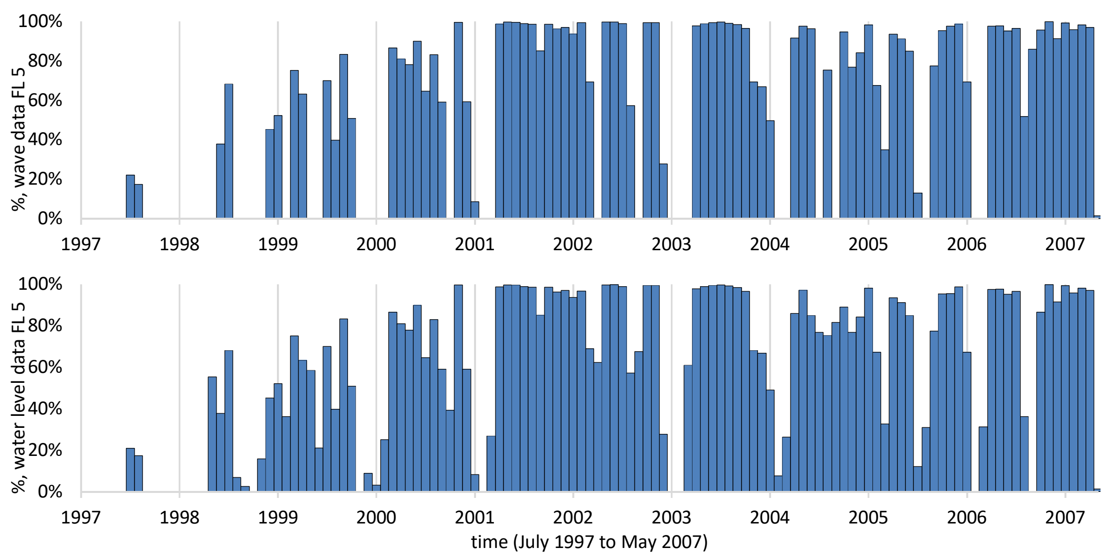

Figure A- 2 Percentage available data per month, FL5

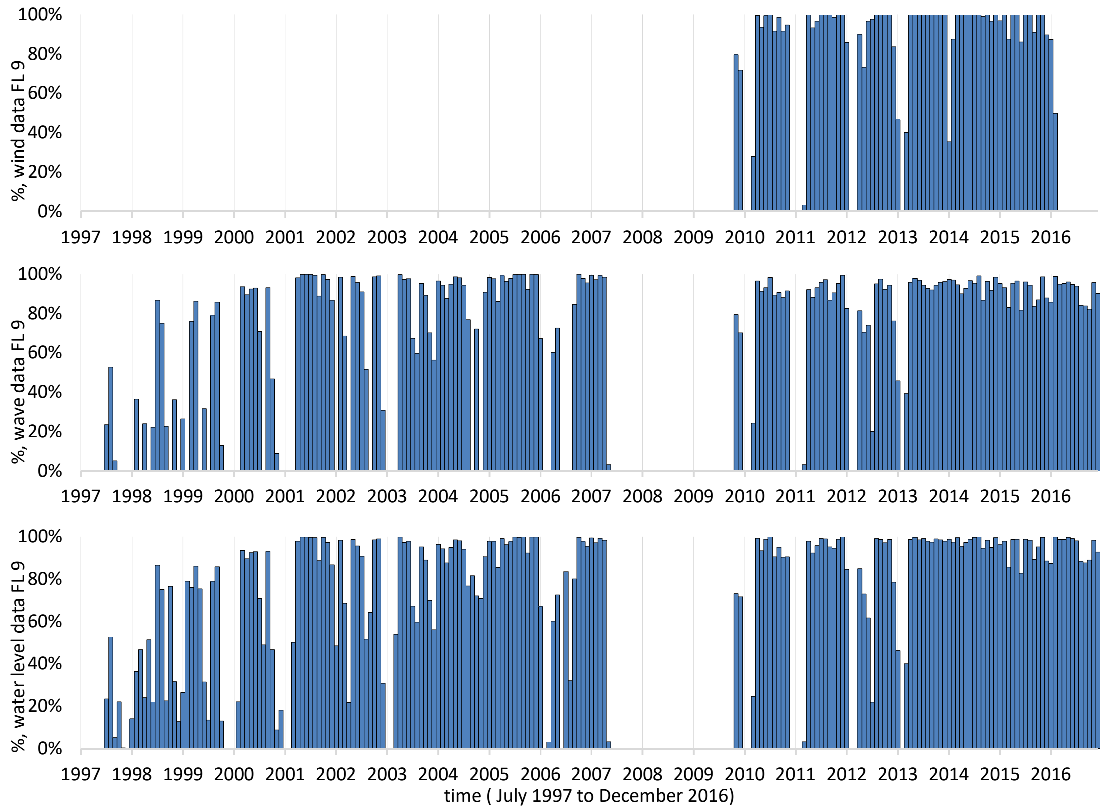

Figure A- 3 Percentage available data per month, FL9

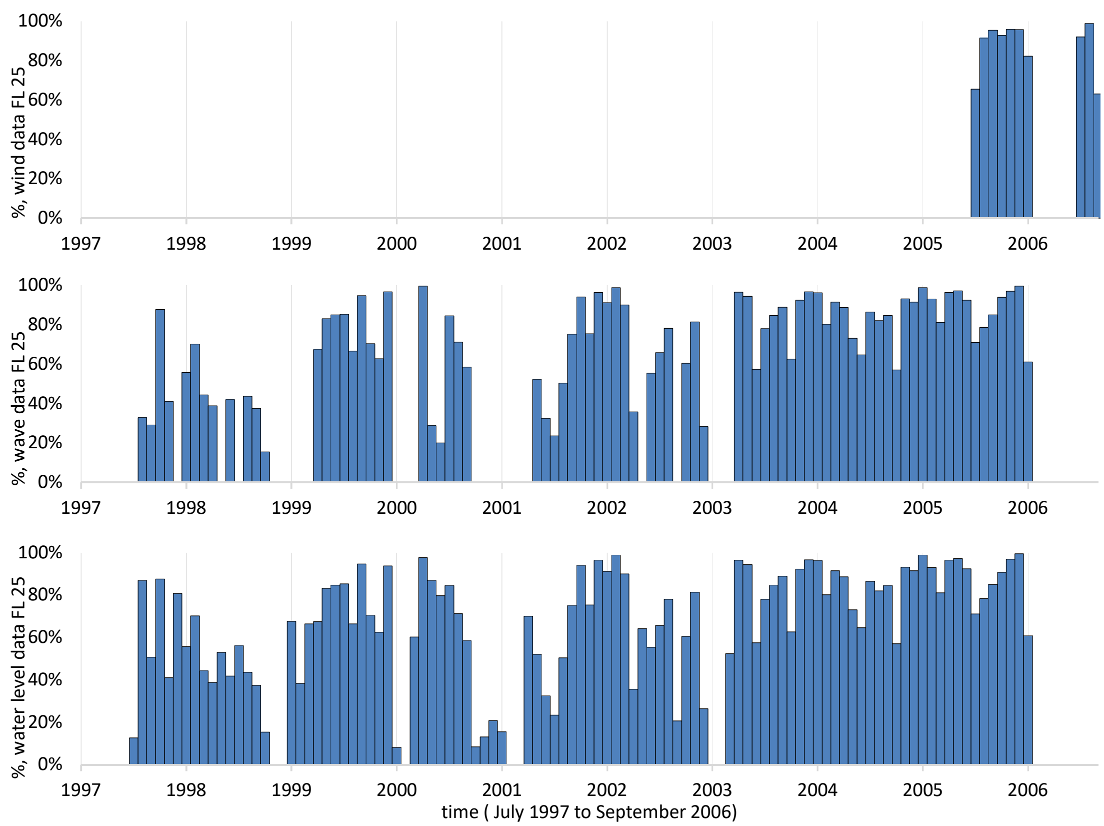

Figure A- 4 Percentage available data per month, FL25

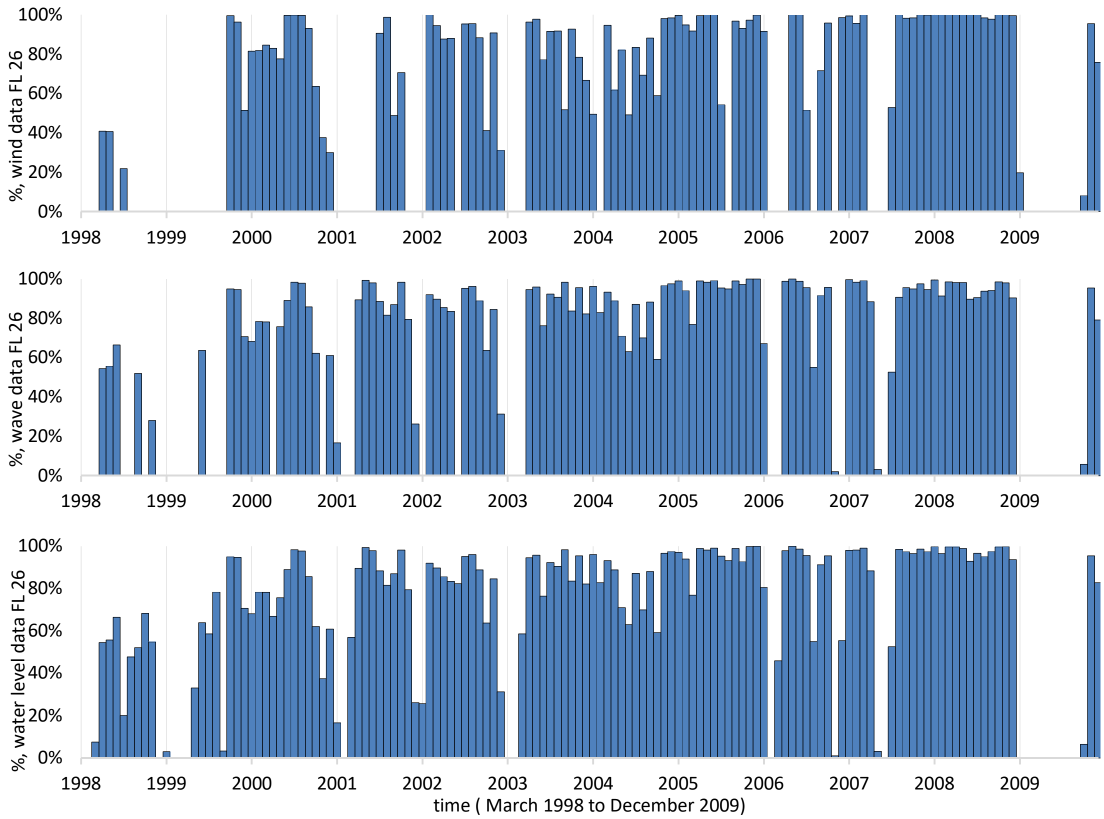

Figure A- 5 Percentage available data per month, FL26

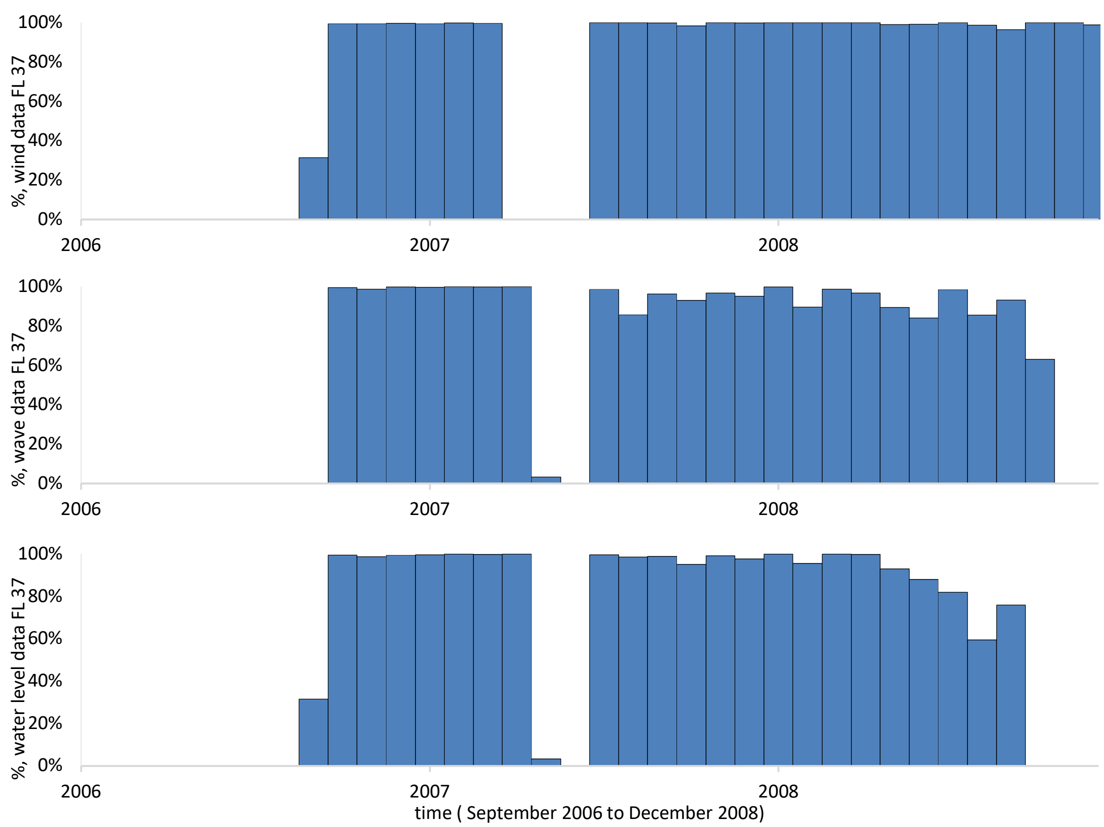

Figure A- 6 Percentage available data per month, FL37

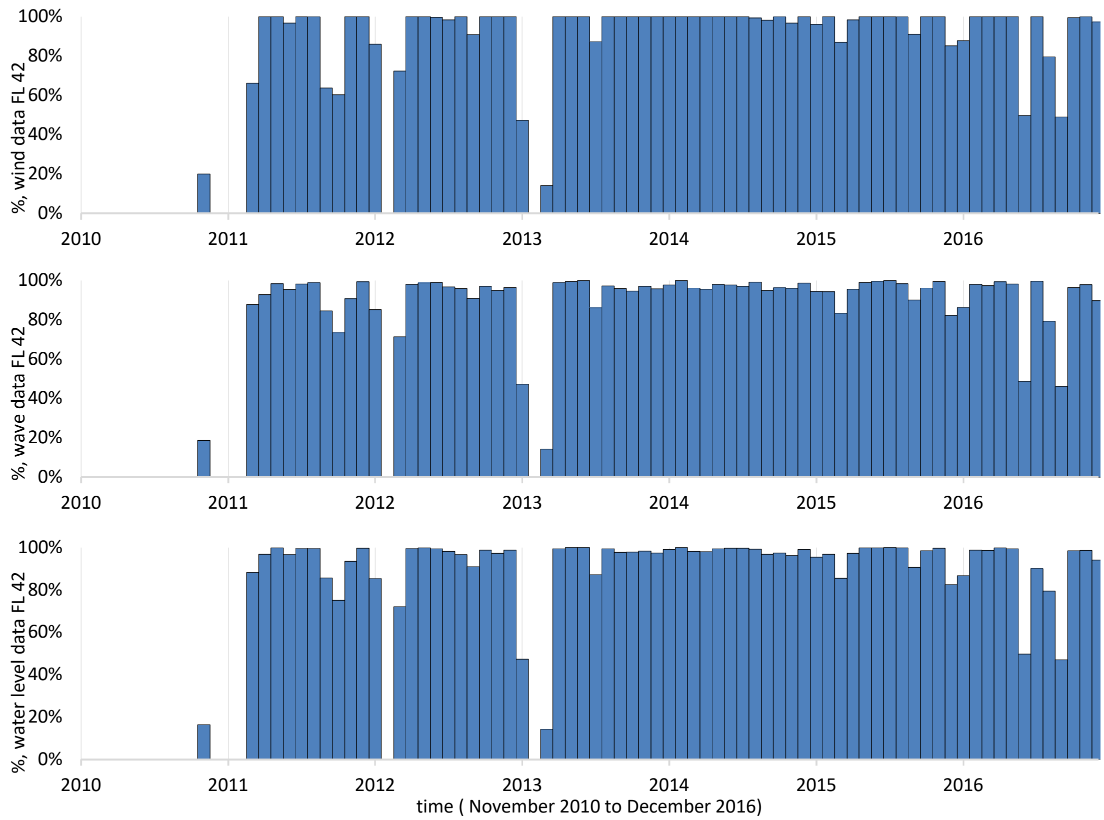

Figure A- 7 Percentage available data per month, FL42

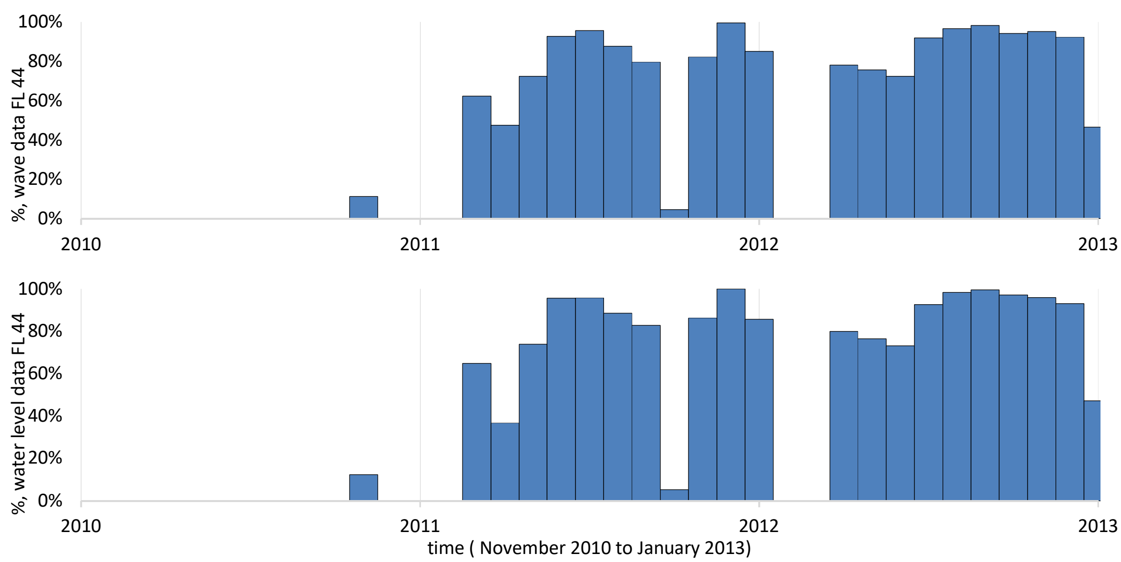

Figure A- 8 Percentage available data per month, FL44

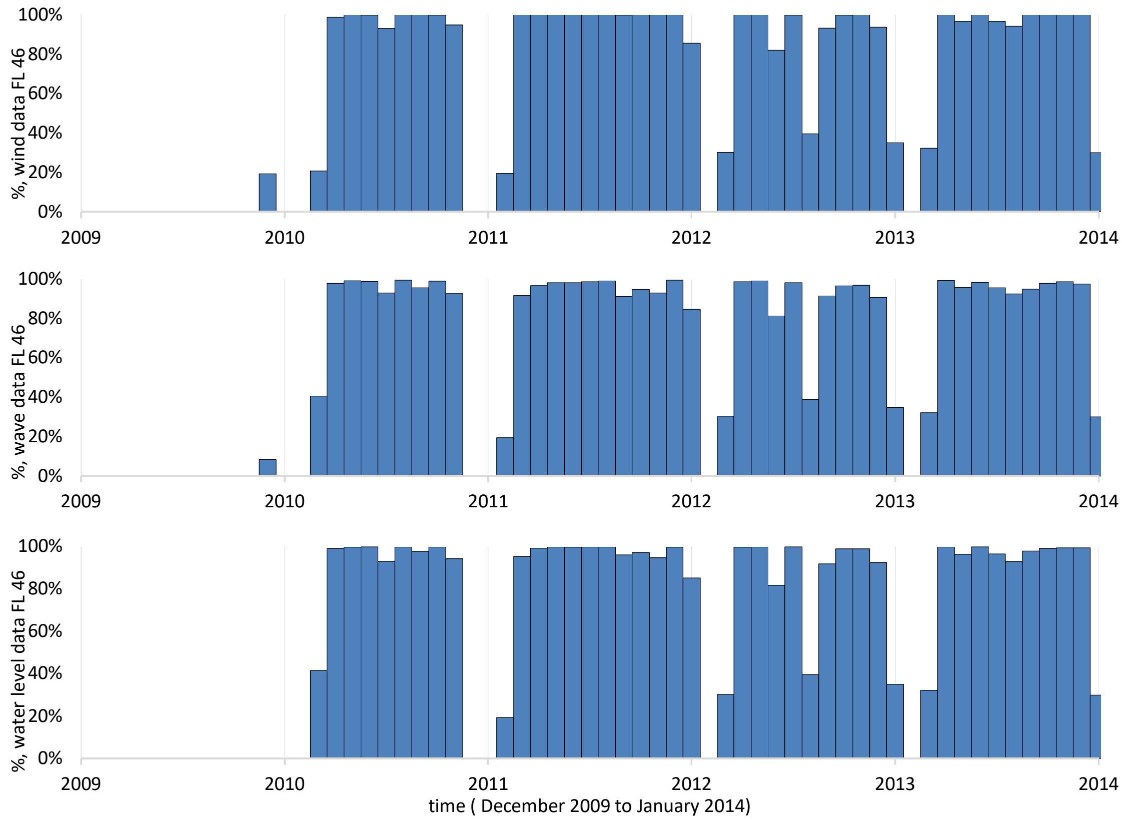

Figure A- 9 Percentage available data per month, FL46

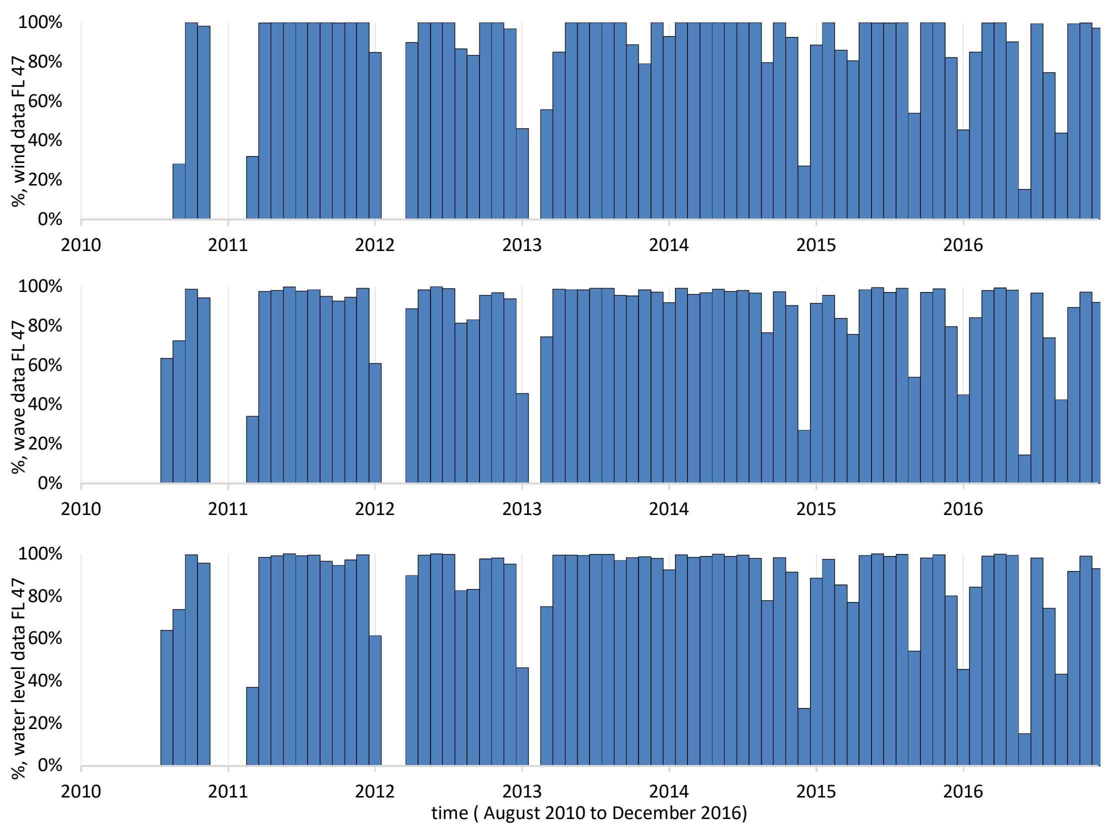

Figure A- 10 Percentage available data per month, FL47 (copy of Figure 2. 4)

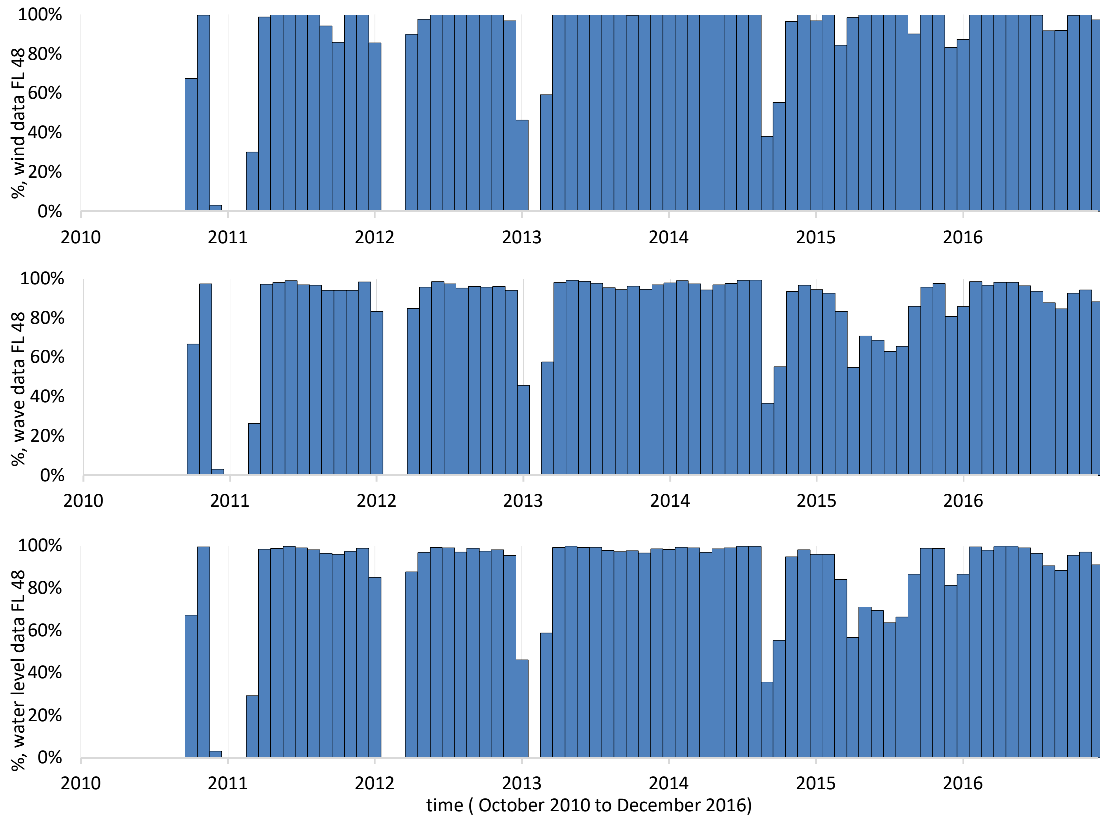

Figure A- 11 Percentage available data per month, FL48

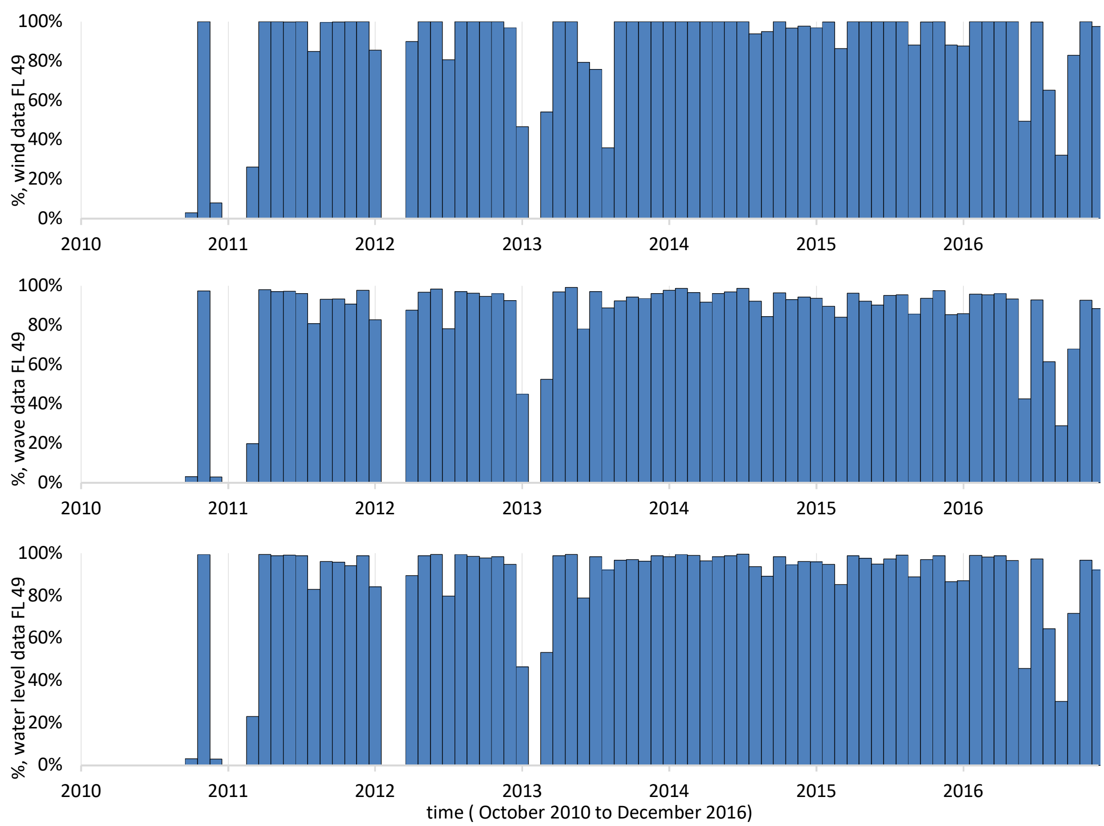

Figure A- 12 Percentage available data per month, FL49

Appendix B. Percentage of the wind for given wind directions and wind threshold

Appendix B refers to Chapter 3.2. It represents the percentage of wind data in a given wind direction for different ranges of wind speed, for all locations on Lake IJssel and Lake Marken. In addition, it is present the percentage of wind data with U_{10} wind speeds above a threshold U_{10}, for winter (Dec-Feb), spring, summer and autumn.

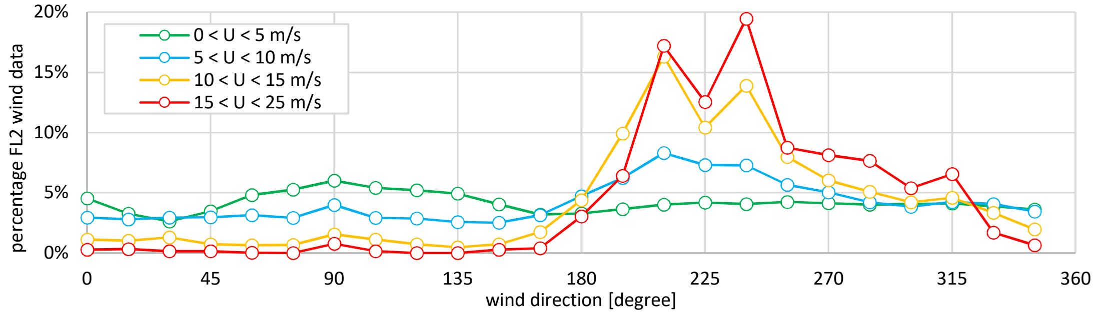

Figure B- 1 Percentage of wind data in a given wind direction for different ranges of wind speeds, FL2

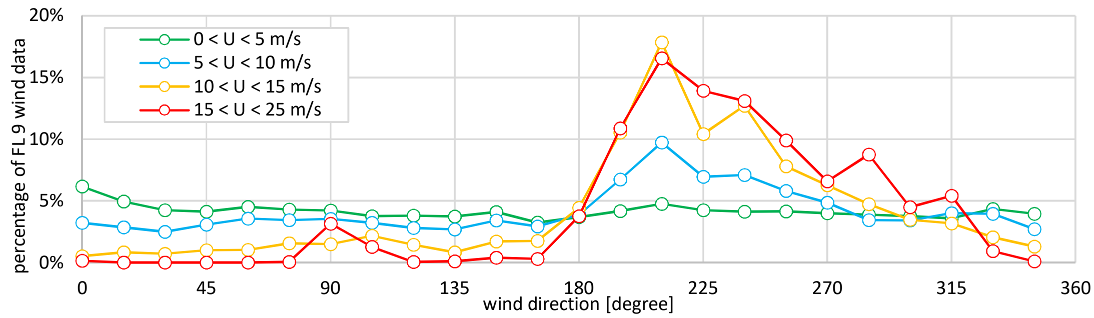

Figure B- 2 Percentage of wind data in a given wind direction for different ranges of wind speeds, FL9

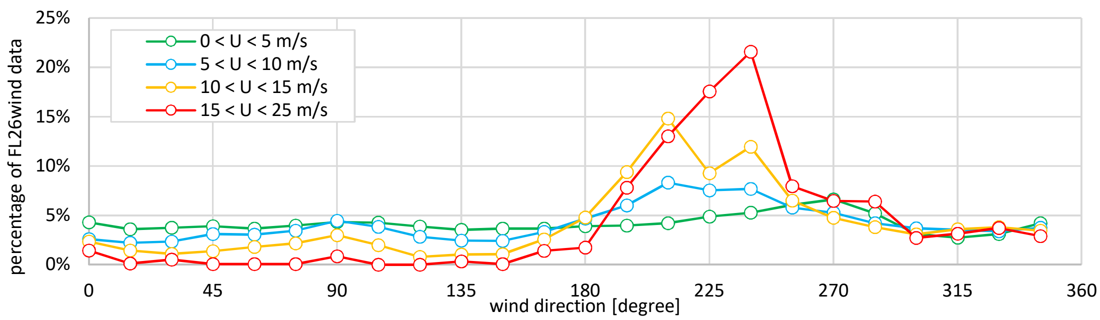

Figure B- 3 Percentage of wind data in a given wind direction for different ranges of wind speeds, FL26

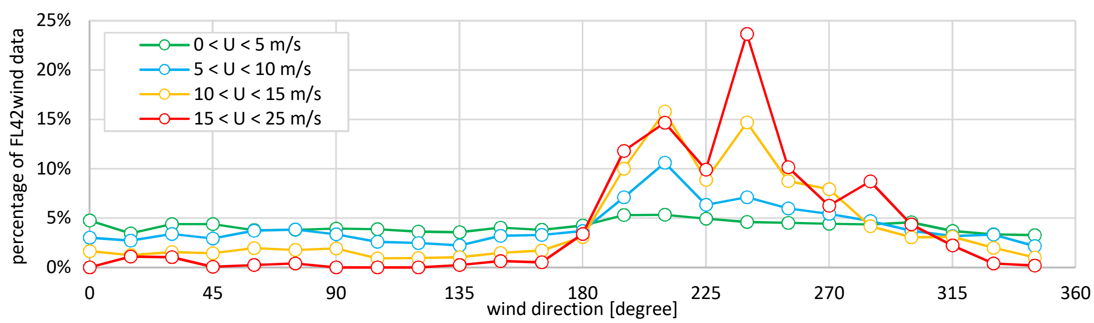

Figure B- 4 Percentage of wind data in a given wind direction for different ranges of wind speeds, FL42

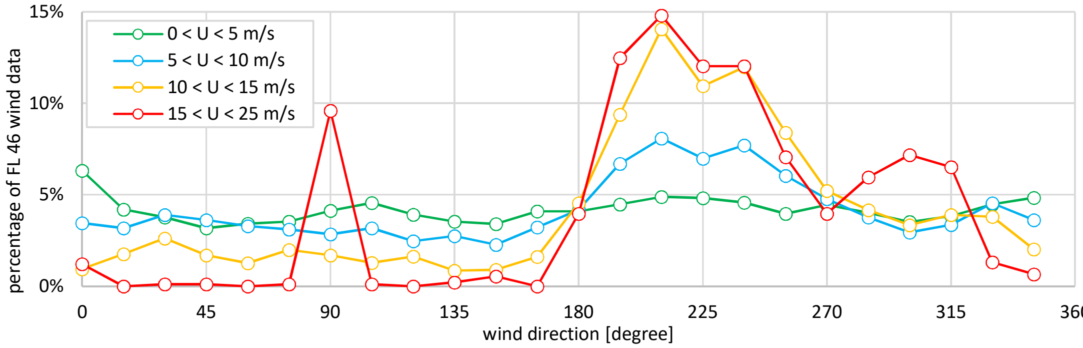

Figure B- 5 Percentage of wind data in a given wind direction for different ranges of wind speeds, FL46

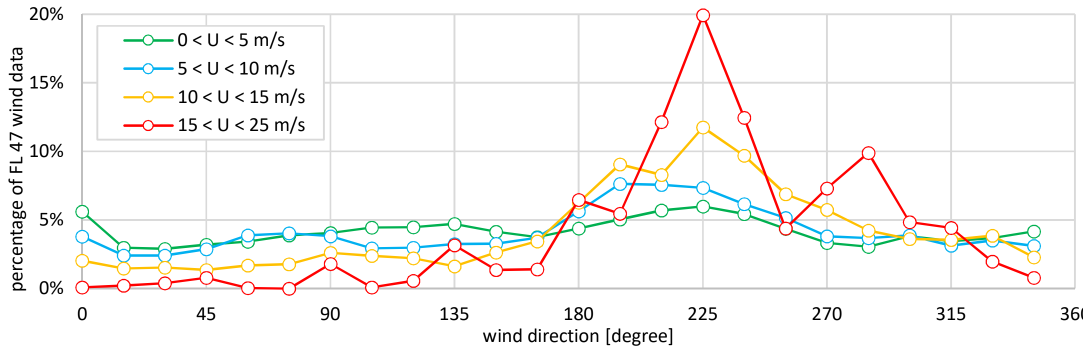

Figure B- 6 Percentage of wind data in a given wind direction for different ranges of wind speeds, FL47

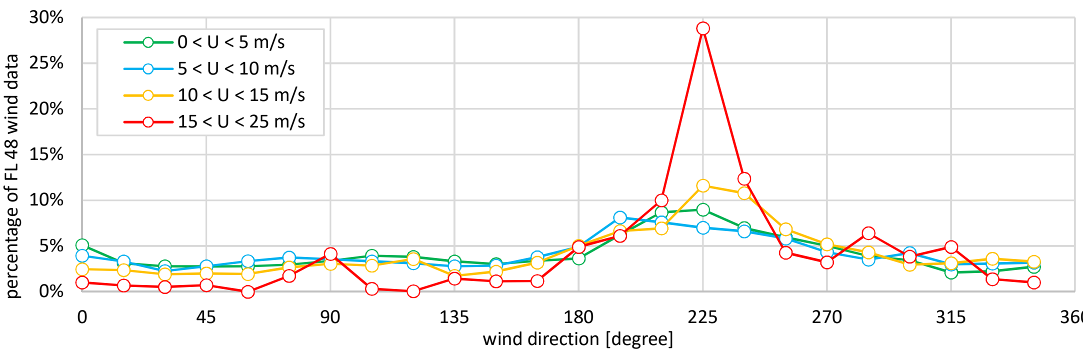

Figure B- 7 Percentage of wind data in a given wind direction for different ranges of wind speeds, FL48

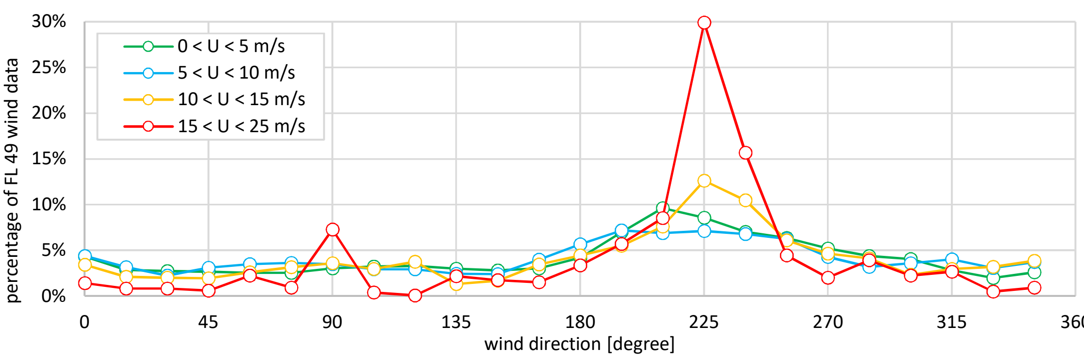

Figure B- 8 Percentage of wind data in a given wind direction for different ranges of wind speeds, FL49

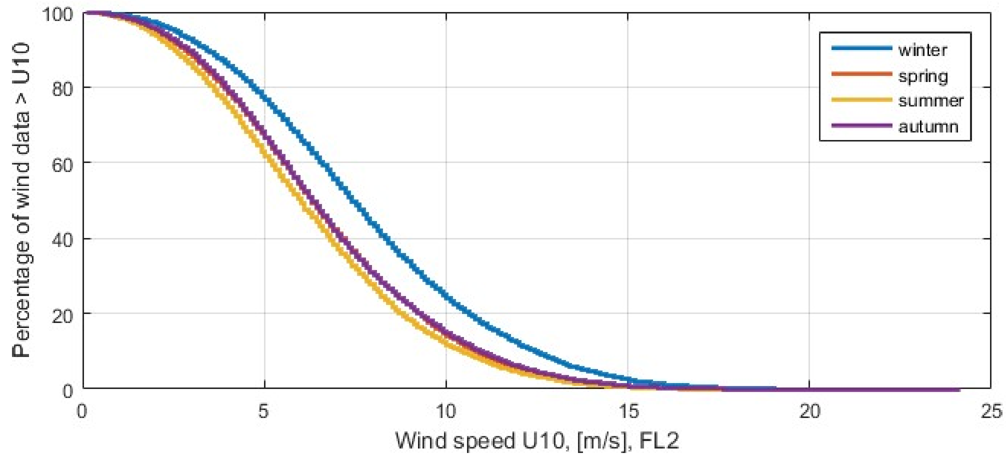

Figure B- 9 Percentage of FL2 data with U_{10} wind speeds above a threshold U_{10}, for winter (Dec-Feb), spring, summer and autumn.

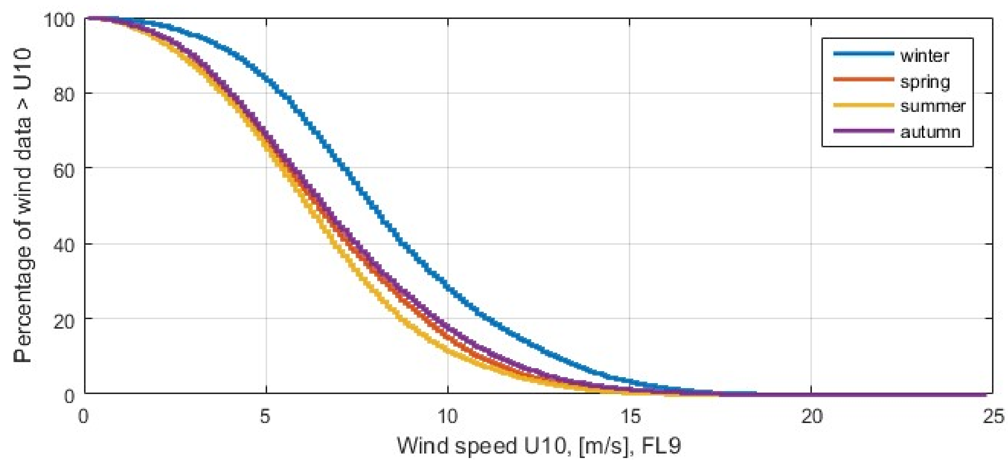

Figure B- 10 Percentage of FL9 data with U_{10} wind speeds above a threshold U_{10}, for winter (Dec-Feb), spring, summer and autumn.

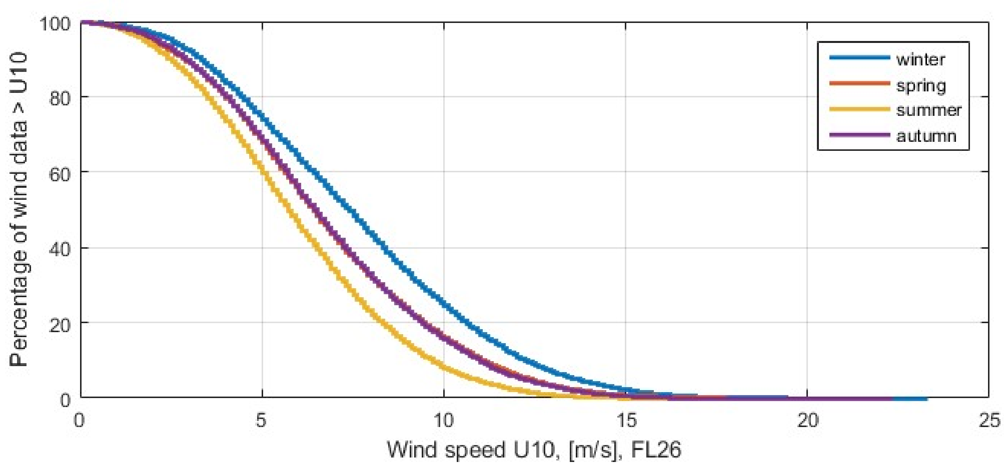

Figure B- 11 Percentage of FL26 data with U_{10} wind speeds above a threshold U_{10}, for winter (Dec-Feb), spring, summer and autumn.

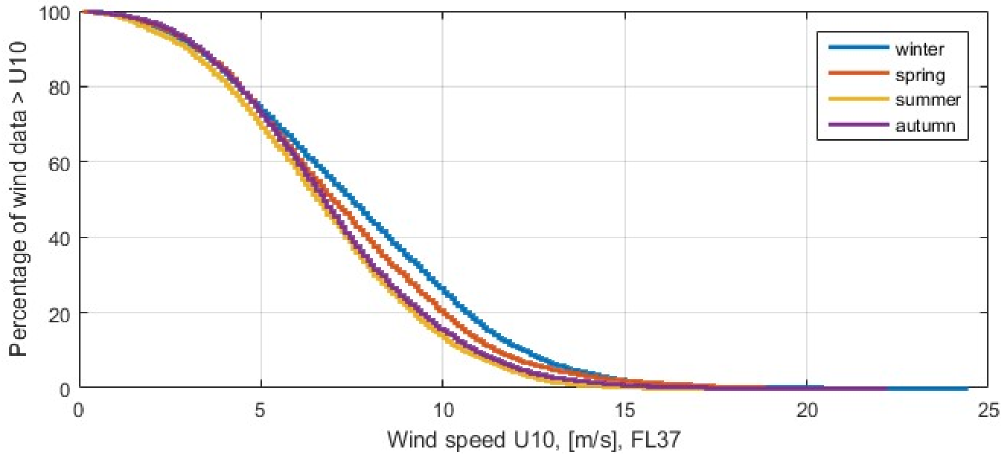

Figure B- 12 Percentage of FL37 data with U_{10} wind speeds above a threshold U_{10}, for winter (Dec-Feb), spring, summer and autumn.

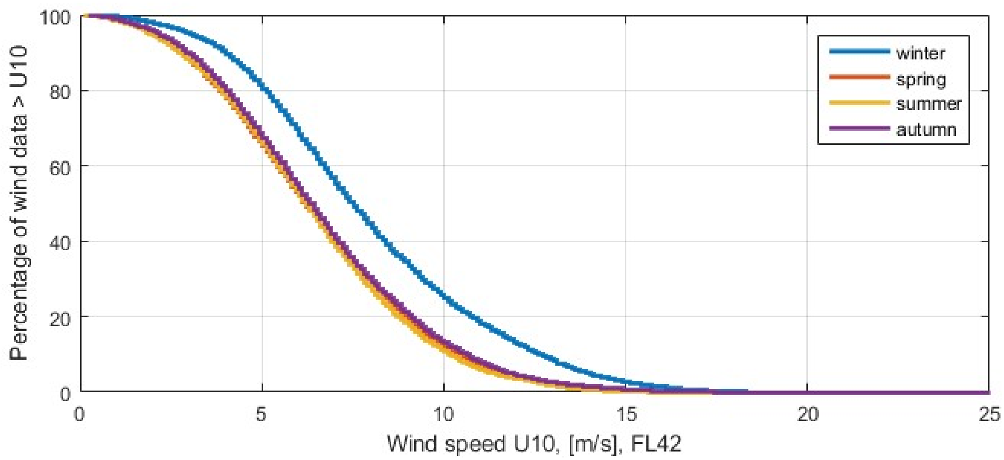

Figure B- 13 Percentage of FL42 data with U_{10} wind speeds above a threshold U_{10}, for winter (Dec-Feb), spring, summer and autumn.

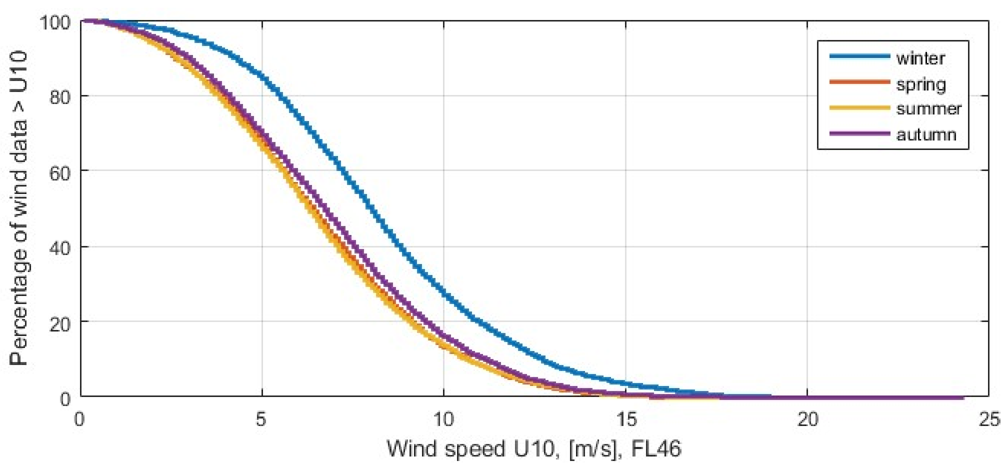

Figure B- 14 Percentage of FL46 data with U_{10} wind speeds above a threshold U_{10}, for winter (Dec-Feb), spring, summer and autumn.

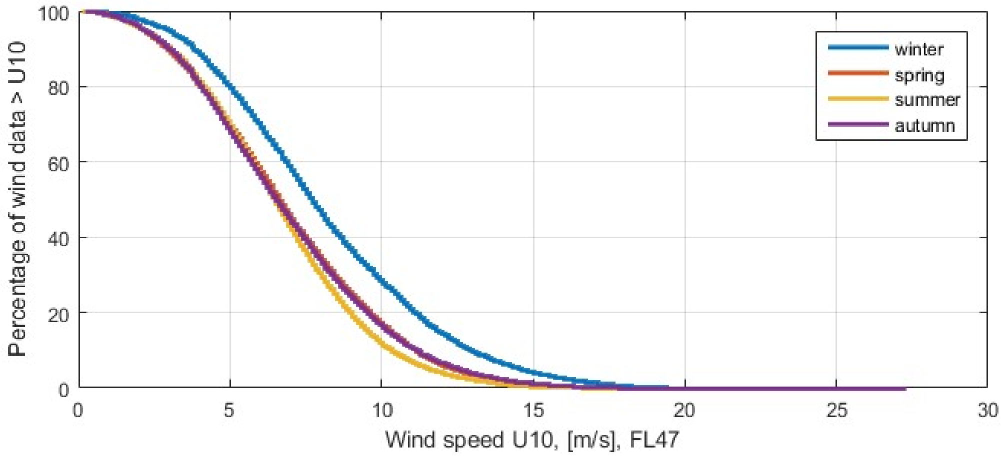

Figure B- 15 Percentage of FL47 data with U_{10} wind speeds above a threshold U_{10}, for winter (Dec-Feb), spring, summer and autumn.

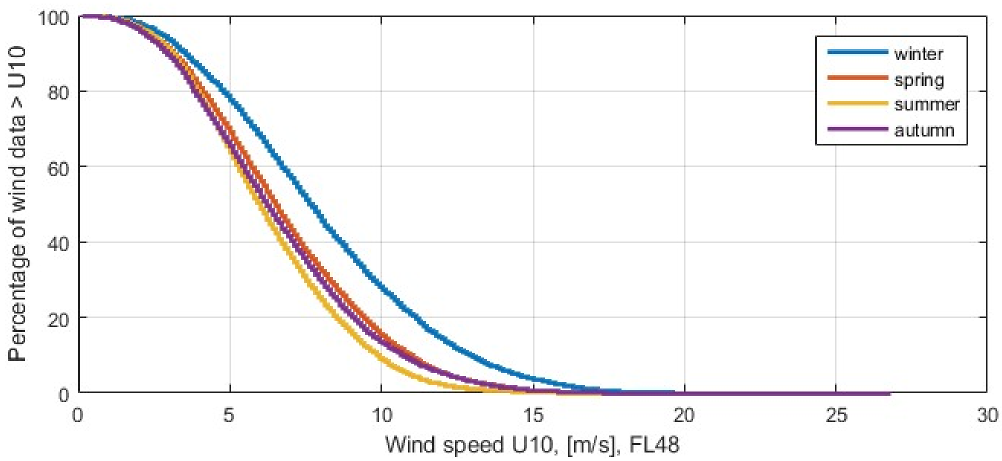

Figure B- 16 Percentage of FL48 data with U_{10} wind speeds above a threshold U_{10}, for winter (Dec-Feb), spring, summer and autumn.

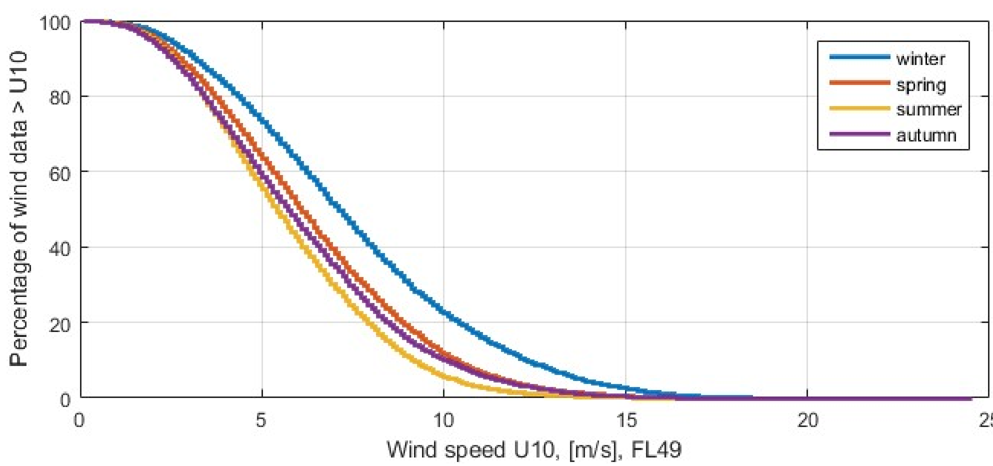

Figure B- 17 Percentage of FL49 data with U_{10} wind speeds above a threshold U_{10}, for winter (Dec-Feb), spring, summer and autumn.

Appendix C. Wind speed ratio between measurement locations

The appendix represents the wind speed ratio between the measurement locations on the Lake IJssel and Lake Marken as a function of wind direction. The calculation interval of wind direction is 15 degree. And the wind speed is considered from 6m/s (the low wind speeds have local causes and effects, because of that the wind speed ratio of two locations sometimes become unrealistically high (see Figure 3. 7 -Figure 3. 9)) .

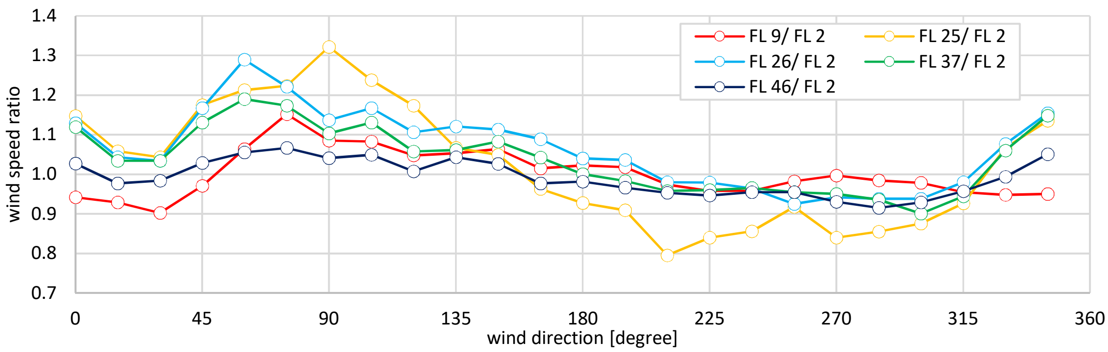

Figure C- 1 Wind speed ratio as a function of wind direction (FL9/FL2; FL25/FL2; FL26/FL2; FL37/FL2; FL46/FL2)

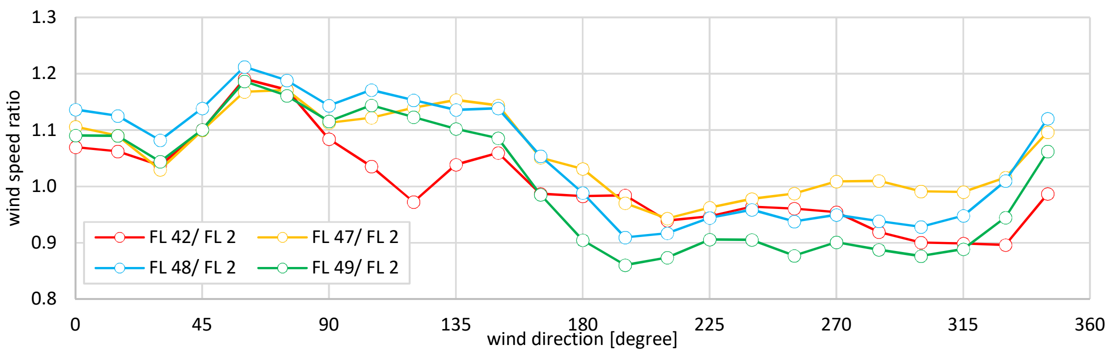

Figure C- 2 Wind speed ratio as a function of wind direction (FL42/FL2; FL47/FL2; FL48/FL2; FL49/FL2)

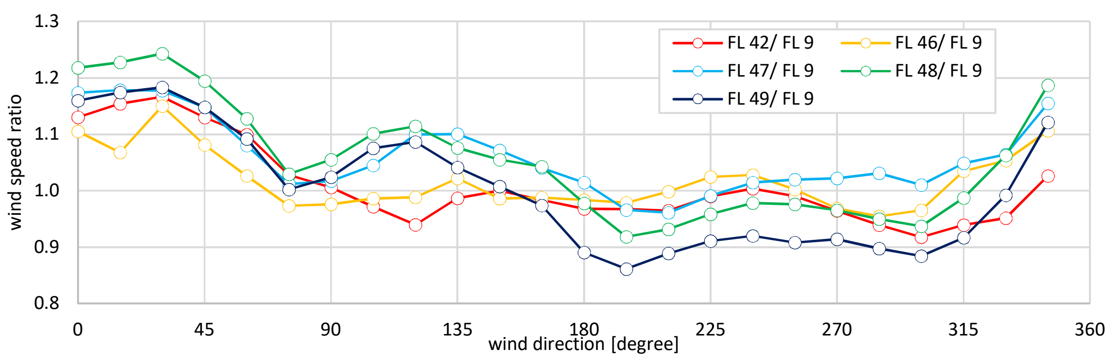

Figure C- 3 Wind speed ratio as a function of wind direction (FL42/FL9; FL46/FL9; FL47/FL9; FL48/FL9; FL49/FL9)

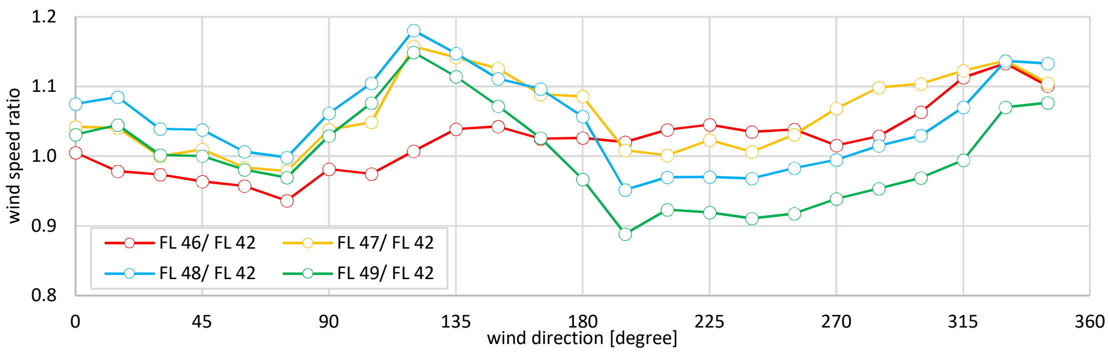

Figure C- 4 Wind speed ratio as a function of wind direction (FL46/FL42; FL47/FL42; FL48/FL42; FL49/FL42)

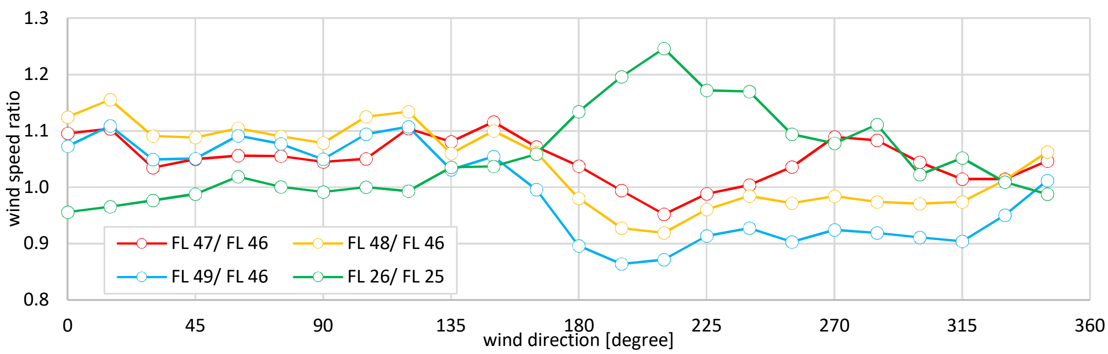

Figure C- 5 Wind speed ratio as a function of wind direction (FL47/FL46; FL48/FL46; FL49/FL46; FL26/FL25)

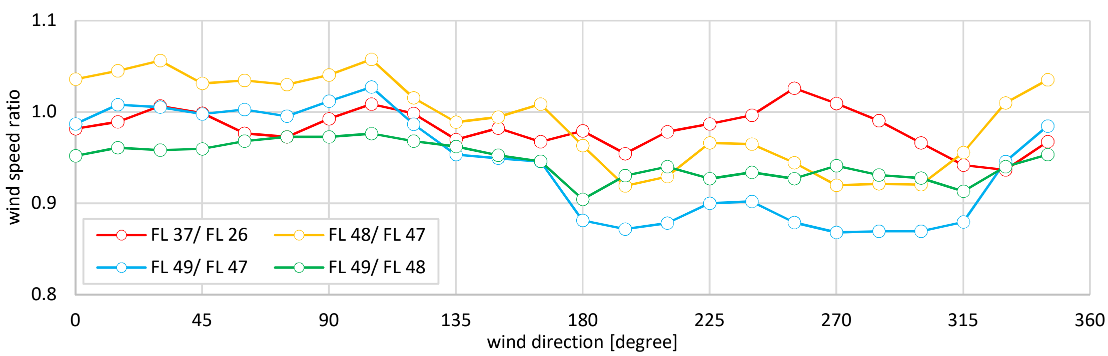

Figure C- 6 Wind speed ratio as a function of wind direction (FL37/FL26; FL48/FL47; FL49/FL47; FL49/FL48)

Appendix D. Wind speed ratio between measurement locations and KNMI meteorological stations

The appendix represents the wind speed ratio of measurement locations on the Lake IJssel and Lake Marken and potential wind speed in five meteorological stations of KNMI as a function of wind direction. The calculation interval of wind direction is 10 degrees. And the wind speed is considered from 6m/s (the low wind speeds have local causes and effects, because of that the wind speed ratio of two locations sometimes become unrealistically high).

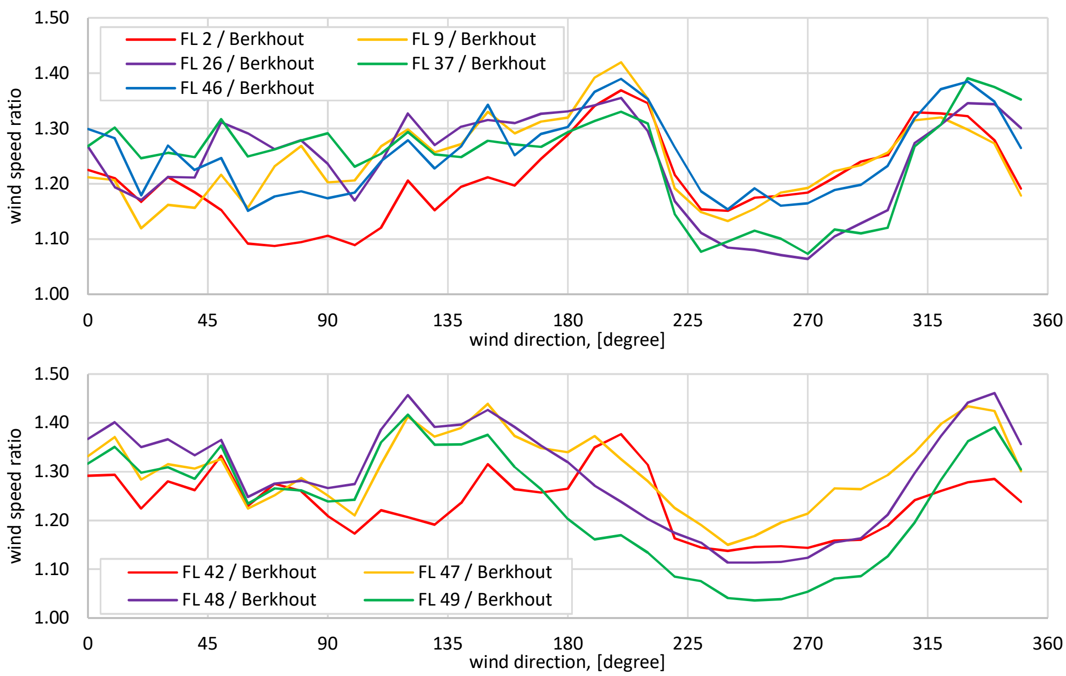

Figure D- 1 Wind speed ratio U_{10}/U_{pot}(Berkhout), as a function of wind direction

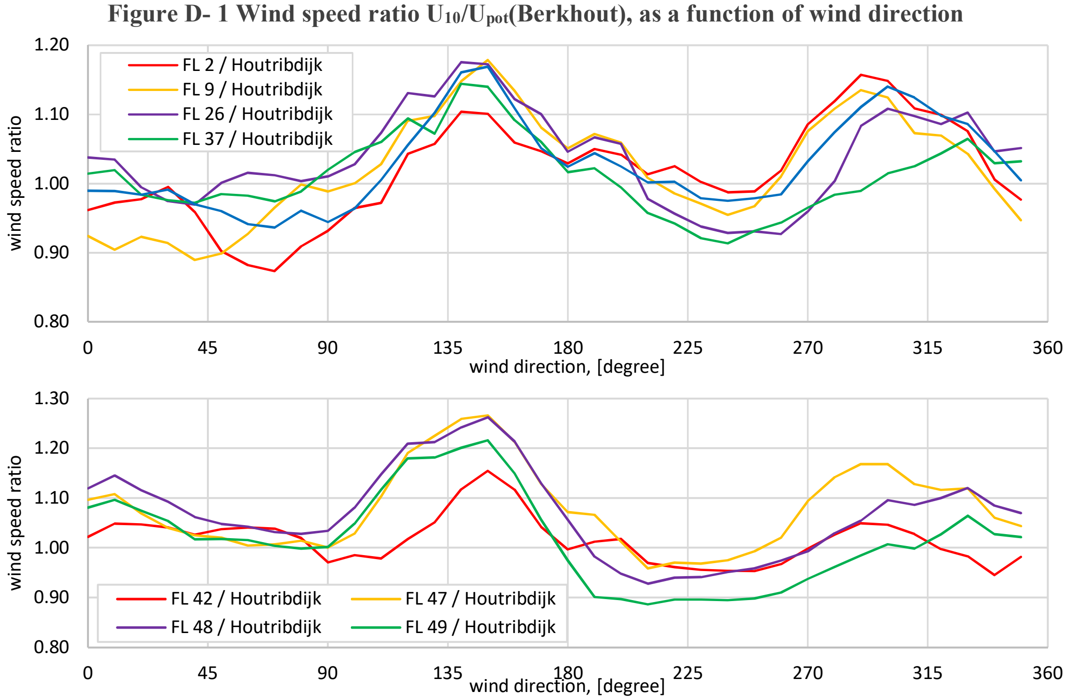

Figure D- 2 Wind speed ratio U_{10}/U_{pot}(Houtribdijk), as a function of wind direction

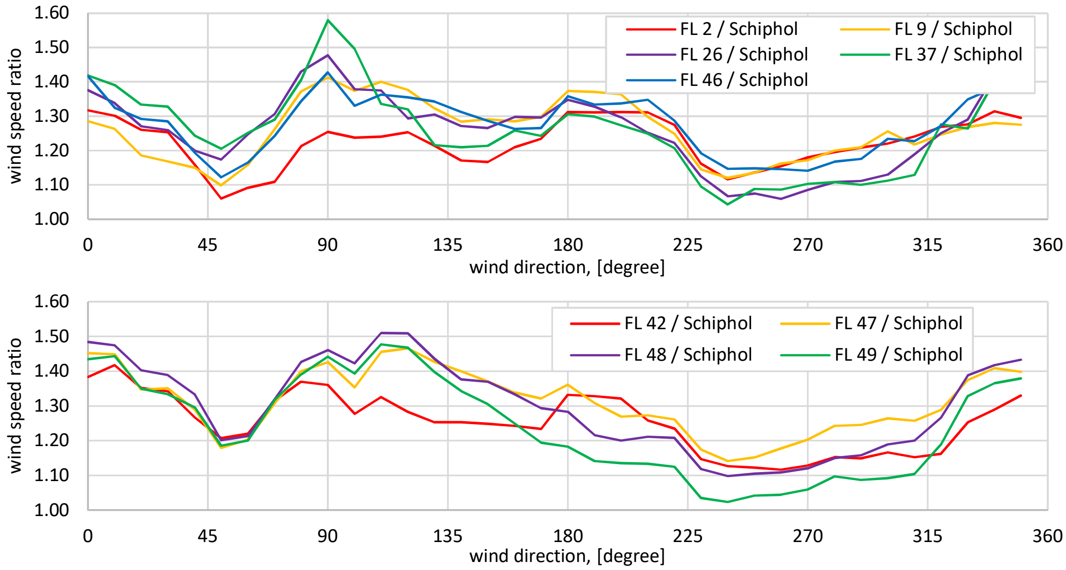

Figure D- 3 Wind speed ratio U_{10}/U_{pot}(Schiphol), as a function of wind direction

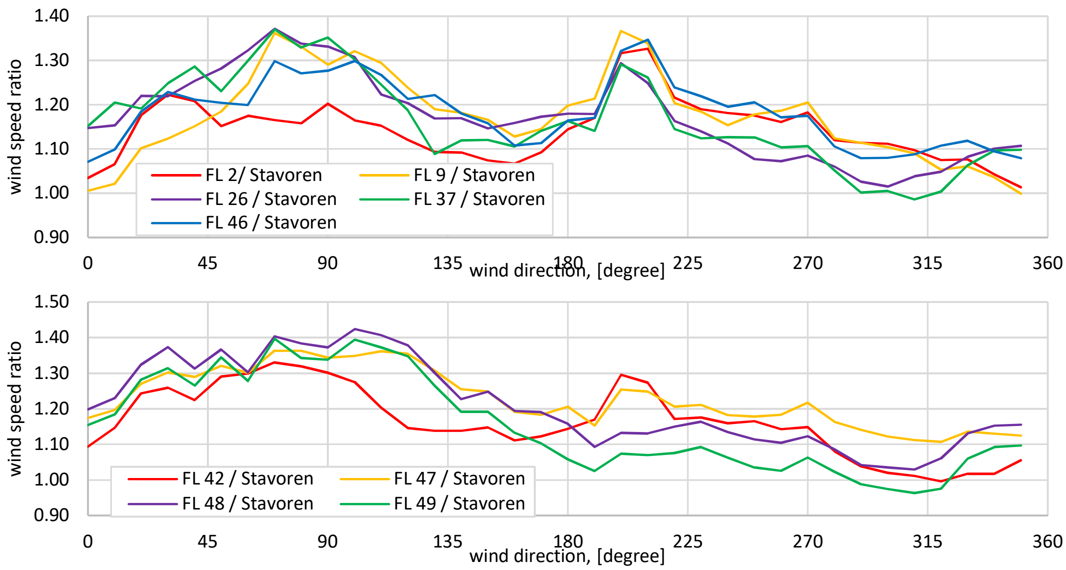

Figure D- 4 Wind speed ratio U_{10}/U_{pot}(Stavoren), as a function of wind direction

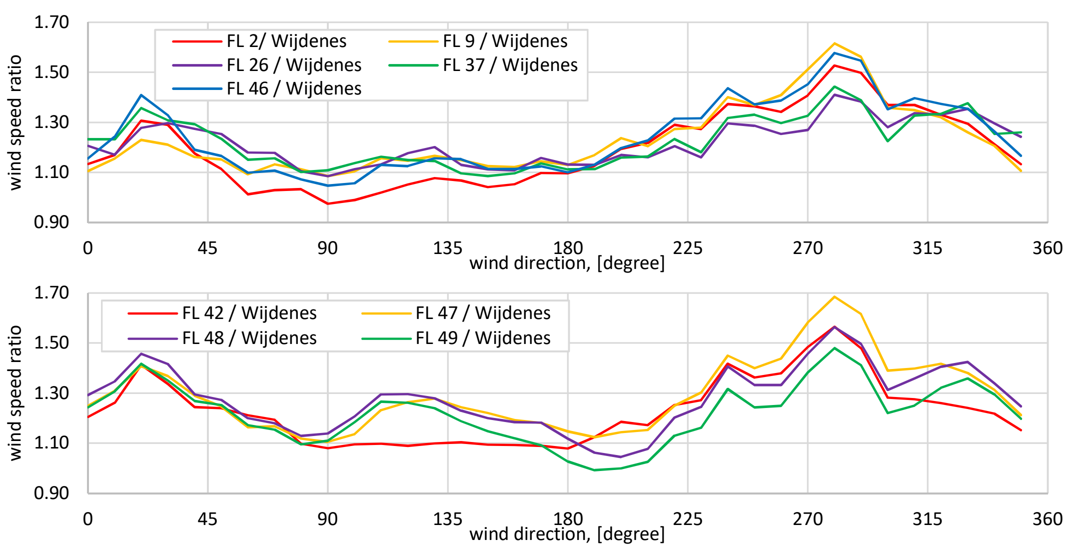

Figure D- 5 Wind speed ratio U_{10}/U_{pot}(Wijdenes), as a function of wind direction

Appendix E. Wave height as a function wind direction

The appendix represents the average wave height (H_{m0}) as a function of wind direction for a range of wind speeds, for all locations. Wind speed and wind direction data of FL 2 are used for location FL 5. Wind speed and wind direction data of FL 42 are used for location FL 44. Wind direction data of FL 26 is used for locations FL 25 and FL 37. Wind direction range is 15 degrees, wind speed interval is 1 m/s for 6m/s, 9m/s and 12m/s wind speed ranges, the interval is 2m/s for 15m/s and 18m/s ranges. And wind speed more than 20 m/s are presented as a 21m/s. The analysis shows November-April period.

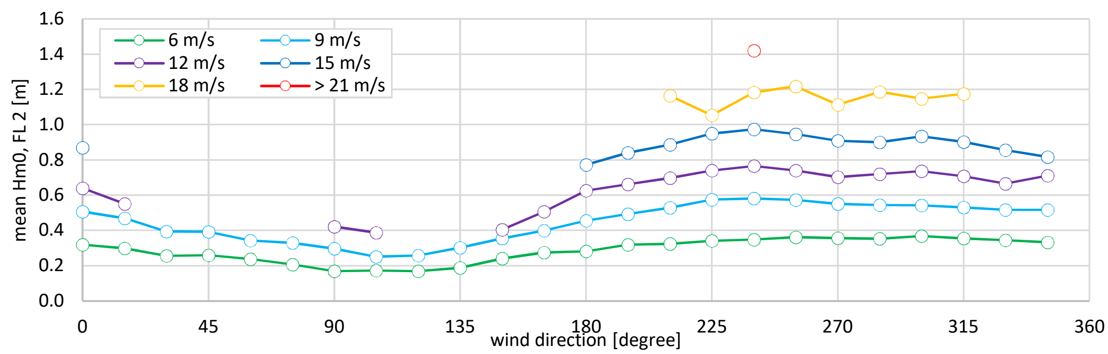

Figure E- 1 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL2

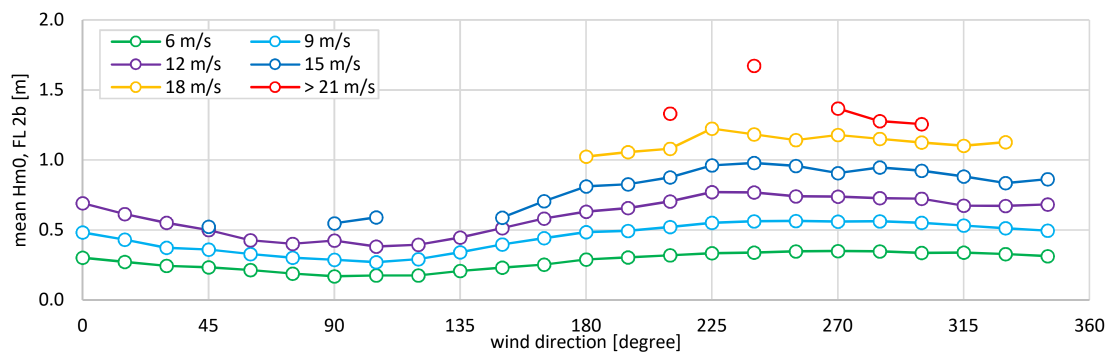

Figure E- 2 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL2b

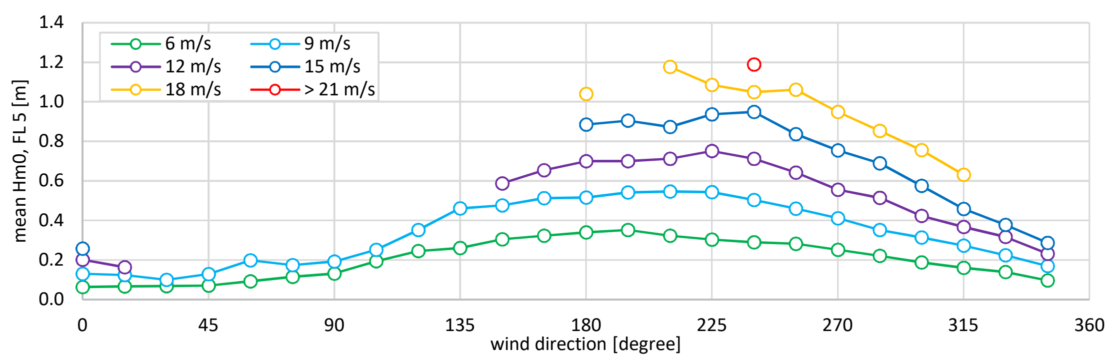

Figure E- 3 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL5 (reference wind speed and wind direction is FL2)

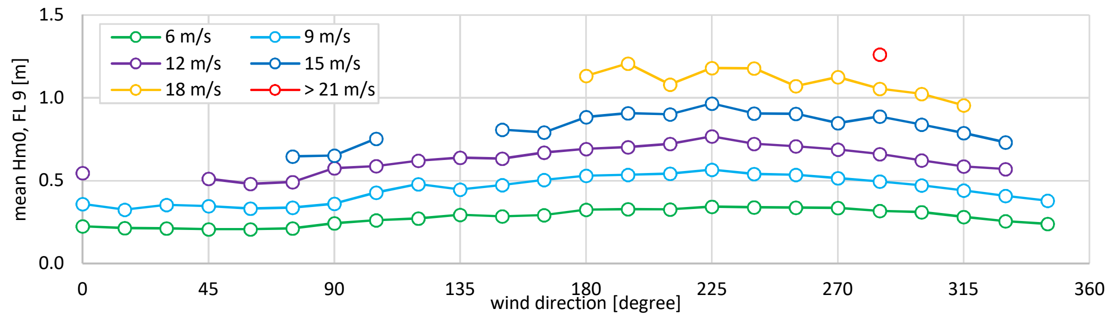

Figure E- 4 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL9

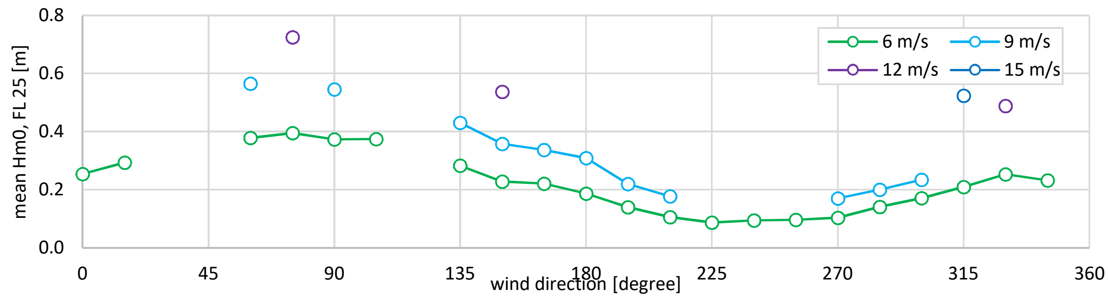

Figure E- 5 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL25 (reference wind direction is FL26)

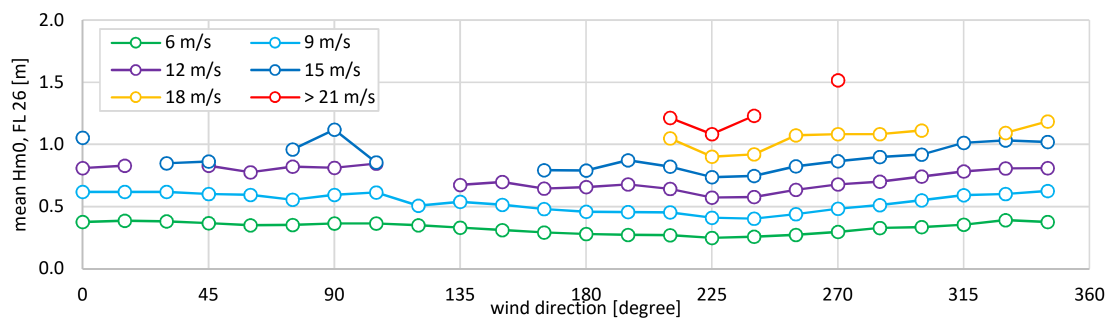

Figure E- 6 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL26

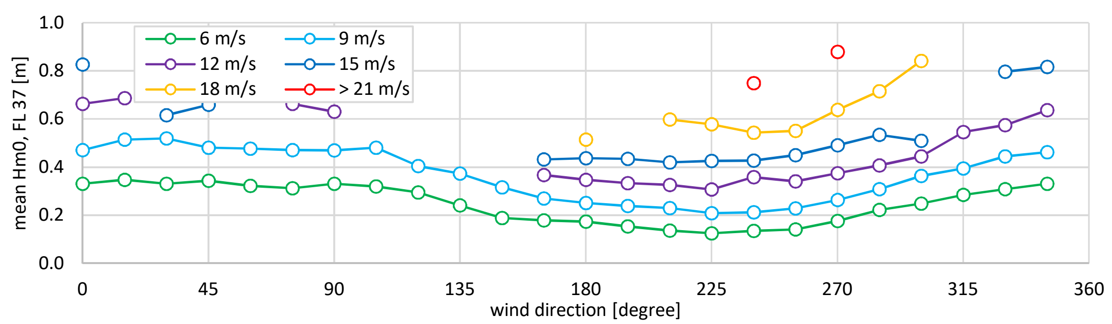

Figure E- 7 Average wave height (Hm0) for a range of wind speeds, as a function of wind direction, FL37 (reference wind direction is FL26)

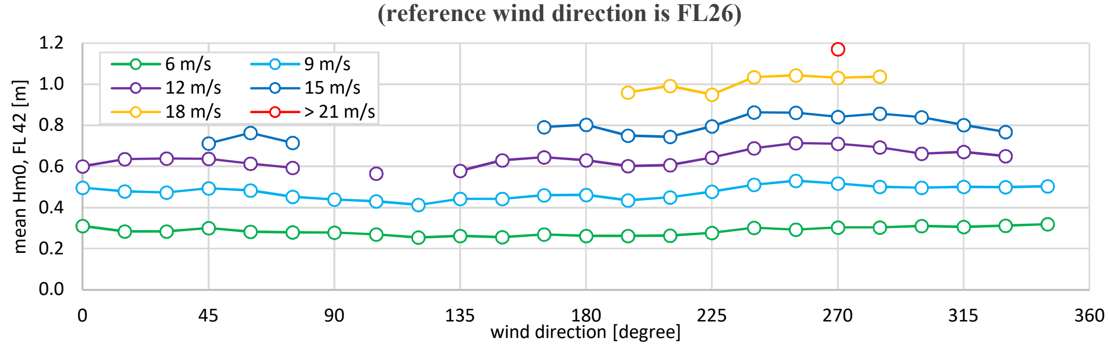

Figure E- 8 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL42

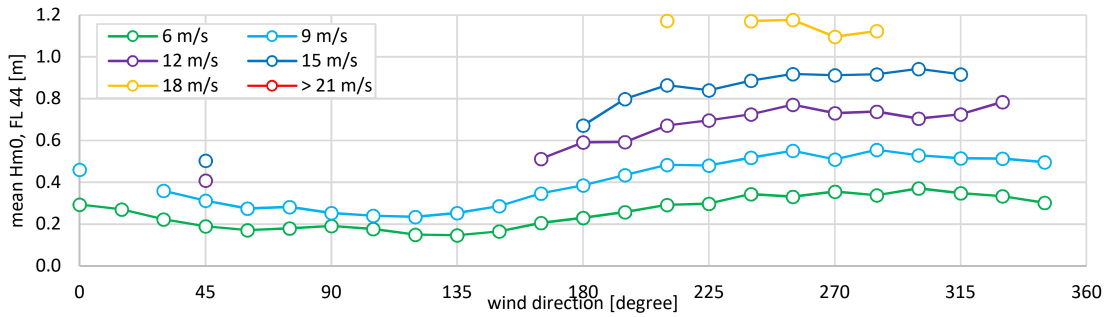

Figure E- 9 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL44 (reference wind speed and wind direction is FL42)

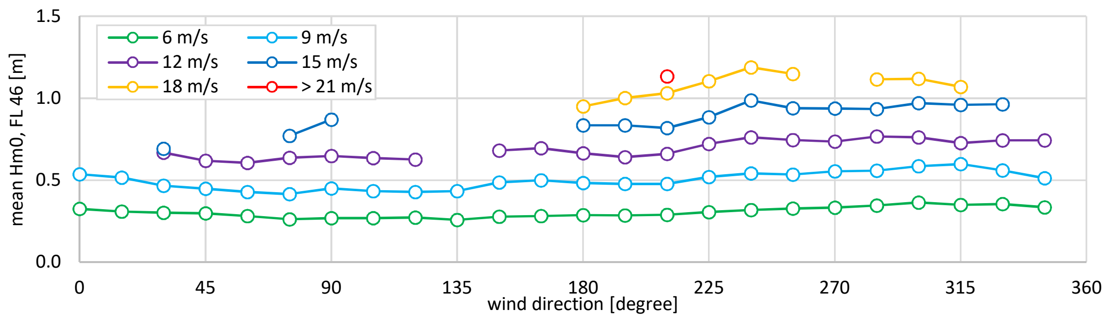

Figure E- 10 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL46

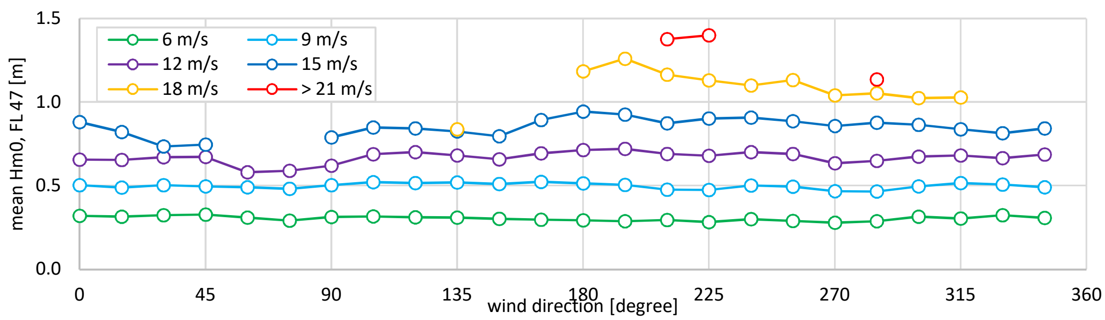

Figure E- 11 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL47

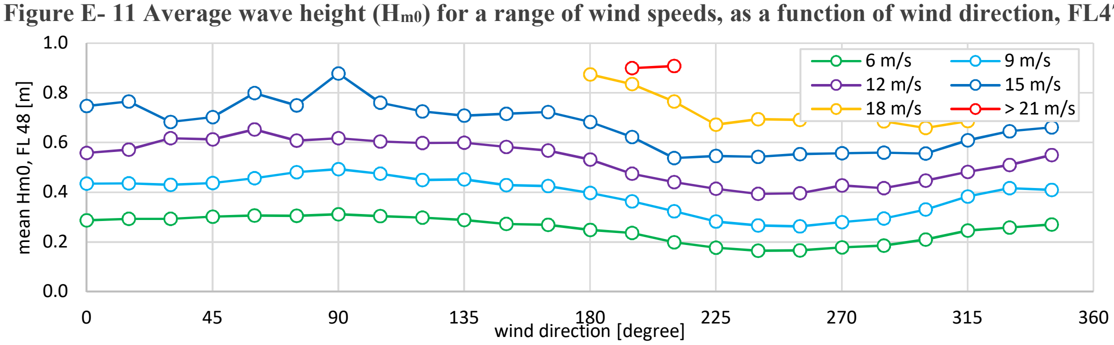

Figure E- 12 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL48

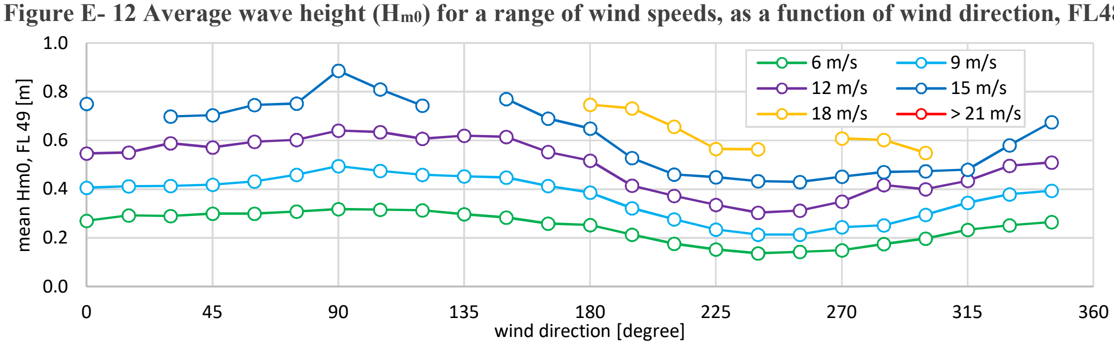

Figure E- 13 Average wave height (H_{m0}) for a range of wind speeds, as a function of wind direction, FL49

Appendix F. Wave period as a function of wind direction

The appendix represents the average wave period (Tm01) as a function of wind direction for a range of wind speeds, for all locations. Wind speed and wind direction data of FL 2 are used for location FL 5. Wind speed and wind direction data of FL 42 are used for location FL 44. Wind direction data of FL 26 is used for locations FL 25 and FL 37. From November to April. Wind direction range is 15 degree, wind speed range is 1 m/s for 6m/s, 9m/s and 12m/s. 2m/s for 15m/s and 18m/s. wind speed more than 20 m/s are presented as a 21m/s.

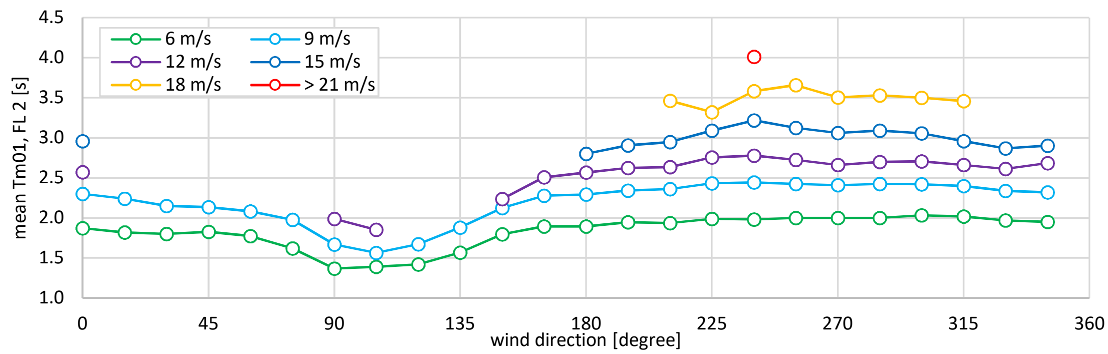

Figure F- 1 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL2

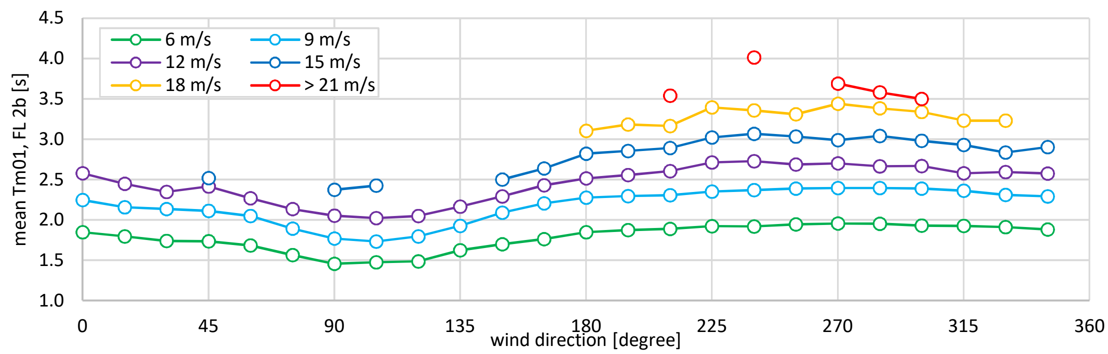

Figure F- 2 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL2b

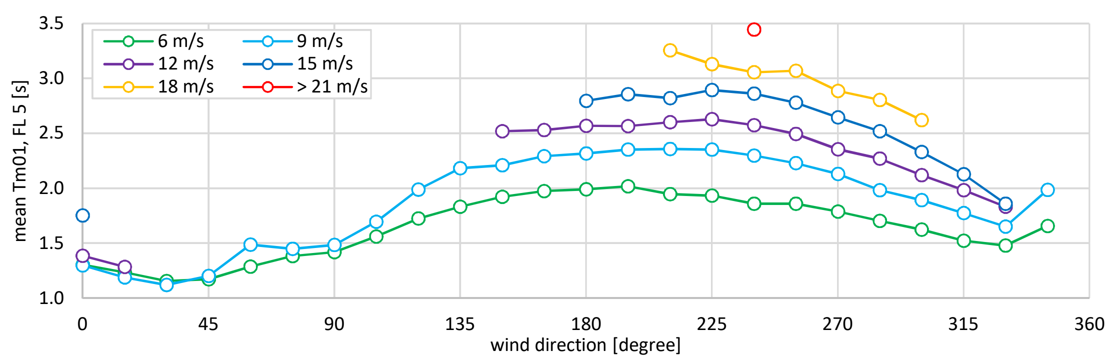

Figure F- 3 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL5 (reference wind speed and wind direction is FL2)

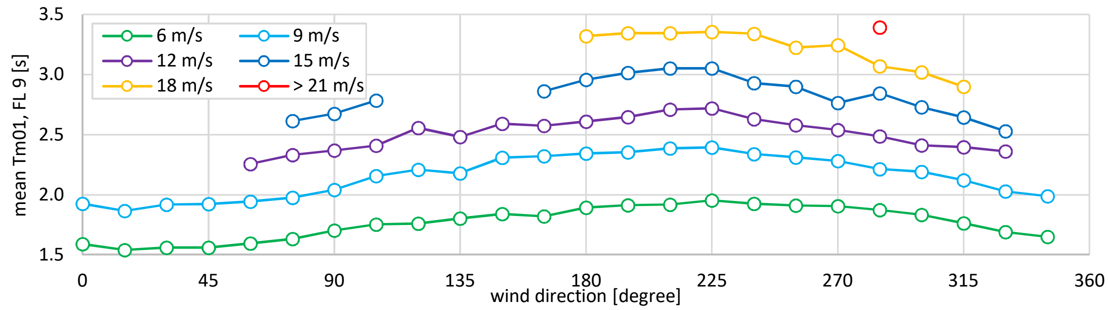

Figure F- 4 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL9

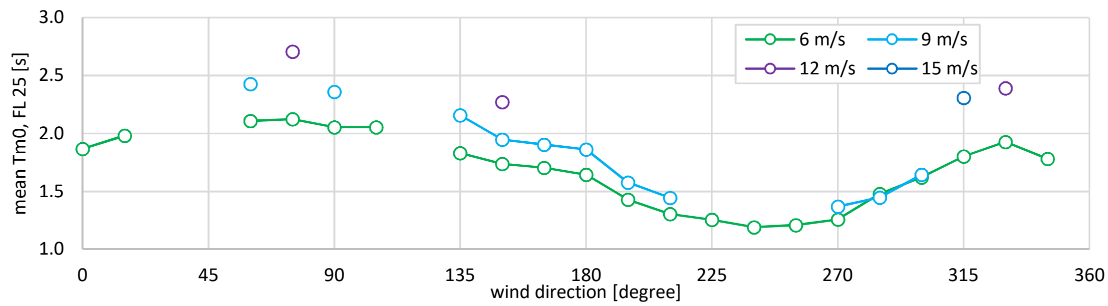

Figure F- 5 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL25 (reference wind direction is FL26)

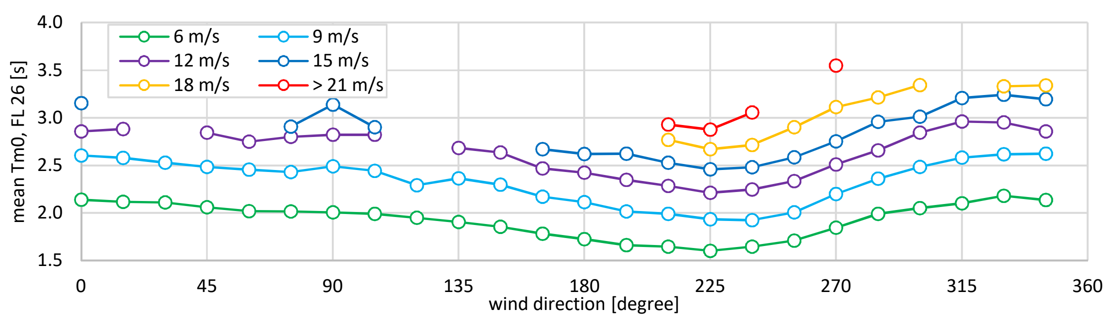

Figure F- 6 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL26

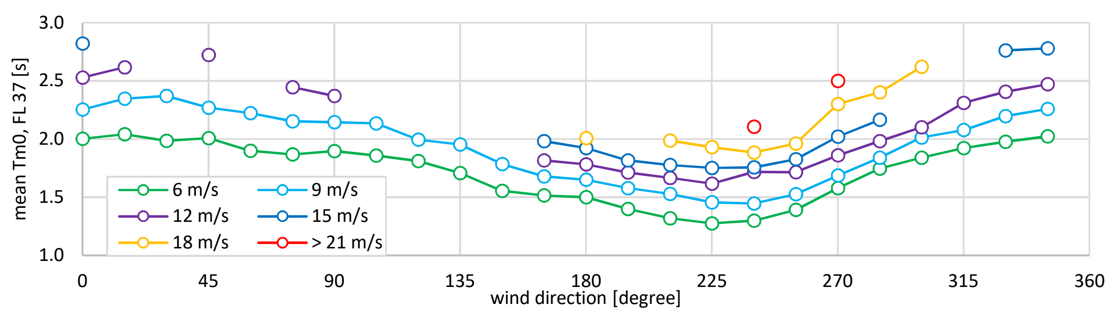

Figure F- 7 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL37 (reference wind direction is FL26)

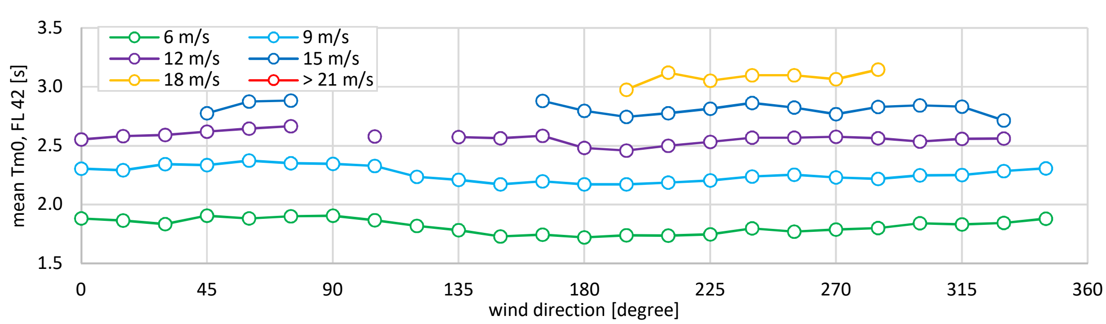

Figure F- 8 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL42

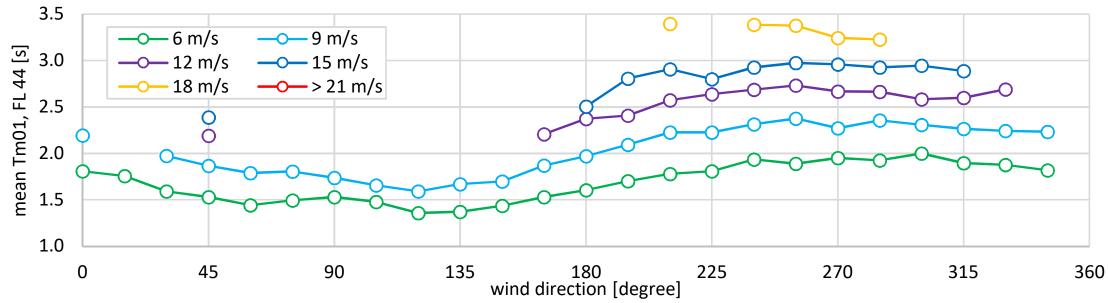

Figure F- 9 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL44 (reference wind speed and wind direction is FL42)

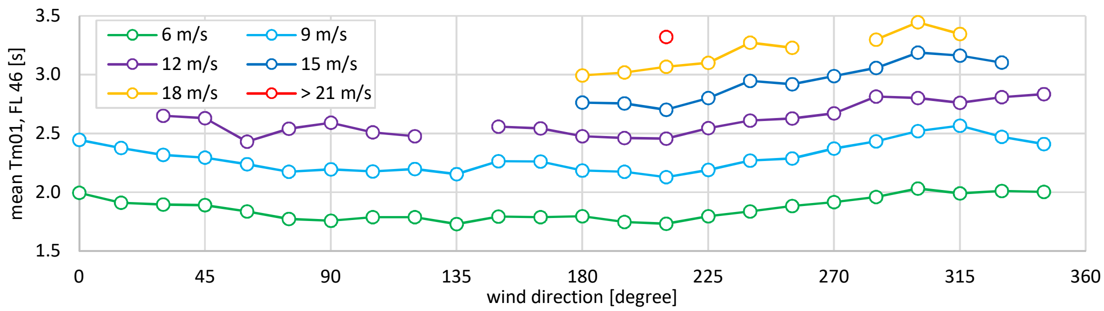

Figure F- 10 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL46

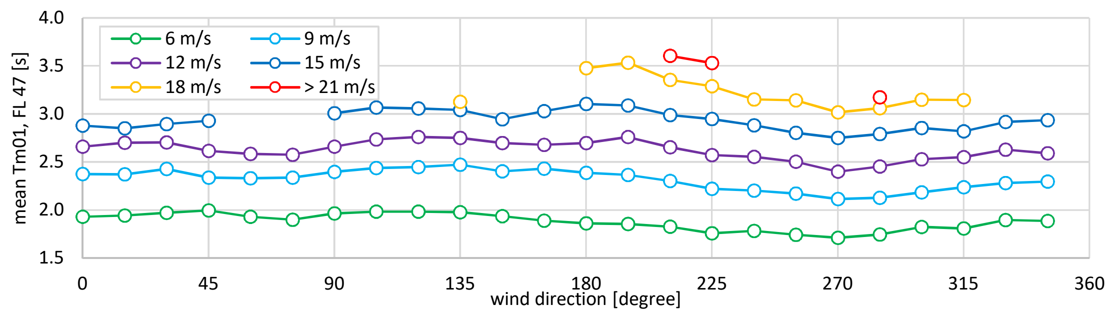

Figure F- 11 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL47

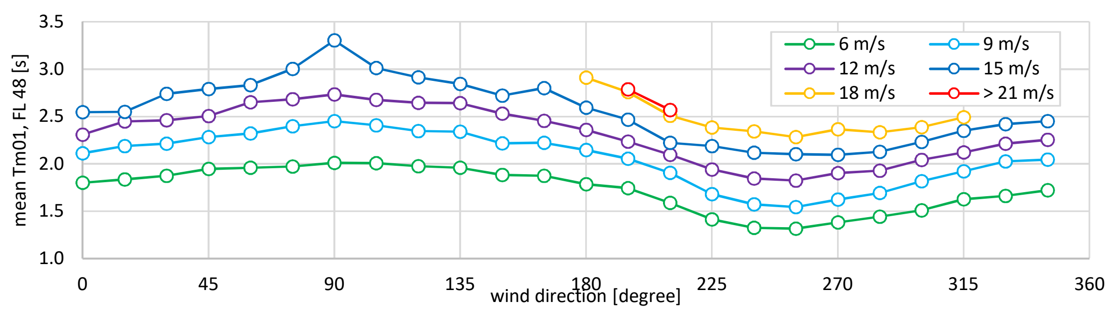

Figure F- 12 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL48

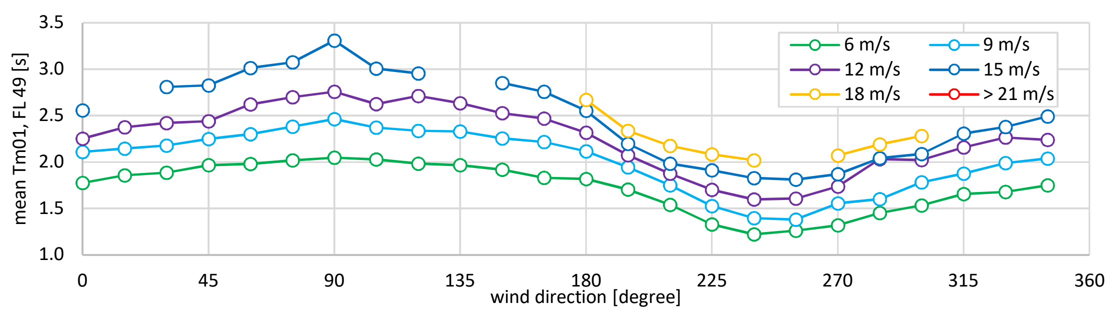

Figure F- 13 Average wave period (T_{m01}) for a range of wind speeds, as a function of wind direction, FL49

Appendix G. The statistics of wave parameters

The appendix represents the statistics of wave parameters (H_{m0}, T_p, T_{m-10}, T_{m01}) and water level (SWL) for November-April period. The ranges of wind speeds are 6 m/s, 12 m/s and 18 m/s (18 m/s represent the range of 17m/s-19m/s).And the interval of wind direction is 15 degrees (for example, 30 degree represents the range of 22.5o-37.5o wind direction). Table (a) represents the averages of water level (SWL), significant wave height (H_{m0}), and wave periods (T_p, T_{m-10}, T_{m01}). Table (b) presents the standard deviation of the same parameters and the number of samples for each range. Table (c) represents the uncertainty (standard deviation) in the mean of same parameters.

Table G. 1 (a) Average still water level, wave height (H_{m0}) and wave period (T_p, T_{m-10}, T_{m01}) for given wind speeds and wind directions, FL2

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
0	-0.19	0.32	2.24	2.20	1.87	0.03	0.64	3.08	3.10	2.57	-	-	-	-	-
30	-0.21	0.26	2.24	2.26	1.80	-	-	-	-	-	-	-	-	-	-
60	-0.28	0.24	2.27	2.10	1.77	-	-	-	-	-	-	-	-	-	-
90	-0.31	0.17	1.78	1.61	1.37	-0.28	0.42	2.44	2.42	1.99	-	-	-	-	-
120	-0.31	0.17	1.92	1.71	1.42	-	-	-	-	-	-	-	-	-	-
150	-0.20	0.24	2.34	2.14	1.80	-0.35	0.40	2.94	2.59	2.24	-	-	-	-	-
180	-0.25	0.28	2.45	2.24	1.89	-0.23	0.63	3.36	2.93	2.57	-	-	-	-	-
210	-0.22	0.32	2.47	2.22	1.93	-0.16	0.70	3.39	2.98	2.64	0.02	1.16	4.45	3.97	3.46
240	-0.21	0.35	2.50	2.31	1.98	-0.01	0.77	3.58	3.20	2.78	0.12	1.18	4.56	4.13	3.58
270	-0.17	0.36	2.61	2.32	2.00	-0.04	0.70	3.53	3.06	2.66	0.26	1.11	4.71	4.12	3.50
300	-0.20	0.37	2.64	2.33	2.03	-0.10	0.74	3.51	3.04	2.71	0.23	1.15	4.69	4.08	3.50
330	-0.15	0.34	2.49	2.26	1.97	-0.13	0.66	3.36	2.99	2.61	-	-	-	-	-

(b) Number of samples and standard deviation of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]																	
	6						12						18					
	Num[7]	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	139	0.13	0.06	0.27	0.30	0.18	24	0.21	0.09	0.22	0.26	0.17	-	-	-	-	-	-
30	170	0.16	0.06	0.15	0.61	0.10	-	-	-	-	-	-	-	-	-	-	-	-
60	181	0.13	0.04	0.19	0.34	0.13	-	-	-	-	-	-	-	-	-	-	-	-
90	300	0.09	0.02	0.60	0.19	0.11	64	0.18	0.04	0.39	0.19	0.08	-	-	-	-	-	-
120	269	0.11	0.04	0.57	0.17	0.12	5	-	-	-	-	-	-	-	-	-	-	-
150	276	0.21	0.06	0.34	0.35	0.22	14	0.08	0.12	0.14	0.15	0.11	-	-	-	-	-	-
180	390	0.21	0.07	0.31	0.33	0.20	75	0.08	0.05	0.17	0.14	0.08	-	-	-	-	-	-
210	449	0.22	0.06	0.23	0.21	0.16	357	0.18	0.07	0.18	0.14	0.10	38	0.14	0.10	0.24	0.20	0.17
240	522	0.20	0.07	0.26	0.23	0.16	252	0.22	0.09	0.21	0.16	0.14	74	0.21	0.12	0.23	0.16	0.15
270	273	0.23	0.06	0.28	0.23	0.16	182	0.19	0.08	0.30	0.17	0.11	44	0.20	0.11	0.30	0.20	0.17
300	276	0.18	0.05	0.22	0.19	0.13	65	0.16	0.05	0.23	0.11	0.10	10	0.31	0.05	0.29	0.25	0.16
330	207	0.19	0.05	0.29	0.21	0.15	58	0.15	0.07	0.22	0.16	0.12	1	-	-	-	-	-

(c) The standard deviation of the mean of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	0.011	0.005	0.023	0.026	0.015	0.042	0.018	0.045	0.052	0.034	-	-	-	-	-
30	0.012	0.005	0.011	0.046	0.008	-	-	-	-	-	-	-	-	-	-
60	0.010	0.003	0.014	0.025	0.009	-	-	-	-	-	-	-	-	-	-
90	0.005	0.001	0.035	0.011	0.006	0.023	0.005	0.048	0.024	0.010	-	-	-	-	-
120	0.007	0.002	0.035	0.011	0.008	-	-	-	-	-	-	-	-	-	-

[7] "Num" is the number of samples in each range of dataset

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
150	0.013	0.004	0.021	0.021	0.013	0.021	0.031	0.037	0.039	0.029	-	-	-	-	-
180	0.011	0.003	0.016	0.017	0.010	0.010	0.006	0.020	0.016	0.010	-	-	-	-	-
210	0.011	0.003	0.011	0.010	0.007	0.009	0.004	0.010	0.007	0.005	0.023	0.017	0.039	0.033	0.027
240	0.009	0.003	0.012	0.010	0.007	0.014	0.005	0.013	0.010	0.009	0.024	0.014	0.027	0.018	0.017
270	0.014	0.003	0.017	0.014	0.009	0.014	0.006	0.022	0.012	0.008	0.030	0.017	0.045	0.031	0.025
300	0.011	0.003	0.014	0.011	0.008	0.020	0.006	0.029	0.014	0.012	0.099	0.015	0.092	0.080	0.049
330	0.013	0.004	0.020	0.015	0.011	0.020	0.009	0.028	0.020	0.016	-	-	-	-	-

Table G. 2 (a) Average still water level, wave height (H_{m0}) and wave period (T_p, T_{m-10}, T_{m01}) for given wind speeds and wind directions, FL2b

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
0	-0.23	0.30	2.25	2.07	1.85	-0.06	0.69	3.10	2.86	2.58	-	-	-	-	-
30	-0.27	0.24	2.16	1.96	1.74	-0.18	0.55	2.98	2.59	2.35	-	-	-	-	-
60	-0.30	0.21	2.21	1.91	1.68	-0.33	0.43	2.92	2.51	2.27	-	-	-	-	-
90	-0.31	0.17	1.63	1.69	1.46	-0.38	0.42	2.33	2.26	2.05	-	-	-	-	-
120	-0.34	0.17	1.79	1.72	1.49	-0.43	0.39	2.47	2.24	2.05	-	-	-	-	-
150	-0.30	0.23	2.20	1.93	1.70	-0.38	0.51	2.97	2.53	2.29	-	-	-	-	-
180	-0.28	0.29	2.39	2.08	1.85	-0.31	0.63	3.29	2.80	2.52	-0.30	1.02	4.09	3.49	3.11
210	-0.24	0.32	2.39	2.11	1.89	-0.21	0.70	3.32	2.89	2.61	-0.24	1.08	4.06	3.52	3.16
240	-0.19	0.34	2.44	2.15	1.92	-0.13	0.77	3.46	3.02	2.73	-0.03	1.18	4.26	3.75	3.36
270	-0.18	0.35	2.56	2.20	1.96	-0.11	0.74	3.61	3.02	2.70	0.12	1.18	4.69	3.98	3.44
300	-0.22	0.34	2.55	2.19	1.93	-0.03	0.72	3.52	2.98	2.67	0.08	1.13	4.56	3.78	3.34
330	-0.21	0.33	2.49	2.16	1.91	-0.15	0.67	3.36	2.88	2.59	0.15	1.13	4.20	3.67	3.23

(b) Number of samples and standard deviation of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]																	
	6						12						18					
	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	424	0.12	0.06	0.28	0.20	0.19	57	0.11	0.08	0.18	0.20	0.16	-	-	-	-	-	-
30	364	0.11	0.05	0.23	0.15	0.15	30	0.12	0.06	0.15	0.09	0.09	-	-	-	-	-	-
60	558	0.12	0.04	0.22	0.13	0.13	36	0.16	0.04	0.19	0.11	0.12	-	-	-	-	-	-
90	582	0.10	0.03	0.28	0.12	0.10	66	0.11	0.04	0.13	0.08	0.10	3	-	-	-	-	-
120	479	0.10	0.03	0.31	0.12	0.12	14	0.06	0.04	0.30	0.12	0.10	-	-	-	-	-	-
150	461	0.11	0.06	0.29	0.18	0.18	49	0.10	0.06	0.16	0.12	0.11	-	-	-	-	-	-
180	660	0.12	0.07	0.27	0.20	0.19	290	0.13	0.07	0.17	0.11	0.11	40	0.09	0.11	0.2	0.13	0.11
210	852	0.13	0.07	0.27	0.20	0.19	955	0.14	0.08	0.19	0.14	0.14	118	0.13	0.14	0.25	0.22	0.18
240	903	0.16	0.07	0.29	0.20	0.19	467	0.15	0.07	0.25	0.16	0.14	107	0.19	0.12	0.26	0.21	0.17
270	621	0.14	0.07	0.30	0.22	0.19	236	0.15	0.06	0.27	0.13	0.12	67	0.14	0.13	0.36	0.32	0.22
300	428	0.13	0.07	0.32	0.30	0.21	126	0.23	0.07	0.24	0.13	0.12	47	0.20	0.10	0.33	0.21	0.16
330	349	0.15	0.07	0.34	0.24	0.21	89	0.16	0.09	0.30	0.20	0.18	21	0.20	0.14	0.5	0.36	0.25

(c) The standard deviation of the mean of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	0.006	0.003	0.014	0.010	0.009	0.015	0.010	0.023	0.026	0.022	-	-	-	-	-
30	0.006	0.003	0.012	0.008	0.008	0.023	0.010	0.027	0.016	0.016	-	-	-	-	-
60	0.005	0.002	0.009	0.006	0.005	0.027	0.007	0.032	0.019	0.019	-	-	-	-	-
90	0.004	0.001	0.012	0.005	0.004	0.013	0.005	0.016	0.010	0.013	-	-	-	-	-
120	0.005	0.001	0.014	0.006	0.005	0.017	0.010	0.080	0.031	0.027	-	-	-	-	-
150	0.005	0.003	0.014	0.008	0.008	0.014	0.008	0.022	0.018	0.015	-	-	-	-	-
180	0.004	0.003	0.011	0.008	0.007	0.007	0.004	0.010	0.007	0.007	0.014	0.017	0.033	0.020	0.017
210	0.004	0.002	0.009	0.007	0.007	0.005	0.003	0.006	0.005	0.004	0.012	0.013	0.023	0.020	0.017
240	0.005	0.002	0.010	0.007	0.006	0.007	0.003	0.012	0.007	0.007	0.018	0.011	0.025	0.020	0.017
270	0.006	0.003	0.012	0.009	0.008	0.010	0.004	0.018	0.009	0.008	0.018	0.016	0.044	0.039	0.026
300	0.006	0.003	0.016	0.014	0.010	0.020	0.006	0.022	0.012	0.011	0.029	0.015	0.048	0.031	0.024
330	0.008	0.003	0.018	0.013	0.011	0.017	0.009	0.032	0.021	0.019	0.043	0.030	0.098	0.078	0.054

Table G. 3 (a) Average still water level, wave height (H_{m0}) and wave period (T_p, T_{m-10}, T_{m01}) for given wind speeds and wind directions, FL5

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
0	-0.23	0.06	1.61	2.24	1.30	-0.09	0.20	1.53	1.77	1.39	-	-	-	-	-
30	-0.21	0.07	1.30	2.03	1.16	-	-	-	-	-	-	-	-	-	-
60	-0.26	0.09	1.46	2.06	1.29	-	-	-	-	-	-	-	-	-	-
90	-0.28	0.13	1.77	2.03	1.42	-	-	-	-	-	-	-	-	-	-
120	-0.28	0.25	2.31	2.03	1.72	-	-	-	-	-	-	-	-	-	-
150	-0.22	0.31	2.57	2.22	1.92	-0.31	0.59	3.46	3.01	2.52	-	-	-	-	-
180	-0.23	0.34	2.67	2.30	1.99	-0.22	0.70	3.59	3.02	2.57	-0.14	1.04	4.65	3.80	3.01
210	-0.24	0.32	2.55	2.22	1.95	-0.13	0.71	3.58	3.04	2.60	0.18	1.18	4.77	4.05	3.26
240	-0.20	0.29	2.43	2.13	1.86	-0.01	0.71	3.56	3.00	2.57	0.15	1.05	4.62	3.84	3.06
270	-0.18	0.25	2.37	2.07	1.79	-0.09	0.56	3.21	2.75	2.35	0.18	0.95	4.40	3.56	2.89
300	-0.19	0.19	2.16	2.01	1.63	-0.14	0.42	2.99	2.51	2.12	0.10	0.76	3.61	3.26	2.62
330	-0.19	0.14	1.92	1.85	1.48	-0.18	0.32	2.59	2.21	1.83	-	-	-	-	-

(b) Number of samples and standard deviation of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]																	
	6						12						18					
	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	164	0.12	0.03	0.83	0.70	0.25	60	0.13	0.06	0.40	0.40	0.17	-	-	-	-	-	-
30	131	0.13	0.05	0.82	0.75	0.23	-	-	-	-	-	-	-	-	-	-	-	-
60	110	0.16	0.03	0.47	0.82	0.21	-	-	-	-	-	-	-	-	-	-	-	-
90	264	0.09	0.04	0.27	0.77	0.15	5	-	-	-	-	-	-	-	-	-	-	-
120	204	0.11	0.07	0.30	0.24	0.18	5	-	-	-	-	-	-	-	-	-	-	-
150	205	0.13	0.09	0.35	0.35	0.24	15	0.08	0.06	0.21	0.14	0.11	-	-	-	-	-	-
180	323	0.12	0.09	0.27	0.28	0.19	92	0.10	0.05	0.18	0.11	0.09	10	0.02	0.02	0.2	0.0471	0.032
210	467	0.14	0.07	0.25	0.21	0.17	514	0.14	0.06	0.19	0.11	0.09	37	0.12	0.15	0.41	0.22	0.16
240	535	0.18	0.06	0.26	0.22	0.16	335	0.20	0.09	0.25	0.14	0.11	76	0.17	0.17	0.23	0.13	0.14
270	330	0.20	0.05	0.25	0.23	0.15	193	0.15	0.06	0.23	0.11	0.08	73	0.13	0.10	0.40	0.18	0.13
300	202	0.14	0.04	0.29	0.42	0.17	59	0.16	0.08	0.15	0.12	0.09	10	0.25	0.15	0.26	0.27	0.23
330	175	0.14	0.05	0.38	0.31	0.17	73	0.13	0.06	0.42	0.23	0.19	8	-	-	-	-	-

(c) The standard deviation of the mean of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	0.009	0.003	0.065	0.054	0.020	0.017	0.008	0.052	0.051	0.023	-	-	-	-	-
30	0.012	0.004	0.072	0.066	0.020	-	-	-	-	-	-	-	-	-	-
60	0.015	0.003	0.045	0.078	0.020	-	-	-	-	-	-	-	-	-	-
90	0.005	0.002	0.017	0.047	0.009	-	-	-	-	-	-	-	-	-	-
120	0.008	0.005	0.021	0.017	0.013	-	-	-	-	-	-	-	-	-	-
150	0.009	0.006	0.024	0.025	0.017	0.022	0.016	0.053	0.036	0.030	-	-	-	-	-
180	0.007	0.005	0.015	0.015	0.010	0.010	0.005	0.019	0.012	0.010	0.007	0.007	0.050	0.015	0.010
210	0.006	0.003	0.012	0.010	0.008	0.006	0.003	0.008	0.005	0.004	0.019	0.025	0.067	0.035	0.026
240	0.008	0.003	0.011	0.010	0.007	0.011	0.005	0.014	0.008	0.006	0.019	0.019	0.027	0.014	0.015
270	0.011	0.003	0.014	0.013	0.008	0.010	0.004	0.017	0.008	0.006	0.015	0.012	0.047	0.021	0.015
300	0.010	0.003	0.020	0.029	0.012	0.021	0.010	0.019	0.016	0.012	0.079	0.049	0.084	0.086	0.074
330	0.011	0.004	0.028	0.023	0.013	0.015	0.007	0.049	0.027	0.022	-	-	-	-	-

Table G. 4 (a) Average still water level, wave height (H_{m0}) and wave period (T_p, T_{m-10}, T_{m01}) for given wind speeds and wind directions, FL9

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
0	-0.22	0.23	1.88	1.80	1.60	-0.08	0.55	2.78	2.51	2.29	-	-	-	-	-
30	-0.22	0.21	1.82	1.76	1.56	-	-	-	-	-	-	-	-	-	-
60	-0.28	0.21	1.98	1.80	1.60	-0.16	0.48	2.84	2.49	2.26	-	-	-	-	-
90	-0.31	0.24	2.10	1.90	1.70	-0.34	0.58	3.02	2.62	2.37	-	-	-	-	-
120	-0.33	0.27	2.14	1.96	1.77	-0.43	0.62	3.02	2.77	2.57	-	-	-	-	-
150	-0.29	0.28	2.40	2.06	1.84	-0.31	0.63	3.30	2.85	2.59	-	-	-	-	-
180	-0.28	0.32	2.47	2.12	1.90	-0.28	0.69	3.41	2.90	2.61	-0.24	1.13	4.25	3.70	3.32
210	-0.21	0.33	2.46	2.13	1.92	-0.19	0.72	3.46	3.00	2.72	-0.15	1.08	4.26	3.75	3.37
240	-0.20	0.34	2.50	2.15	1.93	-0.16	0.72	3.46	2.93	2.63	-0.02	1.18	4.39	3.78	3.36
270	-0.16	0.34	2.50	2.13	1.91	-0.10	0.69	3.45	2.85	2.55	-0.01	1.13	4.49	3.67	3.24
300	-0.17	0.31	2.37	2.07	1.84	-0.12	0.62	3.08	2.68	2.42	-0.13	1.02	3.87	3.40	3.04
330	-0.19	0.26	2.13	1.92	1.70	-0.16	0.57	2.87	2.58	2.33	-	-	-	-	-

(b) Number of samples and standard deviation of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]																	
	6						12						18					
	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	165	0.09	0.05	0.24	0.16	0.15	12	0.15	0.10	0.35	0.25	0.23	-	-	-	-	-	-
30	133	0.10	0.03	0.21	0.10	0.10	5	-	-	-	-	-	-	-	-	-	-	-
60	271	0.10	0.04	0.22	0.11	0.12	23	0.06	0.06	0.16	0.13	0.12	-	-	-	-	-	-
90	199	0.12	0.04	0.17	0.12	0.12	26	0.14	0.12	0.31	0.23	0.21	-	-	-	-	-	-
120	197	0.12	0.06	0.22	0.15	0.16	51	0.13	0.06	0.18	0.08	0.07	-	-	-	-	-	-
150	284	0.12	0.07	0.29	0.18	0.19	66	0.13	0.08	0.20	0.11	0.10	1	-	-	-	-	-
180	267	0.12	0.08	0.31	0.22	0.21	172	0.13	0.06	0.19	0.09	0.09	23	0.09	0.12	0.20	0.13	0.11
210	612	0.14	0.07	0.29	0.21	0.20	583	0.15	0.08	0.20	0.14	0.13	39	0.12	0.15	0.15	0.13	0.13
240	398	0.15	0.08	0.31	0.22	0.21	271	0.16	0.06	0.21	0.13	0.12	90	0.16	0.11	0.26	0.20	0.17
270	322	0.16	0.07	0.33	0.22	0.21	156	0.17	0.06	0.32	0.15	0.12	42	0.16	0.09	0.32	0.22	0.16
300	157	0.17	0.06	0.28	0.17	0.16	64	0.18	0.06	0.28	0.13	0.11	29	0.19	0.06	0.38	0.16	0.14
330	144	0.15	0.05	0.23	0.16	0.16	18	0.12	0.07	0.15	0.18	0.14	5	-	-	-	-	-

(c) The standard deviation of the mean of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	0.007	0.004	0.019	0.012	0.012	0.042	0.029	0.101	0.073	0.066	-	-	-	-	-
30	0.008	0.003	0.018	0.009	0.009	-	-	-	-	-	-	-	-	-	-
60	0.006	0.002	0.014	0.007	0.007	0.012	0.013	0.034	0.028	0.024	-	-	-	-	-
90	0.008	0.003	0.012	0.008	0.009	0.027	0.023	0.061	0.045	0.041	-	-	-	-	-
120	0.008	0.004	0.016	0.011	0.012	0.018	0.008	0.026	0.011	0.009	-	-	-	-	-
150	0.007	0.004	0.017	0.011	0.011	0.016	0.010	0.024	0.014	0.013	-	-	-	-	-
180	0.008	0.005	0.019	0.013	0.013	0.010	0.005	0.014	0.007	0.007	0.018	0.025	0.041	0.027	0.023
210	0.006	0.003	0.012	0.008	0.008	0.006	0.003	0.008	0.006	0.005	0.019	0.024	0.024	0.020	0.020
240	0.007	0.004	0.015	0.011	0.011	0.010	0.004	0.013	0.008	0.007	0.017	0.012	0.027	0.021	0.018
270	0.009	0.004	0.019	0.012	0.012	0.013	0.005	0.026	0.012	0.010	0.025	0.014	0.049	0.034	0.025
300	0.014	0.004	0.022	0.014	0.013	0.022	0.007	0.035	0.016	0.014	0.036	0.012	0.071	0.030	0.026
330	0.013	0.004	0.019	0.014	0.013	0.029	0.016	0.034	0.041	0.033	-	-	-	-	-

Table G. 5 (a) Average still water level, wave height (H_{m0}) and wave period (T_p, T_{m-10}, T_{m01}) for given wind speeds and wind directions, FL25

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
0	-0.34	0.25	2.58	2.14	1.87	-	-	-	-	-	-	-	-	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	-0.31	0.38	2.76	2.36	2.11	-	-	-	-	-	-	-	-	-	-
90	-0.40	0.37	2.66	2.32	2.05	-	-	-	-	-	-	-	-	-	-
120	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
150	-0.43	0.23	2.24	1.97	1.74	-0.36	0.54	3.04	2.64	2.27	-	-	-	-	-
180	-0.37	0.19	2.13	2.03	1.64	-	-	-	-	-	-	-	-	-	-
210	-0.38	0.11	1.40	1.81	1.30	-	-	-	-	-	-	-	-	-	-
240	-0.35	0.09	1.53	1.84	1.19	-	-	-	-	-	-	-	-	-	-
270	-0.34	0.10	1.40	1.80	1.26	-	-	-	-	-	-	-	-	-	-
300	-0.33	0.17	2.43	1.99	1.62	-	-	-	-	-	-	-	-	-	-
330	-0.32	0.25	2.80	2.28	1.93	-0.25	0.49	3.91	2.88	2.39	-	-	-	-	-

(b) Number of samples and standard deviation of water level, Hm0, Tp, Tm-10 and Tm01 for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]																	
	6						12						18					
	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	21	0.03	0.04	0.30	0.16	0.13	2	-	-	-	-	-	-	-	-	-	-	-
30	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	11	0.02	0.02	0.10	0.05	0.03	5	-	-	-	-	-	-	-	-	-	-	-
90	32	0.03	0.02	0.13	0.07	0.06	-	-	-	-	-	-	-	-	-	-	-	-
120	1	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
150	35	0.02	0.03	0.25	0.09	0.09	11	0.01	0.03	0.35	0.07	0.05	-	-	-	-	-	-
180	41	0.05	0.04	0.21	0.26	0.10	-	-	-	-	-	-	-	-	-	-	-	-
210	122	0.04	0.02	0.50	0.12	0.11	-	-	-	-	-	-	-	-	-	-	-	-
240	33	0.05	0.01	0.83	0.18	0.09	-	-	-	-	-	-	-	-	-	-	-	-
270	41	0.05	0.02	0.61	0.17	0.14	1	-	-	-	-	-	-	-	-	-	-	-
300	23	0.06	0.05	0.66	0.35	0.32	-	-	-	-	-	-	-	-	-	-	-	-
330	22	0.02	0.07	0.50	0.34	0.30	10	0.04	0.04	0.40	0.17	0.10	-	-	-	-	-	-

(c) The standard deviation of the mean of water level, Hm0, Tp, Tm-10 and Tm01 for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	0.006	0.008	0.066	0.034	0.028	-	-	-	-	-	-	-	-	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	0.006	0.007	0.031	0.015	0.009	-	-	-	-	-	-	-	-	-	-
90	0.005	0.004	0.023	0.012	0.011	-	-	-	-	-	-	-	-	-	-
120	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
150	0.003	0.005	0.043	0.014	0.016	0.003	0.010	0.106	0.020	0.014	-	-	-	-	-
180	0.008	0.006	0.032	0.040	0.016	-	-	-	-	-	-	-	-	-	-
210	0.004	0.001	0.046	0.011	0.010	-	-	-	-	-	-	-	-	-	-
240	0.009	0.002	0.145	0.031	0.016	-	-	-	-	-	-	-	-	-	-
270	0.008	0.003	0.096	0.026	0.022	-	-	-	-	-	-	-	-	-	-
300	0.012	0.011	0.138	0.073	0.067	-	-	-	-	-	-	-	-	-	-
330	0.005	0.014	0.106	0.072	0.064	0.012	0.013	0.126	0.053	0.031	-	-	-	-	-

Table G. 6 (a) Average still water level, wave height (H_{m0}) and wave period (T_p, T_{m-10}, T_{m01}) for given wind speeds and wind directions, FL26

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
0	-0.20	0.38	2.77	2.38	2.14	-0.10	0.81	3.71	3.17	2.86	-	-	-	-	-
30	-0.24	0.38	2.58	2.40	2.11	-	-	-	-	-	-	-	-	-	-
60	-0.27	0.35	2.52	2.24	2.02	-0.14	0.77	3.44	3.02	2.75	-	-	-	-	-
90	-0.29	0.36	2.49	2.22	2.01	-0.26	0.81	3.44	3.09	2.82	-	-	-	-	-
120	-0.31	0.35	2.48	2.16	1.95	-	-	-	-	-	-	-	-	-	-
150	-0.31	0.31	2.38	2.07	1.85	-0.35	0.70	3.36	2.91	2.64	-	-	-	-	-
180	-0.24	0.28	2.21	1.93	1.73	-0.30	0.66	3.12	2.71	2.43	-	-	-	-	-
210	-0.29	0.27	1.93	1.83	1.65	-0.26	0.64	2.68	2.49	2.28	-0.24	1.05	3.22	3.03	2.77
240	-0.25	0.26	1.95	1.84	1.64	-0.24	0.58	2.71	2.47	2.25	-0.20	0.92	3.18	2.98	2.72
270	-0.23	0.30	2.43	2.08	1.85	-0.19	0.68	3.21	2.80	2.51	-0.14	1.08	4.01	3.51	3.11
300	-0.23	0.34	2.76	2.31	2.05	-0.14	0.74	3.78	3.22	2.85	-0.19	1.11	4.50	3.82	3.35
330	-0.22	0.39	2.90	2.43	2.18	-0.13	0.81	3.89	3.33	2.95	-0.21	1.09	4.53	3.75	3.33

(b) Number of samples and standard deviation of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]																	
	6						12						18					
	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	191	0.18	0.07	0.33	0.24	0.21	83	0.11	0.07	0.27	0.18	0.16	-	-	-	-	-	-
30	254	0.16	0.06	0.26	0.40	0.17	8	-	-	-	-	-	-	-	-	-	-	-
60	239	0.11	0.07	0.29	0.23	0.19	63	0.14	0.06	0.15	0.08	0.08	-	-	-	-	-	-
90	317	0.12	0.08	0.27	0.19	0.19	94	0.11	0.07	0.18	0.10	0.08	-	-	-	-	-	-
120	267	0.10	0.07	0.22	0.19	0.17	8	-	-	-	-	-	-	-	-	-	-	-
150	275	0.12	0.06	0.26	0.18	0.16	31	0.09	0.07	0.19	0.10	0.11	-	-	-	-	-	-
180	397	0.13	0.04	0.21	0.15	0.13	180	0.12	0.06	0.18	0.13	0.11	-	-	-	-	-	-
210	720	0.13	0.04	0.20	0.15	0.11	460	0.17	0.06	0.14	0.10	0.09	58	0.14	0.09	0.14	0.09	0.09
240	543	0.16	0.04	0.32	0.17	0.14	394	0.17	0.07	0.23	0.18	0.16	95	0.19	0.10	0.13	0.12	0.12
270	501	0.17	0.06	0.54	0.31	0.25	220	0.17	0.06	0.48	0.23	0.18	31	0.13	0.06	0.47	0.16	0.13
300	386	0.16	0.07	0.42	0.30	0.26	80	0.16	0.08	0.37	0.24	0.20	20	0.05	0.10	0.41	0.20	0.18
330	222	0.12	0.07	0.32	0.24	0.21	94	0.17	0.10	0.30	0.22	0.18	10	0.05	0.06	0.17	0.10	0.09

(c) The standard deviation of the mean of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	0.013	0.005	0.024	0.017	0.015	0.013	0.008	0.029	0.019	0.018	-	-	-	-	-
30	0.010	0.004	0.016	0.025	0.011	-	-	-	-	-	-	-	-	-	-
60	0.007	0.004	0.019	0.015	0.013	0.017	0.008	0.019	0.010	0.010	-	-	-	-	-
90	0.007	0.004	0.015	0.011	0.011	0.011	0.008	0.018	0.010	0.008	-	-	-	-	-
120	0.006	0.004	0.014	0.012	0.010	-	-	-	-	-	-	-	-	-	-
150	0.007	0.004	0.016	0.011	0.010	0.016	0.012	0.033	0.018	0.019	-	-	-	-	-
180	0.007	0.002	0.011	0.007	0.006	0.009	0.004	0.014	0.009	0.008	-	-	-	-	-
210	0.005	0.001	0.008	0.005	0.004	0.008	0.003	0.007	0.005	0.004	0.018	0.012	0.018	0.012	0.012
240	0.007	0.002	0.014	0.007	0.006	0.008	0.004	0.012	0.009	0.008	0.019	0.011	0.014	0.012	0.013
270	0.008	0.003	0.024	0.014	0.011	0.011	0.004	0.032	0.015	0.012	0.024	0.011	0.084	0.028	0.023
300	0.008	0.004	0.021	0.015	0.013	0.018	0.009	0.041	0.027	0.022	0.010	0.023	0.092	0.045	0.041
330	0.008	0.004	0.021	0.016	0.014	0.018	0.010	0.031	0.023	0.019	0.016	0.020	0.054	0.031	0.030

Table G. 7 (a) Average still water level, wave height (H_{m0}) and wave period (T_p, T_{m-10}, T_{m01}) for given wind speeds and wind directions, FL37

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
0	-0.08	0.33	2.74	2.26	2.00	0.00	0.66	3.50	2.91	2.53		-	-	-	-
30	-0.15	0.33	2.50	2.21	1.99		-	-	-	-		-	-	-	-
60	-0.21	0.32	2.41	2.13	1.90		-	-	-	-		-	-	-	-
90	-0.21	0.33	2.38	2.11	1.90	-0.20	0.63	3.15	2.67	2.37		-	-	-	-
120	-0.26	0.30	2.28	2.01	1.81		-	-	-	-		-	-	-	-
150	-0.27	0.19	1.98	1.80	1.55		-	-	-	-		-	-	-	-
180	-0.21	0.17	1.89	1.75	1.50	-0.32	0.35	2.18	2.01	1.78	-0.49	0.51	2.34	2.25	2.01
210	-0.23	0.14	1.55	1.62	1.32	-0.24	0.33	1.80	1.86	1.67	-0.36	0.60	2.18	2.15	1.99
240	-0.21	0.13	1.49	1.63	1.30	-0.22	0.36	1.95	1.91	1.72	-0.33	0.54	2.06	2.02	1.88
270	-0.19	0.18	2.23	1.89	1.58	-0.13	0.38	2.28	2.14	1.86	-0.09	0.64	2.91	2.70	2.30
300	-0.13	0.25	2.70	2.13	1.84	-0.06	0.44	2.73	2.45	2.10	-0.21	0.84	3.63	3.14	2.62
330	-0.11	0.31	2.75	2.27	1.98	-0.12	0.57	3.43	2.78	2.41		-	-	-	-

(b) Number of samples and standard deviation of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]																	
	6						12						18					
	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	54	0.20	0.07	0.42	0.22	0.21	57	0.12	0.09	0.47	0.27	0.22	-		-	-	-	-
30	21	0.17	0.06	0.34	0.23	0.20	9		-	-	-	-	-		-	-	-	-
60	40	0.15	0.05	0.29	0.17	0.16	4		-	-	-	-	-		-	-	-	-
90	41	0.15	0.04	0.21	0.13	0.11	39	0.10	0.04	0.16	0.10	0.10	-		-	-	-	-
120	42	0.12	0.03	0.16	0.08	0.08	2		-	-	-	-	-		-	-	-	-
150	86	0.08	0.04	0.22	0.13	0.13	1		-	-	-	-	1		-	-	-	-
180	109	0.12	0.04	0.25	0.19	0.13	35	0.13	0.02	0.23	0.08	0.08	12	0.02	0.03	0.12	0.10	0.08
210	173	0.13	0.05	0.37	0.16	0.17	155	0.15	0.03	0.19	0.09	0.08	22	0.05	0.03	0.11	0.05	0.04
240	244	0.13	0.06	0.57	0.18	0.19	157	0.20	0.11	0.50	0.30	0.26	19	0.14	0.03	0.07	0.04	0.04
270	151	0.15	0.06	0.70	0.28	0.26	88	0.18	0.04	0.29	0.18	0.13	27	0.12	0.03	0.49	0.23	0.15
300	111	0.14	0.05	0.56	0.23	0.19	10	0.15	0.06	0.63	0.25	0.19	13	0.08	0.08	0.63	0.29	0.19
330	31	0.12	0.04	0.48	0.19	0.15	16	0.14	0.10	0.83	0.40	0.28	1		-	-	-	-

(c) The standard deviation of the mean of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	0.027	0.009	0.057	0.030	0.028	0.016	0.011	0.062	0.036	0.029		-	-	-	-
30	0.037	0.014	0.073	0.049	0.044		-	-	-	-		-	-	-	-
60	0.024	0.008	0.046	0.027	0.025		-	-	-	-		-	-	-	-
90	0.023	0.007	0.032	0.020	0.017	0.017	0.007	0.025	0.016	0.016		-	-	-	-
120	0.019	0.004	0.025	0.012	0.012		-	-	-	-		-	-	-	-
150	0.008	0.004	0.024	0.014	0.014		-	-	-	-		-	-	-	-
180	0.011	0.004	0.024	0.018	0.013	0.023	0.004	0.039	0.014	0.013	0.006	0.009	0.036	0.029	0.023
210	0.010	0.004	0.028	0.012	0.013	0.012	0.003	0.016	0.007	0.006	0.011	0.006	0.024	0.011	0.007
240	0.008	0.004	0.036	0.012	0.012	0.016	0.008	0.040	0.024	0.021	0.032	0.007	0.016	0.010	0.009
270	0.012	0.005	0.057	0.023	0.021	0.020	0.004	0.031	0.019	0.013	0.022	0.009	0.094	0.044	0.030
300	0.013	0.004	0.053	0.022	0.018	0.049	0.020	0.201	0.081	0.060	0.021	0.022	0.176	0.081	0.053
330	0.022	0.007	0.087	0.034	0.026	0.036	0.025	0.207	0.100	0.071					

Table G. 8 (a) Average still water level, wave height (H_{m0}) and wave period (T_p, T_{m-10}, T_{m01}) for given wind speeds and wind directions, FL42

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
0	-0.23	0.31	2.42	2.09	1.88	-0.27	0.60	3.12	2.78	2.55	-	-	-	-	-
30	-0.23	0.28	2.32	2.04	1.83	-0.24	0.64	3.30	2.84	2.59	-	-	-	-	-
60	-0.25	0.28	2.39	2.09	1.88	-0.26	0.61	3.33	2.90	2.64	-	-	-	-	-
90	-0.28	0.28	2.40	2.12	1.91	-	-	-	-	-	-	-	-	-	-
120	-0.30	0.25	2.25	2.02	1.82	-	-	-	-	-	-	-	-	-	-
150	-0.30	0.26	2.12	1.92	1.73	-0.28	0.63	3.08	2.78	2.56	-	-	-	-	-
180	-0.29	0.26	2.18	1.92	1.72	-0.30	0.63	3.09	2.72	2.48	-	-	-	-	-
210	-0.26	0.26	2.25	1.95	1.74	-0.26	0.61	3.18	2.76	2.50	-0.25	0.99	4.01	3.47	3.12
240	-0.26	0.30	2.27	2.01	1.80	-0.25	0.69	3.16	2.82	2.57	-0.20	1.03	3.86	3.42	3.10
270	-0.24	0.30	2.28	1.99	1.79	-0.27	0.71	3.18	2.82	2.58	-0.24	1.03	3.84	3.39	3.06
300	-0.22	0.31	2.38	2.05	1.84	-0.19	0.66	3.22	2.79	2.54	-	-	-	-	-
330	-0.24	0.31	2.33	2.05	1.85	-0.20	0.65	3.20	2.79	2.56	-	-	-	-	-

(b) Number of samples and standard deviation of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]																	
	6						12						18					
	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	215	0.09	0.07	0.29	0.19	0.19	23	0.06	0.04	0.17	0.14	0.13	-	-	-	-	-	-
30	283	0.09	0.07	0.33	0.21	0.21	32	0.03	0.04	0.14	0.08	0.09	-	-	-	-	-	-
60	287	0.08	0.06	0.28	0.20	0.20	18	0.07	0.06	0.19	0.10	0.09	-	-	-	-	-	-
90	249	0.10	0.05	0.27	0.17	0.17	5	-	-	-	-	-	-	-	-	-	-	-
120	210	0.08	0.05	0.24	0.16	0.16	4	-	-	-	-	-	-	-	-	-	-	-
150	425	0.07	0.06	0.24	0.16	0.17	66	0.06	0.06	0.14	0.09	0.10	1	-	-	-	-	-
180	426	0.07	0.06	0.26	0.17	0.18	115	0.06	0.07	0.14	0.09	0.10	9	-	-	-	-	-
210	855	0.09	0.06	0.26	0.17	0.17	513	0.07	0.05	0.15	0.11	0.10	55	0.09	0.10	0.22	0.16	0.14
240	491	0.08	0.07	0.27	0.20	0.19	295	0.07	0.06	0.16	0.12	0.11	142	0.07	0.07	0.18	0.11	0.09
270	384	0.09	0.07	0.29	0.21	0.20	207	0.08	0.04	0.16	0.10	0.09	37	0.08	0.09	0.24	0.18	0.15
300	289	0.09	0.06	0.25	0.19	0.18	76	0.09	0.05	0.21	0.14	0.12	6	-	-	-	-	-
330	235	0.08	0.06	0.26	0.19	0.18	20	0.09	0.06	0.21	0.14	0.15	-	-	-	-	-	-

(c) The standard deviation of the mean of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	0.006	0.005	0.020	0.013	0.013	0.012	0.009	0.035	0.029	0.027	-	-	-	-	-
30	0.005	0.004	0.019	0.013	0.013	0.006	0.008	0.024	0.015	0.016	-	-	-	-	-
60	0.005	0.004	0.017	0.012	0.012	0.016	0.015	0.046	0.024	0.022	-	-	-	-	-
90	0.006	0.003	0.017	0.011	0.011	-	-	-	-	-	-	-	-	-	-
120	0.005	0.003	0.016	0.011	0.011	-	-	-	-	-	-	-	-	-	-
150	0.004	0.003	0.012	0.008	0.008	0.007	0.008	0.018	0.011	0.012	-	-	-	-	-
180	0.004	0.003	0.013	0.008	0.009	0.006	0.007	0.013	0.009	0.009	-	-	-	-	-
210	0.003	0.002	0.009	0.006	0.006	0.003	0.002	0.007	0.005	0.005	0.012	0.013	0.030	0.022	0.019
240	0.004	0.003	0.012	0.009	0.009	0.004	0.003	0.009	0.007	0.007	0.006	0.006	0.016	0.009	0.008
270	0.005	0.004	0.015	0.010	0.010	0.005	0.003	0.011	0.007	0.006	0.014	0.014	0.040	0.029	0.025
300	0.005	0.003	0.015	0.011	0.010	0.011	0.006	0.024	0.016	0.014	-	-	-	-	-
330	0.005	0.004	0.017	0.012	0.012	0.020	0.012	0.048	0.031	0.033	-	-	-	-	-

Table G. 9 (a) Average still water level, wave height (H_{m0}) and wave period (T_p, T_{m-10}, T_{m01}) for given wind speeds and wind directions, FL44

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
0	-0.35	0.29	2.29	2.04	1.81	-	-	-	-	-	-	-	-	-	-
30	-0.33	0.22	2.01	1.82	1.59	-	-	-	-	-	-	-	-	-	-
60	-0.31	0.17	1.73	1.70	1.44	-	-	-	-	-	-	-	-	-	-
90	-0.45	0.19	1.84	1.72	1.53	-	-	-	-	-	-	-	-	-	-
120	-0.36	0.15	1.63	1.67	1.36	-	-	-	-	-	-	-	-	-	-
150	-0.38	0.17	1.80	1.67	1.44	-	-	-	-	-	-	-	-	-	-
180	-0.34	0.23	2.10	1.84	1.61	-0.29	0.59	3.01	2.61	2.37	-	-	-	-	-
210	-0.28	0.29	2.36	2.01	1.78	-0.21	0.67	3.38	2.86	2.57	-0.02	1.17	4.55	3.82	3.40
240	-0.28	0.34	2.58	2.19	1.94	-0.21	0.72	3.54	2.99	2.69	0.03	1.17	4.40	3.81	3.39
270	-0.24	0.36	2.61	2.19	1.95	-0.22	0.73	3.50	2.97	2.67	-0.10	1.10	4.27	3.63	3.25
300	-0.22	0.37	2.57	2.23	2.00	-0.17	0.70	3.33	2.86	2.58	-	-	-	-	-
330	-0.28	0.33	2.37	2.12	1.88	-0.21	0.78	3.41	2.93	2.69	-	-	-	-	-

(b) Number of samples and standard deviation of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]																	
	6						12						18					
	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	38	0.08	0.09	0.34	0.23	0.24	6	-	-	-	-	-	-	-	-	-	-	-
30	37	0.10	0.07	0.33	0.14	0.20	9	-	-	-	-	-	-	-	-	-	-	-
60	34	0.10	0.03	0.24	0.14	0.10	5	-	-	-	-	-	-	-	-	-	-	-
90	45	0.02	0.03	0.16	0.09	0.09	-	-	-	-	-	-	-	-	-	-	-	-
120	26	0.12	0.02	0.13	0.16	0.07	-	-	-	-	-	-	-	-	-	-	-	-
150	69	0.09	0.03	0.40	0.16	0.14	6	-	-	-	-	-	-	-	-	-	-	-
180	119	0.10	0.07	0.37	0.21	0.20	15	0.09	0.09	0.31	0.27	0.25	6	-	-	-	-	-
210	150	0.12	0.08	0.32	0.22	0.22	113	0.10	0.08	0.26	0.17	0.15	26	0.15	0.11	0.33	0.25	0.20
240	131	0.10	0.10	0.38	0.26	0.26	73	0.13	0.08	0.22	0.16	0.14	24	0.15	0.12	0.33	0.25	0.21
270	103	0.11	0.08	0.29	0.21	0.22	59	0.11	0.06	0.23	0.12	0.11	22	0.10	0.12	0.28	0.23	0.20
300	65	0.11	0.08	0.25	0.17	0.17	30	0.11	0.08	0.20	0.15	0.14	3	-	-	-	-	-
330	60	0.09	0.07	0.27	0.23	0.19	10	0.08	0.04	0.20	0.09	0.10	-	-	-	-	-	-

(c) The standard deviation of the mean of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	0.012	0.015	0.055	0.037	0.039	-	-	-	-	-	-	-	-	-	-
30	0.016	0.012	0.055	0.023	0.033	-	-	-	-	-	-	-	-	-	-
60	0.017	0.006	0.042	0.024	0.018	-	-	-	-	-	-	-	-	-	-
90	0.004	0.004	0.024	0.014	0.014	-	-	-	-	-	-	-	-	-	-
120	0.023	0.004	0.025	0.031	0.014	-	-	-	-	-	-	-	-	-	-
150	0.011	0.004	0.048	0.019	0.017	-	-	-	-	-	-	-	-	-	-
180	0.010	0.006	0.034	0.019	0.019	0.023	0.025	0.080	0.069	0.065	-	-	-	-	-
210	0.010	0.006	0.026	0.018	0.018	0.009	0.007	0.025	0.016	0.014	0.029	0.022	0.064	0.048	0.040
240	0.009	0.008	0.033	0.022	0.022	0.015	0.009	0.026	0.018	0.016	0.031	0.024	0.066	0.051	0.044
270	0.011	0.008	0.028	0.021	0.021	0.015	0.008	0.030	0.016	0.014	0.021	0.025	0.060	0.049	0.042
300	0.013	0.009	0.031	0.021	0.021	0.020	0.015	0.036	0.027	0.025	-	-	-	-	-
330	0.011	0.009	0.035	0.030	0.024	0.027	0.012	0.062	0.030	0.031	-	-	-	-	-

Table G. 10 (a) Average still water level, wave height (H_{m0}) and wave period (T_p, T_{m-10}, T_{m01}) for given wind speeds and wind directions, FL46

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
0	-0.23	0.33	2.50	2.22	1.99	-	-	-	-	-	-	-	-	-	-
30	-0.25	0.30	2.37	2.10	1.90	-0.09	0.67	3.29	2.88	2.65	-	-	-	-	-
60	-0.25	0.28	2.34	2.03	1.84	-0.18	0.61	2.99	2.64	2.43	-	-	-	-	-
90	-0.30	0.27	2.10	1.94	1.76	-0.42	0.65	3.02	2.77	2.59	-	-	-	-	-
120	-0.30	0.27	2.25	1.98	1.79	-0.39	0.63	3.13	2.72	2.48	-	-	-	-	-
150	-0.30	0.28	2.26	1.99	1.79	-0.28	0.68	3.19	2.78	2.56	-	-	-	-	-
180	-0.29	0.29	2.26	1.99	1.80	-0.29	0.66	3.09	2.71	2.48	-0.36	0.95	3.73	3.25	2.99
210	-0.21	0.29	2.19	1.93	1.73	-0.27	0.66	3.00	2.68	2.46	-0.33	1.03	3.66	3.32	3.07
240	-0.16	0.32	2.31	2.05	1.84	-0.18	0.76	3.15	2.84	2.61	-0.02	1.19	3.95	3.55	3.27
270	-0.13	0.33	2.57	2.15	1.92	-0.10	0.74	3.46	2.95	2.67	-	-	-	-	-
300	-0.10	0.36	2.72	2.28	2.03	-0.03	0.76	3.65	3.12	2.80	0.09	1.12	4.55	3.85	3.45
330	-0.16	0.35	2.60	2.24	2.01	-0.05	0.74	3.58	3.08	2.81	-	-	-	-	-

(b) Number of samples and standard deviation of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]																	
	6						12						18					
	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	128	0.09	0.08	0.37	0.27	0.28	5	-	-	-	-	-	-	-	-	-	-	-
30	189	0.10	0.07	0.27	0.19	0.21	14	0.06	0.07	0.14	0.09	0.10	-	-	-	-	-	-
60	142	0.09	0.05	0.23	0.15	0.15	10	0.09	0.02	0.16	0.11	0.11	-	-	-	-	-	-
90	112	0.10	0.05	0.19	0.13	0.14	20	0.05	0.05	0.11	0.12	0.11	3	-	-	-	-	-
120	112	0.11	0.04	0.21	0.15	0.15	13	0.02	0.04	0.12	0.12	0.10	-	-	-	-	-	-
150	144	0.09	0.07	0.22	0.15	0.15	12	0.06	0.10	0.24	0.17	0.13	-	-	-	-	-	-
180	181	0.10	0.07	0.25	0.17	0.17	110	0.11	0.04	0.12	0.09	0.08	13	0.09	0.06	0.16	0.10	0.10
210	250	0.14	0.06	0.25	0.17	0.17	203	0.13	0.07	0.13	0.10	0.09	24	0.14	0.11	0.26	0.17	0.15
240	309	0.18	0.06	0.29	0.18	0.17	119	0.17	0.06	0.18	0.12	0.11	17	0.24	0.08	0.15	0.08	0.08
270	147	0.16	0.06	0.37	0.22	0.20	46	0.16	0.06	0.35	0.16	0.14	8	-	-	-	-	-
300	79	0.19	0.08	0.43	0.29	0.27	59	0.19	0.05	0.24	0.13	0.11	31	0.22	0.09	0.49	0.16	0.14
330	143	0.17	0.08	0.41	0.27	0.26	31	0.21	0.06	0.18	0.12	0.10	3	-	-	-	-	-

(c) The standard deviation of the mean of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	0.008	0.007	0.032	0.024	0.025	-	-	-	-	-	-	-	-	-	-
30	0.007	0.005	0.020	0.014	0.015	0.017	0.019	0.036	0.024	0.027	-	-	-	-	-
60	0.008	0.004	0.019	0.013	0.012	0.027	0.007	0.050	0.034	0.033	-	-	-	-	-
90	0.009	0.005	0.018	0.013	0.013	0.011	0.010	0.025	0.026	0.024	-	-	-	-	-
120	0.011	0.004	0.020	0.014	0.014	0.005	0.010	0.033	0.032	0.028	-	-	-	-	-
150	0.007	0.006	0.019	0.013	0.013	0.016	0.028	0.069	0.049	0.038	-	-	-	-	-
180	0.007	0.005	0.019	0.013	0.012	0.010	0.004	0.012	0.009	0.008	0.026	0.016	0.044	0.027	0.029
210	0.009	0.004	0.016	0.010	0.010	0.009	0.005	0.009	0.007	0.007	0.028	0.023	0.052	0.035	0.030
240	0.010	0.004	0.017	0.010	0.009	0.015	0.005	0.017	0.011	0.010	0.059	0.020	0.035	0.019	0.019
270	0.013	0.005	0.030	0.018	0.016	0.024	0.009	0.051	0.023	0.020	-	-	-	-	-
300	0.021	0.009	0.049	0.033	0.031	0.025	0.007	0.031	0.016	0.015	0.040	0.017	0.088	0.028	0.025
330	0.014	0.007	0.034	0.023	0.022	0.039	0.010	0.032	0.021	0.018	-	-	-	-	-

Table G. 11 (a) Average still water level, wave height (H_{m0}) and wave period (T_p, T_{m-10}, T_{m01}) for given wind speeds and wind directions, FL47

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
0	-0.27	0.32	2.51	2.16	1.93	-0.24	0.66	3.37	2.94	2.66	-	-	-	-	-
30	-0.29	0.32	2.55	2.21	1.97	-0.20	0.67	3.40	2.95	2.70	-	-	-	-	-
60	-0.25	0.31	2.42	2.16	1.93	-0.36	0.58	3.24	2.84	2.58	-	-	-	-	-
90	-0.30	0.31	2.41	2.19	1.96	-0.32	0.62	3.22	2.79	2.66	-	-	-	-	-
120	-0.32	0.31	2.57	2.31	1.98	-0.27	0.70	3.48	2.97	2.76	-	-	-	-	-
150	-0.29	0.30	2.55	2.22	1.94	-0.26	0.66	3.49	2.83	2.70	-	-	-	-	-
180	-0.28	0.29	2.42	2.12	1.86	-0.25	0.71	3.40	2.80	2.70	-0.11	1.18	4.36	3.75	3.48
210	-0.25	0.29	2.39	2.07	1.83	-0.19	0.69	3.37	2.81	2.65	-0.18	1.16	4.22	2.84	3.35
240	-0.22	0.30	2.22	2.03	1.78	-0.24	0.70	3.08	2.73	2.55	-0.28	1.10	3.82	3.47	3.15
270	-0.22	0.28	2.20	1.92	1.71	-0.26	0.63	3.01	2.49	2.40	-0.32	1.04	3.67	3.29	3.02
300	-0.20	0.31	2.30	2.03	1.82	-0.29	0.67	3.14	2.75	2.53	-0.49	1.02	4.01	3.53	3.15
330	-0.29	0.32	2.41	2.13	1.90	-0.20	0.66	3.33	2.83	2.63	-	-	-	-	-

(b) Number of samples and standard deviation of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]																	
	6						12						18					
	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	255	0.08	0.06	0.28	0.21	0.18	15	0.13	0.09	0.21	0.18	0.16	-	-	-	-	-	-
30	151	0.09	0.06	0.27	0.20	0.18	42	0.12	0.09	0.21	0.16	0.12	-	-	-	-	-	-
60	247	0.11	0.06	0.30	0.21	0.20	67	0.13	0.05	0.13	0.07	0.07	-	-	-	-	-	-
90	280	0.10	0.06	0.26	0.26	0.18	41	0.06	0.04	0.11	0.24	0.09	2	-	-	-	-	-
120	217	0.12	0.06	0.32	0.35	0.21	57	0.10	0.06	0.21	0.23	0.15	1	-	-	-	-	-
150	266	0.12	0.06	0.32	0.37	0.21	141	0.11	0.06	0.22	0.43	0.13	-	-	-	-	-	-
180	518	0.12	0.07	0.34	0.31	0.22	226	0.10	0.05	0.19	0.44	0.14	72	0.10	0.10	0.23	0.49	0.14
210	458	0.13	0.06	0.28	0.23	0.19	204	0.13	0.09	0.23	0.34	0.16	63	0.08	0.14	0.33	0.81	0.16
240	328	0.14	0.06	0.26	0.29	0.18	261	0.16	0.07	0.19	0.23	0.12	93	0.10	0.09	0.23	0.16	0.12
270	258	0.16	0.06	0.26	0.19	0.18	100	0.15	0.06	0.16	0.35	0.13	46	0.16	0.08	0.18	0.15	0.12
300	186	0.17	0.05	0.21	0.17	0.16	63	0.16	0.05	0.18	0.18	0.14	47	0.11	0.06	0.25	0.16	0.12
330	211	0.13	0.07	0.29	0.24	0.19	38	0.15	0.07	0.21	0.20	0.14	2	-	-	-	-	-

(c) The standard deviation of the mean of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	0.005	0.004	0.018	0.013	0.012	0.034	0.022	0.055	0.047	0.042	-	-	-	-	-
30	0.007	0.005	0.022	0.016	0.014	0.018	0.014	0.033	0.025	0.018	-	-	-	-	-
60	0.007	0.004	0.019	0.013	0.012	0.016	0.006	0.016	0.009	0.008	-	-	-	-	-
90	0.006	0.003	0.015	0.016	0.011	0.009	0.006	0.018	0.037	0.015	-	-	-	-	-
120	0.008	0.004	0.022	0.024	0.014	0.013	0.007	0.027	0.030	0.020	-	-	-	-	-
150	0.008	0.004	0.019	0.023	0.013	0.010	0.005	0.018	0.036	0.011	-	-	-	-	-
180	0.005	0.003	0.015	0.014	0.010	0.007	0.004	0.012	0.029	0.009	0.011	0.011	0.027	0.058	0.017
210	0.006	0.003	0.013	0.011	0.009	0.009	0.006	0.016	0.024	0.012	0.010	0.018	0.042	0.102	0.020
240	0.008	0.003	0.014	0.016	0.010	0.010	0.004	0.012	0.014	0.007	0.011	0.009	0.024	0.016	0.012
270	0.010	0.004	0.016	0.012	0.011	0.015	0.006	0.016	0.035	0.013	0.023	0.011	0.026	0.021	0.018
300	0.012	0.004	0.015	0.013	0.012	0.020	0.007	0.023	0.022	0.017	0.016	0.008	0.037	0.023	0.017
330	0.009	0.005	0.020	0.017	0.013	0.025	0.011	0.034	0.032	0.023	-	-	-	-	-

Table G. 12 (a) Average still water level, wave height (H_{m0}) and wave period (T_p, T_{m-10}, T_{m01}) for given wind speeds and wind directions, FL48

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
0	-0.28	0.29	2.37	2.03	1.80	-0.18	0.56	2.99	2.58	2.31	-	-	-	-	-
30	-0.27	0.29	2.46	2.10	1.87	-0.17	0.62	3.43	2.75	2.46	-	-	-	-	-
60	-0.24	0.31	2.51	2.18	1.96	-0.08	0.65	3.42	2.94	2.65	-	-	-	-	-
90	-0.28	0.31	2.55	2.24	2.01	-0.30	0.62	3.55	3.03	2.73	-	-	-	-	-
120	-0.31	0.30	2.62	2.21	1.97	-0.28	0.60	3.57	2.96	2.64	-	-	-	-	-
150	-0.28	0.27	2.47	2.12	1.88	-0.23	0.58	3.35	2.85	2.53	-	-	-	-	-
180	-0.29	0.25	2.29	2.03	1.78	-0.28	0.53	3.02	2.64	2.36	-0.17	0.87	3.70	3.29	2.91
210	-0.26	0.20	2.12	1.85	1.59	-0.24	0.44	2.75	2.35	2.10	-0.31	0.76	2.99	2.77	2.51
240	-0.21	0.17	1.49	1.55	1.32	-0.27	0.39	2.09	2.01	1.85	-0.29	0.69	2.64	2.50	2.34
270	-0.19	0.18	1.73	1.62	1.38	-0.28	0.43	2.26	2.07	1.90	-0.50	0.74	2.75	2.54	2.36
300	-0.19	0.21	1.97	1.73	1.51	-0.20	0.45	2.63	2.26	2.04	-0.54	0.66	3.06	2.65	2.39
330	-0.28	0.26	2.11	1.88	1.66	-0.23	0.51	2.84	2.45	2.21	-	-	-	-	-

(b) Number of samples and standard deviation of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]																	
	6						12						18					
	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	260	0.10	0.06	0.30	0.17	0.16	36	0.11	0.07	0.26	0.14	0.11	1	-	-	-	-	-
30	189	0.10	0.06	0.33	0.19	0.19	30	0.17	0.05	0.19	0.08	0.08	2	-	-	-	-	-
60	223	0.11	0.07	0.37	0.23	0.23	39	0.10	0.07	0.18	0.13	0.11	-	-	-	-	-	-
90	292	0.12	0.07	0.30	0.22	0.21	45	0.07	0.04	0.17	0.09	0.09	2	-	-	-	-	-
120	217	0.12	0.06	0.39	0.23	0.22	122	0.08	0.04	0.33	0.13	0.12	-	-	-	-	-	-
150	286	0.13	0.06	0.41	0.25	0.24	85	0.09	0.04	0.36	0.15	0.15	-	-	-	-	-	-
180	534	0.11	0.05	0.35	0.22	0.21	175	0.10	0.04	0.15	0.14	0.13	40	0.07	0.08	0.18	0.15	0.13
210	657	0.12	0.04	0.40	0.23	0.21	211	0.13	0.04	0.33	0.22	0.19	54	0.12	0.08	0.44	0.23	0.19
240	404	0.16	0.03	0.35	0.17	0.15	315	0.17	0.04	0.11	0.09	0.09	89	0.15	0.07	0.11	0.08	0.07
270	297	0.15	0.03	0.36	0.17	0.14	201	0.15	0.03	0.17	0.10	0.08	17	0.12	0.04	0.10	0.07	0.05
300	262	0.17	0.04	0.33	0.17	0.17	73	0.22	0.04	0.23	0.12	0.11	28	0.24	0.06	0.23	0.11	0.10
330	249	0.12	0.06	0.30	0.19	0.19	41	0.15	0.05	0.18	0.09	0.07	2	-	-	-	-	-

(c) The standard deviation of the mean of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	0.006	0.004	0.019	0.011	0.010	0.018	0.012	0.043	0.023	0.019	-	-	-	-	-
30	0.007	0.004	0.024	0.014	0.014	0.030	0.010	0.036	0.014	0.014	-	-	-	-	-
60	0.007	0.005	0.024	0.016	0.016	0.016	0.010	0.028	0.020	0.017	-	-	-	-	-
90	0.007	0.004	0.018	0.013	0.012	0.011	0.006	0.025	0.014	0.014	-	-	-	-	-
120	0.008	0.004	0.027	0.015	0.015	0.007	0.003	0.030	0.012	0.011	-	-	-	-	-
150	0.008	0.003	0.024	0.015	0.014	0.010	0.005	0.039	0.017	0.016	-	-	-	-	-
180	0.005	0.002	0.015	0.010	0.009	0.007	0.003	0.011	0.011	0.010	0.011	0.012	0.029	0.023	0.021
210	0.005	0.002	0.015	0.009	0.008	0.009	0.003	0.023	0.015	0.013	0.017	0.011	0.059	0.032	0.025
240	0.008	0.001	0.017	0.008	0.007	0.009	0.002	0.006	0.005	0.005	0.016	0.007	0.012	0.009	0.007
270	0.009	0.002	0.021	0.010	0.008	0.010	0.002	0.012	0.007	0.006	0.028	0.009	0.024	0.017	0.012
300	0.011	0.003	0.020	0.010	0.010	0.026	0.005	0.026	0.014	0.013	0.046	0.012	0.043	0.021	0.019
330	0.008	0.004	0.019	0.012	0.012	0.023	0.007	0.028	0.014	0.011	-	-	-	-	-

Table G. 13 (a) Average still water level, wave height (H_{m0}) and wave period (T_p, T_{m-10}, T_{m01}) for given wind speeds and wind directions, FL49

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]	[m]	[m]	[s]	[s]	[s]
0	-0.28	0.27	2.31	2.01	1.78	-0.20	0.55	2.96	2.53	2.25	-	-	-	-	-
30	-0.27	0.29	2.47	2.11	1.88	-0.16	0.59	3.31	2.76	2.42	-	-	-	-	-
60	-0.24	0.30	2.56	2.21	1.98	-0.18	0.59	3.44	2.91	2.62	-	-	-	-	-
90	-0.29	0.32	2.61	2.27	2.05	-0.27	0.64	3.69	3.10	2.76	-	-	-	-	-
120	-0.31	0.31	2.62	2.23	1.98	-0.30	0.61	3.72	3.04	2.71	-	-	-	-	-
150	-0.30	0.28	2.53	2.17	1.92	-0.22	0.62	3.39	2.85	2.53	-	-	-	-	-
180	-0.29	0.25	2.43	2.09	1.82	-0.24	0.52	3.14	2.66	2.32	-0.27	0.75	3.55	3.04	2.67
210	-0.27	0.18	2.16	1.86	1.54	-0.26	0.37	2.48	2.15	1.88	-0.39	0.66	2.30	2.38	2.17
240	-0.24	0.14	1.37	1.53	1.22	-0.30	0.30	1.83	1.76	1.60	-0.42	0.56	2.23	2.15	2.02
270	-0.21	0.15	1.66	1.60	1.32	-0.31	0.35	2.11	1.93	1.74	-0.58	0.61	2.35	2.25	2.07
300	-0.25	0.20	2.02	1.79	1.53	-0.37	0.40	2.61	2.26	2.02	-0.66	0.55	2.96	2.53	2.28
330	-0.30	0.25	2.13	1.90	1.68	-0.31	0.50	2.94	2.52	2.26	-	-	-	-	-

(b) Number of samples and standard deviation of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]																	
	6						12						18					
	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	Num	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	346	0.10	0.06	0.36	0.21	0.20	22	0.12	0.08	0.33	0.15	0.13	-	-	-	-	-	-
30	180	0.09	0.04	0.27	0.15	0.13	29	0.15	0.04	0.32	0.14	0.13	1	-	-	-	-	-
60	231	0.11	0.06	0.34	0.22	0.20	57	0.15	0.05	0.19	0.12	0.11	1	-	-	-	-	-
90	242	0.12	0.06	0.35	0.23	0.22	14	0.11	0.07	0.34	0.26	0.20	8	-	-	-	-	-
120	158	0.12	0.05	0.34	0.20	0.18	105	0.06	0.04	0.23	0.11	0.10	-	-	-	-	-	-
150	189	0.12	0.05	0.35	0.20	0.19	48	0.09	0.07	0.36	0.20	0.17	1	-	-	-	-	-
180	592	0.10	0.05	0.33	0.22	0.21	119	0.13	0.05	0.29	0.18	0.17	13	0.08	0.14	0.81	0.30	0.25
210	578	0.13	0.04	0.54	0.24	0.22	192	0.12	0.04	0.52	0.18	0.15	36	0.05	0.08	0.22	0.12	0.09
240	394	0.12	0.03	0.51	0.20	0.17	216	0.15	0.02	0.13	0.08	0.07	46	0.12	0.04	0.08	0.06	0.05
270	275	0.15	0.03	0.42	0.21	0.20	130	0.12	0.05	0.33	0.20	0.18	14	0.08	0.03	0.10	0.07	0.06
300	220	0.12	0.04	0.36	0.22	0.21	40	0.09	0.04	0.27	0.14	0.12	11	0.08	0.05	0.20	0.16	0.12
330	217	0.11	0.06	0.31	0.20	0.20	19	0.08	0.05	0.23	0.10	0.09	-	-	-	-	-	-

(c) The standard deviation of the mean of water level, H_{m0}, T_p, T_{m-10} and T_{m01} for given wind speeds and wind directions

wind dir. [deg.]	wind speed [m/s]														
	6					12					18				
	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}	SWL	H_{m0}	T_p	T_{m-10}	T_{m01}
0	0.005	0.003	0.019	0.011	0.011	0.026	0.016	0.071	0.032	0.027	-	-	-	-	-
30	0.007	0.003	0.020	0.011	0.010	0.028	0.008	0.060	0.027	0.024	-	-	-	-	-
60	0.007	0.004	0.022	0.014	0.013	0.020	0.007	0.025	0.016	0.015	-	-	-	-	-
90	0.008	0.004	0.022	0.015	0.014	0.031	0.020	0.090	0.070	0.053	-	-	-	-	-
120	0.009	0.004	0.027	0.016	0.015	0.006	0.004	0.022	0.011	0.009	-	-	-	-	-
150	0.008	0.004	0.026	0.014	0.014	0.014	0.011	0.053	0.029	0.025	-	-	-	-	-
180	0.004	0.002	0.014	0.009	0.008	0.012	0.005	0.026	0.016	0.016	0.023	0.038	0.225	0.084	0.068
210	0.005	0.002	0.022	0.010	0.009	0.009	0.003	0.037	0.013	0.011	0.009	0.013	0.036	0.019	0.015
240	0.006	0.001	0.026	0.010	0.008	0.010	0.002	0.009	0.005	0.005	0.018	0.006	0.012	0.009	0.007
270	0.009	0.002	0.025	0.013	0.012	0.011	0.004	0.029	0.018	0.016	0.020	0.009	0.027	0.017	0.016
300	0.008	0.003	0.024	0.015	0.014	0.014	0.006	0.043	0.023	0.019	0.024	0.015	0.061	0.047	0.035
330	0.007	0.004	0.021	0.014	0.014	0.018	0.011	0.054	0.022	0.021	-	-	-	-	-

Appendix H. Wave height as a function of effective fetch

The appendix represents the average wave height (H_{m0}) as a function of effective fetch for a range of wind speeds, for the locations which have wind directions. The wave height was averaged for 1km fetch interval and for 6 m/s, 9 m/s, 12 m/s, 15m/s and 18m/s wind speeds.

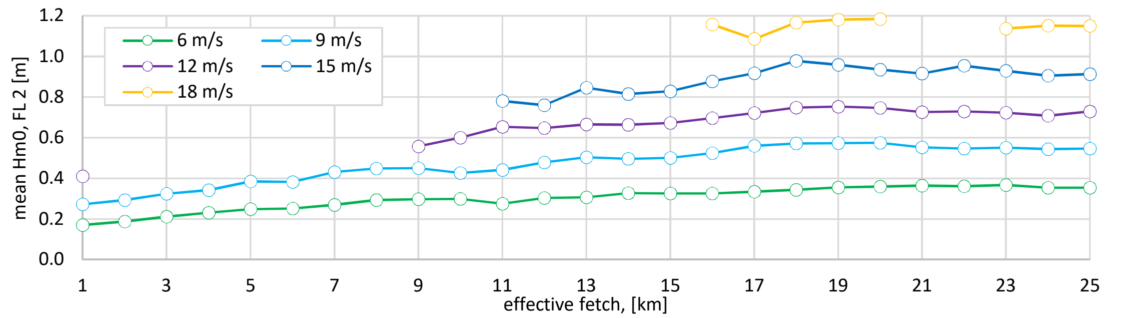

Figure H- 1 Average significant wave height (H_{m0}) as a function of fetch, for given ranges of wind speeds, FL2

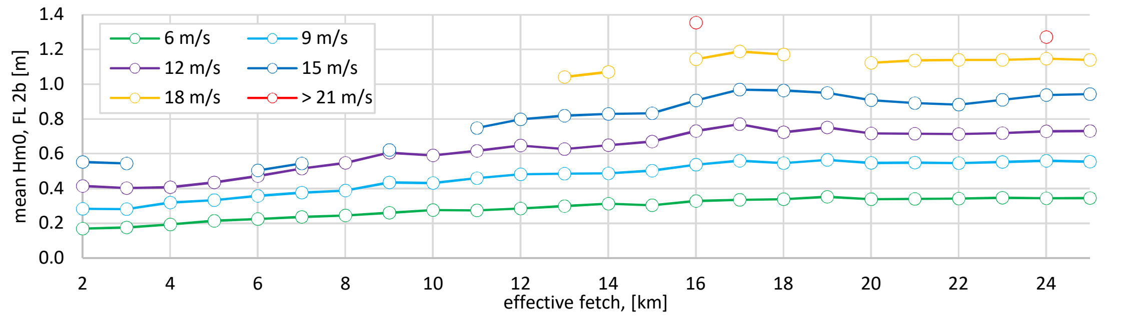

Figure H- 2 Average significant wave height (H_{m0}) as a function of fetch, for given ranges of wind speeds, FL2b

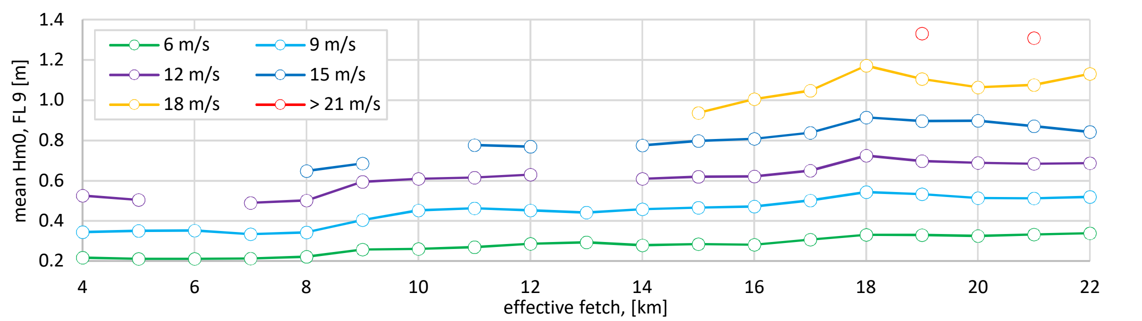

Figure H- 3 Average significant wave height (H_{m0}) as a function of fetch, for given ranges of wind speeds, FL9

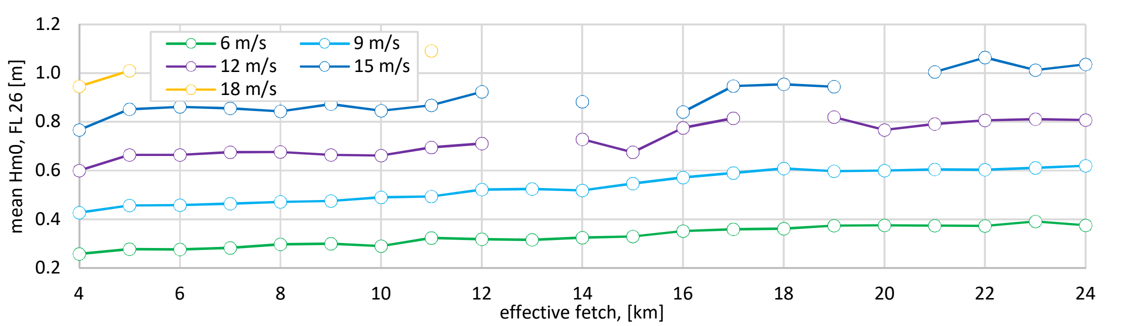

Figure H- 4 Average significant wave height (H_{m0}) as a function of fetch, for given ranges of wind speeds, FL26

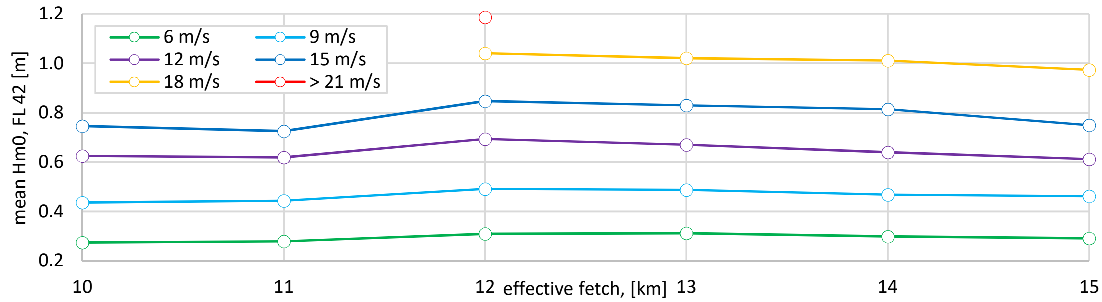

Figure H- 5 Average significant wave height (H_{m0}) as a function of fetch, for given ranges of wind speeds, FL42

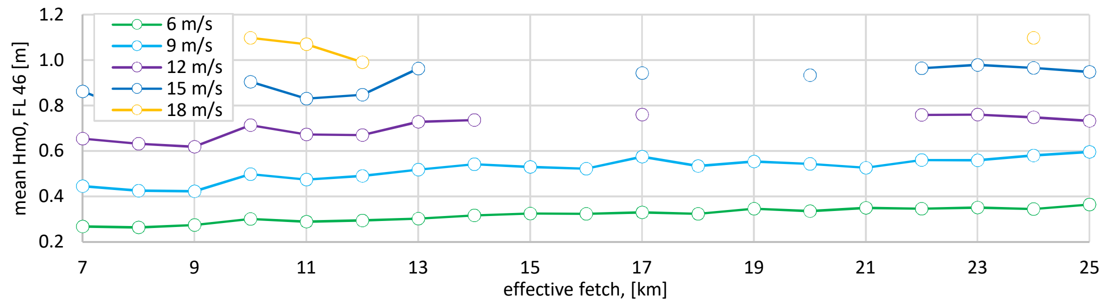

Figure H- 6 Average significant wave height (H_{m0}) as a function of fetch, for given ranges of wind speeds, FL46

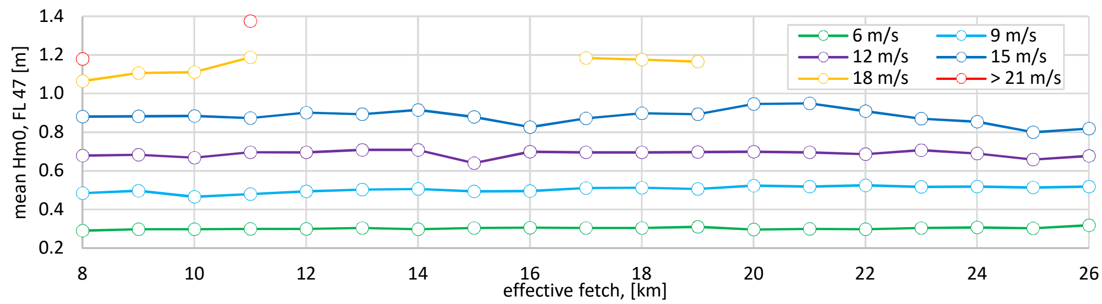

Figure H- 7 Average significant wave height (H_{m0}) as a function of fetch, for given ranges of wind speeds, FL47

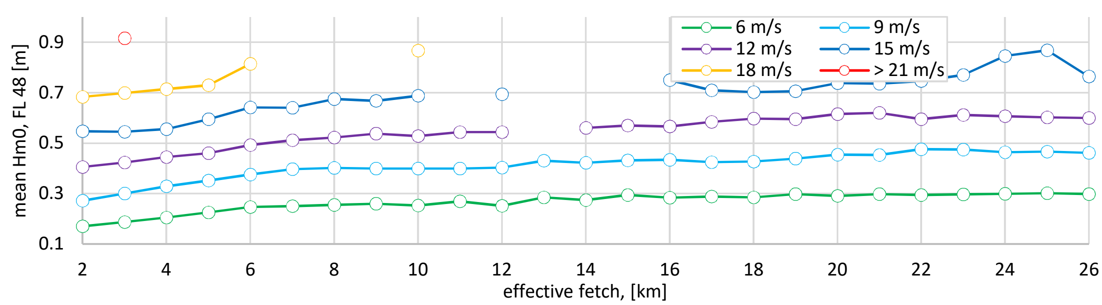

Figure H- 8 Average significant wave height (H_{m0}) as a function of fetches, for given ranges of wind speed, FL48

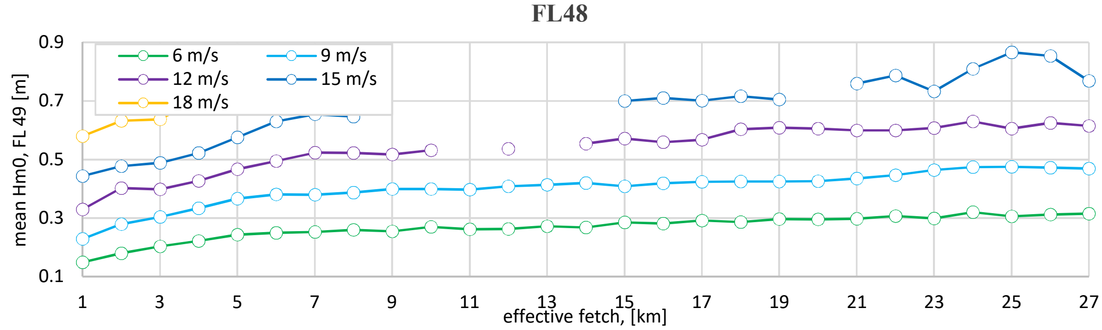

Figure H- 9 Average significant wave height (H_{m0}) as a function of fetches, for given ranges of wind speed, FL49

Appendix J Distribution of experimental range of wave height

Appendix J presents the distribution of experimental wave height (H_{m0}) for all locations.

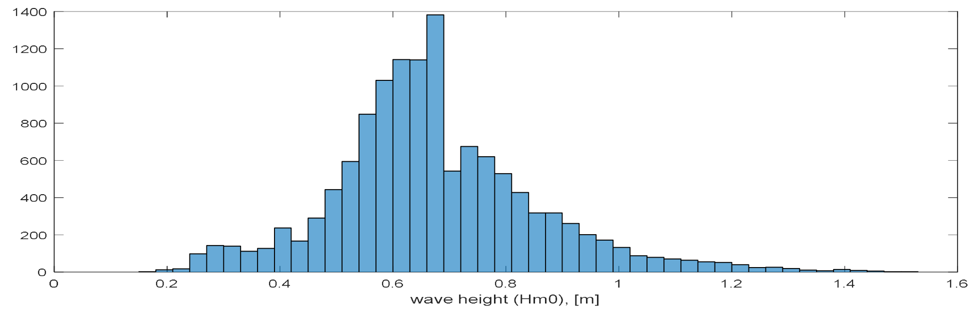

Figure J- 1 Distribution of experimental range of wave height (H_{m0}), FL2

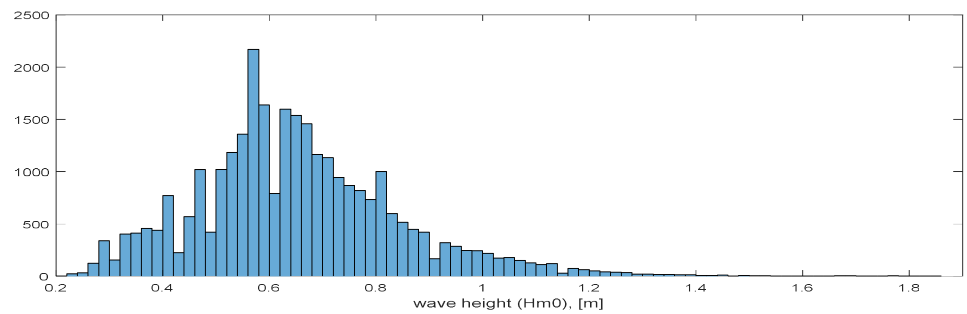

Figure J- 2 Distribution of experimental range of wave height (H_{m0}), FL2b

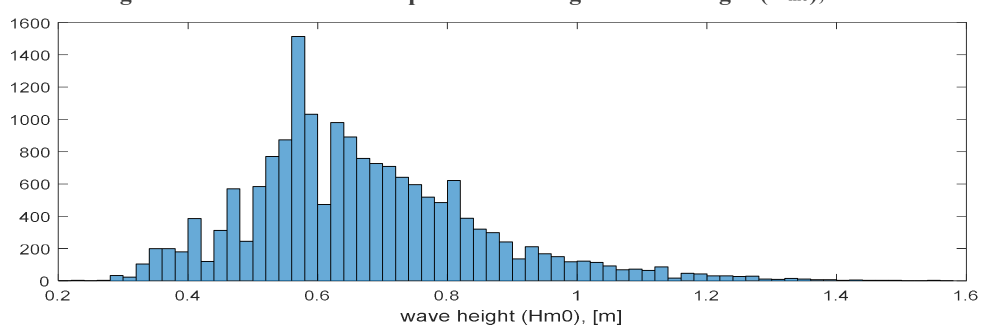

Figure J- 3 Distribution of experimental range of wave height (H_{m0}), FL9

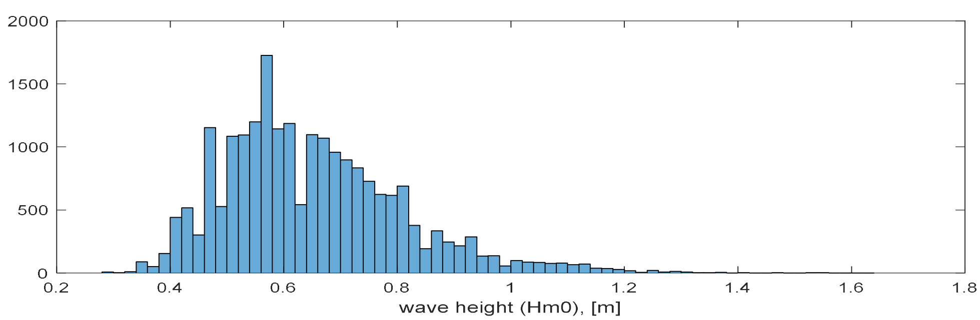

Figure J- 4 Distribution of experimental range of wave height (H_{m0}), FL26

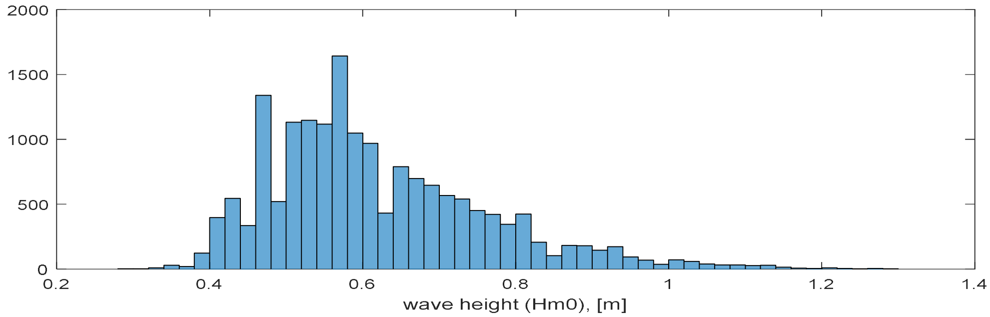

Figure J- 5 Distribution of experimental range of wave height (H_{m0}), FL42

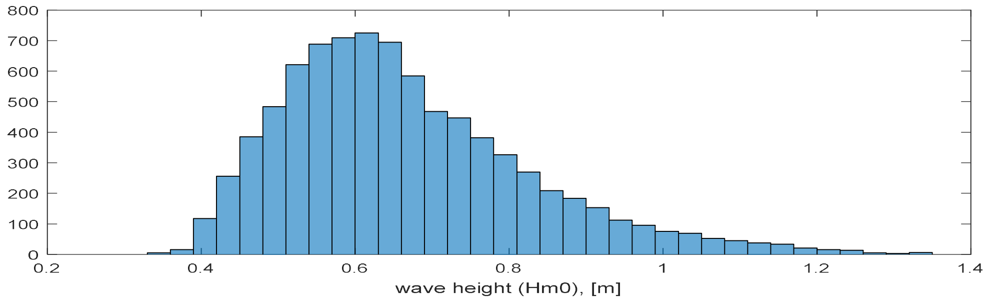

Figure J- 6 Distribution of experimental range of wave height (H_{m0}), FL46

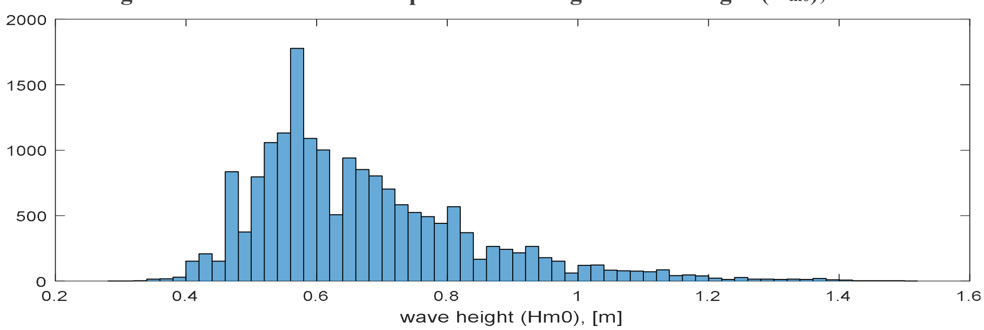

Figure J- 7 Distribution of experimental range of wave height (H_{m0}), FL47

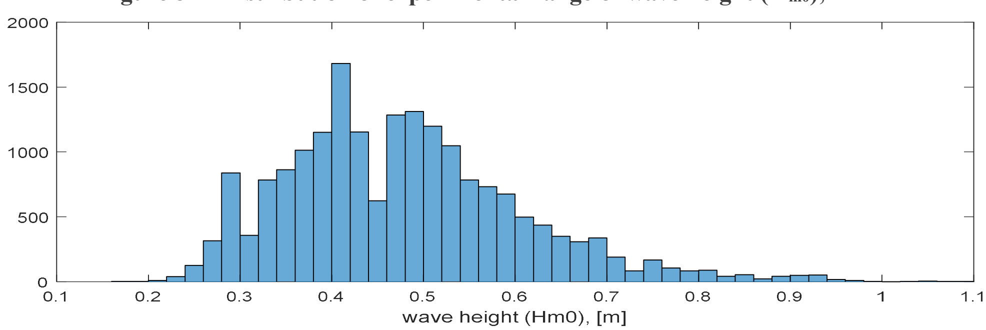

Figure J- 8 Distribution of experimental range of wave height (H_{m0}), FL48

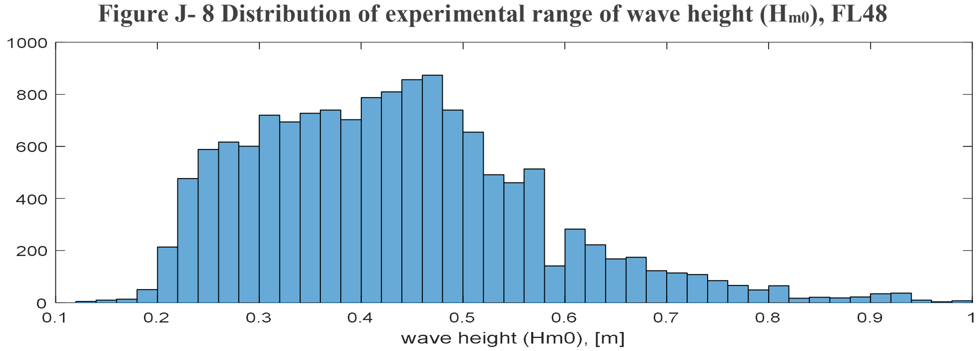

Figure J- 9 Distribution of experimental range of wave height (H_{m0}), FL49