Accuracy wind set-up formula for irregularly shaped lakes with a strong varying water depth

CTB3000 Bachelor Thesis

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Preface

This document, the bachelor thesis, marks the end of my bachelor study Civil Engineering. It is the final test, in which you can bring all your knowledge into practice. I will use this preface to thank my first supervisor ir. H.J. Verhagen for all his help. We had a meeting approximately every week, which were very useful.

Guido van Rinsum
Delft, 15th June 2015

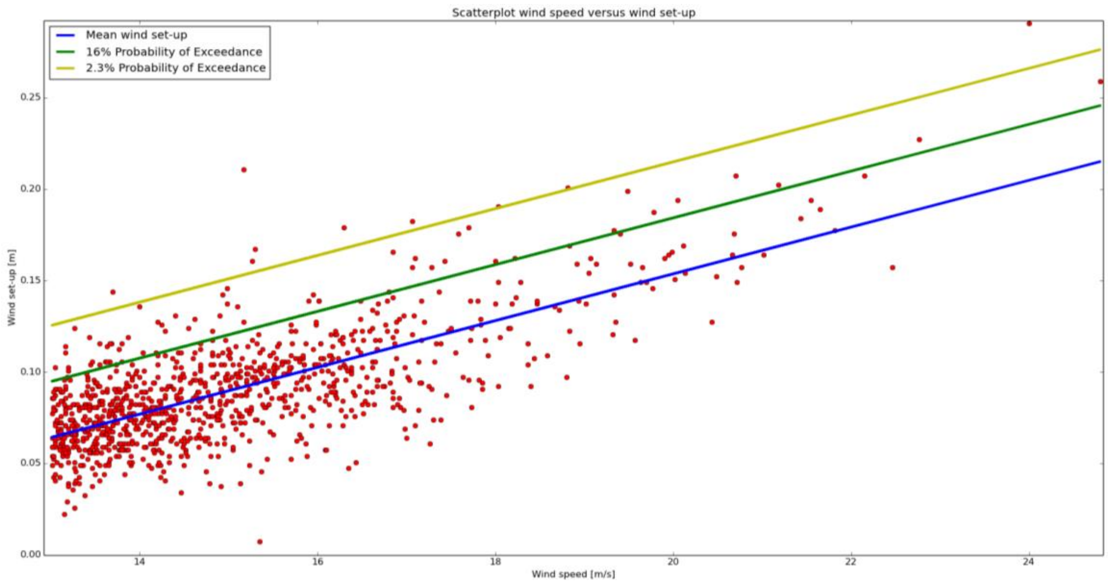
Summary

This document includes a survey whether the wind set-up formula is valid and accurate in case of irregularly shaped lakes with a strong varying water depth. The formula is designed for a pure theoretical situation, the question is whether the formula is valid in situations that differ a lot from the theoretical one. The research is carried out with data (wind speed, wind direction and water depth), from the Grevelingenmeer (Netherlands, province Zeeland).

First several assumptions are made with respect to the relevant wind directions and speeds for the different measure stations. Wind set-up won't be generated when the wind speed is very low. The relevant wind speeds are the mean values per hour above 13 meter per second. The relevancy of the wind directions does depend on the location of the measure station. The mean values of all the data are calculated in order to correct for the setting time of the lake, to arrive at a more or less stationary situation. The fetch is defined as the length of the lake parallel to the wind direction. It is not easy to model the water depth, shallow water does give a higher value for wind set-up in comparison to deep water. However, the water depth of the Grevelingenmeer is strongly varying, so an assumption had to be made. The mean value of the water depth is assumed, in order to balance the varying base of the lake. It is a rough assumption, but possible errors in this approximation are compensated by the friction coefficient kappa.

The conclusion of the main research is that the wind set-up formula is valid and relatively accurate. The order of magnitude of the wind set-up is 10 centimeter, the standard deviation is in the order of 1 centimeter. The dispersion of the wind set-up is independent of the wind speed. Using the original wind set-up formula gives the mean value of the wind set-up. In order to compute the design value of the wind set-up, depending on the allowed probability of exceedance, there has to be added an additional value of wind set-up. So, the dispersion is not caused by a scatter of kappa.

The whole story is summarised by the figure below. The blue line is the mean value of the wind set-up, the extra wind set-up is marked by the other coloured lines. There are two examples of lines with a certain probability of exceedance.



Summary 1. . Scatterplot wind speed versus wind set-up

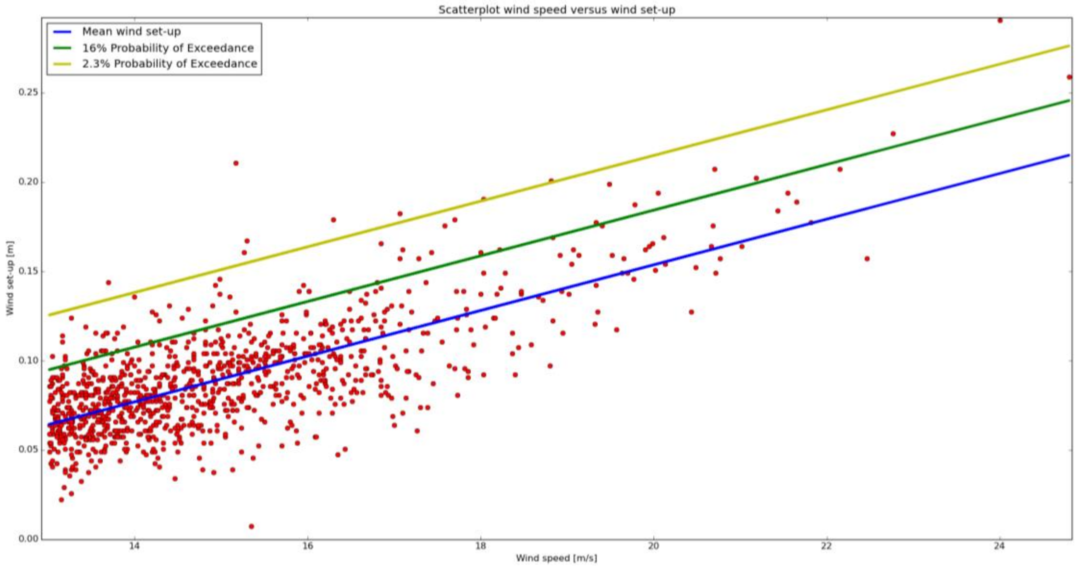
Samenvatting

Dit document bevat een onderzoek naar de geldigheid en nauwkeurigheid van de windopzet formule bij onregelmatig gevormde meren met een sterk variërende waterdiepte. De formule is afgeleid voor een puur theoretische situatie, de vraag is dan dus terecht in hoeverre de formule bruikbaar is voor situaties die sterk van de theoretische afwijken. Deze vraag is onderzocht aan de hand van meetwaardes van windsnelheid, windrichting en waterhoogte van het Grevelingenmeer (Nederland, provincie Zeeland).

Allereerst zijn verschillende onderbouwde aannames gedaan met betrekking tot de voor een meetstation relevante windrichtingen en windsnelheden. Bij zeer lage windsnelheden wordt er geen windopzet gegenereerd. De relevante windsnelheden zijn de uurgemiddelde windsnelheden boven 13 meter per seconde. De relevante windrichtingen hangen af van de locatie van het meetstation. De meetdata wordt gemiddeld over een uur om de insteltijd van het meer in rekening te brengen. De strijklengte wordt gelijk gesteld aan de lengte van het meer evenwijdig aan de windrichting. De waterdiepte is lastig te modeleren, ondiep water levert een hogere waarde van de windopzet ten opzichte van diepe gedeelten. Echter, de waterdiepte in het Grevelingenmeer is dusdanig variabel dat een aanname gedaan moet worden. De gemiddelde diepte is aangenomen, om het bodemprofiel evenwichtig te modeleren. Het is een grove aanname, maar eventuele fouten in deze benadering worden gecompenseerd door de frictie coëfficiënt kappa.

Er wordt geconcludeerd dat de formule bruikbaar is, de windopzet is in de orde van 10 centimeter, de spreiding in de orde van 1 centimeter. De spreiding is onafhankelijk van de windsnelheid, de gemiddelde waarde van de windopzet wordt berekend door de theoretische formule te gebruiken met de waarde voor kappa. Afhankelijk van de toegelaten overschrijdingskans wordt er nog een extra waarde bij opgeteld. De spreiding wordt dus niet veroorzaakt door een variatie in kappa.

Dit alles wordt samengevat in de onderstaande figuur. De blauwe lijn is de lijn van de gemiddelde windopzet. De extra windopzet hangt af van de overschrijdingskans, twee voorbeelden zijn gegeven in de figuur.



Summary 2. Scatterplot wind speed versus wind set-up

Definitions and symbols

Definitions

Standard deviation (Dekking et al., 2005)

$$\sigma = \sqrt{Variance} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \qquad [D.1]$$

Correlation coefficient (Dekking et al., 2005)

$$\rho(X,Y) = \frac{\mathrm{cov}(X,Y)}{\sigma(X)\sigma(Y)} \qquad [D.2]$$

Least squares method (Miller, 2006)

$$E(a,b) = \sum_{n=1}^{N}(y_n - (ax_n + b))^2 \qquad [D.3]$$

'The goal of the method is to minimalize the error'

$$\frac{\partial E}{\partial a} = 0 \;\&\; \frac{\partial E}{\partial b} = 0 \qquad [D.4]$$

Wind set-up

Positive *deviation* in water level due to (high) wind speed

Wind set-down

Negative *deviation* in water level due to (high) wind speed

Setting time

Time needed to arrive at a stationary water level due to wind shear force

List of used symbols

Symbol	**Description**	**Dimension**
W	Wind set-up	[m]
F	Fetch	[m]
u_{10}	Wind speed at 10 meter height	[ms^{-1}]
d	Water depth	[m]
κ	Friction coefficient	[-]
C_d	Drag coefficient	[-]
ρ_a	Air density	[kgm^{-1}]
i	Gradient water surface	[-]
c	Friction constant	[-]
τ	Shear stress	[Nm^{-2}]
w'	Additional wind setup	[m]
n	Probability of exceedance factor	[-]
σ	Standard deviation (wind set-up)	[m]
ϕ	Angle between land and wind	[-]

Table of contents

Chapter 1. Introduction

1.1 Reader's guide

This document contains a survey about the validity and accuracy of the wind set-up formula in case of an irregularly shaped lake with a strong varying water depth. This question arises because the formula is designed for a pure theoretical situation. Chapter one will be an introduction to the problem, first the theoretical model is explained and is problematized in the next paragraph. In chapter two the approach to answer the question is explained and the boundary conditions are formulated. In chapter three the results of the survey are written. The conclusion and discussion are elaborated in chapter four. All the extensive calculations are documented in the appendixes.

1.2 Theoretical model wind set-up

Drag coefficient

Wind is an important factor which causes water level deviations in closed basins and lakes. Wind acts as a stress on the water surface. This shear stress is dependent of a lot of variables, such as wave height and temperature. The shear stress is defined (Vickers & Mahrt, 1997) as the wind velocity at ten meter height squared, multiplied by the air density and the bulk drag coefficient, see equation 1.1.

$$\tau = \rho_a C_d u_{10}^2 \quad [1.1]$$

The bulk drag coefficient is not easy to determine, it is the constant of proportionality that marks the relationship between the wind speed and wind stress on a water surface. The coefficient depends on variables such as: temperature, humidity and wind speed (Smith, 1988).

Equilibrium of forces

Two equations has to be solved in order to model wind set-up. There has to be an equilibrium of forces, the wind acts as a force on the water surface, this will be compensated by a wind set-up. Secondly, the continuity equation holds, a lake does have a fixed amount of water, a wind set-up at one side of the lake has to be compensated by a water level decrease at another place of the lake. In a stationary situation, the wind stress on the water surface (see equation 1.1) will be compensated by a gradient in the water level surface. The following equation holds (Bezuyen et al., 2012):

$$i = c\frac{u_{10}^2}{gd} \quad [1.2]$$

For which:

i	=	Gradient water surface	[-]
c	=	Dimensionless friction constant	[-]
g	=	Gravity	[ms^{-2}]
d	=	Water depth	[m]

This is a simplification because the bottom friction is ignored in the equilibrium of forces. But: 'The dimensionless friction coefficient is chosen in such a way that the bottom friction is compensated' (Bezuyen et al., 2012). The total amount of water does not change, so there will arise a gradient in water level surface. In case of a closed basin, such as a lake, the water level rotates around the center of gravity.

In order to calculate the wind set-up, the gradient (factor *i* in formula 1.2) has to be multiplied by the fetch. The maximum wind set-up is at the location where the fetch is maximum. In case of a rectangular shaped lake, the maximum wind set-up is equal to the (absolute value of the) minimum wind set-up. But this can be different when dealing with an arbitrary shaped basin. The reason is that the distance between the center of gravity and the both sides of the basin can be different. In the most simplified wind set-up model, as mentioned above: a rectangular shaped lake, the highest and lowest wind set-up are equal. The wind set-up is calculated by multiplying the gradient by half of the fetch, because the distance between the center of gravity and the two sides are equal. In the final formula the correct component of the wind (as vector) should be used. The set-up is maximum when it acts parallel to the fetch. It reduces when it blows under an angle. The total amount of wind set-up is multiplied by cosϕ to compensate this effect. The final formula is showed below:

$$W = 0.5\kappa \frac{u_{10}^2}{gd} F \cos\phi \qquad [1.3]$$

For which:

W	=	Wind setup	[m]
κ	=	Friction constant	[-]
u_{10}	=	Wind velocity at 10 meter height	[ms^{-1}]
g	=	Gravity (9.81)	[ms^{-2}]
d	=	Water depth	[m]
F	=	Fetch	[m]
Φ	=	Angle between land and wind	[-]

The above mentioned variables are visualised in figure 1.1.

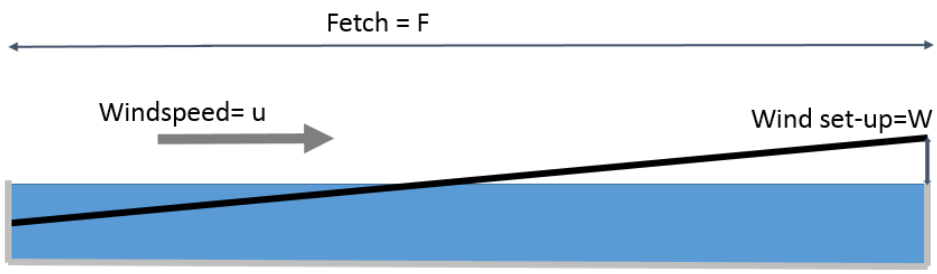


Figure 1.1 Visualisation variables wind set-up formula

Some important points that has to be kept in mind when using or analysing this formula:

- The factor 0.5 is relevant when the lake has a more or less rectangular shape. For explanation: see above.
- There is some time needed to arrive at the stationary situation. The wind set-up and wind speed does not stick together.

1.3 Friction constant kappa

An important empirical factor in equation 1.2 and 1.3 is the friction coefficient κ (kappa). It is an empirical factor that discounts a lot of effects. As elaborated above, the formula is derived for an ideal situation. The factor kappa can be seen as an empirical correction factor for all the imperfections and the shear stress coefficient for the friction between air and water. The empirical factor kappa cannot be calculated using an exact formula. In The Netherlands a factor of 3.5 – 4.0 E-6 is often used (Bezuyen et al., 2012). The Delta Commission proposed a factor of 3.4 E-6 (Delta Commissie, 1991).

It is difficult to determine the factor Φ in case of an irregularly shaped lake, and of course in nature this is often the case. In the following survey, the factor $\cos\phi$ will be discounted in de factor kappa. It will be assumed that the effect of the wind direction is negligible, because only the relevant wind directions will be analysed. Formula 1.3 will reduce to the following equation:

$$W = 0.5\kappa \frac{u_{10}^2}{gd} F \qquad [1.4]$$

1.4 F-hypothesis test

In this survey the statistical F-test is used to analyse a supposed difference in standard deviation. The background of this method will be discussed in this paragraph. The F-test is used to analyse whether two data sets does have the same variance (Buijs, 2012), both variances should be normal distributed. For both data sets the standard deviation can be calculated. The question to be answered is whether it is significantly likely that the two data sets have an equal standard deviation. In order to answer this question the following test statistic will be used.

$$F = \frac{\sigma_1^2}{\sigma_2^2} \qquad [1.5]$$

$$Where: (\sigma_1^2 > \sigma_2^2)$$

With use of F-tables the critical F-values can be found, the input for the tables are the degrees of freedom of the two data sets and the significance level. The degree of freedom of a data set is the total amount of data points minus one.

1.5 Problem definition and goal

The formula elaborated in paragraph 1.2 is anyway valid in case of an ideal situation: rectangular shaped basin with a constant water depth and a long-lasting high wind speed. But the problem is that much lakes in nature are not that properly shaped and the bottom profile is often not uniform. A second problem is that there is only a few information about the mean value and standard deviation of the friction coefficient. Recently Feij (Feij, april 2014) examined this problem for only one location, the IJselmeer (The Netherlands). The IJselmeer is a relatively rectangular shaped lake with a constant water depth.

Research question

> *Is the wind set-up formula valid in case of an irregularly shaped lake with a strong varying water depth?*

Furthermore, the results obtained by Feij will be analysed whether his conclusions can be extended to this survey. The following conclusions will be analysed[1].

- The wind set-up is not proportional to the wind speed squared but the wind speed to the power three.
- The scatter in wind set-up is not due to the friction coefficient, but there will be a constant scatter in wind set-up. This means that an extra value has to be added to the wind set-up. This value does not increase with increasing wind speeds.

[1] For detailed information: Nauwkeurigheid van Formules voor windopzet aan de hand van meetgegevens van het IJselmeer, Feij 2015. http://repository.tudelft.nl/view/ir/uuid:1dfe879b-bf86-408e-8b8c-3d748e40f624/

Chapter 2. Approach

2.1 Research location and measure stations

The research is carried out at the Grevelingenmeer[2] (The Netherlands, province Zeeland). This lake does have a widely varying water depth and is, as you can see in figure 2.1, irregularly shaped. The Dutch water authorities (Rijkswaterstaat) maintain three different measure stations for the water levels in this lake, which data is freely accessible (Rijkswaterstaat HMC Zeeland, 2015). The three stations, in the lake, that are used in this survey are (see also figure 2.1):

- Grevelingendam Hevel West (HEVW)
- Brouwerssluis Binnen (BRBI)
- Bommenede (BOM1)

Figure 2.1. Grevelingenmeer and measure stations Rijkswaterstaat

The wind data (wind speed at 10 meter height and the wind direction) is gathered from another measure station at sea. The decision criteria for choosing this location of the measure station are:

- In the first, place the availability of data over much years
- Secondly, a station close to the water level measure stations, in order to get a good correlation.

Based on this criteria the data is gathered from measure station Brouwershavensche Gat 2 (BG2). The location of this station is approximately 14 kilometre West with respect to station BRBI. See Appendix II for the exact location. The data is used from the following years: 2014, 2013, 2012, 2010, 2008, 2007, 2006, 2005, 2004, 2003, 2002 and 2001. The reason for skipping some years in between is the non-availability of the data files. Based on the dominant wind directions in the Netherlands, only wind set-up at station Grevelingendam Hevel West (HEVW) and wind set-down at Brouwerssluis Binnen (BRBI) are considered in this survey. The data from Bommenede 1 (BOM1) is used as reference water level, this is elaborated in the next paragraph.

2.2 Assumptions in model

In order to analyse the data, assumptions has been made with respect to the relevant wind direction and speed, the method of calculating the mean values of the data and the definition of wind set-up. These topics will be thoroughly discussed in this paragraph, Appendixes II till V are the support for all the assumptions.

[2] For all the detailed information about the Grevelingenmeer. See Appendix I.

Computation mean value data

In order to compute the wind set-up, a stationary situation is considered. It is discussed in paragraph 1.2 that the water level does not go along immediately with the deviation in wind speed. It makes therefore no sense to compare the 10-minute wind data with the water level data. The time needed to arrive at the stationary situation is defined as the setting time. To compute the setting time of the lake, six different storms at different times are considered. The wind speed, wind direction and water level of the lake, at station Grevelingendam Hevel West (HEVW), is plotted for each storm. The relevant wind speed and relevant wind directions are not yet determined, so at first instance a wind speed greater than 15 [m/s] and a wind direction between 260 and 300 degree are considered. This assumptions are checked afterwards. In Appendix III. (Determination of relevant wind directions and time lag water level deviation) the six storms are analysed one by one. The general conclusion is that the time lag between a relatively constant high wind speed and the stationary situation in wind set up is between 40 and 60 minutes, therefore the mean value will be calculated over 60 minutes, see equation 2.1.

$$d_{mean} = \frac{d_i + d_{i+1} + d_{i+2} + d_{i+3} + d_{i+4} + d_{i+5}}{6} \qquad [2.1]$$

Assumption 2.1. The mean value is calculated using the average of six sequential data points: the average of 60 minutes. See equation 2.1.

Wind set-up

Wind set-up is the deviation in water surface due to the wind friction. But the problem in determining this value is that it is not easy to analyse what the mean water level of the lake is, during wind set-up. The Grevelingenmeer is a lake with a relatively constant water level, which is NAP-0.20 (Deltares, 2008). But obviously the water level will fluctuate. To illustrate the non-constant water level at the Grevelingenmeer the water level at station HEVW between 1 January 2014 (02:50 and 23:40) is plotted, see figure 2.2. It can be seen that the absolute difference between the different water levels is approximately 20 centimeter, this is not negligible.

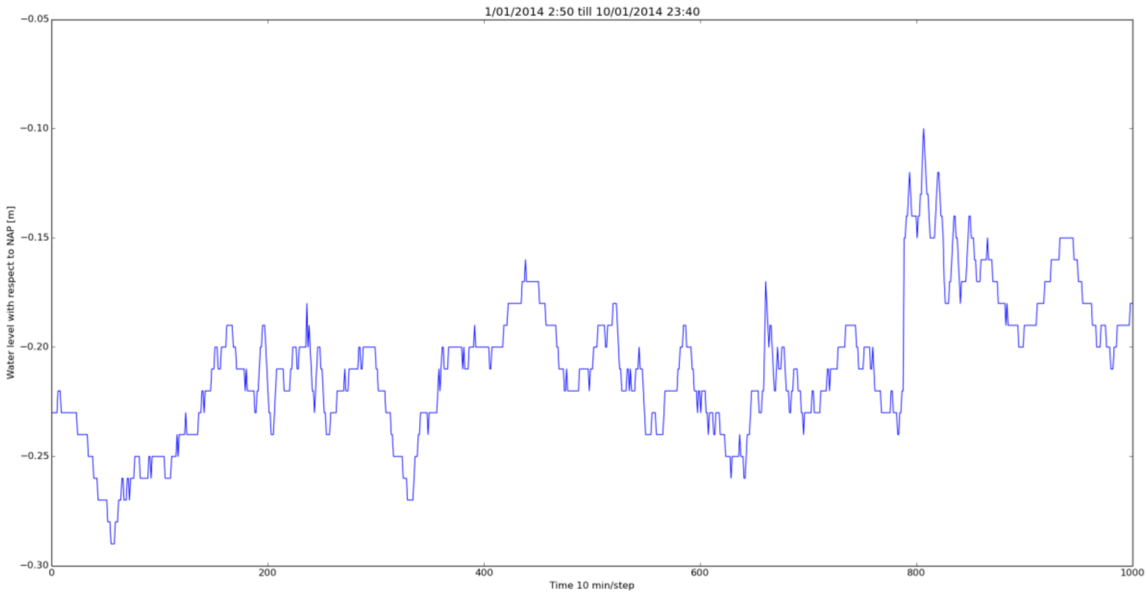


Figure 2.2. Water level Grevelingen. Station HEVW, January 2014

When determining the wind set-up, it has to ensured that the reference water level is not affected by the wind, or as little as possible. First the wind set-up at station Grevelingendam Hevel West (HEVW) is considered. The same assumptions as with determining the mean value holds: a high wind speed, above 15 [m/s], and a wind direction between 260 and 300 degree, this assumptions are checked afterwards.

In Appendix IV the behaviour of the water level at the other two stations (BRBI and BOM1), during wind set-up at station HEVW is elaborated. It is reasonable to expect a lower water level at station Brouwerssluis Binnen (BRBI) during high wind speeds in the mentioned wind direction. In Appendix IV, Figure IV.1 can be seen that there is hardly a correlation between the water level at BOM1 and the wind speed (correlation coefficient -0.11) but there is a little negative correlation between the water level at BRBI and the wind speed (correlation coefficient -0.49). This findings are supported by the following six graphs in Appendix IV, the overall trend is a relatively constant water level at BOM1 and a decreasing water level at BRBI. The decreasing water level at BRBI (in case of wind set-up at HEVW) is not the research question, but it can be concluded that the water level at BOM1 is a good reference level. It is not easy to determine the reference level, so a small deviation is possible. Additionally, it is logical that the water level at BRBI decreases during wind set-up at station HEVW, because the total amount of water in the lake does not change. So a wind set-up at one side of the lake has to be compensated by a decrease in water level at another side of the lake.

Assumption 2.2. The wind set-up at Grevelingendam Hevel West is defined as the difference between the water level at HEVW and BOM1. See equation 2.2

$$W_{HEVW} = H_{HEVW} - H_{BOM1} \qquad [2.2]$$

For which

W	=	Wind set-up	[m]
H	=	Water depth with respect to NAP	[m]

Secondly the wind set-down of the water level at station Brouwerssluis Binnen is studied. The same procedure is used as above. The boundary conditions are the following: the relevant wind directions are assumed to be between 250 and 270 degree and the wind speed has to be high, above 15 [m/s]. Measure station BOM1 is again the best reference water level, as can be seen in Appendix V.

$$W_{BRBI} = H_{BRBI} - H_{BOM1} \qquad [2.3]$$

Assumption 2.3. The wind set-up at Brouwerssluis Binnen is defined as the difference between the water level at BRBI and BOM1. See equation 2.3

Wind direction

The relevant wind directions for station HEVW can easily be graphically approximated when looking at de outlay of the lake. In Appendix II all the measure stations and the relevant wind direction, are showed. First the wind set-up at station Grevelingendam Hevel West is considered, the relevant wind directions are between 260 and 310 degree. This graphical procedure is supported by Appendix III, see the explanation per graph. These angles are chosen because of the fact the wind must have a relative long fetch to generate wind set-up and the wind has to be in the direction of the measure station.

Assumption 2.4. Wind directions between 260 and 310 degree at station Grevelingendam Hevel West (HEVW) are relevant.

For station Brouwerssluis Binnen (BRBI) the relevant wind directions are also graphically approximated. The relevant wind directions are between 250 and 270 degree. The reason for this small interval is the fact that the wind direction has to be in the direction of the small bay in the lake.

Assumption 2.5. Wind directions between 250 and 270 degree at station Brouwerssluis Binnen (BRBI) are relevant.

Wind speed

Only high wind speeds are able to generate wind set-up. A graph (see figure 2.3) is made of all the relevant wind data for station HEVW, in order to determine the wind speeds that have to be taken into account. The relevancy of the data depends on boundary condition 2.1 till 2.4 (See above).

The scatterplot is divided in two sections:

- Wind speed between 0 and 13 [m/s]; correlation coefficient scatterplot: 0.47
- Wind speed above 13 [m/s]; correlation coefficient scatterplot: 0.68

The first section is not the part of interest for the research, because easily can be seen that there are approximately as much data points with no, or negative wind set-up, as there are with little wind set-up and additionally, the correlation is low. The second section is relevant because wind set-up is generated. Of course the scatter is wide, but the correlation is higher. To conclude: the relevant wind speeds are above 13 [m/s]. The Koninklijk Nederlands Meteorologisch Instituut (KNMI) defines this wind speed as 'strong wind'[3].

Assumption 2.6. The relevant wind speed is above 13 [m/s].

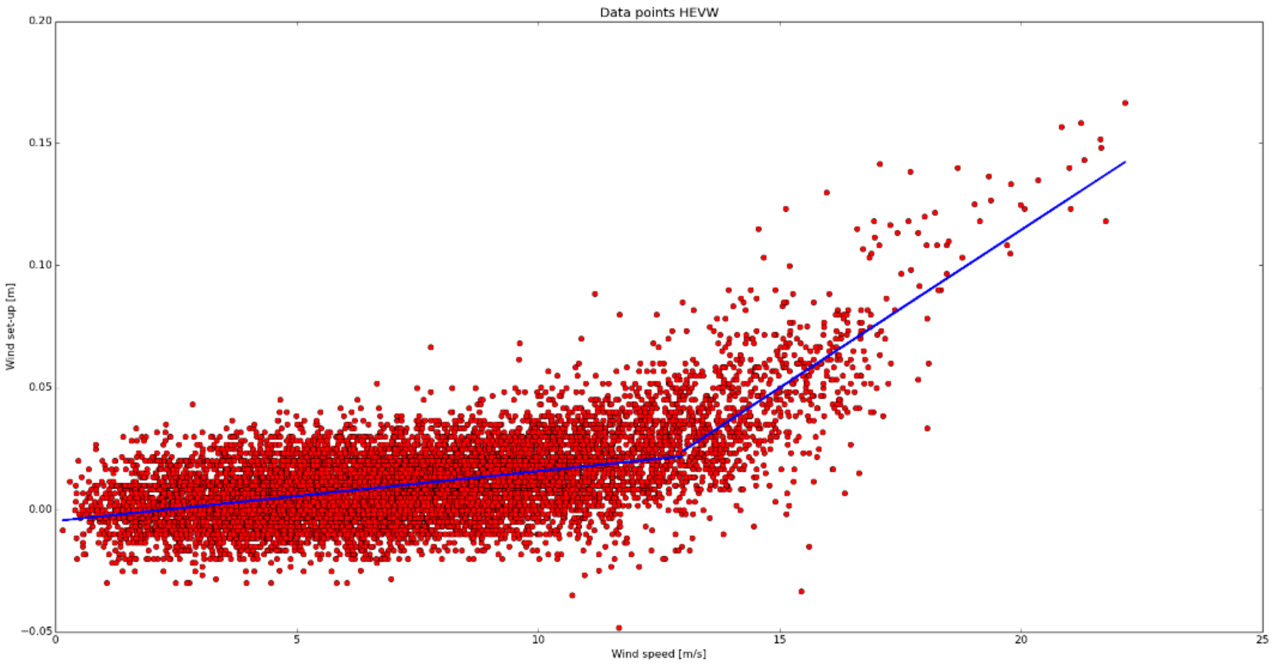


Figure 2.3. Scatter plot wind-set up station HEVW

[3] http://www.knmi.nl/cms/content/28976/windschaal_van_beaufort_compleet

2.3 Data analysis

All the data extracted from the Rijkswaterstaat website (Rijkswaterstaat HMC Zeeland, 2015) is put together in a Comma Separated Value File[4] (CSV-file). The rough data CSV-file contains the following quantities with a time spacing of 10 minutes:

- Water depth at the stations HEVW, BRBI and BOM1
- Wind direction and speed at station BG2
- Date and time at the four measure stations

The data is analysed using Python Programming[5]. Obviously the data is nog homogeneous, every once in a while a stations provides no data. The first step in programming is to get a good matrix with all the relevant data. This is done by checking whether each value in the matrix is a floating element (number) or a string (an error message). A full row is skipped when one or more values of a row is not a number. Because all the values should be known in order to analyse the wind set-up. What results is a matrix with relevant data with a time spacing of ten minutes. The next step in the programme is to calculate the mean values of the data. The mean value is calculated with six sequential data points. The last step is to extract the relevant values, depending on the wind speed and direction. This whole procedure is visualized in figure 2.4. The explanation why the slope of the fitted line is the value of kappa is given in Appendix VII.

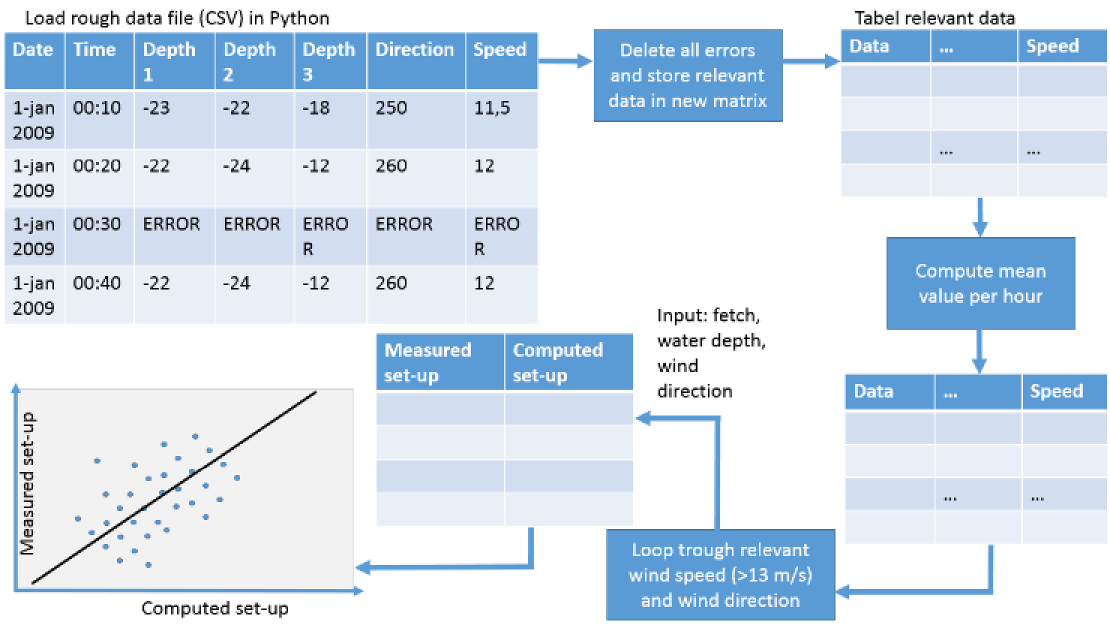


Figure 2.4. Visualisation programming procedure

[4] For more information about CSV-files see: http://en.wikipedia.org/wiki/Comma-separated_values

[5] More information about this programming language can be found at: https://www.python.org/

Chapter 3. Results

3.1 Results wind set-up at Grevelingendam Hevel West (HEVW)

All the full calculations used in this paragraph can be found in Appendix XIII.

Reference water level

A plot is made of all the relevant (Relevancy depends on wind speed, wind direction) wind set-up values, based on the assumptions elaborated in the previous chapter. With on the horizontal axis the value of the computed wind set-up (without the value of kappa) and on the vertical axis the value of the measured wind set-up. For this first computation the average water depth of 5.4 meter (Deltares, 2008) and a fetch of 18.2 kilometre (see Appendix II) is used. The least squares method[6] is used for fitting a line through all the data points. As explained in Appendix VII. the line has to go through the origin. Obviously this point is known, because when the wind speed is zero, no wind set-up is generated. But when fitting the line, it does not go exactly through the origin. The y-intercept is approximately -4.1 centimeter (see figure 3.1). There are two possible reasons for this error:

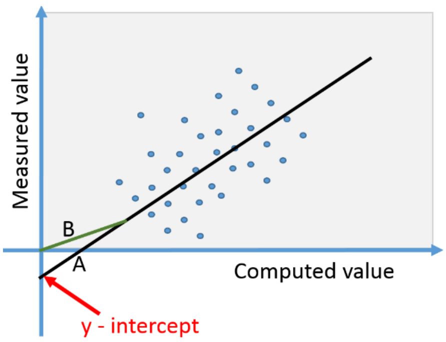


Figure 3.1. Visualisation fitted line

- First, there can be a systematic deviation in the wind set-up formula, which causes the line not to go through the origin. This can be the case because the formula is not used for low wind speeds. The systematic deviation is visually shown in figure 3.1, for relative high wind speeds the graph follows the black line through the data points, but for low wind speeds the wind set-up follows the green (See B in figure 3.1) path.
- A second option is that the reference water level is a little bit to high estimated, in reality the reference water level is 4.1 centimeter lower. A possible reason for this error is because of the fact that there is no fixed reference water level. In periods of high wind speeds all the measure stations can be affected. In chapter 2.2 it is showed that Bommenede is a good reference level, but a small error is possible.

The second option will be the starting point in analysing the wind set-up at station Grevelingendam Hevel West. Because of the fact that the deviation is small and is likely to be caused by an error in the reference water level.

Assumption 3.1. The reference water level for wind set-up at station Grevelingendam Hevel West is 4.1 centimeter lower than the water level at Bommenede 1.

This assumption is implemented in the model by adding 4.1 centimeter to each value of the measured wind set-up. The result is that each data point becomes 4.1 centimeter higher, and thus the fitted line goes through the origin. The scatterplot with the least squares estimate is shown in figure 3.2, the slope of the

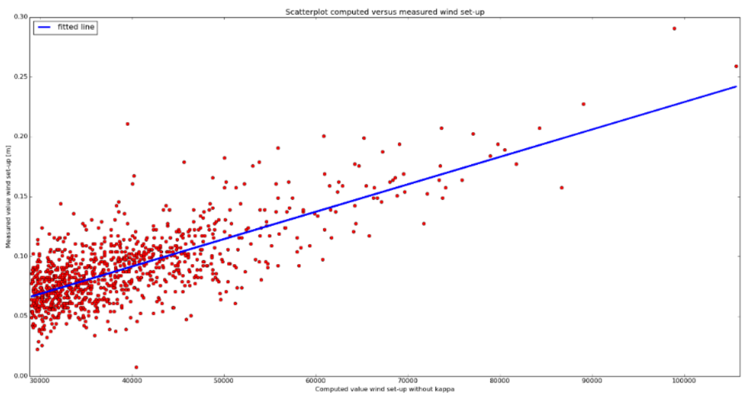


Figure 3.2. Scatterplot computed versus measured wind set-up

[6] See chapter definitions page 9

line is 2.29 E-6, which is the estimated value of kappa[7]. Figure 3.2 is also in Appendix VIII, but in a bigger size.

Distribution kappa

Obviously all the data points are not on one line, the data points are distributed around the least squares estimate line. The distribution of kappa should be known in order to interpret the data. For each data point the difference between the slope of the line through the origin and this specific point and the slope of the least squares estimate line is calculated. This gives the deviation of kappa per data point. All this values are plotted in a normalized cumulative histogram (see figure 3.3). Additionally the standard cumulative normalized normal distribution is plotted (see red line graph). The red line in the graph is obtained with the computed mean value and standard deviation of the data. It is very likely that the data is normally distributed, according to this figure 3.3, because the red line and the blue histogram are nearly similar. There is also additional evidence provided in Appendix VIII.

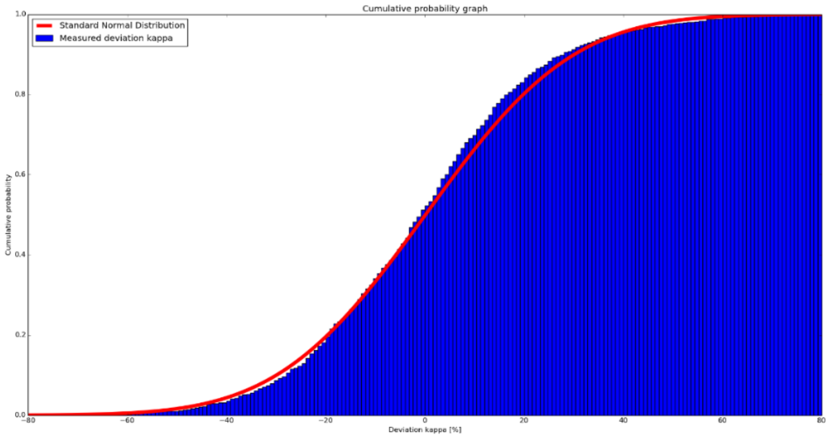


Figure 3.3. Cumulative probability graph deviation kappa

Assumption 3.2. Kappa is normally distributed.

Scatter plot

There are two possibilities which can cause the scatter in the graph.

- Option 1. The scatter can be due to (normal) distributed values of kappa. The formula will be the following (visualisation, see figure 3.4 option 1):

$$W = 0.5F(\kappa \pm n\sigma)\frac{u_{10}^2}{gd} \qquad [3.1]$$

σ = standard deviation kappa [-]

- Option 2. The scatter is independent of the wind speed and thus constant over the full range of wind speeds. The formula will be the following (visualisation see figure 3.4 option 2):

$$W = 0.5F\kappa\frac{u_{10}^2}{gd} \pm n\sigma \qquad [3.2]$$

σ = standard deviation wind set-up [m]

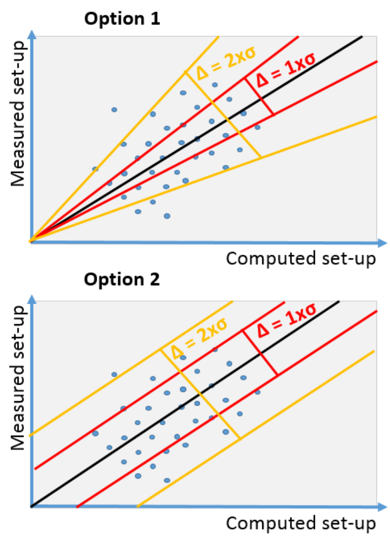


Figure 3.4. Visualisation possibilities way of distribution data points

[7] See Appendix VII for the explanation

The two options mentioned on the previous page are discussed in Appendix VIII. Option 1 is analysed first. A plot of the different values of kappa with respect to the wind speed is made. The spread of the values of kappa is decreasing, as can be seen in figure 3.5. The number of data points is also decreasing, so only looking at the graph is not enough. A statistical F-test is elaborated, there is checked whether there is a significant difference in standard deviation between the first part, wind speed between 13 and 18 [m/s], and the second part, wind speed above 18 [m/s], of the graph. A significance level of one percent is used. The result is that, with a high level of certainty, the standard deviation is decreasing with higher wind speeds. The statistical result is supported by the graph.

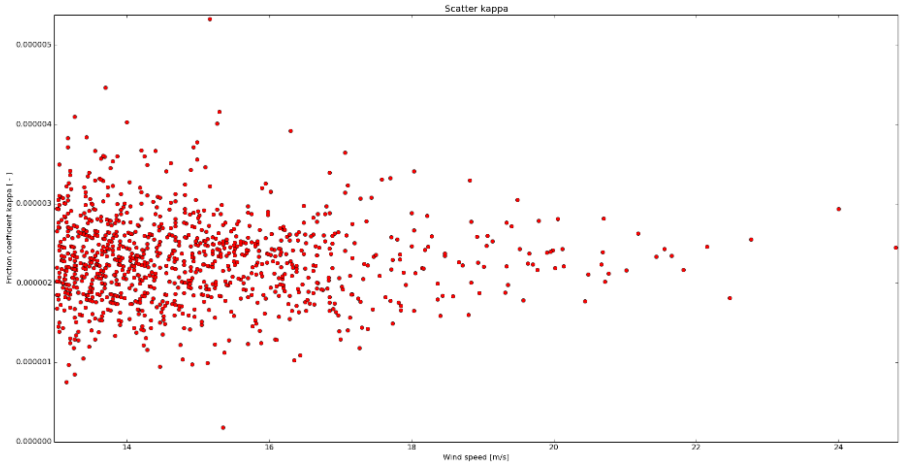


Figure 3.5. Values of kappa per data point (wind speed)

Secondly option 2 is discussed. For this purpose a plot is made of the different values of the deviations in wind set-up versus the wind speed. The same statistical F-test is conducted to analyse whether there is a difference in standard deviation, also the same intervals as above are used. First the interval with wind speeds between 13 and 18 [m/s] and secondly the wind speeds above 18 [m/s]. The result is that there is no significant difference in standard deviation between the two intervals. This statement is supported by figure 3.6. Most of the points are between a deviation in wind set-up of +5 [cm] and -5 [cm].

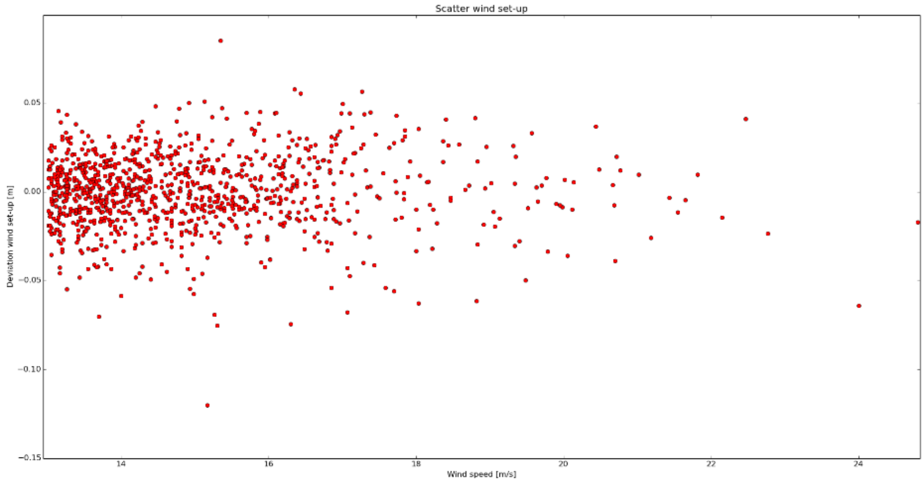


Figure 3.6. Values of deviations wind set-up per data point (wind speed)

From the figures above and the additional calculations in Appendix VIII. is concluded that option 2 (see figure 3.4) is the best way to model the wind set-up. The standard deviation of the wind set-up is constant over the whole range of wind speeds.

3.2 Wind set-down at Brouwerssluis Binnen (BRBI)

All the extensive calculations used in this paragraph can be found in Appendix IX

Reference water level

The same reference water level problem as explained in paragraph 3.1 is encountered when analysing the wind set-down at station Brouwerssluis Binnen (BRBI). The water level at station Bommenede (BOM1) is the reference level, but off course this can deviate a little bit. Wind acts also on the water surface at that station and can therefore deviate a little bit. The first least squares estimate through the scatter plot leads to a y-intercept of approximately +2.3 centimeter. It will be assumed that the reference water level is in reality this amount higher. For the full explanation and the support for this assumption see paragraph 3.1: reference water level.

Assumption 3.3. The reference water level for wind set-down at station Brouwerssluis Binnen is 2.3 centimeter higher than the water level at Bommenede 1.

This assumption is implemented in the Python script by subtracting this amount from the wind set-down. Subtracting because the wind set-down is negative. The scatterplot with the least squares estimate is shown in figure 3.7, the slope of the line is -1.75 E-6, which is the estimated value of kappa[8]. Figure 3.7 is also in Appendix IX, but in a bigger size.

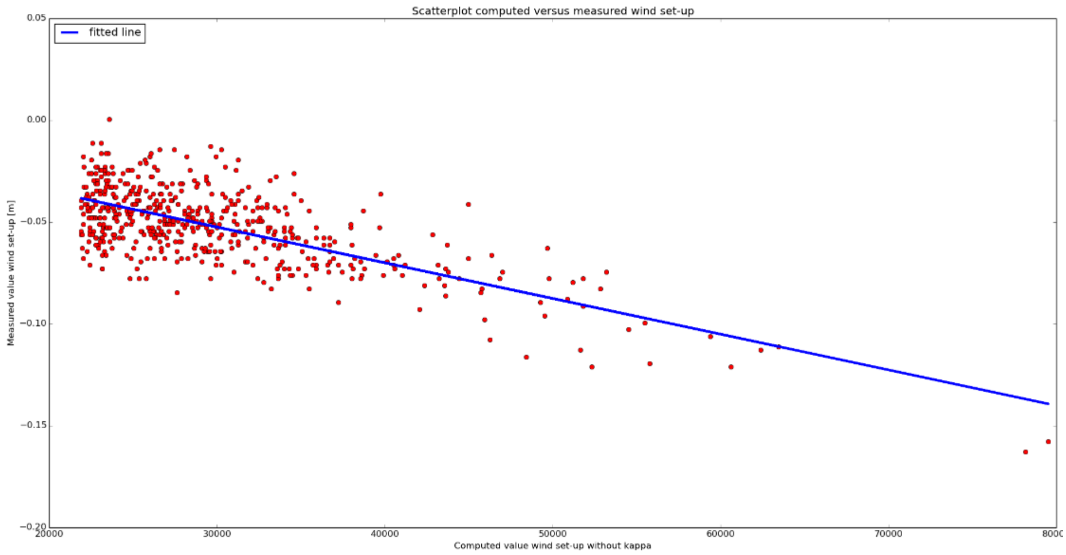


Figure 3.7. Scatterplot computed versus measured wind set-down

Distribution kappa

In Appendix IX it is elaborated that it is very likely that the value kappa is normal distributed. This is done by plotting the standard normalized cumulative normal distribution line and the different values of kappa. The boxplot as well as the histogram are in such a way that the normal distribution is a safe assumption. For all the details about the method see paragraph 3.1, the same method is used.

Scatter plot

Also for station Brouwerssluis Binnen is studied whether the scatter is related to the wind speed or that the deviation is constant over the whole range of wind speeds. The same method as described in the previous paragraph is used.

[8] See Appendix VII for the explanation

The two options mentioned in the previous paragraph (see figure 3.4) are examined. First, the different values of kappa with respect to the wind speed are plotted (see figure 3.8). The number of data points and the scatter of kappa are decreasing. The decrease is statistically significant as can be seen in Appendix IX, the calculation is based on the statistical F test.

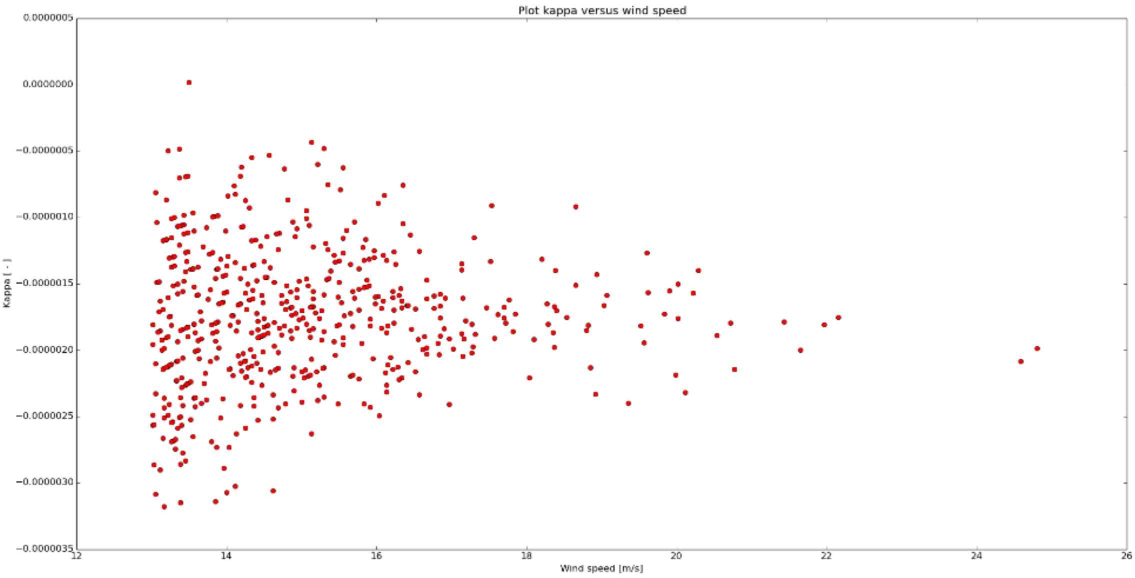


Figure 3.8. Different values of kappa with respect to wind speed (Station: BRBI)

Secondly option 2 is discussed. For this purpose a plot (see figure 3.9) is made of the different values of the deviations in wind set-down versus the wind speed. The same statistical F-test is conducted to analyse whether there is a difference in standard deviation. The result is that there is no significant difference in standard deviation between the two intervals. This statement is supported by figure 3.9. Most of the points are between a deviation in wind set-down of +3 cm and -3 cm.

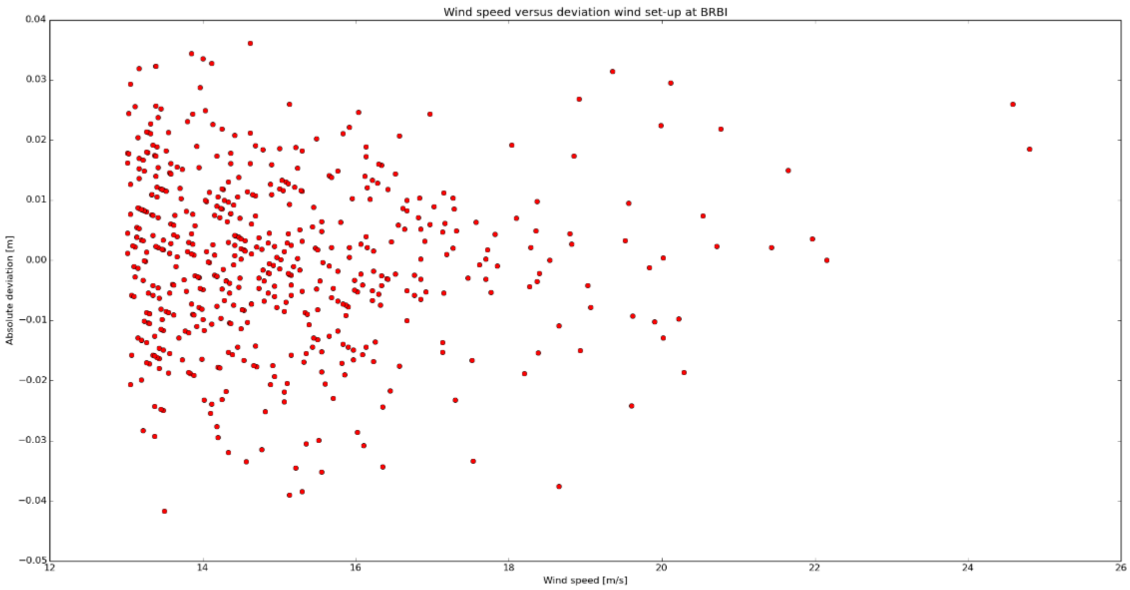


Figure 3.9. Different values of deviation in wind set-up with respect to wind speed (Station: BRBI)

From the figures above and the additional calculations in Appendix IX. can be concluded that option 2 (see figure 3.4) is the best way to model the wind set-down. The standard deviation is constant over the whole range of wind set-down.

3.3 Order of wind speed in wind set-up formula

The original wind set-up formula (see paragraph 1.2, equation 1.3) consist of the wind speed squared. Feij concluded in his investigation of the wind set-up for the IJselmeer that a third order dependency is a better approximation. In order to analyse the appropriate order for the Grevelingenmeer a plot is made of the measured wind set-up versus the computed wind set-up (with the yet determined value of kappa). The value of wind set-up is computed with the original u-squared formula. The result can be seen in figure 3.10.

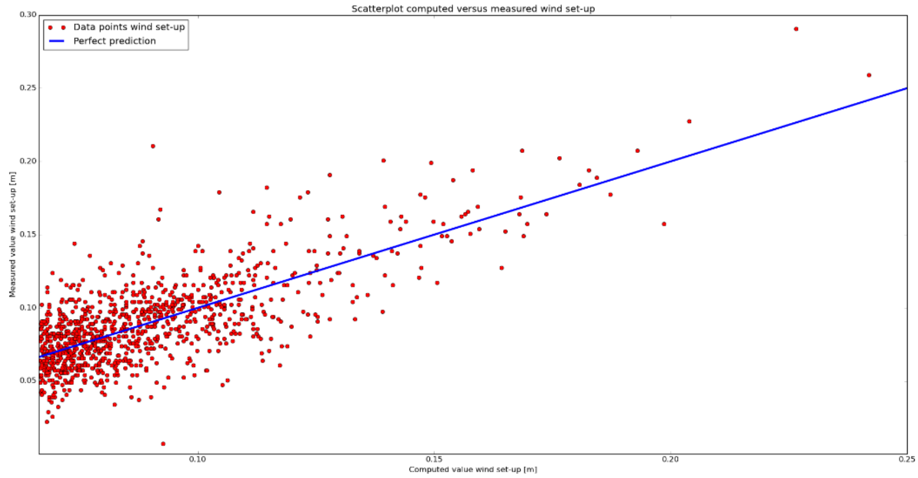


Figure 3.10. Scatterplot u squared

The line of perfect prediction does go quite well through the data points, there is no difference for higher wind speeds. What has to be observed for a third order dependency of the wind speed is a faster increasing wind set-up for higher wind speeds. The amount of data points is far less in the section above approximately 15 centimeter wind set-up, but the scatter does not tend to increase. In figure 3.11 the data points are plotted with the wind speed to the power three formula. The scatter is bigger and there are more points under the perfect prediction line.

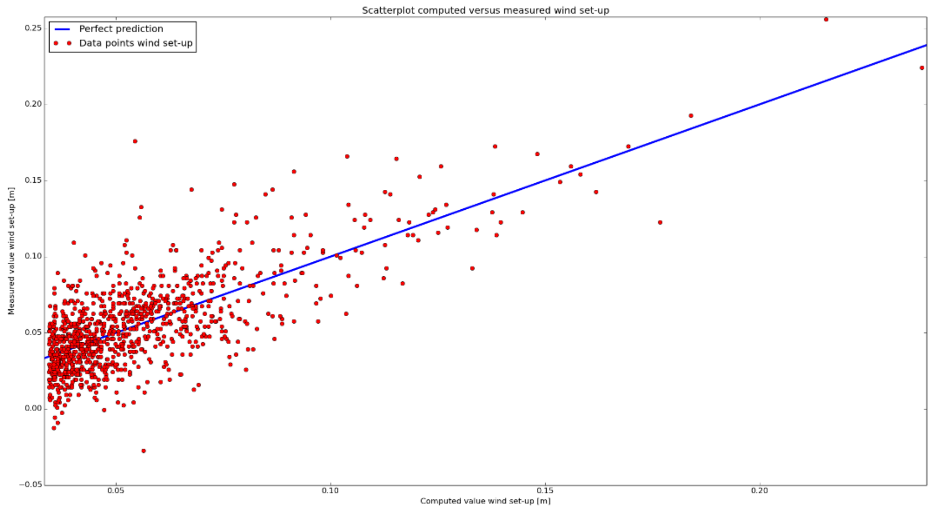


Figure 3.11. Scatterplot u to the power three

Additionally the standard deviation for both formulas is given below

- u-squared formula. Standard deviation wind set-up = 0.02 meter
- u-power off three formula. Standard deviation wind set-up = 0.03 meter

To conclude: there is no reason to assume a third order dependency of the wind speed. Because it gives not a better result, the standard deviation is even worse.

Chapter 4. Conclusion and discussion

This paragraph has the following structure. First the specific conclusions with respect to the Grevelingenmeer are summarised, also the differences between wind set-up and wind set-down are discussed. Secondly, the results from this survey are compared with the results obtained by Feij. A general recommendation is made in the third part of this chapter. Fourth, the results are discussed and interpreted. Lastly, some critical remarks on the conducted survey.

4.1 Conclusion Grevelingenmeer

Conclusions regarding the validity of the wind set-up formula Grevelingenmeer

- Wind set-up formula valid for Grevelingenmeer (Wind speed squared)
  There is a positive correlation of 0.74 (wind set-up) between the wind speed and wind set-up. And a negative correlation of -0.71 (wind set-down) between the wind speed and wind set-down.
- Distribution data points independent of the wind speed.
  The scatter does not increase with increasing wind speeds, the deviation in wind set-up remains more or less the same.
- Wind set-up measurements likely normal distributed
- Factor kappa wind set-up HEVW equals 2.29 E-6 [-]
- Factor kappa wind set-down BRBI equals 1.75 E-6 [-]
- Standard deviation wind set-up HEVW equals 0.02 meter
- Standard deviation wind set-down BRBI equals 0.01 meter

The result of this survey is summarised in figure 4.1 and 4.2 these graphs are also in Appendix X, but in a bigger size. The blue line in the figures is the perfect prediction line. Some points are on this line, but obviously most of the points are above or below the line. Furthermore the standard deviation of the wind set-up can be seen in the graph. For example all the points between the two green lines are all the points that deviate only one standard deviation (or less) from the mean value.

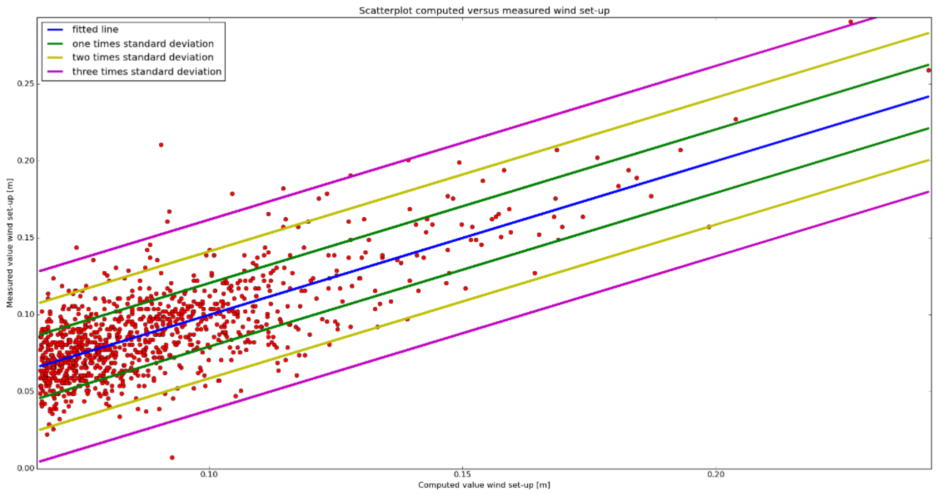


Figure 4.1. Computed and measured wind set-up at station Grevelingendam Hevel West (HEVW)

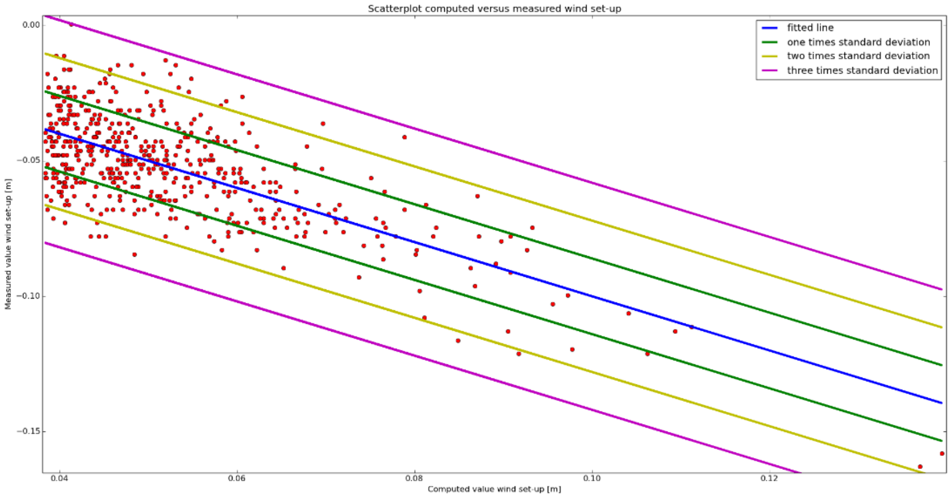


Figure 4.2.Computed and measured wind set-up at station Brouwerssluis Binnen (BRBI)

When calculating the design wind set-up, the extra wind set-up due to the uncertainty have to be taken into account. The amount of extra wind set up depends on the allowed probability of exceedance.

Differences between wind set-up and set-down

The observed differences between the wind set-up at Grevelingendam Hevel West (HEVW) and the wind set-down at Brouwerssluis Binnen (BRBI) are:

- The absolute value of the wind set-up is lower at BRBI with respect to HEVW There are two reasons for this phenomenon, first the fetch is lower for BRBI and secondly the factor kappa is lower (about 25%).
- The standard deviation of the wind set-down at BRBI (1 centimeter) is lower with respect to wind set-up at station HEVW (2 centimeter). The two standard deviations are in the same order of magnitude. There are two possible reasons for the small difference:
    - A first possible reason for the difference in standard deviation can be the outlay of the lake. Measure station BRBI is located in a harbour and sluice part of the lake, it can be seen as a basin connected with the remainder of the lake. While the measure station HEVW is located at the other side of the lake, the border edge on this side is not straight. In summary, the location BRBI does fit better to the theoretical situation of a perfect basin.
    - A second possible reason for the lower standard deviation is the fact that the relevant wind directions for BRBI are in total 20 degree and the relevant wind directions for HEVW are in total 50 degree. It is reasonable to expect a wider range of data points in case of a greater range of wind speeds. All the mentioned wind directions are considered relevant and will generate wind set-up, but there can be small differences which causes the greater standard deviation.

4.2 Comparison results IJselmeer (Feij) with Grevelingenmeer

Result Feij: the wind set-up at the IJselmeer is proportional to the wind speed to the power three

The results from the Grevelingenmeer are different from the results obtained from the IJselmeer. The alternative formula[9] proposed by Feij does not give a better result. Wind set-up at the Grevelingenmeer is proportional to the wind speed squared.

[9] Wind set-up formula with wind speed to the power three

Result Feij: friction coefficient kappa equals 2.19 E-6
Feij has found two different values of kappa, because he used two design formulas. Only the value of kappa with respect to the formula with the wind speed squared will be discussed. Because it makes no sense to compare two different friction parameters. The value of kappa for wind set-up at the Grevelingenmeer (HEVW) equals 2.29 E-6 and the value of the IJselmeer is equal to 2.19 E-6 (Feij, april 2014). The two friction coefficients are nearly equal. But Feij concluded that this approximation of the wind set-up is not accurate.

Standard deviation wind set-up
The hypothesis beforehand was that the Grevelingenmeer would have a bigger deviation in wind set-up due to all the irregularities in fetch and water depth. But when comparing the results from the IJselmeer (Standard deviations 0.033, 0.036 and 0.047 respectively for the different subareas) with the Grevelingenmeer (Standard deviations 0.02 and 0.01 respectively for wind set-up at HEVW and wind set-down at BRBI) the latter appears to have the smallest deviation. Possible reasons for these differences can be the different assumptions with respect to relevant wind directions and speeds. But the differences are very small, so there is not a significant difference between the two locations.

4.3 General recommendation
The generalisation is based on this survey and partially on the work of Feij (Feij, april 2014). For a full general conclusion more analysis of different lakes is needed. The proposed wind set-up formula is given below. The difference with the theoretical wind set-up formula, elaborated in the introduction[10], is the additional wind set-up. The mean value of the wind set-up is calculated without this factor. The design wind set-up should be calculated with an additional wind set-up. The magnitude of this factor depends on the allowed probability of exceedance:

$$W = 0.5\kappa \frac{u_{10}^2}{gd} \cos(\phi)\,\mathrm{F} \pm \mathrm{w'} \qquad [4.1]$$

For which:

W	=	Wind setup	[m]
κ	=	Friction constant	[-]
u_{10}	=	Wind velocity at 10 meter height	[ms^{-1}]
g	=	Gravity (9.81)	[ms^{-2}]
d	=	Water depth	[m]
F	=	Fetch	[m]
w'	=	Additional wind set-up	[m]
ϕ	=	Angle between land and wind	[-]

All the factors in the formula will be discussed below. This is a general recommendation, so exact values for the factors kappa and additional wind set-up can't be given, because they can vary between different basins and lakes.

Kappa (κ)
Kappa is an empirical friction factor, the factor is different for each situation. The order of magnitude is 10^{-6} (Based on this research and the recommendations of the Delta Commission). For an appropriate

[10] Paragraph 1.2, equation 1.3

value of this factor the specific situation has to be studied. But for a first estimate the value proposed by the Delta Commission or the value of this survey can be taken.

Depth

The water depth is easy to determine in a pure theoretical situation with a constant water depth. But it becomes difficult in case of a lake with a widely varying water depth. Wind does have a bigger influence on the water level gradient in shallow water. So it is logical to assume that shallow parts of the lake contribute more to the water level elevation than deep parts. It seems to be accurate to use the mean value of the water depth, only based on comparing the results of the Grevelingenmeer with the IJselmeer. Because the results for kappa are more or less the same. But, it is only based on one location, so a general conclusion is not possible. This topic will be discussed further in the next paragraph.

Additional wind set-up (w')

The additional wind set-up is independent of the wind speed. Each lake does have a standard deviation of the wind set-up. This standard deviation will vary between the different lakes. The order of magnitude is in centimeters.

$$w' = \mathrm{n}\,\sigma_{lake} \qquad [4.2]$$

For which:

w'	=	Additional wind setup	[m]
n	=	Probability of exceedance factor	[-]
σ_{lake}	=	Standard deviation wind set-up	[m]

The factor n depends on the probability of exceedance. Some n-values are given below in table 4.1.

Probability of exceedance [%]	**n**
40	0,25
30	0,52
20	0,84
10	1,28
5	1,64
1	2,33

Table 4.1. n-factors additional wind set-up

cos(*ϕ*)

The angle between land and wind is not used in this survey, because this factor was not relevant in this case. Therefore a conclusion on this factor is not possible. It is the reduction factor for the wind direction.

Fetch

The fetch is the length of the lake at which the wind friction is active. This schematization seems to be accurate, see next paragraph 4.4: water depth and fetch. The factor 0.5 in the formula comes from the rotation of around the 'centre of gravity' of the lake (see paragraph 1.2)

4.4 Discussion

The implications of the conclusions drawn in paragraph 4.1 and 4.3 are discussed in this paragraph.

Smaller design wind set-up

First of all, the quadratic relationship between the wind set-up and wind speed means that the design wind set-up will be far less compared to the wind speed to the power three dependency. In the second place the fact that the scatter does not increase with increasing wind speeds also results in a lower design wind set-up.

Thirdly, the recommended values presented by the Delta Commission (Delta Commissie, 1991) are in the same order of magnitude (10^{-6}) as obtained in this research and by Feij. But they are more conservative, more or less 50% higher than obtained in this research.

The schematisation: water depth and fetch

As mentioned above, the Grevelingenmeer is not a perfect shaped basin. The question which water depth and fetch should be taken into account in order to model it as a perfect shaped basin has to be answered. In this survey the mean water depth and the fetch along the wind direction are used. The calculated friction coefficient kappa is slightly different from the coefficient obtained for the IJselmeer (Grevelingenmeer 2.29 E-6, IJselmeer 2.19 E-6). There can be two reasons for this result. First, it can be a coincidence that the results are more or less the same. Or secondly, the reason can be a very good schematisation of the lake. If the latter is the case, it can be concluded that using the mean value of the water depth is a good way to model wind set-up in a lake with a widely varying water depth.

The values of kappa are a little bit different. The values of kappa depends on the assumptions made for the water depth and fetch. Looking at the values for water depth and fetch which gives the same value of kappa leads to the schematisation of the irregularly shaped lake with a widely varying water depth as if it is like the IJselmeer (more or less a properly shaped basin). A water depth of 5.16 meter (24 centimeter lower than the mean value) leads to the same value of kappa (IJselmeer and Grevelingenmeer both 2.19 E-6). An implication of this value can be that the shallow parts of the lake contribute more to the wind set-up. But this method is a bit arbitrary, because the value of the fetch is assumed to be exact. The fetch of 18.2 kilometre is a rough assumption as can be seen in Appendix II. The fetch is measured parallel to the wind direction, but there are two small islands on that fetch. So the fetch is not homogeneous, it seems likely that the fetch can differ from this ‘exact’ solution. In summary, it is not possible to draw an overall conclusion with respect to the right schematisation of the lake in order to model it as if it is a properly shaped basin. More different lakes has to be studied to answer this question.

Different values for kappa

Al lot of different values for the friction coefficient kappa has passed by. All the different factors are summarised in table 4.2 in order to get a good overview.

Survey Grevelingenmeer	**Location I**	**Location II**	**Location III**
Wind set-up (u-squared formula)	2,29 E-6	-	-
Wind set-down (u-squared formula)	1,75 E-6	-	-
Survey IJselmeer (Feij, april 2014)			
Wind set-up (u-squared formula)	2,19 E-6	-	-
Wind set-up (u-power three formula)	1,68 E-7	1,75 E-7	2,28 E-7
Delta Commission (Bezuyen et al.,2012)			
Wind set-up (u-squared formula)	3,5 - 4,0 E-6	-	-

Table 4.2. Overview values kappa

4.5 Critical remarks

Low wind speeds

A critical remark on the research carried out is the availability of the data. There is a lot of data with low wind speeds, but far less with high wind speeds. The highest wind speed in the data set is approximately 25 meter per second and the number of data points is low in the high wind speeds zone. The method described in this document is accurate for the region with a high data density, but less accurate for very high wind speeds. It is assumed that the behaviour of the wind set-up is the same for very high wind speeds as it is for the studied region. The trend is extrapolated to high wind speeds. This is an assumption that can't be checked in this survey due to the lack of data points. This problem is inherent to this type of survey, there is not much data with the design wind speed. Also the survey of Feij for the IJselmeer does not have very much high wind speeds. The reason for the fact that the absolute value of the wind set-up is much larger at the IJselmeer, is the longer fetch.

Small error in computation mean values

The Python script for analysing the data does analyse first whether the data is relevant. The measure stations are not perfect, every once in a while the station does not provide data but an error. The Python script skips this lines in the CSV-file by looking whether a value is a number (floating element) or an error (string). The mean values are calculated, after this cleaning up of the data file, with use of six sequential data points. But there arises a problem when there was an error in between. Skipping of a line in the data set implies that the mean value is calculated with use of six data points that are not exactly consecutive in time. The amount of errors is small with respect to the whole data set, so it is assumed that this error does not influence the results significantly.

Research in context to the scientific method

The survey to answer the research question, mentioned in the introduction, is not complete. One lake is studied in order to get an answer to the research question, the induction is elaborated for the Grevelingenmeer and compared with the results of the IJselmeer. Conclusions, with respect to for example the friction coefficient kappa, are drawn for this lake and the results are generalized in the paragraph 4.3. But whether the general formula is valid in general for closed basins and lakes should be studied at more locations. In order to come to a full general conclusion, the full scientific method (see figure 4.3) has to be elaborated.

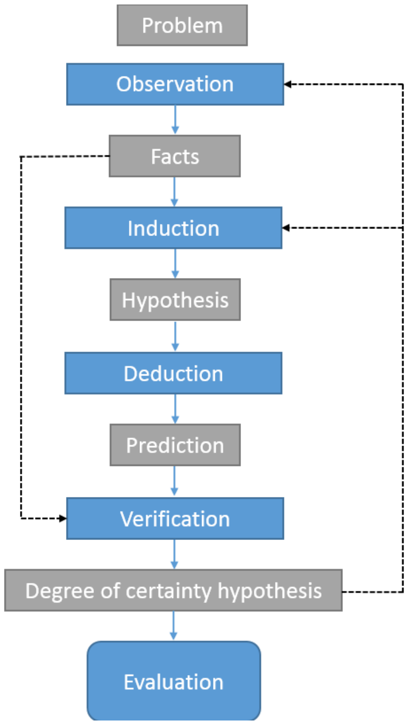


Figure 4.3. Scientific method

4.6 Further research

The results obtained in this survey are based on one research location and partially on the results examined by Feij (Feij, april 2014). It is desirable get more research at different locations, in order to get more support for the general recommendation. See paragraph 4.5: research in context to the scientific method.

Secondly, the question which schematisation (water depth) and fetch has to be taken into account in order to model an irregularly shaped lake as if it is a well-shaped basin has to be studied in more detail.

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Appendix I. Information Grevelingenmeer

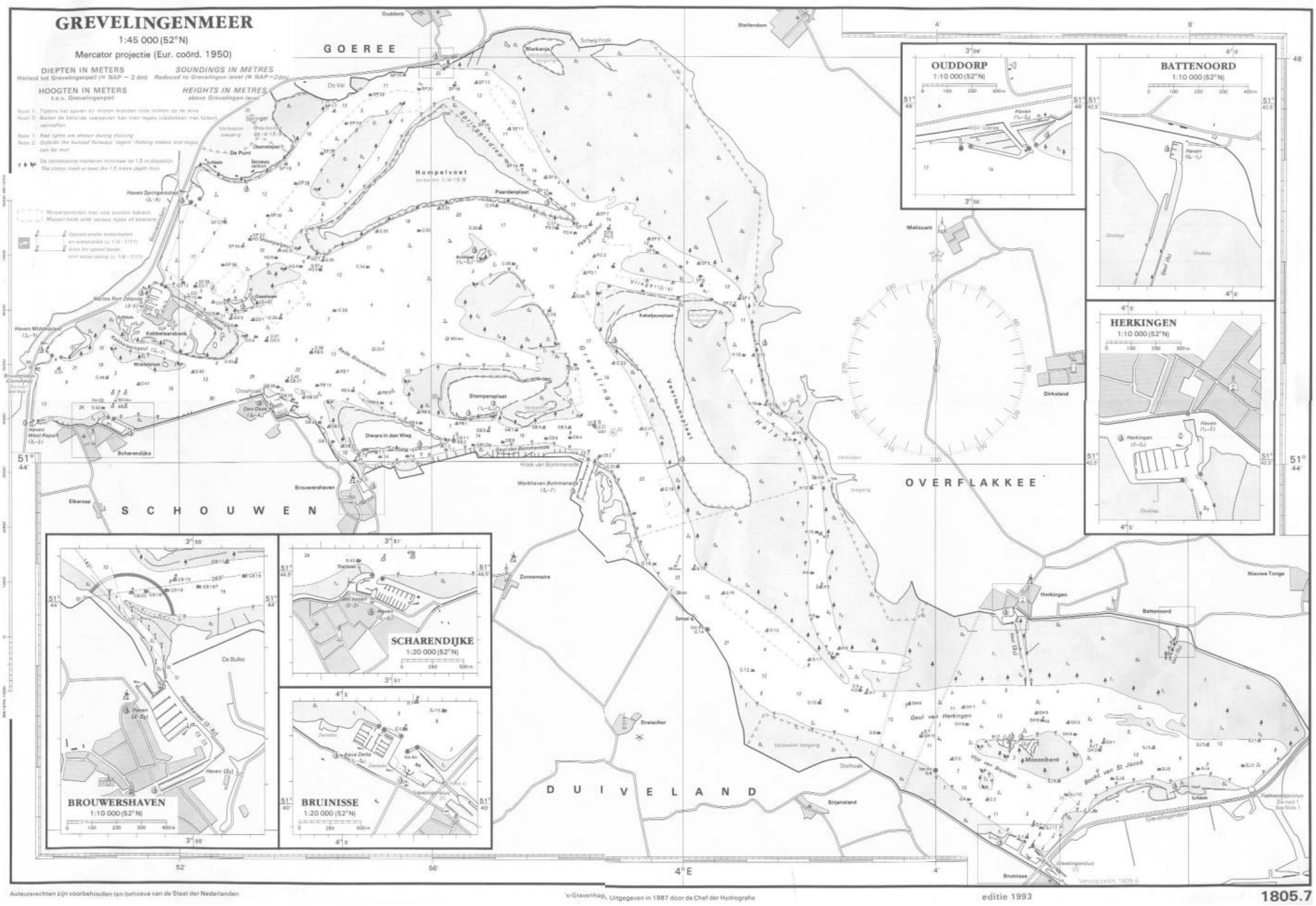


Figure I. 1. Map Grevelingenmeer Source: (Staat der Nederlanden, 1993)

General information Grevelingenmeer (Deltares, 2008)

Mean depth	5.4	[m]
Maximal depth	48	[m]
Water volume	575	[m^3]
Average water depth	NAP -0.20	[m]

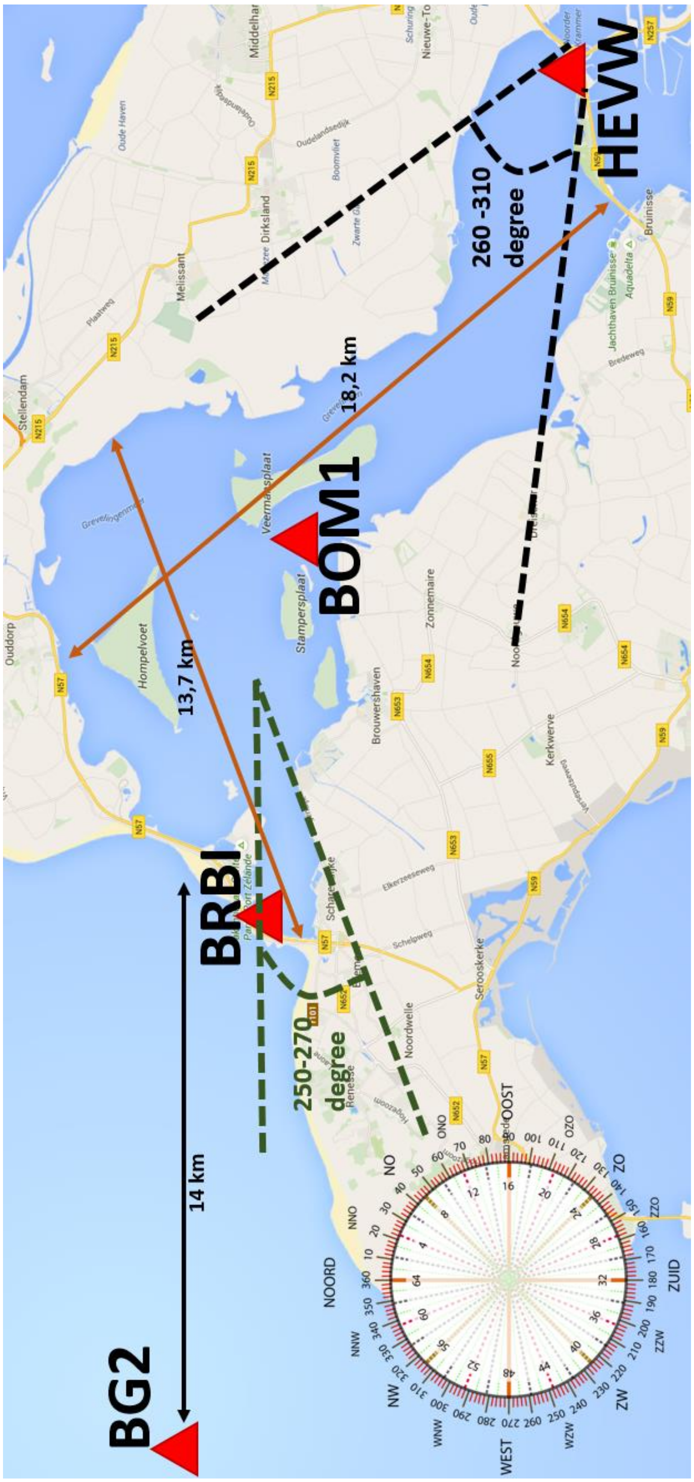
Table I. 1. General information Grevelingenmeer

Data analysis water depth

Measure station	Median water depth	Mean water depth
BRBI	NAP -0.20 [m]	-0.202 [m]
BOM1	NAP -0.20 [m]	-0.201 [m]
HEVW	NAP -0.20 [m]	-0.200 [m]

Table I. 2. Data analysis water depth

Appendix II. Location measure stations relevant wind directions and fetch[11]



The red triangles are the four measure stations:

- Grevelingendam Hevel West (HEVW), water measure station.
- Bommenede (BOM1), water measure station
- Brouwerssluis Binnen (BRBI), water measure station.
- Brouwershavenschegat 2 (BG2), wind measure station.

The brown lines are the fetches for the wind set-up and set-down at stations HEVW and BRBI.

The distances are calculated with the measure tool in Google Maps.

Furthermore the relevant wind directions are shown for wind set-up at station HEVW and wind set-down at station BRBI.

Figure II. 2. Map measure stations and relevant wind directions

[11] Source Map: Google Maps; Compass Card: http://nl.wikipedia.org/wiki/Windstreek#/media/File:Kompasroos.png
Measure tool: https://support.google.com/maps/answer/1628031?hl=nl

Appendix III. Relevant wind directions and time lag water level deviation

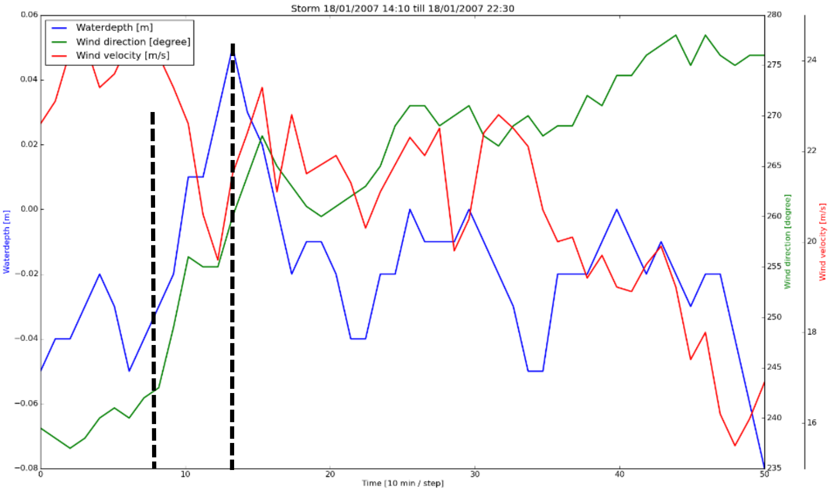


Figure III. 1. Storm 18/01/200 (14:10) till 18/01/2007 22:30

The water level starts to rise substantially after a change in wind direction from 240 to 250 degree. At the same time the wind speed drops, but is still high (> 20 m/s). After T = 10 the deviation in water level follows more or less the wind speed, with a delay. So, we observe no wind set-up for a wind direction below 250 degree. The water level starts to rise in approximately 50 minutes. The delay is important for the method to be used to calculate the mean values of the water level and wind speed. The wind directions above 250 till 280 are relevant, because they generate wind set-up.

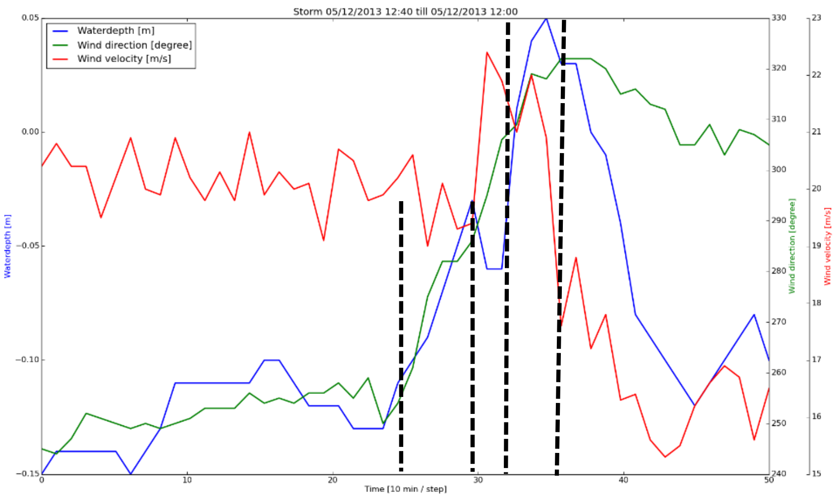


Figure III. 2. Storm 01/02/2008 (19:20) till 02/02/2008 (03:40)

The wind speed is high enough to generate wind set-up on the interval T = 0 till T = 40, after that time the wind speed weakens. But the wind set-up is only generated after the wind direction is above 250 degree. Two intervals are marked in the graph. The first wind set-up is generated due to a relatively constant high wind speed of 20 [m/s] on the interval T = 0 till T = 30. After T = 30 the wind speed increases for a short time which generate the second wind set-up. The time until a relative stationary situation is roughly 60 and 45 minutes respectively.

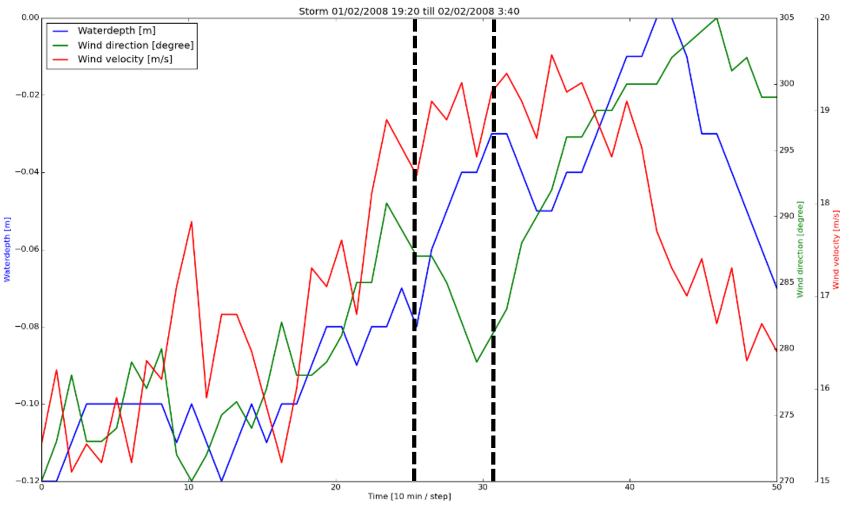


Figure III. 3. Storm 05/12/2013 12:40 till 05/12/2013 (12:00)

The water level elevation follows more or less the deviation in wind speed. Which means that all the wind directions are in the range of wind set-up generation. The wind direction is between 270 and 305 degree. The peak in wind speed at T = 10 is too short to generate wind set-up.

The marked section in the graph shows a time needed to generate wind set-up, this time is approximately 60 minutes.

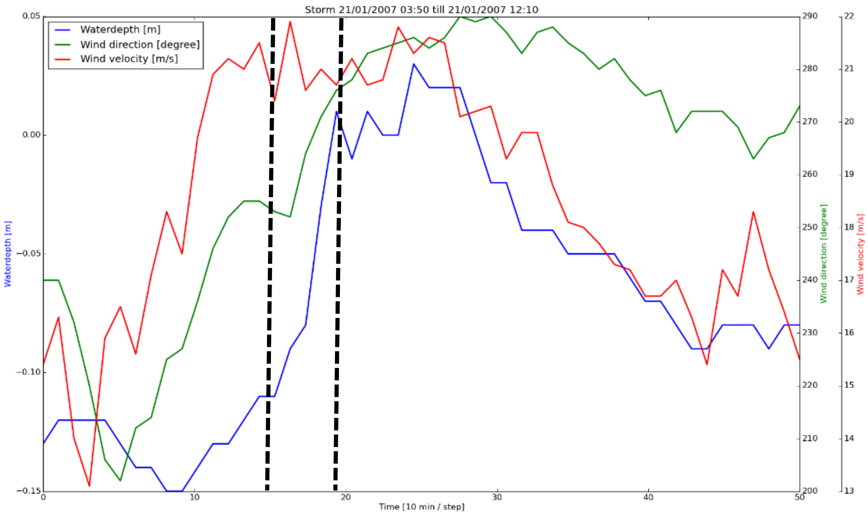


Figure III. 4. Storm 21/01/2007 (03:50) till 21/01/2007 (12:10). Station: HEVW

Wind set-up starts to be generated (first black line) when the wind direction is above 250 degree. At that moment the wind speed is high enough to generate wind set-up (> 20 m/s). Before that time the wind speed is already high, but the wind direction is not good. The time needed for reaching a relatively stationary situation can be observed between the two black lines: 40 minutes. After that time the wind remains constant and so the water level. At time T=30 the wind speed weakens and the water level decreases.

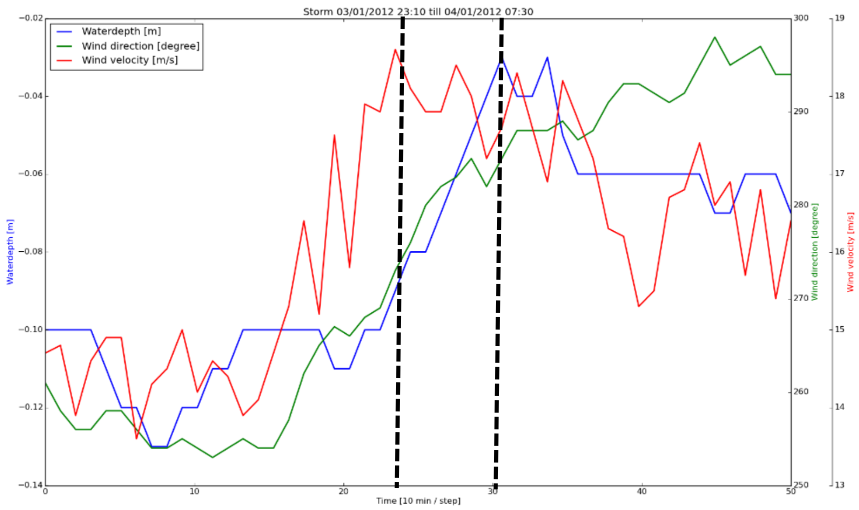


Figure III. 5. Storm 03/01/2012 (23:10) till 04/01/2012 (07:30)

The deviation in water level stick to the wind speed variations, which means that all the wind directions are relevant in this case. The wind directions are between 250 and 300 degree. This is consistent with all the previous graphs, which showed a relevant wind direction greater than 250 degree.

The time needed to arrive at a relatively stationary situation is approximately 60 minutes (marked by the two black lines).

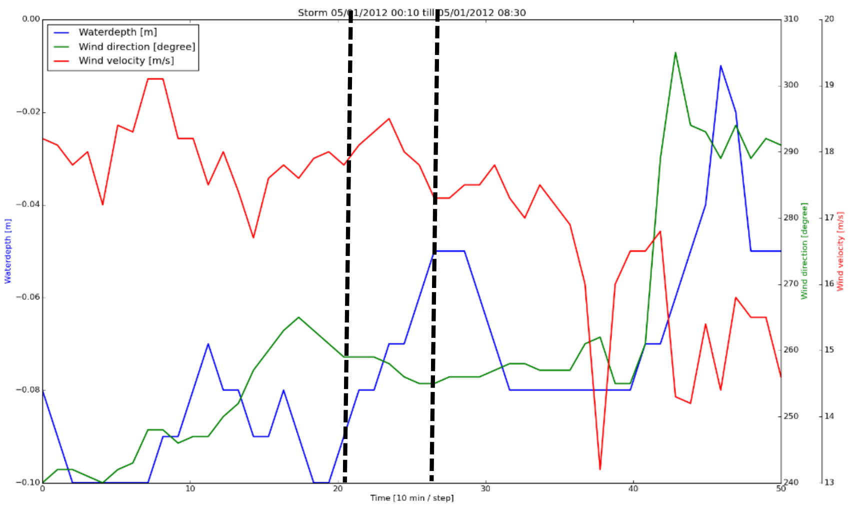


Figure III. 6. Storm 05/01/2012 (00:10) till 05/01/2012 (08:30)

In this graph it can be seen that there is no wind set-up generated for a wind direction below 250 degree. The wind speed is not very high, but high enough to generate wind set-up (approximately 18 [m/s]).

The time needed to reach the stationary situation is more or less 60 minutes (marked by the two black lines).

Appendix IV. Determination reference water level wind set-up HEVW

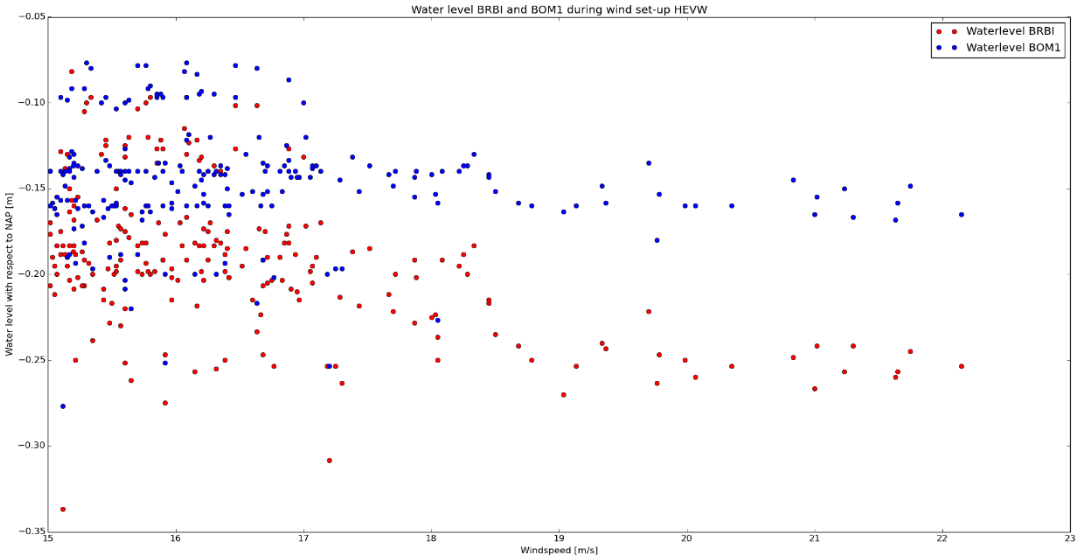


Figure IV. 1. Scatter plot water level BRBI and BOM1 during wind set-up HEVW

Please note that the plotted water level is not corrected for the wind set-up, water level is not with respect to NAP, because we want to determine the reference level in the lake.
Correlation coefficient water level BRBI – Wind speed = - 0.49 (low correlation)
Correlation coefficient water level BOM1 – Wind speed = - 0.11 (no correlation)

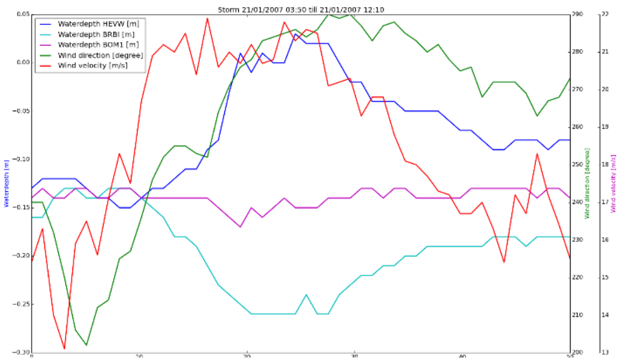


Figure IV. 3. Storm 21/01/2007 (03:50) till 21/01/2007 (12:10)

Absolute difference in water level at station BOM1 is very small during a storm. The water level at BRBI tends to decrease when the wind set-up is generated at HEVW. Which is explainable using the volume balance of the lake.

Absolute difference in water level at station BOM1 is very small during a storm. The

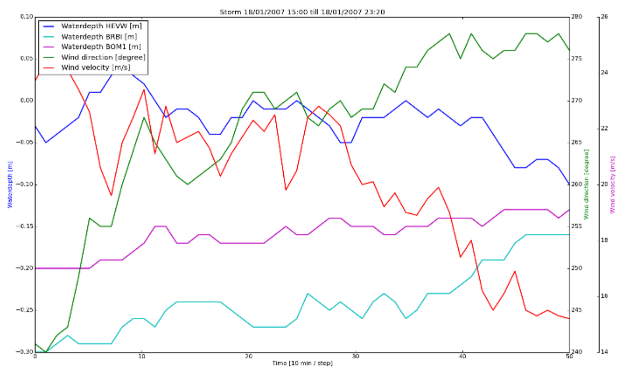


Figure IV. 2. Storm 18/01/2007 (15:00) till 18/01/2007 (23:20)

Absolute difference in water level at station BOM 1 during the storm is very small at station BRBI the water level fluctuates more. Which means that the water level at BOM1 is the best reference water level, in this specific case.

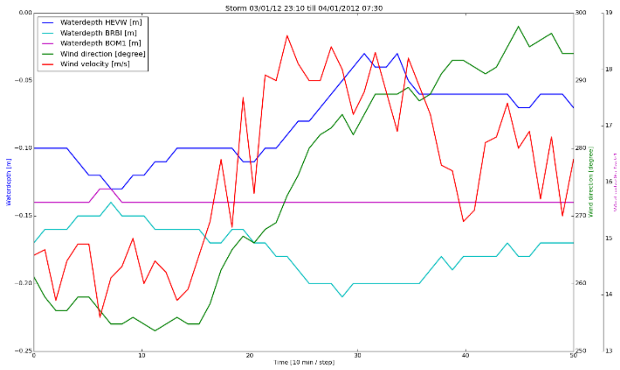


Figure IV. 7. Storm 03/01/2012 (23:10) till 04/01/2012 (07:30)

Absolute difference in water level at station BOM1 hardly fluctuates. The water level at BRBI tends to decrease when the wind set-up is generated at HEVW.
Which means that the water level at BOM1 is the best reference water level, in this specific case.

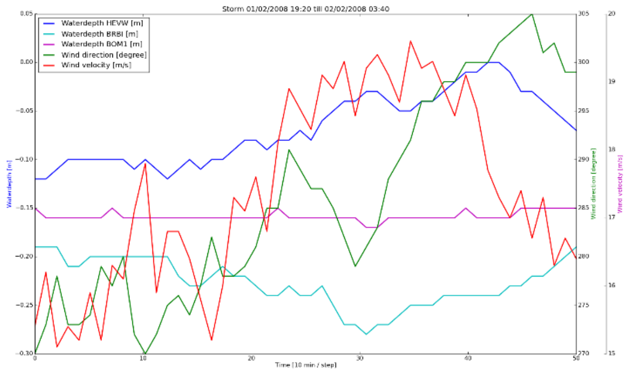


Figure IV. 6. Storm 01/02/2008 (19:20) till 02/02/2008 (03:40)

Absolute difference in water level at station BOM1 hardly fluctuates. The water level at BRBI tends to decrease when the wind set-up is generated at HEVW but the difference is not very big.

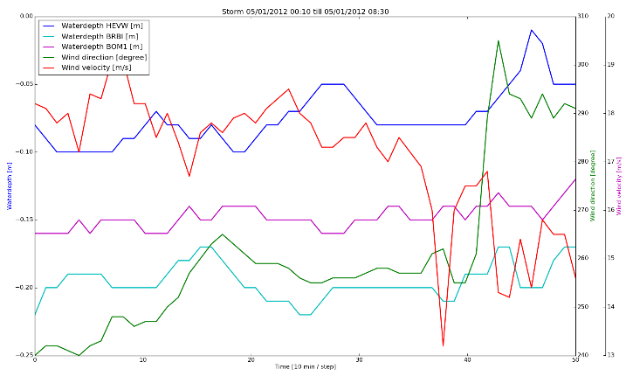


Figure IV. 5. Storm 05/01/2012 (00:10) till 05/01/2012 (08:30)

Both the water levels at BRBI and BOM1 do not vary very much. But also the wind set-up at HEVW is not very big and last also for a short time. The question is whether a full wind set-up is generated.
Therefore it is not easy to draw a conclusion based on this graph.

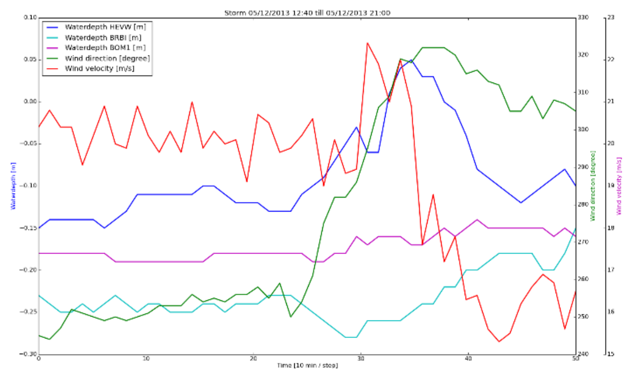


Figure IV. 4. Storm 05/12/2013 (12:40) till 05/12/2013 (23:00)

Absolute difference in water level at station BOM1 is not very big. The water level at BRBI tends to decrease when the wind set-up is generated at HEVW.

Appendix V. Determination reference water level wind set-down BRBI

During high wind speeds and a wind direction between 250 and 270 degree, there will be a decrease in water level at station BRBI. In this Appendix the reference water level will be determined in case of wind set-down at station Brouwerssluis Binnen.

The graph below is obtained with the following boundary conditions

I. Wind speed above 13 [m/s]

II. Wind direction between 250 and 270 degree

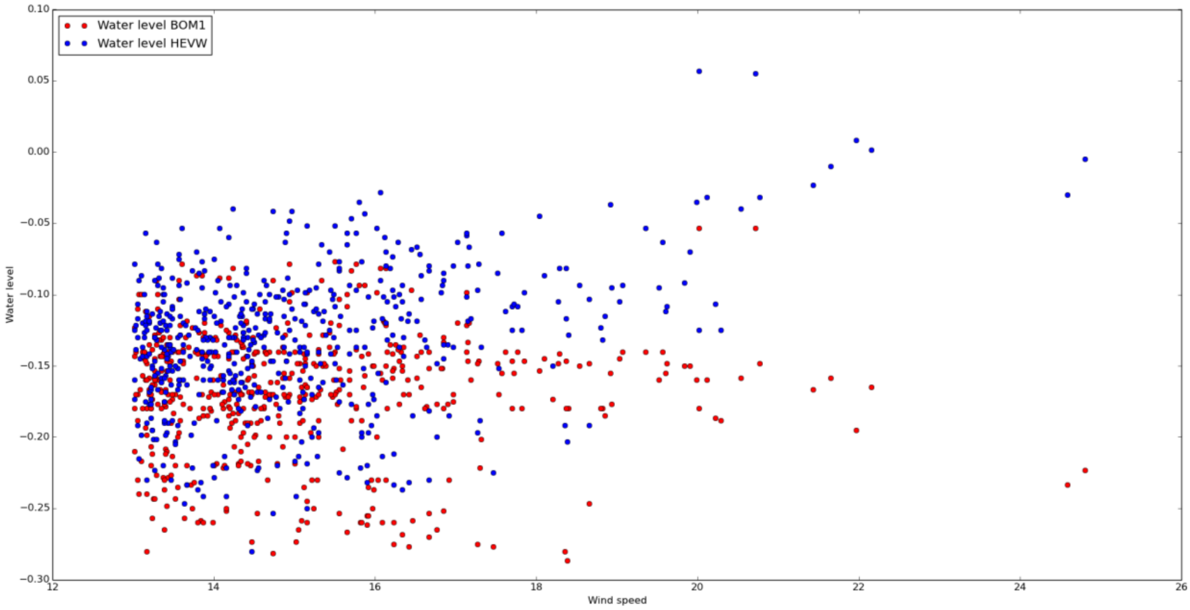


Figure V. 1. Reference water level wind set-up Brouwerssluis Binnen

Please note that the plotted water level is not corrected for the wind set-up, water level is with respect to NAP, because we want to determine the reference level in the lake. Correlation coefficient water level BOM1 – Wind speed = - 0.010 (no correlation) Correlation coefficient water level HEVW – Wind speed = 0.37 (low correlation)

There can be concluded that the reference water level for wind set-up at Brouwerssluis Binnen (BRBI) is Bommenede (BOM1). Because the water level is not correlated with the wind speed that generate wind set-up at BRBI.

Appendix VI. Data analysis Python script

This first script contains the basis for all the graphs and computations. For each output this code is a little bit modified. All this scripts are not put in this document, because they are more or less the same. On the next page a script with all the used python functions is showed.

```
#Import needed packages
from pylab import *
import csv
import numpy

#Define formula to confirm whether a value is a floating element or a string
def isfloat(value):
    try:
        float(value)
        return True
    except ValueError:
        return False

#Load data
reader=csv.reader(open("Combined_origineel.csv","rb"),delimiter=';')
r=list(reader)
x=numpy.matrix(r)

#Count the amount of relevant rows (skip al errors) and store in a new matrix
A=0; Z=0;
for i in range(len(x)):
    if (isfloat(x[i,2])==True) and (isfloat(x[i,3])==True) and (isfloat(x[i,4])==True) and (isfloat(x[i,5])==True) and (isfloat(x[i,6])==True):
        A = A + 1
Data = zeros([A,size(x)/len(x)-1])
for i in range(len(x)):
    if (isfloat(x[i,2])==True) and (isfloat(x[i,3])==True) and (isfloat(x[i,4])==True) and (isfloat(x[i,5])==True) and (isfloat(x[i,6])==True):
        for j in range(size(x)/len(x)-2):
            Data[Z,j]=x[i,j+2]
            Data[Z,5] = i                       #Gives a number to trace back the date and time
        Z = Z + 1

#Convert the data in the right dimensions [m] and [m/s]
Data[:,0]=0.01*Data[:,0]; Data[:,1]=0.01*Data[:,1]; Data[:,2]=0.01*Data[:,2]; Data[:,4]=0.1*Data[:,4]

#Convert the Data to mean data
GemData = zeros([len(Data)/6,size(Data)/len(Data)])
for i in range(len(Data)/6):
    for j in range(size(Data)/len(Data)):
        GemData[i,j] = (Data[6*i,j]+Data[6*i+1,j]+Data[6*i+2,j]+Data[6*i+3,j]+Data[6*i+4,j]+Data[6*i+5,j])/6

#Count relevant data and store in matrix
R=0; Q=0; Fetch=18200; Depth=5.4;
for i in range(len(GemData)):
    if ((GemData[i,3] > 260) and (GemData[i,3] < 310.0) and (GemData[i,4]>13)):
        R = R + 1
PlotData = zeros([R,5])
for i in range(len(GemData)):
    if ((GemData[i,3] > 260) and (GemData[i,3] < 310.0) and (GemData[i,4]>13)):
        PlotData[Q,0]=GemData[i,4]                          #Store wind speed
        PlotData[Q,1]=GemData[i,3]                          #Store wind direction
        PlotData[Q,2]=GemData[i,1]                          #Store water depth
        PlotData[Q,3]=GemData[i,2]-GemData[i,1]+0.0406873555562   #Store wind set-up at HEVW, corrected for the 4.1 centimetre error
        PlotData[Q,4]=0.5*Fetch/(9.81*Depth)*GemData[i,4]**2      #Store and compute wind set-up **
        Q = Q + 1

#Compute and print correlation and plot computed value wind set-up versus measured value
print 'The correlation is: ', numpy.corrcoef(PlotData[:,4], PlotData[:,3])[0, 1]
plot(PlotData[:,4],PlotData[:,3], 'ro')

#Fit line trough data points
c,d = polyfit(PlotData[:,4],PlotData[:,3],1)
print 'fitted slope, parameter c = ',c
print 'fitted y-intercept parameter d = ',d
y_fit1= c*PlotData[:,4]+d
plot(PlotData[:,4], y_fit1, 'b', linewidth=3.0,label='Mean wind set-up')

#Compute standard deviation kappa
S = zeros([len(PlotData),1])
for i in range(len(PlotData)):
    S[i,0] = PlotData[i,3]/PlotData[i,4]
print 'Standard Deviation kappa', np.std(S[:,0])

#Graph settings
xlabel('Computed value wind set-up without kappa')
ylabel('Measured value wind set-up [m]')
title('Scatterplot wind speed versus wind set-up')
legend(loc=2)
show()
```

```
#Import needed packages
from pylab import *
import csv
import numpy

#Computation correlation coefficient
print 'The correlation is: ', numpy.corrcoef(PlotData[:,4], PlotData[:,3])[0, 1]

#Fit line trough data points and plot the line
c,d = polyfit(PlotData[:,4],PlotData[:,3],1)
print 'fitted slope, parameter c = ',c
print 'fitted y-intercept parameter d = ',d
y_fit1= c*PlotData[:,4]+d
plot(PlotData[:,4], y_fit1, 'b', linewidth=3.0,label='fitted line')

#Computation standard deviation
print 'Standard Deviation', np.std(PlotData[:,4])

#Relative boxplot
a = boxplot(PlotData[:,5]/c*100)
show()

#Plot histogram
b = hist(DevKappa[:,0]/c*100,range = (-80,80), bins = 200,normed=True, cumulative=True, label='Measured deviation kappa')
title('Cumulative probability graph')
xlabel('Deviation kappa [%]')
ylabel('Cumulative probability')

#Plot standard normal distribution
mu = mean(DevKappa[:,0]/c*100)
sigma = np.std((DevKappa[:,0]/c*100))
x = linspace(-80,80,1000)
y = norm.cdf(x,mu,sigma)
plot(x,y,'r', linewidth=6.0, label='Standard Normal Distribution')
legend(loc='2')
show()

#Compute median
MED = median(PlotData[:,4])
```

Appendix VII. Determination kappa

The wind set-up is calculated with use of the wind set-up formula. The formula explained in the first chapter can be seen below (also equation 1.3).

$$W = 0.5\kappa \frac{u_{10}^2}{gd} \mathrm{F} \cos\phi \qquad \text{[VII.1]}$$

In a complete theoretical situation, the computed and measured wind set-up are the same and the factor kappa is equal for each wind set-up. But this is not the case in nature. The factor kappa is analysed per individual wind set-up. The method used to analyse kappa (Feij, april 2014) is explained below. Visually in figure VII.1 and analytically underneath.

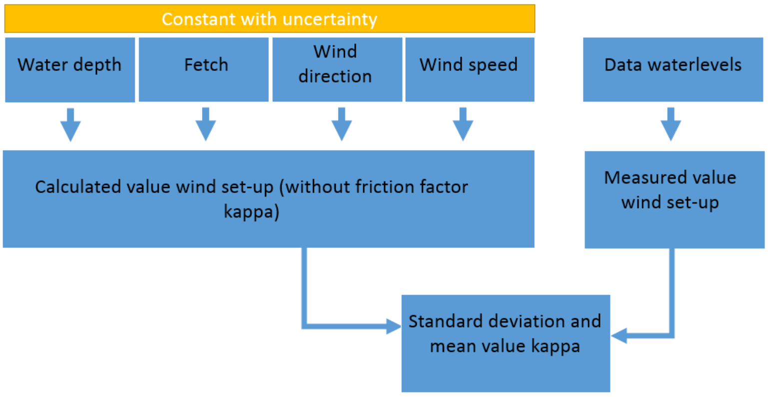


Figure VII. 1. Visualisation determination kappa

A graph is made of all the data points, on the horizontal axis the calculated wind set-up, without the factor kappa and angle ϕ will be given, see (equation VII.2). And on the vertical axis the measured wind set-up.

$$W_{computed} = 0.5\kappa \frac{u_{10}^2}{gd} \mathrm{F} \qquad \text{[VII.2]}$$

The measured and computed wind set-up should be the same, so the following holds:

$$W_{measured} = W_{computed} \qquad \text{[VII.3]}$$

$$W_{measured} = 0.5\kappa \frac{u_{10}^2}{gd} F \qquad \text{[VII.4]}$$

$$\kappa = \frac{W_{measured}}{0.5 \frac{u_{10}^2}{gd} F} \qquad \text{[VII.5]}$$

The final equation VII.5 is the slope of the line through the origin and the data point. This method is illustrated in figure VII.2.

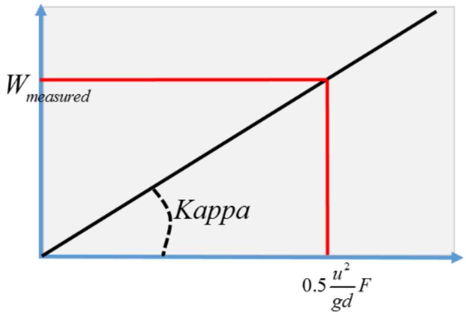


Figure VII. 2. Determination kappa

Appendix VIII. Analysis wind set-up HEVW

VIII.1 In and output model

Input model

Fetch	18200 meter (see appendix II)
Water depth (average)	5.4 meter (see appendix I)
Wind speed	Mean wind speed per hour (CSV-file)
Wind set-up	Mean water level per hour (CSV-file)

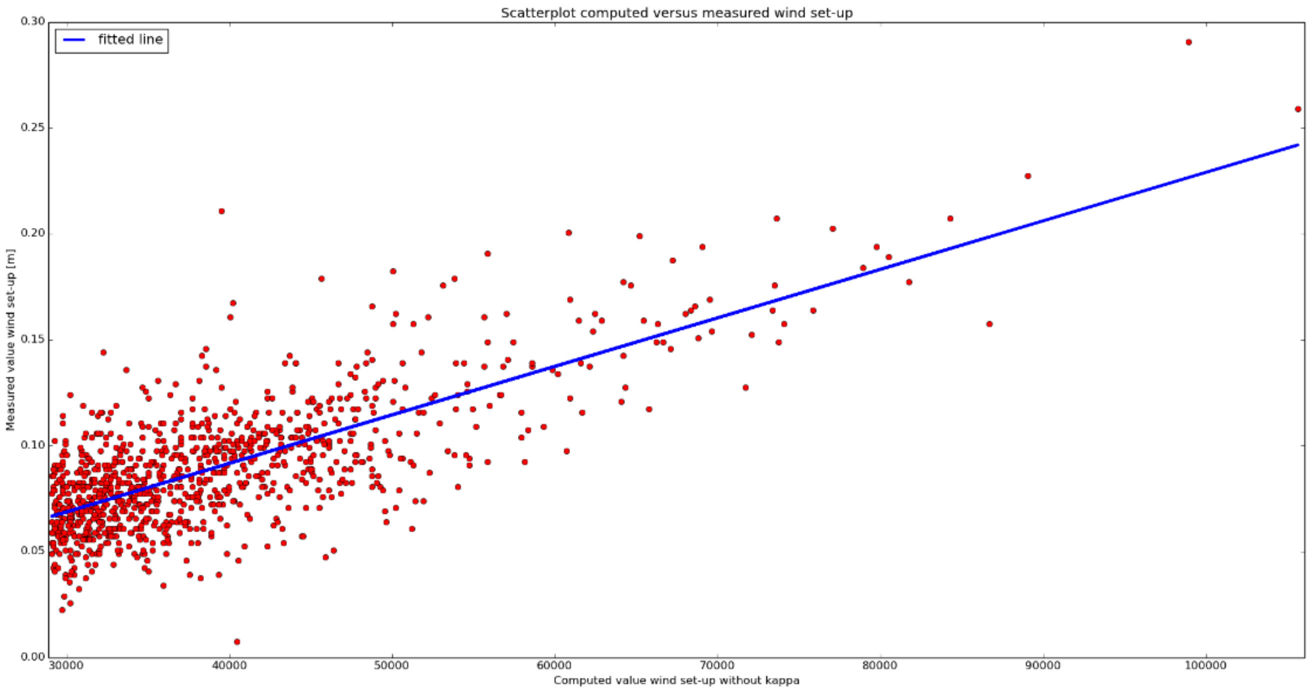


Figure VIII. 1. Scatterplot computed versus measured wind set-up

Output model

y-intercept fitted line	-1.67e-14 (= 0)
Slope fitted line (kappa)	2.2896 E-6
Correlation coefficient	0.74
Number of measurements	1039

VIII.2 Scatter kappa

In order to determine the distribution of the values of kappa the following quantities are calculated.

1. Per data point the exact value of kappa

$$\kappa = \frac{W_{measured}}{\frac{u^2}{gd}F} \quad \text{[VII.1]}$$

2. Per data point the deviation of [VII.1] with respect to the slope of the line (2.2896 E-6)
3. The mean value of the data obtained at point [2]
4. The standard deviation of the data obtained at point [2]

The distribution of the values of kappa is the point of interest and is therefore analysed. Point 3 and 4 are used to calculate the exact solution of the normal distribution. As can be seen on the next page, it is likely that the data is normally distributed.

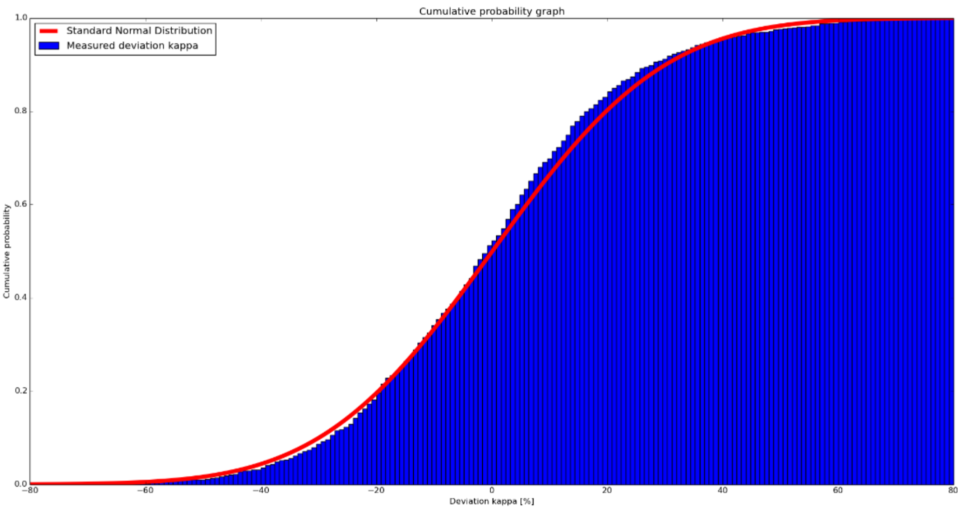


Figure VIII. 2. Cumulative probability graph deviation kappa

Figure VIII.2, support the hypothesis that the data is normal distributed. The normalized histogram does match very well with the standard (red line) solution of the normalized cumulative normal distribution.

In order to calculate the standard solution the mean value and standard deviation of the data is calculated.

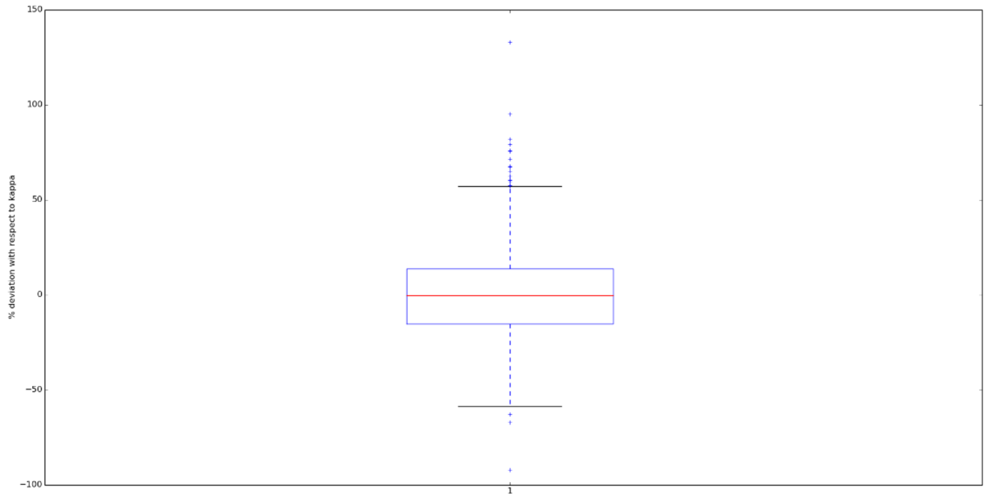


Figure VIII. 3. Boxplot deviation kappa

Also in figure VIII.3, can be seen that the data is presumably normal distributed. A boxplot is made of the different values of kappa. The boxplot is approximately symmetrical. Which is the case in a normal distributed data set.

The two graphs shows that the data set is presumably normal distributed.

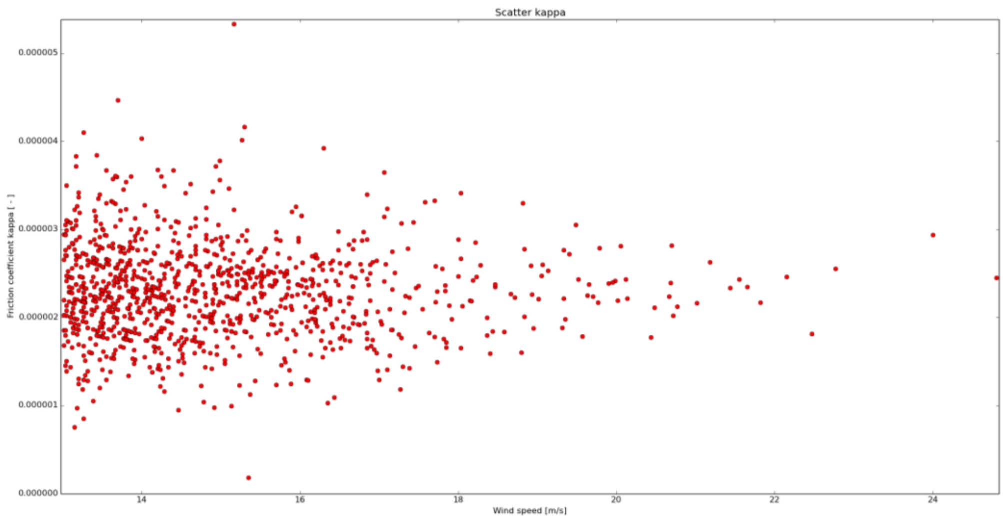


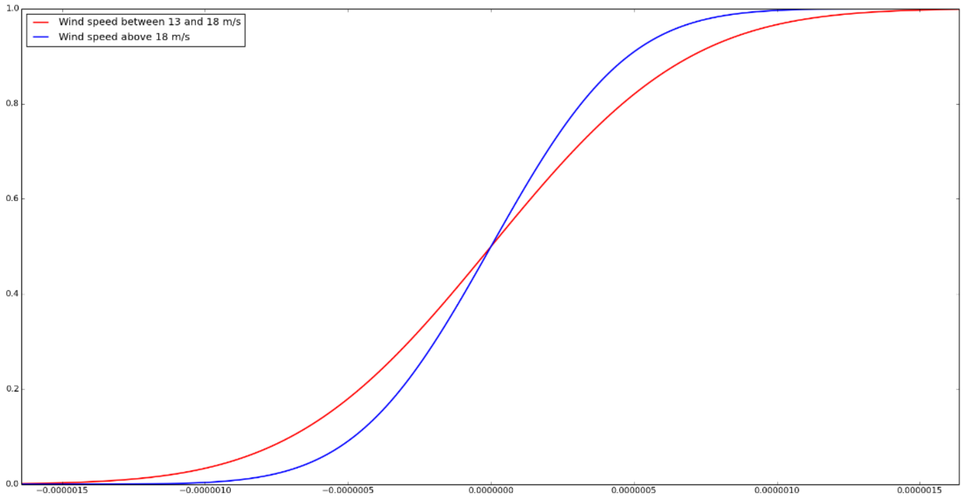
Figure VIII. 4. Scatter kappa

What is studied next is the question whether the distribution of kappa decreases with increasing wind speeds.

In figure VIII.4, the wind speed versus the associated value of kappa is plotted. It can be seen that the scatter tends to decrease. But the number of points also decreases. It is therefore not possible to draw a conclusion only based on visual inspection of the graph. In the next section the full method will be elaborated.

To analyse whether the decrease of the variance of kappa is significant, two parts of the data set is analysed. First all the data points with a wind speed between 13 and 18 [m/s], and secondly all data points above a wind speed of 18 [m/s]. The intervals are chosen based on the graph. This leads to the following results.

Interval	Number of points	Degrees of freedom	Standard deviation [-]
13-18 [m/s]	969	968	5.46235 E-7
> 18 [m/s]	70	69	3.74323 E-7



In figure VIII.5 can be seen that the normal distribution of both samples are not the same. The variance is greater for the data set with a wind speed between 13 and 18 [m/s]. Whether it is significantly different is analysed below, with use of the F-test.

Figure VIII. 5. Cumulative normal distribution two parts data set

The mean value of the data points is also not exactly the same, but for this calculation the mean value will be assumed to be equal. This is allowed because only the deviation of the variances will be studied.

Statistical F-test

$$H_0 : \sigma_1 = \sigma_2$$
$$H_1 : \sigma_1 > \sigma_2$$
$$F = \frac{\sigma_1^2}{\sigma_2^2} = \frac{(5.46235*10^{-7})^2}{(3.74323*10^{-7})^2} = 2.12$$

Critical F-value can be calculated using F-tables. In this calculation a web-application (Online Critical F value calculator, 2013) is used. The exact critical F value is 1.56 (with a significance level of 1%, α=0.01).

2.12 is much greater than 2.12 , so the alternative hypothesis is true, with a high degree of certainty α=0.01.

The result is not only based on the statistical test, but also on common sense when analysing the graph.

VIII.3 Scatter wind set-up

The question whether the wind set-up deviation is constant over the whole range of wind speeds will be answered in this appendix. First will be showed that it is likely that this data is also normally distributed. And secondly will be showed that the standard deviation is presumably constant over the whole range of wind speeds.

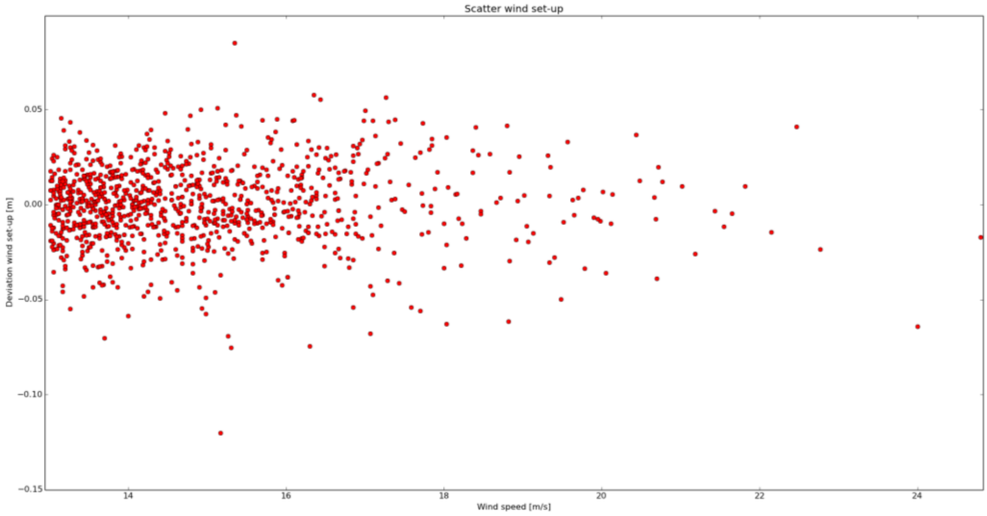


Figure VIII. 6. Scatter wind set-up with respect to wind speed

Please note: the deviation in wind set-up is measured in the vertical direction with respect to the least squares estimate line.

Figure VIII.6 shows that the deviation in wind set-up seems to be constant over the whole range of wind speeds. The higher the wind speed the less dense the data points.

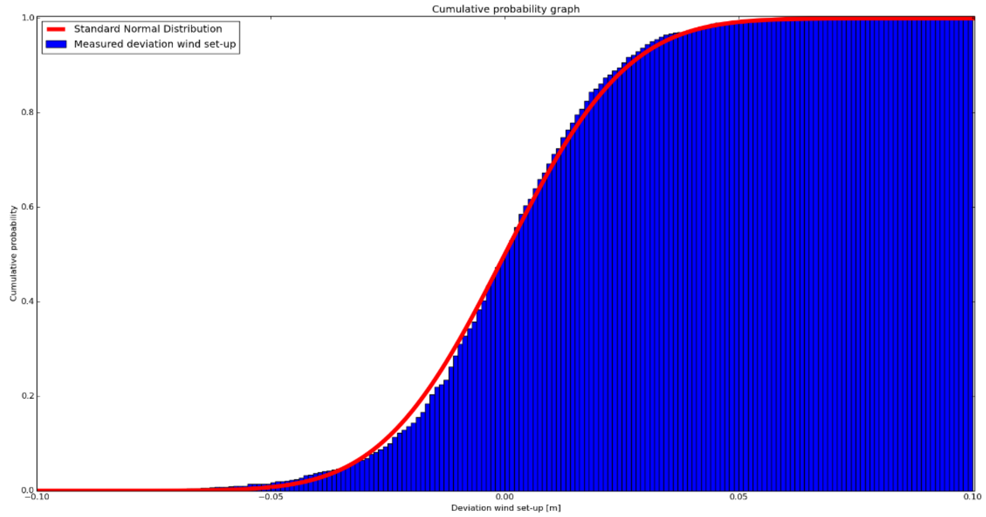


Figure VIII. 6. Cumulative probability graph deviation wind set-up

Figure VIII.7 shows that the deviation in wind set-up seems to be normally distributed. The blue histogram fits quite well to the red line which is the standard cumulative normal distribution.

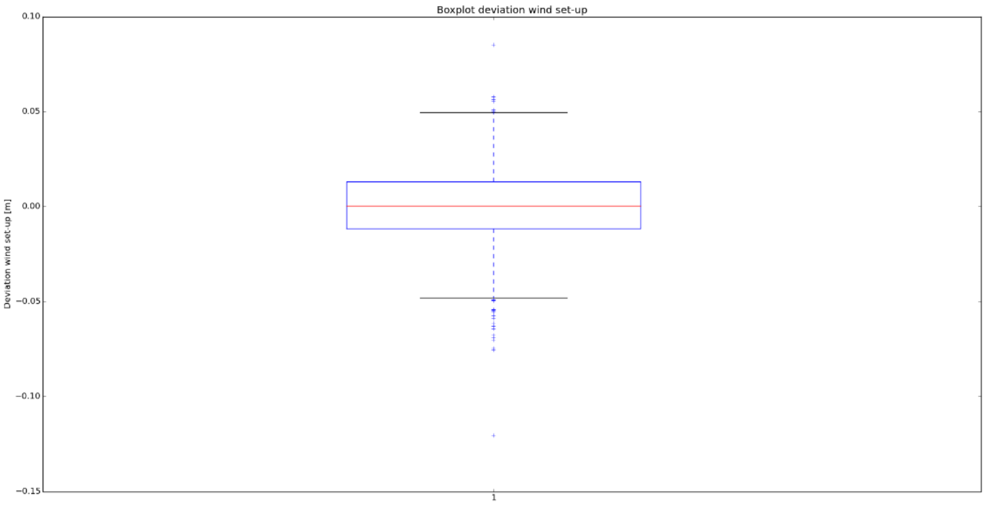


Figure VIII. 8. Boxplot deviation wind set-up

Also figure VIII.8 support the hypothesis that the data is normally distributed. The boxplot is symmetrical, which means that the Gaussian distribution is approached.

When looking at the graph, it seems to be the case that the scatter stays the same, at each wind speed. This will be statistically checked with the above mentioned F-test. The same interval analysed as before. The first interval with a wind speed between 13 and 18 m/s and the second interval above 18 m/s.

Interval	**Number of points**	**Degrees of freedom**	**Standard deviation [m]**
>13	1039	1038	0.020639
13-18 [m/s]	969	968	0.020274
> 18 [m/s]	70	69	0.024027

Statistical F-test

$$H_0 : \sigma_1 = \sigma_2$$
$$H_1 : \sigma_1 \neq \sigma_2$$
$$F = \frac{\sigma_2^2}{\sigma_1^2} = \frac{(0.0240267)^2}{(0.0202744)^2} = 1.40$$

Critical F-value can be calculated using F-tables. In this calculation a web-application (Online Critical F value calculator, 2013) is used. The exact critical F value is 1.46 (with a significance level of 1%, α=0.01).

1.40 is less than 1.46, so the alternative hypothesis is rejected, the zero hypothesis holds.

The result is not only based on the statistical test, but also on common sense when analysing the graph.

Appendix IX. Analysis wind set-up BRBI

IX.1 In and output model

Input model

Fetch	13700 meter (see appendix II)
Water depth (average)	5.4 meter (see appendix I)
Wind speed	Mean wind speed per hour (CSV-file)
Wind set-up	Mean water level per hour (CSV-file)

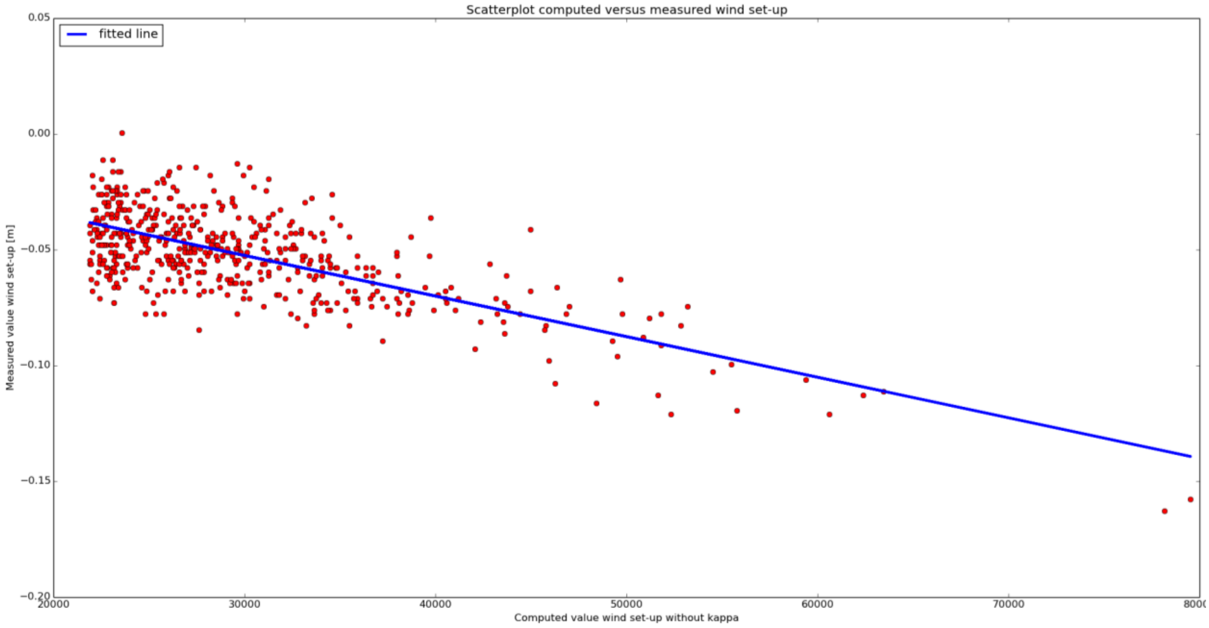


Figure IX 1. Scatterplot computed versus measured wind set-up

Output model

y-intercept fitted line	-3.377 E-15 (= 0)
Absolute value slope fitted line (kappa)	1.753 E-6
Correlation coefficient	-0.71
Number of measurements	538

IX.2 Normal distribution kappa

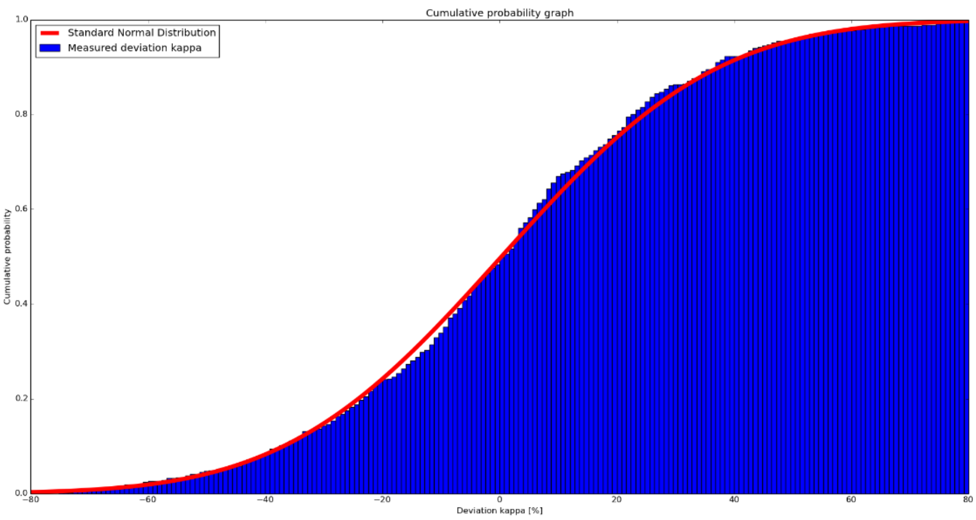
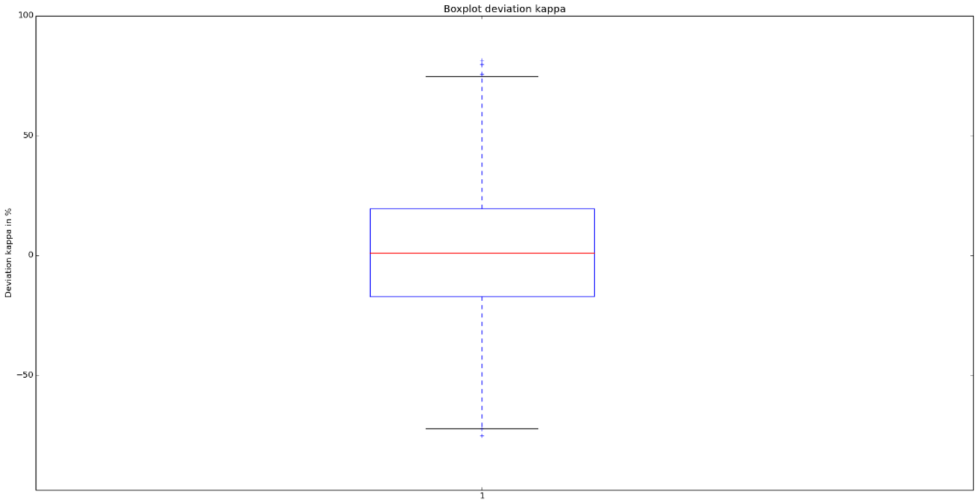


Figure IX 2. Cumulative probability graph deviation kappa

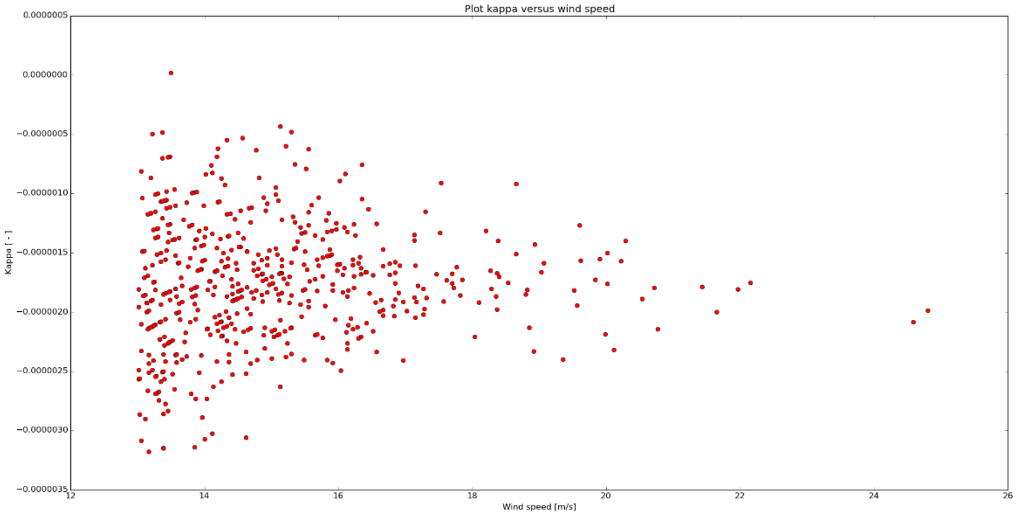
In figure IX.2 can be been that it is likely that the data is normally distributed. The red line (standard normalized cumulative normal distribution) does fit quite well with. Additional evidence can be found in figure IX.3 on the next page.



In figure IX.3. The boxplot with the deviation of kappa (percentages) is more or less symmetrical. Which means that it is likely a normal distributed data set.

Figure IX 3. Boxplot deviation kappa

IX.3 Kappa versus wind speed



In figure IX.4 can be seen that the scatter of kappa tends to decrease with increasing wind speed. Whether this decrease is statistically significant is elaborated below. The statistical F-test is used.

Figure IX 4. Kappa versus wind speed

To analyse whether the decrease of the variance of kappa is significant, two parts of the data set is analysed. First all the data points with a wind speed between 13 and 18 [m/s], and secondly all data points above a wind speed of 18 [m/s]. The intervals are chosen based on the graph. This leads to the following results.

Interval	**Number of points**	**Degrees of freedom**	**Standard deviation [-]**
13-18 [m/s]	492	491	5.21909 E-7
> 18 [m/s]	42	41	3.04616 E-7

Statistical F-test

$$H_0 : \sigma_1 = \sigma_2$$
$$H_1 : \sigma_1 > \sigma_2$$
$$F = \frac{\sigma_2^2}{\sigma_1^2} = \frac{(5.21909 * 10^{-7})^2}{(3.04616 * 10^{-7})^2} = 2.94$$

Critical F-value can be calculated using F-tables. In this calculation a web-application (Online Critical F value calculator, 2013) is used. The exact critical F value is 1.81 (with a significance level of 1%, α=0.01).

2.94 is much greater than 1.81, so the zero hypothesis is rejected, the alternative hypothesis holds. The result is not only based on the statistical test, but also on common sense when analysing the graph.

IX.4 Scatter wind set-up

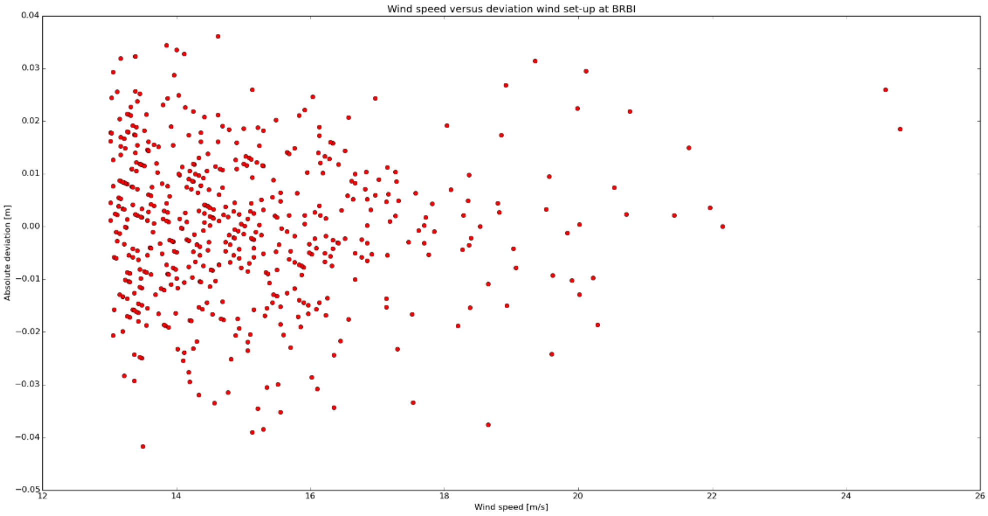


Figure IX 5. Wind speed versus deviation wind set-up at BRBI

To analyse whether the decrease of the variance of kappa is significant, two parts of the data set is analysed. First all the data points with a wind speed between 13 and 18 [m/s], and secondly all data points above a wind speed of 18 [m/s]. The intervals are chosen based on the graph. This leads to the following results.

Interval	**Number of points**	**Degrees of freedom**	**Standard deviation [-]**
>13	534	533	0.013970
13-18 [m/s]	492	491	0.013778
> 18 [m/s]	42	41	0.014289

Statistical F-test

$$H_0 : \sigma_1 = \sigma_2$$
$$H_1 : \sigma_1 \neq \sigma_2$$
$$F = \frac{\sigma_2^2}{\sigma_1^2} = \frac{(0.014289)^2}{(0.013778)^2} = 1.076$$

Critical F-value can be calculated using F-tables. In this calculation a web-application (Online Critical F value calculator, 2013) is used. The exact critical F value is 1.63 (with a significance level of 1%, α=0.01).

1.08 is much less than 1.63, so the zero hypothesis is not rejected, the zero hypothesis holds. The result is not only based on the statistical test, but also on common sense when analysing the graph.

Appendix X. Conclusion wind set-up

The two figures of paragraph 4.1 are also in this paragraph, but in a bigger size. For all the background and explanations, see paragraph 4.1.

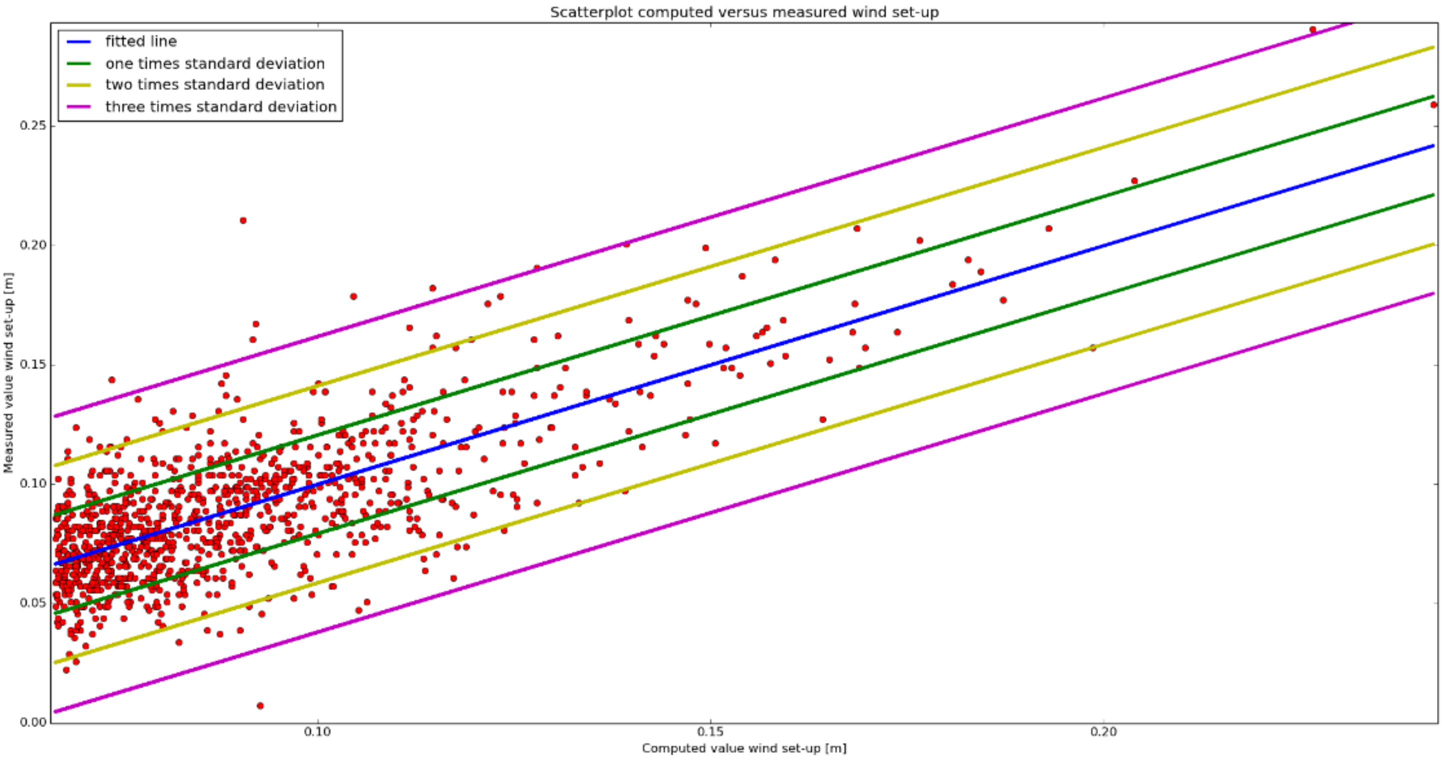


Figure X. 2. Wind set-up station Grevelingenmeer dam West

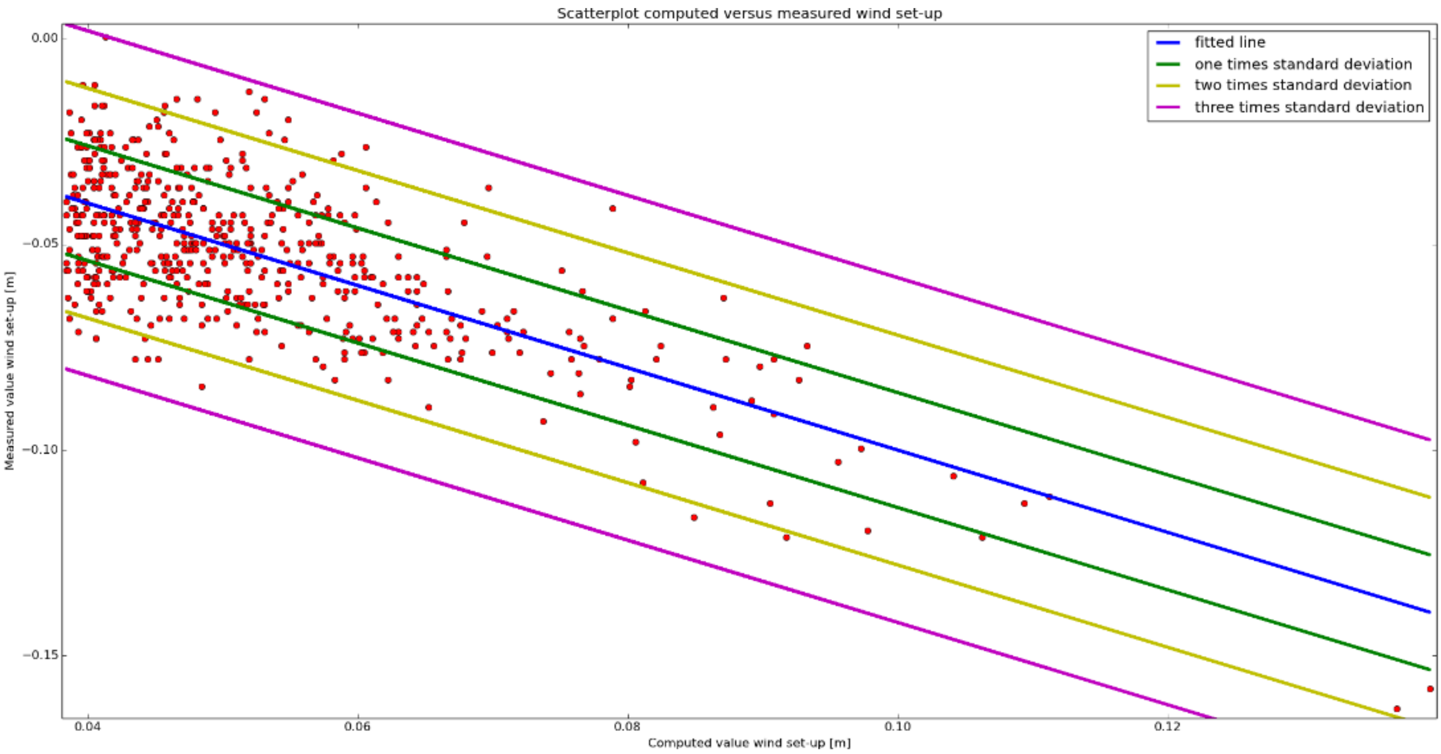


Figure X. 1. Wind set-up station Brouwerssluis Binnen