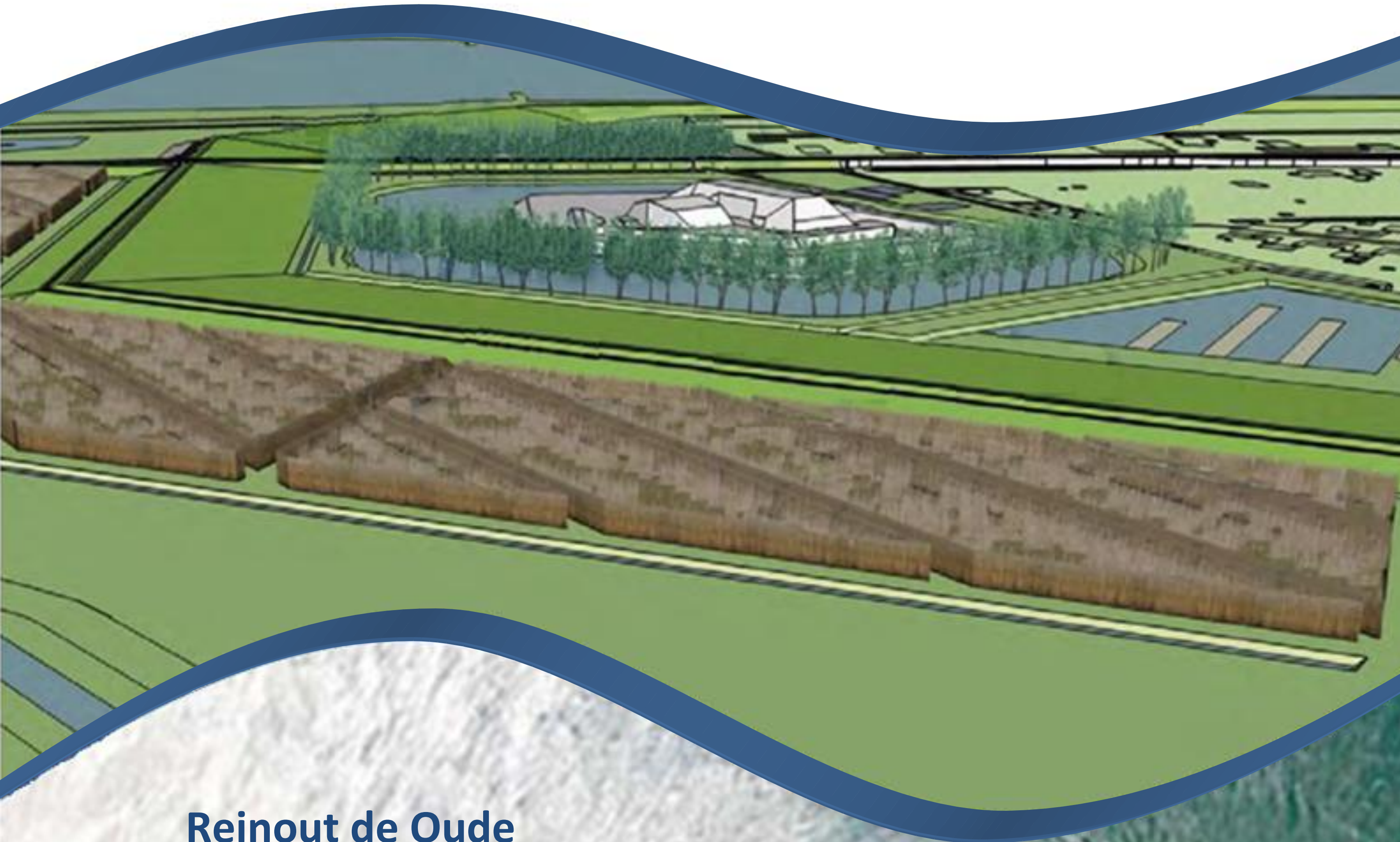
Modelling wave attenuation by vegetation with SWAN-VEG

Model evaluation and application to the Noordwaard polder



Reinout de Oude

January 2010

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Modelling wave attenuation by vegetation with SWAN-VEG

Model evaluation and application to the Noordwaard polder

Final Report

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Master Thesis of:
R. de Oude
Water Engineering & Management
Universty of Twente

Supervisors:

Dr. ir. D.C.M. Augustijn
Water Engineering & Management
Universty of Twente

Dr. K.M. Wijnberg
Water Engineering & Management
Universty of Twente

Ir. F. Dekker
Dept. River and Coastal Engineering
DHV

Drs. M.B. de Vries
Dept. Ecosystem Analysis and Assessment
Deltares

UNIVERSITY OF TWENTE.

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Enabling Delta Life

Front cover: “Inside breaking wave” photo by Phil Colla, 2008 and Noordwaard 3D from *leren van innoveren deel 1* NWP

Summary

Bio-engineering is a novel way to reduce the application or dimensions of hard constructions. For a project in the Noordwaard an idea came up to implement a vegetation field in front of the dike to attenuates waves which are generated by severe storms. This allows a lower dike height while maintaining the required safety level. So far there was no suitable model available to quantify the effect of vegetation on the wave height. Recently Deltares [2009] developed the SWAN-VEG model to determine the effect of vegetation on the wave height. In order to use this model, it is tested to find out whether the model can describe real cases well enough. Then the model can be used to determine the effect of the vegetation field on the wave height along the dike at Fort Steurgat.

The SWAN-VEG model consists of the original SWAN model to which a vegetation module is added. This module consists of an energy dissipation term due to vegetation. The dissipated energy is subtracted from the incoming wave energy, which results in less wave energy behind the vegetation field and thus a lower wave height. Vegetation is modelled as cylindrical obstacles, the vegetation characteristics as height, width, density and drag coefficient are used to determine the magnitude of the dissipation term. Also wave characteristics like significant wave height and peak period influence the energy dissipation term.

To test the SWAN-VEG model a sensitivity analysis is done by varying the input parameters of the vegetation module. The results show more, wider, higher or stiffer vegetation results into a lower wave height behind the vegetation field. The analysis also shows that for waves with a larger wave height more energy dissipation occurs resulting in a larger reduction of wave height. The same accounts for the wave peak period, waves with a longer peak period show a lower wave height behind the vegetation field compared to waves with a shorter peak period. Due to the determination of the energy dissipation term the SWAN-VEG model is only suitable to model the effect of vegetation on the wave height for waves with a peak period of 2 seconds and longer. The dissipation term shows a large increase for shorter peak periods which cannot be explained physically. An analytical solution of the energy dissipation term, given by Mendez and Losada [2004] presents similar results. However their approach assumes a constant group velocity which causes a difference with SWAN-VEG for waves with a small peak period (< 6 seconds). For these waves SWAN-VEG determines a reduction of the group velocity, therefore the SWAN-VEG results show a larger wave height behind the vegetation field compared to the Mendez and Losada results.

In addition experiments with flexible vegetation are modelled to test whether the model is able to describe experiments by calibration of the drag coefficient. Experiments are carried out in a wave flume with three types of flexible vegetation: *Echinodorus grandiflorus, Cabomba caroliniana* and *Nymphaea rubra*. The calibration is carried out for a dense vegetation field, experiments with lower densities are used for validation. Results show SWAN-VEG is able to describe the experimental outcomes of vegetation with a vegetation parameter ranging from 0.3 to 5 m^{-1}. The model is however not able to describe other process apart from the drag force which attenuates the waves, examples of these

processes are floating leaves and very dense vegetation which acts like one porous block rather than single plants. Calibration and validation show the wave height of the experimental results, with varying wave conditions, can be described with one drag coefficient per species. These results however improve if the relation between the drag coefficient and Keulegan-Carpenter is taken into account in order to determine a drag coefficient per wave condition. Based on the results of the sensitivity analysis, calibration and validation the suitability of the SWAN-VEG model is determined, concluding SWAN-VEG is an appropriate tool to quantify the effect of vegetation on the wave height.

The model is used to verify the design of a vegetation field in front of a dike located near Fort Steurgat in the North-Eastern corner of the Noordwaard. A first design of the dike resulted in a dike height of 5.5 m.+NAP, causing much resistance from the inhabitants. Studies show a dike height of 4.3 m+NAP can be implemented if the wave height at extreme conditions is reduced with at least 40%. The significant wave height in the Noordwaard is reassessed with the SWAN model using detailed water and wind conditions for a return period of 1/2000 years. The results show a wave height of around 1.1 meter at Fort Steurgat.
The vegetation field, about 80 meter in length, consists of *Salix alba* species placed on a bank in front of the dike. According to the SWAN-VEG model the bank and willows reduce the wave height with 68% to 76%. The results show wave growth inside the vegetation field due to the wind, which is not realistic as the water is sheltered for wind by the emergent vegetation. Compensating the results for this effect by assuming no wind inside the vegetation field, the reduction of the wave height is up to 80%. It is recommended to take a wave height of 0.3 meter into account along the dike at Fort Steurgat. Based on these results it is concluded the vegetation field is able to decrease the wave height sufficiently to implement the dike with a height of 4.3m.+NAP.

This study shows SWAN VEG is a suitable tool to quantify the effect of a vegetation field on the wave height. The model shows more, wider, larger or less flexible vegetation results in more dissipation of wave energy. Also larger and longer waves result in a relative larger loss of energy and a larger decrease of the wave height. The model is able to describe experiments with a vegetation parameter ranging from 0.3 to 5 m^{-1} and for waves with a peak period longer than 2 seconds. The model results verify the vegetation field design in the Noordwaard reduces waves to a height of 0.3 meter which is enough to implement the dike of 4.3 m.+NAP in height.
It is recommended to analyse the group velocity in the vegetation field with experiments to verify whether the model gives an appropriate estimation of the group velocity. Also, further verification of the model can be done for vegetation with a vegetation parameter ranging from 5 to 20 m^{-1}. The model can be improved by adding an application to switch off the wind for specified areas. This will limit the wave growth inside the vegetation field.

Preface

This report marks the end of my study Water Engineering and Management at the University of Twente. About one year ago I started to look for in interesting topic for my master thesis. The motion of waves has always intrigued me and this is the reason I wanted to do a project focused on waves. It was therefore a very nice opportunity I could do my master thesis at Deltares, within the department of Hydraulic Engineering, to analyse and model the attenuation of waves by vegetation. By this project I learned a lot about wave modelling with SWAN and the impressive opportunities of applying vegetation as wave breaker. Besides of this I also experienced the open atmosphere at Deltares where everybody was always willing to answer my questions.

I would like to thank my supervisors who helped me writing this report. Frank Dekker, thank you for all your useful help with SWAN model, critical reviews and energy you have put in this project. Denie Augustijn and Kathelijne Wijnberg thanks for all the advice, comments and discussions about the project and report. Mindert de Vries thanks for all your enthusiasm about vegetation and your ideas about the Noordwaard project. I also would like to thank my family and friends for their support and last but not least, thank you to all my study mates in Enschede and my fellow graduates at Deltares for all the ideas, discussions, coffee breaks and good times!

Enjoy Reading!

Reinout de Oude
Delft, January 2010

Contents

Summary iv
Preface vii
Contents viii
List of symbols xi
1 Introduction 1
1.1 Background 1
1.2 Objectives and research questions 2
1.3 Methodology 2
1.4 Scope 3
1.5 Outline 3
2 SWAN-VEG Model 4
2.1 Description of waves and SWAN 4
2.2 Vegetation module 5
3 Sensitivity analysis 7
3.1 Introduction 7
3.2 Model setup 8
3.3 Varying vegetation characteristics 9
3.3.1 Vegetation parameter 9
3.3.2 Vegetation height 11
3.3.3 Vegetation field 12
3.3.4 Vegetation layers 12
3.4 Wave characteristics 14
3.4.1 Significant wave height 14
3.4.2 Peak period 15
3.5 Discussion 17
3.6 Conclusion 21
4 Calibration and Validation of SWAN-VEG for flexible vegetation 22
4.1 Approach 22
4.2 Experiments 22
4.2.1 Experimental setup 23

4.2.2 Vegetation description 24
4.2.3 Determination of applicable data for calibration and validation 25
4.3 Development of numerical model 25
4.3.1 Model Setup 25
4.3.2 Scaling of tests 26
4.3.3 Determination effect of vegetation 26
4.3.4 Calibration Criteria 27
4.4 Results of Echinodorus grandiflorus 27
4.5 Results of Cabomba caroliniana 29
4.6 Results of Nymphaea rubra 32
4.7 Relation drag coefficient and Keulegan-Carpenter number 34
4.8 Discussion 38
4.9 Conclusion 38
5 Analysis of wave conditions at Fort Steurgat 40
5.1 Background and situation description 40
5.2 Objectives 42
5.3 Methodology 42
5.3.1 Scenarios 43
5.3.2 Cases 43
5.3.3 Output locations 44
5.3.4 Numerical model 44
5.3.5 Limitations 44
5.4 Model Setup 44
5.4.1 Boundary Conditions 44
5.4.2 Computational grid 45
5.4.3 Bathymetry 46
5.4.4 Obstacles 47
5.4.5 Vegetation design 48
5.4.6 Other settings 50
5.5 Modelling results 50
5.5.1 Reassessment of the wave conditions without vegetation 50
5.5.2 Assessment of effect vegetation field on wave height 51
5.5.3 Results of different return periods 54

5.6 Discussion 55
5.7 Conclusion 57
6 Conclusions and Recommendations 59
6.1 Conclusions 59
6.2 Recommendations 61
Recommendations SWAN-VEG model 61
Recommendations Noordwaard case study 61
References 63

Appendix A – Background of SWAN-VEG 65
Appendix B - Verification of the model 68
Appendix C – Sensitivity Analysis 69
Appendix D – Overview of wave spectrum per wave period 74
Appendix E – Wind Conditions of Schiphol Airport 78
Appendix F – Model grids 80
Appendix G – Tables and figures of wave conditions Fort Steurgat 83

List of symbols

α_K	Parameter define shape of levee
α_T	Slope of trendline
αh	Vegetation height
β	Energy dissipation term according to Mendez and Losada equation
β_K	Parameter define shape of levee
γ	Scaling factor
ε_v	Energy dissipation term
ζ	Water surface elevation
θ	Wave direction
ρ	Water density
σ	Angular frequency
a	Amplitude
b_v	Stem width
c	Wave velocity
C_D	Drag coefficient
c_g	Wave group velocity
c_x	wave propagation in x direction
c_y	Wave propagation in direction
c_θ	Wave propagation in θ-space
c_σ	Wave propagation in σ-space
d	Height of levee
E	Wave energy
F	Wave energy flux
F_x	Resistance force due to vegetation in direction of wave propagation
g	Acceleration due to gravity
h	Water depth
H	Wave height
H_{rms}	Root-mean-square wave height
$H_{rms,0}$	Root-mean-square wave height at location of boundary condition
H_S	Significant wave height
$\widetilde{H_s}$	Average significant wave height

k	Wave-number
K_t	Transmission coefficient
L	Wave length
L_{mean}	Mean wave length
N	Density of vegetation
N_A	Wave action
n	n-Number
R^2	Coefficient of determination
$S_{ds,b}$	Dissipation by bottom friction
$S_{ds,br}$	Dissipation by depth-induced breaking
$S_{ds,veg}$	Dissipation caused by the vegetation
$S_{ds,w}$	Dissipation by white-capping
S_{in}	Generation by wind
S_{rr}	Sum of the squares of the residuals
S_{tt}	Sum of the squares of the deviation from the mean
t	Time step
T	Wave period
T_{mean}	Mean wave period
T_P	peak wave period
u	Orbital velocity in horizontal direction
U_{10}	Wind speed at 10 meter above surface
u_{max}	Maximum horizontal velocity of the orbital motion of a wave
V	Vegetation parameter
w	Orbital velocity in vertical direction
X_{veg}	Vegetation field length
x_i	Remaining wave height modelled in SWAN-VEG for experiment *i*
$\bar{y}$	Average remaining wave height of experiments
y_i	Remaining wave height measured for experiment *i*
z	Vertical elevation

1 Introduction

This chapter provides the background of this study for modelling wave attenuation by vegetation, leading to the objectives and research questions. Next the methodology is described to answer these research questions. The chapter ends with the scope and outline of this study.

1.1 Background

As part of the project "Room for the River" [Deltares, 2009a] the river dike near Werkendam is partly removed. This will cause the Noordwaard to be inundated during events of a high water level on the River Nieuwe Merwede in order to the water level; Figure 1-1 shows a schematisation of the Noordwaard as inundation area. In case of a 1/2000 year flooding event the average water depth in the polder will be 3 meter whereby, in combination with a severe storm, waves up to 1 meter high will develop. A new dike is required in the North Eastern corner of the Noordwaard to protect the inhabitants at Fort Steurgat. A first dike design resulted in a dike height of 5.5 m.+NAP, leading to much resistance from the inhabitants. Therefore the idea came up to implement a vegetation field in front of the dike to attenuate the waves, allowing a lower dike height.

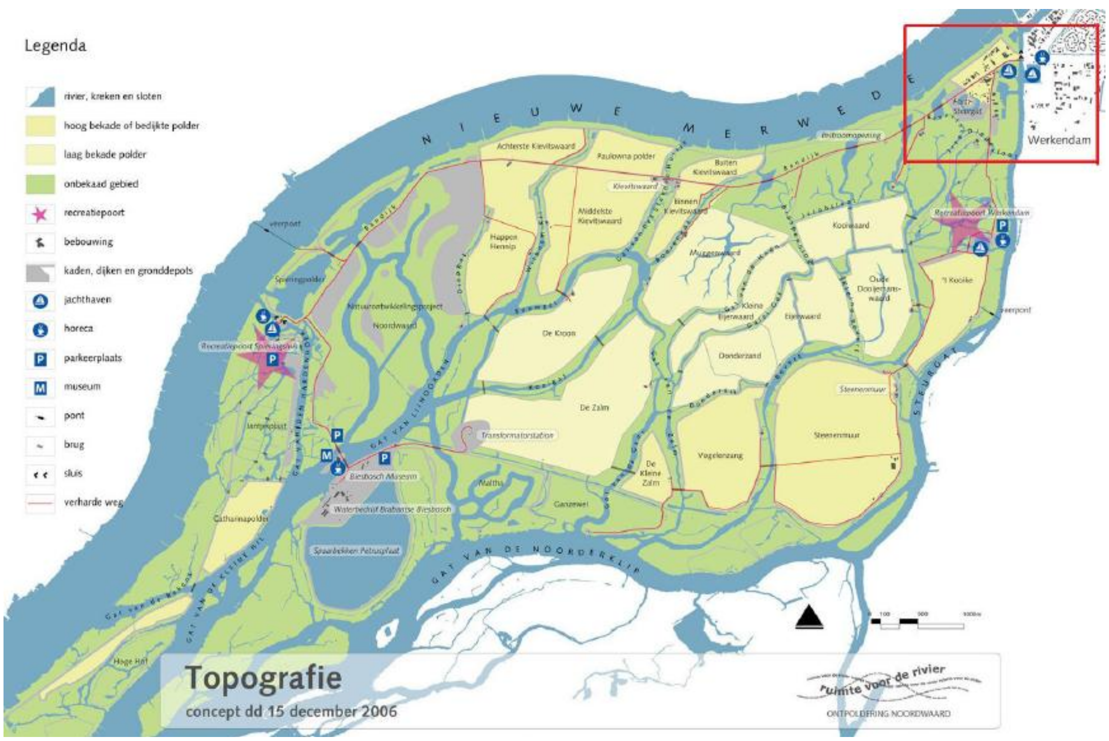


Figure 1-1 – Lay out of the Noordwaard as inundation area. [Bureau Noordwaard, 2007]

The implementation of a vegetation field is based on the objective of the Dutch government to implement more "soft solutions" as shore protection rather than physical measures. This means flood protection is provided by the use of nature and vegetation, also referred to as bio-engineering, rather than the construction of dikes and dams, referred to as "hard solutions". Vegetation occurs in nature as natural shore protection, for example the mangrove forests in the tropics and the salt marshes in the

South-West delta of the Netherlands and the Wadden Sea. Vegetation stabilises the bed, decreases flow velocity and attenuates waves.
In order to quantify the effect of the vegetation on the wave height in the Noordwaard, a new module is implemented in the SWAN wave model [Deltares, 2009a] that includes the vegetation as cylindrical obstacles. This module is based on a method developed by Dalrymple et al. [1984], Kobayashi et al. [1993] and Mendez and Losada [2004]. The new model is referred to as SWAN-VEG. Before the model is applied, it first needs to be validated to what extend it can be applied to quantify the energy dissipation caused by the vegetation.
The current design of the vegetation field in the Noordwaard is based upon fetch calculations to determine the wave conditions. A 1D application of the SWAN-VEG model is used to analyse the effect of the vegetation field on the wave height, by applying a cross section of the vegetation field.
In case the SWAN-VEG model is able to quantify wave attenuation by vegetation adequately, 2D modelling of the Noordwaard provides a more accurate prediction of the effect of the vegetation field on the wave height. A 2D application of the SWAN-VEG model enables a more detailed determination of wave height along the dike at Fort Steurgat, taking into account the variation of bathymetry, location of obstacles, and vegetation field. SWAN-VEG also enables the determination of wave conditions based on wind speed and wind direction; to analyse the reduction of wave height per wind direction.

1.2 Objectives and research questions

Based on the background the objective of this study is twofold and stated as follows:

- Determination of the suitability of the SWAN-VEG model in describing the effect of vegetation on wave conditions.
- Verification of the effects of the vegetation field on the wave conditions in the Noordwaard with the SWAN-VEG model.

To achieve these objectives two research questions are formulated:

1. To what extend is the SWAN-VEG model able to quantify the effect of vegetation on the wave conditions?
2. What is the effect of the vegetation field on the wave conditions in front of Fort Steurgat?

1.3 Methodology

To analyse the suitability of the SWAN-VEG model, first a sensitivity analysis is carried out by varying the wave and vegetation characteristics which are implemented in the module. The sensitivity analysis gives useful information about how the model works and whether this is in accordance with the theory. The parameters of the vegetation module are varied as these describe the effect of vegetation on the wave conditions. Next the model is calibrated and validated using data from flume experiments carried out by Penning et al. [2008] with flexible vegetation. The results of the calibration and validation determine whether the model is able to quantify the effect of vegetation on the waves and determine what the limitations of SWAN-VEG are. Taking this into account, the model is used to determine the effect of the vegetation field on the wave height at Fort Steurgat. This is done by setting up a SWAN-VEG model of the Noordwaard, taking into account the spatial variation of the bathymetry and the obstacles in the

Noordwaard. The generation of waves under extreme conditions are evaluated as well as the effect of the vegetation field on the wave height.

1.4 Scope

The scope of this study is to test the SWAN-VEG model by carrying out a sensitivity analysis, calibration and validation of the model and to apply the model for the Noordwaard case. The following aspects are not conducted in this study:

- No modification to the code of SWAN or the vegetation module.
- No addition experiments are carried out; only the experiments of Penning et al. [2008] are used.
- The module is added to the SWAN 40.55 model, the SWAN model itself is not analysed in this study. Only the new vegetation module is analysed and only the parameters of the vegetation module are varied the sensitivity analysis.
- The bed level changes and currents are not modelled in the Noordwaard study.

1.5 Outline

This study is about testing the SWAN-VEG model and applying it to a case in the Noordwaard. Chapter 2 describes the theory behind the vegetation model and how it is incorporated in the original SWAN model. In chapter 3 the sensitivity analysis is described, varying the vegetation and wave parameters which are implemented in the vegetation module. The calibration and validation based on experiments with flexible vegetation are described in chapter 4 and in Chapter 5 the application of SWAN-VEG to the Noordwaard case is described. In this chapter the results of previous studies are compared to the more detailed 2D calculations of SWAN-VEG. This study ends with the conclusions in chapter 6 and also provides recommendations for further research.

2 SWAN-VEG Model

This chapter describes the SWAN-VEG model. This model enables the determination of the effect of vegetation on wave conditions. The first section gives a brief description of the SWAN model and describes how the vegetation module is added to the SWAN model. The second section describes how the module works, on which equations it is based and what the input parameters are.

2.1 Description of waves and SWAN

Before the vegetation module is described, first the modelling of waves by SWAN is explained. Waves are characterised by their height, length and wave period. The most important wave characteristics are given in Figure 2-1 and Box 1-1.

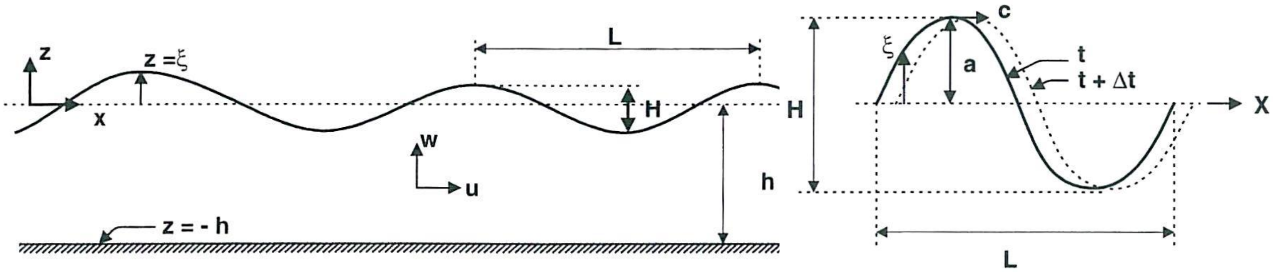


Figure 2-1 - wave characteristics.

Here:

z = vertical elevation [m.+NAP]
h = water depth [m]
H = wave height [m]
L = wave length [m]
t = time step [s]

w = orbital velocity in vertical direction [m· s^{-1}]
u = orbital velocity in horizontal direction [m· s^{-1}]
T = wave period [s]
ζ = water surface elevation [m]

In addition, the wave energy is determined: $E = \frac{1}{8}\rho g H^2$[kg·s^{-2}]

With:

ρ = water density [kg·m^{-3}]
g = acceleration due to gravity [m· s^{-2}]

Other wave characteristics are:

amplitude: a = $\frac{1}{2}H$[m]
wave-number: $k = \frac{2\pi}{L}$[m^{-1}]
wave velocity: $c = \frac{L}{T} = \frac{\sigma}{k}$ [m·s^{-1}]
wave energy flux: $F = E \cdot c_g$ [kg·m·s^{-3}]

n-number: $n = \frac{1}{2}\left(1 + \frac{2kh}{\sinh(kh)}\right)$ [-]
angular frequency: $\sigma = \frac{2\pi}{T}$ [s^{-1}]
wave group velocity: $c_g = c \cdot n$ [m·s^{-1}]

Box 1-1 – description of wave characteristics. [Hulscher et al. 2007]

A wave does not transport water particles but wave energy, therefore to determine the propagation of waves the wave energy flux is the most relevant parameter, rather than other wave parameter to determine the propagation of waves.

SWAN (Simulating Waves Nearshore) is a numerical model which determines the wave energy flux to determine the generation, propagation and dissipation of waves (see Appendix A). The model describes the wave energy as a 2 dimensional energy spectrum, as a function of the wave frequency (T^{-1}) [Hz] and the wave direction θ [°]. The frequency where most of the energy is denoted is called the peak frequency corresponding with the peak wave period, T_P. The wave energy is based on the significant wave height which is the average wave height of the one-third largest waves, called H_S [m]. Booij et al. [1999] and Ris [1997] give a further description of the SWAN model.

2.2 Vegetation module

In this study the SWAN-VEG model is used, which takes the effect of vegetation on waves into account. For waves propagating in a certain x-direction, the wave energy flux remains constant if no energy is lost or gained. This is denoted as:

$$\frac{\partial F}{\partial x} = 0 \rightarrow \frac{\partial}{\partial x}\left[E \cdot c_g\right] = 0 \tag{2.1}$$

However, the vegetation causes a loss of energy resulting into a decrease of the wave energy flux and new wave conditions. This is schematised in Figure 2-2. Here the vegetation module determines an energy dissipation term ε_v [kg·s^{-3}] which is subtracted from the wave energy flux. The original SWAN model itself does not change, only an extra dissipation term is added to the model.

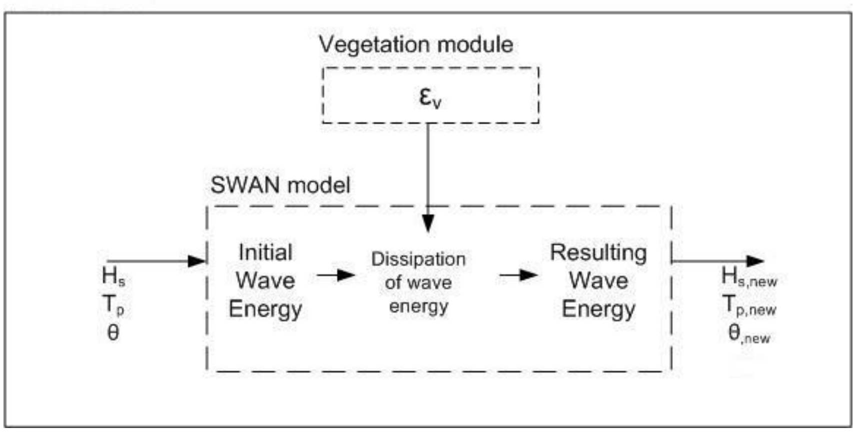


Figure 2-2 - schematisation of SWAN-VEG model.

The vegetation is modelled as cylindrical obstacles causing a drag force. This force is translated into an amount of energy that gives the following energy dissipation term ε_v based on Dalrymple et al. [1984] and Kobayashi et al. [1993] and according to Mendez and Losada [2004]:

$$\varepsilon_v = \frac{1}{2\sqrt{\pi}} \rho C_D b_v N \left(\frac{kg}{2\sigma}\right)^3 \frac{\sinh^3(k\alpha h) + 3\sinh(k\alpha h)}{3k\cosh^3(kh)} H_{rms}^3 \tag{2.2}$$

In case of only energy dissipation due to vegetation (Figure 2-2), this gives the following description of the wave energy flux:

$$\frac{\partial F}{\partial x} = -\varepsilon_v \ \rightarrow \frac{\partial}{\partial x}\left[E \cdot c_g\right] = -\varepsilon_v \qquad (2.3)$$

The implementation of the dissipation term, given by equation 2.2, in the SWAN model is further described in Appendix A. This Appendix describes the physical basics of SWAN and how the vegetation module is added to SWAN. The dissipation term is always negative as it causes a loss of energy. Equation 2.2 shows the dissipation term is a function of the following wave and vegetation conditions:

- Drag coefficient, C_D [-]
- Stem width, b_v [m]
- Density of vegetation, N [#·m^{-2}]
- Vegetation height, αh [m]
- Root-mean-square wave height, H_{rms}. In the SWAN model the significant wave height H_S is used: $H_s = 2\sqrt{2} \cdot H_{rms}$
- Wave period T, to determine the wave-number and the angular frequency σ.

The drag coefficient, stem width and density are combined and called the vegetation parameter, V [m^{-1}] (C_D*b_v*N).

The implementation of the vegetation module in SWAN is verified by comparing the output of the original SWAN model with the SWAN-VEG model keeping the dissipation term 0 (no vegetation). Since both simulations give identical results, the (vegetation) module does not influence the original model. More about the verification can be found in Appendix B.

Next chapter describes the sensitivity analysis of the parameters. Only the parameters of the vegetation module are varied because only these describe the effect of the vegetation on the waves.

3 Sensitivity analysis

This section describes the sensitivity analysis of the SWAN-VEG model. The objective is to analyse the effect of varying the input parameters on the output of the model and whether this is in accordance with the theory. The effect of varying each parameter shows how the model reacts on the input parameters, whether more or less energy is dissipated. This gives a better understanding of the model and the use of vegetation for the dissipation of waves. The first section serves as an introduction and describes the determination of an analytical solution to compare the SWAN-VEG model with the theory. Next sections describe the sensitivity analysis with a distinction between the vegetation parameter and wave parameters. The final section presents the discussion and conclusion of the results.

3.1 Introduction

The output variable used to assess the effect of varying the input parameters is the significant wave height. This variable is chosen because it is a clear indicator of the decrease in wave energy. It also appeared that other wave characteristics, like mean wave period and mean wave length react in exact the same pattern as the significant wave height, as appendix C shows.

A comparison is made between the SWAN-VEG model and the analytical equation of the energy dissipation given by Mendez and Losada [2004]. This equation will be referred to as the Mendez and Losada (M&L equation). The comparison between SWAN-VEG and M&L equation is carried out for the vegetation and wave characteristics and verifies whether the model behaves as expected in the theory.

Mendez and Losada use equations 2.2 and 2.3 to derive an analytical expression that describes the effect of the vegetation on the wave height as a function of the propagation direction. First substituting the equation for wave energy in equation 2.3 gives:

$$\frac{\partial F}{\partial x} = -\varepsilon_v \;\rightarrow \frac{\partial}{\partial x}\left[\frac{1}{8}\cdot \rho g H_{rms}^2 \cdot c_g\right] = -\varepsilon_v \qquad (3.1)$$

The equation is simplified, with the assumption of constant wave group velocity, by dividing the energy dissipation term with the constant parameters. This gives:

$$\frac{\partial H_{rms}^2}{\partial x} = \frac{-\varepsilon_v}{\frac{1}{8}\rho g\, c_g} = -\frac{2}{3\sqrt{\pi}} C_D b_v N k \frac{\sinh^3(k\alpha h)+3\sinh(k\alpha h)}{(\sinh(2kh)+2kh)\ \sinh(kh)} H_{rms}^3 \qquad (3.2)$$

This equation is solved by applying the boundary conditions $H_{rms}(x=0) = H_{rms,0}$. The wave height at location x is equal to:

$$H_{rms} = \frac{H_{rms,0}}{1+\beta x} \qquad (3.3)$$

where:

$$\beta = \frac{1}{3\sqrt{\pi}} C_D b_v N H_{rms,0} k \frac{\sinh^3(k\alpha h)+3\sinh(k\alpha h)}{(\sinh(2kh)+2kh)\ \sinh(kh)} \qquad (3.4)$$

This analytical solution is compared with the SWAN-VEG model, using the numerical solution of equation 2.2 and 2.3. In this model the group velocity is not assumed to be constant but varying due to the mean wave length, L_{mean}, and mean wave period, T_{mean}, which both decrease due to the reduction of wave energy. The wave group velocity is defined as:

$$c_g = \frac{L_{mean}}{T_{mean}} \cdot n \qquad (3.5)$$

3.2 Model setup

For the sensitivity analysis a case is required, defining an area, the bathymetry and default wave and vegetation conditions. It is chosen to use a simple basin for the sensitivity analysis so the basin itself will not affect the wave characteristics. The basin has a length of 30 meters and a width of 100 meters, this width is required to eliminate the boundary effects at the middle of the basin. A schematisation is shown in Figure 3-1, the colours indicate the bottom elevation, ranging from -1 to -0.5 meter and the white square represents the location of the vegetation field.

The waves are defined with a nautical direction of 270^o this means the waves travel from left to right in Figure 3-1. The model has grids cells of 0.25x0.25 meter; a high resolution to increase the accuracy of the model output. Appendix D describes the justification of the grid dimension and basin width.

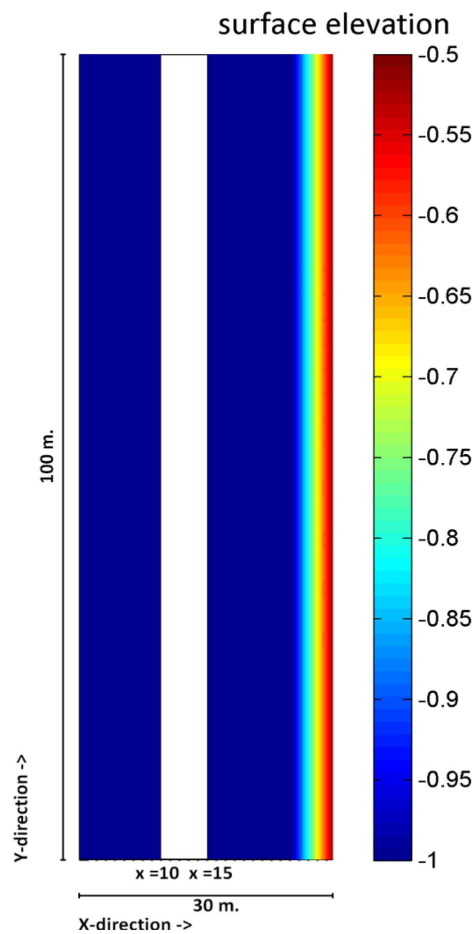


Figure 3-1 - basin schematisation.

At the end of the basin a slope is added to avoid reflection which is required in real cases. The model results however show this is not required in the model, as no reflection occurs. The slope does cause shoaling and wave breaking in the model, this is visible in the model results but it does not influence the results of the sensitivity analysis and will therefore not be analysed. In the basin a vegetation field is added with a length of 5 meters at the location x = 10 to x = 15 and exists over the entire width of the basin. Because the basin is uniform over its width, the width is not taken into account for the sensitivity analysis; only the variation over the length is investigated.

In the analysis each parameter is varied while keeping other parameters constant. Therefore a default case is defined, describing the hydrodynamic and vegetation conditions for the references values. These default conditions are given in Table 3-1.

The significant wave height is translated in a JONSWAP wave spectrum by the SWAN model.

Parameter:	default value:
Water level, h [m]	1
Significant wave height, H_s [s]	0.2
Peak period, T_p [s]	4
Vegetation parameter, V [m^{-1}]	4
Vegetation height, αh [m]	1
Vegetation field length, X_{veg} [m]	5

Table 3-1 - Default hydrodynamic and vegetation conditions.

3.3 Varying vegetation characteristics

In this section the results are presented of varying the vegetation characteristics. These are:

- Vegetation parameter V, which represents the combination of the drag coefficient, density and width of the vegetation.
- Vegetation height αh.

Other aspects which are not parameters in the module but are in the setup of the model are vegetation field length X_{veg} and the composition of vegetation layers; varying these aspects also influence the effect of the vegetation field on the wave height and are therefore varied as well.

In the sensitivity analysis, one by one the parameters are varied for a specified range. The other parameters are kept on their default values as given in Table 3-1.

3.3.1 Vegetation parameter

The vegetation parameter is varied from 0 to 20, with several values in between. The applied values are given in Table 3-2 with a description of the meaning of the respective value:

V [m^{-1}]	Description:
0	No vegetation
2	Low density and small diameter for flexible plants
6	Low density and small diameter for rigid plants
10	High density or large diameter for rigid plants
20	Maximum value of vegetation parameter for rigid plants

Table 3-2 – Overview values and meaning of vegetation parameters.

Rigid plants have a drag coefficient, C_D, of approximately 1, while flexible plants have a C_D smaller than 1 [Mendez and Losada, 2004; Deltares, 2009a]. So for the same density N and stem diameter b_v a flexible plant has a smaller vegetation parameter than a rigid plant.

A maximum value of the vegetation parameter exists because the diameter of the vegetation limits the number of plants on 1 m^2. The maximum value of the C_D is 1 for rigid vegetation. To determine the maximum value for b_v*N an assumption concerning the stem width is made. The highest value for b_v*N is obtained with a large density (N) and a small stem diameter (b_v), because the density is a quadratic factor while the diameter a linear factor to determine the maximum for V. The smallest diameter for rigid plants in nature is assumed to be 3 mm based on small branches of shrubs. Assuming the minimal distance between two plants is 10 mm, the density will be at maximum $6 \cdot 10^3$ stems·m^{-2}, this results into a maximum value for V of close to 20 which may occur in nature.

Varying V for the values given in Table 3-2 gives the resulting wave height along the length in x-direction of the basin as presented in Figure 3-2. In addition, Figure 3-3 presents the significant wave height at 2.5 meter behind the vegetation field (location x =17.5) for the different values of V.

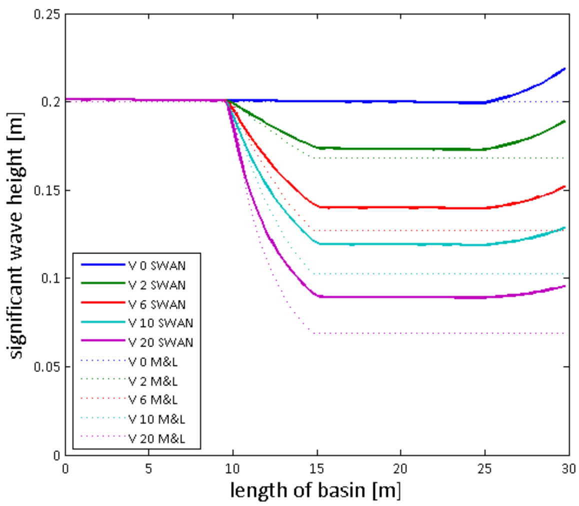


Figure 3-2 - Effect on H_s of varying vegetation parameter.

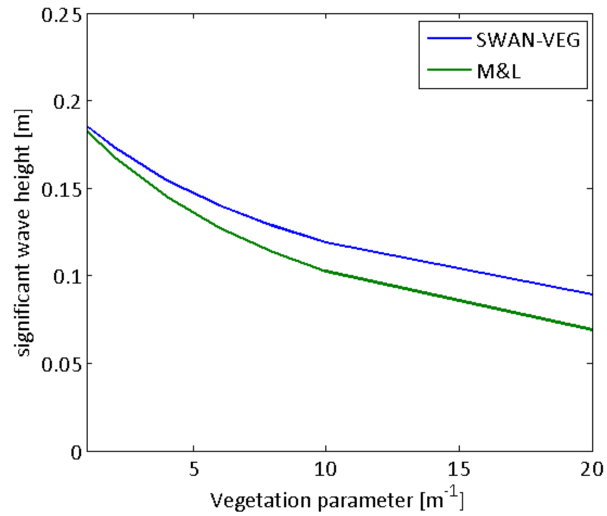


Figure 3-3 – H_s behind vegetation field (x=17.5) as function of V.

The following is observed in Figure 3-2 and Figure 3-3:

- An increasing V results in a smaller significant wave height behind the vegetation field, as more energy is being dissipated. Figure 3-3 shows this by a decrease of the wave height over the vegetation parameter; the slope decreases as V increases, this show the relation between the wave height and vegetation parameter is non-linear.
- There is a non-linear trend in the decreasing wave height along the vegetation field. This is best visible for the results of V is 20 m^{-1}, but also account for each value of V. At the first part of the field (Figure 3-2) the lines are steeper than the last part, so most of the energy is dissipated at the start of the vegetation field.
- The M&L equation shows similar behaviour as the model. The two above observations are also valid for the equation. However, the equation shows more energy dissipation compared to SWAN-VEG. The difference increases with the increasing vegetation parameter.

Based on these observations it is concluded increasing the vegetation parameter results in an increase of the energy dissipation, which results in a lower significant wave height behind the vegetation field. This is as expected since a larger vegetation parameter, caused by more, wider or stronger vegetation, will cause more dissipation of energy. The results show that for the maximum value of V the wave is not completely attenuated. So even with a very high density and rigid plants, a vegetation field cannot be compared with a complete obstruction like a bank or embankment.

The M&L equation shows a similar trend, but gives slightly more dissipation. The figures show this discrepancy is increasing with increasing vegetation parameter in absolute numbers, the relative difference is however constant. The difference between M&L equation and SWAN-VEG is expounded further in the discussion section of this chapter.

3.3.2 Vegetation height

Next the vegetation height (αh) is varied. The water depth in the basin is 1 meter, the vegetation is varied between 0 and 1.2 meter; so both the effect of submerged and emergent vegetation is taken into account as Table 3-3 shows.

αh [m]	Description:
0	No vegetation
0.2	Submerged vegetation
0.4	Submerged vegetation
0.6	Submerged vegetation
0.8	Submerged vegetation
1.0	Nearly emergent vegetation
1.2	Emergent vegetation

Table 3-3 - Varying vegetation height.

Based on the theory it is expected taller vegetation causes more energy dissipation, resulting in a lower wave height. Figure 3-4 and Figure 3-5 present the results of varying the vegetation height calculated by the SWAN-VEG model and the M&L equation.

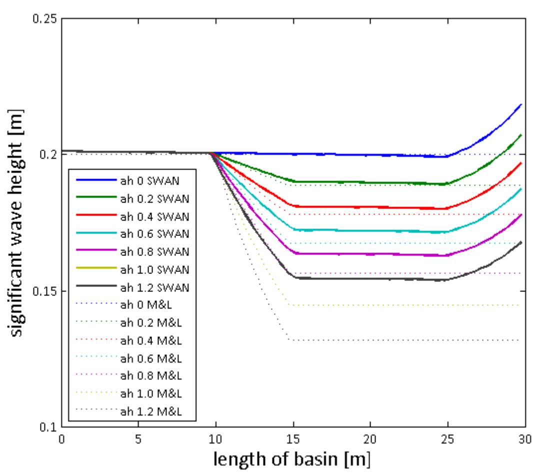


Figure 3-4 - Effect on H_s of varying vegetation height.

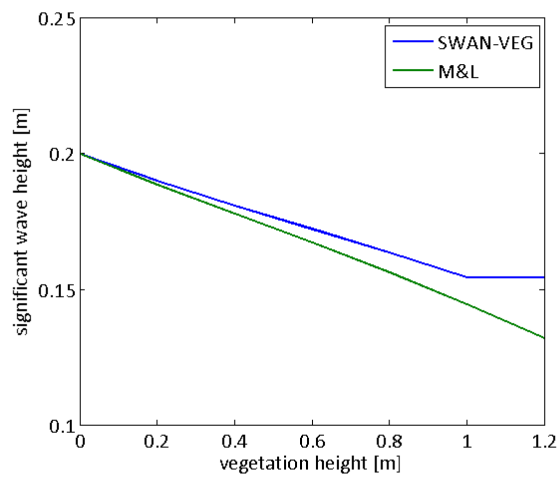


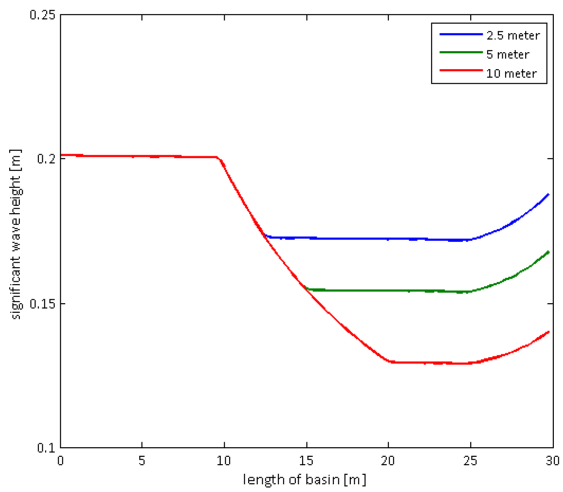
Figure 3-5 - H_s behind vegetation field (x=17.5) as function of αh.

In Figure 3-4 the model results for the vegetation height αh is 1.0 and 1.2 meter are equal so the two lines are exactly the same. This is also indicated by Figure 3-5 which shows a horizontal line for αh larger than 1. It indicates the vegetation above the water level does not influence the amount of energy dissipation. This differs with the M&L equation because this does not take into account whether the vegetation height exceeds the water depth and is therefore only applicable if αh is smaller than or equal to the water depth.

For the SWAN-VEG model and M&L equation, the figures show an increase of the vegetation height results in a more or less linear decrease of the wave height due to the dissipation of wave energy, which is in accordance with the expectation. The SWAN-VEG model again shows less dissipation than calculated by the M&L equation.

3.3.3 Vegetation field

Besides varying the vegetation characteristics, also the length of the vegetation field X_{veg} is varied. In the previous analysis the vegetation field had a length of 5 meters. In this analysis the field length is now varied for the values as Table 3-4 shows, this is only conducted with SWAN-VEG model as the field length is not a function parameter. The result of varying the vegetation field in the SWAN-VEG model is shown in Figure 3-6.



X_{veg} [m]
2.5
5.0
10.0

Table 3-4 - varying vegetation field length.

Figure 3-6 - Effect on H_s of varying vegetation field length.

The results show the length of the vegetation field has no effect on the dissipation rate; the lines describing the dissipation over the vegetation length are the same for each case. This is as expected the vegetation length X_{veg} has no influence on energy dissipation term (see eq. 2.2). X_{veg} only determines the final wave height behind the vegetation field, a longer vegetation field results into a lower wave height behind the vegetation field. The results show again, like the results of the vegetation parameter, more energy is dissipated at the first part of the field, as the slope of the line becomes less steep over the vegetation field.

3.3.4 Vegetation layers

Many plants consist of a stem with a canopy on top of the stem. This stem and canopy normally differ in characteristics, i.e. the stem diameter, flexibility and density differ from the canopy characteristics, what results in a different vegetation parameter for canopy and stem. In order to represent this aspect in the model, it is possible to implement different layers of vegetation, each with a different vegetation parameter. As the variation of the vegetation parameter showed, different vegetation parameters show different results of energy dissipation.

In this analysis the sensitivity of $_{Hs}$ to three compositions of vegetation is tested. These compositions are:

- One with a constant vegetation parameter of 4.

- One with a constant vegetation parameter of 10.
- One with a 0.5 meter high layer with a parameter of 10 on top of a 0.5 meter high layer with a parameter of 4.

A schematisation of these three cases is given in Figure 3-7.

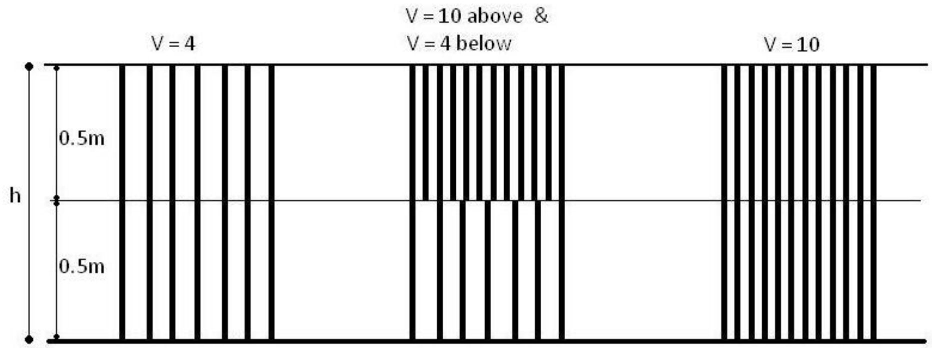


Figure 3-7 - Schematisation of the three compositions.

The result of each case is presented in Figure 3-8.

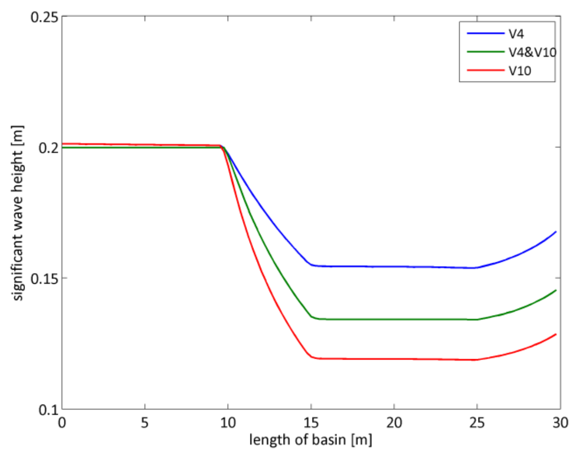


Figure 3-8 – Effect on H_s for implanting different types of vegetation layers.

The result of the composition V4&V10 is in between the results of the other compositions. This result is as expected; the vegetation with the different layers has an average vegetation parameter in between 4 and 10, and therefore the H_s over the length of the basin is in between the results of these layers. In this SWAN-VEG model an average vegetation parameter can be determined which has the same results as the composition of different layers. The average vegetation parameter is calculated by weighted averaging depending on the vegetation height. For the composition V4&V10 it gives an average vegetation parameter of 7. The model results of these are identical.

The position of the layers in the model does not affect the amount of energy dissipation; in this vegetation module it makes no difference whether the layer with a larger vegetation parameter is located at the surface or at the bottom, the amount of energy dissipation is the same. Therefore this model is only applicable for shallow water waves with uniform energy transport over the water depth.

For deep and intermediate waves the water depth is relatively deeper and the wave energy is not constant over the water depth. For these waves the position of the vegetation layers (should) influence the amount of energy dissipation. Therefore an improved vegetation model is made which takes into account the position of the vegetation layer over the water depth [Suzuki et al., 2009]. This model is developed at the same moment as this study is conducted and could therefore not be used.

3.4 Wave characteristics

In this section the results are presented of varying the wave characteristics. These are:

- Initial significant wave height (H_s).
- Peak wave period (T_p) which affect the energy dissipation term via the wave-number k.

One by one the parameters are varied over a specified range, described per parameter. The other parameters are kept constant on their default value as given in Table 3-1, except for the analysis of the significant wave height; here both the water level and vegetation height are increased to 5 meter. Waves with a larger wave height would otherwise experience shoaling and depth induced breaking. This would cause a reduction of wave energy not caused by the vegetation field and thus affecting the results of this analysis.

3.4.1 Significant wave height

The significant wave height is varied over values as given in Table 3-5:

H_s [m]
0.1
0.2
0.5
1.0
2.0

Table 3-5 - varying significant wave height.

The peak wave period is kept constant at 4 seconds what results, with a height of 2 meter into very steep and less realistic waves. However it is required to keep the wave period constant in order to determine the effect of increasing the wave height on the attenuation of waves.

The results are presented in Figure 3-9 and Figure 3-10. In Figure 3-10 the effect of varying the wave height is presented by the remaining wave height as a percentage of the initial wave height. The percentage remaining wave height (RWH) is determined by comparing the wave height behind the vegetation field(x=17.5) with the initial wave height (x=0):

$$RWH = \frac{\text{Hs}(x = 17.5)}{\text{Hs}(x = 0)} * 100\% \qquad (3.6)$$

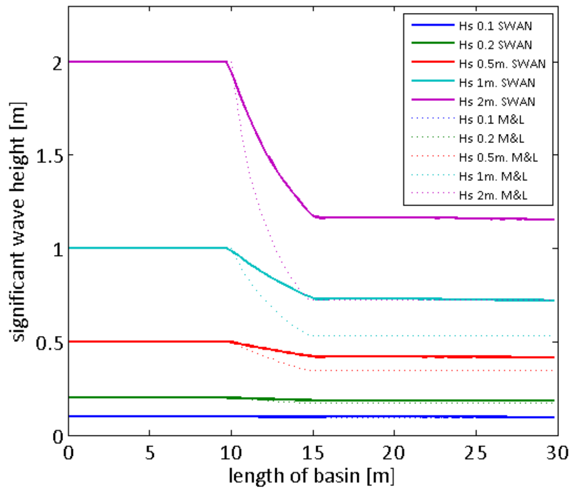


Figure 3-9 – Effect on H_s on varying initial significant wave heights.

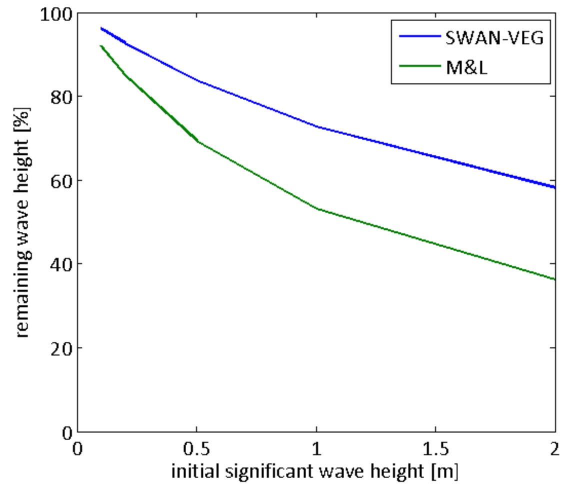


Figure 3-10 – perc. RWH as function of initial wave height behind vegetation field (x= 17.5).

The figures show relative reduction in significant wave height H_s due to the vegetation field increases with an increasing initial significant wave height. Figure 3-10 shows that for larger initial waves the slope of the percentage remaining wave height decreases, indicating energy dissipation becomes less effective.

Both Figure 3-9 and Figure 3-10 show again a difference between the SWAN-VEG model and the M&L equation. The equation gives much more reduction of the wave height and this difference increases with increasing wave height. The difference between the model and equation is further analysed in the discussion.

3.4.2 Peak period

In this section the peak wave period is varied. The peak wave period is varied over the periods given in Table 3-6. This variation is applied in the SWAN-VEG model via the wave-number k and the angular frequency σ and in the M&L equation via the wave-number k which can be determined via the angular frequency eq. 3.7 and 3.8.

T_p [s]
1
2
4
6
8
10

Table 3-6 - varying peak wave period.

$$\sigma = \frac{2\pi}{T_p} \qquad (3.7)$$

$$\sigma^2 = gk\tanh(kh) \qquad (3.8)$$

For this case the process of white-capping is switched off in the model, because for very short periods the waves might break due to the steepness of the waves, H/L. The result of varying the peak period in both the model and equation is presented in Figure 3-11 and Figure 3-12:

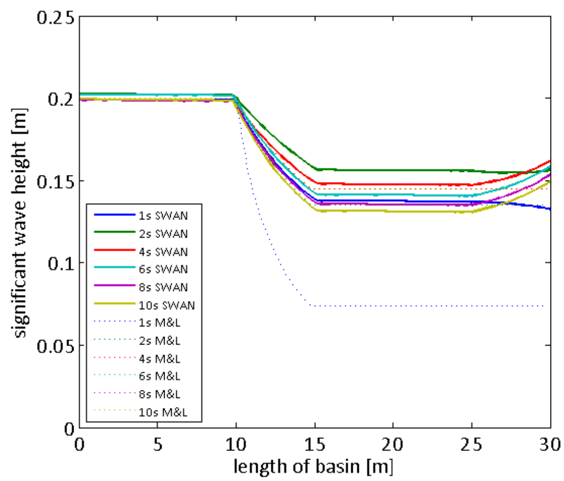


Figure 3-11 - Effect on H_s of varying peak period.

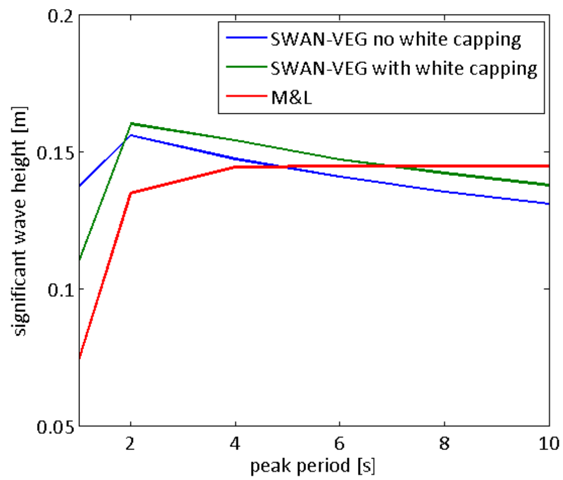


Figure 3-12 - H_s behind vegetation field (x=17.5) as function of T_p.

Figure 3-11 and Figure 3-12 show some interesting results:

- The model reveals an increase of the peak period gives an increase of the energy dissipation which leads into a lower wave height behind the vegetation field. The peak period of 1 second is an exception to this trend; the wave height for this period is notable small, it is in between the wave height corresponding to waves with a peak period of 6 and 8 seconds.
- The M&L equation shows an opposite trend, an increasing period result in less dissipation of wave energy and thus a larger wave height. This trend reaches an equilibrium for period longer than 4 seconds, for all these periods the final wave heights are the same, which is best visible in Figure 3-12.
- Figure 3-12 gives the results of the M&L equation and the SWAN-VEG model results for both with and without white-capping, because all other analyses are done with white-capping in the model. For a peak period of 1 second more energy dissipation occurs compared to without white-capping. The longer periods are also affected by white-capping, here no white-capping results into more loss of energy. This is probability caused by a small difference in the setup of the model case.

The results of both the model and the equation show at a peak period of 1 second relative very large energy dissipation compared to other periods. This large energy dissipation cannot be explained by physical processes. The results is opposite to the trend of the results of the other periods, so it is doubtful whether the model is able to give a good representation of short waves around 1 second; this will be further analysed in the discussion.

The results show a principle difference between the SWAN-VEG model and the M&L equation. In all the other analyses the trend of the SWAN-VEG model and the M&L equation was the same, here the model and equation show an opposite trend. This difference and the consequent underestimation of the wave height by the M&L equation compared to the SWAN-VEG model are analysed in the discussion.

3.5 Discussion

All results show a difference between the SWAN-VEG model and the M&L equation. The principle difference between the SWAN-VEG model and the M&L equation appeared in the analysis of the peak period as presented in Figure 3-12. The difference seems to be due to the analytical approach of the M&L equation and due to the determination of the wave energy spectrum in SWAN, causing for all the cases a difference between SWAN-VEG and M&L equation This difference is here investigated by analysing the approach of SWAN-VEG and the M&L equation, the energy dissipation term and the influence of the vegetation field length.

Analytical versus numerical approach

Equation 3.2 shows the simplification to derive the M&L equation with the assumption of a constant wave group velocity in the vegetation field over the x-direction. This is further is illustrated in equation 3.10 and 3.11. It means that for the determination of the energy loss due to vegetation, the SWAN-VEG model takes the wave energy flux into account while the M&L equation is simplified to the squared wave height. Results of the SWAN-VEG model however show that the group velocity is not constant, but decreases in the vegetation field.

SWAN-VEG model: $$\frac{1}{8}\cdot\rho g\cdot\frac{\partial}{\partial x}\left[H_{rms}^2\cdot c_g\right]=-\varepsilon_v \quad (3.10)$$

M&L equation: $$\frac{1}{8}\cdot\rho g c_g\cdot\frac{\partial}{\partial x}\left[H_{rms}^2\right]=-\varepsilon_v \quad (3.11)$$

The dissipation term is negative so the left part of equation 3.10 and 3.11 has to decrease. In the M&L equation this can only be achieved by a decrease of the squared wave height. For the SWAN-VEG model the energy flux has to decrease which is achieved by a reduction of the squared wave height and/or by the group velocity. For a defined case the energy dissipation terms have the same value for the SWAN-VEG model as for the M&L equation. So a reduction of the group velocity in the SWAN-VEG model causes a smaller reduction of the squared wave height compared to the M&L equation. This a reason why for each case of the sensitivity analysis the M&L equation give an overestimation compared to the SWAN-VEG results as the SWAN-VEG model determines a reduction of the group velocity for waves with a period of 4 seconds.

Analysis of dissipation term

The energy dissipation terms of the M&L equation and the SWAN-VEG model are analysed. The energy dissipation term ε_v implemented in SWAN-VEG is described by equation 2.2 and the energy dissipation term β, used in the M&L equation, is given by 3.4. The variations of these terms over the wave peak period are presented in Figure 3-13 and Figure 3-15.

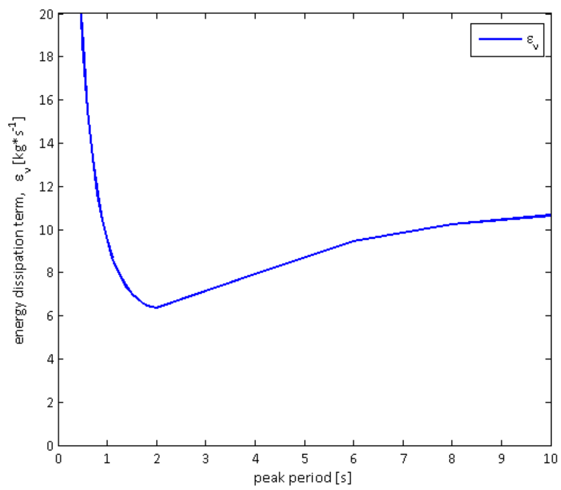


Figure 3-13 - energy dissipation term ε_v as a function of peak wave period.

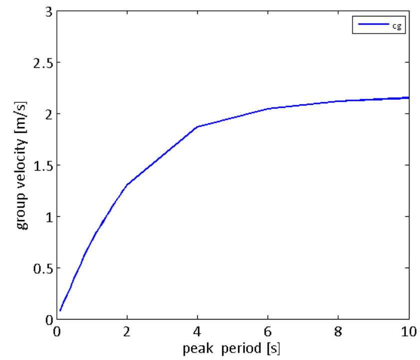


Figure 3-14 – Initial group velocity as a function of peak wave period.

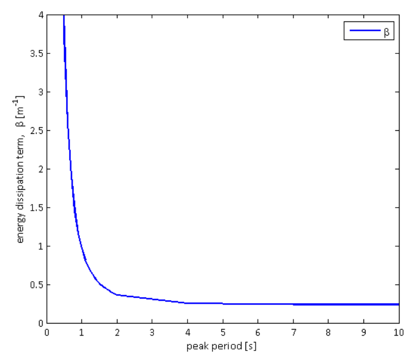


Figure 3-15 – energy dissipation term β as a function of peak wave period.

The terms differ in value, unit and shape because β is the analytical solution of ε_v. However their decrease of wave height is the same for assuming a constant group velocity given in Figure 3-14. SWAN-VEG model results however show the group velocity is not constant over the vegetation field, but decreases for the smaller wave periods over the vegetation field as Figure 3-17 and Table 3-7 show. Equation 3.11 and the determination of β are therefore not right for small periods. The SWAN-VEG model results assumption can so far not be verified, but it is logic if the total energy flux is reduced this affects all wave parameters; including wave height, mean wave period and mean wave length resulting in a smaller group velocity.

The wave energy flux reduction is the same for the SWAN-VEG model and M&L equation, a constant group velocity gives for both the results of Figure 3-15. However as the SWAN-VEG model shows due to the reduction of the group velocity the difference occurs; what results in a higher wave height for the SWAN-VEG compared to the M&L equation and shows a decreasing wave height for increasing wave period. Figure 3-13 shows the slope of the dissipation reduces with increasing period so the influence of increasing peak period decreases.

Figure 3-13 and Figure 3-15 also show another interesting aspect. The large increase of the energy dissipation term for periods smaller than 2 seconds is due to the equation which goes to an infinite value for waves with a period close to zero. It is not logic concerning the physical processes waves with a very short period cause so much dissipation of energy and this is therefore considered as a limitation of the theory. The SWAN-VEG model is not applicable for waves with a peak period shorter than 2 seconds.

Influence of vegetation field and group velocity

To describe the effect of wave group velocity reduction in a better a way another case is used, described by Deltares [2009a]. The results of this case are reproduced and presented in Figure 3-16. In this case the basin has a length of 50 meter and a uniform vegetation field in the basin; all other parameters have the default value as for the case of the sensitivity analysis given in Table 3-1.

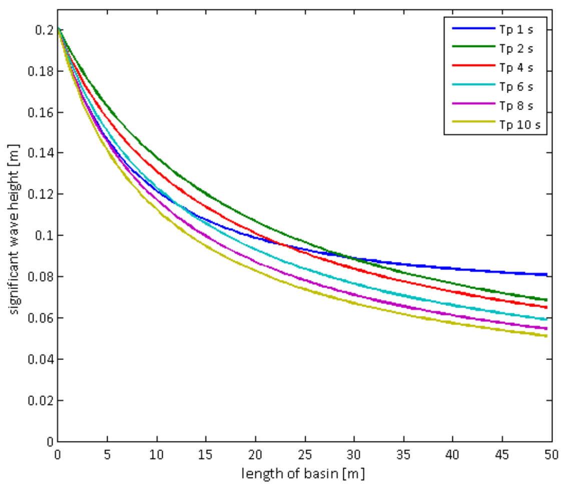


Figure 3-16 - Significant wave height by varying the T_p over a 50 meter vegetation field.

Figure 3-16 shows the wave height over the vegetation field for different peak periods. The results are in accordance with the energy dissipation term as given in Figure 3-13; an increasing dissipation, and thus a smaller wave height behind the vegetation field, for increasing wave period. An exception to this trend is the peak period of 1 second, as the model determines a very large dissipation term.

The wave height for the waves with a peak period of 1 second is analysed. At the start of the basin the dissipation is very large, resulting in a steep slope, and large reduction of the wave height in Figure 3-16. Gradually this steep slope becomes more gentle. This is caused by the reduction of the group velocity, resulting in less reduction of the wave height. At the end of the basin the wave height is higher compared to the results of the other wave periods. For the peak periods of 2 seconds and longer, the reduction of the group velocity is relative smaller and the wave height reduction shows the same trend as the dissipation term; a lower wave height behind the vegetation field for larger wave periods. This analysis shows the wave height is influenced by the group velocity and the reduction of the group velocity has a large effect on the wave height.

Difference sensitivity analyse for peak period

With this analysis the difference between the results of the M&L equation and the SWAN-VEG model in the sensitivity analysis are explained. The results of the M&L equation in Figure 3-11 and Figure 3-12 are affected by the assumed constant group velocity and therefore in accordance with the energy dissipation term β, given in Figure 3-15. In the SWAN-VEG model the group velocity is not constant in the vegetation field as Figure 3-17 and Table 3-7 show. Table 3-7 shows a decrease of the group velocity by comparing the final group velocity behind the vegetation field with the initial group velocity in front of the vegetation field. It shows the group velocity reduces for each peak period, with the largest reduction for the smallest periods. The result of the SWAN-VEG model in Figure 3-11 and Figure 3-12 are therefore in accordance with Figure 3-13 and the change of the group velocity.

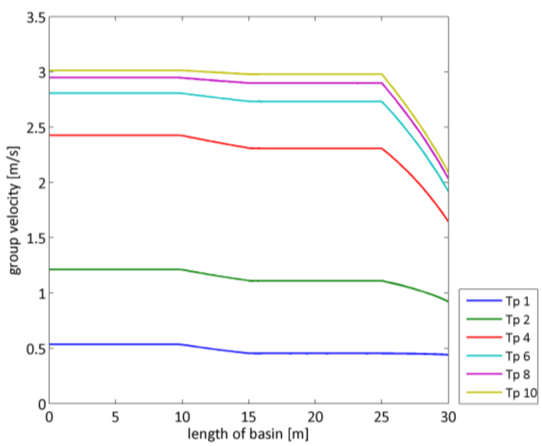


Figure 3-17 - change of group velocity in the vegetation field.

Peak period [s]	decrease c_g in percentage [%]
1	15.3
2	8.5
4	4.9
6	2.7
8	1.6
10	1.2

Table 3-7 - decrease of group velocity.

The wave height for the waves with a peak period of 1 second is not realistic as the analysis show both the SWAN-VEG model and M&L equation give a very large and unrealistic dissipation term. For the peak period of 1 second, the wave height results of SWAN-VEG are higher than for the M&L model as the group velocity reduces which gives relative a smaller decrease of wave height.

Figure 3-12 shows SWAN-VEG en M&L equation results approach each other until periods of 5 seconds, this is logic as the group velocity reduction becomes smaller, so there is less difference between the SWAN-VEG model and M&L equation. For periods longer than the 5 second the SWAN-VEG model shows more energy dissipation. This indicates more energy dissipation occurs than can be attributed to the energy dissipation by vegetation, but is caused by bed friction in the basin.

Overall, the results of the sensitivity analysis showed a small difference between the SWAN-VEG model results and the M&L equation results. This difference is caused by assumption of a constant group velocity in the M&L equation which shows for a period of 4 seconds a small difference.

Spectrum

In order to find out whether the wave energy spectrum influences the results, the wave energy spectrum for each period is analysed (appendix E). For the peak period of 1 second much energy dissipation occurs, this is also visible in the results of the energy spectra. The energy spectrum at the location behind the vegetation field shows a big decrease of energy, especially at the frequency of 1 second, causing the peak to shift to a frequency of 1.6 Hz. This relative large reduction compared to the total wave energy is not the case for the other periods; here the reduction of wave energy is more spread over all the frequencies. It is unknown whether the shift of the peak period for 1 second is caused by a bug of the model or due to the larger energy dissipation. This however does influence the determination of the wave mean period and thus the group velocity. If this shift of the peak would not appear the group velocity is likely to be larger as more energy is attributed to the longer periods, causing a larger wave height reduction than currently is determined.

3.6 Conclusion

The results of the sensitivity analysis are in general well understood and in accordance with the theory. The analysis shows:

- More, wider, higher or less flexible vegetation results into more energy dissipation and a lower wave height behind the vegetation field.
- An analysis of the vegetation parameter shows a value of 20 is the maximum vegetation parameter, in addition only the submerged vegetation effects the attenuation of waves.
- For waves with a larger wave height the results show more energy dissipation.
- The SWAN-VEG model is only suitable for waves with a period of 2 seconds or longer, for smaller periods the energy dissipation is very large which cannot be physically explained.
- An analytical solution of the theory of Mendez and Losada shows similar results as the SWAN-VEG model, however this approach is only applicable for waves with a constant group velocity over the vegetation field which, in this analysis, is the case for waves with a period of 6 seconds and longer. For shorter periods the M&L shows an overestimation of the wave height reduction.

Overall it can be concluded SWAN-VEG is a suitable model to describe the effect of the vegetation on the wave conditions taking into account the limitation concerning the wave period. Next chapter describes the analysis whether the SWAN-VEG model is able to describe real cases. This is in order to answer the research question to what extend the model is able to describe the effect of vegetation on the wave conditions.

4 Calibration and Validation of SWAN-VEG for flexible vegetation

This chapter describes the calibration and validation of SWAN-VEG. The calibration and validation are done to verify whether the SWAN-VEG model is able to quantify the decrease of wave height due to the vegetation by comparing model results with experimental results.

First the approach is presented, followed by the setup of the experiments used for calibration and validation of the model. Thereafter, the model setup and the results of the calibration and validation are described. Next the relation between the drag coefficient and Keulegan-Carpenter number is analysed. The chapter ends with a discussion and conclusion on the calibration and validation.

4.1 Approach

The SWAN-VEG model is calibrated and validated with the use of data obtained in flume experiments by Penning et al. [2008]. In the experiments the effect of vegetation on wave height is analysed for three different macrophyte species and various wave regimes and water depths. These experiments are reproduced with the SWAN-VEG model. The experiments are carried out with a high and low vegetation density. The experiments with the high density are used to determine the drag coefficient, the experiments with the low density are modelled with the determined the drag coefficient in order to verify the drag coefficient. The objective is to find one drag coefficient per species, describing the effect of the plant on the wave height. The calibration will be done by modelling all runs with one drag coefficient, this processes will be repeated until the SWAN-VEG model describes the total set of experiments well enough. This criterion whether the model describes the experiments well enough is quantified in section 4.3.

Mendez and Losada [2004] however show the drag coefficient is dependable on the Keulegan-Carpenter number, an indication of the wave conditions over the width of the obstacle. So the drag coefficient also depends on the wave characteristics, what suggests a calibration per run would give a better result; relating the drag coefficient to the corresponding KC-number of the run. For application of the model this is however not practical, for each case and scenario the KC-number has to be determined and a corresponding drag coefficient has to be calculated or achieved by experiments, resulting in a large set of drag coefficients. It is more straightforward if one drag coefficient per species can be used independent of the KC-number. This is analysed in the calibration and validation.

In order to analysis the sensitivity of the drag coefficient for the KC-number a second calibration is carried out with dividing the total set in three ranges of the KC-number and a determination of drag coefficient per range. This also gives insight how sensitive the drag coefficient is for the KC-number.

4.2 Experiments

In this section the experiments of Penning et al. [2008] are described. First the flume is described as well as the hydrodynamic conditions in the flume. Next the vegetation species are described which were used for the dissipation of wave energy, followed by the determination of the applicability of the data for the calibration and validation.

4.2.1 Experimental setup

The experiments are done in a flume of schematised in Figure 4-1. The flume has a length of 29 meter and a width of 0.8 meter. At the end of the flume a beach with a slope of 1:8 was created to prevent reflection of waves. The start of the flume is defined by a line of slats just behind the wave generator. The slats are used to generate parallel waves through the flume. The bed of the flume consists of pebbles with an average diameter of 3.5 centimetre. These are used as foundation for the vegetation field keeping it at its location during the experiments.

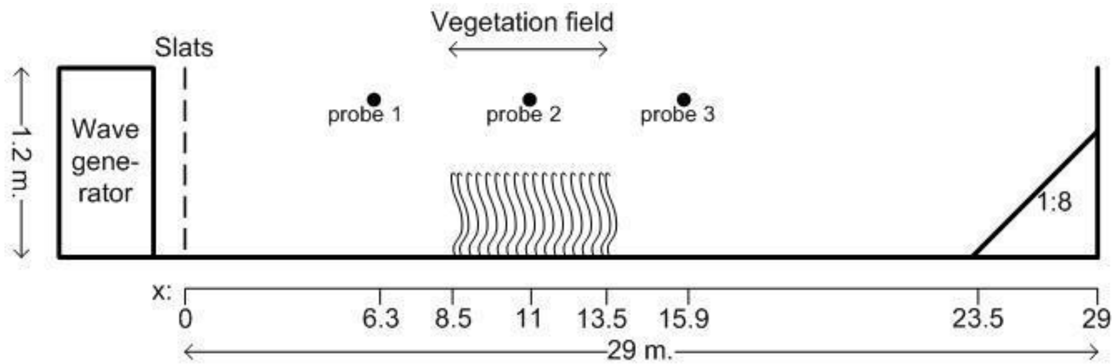


Figure 4-1 – Flume schematisation (not to scale).

The vegetation field with a length of 5 meters and covers the entire width of the flume. The vegetation field is located 8.5 meter to 13.5 meter from the wave generator. Three probes are used during the experiments to measure the wave height, a probe in front of the vegetation field (x = 6.3), inside the vegetation field (x = 11) en behind the vegetation field (x = 15.9).

The experiments are carried out with regular waves. The wave energy and wave period are varied as well as the water depth. These varying parameters are given in Table 4-1 and are the required input parameters for the wave generator at the start of basin. The wave energy is an input parameter for the wave generator, for the model this is the significant wave height. The probes in the flume measure significant wave height which can be compared with the model results. The combination of parameters make in total 90 runs per species. Also all runs are done without vegetation in order to achieve a reference to determine the effect of vegetation.

Water depth [m]:	Wave peak period [s]:	Wave energy [Volt]:
0.3	0.5	0.5
0.4	0.67	1
0.5	1	1.5
0.6	1.33	
0.7	2	
0.8		

Table 4-1 - hydrodynamic conditions.

4.2.2 Vegetation description

The experiments were carried with three species of vegetation: *Echinodorus grandiflorus, Cabomba caroliniana* and *Nymphaea rubra* (water lily), of each species examples are shown in Figure 4-2. These plants were chosen because of their difference in bio-morphology, even though all species are characterised as flexible vegetation. Echinodorus grandiflorus is characterised by a stem with one single, flexible leave on top of it. Cabomba caroliniana is a very flexible plant with many small leaves on a single stem. These leaves are uniform over the entire stem of the plant. Nymphaea rubra has, like the Echinodorus grandiflorus, a stem with a single flexible leave on top. The leave is large and floats on the water surface. The maximum plant height is up to 0.5 meter in the experiment, so the experiments for Nymphaea rubra have only been carried out for a water depth up to 0.5 meter, in order not to drown the plant.

The SWAN-VEG model has the ability to model the leaves and stems separately by the use of two layers. However this also requires a drag coefficient for the stems and for the leaves. Those cannot be obtained by the experiments as in each case both the leaves and stem are submerged. Therefore the species are modelled by one layer, using the height-averaged width. As a result the drag coefficient of the entire plant is determined.

Figure 4-2 – Photos of Echinodorus Grandiflorus [aqua-fish.net, 2009], Cabomba Caroliniana [Aquabase.org, 2009] and Nymphaea Rubra [Wikimedia.org, 2009].

Table 4-2 shows the vegetation characteristics of the three vegetation species. For Nymphaea Rubra the plant height is determined by the water depth (h) because the leaves float on top of the water surface, the width of the plants varies as is the height-averaged width. The experiments have been carried out with two different densities. The first density is used for calibration and the second density, which is around half the first density, is used for validation.

Species:	Height [cm]	Width [cm]	Density 1 [N·m^{-2}]	Density 1 [N·m^{-2}]
Echinodorus Grandiflorus	42.6	1.7	480	240
Cabomba Caroliniana	46.0	3.0	1410	581
Nymphaea Rubra	*h*	4.7/3.8	66	41

Table 4-2 - Vegetation characteristics.

4.2.3 Determination of applicable data for calibration and validation

As the previous section describes, two data sets of wave height are used for determining the effect of the vegetation: the wave height of the runs without vegetation and the runs with the vegetation. Both sets have to be analysed to determine whether they are suitable for calibration and validation.
The following behaviour of waves in the flume for the runs with and without and vegetation is expected:

- Friction, leading to a decrease in wave height
- No shoaling due to a constant water depth
- No reflection due to a sloping beach at the end of the flume.
- Vegetation causes a decrease of the wave height (only for runs with vegetation).

Only the hydrodynamic scenarios which satisfy these criteria are included in the calibration and validation. This means that only the runs are used which showed that:

- The wave height at probe 2 is equal to or smaller than the wave height at probe 1.
- The wave height at probe 3 is equal to or smaller than the wave height at probe 1 and probe 2.
- The wave height of the runs with vegetation has at probe 2 and 3 a smaller height than the wave height of the runs without vegetation.

Not all 90 experiment runs given by Table 4-1 meet these criteria. The waves with a period shorter than 1 second were in general not suitable and also several other runs with a longer wave period. It seems this is caused by the setup of the experiment and errors in measuring.
The last criterion is not the case for all runs and varies for the different vegetation species. The cause of this can be due to the reflection or shoaling caused by the vegetation or by a shift of the probes, thus an error in measuring. It occurred only for a few runs, the other runs show the expected trend of a decreasing wave height. In the section describing the results of each vegetation type, the runs are given which meet these criteria and are used in the analysis.

4.3 Development of numerical model

In this section the development of the numerical model is described. It describes the setup of the model, which probes are used, the determination of the bed friction and it describes how the experiments are scaled before modelling. In addition the determination of the effect of vegetation is described and which criterion has to be met in order to consider the drag coefficient well calibrated.

4.3.1 Model Setup

As is described before, the experiments have been carried out in a flume. In this flume the effect of the sides are considered to be negligible. To prevent the effect of the boundaries in the model, the grid of the model is around 4 times wider than its length, like the basin used for the sensitivity analysis. The bathymetry describes the flume as given in Figure 4-1 including the slope at the end to prevent reflection of waves.
Before the actual calibration is carried out, first the bed friction is determined to represent the pebbles in the flume so the wave heights for the runs without vegetation can be reproduced by the model. The bed friction is calibrated by varying the Collins parameter [Deltares, 2009b]. A Collins parameter of 1.5 is best for most runs and will be used for all the runs. Note that the effect of bottom friction on wave

heights is much less compared to the resistance of the vegetation. So although the Collins parameter of 1.5 is not perfect for each wave run the effect of this is negligible for the determination of the remaining wave height.

Only the measurements in and behind the vegetation field are used for calibration and validation, probe 2 and 3, one runs thus consist out of two measurements, probe 2 and 3. In the experiments the wave height in front of the vegetation field is influenced by the vegetation which cannot be represented by the model. Therefore the wave height at probe 1 is not used. The wave height at the boundary condition (which is at the location of the slats) is based upon the wave height at probe 1. At the boundary the wave height is slightly higher than at probe 1 because the wave height slightly decreases due to the bed friction. The wave height at the boundary had to be varied until the modelled wave heights correspond with the measured wave heights without vegetation.

4.3.2 Scaling of tests

Based on the sensitivity analysis and the wave period of this experiment, the dimensions are scaled before running into the model. As the sensitivity analysis has shown, the model is not suitable for modelling waves with a period smaller than 2 seconds. The model gives better results for a wave period between 4 and 8 seconds, therefore the model is scaled in order to achieve wave periods of 4 to 8 seconds. The model is scaled according to Froude scaling [as used by WL Delft hydraulics, 2007]; all length scales are multiplied with factor γ and all time scales are multiplied with the square-root of γ. It is chosen to scale the experiment with a factor $\gamma=16$ so the wave period is scaled with a factor 4, turning the wave periods, ranging from 0.67 to 2 seconds, into a wave periods ranging from 2.67 to 8 seconds. As a result all runs now have a period of 2 seconds or longer, what can be described by the model. The wave heights now range from 0.3 meter up to nearly 2 meter and the water depth is up to 12.8 meter.

To prevent any confusion in the report, always the non-scaled values are given, since the scaling is only a method to achieve good model results. So for the comparison with the data, the model results are all scaled back to normal conditions.

4.3.3 Determination effect of vegetation

The effect of the vegetation on the wave height is determined by calculating the percentage remaining wave height. This is done by relating the wave height for runs with vegetation to those without vegetation:

$$\textit{remaining wave height}(\%) = \frac{H_{\textit{with vegetation}}}{H_{\textit{without vegetation}}} * 100\% \qquad (4.1)$$

The remaining wave height is determined at the location inside and behind the vegetation field, at probe 2 and probe 3; as a result per run two values of remaining wave heights are determined. A low percentage of remaining wave height means a large reduction of the wave height so much energy is dissipated by the vegetation.

The wave height is measured by the probes for a period of 80 seconds and a sampling frequency of 20 Hz, the average wave height during this period is used to determine the wave height.

4.3.4 Calibration Criteria

The calibration is carried out by varying the drag coefficient until the model describes the data of the experiments well enough. This will be analysed by plotting the percentage remaining wave height of the model runs against the percentage remaining wave height of the experiments, in order to determine a trendline with the least-squares-regression-line. The objective is to achieve a trendline with the equation y = α_Tx with α_T close to 1, here α_T between 0.975 and 1.025 is considered to be acceptable. In that case the model results are considered to describe the experiments close enough for the entire set of experiments with one determined drag coefficient for the total data set. It is assumed that the drag coefficient is not dependable on the model setup.

In addition the coefficient of determination (R^2) is determined which indicates how well the result fits with the determined trendline this describes how well the model is able to describe the experiments with the determined drag coefficient. The coefficient of determination is determined by:

$$R^2 = \frac{S_{tt} - S_{rr}}{S_{tt}} \tag{4.2}$$

Here:

$S_{tt} = \sum_{i=1}^{n}(y_i - \bar{y})^2$

$S_{rr} = \sum_{i=1}^{n}(y_i - \alpha x_i)^2$

y_i = remaining wave height measured for experiment *i*

x_i = remaining wave height modelled in SWAN-VEG for experiment *i*

$\bar{y}$ = average remaining wave height of experiments

S_{rr} is the sum of the squares of the residuals, which defines the spreading between the dataset and the trendline. S_{tt} is the sum of the squares of the deviation from the mean, thus the spread between the data and its mean. This approach determined how well the model describes the results compared the mean value of the experiments. In this analysis the R^2 is equivalent to the so called Brier skill score [Sutherland et al., 2004]. This Brier skill score also allows negative values of R^2, as not the optimum R^2 is determined but is related to the objective of α_T is equal to 1. In case of a perfect fit, S_{rr} is zero and thus R^2 is 1, if the S_{rr} is larger than the S_{tt}, the spreading between the data set and trendline is larger than the deviation from the mean and R^2 becomes negative. Sutherland et al, [2004] describes if R^2 is larger than 0.2 there is a trend between the model and experimental results and if R^2 is larger than 0.5 there is a clear trend between the results. Based on this classification it is assumed that if the R^2 is larger than 0.2 the model is able to describe the experiments.

4.4 Results of Echinodorus grandiflorus

This section presents the calibration of the drag coefficient of Echinodorus grandiflorus and the validation, describing the boundary conditions and the results of the calibration and validation. The calibration is carried out with the first density and the validation with the second, lower density.

Wave conditions

Table 4-3 presents the runs which are used for the calibration and validation; these runs meet the criteria as given in section 4.1.3. In total 27 runs are used for calibration and 26 for the validation, the run highlighted in blue did not met the criteria for the second density.

Water depth [m]	Voltage [V]	Wave peak period [s]	H_s at probe 1 [cm]	H_s at probe 2 [cm]	H_s at probe 3 [cm]
0.3	0.5	2	1.96	1.80	1.61
		1.33	2.04	1.78	1.54
		1	2.1	1.90	1.76
	1	2	3.88	3.46	2.90
		1.33	4.18	3.62	3.04
		1	4.12	3.76	3.29
	1.5	2	5.93	5.15	4.28
		1.33	6.26	5.37	4.24
		1	6.67	5.58	4.88
0.4	0.5	2	2.16	2.16	2.16
		1.33	2.32	2.30	2.10
		1	2.4	2.33	2.26
	1	2	4.49	4.38	3.82
		1.33	5.07	4.58	4.10
		1	5.16	4.88	4.72
0.5	0.5	1.33	2.72	2.66	2.52
		0.67	2.28	2.09	1.90
	1	1.33	5.7	5.41	4.93
		1	6.05	5.70	5.24
	1.5	1.33	8.51	7.94	7.51
0.6	0.5	2	2.68	2.55	2.08
		1.33	2.82	2.70	2.68
	1.5	1.33	9.36	9.28	8.91
0.7	0.5	1.33	3.4	3.28	2.96
	1	1.33	7.3	6.66	6.32
		1	6.57	6.55	6.28
	1.5	2	7.97	7.72	7.3
		1.3	10.82	9.78	9.5
0.8	1.5	2	9.84	9.10	8.91

Table 4-3 - Runs used for Echinodorus grandiflorus, the wave height account for the runs without vegetation.

Results

The calibration resulted into a C_D of 0.11 as Table 4-4 shows. The results of the calibration and validation for the RWH at probe 2 and 3 are given in Figure 4-3 and Table 4-5 of the calibration and in Figure 4-4 and Table 4-6 of the validation.

	αh : [cm]	b_v: [cm]	N [#/m^2]	C_D: [-]	V: [#/m]	Number of measurements, n:
Calibration:	42.6	1.7	480	0.11	0.91	54
Validation:	42.6	1.7	240	0.11	0.45	52

Table 4-4 - Vegetation characteristics Echinodorus grandiflorus.

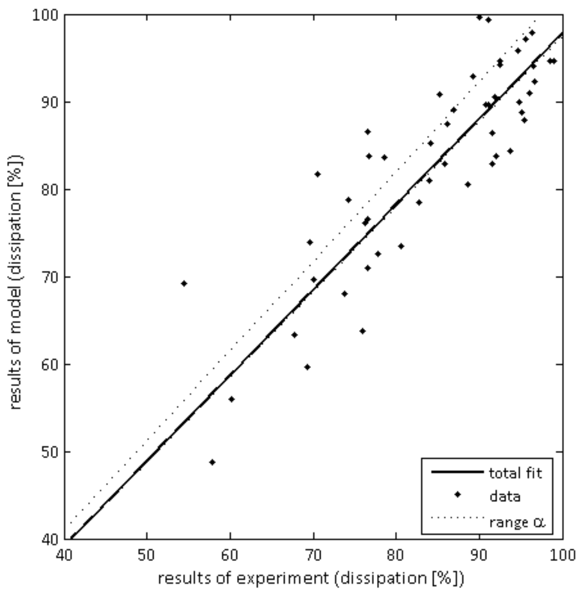


Figure 4-3 – Result of calibration C_D.

	α_T	R^2
Total fit	0.9775	0.68

Table 4-5 - characteristics of calibration results.

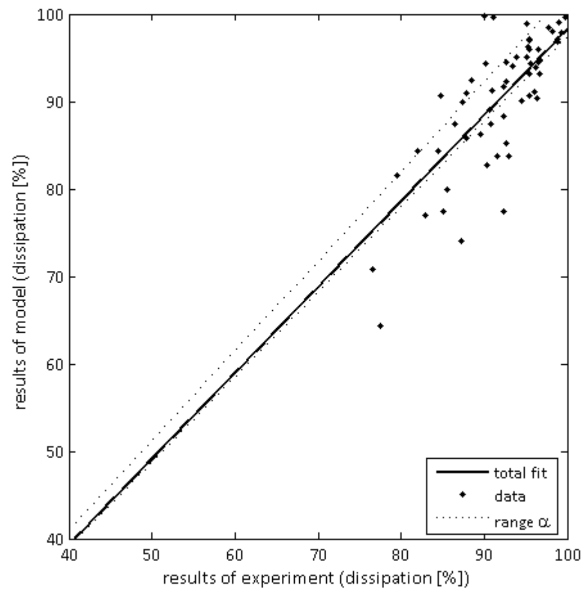


Figure 4-4 – Result of validation.

	α_T	R^2
Total fit	0.9821	0.61

Table 4-6 – characteristics of validation results.

The comparison between the data of the experiment and the model results is quite well for the calibration, the trendline of the total fit gives an α_T of 0.9775. The R^2 larger than the required 0.2 and also higher than 0.5 which means the variation around the trendline is limited and the model is able to give a good representation of the experiments. The validation gives results which are comparable to those of the calibration. This is a good result and means the drag coefficient is well determined and applicable for other cases with Echinodorus grandiflorus. The results show SWAN-VEG is able to describe the experimental results.

4.5 Results of Cabomba caroliniana

Cabomba caroliniana is a very flexible plant, which consist of one stem with leaves over the entire length of the stem. First the wave conditions are described and in addition the model results with an analysis of the results.

Wave conditions

Table 4-7 gives the runs which are used for calibration and validation. All the runs given below are used for validation, but only the highlighted scenarios are used for calibration. In total 14 runs are used for calibration and 21 runs for validation.

Water depth [m]	Voltage [V]	Wave peak period [s]	H_s at probe 1 [cm]	H_s at probe 2 [cm]	H_s at probe 3 [cm]
0.3	0.5	2	1.96	1.80	1.61
		1.33	2.04	1.78	1.54
		1	2.10	1.90	1.76
	1	2	3.88	3.46	2.90
		1.33	4.18	3.62	3.04
		1	4.12	3.76	3.29
	1.5	1.33	6.26	5.37	4.24
		1	6.67	5.58	4.88
0.4	0.5	2	2.16	2.16	1.94
		1.33	2.32	2.30	2.10
		1	2.4	2.33	2.26
	1	1.33	5.07	4.68	4.10
		1	5.16	4.88	4.72
0.5	0.5	1.33	2.72	2.66	2.52
		0.67	2.28	2.09	1.90
	1	1	6.05	5.70	5.24
0.6	0.5	2	2.68	2.55	2.08
		1.33	2.82	2.70	2.68
0.7	0.5	1.33	3.4	3.28	2.96
	1	1.33	7.3	6.66	6.32
		1	6.57	6.55	6.28

Table 4-7 - Runs used for Cabomba caroliniana, the wave height account for the runs without vegetation.

The experiment description did not give a measured width of the plant; therefore this has to be assumed. The leaves itself were measured and have a length of 0.03 meter. These are in general under an angle of 30-45° with the stem; this is at both sides of the stem resulting in a width ranging from 0.025 to 0.035 meter, so a width of 0.03 meter is chosen as width of the plant.

Results

During the calibration it appeared the model has problems describing runs with large amounts of energy dissipation resulting in a small remaining wave height. The model is able to describe large amount of energy dissipation but here the difficulty is to determine a C_D which can determine the right wave height at probe 2 and 3. The decrease described by probe 2 and 3 differs from the decrease by the model. In the experiment the decrease between probe 2 and 3 is quite large, while in the model most of the energy is dissipated in the first part of the flume resulting into only a small decrease between probe 2 and probe 3. Also the required drag coefficient is much larger than for the runs with a moderate reduction. Based on this it seems for runs with larger energy dissipation also other processes take place than only the drag force caused by the stem of the plant.

Therefore it is chosen to calibrate the model for the experiments which have at least a remaining wave height of 50% which is the case for 6 runs. For the validation all runs have a remaining wave height of more than 50% so all are used for validation. Table 4-7 includes all the runs thus also with a reduction of more than 50% The calibration resulted in a drag coefficient of 0.08 as Table 4-8 shows, defining a vegetation parameter for the calibration and validation.

	αh : [cm]	b_v: [cm]	N [#/m^2]	C_D: [-]	V: [#/m]	Number of measurements, n:
Calibration:	46	3	1410	0.08	3.38	13
Validation:	46	3	581	0.08	1.39	42

Table 4-8 - Vegetation characteristics Cabomba caroliniana.

The results of the RWH at probe 2 and 3 are given in Figure 4-5 and Table 4-9 for the calibration and in Figure 4-6 and Table 4-10 for the validation.

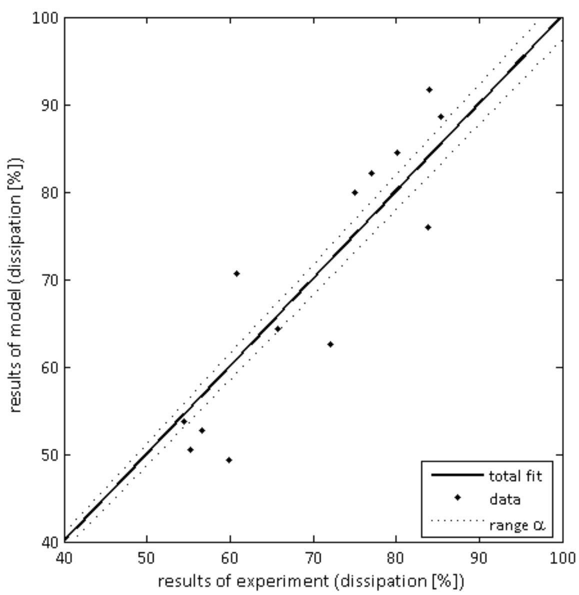


Figure 4-5 – Result of calibration C_D.

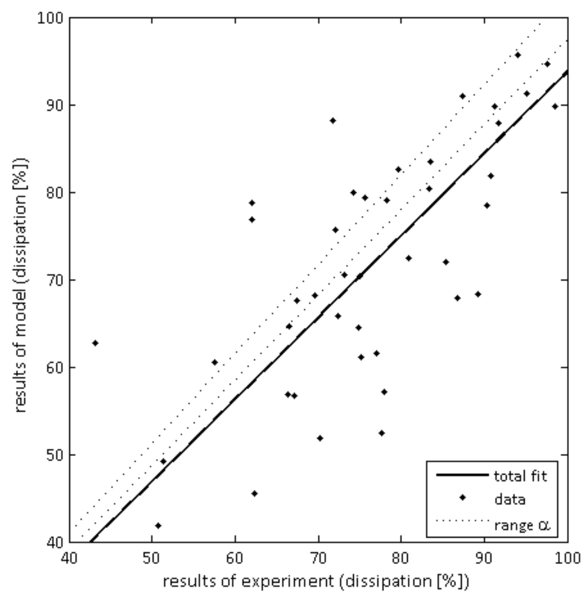


Figure 4-6 – Result of validation.

	α_T	R^2
Total fit	1.0010	0.80

Table 4-9 - characteristics of calibration results.

	α_T	R^2
Total fit	0.9372	0.46

Table 4-10 – characteristics of validation results.

The result for the calibration set is very good, α_T has a perfect value of 1 and the R^2 is also very good with a value of 0.80. The results show there is some difference between the results of calibration and the validation. The value of α_T is smaller than during the calibration and also the variation around the trendline is larger, indicated by the smaller R^2. However for both the calibration and validation the R^2 is larger than 0.2, which indicates the model is able to describe these experimental results.

The reason for this difference can be caused by two cases. First, the data set used for the calibration is small which might influence the determination of the right drag coefficient. Second, the density of the vegetation influences the drag. Based on the photos and movies of the experiments it seems for experiments with the high density the vegetation more acts like one “porous block” rather than single plants, because over the vegetation field the plants show a uniform motion. With fewer plants this effect of the porous block seems to be much smaller as here the plants have their own motion showing no interaction between the plants. This might be the reason for the difference, but cannot be verified, so it is recommended to do further research on this aspect.

4.6 Results of Nymphaea rubra

This section presents the calibration and validation results of Nymphaea rubra. First the wave conditions are described and an assumption considering the height had to be made. In addition the model results are given of both the calibration and validation and an analysis of the results.

Wave conditions

Nymphaea rubra is a flexible plant which is also very buoyant, due to the leaves which float on the water surface under normal conditions. Because the leave need to float on the water surface the experiments have only been carried out for a water depth of 0.4 and 0.5 meter. If the water depth would be larger the plant would drown, it is unknown why no experiments with a water depth of 0.3 have been carried out.

Table 4-11 shows the runs which were used. All the runs are used for the calibration, the highlighted runs are not used for validation, because these do not meet the criteria given in 4.1.3.

Water depth [m]	Voltage [V]	Wave peak period [s]	H_s at probe 1 [cm]	H_s at probe 2 [cm]	H_s at probe 3 [cm]
0.4	0.5	2	2.16	2.16	1.94
		1.33	2.32	2.30	2.10
		1	2.4	2.33	2.26
	1	2	4.49	4.38	3.82
		1.33	5.07	4.68	4.10
		1	5.16	4.88	4.72
	1.5	2	6.68	6.64	5.86
		1.33	7.83	6.88	6.00
0.5	0.5	1.33	2.72	2.66	2.52
		0.67	2.28	2.09	1.90
	1	1.33	5.7	5.41	4.93
		1	6.05	5.70	5.24
	1.5	1.33	8.51	7.94	7.51

Table 4-11 – Runs used for Nymphaea rubra, the wave height account for the runs without vegetation.

The leaves of Nymphaea rubra have to float on the water surface, but the photos of the experiments show this is not always the case. Therefore the height of the leaves had to be assumed, the photos show the leaves are in a vertical position for several cases and based on this, the assumption is made that the leaves have on average a vertical height of 0.1 meter. In comparison, the leave length is 0.19 meter.

Results

The calibration resulted in a drag coefficient of 0.16 as Table 4-12 shows. The results of the RWH at probe 2 and 3 are given in Figure 4-7 and Table 4-13 of the calibration and in Figure 4-8 and Table 4-14 of the validation.

	αh : [cm]	b_v: [cm]	N [#/m^2]	C_D: [-]	V: [#/m]	Number of measurements, n:
Calibration:	40/50	4.7/3.8	66	0.16	0.50/0.42	26
Validation:	40/50	4.7/3.8	41	0.16	0.31/0.25	20

Table 4-12 - Vegetation characteristics of Nymphaea rubra.

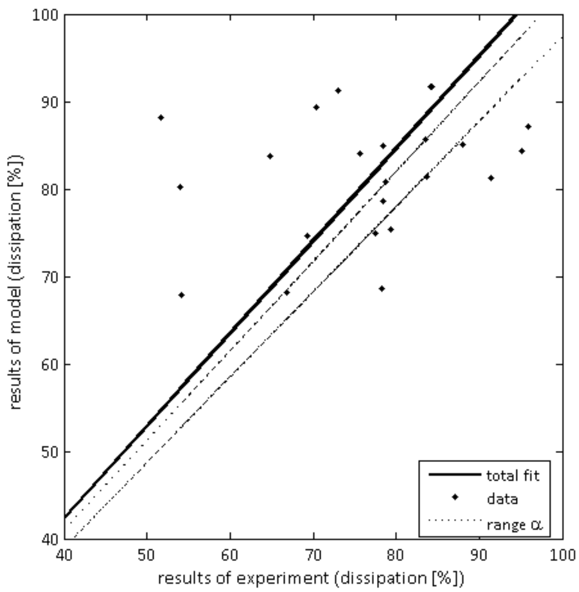


Figure 4-7 – Result of calibration C_D.

	α_T	R^2
Total fit	1.0585	-3.77

Table 4-13 - characteristics of validation results.

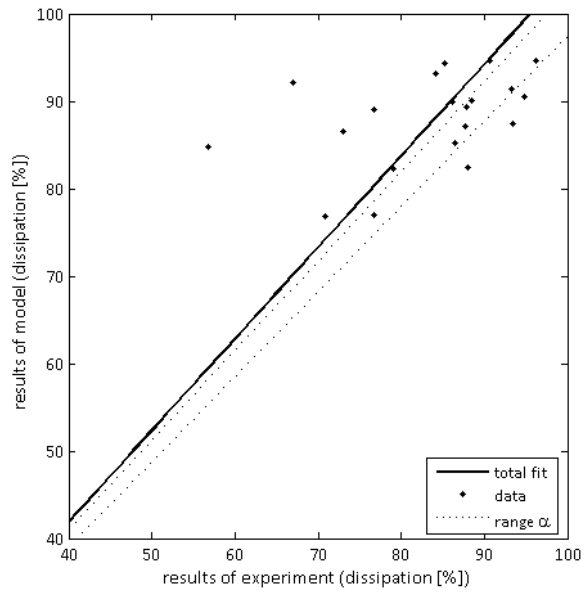


Figure 4-8 – Result of validation.

	α_T	R^2
Total fit	1.0465	-2.38

Table 4-14 – characteristics of validation results.

The value of α_T for the total data set is too high and does not fit in the range of α_T. For the calibration it was unable to achieve a better value for α_T. Also the R^2 is negative what shows there is no trend of the model results describing the experimental results. The figures show nearly all results of the model are in between a remaining wave height of 90 to 70% while the experimental results are in between 50 to 100%, this shows the model results are insensitive for the varying wave conditions. A reason why the model is unable to describe the experiments of Nymphaea Rubra can be caused by the floating leaves. This leaves float on the water surface causing a damping of the waves what reduces the wave height. This cause of wave attenuation is not taken into account in the SWAN-VEG model and seems to cause the inability of the model to describe the experiments.

4.7 Relation drag coefficient and Keulegan-Carpenter number

Several studies [Kobayashi et al., 1993; Mendez et al., 1999; Mendez and Losada, 2004] have tried to find a relation to determine the drag coefficient. As a result these studies suggest the drag coefficient is dependable on the varying wave conditions besides the vegetation species.

Mendez and Losada [2004] suggest a relation exists between the Keulegan-Carpenter number and the drag coefficient; a increasing of the Keulegan-Carpenter cases a drag coefficient, especially for small values of the Keulegan-Carpenter number. The Keulegan-Carpenter number (KC-number) is a dimensionless number which describes the relative importance of the drag forces over inertia for vertical obstacles (e.g. piles) in an oscillating flow [Keulegan and Carpenter, 1958]. The KC-number is calculated with the following equation:

$$KC = \frac{u_{\max} T_p}{b_v} \tag{4.3}$$

Here u_{max} [m/s] is the maximum horizontal velocity of the orbital motion of a wave, T_P [s] is the peak period and b_V [m] is the width of the vegetation. The maximum horizontal velocity is determined at the water surface, which is calculated by the following equation:

$$u_{\max,surface} = \frac{\sigma a}{\tanh(kh)} = \frac{\left(\frac{\pi H}{T_P}\right)}{\tanh\left(\frac{2\pi h}{L}\right)} \tag{4.4}$$

Here H [m] is the significant wave height, a [m] is the wave amplitude which is half the significant wave height, T_p [s] the peak period, L [m] the wave length, k [m^{-1}] is the k-number, σ [s^{-1}] the angular frequency and h [m] the water depth. As equations 4.3 and 4.4 show, the KC-number is determined by both wave conditions and vegetation conditions. If there is a relation between the KC-number and the drag coefficient for one vegetation species, thus constant value of b_V, the drag coefficient is dependable on the wave conditions as well, besides the flexibility of the vegetation.

The previous section gave a description of the calibration and validation which shows the determination of one drag coefficient per species. This gave in several cases a good result. In this section the effect of the KC-number is analysed in order to find out how sensitive the drag coefficient is for the varying wave conditions. For practical use it seems to be unrealistic to determine a drag coefficient per wave condition, however a study of determining a drag coefficient per KC-number gives an indication how sensitive the drag coefficient is for varying wave conditions.

The relation between the drag coefficient and KC-number is analysed by grouping the runs on their KC-number, for each group a new calibration is done to determine a drag coefficient per group. The runs are divided in three groups; a relative high, medium or low KC-number. The groups are determined by calculating the highest KC-number of the total group and dividing the total range in three ranges of the same length. The groups per species are given in Table 4-15. Per vegetation type the groups differ because the KC-number is dependable on the vegetation width. For Caroliniana cabomba only two groups are defined as the high KC-number otherwise would exist out of only one run.

KC-group	Echinodorus Grandiflorus	Caroliniana Cabomba	Nymphaea Rubra
Low KC-Number:	0 - 6	0 - 4	0 – 4
Middle KC-Number:	6 - 12	4 -8	4 - 8
High KC-Number:	12 - 18		8 - 12

Table 4-15 - definition KC-number-groups.

The number of groups is arbitrary, but the objective is just an indication of a dependency of the drag coefficient on the KC-number. In the comparison between modelled and measured percentage remaining wave height, the KC-groups will be indicated by different colours and by a different value of α_T.

Results of Echinodorus grandiflorus:

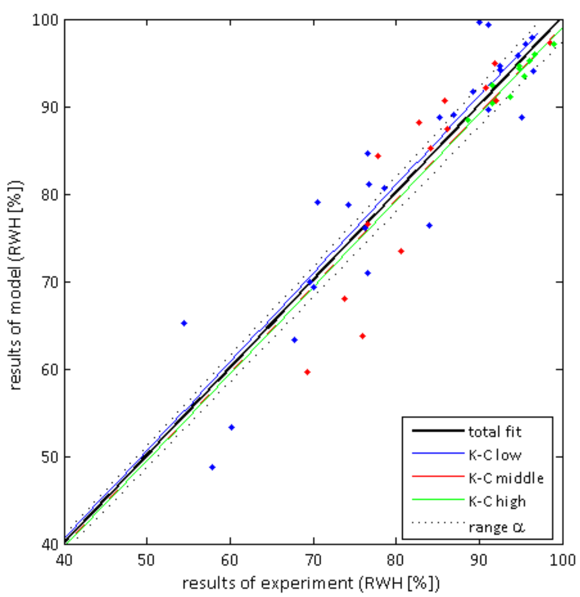


Figure 4-9 - Results Calibration per KC-group.

	alpha	R^2
total fit	0.9775	0.68
low KC	1.0108	0.68
middle KC	0.9510	0.84
high KC	0.9344	0.78

Table 4-16 - Results first calibration with C_D 0.11 and V 0.9.

	alpha	R^2	C_D [-]	V [m^{-1}]
total fit	1.0019	0.85		
low KC	1.0123	0.85	0.13	1.09
middle KC	0.9911	0.77	0.09	0.74
high KC	0.9955	0.84	0.06	0.46

Table 4-17 - Results Calibration per KC-group.

Table 4-16 shows the result per KC-group with a C_D of 0.11, Figure 4-9 and Table 4-17 shows the results with a different C_D per group. It shows with a constant C_D the different KC-groups have a value of α_T which is not within the required range (Table 4-16). This is improved by determining a varying C_D per group ranging from 0.13 to 0.06. Now more variance is explained, indicated by the increased R^2 for the total fit to a value of 0.85. The model is thus even more able to describe the experiments by taking into account a different C_D per KC-number.

The results show that for the low KC-numbers the C_D was underestimated and for the middle and high KC-numbers the C_D was overestimated compared to the constant C_D of 0.11.

Results of Cabomba caroliniana:

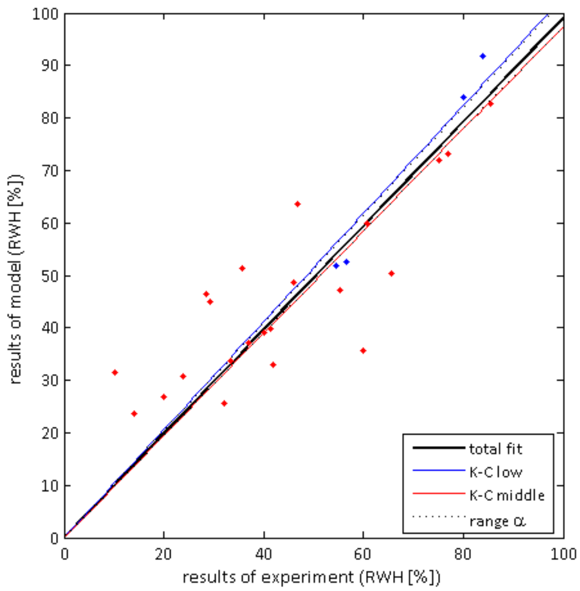


Figure 4-10 - Results Calibration per KC-group.

	alpha	R^2
total	1.0010	0.80
low KC	0.9854	0.75
middle KC	1.0137	0.94

Table 4-18 - Results first calibration with C_D 0.08 and V 3.4.

	alpha	R^2	C_D[-]	V[m^{-1}]
total	0.9901	0.68	-	-
low KC	1.0204	0.94	0.12	5.08
middle KC	0.9750	0.51	0.07	2.96

Table 4-19 - Results Calibration per KC-group.

Table 4-18 shows the result per KC-group with a constant C_D of 0.08, Figure 4-10 and Table 4-19 shows the results of a different C_D per group. For the first calibration and validation the model had difficulties to describe the experiments with a remaining wave height smaller than 50%. By determining a C_D per KC-group the model is able to describe these cases as well, because these are in general the runs with a middle KC-number.

Therefore the results of Table 4-18 cannot be compared with the results of Table 4-19 because the data set has increased to 24 measurements. The middle KC-group can now be described by the model with a R^2 of 0.51, but the figure still shows some variance. It seems the results with a lower remaining wave height are even more affected by the fact that the vegetation start to act like a porous block than for runs with a higher remaining wave height. This is indicated by a constant overestimation of the remaining wave height. More energy is dissipated than can be explained by the model what can be caused by the vegetation acting as a porous block. The results are very sensitive for the C_D as for the middle KC-group the C_D is 0.07 while for the total group it is 0.08.

Like the results of Echinodorus Grandiflorus, the C_D is largely underestimated for the low KC-numbers and slightly overestimated for the middle KC-group compared to a constant C_D of 0.08.

Results of Nymphaea rubra:

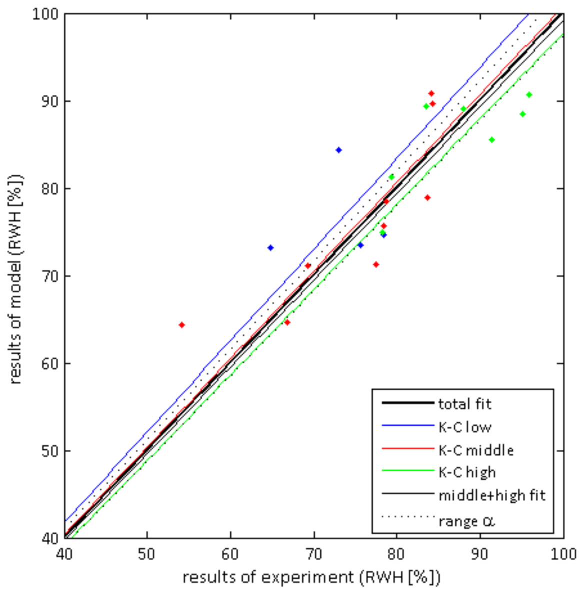


Figure 4-11 - Results Calibration per KC-group.

	alpha	R^2
Total fit	1.0585	-3.7720
low KC	1.2988	-16.7029
middle KC	1.0430	0.5971
high KC	0.9262	0.5198
middle + high KC	0.9835	0.1814

Table 4-20 - Results first calibration with C_D 0.16 and V 0.50/0.42.

	alpha	R^2	C_D [-]	V [m^{-1}]
Total fit	1.0007	0.55	-	-
low KC	1.0423	-1.06	0.23	0.71/0.60
middle KC	1.0079	0.67	0.12	0.36/0.31
high KC	0.9771	0.31	0.11	0.34/0.29
middle + high KC	0.9922	0.68	-	-

Table 4-21 – Results Calibration per KC-group.

Table 4-20 shows the result per KC-group with a constant C_D of 0.16, Figure 4-11 and Table 4-21 show the results of a different C_D per group. For the calibration and validation with one C_D the model was unable to describe the experiments. Table 4-20 shows this is mostly due to the group with low KC-number with a very large value of α_T and a very negative R^2. The combined group of middle and high KC-number is better and almost reaches the required 0.2 for R^2.

Varying the C_D per KC-group gives a better description of the experiments by the model. However, again the model is unable to describe the experiments with a low KC-number. The results of the groups with middle and high KC-number are much better and the experimental results of the combined group can be described by the model indicated by the R^2 of 0.68, also for these groups the C_D is almost the same. Here again the results show the C_D for the low KC-group was underestimated and for the middle and high group it was overestimated compared to the C_D of 0.16. It shows that the model is also able to describe Nymphaea rubra with only one C_D if the floating leaves (low KC-group) are not taken into account.

The photos and movies of the experiments show that for the runs with a larger wave height the leaves are more erected. These runs have a larger KC-number so for these the effect of the damping leaves floating on the water surface is less. This states the assumption that the inability of the model to describe the experiments of Nymphaea rubra is caused by the floating leaves. The model is able to describe the experiments when the effect of the floating leaves decreases.

4.8 Discussion

The calibration and validation show that in the experiments processes occur which influence the wave height, but are not taken into account in the SWAN-VEG model. These processes are:

- The results of Nymphaea rubra are a clear example of how the floating leaves have a large effect on the reduction of the wave height. The floating leaves only have large effect on the results for conditions with a low KC-number as for these conditions the leaves float on the water surface. For the low KC-group the model is unable to describe the experimental results. SWAN-VEG is able to describe the experiments for middle and low group as the leaves here has less effect.
- The results of Cabomba caroliniana show the plants “merge” together acting as a porous block rather than single plants. This effect of the porous block can be compensated by adapting the C_D.
- The sides of the flume which cause friction, reducing the wave height.

This indicates a disadvantage of the model; the effects of these processes can be compensated by adapting the C_D as this is the only calibration parameter, what makes it into a bulk or calibration coefficient. The C_D can describe all the processes in the flume but these are not necessarily a result of the drag force. This makes the C_D more case dependable rather than species dependable.

Overall the values of the calibrated drag coefficients for these three types of flexible vegetation seem to be quite reasonable compared the drag coefficient of Kelp with a drag coefficient of 0.2 [Mendez and Losada, 2004] which is also a flexible plant of similar characteristics. This analysis confirms the result of Mendez and Losada, the drag coefficient decreases as the Keulegan-Carpenter number increases. Interesting is however the C_D used to describe the friction caused by vegetation on the flow velocity is completely different compared to the C_D used to determine the effect of vegetation on the waves. As Galema [2009] shows, several studies which analyse the resistance caused by vegetation on the flow velocity show the C_D used for flow velocity is around a value of 2-3 for flexible vegetation and decreases to 0.5-1 for rigid vegetation. This in contradiction with the C_D used to determine the wave attenuation by vegetation. Here the C_D is very small (0.1-0.3) for flexible vegetation and is assumed to be 1 for rigid (cylindrical) vegetation [Mendez and Losada, 2004; Deltares, 2009a]
Another aspect which could influence the results is the determination of the wave height during the experiments. There are some uncertainties in the measurements as the probes moved during the experiment. The results of the experiments are described by the percentage remaining wave height. However a difference of 1 mm in wave height cases a difference of at least 1% remaining wave height, a probe which moved a few centimetre has thus a significant effect on the percentage remaining wave height.

4.9 Conclusion

The objective of the calibration and validation is to test whether the SWAN-VEG model is able to quantify the decrease of the wave height due to vegetation by comparing model results with experimental results. The results in describing Echinodorus grandiflorus was quite well, the experiments of Caroliniana cabomba can be described for certain conditions and the experiments of Nymphaea rubra cannot be described.

The modelling results confirm there is a dependency of the drag coefficient on the wave conditions, which was found in literature: with an increasing KC-number the drag coefficient decreases. This analysis also gives better insight in the processes taking place in the model. The analysis shows some improvements of the results and several other aspects that clarify the problems of modelling the experiments. It is important to analyse which process take place and whether all of these can be described by the model. Processes like wave damping by floating leaves and vegetation field acting as one block influence the description of the experiments by the model. Taking these processes into account or trying to model these processes influences the drag coefficient has a negative influence in the description of the experiment by the SWAN-VEG model, it therefore recommended to determine a drag coefficient which is not influence by these processes. For verification or designing a vegetation field this processes can influence the results in a positive way as these processes case an extra reduction of the wave height which are not taken into account by the model. But only if the determination of the drag coefficient is not influenced by these processes. The compensation of these processes by adapting the drag coefficient also has a large effect on the different drag coefficient per KC-group as the influence of these processes can be dependable on the wave conditions and thus the KC-number.

Overall it can be concluded that it is verified the model can describe the experiments with a vegetation parameter ranging in between 0.3 and 5 m^{-1}. Here one drag coefficient can be used to describe the vegetation field and its effect on the wave height. The results however improve if the C_D is adjusted for a low or high KC-number compared to the KC-number (range) of the waves for which the C_D is determined. Only if the corresponding KC-number is known the effect of varying KC-number can be taken into account, otherwise there is no reference whether the KC-number is considered high or low. If the KC-number is unknown a reasonable result can be obtained by an average drag coefficient independently of the KC-numbers.

5 Analysis of wave conditions at Fort Steurgat

In this chapter the assessment of extreme wave conditions in front of the dike at Fort Steurgat is described. Based on the results of the sensitivity analysis, calibration and validation it is concluded the SWAN-VEG model is able to quantify the effect of vegetation on the wave height. The vegetation parameter of the vegetation field in front of the dike is in the same order (2.7 m^{-1}) as the vegetation parameter of the experiments which ranging from 0.5 to 5.0m^{-1}. This shows the model is able to describe the effect of this vegetation field on the waves and gives confidence in the model results. The assessment is done by numerical 2D wave modelling for different cases, including vegetation, and different scenarios. This chapter starts with an introduction resulting in the objectives of this chapter, followed by the methodology and model setup. In section 5.5 modelling results are presented en discussed.

5.1 Background and situation description

As part of the project “Room for the River” several measures are taken to increase the flow capacity of rivers and to reduce flood risks. One of the measures is the connection of the Noordwaard polder with the floodplains of the River Nieuwe Merwede near Werkendam, shown in Figure 5-1. The dikes of the Noordwaard polder will be partly removed and four openings are created in the Merwededijk, the Northern dike of the Noordwaard. A threshold with a level of 2.00m.+NAP is created such that the polder will inundate several times a year. The Noordwaard will only be inundated if the water level at the River Nieuwe Merwede exceeds this level. Due to the gradient of the surface, the water flows out the Noordwaard into the River Hollands Diep, which is located South-West of the Noordwaard, here a part of the dike is removed as well to create the outflow. The water level of River Hollands Diep is influence by the tide, so water can also flow via the South-Western opening into the Noordwaard.

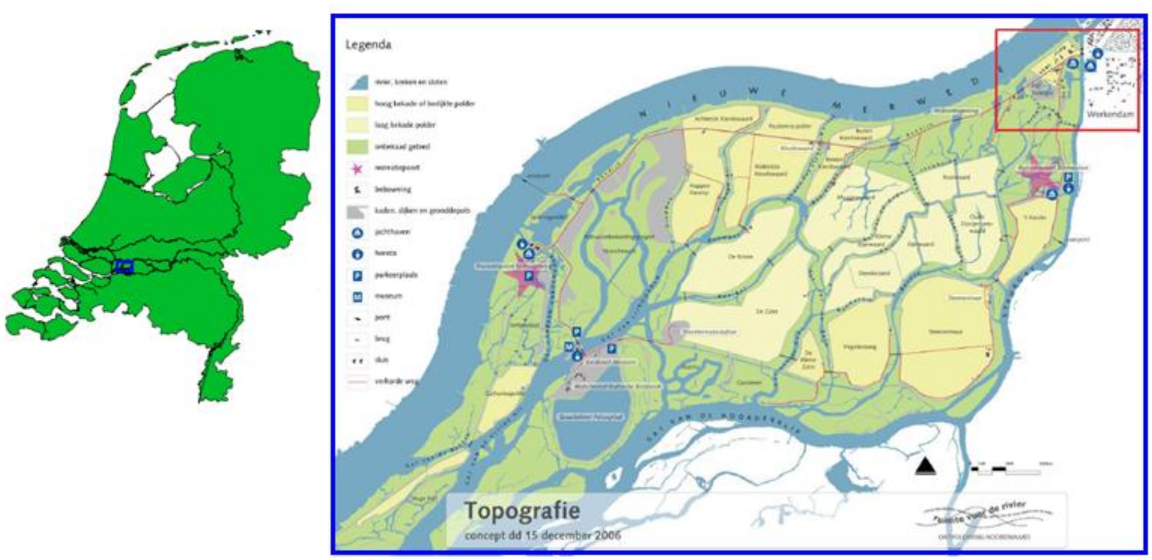


Figure 5-1 – Lay out of the Noordwaard as inundation area. [Bureau Noordwaard, 2007]

The objective of this measure is to decrease the water level in the River Nieuwe Merwede near Gorinchem with 30 centimeter. Because of the partly removal of the dike additional measures are needed to comply with the safety standard according to a return period of 1/2000 year.

In the North-Eastern corner of the Noordwaard Fort Steurgat is located (Figure 5-2) which is used as a residential area. As part of the plan for the Noordwaard a dike is proposed to protect Fort Steurgat from floods. A first design of the dike, with a height between 5-5.5 m.+NAP, resulted in much resistance from the inhabitants of Fort Steurgat because it is too high to fit into the landscape. Therefore it is suggested to plant willow in front of the dike, placed on a bank, to reduce the wave impact. Because the dike height is based on the water level, wave height and a safety margin, the reduction of the wave height allows a lower dike height while maintaining the required safety conditions.

Figure 5-2 - Location of Fort Steurgat in North-Eastern corner of the Noordwaard and design of vegetation field.

For the analysis of the wave conditions in the Noordwaard and the innovative design of the dike with a vegetation field, several studies have been carried out. Here an overview of these studies is given:

- First analysis of the wave conditions and dike height at Fort Steurgat, Bureau Noordwaard [2008]. This study describes the wave conditions in the Noordwaard based on fetch calculations. This study concludes for the design event of 1/2000 year, the wave height will be up to 1.2 meter at the location of the dike. This study is used to determine the initial dike height of 5.5 m.+NAP with a dike overtopping of 0.1 l/s/m.
- First design of innovative dike with a vegetation field, Deltares [2009a]. This study presents a first design of the vegetation field which is based on the wave conditions as given by Bureau Noordwaard [2008]. This design is schematised in Figure 5-2 by the striped light and dark green area. The design consists of a field of willows which should reduce the wave height with 80% according to a 1D calculation with SWAN-VEG.
- Detailed design of vegetation field, Royal Haskoning [2009]. In this study a detailed design of the vegetation field is made based on the calculations of Deltares [2009a] and an analysis of several reduction factors and its resulting dike height are given. The origin of these factors is unknown. Royal Haskoning [2009] concludes a reduction of 40% is required to implemented a dike with a height of 4.3 m.+NAP, but they expect the reduction will be around 60%, based on expertise rather than on calculations.

The new design of the dike shows a reduction of the dike height of 1.2 meter. This is partly due to the vegetation field but also by allowing a dike overtopping of 1 l/s/m instead of 0.1 l/s/m, which gives a reduction of 0.5 meter. The 40% reduction of the wave height by the vegetation field allows a decrease of the dike height of 0.7 meter.

With the SWAN-VEG model it opens up the opportunity to model the effect of the vegetation field on the wave height in 2D, determining the wave height along the dike. The original SWAN model in addition makes it possible to determine the wave conditions in the entire Noordwaard taking into account the spatial variation of the bathymetry and the location of the obstacles. In this study these two aspects are carried out and analysed. By modelling in 2D also the wind direction can be varied to determine the largest waves and its direction which will be used for the design criteria. This 2D modelling has not been done before and will result into more detailed wave conditions in the Noordwaard and a more detailed analysis of the effect of the vegetation field on the wave height along the dike at Fort Steurgat.

5.2 Objectives

The design of the vegetation field in front of the dike is made by Deltares [2009a] based on the fetch calculation as presented by Bureau Noordwaard [2008]. The design itself is evaluated by Royal Haskoning and the height of the innovative dike is determined. The next step is to analyse this situation with a 2D application of the SWAN and SWAN-VEG model to determine the wave conditions in the Noordwaard and to quantify the effect of the vegetation field on the wave height.
The model also opens up the opportunity to model the Noordwaard with more frequent return periods, obtaining data to compare the model results with field measurements which might be carried out in the future. This gives a further insight in the suitability of the model and its ability to describe field experiments.
For modelling the wave conditions at the dike near Fort Steurgat the following objectives are determined:

1. Reassessment of the wave conditions during a 1/2000 year event by modelling with SWAN, with more detailed water en wind conditions. First this is done without vegetation at Fort Steurgat so a comparison can be made between the results of Bureau Noordwaard [2008].
2. Verification of the wave conditions during a 1/2000 year event with the vegetation field at Fort Steurgat to verify the dike height of 4.3m.+NAP. The vegetation field will be implemented in the SWAN-VEG model, so the effect of the vegetation field can be determined and compared with the results of Deltares [2009a] and Royal Haskoning [2009].
3. Assessment of wave conditions for scenarios with different wind and water conditions related to a certain return period. Besides the conditions of 1/2000 event also scenarios that occur more frequent are analysed.

5.3 Methodology

In this section the approach is described for modelling the wave conditions at Fort Steurgat. The scenarios and cases are given as well as the output locations used to evaluate the wave height reduction. The scenarios are a combination of water level and wind speed per return period, the cases are variations to the design. At the end the limitations of this approach are given.

5.3.1 Scenarios

In this study four scenarios with different return periods are investigated: the design standard of 1/2000 year and more frequent scenarios of 1/100 year, 1/10 year and 1/year. The waves in the Noordwaard are generated by the wind. For each return period a water level is defined [Bureau Noordwaard, 2007] and a wind speed per direction is determined [Geerse et al., 2002]. Since both the water level and wind conditions have a return period of 1/2000 year, the total return period will therefore be much smaller than 1/2000 year. However the conditions of a combined return period are unknown so therefore the 1/2000 return per conditions is used. This is a conservative approach what will results in an overestimation of the wave height, which increases the reliability of the vegetation field. In comparison, the study by Bureau Noordwaard [2008] used a constant wind speed of 35 m/s for each wind direction. Per scenario 6 wind directions are taken into account ranging from South to West-Northwest, because these wind directions result into the largest wave setup at Fort Steurgat. This gives with the four return periods 24 simulations. An overview of the water levels, wind directions and wind speeds per scenario is given in section 5.4.1.

5.3.2 Cases

The design of the vegetation field consists of a bank and the vegetation planted on top of the bank. Three different cases representing different stages of the design:

- No bank and no vegetation in front of the dike. Case name: *No bank, no vegetation*.
- The bank in front of the dike but without the willow trees. Case name: *Bank, no vegetation*.
- The bank in front of the dike including the willow trees. Case name: *Bank and vegetation*.

The bank and the vegetation are schematised in Figure 5-3 with a schematisation of the design; a detailed description of the design is given in section 5.4.5.

These three cases are analysed for each scenario and for six different wind directions varying from South to West-Northwest, in total 72 simulations are carried out. The bank, vegetation and the wind direction in relation to the position of the dike are schematised in Figure 5-3.

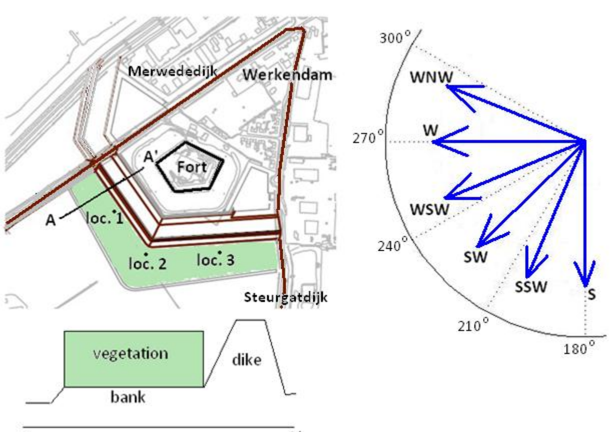


Figure 5-3 – schematisation of bank and dike, output locations and wind direction.

5.3.3 Output locations

To determine the wave height reduction three output locations are specified along the dike where the wave conditions are evaluated. These are all locations at the toe of the dike, behind the vegetation field. The locations are shown in Figure 5-3.

5.3.4 Numerical model

For this assessment the models SWAN and SWAN-VEG are used. The original SWAN 40.55 model is used for the cases *No bank, no vegetation* and *Bank, no vegetation.* The SWAN-VEG model is used for the case *Bank and vegetation*. The models are described in Chapter 2.

5.3.5 Limitations

In this analysis several aspects are not taken into account:

- Bed level changes. Due to waves and currents erosion and sedimentation might occur in the Noordwaard. The amount of sedimentation and erosion in the Noordwaard is unknown as well as its effect on the waves and/or vegetation or how the bed level changes are influence by the vegetation. Because this data is unknown it could not be taken into account in the assessment.
- Currents in the Noordwaard. In the Noordwaard currents will occur because the water flows through four openings into the area. Especially near the openings it is assumed high flow velocities will occur. However no information is available about the currents and are therefore not taken into account in this analysis.

The bed level changes and currents can both cause an increase and decrease of the wave height. The currents can cause diffraction, depending on the direction and bathymetry this cause either way an increase or decrease of the wave height. The bed level changes cases the bed to increase or increase affecting the wave conditions. In this discussion it will be analysed what the effect of both aspects are or whether other influences diminish the uncertainty concerning the bed level changes and currents.

5.4 Model Setup

In this section the model setup is presented, describing the input for the model. The boundary conditions of the scenarios are determined and the computation grid with the bathymetry of the Noordwaard is given. In addition the vegetation field is described and how this is modelled in the SWAN-VEG model.

5.4.1 Boundary Conditions

The wind speeds are based upon data from Schiphol Airport, given in Appendix E. This is the nearest location for which the wind speed per return period is available. Schiphol is located closer to the sea and might therefore give an overestimation of the wind conditions at the Noordwaard. However with South-Western and Western storms, the wind blows over the islands of Zeeland and several rivers which may not reduce the wind speed that much. Therefore the Schiphol data are considered to give a reasonable indication for wind conditions in the Noordwaard. Per return period the maximum wind speed is achieved from the table (Appendix E) for different wind directions. The wind directions are given per 30^0 while for the model it is chosen to vary the wind direction per 22.5^0. To achieve all wind speeds the weighted average is determine by two nearest wind directions. The wind speeds given by Geerse et al. [2002] is the potential wind speed, this is the wind speed at ground level. For the model the wind speed at 10 meters above the surface, U_{10} is required, therefore the wind speeds are multiplied with a factor of 1.05 [Slomp et al.,2005]. The water level per return period is given by Bureau Noordwaard [2007]. The scenarios for the different return periods are presented in Table 5-1.

Several assumptions here are made in order to determine the wind conditions. Since these are the direct input to determine the wave conditions these assumptions can cause an over- or underestimation in the wave height. In addition the water level is determined by a flood return period of 1/2000 year, the wind speed by a storm return period of 1/2000 year, the change that both 1/2000 years event occur is smaller resulting a less frequent return period. Based on the use of the Schiphol data and the overestimation of the return period it is most likely this will be an overestimation of the wave conditions determining the worst-case wave heights per return period.

Return Period:	Water level: [m.+NAP]	Wind speed U_{10}: [m/s]	Wind direction: [^{o}] (dir.)	
1/2000 year	3.5	24.8	180^o	(S)
		29.0	202.5^o	(SSW)
		32.0	225^o	(SW)
		33.9	247.5^o	(WSW)
		35.2	270^o	(W)
		33.9	292.5^o	(WNW)
1/100 year	3.0	21.5	180^o	(S)
		24.9	202.5^o	(SSW)
		27.2	225^o	(SW)
		28.5	247.5^o	(WSW)
		29.3	270^o	(W)
		28.1	292.5^o	(WNW)
1/10 year	2.5	18.4	180^o	(S)
		21.1	202.5^o	(SSW)
		22.8	225^o	(SW)
		23.7	247.5^o	(WSW)
		24.1	270^o	(W)
		22.6	292.5^o	(WNW)
1/year	2.1	6.3	180^o	(S)
		7.9	202.5^o	(SSW)
		8.4	225^o	(SW)
		8.1	247.5^o	(WSW)
		7.4	270^o	(W)
		5.8	292.5^o	(WNW)

Table 5-1 - water and wind conditions applied for the different return periods.

5.4.2 Computational grid

For the analysis two domains are used. One domain is the entire Noordwaard with a resolution of 50 by 50 meters, a second domain of Fort Steurgat is nested in the first domain. This domain has a resolution of 10 by 10 meters. The first domain is used to determine the wave conditions in the Noordwaard which are the boundary conditions for the second domain, so in total two calculations are done by the model.

The second domain gives detailed wave conditions around Fort Steurgat which are used to evaluate the waves. In appendix F figures of both grids are presented.

5.4.3 Bathymetry

The bathymetry of the Noordwaard is based on GIS sample data of Baseline IP Noordwaard [Bureau Noordwaard, 2009]. This data gave the surface elevation with a resolution of 5 by 5 meters.

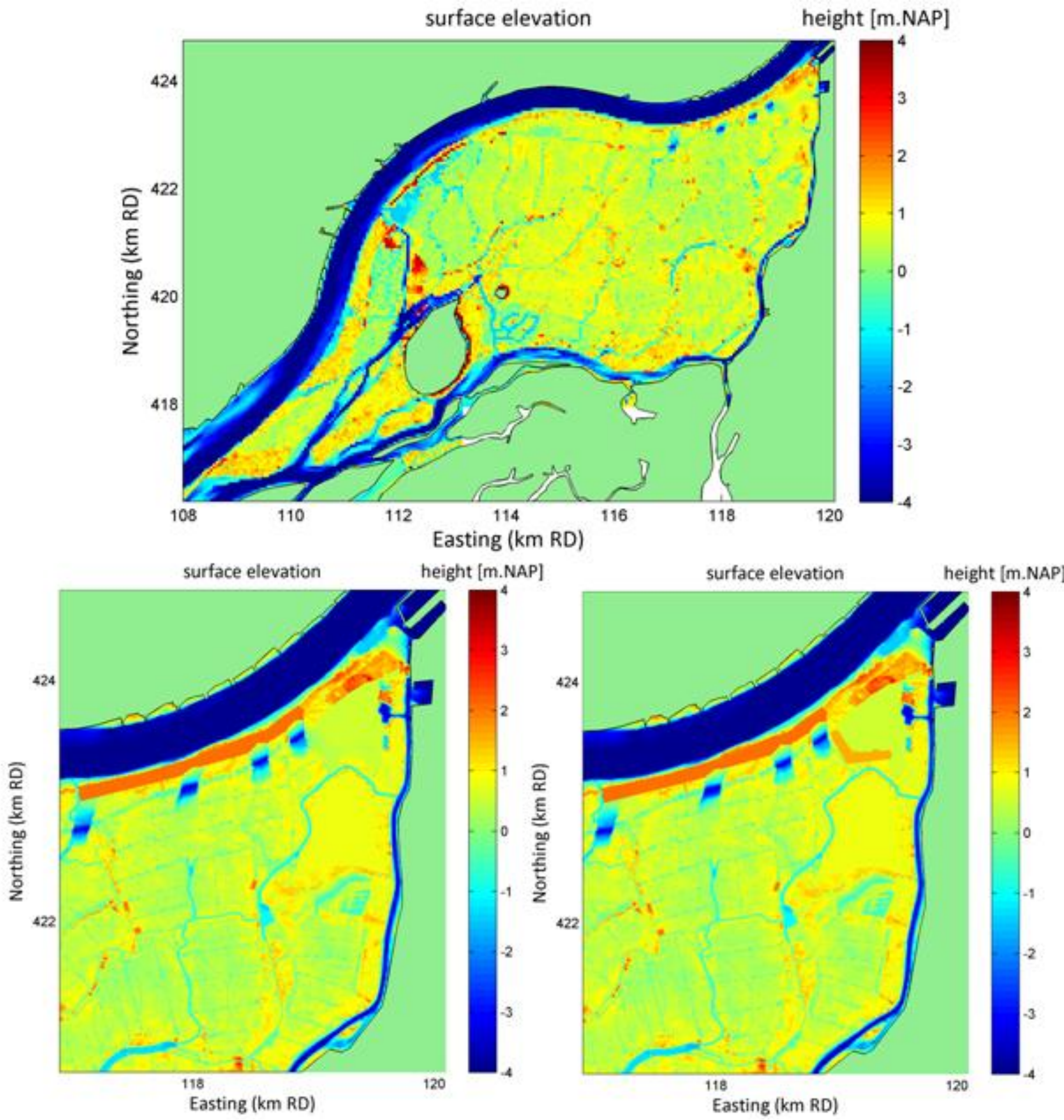


Figure 5-4 - bathymetry of Noordwaard (top), bathymetry Fort Steurgat without bank (left) and with bank (right).

Figure 5-4 shows most of the surface elevation is between the 0 and 1 m.+NAP. During the 1/2000 year event, with a water level of 3.5m.+NAP, the average water depth will be between 2.5 and 3.5 meters. Several adjustments are made to the data before determining the bathymetry:

- In front of the four openings of the dike a threshold is created with a height of 2.00 m.+NAP. This was not present in the GIS-data. Based on Bureau Noordwaard [2009] the surface elevation is adjusted at the 4 dike openings to a constant bed level of 2.00 m.+NAP. The four openings are indicated in Figure 5-4 by the four blue spots just South of the river and the threshold indicated by the orange line. The dike near Fort Steurgat is not modeled because this obstacle is very close to the output locations and would influence the wave height at these locations given the grid resolution. The dike would not influence the effect of the vegetation field, as with the slope of the dike will prevent for reflection, therefore it is unnecessary to implement the dike in the model.
- South of Fort Steurgat the bathymetry is adjusted because the data showed a surface elevation which is due to the planned recreation area in this area. However the plan for this recreation area is uncertain and therefore not taken into account in this analysis. A situation without the recreation area would results into larger wave conditions at the dike and is therefore more appropriate to verify the design. So the bed level is changed to the average bed level in the area near Fort Steurgat of 0.70 m.+NAP.
- The GIS data also provided the height of levees, dikes and other obstacles. In the model these are not modelled as part of the bathymetry but as obstacles. In the bathymetry data these obstacles are removed. The implementation of obstacles is described in the following section.

5.4.4 Obstacles

In the Noordwaard several levees are constructed to protect certain locations. These levees have different heights due to different safety levels. The heights of these levees are shown in Figure 5-5.

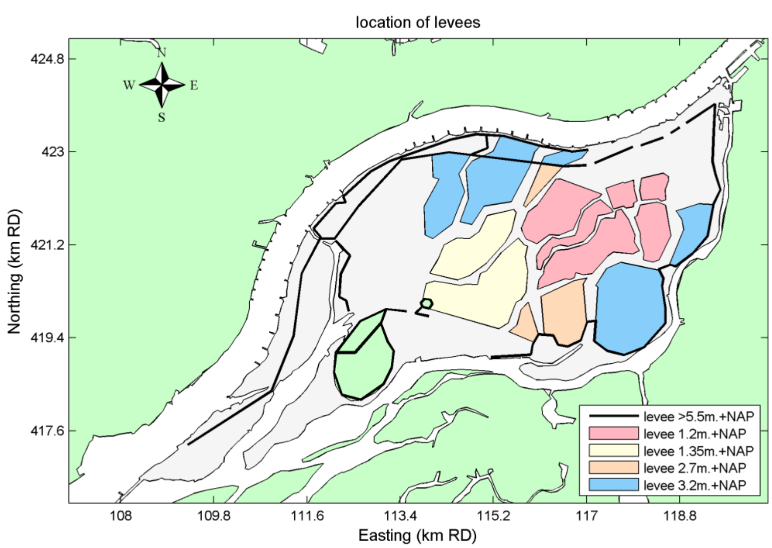


Figure 5-5 – Schematisation of Noordwaard in future situation with location of levees with different safety standards.

In the model the levees are implemented as obstacles. First these levees were modelled as dams, implementing the levee height in the model. However the model results showed a complete dissipation due to these small dams which is not realistic. Therefore these obstacles are modelled as “sheets” which are vertical barriers with an infinite height and a transmission coefficient determining the amount of wave reduction due to the sheets. This transmission coefficient depends on the height of the levee, the water level and the wave height, this approach gives a more realistic effect of the levees than the dams. The transmission coefficient K_t [-] is the ratio of the wave height at the down-wave side of the levee over the wave height at the up-wave side; a coefficient of 1 means complete propagation of the wave and a coefficient of 0 means complete blockage of the wave. The formula to determine this coefficient is determined by Goda [1967] as give by [Deltares, 2009b] and reads as:

$$K_t = 0.5\left[1 - sin\left(\frac{\pi}{2\alpha}\left(\frac{d-h}{\widetilde{H_s}} + \beta\right)\right)\right] \quad \text{for} \quad -\beta_K - \alpha_K < \frac{d-h}{\widetilde{H_s}} < \alpha_K - \beta_K \qquad (5.1)$$

Here:
d = height of levee [m.+NAP]
h = water level [m.+NAP]
$\widetilde{H_s}$ = average wave height in front of the levee [m]
The coefficients α_K[-] and β_K[-] define the shape of the levee and are set to α_K = 2.6 and β_K = 0.15 which is in accordance with the shape of a dike. [Seeling, 1979 as given in Deltares, 2009b].
The wave height depends on the wind conditions and water depth, and differs per scenario. For each scenario an average wave height is determined based on model calculations in SWAN. Applying formula 5.1 for the levees of 1.2 and 1.35 m.+NAP it appeared these levees have no effect on the wave height. The transmission coefficients for the levees of 2.7 and 3.2m.+NAP are given in Table 5-2.

Return period	Water level [m]	Wave height [m]	Levee height [m]	K_t [-]
1/2000 year	3.5	1	2.7	0.69
			3.2	0.55
1/100 year	3.0	0.75	2.7	0.58
			3.2	0.38
1/10 year	2.5	0.5	2.7	0.33
			3.2	0.09
1/ year	2.1	0.25	2.7	0.0
			3.2	0.0

Table 5-2 - transmission coefficient for the different scenarios.

Figure 5-5 also shows the dikes which will remain in the area and have a safety standard with a return period of 1/2000 year (>5.5m.+NAP). These dikes are modelled as sheets as well, with a transmission coefficient of 0. The disadvantage of this method is that the transmission coefficient is fixed based on the average wave height. A wave propagates over several levees, so the wave height changes over the area and therefore the transmission coefficient should change as well.
In the Noordwaard a drink water supply point is located which will not be inundated in order to maintain the supply of fresh water, the location of this supply point is indicated in the figure by the droplet shaped “land” piece in the Noordwaard. The dikes and this water supply point seem to limit the propagation of waves generated outside the Noordwaard to travel into the polder. Waves generated during Western and North-Western storms might propagate from the river into the Noordwaard via the four openings. The analysis will show what the effect will be of these waves.

5.4.5 Vegetation design

As described in the introduction, the layout of the vegetation field is made by Deltares [2009a]. The design consists of a bank of up to 100 meter in length and 0.8 meter in height on which the willow trees are planted. This bank is required so the willows are not continuously in the saturated soil. The willow tree Salix Alba (Figure 5-7) is chosen because it can cope with long inundation periods, has woody branches and grows in clay soil. It consists of a stub from which the branches grow. The vegetation field of willows is implemented in the SWAN-VEG model; wherefore height, vegetation parameter and location of the vegetation field are required.

The stub has an average height of 0.3 meter, is considered to be rigid vegetation and has a lower density than the branches. Therefore the willow field is schematised (Figure 5-6) by two layers, one layer represents the stubs and the other layer represents the branches. Deltares [2009a] gives an overview of the willow characteristics; these data are used to determine the vegetation parameter. The vegetation characteristics like density and width are measured, the drag coefficient is based on literature and expertise [Deltares, 2009a]. Chapter 4 showed one drag coefficient can be used to describe the effect for varying or unknown wave conditions not taking the Keulegan-Carpenter number into account. In this analysis the average characteristics are used for willows with 3 year old branches. This gives the following vegetation characteristics which are implemented in the model:

	Height [m]:	Width [m]:	Density [#·m^{-2}]:	Drag coefficient [-]:	Vegetation parameter [[m^{-1}]:
Stubs	0.3	0.2	4.3	1	0.9
branches	2.7	0.015	4.3*60 = 258	0.8	3.1

Table 5-3 - characteristics of willow.

For the stubs the assumption is made that they are not flexible at all, so a drag coefficient of 1 is used. The branches have an average density of 60 branches per stub what results into 258 branches per square meter. In the model the height of the willow is set to 3 meter such that the willows are above the water level during storm conditions. The vegetation above the water level does not influence the amount of energy dissipation as shown by the sensitivity analysis.

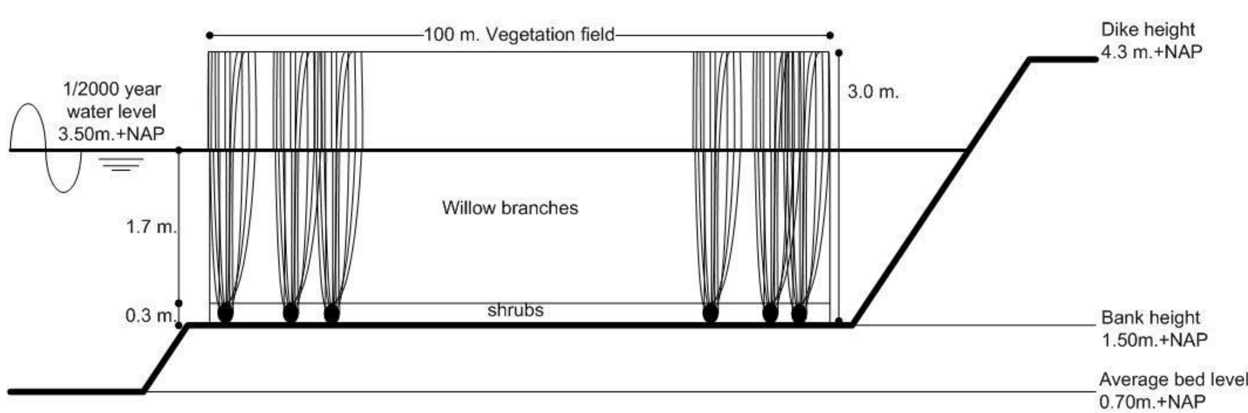


Figure 5-6 - Schematisation of willow field by two layers

The length of the vegetation field varies from 60 meter at the side near the Merwededijk and Steurgatdijk, up to 100 meters at the bend, schematized in Figure 5-3. The length of the vegetation field is defined as the length normal to the dike.

5.4.6 Other settings

For modelling the wave conditions in the Noordwaard with SWAN and SWAN-VEG several others model settings are required. The spectral resolution is set to a range of 0.05-3 Hz which is typical for wind generated waves with short periods. The accuracy of the output is set to a relative change of 0.01 between two iterations for both the wave height and peak period. This must be the case for 99% or more of all wet points.

Figure 5-7 - Salix Alba trees.

5.5 Modelling results

The SWAN model is used to determine the wave conditions in the Noordwaard with the described model setup, conditions and scenarios. First the wave conditions in the Noordwaard are analysed and compared with the results of the so called 'fetch calculations" as given by Bureau Noordwaard [2008]. Next the results for the different scenarios and cases of the wave conditions are analysed.

5.5.1 Reassessment of the wave conditions without vegetation

The first objective of this chapter is to reassess the wave conditions at Fort Steurgat for the 1/2000 year event with SWAN model and with more detailed water and wind conditions. Table 5-4 shows the maximum wave conditions per output location as a result of the fetch calculations by Bureau Noordwaard [2008] and the results of the SWAN model. The results of the SWAN model are quite comparable, the wave height differs up to 10% and around 1 second shorter wave period. These are not large differences taking into account the different approaches and input parameters. For the fetch length calculations a constant wind speed of 35 m/s is used, while in the SWAN model the wind speed differs per direction as shown in Table 5-1. The results show the wind directions of 225^{o} and 247.5^{o} give the maximum wave conditions at the dike.

	Results study Bureau Noordwaard (2008)			**Results of this study with SWAN model**			
Location	Wind speed [m/s]	H_s [m]	T_p [s]	Wind direction [^{o}]	Wind speed [m/s]	H_s [m]	T_p [s]
1	35.0	1.2	4.8	225	32.0	1.07	3.5
2	35.0	1.2	4.6	247.5	33.9	1.09	3.5
3	35.0	1.0	3.9	225/247.5	32.0/33.9	1.04	3.5

Table 5-4 – Comparison between fetch calculations and SWAN results of maximum wave conditions per output location.

Table 5-4 shows the wave height varies 5 centimetre along the toe of the dike. These results are now used as a reference to determine the wave energy dissipation due to the bank and the vegetation field. Concluding, the model gives more detailed results but there are no large differences with the fetch calculations.

5.5.2 Assessment of effect vegetation field on wave height

The second objective of this chapter is to verify the wave conditions with the vegetation field at Fort Steurgat for the event of 1/2000 years. In this analysis the wave height reduction due to the vegetation field in SWAN-VEG is compared with the results given by Deltares [2009a]: up to 80 % reduction, and Royal Haskoning [2009]: 60% reduction. The wave height reduction (WHR) is a percentage describing the ratio between the wave height with bank and vegetation and the wave height without bank and vegetation. It is important to notice that the wave height without bank and vegetation of the SWAN model differs from the wave height used in the calculation of Deltares and Royal Haskoning (see Table 5-4) because of the different boundary conditions and method of determination. Therefore also the absolute wave heights are compared.

The wave height reduction due to the vegetation is verified for an event with a return period of 1/2000 year and has been carried out for all 6 wave directions: Table 5-5 gives the results of the maximum wave conditions per location, appendix G-1 shows the result for each wind direction.

Loc.	Wind dir. [^{o}]	Wind speed [m/s]	No bank, no vegetation		Bank, no vegetation		Bank and vegetation		WHR Bank	WHR Veg.	WHR Bank+ veg.
			H_s [m]	T_p [s]	H_s [m]	T_p [s]	H_s [m]	T_p [s]	[%]	[%]	[%]
1	225	32.0	1.07	3.5	0.85	3.5	0.26	1.1	20.6	69.4	75.7
2	247.5	33.9	1.09	3.5	0.86	3.9	0.26	1.1	21.1	69.8	76.1
3	225	32.0	1.04	3.5	0.85	3.9	0.29	1.5	18.3	65.9	72.1
	247.5	33.9	1.04	3.5	0.86	3.9	0.33	1.7	17.3	61.3	68.3

Table 5-5 - Effect of design for maximum initial wave conditions.

The reduction of the wave height for the case *Bank and vegetation* is in between 68.3 and 76.1%. The wave height is reduced to 0.26-0.33 meters, the case *Bank, no vegetation* gives a reduction of around 20%.

The results as given in Appendix Table G-1 however show the wave height reduction due to the vegetation field is not constant for each wind direction. It varies over the 6 directions between 58.3-73.3%. The reduction due to the bank is more or less constant in absolute numbers, because the waves decrease in height due to wave breaking on the bank, this results into a maximum wave height around 0.85 meters. Another effect of the bank is the change of the wave direction perpendicular to the edge of the bank. The effect of the entire design varies between 62.1-76.6%, with a wave height between 0.20-0.35 meters.

The study of Royal Haskoning [2009] assumes a reduction of 60% due to the vegetation field and a reduction of 40% is required to build the dike with a height of 4.3m.+NAP, this reduction is related to the wave heights given by Bureau Noordwaard [2008]. Table 5-6 gives the corresponding wave height for these reduction factors and the maximum wave height at the three output locations as determined by the SWAN-VEG model, with the corresponding wind conditions.

Loc.	**Wind dir. [°]**	**Wind speed [m/s]**	**Results SWAN** Maximum remaining wave height H_s [m]:	**Royal Haskoning** 40% reduction H_s [m]:	**Royal Haskoning** 60% reduction H_s [m]:	**Deltares** 80%reduction H_s [m]:
1	292.5	33.9	0.28	0.7	0.5	0.2
2	292.5	33.9	0.30	0.6	0.4	0.2
3	270	35.2	0.35	0.5	0.3	0.2

Table 5-6 - Wave height at the dike derived by different studies.

Table 5-6 shows the wave height at location 3 is larger than the wave height calculated by Royal Haskoning [2009] with a wave height reduction of 60%. However it is lower than the maximum wave height required for a dike with a height of 4.3m.+NAP.

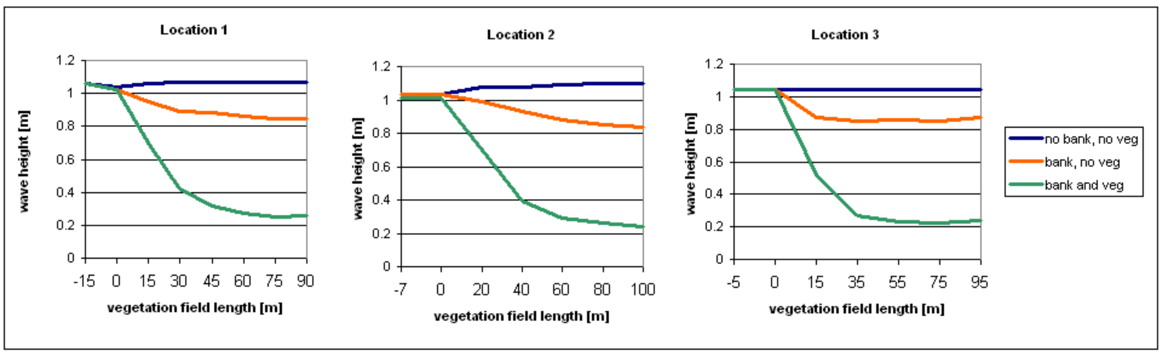


Figure 5-8 - wave height in vegetation perpendicular to location 1, 2 and 3 for WSW wind direction.

The result in Figure 5-8 shows that most of the reduction takes place in the first part of the vegetation field in the first 40 meter nearly all the wave height reduction takes place. The second part is required for maintenance, half the vegetation field can be trimmed and still the required maximum wave height is achieved.

Table 5-5 and Appendix G show the peak period reduces of around 3.5 seconds to periods around 1 second. The sensitivity analysis in chapter 3 showed that the SWAN-VEG model is unable to model these short periods as it determines an energy dissipation which is far too high. The small periods are also unexpected as the sensitivity analysis showed that the peak period, in contrast to the mean period, is constant over the vegetation field. Another aspect is the results per wind direction also vary over the three output locations. As appendix G-1 shows, for the wind directions of 247.5°, 270° and 292.5° the reduction in wave height at location 3 is much less than at location 1 and 2.

Both aspects can be attributed to wave growth by the wind inside the vegetation field. This is based on an analysis of the wave directions in the vegetation field and an analysis of the wave spectrum. Here the wave energy spectrum at location 1 for the wind direction 292.5^0 is taken as an example, Figure 5-9, but this aspect occurs for each wind direction and location.

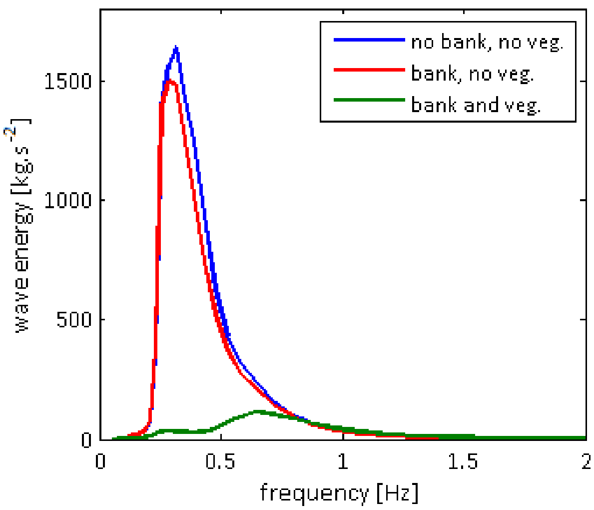


Figure 5-9 - wave energy spectrum for wind direction 292.5^0 at location 1.

The spectrum shows two peaks: the incoming wave generated by the wind over the Noordwaard with a period around 3.5 seconds and which is reduced by the vegetation field compared to the spectrum without vegetation. The second peak in the spectrum has a period of 1.5 seconds which indicates it is generated by the wind over a very short distance and still growing. The peak period accounts for the waves which are generated by the wind causing wave growth inside the vegetation field. These wind waves cause different wave heights per location as the fetch length in the vegetation field differs per location and wind direction, location 3 has a large fetch length along the dike for the Western winds causing a larger wave height at this location. The energy dissipation occurs for the wave with a peak period of around 3 to 4 seconds and not for the waves with a period shorter than 2 seconds as these are new waves due to the wind. The model is thus suitable despite the short peak period as the dissipation occurs for the wave with a period of 3 to 4 seconds, which is longer than the limitation of the model described in the sensitivity analysis, the peak period is caused by wave growth due to the wind inside the vegetation field.

The wave growth by the wind inside the vegetation field is not realistic as the water is sheltered from the wind by the willows. In SWAN-VEG it is not possible to switch off the wave growth by wind for specific areas. It is recommended to implement this option in SWAN-VEG. This effect is also present at all three locations and results in an over prediction of the wave height at the toe of the dike.

In order to determine the effect of the vegetation without wave growth due to the wind, the energy due to wind in the vegetation field is subtracted from the total wave energy. This way the wave energy behind the vegetation field is determined without the influence of the wind. This method however is not completely valid as the sensitivity analysis shows that the group wave velocity decreases due to subtraction of wave energy. The incoming waves have a period of 4 seconds, for this period the group velocity only slightly decreases and thereby it is hard to determine the right group velocity as the spectrum is influenced by the wave growth, therefore the slight reduction of the group velocity is ignored.

Loc.	Wind dir. [°]	Wind speed [m/s]	Results SWAN Maximum RWH H_s [m]:	Reduction [%]:	Royal Haskoning 40% reduction H_s [m]:	Royal Haskoning 60% reduction H_s [m]:	Deltares 80%reduction H_s [m]:
1	202.5	29.0	0.20	79.9	0.7	0.5	0.2
	225	32.0	0.20	80.8			
	247.5	33.9	0.20	81.3			
2	225	32.0	0.20	82.0	0.6	0.4	0.2
	247.5	33.9	0.20	82.8			
3	202.5	29.0	0.19	80.9	0.5	0.3	0.2

Table 5-7 –wave height at the dike without wave growth due to the wind.

Table 5-7 shows the wave height is 8 to 16 centimeter lower without the effect of the wind. As a result the remaining wave height is 0.20 meter for each location and is the maximum wave height for several wind conditions. The results show that the reduction is equal to the wave reduction as calculated by Deltares [2009a]. This approach gives however the most positive results by completely ignoring the wind inside the vegetation. The wind effect will be significantly be reduced by the willows but whether the wind speeds is reduces to zero is uncertain.

5.5.3 Results of different return periods

The wave conditions at the toe if the dike are also determined for the different scenarios with a return periods of 1/100 year, 1/10year and 1/year. The results of these analyses are shown in appendices G-2, G-3 and G-4 and Figure 5-10. The results show that for a lower water level and wave heights, due to a smaller wind speed, the bank gives in percentage more reduction, especially for the scenarios of 1/100 and 1/10 year. As for each water level the maximum wave height, which is able to propagate over the bank, can be determined. The waves decrease in height due to breaking on the bank, wave breaking depends on the wave height and water level. The wave heights for the 1/year events are small in relation to the water depth so less breaking occurs.

For the scenarios with a smaller wave height due to the wind and the effect of the bank, less energy is dissipated by the vegetation. This is in accordance with the results of the sensitivity analysis which showed that for a lower initial wave height the effect of the vegetation is smaller resulting into more or less the same final wave height for each period. Here this pattern occurs as well. The wave height after the vegetation field is for the scenarios of 1/2000 year, 1/100 year and 1/10 year all in the range of 0.15-0.3 meter, while the initial wave height varies between 1.09-0.44 meters. The results also show the combined effect of the bank and vegetation field is in all cases in between 60% and 75%. For the scenario of 1/year the wind generated waves are almost too small to be affected by the bank and also the effect of the vegetation is smaller (45-67%) which results in waves of 0.09 and 0.06 meter high.

The results show that the difference between the three output locations becomes less if the waves and wind speed is smaller. This is also an indicator that difference is caused by the wind. The waves at the output locations are however still dominated by the wind as the short peak periods indicate. Compensating for this effect results into lower wave heights and constant for each output location as Figure 5-10 shows.

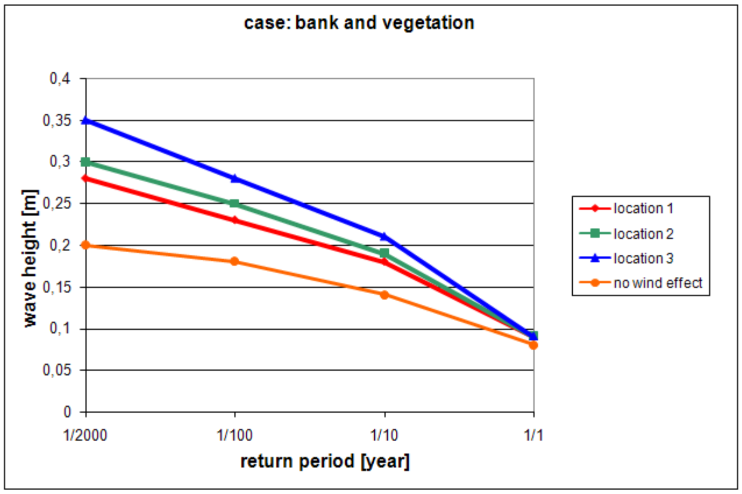


Figure 5-10 –wave height for different return periods

5.6 Discussion

Considering the input and results of this study several remarks can be made. These are described per subject as presented below.

Uncertainties in model setup

Several aspects cause an uncertainty considering the wave height which will appear in the Noordwaard. Theses aspects are the wind and water level conditions, currents and bed level changes and the location of obstacles and determination of transmission coefficient. The wind conditions in the Noordwaard are overestimated as the wind data of Schiphol Airport is used which is located closer to the sea with larger wind speeds. The wind speeds above water is higher than above land but this is compensated by using the U_{10} wind speed. In addition the total return period of the water level and wind speeds is smaller than 1/2000 year. The effect of currents and bed level changes are unknown and can therefore cause larger of smaller wave heights. The uncertainty in the transmission coefficient seems to have a little influence on the wave height because the reduction caused by the levees is compensated by the wave growth due to the wind, the distance between the levees and Fort Steurgat is large enough to achieve the maximum depth-induced wave height.

The uncertainties considering the wave height in the Noordwaard are limited as the wave height is limited by the water depth. The results with the bank show the wave height near Fort Steurgat is maximized by the bank as the waves break due to the height of the bank. It results into a constant wave height at the bank which is not sensitivity for the uncertainties described above. The water depth and the bank height are thus determinative for the maximum wave height. An increase or decrease of the water level has more effect as this would change the water depth, influence the effect of the bed on the wave height.

Variation in water level

For modelling it is assumed the water level is constant over the entire Noordwaard, because in SWAN only one water level can be implemented and is thus constant over the entire area. However due to the

gradient of the bed level the water level differs over the area. This difference can be up to 50 centimetre for the 1/2000 year event [Bureau Noordwaard, 2007]. For each scenario the water level at the four openings is used, which is higher than the water level in the Noordwaard. The four openings are located close to the bank so it can be assumed this water level is representative for the water level at Fort Steurgat. The waves in the South Eastern area of the Noordwaard are slightly overestimated as the water depth in reality is smaller than is implemented in the model.
The wind also causes a set up of the water level due to the shear stresses of the wind on the water surface. As a result the water level at Fort Steurgat will be higher than in the South-West area of the Noordwaard, however the water level in the Noordwaard is already lower than at Fort Steurgat due to the gradient of bed level in the Noordwaard. The exact value of the set up and whether it is compensate by the flow in South West direction is however unknown. But the effect on the wave height is assumed to be small as a 0.1 meter increase of the water level causes an increase of the wave height of 3 to 5 centimetre.

Uncertainties in vegetation characteristics

The results of chapter 4 showed one drag coefficient per species could be used to determine the effect of a vegetation field on the wave height. It also shows that for a relative larger Keulegan-Carpenter number the drag coefficient is smaller than for the total group.
Based on the wave and vegetation conditions the Keulegan-Carpenter number on the bank, just in front of the vegetation field, is around 55. This is compared to the experiments in chapter 4 a very high KC-number. However the KC-number corresponding to the drag coefficients of 0.8 and 1.0 are unknown, therefore it is not possible to say whether the drag coefficient should be under- or overestimated or whether the drag coefficient is well determined. Now it is assumed these drag coefficient is independent of the KC-number, resulting in a reasonable determination of the effect of willows on the wave height. However there is some difference between the required and achieved wave height reduction so even with an overprediction of the drag coefficient the vegetation field still will be an effective method to decrease the wave height at Fort Steurgat.

Another aspect is the vegetation parameter is based upon three year old branches and vegetation which exist over the entire area of the vegetation field. Depending on the maintenance strategy of pollarding the willows; either the vegetation parameter or vegetation field will be affected. The results show half the vegetation field is large enough to achieve the required reduction. It is however interesting to find out what the optimum maintenance strategy will be.

Wave growth due the wind

A limitation of the model is the wave growth inside the vegetation field due to the wind. In the vegetation field the water is sheltered from the wind and therefore wave growth due to the wind would be limited. The results therefore show an overestimation of the waves in the vegetation field. This overestimation is quantified by subtracting the wave energy due to the wind from the total energy. A better solution would be if for specific areas the wind could be switched off. The wave growth due to the wind causes a peak period of 1-2 seconds for the case with vegetation. The energy reduction occurs for the waves with a period of 3-4 seconds; the wind causes new waves with a higher amount of energy and thus determines the new peak period.

This wind aspect is also the case for all other obstacles above the water level. In the model behind each obstacle immediately wave growth appears due to the wind. However at the lee side the water is sheltered, so wave growth should start further away from the obstacle. In this case however this will not affect the results as the influence is limited and the distance between the levees and Fort Steurgat is relative large.

Design of the Noordwaard and vegetation field

The implementation of the vegetation field is done to increase the ecological value of the Noordwaard. This advocates for a vegetation field stretching over the entire Noordwaard, creating a new nature area like the Southern located national park the Bieschbosch. However, the objective of the Noordwaard project is to decreasing the water level at the River Nieuwe Merwede by creating an inundation area with a constant discharge into the River Hollands Diep. Therefore the obstacles in the flow area must be minimized, allowing only a vegetation field close to Fort Steurgat. As a result the variations in the design are very limited and both Deltares [2009a] and Royal Haskoning [2009] concluded that the current design of the vegetation field is the best; obtaining the required wave height reduction and it does not influence the flow through the Noordwaard. The large reduction of the wave height compared to the required wave height suggests an optimisation of the vegetation field, however maintenance must be able to be carried out by pollarding half the vegetation field after analysing the maintenance strategy the vegetation can be optimised.

Other aspects

For the determination of the bathymetry the recreation area South of Fort Steurgat is not taken into account. In case the recreation area will be constructed, the surface level is increased due to the implementation of a bank. A bank is an effective method to reduce the wave height, so the waves approaching the Southside of the dike (location 3) would be smaller due to the recreation area.

The results show the bank is effective in the reduction of the wave height. The implementation of only a bank with a height at 3.00 m.+NAP would probably result into a similar reduction of the wave height. This would make a very wide dike which would not be over topped by waves. However this would not increase the ecological value of the Noordwaard, which is the main reason why the decision is made for the innovative design with bank and vegetation field.

5.7 Conclusion

The analysis of the wave conditions at Fort Steurgat by the 2D SWAN and SWAN-VEG model shows several interesting results. The analysis with the 2D model gives more detailed results of the waves which will occur at Fort Steurgat for a return period of 1/2000 year. The results show a slightly lower wave height and around 1 second shorter wave period, which are not big difference given the different method and input conditions. The implementation of the design including a bank and vegetation field result into a constant wave height due to the bank, limiting the effect of several uncertainties. The bank and vegetation field reduced the wave height significantly with 60-75%. The result show a drawback of the model; wave growth in the vegetation field by the wind, while it is likely the willow trees shelter the water preventing wave growth in the vegetation field. Compensation for this effect results in a wave height reduction of 80% by the bank and vegetation field and constant wave height of 0.2 meter along the dike at Fort Steurgat. However this is the most positive approach by assuming a total reduction of the wind speed inside the vegetation field. It is therefore advised to assume a constant wave height of 0.25 to 0.3 meter along the dike at Fort Steurgat, assuming a small reduction of the wind speed in the vegetation field.

Overall the uncertainties are overestimated what results in the worst-case wave conditions of which will appear in the Noordwaard for the return period of 1/2000 year. This makes that the wave conditions for the cases without the vegetation field is reliable and will probably by smaller than calculated.

Concerning the effect of the willows on the wave height an uncertainty is caused by the determination of the drag coefficient. It is not possible to say whether it is likely this is over or under predicted as the origin of the drag coefficient is unknown. The reliability of the effect of the vegetation field on the wave height depends on the determination of the drag coefficient.

There is large margin between the obtained wave height of 0.3 meter along the dike and the minimum required wave height of 0.5 to implement the dike with a height of 4.3m.+NAP. So even with an overprediction of the drag coefficient the vegetation field is still an effective method to decrease the wave height at Fort Steurgat.

6 Conclusions and Recommendations

This final chapter presents the conclusions of study by answering the research questions in order to achieve the objectives of this study. Next several recommendations are described for further research and improving the model and for the Noordwaard case study.

6.1 Conclusions

This section presents the answers to the research questions as provided in chapter 1. They give comprehensive answers to meet the two objectives of this study:

- Determination of the suitability of the SWAN-VEG model in describing the effect of vegetation on wave conditions.
- Verification of the effects of the vegetation field on the wave height in the Noordwaard with the 2D SWAN-VEG model.

To what extend is the SWAN-VEG model able to quantify the effect of vegetation on the wave conditions?

From the sensitivity analysis (Chapter 3) it can be concluded that more, wider, higher or less flexible vegetation results into and a lower wave height behind the vegetation field. It also shows that for waves with a larger wave height relative more energy dissipation occurs than for smaller waves. The same accounts for the wave peak period, waves with a longer peak period will experience more energy dissipation what results in less reduction of the group velocity and a lower wave height behind the vegetation than for waves with a shorter wave period. A limitation of the SWAN-VEG model is it is only suitable to quantify the effect of the vegetation on the wave height for waves with a peak period of 2 seconds or longer. This is due to the determination of the energy dissipation term; for very small periods the term shows a very large energy dissipation which cannot be explained by physical processes.

An analytical solution of the energy dissipation term given by Mendez and Losada [2004] gives similar results as the SWAN-VEG model but appears only to be suitable for waves with a peak period of 6 seconds and longer in this study, the results between SWAN-VEG and the M&L equation differ due to the assumption of a constant group velocity in the vegetation field.

The calibration and validation (Chapter 4) shows the SWAN-VEG model is able to quantify the effect of plants on the wave height for vegetation with a vegetation parameter ranging between 0.3 and 5.0 m^{-1}. This accounts for all plants, rigid or flexible, as long as the combination of the drag coefficient, plant width and density is within the given range.

The results of the calibration and validation show the model can quantify the experimental results, even with the use of one drag coefficient, independent for varying wave conditions. The results can be further improved if the drag coefficient is determined for different Keulegan-Carpenter numbers.

The calibration and validation in addition show that in experiments also other processes take place which reduce the wave height but these processes are not taken into account in SWAN-VEG. Examples of such processes are floating leaves and very dense vegetation which acts as porous block rather than single plants.

Taking all these aspects into account the SWAN-VEG model is suitable to quantify the effect of the vegetation on the wave height for waves with a peak period longer than 2 seconds. The model is verified to be able to describe experimental results with a vegetation parameter ranging from 0.3 to 5 m^{-1} with the use of one drag coefficient per species.

What is the effect of the vegetation field on the height of the waves in front of Fort Steurgat?
The willows which are investigated have an average vegetation parameter of 2.7 m^{-1}. This is within the range of which is verified SWAN-VEG is able to quantify the effect of vegetation on the wave height. The SWAN-VEG model is thus able to determine the effect of the willows on the wave height at Fort Steurgat.
To determine the effect of the vegetation field, first the wave conditions are reassessed by more detailed water and wind conditions in the SWAN model. This gives a more detailed description of the wave height for the return period of 1/2000 year. The waves at Fort Steurgat are around 1.0 to 1.1 meters in height, which is not a large difference compared to the wave height calculations based on fetch length calculations. The reduction of the wave height due to the bank and vegetation field for the design event of 1/2000 year, determined with the SWAN-VEG model, is in between 60% and 75%. The wave height is reduced to 0.85 meter by the implementation of the bank and reduces to 0.2-0.35 meter due to the willows.
A limitation of the SWAN-VEG model is the wind cannot be switched off for specific locations were vegetation exists. In the current model wave growth due to the wind appears inside the vegetation field, increasing the wave height along Fort Steurgat. This effect seems to be unlikely; the emergent vegetation will shelter the water for the wind reducing the wave growth. It is therefore recommended to assume a small wind speed reduction resulting in a wave height of 0.25-0.3 meter along Fort Steurgat, enough to implement the dike with a height of 4.3m.+NAP at Fort Steurgat.
The analysis for more frequent return periods show the wave height at Fort Steurgat varies between 0.1 to 0.3 meter. Results show that for each scenario the bank is an effective wave breaker. The effect of the vegetation field reduces if the wave height reduces with in accordance with the results of the sensitivity analysis.

Having explored the answer to all research questions, a final statement can be made regarding the objectives. The model is suitable to quantify the effect of a vegetation field on the wave height for cases with a peak period longer than 2 seconds and verified for cases with a vegetation parameter ranging from 0.3 to 5 m^{-1}. The effect of a vegetation field on the wave height can be determined with one drag coefficient for varying wave conditions. However the results improve if the relation between the drag coefficient and wave conditions is taken into account, expressed by the Keulegan-Carpenter number.
The model results verify the vegetation field at Fort Steurgat. The results show the effect of the willows on the wave height is as expected. A wave height of up to 80% can be achieved by the willows if the effect of the wind inside the vegetation field is ignored. It is recommended to take a wave height of 0.25 to 0.3 meter into account along Fort Steurgat. Which is enough for the implementation of the dike with a height of 4.3m.+NAP at Fort Steurgat.

6.2 Recommendations

Based on the results of this study several recommendations are made. These recommendations are divided in recommendations for the SWAN-VEG model and recommendations for the Noordwaard case study.

Recommendations SWAN-VEG model

- The difference between the SWAN-VEG model and the analytical solution of Mendez and Losada is caused by the assumption that the group velocity remains constant in the vegetation field according to Mendez and Losada while it decrease for the SWAN-VEG model results. A further research and experiments would give better insight in the process which take place in the vegetation and whether or not the group velocity changes.
- The SWAN-VEG model which is used in this study does not take into account the position of vegetation layer in relation to the water depth; it only takes into account the height of the vegetation, αh. Therefore the model is only suitable for shallow waves of which the wave energy is constant over the water column. It is recommended to take the position of the layer into account as well, because it enables to model deep and intermediate waves as well. This recommendation is already partly carried out by Suzuki et al. [2009] who wrote a new formulation which now needs to be implemented into the SWAN-VEG model.
- The calibration and validation verified the model is able to quantify the effect of a vegetation field on the wave height for a field with a vegetation parameter ranging from 0.3 to 5 m^{-1}. The sensitivity analysis showed that the vegetation parameter ranges from 0 to a maximum value of around 20. It is recommended to determine whether the model is able to describe plants with a vegetation parameter ranging from 0 to 0.3 m^{-1} and from 5 to 20 m^{-1} as well. This increase the range for which is verified the SWAN-VEG model is able to quantify the effect of the vegetation on wave height and increases the suitability of the SWAN-VEG model.
- The calibration and validation showed also other processes might take place which cause a reduction of the wave height besides the drag force of the plants acting on the waves. Further research is required whether these aspects can be modelled; this would improve the suitability of the SWAN-VEG model for describing the effect of the vegetation on the wave height.
- Concerning the application of the model for the Noordwaard it showed that wave growth due to the wind appears inside the vegetation field. The model would improve if the wind can be switched off or reduced for specified locations. Also at the lee side of obstacles the wind should be reduced because here the wind speed will be smaller than currently is modelled.

Recommendations Noordwaard case study

- For the determination of the drag coefficient of the willows a drag coefficient had to be assumed based on literature and expertise because no (described) experiments have been carried out to determine the drag coefficient. It is recommended to verify the drag coefficient with experiments in order to get a more robust verification of the effect of the willows on the wave height. Also the Keulegan-Carpenter number corresponding to the drag coefficient can be determined in order to determine how this relates to the Keulegan-Carpenter number of the waves in the Noordwaard.

- Because maintenance to the willows has to be carried out, it is recommended to model several maintenance scenarios. Now the assumption is made that with pollarding half the vegetation field enough vegetation remains to comply with the safety standards. Several model runs would verify this assumption.

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Appendix A – Background of SWAN-VEG

This Appendix presents the physical background of SWAN by its basic equation, the determination of the energy dissipation term by vegetation and how this is implemented in SWAN.

Physical background of SWAN

In SWAN waves are described by the two-dimensional wave action density spectrum $N_A(\sigma,\theta)$, varying over the angular wave frequency σ and the wave direction θ. The wave action density is taken into account rather than the wave energy density as the wave action density is conserved with the presence of currents and the wave energy density is not. The action density is equal to the energy density divided by the relative frequency:

$$N_A(\sigma,\theta) = \frac{E(\sigma,\theta)}{\sigma} \qquad \text{(A.1)}$$

In SWAN the evolution of the wave spectrum is described by the spectral action balance:

$$\frac{\partial}{\partial t}N_A + \frac{\partial}{\partial x}c_x N_A + \frac{\partial}{\partial y}c_y N_A + \frac{\partial}{\partial \sigma}c_\sigma N_A + \frac{\partial}{\partial \theta}c_\theta N_A = \frac{S}{\sigma} \qquad \text{(A.2)}$$

The first term at left-hand side represents the local rate of change of action density in time. The second and third term represent propagation of action in geographical space (with propagation velocity c_x and c_y in x- and y-direction, respectively). The forth term represents the shifting of the relative frequency due to variations in depth and currents (with propagation velocity in c_σ in σ-space). The fifth term represents depth-induced and current induced refraction (with propagation velocity in c_θ in θ-space). The right-hand side term is the energy density representing the effects of generation, dissipation and non-linear wave-wave interaction. [Deltares, 2009b]

Here the following processes are taken into account:

- Generation by wind, $S_{in}(\sigma,\theta)$
- Dissipation by whitecapping, $S_{ds,w}(\sigma,\theta)$; bottom friction, $S_{ds,b}(\sigma,\theta)$; and depth-induced breaking, $S_{ds,br}(\sigma,\theta)$
- Non-linear wave-wave interaction (quadruplets and triads), further described in Deltares [2009b].

In SWAN-VEG a forth dissipation term is added to the model for the determination of the energy dissipation caused by the vegetation: $S_{ds,veg}$. The determination of this term is described in the following paragraph.

Determination of energy dissipation term by vegetation

The approach given by Dalrymple et al. [1984], Kobayashi et al. [1993] and Mendez and Losada [2004] determined the effect of vegetation on the wave conditions be schematising the vegetation species as cylindrical obstacles. The resistance of these obstacles can be determined by computing the horizontal drag force of the cylinders:

$$F_x = \frac{1}{2}\rho C_D b_v N u|u| \qquad \text{(A.3)}$$

Here:

F_x = resistance due to vegetation in direction of wave propagation (x-direction) [N]

ρ = water density [kg·m^{-3}]
C_D = drag coefficient of vegetation [-]
b_v = stem width [m]
N = number of stem per m^2 [#·m^{-2}]
u = orbital velocity in x-direction [m·s^{-1}]

Only the resistance in x direction is taken into account because the energy dissipation in z (vertical) direction is considered to be negligible. With the drag force the energy dissipation can be determined by:

$$\varepsilon_v = \overline{\int_{-h}^{-h+\alpha h} F_x u \, dz} \tag{A.4}$$

With the additional quantity:

h = water depth [m]

The energy dissipation is determined by the integral of the drag force times the flow velocity over the vegetation height (αh). The overbar indicates the time average in wave period and velocity. Substituting equation A.3 into A.4 gives the following equation [Dalrymple et al., 1984] describing the dissipation due to vegetation:

$$\varepsilon_v = \frac{2}{3\pi} \rho C_D b_v N \left(\frac{kg}{2\sigma}\right)^3 \frac{\sinh^3(k\alpha h) + 3\sinh(k\alpha h)}{3k\cosh^3(kh)} H^3 \tag{A.5}$$

With the additional quantities and parameters:
g = acceleration due to gravity [m· s^{-2}]
H = wave height [m]
k = wave-number [m^{-1}]
σ = angular frequency [s^{-1}]
αh = vegetation height [m]

This equation accounts for monochromatic waves (constant wave height and wave period), in real cases however each wave is different from the previous wave, varying in height, period and direction. The variation in height and period can be solved by assuming random waves determined by a Rayleigh distribution. This gives the root-mean-square wave height H_{rms}. This gives the following energy dissipation according to Mendez and Losada [2004]:

$$\frac{\partial\left(\frac{1}{8}\rho g H_{rms}^2 c_g\right)}{\partial x} = -\frac{1}{2\sqrt{\pi}} \rho C_D b_v N \left(\frac{kg}{2\sigma}\right)^3 \frac{\sinh^3(k\alpha h) + 3\sinh(k\alpha h)}{3k\cosh^3(kh)} H_{rms}^3 \tag{A.6}$$

Dividing both term with the density ρ and the gravity acceleration g, gives:

$$\frac{\partial\left(\frac{1}{8}H_{rms}^2 c_g\right)}{\partial x} = -\frac{1}{2g\sqrt{\pi}} C_D b_v N \left(\frac{kg}{2\sigma}\right)^3 \frac{\sinh^3(k\alpha h)+3\sinh(k\alpha h)}{3k\cosh^3(kh)} H_{rms}^3 \tag{A.7}$$

This equation is implemented in the SWAN-VEG model with some adjustments for the energy spectrum (Deltares 2009b). The SWAN model is based on the balance of the wave action density spectrum; as a result the root-mean-square wave height is converted in the wave energy which is a function of the frequency and the direction of the waves.

$$H_{rms} = 2\sqrt{2}\sqrt{\int_0^\infty \int_0^{2\pi} E(\sigma,\theta)\mathrm{d}\theta\mathrm{d}\sigma} \tag{A.8}$$

Here each wave parameter becomes a function of the frequency as well. As a result the equation which is implemented in SWAN describing the energy dissipation due to the vegetation reads as follows:

$$S_{ds,veg} = \int_0^\infty \int_0^{2\pi} \frac{8\sqrt{2}}{g\sqrt{\pi}} \rho C_D b_v N \left(\frac{gk(\sigma)}{2\sigma(\sigma)}\right)^3 \frac{\sinh^3(k(\sigma)\alpha h)+\sinh(k(\sigma)\alpha h)}{3k(\sigma)\cosh^3(k(\sigma)h)} \sqrt{E(\sigma,\theta)}\; E(\sigma,\theta)\mathrm{d}\theta\mathrm{d}\sigma \tag{A.9}$$

Appendix B - Verification of the model

Before the sensitivity analysis is done, first is verified whether the SWAN-VEG model gives the same results as the original SWAN model, whereby the vegetation parameters in SWAN-VEG are set to zero. If this is the case the implementation of the vegetation module has not affected the basic core of the model. In addition it is analysed whether the SWAN-VEG model gives a significant reduction for a case with vegetation, to analyse the difference between SWAN and SWAN-VEG.The analysis is carried out with the initial conditions as described in chapter 3.2.

Two cases are carried out:

- No vegetation, the vegetation characteristics are set to zero (αh and/or V are set to zero)
- With vegetation

The results are shown in Figure B- 1.

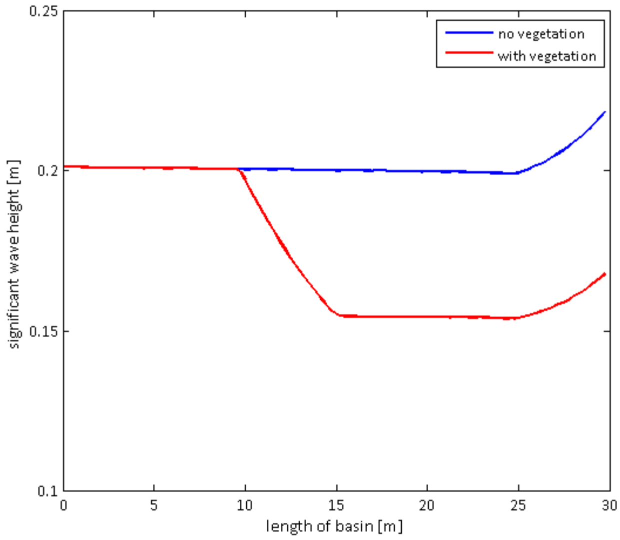


Figure B- 1 - Results with and without vegetation

The figure shows a clear difference between model results with or without the vegetation. The calculation with the original SWAN model gives the same result as the calculation without vegetation in SWAN-VEG. Based on these results it can be stated that with the vegetation parameters set to zero the model works well en gives the same result as the original SWAN model, so the vegetation module does not influence the original SWAN model. Since the SWAN model is well validated [Booij et al., 1999] the sensitivity analysis will focus on the parameters in the vegetation module.

Appendix C – Sensitivity Analysis

Analysis for each wave parameter

This appendix shows varying the vegetation parameter has for each wave characteristic the same relative change. First the results of the significant wave height are presented, in addition the results of the mean wave period, mean wave length and energy dissipation. All the results show the same pattern in reduction.

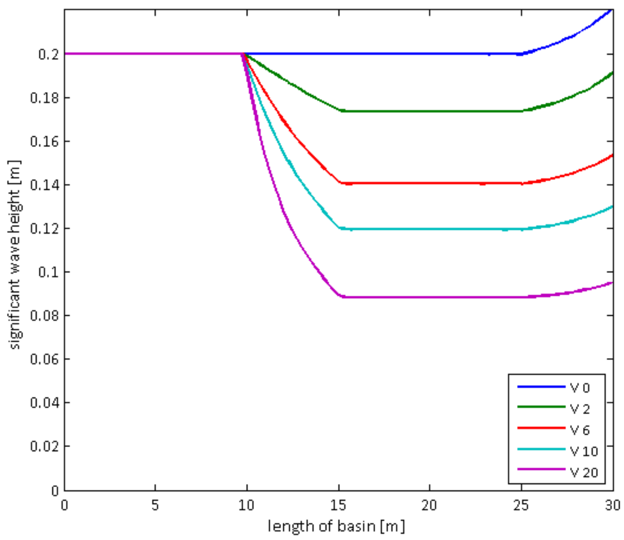


Figure C-1 – variation significant wave height due to varying vegetation parameter

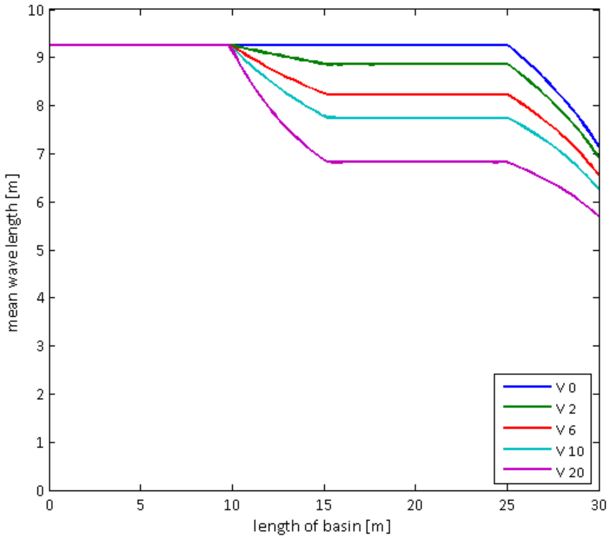


Figure C-2 - variation mean wave length due to varying vegetation parameter

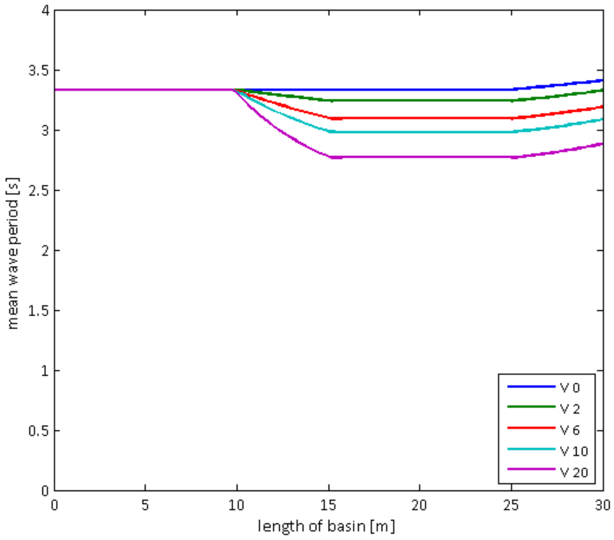


Figure C-3 - variation mean wave period due to varying vegetation parameter

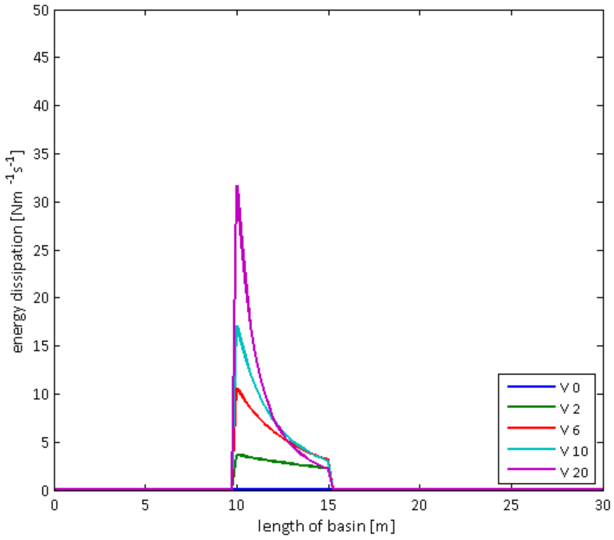


Figure C-4 - variation energy dissipation due to varying vegetation parameter

Analysis of wave spectrum

The vegetation field causes a dissipation of wave energy. The wave energy in the SWAN model is described by a wave energy spectrum. A regular wave with one period is described by a single peak at that specific frequency and the energy decreases to zero for the smaller and larger frequencies, resulting in a peak-shaped wave energy spectrum. The width of the peak is influenced by the peak enhancement factor, increasing this factor results into a smaller variation, so relative more wave energy is account to the peak frequency.

Due to the vegetation field energy is dissipated what results in a loss of wave energy. Figure C-5 shows the energy spectrum at the locations in front of (x = 5), in (x=12.5) and behind (x=17.5) the vegetation field.

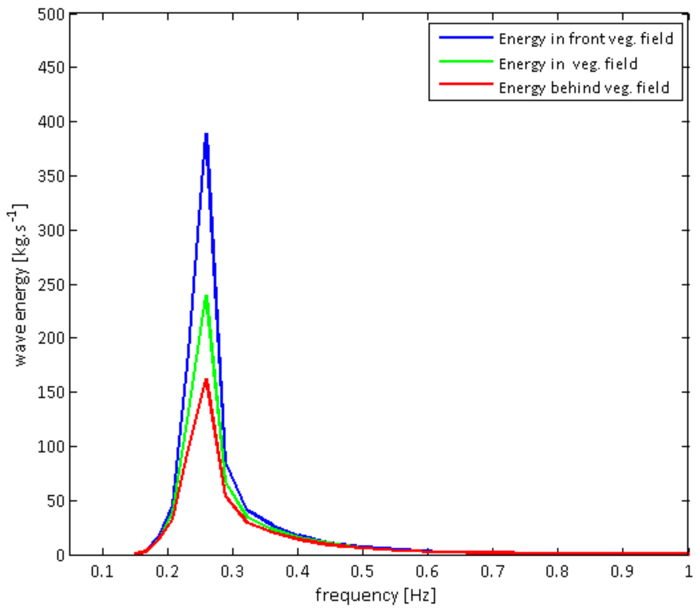


Figure C-5 - Energy spectrum in front, in and after the vegetation field

The figure shows the width of the peaks is small because a peak enhancement factor of 7 is chosen. Here the hydrodynamic and vegetation parameters of the default case are used. The total amount of energy as determined by the integral of each graph is given in Table :

Location:	Wave energy [J/m^2]:
In front of vegetation field (x = 5 m.)	24.81
In vegetation field (x = 12.5 m.)	17.78
Behind vegetation field (x = 17.5 m.)	13.69

Table C-1 - Wave energy per location

The wave energy per location shows the vegetation the energy is decrease due to the vegetation. In the first 2.5 meter the energy is decreased with approximately 8 J/m^2 while in the second 2.5 meter of the vegetation field the energy is decreased with 4 J/m^2.

The figure shows the wave energy is concentrated at the peak frequency of 0.25 Hz, which equals with the peak wave period of 4 seconds. The energy is decreasing over the frequency domain, so the shape of the spectrum remains constant and the peak remains at 0.25 Hz what means that the peak period of the wave does not change.

Verification of model parameters

The model parameters which are used for the model setup of the sensitivity are analysed, it concerns the width of the flume width and the resolution of the grid. This analysis shows how these parameters influence the model results. The basin width is important because the sides of the basin affect the wave height in the basin. If the basin is wide enough the middle of the basin will not be influenced by the sides.The grid is used to define the area where the waves take place and where the vegetation is located. The grid size and resolution also define at which location the calculations will be carried out and the distance between the calculation points. For making a model it is useful to investigate whether the grid dimensions affect the model output.

The width of the basin is varied with 25, 50 100 and 200 meter. The results are shown in Figure C-6.

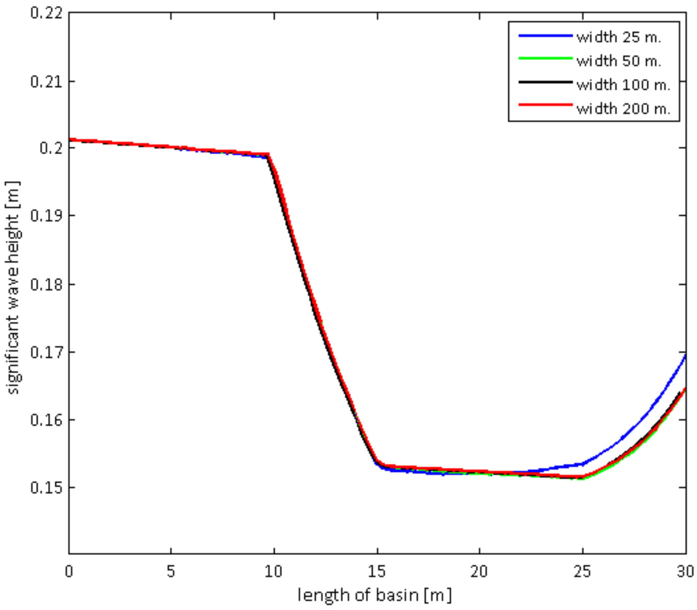


Figure C- 6 - Effect in H_S of varying basin width along the length of basin

The figure shows all the widths are fine for this case. Only at the end of the basin at the sloping bottom, the width of 25 meter gives a different result than the other three. For the sensitivity analysis a width of 100 meter is chosen and this result confirms that this width does not influence the results of the sensitivity analysis.

The cell width of the grid is varied for 0.1, 0.2, 0.25, 0.5 and 1 meter. Figure C- shows the results:

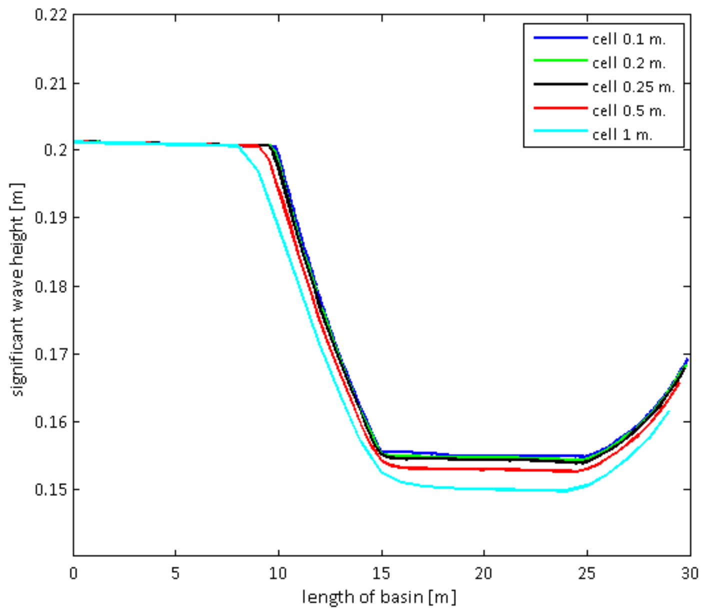


Figure C- 7 - Effect in H_S of varying the width of the grid cell along the length of basin

The figure shows a finer grid gives more detailed results than a course grid. The cell width of 0.1, 0.2 and 0.25 all give nearly the same result. For the sensitivity analysis a cell width of 0.25 meter was chosen and these results show this width did not influence the results of the sensitivity analysis.

Appendix D – Overview of wave spectrum per wave period

In order to analyse the difference in results for the 1 seconds peak period and the larger periods, the energy spectra are analysed. As shown in the part about the analysis of the wave spectrum, the wave energy decreased due to the vegetation. Figure C- showed that the shape of the spectrum remains constant but the height decreased because energy is dissipated. Figure D-1 shows for a peak period of 1 second the wave energy decreases as well, but the shape of the spectrum does not remain constant.

At a frequency of 1.6 Hz and higher, the energy is the same for all locations. For the location behind the vegetation field, this causes a second small peak at the frequency of 1.6 Hz. The reason for this is unknown; the frequency domain is much larger than 1.6 Hz, ranging from 0 to 4 Hz. The results of the other periods (Figures D-2 until D-6) show the shape remains constant.

Figure D-1 also shows for a peak period of 1 second the amount of energy being dissipated is quite high. Although the change in shape, which could cause a larger amount of energy dissipation; also at the peak much more energy is being dissipated than for a period of 2 seconds, which was also conclued in the analysis and is due to a limitation of the SWAN-VEG model.

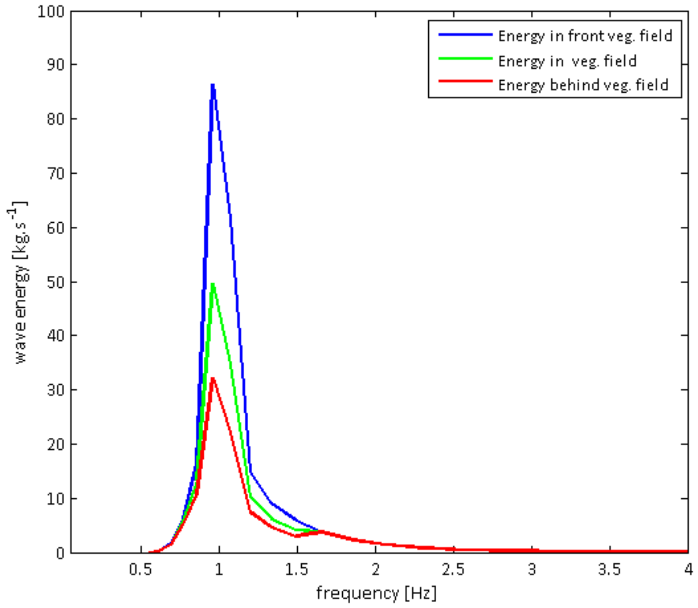


Figure D-1 - Wave spectra for peak period of 1 second

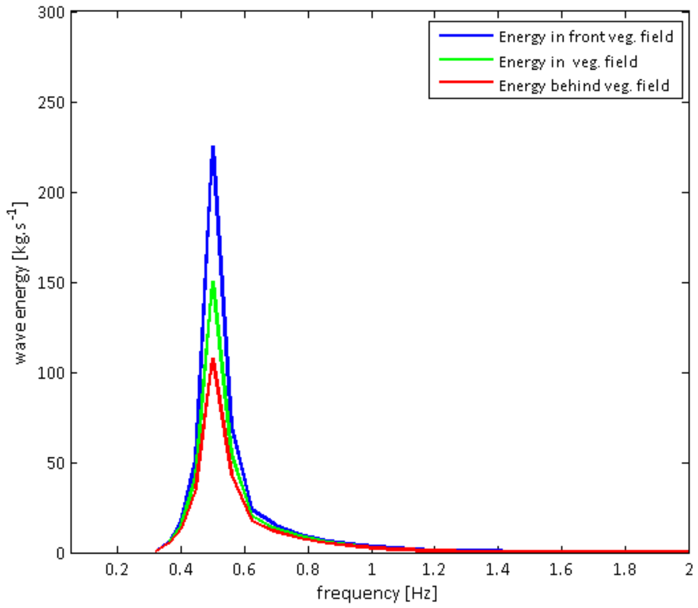


Figure D-2 - Wave spectra for peak period of 2 seconds

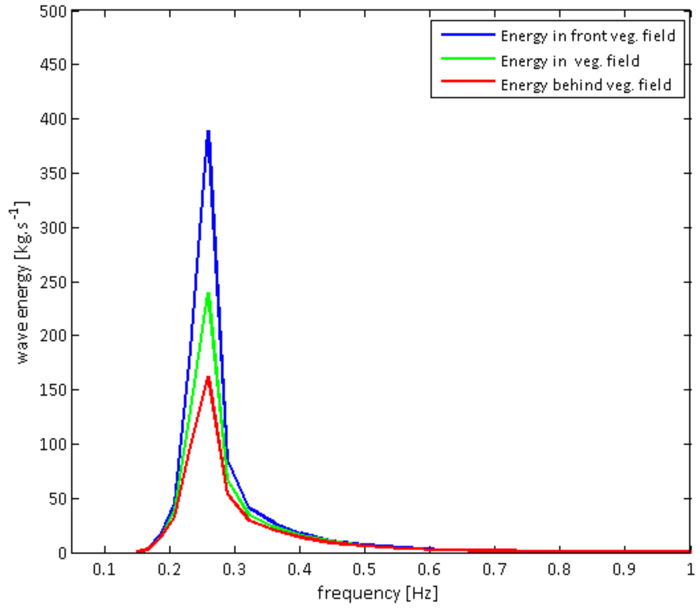


Figure D-3 - Wave spectra for peak period of 4 seconds

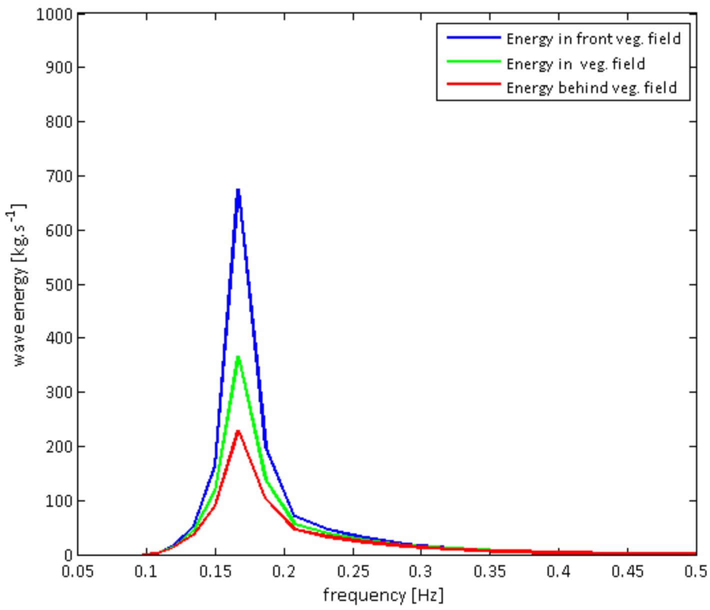


Figure D-4 - Wave spectra for peak period of 6 seconds

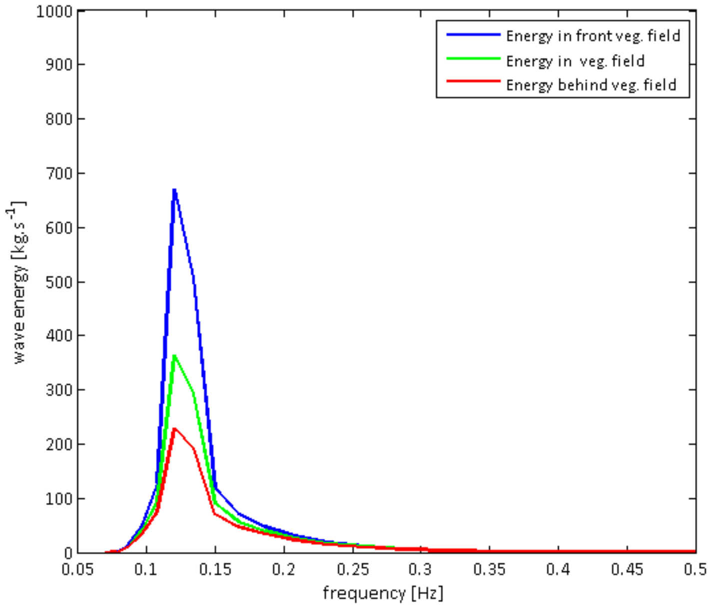


Figure D-5 - Wave spectra for peak period of 8 seconds

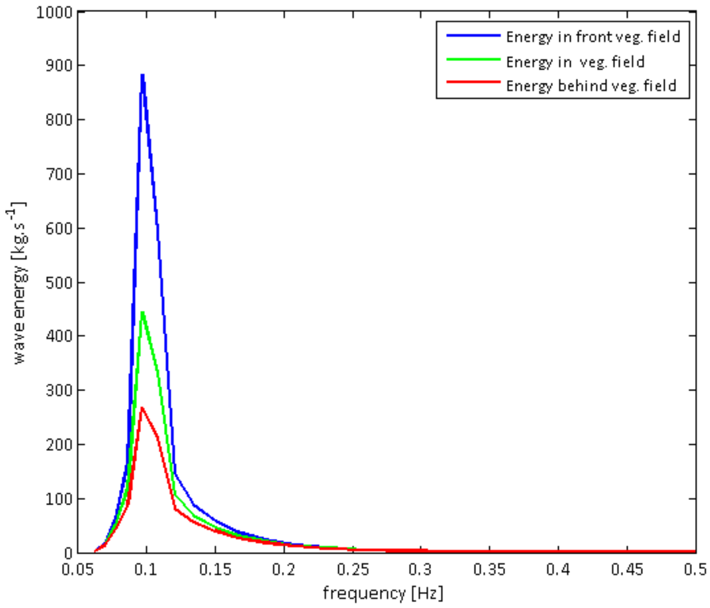


Figure D-6 - Wave spectra for peak period of 10 seconds

Appendix E – Wind Conditions of Schiphol Airport

Wind table taken from Geerse et al.[2003]

Rijkoort-Weibull winterhalfjaartabel 30°-sectoren

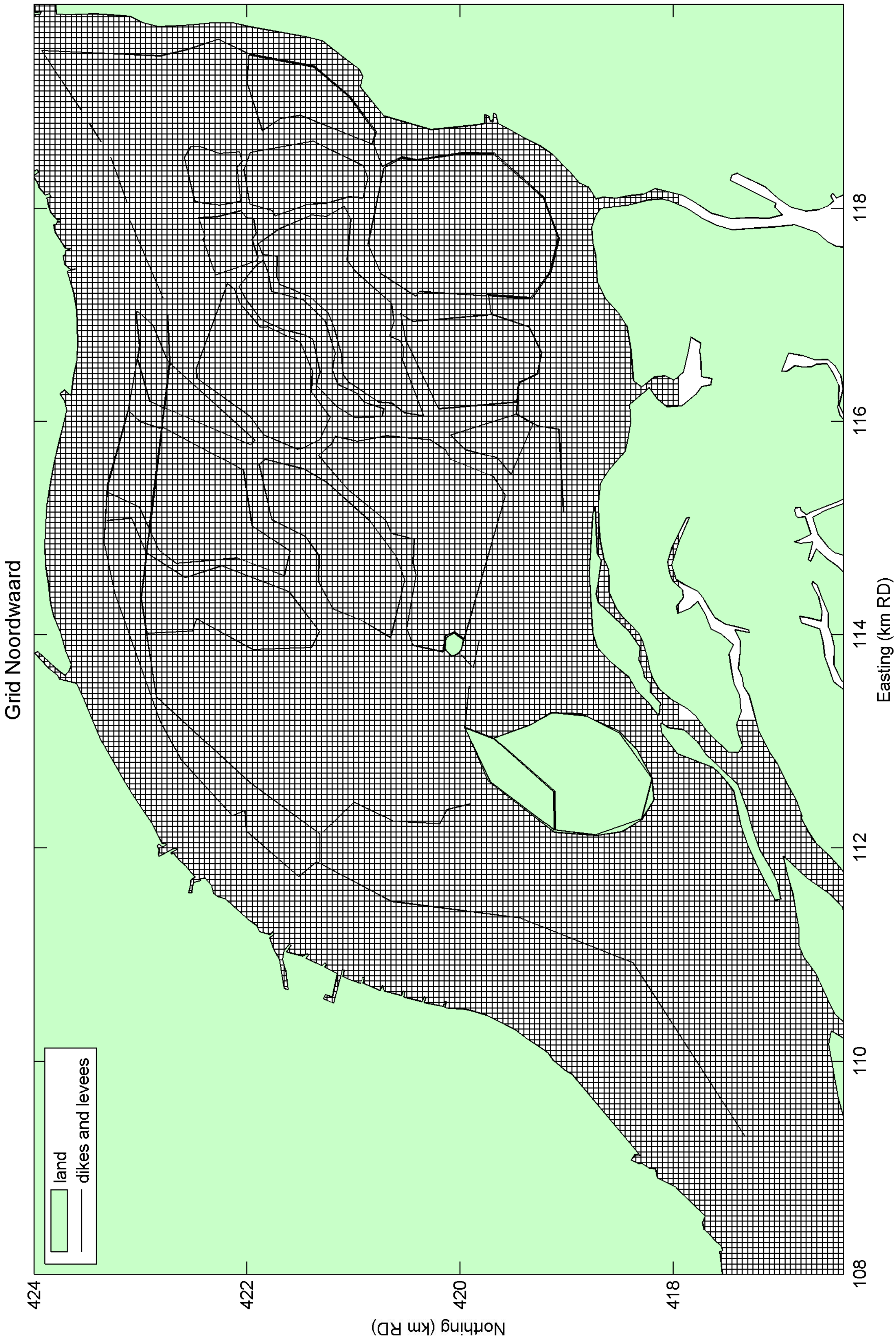
Gecombineerde overschrijdingskansen van de windsnelheid en de windrichting ($J(u,r)$) voor het winterhalfjaar voor 30°-sectoren, u is hier de windsnelheid [m/s] r is hier the herhalingstijd gegeven per snelheid en windrichting; tevens zijn de kansen op de richtingen aangegeven (P(r)).
Overgenomen uit [Twuiver, 1999].

u \ r	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**
P(r)	*0.068138*	*0.081192*	*0.076607*	*0.069471*	*0.079911*	*0.109482*
0	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
1	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
2	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
3	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
4	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
5	9.9998E-01	9.9999E-01	9.9989E-01	9.9985E-01	1.0000E+00	1.0000E+00
6	9.9956E-01	9.9980E-01	9.9869E-01	9.9803E-01	9.9996E-01	1.0000E+00
7	9.9567E-01	9.9797E-01	9.9156E-01	9.8684E-01	9.9914E-01	9.9999E-01
8	9.7631E-01	9.8822E-01	9.6537E-01	9.4630E-01	9.9182E-01	9.9987E-01
9	9.1720E-01	9.5494E-01	8.9977E-01	8.5031E-01	9.5684E-01	9.9859E-01
10	7.9651E-01	8.7635E-01	7.8032E-01	6.9115E-01	8.5835E-01	9.9059E-01
11	6.2092E-01	7.4106E-01	6.1475E-01	4.9639E-01	6.8243E-01	9.5966E-01
12	4.2871E-01	5.6423E-01	4.3364E-01	3.1241E-01	4.6832E-01	8.8079E-01
13	2.6254E-01	3.8255E-01	2.7257E-01	1.7275E-01	2.7748E-01	7.4107E-01
14	1.4404E-01	2.3100E-01	1.5302E-01	8.4571E-02	1.4419E-01	5.5979E-01
15	7.1705E-02	1.2511E-01	7.7176E-02	3.6929E-02	6.6941E-02	3.7815E-01
16	3.2772E-02	6.1345E-02	3.5193E-02	1.4455E-02	2.8172E-02	2.3026E-01
17	1.3880E-02	2.7463E-02	1.4582E-02	5.0811E-03	1.0846E-02	1.2797E-01
18	5.4848E-03	1.1295E-02	5.5079E-03	1.6031E-03	3.8365E-03	6.5682E-02
19	2.0313E-03	4.2848E-03	1.8998E-03	4.5310E-04	1.2489E-03	3.1409E-02
20	7.0677E-04	1.5028E-03	5.9922E-04	1.1447E-04	3.7408E-04	1.4070E-02
21	2.3115E-04	4.8797E-04	1.7308E-04	2.5794E-05	1.0301E-04	5.9209E-03
22	7.0987E-05	1.4680E-04	4.5876E-05	5.1773E-06	2.6045E-05	2.3427E-03
23	2.0426E-05	4.0932E-05	1.1188E-05	9.2505E-07	6.0372E-06	8.7135E-04
24	5.4925E-06	1.0580E-05	2.5178E-06	1.4729E-07	1.2809E-06	3.0442E-04
25	1.3767E-06	2.5354E-06	5.2417E-07	2.1025E-08	2.4830E-07	9.9795E-05
26	3.2101E-07	5.6328E-07	1.0107E-07	2.1939E-09	4.3945E-08	3.0662E-05
27	6.9526E-08	1.1619E-07	1.8246E-08	2.2495E-10	6.9012E-09	8.8203E-06
28	1.3969E-08	2.2257E-08	3.4171E-09	0.0000E+00	1.0541E-09	2.3729E-06
29	2.5870E-09	3.9221E-09	0.0000E+00	0.0000E+00	0.0000E+00	5.9640E-07
30	4.2466E-10	1.4379E-10	0.0000E+00	0.0000E+00	0.0000E+00	1.3985E-07
31	4.2312E-11	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	3.0623E-08
32	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	6.0201E-09
33	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	7.4843E-10
34	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
35	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
36	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
37	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
38	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
39	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
40	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
41	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
42	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

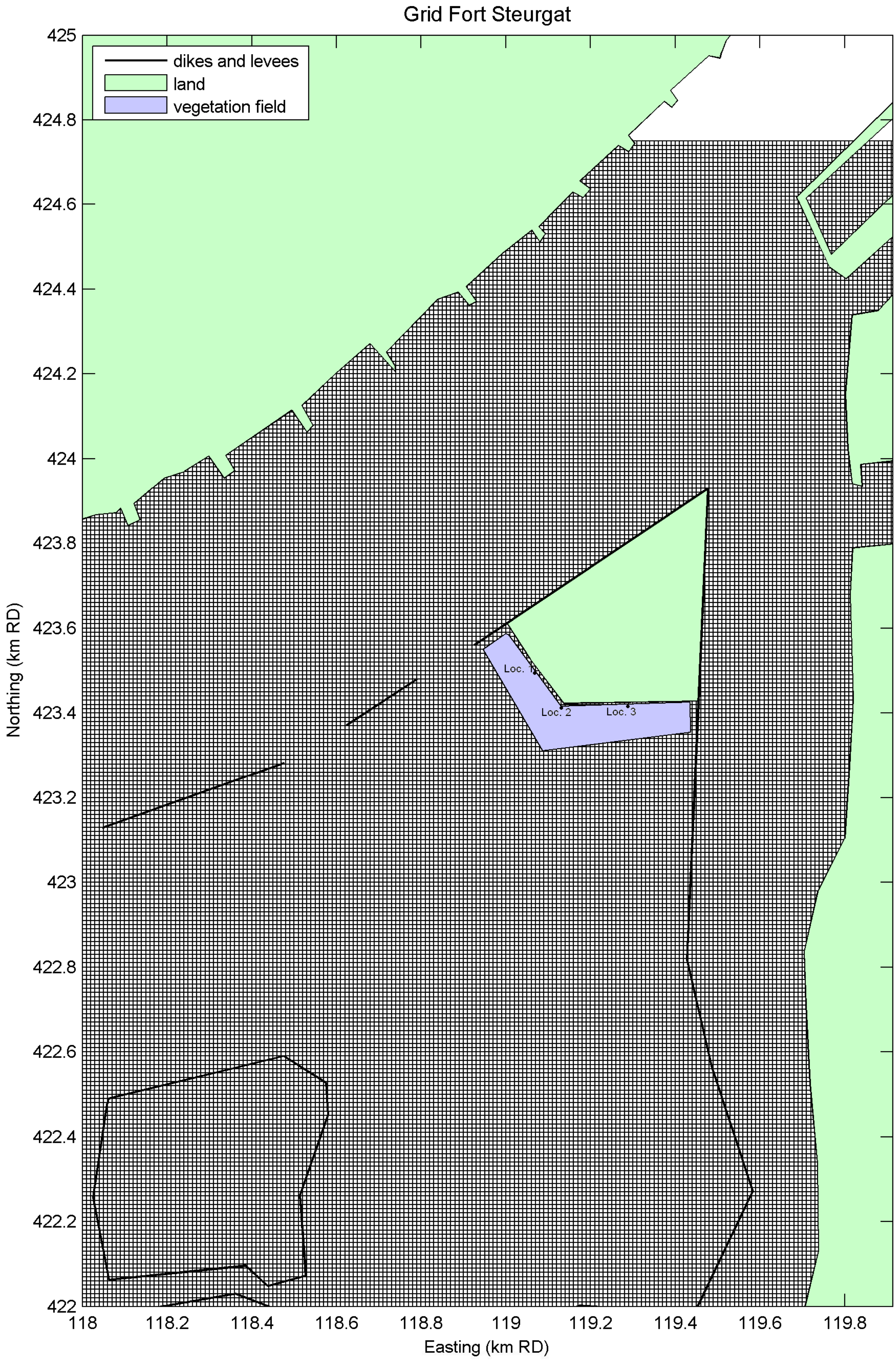
u \ r	**210 °**	**240 °**	**270 °**	**300 °**	**330 °**	**360 °**
P(r)	*0.136398*	*0.135235*	*0.101951*	*0.059326*	*0.036995*	*0.045294*
0	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
1	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
2	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
3	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
4	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
5	1.0000E+00	1.0000E+00	1.0000E+00	9.9999E-01	9.9999E-01	9.9992E-01
6	1.0000E+00	1.0000E+00	1.0000E+00	9.9989E-01	9.9986E-01	9.9898E-01
7	1.0000E+00	1.0000E+00	1.0000E+00	9.9929E-01	9.9890E-01	9.9334E-01
8	1.0000E+00	1.0000E+00	9.9999E-01	9.9698E-01	9.9469E-01	9.7229E-01
9	9.9997E-01	9.9997E-01	9.9989E-01	9.9036E-01	9.8165E-01	9.1779E-01
10	9.9971E-01	9.9975E-01	9.9929E-01	9.7508E-01	9.5097E-01	8.1405E-01
11	9.9791E-01	9.9845E-01	9.9677E-01	9.4553E-01	8.9314E-01	6.6324E-01
12	9.8978E-01	9.9310E-01	9.8880E-01	8.9626E-01	8.0286E-01	4.9042E-01
13	9.6425E-01	9.7694E-01	9.6894E-01	8.2423E-01	6.8335E-01	3.2926E-01
14	9.0585E-01	9.3953E-01	9.2886E-01	7.3066E-01	5.4683E-01	2.0271E-01
15	8.0469E-01	8.7109E-01	8.6176E-01	6.2168E-01	4.1023E-01	1.1608E-01
16	6.6668E-01	7.6917E-01	7.6661E-01	5.0680E-01	2.8883E-01	6.2716E-02
17	5.1265E-01	6.4217E-01	6.5012E-01	3.9611E-01	1.9165E-01	3.2327E-02
18	3.6687E-01	5.0613E-01	5.2463E-01	2.9764E-01	1.2057E-01	1.6010E-02
19	2.4607E-01	3.7766E-01	4.0352E-01	2.1585E-01	7.2446E-02	7.6423E-03
20	1.5599E-01	2.6824E-01	2.9702E-01	1.5174E-01	4.1873E-02	3.5165E-03
21	9.4181E-02	1.8251E-01	2.1032E-01	1.0385E-01	2.3438E-02	1.5575E-03
22	5.4502E-02	1.1968E-01	1.4405E-01	6.9442E-02	1.2775E-02	6.6290E-04
23	3.0373E-02	7.6024E-02	9.5927E-02	4.5488E-02	6.8058E-03	2.7069E-04
24	1.6353E-02	4.6979E-02	6.2388E-02	2.9243E-02	3.5511E-03	1.0595E-04
25	8.5246E-03	2.8328E-02	3.9773E-02	1.8467E-02	1.8155E-03	3.9723E-05
26	4.3083E-03	1.6705E-02	2.4924E-02	1.1462E-02	9.0883E-04	1.4265E-05
27	2.1128E-03	9.6483E-03	1.5385E-02	6.9911E-03	4.4501E-04	4.9057E-06
28	1.0057E-03	5.4638E-03	9.3677E-03	4.1905E-03	2.1289E-04	1.6156E-06
29	4.6483E-04	3.0358E-03	5.6320E-03	2.4680E-03	9.9418E-05	5.0956E-07
30	2.0858E-04	1.6556E-03	3.3452E-03	1.4281E-03	4.5265E-05	1.5384E-07
31	9.0866E-05	8.8649E-04	1.9635E-03	8.1184E-04	2.0110E-05	4.4224E-08
32	3.8419E-05	4.6609E-04	1.1390E-03	4.5346E-04	8.7079E-06	1.2646E-08
33	1.5761E-05	2.4064E-04	6.5294E-04	2.4889E-04	3.6750E-06	1.5358E-09
34	6.2714E-06	1.2199E-04	3.6987E-04	1.3425E-04	1.5114E-06	1.9298E-11
35	2.4191E-06	6.0722E-05	2.0700E-04	7.1187E-05	6.0564E-07	0.0000E+00
36	9.0418E-07	2.9670E-05	1.1443E-04	3.7110E-05	2.3648E-07	0.0000E+00
37	3.2723E-07	1.4229E-05	6.2467E-05	1.9024E-05	8.9744E-08	0.0000E+00
38	1.1498E-07	6.6959E-06	3.3665E-05	9.5910E-06	3.2682E-08	0.0000E+00
39	3.8603E-08	3.0912E-06	1.7907E-05	4.7566E-06	1.1798E-08	0.0000E+00
40	1.2508E-08	1.3996E-06	9.3983E-06	2.3210E-06	0.0000E+00	0.0000E+00
41	4.1906E-09	6.2130E-07	4.8657E-06	1.1142E-06	0.0000E+00	0.0000E+00
42	2.1426E-09	2.7029E-07	2.4844E-06	5.2669E-07	0.0000E+00	0.0000E+00

Appendix F – Model grids

- Figure grid of the Noordwaard
- Figure grid of Fort Steurgat and location vegetation field and output location 1,2 and 3.



Grid Noordwaard and location dikes and levees	Noordwaard	
	F	



Grid Fort Steurgat and location dikes, levees and the vegetation field the numbers represent the output locaitons	Fort Steurgat	
Deltares Delft Hydraulics	F	

Appendix G – Tables and figures of wave conditions Fort Steurgat

Appendix Table G-1 - wave height and wave peak period for 1/ 2000 year return period
Appendix Table G-2 - wave height and wave peak period for 1/ 100 year return period
Appendix Table G-3 - wave height and wave peak period for 1/ 10 year return period
Appendix Table G-4 - wave height and wave peak period for 1/ year return period

Appendix Figures G-1

- Significant wave height and wave peak period for 1/ 2000 year return period at Noordwaard, case: No Bank, no Vegetation
- Significant wave height and wave peak period for 1/ 2000 year return period at Fort Steurgat case: Bank, no Vegetation
- Significant wave height and wave peak period for 1/ 2000 year return period at Fort Steurgat case: Bank and Vegetation

Appendix Figures G-2

- Significant wave height and wave peak period for 1/ 100 year return period at Fort Steurgat

Appendix Figures G-3

- Significant wave height and wave peak period for 1/10 year return period at Fort Steurgat

Appendix Figures G-4

- Significant wave height and wave peak period for 1/ year return period at Fort Steurgat

Appendix Table G-1

1/2000 year Wind direction	Wind speed [m/s]:	Location:	Initial case		Bank		Bank and vegetation		Eff. Bank	Eff. vegetation	Eff bank and vegetation
South (180°)	24.8	1	0.86	3.2	0.78	3.2	0.25	1.3	9.3	67.9	70.9
		2	0.84	3.2	0.78	3.2	0.22	1.0	7.1	71.8	73.8
		3	0.80	2.8	0.75	3.2	0.20	1.1	6.3	73.3	75.0
South-Southwest (202.5°)	29.0	1	1.02	3.5	0.83	3.5	0.26	1.3	18.6	68.7	74.5
		2	1.01	3.5	0.83	3.5	0.23	1.0	17.8	72.3	77.2
		3	0.98	3.5	0.82	3.5	0.24	1.3	16.3	70.7	75.5
Southwest (225°)	32.0	1	1.07	3.5	0.85	3.5	0.26	1.1	20.6	69.4	75.7
		2	1.07	3.5	0.85	3.9	0.25	1.0	20.6	70.6	76.6
		3	1.04	3.5	0.85	3.9	0.29	1.5	18.3	65.9	72.1
West-Southwest (247.5°)	33.9	1	1.05	3.5	0.84	3.5	0.26	1.1	20.0	69.0	75.2
		2	1.09	3.5	0.86	3.9	0.26	1.1	21.1	69.8	76.1
		3	1.04	3.5	0.86	3.9	0.33	1.7	17.3	61.6	68.3
West (270°)	35.2	1	0.97	3.5	0.82	3.5	0.27	1.3	15.5	67.1	72.2
		2	1.06	3.5	0.86	3.9	0.28	1.4	18.9	67.4	73.6
		3	1.00	3.5	0.84	3.9	0.35	1.7	16.0	58.3	65.0
West-Northwest 292.5°)	33.9	1	0.80	3.2	0.76	3.2	0.28	1.3	5.0	63.2	65.0
		2	0.94	3.2	0.83	3.5	0.30	1.7	11.7	63.9	68.1
		3	0.87	3.5	0.79	3.5	0.33	1.7	9.2	58.2	62.1

Appendix Table G-2

1/100 year Wind direction	Wind speed [m/s]:	Location:	Initial case		Bank		Bank and vegetation		Eff. Bank	Eff. vegetation	Eff bank and vegetation
South (180°)	21.5	1	0.68	2.9	0.58	2.9	0.21	1.3	14.7	63.8	69.1
		2	0.66	2.9	0.59	2.9	0.18	0.9	10.6	69.5	72.7
		3	0.63	2.9	0.57	2.9	0.17	1.0	9.5	70.2	73.0
South-Southwest (202.5°)	24.9	1	0.81	3.2	0.62	3.2	0.21	1.1	23.5	66.1	74.1
		2	0.80	3.2	0.62	3.2	0.20	1.0	22.5	67.7	75.0
		3	0.78	3.2	0.61	3.2	0.20	1.1	21.8	67.2	74.4
Southwest (225 °)	27.2	1	0.84	3.2	0.63	3.2	0.21	1.0	25.0	66.7	75.0
		2	0.85	3.2	0.63	3.5	0.21	1.0	25.9	66.7	75.3
		3	0.84	3.2	0.62	3.2	0.23	1.4	26.2	62.9	72.6
West-Southwest (247.5 °)	28.5	1	0.82	3.2	0.62	3.2	0.22	1.0	24.4	64.5	73.2
		2	0.86	3.2	0.64	3.5	0.22	1.0	25.6	65.6	74.4
		3	0.83	3.2	0.63	3.5	0.26	1.5	24.1	58.7	68.7
West (270 °)	29.3	1	0.75	2.9	0.61	3.2	0.23	1.1	18.7	62.3	69.3
		2	0.83	3.2	0.64	3.2	0.23	1.3	22.9	64.1	72.3
		3	0.79	3.2	0.60	3.2	0.28	1.5	24.1	53.3	64.6
West-Northwest 292.5°)	28.1	1	0.60	2.9	0.56	2.9	0.23	1.3	6.7	58.9	61.7
		2	0.71	2.9	0.61	3.2	0.25	1.4	14.1	59.0	64.8
		3	0.66	2.9	0.57	3.2	0.26	1.5	13.6	54.4	60.6

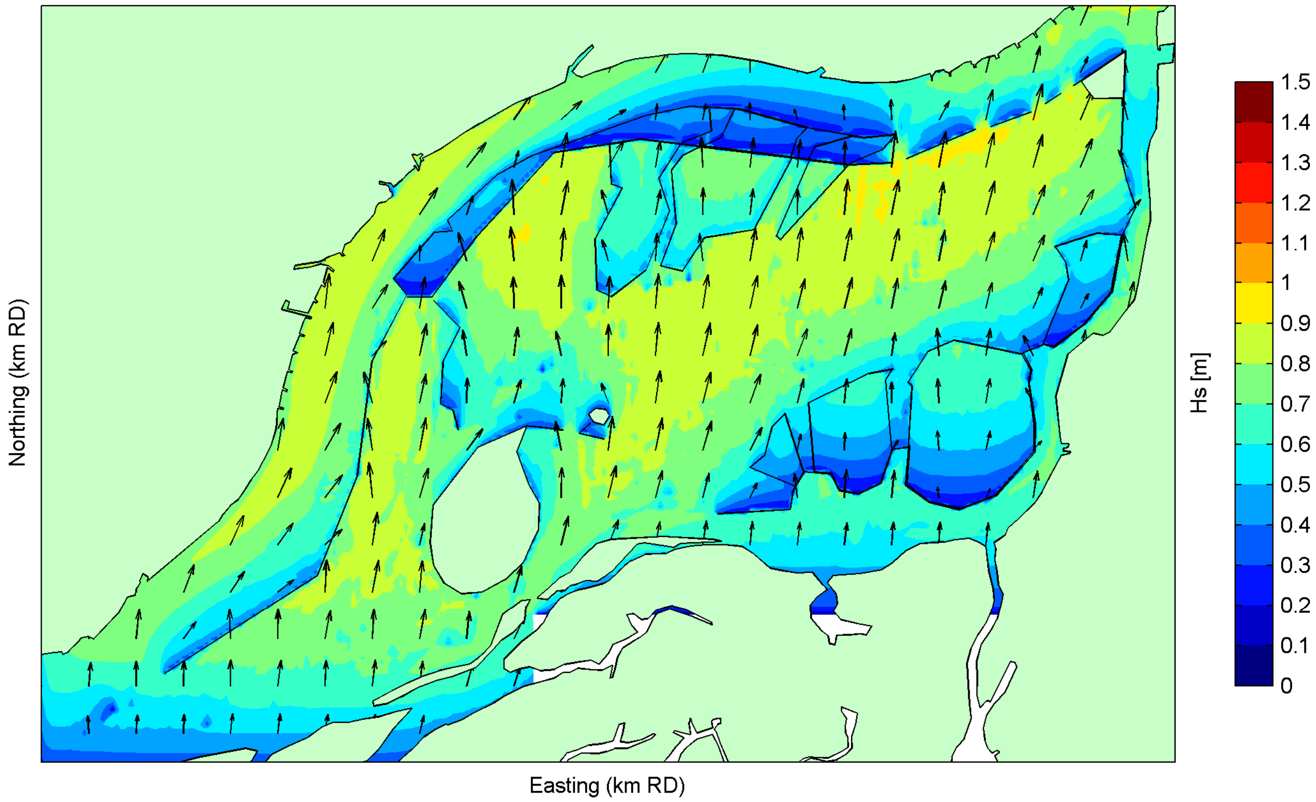
Appendix Table G-3

1/10 year Wind direction	Wind speed [m/s]:	Location:	Initial case		Bank		Bank and vegetation		Eff. Bank	Eff. vegetation	Eff bank and vegetation
South (180^{o})	18.4	1	0.52	2.3	0.39	2.3	0.17	1.1	25.0	56.4	67.3
		2	0.50	2.3	0.40	2.3	0.15	0.9	20.0	62.5	70.0
		3	0.48	2.3	0.38	2.3	0.14	0.9	20.8	63.2	70.8
South-Southwest (202.5^{o})	21.1	1	0.61	2.6	0.41	2.9	0.17	1.0	32.8	58.5	72.1
		2	0.60	2.6	0.41	2.9	0.16	0.9	31.7	61.0	73.3
		3	0.59	2.6	0.39	2.9	0.16	1.0	33.9	59.0	72.9
Southwest (225^{o})	22.8	1	0.64	2.6	0.41	2.9	0.17	1.0	35.9	58.5	73.4
		2	0.64	2.6	0.42	2.9	0.16	0.9	34.4	61.9	75.0
		3	0.63	2.6	0.39	2.6	0.18	1.3	38.1	53.8	71.4
West-Southwest (247.5^{o})	23.7	1	0.62	2.6	0.41	2.6	0.17	1.0	33.9	58.5	72.6
		2	0.64	2.6	0.42	2.9	0.17	1.0	34.4	59.5	73.4
		3	0.63	2.6	0.39	2.6	0.20	1.4	38.1	48.7	68.3
West (270^{o})	24.1	1	0.59	2.6	0.41	2.6	0.18	1.0	30.5	56.1	69.5
		2	0.61	2.6	0.42	2.9	0.18	1.1	31.1	57.1	70.5
		3	0.59	2.6	0.38	2.6	0.21	1.4	35.6	44.7	64.4
West-Northwest 292.5^{o})	22.6	1	0.44	2.3	0.38	2.3	0.18	1.1	13.6	52.6	59.1
		2	0.51	2.3	0.41	2.6	0.19	1.3	19.6	53.7	62.7
		3	0.48	2.3	0.36	2.6	0.19	1.4	25.0	47.2	60.4

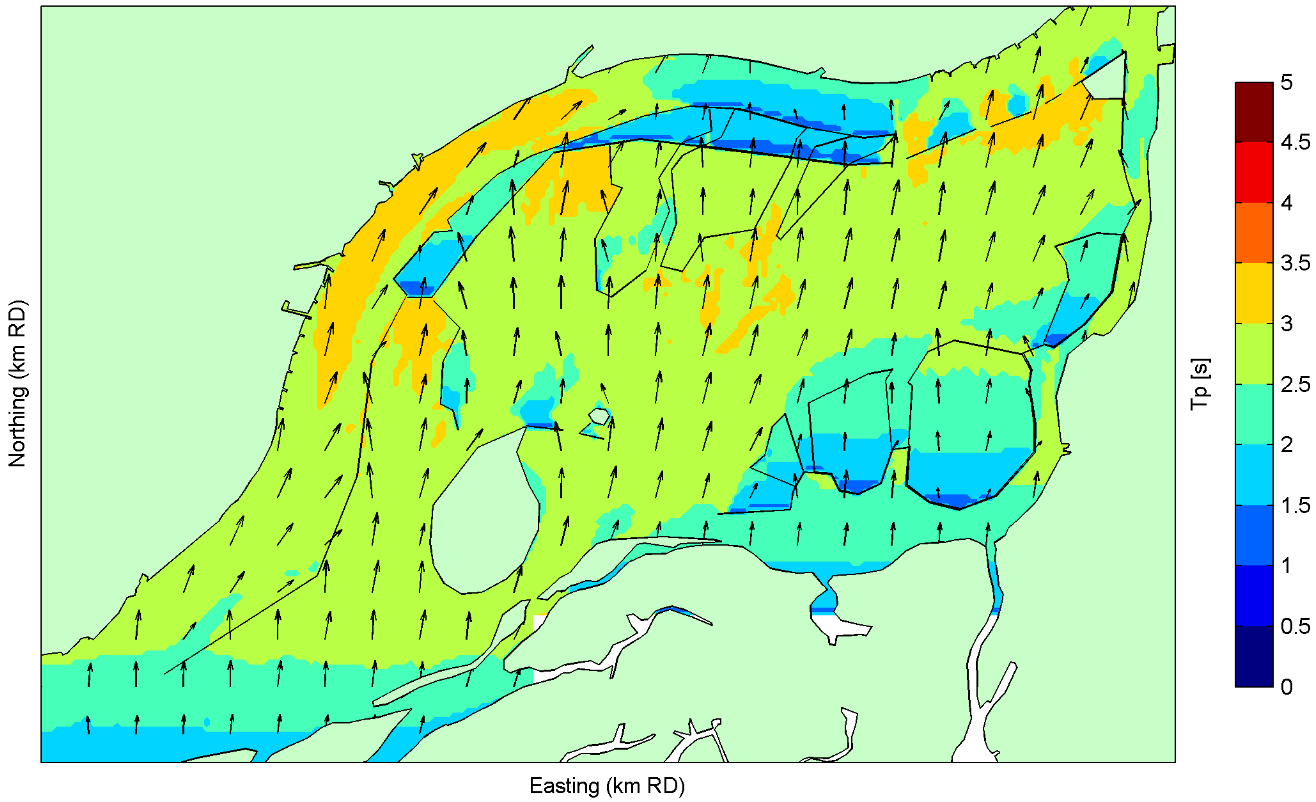
Appendix Table G-4

1/year Wind direction	Wind speed [m/s]:	Location:	Initial case		Bank		Bank and vegetation		Eff. Bank	Eff. vegetation	Eff bank and vegetation
South (180°)	6.3	1	0.17	1.5	0.15	1.5	0.08	1.5	11.8	46.7	52.9
		2	0.16	1.5	0.16	1.5	0.07	1.4	0.0	56.3	56.3
		3	0.16	1.5	0.14	1.4	0.07	1.4	12.5	50.0	56.3
South-Southwest (202.5°)	7.9	1	0.23	1.7	0.19	1.7	0.09	1.7	17.4	52.6	60.9
		2	0.23	1.7	0.20	1.7	0.09	1.7	13.0	55.0	60.9
		3	0.23	1.7	0.18	1.7	0.08	0.8	21.7	55.6	65.2
Southwest (225 °)	8.4	1	0.25	1.9	0.210 22	1.9	0.09	1.8	16.0	57.1	64.0
		2	0.26	1.9	0.22	1.9	0.09	1.5	15.4	59.1	65.4
		3	0.26	1.9	0.19	1.9	0.09	0.9	26.9	52.6	65.4
West-Southwest (247.5 °)	8.1	1	0.23	1.7	0.20	1.9	0.09	1.7	13.0	55.0	60.9
		2	0.24	1.9	0.21	1.9	0.09	1.9	12.5	57.1	62.5
		3	0.24	1.7	0.18	1.7	0.08	0.9	25.0	55.6	66.7
West (270 °)	7.4	1	0.18	1.7	0.17	1.7	0.08	1.7	5.6	52.9	55.6
		2	0.20	1.7	0.18	1.7	0.08	0.8	10.0	55.6	60.0
		3	0.19	1.7	0.16	1.7	0.08	0.8	15.8	50.0	57.9
West-Northwest 292.5°)	5.8	1	0.11	1.4	0.10	1.4	0.06	1.4	9.1	40.0	45.5
		2	0.12	1.4	0.11	1.4	0.06	0.8	8.3	45.5	50.0
		3	0.12	1.4	0.10	1.4	0.06	0.8	16.7	40.0	50.0

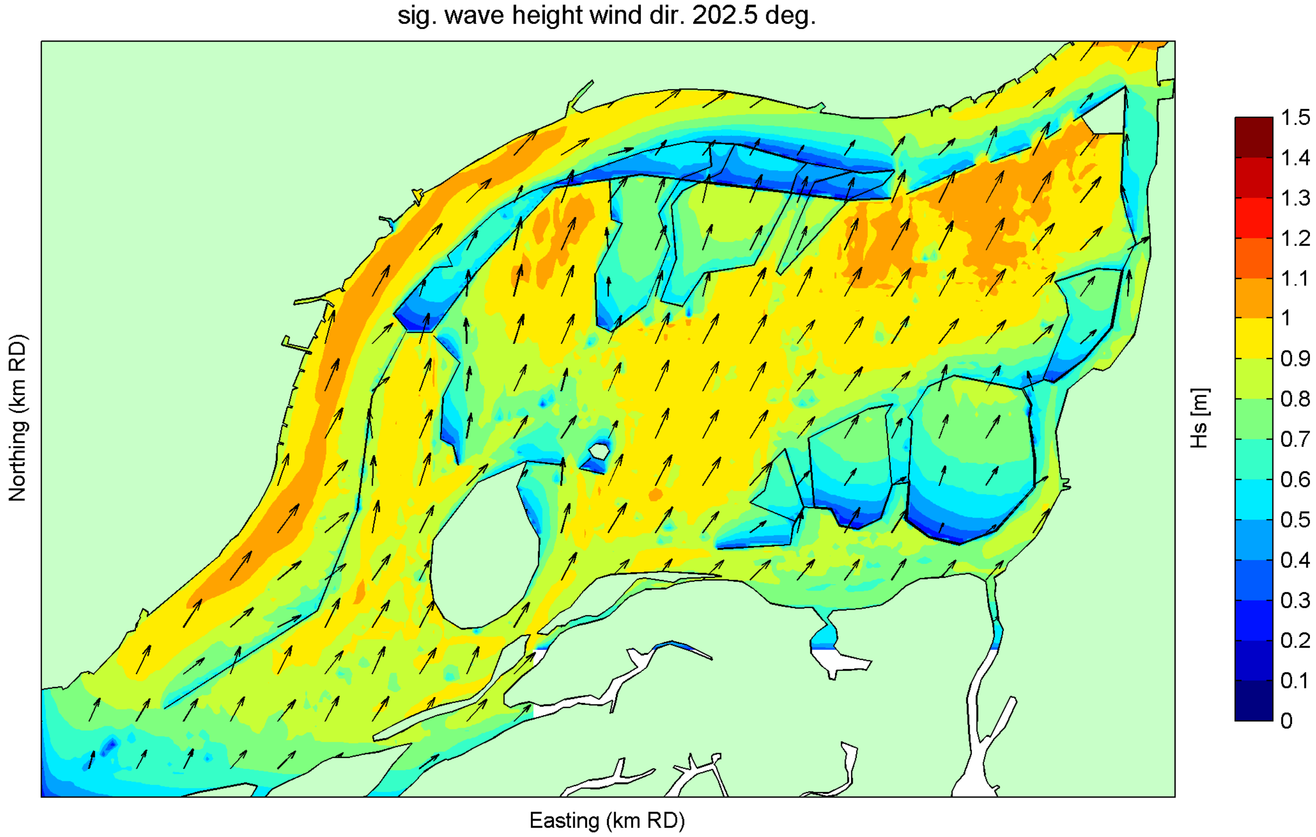
sig. wave height wind dir. 180 deg.

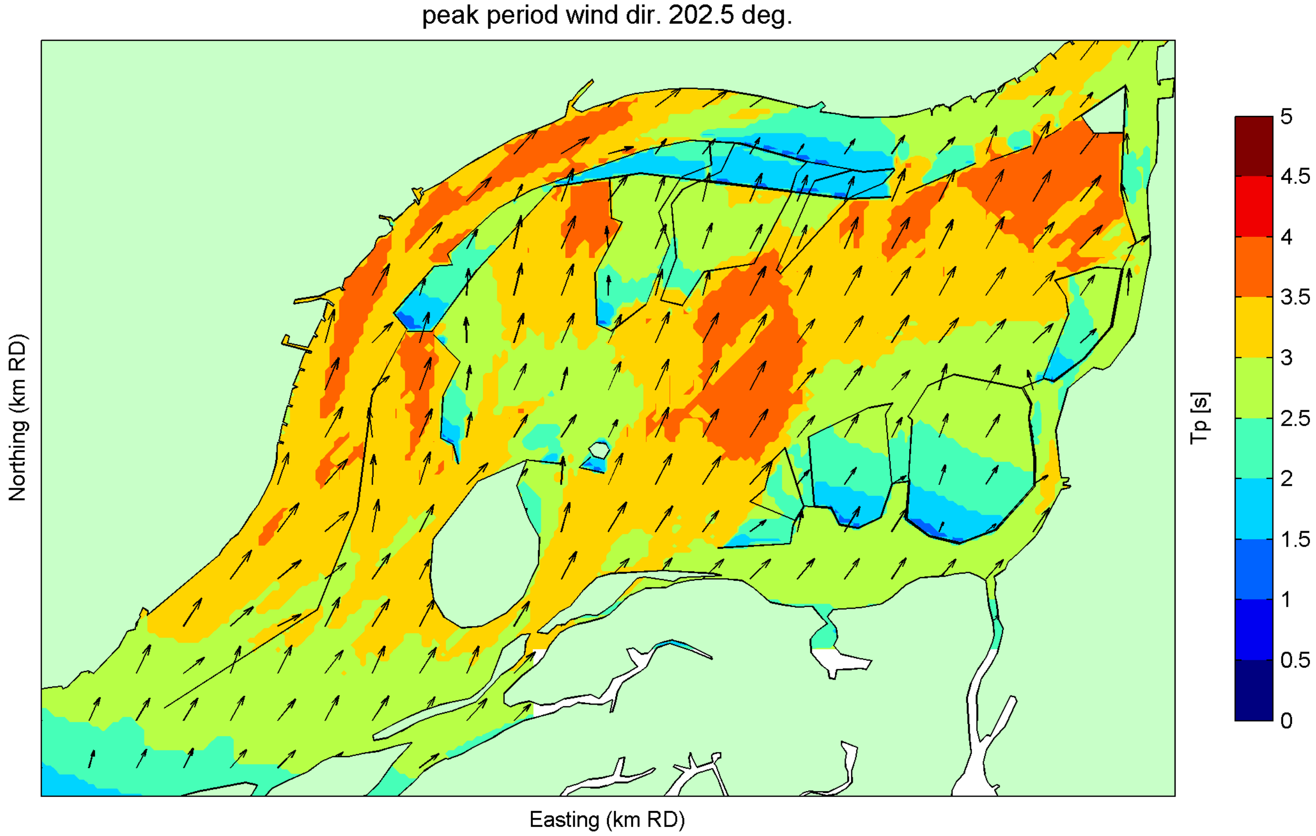


peak period wind dir. 180 deg.



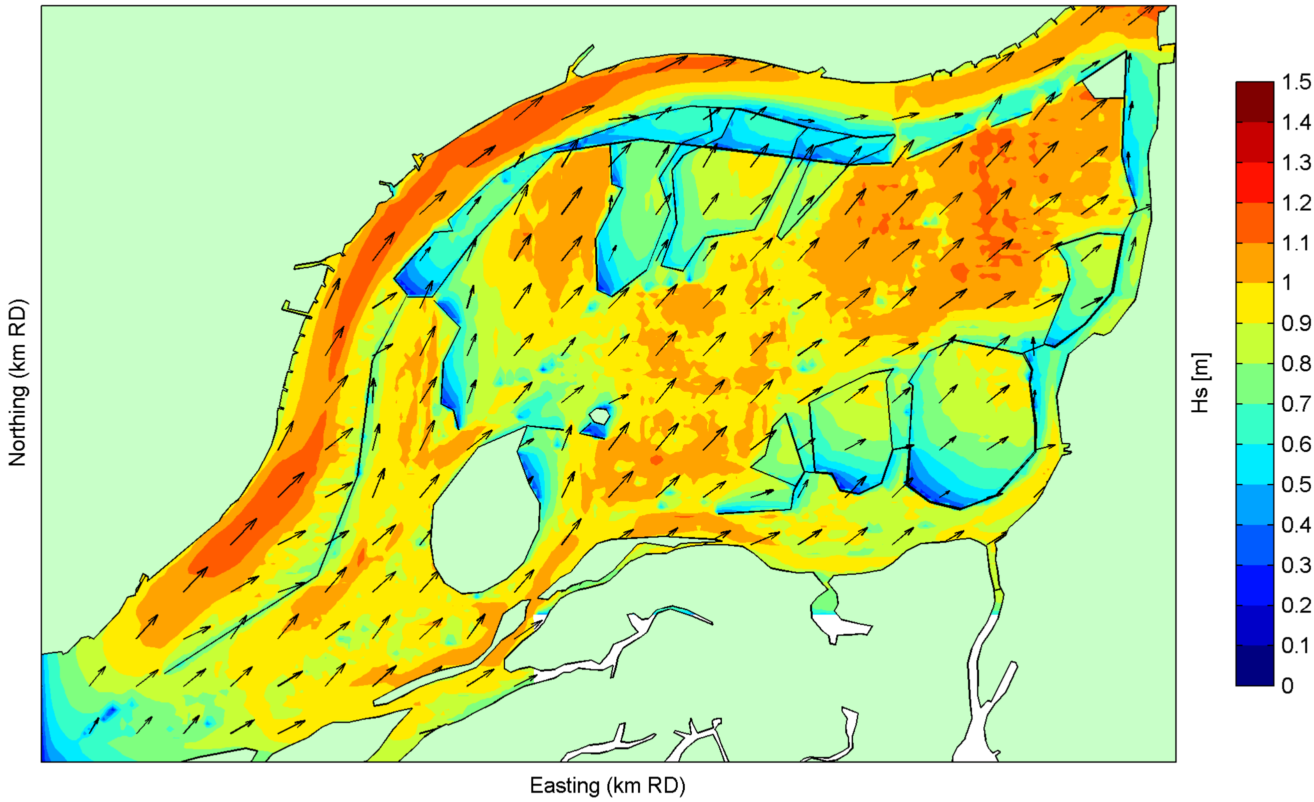
case No Bank, No Vegetation Hs and Tp in Noordwaard 1/2000 year event; 3.5 m.+NAP	Noordwaard	
	SWAN-VEG	
Deltares Delft Hydraulics	G-1	



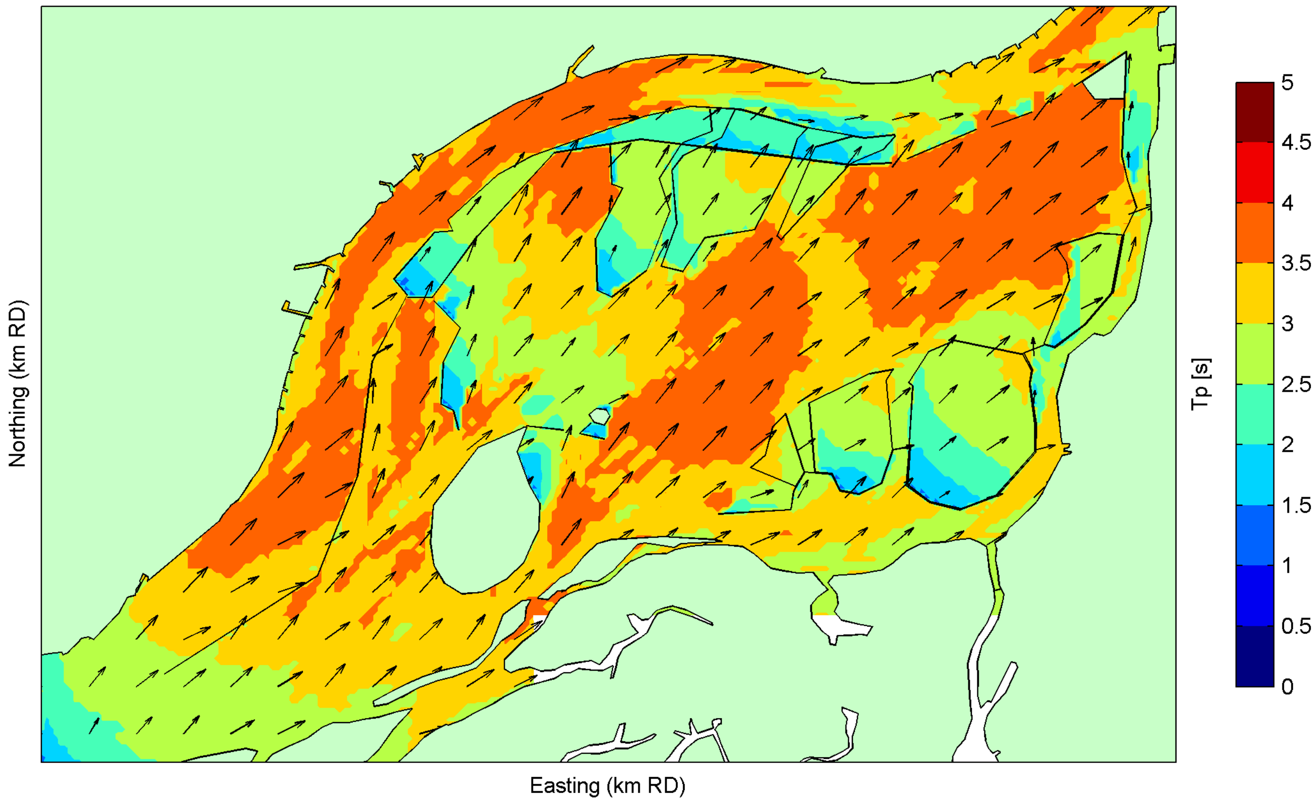


case No Bank, No Vegetation Hs and Tp in Noordwaard 1/2000 year event; 3.5 m.+NAP	Noordwaard SWAN-VEG
Deltares Delft Hydraulics	G-1

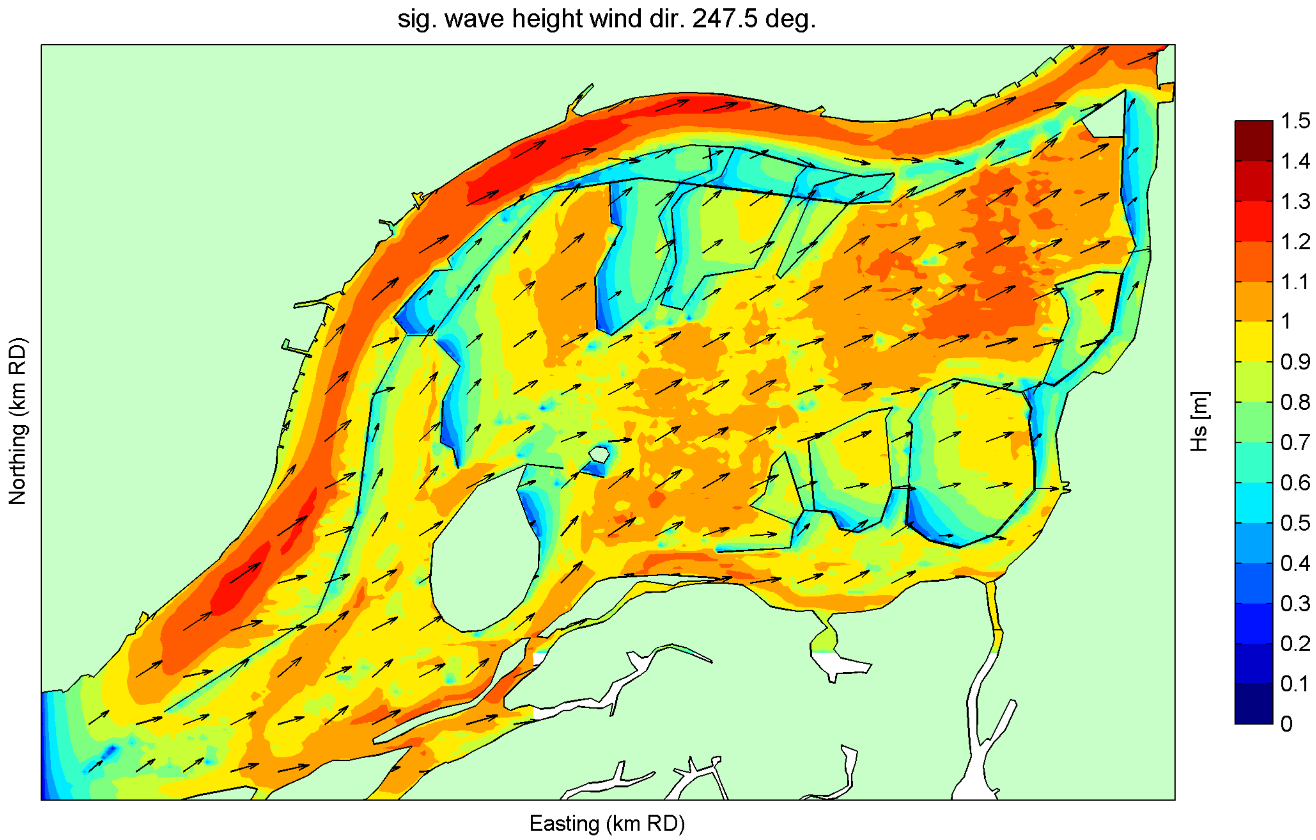
sig. wave height wind dir. 225 deg.

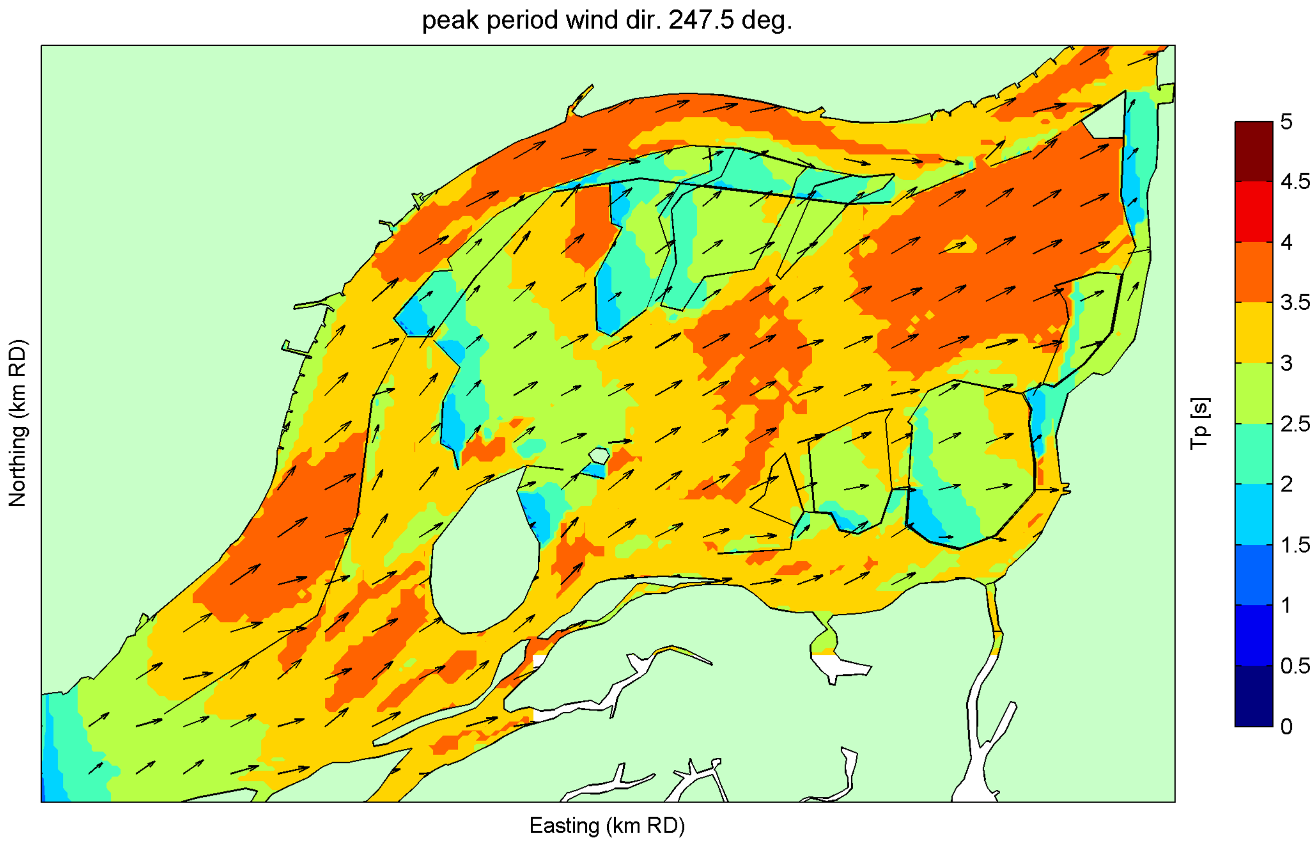


peak period wind dir. 225 deg.



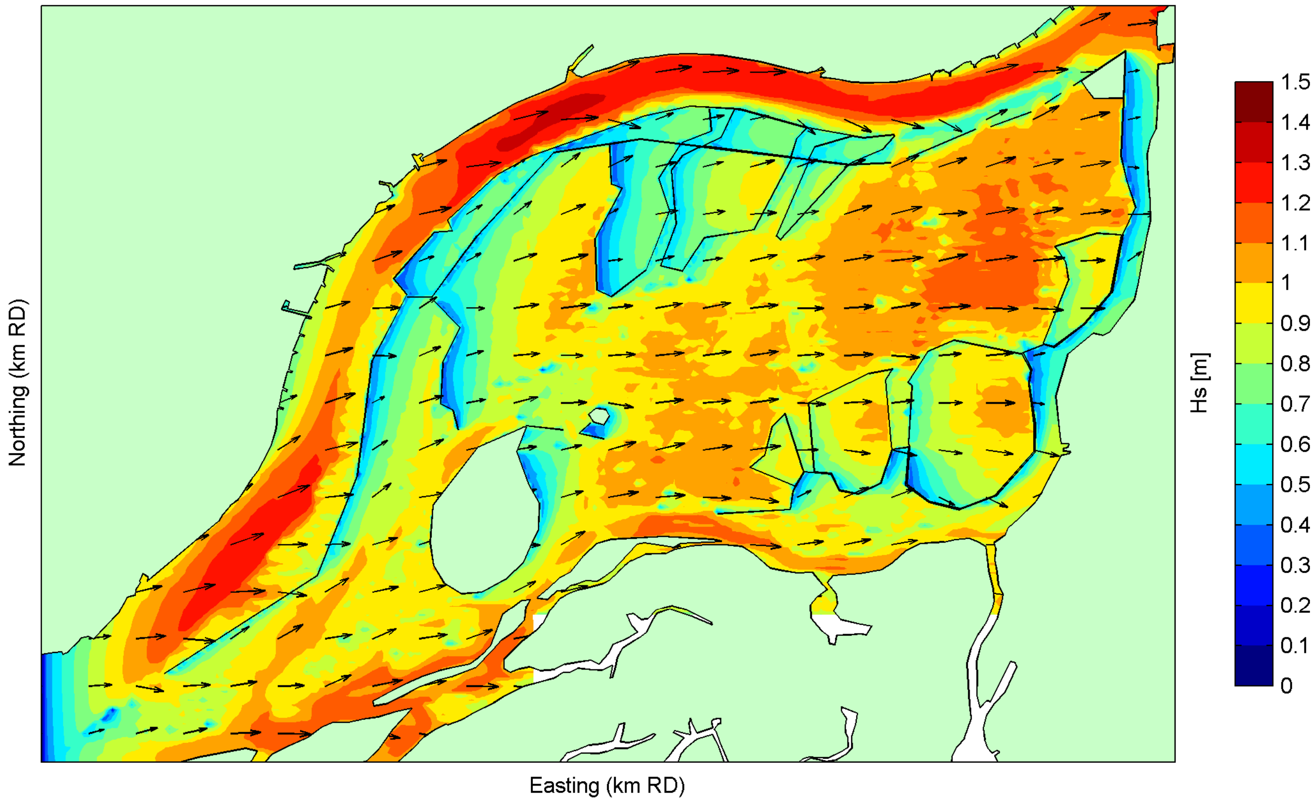
case No Bank, No Vegetation Hs and Tp in Noordwaard 1/2000 year event; 3.5 m.+NAP	Noordwaard
	SWAN-VEG
Deltares Delft Hydraulics	G-1



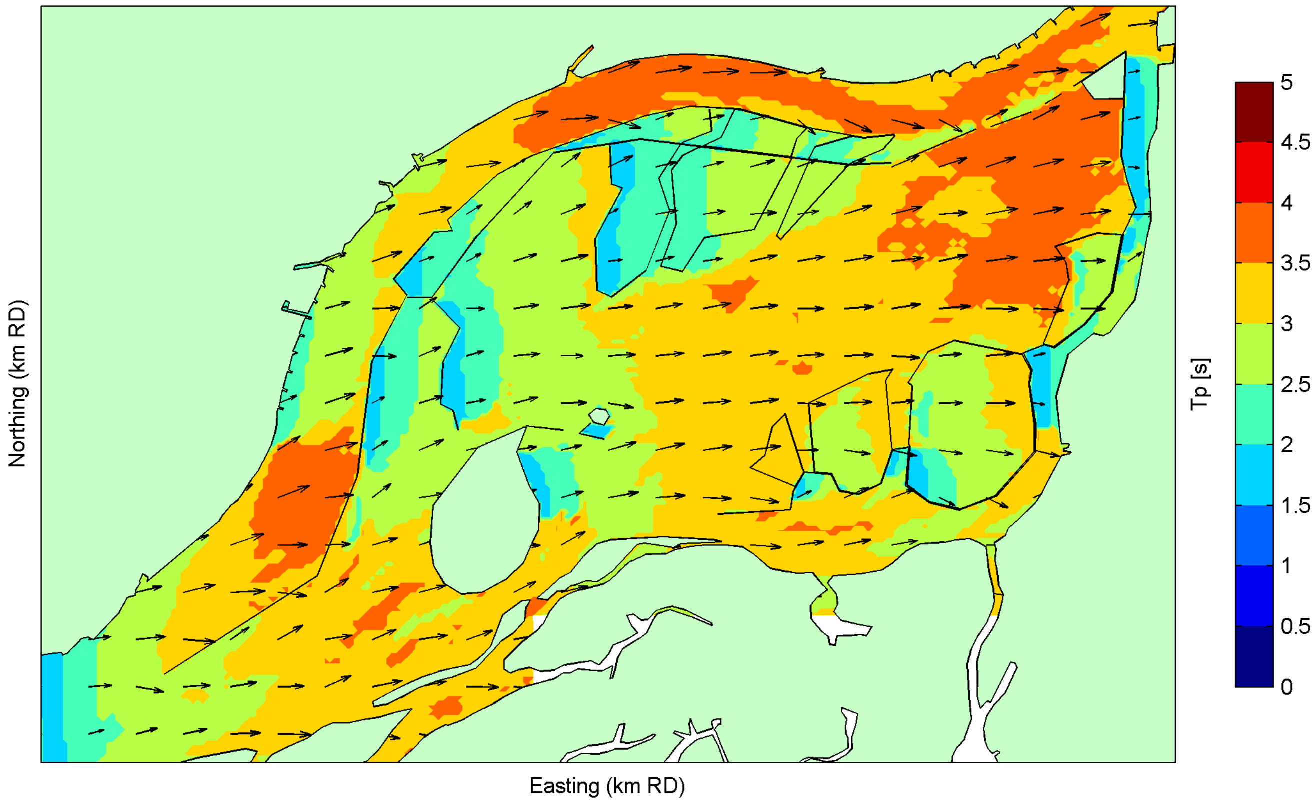


case No Bank, No Vegetation Hs and Tp in Noordwaard 1/2000 year event; 3.5 m.+NAP	Noordwaard	
	SWAN-VEG	
Deltares Delft Hydraulics	G-1	

sig. wave height wind dir. 270 deg.

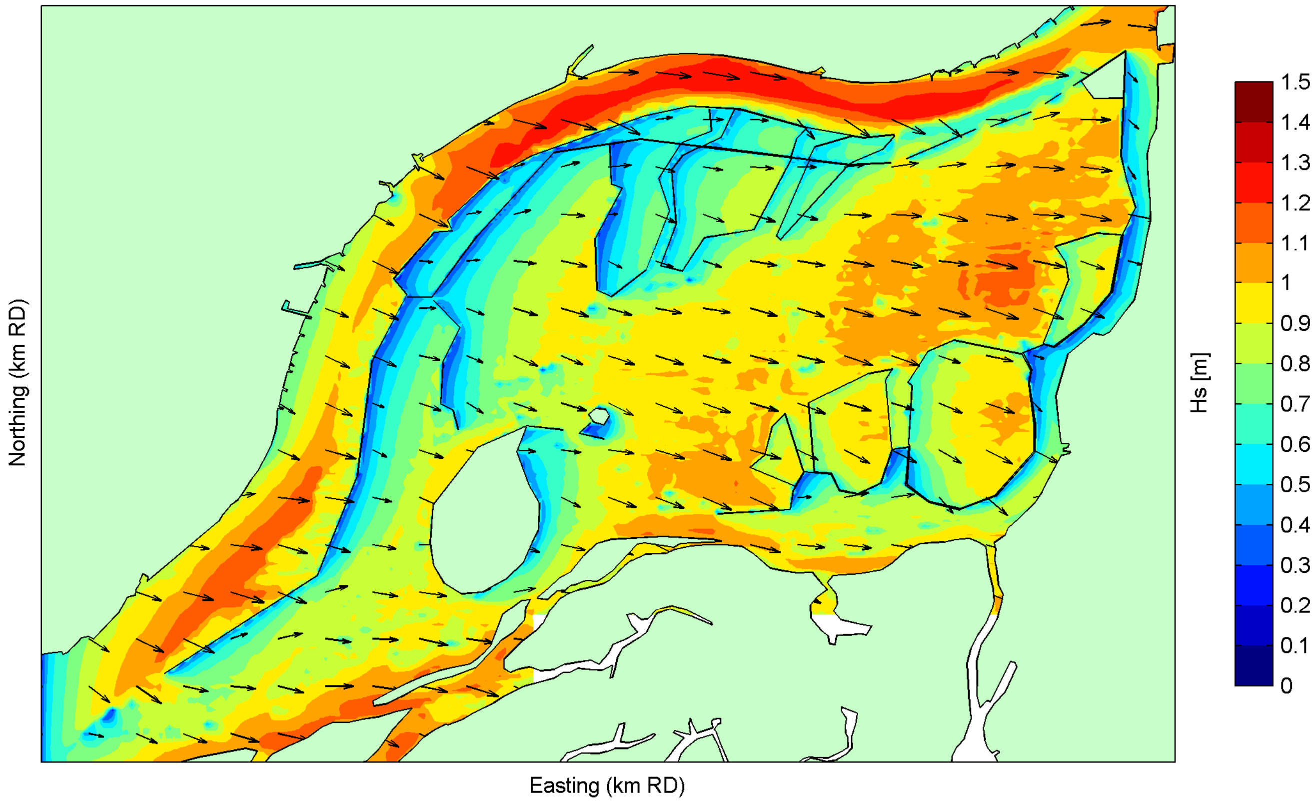


peak period wind dir. 270 deg.

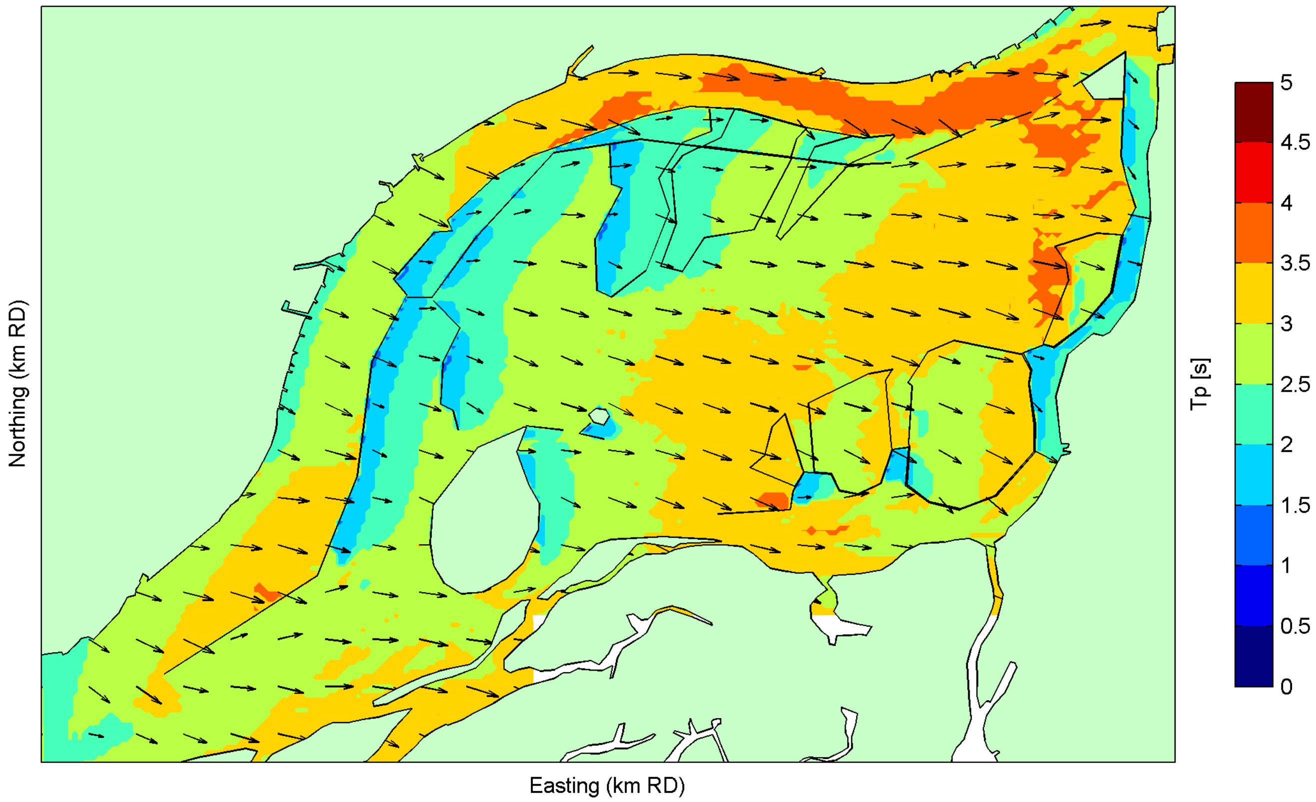


case No Bank, No Vegetation Hs and Tp in Noordwaard 1/2000 year event; 3.5 m.+NAP	Noordwaard	
	SWAN-VEG	
Deltares Delft Hydraulics	G-1	

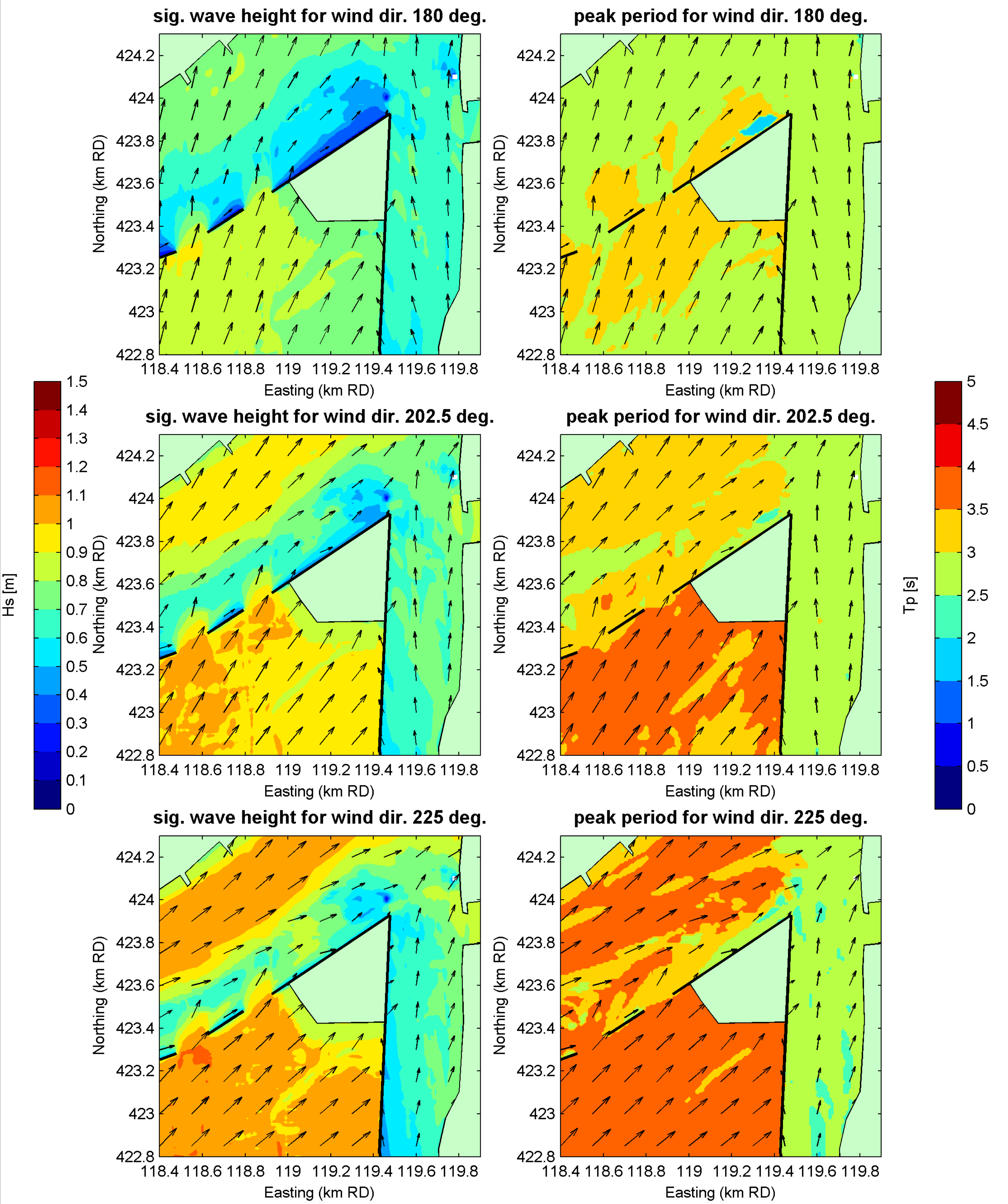
sig. wave height wind dir. 292.5 deg.



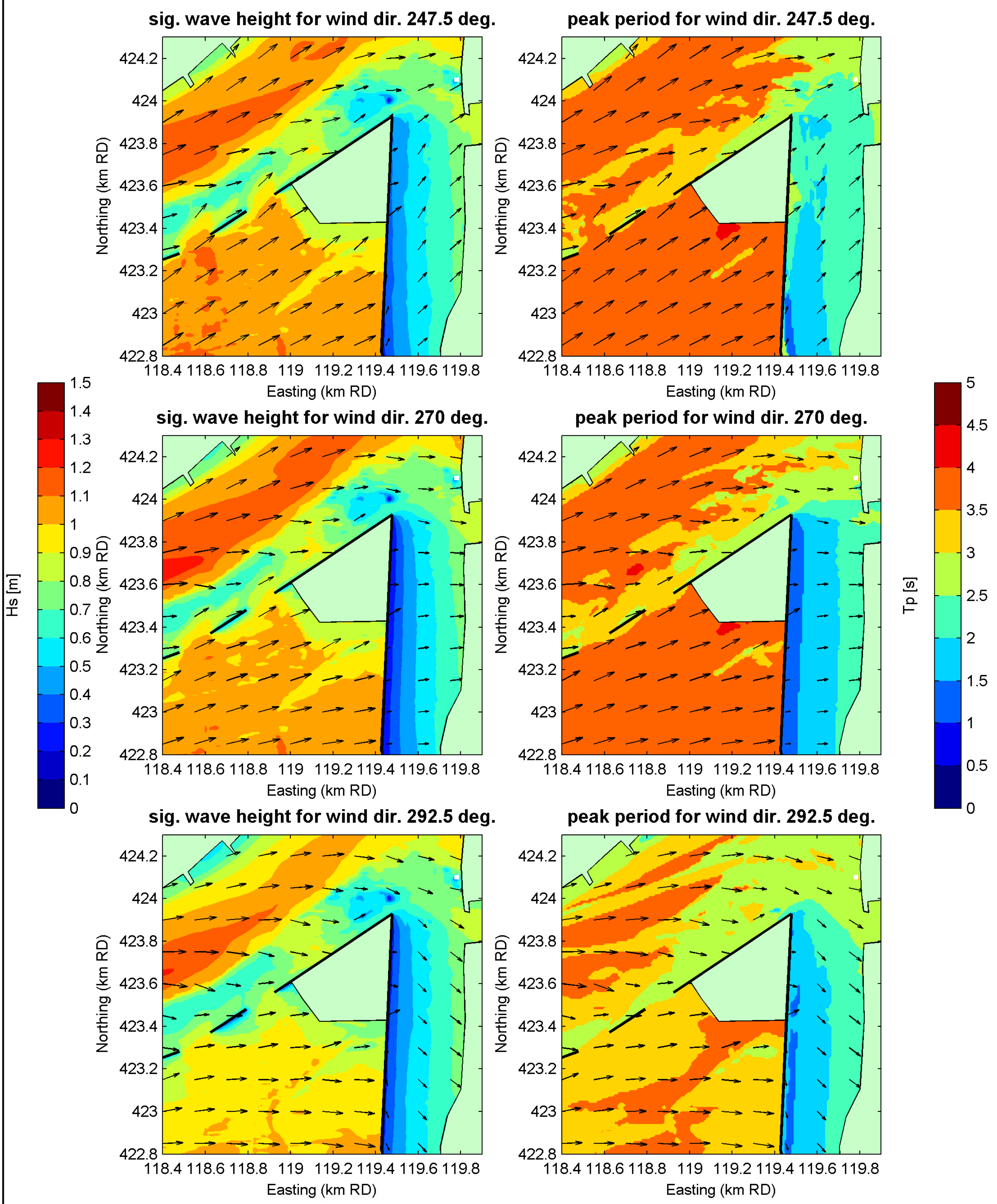
peak period wind dir. 292.5 deg.



case No Bank, No Vegetation Hs and Tp in Noordwaard 1/2000 year event; 3.5 m.+NAP	Noordwaard	
	SWAN-VEG	
Deltares Delft Hydraulics	G-1	



case Bank, No Vegetation Hs and Tp at Fort Steurgat 1/2000 year event; water level 3.5+NAP	Fort Steurgat	
	SWAN-VEG	
Deltares Delft Hydraulics	G-1	



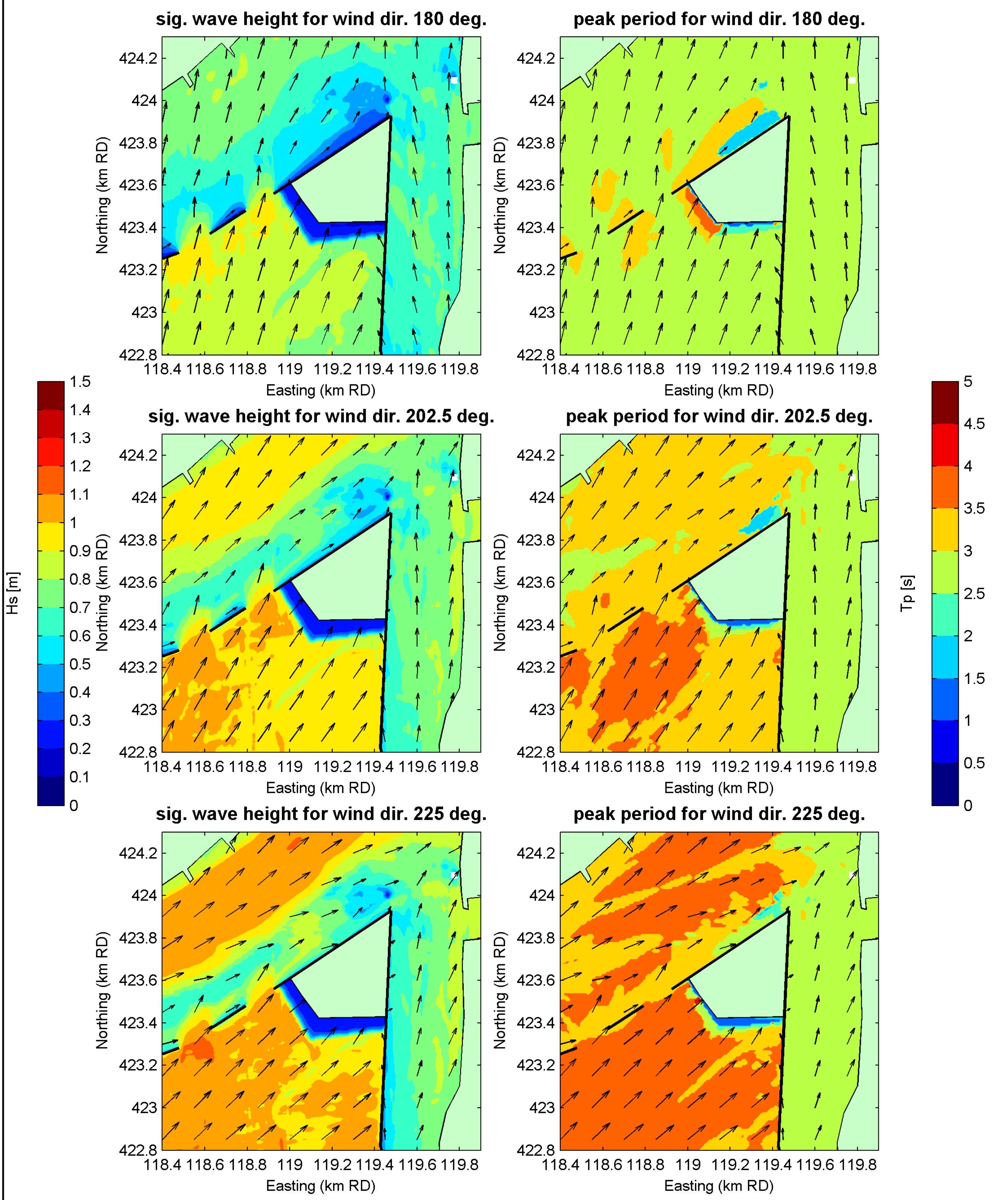
case Bank, No Vegetation
Hs and Tp at Fort Steurgat
1/2000 year event; water level 3.5+NAP

Fort Steurgat

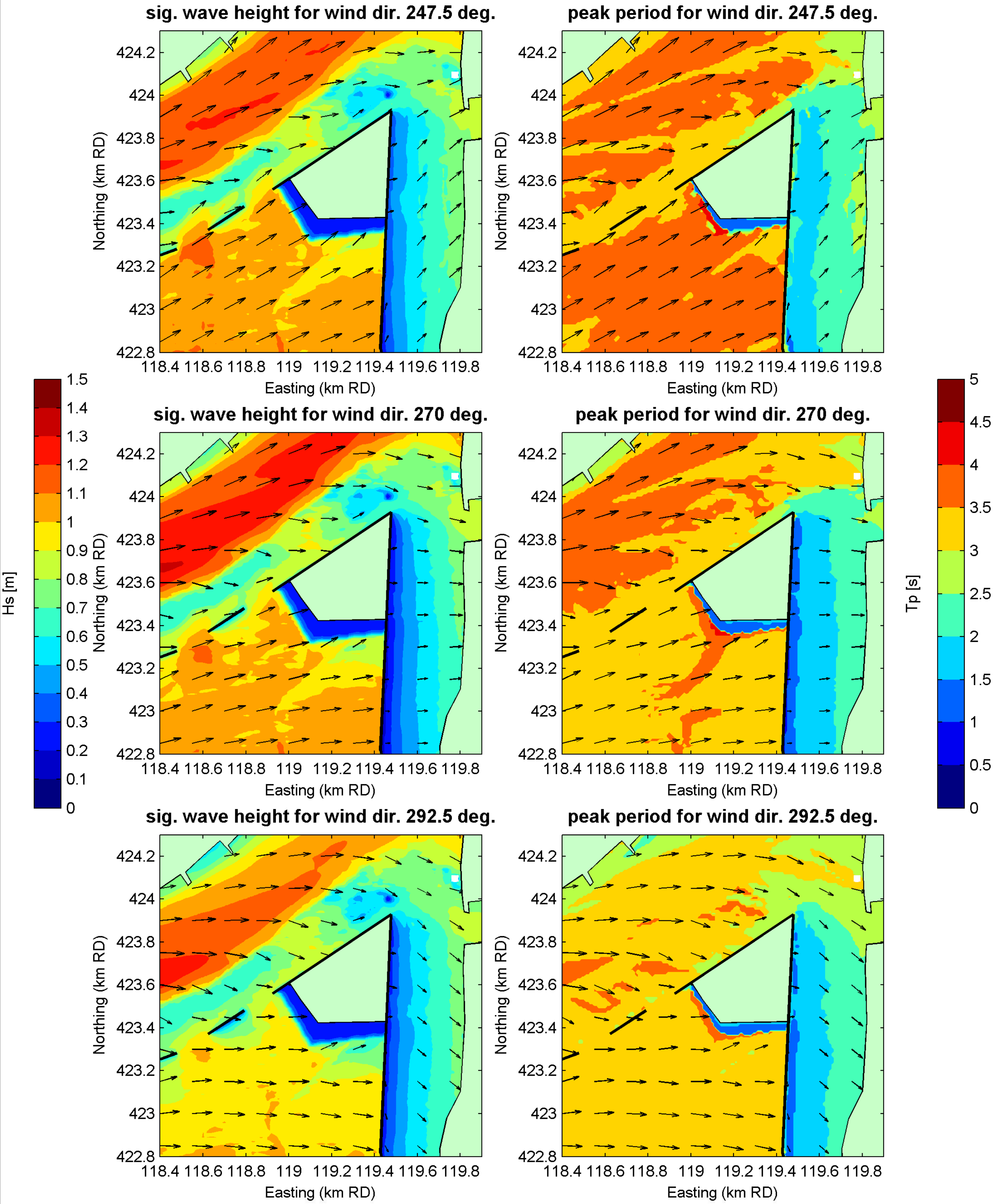
SWAN-VEG

Deltares
Delft Hydraulics

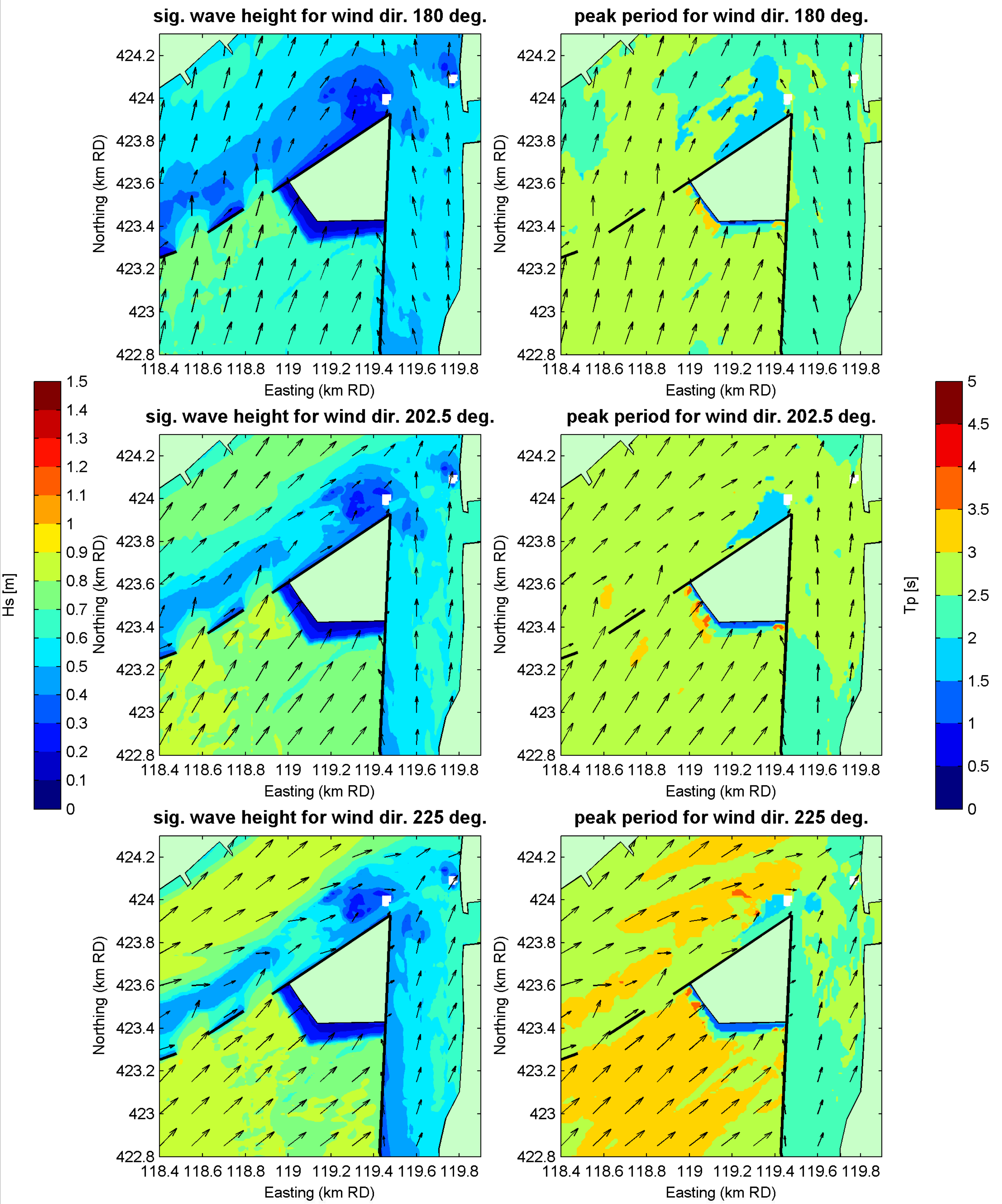
G-1



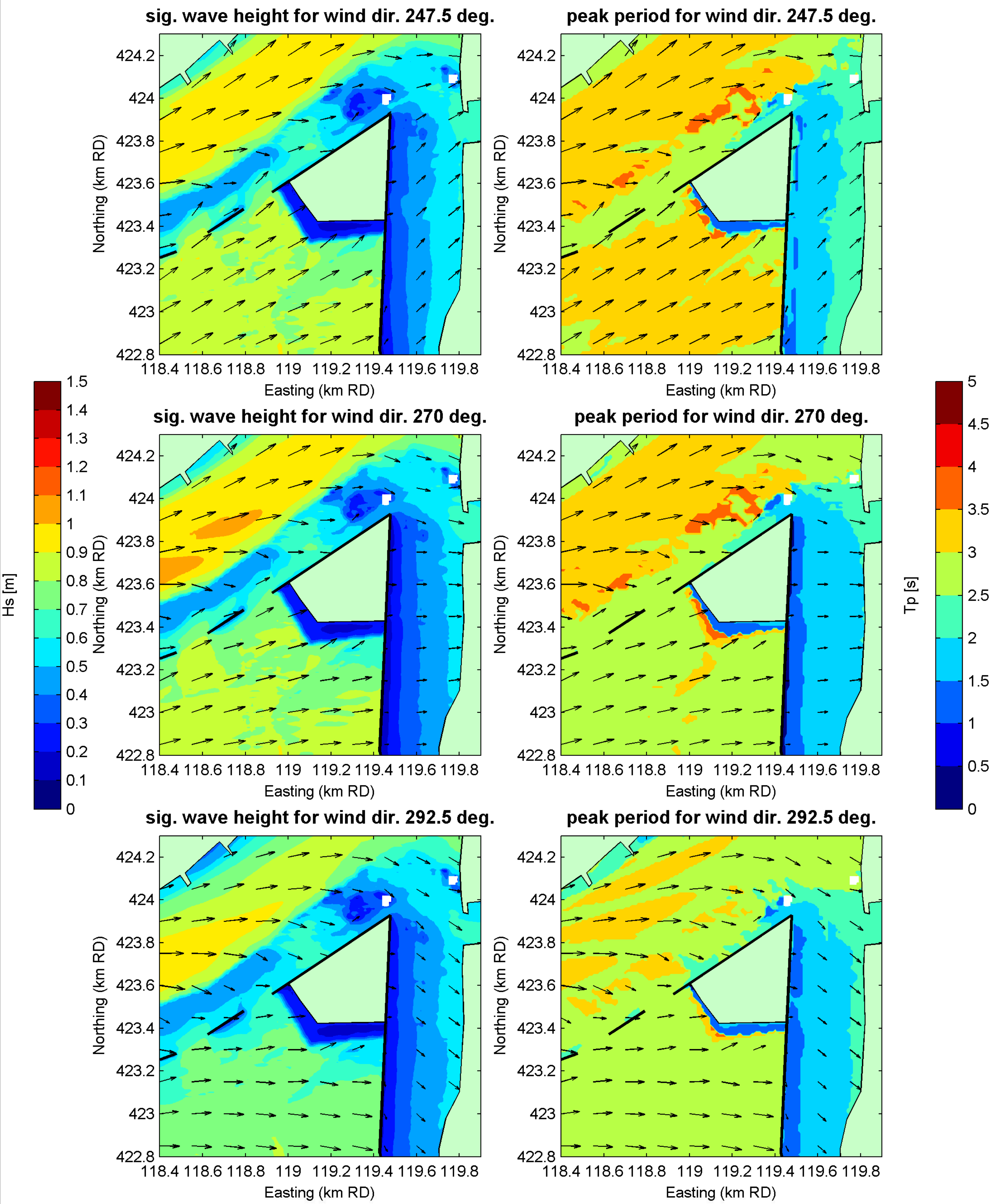
case Bank and Vegetation Hs and Tp at Fort Steurgat 1/2000 year event; water level 3.5+NAP	Fort Steurgat	
	SWAN-VEG	
Deltares Delft Hydraulics	G-1	



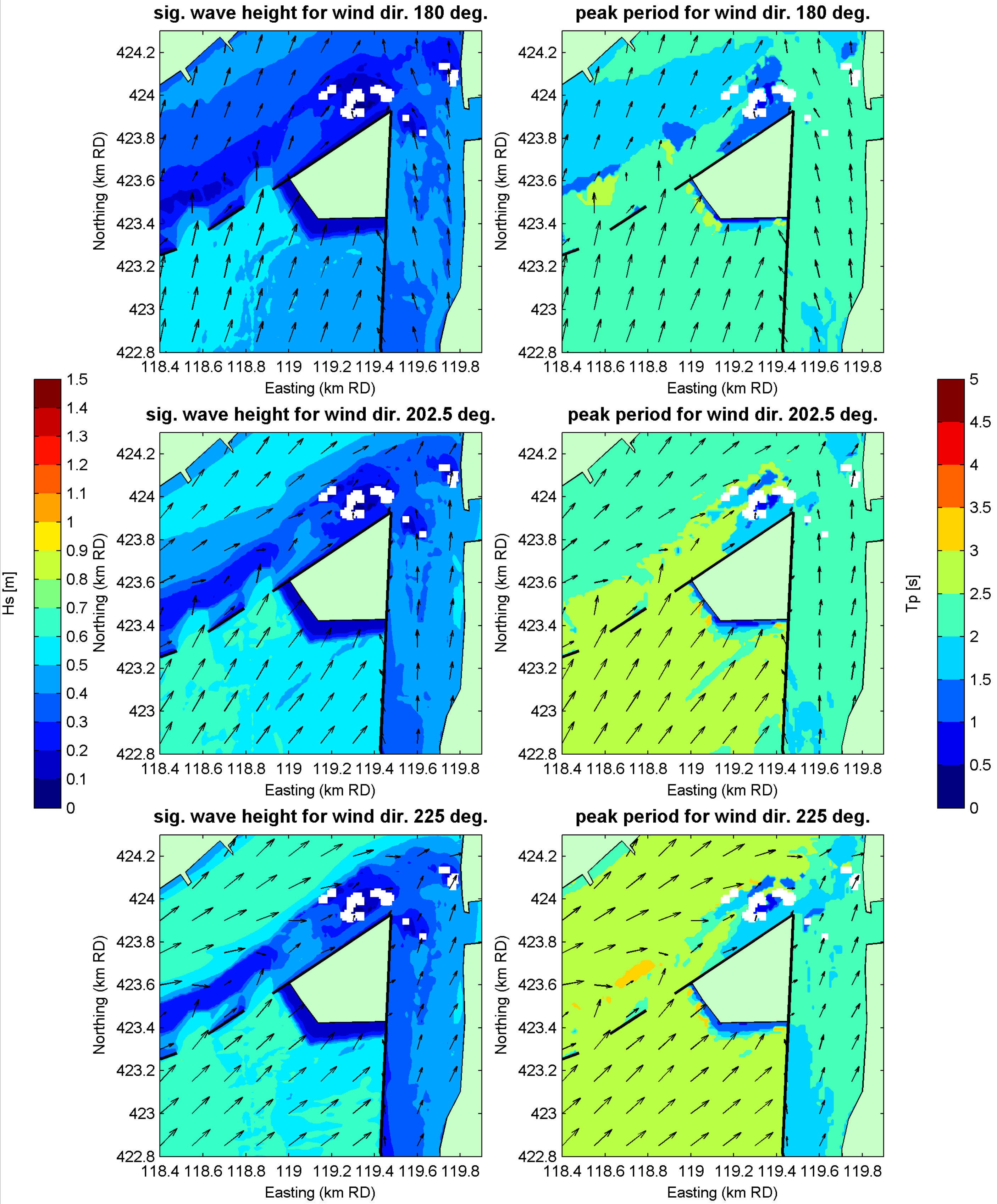
case Bank and Vegetation Hs and Tp at Fort Steurgat 1/2000 year event; water level 3.5+NAP	Fort Steurgat	
	SWAN-VEG	
Deltares Delft Hydraulics	G-1	



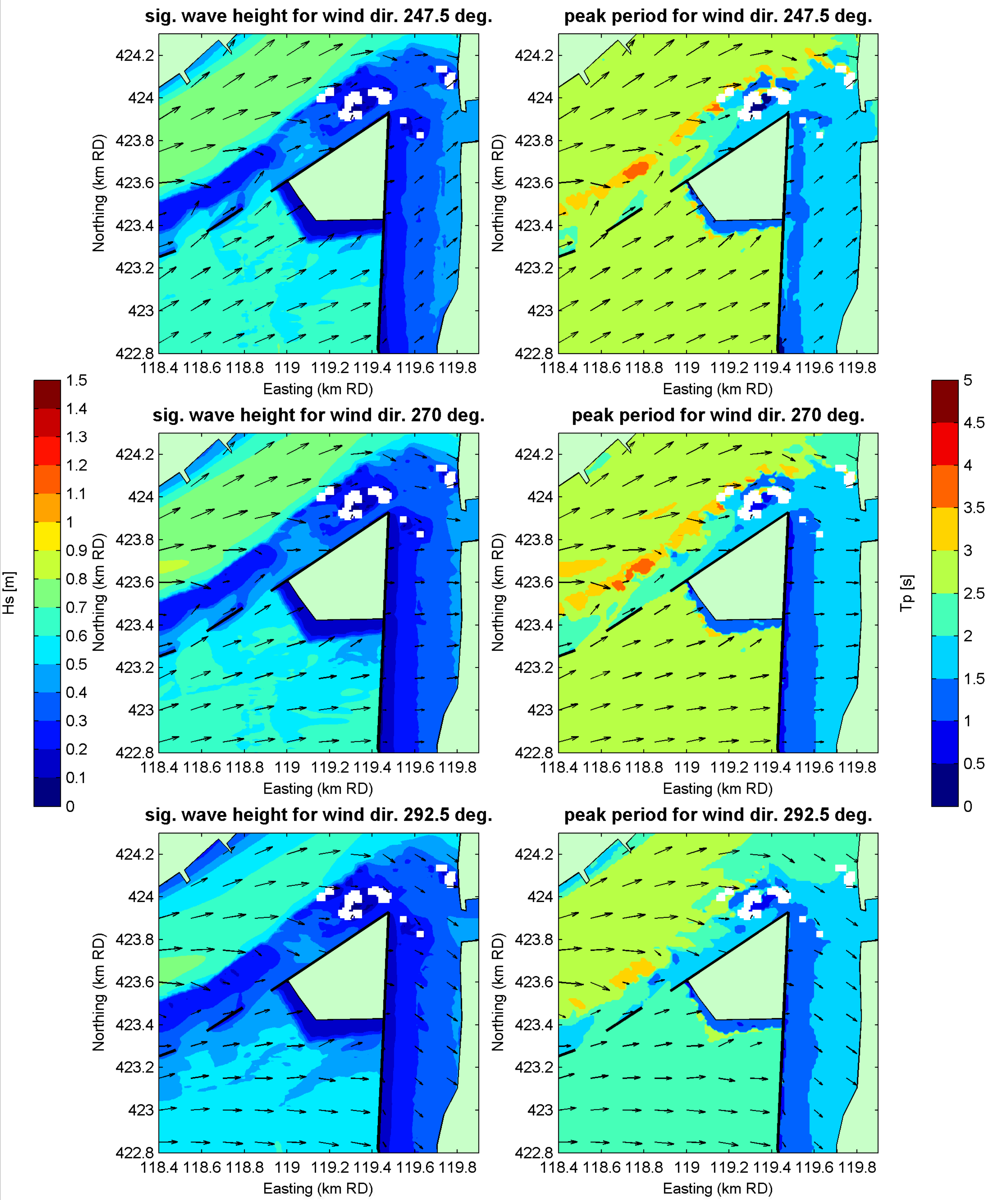
case Bank and Vegetation Hs and Tp at Fort Steurgat 1/100 year event; water level 3.0+NAP	Fort Steurgat	
	SWAN-VEG	
Deltares Delft Hydraulics	G-2	



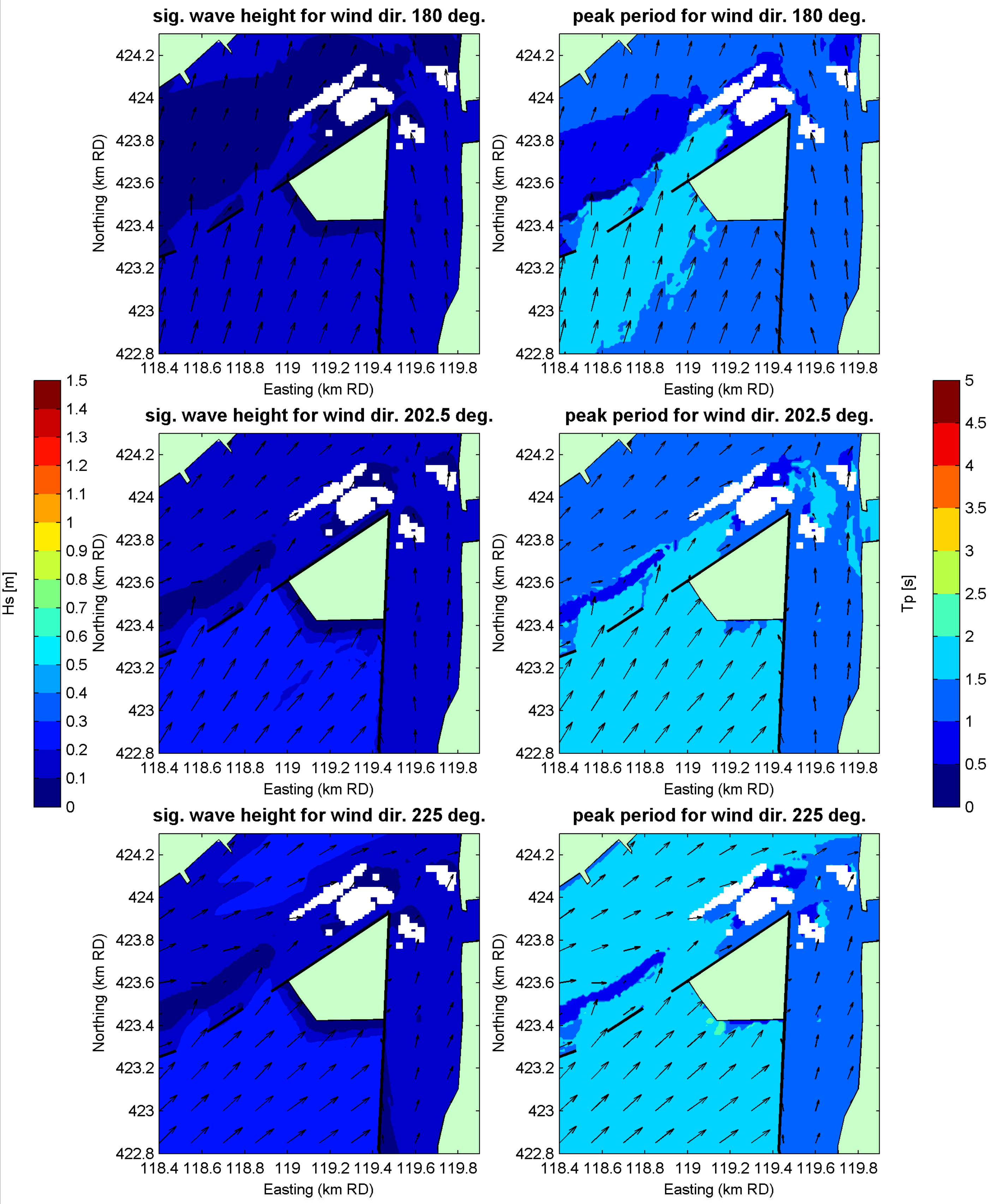
case Bank and Vegetation Hs and Tp at Fort Steurgat 1/100 year event; water level 3.0+NAP	Fort Steurgat	
	SWAN-VEG	
Deltares Delft Hydraulics	G-2	



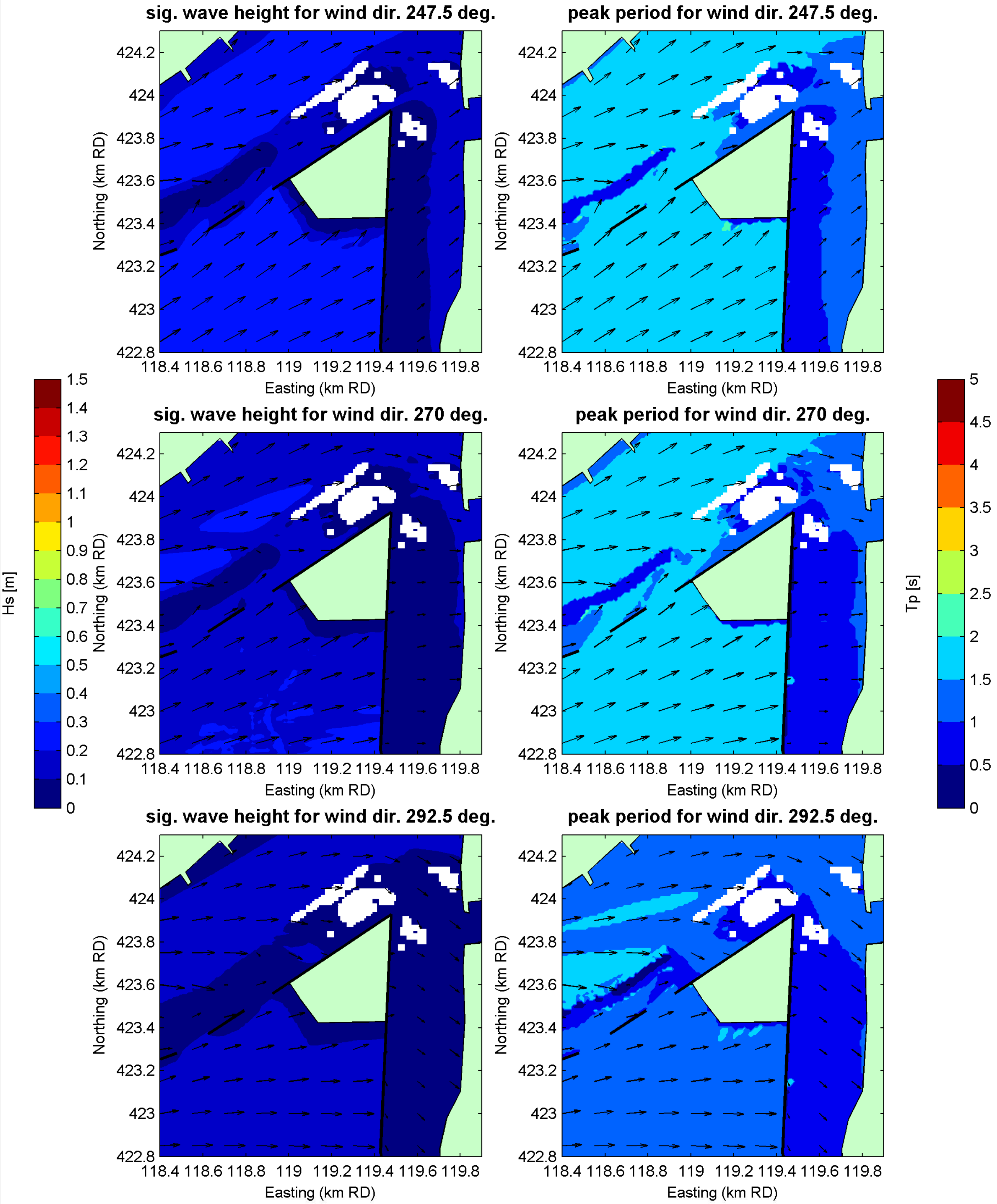
case Bank and Vegetation Hs and Tp at Fort Steurgat 1/10 year event; water level 2.5+NAP	Fort Steurgat SWAN-VEG
	G-3



case Bank and Vegetation Hs and Tp at Fort Steurgat 1/10 year event; water level 2.5+NAP	Fort Steurgat	
	SWAN-VEG	
	G-3	



case Bank and Vegetation Hs and Tp at Fort Steurgat 1/1 year event; water level 2.0+NAP	Fort Steurgat
	SWAN-VEG
Deltares Delft Hydraulics	G-4



case Bank and Vegetation Hs and Tp at Fort Steurgat 1/1 year event; water level 2.0+NAP	Fort Steurgat	
	SWAN-VEG	
	G-4	