APPENDICES

APPENDIX A

Offshore Waves

A Offshore Wind and Wave Conditions

A.1 Data basis

The offshore wind and wave data were extracted from the PERGOS database. The PERGOS database applies the hindcast modelling methodology developed at Oceanweather and DHI for the specification of wind, wave, current and water level fields in historical time periods.

Data from PERGOS grid points 2259, 2501, 2748 and 2990 were purchased and used to describe the offshore wind and wave conditions. Figure A.1 shows the positions of these points.

The available time series covers 27 years: 1 January 1983 to 31 December 2009. Data are available at one-hourly intervals.

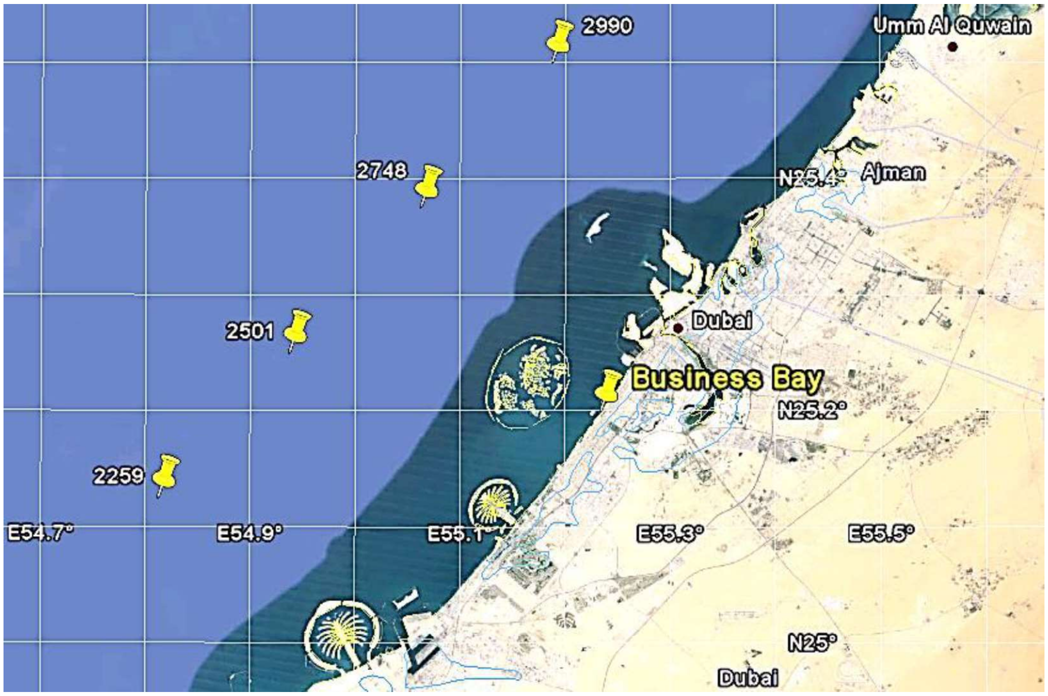

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Figure A.1 PERGOS grid points where wind and wave conditions were extracted for this study

Table A.1 Coordinates and water depths at the 4 offshore grid points used to describe the offshore wind and wave conditions

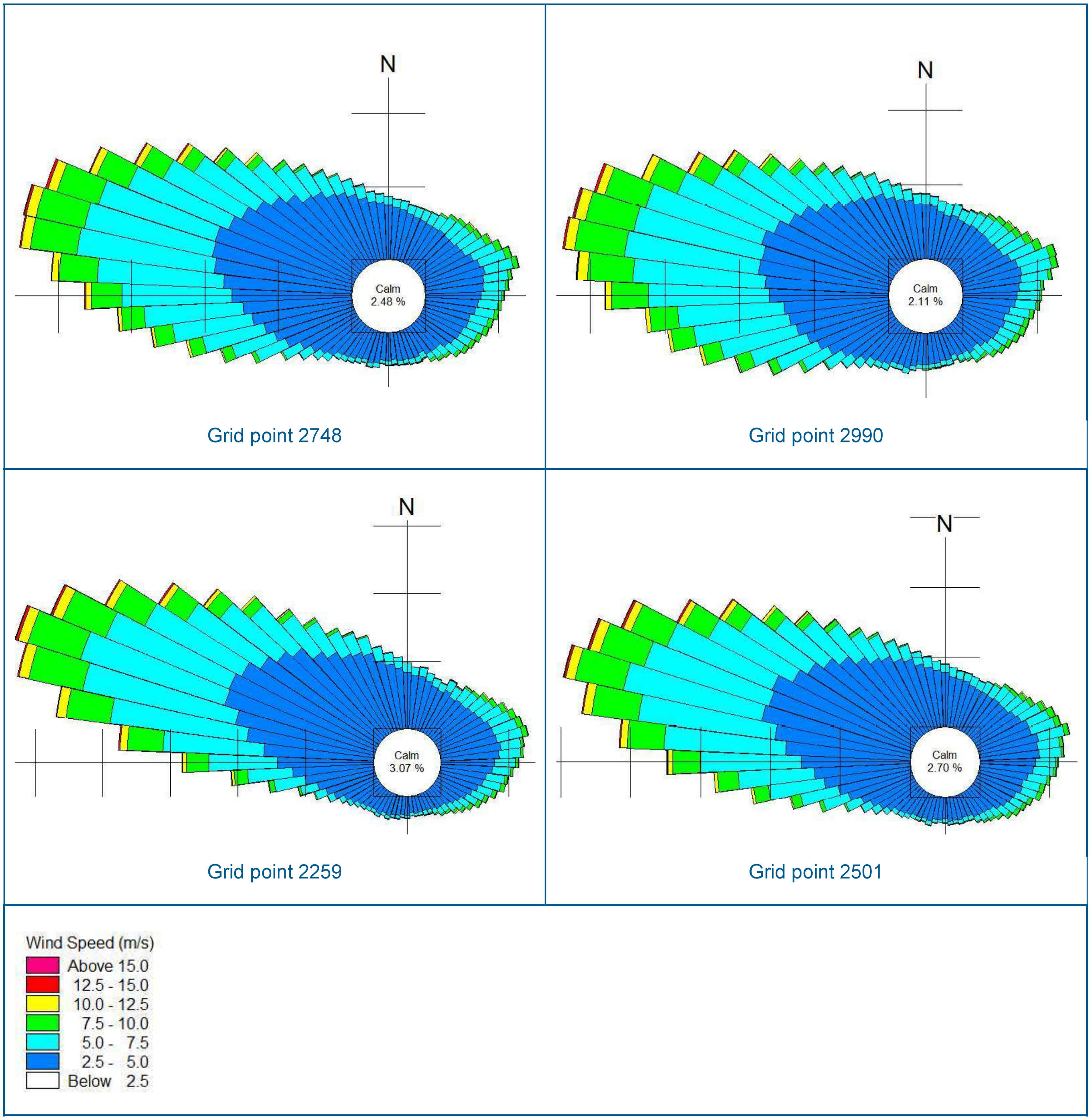
Grid Point	Easting (°E)	Northing (°N)	Easting (mDLTM)	Northing (mDLTM)	Appr depth (mDCD)
2259	54.8125	25.125	447475	2780002	20
2501	54.9375	25.25	460122	2793807	20
2748	55.0625	25.375	472743	2807623	20
2990	55.1875	25.5	485339	2821451	20

A.2 Wind conditions

Figure A.2 shows the wind roses and Figure A.3 illustrates the wind directions against wind speeds in a scatter plot.

It is seen that wind from west-north-westerly directions prevails both in occurrence and in strength and that the next most dominant wind direction is east-north-east.

Wind speeds exceed exceptionnally 17m/s.



Grid point 2748

Grid point 2990

Grid point 2259

Grid point 2501

Figure A.2 Wind roses, grid points 2259, 2501, 2748 and 2990, 27-year period 1983 – 2009
'Calm' corresponds to wind speed <2.5m/s
Each sector corresponds to 5°, directions are those from which the wind is blowing

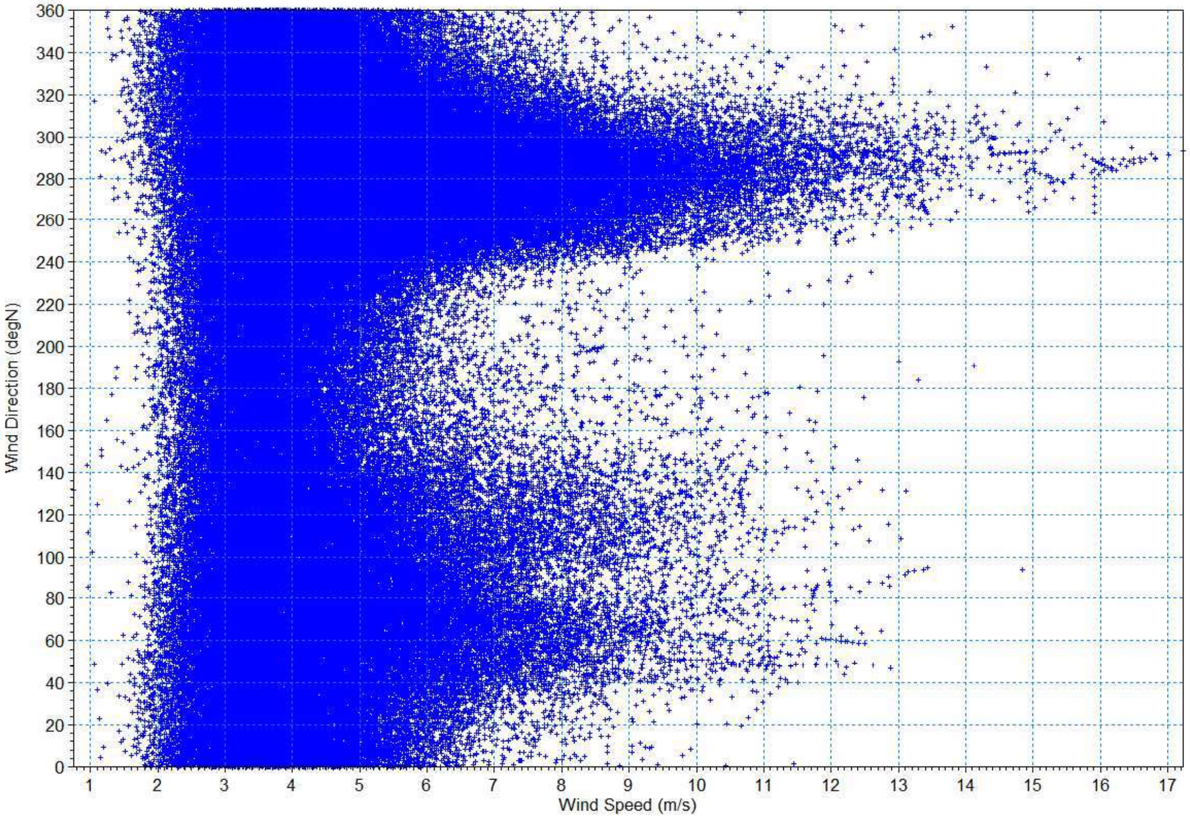


Figure A.3 Scatter plot of wind direction (from which the wind is blowing) against wind speed
Grid point 2748, 27-year period 1983 – 2009

A.3 Wave conditions

A.3.1 Definition of wave parameters

Wave conditions are presented in the following in the form of wave heights, wave periods and wave directions.

Wave heights are given as significant wave heights calculated as $H_{m0} = 4*\sqrt{m_0}$, m_0 being the zero'th moment of the surface elevation spectrum. The significant wave height was originally defined as the average of the highest one third of all individual waves in a storm; the wave height of each individual wave being the vertical distance between the wave crest and the wave trough. Nowadays, the value of H_{m0} is generally used as significant wave height because numerical models calculate and operate with this parameter. For wave conditions in deep water where no wave breaking takes place, H_{m0} is close to being equal to the average of the highest one third of all individual waves in a storm, ie the original definition of the significant wave height. In shallow water, the value of H_{m0} may deviate substantially from the average of the highest one third of all individual waves in a storm/sea state.

Wave periods are given as the peak wave period, T_p, which corresponds to the wave period with the highest spectral density (energy).

Wave directions are given as mean wave direction (MWD) from which the waves are coming.

The PERGOS model splits the total spectrum of the wave fields into the “Sea” partition and the “Swell” partition. The “Sea” partition corresponds to the waves generated by the local wind field, while the “Swell” partition corresponds to the waves generated by wind fields farer away and which have therefore travelled over a longer distance before reaching the given position. All wave fields are therefore defined in the PERGOS database by the following parameters:

• Total wave.	$H_{m0,tot}$, $T_{p,tot}$ and MWD,$_{tot}$
• Sea:	$H_{m0,sea}$, $T_{p,sea}$ and MWD,$_{sea}$
• Swell:	$H_{m0,swell}$, $T_{p,swell}$ and MWD,$_{swell}$

A.3.2 Wave climate

The following figures illustrate the wave conditions off the project site by means of wave roses and scatter plots of the wave conditions at the four offshore grid points 2259, 2501, 2748 and 2990 (see Figure A.1 for the location of these grid points).

Wave roses

Figure A.4 shows for each of the four grid points the wave rose for total wave, ie total spectrum of sea and swell. Figure A.5 shows for the two midmost positions, which are the most representative positions for the project site, wave roses for the sea and swell partitions.

Scatter plots

Figure A.6 and Figure A.7 present scatter plots of the wave data at grid point 2748: mean wave direction (MWD) against significant wave height (H_{m0}) in Figure A.6 and peak wave period (T_p) against significant wave height (H_{m0}) in Figure A.7.

Findings

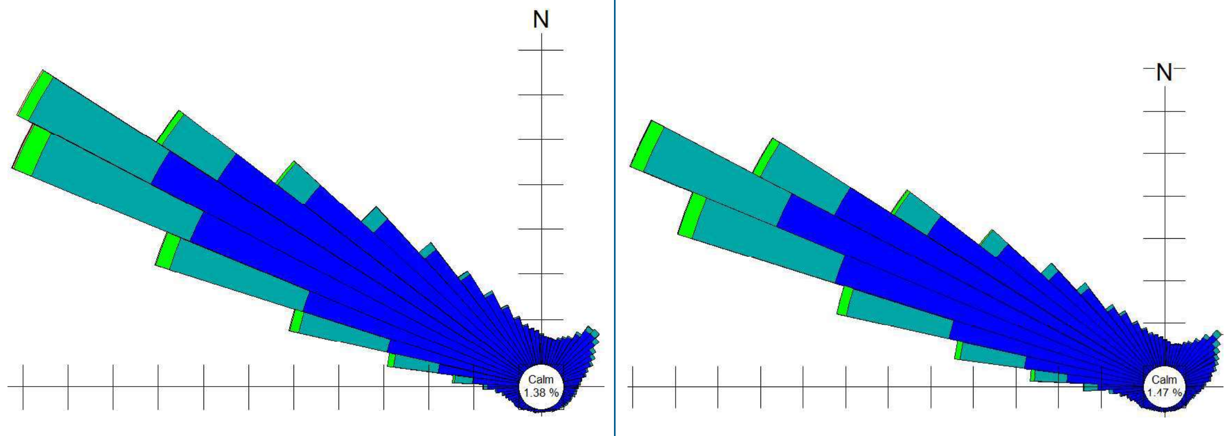
It is seen that wave heights are governed by sea waves (Figure A.8).

The figures show also that the prevailing wave direction is from north-west. A secondary wave direction is from north-east; however, waves from this direction do not affect the project site and are much less frequent than waves from north-west.

It is also seen (Figure A.4) that the prevailing wave direction turns slightly towards west from the southernmost grid point (2259) to the northernmost grid point (2990) so that the prevailing direction is 305°N at grid point 2259 and 295°N at grid point 2990.

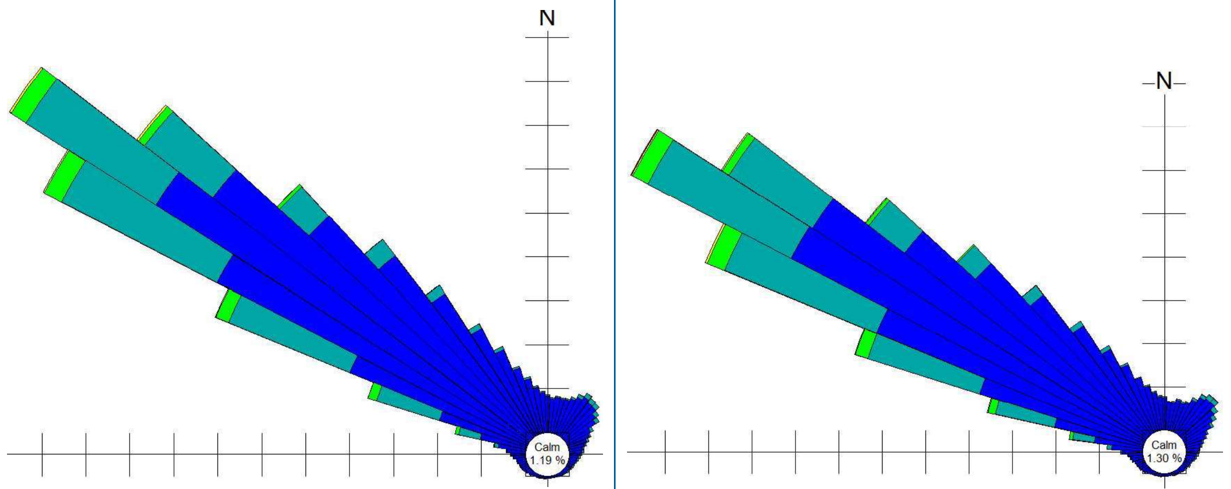
Figure A.5 indicates that directions of swell waves are generally slightly more northerly than sea waves.

Wave heights occasionally exceed H_{m0} = 4.0m.



Total wave, $H_{m0,tot}$ – Grid point 2748

Total wave, $H_{m0,tot}$ – Grid point 2990

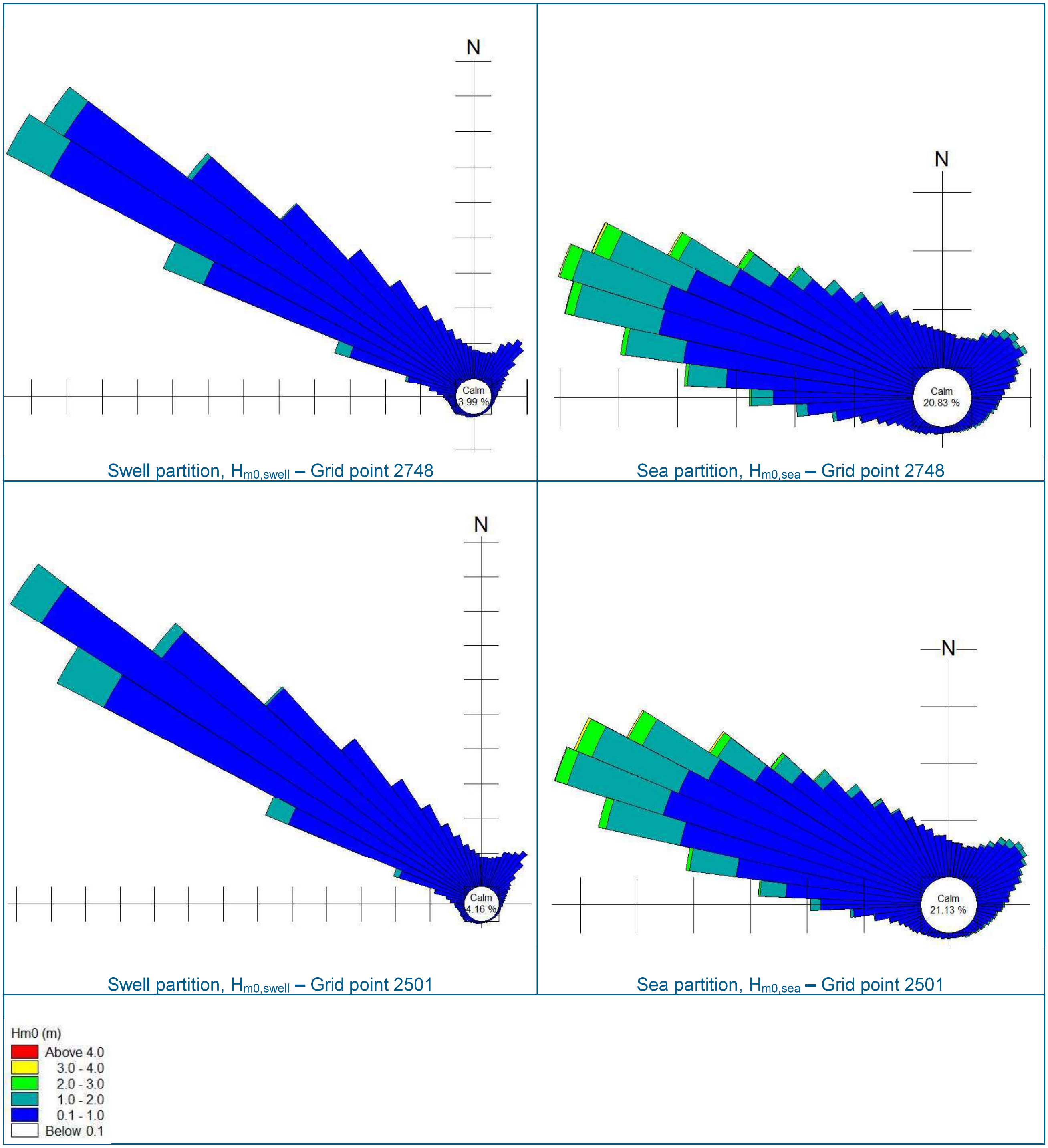


Total wave, $H_{m0,tot}$ – Grid point 2259

Total wave, $H_{m0,tot}$ – Grid point 2501

Hm0 (m)
🟥 Above 4.0
🟨 3.0 - 4.0
🟩 2.0 - 3.0
🟩 1.0 - 2.0
🟦 0.1 - 1.0
☐ Below 0.1

Figure A.4 Wave roses of significant wave heights, H_{m0} (total wave)
Grid points 2259, 2501, 2748 and 2990, 27-year period 1983 – 2009
'Calm' corresponds to $H_{m0} < 0.1$m
Each sector corresponds to 5°, directions are those from which the waves are coming



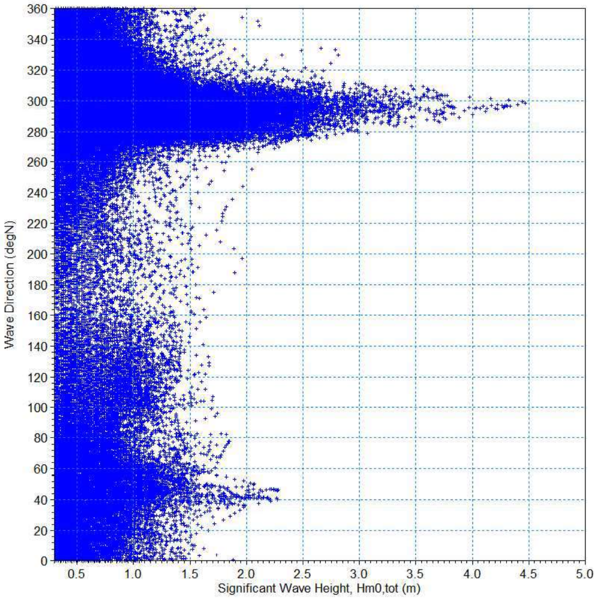
Swell partition, $H_{m0,swell}$ – Grid point 2748

Sea partition, $H_{m0,sea}$ – Grid point 2748

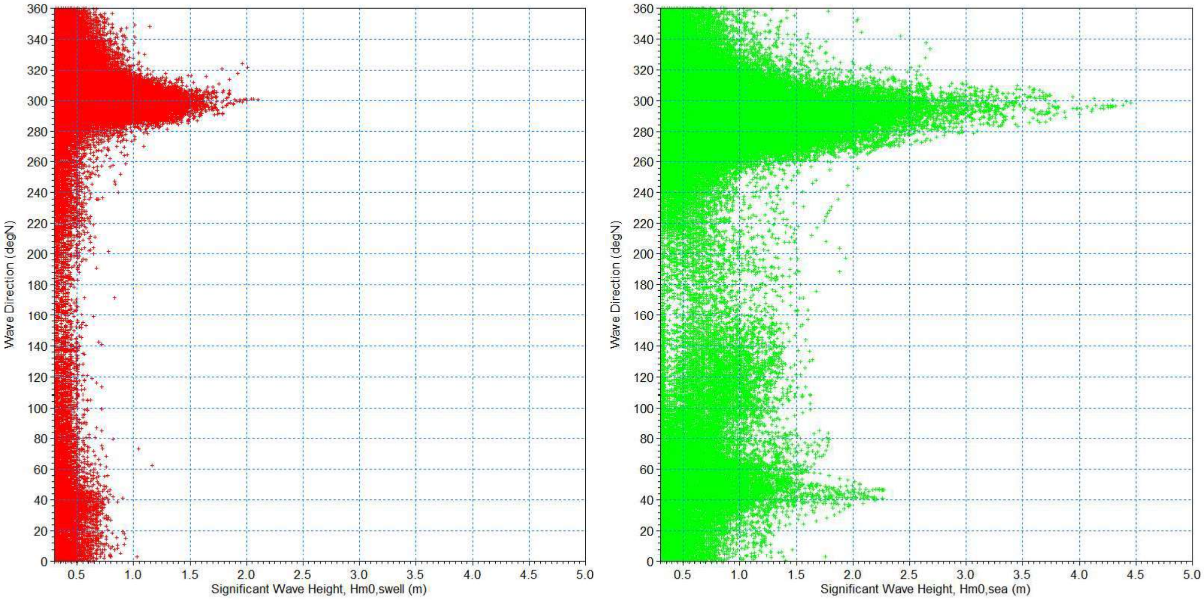
Swell partition, $H_{m0,swell}$ – Grid point 2501

Sea partition, $H_{m0,sea}$ – Grid point 2501

Figure A.5 Wave roses of significant wave heights, H_{m0} for sea (right) and swell (left) partitions
Grid points 2748 (top) and 2501 (bottom), 27-year period 1983 – 2009
'Calm' corresponds to $H_{m0} < 0.1$m
Each sector corresponds to 5°, directions are those from which the waves are coming



Total wave height

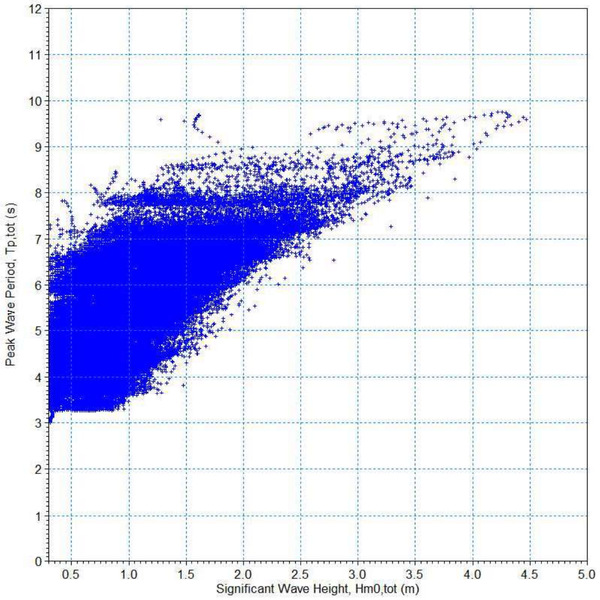


Swell partition

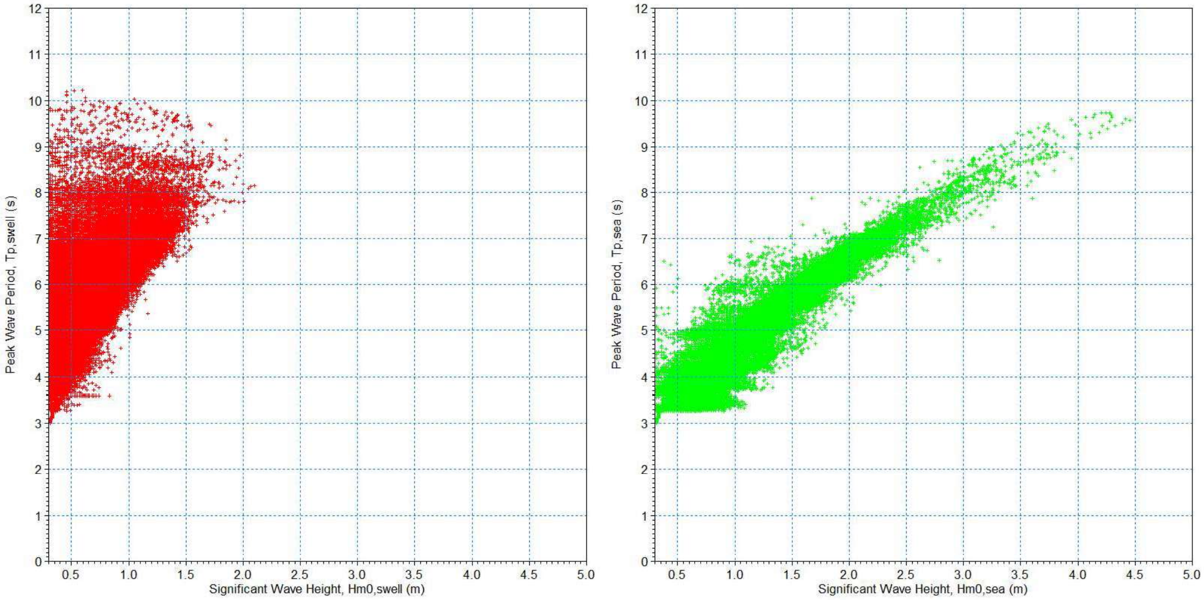
Sea partition

Figure A.6 Scatter plots of mean wave direction (MWD) against significant wave height

Grid point 2748, 27-year period 1983 – 2009



Total wave height



Swell partition

Sea partition

Figure A.7 Scatter plots of peak wave period (T_p) against significant wave height

Grid point 2748, 27-year period 1983 – 2009

A.3.3 Extreme wave conditions

Wave heights with average return periods of 1, 5, 10, 25, 50 and 100 years were estimated based on an extreme value analysis of the PERGOS data.

The analysis was performed using the 27-year time series of significant wave heights of ‘total wave’ at grid point 2748, see Figure A.1. The method based on a ‘Peak-over-Threshold’ (POT) analysis of independent events, with threshold = 2.65m, was applied. Figure A.8 shows the fits of an exponential distribution and a Weibull distribution.

The analysis was made including waves from all directions. This is justified because wave directions of extreme waves (H_{m0} > 2.65m) are concentrated in a narrow directional interval (280°N – 310°N, see Figure A.6).

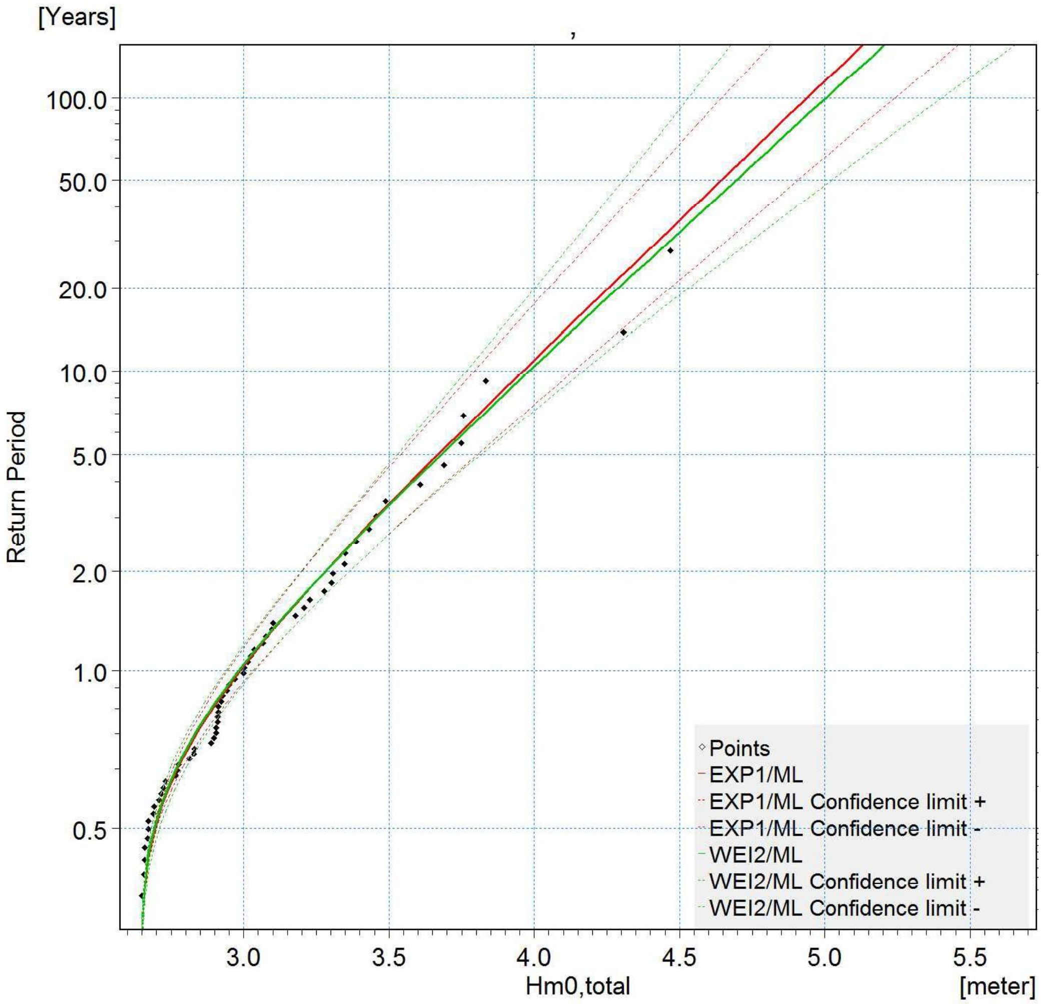


Figure A.8 Wave height distribution (omnidirectional waves) of independent events with $H_{m0,tot}$ > 2.65m
Offshore grid point 2748, 27-year period 1983 – 2009
The bold lines show the estimated fit to the distributions (red: exponential distribution, green: Weibull distribution).
The thin lines are the 68% confidence limits (when assuming a Gauss distribution of the events)

Table A.2 presents significant wave heights estimated for return periods of 1, 5, 10, 25, 50 and 100 years. The table presents also the standard deviations, corresponding to the 68% confidence limits, of the central estimates. It is seen that the extreme wave heights estimated using the exponential distribution and those using the Weibull distribution are quite similar.

Extrapolations of extreme conditions at these levels become significantly less accurate due to wider confidence bands at the tail of the distribution and should be used with extreme caution.

Table A.2 Estimated significant wave heights (total waves, omnidirectional) for return periods of 1, 5, 10, 25, 50 and 100 years and corresponding standard deviation.
Offshore grid point 2748, 27-year period 1983 – 2009

Return period		Weibull	Exponential
1 year	H_{m0} (m), central estimate Std. Dev.(m)	3.0 <0.1	3.0 <0.1
5 years	H_{m0} (m), central estimate Std. Dev.(m)	3.6 0.1	3.6 0.1
10 years	H_{m0} (m), central estimate Std. Dev.(m)	4.0 0.2	3.9 0.2
25 years 1)	H_{m0} (m), central estimate Std. Dev.(m)	4.4 0.3	4.3 0.3
50 years 1)	H_{m0} (m), central estimate Std. Dev.(m)	4.7 0.4	4.6 0.3
100 years 1)	H_{m0} (m), central estimate Std. Dev.(m)	5.0 0.4	4.9 0.3

1) Extrapolations of extreme conditions at these levels become significantly less accurate due to wider confidence bands at the tail of the distribution and should be used with caution.

APPENDIX B

Model Set-up: MIKE 21 SW
- Model set-up used for wave transformation

B Model set-up used for Wave Transformation Simulations

B.1 Numerical wave model, MIKE 21 SW

The propagation of the waves from offshore to the site was calculated using DHI's numerical wave model, MIKE 21 SW.

MIKE 21 SW is a spectral wind-wave model which simulates the wave conditions taking into account the effects of, depth refraction, shoaling, wave breaking, bottom friction, wave-wave interaction, wind and diffraction.

A detailed description of the model is attached in Appendix G.

B.2 Model bathymetry

The model bathymetry is based on a combination of LIDAR-based measurements and extraction from electronic sea charts. The LIDAR-based data were measured in 2004 and 2007 and were provided by Dubai Municipality. The license for the LIDAR data is available for this project only.

Figure B.1 shows the model extent and the mesh used for the wave transformation study. The detailed mesh and bathymetry conditions at the site appear from Figure B.2.

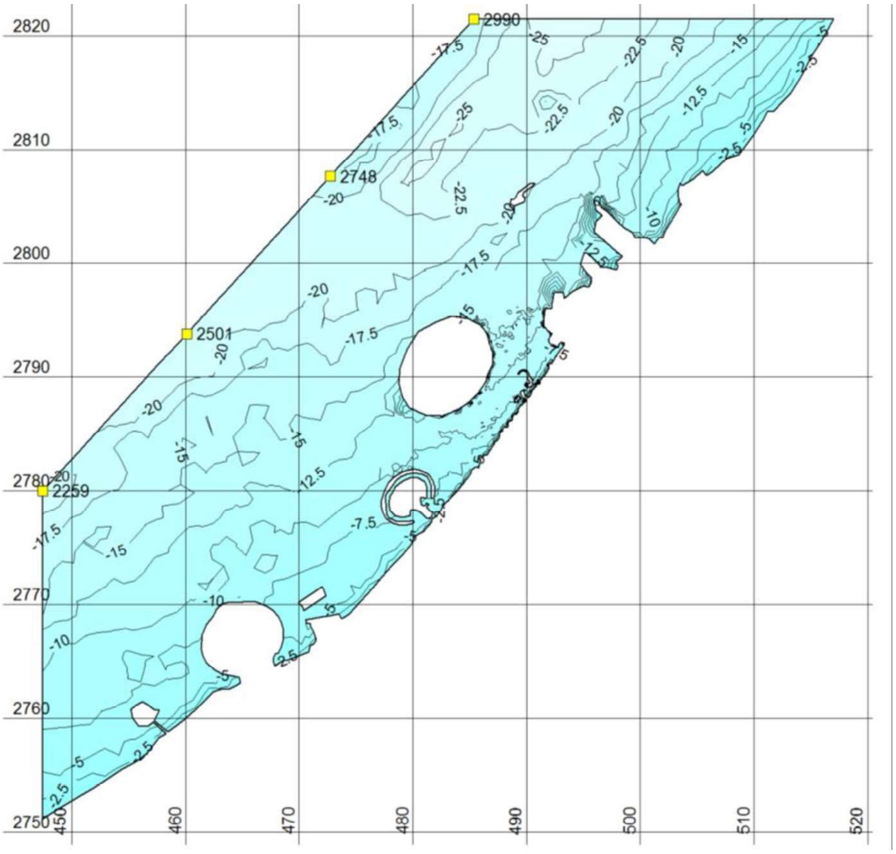


Figure B.1 Model extent and bathymetry (depths in mDMD)

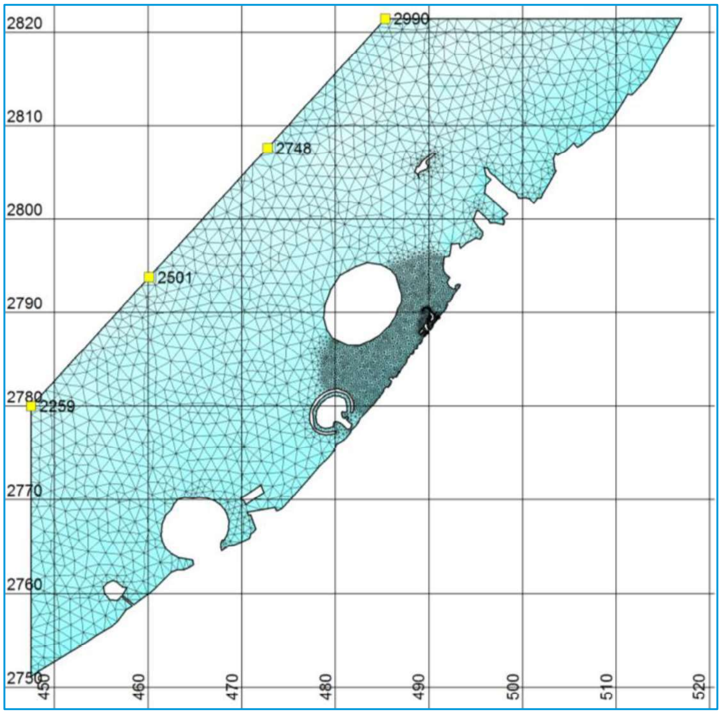


Figure B.2 Bathymetry at the site (depths in mDMD)

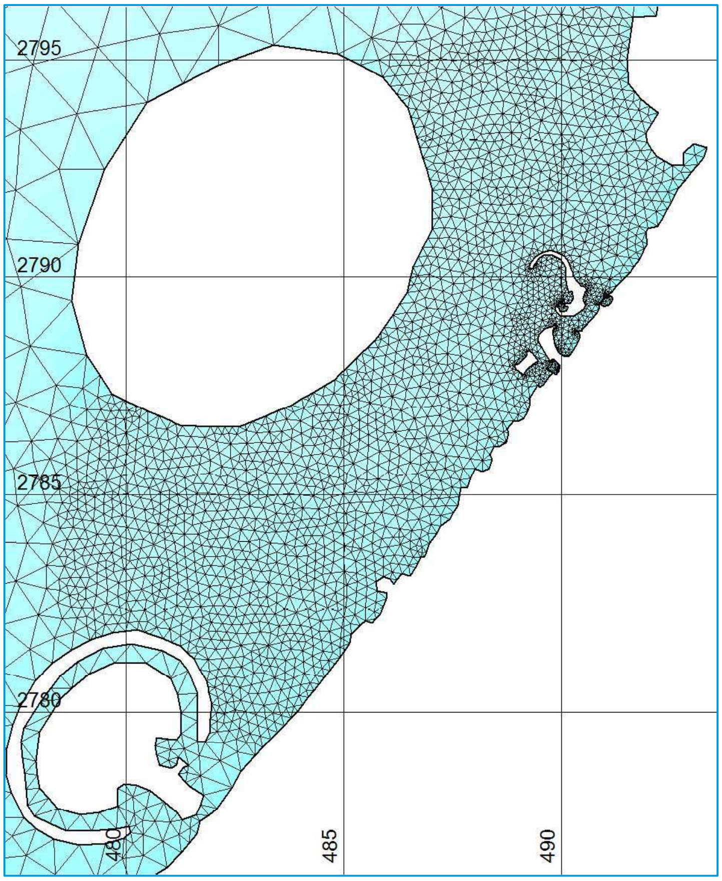


Figure B.3 Bathymetry at the site (depths in mDMD)

B.3 Waves on the model boundary

Wave conditions at the model boundaries were defined by the PERGOS wave data. The PERGOS grid points 2259, 2501, 2748 and 2990 are indicated on Figure B.1 and Figure B.2. Wave conditions along the north-westerly model boundary were interpolated between wave conditions at these four grid points. Wave conditions at the northern model boundary were those from grid point 2990, and wave conditions at the western model boundary were those from grid point 2259.

B.4 Wind

Wind speed and direction were defined by the PERGOS wind data at grid point 2748, which was the most representative for the study site. Wind speed and direction were constant over the model area during each 3-hourly event.

B.5 Wave reflection

Partial wave reflection was assumed from the perimeter structures of The World Islands, see Figure B.4. A wave reflection coefficient of 0.4 (or 40%) was assumed. No wave reflection was assumed at all other structures. The wave conditions simulated at the structures of the site represent hence the incident wave conditions.

Wave reflections from the structures at the site were taken into account by the wave agitation simulations (see Appendix C for the set-up of the wave disturbance model).

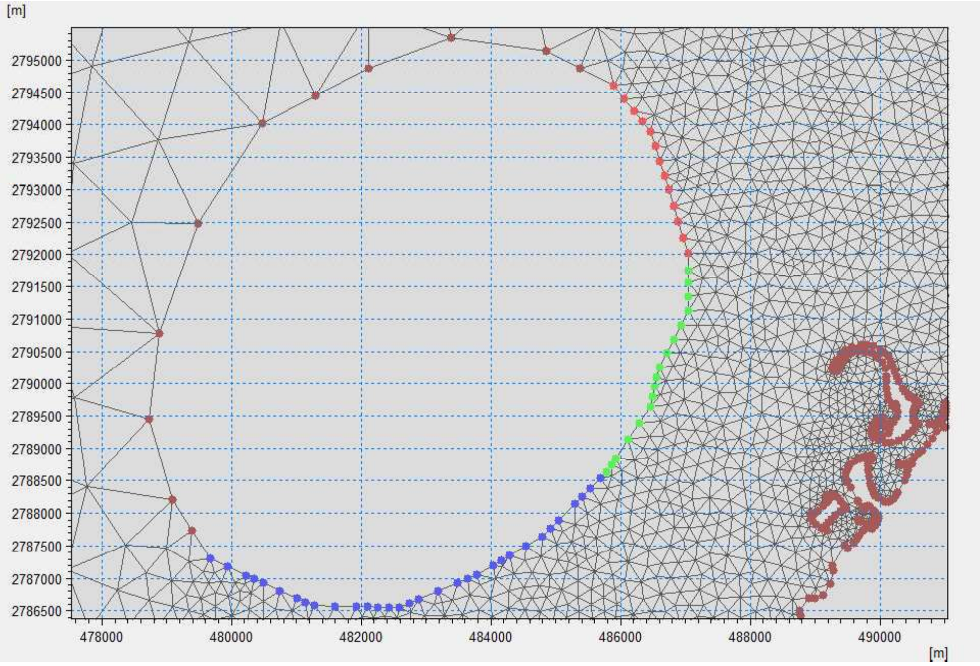


Figure B.4 The red, green and blue dots outline where the perimeter of The World Islands was assumed to reflect waves partially

B.6 Water level

The water level was assumed constant in the model area, but varied in time according to the water level specified at PERGOS grid point 2748.

B.7 Wave transformation simulations

All 3-hourly events during the 27 years covered by the PERGOS data were simulated in the wave transformation study as quasi stationary sea states.

The transformation of simultaneous sea and swell waves was simulated in a fully spectral formulation of the two sea states.

APPENDIX C

Model Set-up: MIKE 21 BW
- Model set-up used for wave disturbance simulations

C Model Set-up used for Wave Disturbance Simulations

C.1 Numerical wave model, MIKE 21 BW

The model applied for the modelling was the MIKE 21 BW Boussinesq wave module.

MIKE 21 BW was developed by DHI for the assessment of wave dynamics in ports and coastal areas. It is a time-domain, phase-resolving model capable of reproducing the combined effects of most wave phenomena including refraction, shoaling, diffraction, breaking, partial reflection and transmission, non-linear wave-wave interaction, frequency dispersion, and directional dispersion. The model simulates three-dimensional (3D) natural irregular waves (sea states). The model is a so-called Boussinesq type of wave model.

The model requires the following input:

- A digitised bathymetry
- Basic model parameters describing the extent of the model area, the grid spacing of the computational model grid, the time step and the duration of the simulation
- Incident wave conditions described by flux time series on the boundaries of the model area or at internal generation lines. Prior to simulation, these time series are generated on the basis of specified wave spectra
- Porosities (‘reflection and transmission coefficients’) to describe the reflection and transmission characteristics for all structures and natural obstructions (breakwaters, quay walls, cliffs, beaches, etc) in the model area. The reflection is described by specification of the porosity of the nearest grid points to the reflective object
- Description of so-called sponge layers, which are areas absorbing all wave energy propagating into the area (ie no reflection). Sponge layers are used to ensure that no unwanted and unnatural reflections occur in the model area (eg from the boundaries of the model).

A detailed description of the model is attached in Appendix H.

C.2 Model bathymetry

The model bathymetry was based on a combination of LIDAR-based measurements and extraction from electronic sea charts. The LIDAR-based data were measured in 2004 and 2007 and were provided by Dubai Municipality. The license for the LIDAR data is available for this project only.

The model grid size was 2m.

The causeway/bridge to Jamana Island was on the eastern boundary of the wave agitation model. Waves were absorbed along this structure, and wave penetration across the structure was not simulated.

Due to restrictions related to the model (Boussinesq) equations, the maximum water depth was truncated at -10mDMD and the minimum depth was truncated at -2mDMD.

Figure C.1 shows the model bathymetry with depth contours.

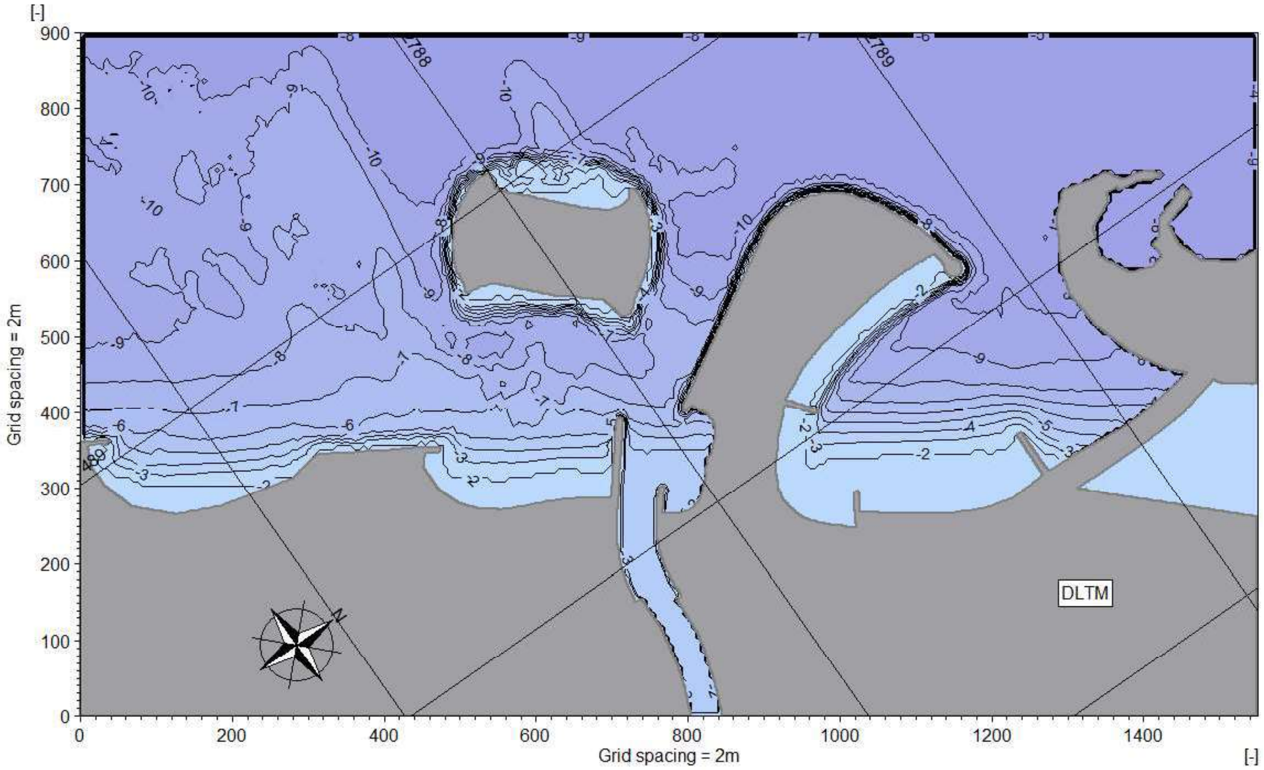


Figure C.1 Model bathymetry (mDMD) – Initial layout

C.3 Wave reflection (sponge and porosity layers)

Offshore model boundaries were made wave absorbing, meaning that all wave energy reaching these model boundaries were absorbed to avoid waves being reflected back into the model domain. The width of the sponge layers was 100m to ensure full absorption.

Along revetments and breakwaters, partial reflection was assumed. For the structures being important for the wave agitation in the harbour, the reflection properties were estimated and modelled based on the actual structure type and the local wave conditions. For the present wave conditions and breakwater/revetment structures, the reflection was estimated being in the range of 40-60%, depending on wave period and depth at structure. The vertical block wall in the marina was assumed almost fully reflective (98% reflective).

Waves were absorbed along all beaches in order to simulate and assess the conditions of incident waves only.

Figure C.2 shows where full and partial reflection was assumed and where the waves were absorbed.

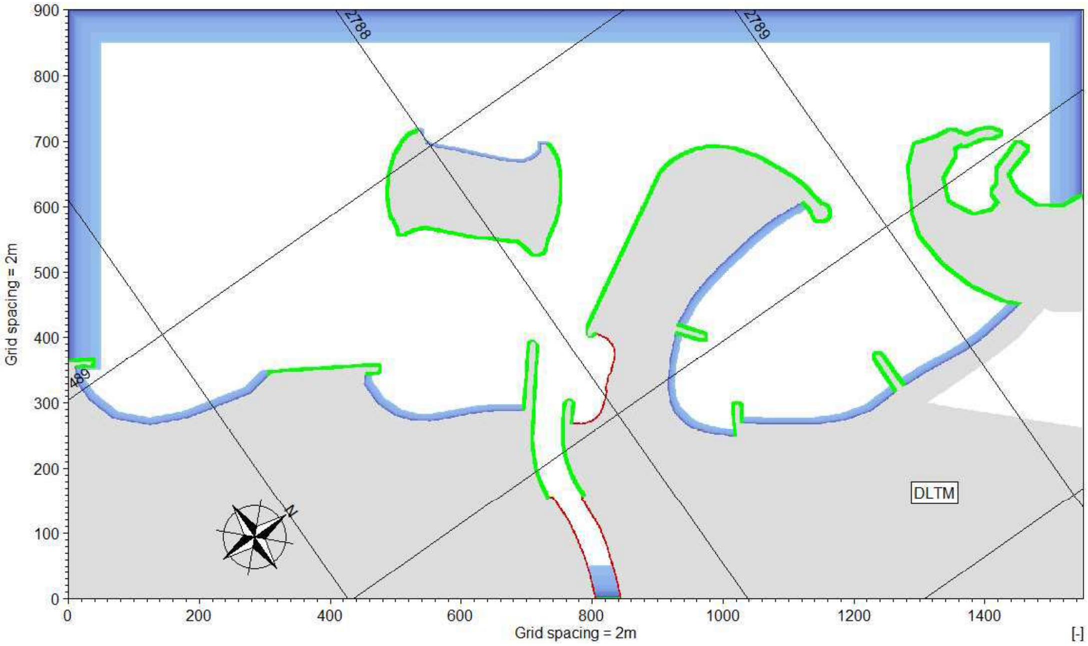


Figure C.2 Wave reflection and absorption properties assumed in the model.
Red: vertical quay wall being fully reflective
Green: Revetment/breakwater structure being partly reflective
Blue: absorbing boundaries

C.4 Generation of incident waves

The incident waves were generated along the north-western and the south-western model boundaries. Both generation lines were used for waves from south-westerly directions; for waves from north-westerly directions only the north-western generation line was used.

In order to cover the relevant wave conditions for wave disturbance in the marina and the wave climate along the beaches to be investigated, the combinations of wave direction and wave period as shown in Table C.1 were included in the programme of wave disturbance simulations. All combinations were applied for the assessment of the beach development. Only the coloured combinations were applied for the assessment of wave disturbance in the marina.

Table C.1 Modelled wave scenarios.

		Peak Wave Period, T_p (s)				
Wave direction	**MWD (°N)**	**4**	**6**	**7**	**8**	**10**
North-westerly	**350**	X	X		X	
	340	X	X	X	X	X
	330	X		X		X
	320		X		X	
South-westerly	**255**	X	X		X	
	250	X	X	X		X

The wave generation lines and the modelled wave directions are indicated in Figure C.3.

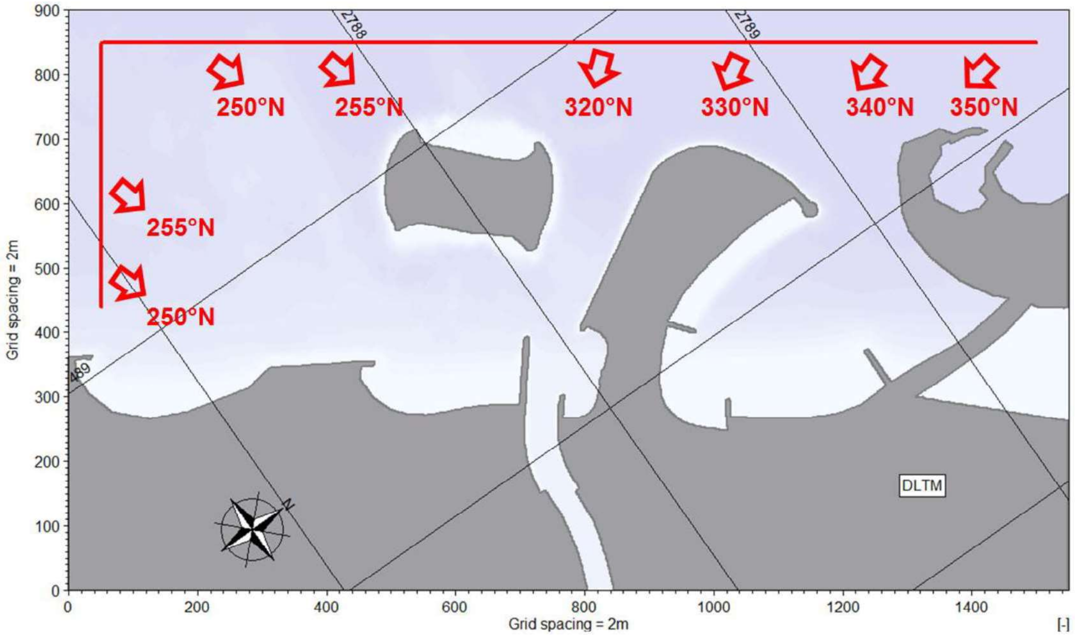


Figure C.3 Wave generation lines and modelled wave directions

Directional irregular waves conforming to standard JONSWAP spectra with corresponding wave height (0.5m H_{m0}), wave period (T_p), and mean wave direction were used for defining the incident wave conditions.

The directional spreading was modelled as $\cos^8 (\theta - \theta_{mean})$, where θ was the direction and θ_{mean} the mean wave direction. The maximum deviation from the mean wave direction was 20°.

Due to restrictions related to the model (Boussinesq-equations), the minimum wave period included was 3.2s for T_p=4s, 4s for T_p=6s and T_p=7s and 5s for T_p=8s and T_p=10s.

C.5 Simulation duration and time step

The duration of each simulation corresponded to 40 min of which the last 30 minutes were applied for calculation of the wave height coefficients.

The time step of the calculations was 0.025s.

C.6 Water level

For all simulations, a water level corresponding to MSL (=+1.1mDMD) was assumed.

APPENDIX D

Model Set-up: MIKE21 HD/ST FM
- Model setup-up used for canal stability assessment

D Model Set-up used for Channel Stability Assessment

D.1 Model domain

The flow was solved on a 2D flexible mesh consisting of triangular elements. The size of the elements (defined as the length between centres of neighbouring elements) varied from approximately 7m near the marina to 100m on deeper water.

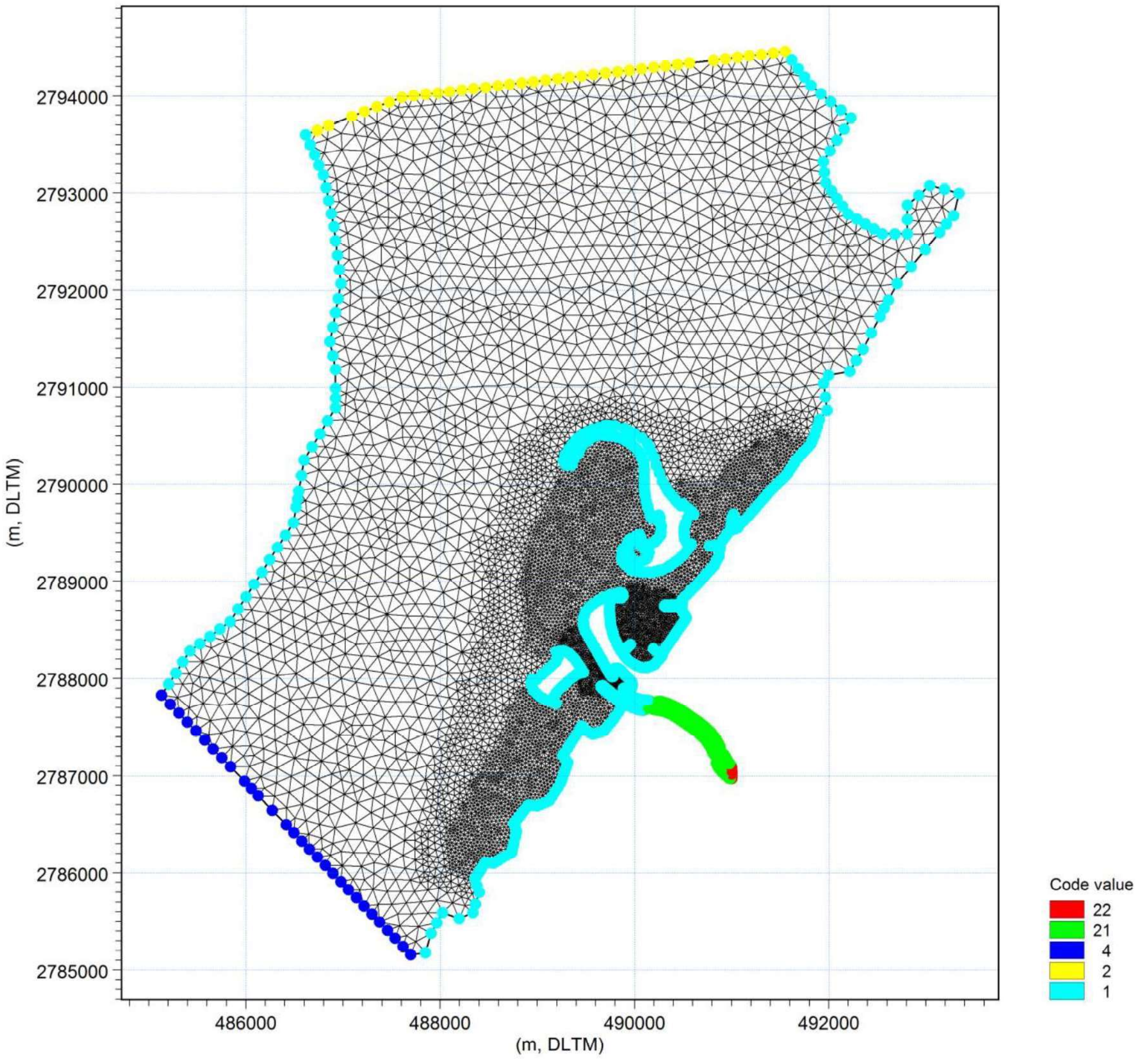


Figure D.1 Model domain used for 2D sand transport calculations. Code values refer to boundary conditions listed in the model set-up.

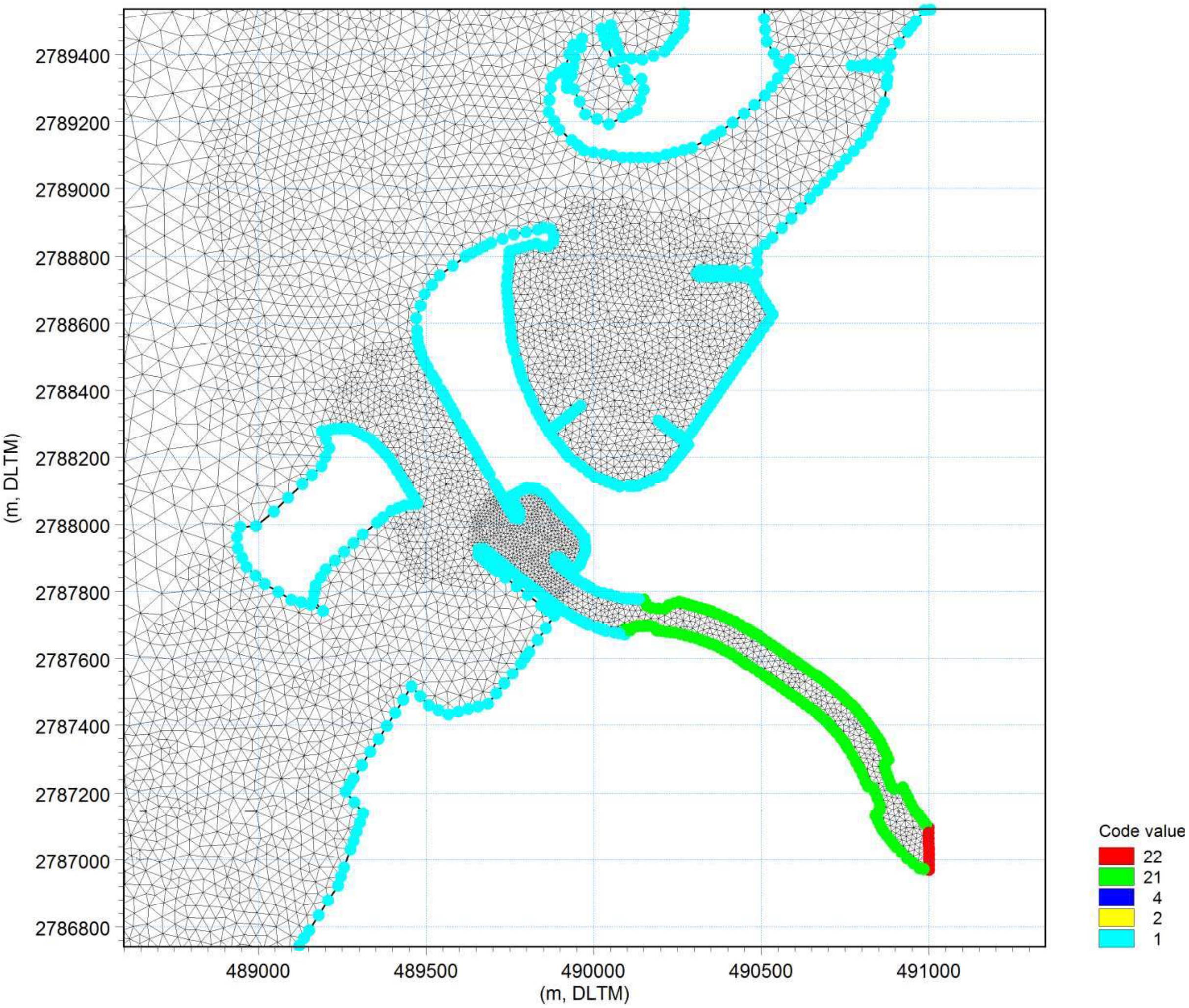


Figure D.2 Close-up of the model domain near Jumeirah Peninsula. Code values refer to boundary conditions listed under model set-up.

D.2 Numerical flow model, MIKE 21 HD FM

Table D.1 Model parameters used for the 2D flow calculations. Numbers in () under boundary conditions refer to code values shown in the figures with the model domain.

Parameter	Value / Description
Simulated period	2012-12-09 03:00 – 2012-12-24 03:00
Engine	FemEngineHD.exe, ver. 2012 SP 1
Modules	Hydrodynamics only
Flood and dry	Standard flood and dry
Density	Barotropic
Eddy viscosity	Smagorinsky formulation, constant value: 0.3 (from WQ study)
Bed resistance	Manning number: M=42m$^{1/3}$/s (corresponding to k=0.05m used in WQ study)
Coriolis forcing	Varying in domain
Wind forcing	• Constant in domain, varying in time • Gulf wind model (from WQ study) • Wind friction coefficient: 0.001255
Additional source terms	• Ice coverage: not incl. • Precipitation/Evaporation: not incl. • Wave radiation: Not incl.
Boundary conditions	• Land (1): Zero velocity (no slip) • North (2): Water level (varying in time and along boundary), from WQ study • West (4): Velocity components (varying in time and along boundary), from WQ study • Inner canal sides (21): Zero normal velocity • Business Bay canal (22): Discharge (varying in time), from WQ study

D.3 Model Set-up for Sand Transport model, STP

The sand transport module MIKE 21 ST FM relies on pre-compiled sediment transport tables for estimating the sand transport in each computational element for a given wave height, wave direction, wave period, current speed, current direction, water depth and grain size characteristics. The set-up used to compile the sediment transport tables is shown below.

Table D.2 Model set-up for calculation of sediment transport tables (used by MIKE 21 ST FM)

Parameter	Value / Description
Model engine	stbase_q3.exe, ver. 2012 SP 1
Sand transport table name	Stokes1_d0.13_S1.7_NoUndertow_SmallHs
General parameters	• Tol. in concentration: 0.00005 • Max. num. wave periods: 1000 • Steps pr. period: 140 • Rel. sed. density: 2.65 • Critical Shields value: 0.045 • Water temperature: 30 deg. C
Effects	• Ripples: not incl. • Bed slope: not incl. • Bed concentration: Empirical • Streaming: included • Density currents: not incl. • Centrifugal acc. : not incl. • Undertow: not incl.
Wave parameters	• Near bed orb. vel.: Stokes 1st order • Wave breaking, Gamma 1: 2, Gamma 2: 0.8
Table resolution	(min val./ spacing / num. values) • Current speed: 0.05 / 0.1 / 9 • Wave height: 0.05 / 0.1 / 12 • Wave period: 2 / 1 / 10 • H_{m0}/depth: 0.005 / 0.05 / 16 • Angle current/wave: 0 / 15 / 25 • Grain size: 0.13 • Geometric spreading: 1.7

D.4 Model set-up for MIKE 21 ST FM

The sand transport module is used to calculate sand transport across a number of cross-sections. The module is run in a de-coupled manner where flow fields and wave fields are specified and the 2D sand transport is calculated by use of the sand transport table described in Section D.3.

Sand transport discharges were calculated for 8 different wave fields occurring over the simulation period: 2012-12-09 03:00 to 2012-12-24 03:00. The annual sand transport is defined as a weighted sum of the frequency of occurrence of each wave field.

APPENDIX E

Model Set-up: LittoralProcessesFM
- Model set-up used for beach stability analysis

E Model Set-up: Littoral Transport Model

The main parameters are presented in Table E.1.

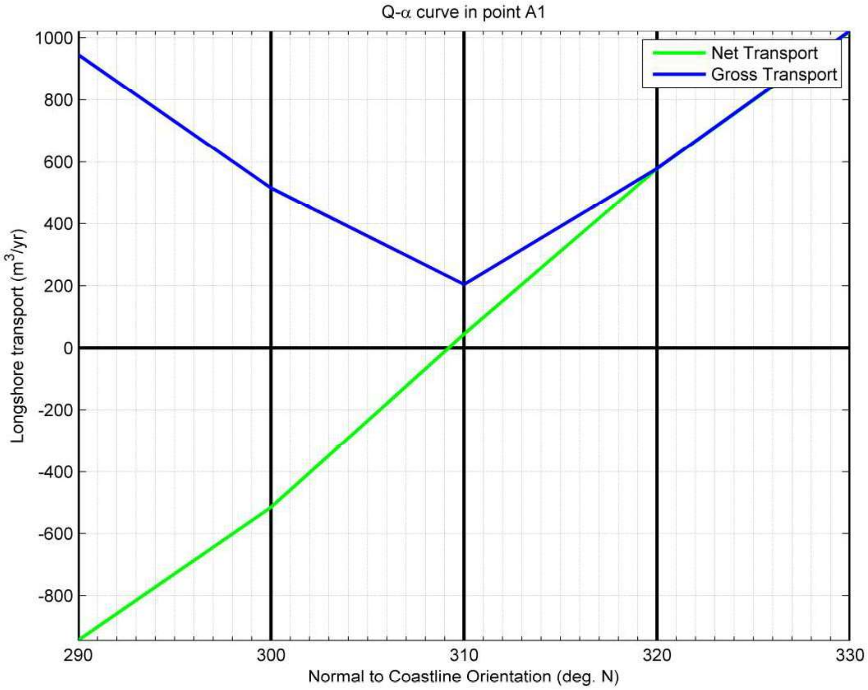
Table E.1 Parameters used for the littoral drift model

Parameter	Value / Description
Simulated period	2000 – 2009 (included)
Cross-shore grid spacing	0.25m
Bed roughness height	4mm
Ambient water	• Varying water level • Water temperature: 24 deg.C
Current	none
Waves	Battjes & Janssen description
Wave breaking parameters	• Alpha = 1 • Gamma (wave steepness) = 2 • Gamma = 0.8
Sediment	• Graded sand, 6 Fractions • Material relative density: 2.65kg/m^3 • Mean grain diameter: d_{50} = 0.25mm • Grading coefficient: $\sigma_g = \frac{\sqrt{\ 84}}{\sqrt{d16}} = 1.5$
Bed parameters	• Porosity: 0.4 • Ripples included: C1=0.1, C2=2, C3=16, C4=3 • Critical Shields parameter: 0.045
Calculation parameters	• Wave theory: Stokes 5th order • Empirical description of bed concentration • Tolerance: 0.001 • Max. no. of periods: 1000 • No. of time steps per period: 140

APPENDIX F

Beach Plan Form Model: Q-α Curves

F Beach Plan Form Model : Q-α Curves


Q-α curve in point A1

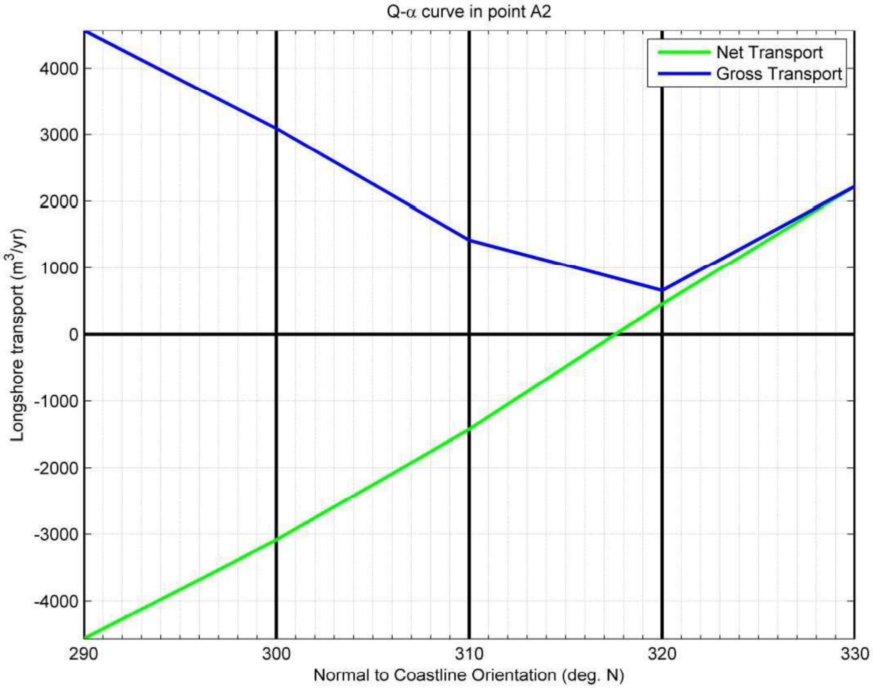
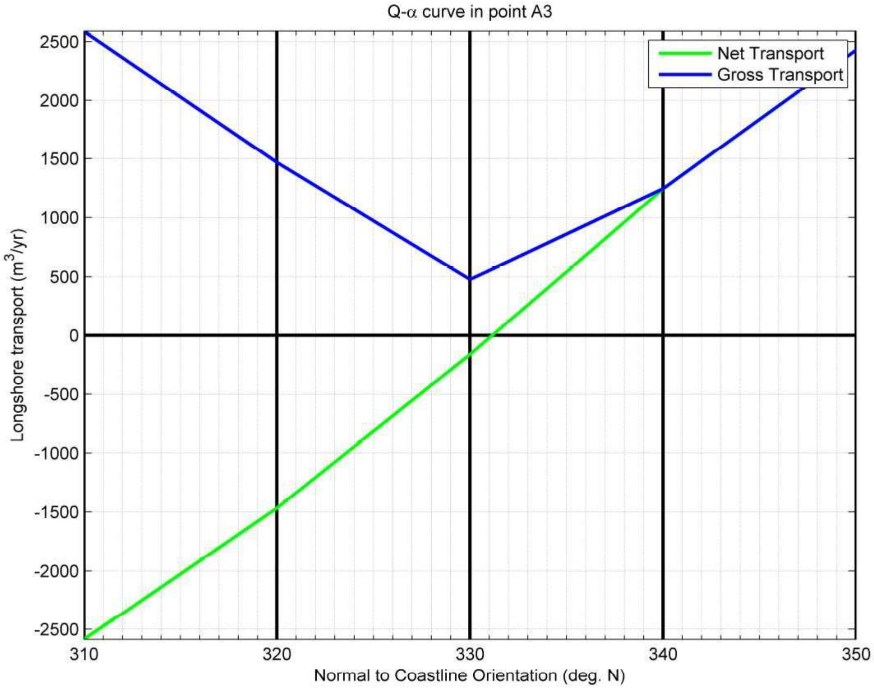

Q-α curve in point A2

Figure F.1 Q-α curve at point A1 (upper) and A2 (lower)



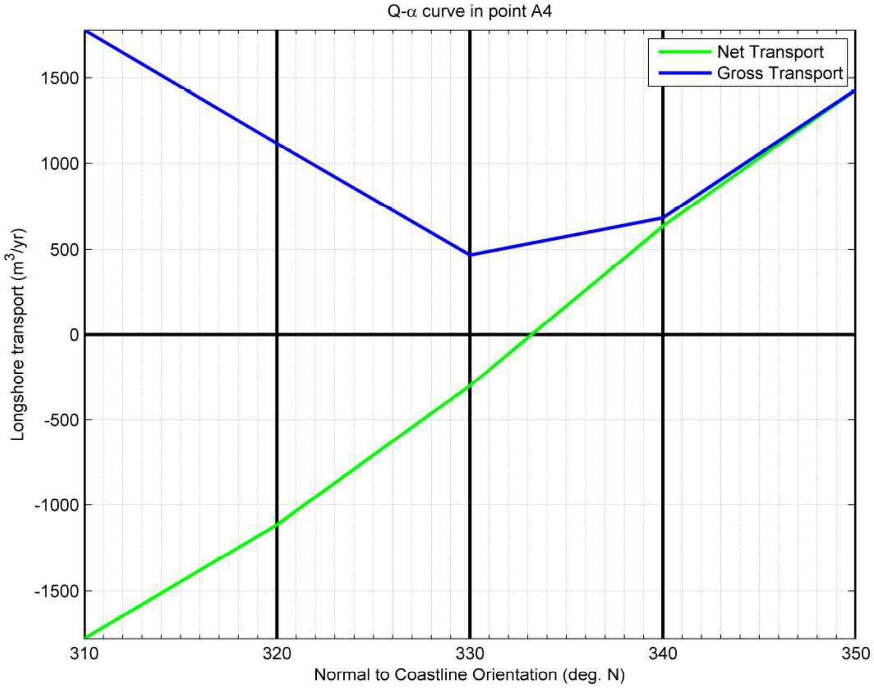
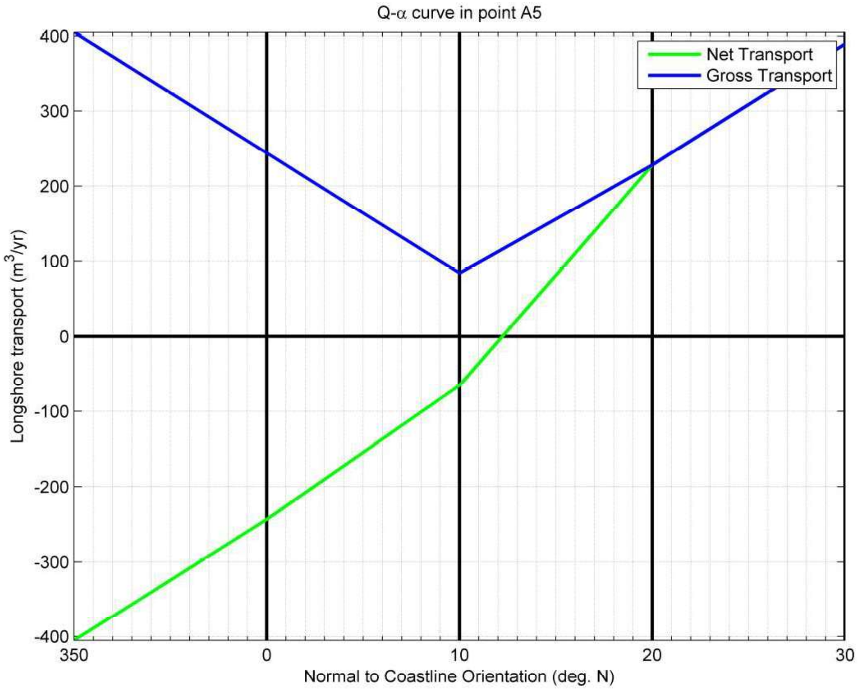


Figure F.2 Q-α curve at point A3 (upper) and A4 (lower)



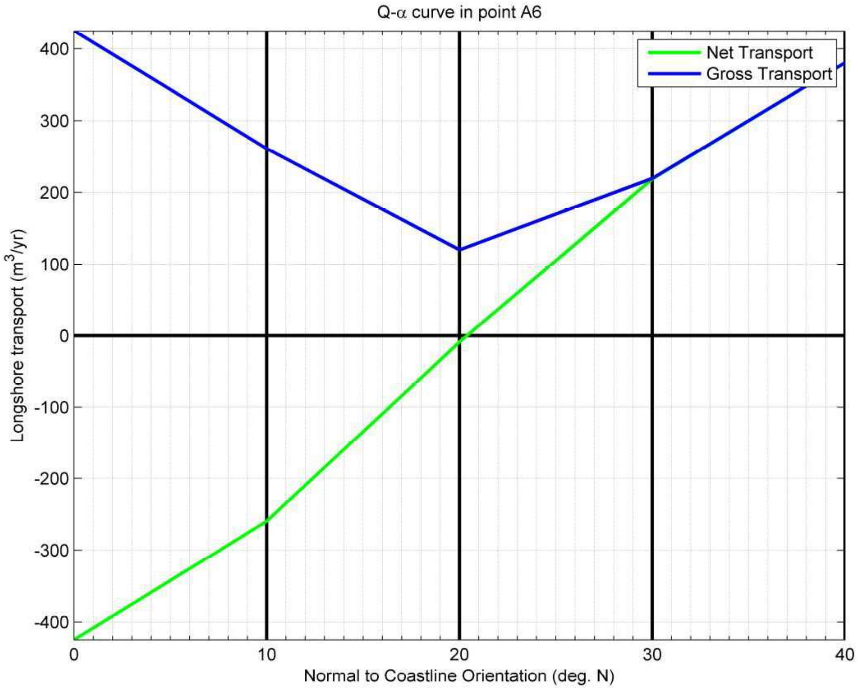
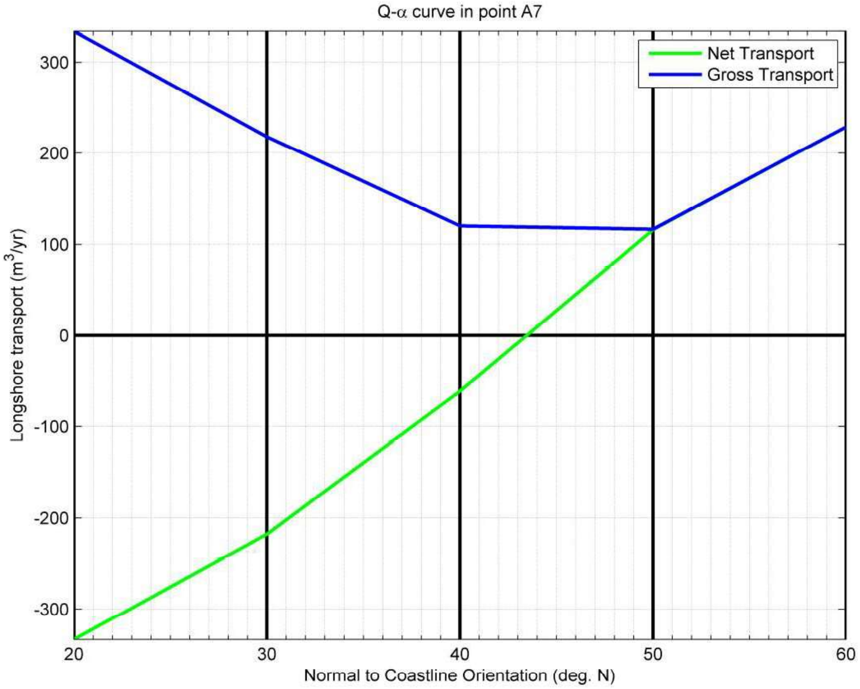


Figure F.3 Q-α curve at point A5 (upper) and A6 (lower)



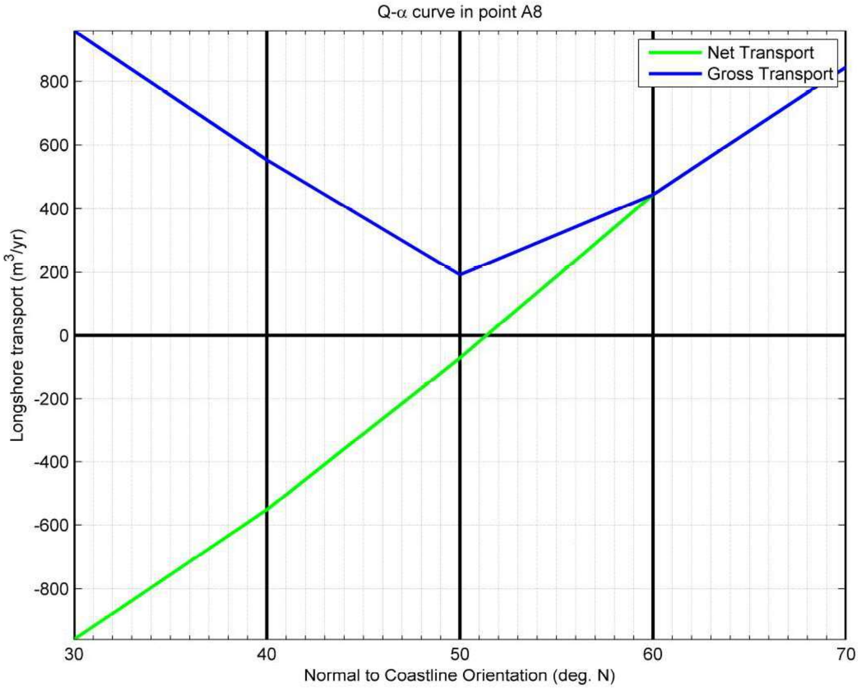


Figure F.4 Q-α curve at point A7 (upper) and A8 (lower)

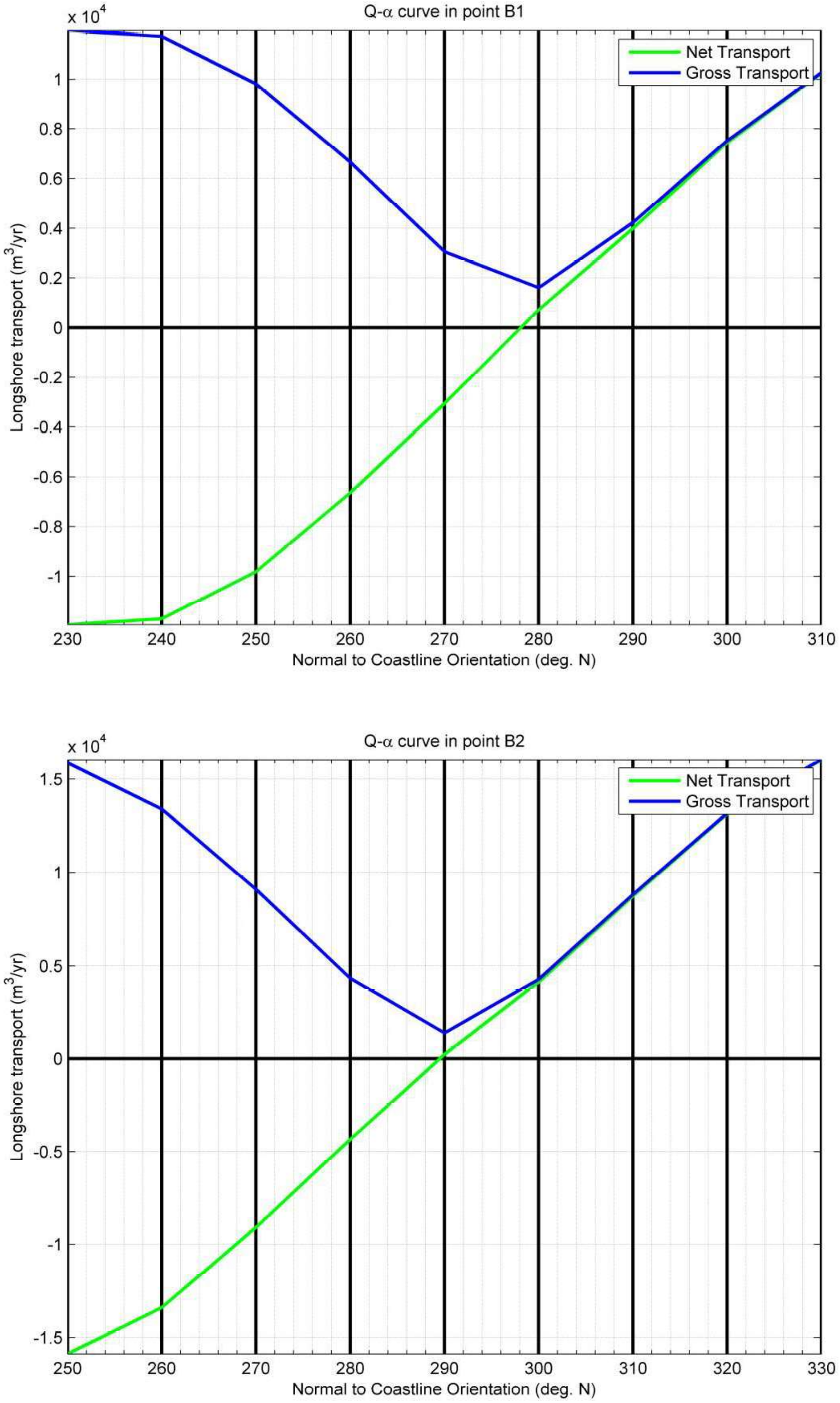


Figure F.5 Q-α curve at point B1 (upper) and B2 (lower)