Rijksdienst voor Ondernemend Nederland

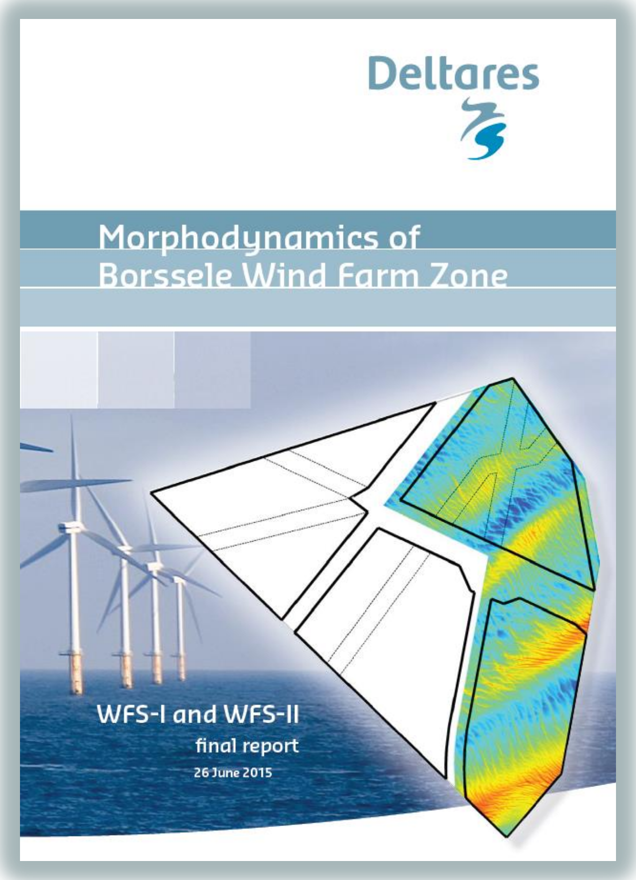
Deltares
Enabling Delta Life

Morphodynamics of Borssele Wind Farm Zone

Sites I and II
commissioned by RVO

Tim Raaijmakers
Hendrik Jan Riezebos
Thaiënne van Dijk
Tommer Vermaas
Bas Borsje
Robert Hasselaar

Webinar 20 October 2015


Deltares

Morphodynamics of
Borssele Wind Farm Zone

WFS-I and WFS-II
final report
26 June 2015

Introduction to morphodynamics team @ webinar

Presenter:

Tim Raaijmakers

Senior researcher/advisor, Programme Manager Offshore Engineering,
Project Leader Morphodynamics study

Moderators:

Hendrik Jan Riezebos

Researcher/advisor Offshore Engineering and co-author of Morphodynamics report

Thaiënne van Dijk

Specialist Marine Geology at Deltares,
Assistant Professor in Marine Systems at the University of Twente

Frank van Erp

Senior advisor Renewable Energy - RVO

Overview of phases of morphodynamics desk studies

Goal: to determine design seabed levels resulting from autonomous morphodynamical processes for Borssele Wind Farm Zone in period 2015-2046

Phase I: Desk study morphodynamics for entire Borssele Wind Farm Zone

- Based on in-house bathymetrical data (most recent: 2010)
- Delivery date of report: December 2014

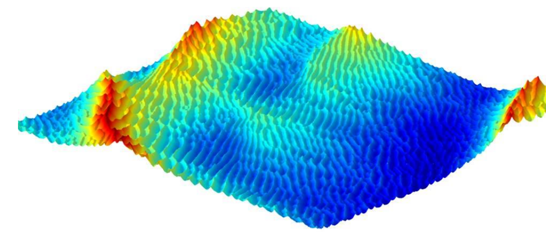
Phase IIa: update of desk study for BWFS-I and II

- Extension based on additional survey by Deep of BWFS I and II
- Delivery date of report: June 2015
- Topic of today's webinar

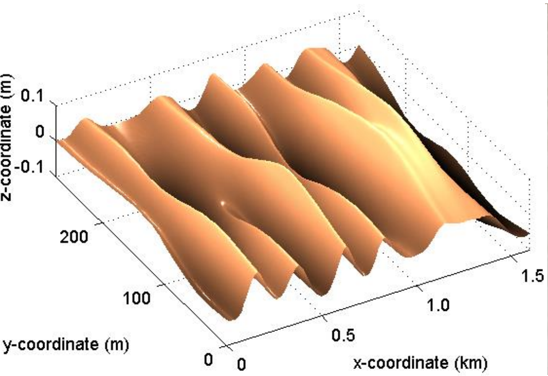
Phase IIb: update of desk study for BWFS-III and IV

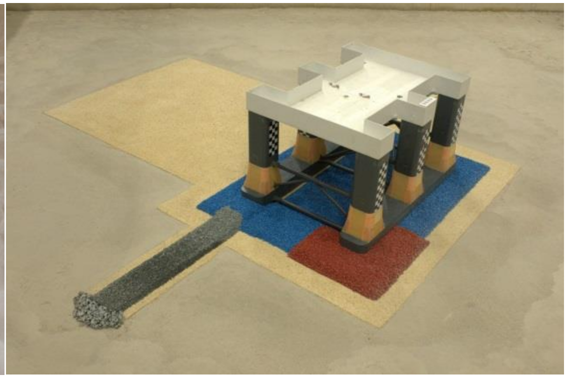
- Extension based on additional survey by Fugro of BWFS III and IV
- Will be based on new site contours (including Site V)
- Delivery date of report: November 2015

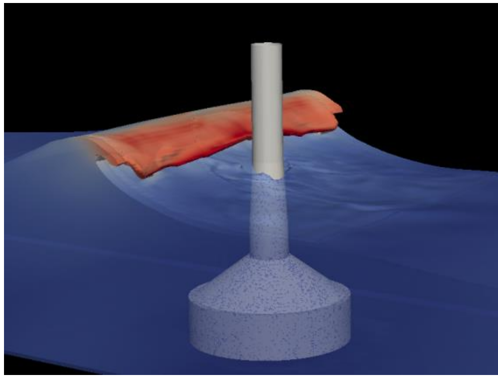
Contents of presentation



- Introduction Deltares
- Introduction Morphodynamics
- Methodology of this study
- Results
- Conclusions and Recommendations







Deltares

Introduction to Deltares

Deltares is an **independent** institute for **applied research** in the field of **water, subsurface and infrastructure**.

- merger since 2008 of WL | Delft Hydraulics, GeoDelft and parts of TNO and Rijkswaterstaat
- applied research & specialist consultancy
- independent: serving companies and governments

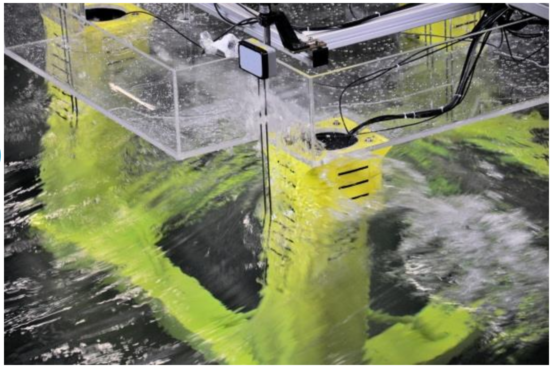
- extensive hydraulic/geotechnical laboratories and computer modelling facilities
- active in research networks: JIP, EU, FLOW, TKI,...
- open-source policy: “dare to share”

- > 800 staff (mostly MSc/PhD), > 28 nationalities
- main offices in Delft and Utrecht, The Netherlands
- branch offices in Singapore, USA, Jakarta, Abu Dhabi/Dubai, Rio de Janeiro

Deltares’ campus in Delft

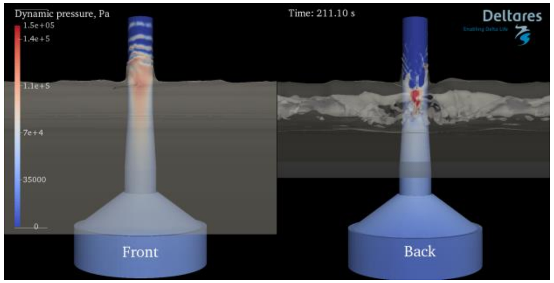
Deltares

Deltares' activities in offshore wind



Hydrodynamics

- ✓ Metocean/environmental conditions (waves, currents, water levels)
- ✓ Operational forecasting systems (for installation and O&M)
- ✓ Wave loads / impacts on foundations

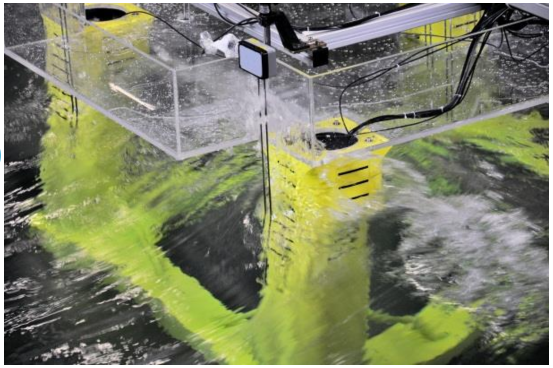


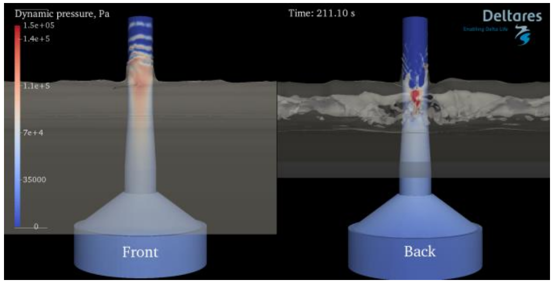
Geotechnics

- ✓ Geotechnical design of foundations (e.g. cyclic liquefaction)
- ✓ Pile installation techniques (impact-driving, vibrating)
- ✓ Cable burial techniques (jetting, ploughing, trenching, self-burial)
- ✓ External threats to electricity cables (anchors, fishnets, objects)

Deltares

Deltares' activities in offshore wind





Hydrodynamics

- ✓ Metocean/environmental conditions (waves, currents, water levels)
- ✓ Operational forecasting systems (for installation and O&M)
- ✓ Wave loads / impacts on foundations

Geotechnics

- ✓ Geotechnical design of foundations (e.g. cyclic liquefaction)
- ✓ Pile installation techniques (impact-driving, vibrating)
- ✓ Cable burial techniques (jetting, ploughing, trenching, self-burial)
- ✓ External threats to electricity cables (anchors, fishnets, objects)

Morphology & morphodynamics

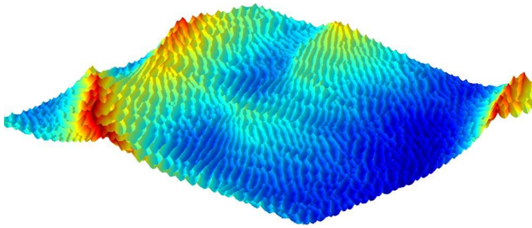
- ✓ Offshore geology, seabed characteristics
- ✓ Scour and scour protection for all kinds of foundations
- ✓ Bed level changes due to morphodynamics (e.g. sand waves)
- ✓ Cable routing and site selection in morphodynamic areas

Offshore surveying

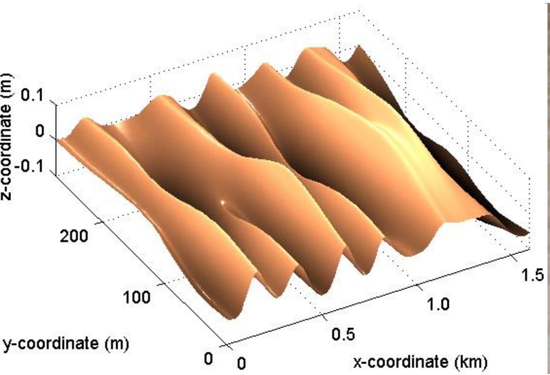
- ✓ Seismic, sonar and other hydrographic surveys

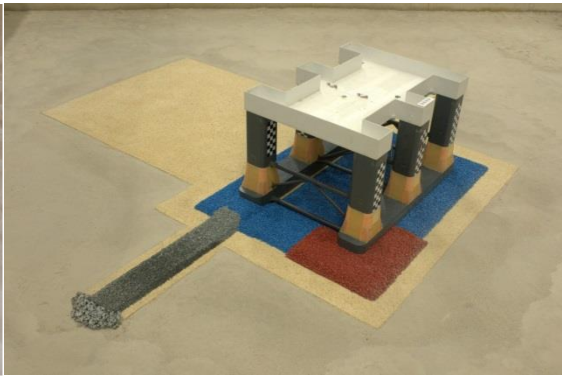
Deltares

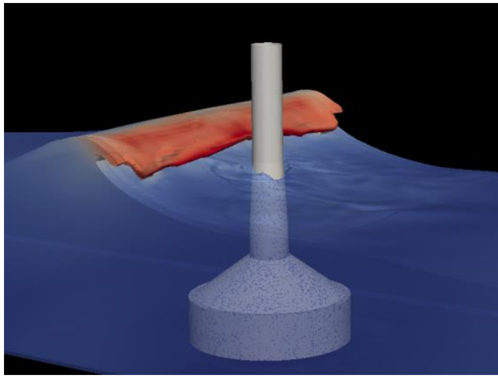
Contents of presentation



- Introduction Deltares
- Introduction Morphodynamics
- Methodology of this study
- Results
- Conclusions
- Recommendations for design





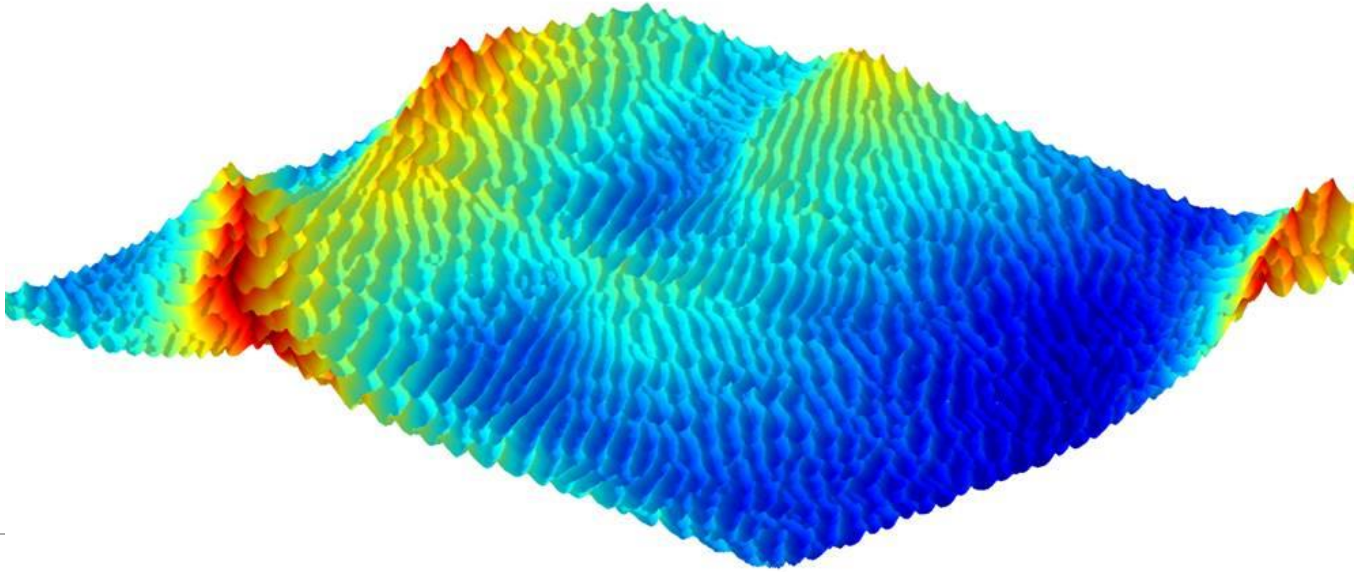


Deltares

Seabed Morphodynamics - definition

*“**Morphodynamics**, the study of landscape changes due to erosion and sedimentation” [wiktionary]*

*“**Morphodynamics** refers to the study of the interaction and adjustment of the seafloor topography and fluid hydrodynamic processes, seafloor morphologies and sequences of change dynamics involving the motion of sediment. Hydrodynamic processes include those of waves, tides and wind-induced currents.” [wikipedia]*



Deltares

Seabed Morphodynamics

Distinguish between hydrodynamic driving forces:

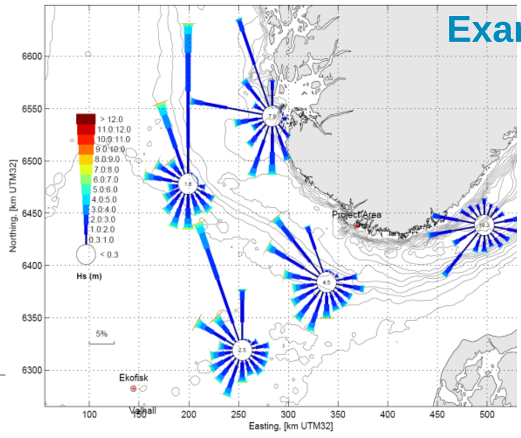
- Coastal profile: often (storm) wave-driven
- Estuaries with tidal channels and flats
- Offshore seabed with sand banks, sand waves, megaripples etc.

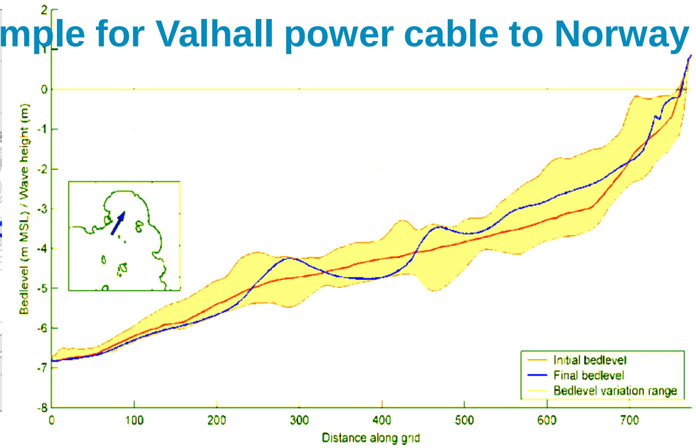
The export cable crosses all area types: requires combination of numerical modelling of storm events (e.g. XBeach, UNIBEST), tidal climate (e.g. Delft-3D) and data-driven methods.

200 years of morphodynamic development in the Western Scheldt, modelled in Delft3D (Van der Wegen and Roelvink, 2012)

Link

Example for Valhall power cable to Norway





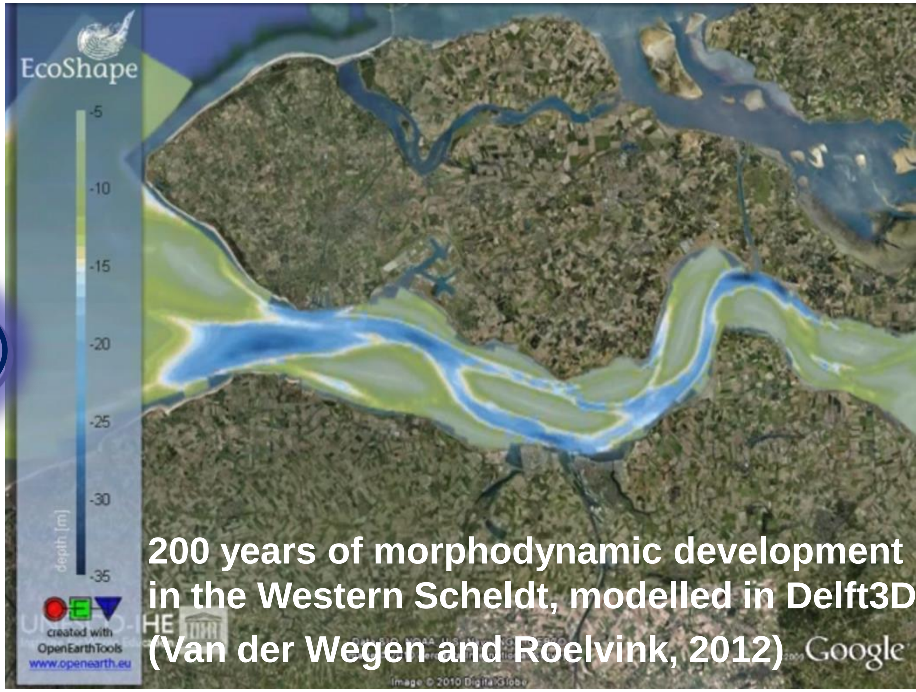
Seabed Morphodynamics

Distinguish between hydrodynamic driving forces:

today

- Coastal profile: often (storm) wave-driven
- Estuaria with tidal channels and flats
- Offshore seabed with sand banks, sand waves, megaripples etc.

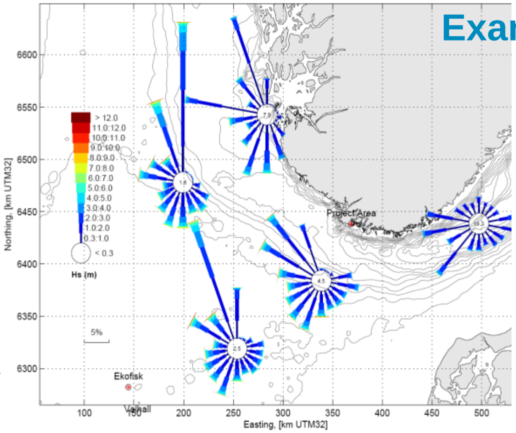
The export cable crosses all area types: requires combination of numerical modelling of storm events (e.g. XBeach, UNIBEST), tidal climate (e.g. Delft-3D) and data-driven methods

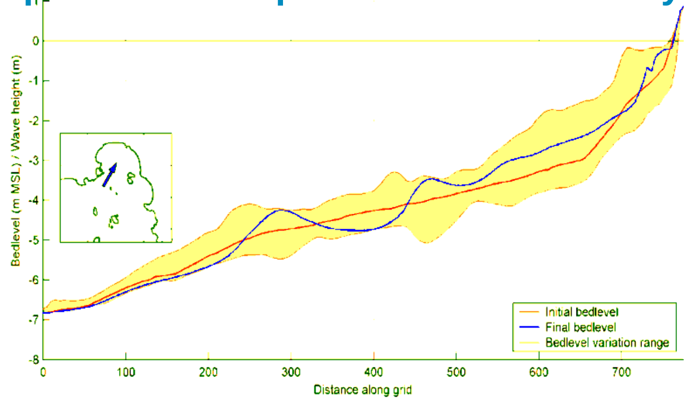


200 years of morphodynamic development in the Western Scheldt, modelled in Delft3D (Van der Wegen and Roelvink, 2012)

Link

Example for Valhall power cable to Norway





Overview of offshore morphodynamic seabed features

	Length	Height	Mobility	Threat to Foundations & Cables
Ripples:	Centimeters	Centimeters	Mobile and Transient	Minimal
Mega-Ripples:	10s of meters	Decimeters	Mobile and Transient	Minimal
Sand Waves:	100s of meters	Meters	Mobile and Persistent	Large
Sand Banks:	Kilometers	10s of meters	Stationary	Minimal

Deltares

Overview of offshore morphodynamic seabed features

	Length	Height	Mobility	Threat to Foundations & Cables
Ripples:	Centimeters	Centimeters	Mobile and Transient	Minimal
Mega-Ripples:				
Sand Waves:				
Sand Banks:	Kilometers	10s of meters	Stationary	Minimal

Ripples and Mega-Ripples too low

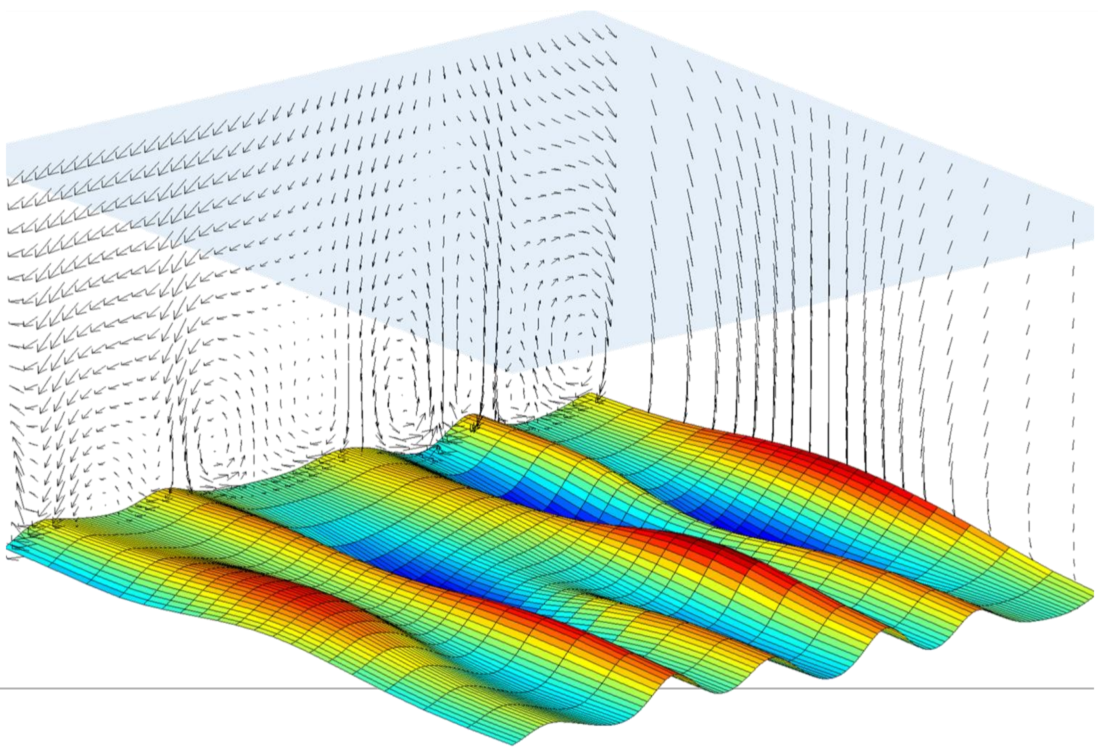
&

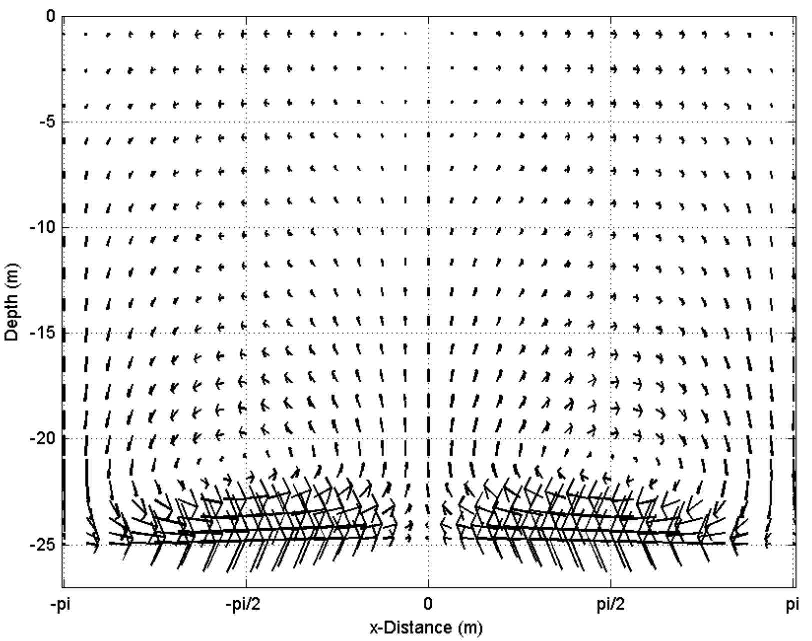
Sand Banks too slow

Sand Wave Morphodynamics

- Inherent property of sandy seabeds
- Development due to tidally averaged recirculation cells
- Global phenomenon of sandy beds in shallow seas !

- Sand wave length: typically 200-600 meters
- Sand wave height: 10-30% of the water depth
- Migration Rate: up to 10s of meters per year

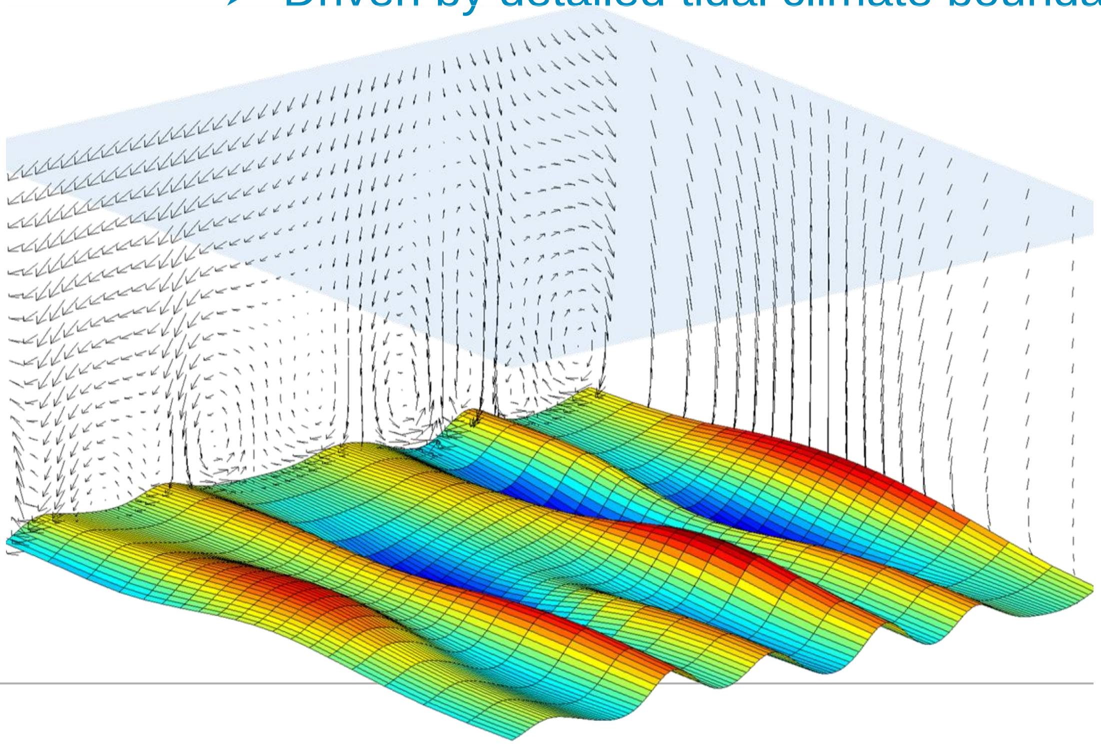


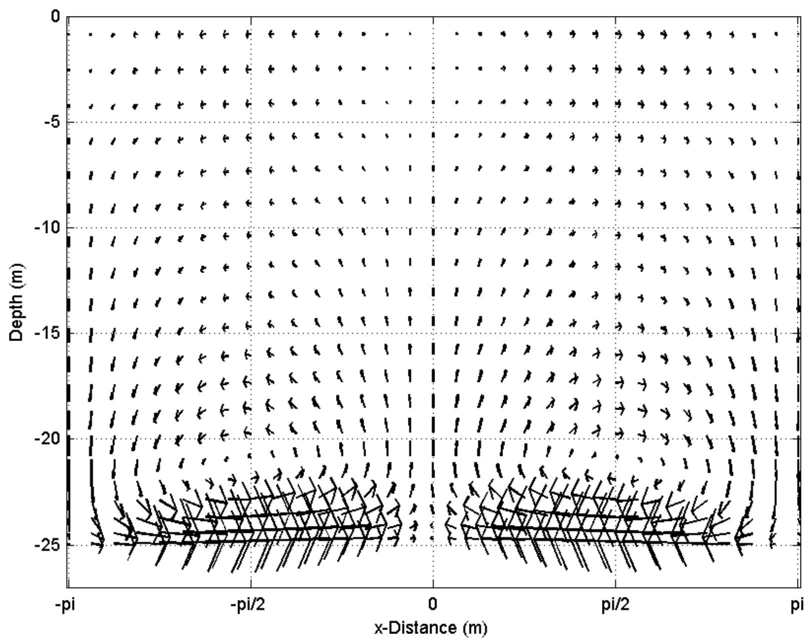


Sand Wave Morphodynamics – Analysis techniques

Two methods to investigate sand wave characteristics:

1. Data-driven analysis based on seabed surveys
   - Preferably 3 (or more) good quality surveys
   - Preferable covering a time span of 10 years (or more)
2. Numerical modelling
   - Using a process-based morphological model (e.g. Delft3D)
   - Driven by detailed tidal climate boundary conditions





Sand Wave Morphodynamics – Analysis techniques

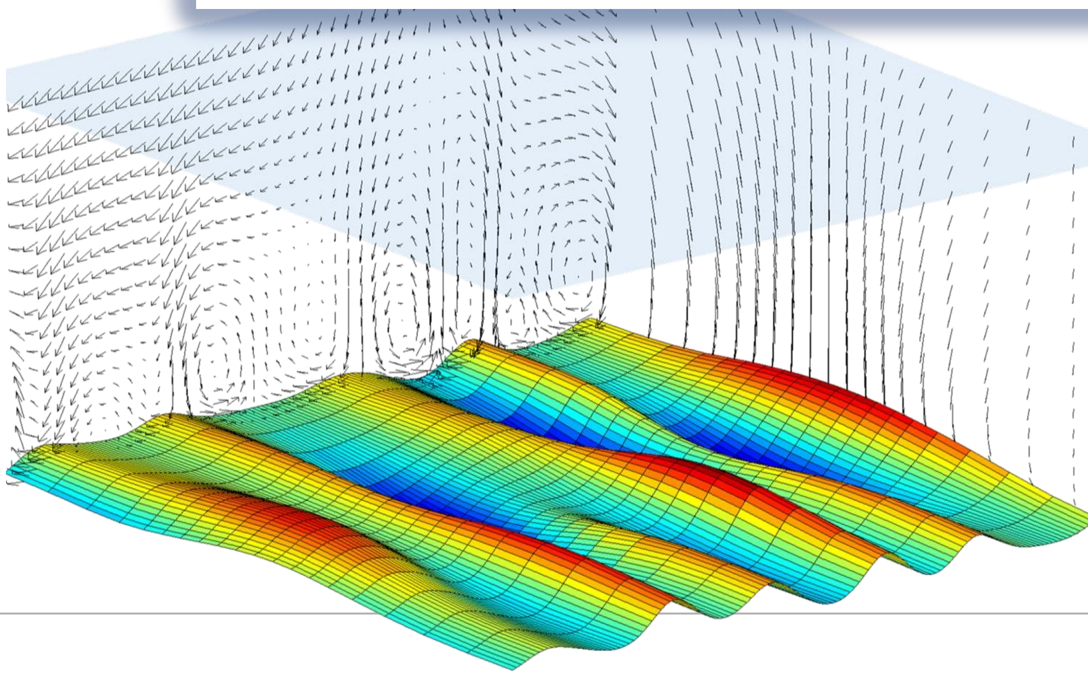
Two methods to investigate sand wave characteristics:

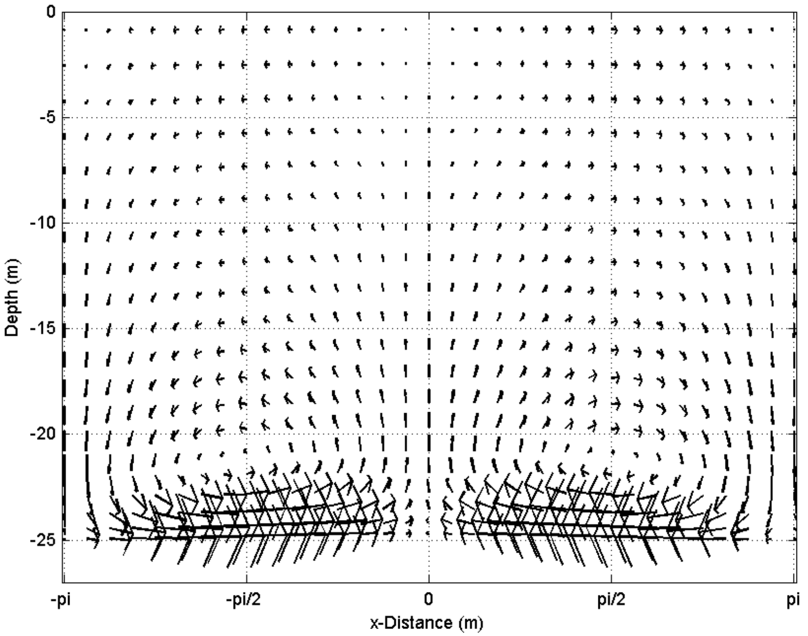
1. Data-driven analysis based on seabed surveys

Most reliable, if data is available

2. Numerical modelling

Only option, if limited/no data is available; useful to investigate dependencies on governing parameters

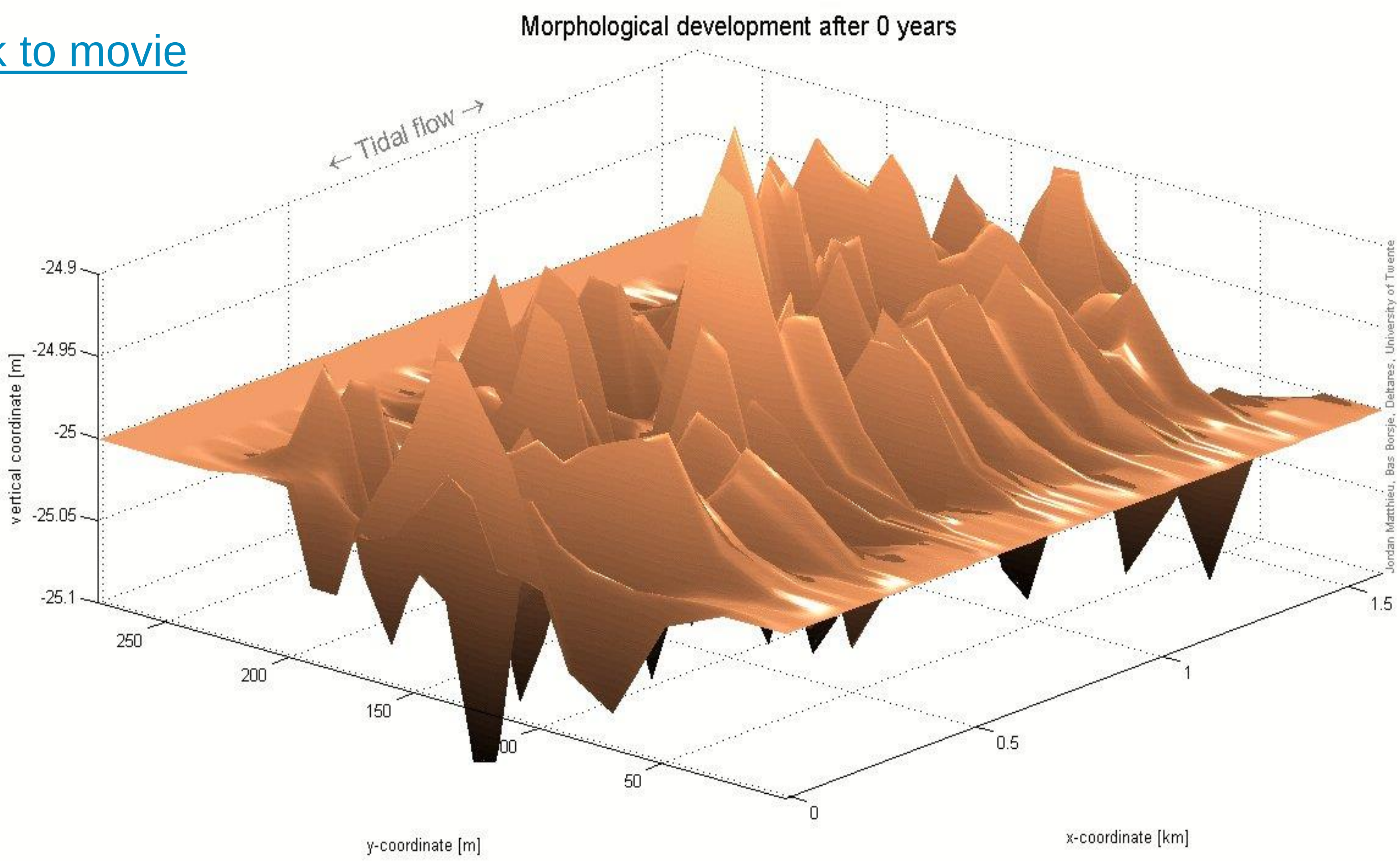




Example of Sand Wave Model in Delft-3D

Self-organizing of random bed perturbations into natural sand wave fields that correspond to the local hydrodynamic forcing, water depth and seabed material

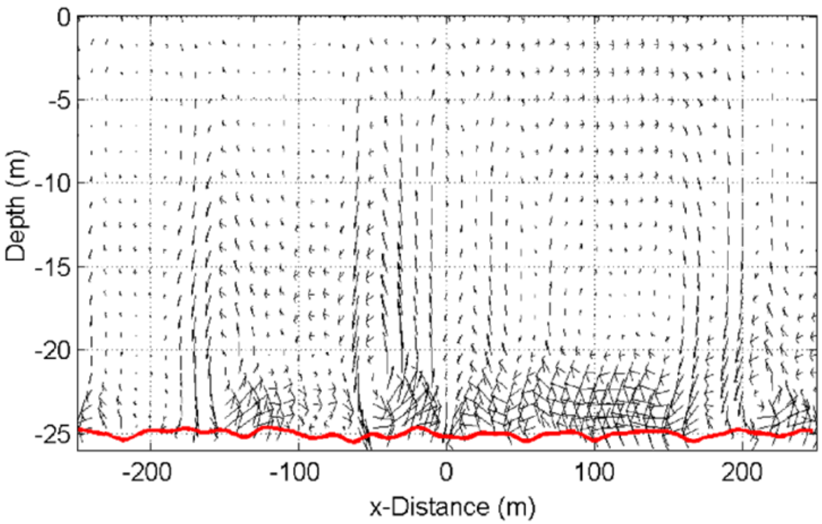
Link to movie

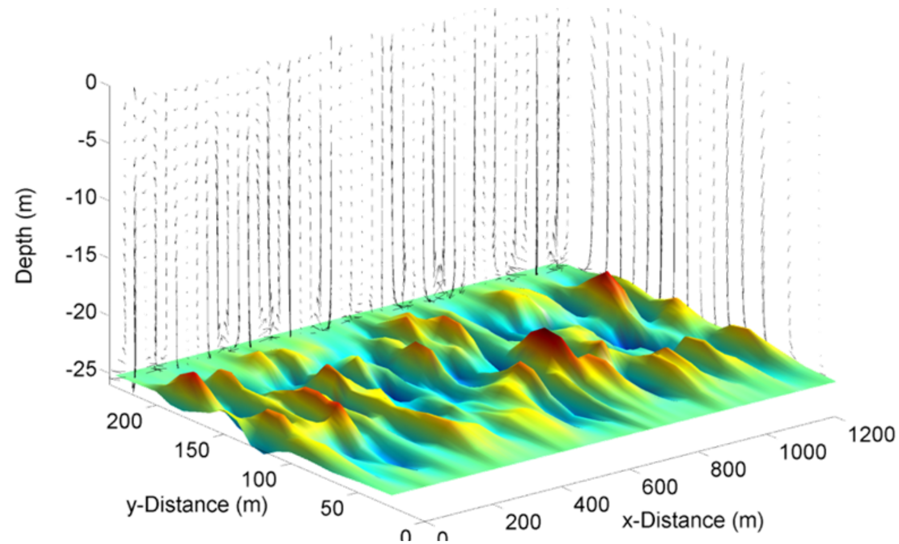


Deltares

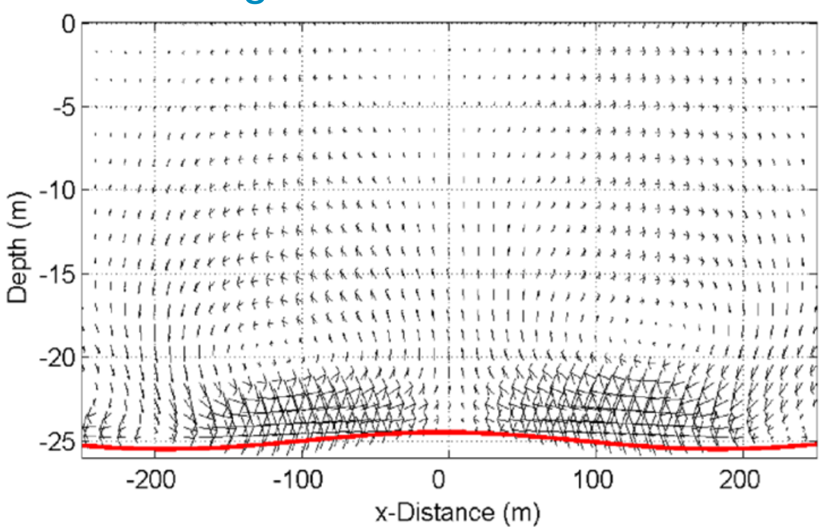
3D-Sand Wave Model in Delft-3D

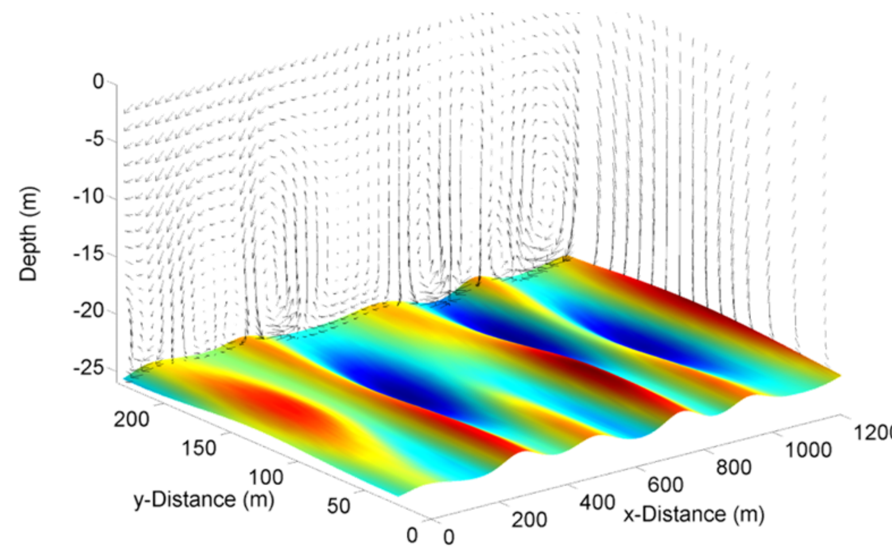
t = 0: Random bed perturbations and chaotic velocity field





Self-organized seabed with tidal-averaged velocity recirculation cells





Sand waves and their environmental dependencies

Migration Rate:

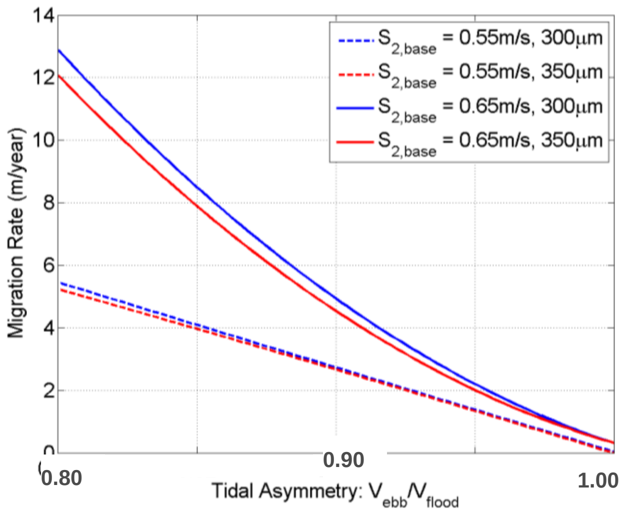
- Grain size
- Tidal asymmetry
- Wavelength

Amplitude:

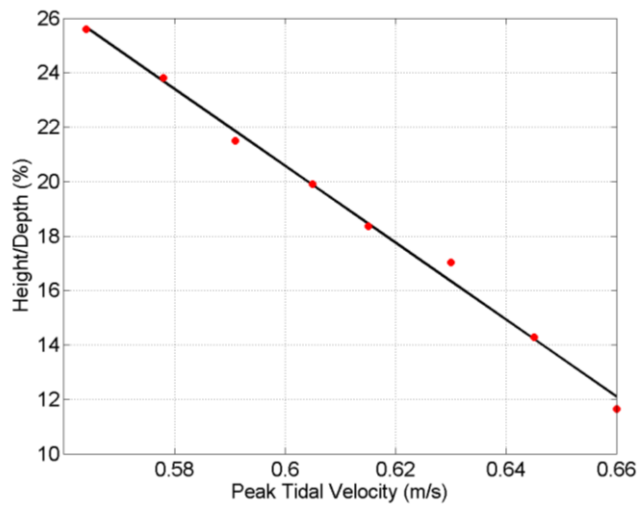
- Grain size
- Tidal asymmetry
- Peak tidal velocity
- Water depth

Wavelength:

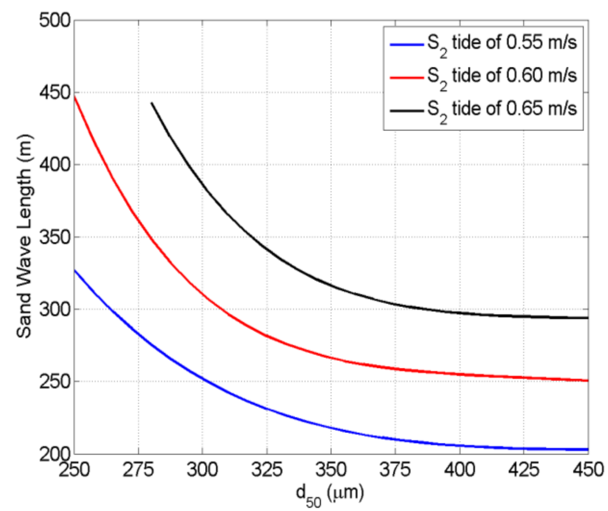
- Grain size
- Peak tidal velocity



Migration rate vs. tidal asymmetry



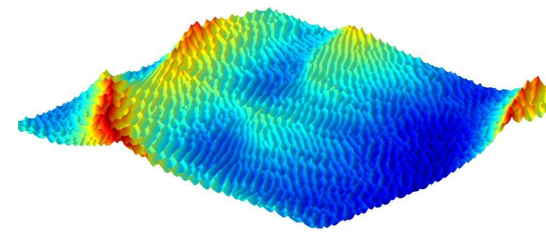
Rel. wave height vs. peak tidal velocity



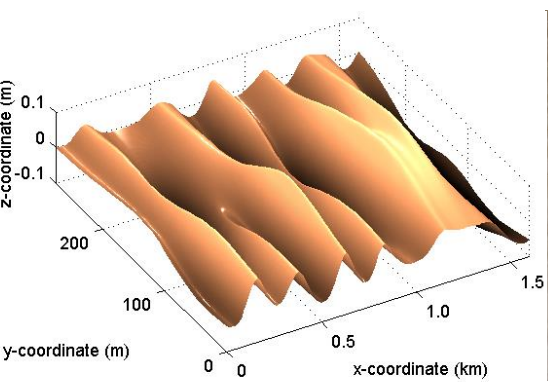
Sand wavelength vs. grain size

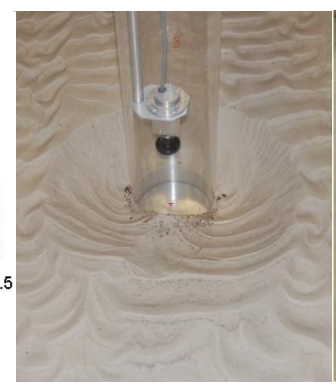
Deltares

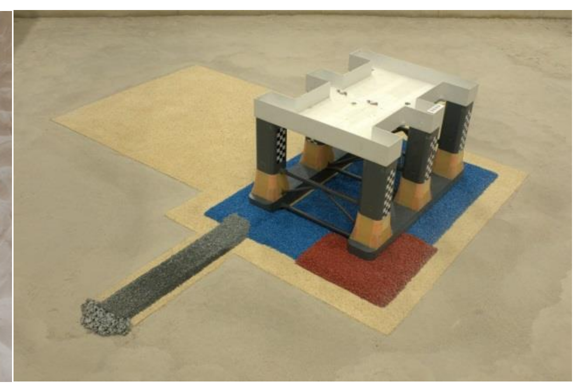
Contents of presentation

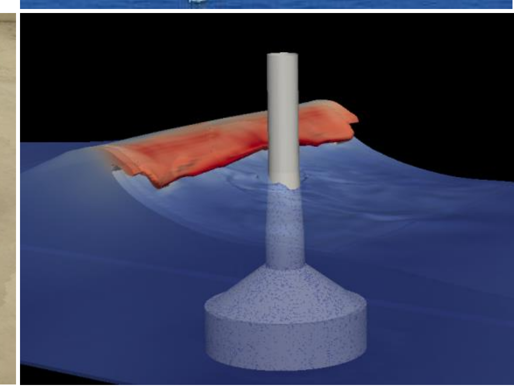


- Introduction Deltares
- Introduction Morphodynamics
- Methodology of this study
- Results
- Conclusions and Recommendations









Required Design Seabed Levels

Reference SeaBed Level (RSBL)

The lowest possible seabed level in the period 2015-2046

RSBL = Static Seabed Level - Max. Negative Envelope of Sand Wave Field until 2046 + Uncertainty Band

Maximum SeaBed Level (MSBL)

The highest possible seabed level during the lifetime of the wind parks

MSBL = Static Seabed Level + Max. Positive Envelope of Sand Wave Field until 2046 + Uncertainty Band

Required Design Seabed Levels

Reference SeaBed Level (RSBL)

The lowest possible seabed level in the period 2015-2046

RSBL = Static Seabed Level - Max. Negative Envelope of Sand Wave Field until 2046 + Uncertainty Band

Maximum SeaBed Level (MSBL)

The highest possible seabed level during the lifetime of the wind parks

MSBL = Static Seabed Level + Max. Positive Envelope of Sand Wave Field until 2046 + Uncertainty Band

Maximum seabed lowering in period 2015-2046

Difference between 2015-bathymetry and RSBL

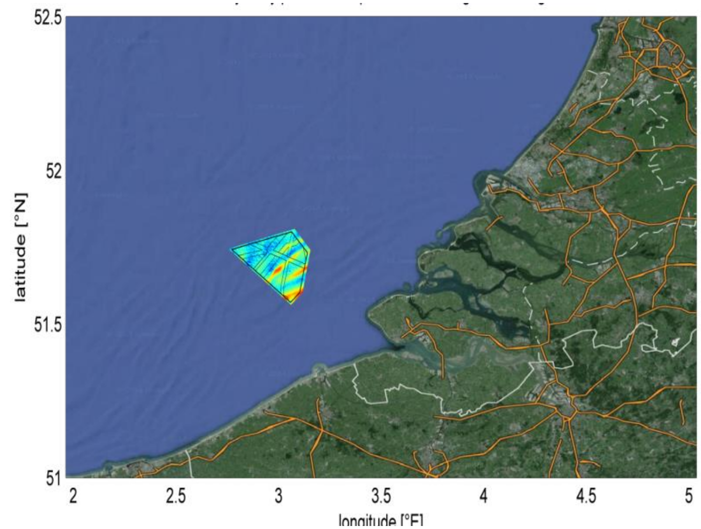
Maximum seabed rising in period 2015-2046

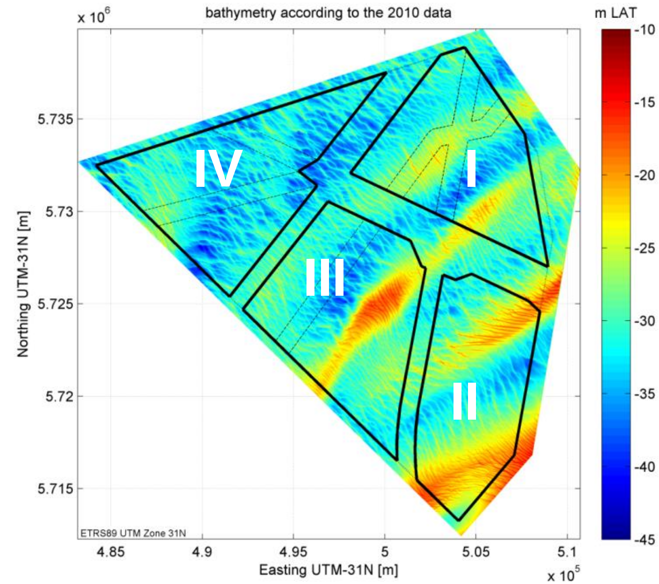
Difference between 2015-bathymetry and MSBL

Methodology and calculation steps (I)

In order to predict these levels for the BWFZ,
the following techniques were used:

1. Obtaining 3 bathymetrical datasets
2. Large-scale bathymetric filtering to distinguish between the “static” and “mobile” seabed features
3. Filtering and analysis of megaripples (to be part of the uncertainty band)
4. Extraction of the sand wave field (excluding sand banks and megaripples) for sand wave analysis
5. Automated detection of sand wave migration directions
6. Fourier analysis on individual sand waves to determine sand wave migration rates





Deltares

Methodology and calculation steps (II)

...

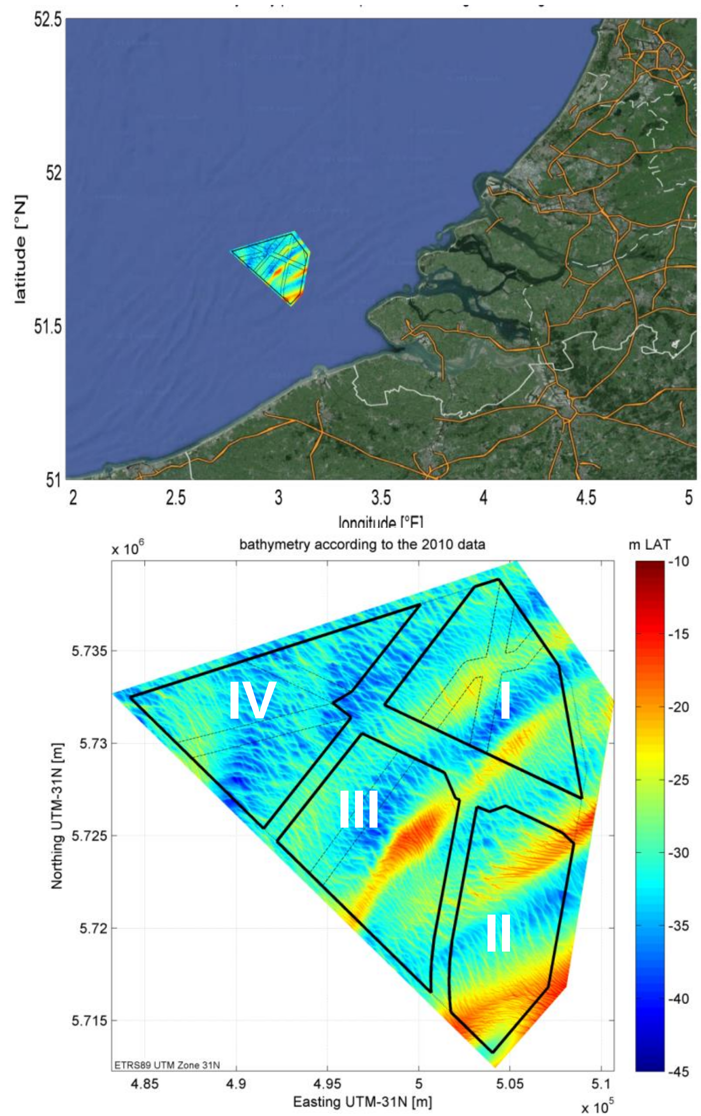
7. Estimating uncertainty range based on measurement errors, processing inaccuracies and smaller scale seabed features such as megaripples

8. Migration of sand wave fields with calculated migration rates and directions

9. Combining migrated sand wave fields with “static” bathymetry and uncertainty range to compute RSBL and MSBL

10. Comparing the isopach of the base of the Holocene Formation with the RSBL to avoid overly conservative downward bed level changes

11. Translate RSBL and MSBL into zones with various recommendation levels for offshore foundations and cables



Methodology and calculation steps (III)

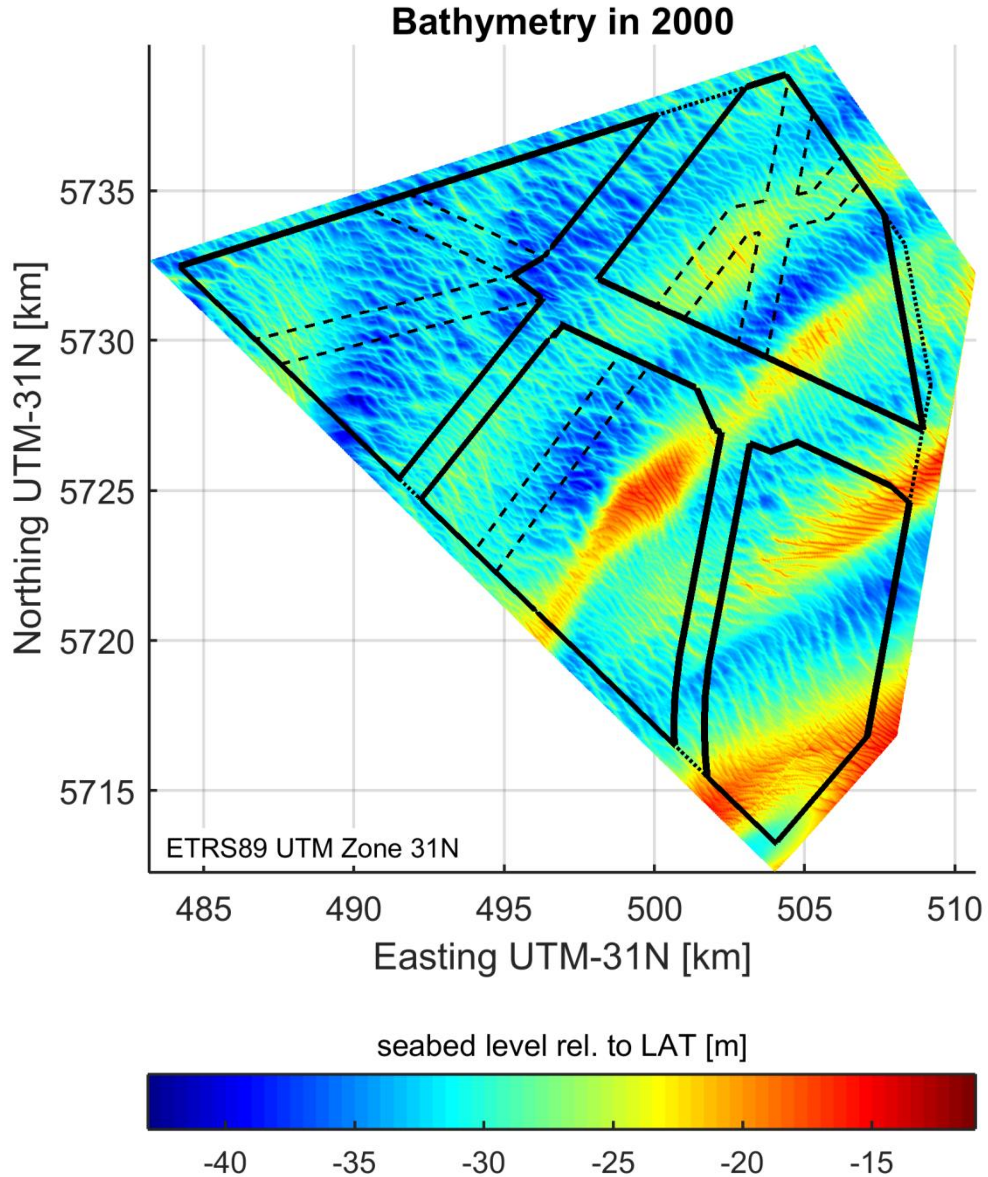
Definitions of various bathymetrical data sets used in this study

Short name	Description	Sand banks	Sand waves	Mega-ripples
2015 bathymetry	Full measured bathymetry by Deep in 2015	X	X	X
Static bathymetry	Long-term mean bathymetry (for the considered period / lifetime of wind farms)	X		
Quasi-static bathymetry	Bathymetry with megaripples filtered out	X	X	
Mobile bathymetry	Bathymetry with mobile morph. seabed features (sand wave directions + Fourier analysis)		X	X
Sand Wave field	Sand wave field without megaripples (to migrate future bathymetries, RSBL, MSBL)		X	
Megaripple field	Megaripple field (to determine uncertainty band)			X

Methodology – Bathymetry 1999/2000/2001

Bathymetry constructed of 4 SBES in 1999, 2000 and 2001, taken by the Netherlands Hydrographic Office of the Royal Netherlands Navy.

(note the site contours have changed in the meantime and Site V has been added in the northern part of Site III)

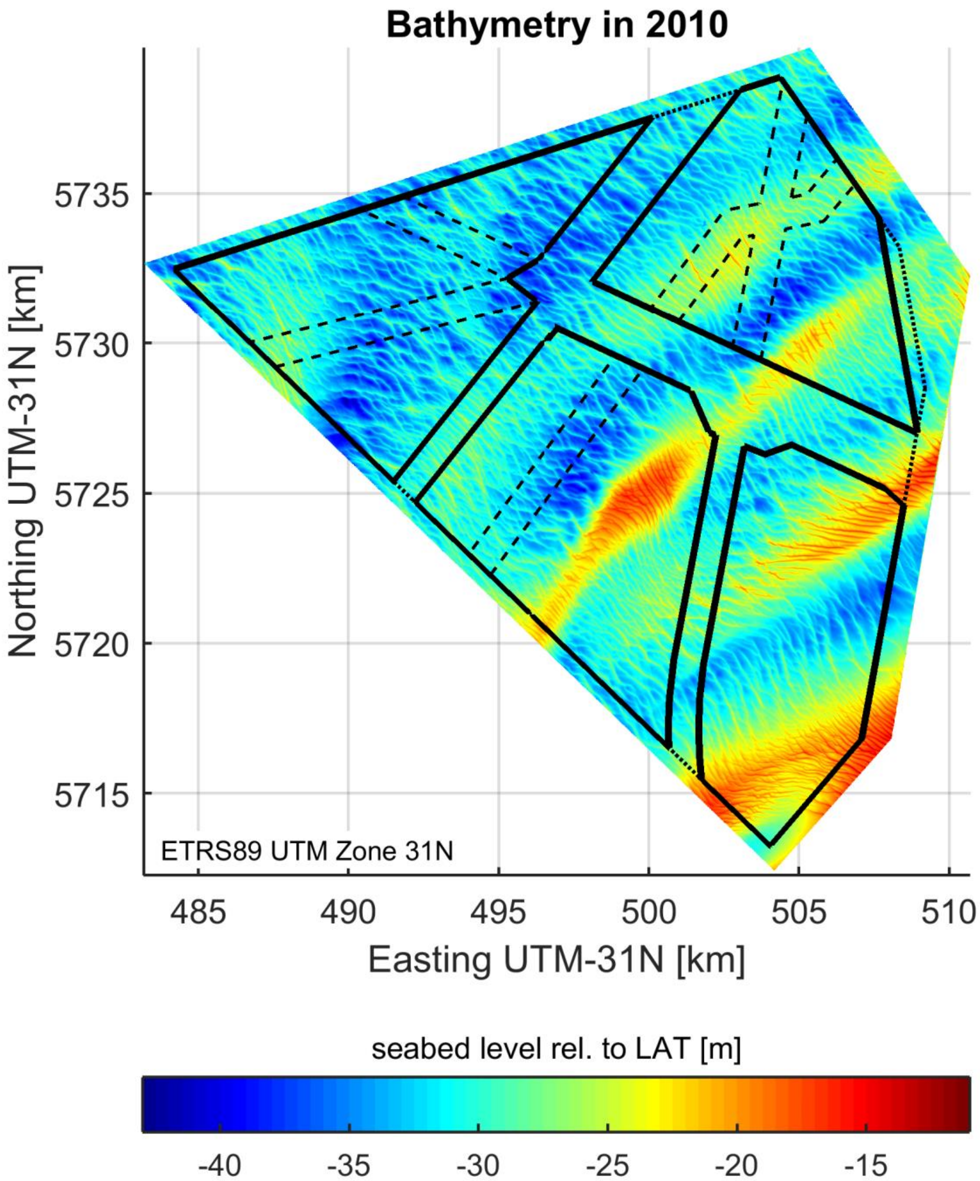


Methodology – Bathymetry 2010

Bathymetry constructed of
3 MBES in 2010,

taken by the Netherlands Hydrographic Office of the Royal Netherlands Navy.

(note the site contours have changed in the meantime and Site V has been added in the northern part of Site III)

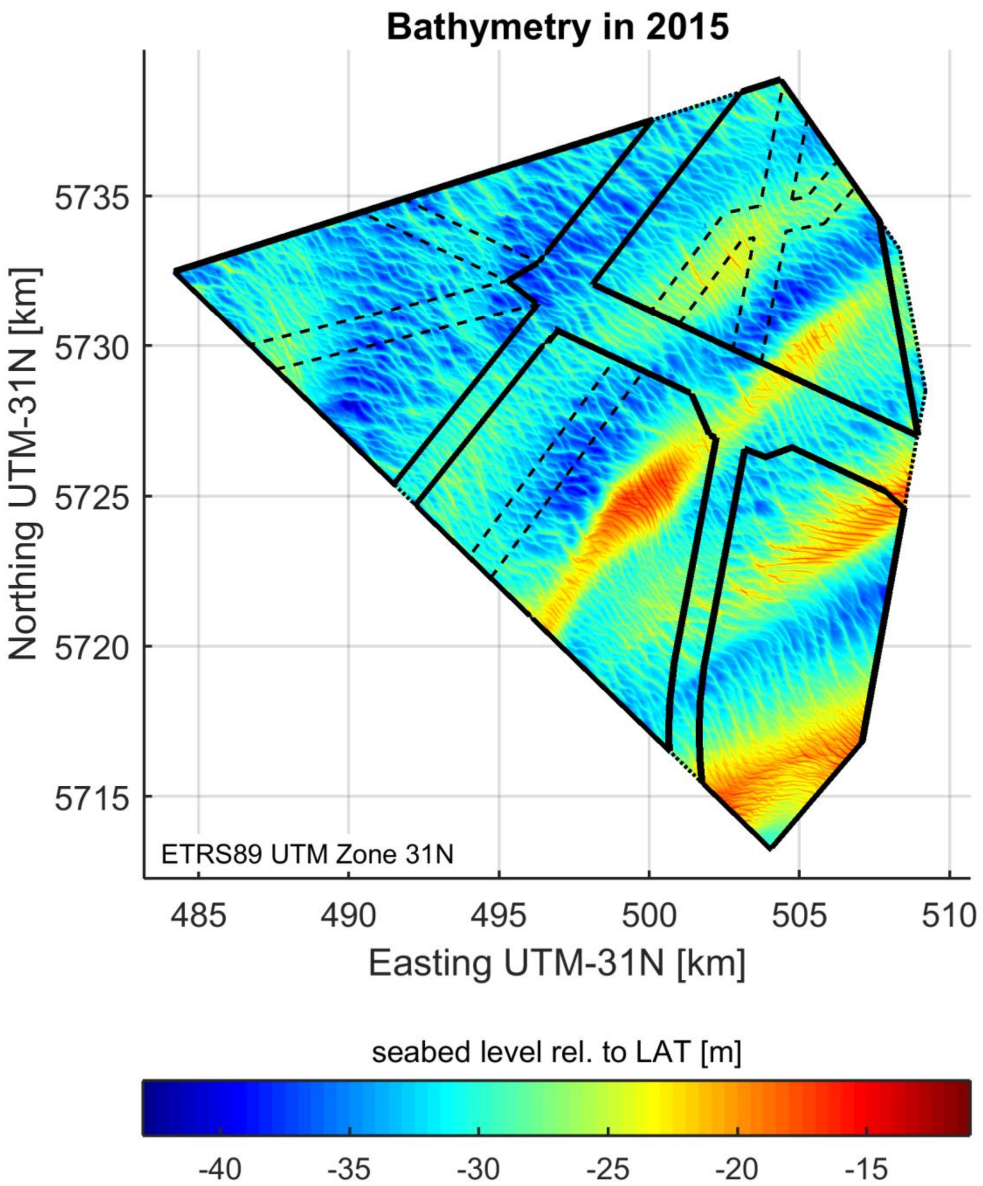


Methodology – Bathymetry 2015

Bathymetry constructed of
2 MBES in 2015, taken by:

- Deep (Site I and II)
- Fugro (Site III and IV)

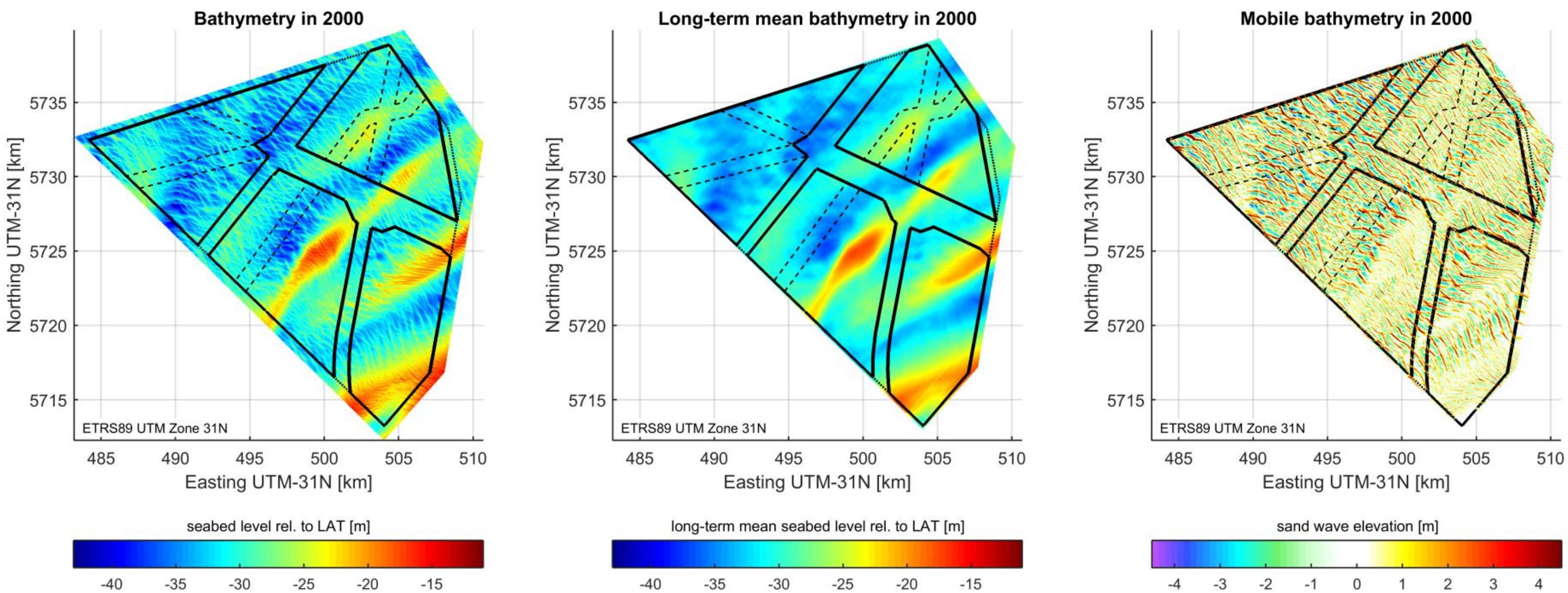
(note the site contours have changed in the meantime and Site V has been added in the northern part of Site III)



Methodology – Large-scale bathymetric filtering

- Goal is to separate **mobile** and **static** bathymetry
- **Sand waves** have an average crest orientation around the **SE-NW-axis** and the sand banks have an average orientation more or less perpendicular to the sand waves
- For filtering it was decided to use an **ellipsoid** with the long axis under an angle of **45°N**. The filter size along the long axis was chosen at **1000m**, while the filter size along the short axis was only **50m**.
- In this way, averaging over the sand waves did **not cause too much smoothening of the sand banks**, while a filter size of 1000m is longer than the longest observed sand wave lengths in the BWFZ, ensuring that all sand waves are filtered out

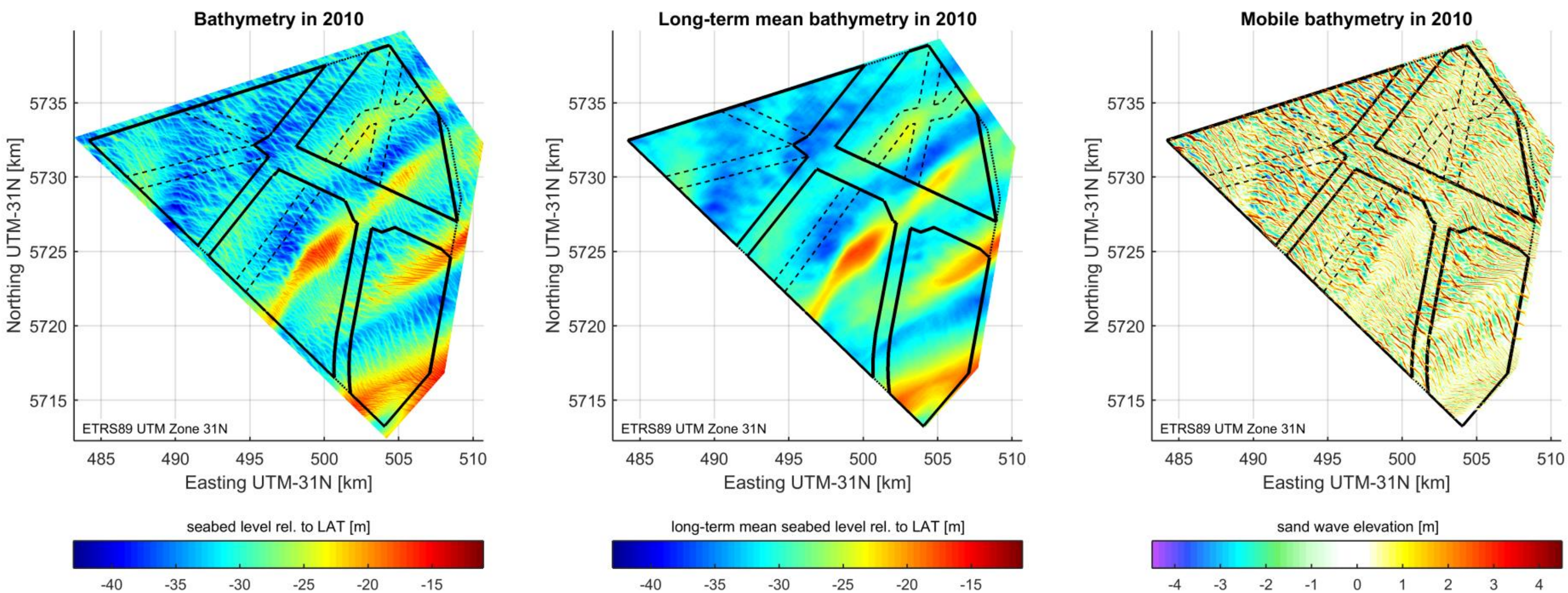
2000-bathymetry - static bathymetry = mobile bathymetry



Methodology – Large-scale bathymetric filtering

- Goal is to separate **mobile** and **static** bathymetry
- **Sand waves** have an average crest orientation around the **SE-NW-axis** and the sand banks have an average orientation more or less perpendicular to the sand waves
- For filtering it was decided to use an **ellipsoid** with the long axis under an angle of **45°N**. The filter size along the long axis was chosen at **1000m**, while the filter size along the short axis was only **50m**.
- In this way, averaging over the sand waves did **not cause too much smoothening of the sand banks**, while a filter size of 1000m is longer than the longest observed sand wave lengths in the BWFZ, ensuring that all sand waves are filtered out

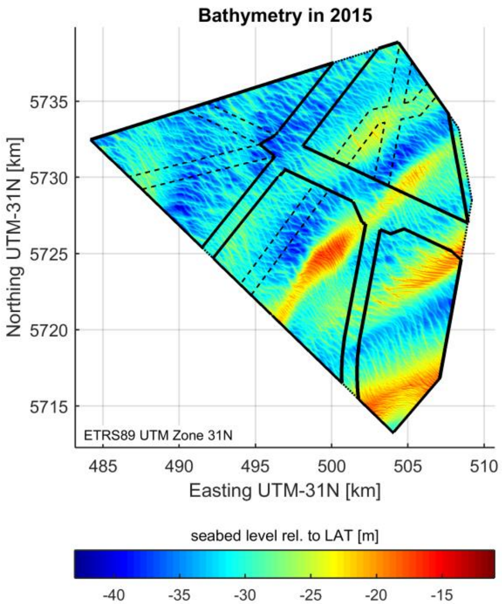
2010-bathymetry - static bathymetry = mobile bathymetry

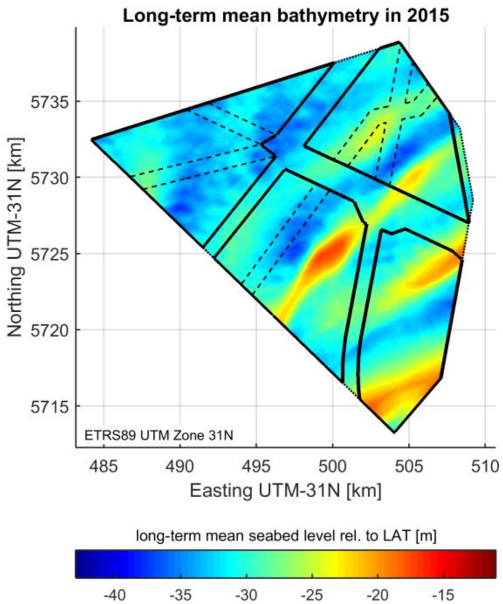


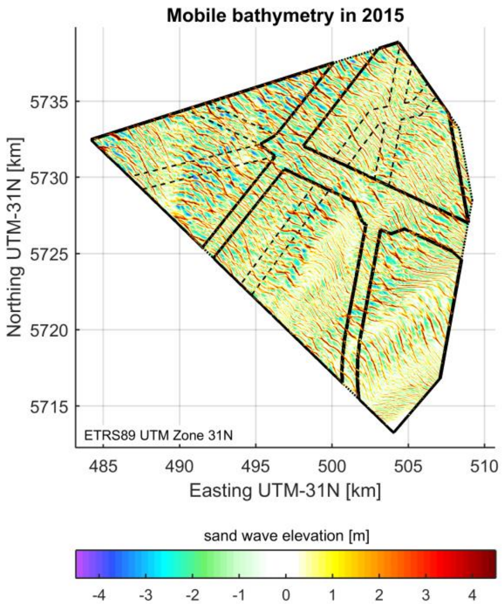
Methodology – Large-scale bathymetric filtering

- Goal is to separate **mobile** and **static** bathymetry
- **Sand waves** have an average crest orientation around the **SE-NW-axis** and the sand banks have an average orientation more or less perpendicular to the sand waves
- For filtering it was decided to use an **ellipsoid** with the long axis under an angle of **45°N**. The filter size along the long axis was chosen at **1000m**, while the filter size along the short axis was only **50m**.
- In this way, averaging over the sand waves did **not cause too much smoothening of the sand banks**, while a filter size of 1000m is longer than the longest observed sand wave lengths in the BWFZ, ensuring that all sand waves are filtered out

2015-bathymetry - static bathymetry = mobile bathymetry

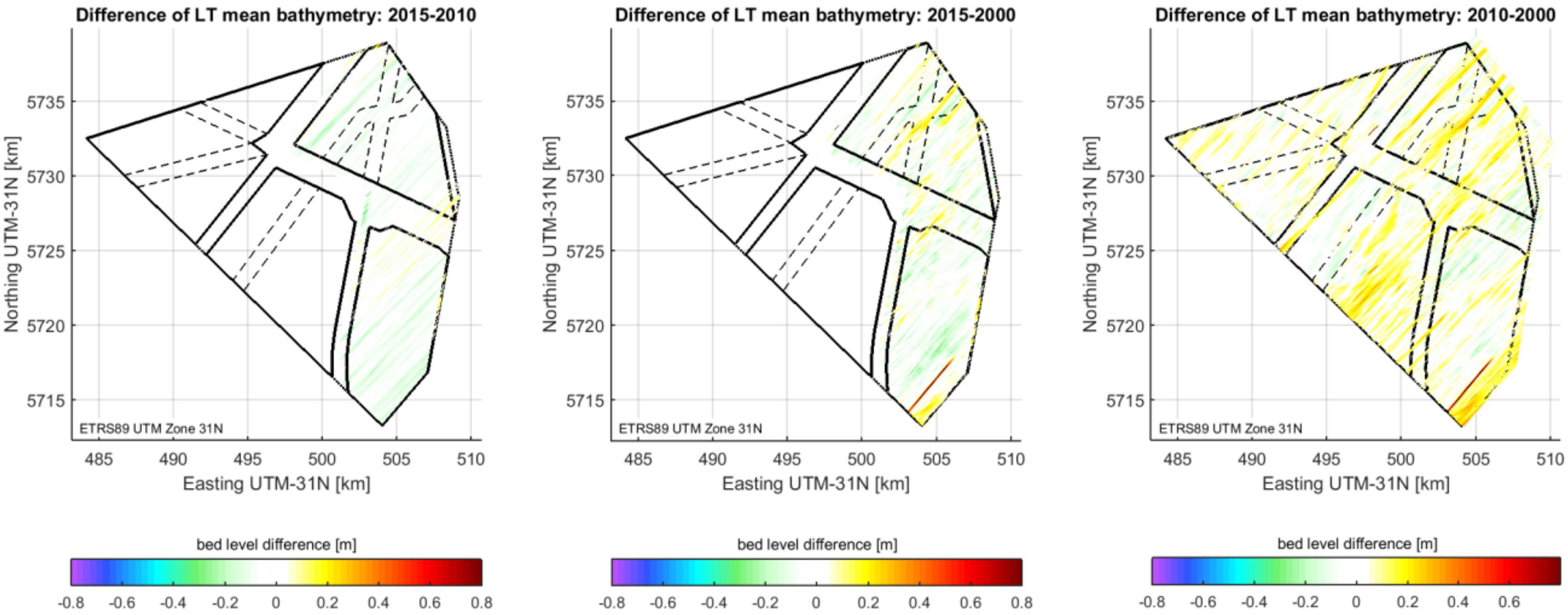






Methodology – Check difference between static bathies

If the filtering method is accurate and if the Static Bathymetries are indeed "static", the differences between different years should be negligible:

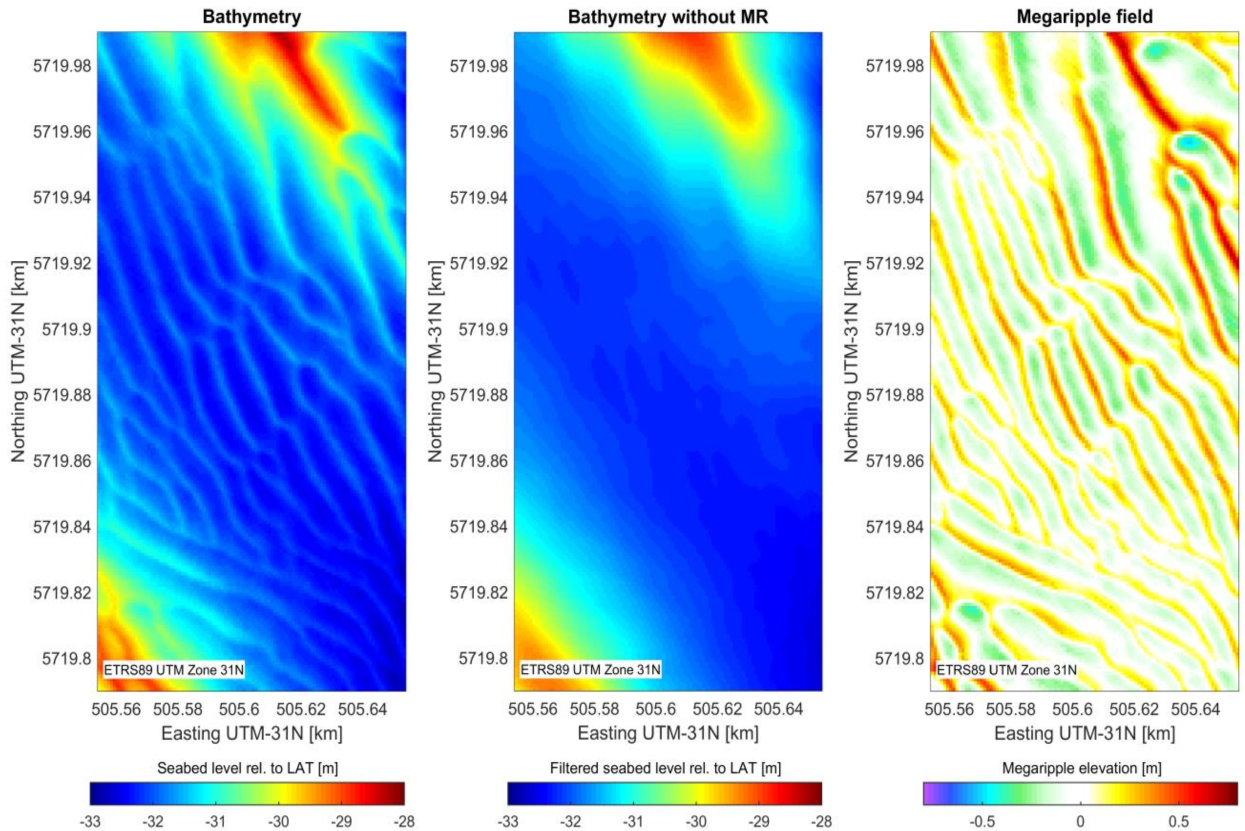


- Differences are minor: but no migration or growing/shrinking of sand banks can be observed.
- Assumption of static sand banks over periods of decades seems valid.

Methodology – megaripple analysis (I)

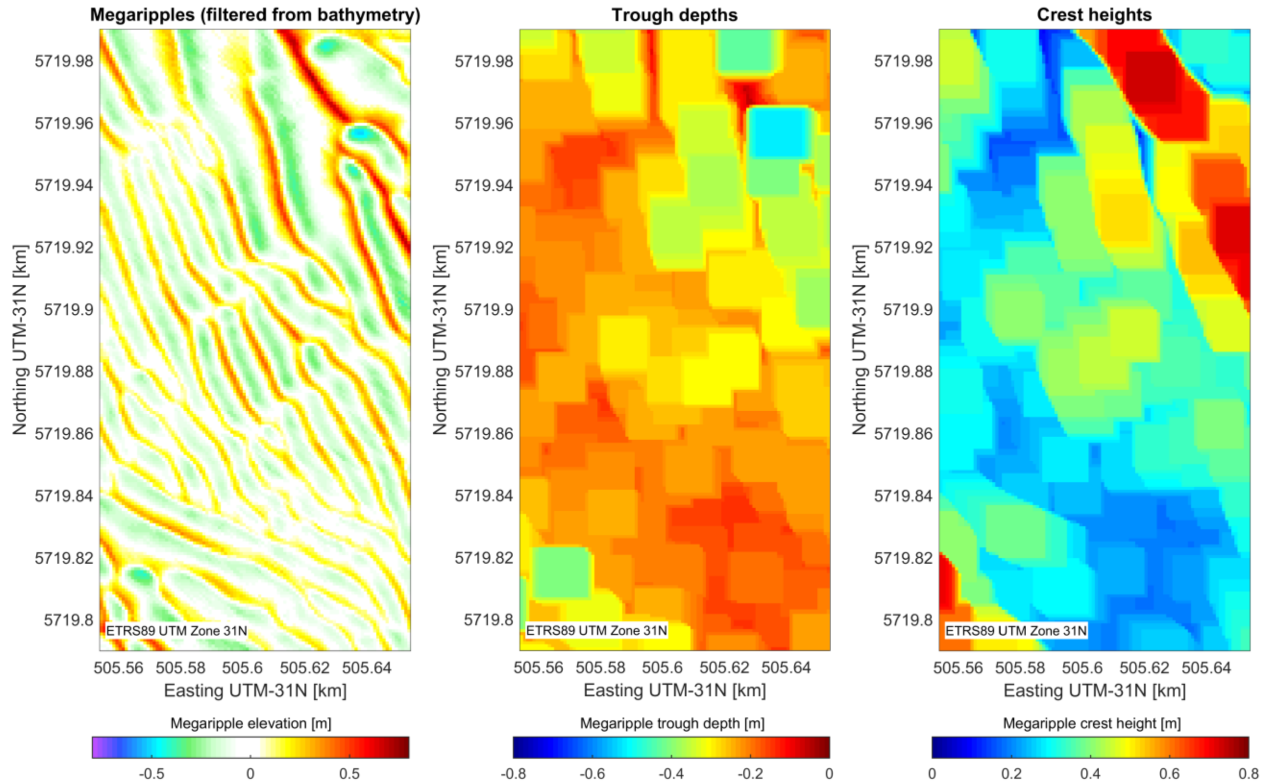
- megaripples have large migration speeds: many megaripples will pass at each foundation throughout the lifetime of wind farms.
- the migration of the megaripples will and cannot be determined from the data
- solution: analyse the megaripple field and include some representative statistical values in the uncertainty band

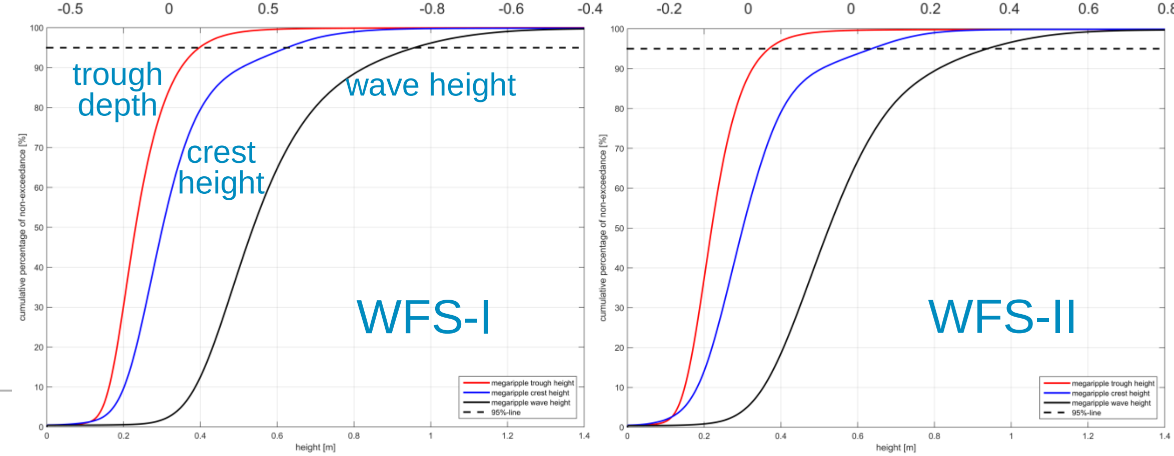
- typical wavelengths of 8-15m
- bathymetry filtered with block filter of 15m to obtain “Sand Wave Field”
- 2015-survey (1x1m) used for analysis
- rather irregular megaripple pattern



Methodology – megaripple analysis (II)

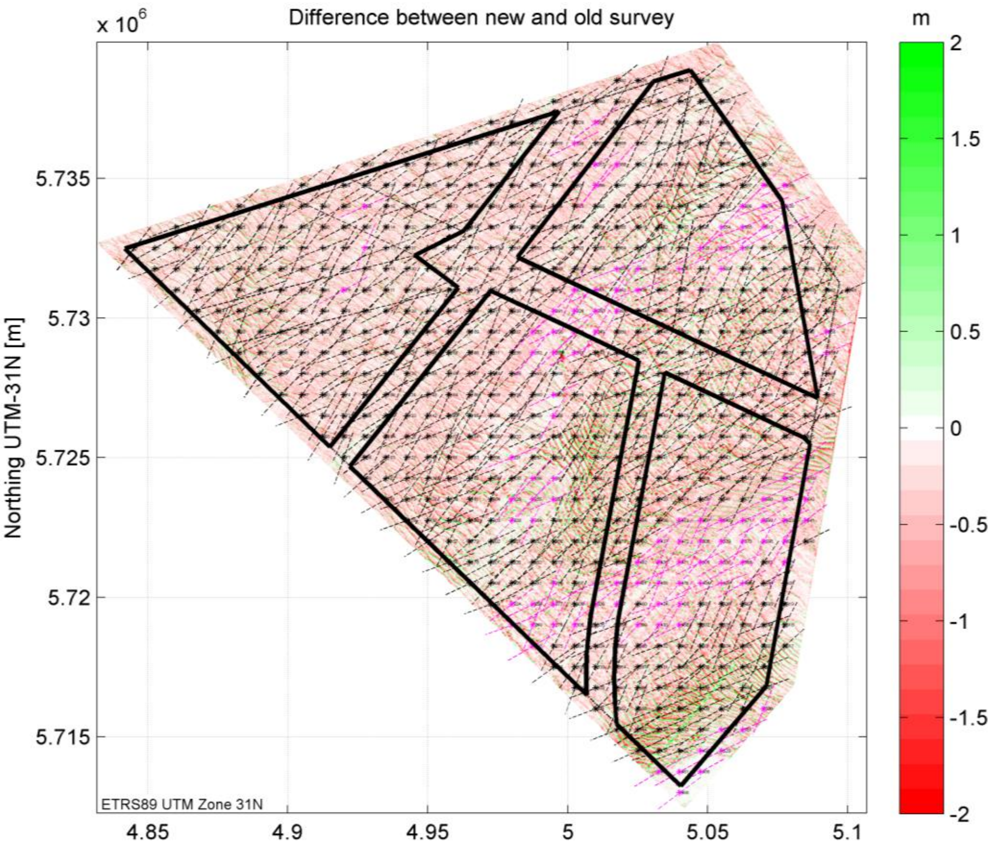
- Megaripple field analyzed to determine trough depths and crest heights
- Non-exceedance curves determined for WFS-I and WFS-II
- The 95% non-exceedance values:
  ~0.40m: trough depth
  ~0.60m: crest height
- These values will be included as uncertainty





Methodology – Direction of sand wave migration

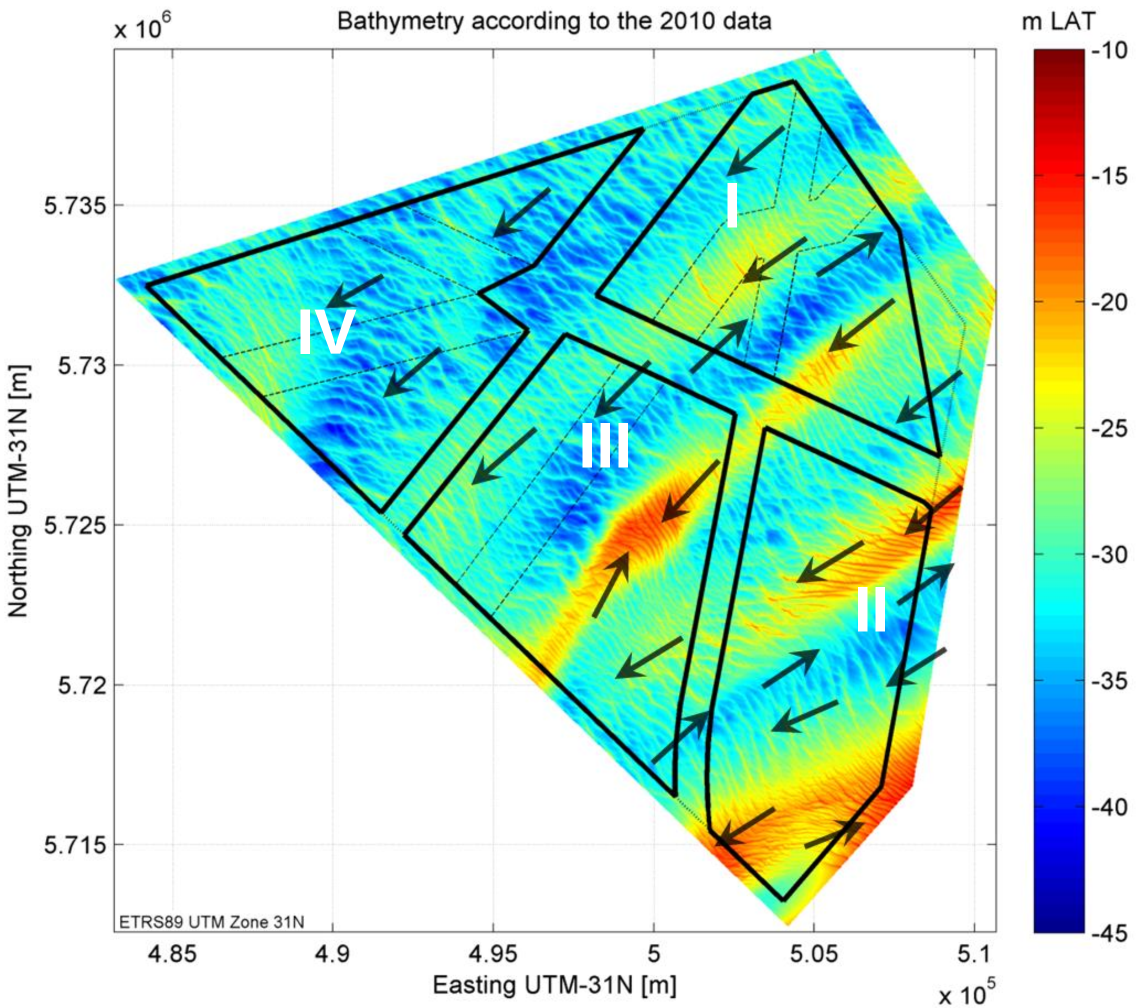
- Analyze sand wave fields at many different transects
- Determine migration directions by finding the best fit (optimizing cost function)
- Directions determined for 3 combinations of differences between Mobile Bathymetries for 665 random transects:
  - ✓ 2010 – 2000
  - ✓ 2015 – 2000
  - ✓ 2015 – 2010



purple transects: migration to NE
black transects: migration to SW

Methodology – Direction of sand wave migration

- The sand waves in the BWFZ are migrating to the southwest (ebb direction) as well as to the northeast (flood direction)
- With a main axis of approximately 230°N and 50°N. This axis varies over the area with a variation of up to 30°



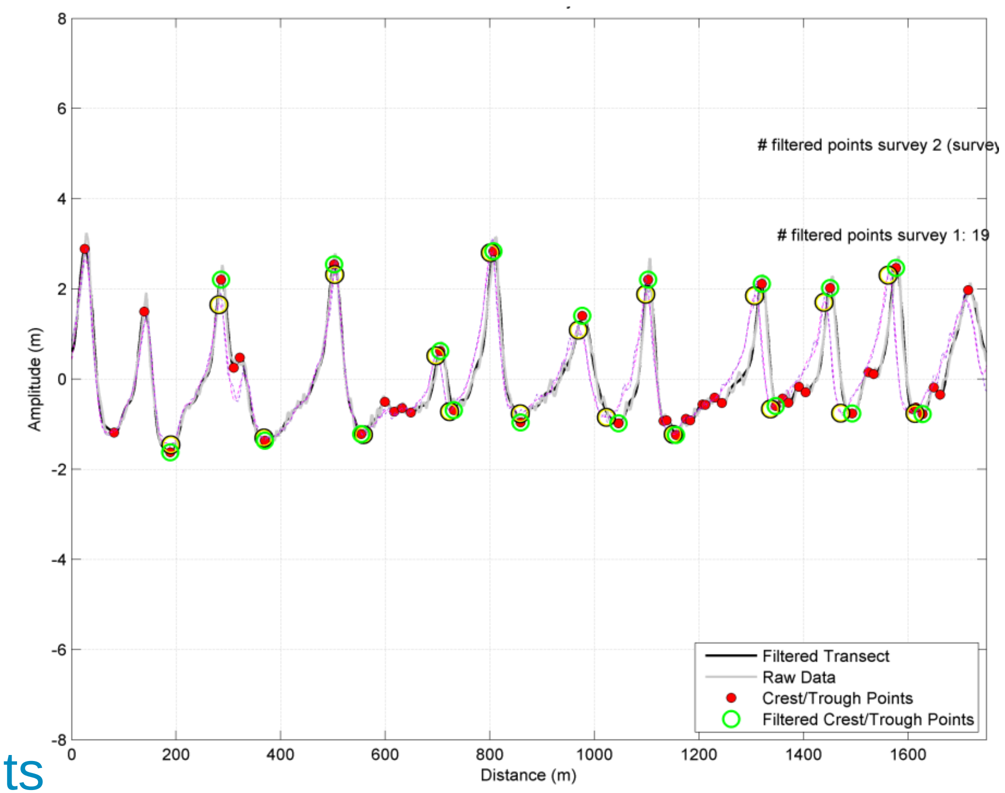
Schematized and simplified migration directions

Methodology - Fourier analysis on transects

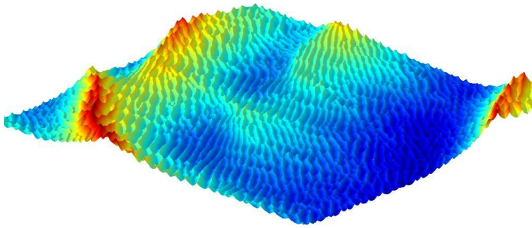
- Identify crests and troughs
- Track identified points
- Obtain statistics per transect

- Some manual steps:
  - Check each transect
  - Generation / extinction of small waves / megaripples

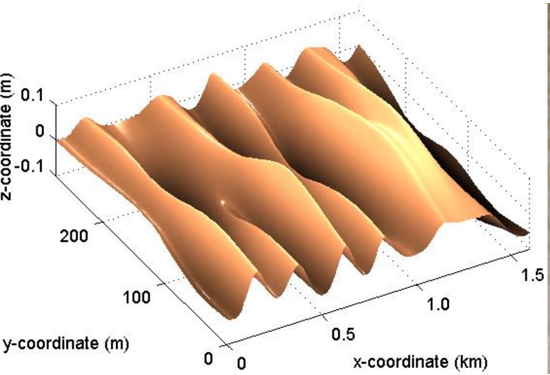
- Sand wave statistics are determined by combining results for each transect and 3 survey combinations (2000/2010, 2000/2015, 2010/2015)

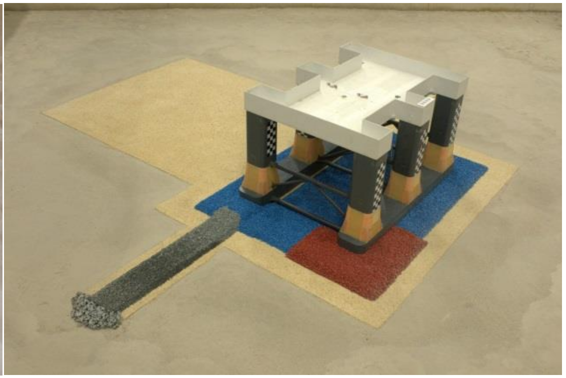


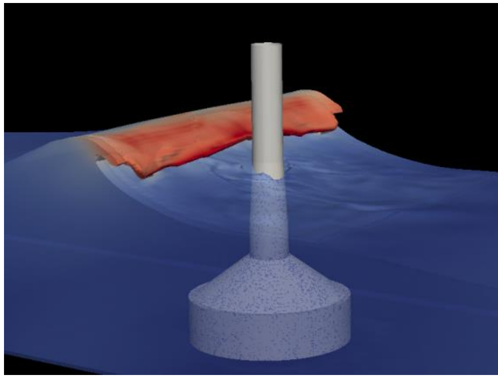
Contents of presentation



- Introduction Deltares
- Introduction Morphodynamics
- Methodology of this study
- Results
- Conclusions and Recommendations



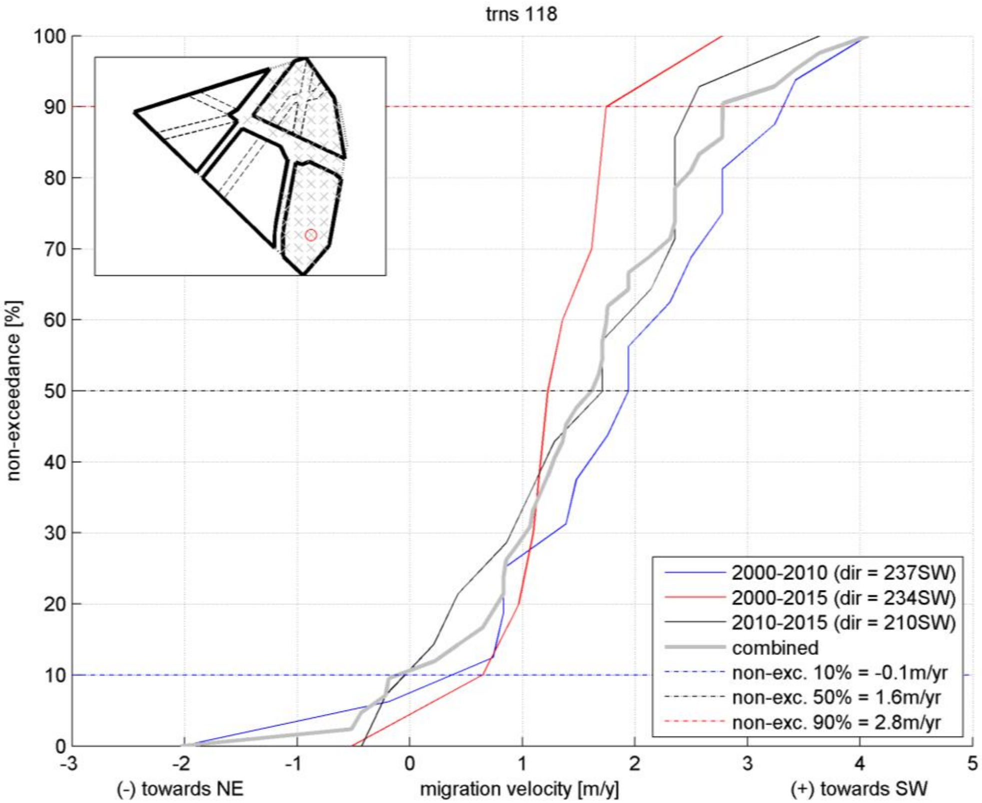




Deltares

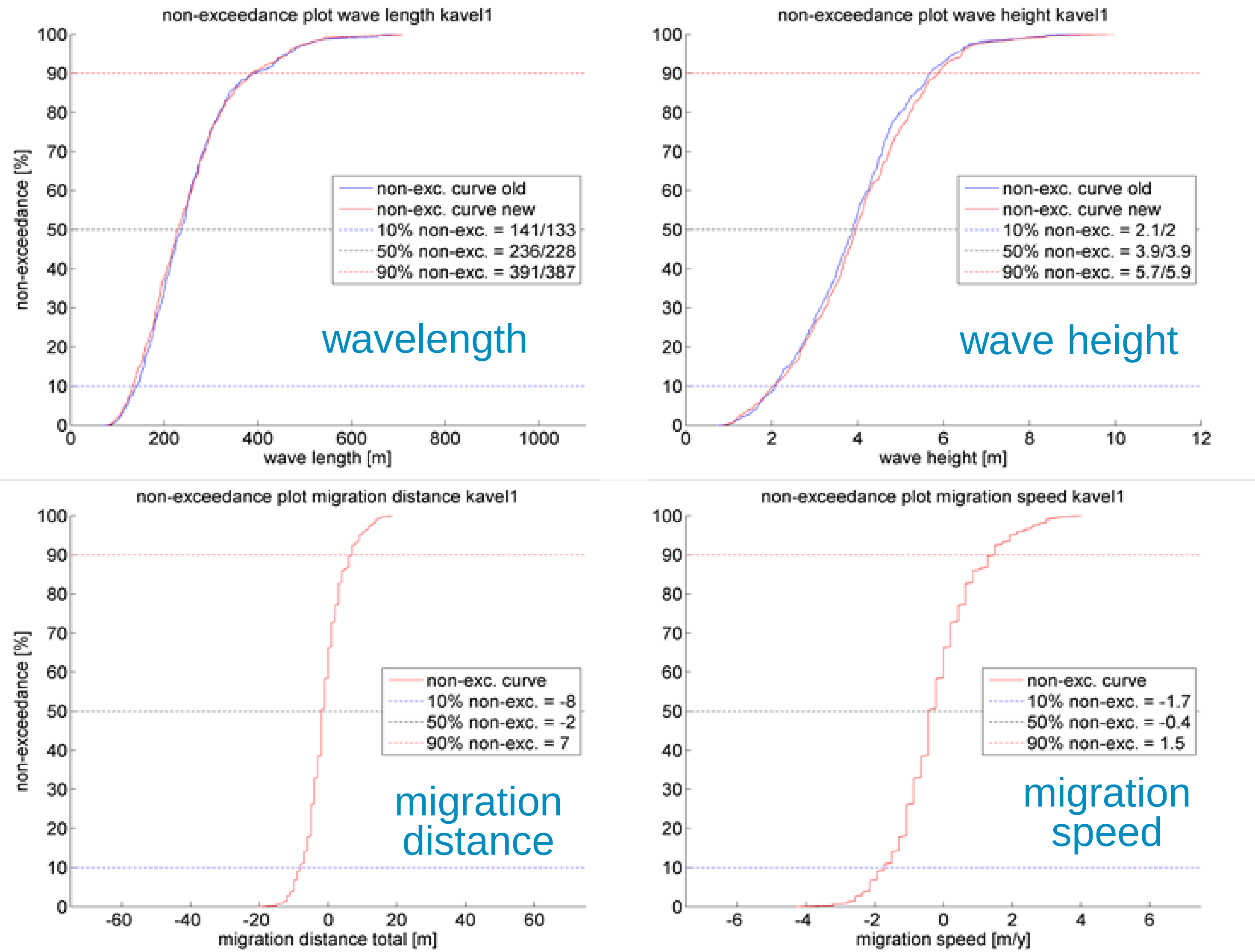
Results – Sand Wave Statistics

- Non-exceedance curves for migration rate are determined per transect and for each of the three bathymetry-combinations
- 10%-value represents the conservative most NE-directed migration rate
- 50%-value represents the best estimate migration rate
- 90%-value represents the conservative most SW-directed migration rate
- Note that the actual directions are taken into account instead of SW/NE



Results – sand wave statistics WFS-I

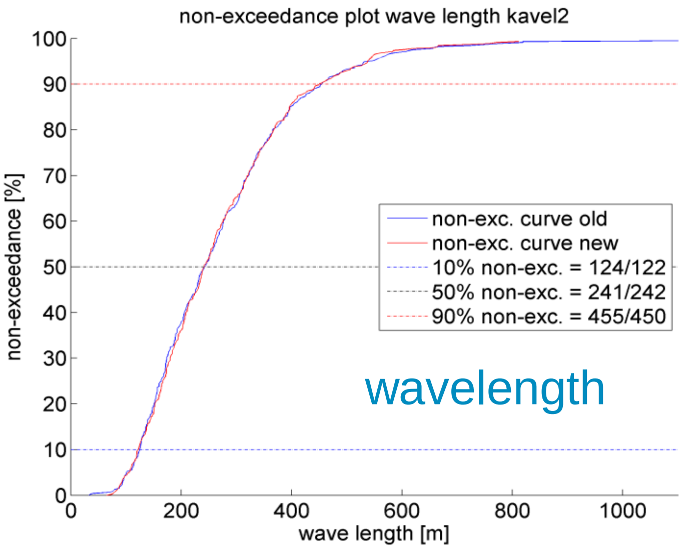
Exceedance curves for 2010/2015

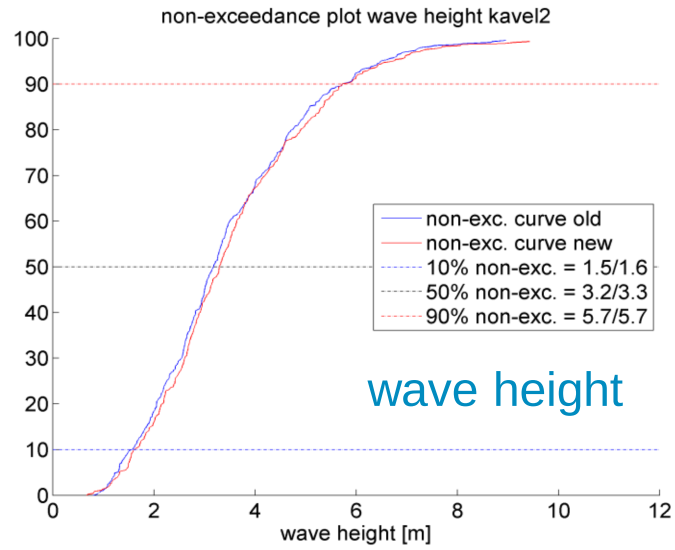


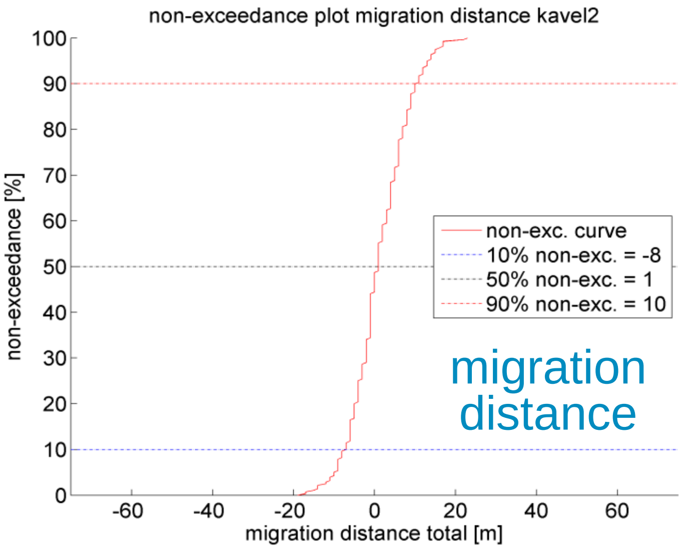
positive is towards SW; negative towards NE

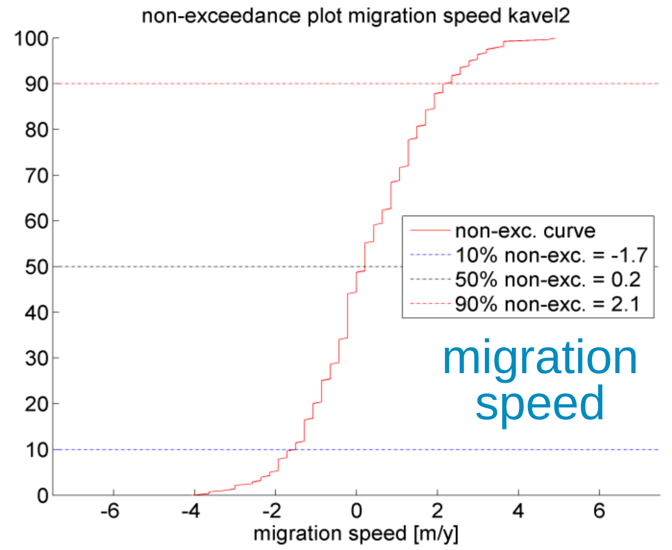
Results – sand wave statistics WFS-II

Exceedance curves for 2010/2015 (positive is towards SW; negative towards NE)









Deltares

Results – tables of sand wave statistics

Sand wave statistics for WFS-I

Parameter	10% non-exceedance (2010/2015)	50% non-exceedance (2010/2015)	90% non-exceedance (2010/2015)
Migration distance [m]	-8	-2	7
Migration speed [m/yr]	-1.7	-0.4	1.5
Wave length [m]	141/133	236/228	391/387
Wave height [m]	2.1/2	3.9/3.9	5.7/5.9

Sand wave statistics for WFS-II

Parameter	10% non-exceedance (2010-2015)	50% non-exceedance (2010-2015)	90% non-exceedance (2010-2015)
Migration distance [m]	-8	1	10
Migration speed [m/yr]	-1.7	0.2	2.1
Wave length [m]	124/122	241/242	455/450
Wave height [m]	1.5/1.6	3.2/3.3	5.7/5.7

Results – dealing with uncertainty

Several sources of uncertainty:

I. Uncertainty due to data collection and differences in the collection of data
(e.g. SBES (shoal-biased, lower density) vs. more accurate MBES)

II. Uncertainty in the pre-processing of data
(e.g. vessel movements, tidal reduction, gridding)

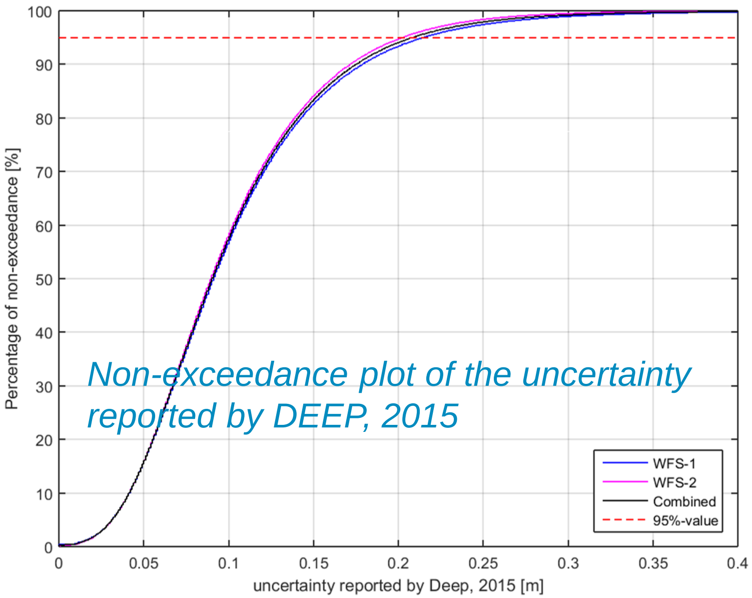
III. Uncertainty in the methodology of analysis and prediction
(e.g. assumption of shape-retaining sand waves, megaripple migration)

Uncertainty band in this study consists of contributions related to:

- survey inaccuracies
- existence of megaripples

survey uncertainty (95%) = 0.20m
megaripple uncertainty (95%) = 0.60m
uncertainty upward = 0.80m

survey uncertainty (95%) = -0.20m
megaripple uncertainty (95%) = -0.40m
uncertainty downward = -0.60m

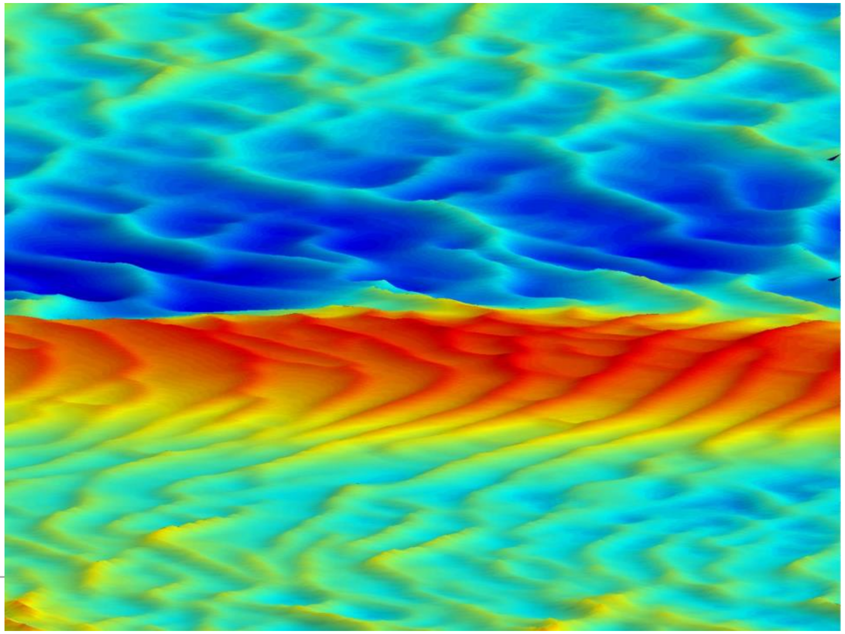


Non-exceedance plot of the uncertainty reported by DEEP, 2015

Results – predicting future bathymetries until 2046

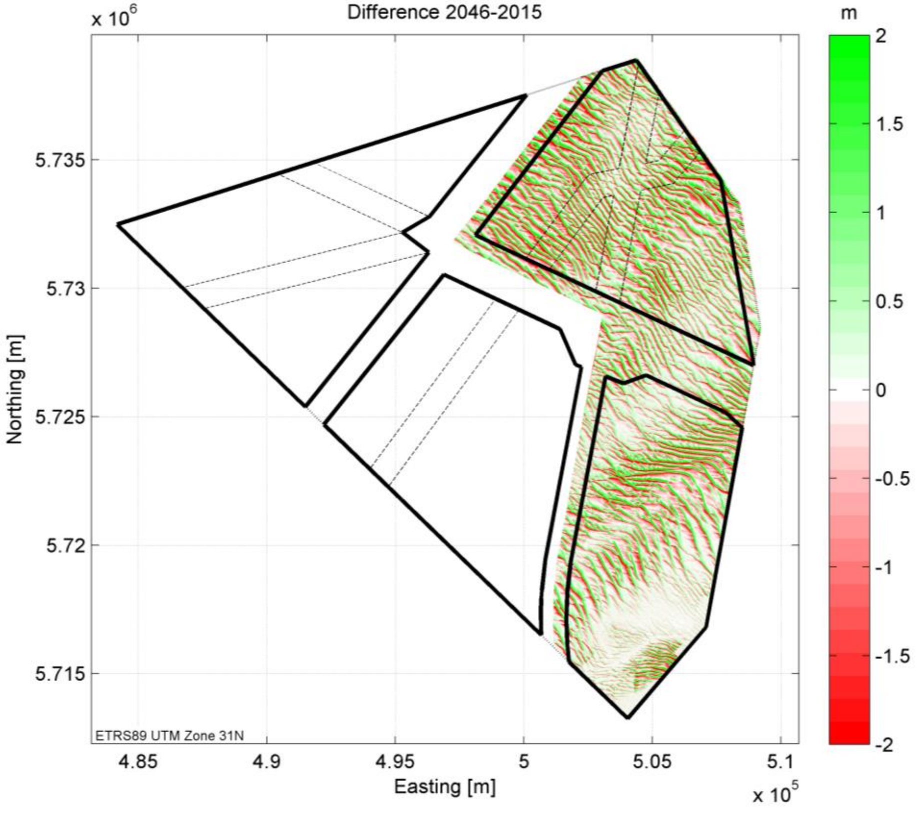
- In total, 9 estimates for the migrated sand wave field are determined for each year in the period 2015-2046
- These 9 estimates consist of 3 sand wave migration directions (2000/2010, 2000/2015, 2010/2015) times 3 estimates for the migration rate (10%, 50% and 90% determined from sand wave statistics)
- Predicted bathymetries for year 20XX are reconstructed by combining:
  - ✓ Static Bathymetry 2015
  - ✓ Migrated Sand Wave Field 2015 until year 20XX
  - ✓ Uncertainty Band

Movie illustarting seabed predictions (300yr!) for one out of nine maps of migration directions and migration rates

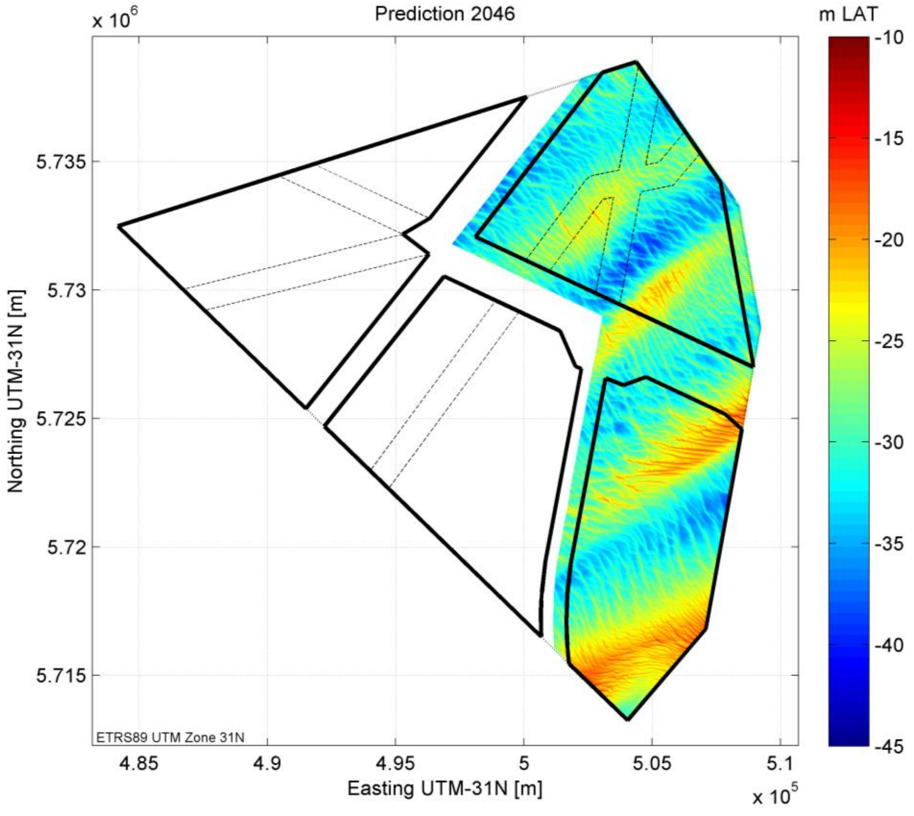


Results – 1/9 predicted bathymetry in 2046

(1/9) migrated sand wave fields



(1/9) bathymetries 2046



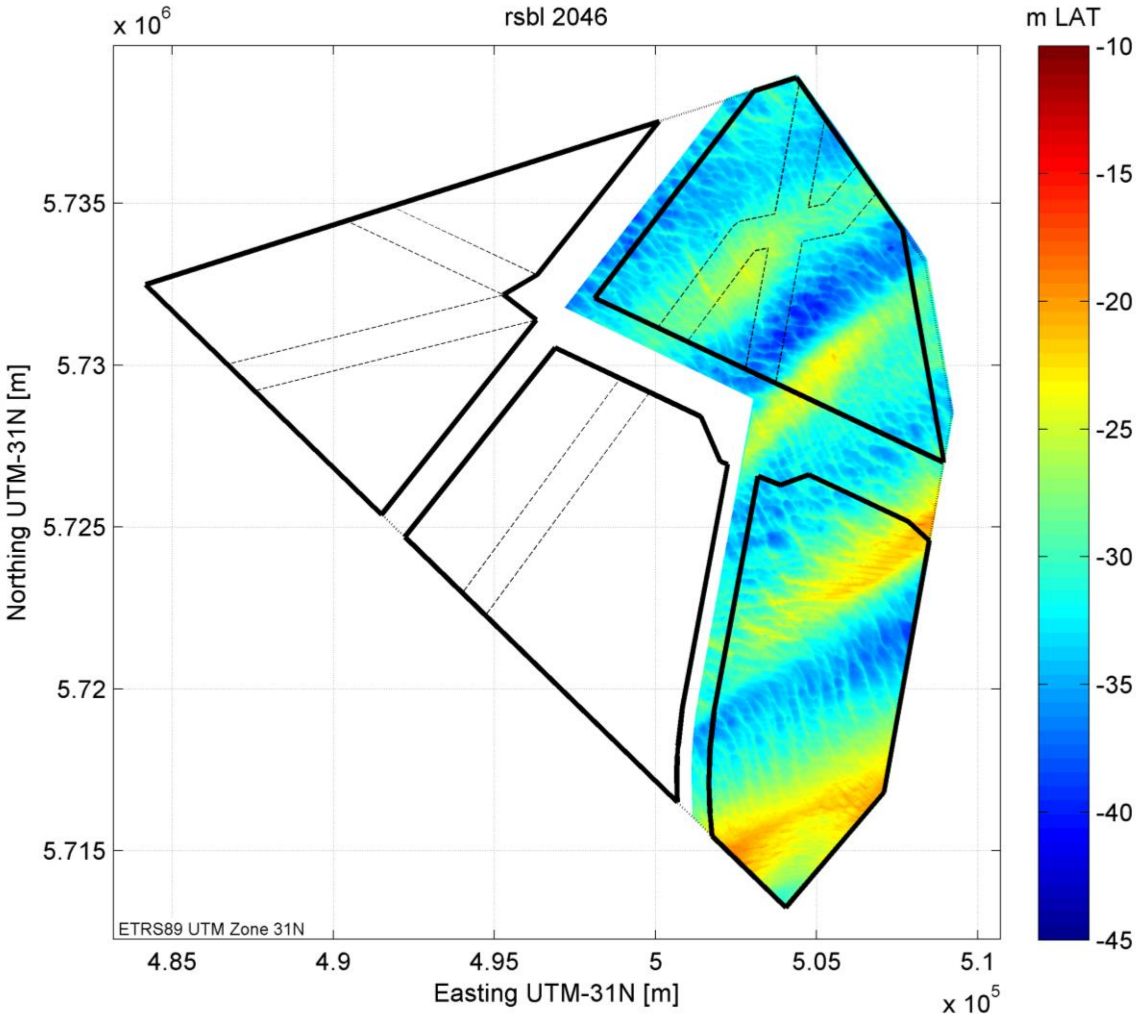
Results – determining RSBL

Reference SeaBed Level

The lowest possible seabed level during the lifetime of the wind parks

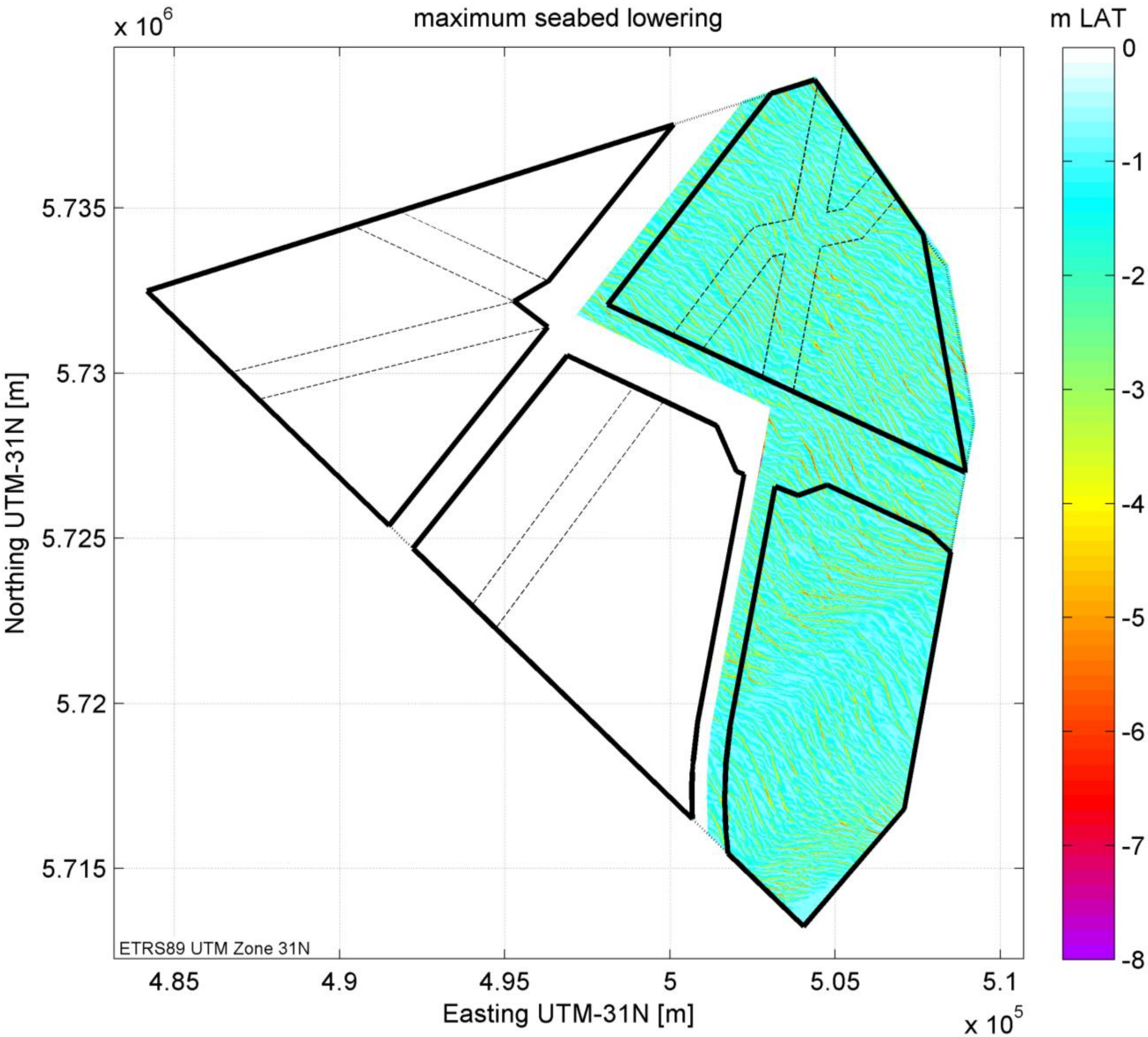
RSBL = Static Seabed Level - Max. Negative Envelope of Sand Wave Field until 2046 - Uncertainty Band

The RSBL varies between -16.1m and -40.3m LAT



Results – Maximum Potential Seabed Lowering

Difference between 2015-bathymetry and RSBL



Deltares

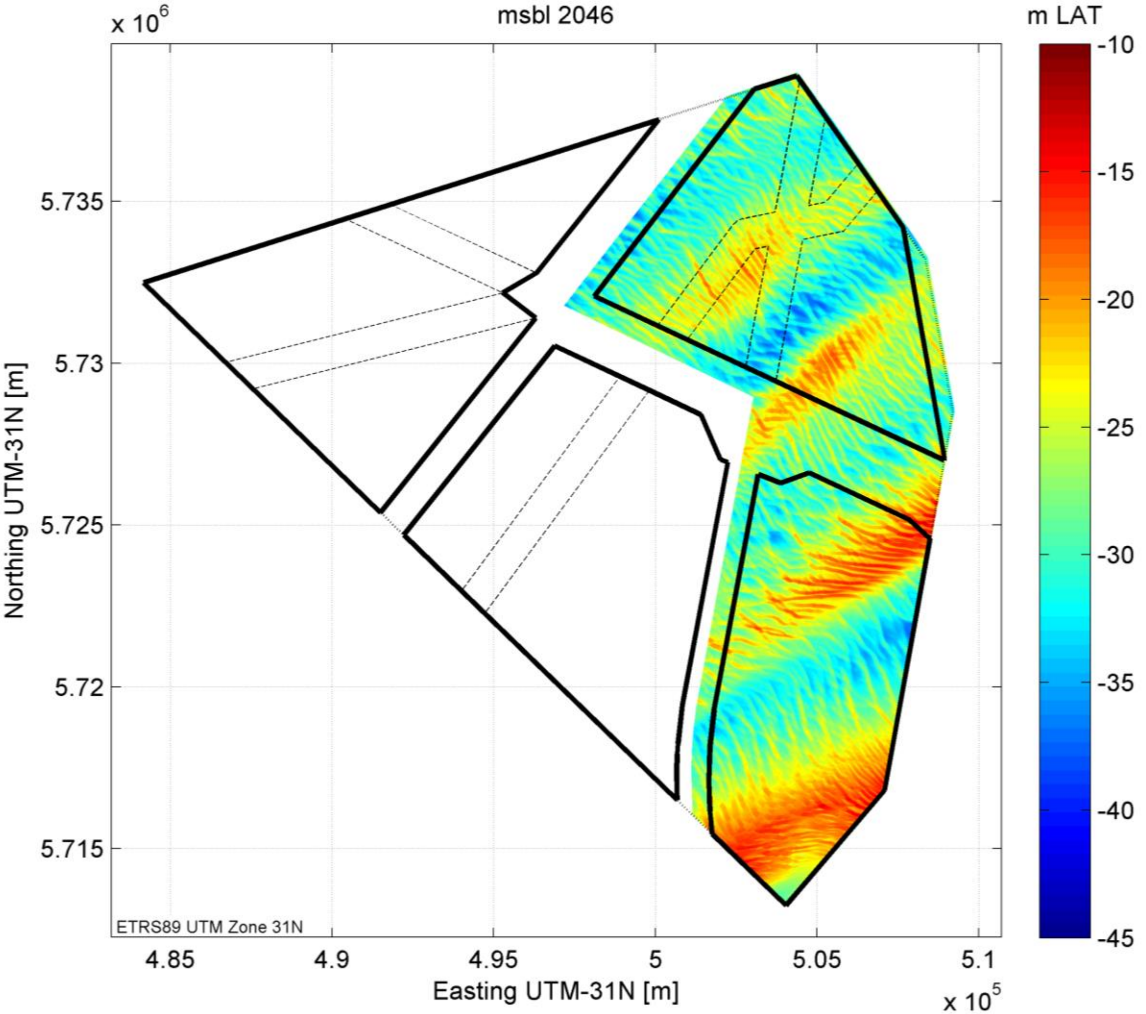
Results – determining MSBL

Maximum SeaBed Level

The highest possible seabed level during the lifetime of the wind parks

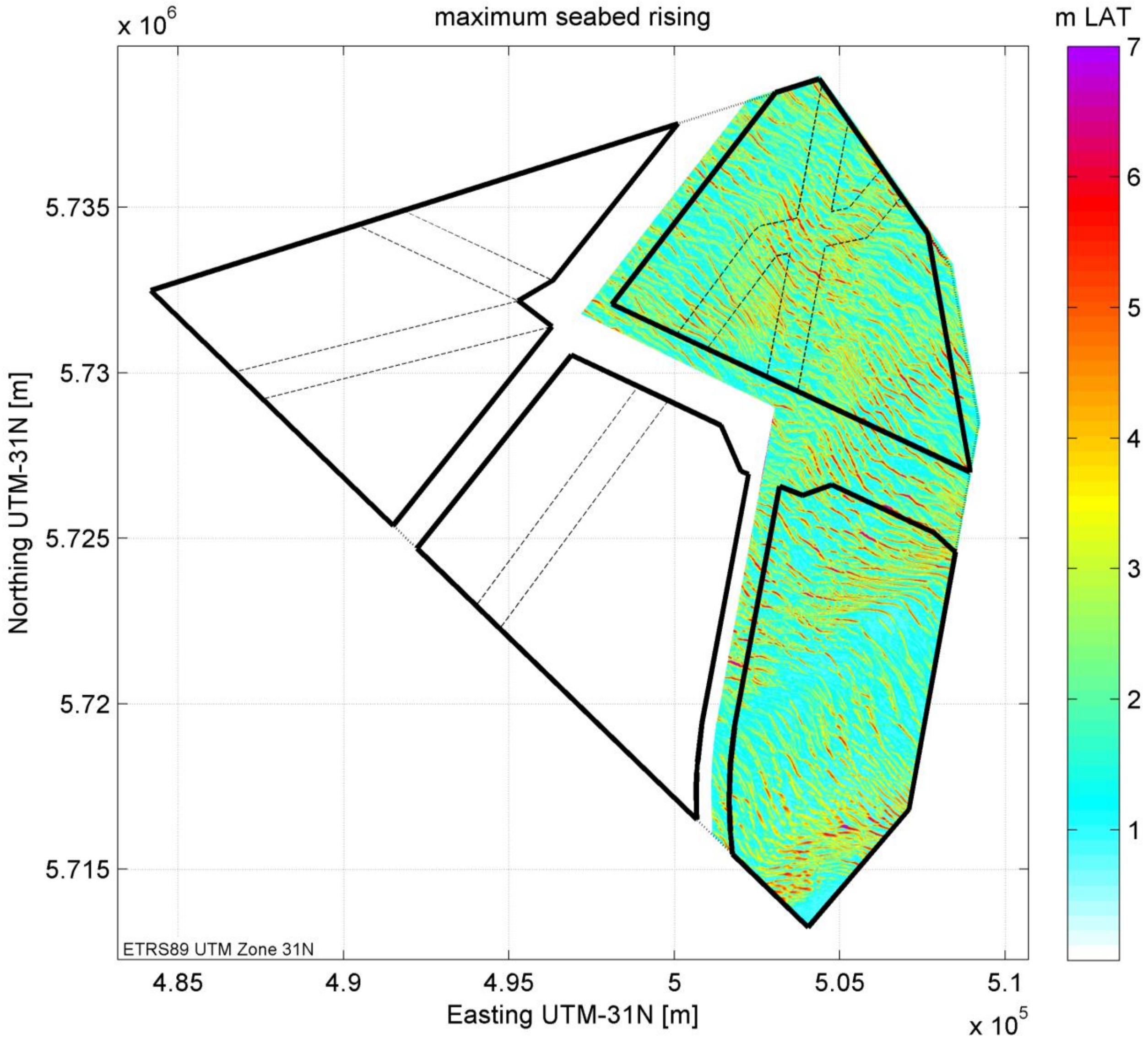
MSBL = Static Seabed Level + Max. Positive Envelope of Sand Wave Field until 2046 + Uncertainty Band

The MSBL varies between -13.3m and -38.2m LAT



Results – Maximum Potential Seabed Level Rise

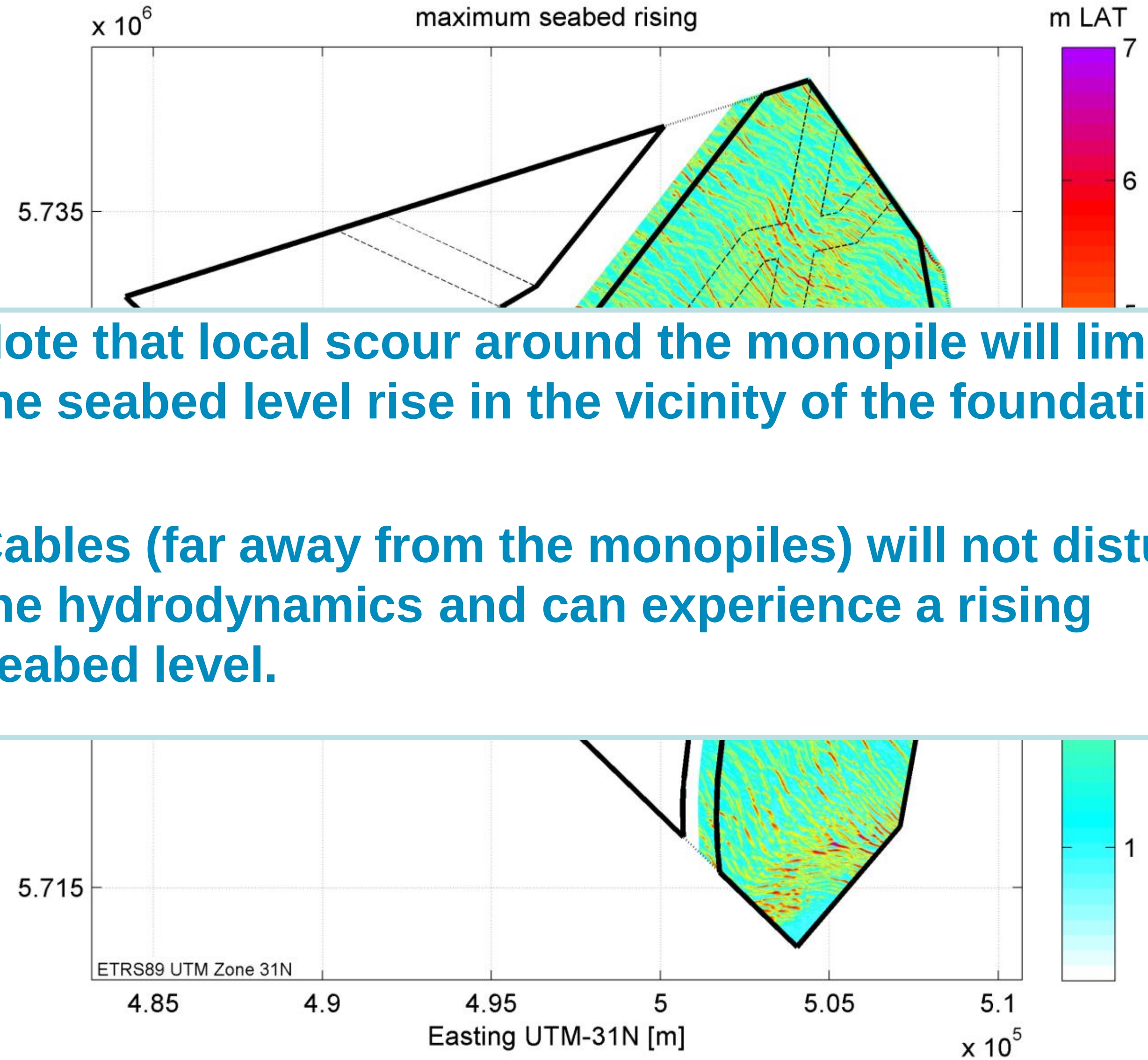
Difference between 2015-bathymetry and MSBL



Deltares

Results – Maximum Potential Seabed Level Rise

Difference between 2015-bathymetry and MSBL



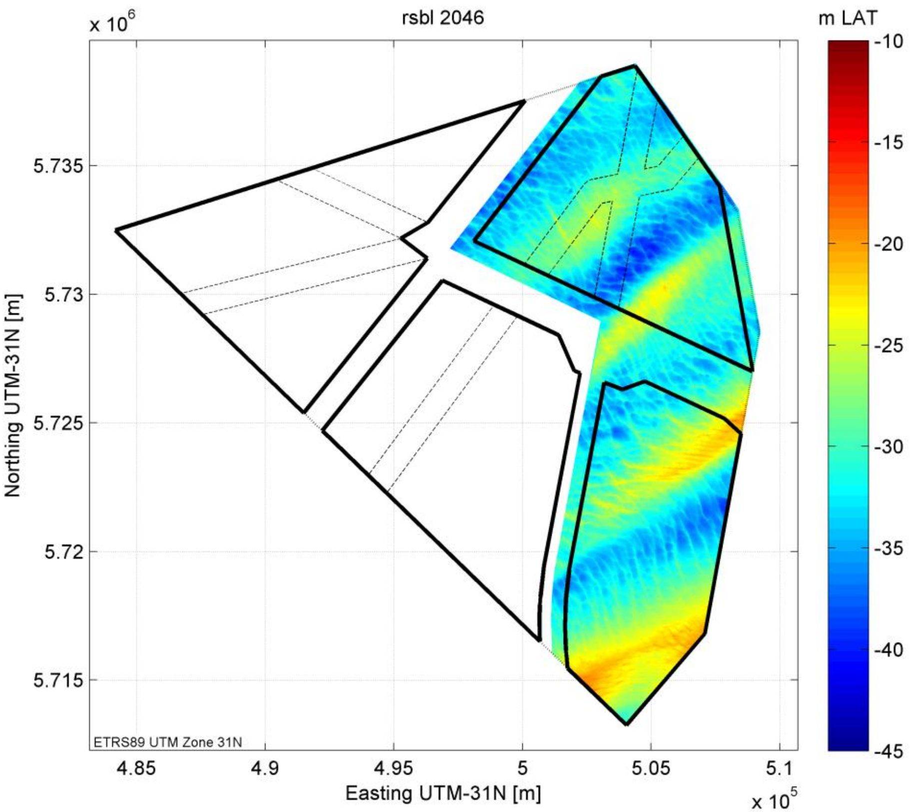
Note that local scour around the monopile will limit the seabed level rise in the vicinity of the foundation!

Cables (far away from the monopiles) will not disturb the hydrodynamics and can experience a rising seabed level.

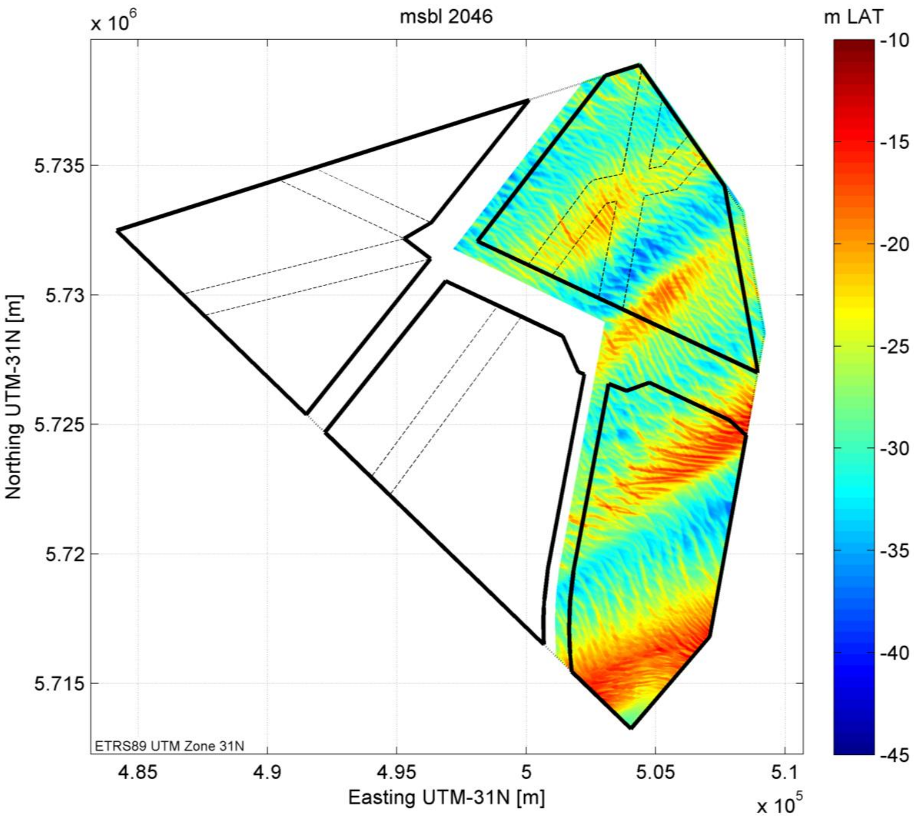
Deltares

Results – comparing RSBL with MSBL

Maximum vertical range in (autonomous) morphological seabed changes



RSBL
(between -16.1m and -40.3m LAT)



MSBL
(between -13.3m and -38.2m LAT)

Deltares

Classification zones

- Next step: translate MSBL and RSBL and corresponding seabed changes to “Classification Zones”
- Classification chosen less strict for rising seabed levels. The reasoning behind this is that close to the structures, local scour will counteract rising seabed levels. This does not apply to the electricity cables, which are buried in the seabed; rising seabed levels can be of influence on the maximum cable temperature.

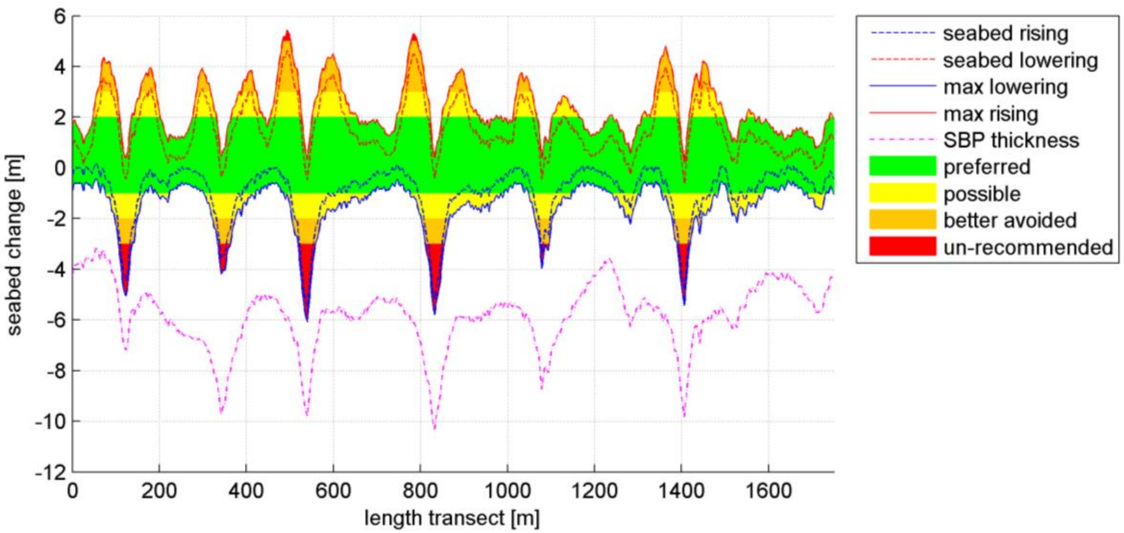
Classification of zones	Bed level lowering [m]	Bed level rising [m]
Preferred	$0 > dz \geq -1$	$0 < dz \leq 2$
Possible	$-1 > dz \geq -2$	$2 < dz \leq 3$
Better avoided	$-2 > dz \geq -3$	$3 < dz \leq 5$
Unrecommended	$dz < -3$	$dz > 5$

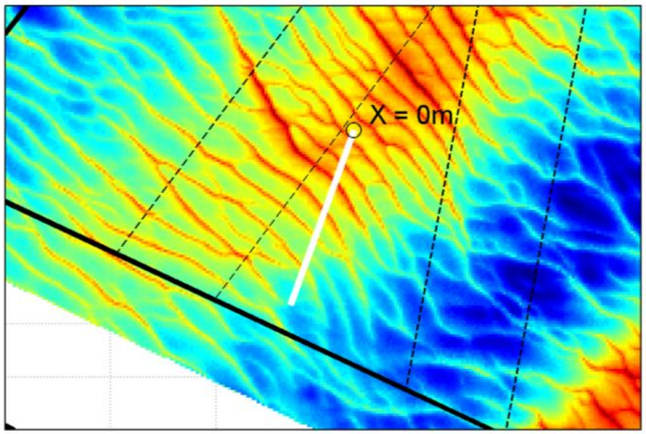
- Classification Zones are for indicative and illustrational purposes only. Actual classification is dependent on the design of the support structures and properties of electricity cables and should be adjusted accordingly once this information is available.

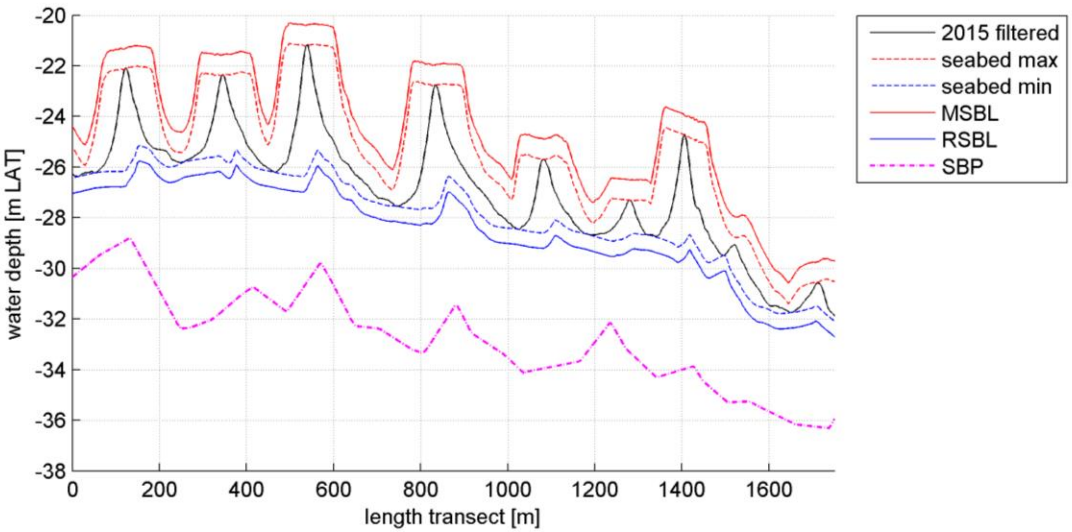
Classification zones: example for one transect

Example for one transect:

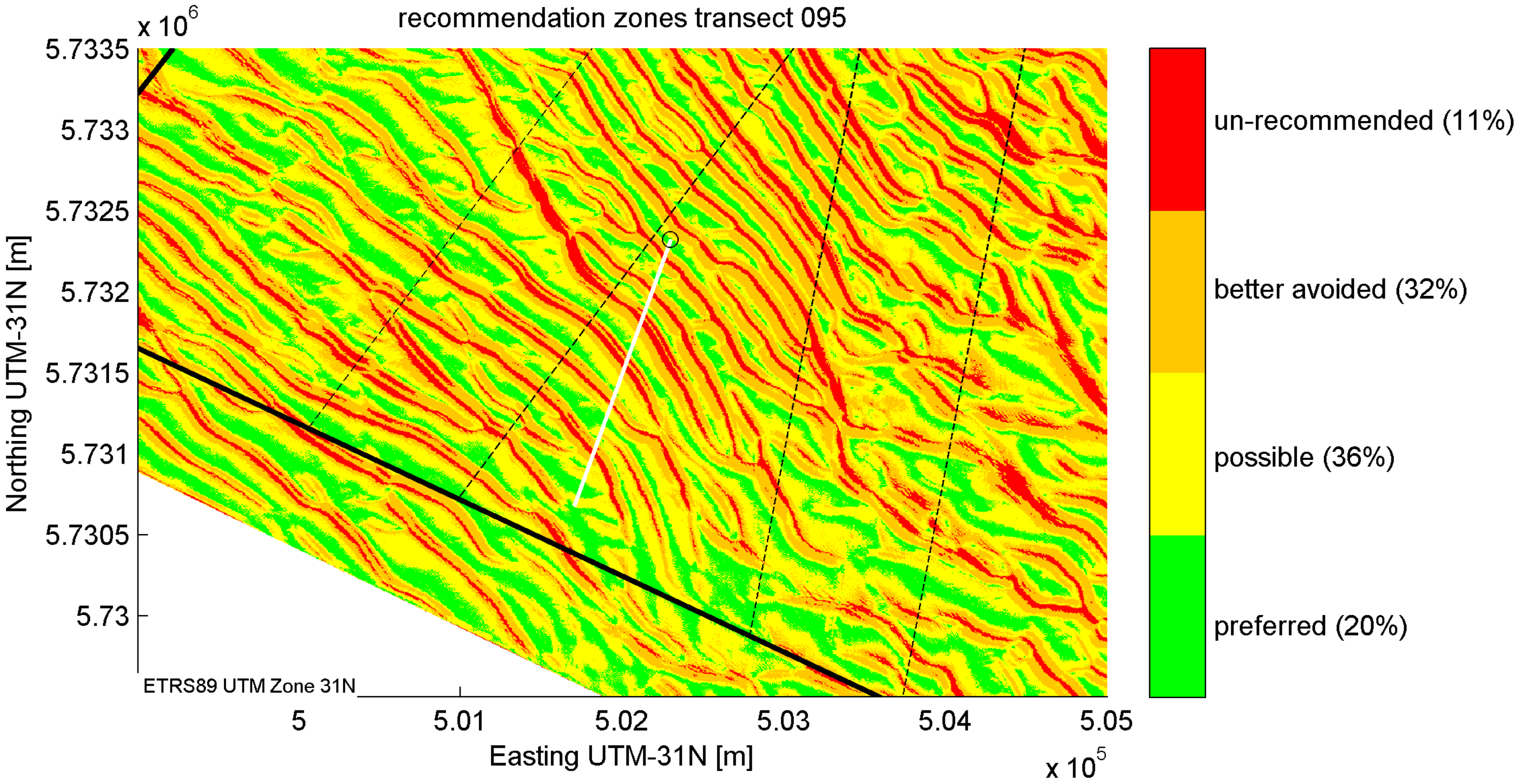
- Classification calculated for both rising and lowering seabed
- Most strict classification (rising/lowering) is used





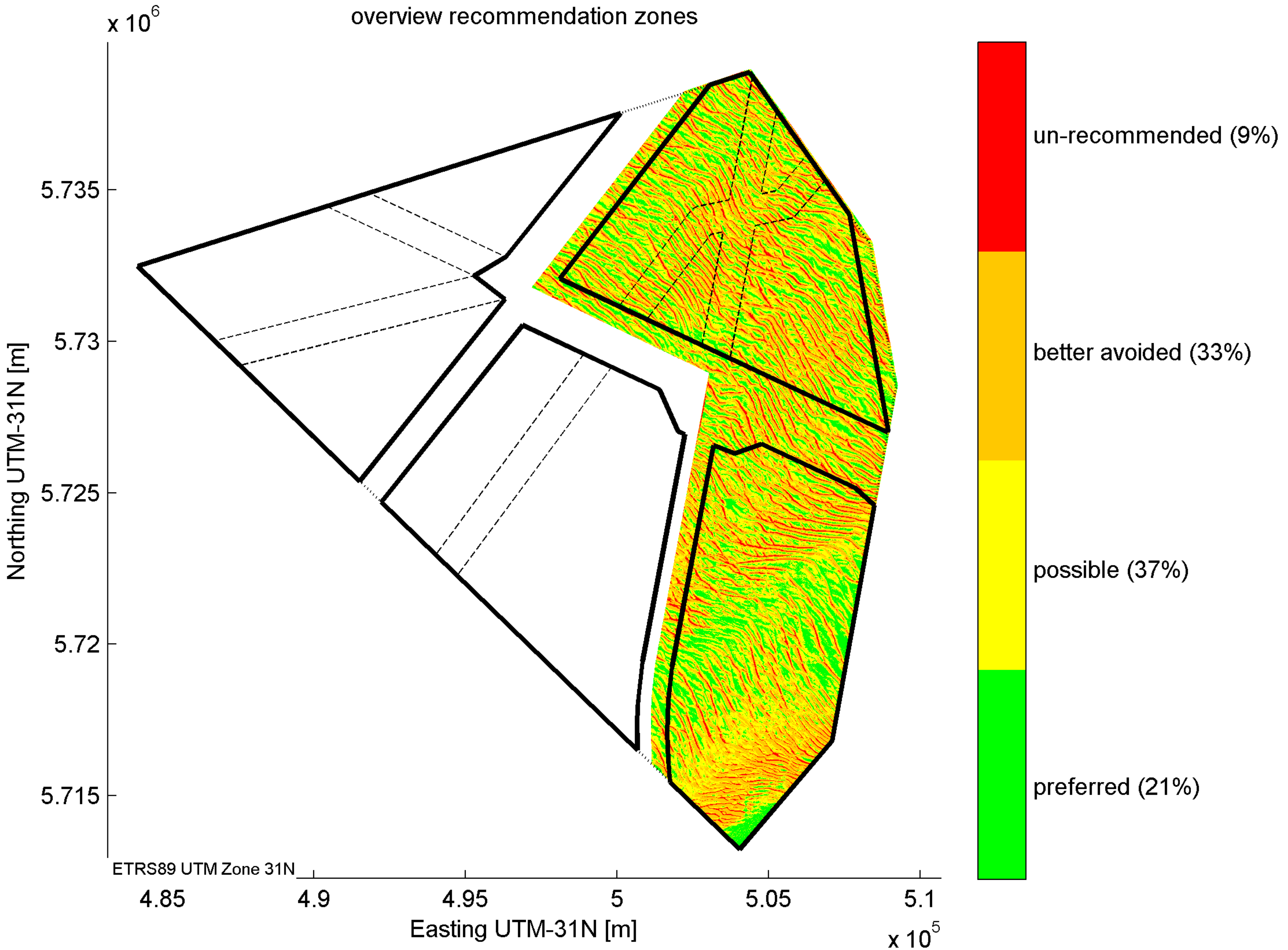


Classification zones for southern part Site I

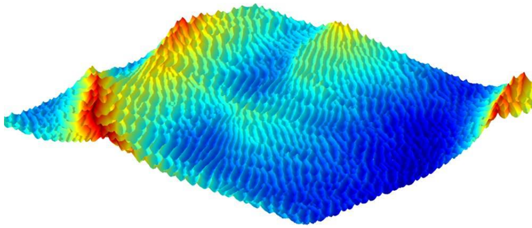


Deltares

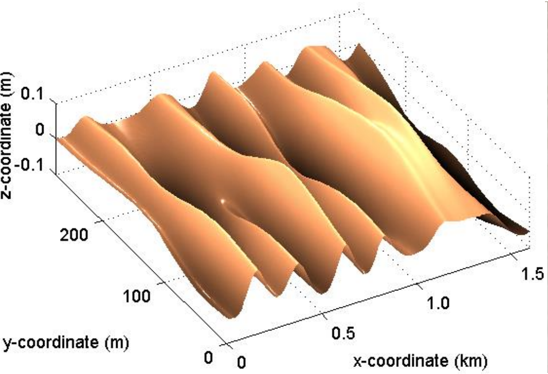
Classification zones for Site I and II

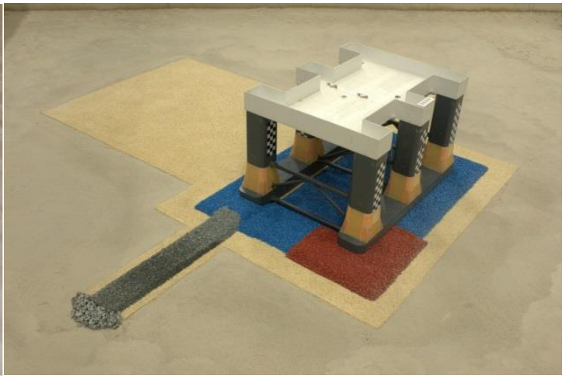


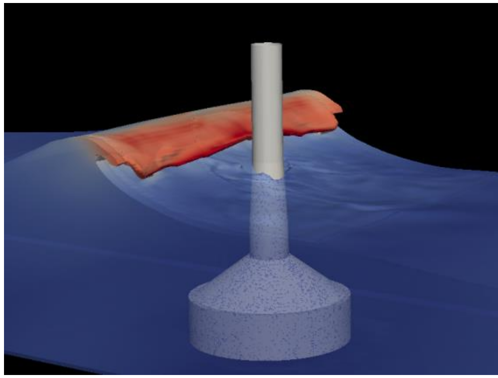
Contents of presentation



- Introduction Deltares
- Introduction Morphodynamics
- Methodology of this study
- Results
- Conclusions and Recommendations







Deltares

Conclusions (I)

- The bathymetry in BWFZ consists of a complex system of shore-parallel sand banks covered with shore-perpendicular sand waves; covered with highly mobile megaripples.
- The sand banks are considered to be static over the lifetime of the wind parks to be developed in the area (negligible change observed in 15 years).
- The sand waves are (mostly) mobile, have an average length of 230m, average height of 4m and typical migration speeds are in the order of -1.7m/yr (governing NE-direction) to 2.1 m/yr (governing SW-direction).

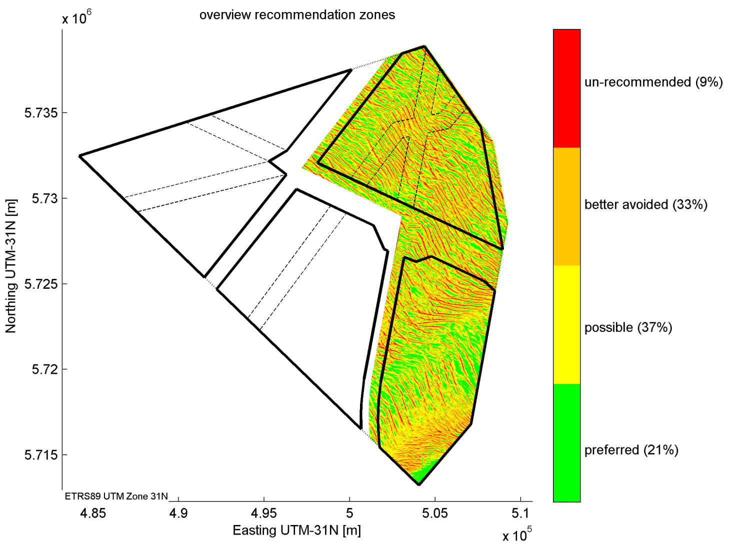
Area	Wave height 50% non-exceedance [m] (2010/2015)	Wavelength 50% non-exceedance [m] (2010/2015)	Migration speed 10% non-exceedance [m/yr]	Migration speed 90% non-exceedance [m/yr]
WFS-I	3.9/3.9	236/228	-1.7	1.5
WFS-II	3.2/3.3	241/242	-1.7	2.1
WFS-I and II combined	3.6/3.7	239/236	-1.7	1.9

- Megaripples are very mobile, but limited in height: therefore they are added as an uncertainty band on top of the predictions

Deltares

Conclusions (II)

- Seabed changes are predicted for a range of predictions of sand wave migration (3 migration directions x 3 migration speeds)
- Maximum SeaBed Level (MSBL) and Reference SeaBed Level (RSBL) are determined.
- This results in maximum potential seabed lowering and rising until 2046
- Classification Zones (*preferred / possible / better avoided / unrecommended*) are determined based on estimated ranges for downward and upward seabed changes



Recommendations for design

A. Further improve accuracy of morphodynamic predictions:

- Set up a detailed hydrodynamic model of the area and simulate the tidal currents to assess tide-averaged sediment transport rates.

- In case of an additional pre-installation survey (~2018): re-run analysis and further narrow down uncertainty ranges, which will be beneficial for scour mitigation strategy and/or cable burial depth

B. Include morphodynamic activity in wind farm design:

- Take predicted morphodynamic seabed changes into account in determining WTG-locations and cable trajectories

- Consider morphodynamic changes in combination with scour mitigation strategy

- Deploy continuous cable burial depth monitoring system coupled with morphodynamic prediction model to guarantee cable safety

Thank you for your attention!

¿Questions?

Scale model in Deltares' Atlantic Basin
of Dolwin-2 transformer platform
located in German Bight (North Sea)

More information? Email: tim.raaijmakers@deltares.nl