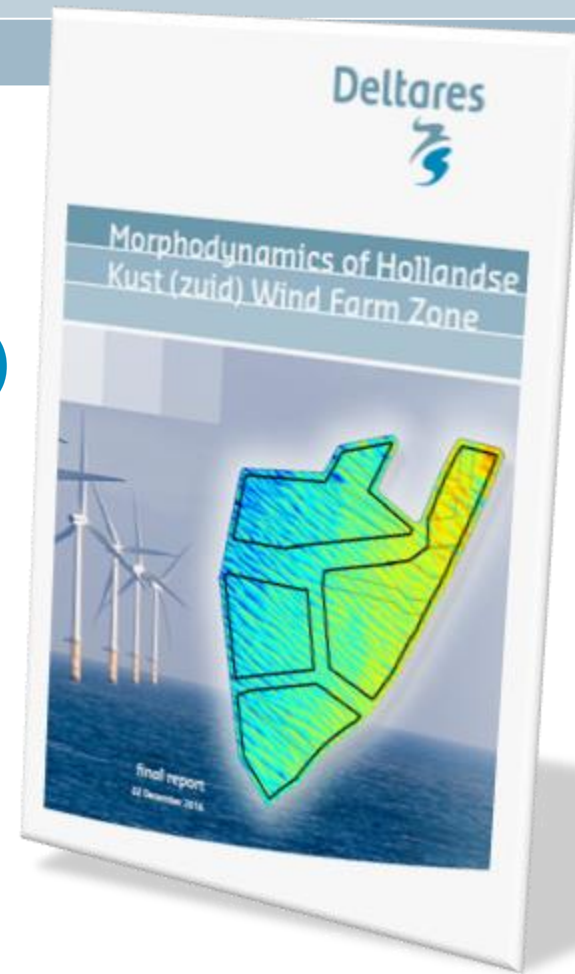
Rijksdienst voor Ondernemend Nederland

Deltares
Enabling Delta Life

# Morphodynamics of Hollandse Kust (zuid) Wind Farm Zone


## 24 January 2017




Tom Roetert
Andrea Forzoni
Roderik Hoekstra
Bas Borsje
Bo Paulsen
Pim van Steijn
Thaiënne van Dijk
Tim Raaijmakers

# Objectives of the morphodynamics assessment

## Objectives of this study (as specified by RVO)

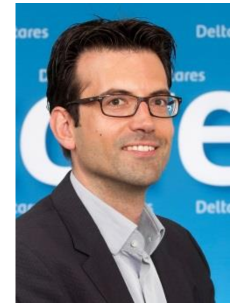
- Characterize the seabed features in the Hollandse Kust (zuid) wind farm zone (HKZ WFZ)
- Assess the morphodynamics in HKZ WFZ
- Predict the changes in seabed levels in HKZ WFZ to support the design, installation and maintenance of wind turbines, inter array cables, substations and their support structures for the period 2016-2056

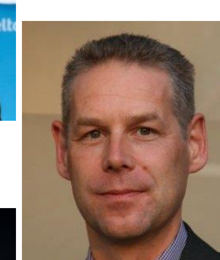
# Introduction to morphodynamics team

**Presenter:**

## Tim Raaijmakers

*Senior researcher/advisor, Programme Manager Offshore Engineering at Deltares*
*PhD researcher at TU Delft*
*Project Leader Morphodynamics study*





**Moderators:**

## Frank van Erp

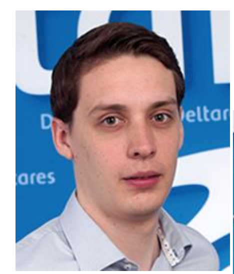
*Senior advisor Offshore Wind Energy, RVO.nl (NEA)*

## Ben de Sonneville

*Senior Consultant at BLIX Consultancy BV*

## Thaiënne van Dijk

*Specialist Marine Geology at Deltares*
*Assistant Professor in Marine Systems at University of Twente*
*Reviewer of Morphodynamics study*



## Tom Roetert

*Researcher/advisor Offshore Engineering at Deltares*
*Co-author of Morphodynamics study*

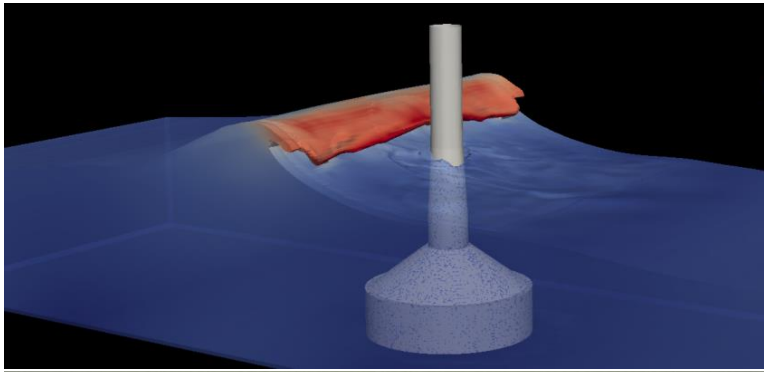
## Andrea Forzoni

*Researcher/advisor Geology at Deltares*
*Co-author of Morphodynamics study*

# Deltares: facts and figures

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
- > 800 staff (mostly MSc/PhD), > 28 nationalities
- open-source policy: “dare to share”



Deltares’ campus in Delft

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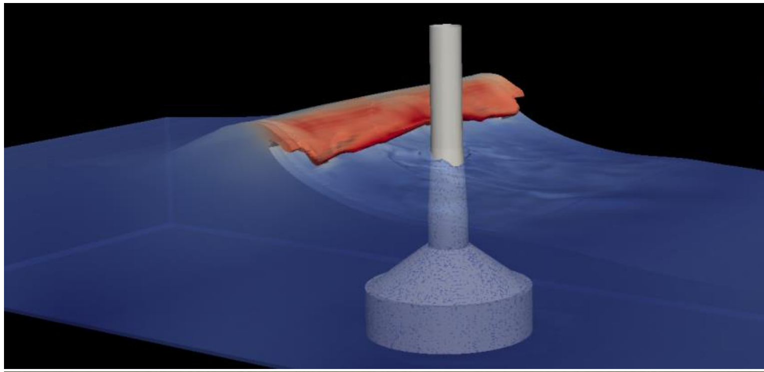

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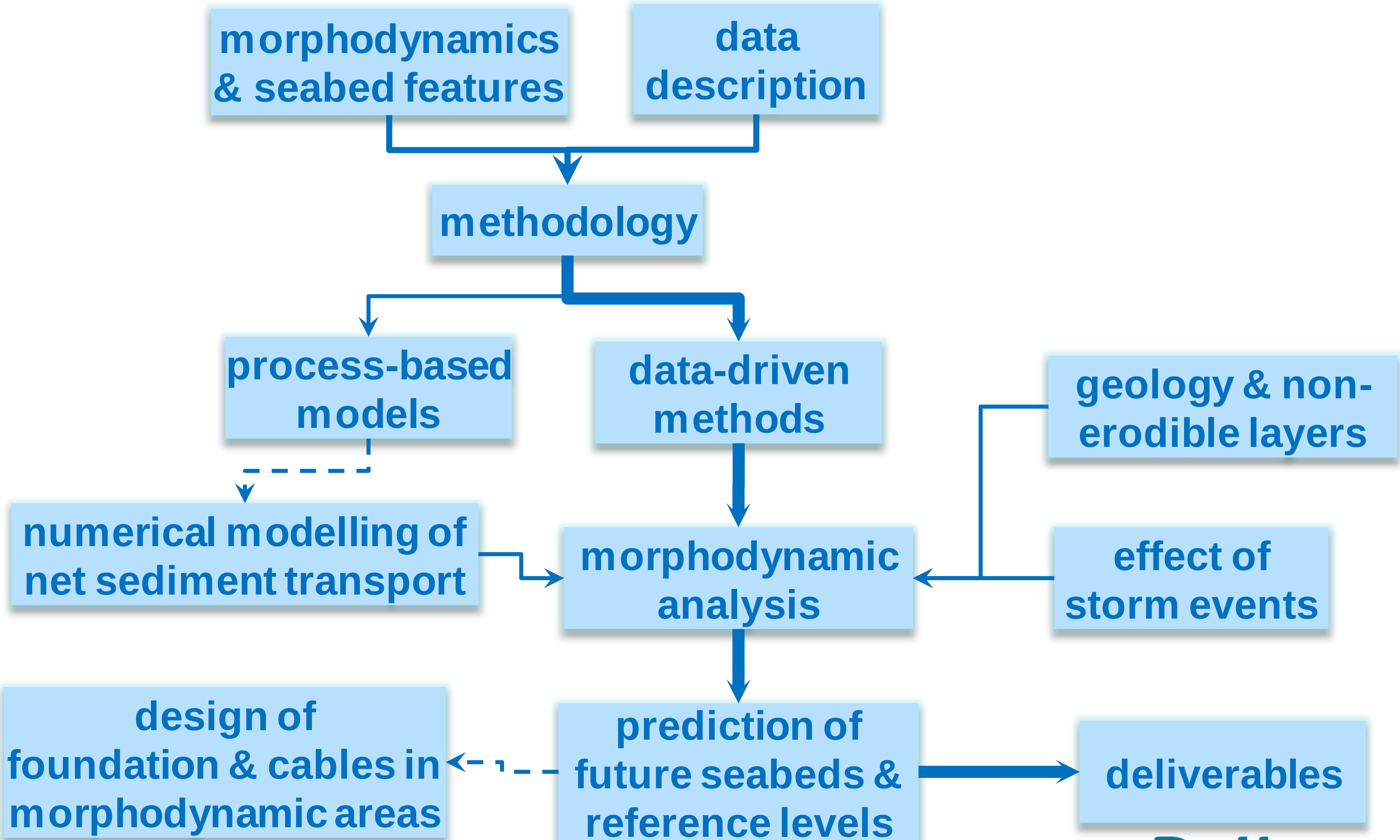

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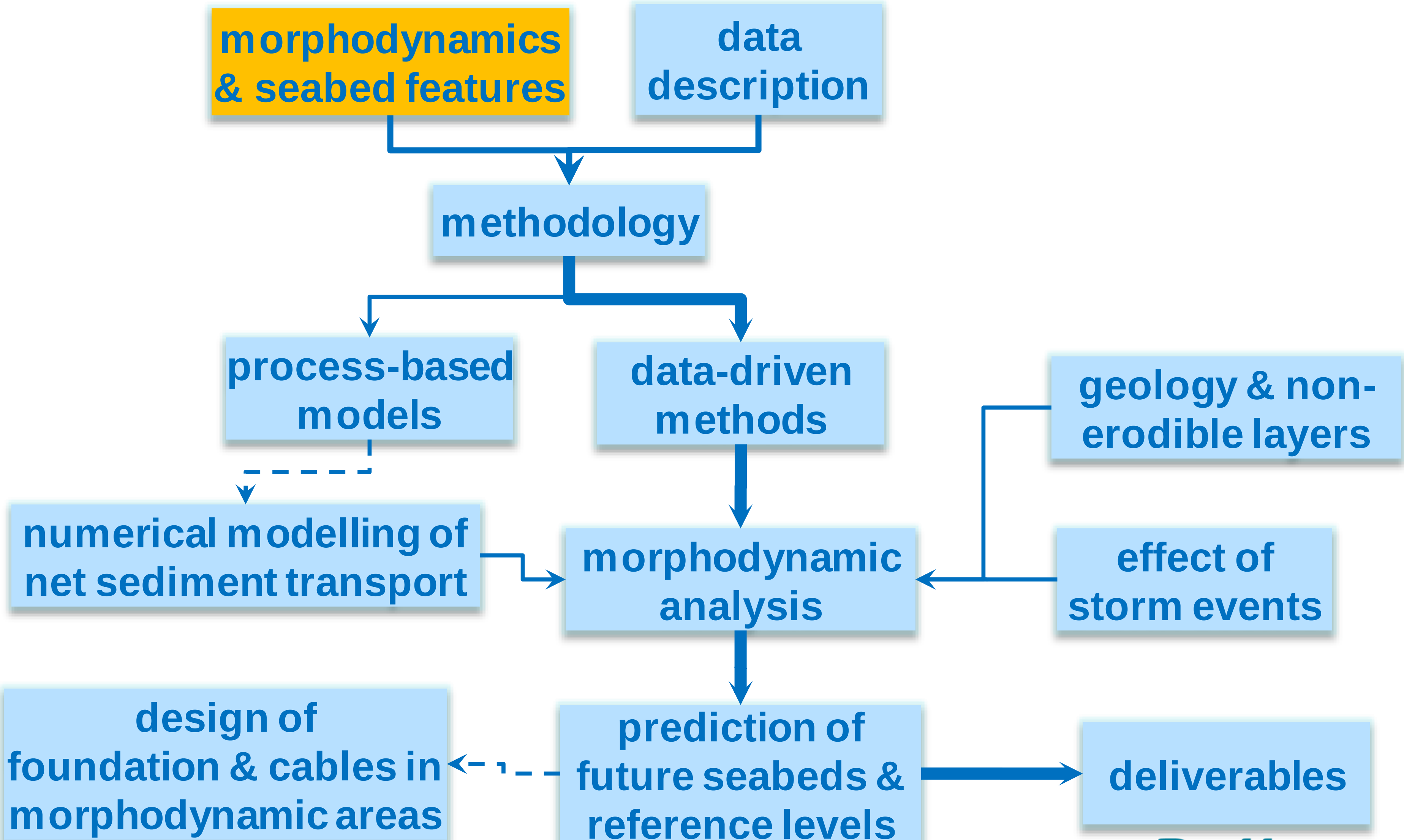


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# Seabed Morphodynamics - definition

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

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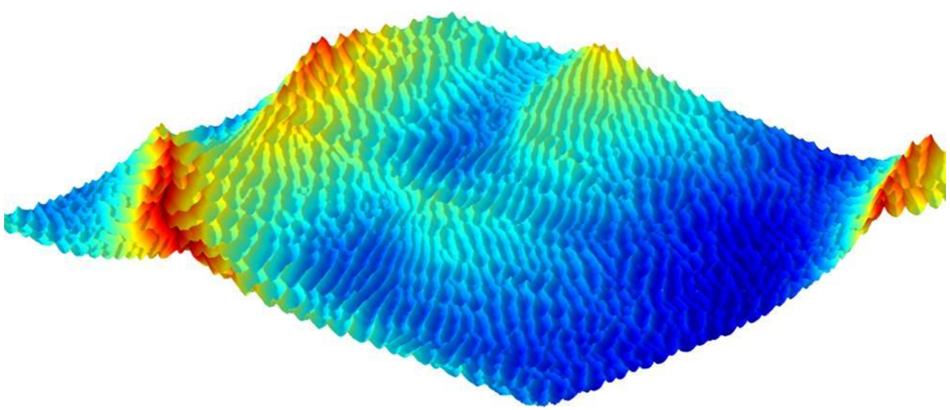
## Global / large-scale morphodynamics

*Sand banks and sand waves in Borssele windfarm area*

In new DNVGL-guideline: “general seabed level change” (DNVGL-ST-0126, April 2016)



## Local morphodynamics

Local erosion around a structure:
*scour Dolwin Beta HVDC platform*

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# Seabed Morphodynamics (large-scale / autonomous)

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.



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**this study**

# Seabed Morphodynamics (large-scale / autonomous)

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.

**this study**

| | Wavelength | Wave height | Mobility | Threat to foundations and cables |
|---|---|---|---|---|
| Ripples | O(0.1) m | O(0.01) m | Mobile and transient | Minimal |
| Megaripples | O(10) m | O(0.1) m | Mobile and transient | Minimal |
| **Sand waves** | **O(100) m** | **O(1) m** | **Mobile and persistent** | **Large** |
| Sand banks | O(1000) m | O(10) m | Stationary | Minimal |

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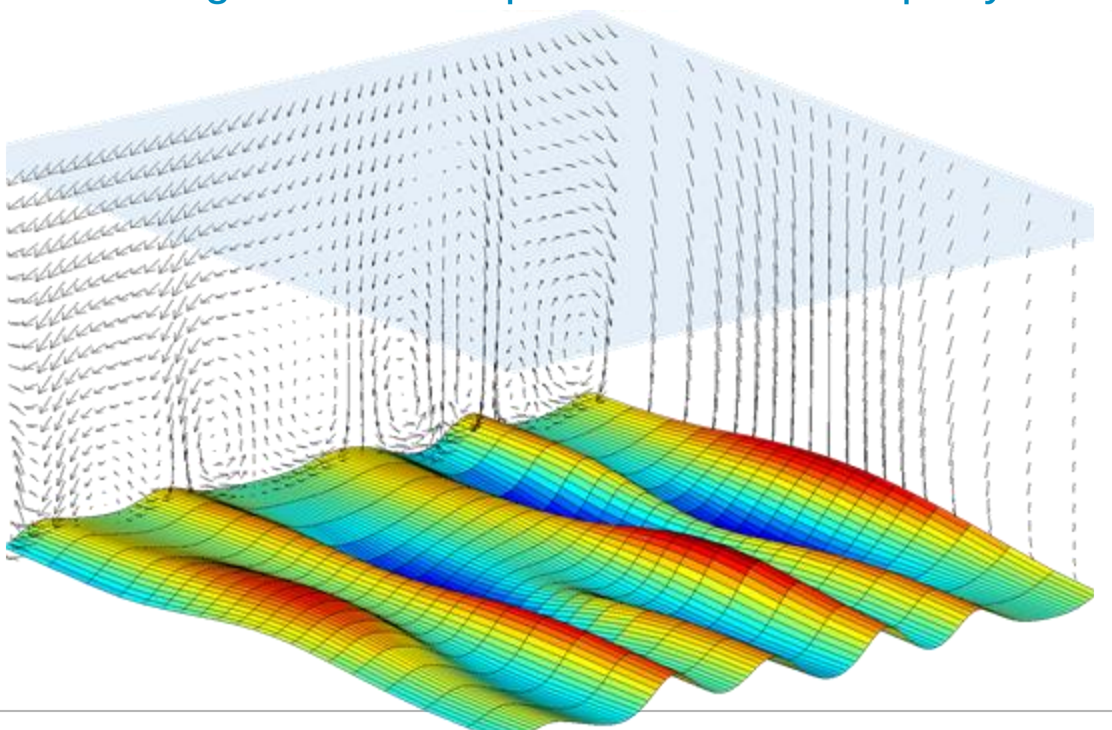
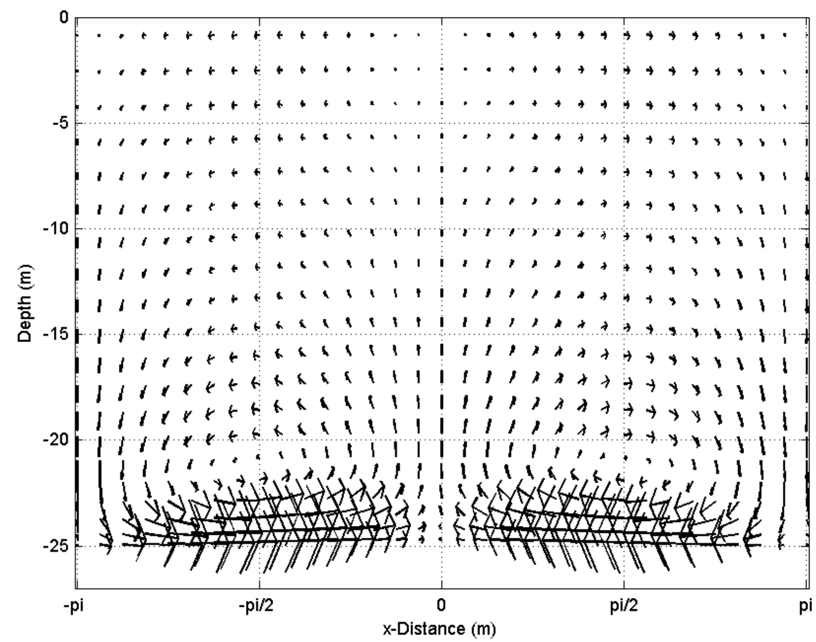
# Sand Wave Morphodynamics

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

- Sand wave length: typically 200-1000 meters
- Sand wave height: 10-30% of the water depth
- Migration rate: up to 10s of meters per year



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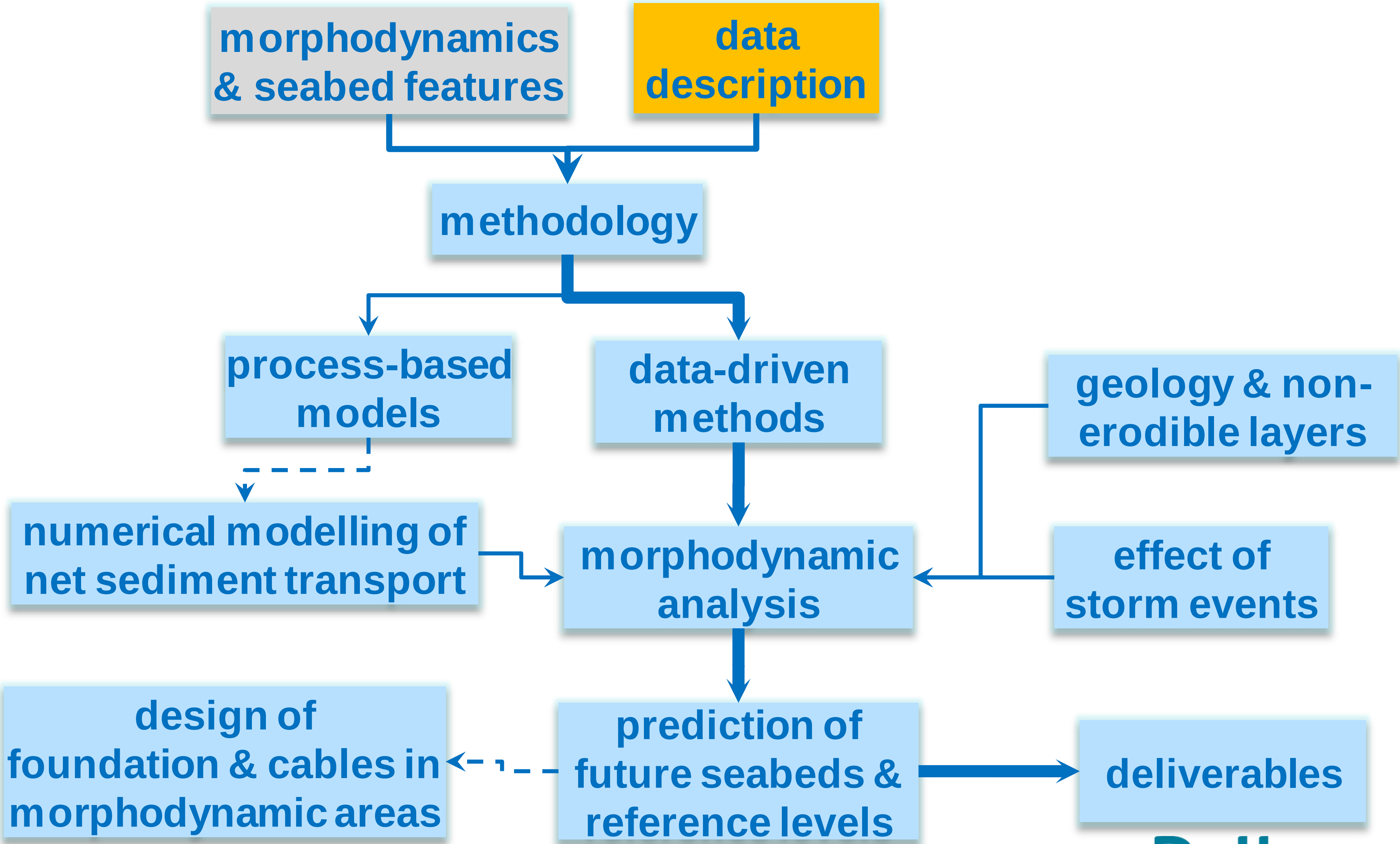
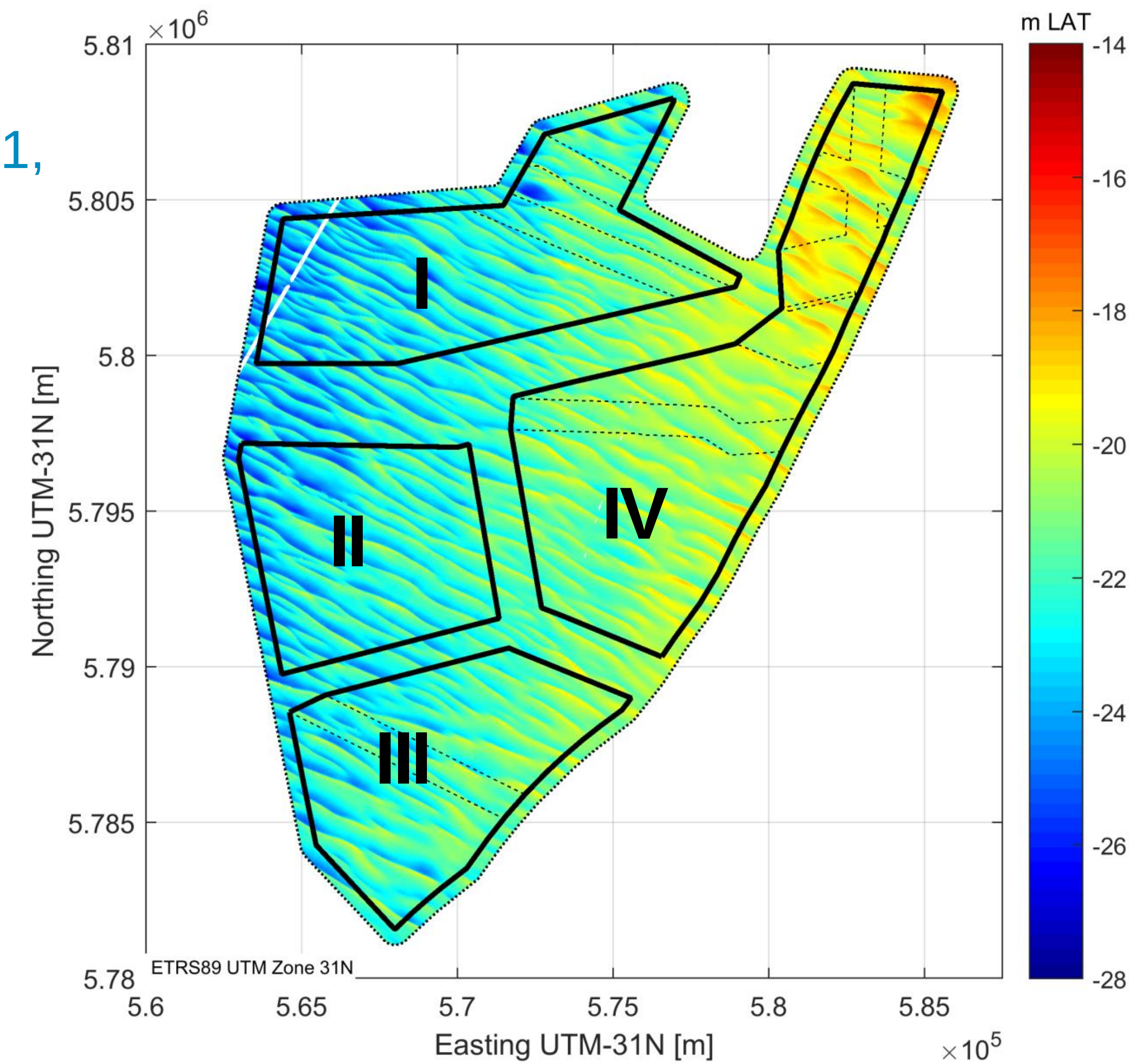


# Data description – Bathymetry 2000

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



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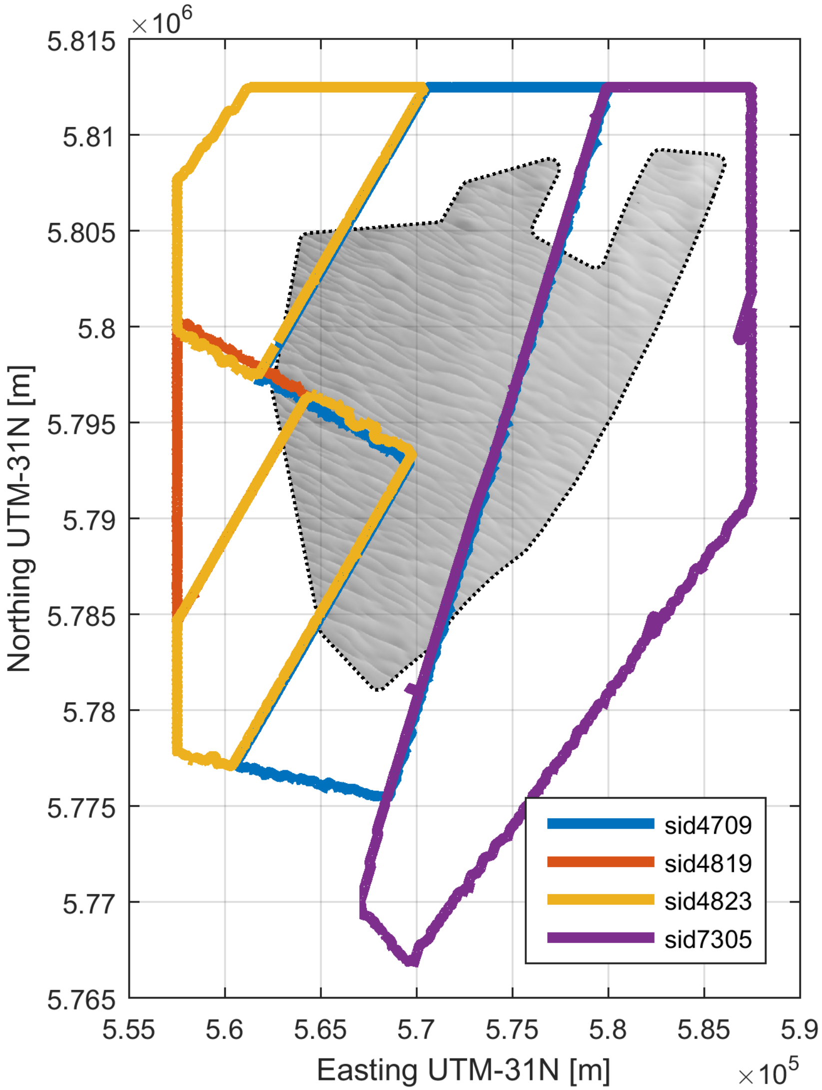


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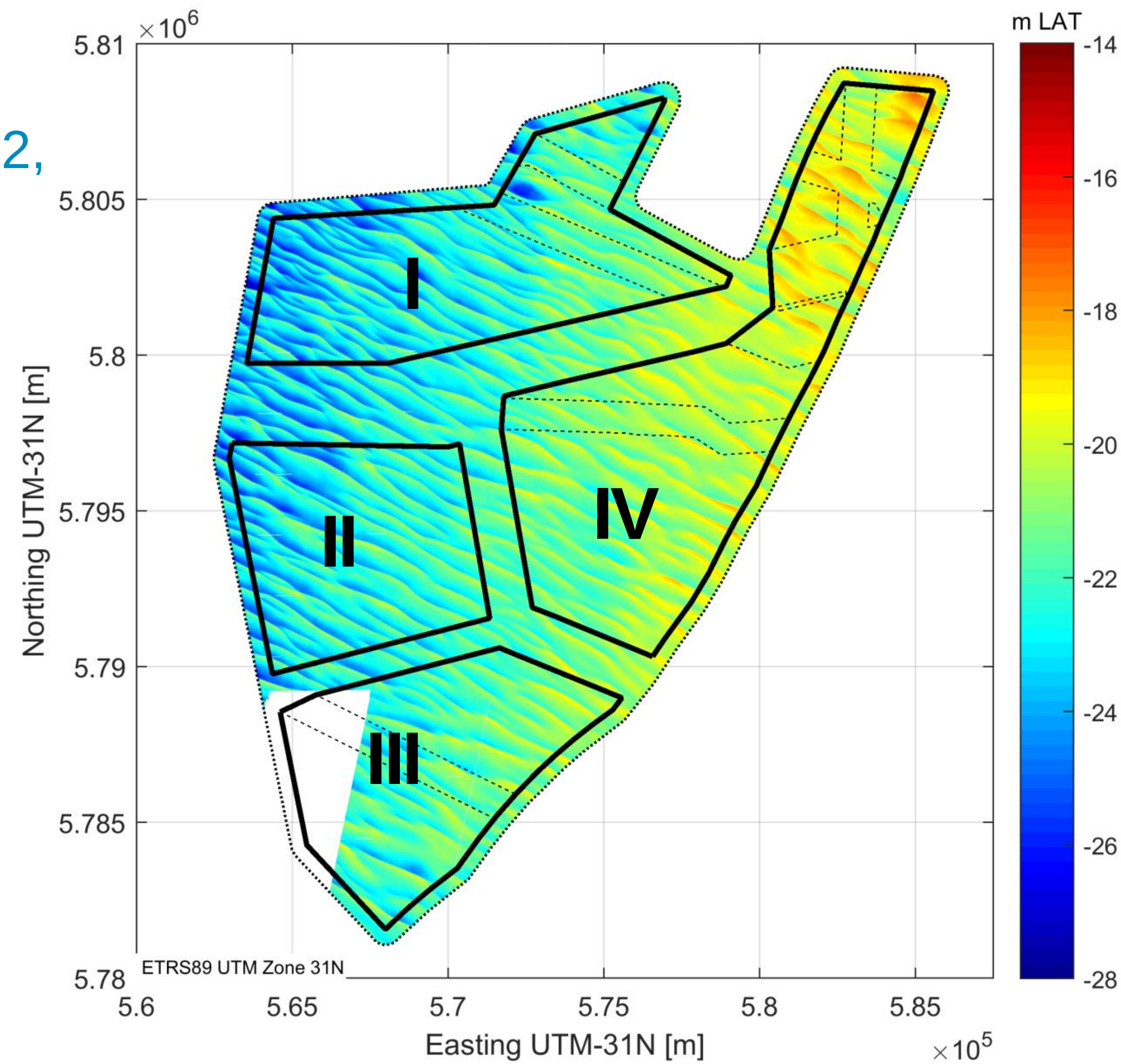


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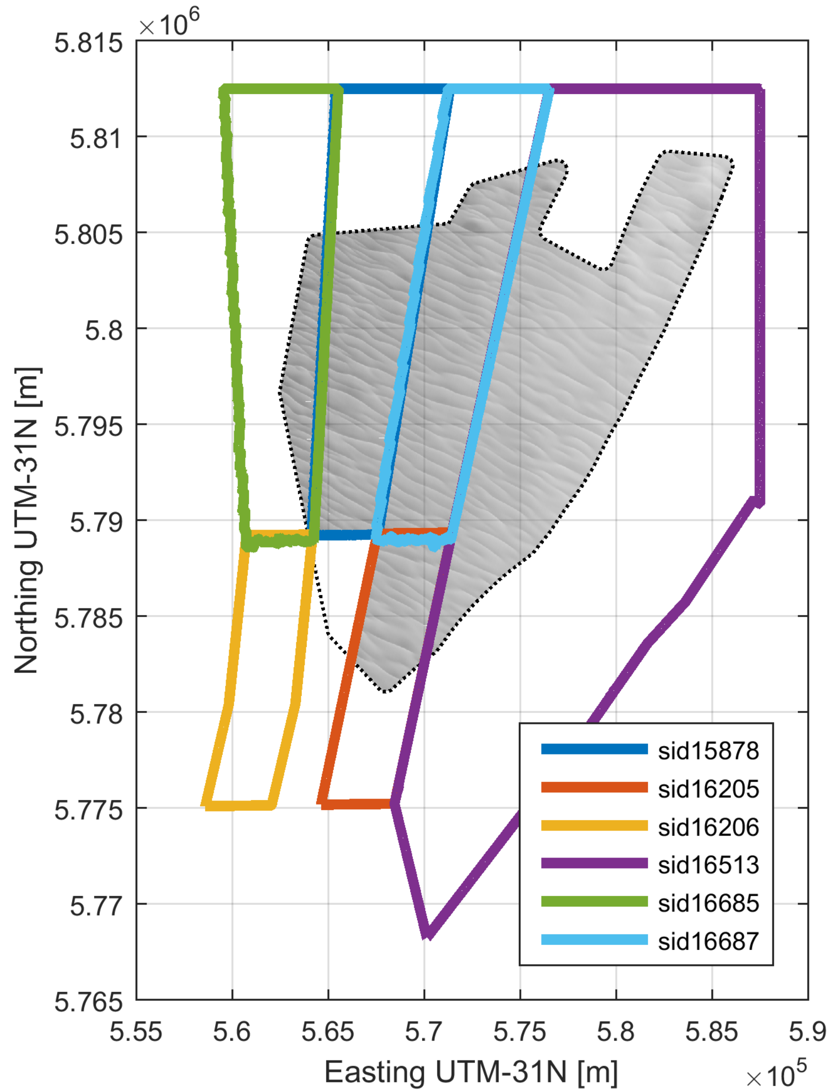


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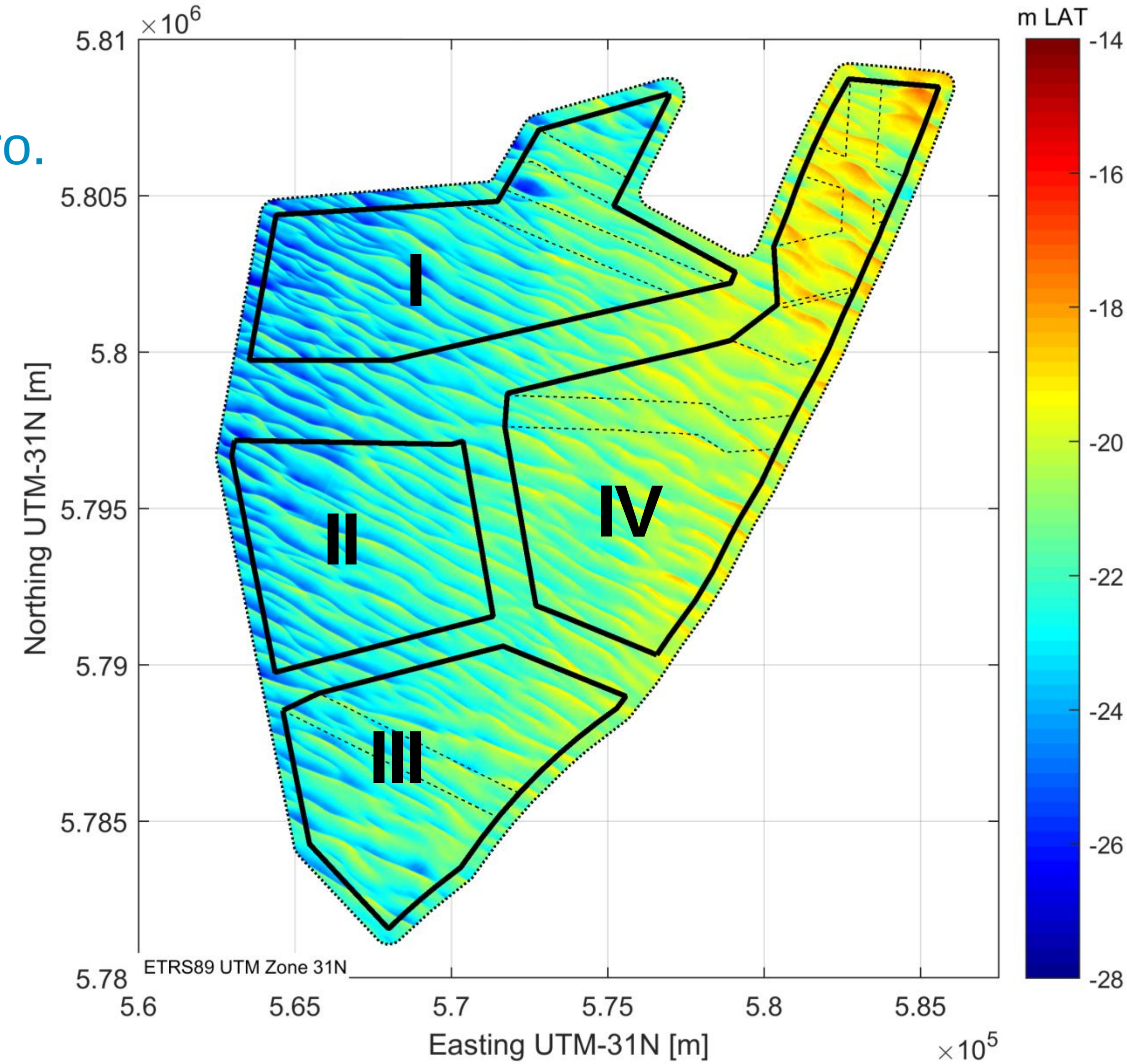
# Data description – Bathymetry 2016

Bathymetry constructed of 1 MBES in 2016, taken by Fugro.

| Water depth rel. to LAT | I | II | III | IV |
|---|---|---|---|---|
| Minimum (shallowest) | -18.1 | -18.6 | -18.9 | -15.8 |
| Maximum (deepest) | -26.9 | -26.3 | -24.9 | -23.6 |

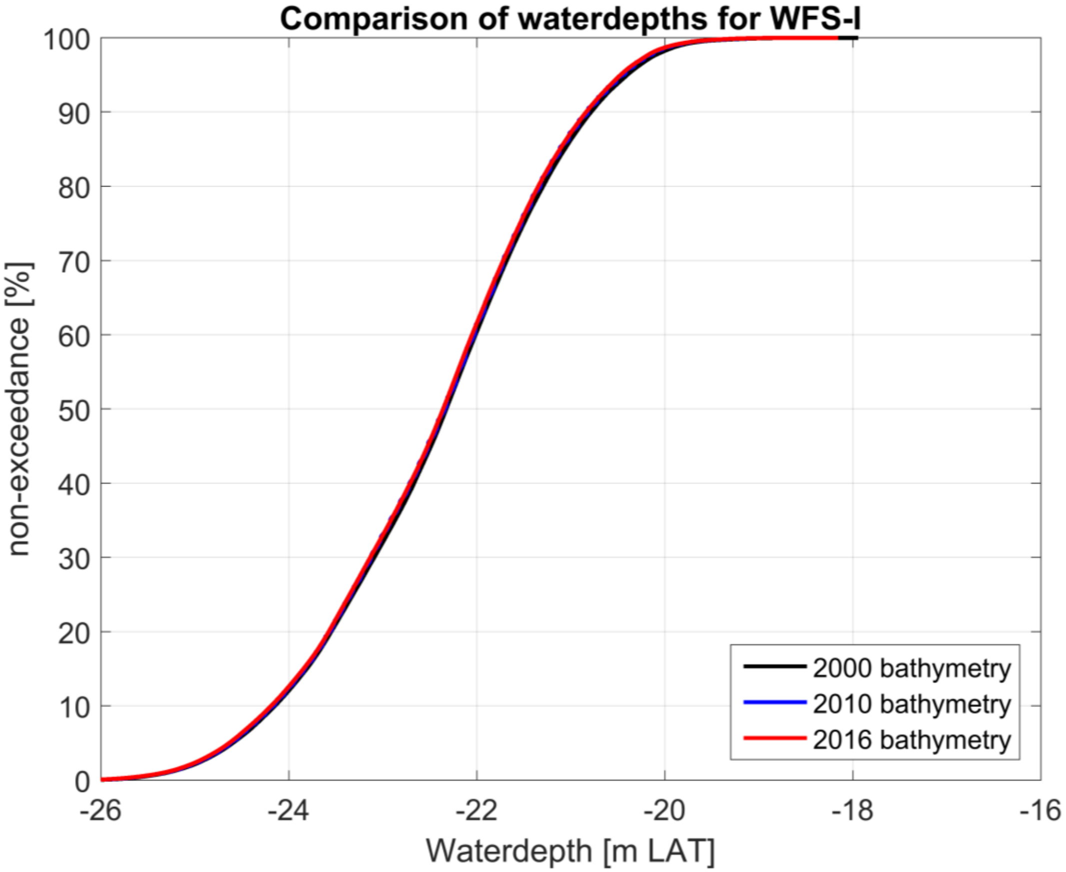


# Check for water depth range: WFS-I

Non-exceedance curves of water depths in WFS-I for all datasets:

Similar curve and no systematic offset, indicating that measurement methods and amplitudes of seabed features are comparable.

| Water depths in WFS-I rel. to LAT | | | |
|---|---|---|---|
| **Exceedance values** | **2000** | **2010** | **2016** |
| 1 ‰ | -26.0 | -26.0 | -26.0 |
| 10 ‰ | -25.3 | -25.3 | -25.3 |
| 990 ‰ | -19.8 | -19.9 | -19.9 |
| 999 ‰ | -19.1 | -19.2 | -19.2 |

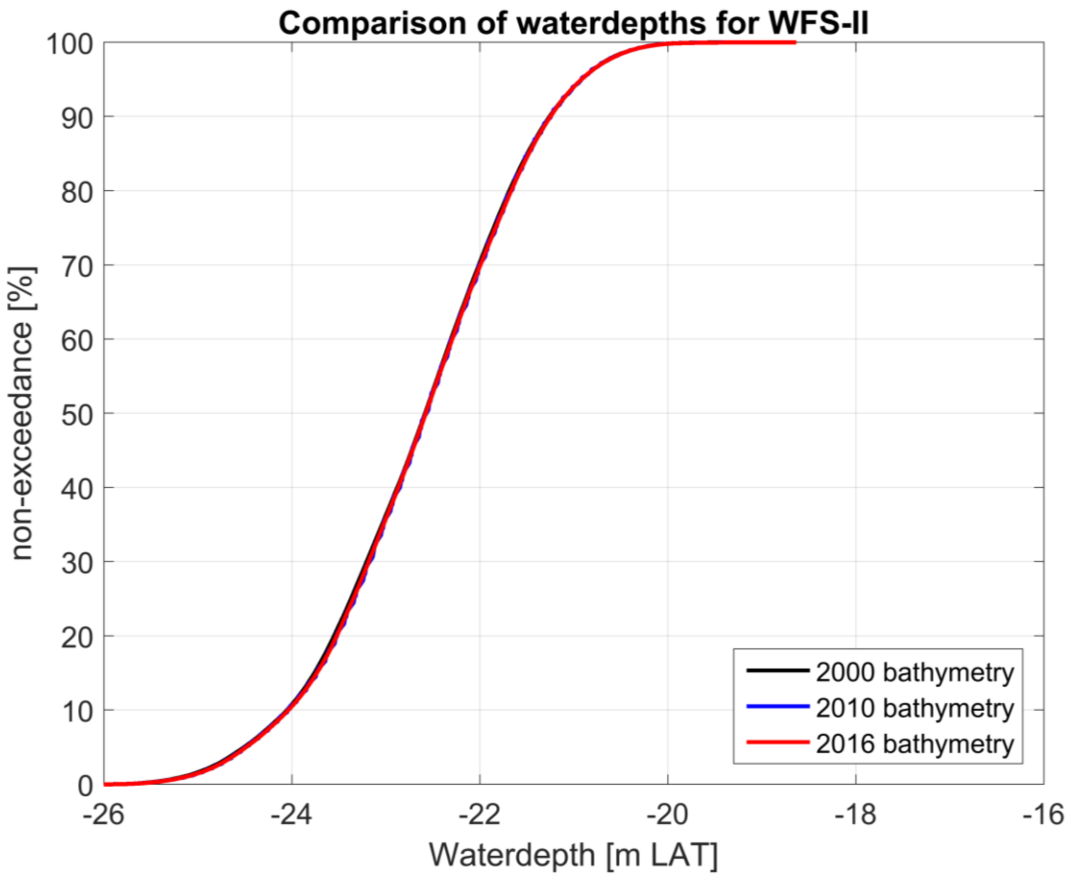


# Check for water depth range: WFS-II

Non-exceedance curves of water depths in WFS-II for all datasets:

Similar curve and no systematic offset, indicating that measurement methods and amplitudes of seabed features are comparable.

| Water depths in WFS-II rel. to LAT | | | |
|---|---|---|---|
| **Exceedance values** | **2000** | **2010** | **2016** |
| 1 ‰ | -25.7 | -25.7 | -25,7 |
| 10 ‰ | -25.2 | -25.1 | -25.1 |
| 990 ‰ | -20.4 | -20.4 | -20.4 |
| 999 ‰ | -19.9 | -19.9 | -19.8 |

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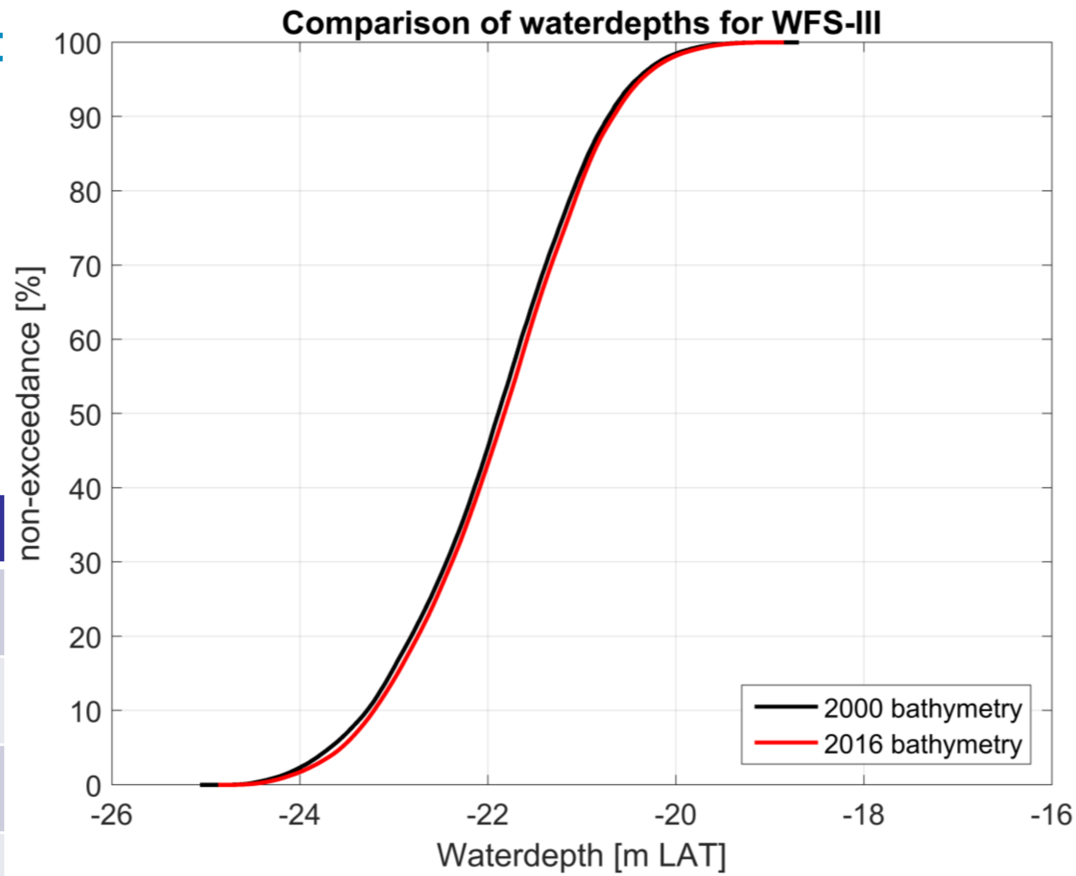
# Check for water depth range: WFS-III

Non-exceedance curves of water depths in WFS-III for all datasets:

Similar curve and no systematic offset, indicating that measurement methods and amplitudes of seabed features are comparable.

| Water depths in WFS-III rel. to LAT | | | |
|---|---|---|---|
| **Exceedance values** | **2000** | **2010** | **2016** |
| 1 ‰ | -24.6 | | -24.5 |
| 10 ‰ | -24.3 | | -24.2 |
| 990 ‰ | -19.9 | | -19.8 |
| 999 ‰ | -19.4 | | -19.3 |



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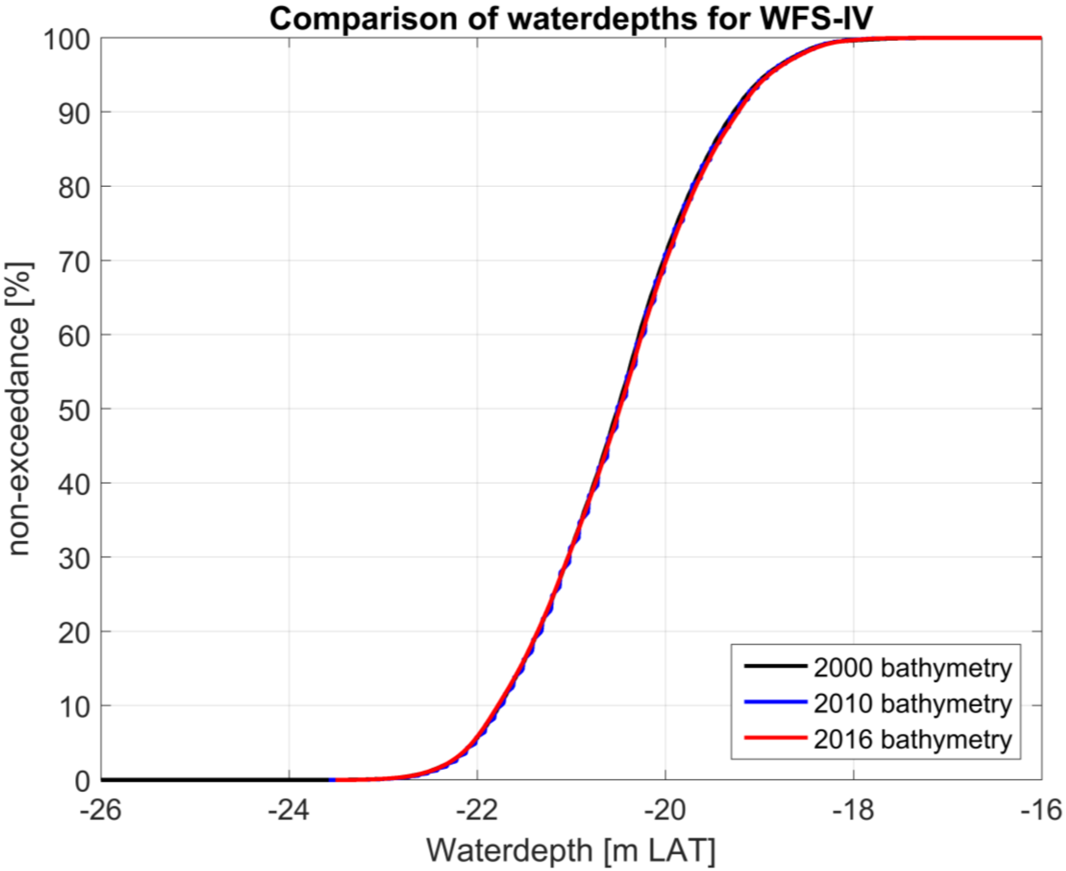
# Check for water depth range: WFS-IV

Non-exceedance curves of water depths in WFS-IV for all datasets

Similar curve and no systematic offset, indicating that measurement methods and amplitudes of seabed features are comparable.

| Water depths in WFS-IV rel. to LAT | | | |
|---|---|---|---|
| Exceedance values | 2000 | 2010 | 2016 |
| 1 ‰ | -23.1 | -23.0 | -23.1 |
| 10 ‰ | -22.6 | -22.5 | -22.6 |
| 990 ‰ | -18.4 | -18.3 | -18.3 |
| 999 ‰ | -17.6 | -17.8 | -17.8 |

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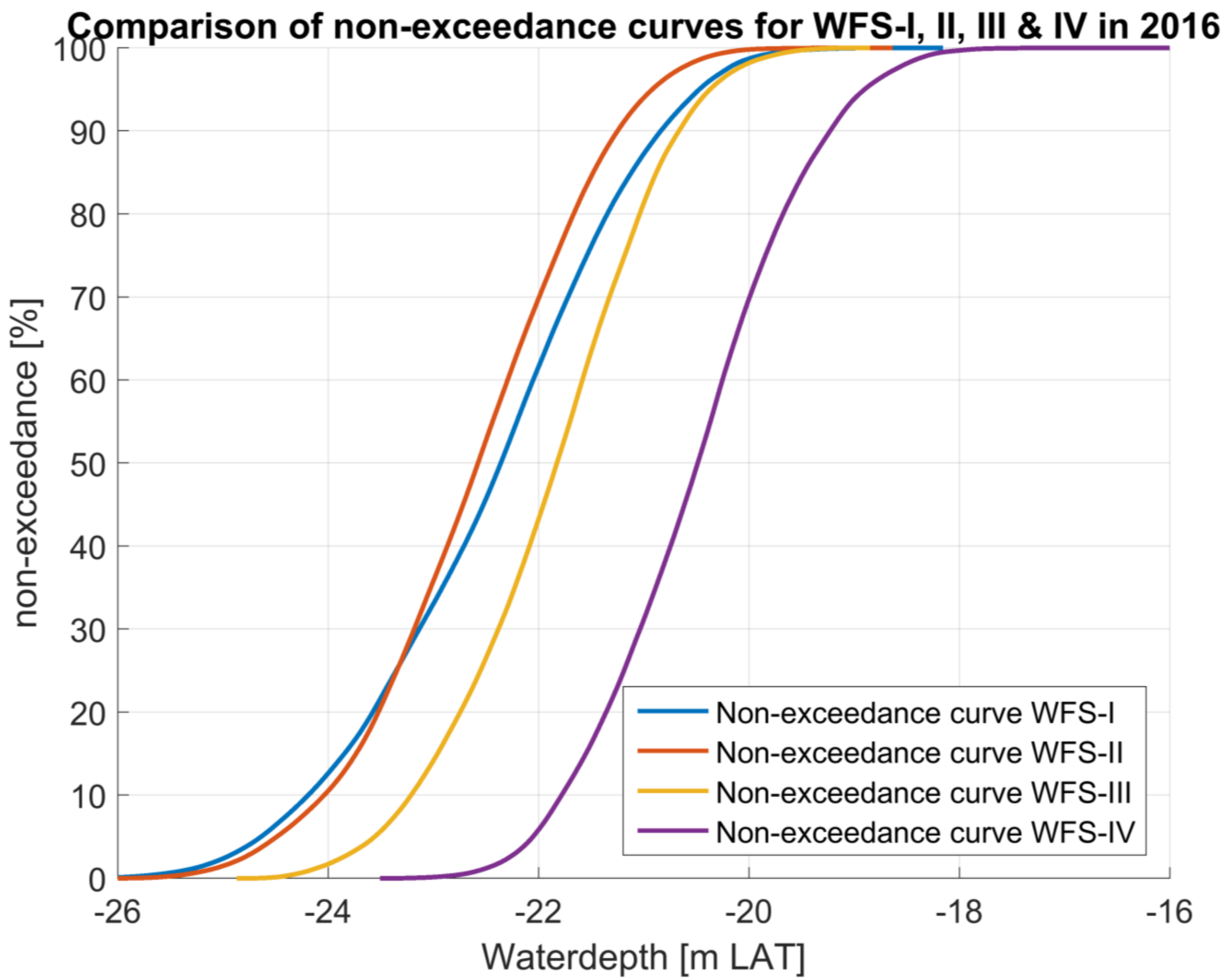
# Comparison of water depths in all sites

## Non-exceedance curves of the four WFS in HKZ

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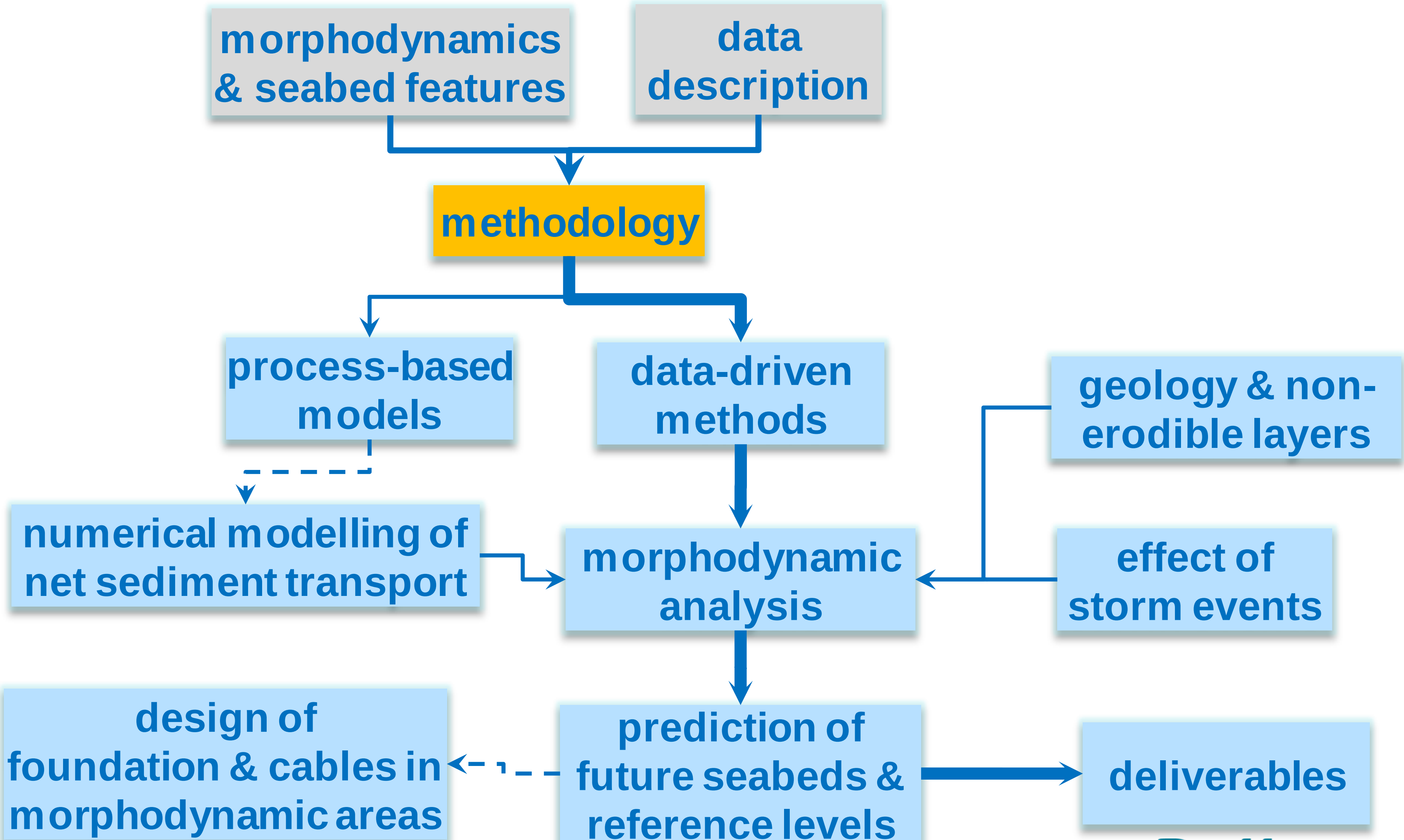


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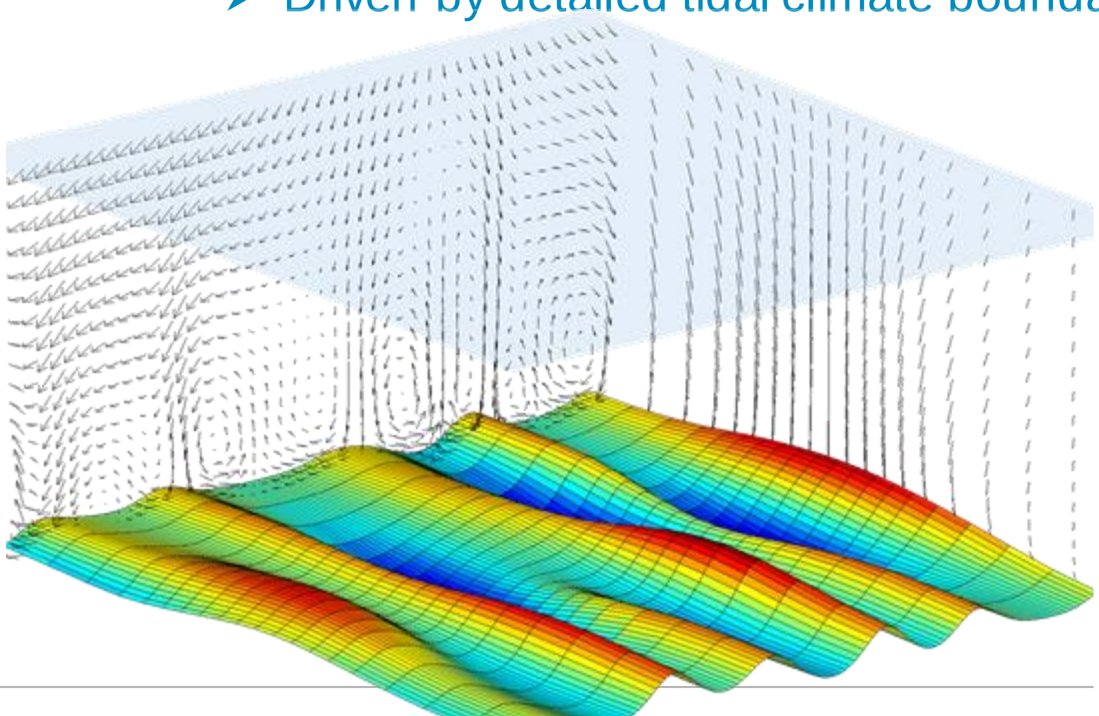
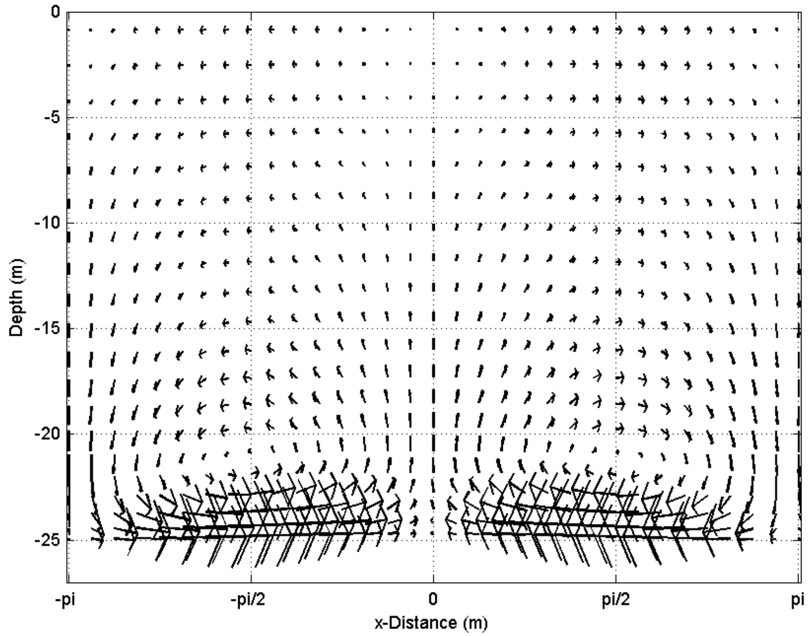
# Sand Wave Morphodynamics – Analysis techniques

**Methods to investigate sand wave characteristics:**

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





# Sand Wave Morphodynamics – Analysis techniques

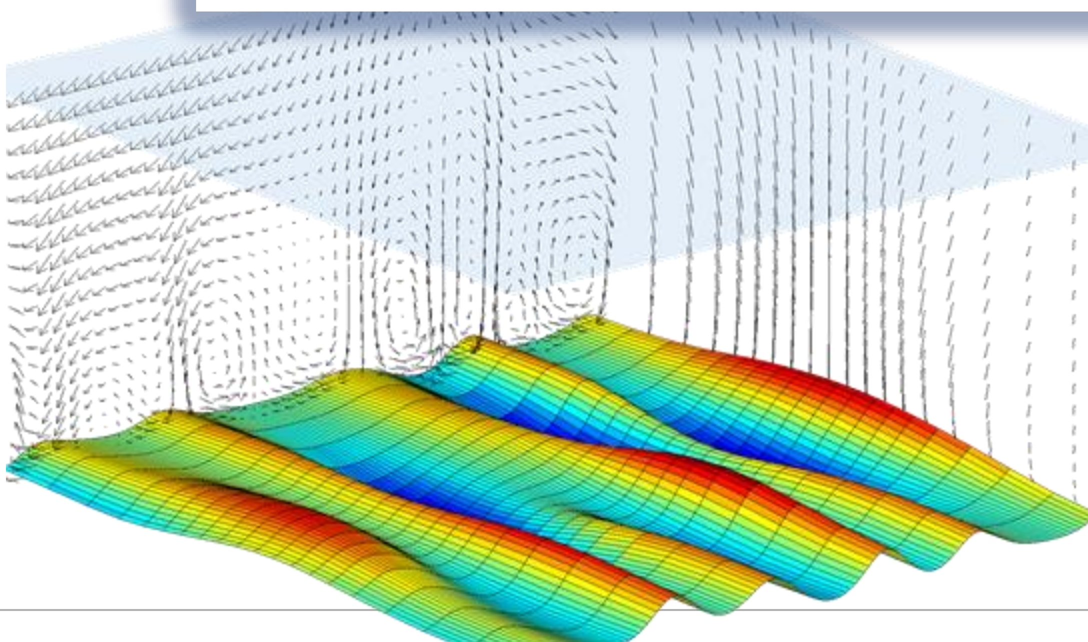
**Methods to investigate sand wave characteristics:**

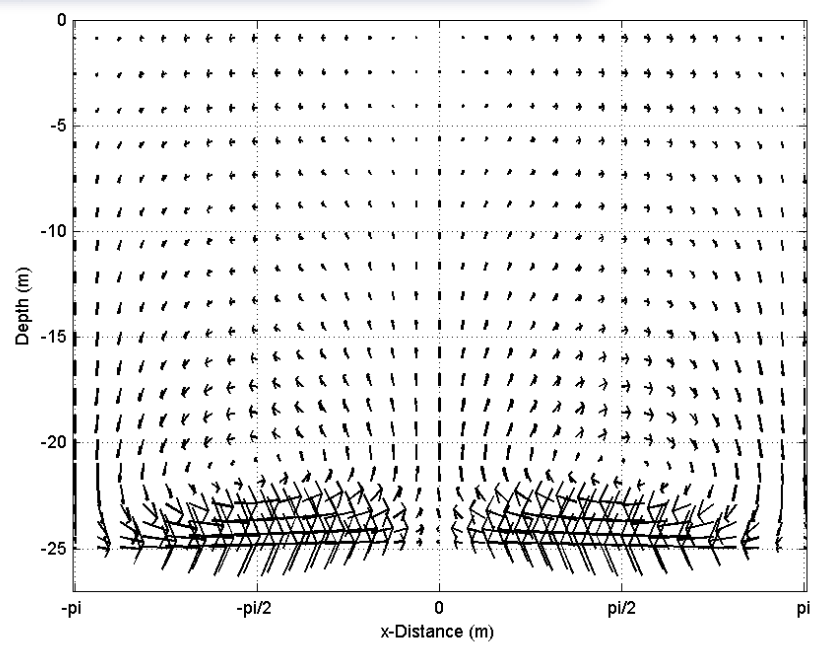
1. Data-driven analysis based on seabed surveys

> Most reliable, if data is available

2. Numerical modelling

> Only option, if data is scarce;
> useful to investigate dependencies on governing parameters





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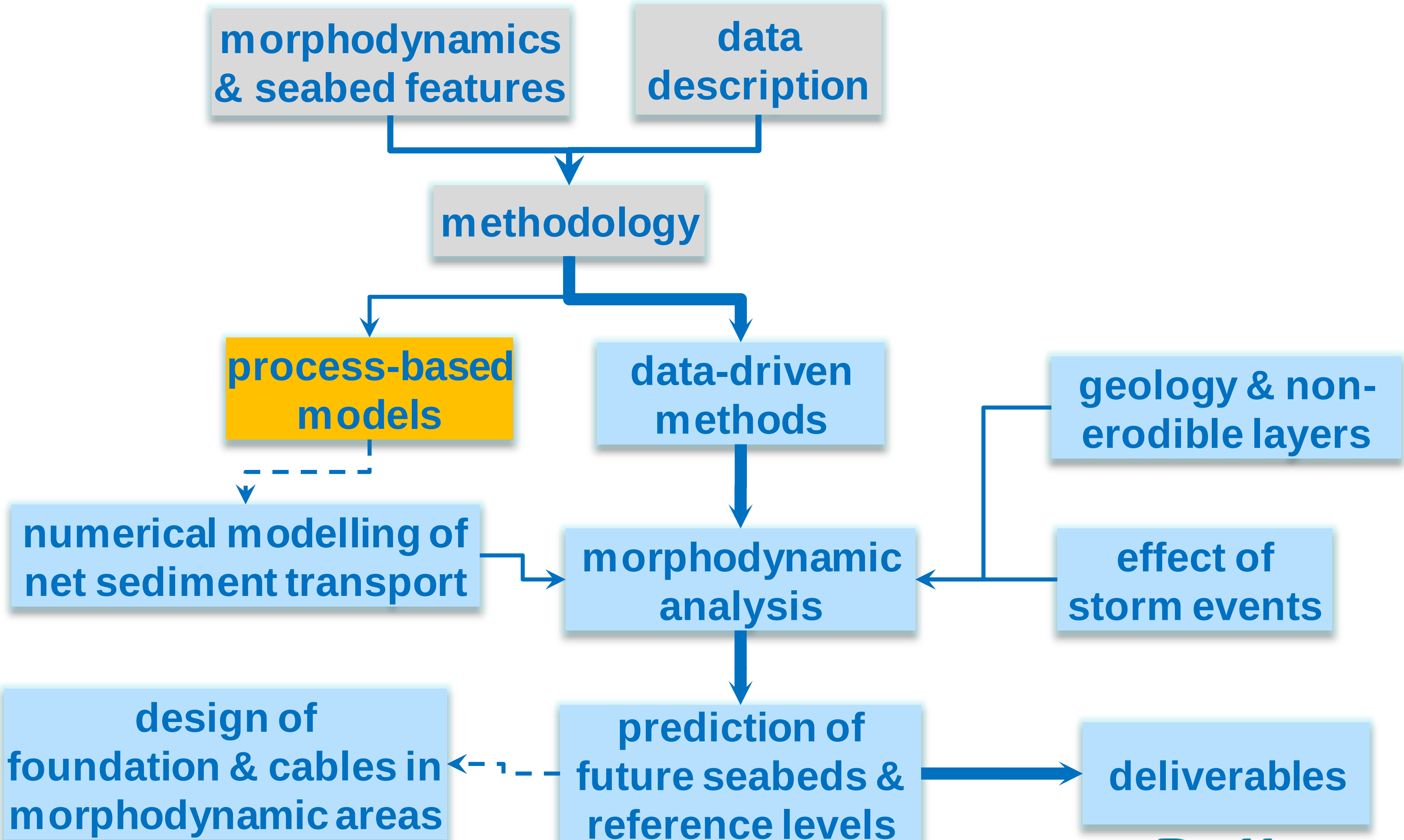
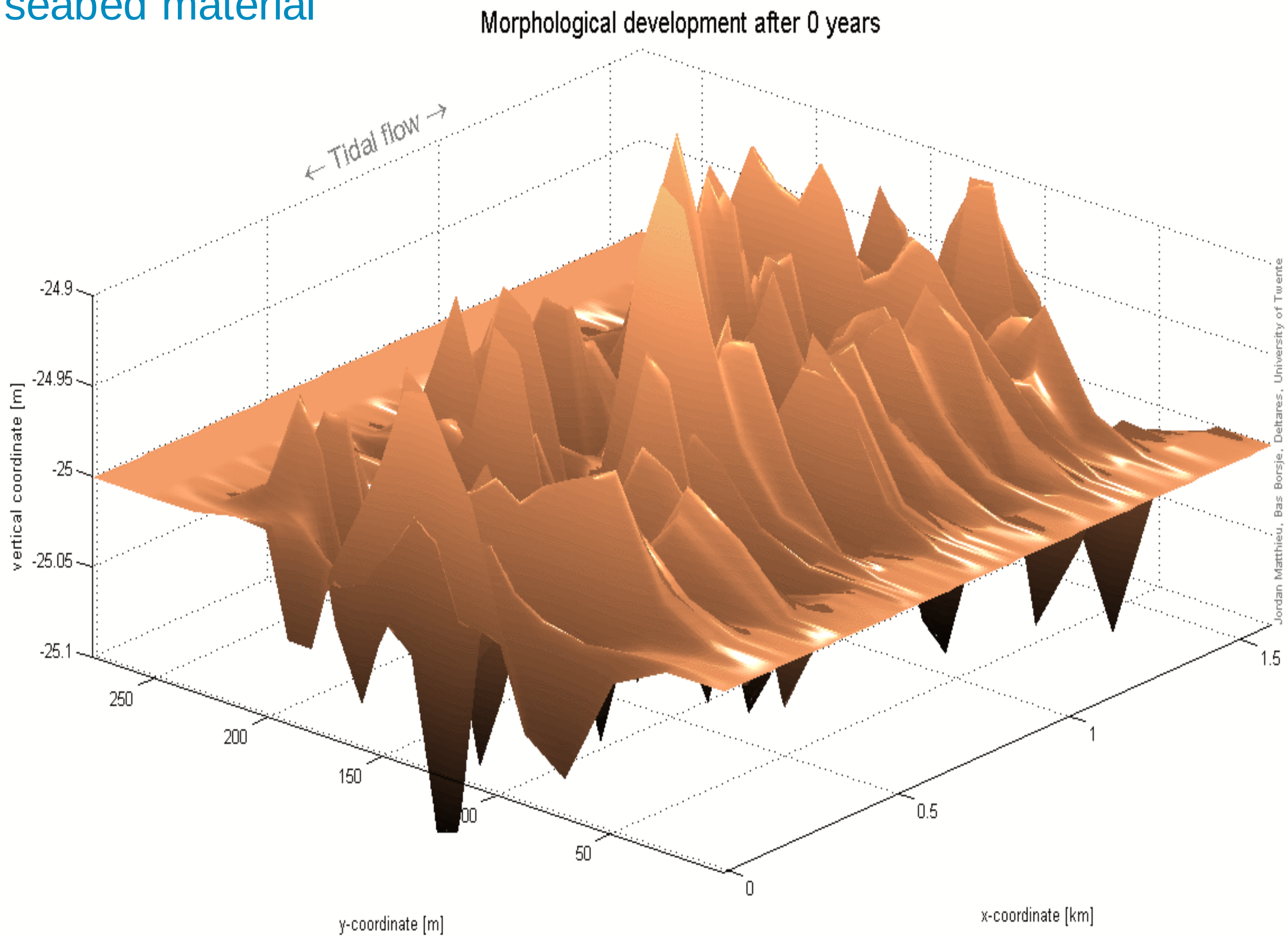


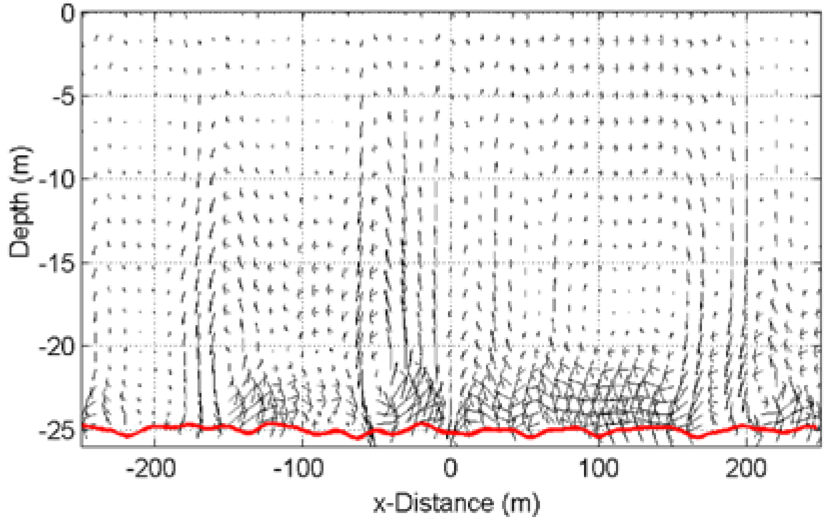
# Example of Sand Wave Model in Delft-3D

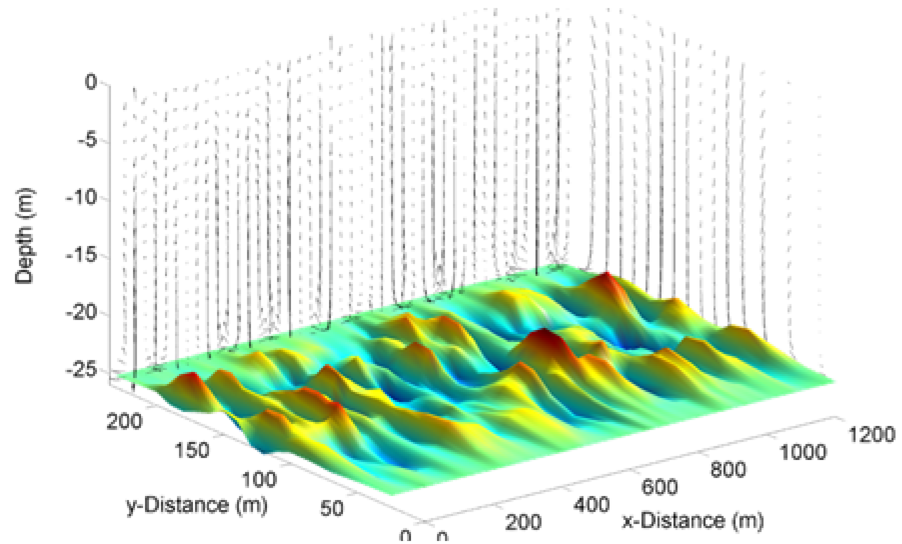
Self-organizing of random bed perturbations into natural sand wave fields that belong to the local hydrodynamic forcing, water depth and seabed material



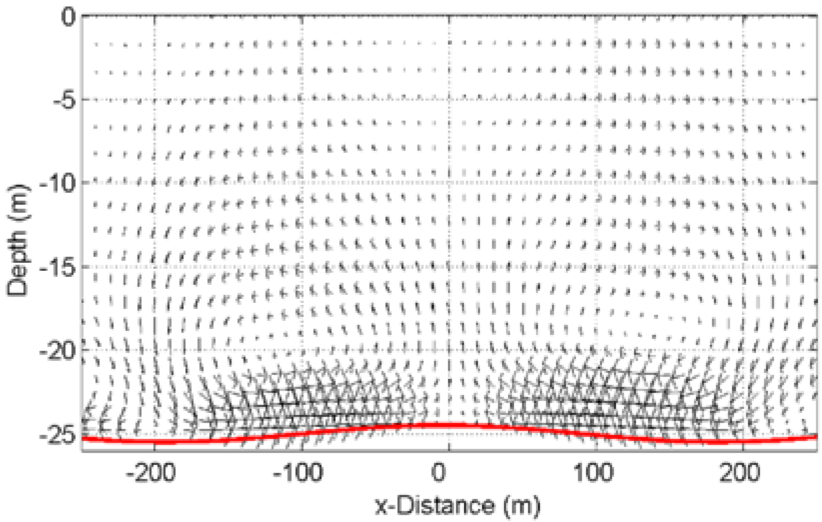
# 3D-Sand Wave Model in Delft-3D

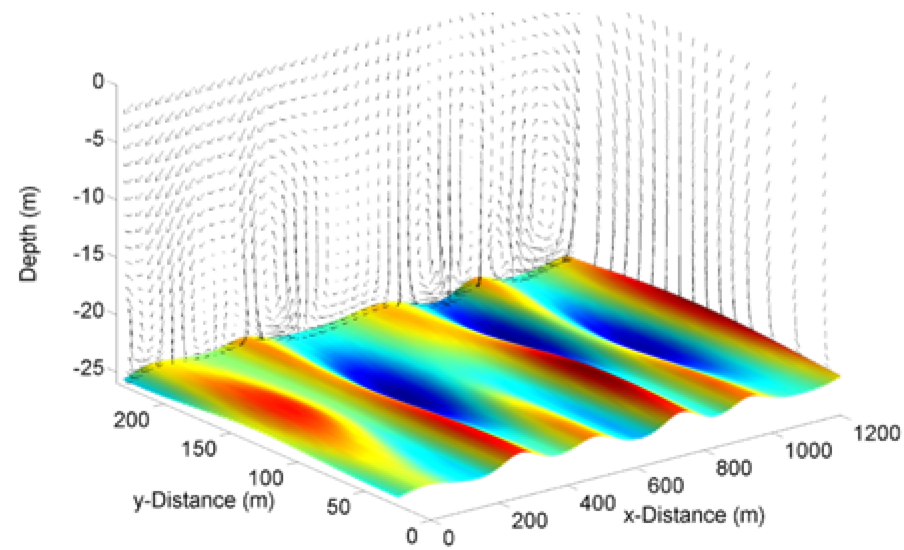
t = 0: Random bed perturbations and chaotic velocity field




Self-organized seabed with tidal-averaged velocity recirculation cells



# Sand waves and their environmental dependencies

## Migration Rate:

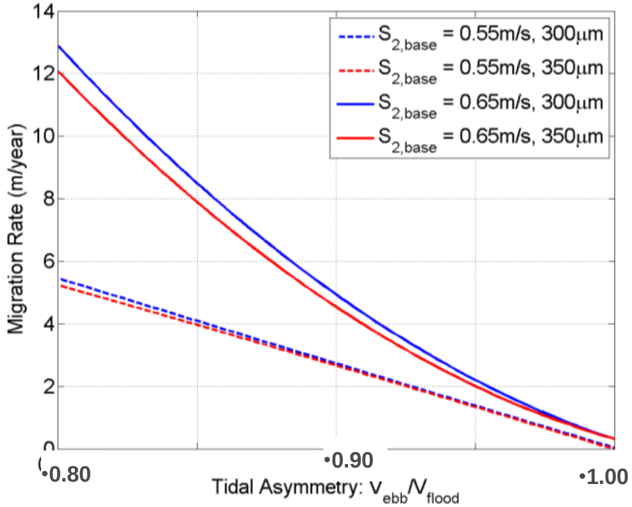
- Grain size
- Tidal asymmetry
- Wave length

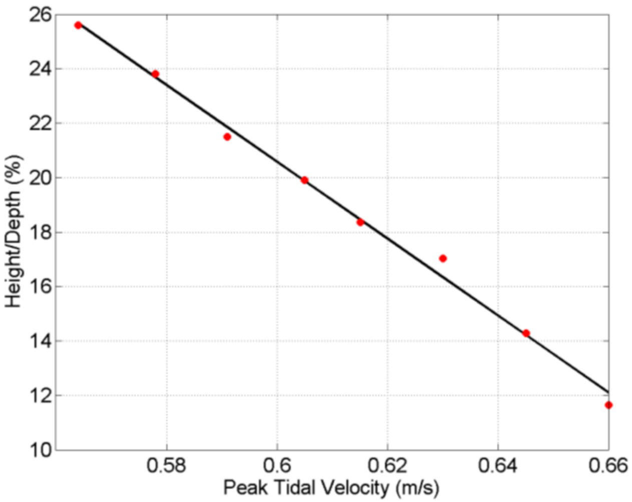
## Amplitude:

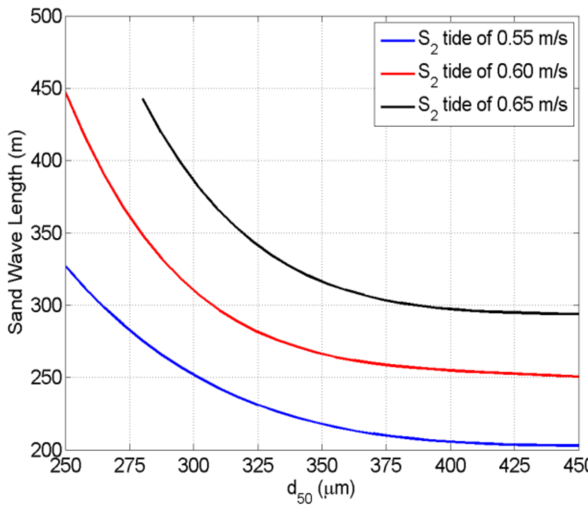
- Grain size
- Tidal asymmetry
- Peak tidal velocity
- Water depth

## Wavelength:

- Grain size
- Peak tidal velocity




[Recent advancements by Van Gerwen & Borsje (2016) to obtain equilibrium sand waves in Delft-3D]

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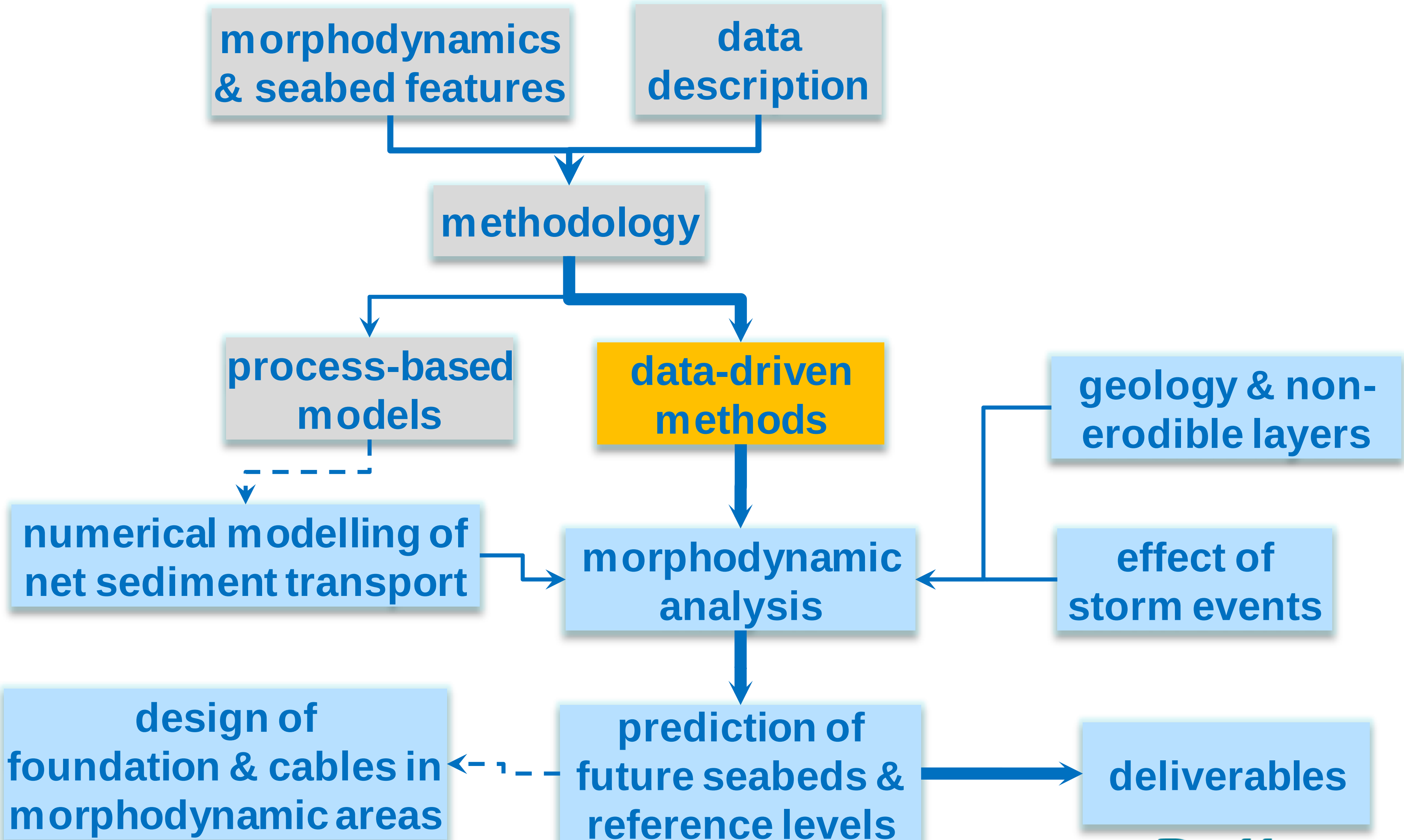
# Structure of presentation



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# Required Design Seabed Levels

**Lowest SeaBed Level (LSBL)**

The *lowest* possible seabed level in the period 2016-2051

*Static Seabed Level*

\- *Maximum Negative Envelope of Sand Wave Field until 2051*

\- *Uncertainty Band*

*Lowest SeaBed Level (LSBL)*

**Highest SeaBed Level (HSBL)**

The *highest* possible seabed level in the period 2016-2051

*Static Seabed Level*

\+ *Maximum Positive Envelope of Sand Wave Field until 2051*

\+ *Uncertainty Band*

*Highest SeaBed Level (HSBL)*

# Required Design Seabed Levels

**Maximum seabed lowering in period 2016-2051**

*Lowest SeaBed Level (LSBL)*
*- 2016-bathymetry*
*Maximum seabed lowering (negative values)*

**Maximum seabed rising in period 2016-2051**

*Highest SeaBed Level (HSBL)*
*- 2016-bathymetry*
*Maximum seabed rising (positive values)*

Note that all these levels are design levels which should be sufficiently conservative. Depending on the O&M strategy, different seabed levels can be used. Therefore, also Best-Estimate Bathymetries are delivered.



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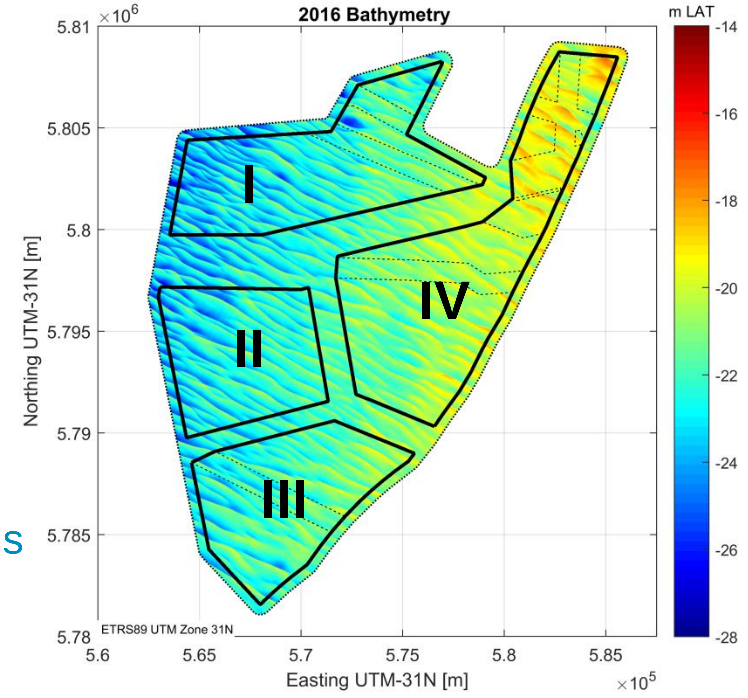
# Methodology and calculation steps (I)

In order to predict these levels for the HKZWFZ, 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. Extraction of the sand wave field (excluding sand banks and megaripples) for sand wave analysis
4. Automated detection of sand wave migration directions
5. Cross correlation technique on individual sand waves to determine sand wave migration rates
6. Fourier analysis on individual sand waves to determine sand wave characteristics (length & height)
7. Filtering and analysis of megaripples (to be included in the uncertainty band)

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# Methodology and calculation steps (II)

...

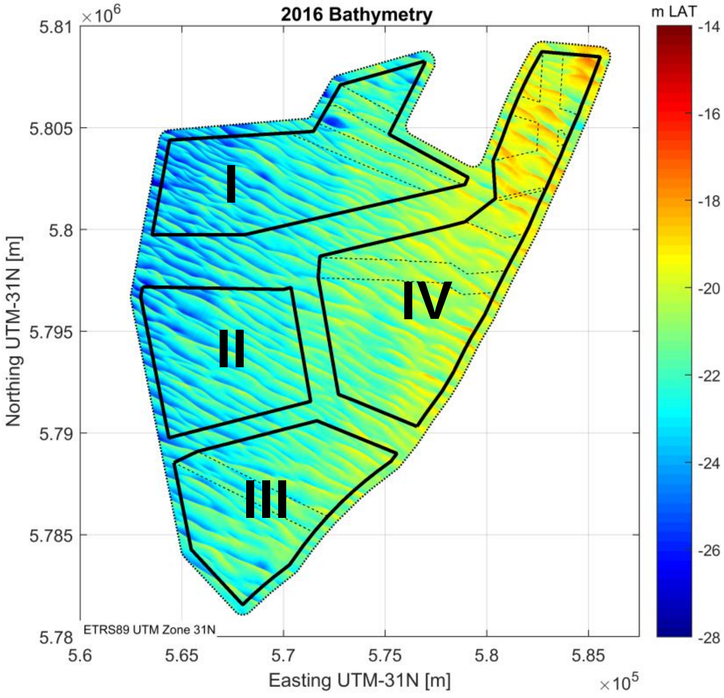
8. Estimating uncertainty range based on measurement errors, processing inaccuracies and smaller scale seabed features such as megaripples

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

10. Combining migrated sand wave fields with “static” bathymetry and uncertainty range to compute LSBL and HSBL

11. Comparing the isopach of the base of the Holocene Formation and the top of the non-erodible layer with the LSBL to avoid overly conservative downward bed level changes

12. Translate LSBL and HSBL into zones with various recommendation levels for offshore foundations and cables

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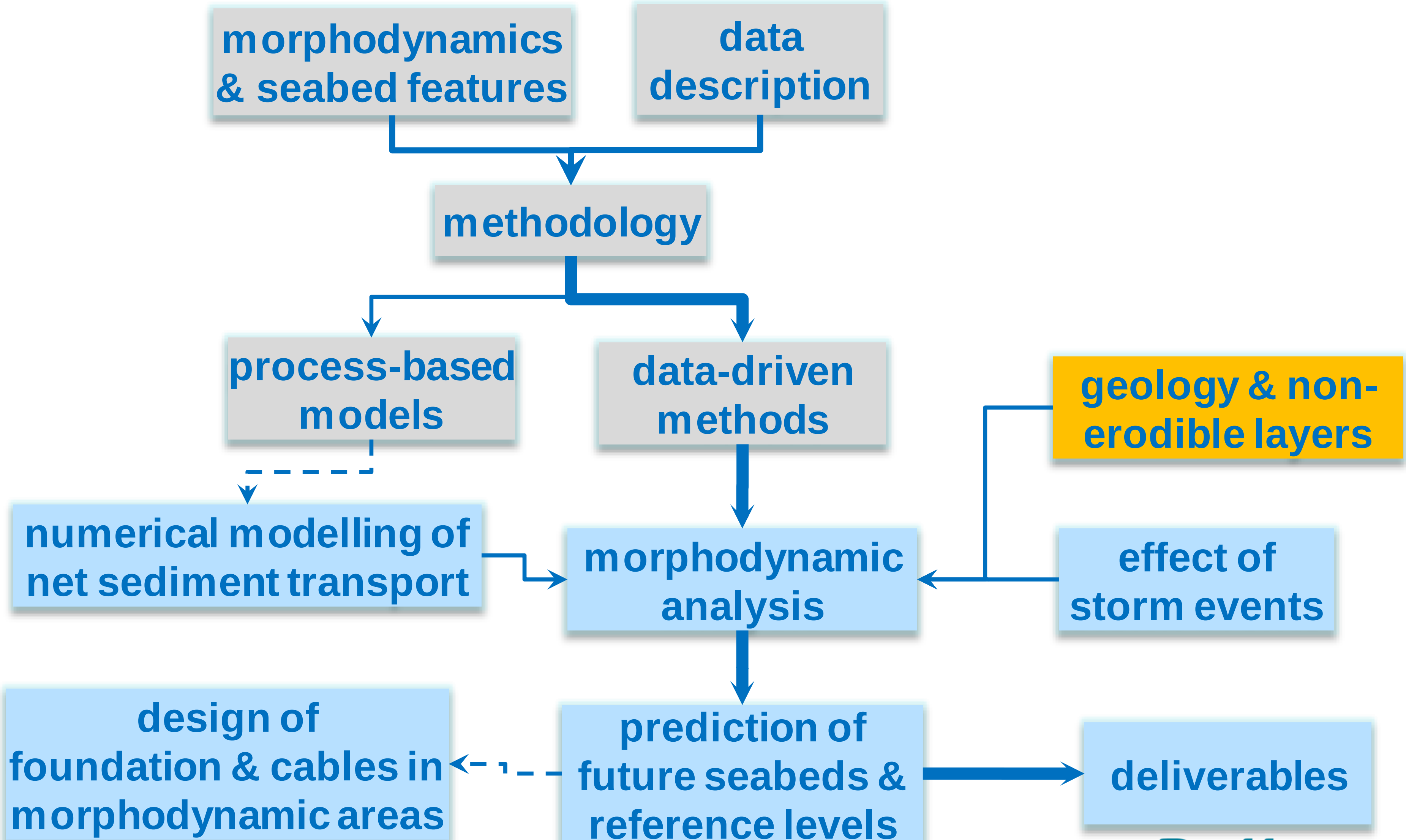
# Names of different bathymetrical data sets

## Definitions of various bathymetrical data sets used in this study:

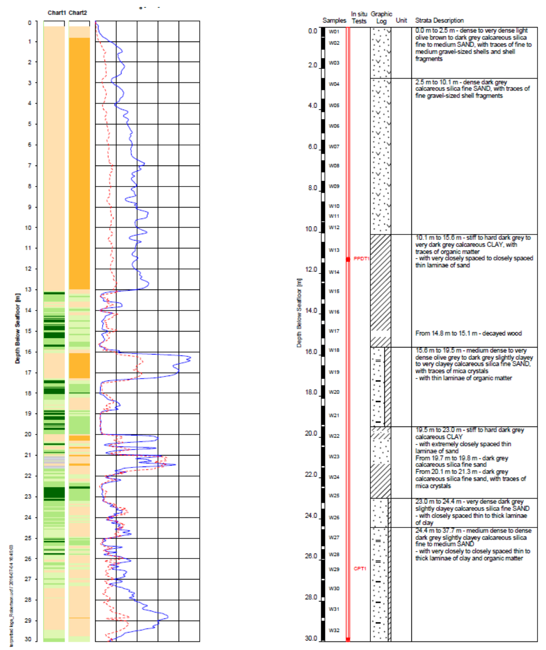
| Short name | Description | Long-term mean seabed | Sand waves | Mega-ripples |
|---|---|---|---|---|
| 2016 Bathymetry | Full measured bathymetry by Fugro | √ | √ | √ |
| Static Bathymetry | Long-term mean bathymetry (for the considered period / lifetime of HKZ WFZ) | √ | x | x |
| Mobile Bathymetry | Filtered bathymetry with sand waves and megaripples only | x | √ | √ |
| Sand Wave Field | Filtered bathymetry with sand waves only | x | √ | x |
| Megaripple Field | Filtered bathymetry with megaripples only | x | x | √ |

# Structure of presentation

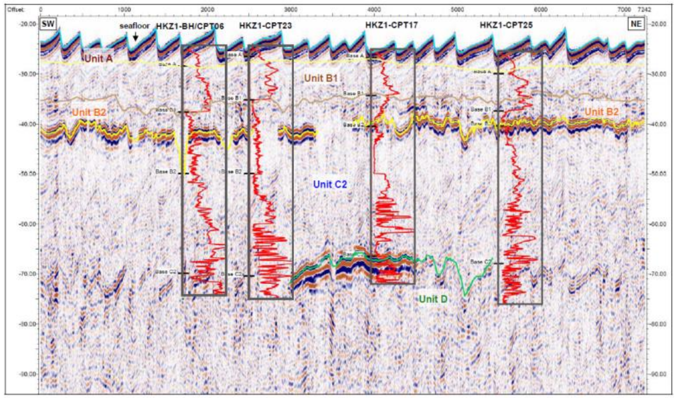


# Geological characterization - Data analysis

- Boreholes => lithology, sediment grain size, and description
- CPT=> indication of lithology and grain-size
- Seismics: depth of different horizons => depth and distribution of geological formations




| Unit | Thickness | Lithology |
| --- | --- | --- |
| **Southern Bight Formation** | 3-6 m typically 4 m | Brown-yellow, dense, fine to coarse SAND, with $CaCO_3$, shells and shell fragments (0-20%), sparse clay and silt laminae, locally with gravel. |
| **Kreftenheye Formation** | 5-25 m typically 10 m | Grey, fine to medium, dense SAND, with gravel (up to 10%), shell fragments, wood fragments, and clay pebbles. |
| **Brown Bank Member** | 0-13 m | Interbedded firm CLAY, PEAT, SILT and dense SAND. |
| **Eem Formation** | 8-32 m | Medium dense, fine to coarse SAND with shells, interbedded clay and locally gravel. |

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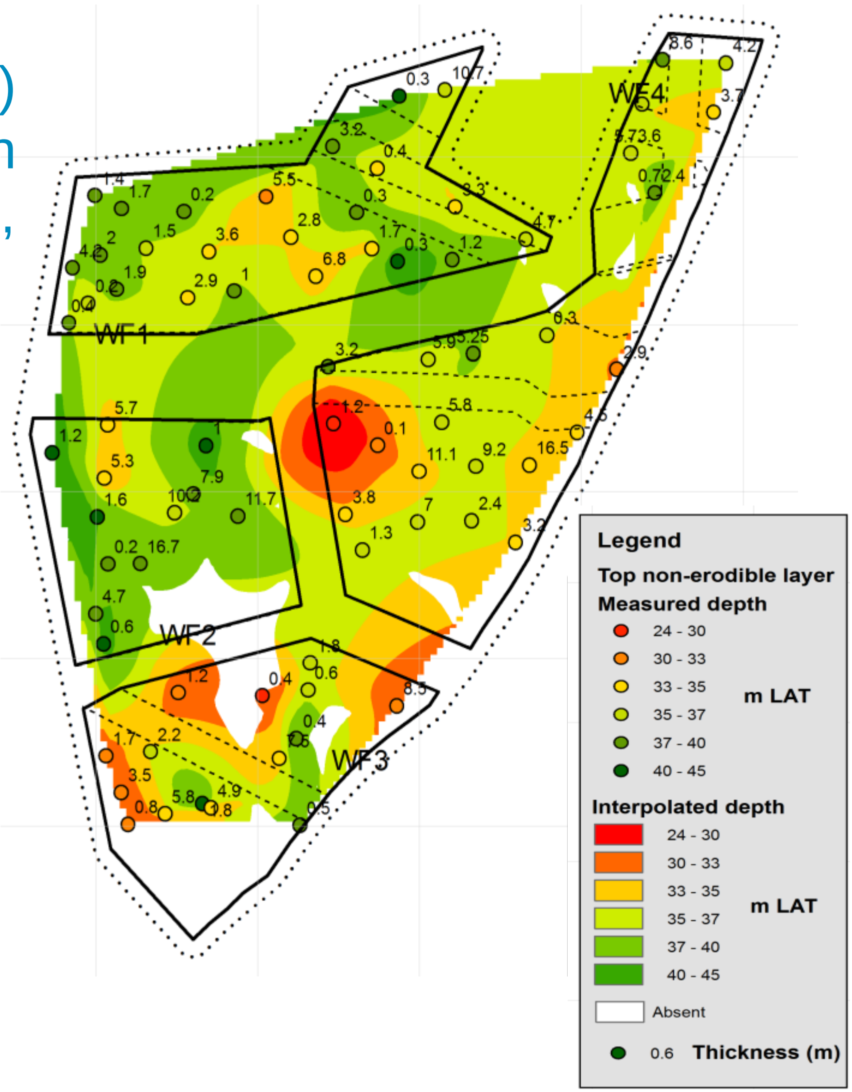
# Geology analysis and visualization in GIS (I)

Non-erodible layers (clay, silt, peat) within the upper 20m per observation point and interpolated grid (depth, layer thickness)

- ➢ No clay layer within the upper 2-3 m
- ➢ 3-5 m depth: only 1 location with clay
- ➢ 5-20 m depth: widespread clay layers

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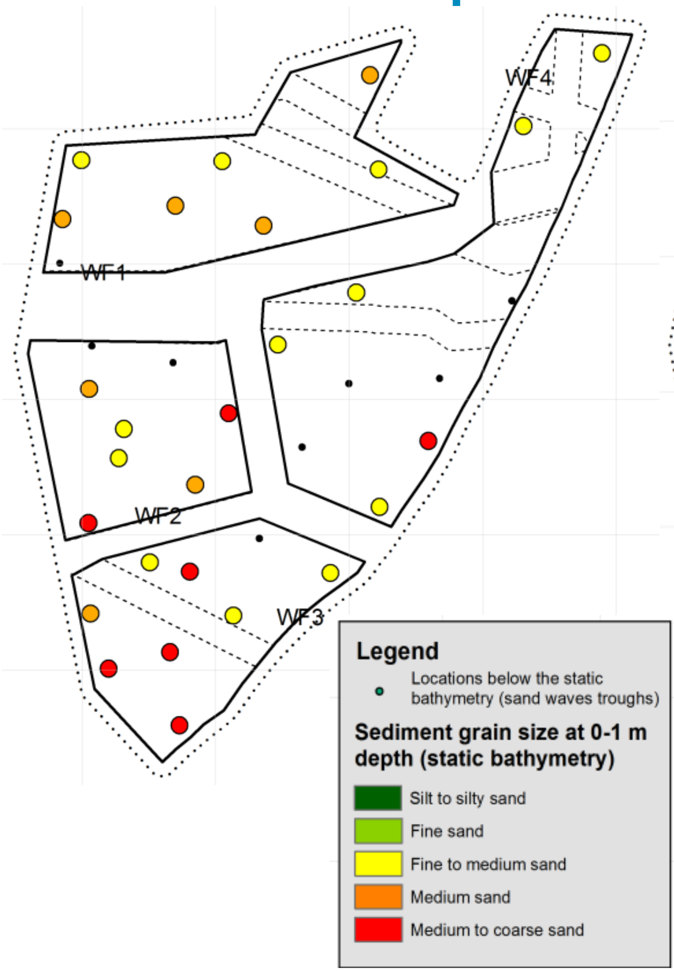
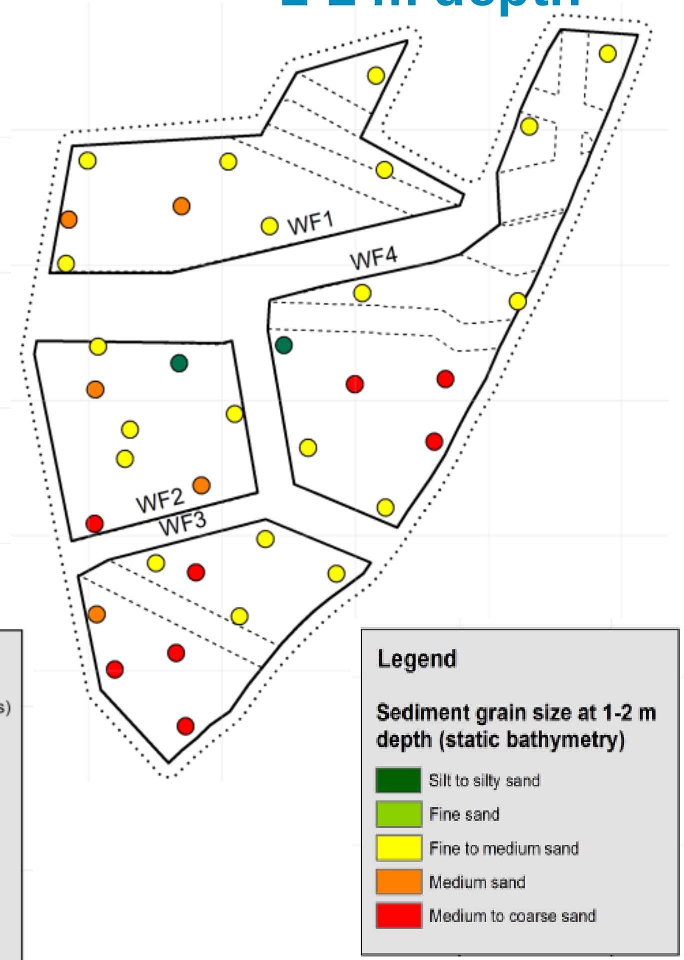
# Geology analysis and visualization in GIS (II)

## Lateral and vertical variability of grain size (static bathymetry reference)

### 0-1 m depth




### 1-2 m depth




**General trend**

NE –> SW

finer –> coarser

**0-1 m depth**

fine to coarse sand

**1-2 m and deeper**

Silt and silty sand in central area, sandy elsewhere

# Conclusions on geology

- Non-erodible layers are located too deep to affect the morphodynamics

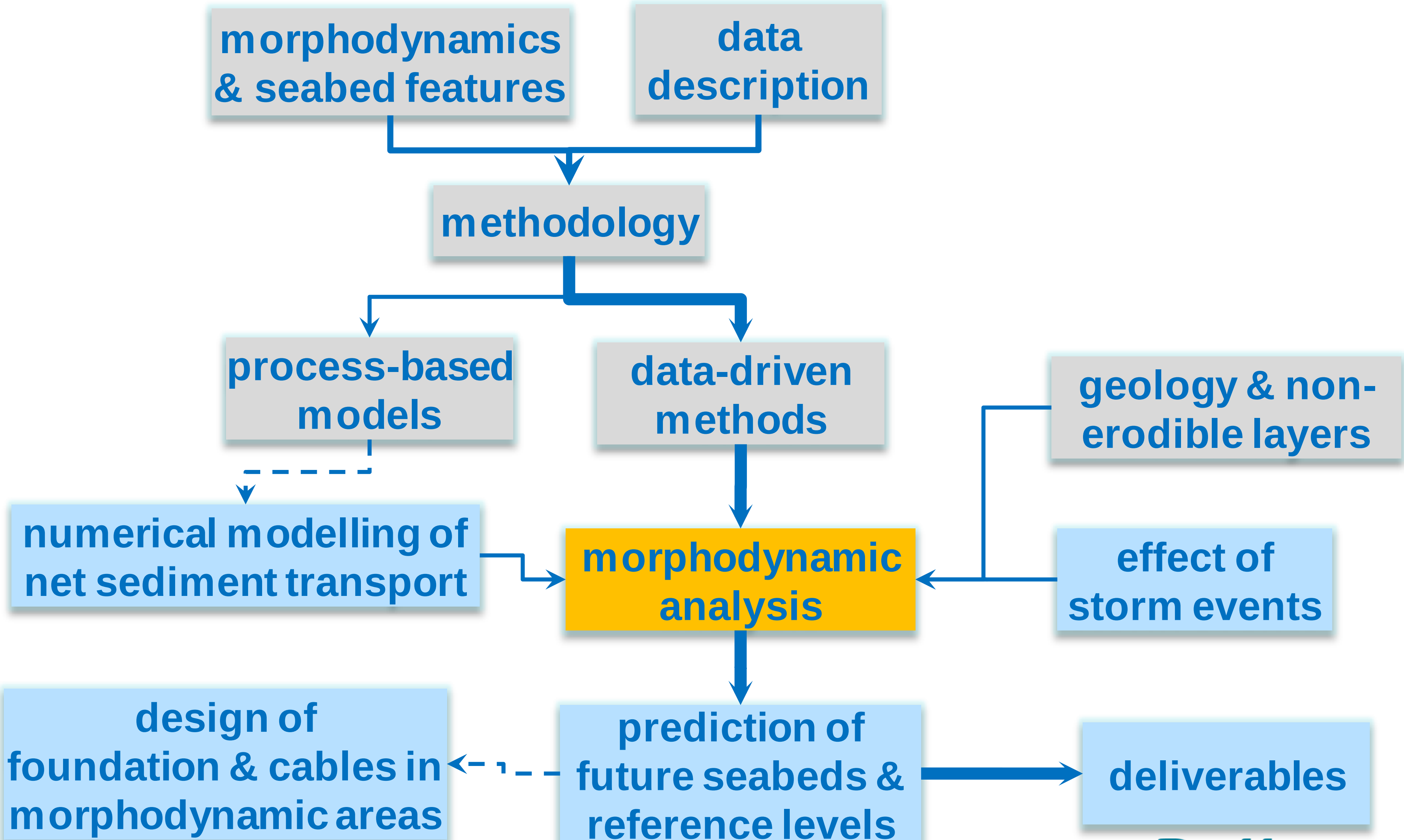
- Sediment grain size:
  - lateral and vertical variability
  - fine to coarse sand
  - silt at depth in the central part of the area

  => expected minor effect on morphodynamics

- Note 1: absence of evidence in areas with no data. Non-erodible layers may be present. Still, if so, small areal extent

- Note 2: sediment grain size affected by seafloor morphology: grain sorting within sand waves

# Structure of presentation

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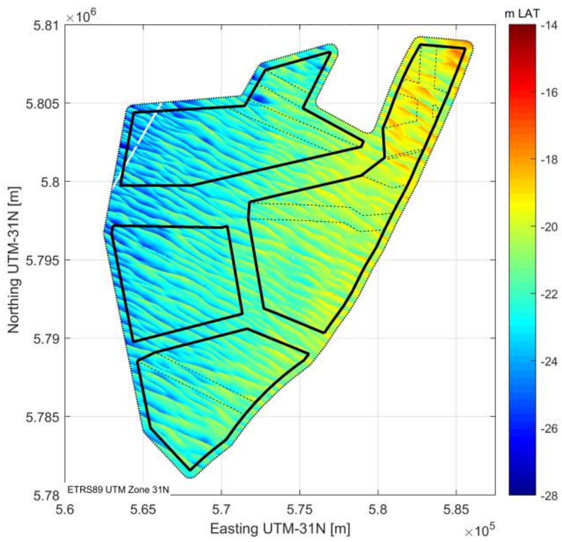
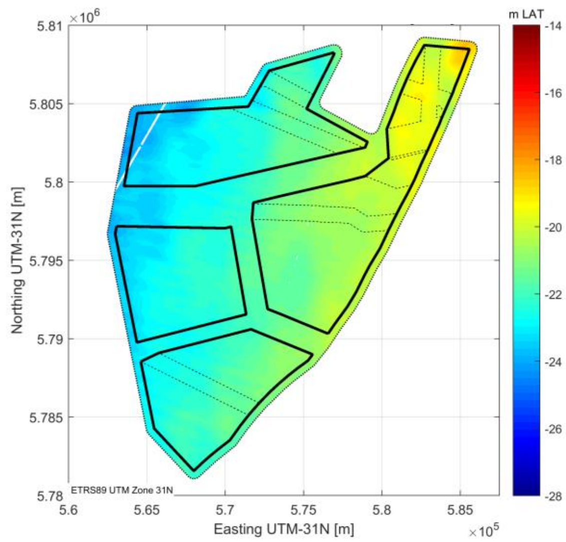
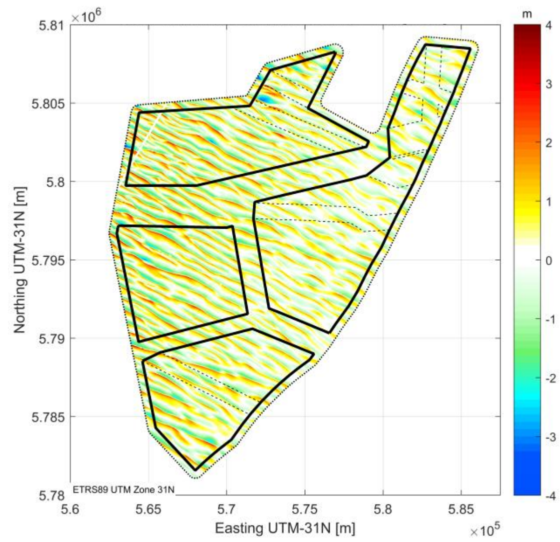
# Large-scale bathymetric filtering

- Goal is to separate **mobile** and **static** bathymetry
- **Sand waves** have an average crest orientation around the **NNE - SSW**
- For filtering it was decided to use a **block filter.** The filter size was chosen at **1400m**.
- In this way, averaging over the sand waves did **not cause too much smoothening of the static bathymetry**, while a filter size of 1400m is longer than the longest observed sand wave lengths in the HKZWFZ, ensuring that all sand waves are filtered out

*2000-bathymetry* - *static bathymetry* = *mobile bathymetry*

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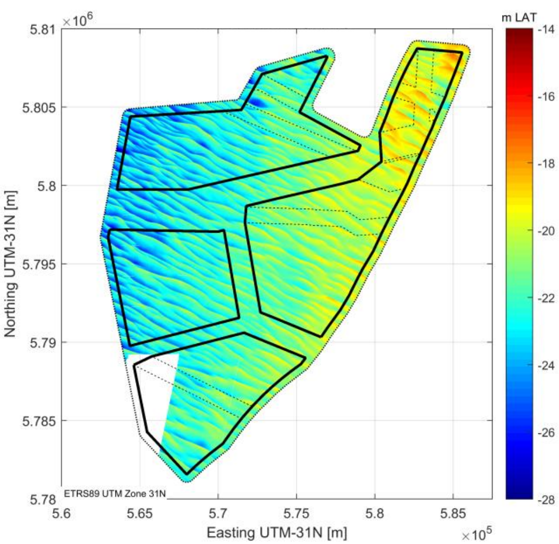
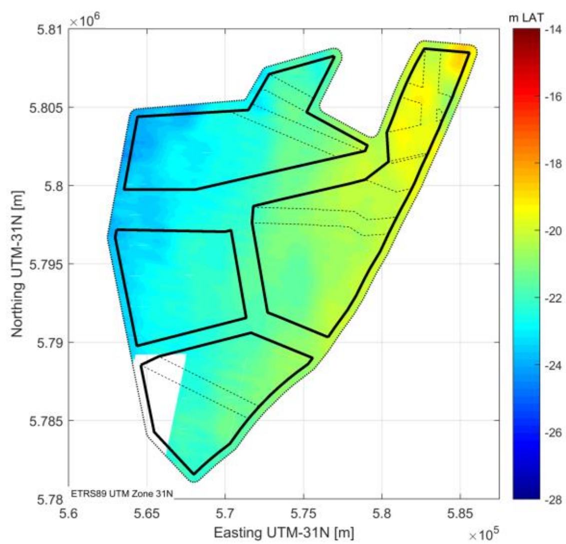
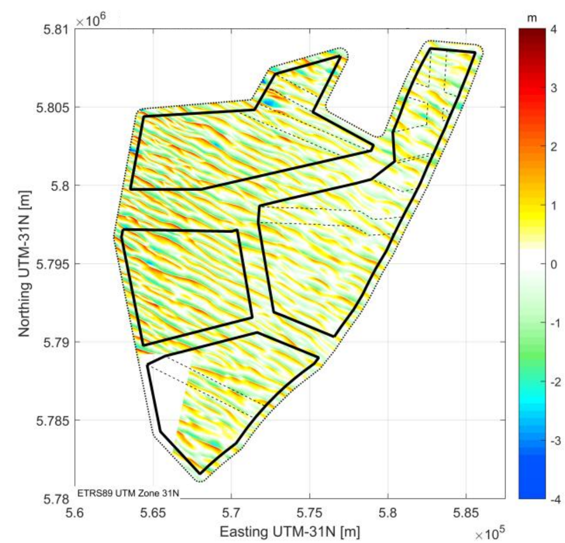
*2010-bathymetry - static bathymetry = mobile bathymetry*

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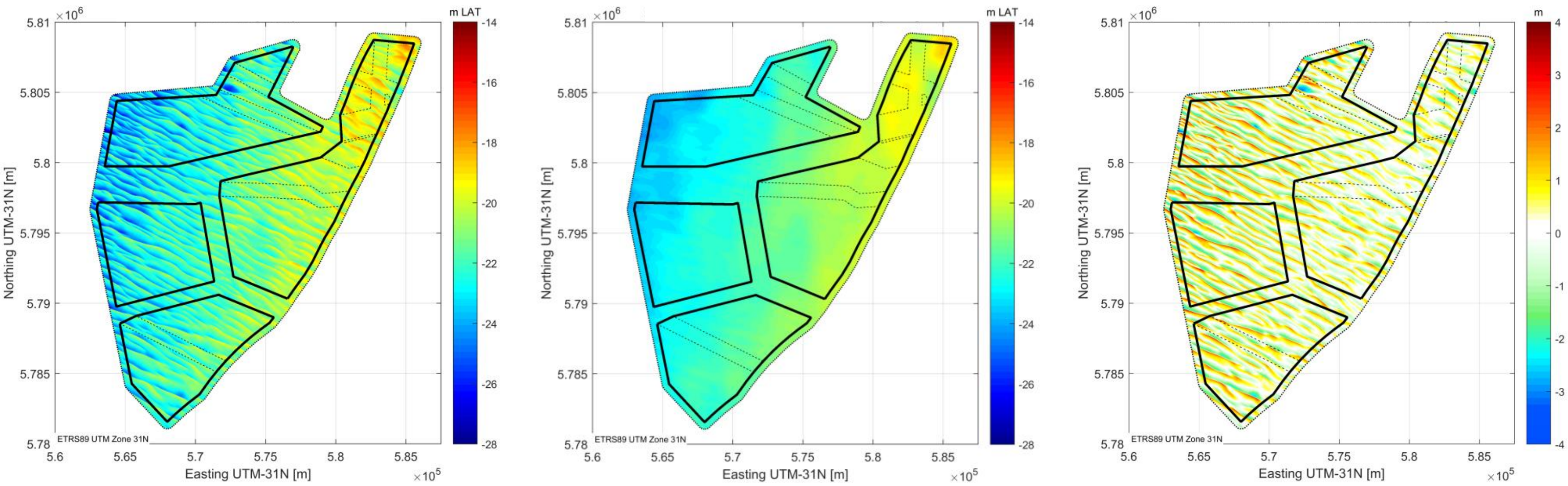
*2016-bathymetry - static bathymetry = mobile bathymetry*

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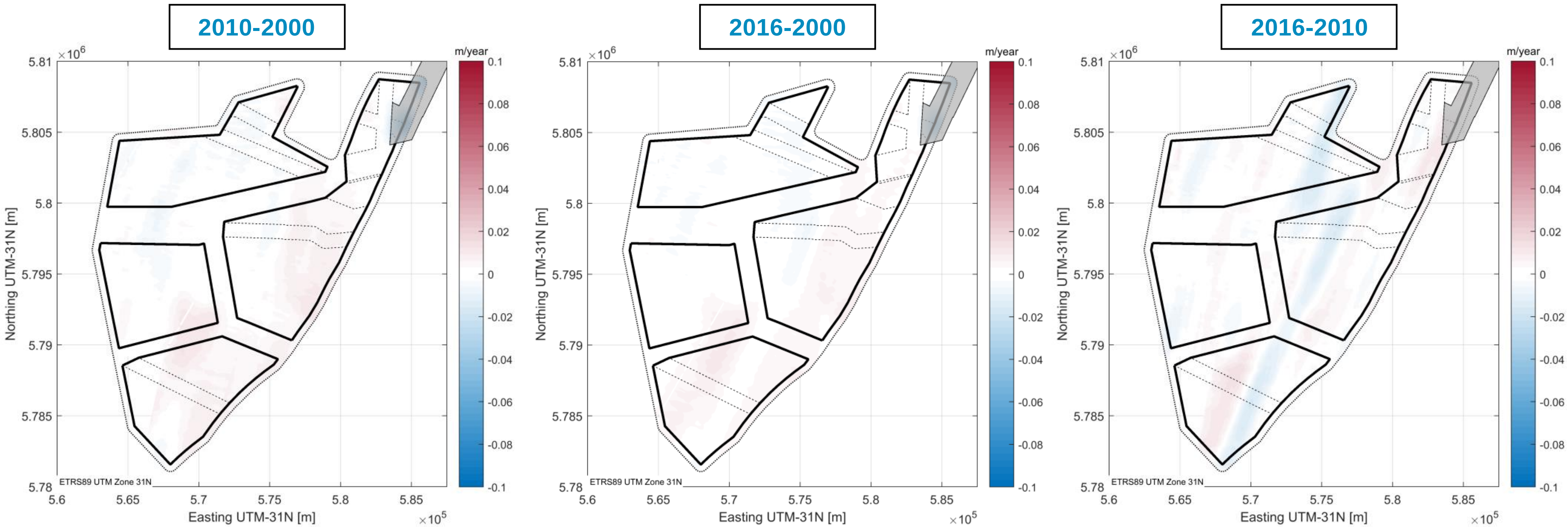
# Large-scale seabed dynamics

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 ~dm): no migration or growing/shrinking of sand banks can be observed.
- Assumption of static seabed over periods of decades seems valid.

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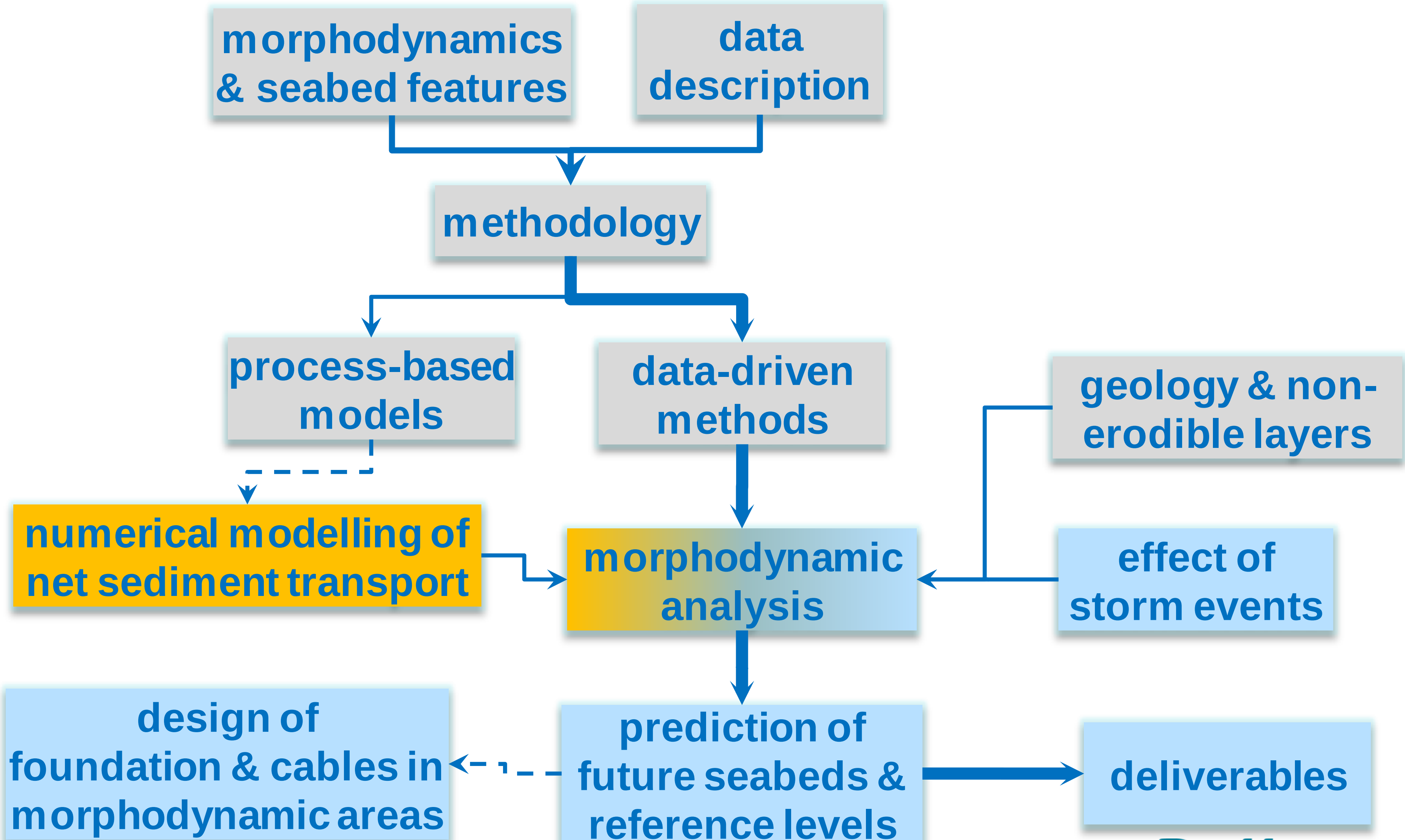
# Structure of presentation

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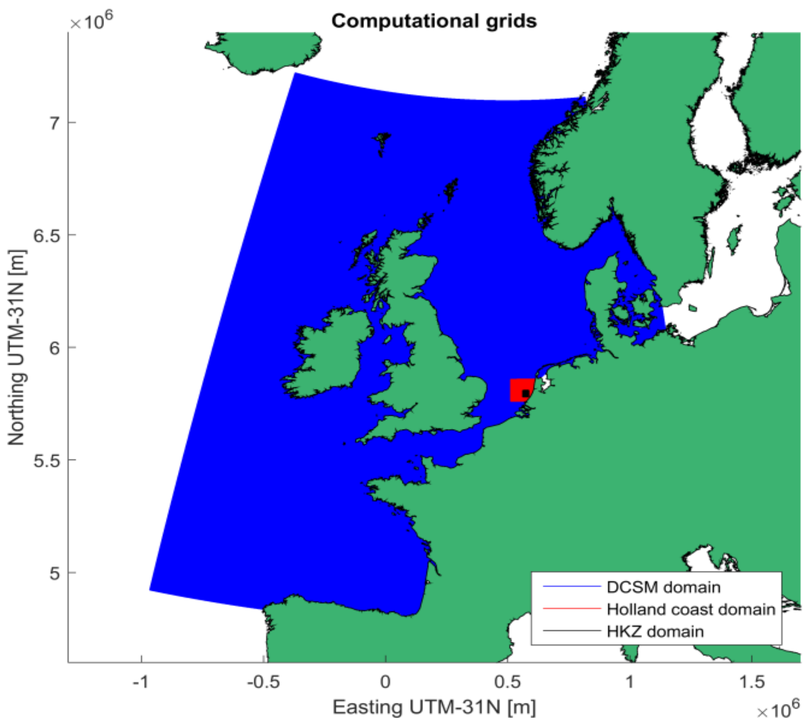
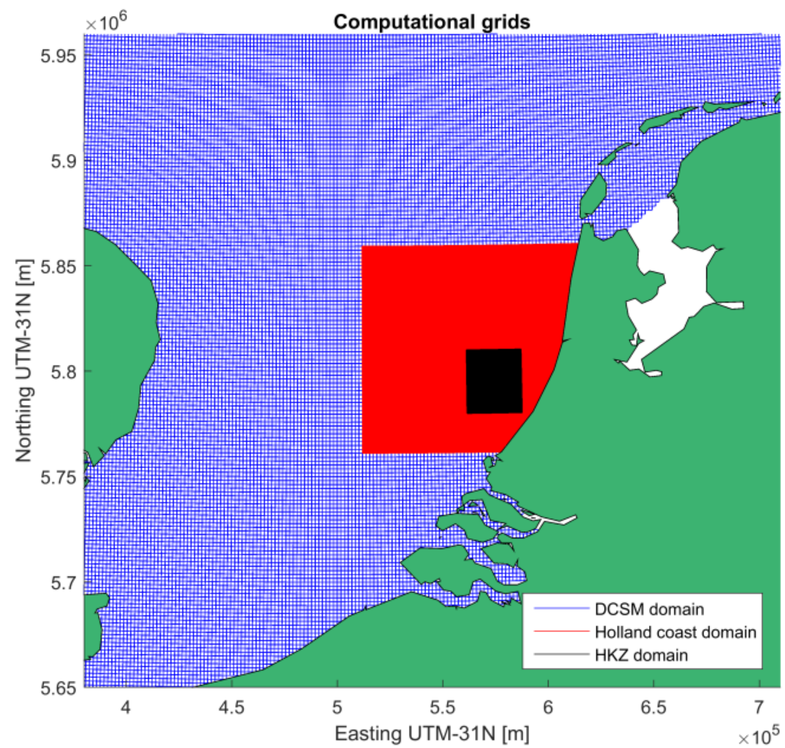
# Tidal flow and global net-sediment transport

## Numerical model setup

- Hindcast for June until August 2016
- Boundary conditions Holland coast domain derived form Dutch Continental Shelf Model (DCSM)
- HKZ domain is online coupled to the Holland Coast domain, grid resolution of 50m

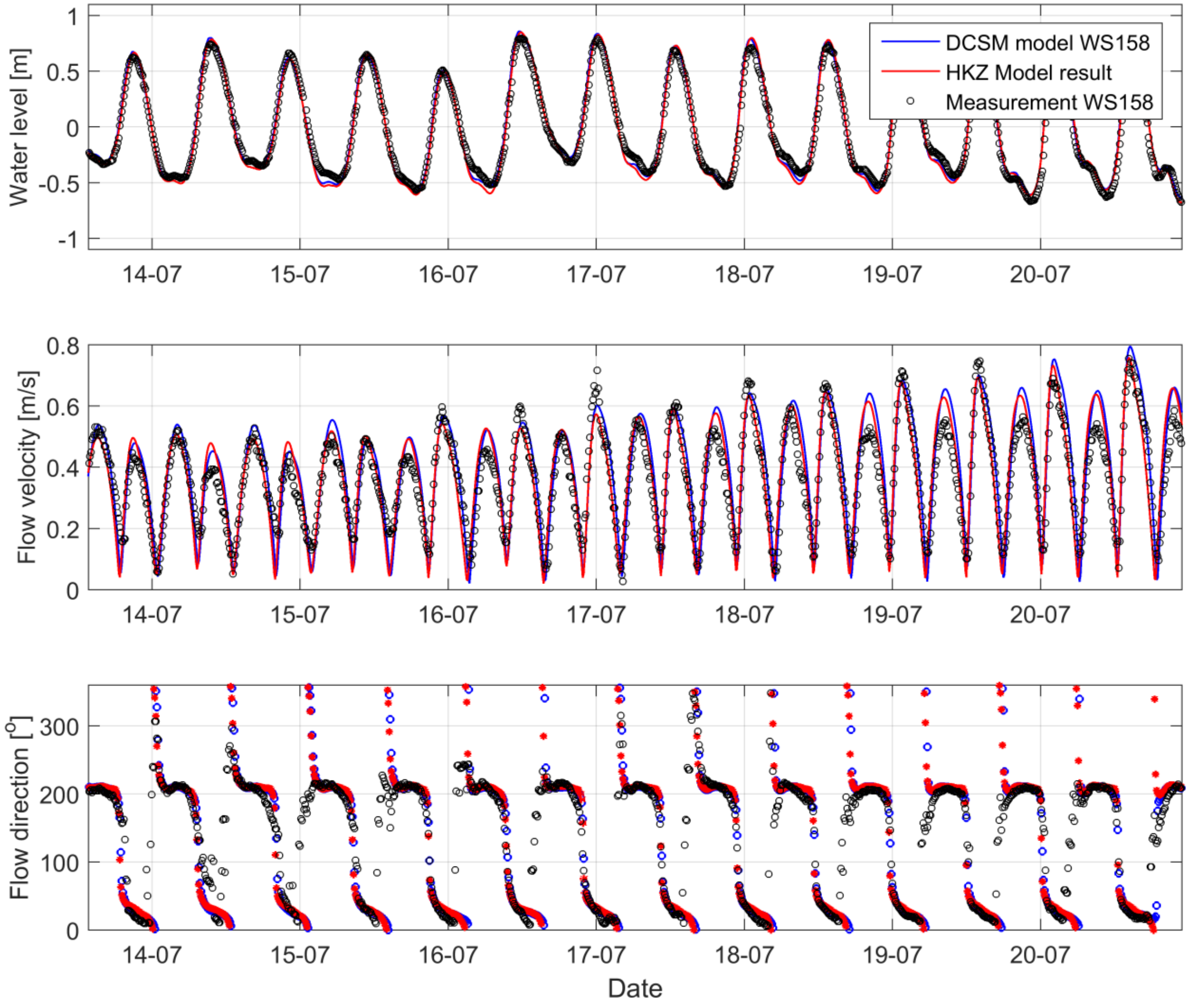


# Tidal flow and global net-sediment transport

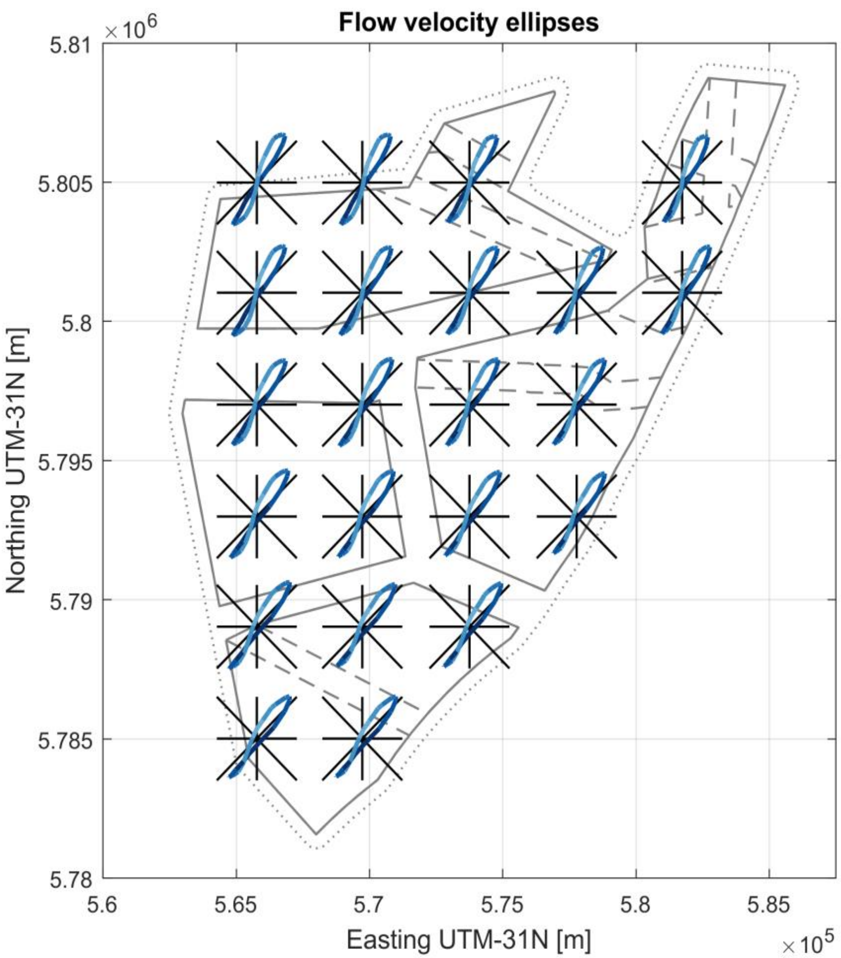
## Model validation

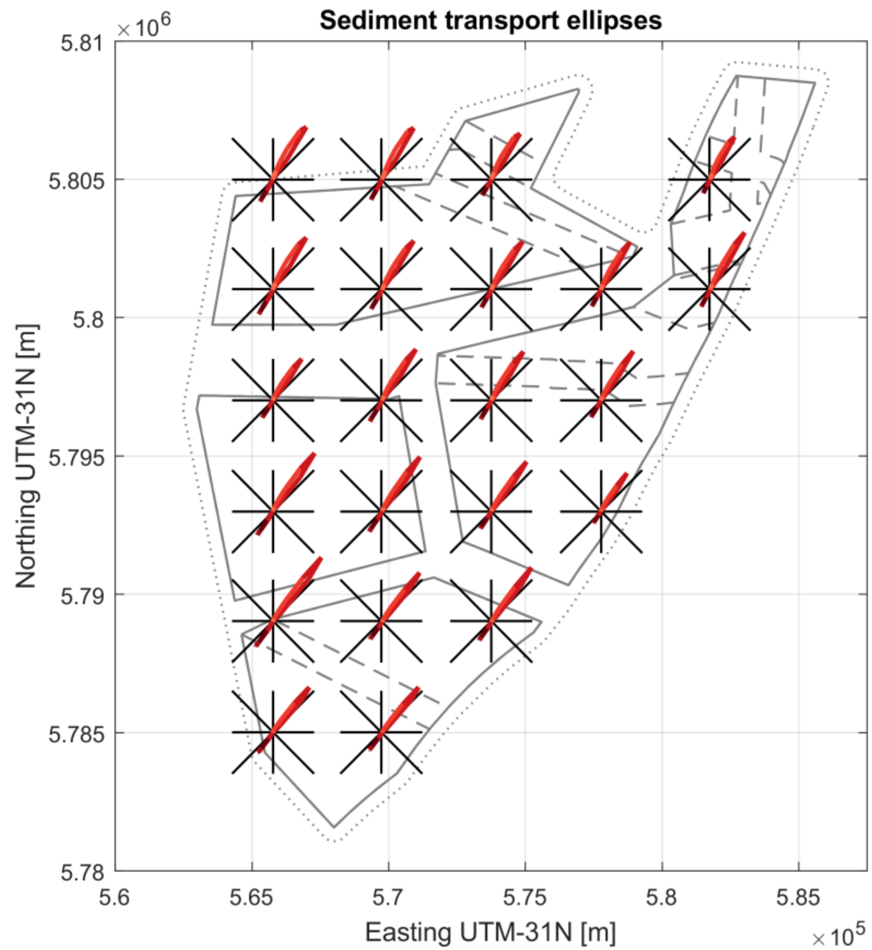
- Wave buoy measurements
- Comparison DCSM model and HKZ model domain



# Tidal flow and global net-sediment transport

## Asymmetry in tidal flow and sediment transport over one tidal cycle

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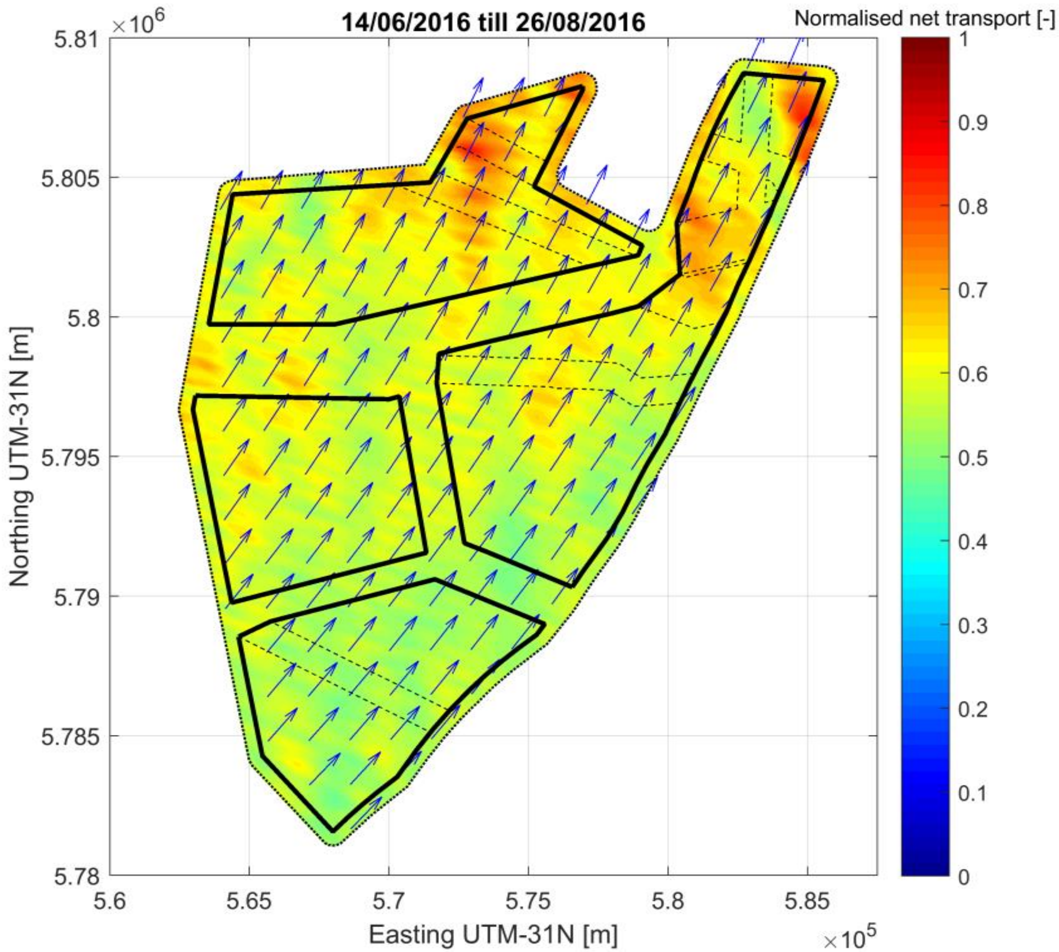
# Tidal flow and global net-sediment transport

- Time averaged net-sediment transport rate averaged over 5 spring-neap tidal cycles
- Net-sediment transport towards the NNE: 20°N to 43°N
- More northward directed and larger net-sediment transport rate in the northern part: indication for faster moving sand waves

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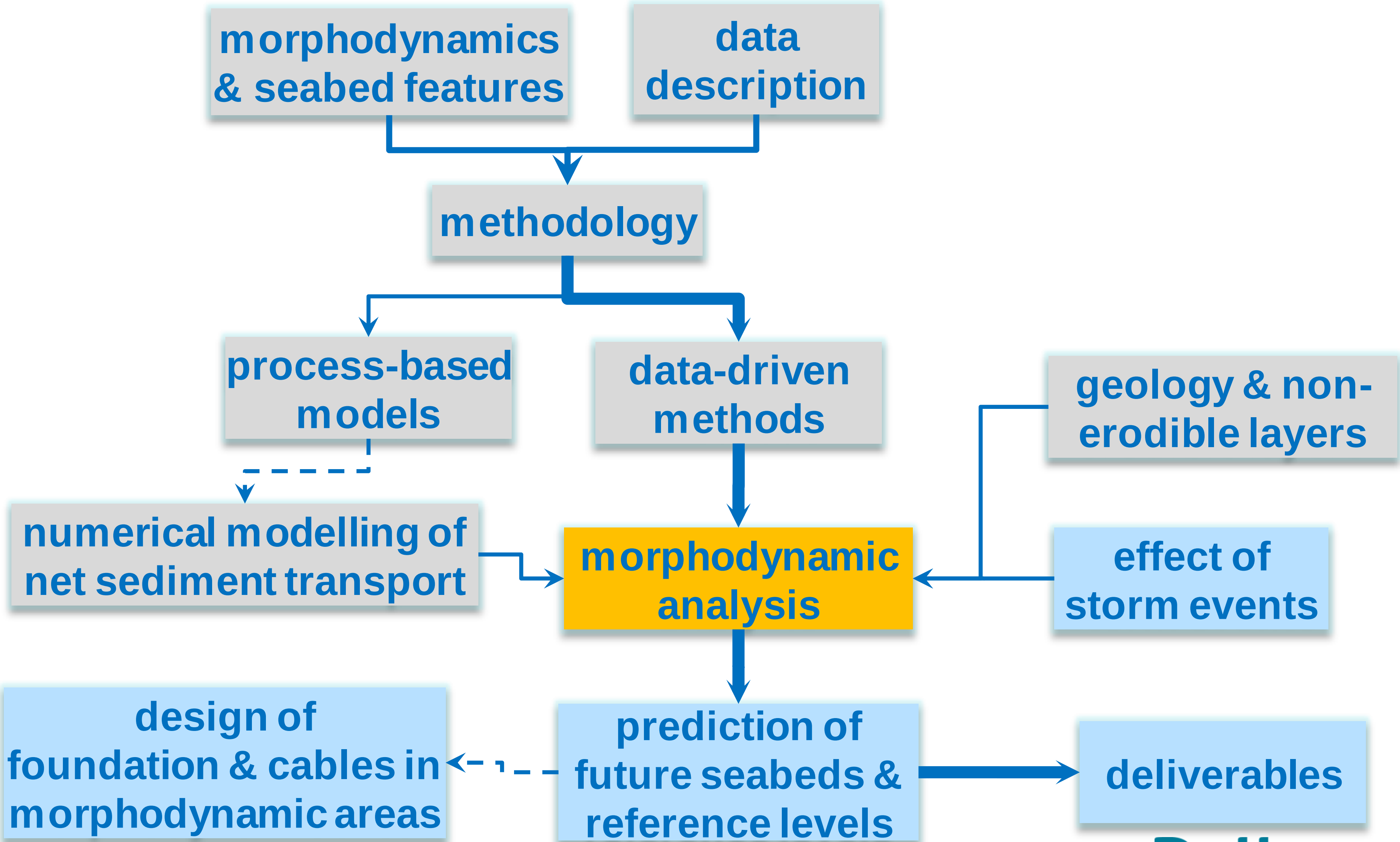
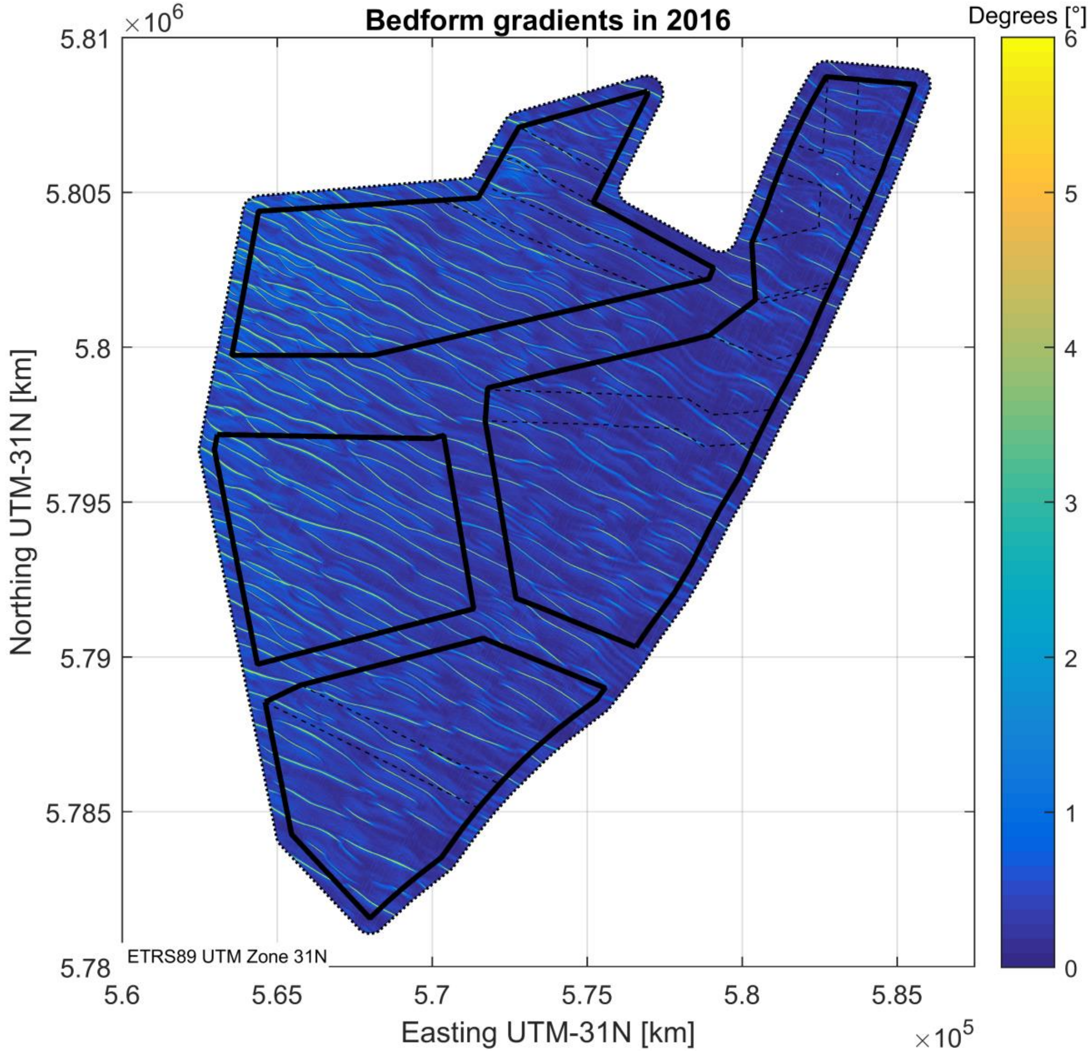


# Direction of sand wave migration (I)

Assumption: sand waves migrate in the direction of the steepest bed slope

1. Determine steepest bed level gradients in the Sand Wave Field (megaripples and smaller bed forms filtered out)
2. Find corresponding directions where the steepest gradients are found

Bed gradients in the Sand Wave Field of 2016

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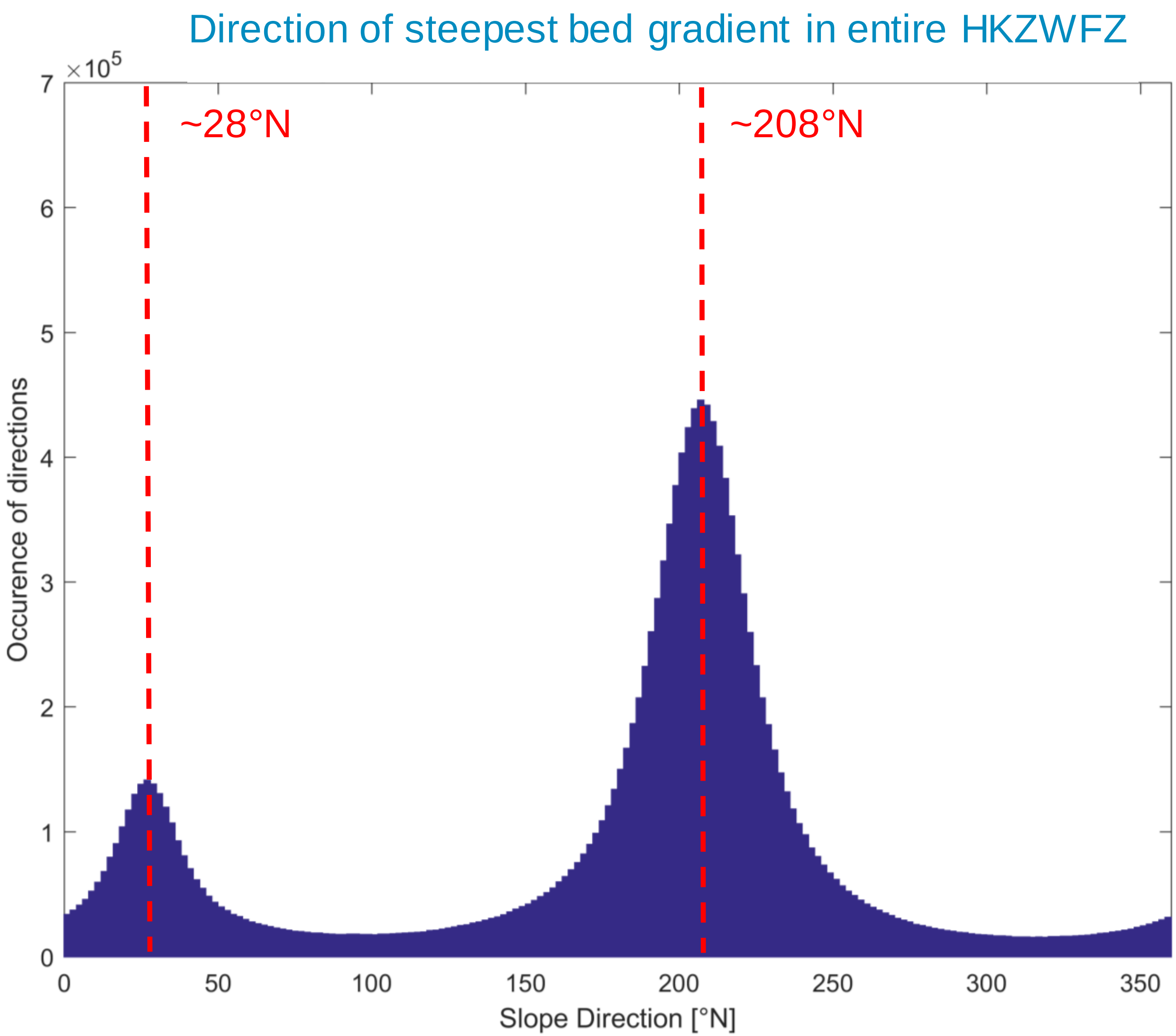


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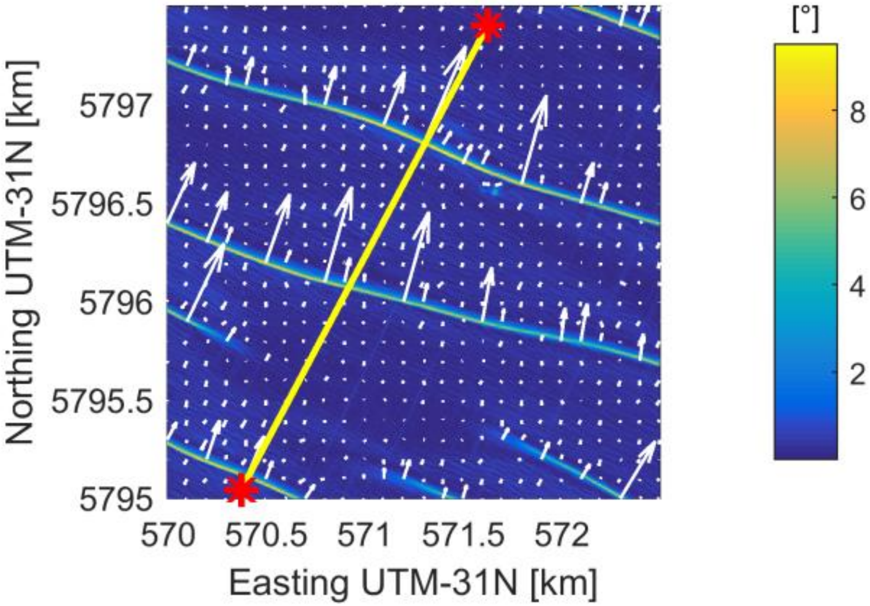
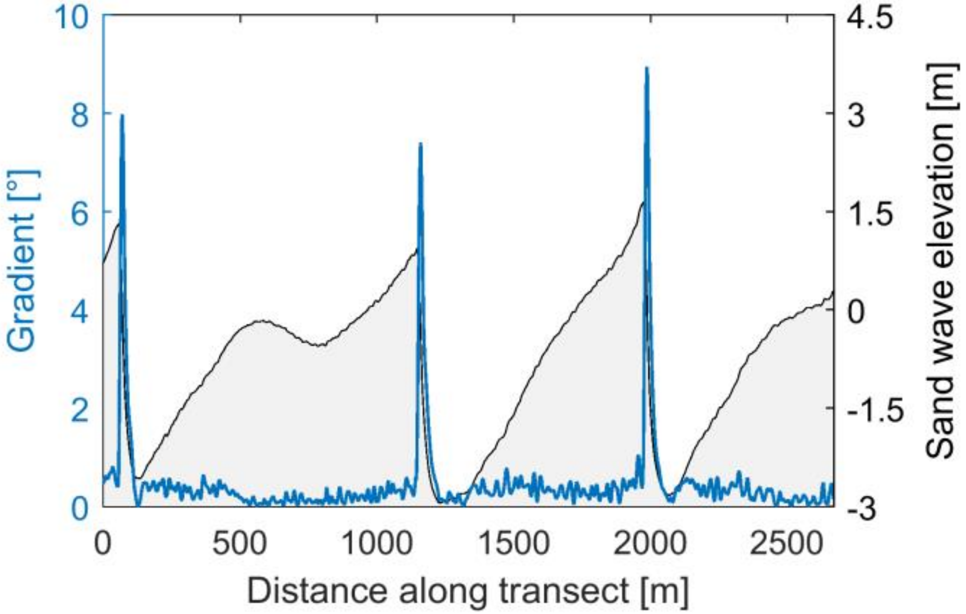
# Direction of sand wave migration (II)

direction of steepest gradient

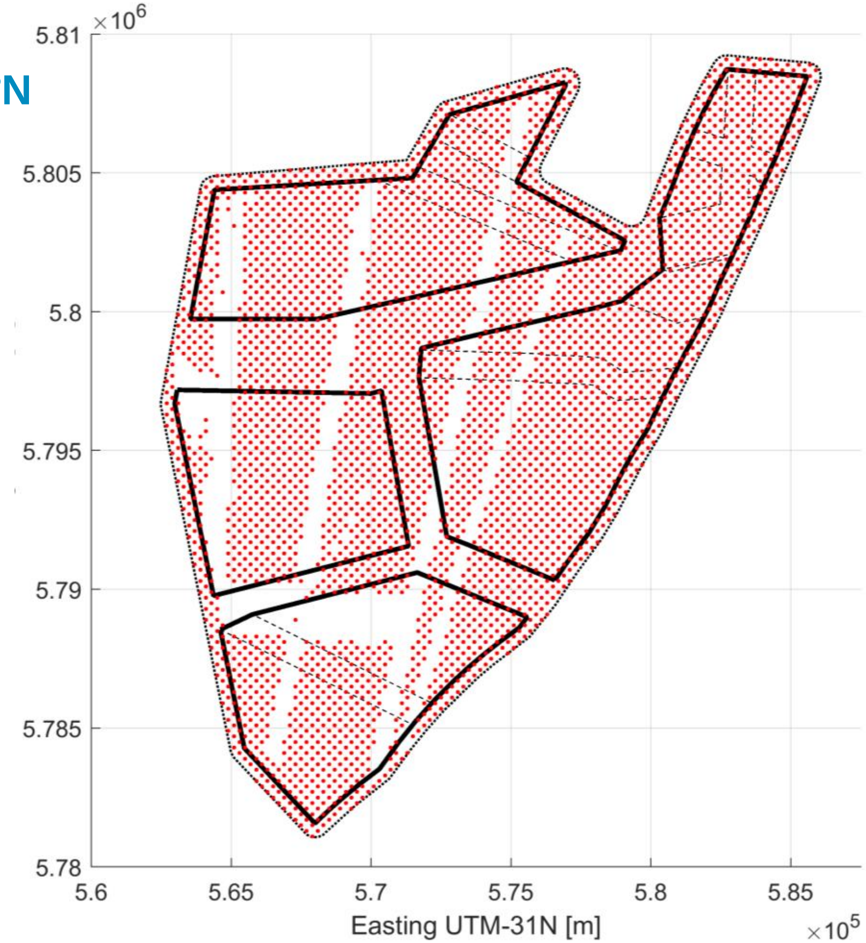



Gradient and sand wave elevation along transect



# Direction of sand wave migration (III)

3. Block filtering (1400m) of steepest slopes around each of the 3904 transects
4. Migration directions of all transects for all three bathymetric surveys are combined
5. Main migration directions of approximately **28°N** with variations up to about **20-30**° around the main axis



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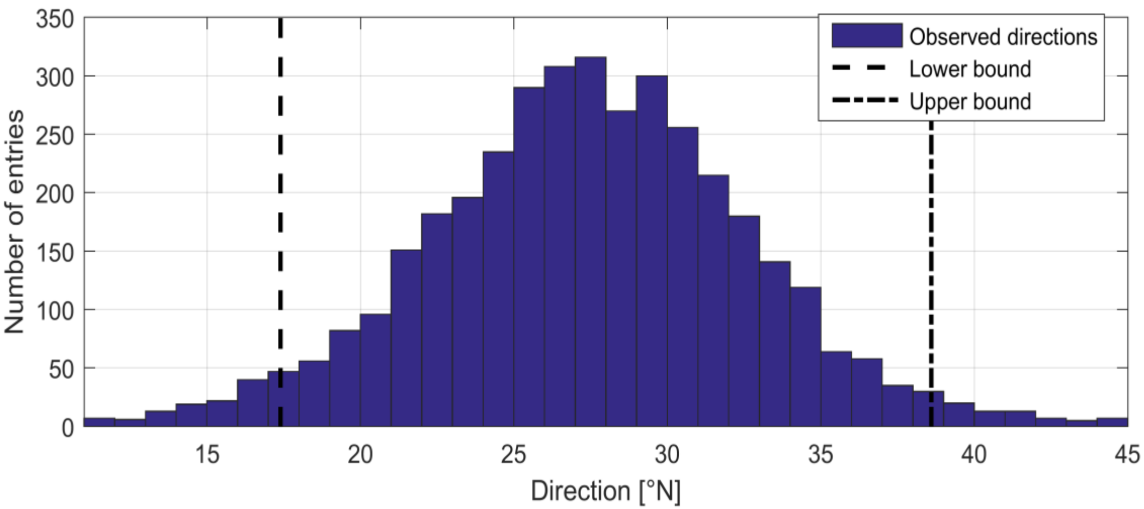
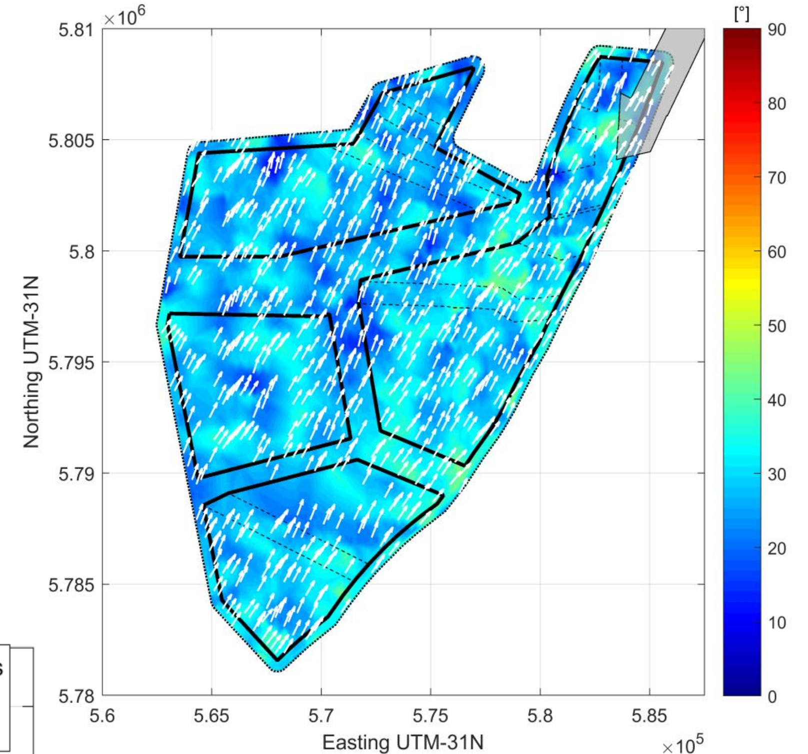
| Smallest angle of migration | Most likely angle of migration | Largest angle of migration |
|---|---|---|
| $17^{\circ}N$ | $28^{\circ}N$ | $43^{\circ}N$ |




no trend in migration direction over HKZ WFZ

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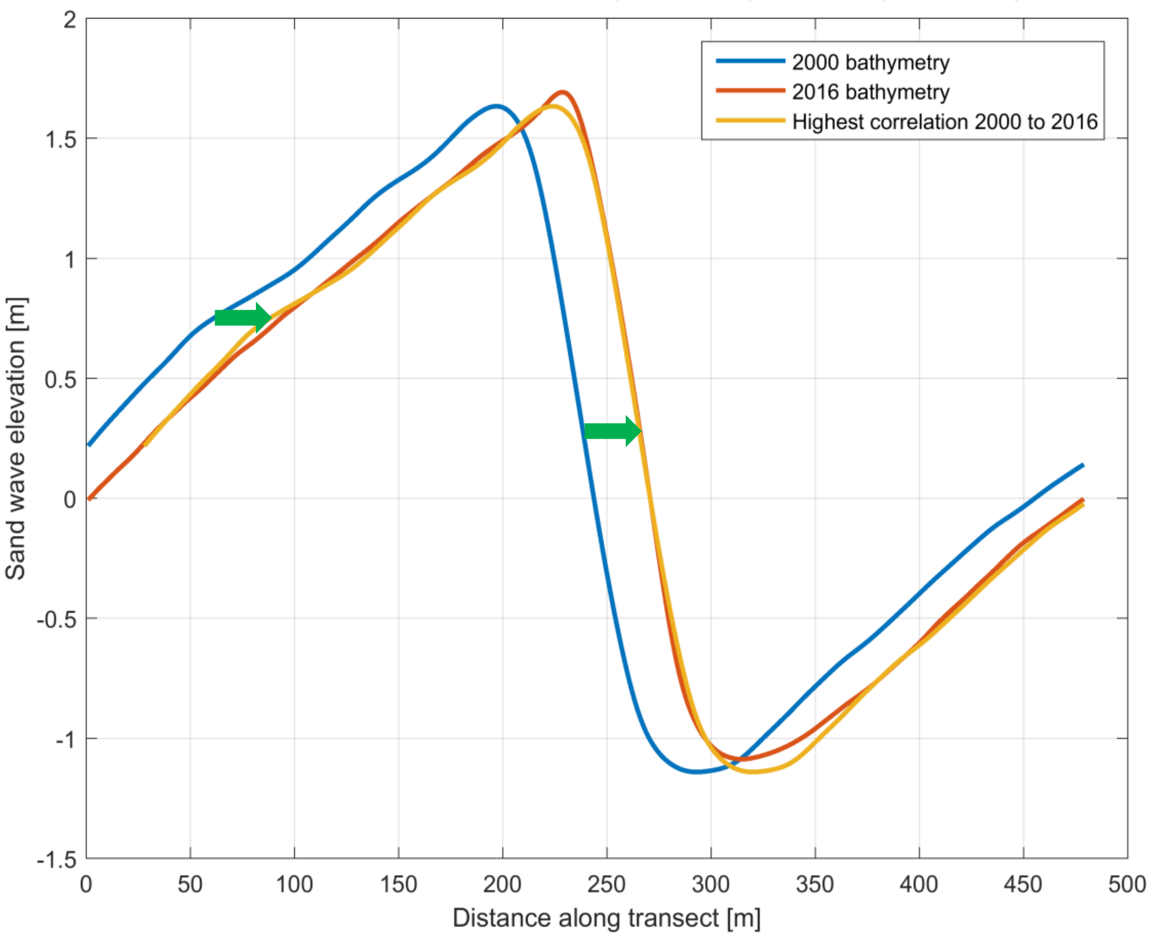
# Sand wave migration speed (I)

- Identifying individual sand waves for each transect per migration direction
- 1D cross correlation on all individual sand waves
- Combining information per transect and per migration direction for all bathymetrical combinations

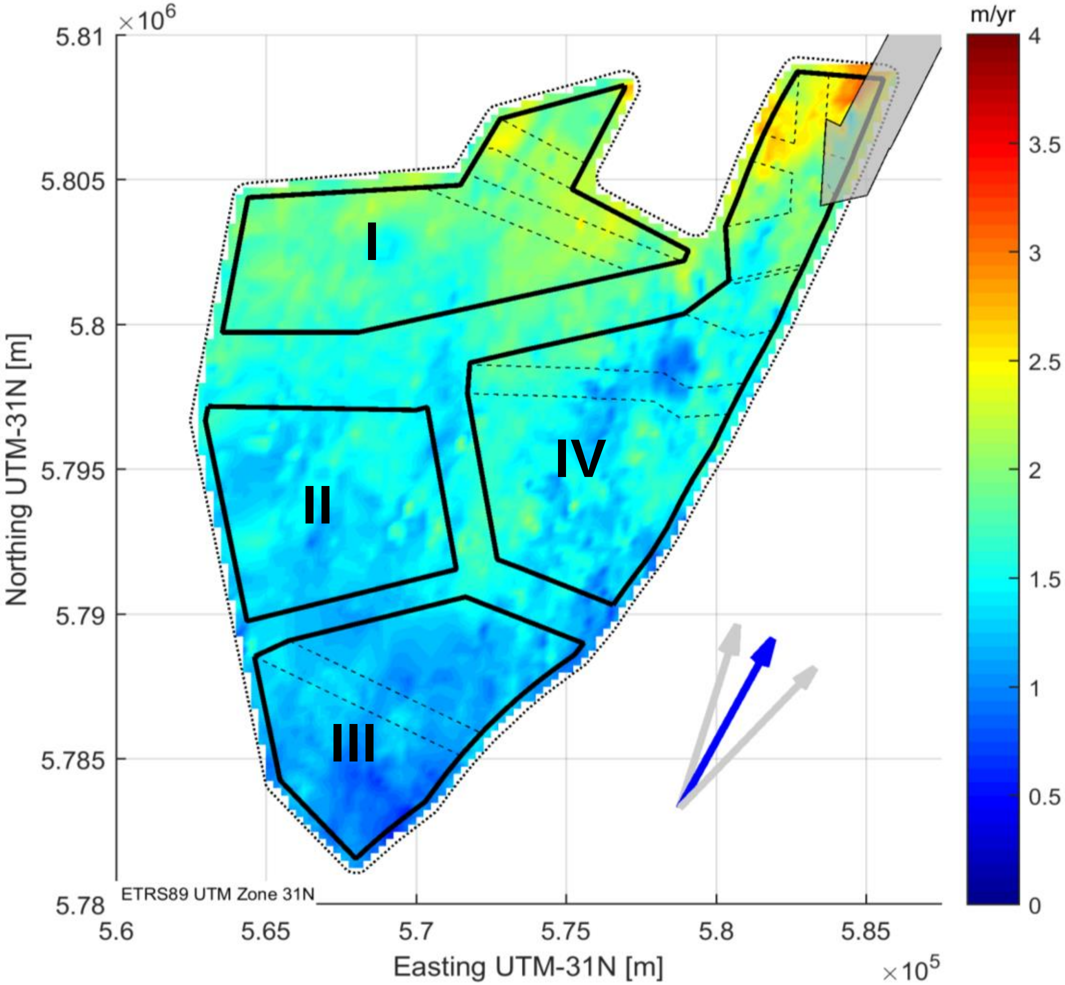


# Sand wave migration speed (II)

- Identifying individual sand waves for each transect per migration direction
- 1D cross correlation on all individual sand waves
- Combining information per transect and per migration direction for all bathymetrical combinations

- Migration speed increases from south to north

Migration speed for median migration direction

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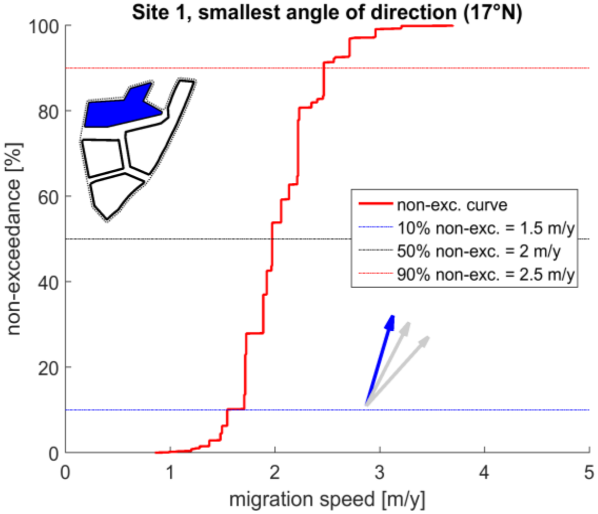
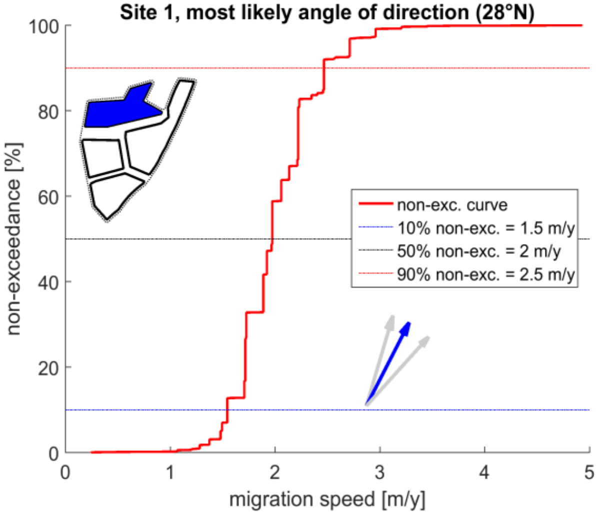
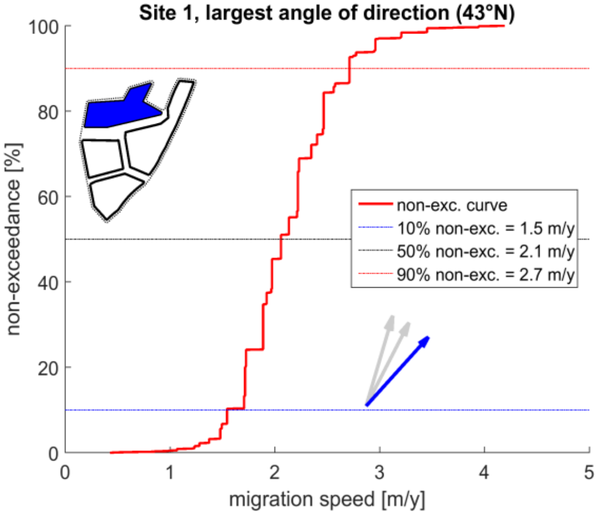
# Sand wave migration speed (III)

## Exceedance curves for migration speeds for 3 migration directions for WFS-I



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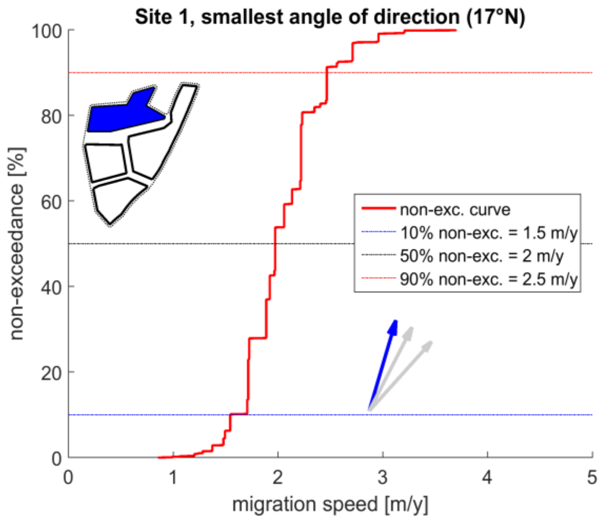


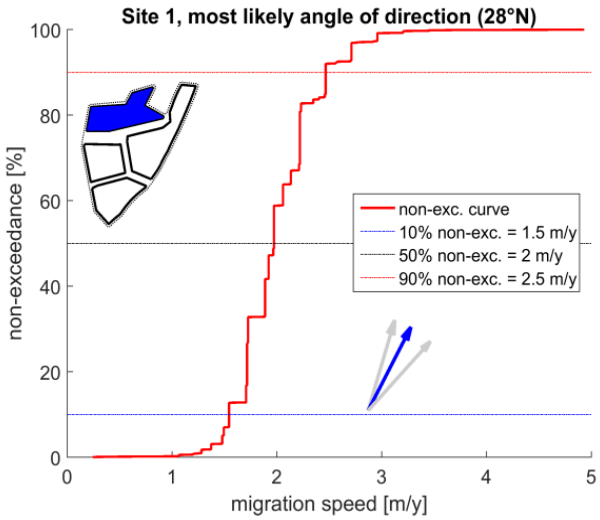


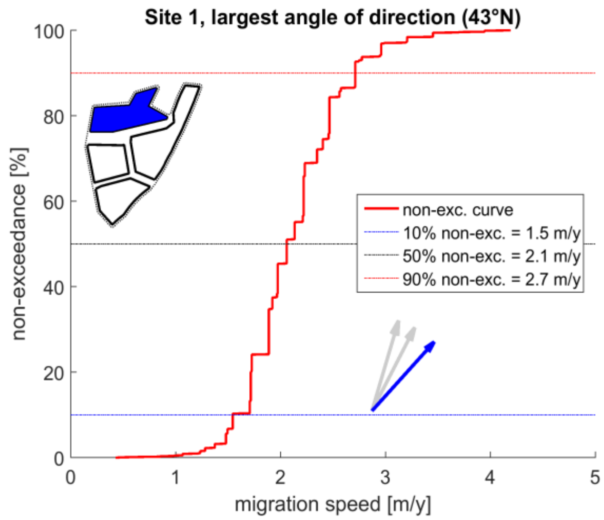


| Wind farm site | Migration speed ($17°N$) [m/yr] 10% / 50% / 90% | Migration speed ($28°N$) [m/yr] 10% / 50% / 90% | Migration speed ($43°N$) [m/yr] 10% / 50% / 90% |
|---|---|---|---|
| I | 1.5 / 2.0 / 2.5 | 1.5 / 2.0 / 2.5 | 1.5 / 2.1 / 2.7 |
| II | 1.2 / 1.5 / 2.0 | 1.2 / 1.5 / 2.0 | 1.2 / 1.5 / 2.1 |
| III | 0.8 / 1.2 / 1.7 | 0.8 / 1.2 / 1.6 | 0.7 / 1.2 / 1.9 |
| IV | 0.9 / 1.7 / 2.6 | 0.9 / 1.5 / 2.6 | 0.9 / 1.7 / 3.0 |
| All sites | 1.1 / 1.7 / 2.5 | 1.1 / 1.7 / 2.3 | 1.0 / 1.7 / 2.6 |



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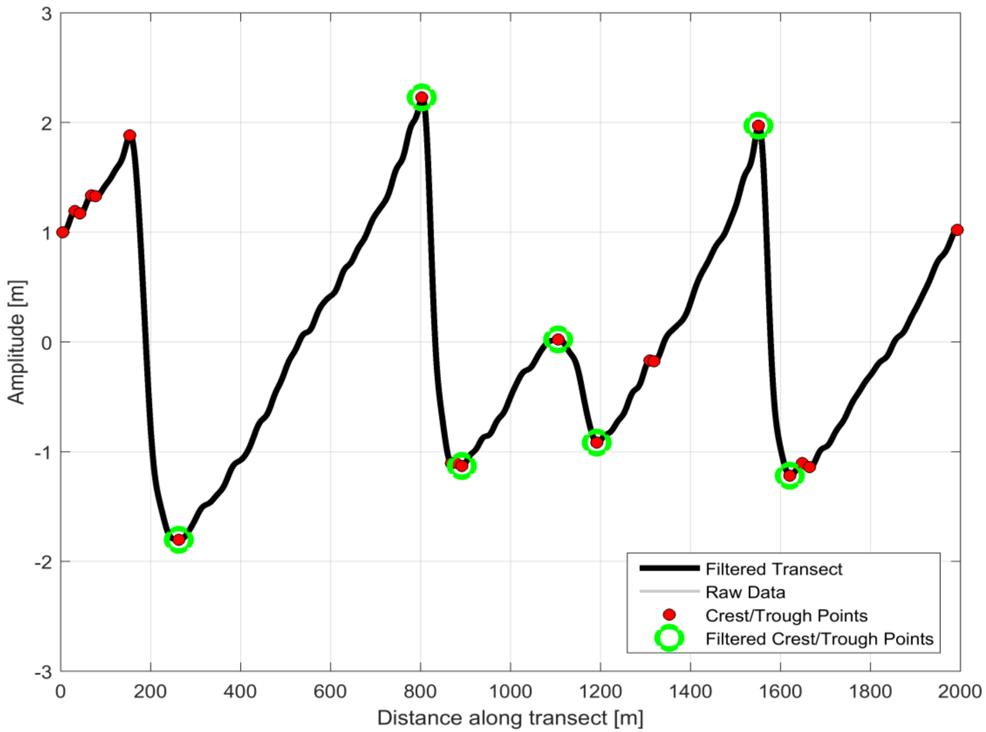
# Fourier analysis on transects (I)

- Identify crests and troughs
- Obtain statistics per transect such as sand wave height, length an L/H ratio

- Sand wave statistics are determined by combining results for each transect in the main migration directions and 3 survey combinations (2000/2010, 2000/2016, 2010/2016)

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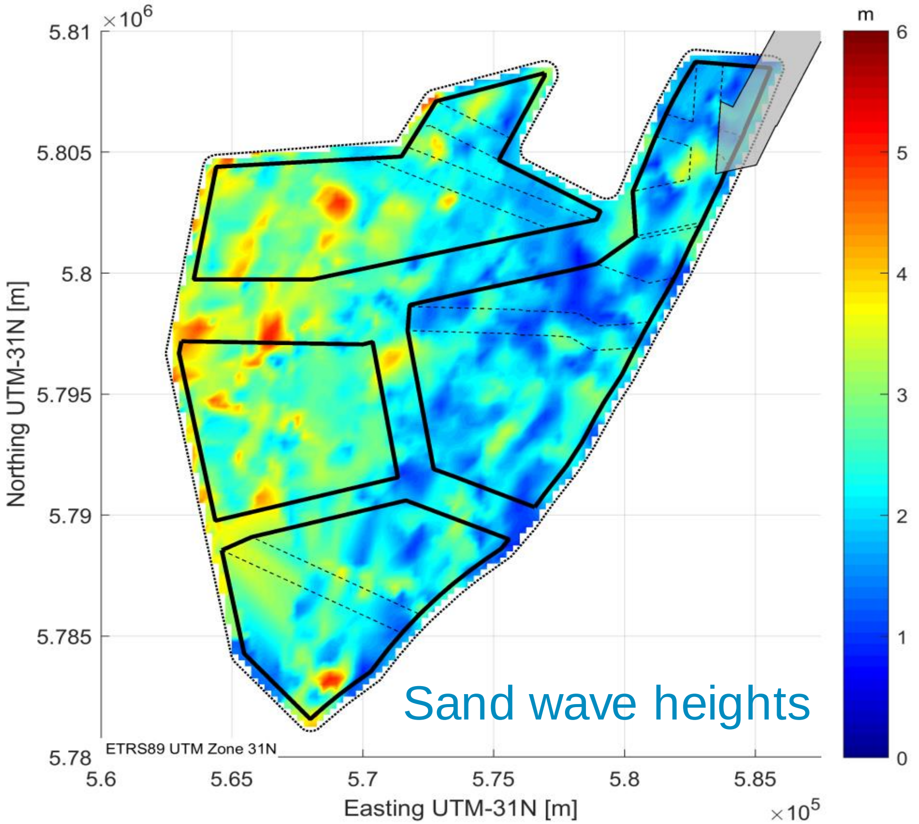
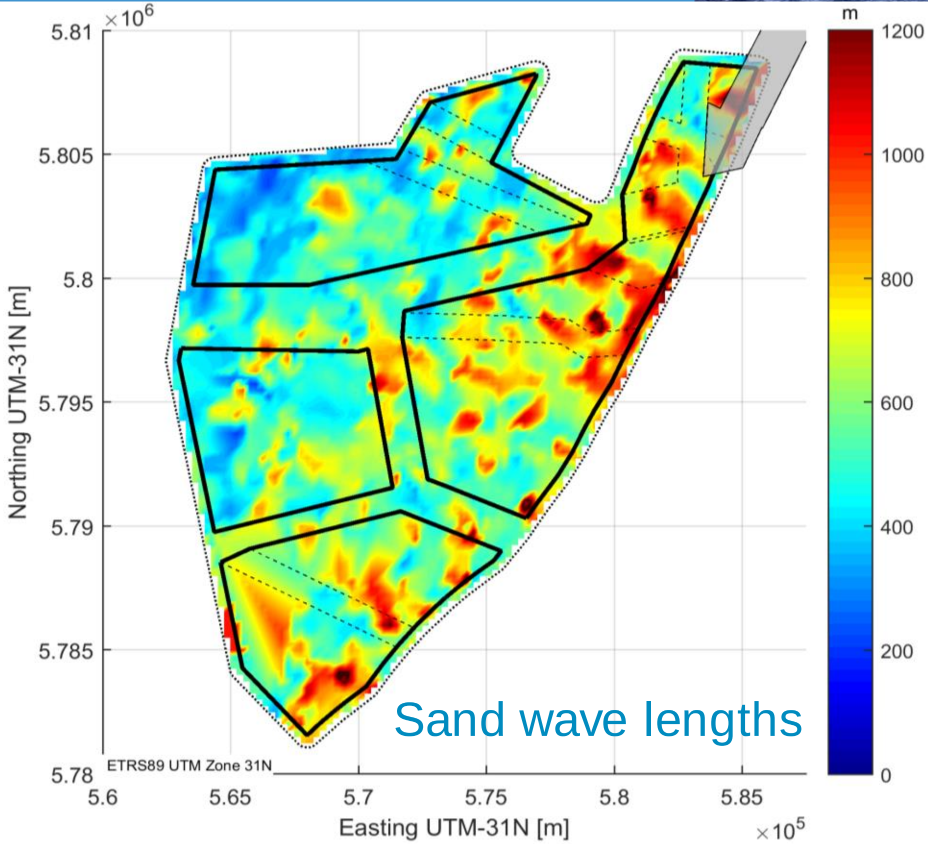
# Fourier analysis on transects (II)




| Sand wave property | Wind Farm Site | | | | All sites |
|---|---|---|---|---|---|
| | I | II | III | IV | |
| Sand wave height 10% / 50% / 90% [m] | 1.5 / 2.5 / 4.0 | 1.9 / 2.7 / 3.9 | 1.4 / 2.3 / 3.3 | 1.1 / 1.9 / 2.7 | 1.3 / 2.3 / 3.6 |
| Sand wave length 10% / 50% / 90% [m] | 238 / 427 / 708 | 265 / 503 / 757 | 388 / 578 / 918 | 391 / 631 / 950 | 287 / 511 / 832 |
| Sand wave L/H ratio 10% / 50% / 90% | 96 / 176 / 289 | 103 / 193 / 285 | 167 / 257 / 442 | 212 / 324 / 607 | 113 / 222 / 431 |

# Comparison Sand Waves Borssele – Hollandse Kust (zuid)

## Borssele

- Sand waves in the Borssele wind farm zone migrate in both directions (NE & SW)
- “Shark tooth”-shaped sand waves
- More variation in sand wave dimensions and migration rate, due to a more complex bathymetry (sand banks and channels)

# Comparison Sand Waves Borssele – Hollandse Kust (zuid)

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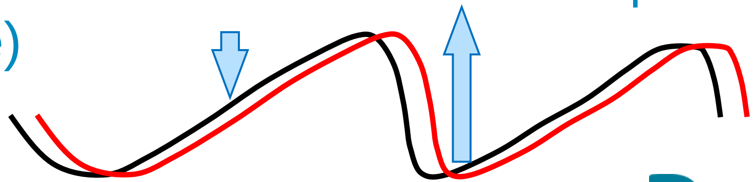
- More variation in sand wave dimensions and migration rate, due to a more complex bathymetry (sand banks and channels)

## Hollandse Kust (zuid)

- Sand waves in the Hollandse Kust (zuid) wind farm zone migrate towards the NNE
- “Saw tooth” shaped sand waves
- Sand wave dimensions and migration rate show clear patterns (nearshore – offshore variation for sand wave dimensions | north-south variation in migration rate)



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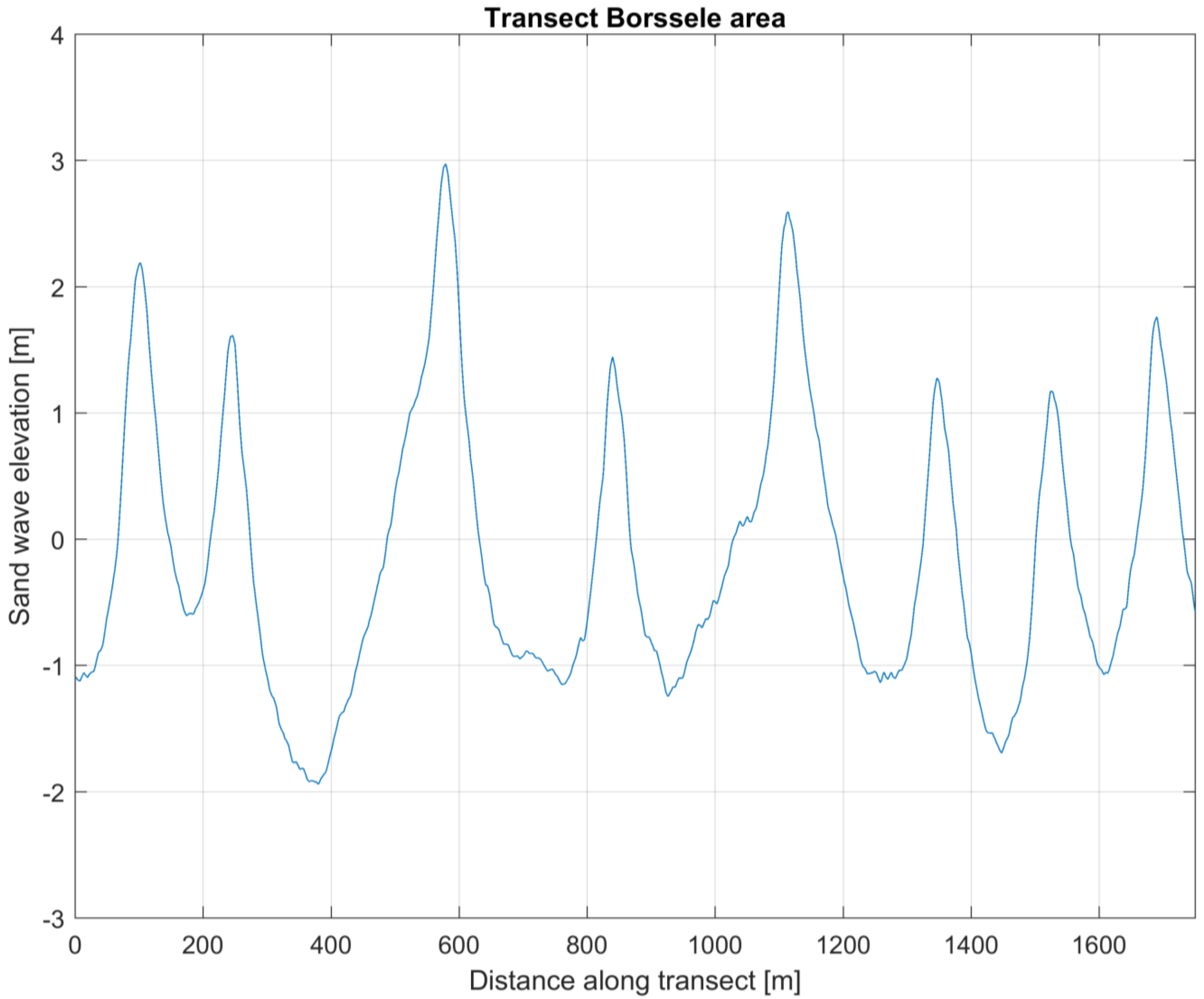

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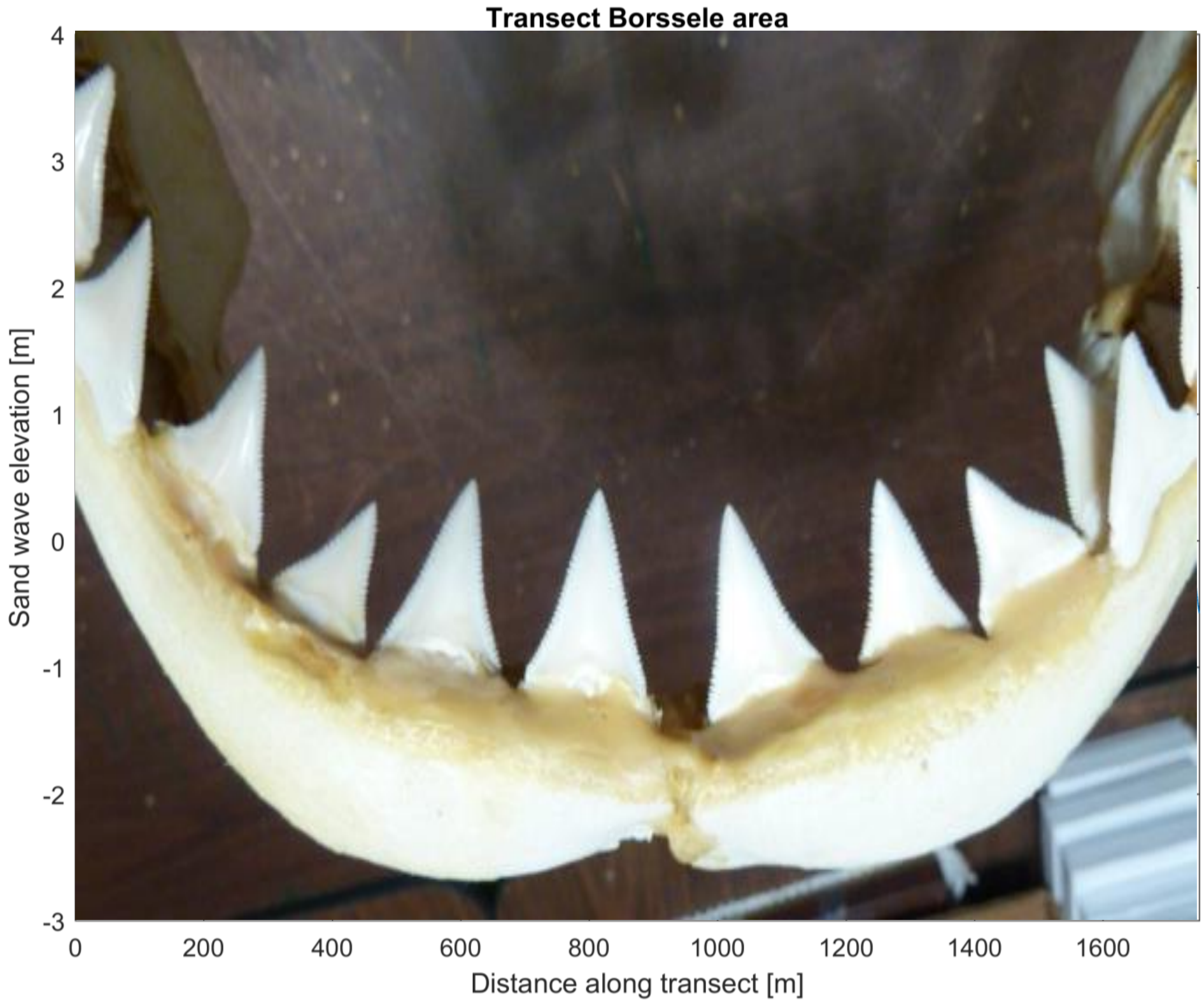




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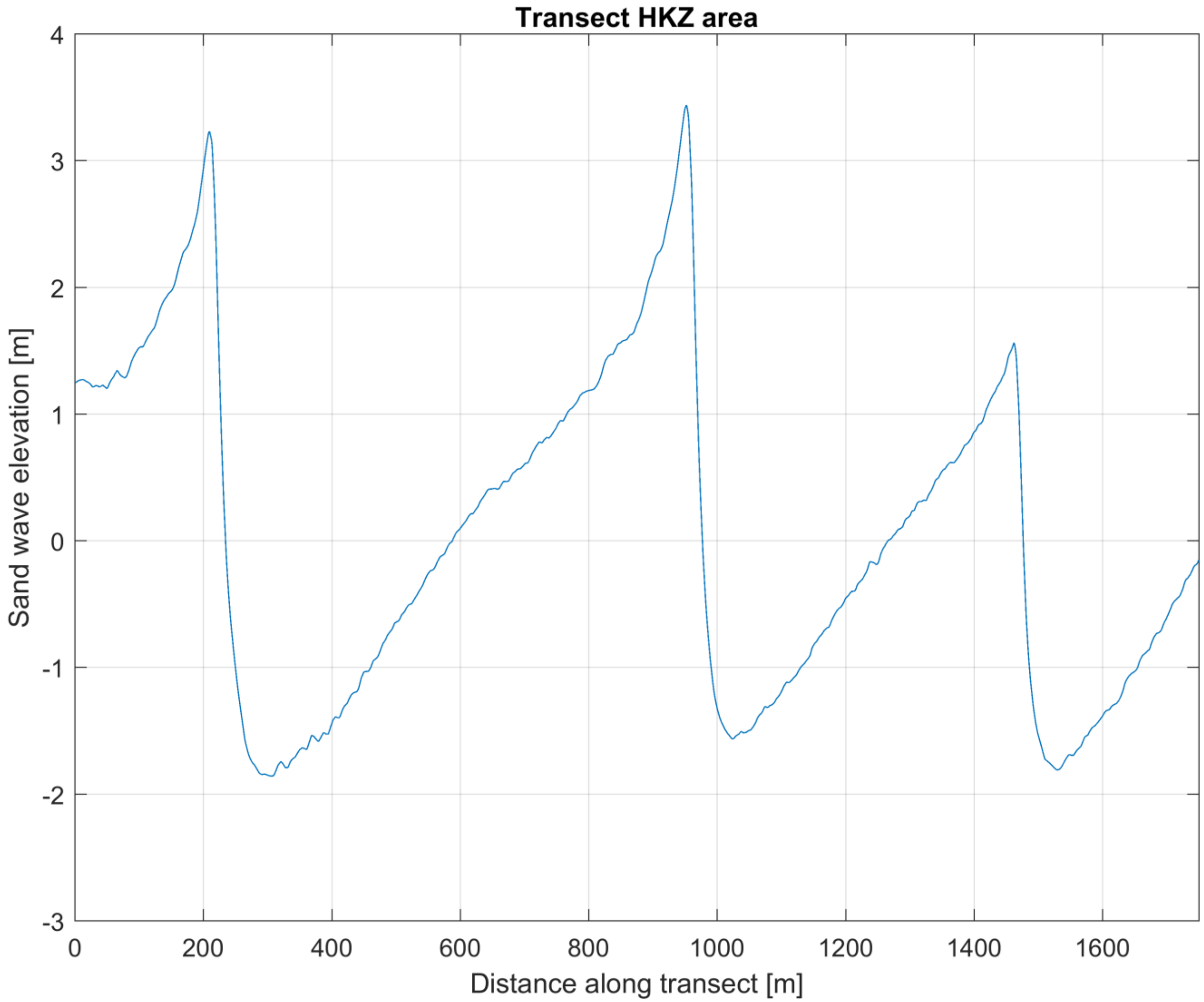




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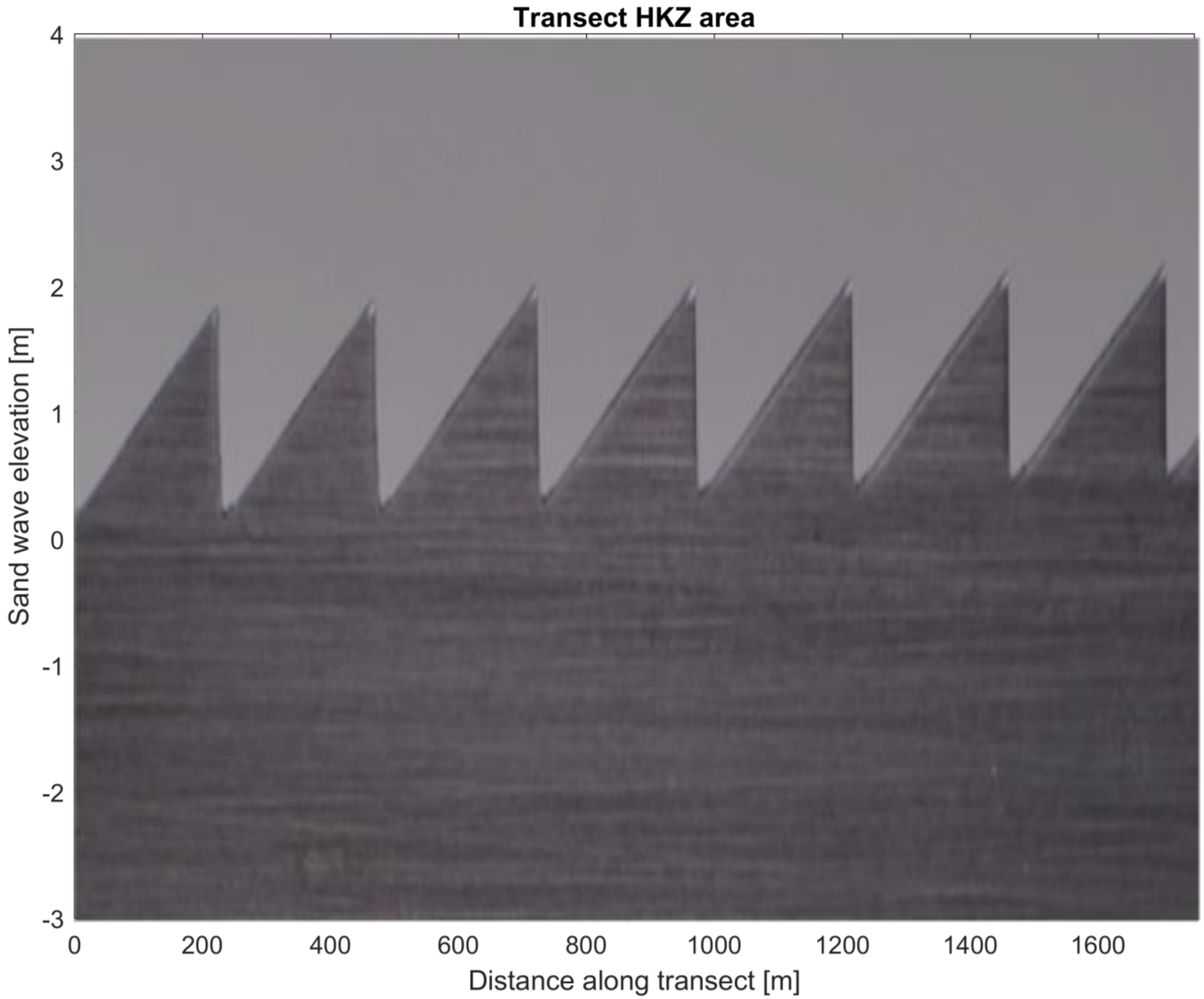




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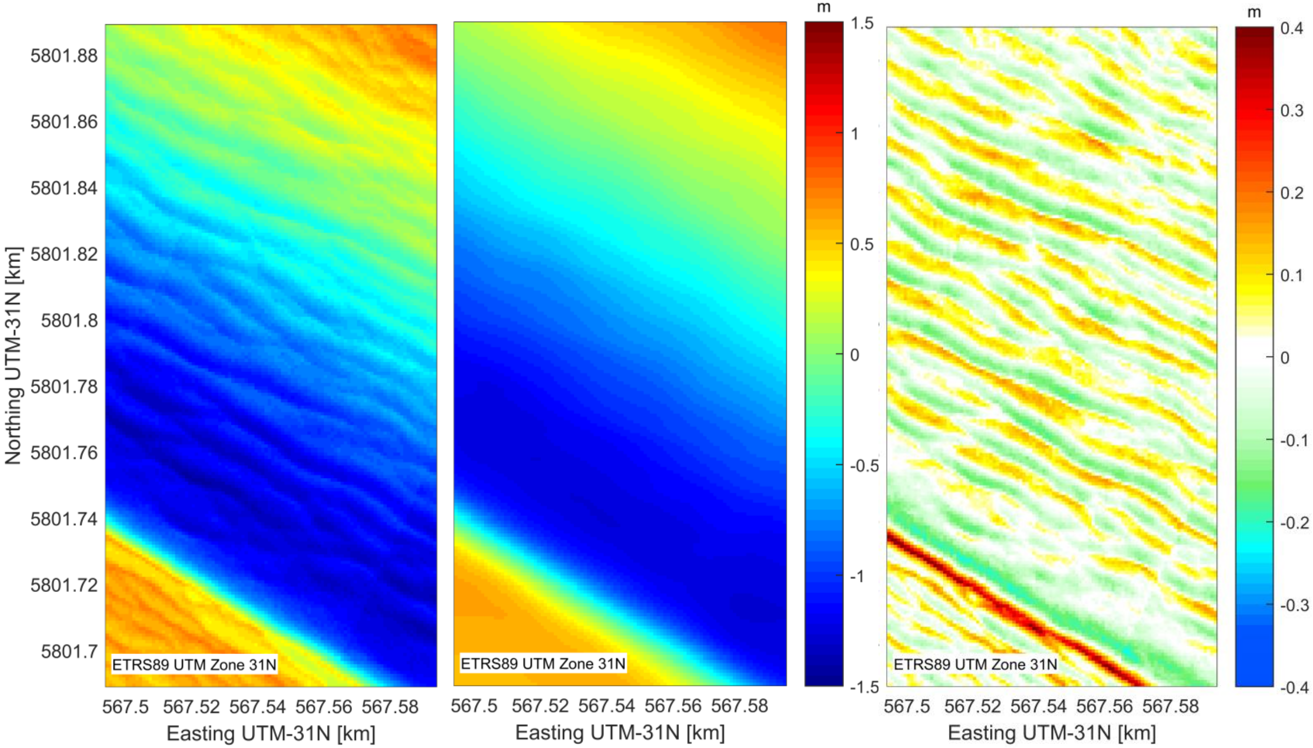
# Megaripple analysis: megaripple extraction

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

- typical wavelengths of 8-20m
- bathymetry filtered with block filter of 15m to obtain "Sand Wave Field"
- 2016-survey (0.50 x 0.50m) used for analysis
- rather regular megaripple pattern

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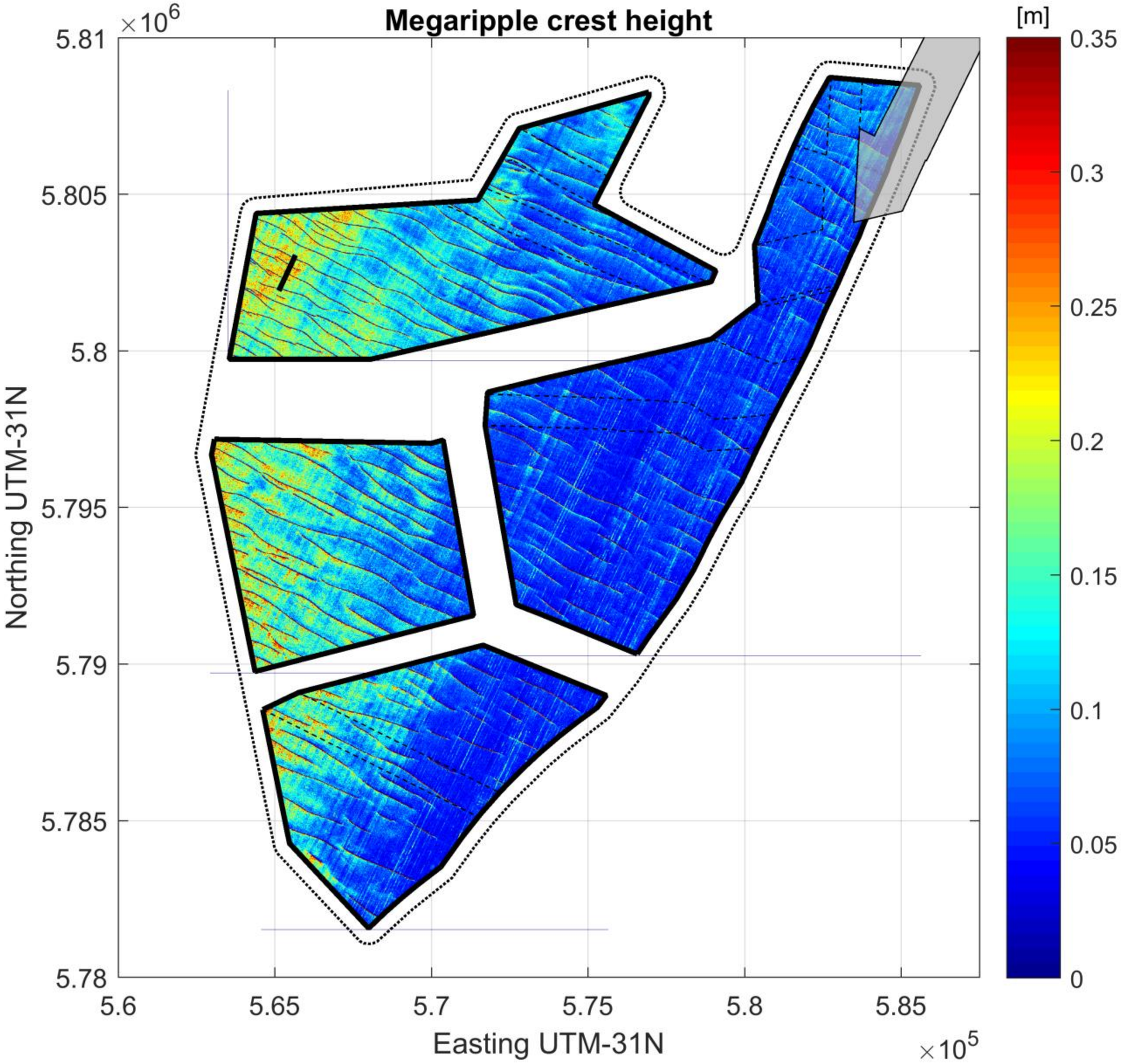
# Megaripple analysis: crest heights

- Megaripple field analysed to determine trough depths and crest heights
- Representative values for
  trough depth: ~0.15m
  crest height: ~0.25m
- These values will be included in the uncertainty band



# Megaripple analysis: trough depths

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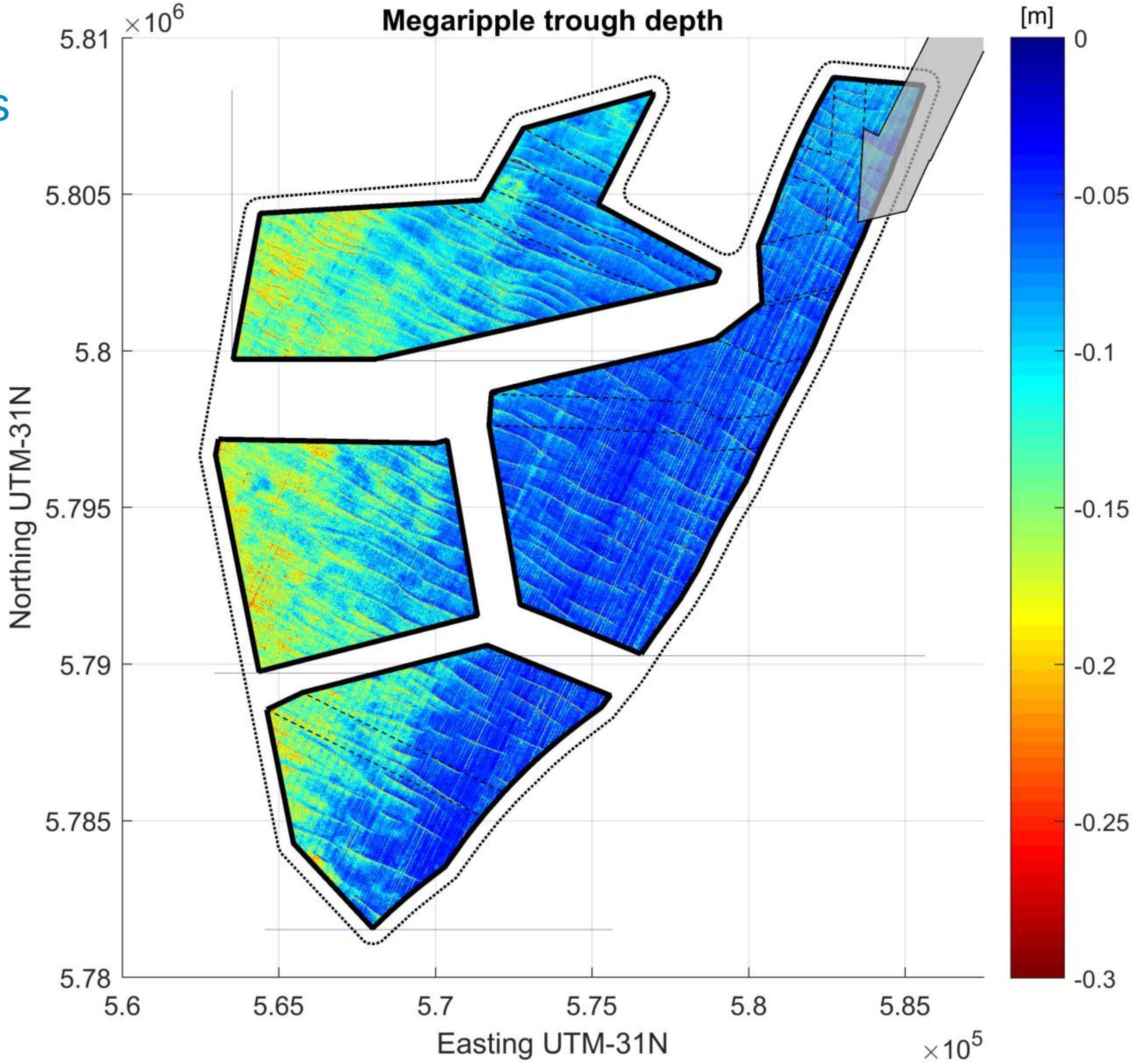




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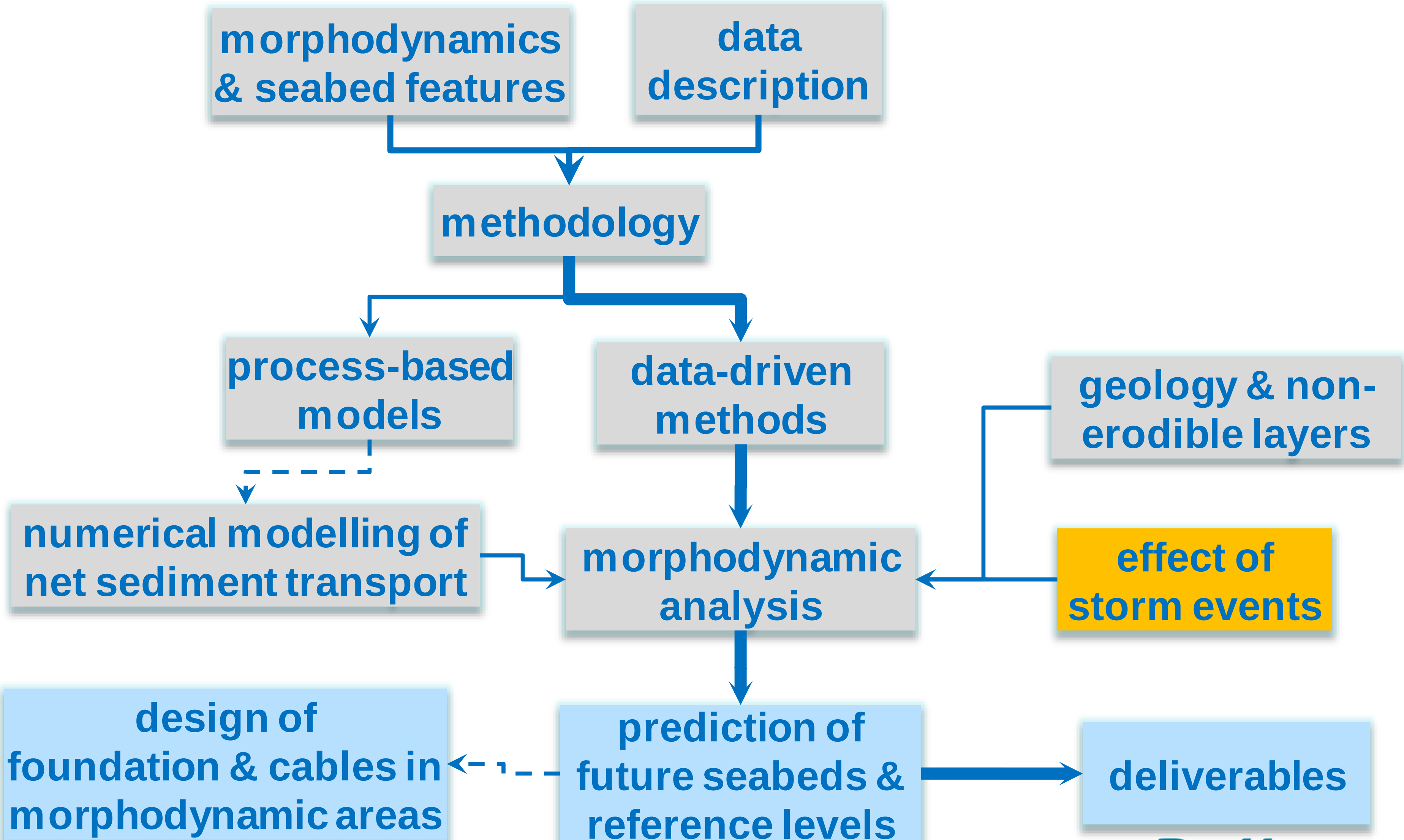
# Structure of presentation

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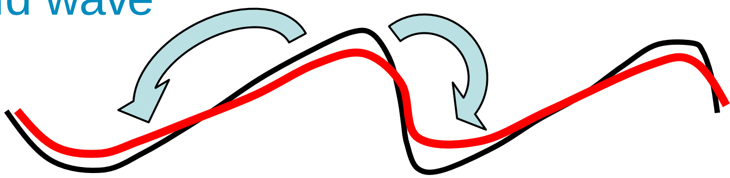
# Storm analysis: objectives and methodology

## Objective

Investigate the possible storm-induced changes to the seabed

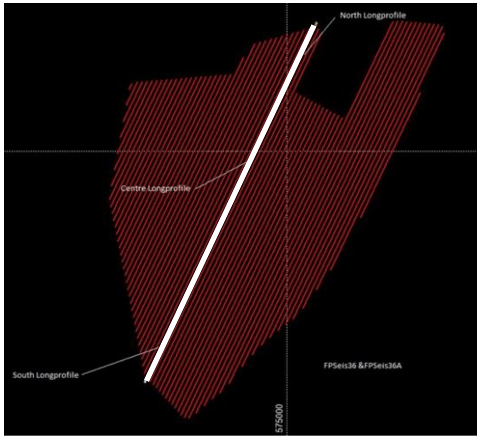
## Underlying assumption

During storms, high waves cause an increased sediment transport, especially on top of the more shallow sand wave crests and hence may smooth the sand waves



## Methodology

- Collect and analyze hydrodynamics during the storm (waves, water levels, currents)
- Analyze the pre and post storm seabed profiles (surveyed by Fugro)
- Assess the potential storm effects on future seabed levels (i.r.t. their return period)

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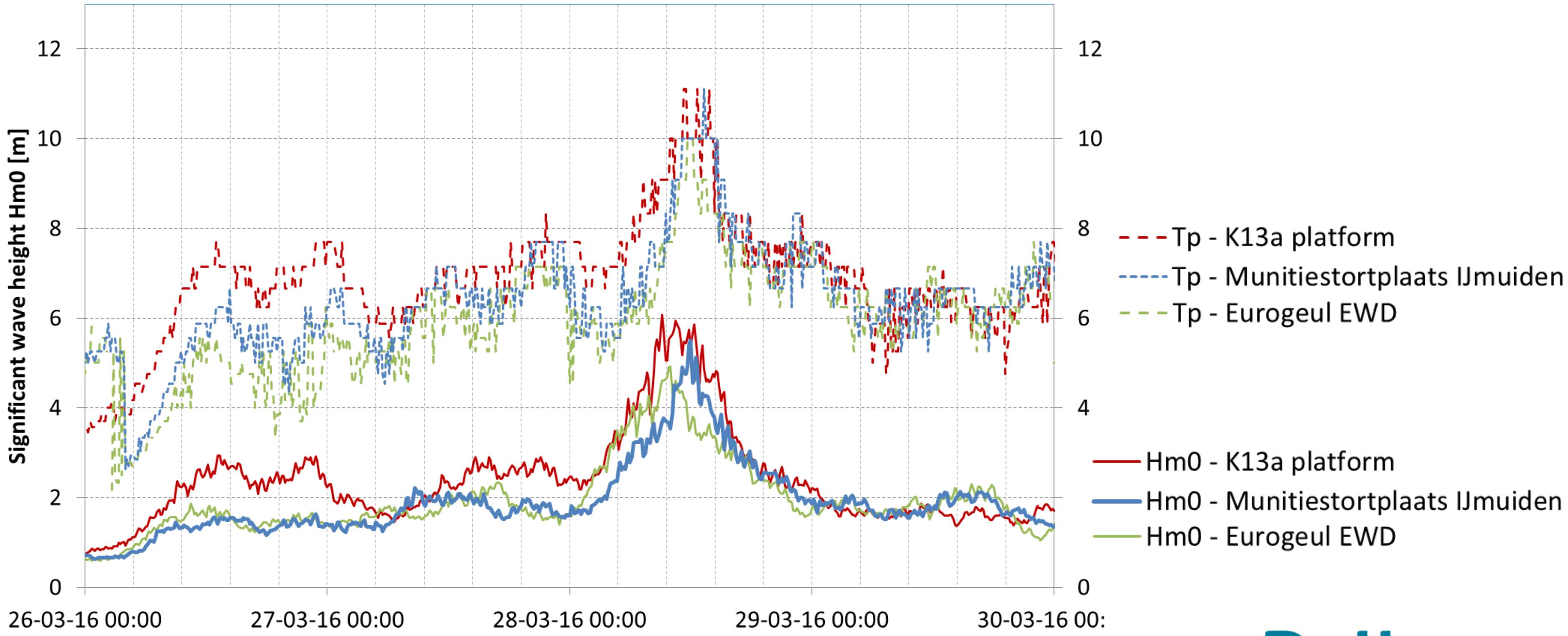
# Storm analysis: Easter Storm

- "Easter Storm" occurred on 28 March 2016
- Another seabed survey was taken by Fugro on 1 April 2016 (only 4 days later) on a profile that was initially surveyed on 18 March (10 days before storm)
- Only 2 weeks in between surveys: ~ 1 spring-neap-cycle

(from neap tide to neap tide, with spring tide on 25 March 2016)

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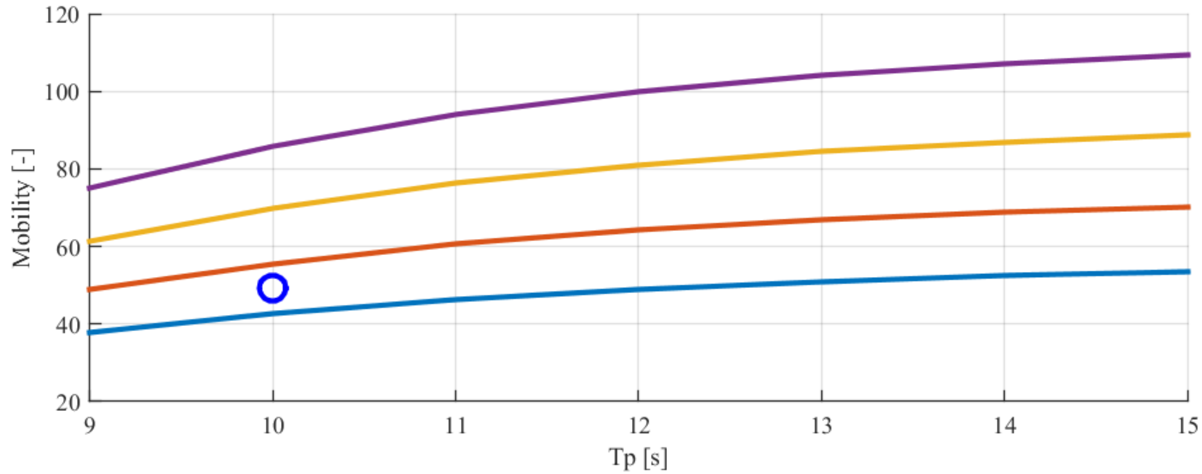
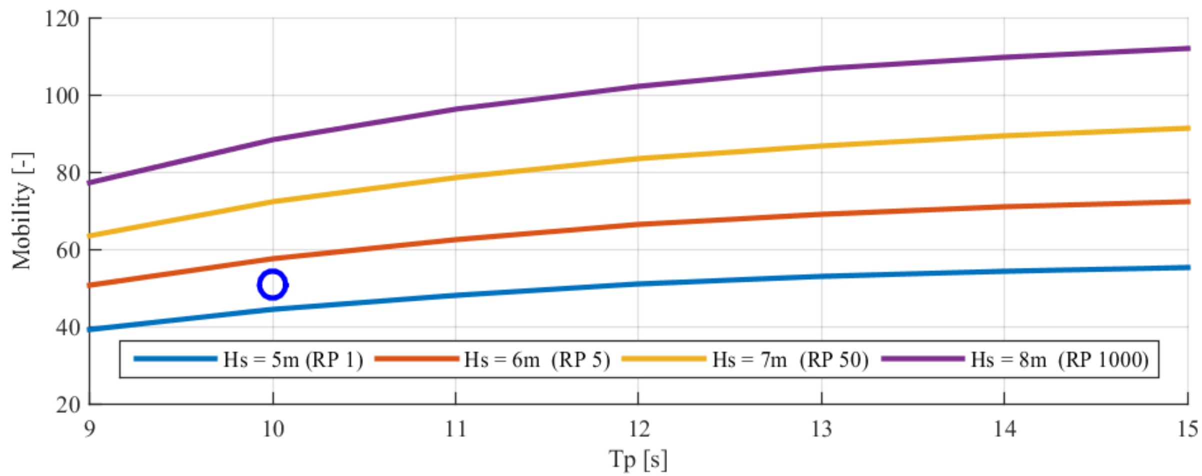
# Storm analysis: seabed mobility

- Easter Storm had a return period of ~2-3 years acc. to metocean study by DHI
- The relative mobility of the seabed sediment was calculated for extreme conditions with return periods of 1, 5, 50 and 1000 year
- Significant sediment transport during storm: good test case for effect of storms on sand waves!!




Note: exact extreme values of metocean study by DHI were not known during this study; presented values are preliminary results

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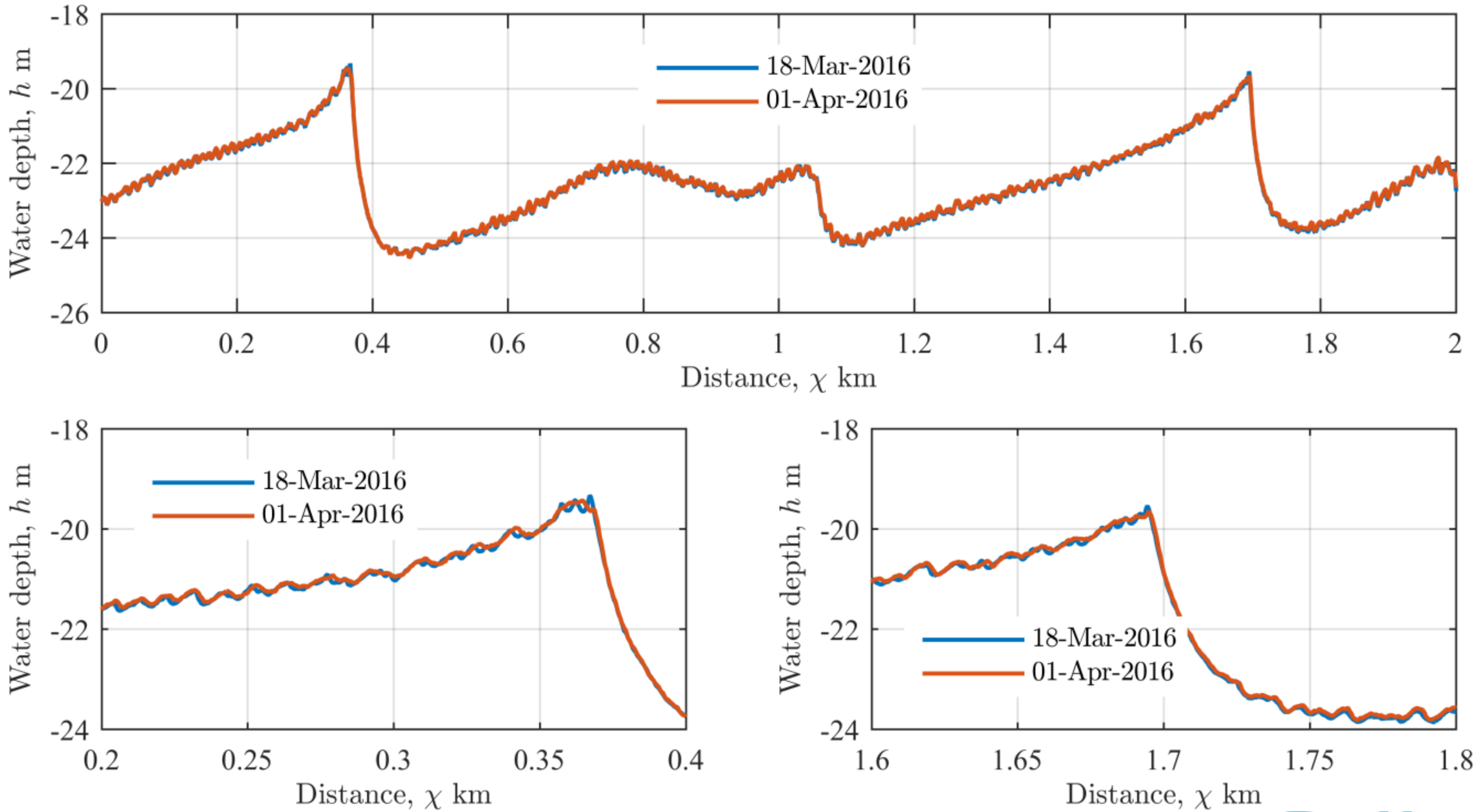
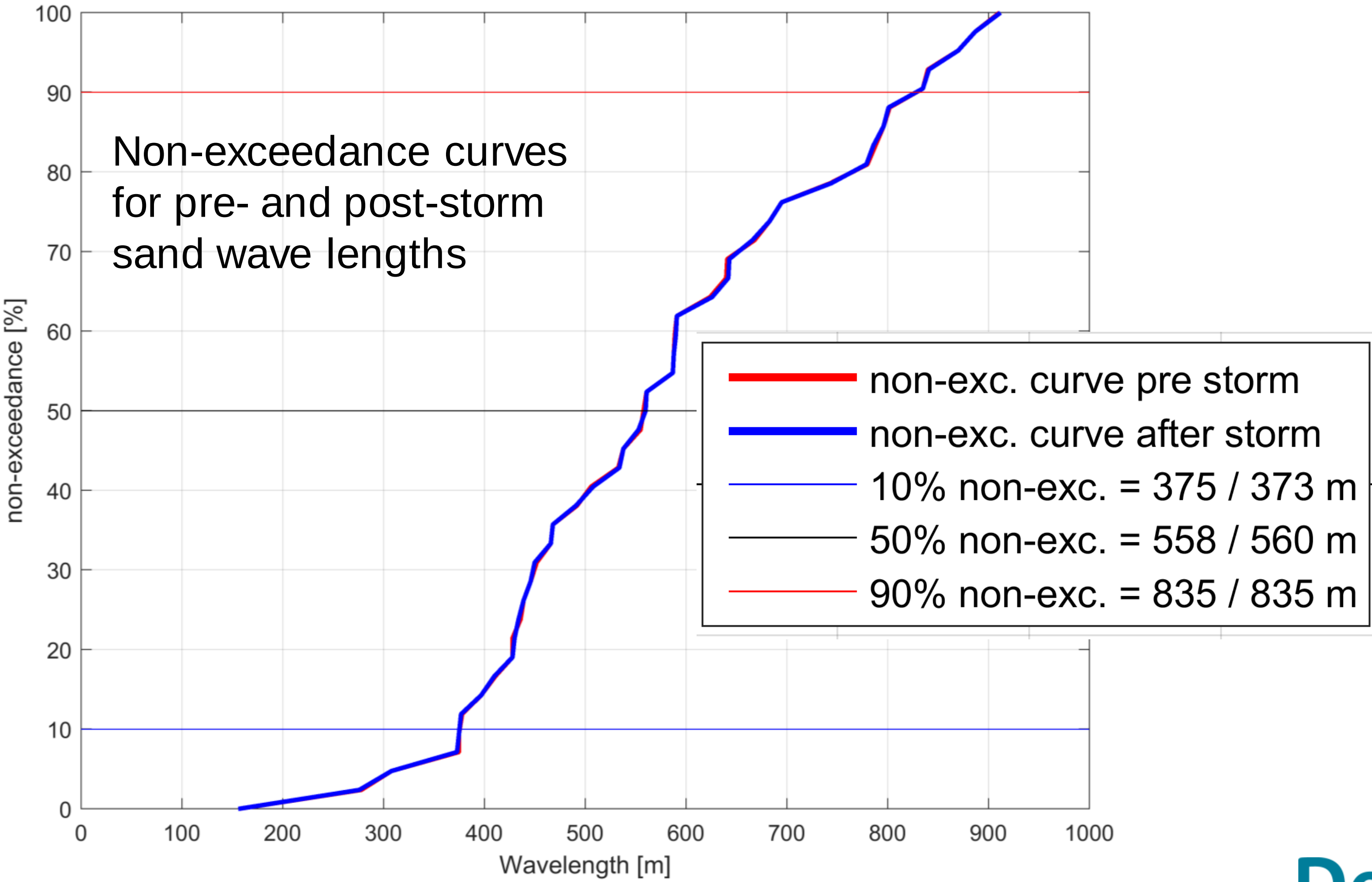
# Storm analysis: surveyed seabed profiles

- Zoom of two surveyed profiles (only 2 km)
- No visible changes to sand wave profiles



# Storm analysis: pre- and post-storm sand wave lengths

- Profiles analyzed using the exact same techniques as rest of study
- Fourier analysis reveals: No changes in sand wave lengths!

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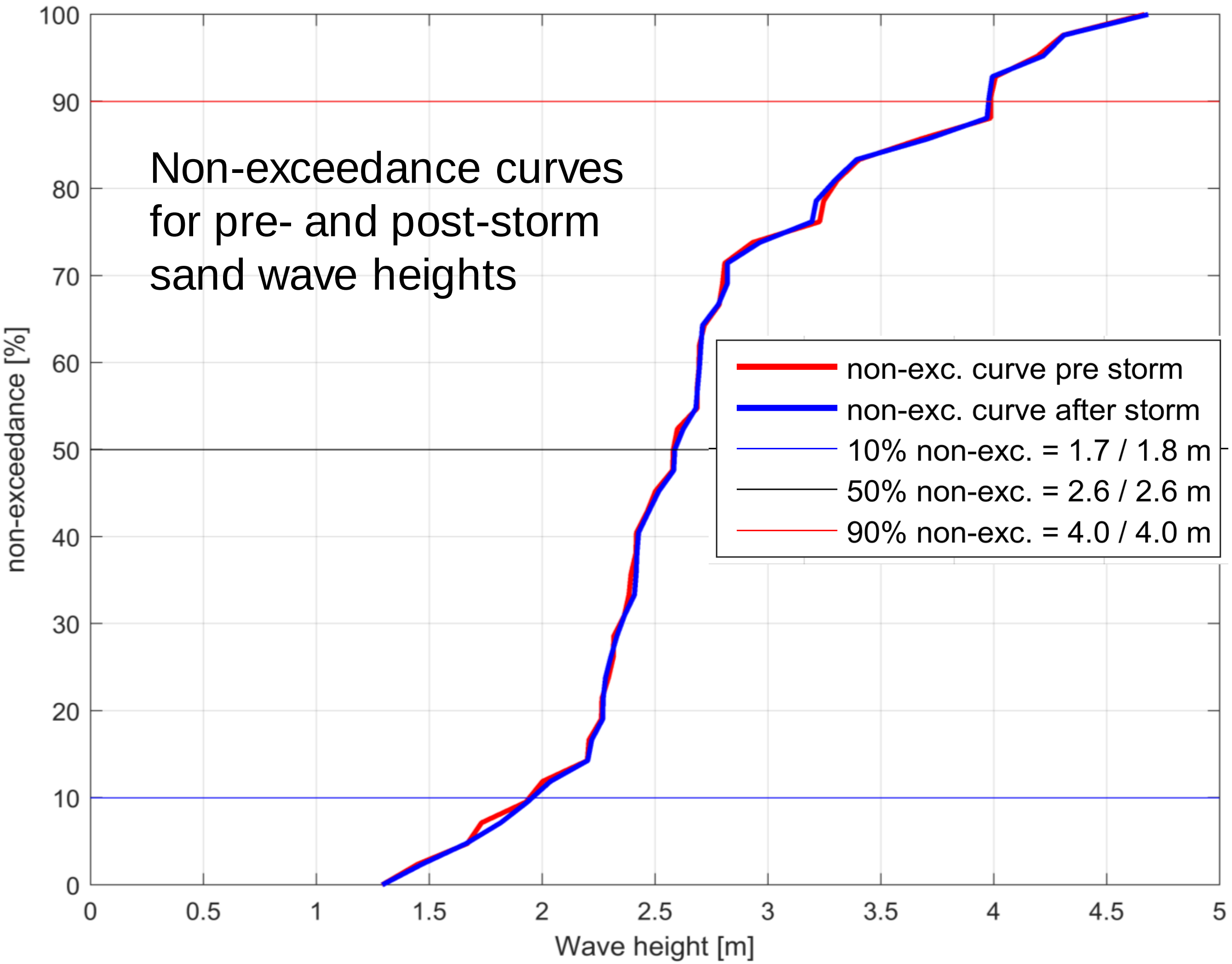
# Storm analysis: pre- and post-storm sand wave heights

- Fourier analysis reveals: Also no changes in sand wave heights!



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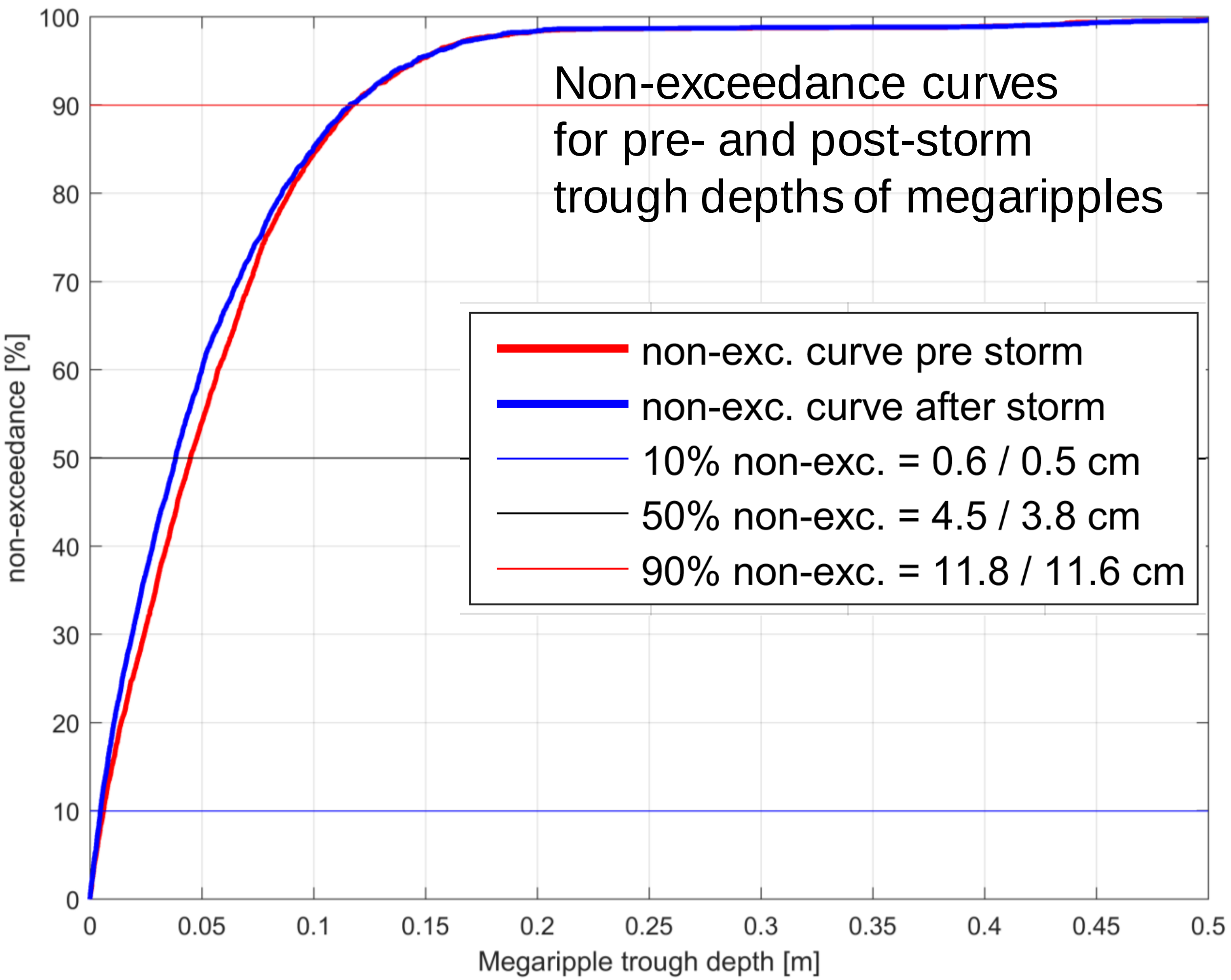
# Storm analysis: pre- and post-storm megaripples

➢ Megaripples were also analyzed: some reduction in trough depths

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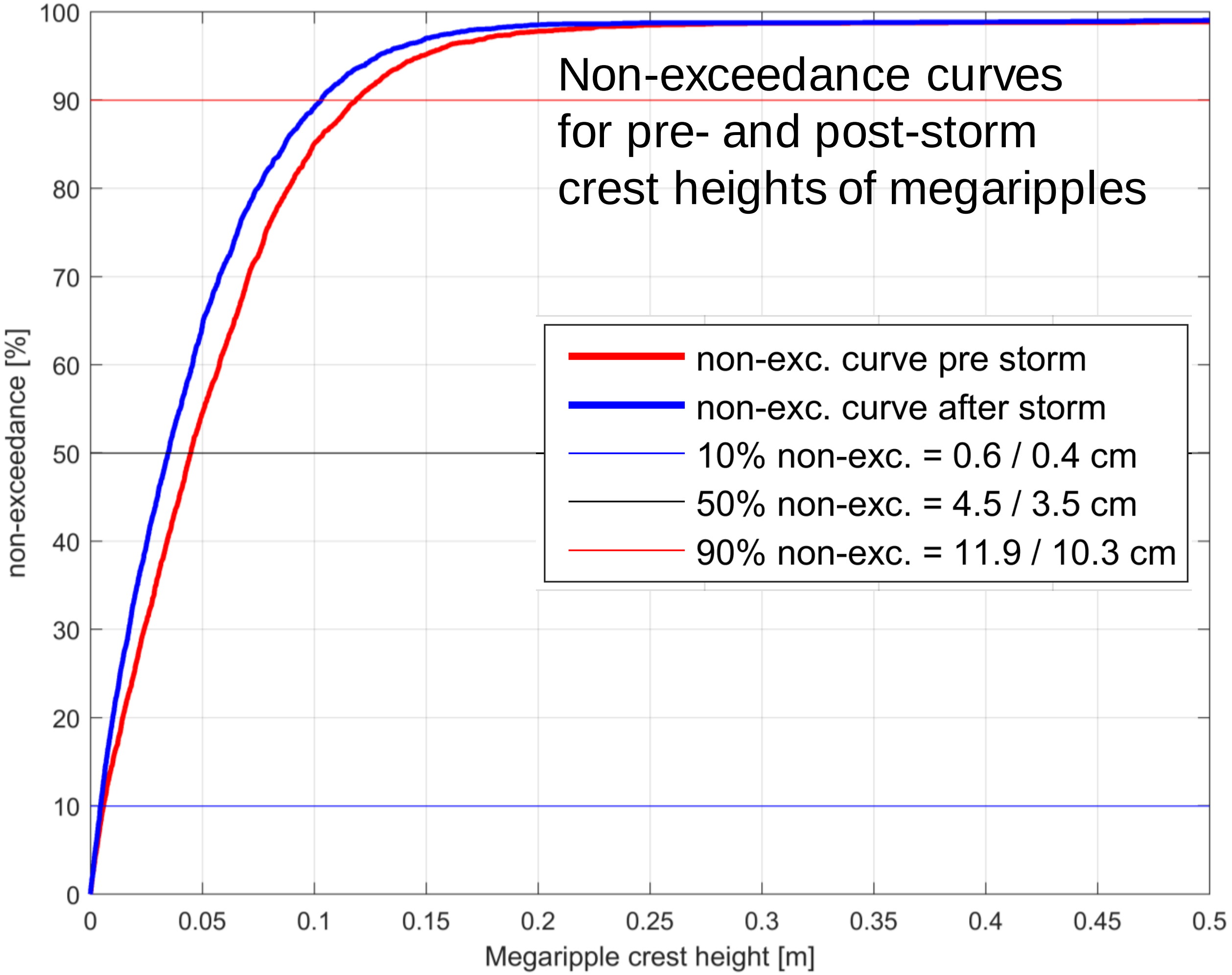
# Storm analysis: pre- and post-storm megaripples

- Storm cause some flattening / smoothing of the megaripples
- The megaripple crests reduced in height

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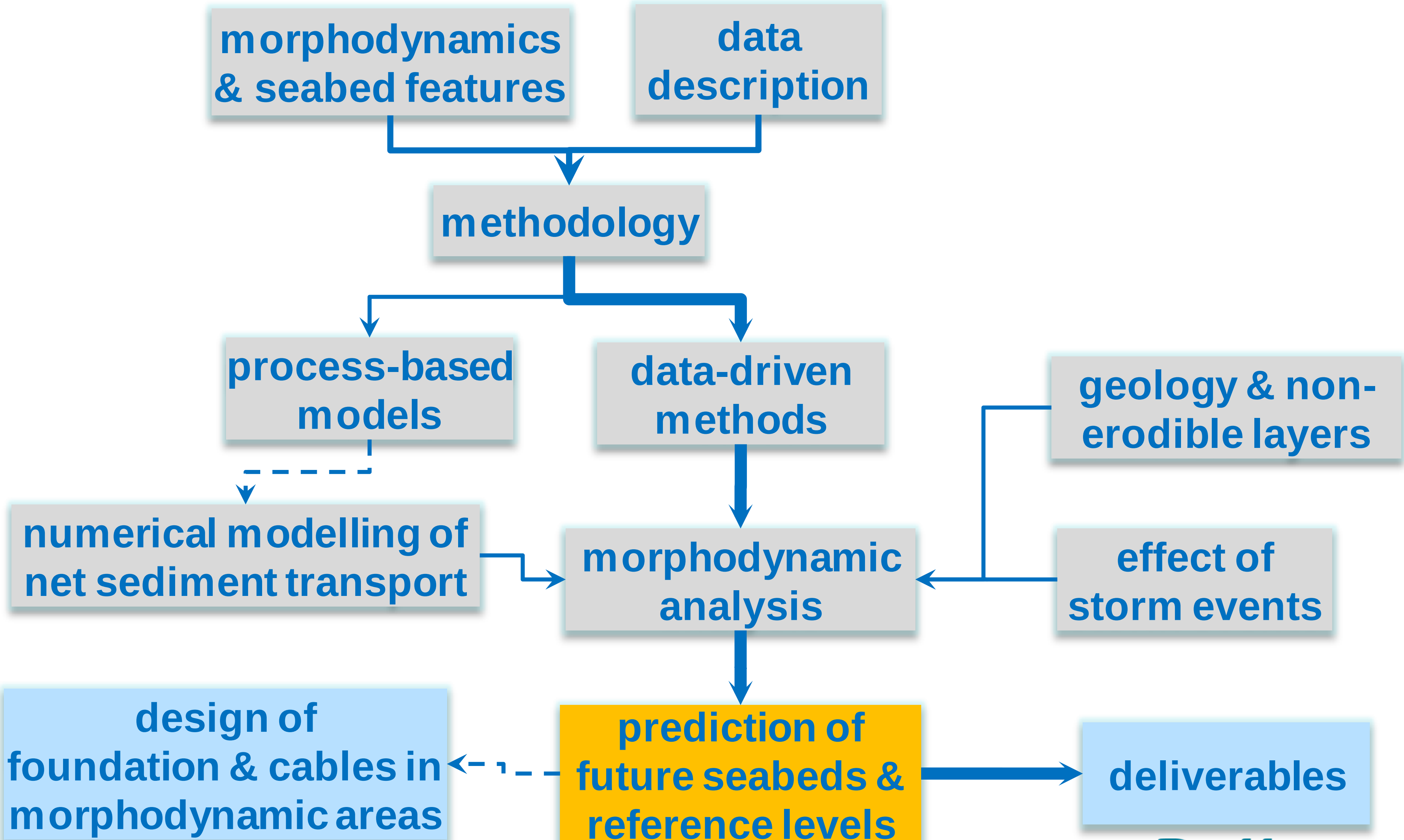
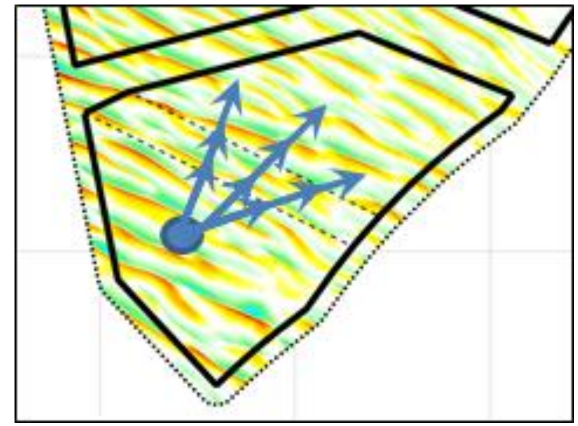
# Structure of presentation



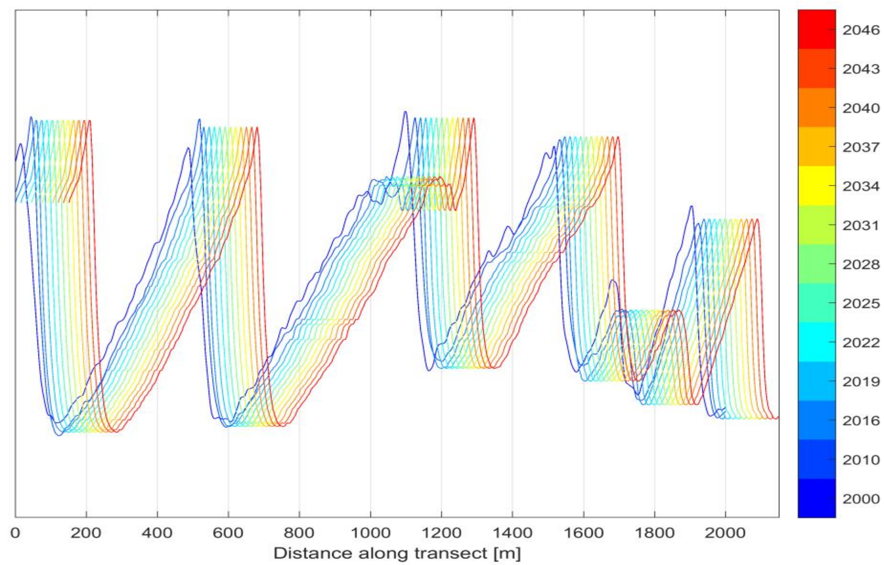
# Predicting future bathymetries until 2051

- In total, 9 estimates for the migrated sand wave field are determined for each year in the period 2016-2051



- These 9 estimates consist of:
  3 sand wave migration directions
  (lower bound – best estimate – upper bound)
  x 3 estimates for the migration rate
  (minimum, mean and maximum migration rate)

- Predicted bathymetries for year 20XX are reconstructed by combining:
  - ✓ Static Bathymetry 2016
  - ✓ Migrated Sand Wave Field 2016 until year 20XX
  - ✓ Uncertainty Band

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# Dealing with uncertainty

Vertical uncertainty band consists of contributions related to:

- survey inaccuracies
- existence of megaripples
- spatial resolution uncertainty (‘missing extreme levels’)

| | | |
|---|---|---|
| survey uncertainty, specified by Fugro (95%) | = | 0.182m |
| megaripple crest height | = | 0.25m* |
| spatial resolution uncertainty | = | 0.05m |
| **uncertainty upward** | **=** | **0.50m** |

| | | |
|---|---|---|
| survey uncertainty, specified by Fugro (95%) | = | -0.182m |
| megaripple trough depth | = | -0.15m* |
| spatial resolution uncertainty | = | -0.05m |
| **uncertainty downward** | **=** | **-0.40m** |

* upward megaripple uncertainty is larger than downward uncertainty due to higher crests and shallower troughs

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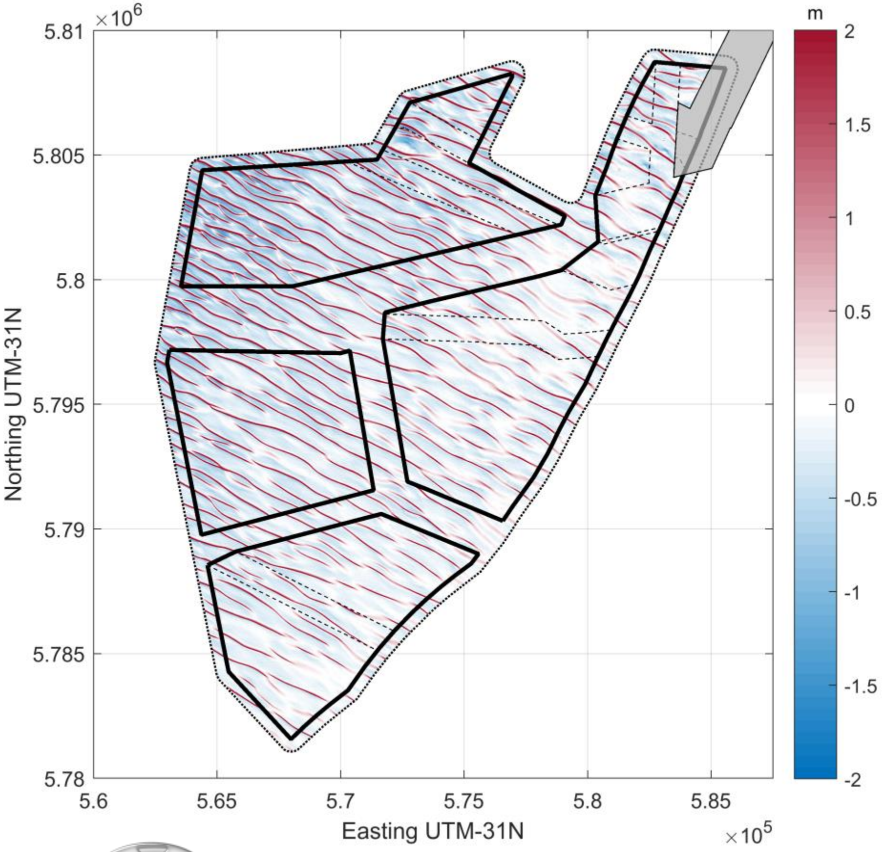
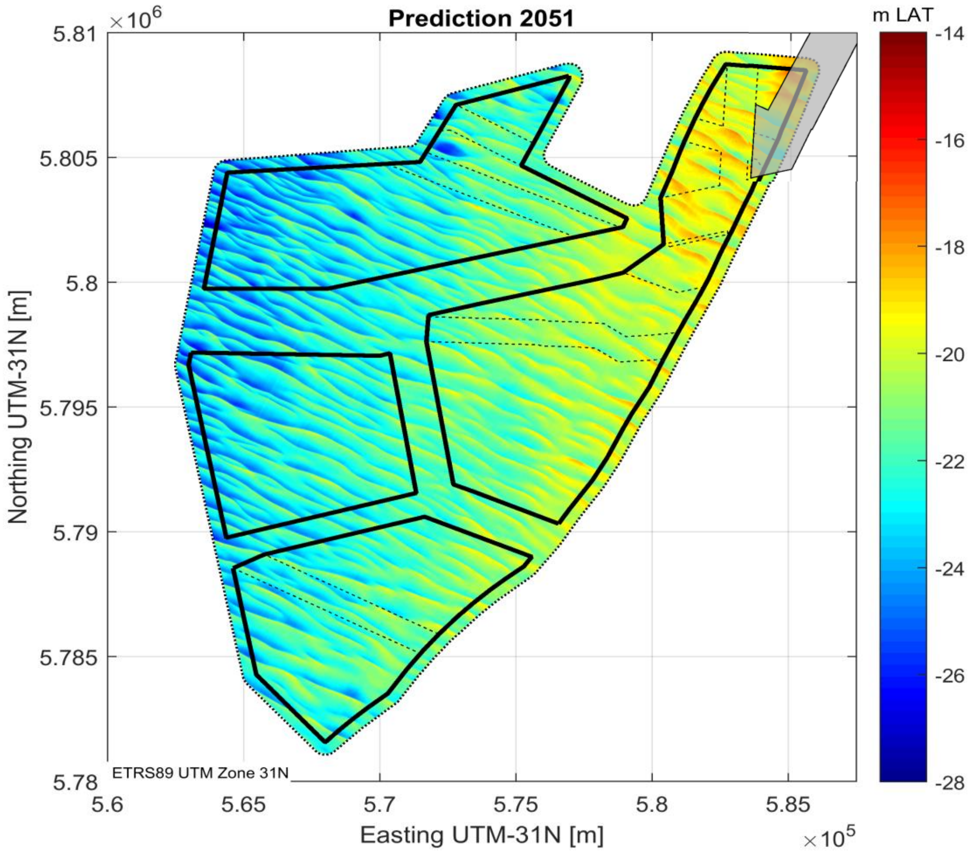
# Best-Estimate Bathymetry 2051: $BEB_{2051}$

migrated Sand Wave Field

combined with
Static Bathymetry: $BEB_{2051}$




[Movie illustrating future Best-Estimate Bathymetries]()

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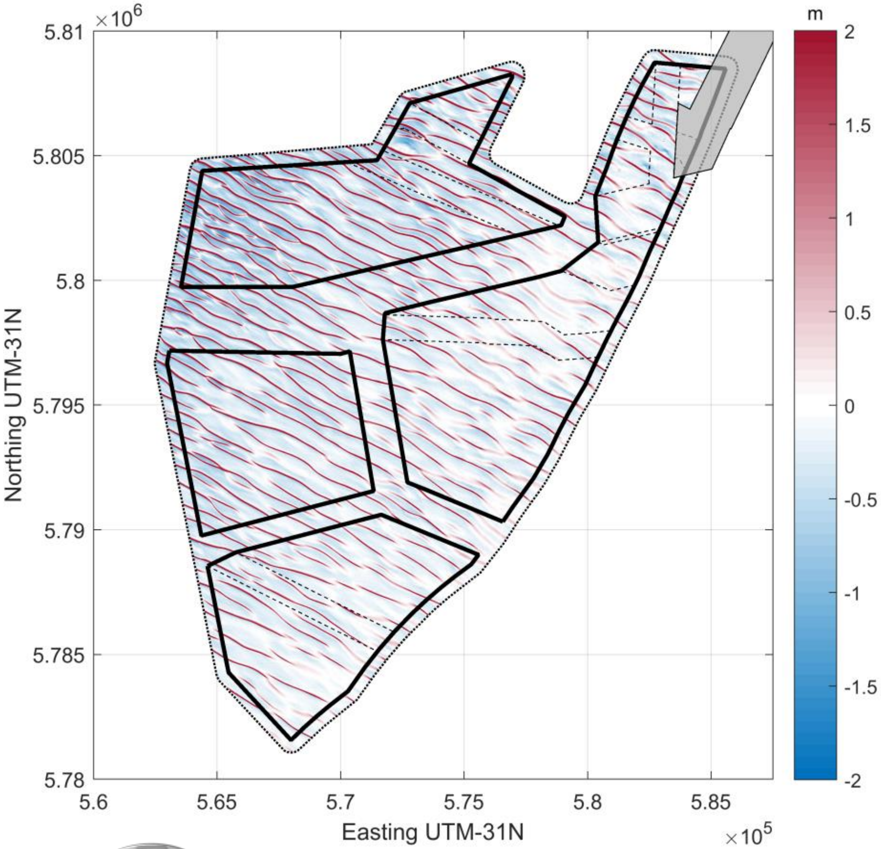
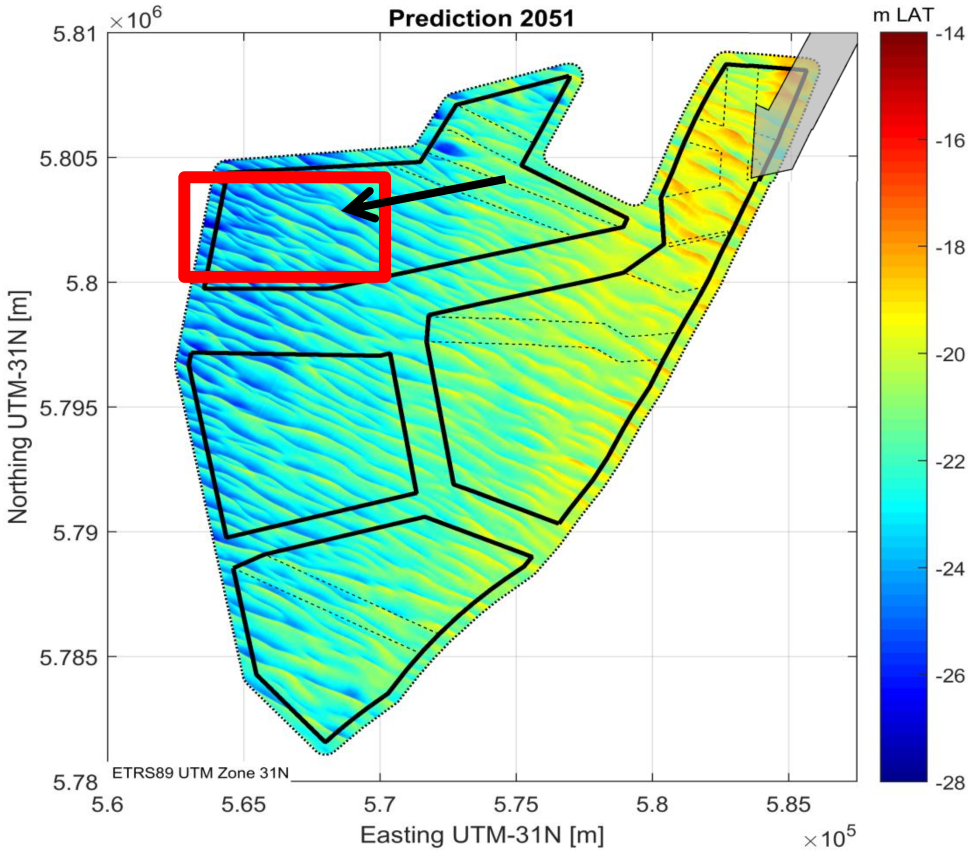
# Best-Estimate Bathymetry 2051: $BEB_{2051}$

migrated Sand Wave Field

combined with
Static Bathymetry: $BEB_{2051}$




*Movie illustrating future Best-Estimate Bathymetries*

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# Lowest SeaBed Level: LSBL

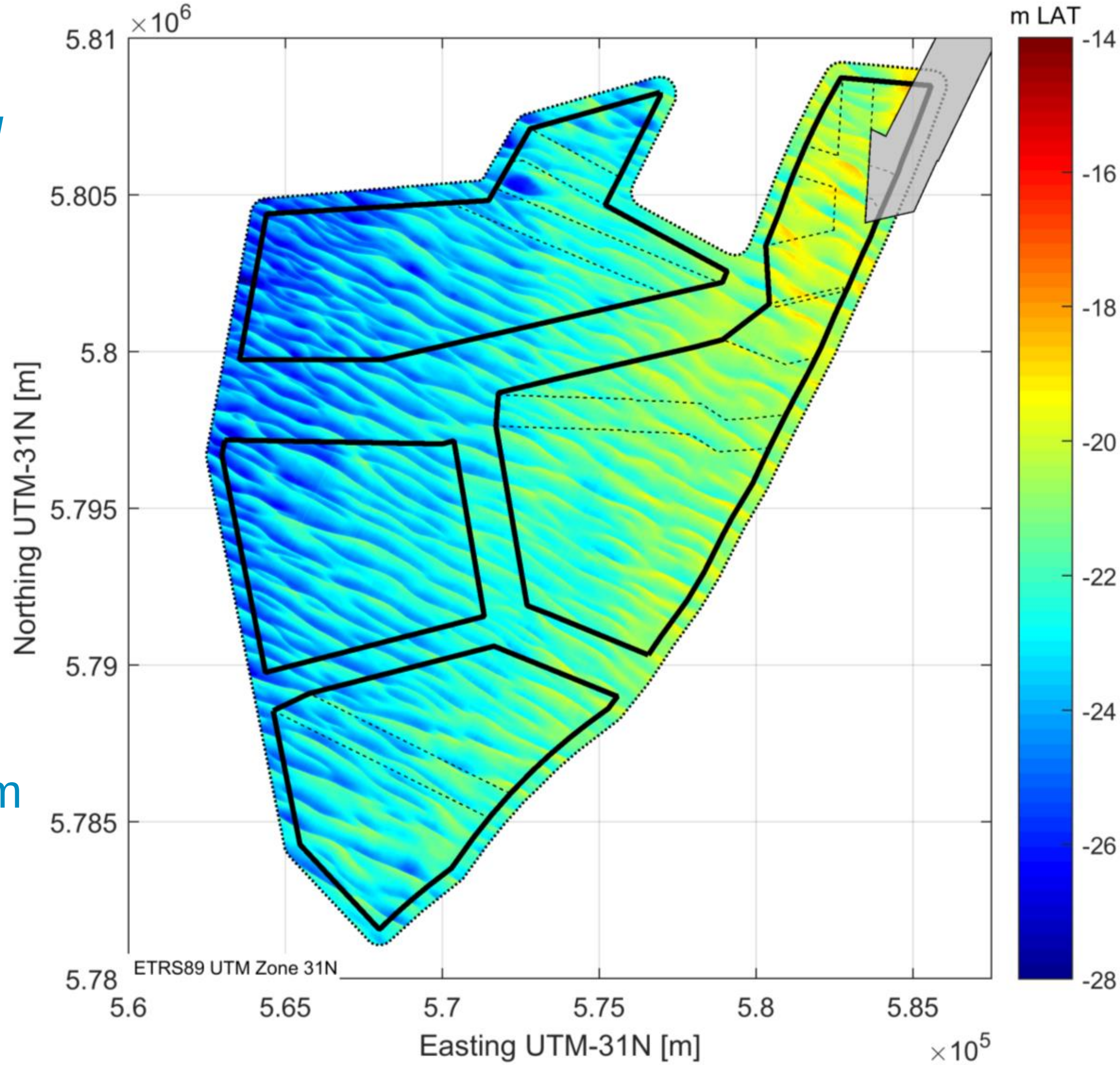
**Lowest SeaBed Level**

*The lowest possible seabed level during the lifetime of the wind parks (i.e. 2016-2051)*

+ Static Seabed Level
- Lower envelope of Sand Wave Field until 2051
- <u>Downward uncertainty band</u>

Lowest SeaBed Level (LSBL)

The LSBL varies between -17.8 m and -28.3 m LAT

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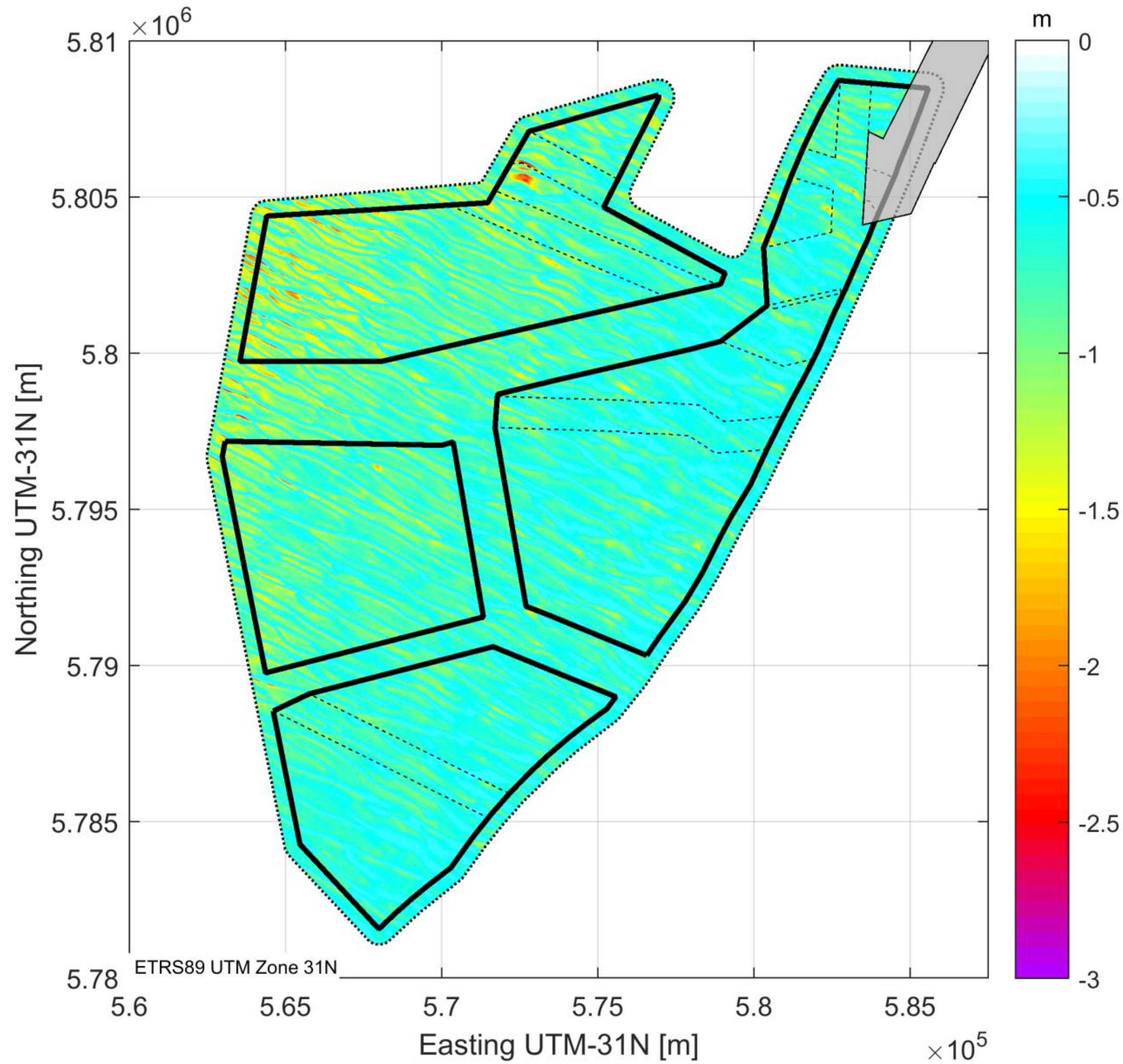
# Maximum Potential Seabed Lowering

Maximum Potential Seabed Lowering =

Difference between

2016-bathymetry and LSBL




*[Movie illustrating cumulative downward seabed movement]()*

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# Highest SeaBed Level: HSBL

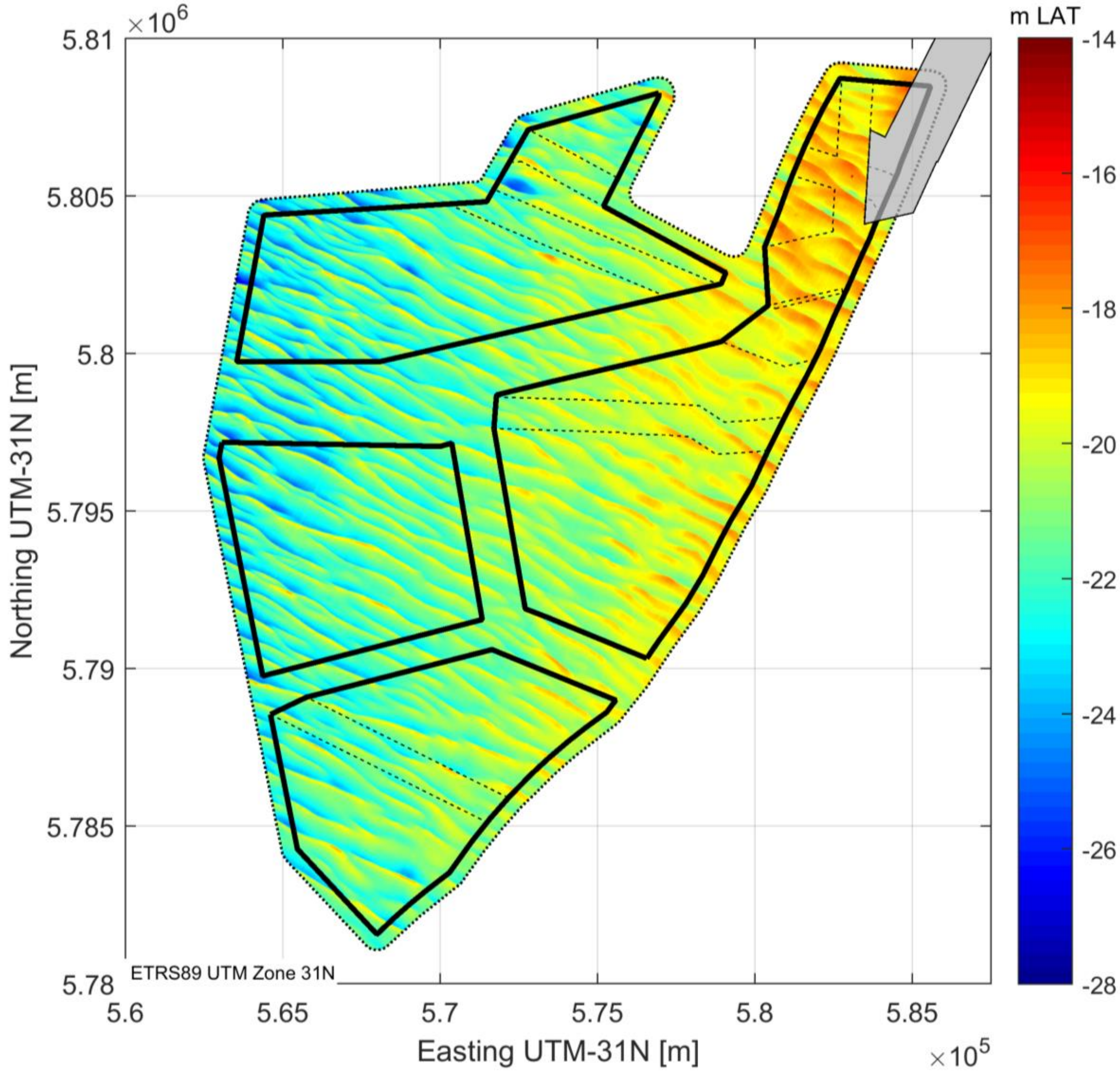
**Highest SeaBed Level**

*The highest possible seabed level during the lifetime of the wind parks (i.e. 2016-2051)*

+ Static Seabed Level
+ Upper envelope of Sand Wave Field until 2051
+ Upward uncertainty band

Highest SeaBed Level (HSBL)

The HSBL varies between -15.3 m and -27.3 m LAT

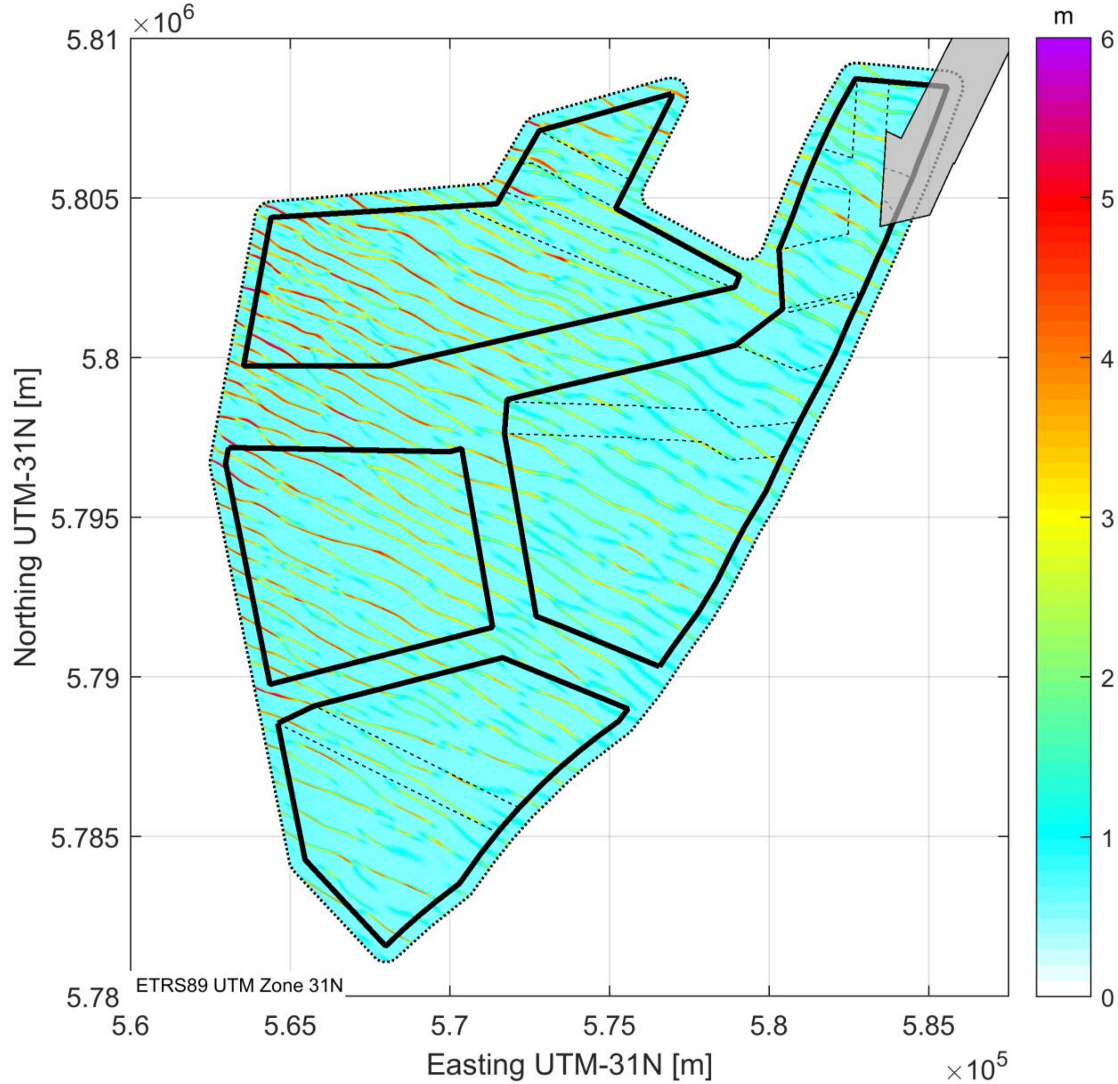


# Maximum Potential Seabed Rising

Maximum Potential Seabed Rising =

Difference between

2016-bathymetry and HSBL




*[Movie illustrating cumulative upward seabed movement]*



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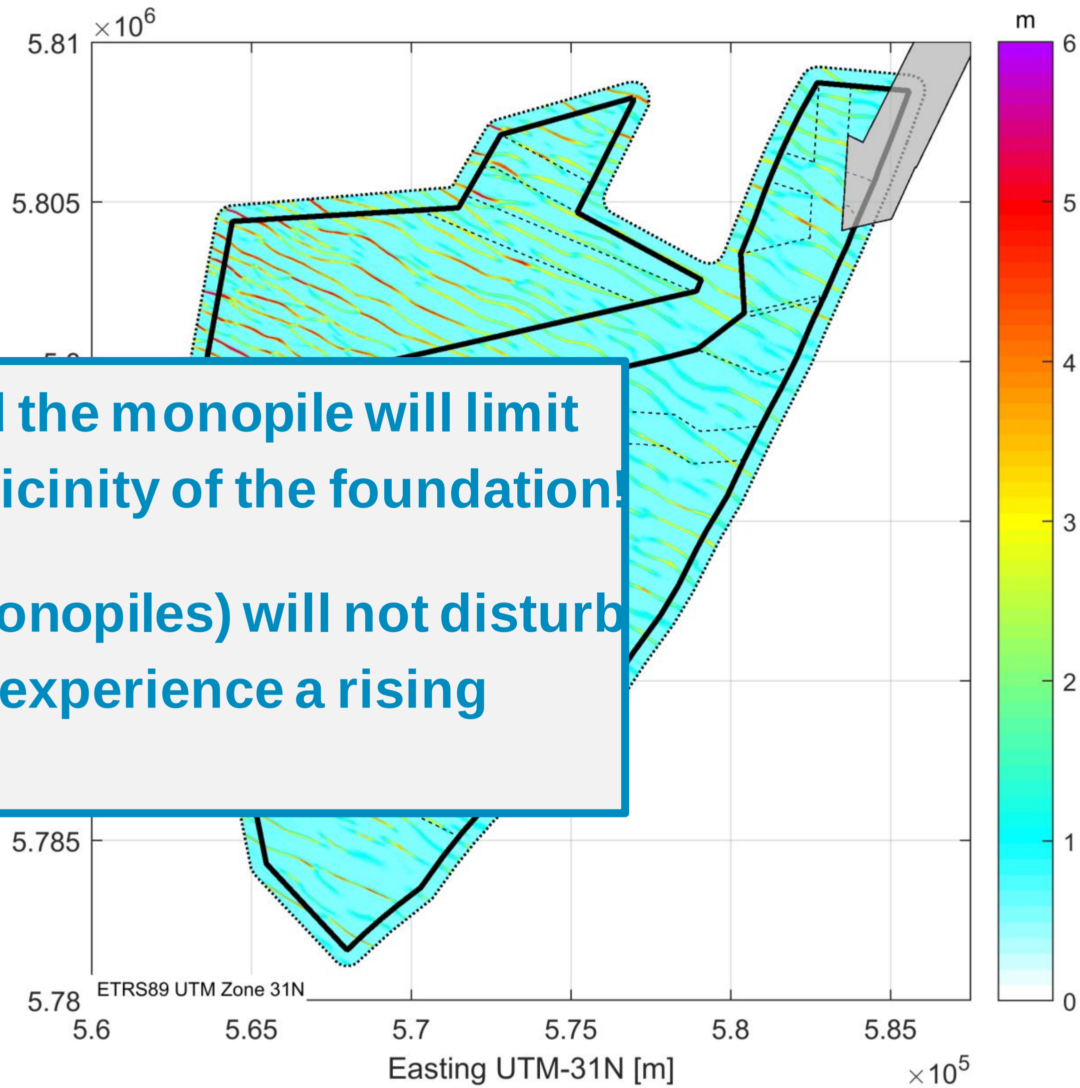
# Maximum Potential Seabed Rising

Maximum Potential Seabed Rising =
Difference between
2016-bathymetry and HSBL




**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.**

*Movie illustrating cumulative upward seabed movement*

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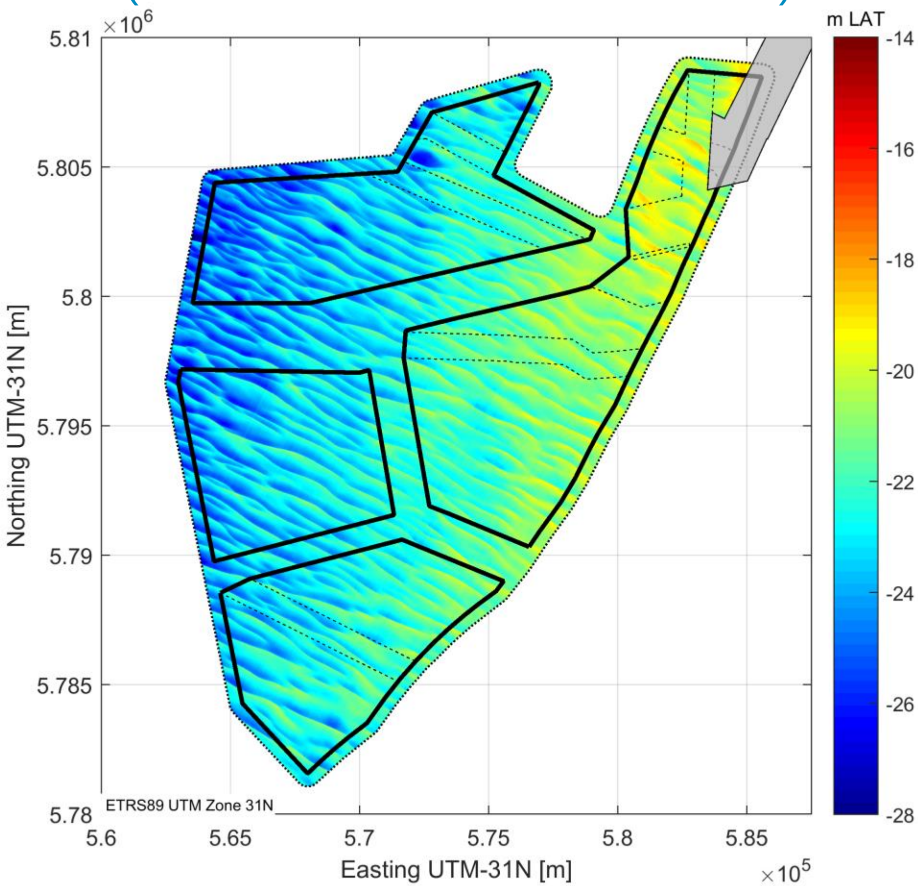
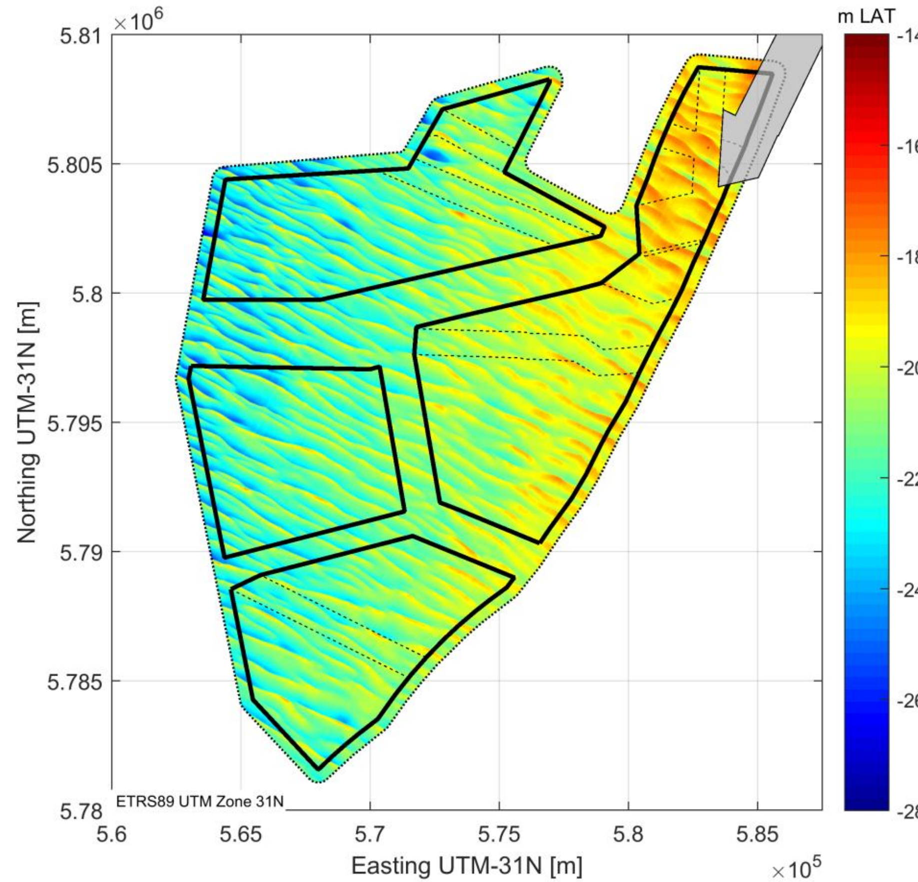
# Comparison between LSBL and HSBL

Difference between HSBL and LSBL = Maximum vertical range due to (autonomous) morphological seabed changes

LSBL
(between -17.8 m and -28.3 m LAT)




HSBL
(between -15.3 m and -27.3 m LAT)

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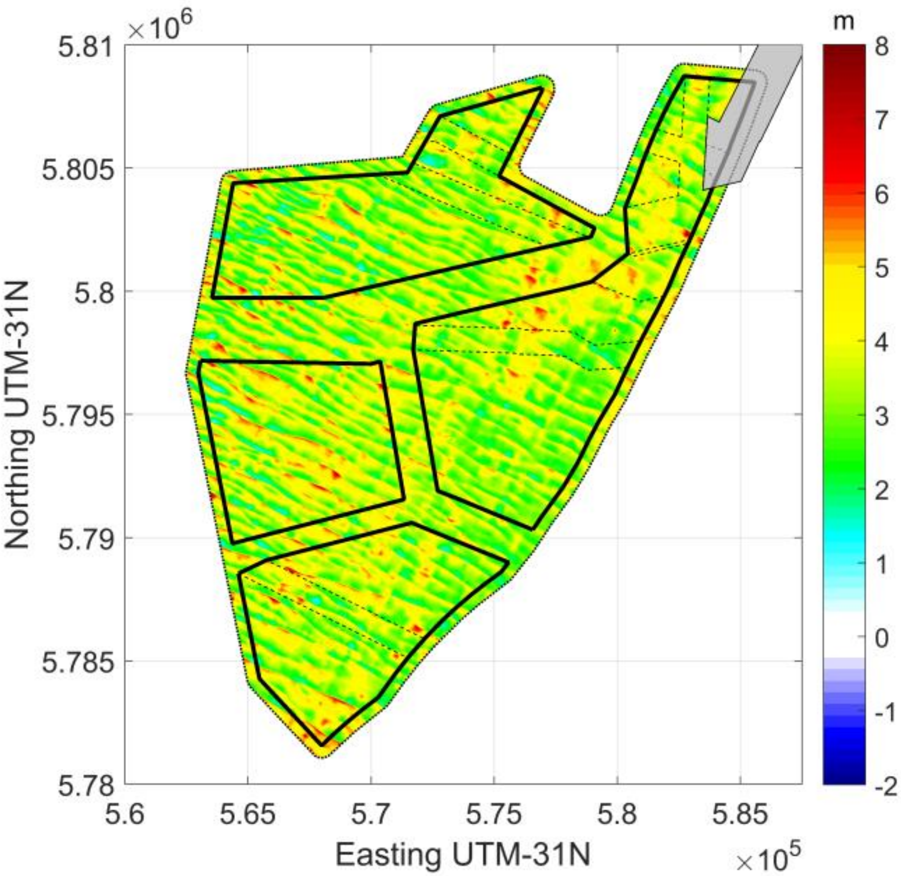
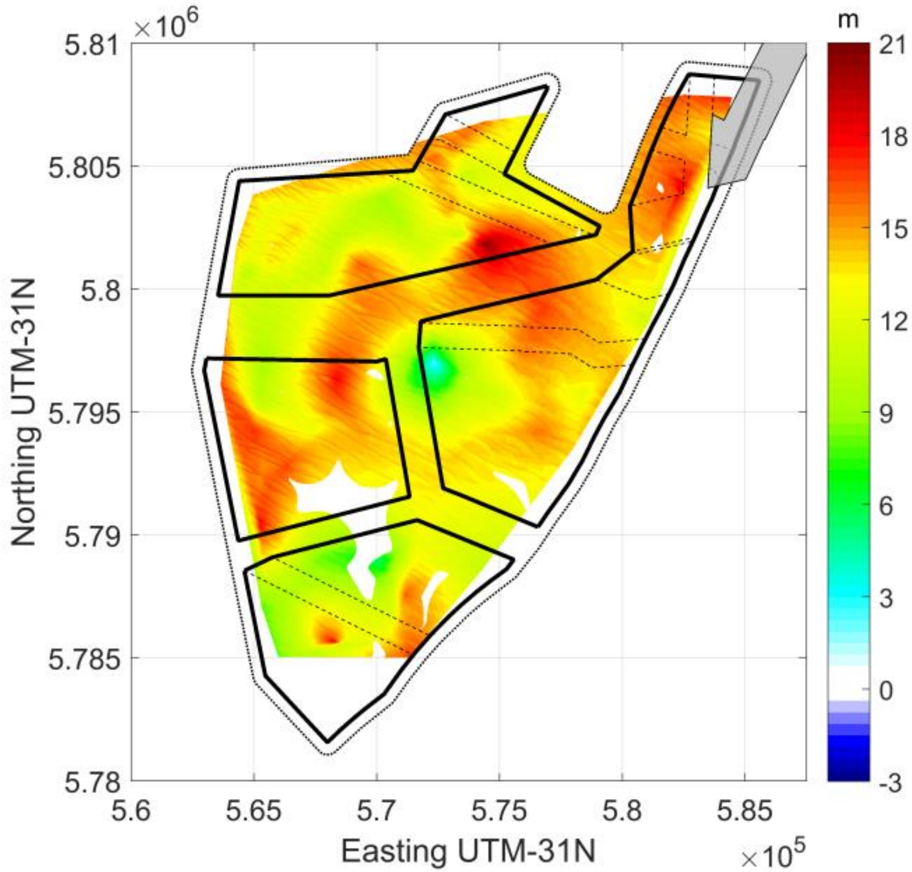
# Determining remaining layer thickness

Remaining layer thickness between LSBL and the Base of the Holocene formation




Remaining layer thickness between LSBL and the top of the non-erodible layer



# Classification zones (I)

- Next step: translate HSBL and LSBL and corresponding seabed changes to “Classification Zones”
- Classification is 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.)*

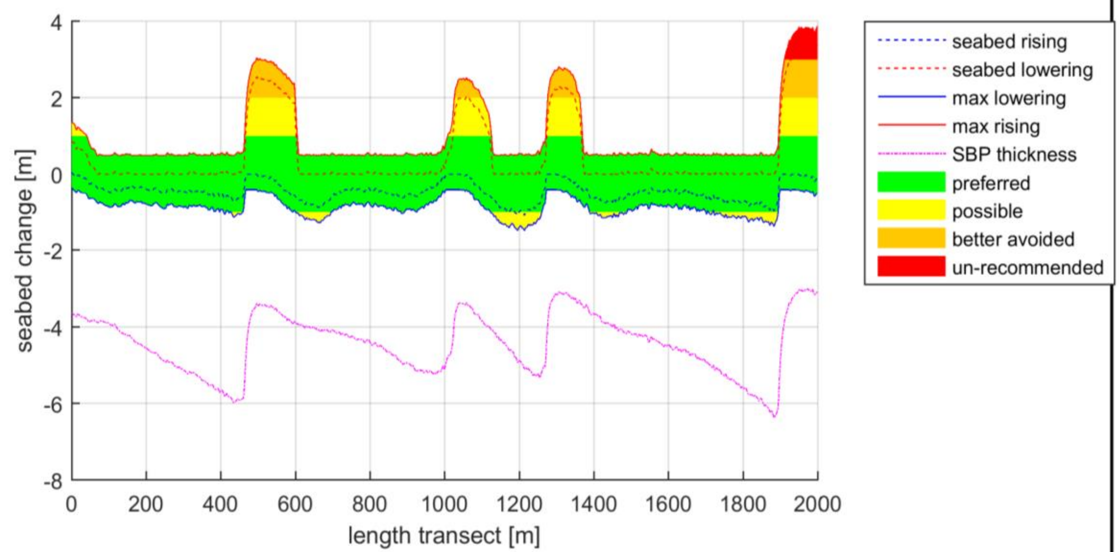
| Classification of zones | Bed level lowering [m] | Bed level rising [m] |
|---|---|---|
| **Preferred** | 0 > dz ≥ -1 | 0 < dz ≤ 1 |
| **Possible** | -1 > dz ≥ -1.5 | 1 < dz ≤ 2 |
| **Better avoided** | -1.5 > dz ≥ -2 | 2 < dz ≤ 3 |
| **Unrecommended** | dz < -2 | dz > 3 |

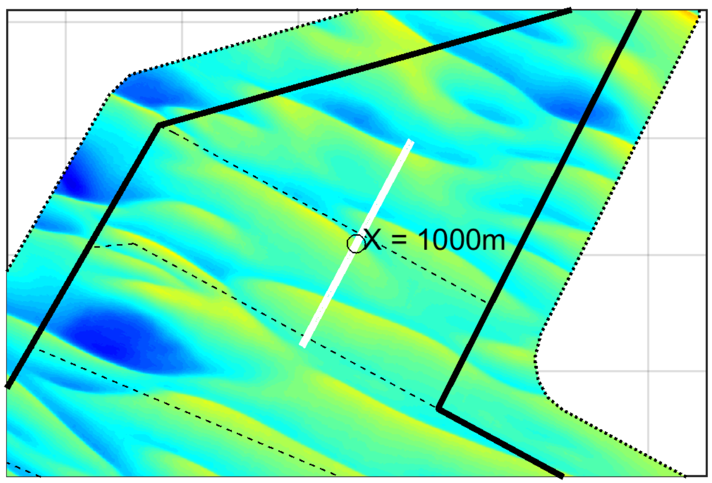
- Classification Zones are for indicative and illustrational purposes only. Actual classification is dependent on the design of the support structures and properties of electricity cables and should be adjusted accordingly by windfarm developer once this information is available.

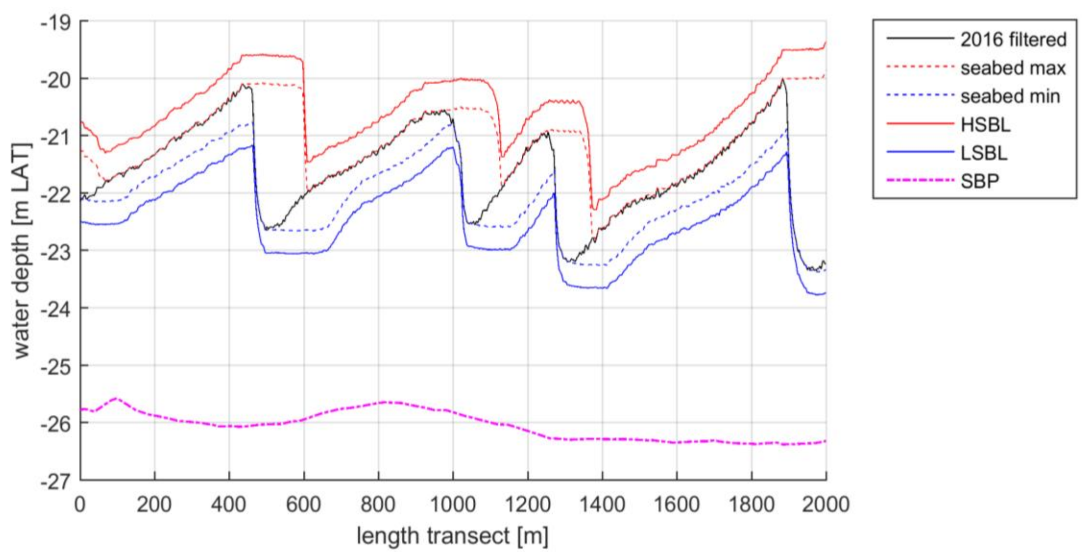
# Classification zones (II)

Example for one transect:

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

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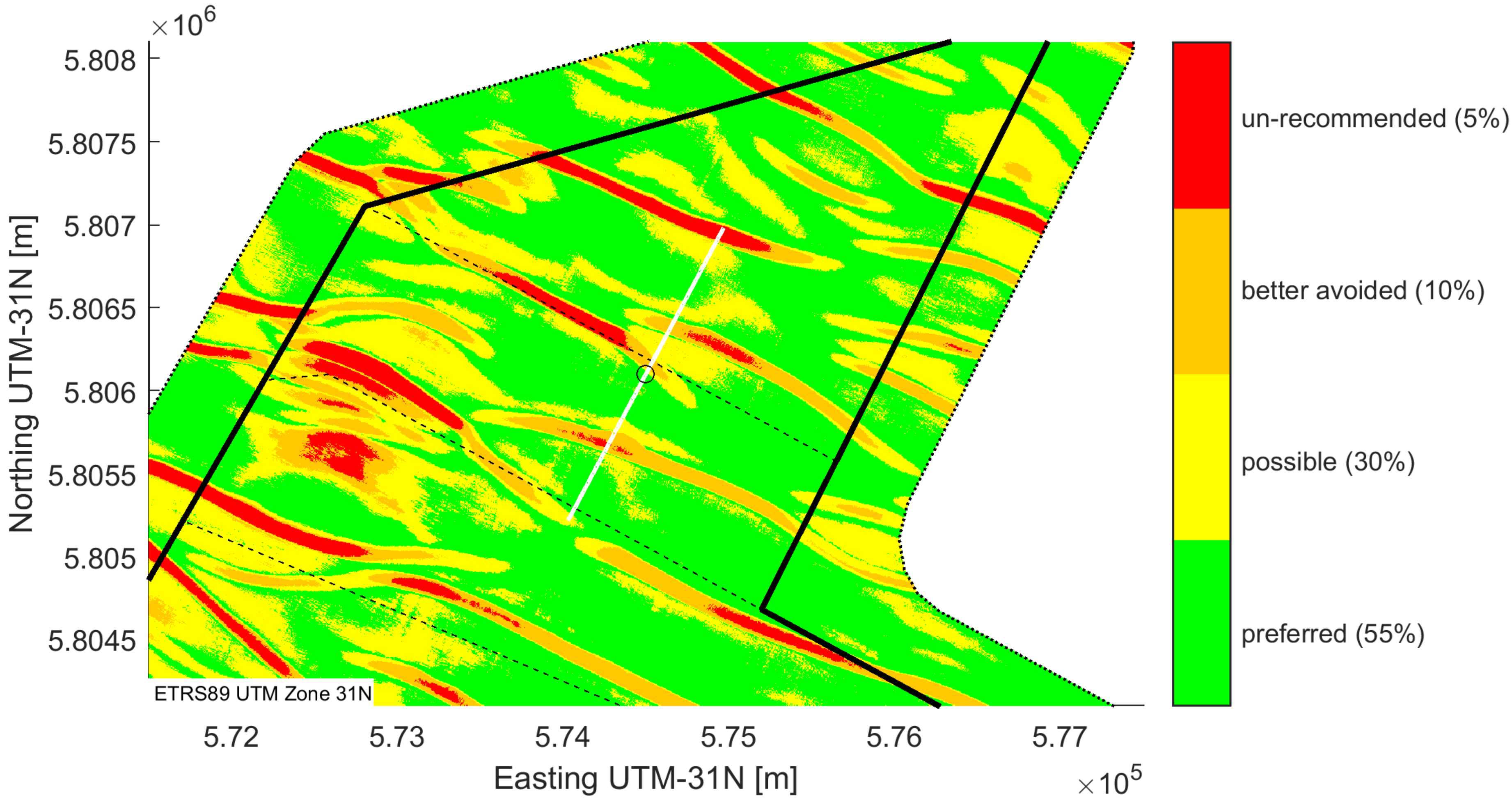
# Classification zones for northern part Site I

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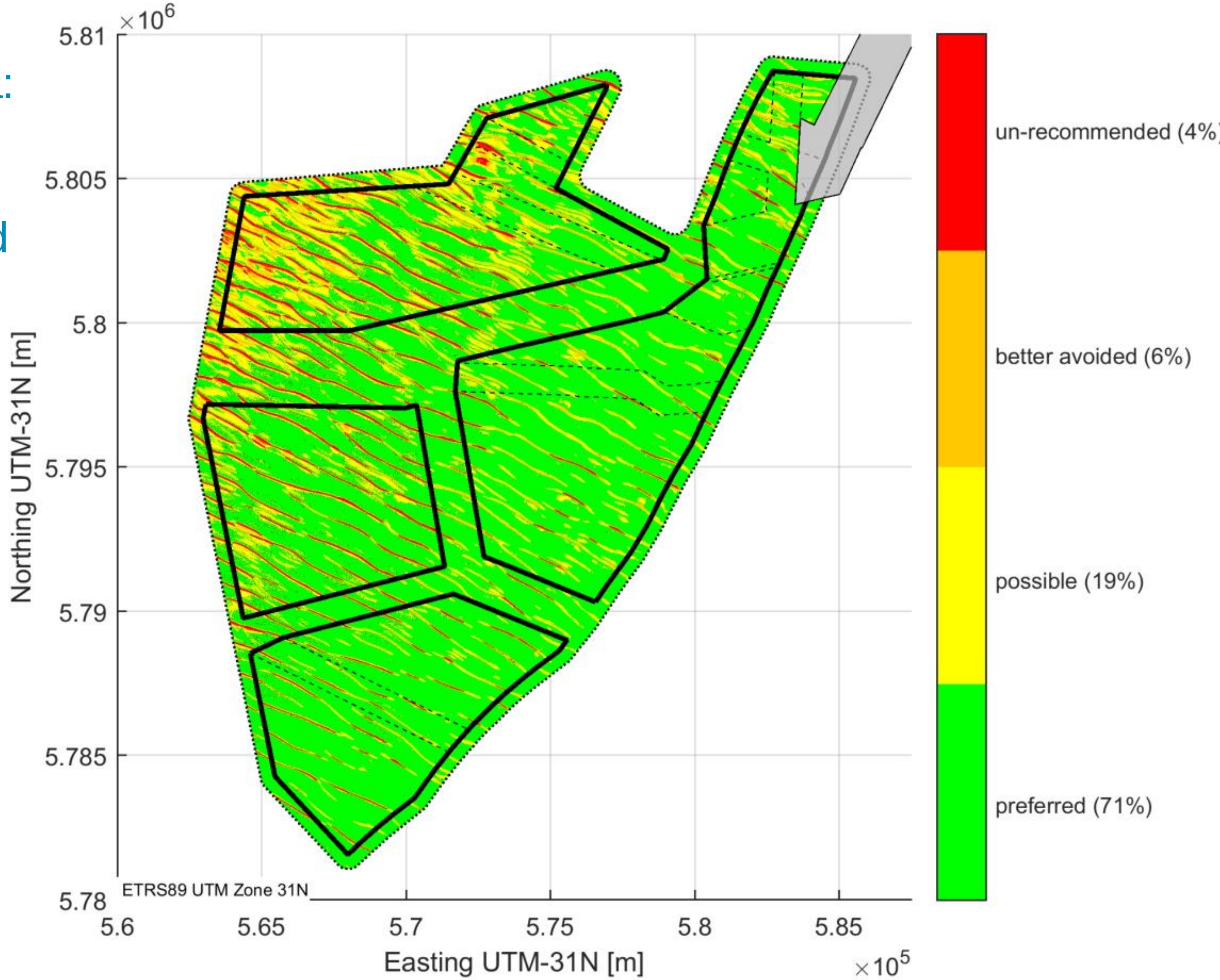
# Classification zones for entire HKZ WFZ

For the assumed criteria:

- 71% = preferred
- 10% = better avoided or un-recommended

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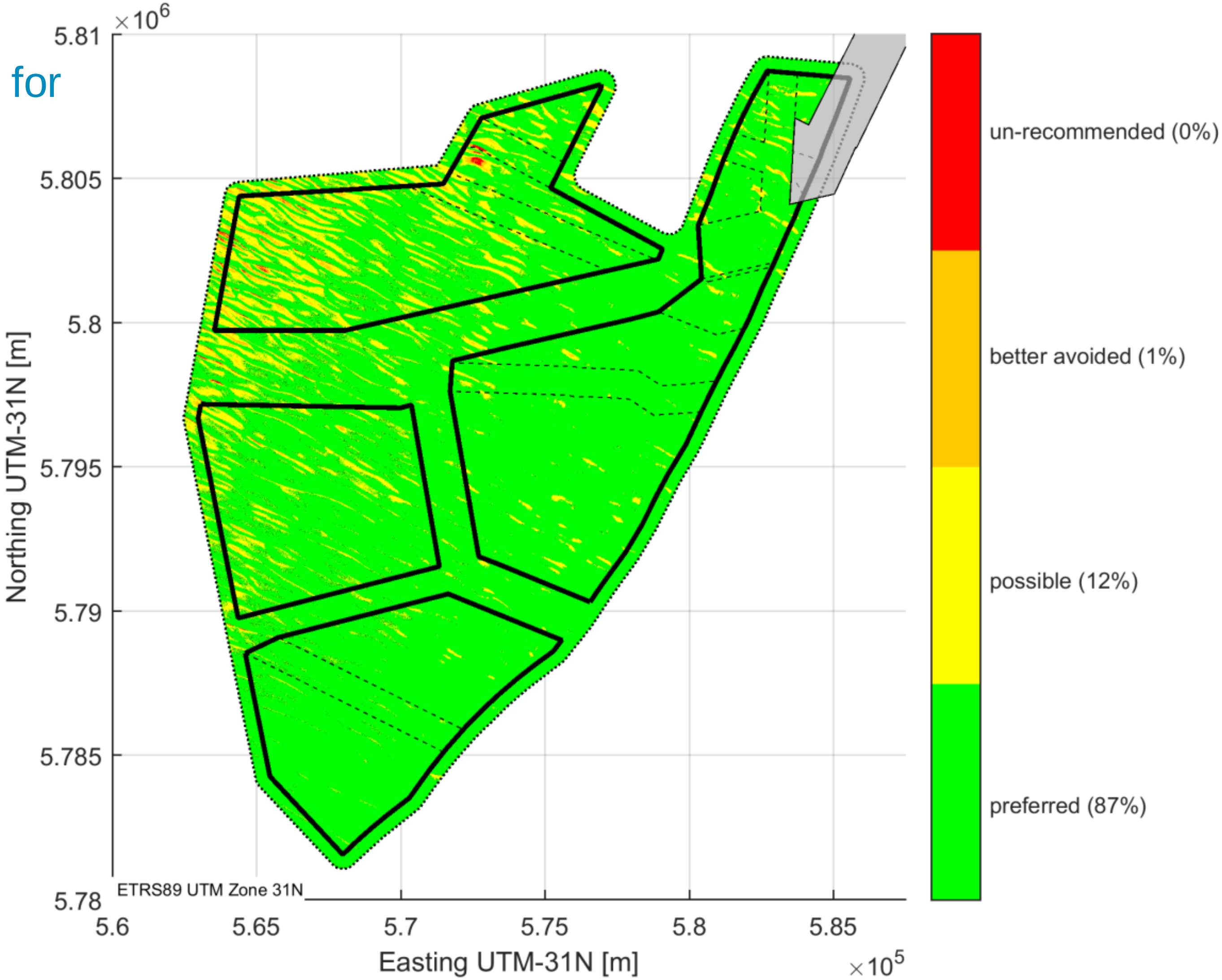
# Classification zones for HKZWFZ (lowering only)

For the assumed criteria for lowering only:

- 87% = preferred
- 1% = better avoided or un-recommended

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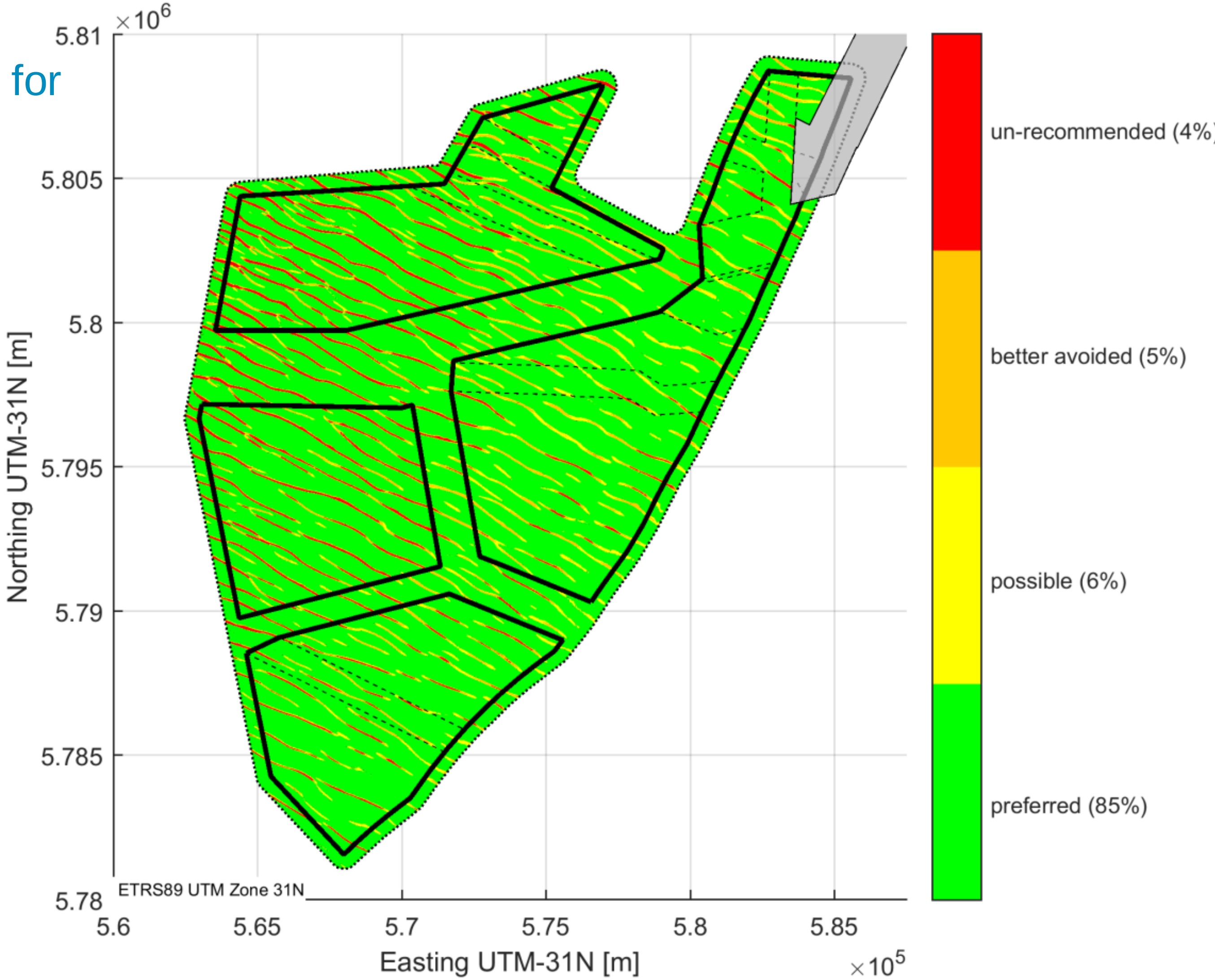
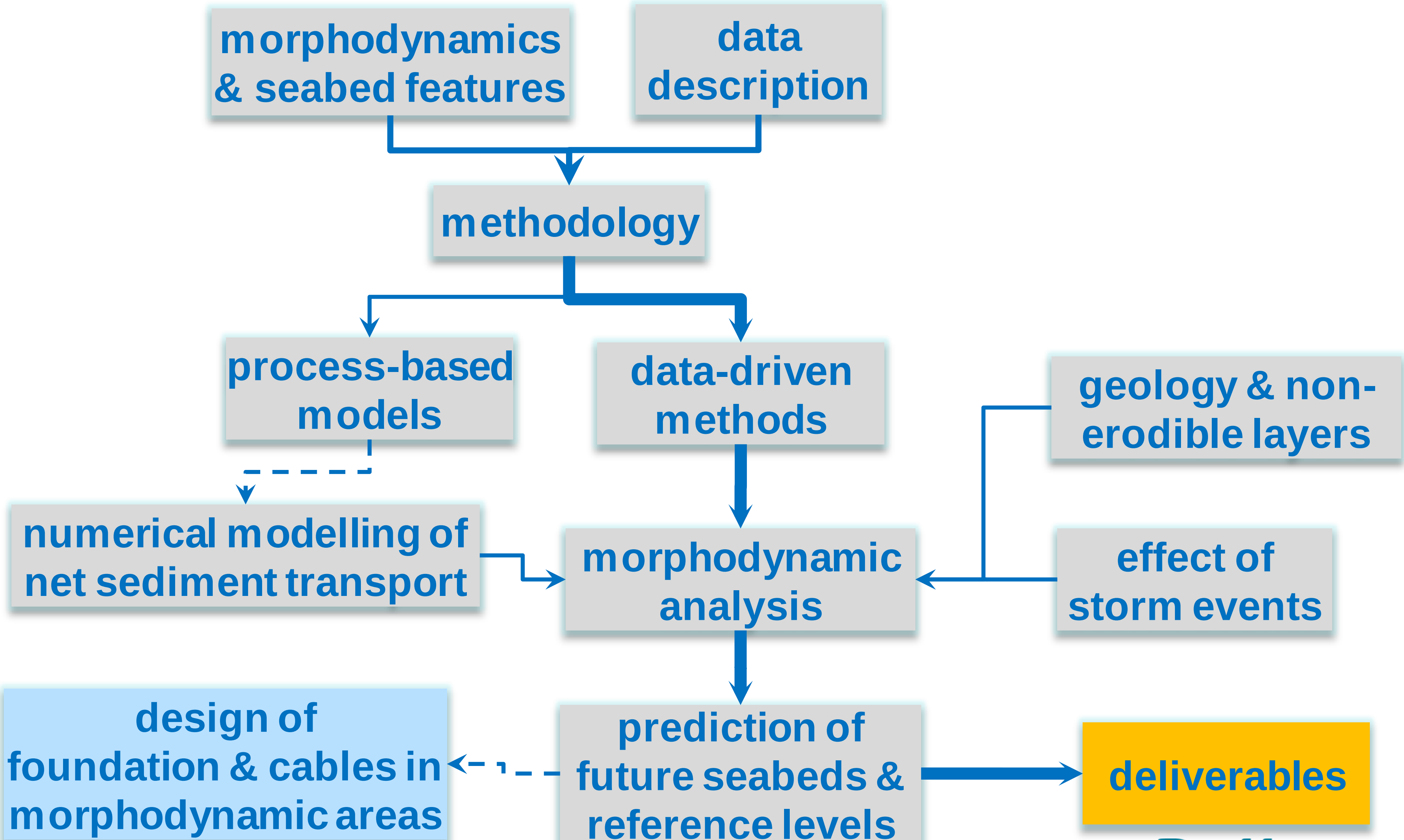
# Classification zones for HKZWFZ (rising only)

For the assumed criteria for lowering only:

- 85% = preferred
- 9% = better avoided or un-recommended



# Structure of presentation

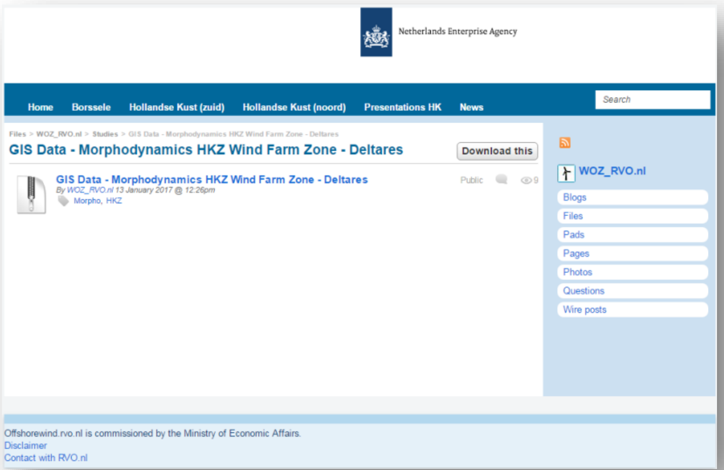


# GIS database

The following GIS-data are provided on the RVO-website (along with the report and this webinar):

- ✓ for time spans of 5 year
- ✓ within the period of 2016-2056

- ➢ Best Estimate Bathymetry (BEB)
- ➢ Lowest SeaBed Level (LSBL)
- ➢ Highest SeaBed Level (HSBL)
- ➢ Classification zones for wind farm design based on:
  - seabed lowering
  - seabed rising
  - combined lowering and rising (for the period 2016 – 2051 only)


http://offshorewind.rvo.nl/file/view/48064122/gis-data-morphodynamics-hkz-wind-farm-zone-deltares

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- ➢ Classification zones for wind farm design based on:
  - seabed lowering
  - seabed rising
  - combined lowering and rising (for the period 2016 – 2051 only)

**Example**

$BEB_{2031}$ = the predicted bathymetry with the smallest overall error when compared with the actual, surveyed bathymetry in 2031.

> Do not use for design of foundations and cables, but to assess O&M costs

**Example**

$LSBL_{2031}$ = the lowest seabed that can occur between 2016 and 2031 (lower envelope)

> Use LSBL and HSBL for design of foundations and cables

http://offshorewind.rvo.nl/file/view/48064122/gis-data-morphodynamics-hkz-wind-farm-zone-deltares

# Conclusions (I)

- The bathymetry in HKZWFZ has a relatively uniform morphology without prominent sand banks or other large-scale features
- The large-scale seabed is considered to be static over the lifetime of the wind parks to be developed in the area (negligible changes in 15 years)
- The sand waves are (mostly) mobile, have an average length of 511m, average height of 2.3m and typical migration speeds are in the order of 1.7 m/yr in north-northeastern direction

| Wind Farm Sites (WFS) | Sand wave height non-exceedance (2016) [m] | | Sand wave length non-exceedance (2016) [m] | | Migration speed [m/yr] in most frequently observed direction 28°N | |
|---|---|---|---|---|---|---|
| | 50% | 90% | 50% | 90% | 50% | 90% |
| WFS-I | 2.5 | 4.0 | 427 | 708 | 2.0 | 2.5 |
| WFS-II | 2.7 | 3.9 | 503 | 757 | 1.5 | 2.0 |
| WFS-III | 2.3 | 3.3 | 578 | 918 | 1.2 | 1.6 |
| WFS-IV | 1.9 | 2.7 | 631 | 950 | 1.5 | 2.6 |
| Combined HKZWFZ | 2.3 | 3.7 | 511 | 832 | 1.7 | 2.3 |

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



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# Conclusions (II)

- Seabed changes are computed for a range of predictions of sand wave migration (3 migration directions x 3 migration speeds)
- Lowest SeaBed Level (LSBL) and Highest SeaBed Level (HSBL) are determined.
- This results in maximum potential seabed lowering and rising until 2051
- Classification Zones (*preferred / possible / better avoided / unrecommended*) are determined based on estimated ranges for downward and upward seabed changes



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# Recommendations for design

## A. Further improve accuracy of morphodynamic predictions:

- In case of an additional pre-installation survey (~2020): re-run analysis and further narrow down uncertainty ranges, which can still be beneficial for scour mitigation strategy and/or cable burial depth

## B. Include morphodynamic activity in wind farm design:

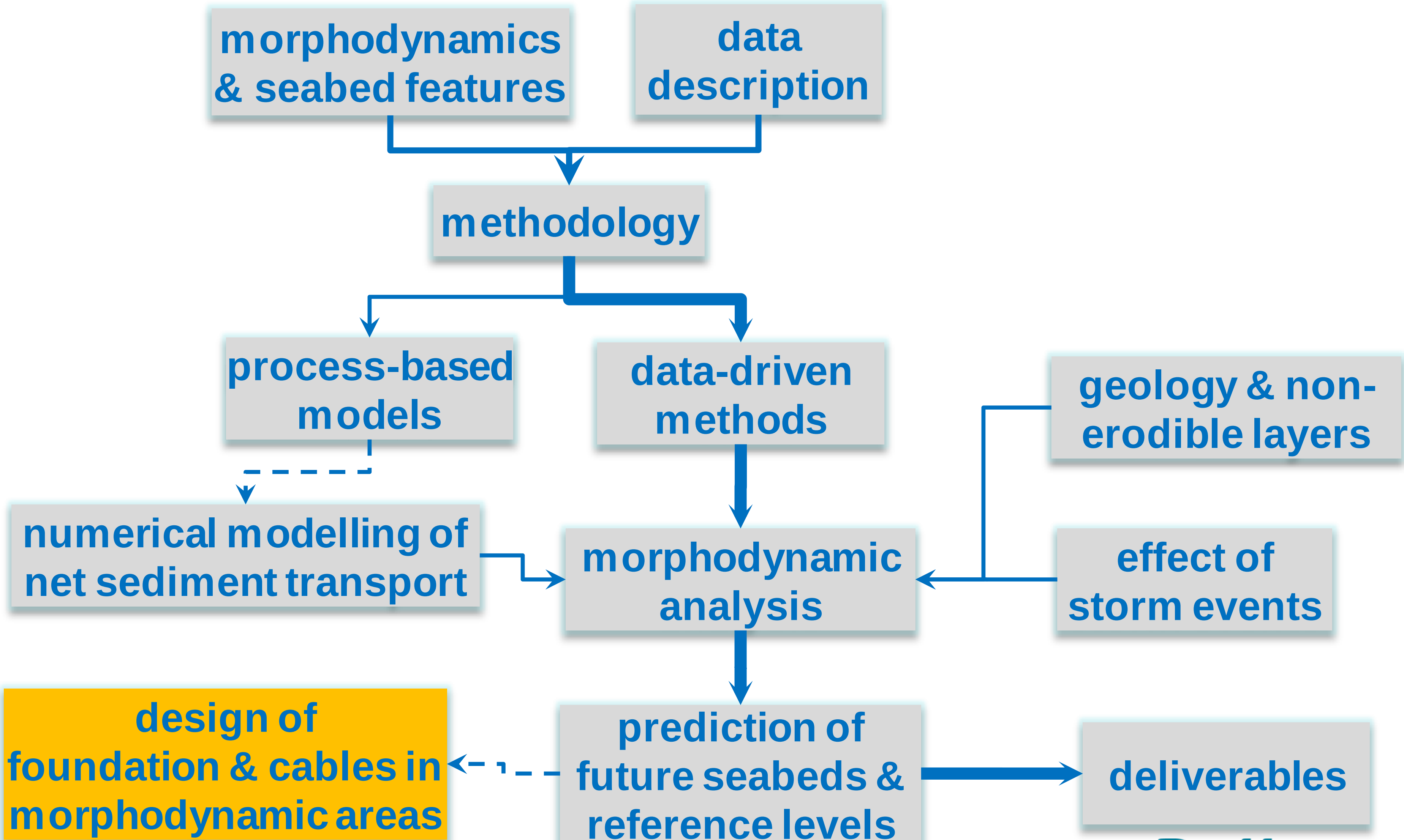
- Take predicted morphodynamic seabed changes into account in determining WTG-locations and cable trajectories
- Consider morphodynamic changes in combination with scour mitigation strategy
- Deploy continuous cable burial depth monitoring system coupled with morphodynamic prediction model to guarantee cable safety

# Key take-aways

- Sand waves are the dominant seabed features
- Sand waves in HKZ have a medium size and migrate with moderate speed & ~constant direction
- Future seabed levels are well predictable
- A sufficiently large area is available for foundations and cables, when considering morphodynamics


more information? tim.raaijmakers@deltares.nl

# Structure of presentation

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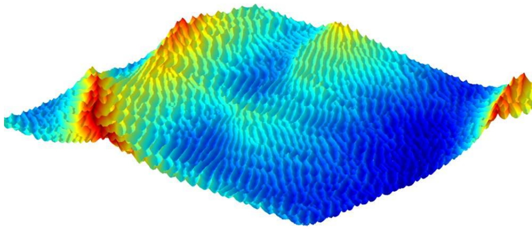
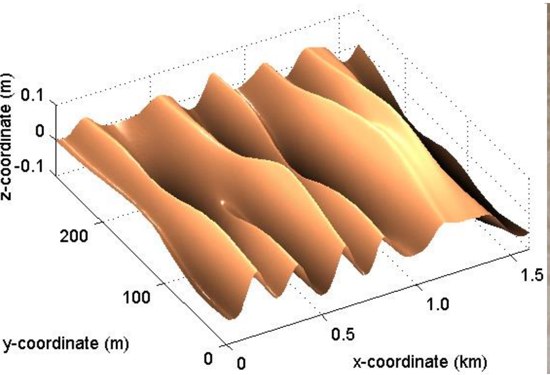
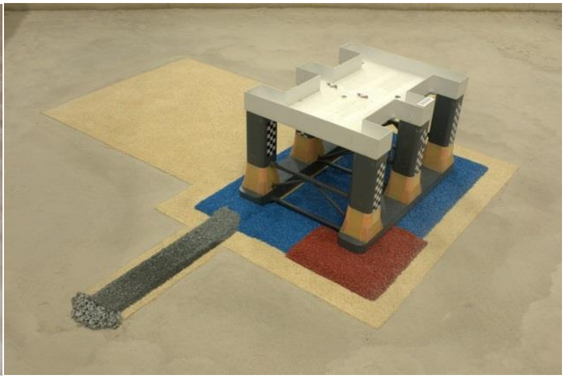
# Wind farm design in morphodynamic areas

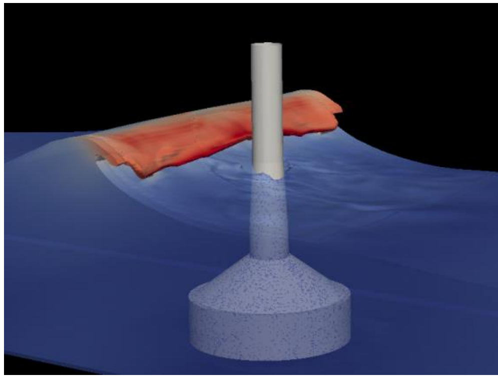


Some tips and tricks for dealing with morphodynamics in windfarm design
*(outside the scope of the morphodynamics study for RVO)*

- Foundations in a morphodynamic environment
- Cable routing in a morphodynamic environment





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# Scour mitigation in morphodynamic areas

Besides autonomous large-scale morphological developments which cause "global" bed level changes, scour (i.e. local erosion around foundation) will develop around the foundations.

The following scour mitigation strategies can be followed:

1. Allow scour development and take lowering of pile fixation into account in design: lowering = morphological lowering + scour

2. Apply scour protection around foundations and maintain initial pile fixation level: scour protection should deal with morphological lowering

3. Allow scour development to certain depth and then protect seabed: fixation level will be lower and scour protection has to deal with some lowering.

# Scour mitigation in morphodynamic areas

Besides autonomous large-scale morphological developments which cause “global” bed level changes, scour (i.e. local erosion around foundation) will develop around the foundations.

The following scour mitigation strategies can be followed:

1. Allow scour development and take lowering of pile fixation into account in design: lowering = morphological lowering + scour

   **Most logical option in areas where small scour is predicted**

2. Apply scour protection around foundations and maintain initial pile fixation level: scour protection should deal with morphological lowering

   **Most logical option in areas where large scour is predicted and potential morphological seabed lowering is limited**

3. Allow scour development to certain depth and then protect seabed: fixation level will be lower and scour protection has to deal with some lowering.

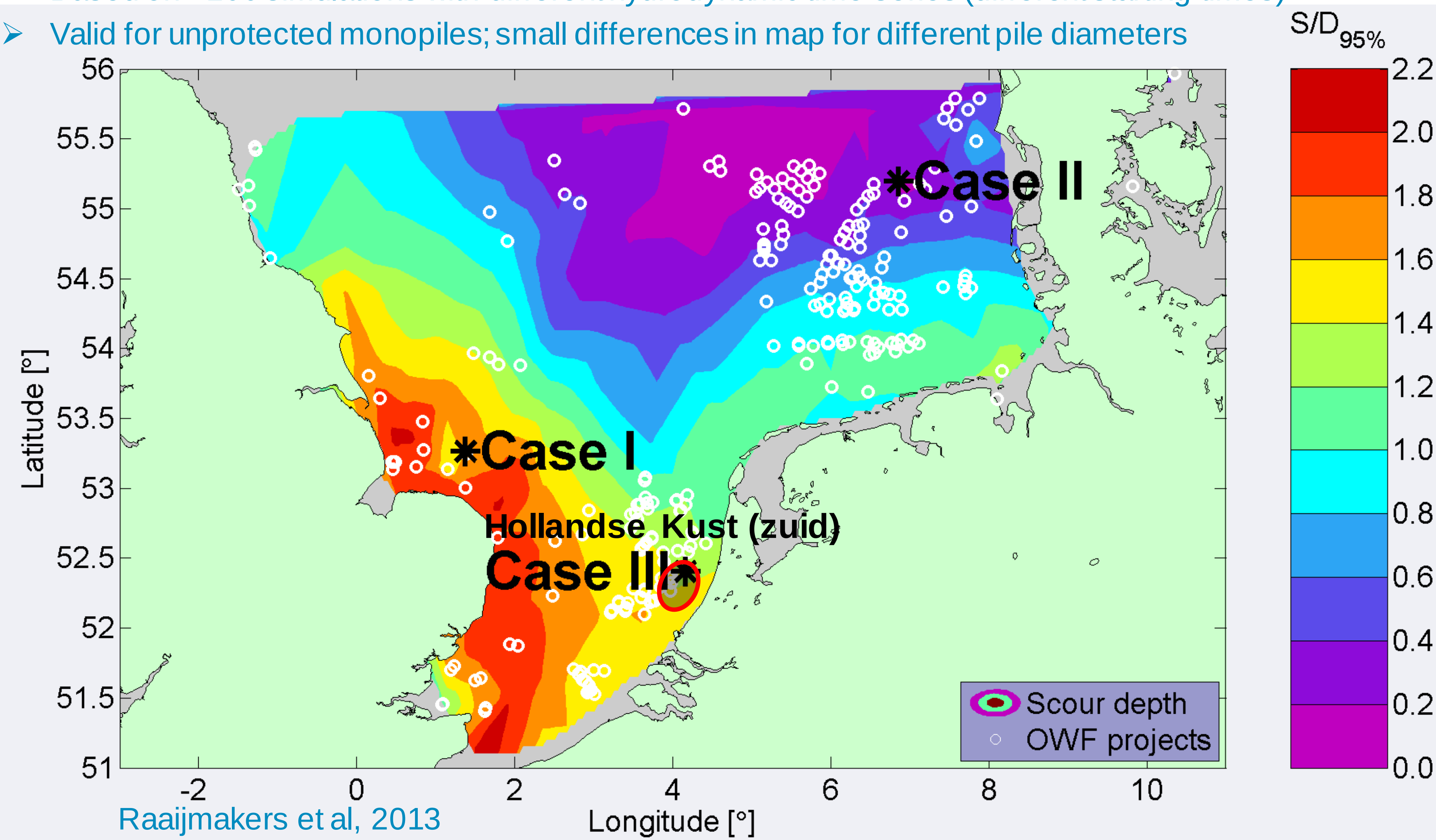
   **Most logical option in areas where large scour and large morphological seabed lowering is predicted**

# Strategy 1: predicting scour development

**Example of scour prediction for monopiles (example for $D_{pile}$ = 6m)**

Model assumptions:

- Non-cohesive soil (= sandy seabed): so model is conservative in areas where cohesive soil is present
- Based on >100 simulations with different hydrodynamic time series (different starting times)
- Valid for unprotected monopiles; small differences in map for different pile diameters



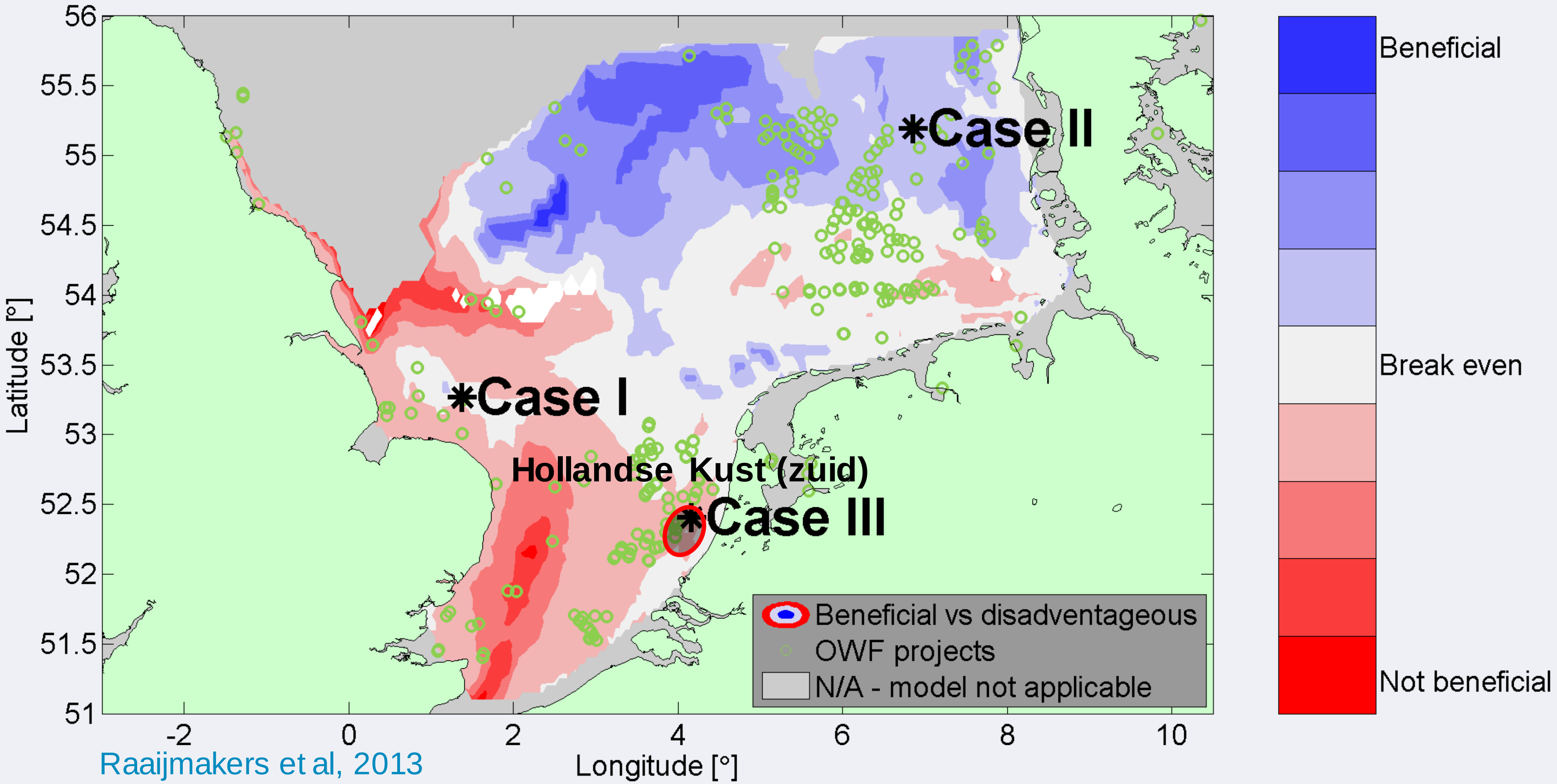

Raaijmakers et al, 2013

# Scour: to protect or not to protect?

Cost of scour protection vs. additional steel (example for monopiles)

Blue colours mean there is a real potential for leaving out the scour protection

In Hollandse Kust (zuid) installing scour protection is most likely more cost-efficient.

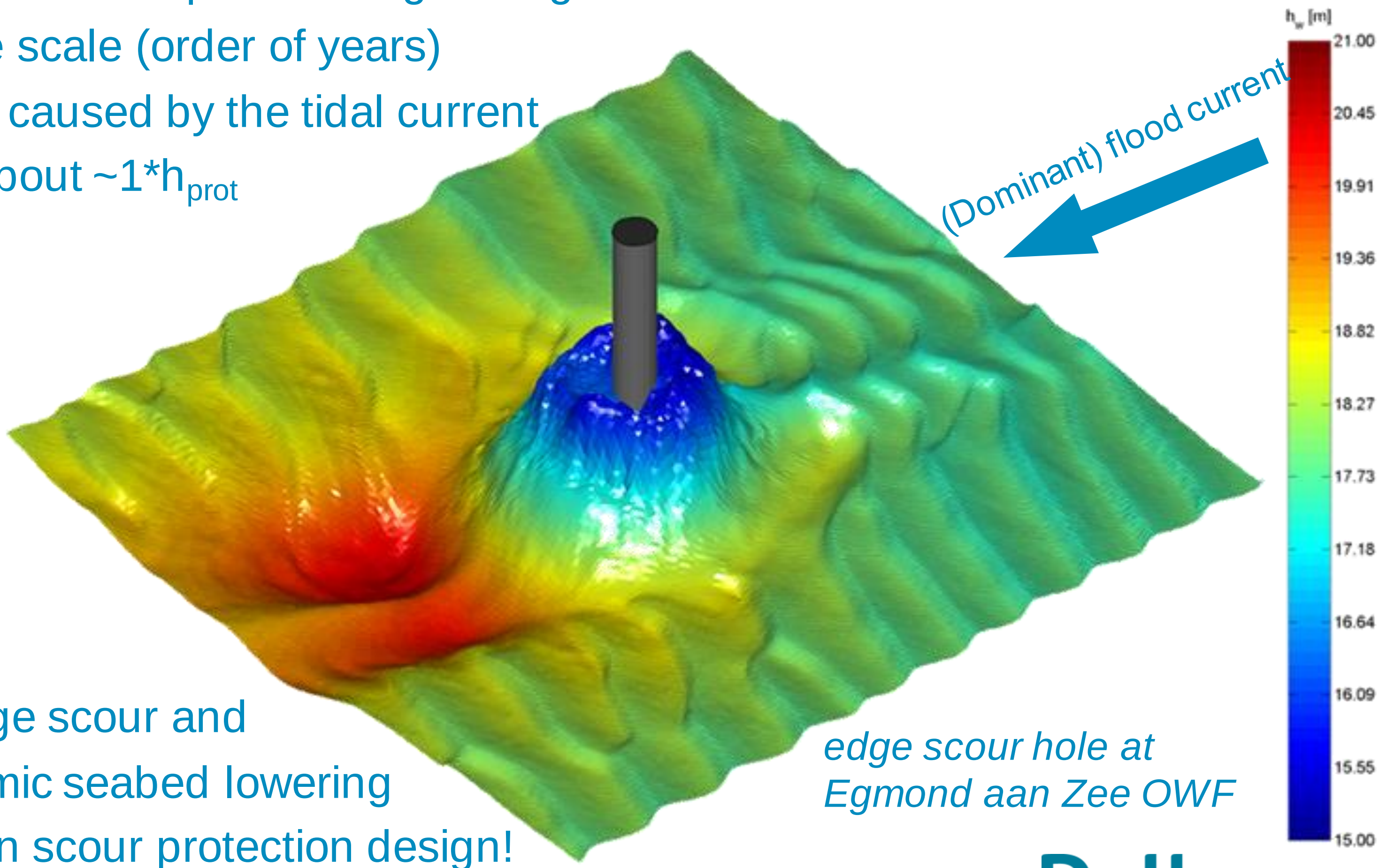



Raaijmakers et al, 2013

# Strategy 2: Considering edge scour around protections

- Strategy 2: a scour protection is installed around the foundations
- But even if a scour protection is in place

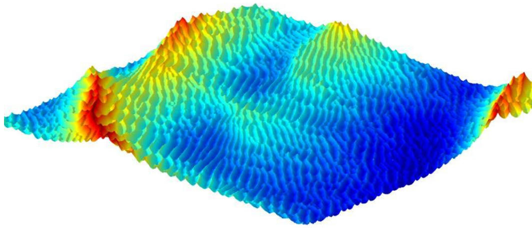
  .... still scour will develop at the edges: edge scour
- At slower time scale (order of years)
- Edge scour is caused by the tidal current
- Depth up to about ~1*$h_{prot}$




*edge scour hole at Egmond aan Zee OWF*

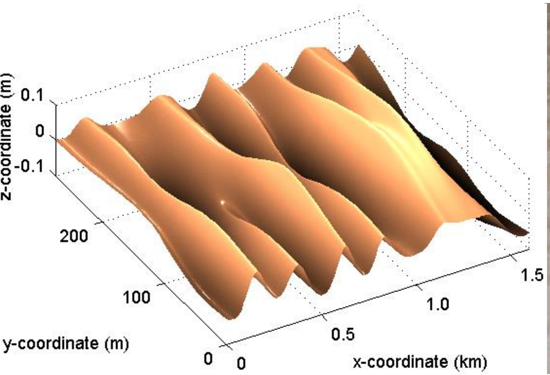
- Take both edge scour and morphodynamic seabed lowering into account in scour protection design!

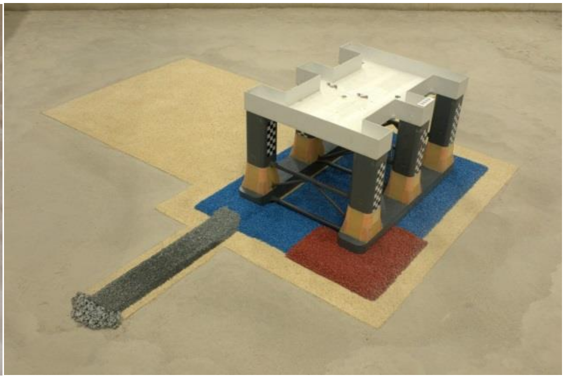
# Contents of presentation

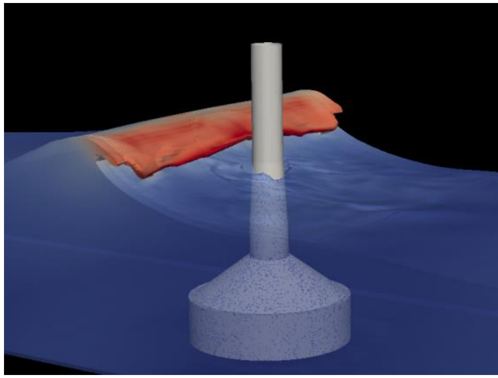


Some tips and tricks for dealing with morphodynamics in windfarm design
*(outside the scope of the morphodynamics study for RVO)*

- Foundations in a morphodynamic environment
- Cable routing in a morphodynamic environment





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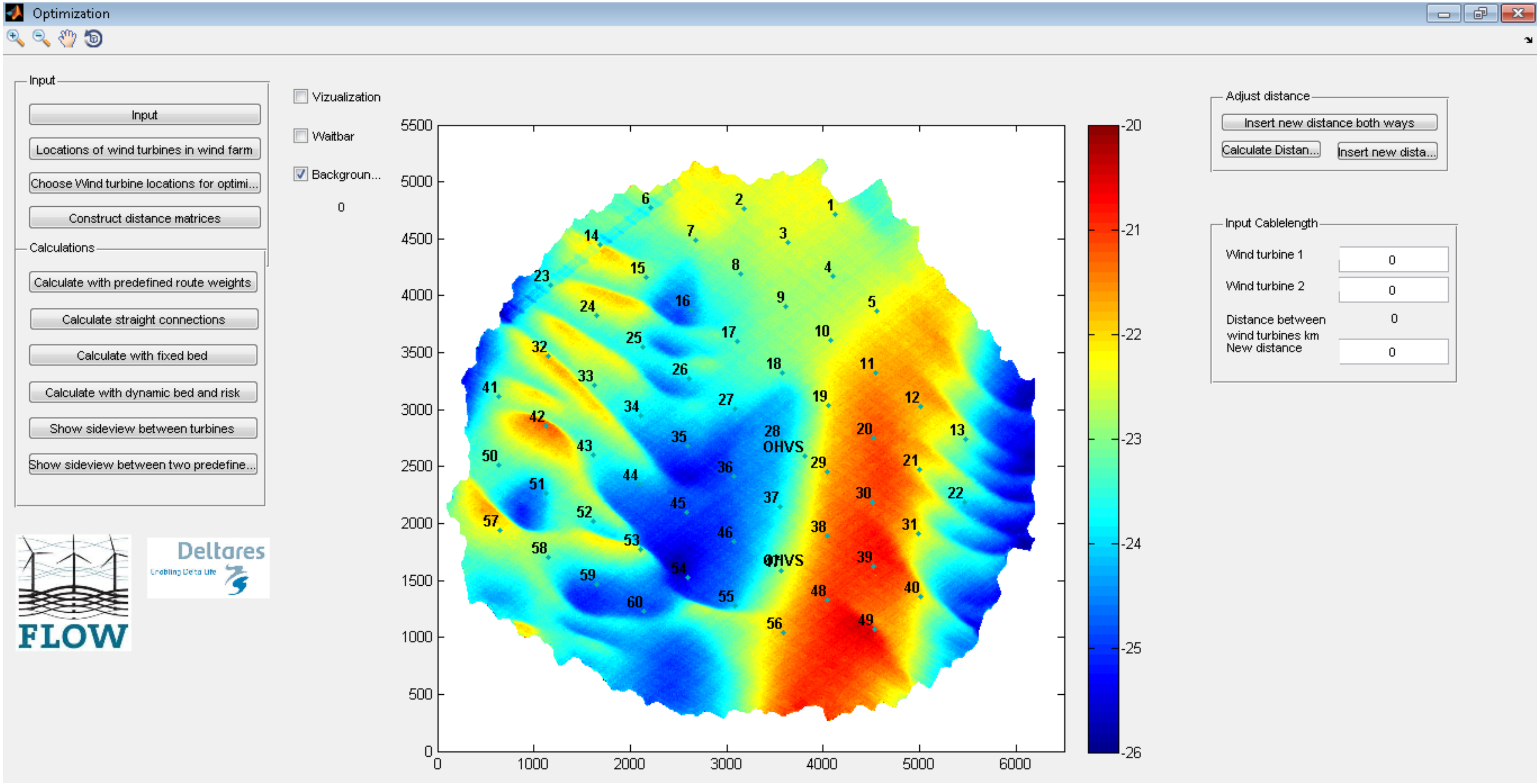
# Cable route optimization tool (I)

## Case study based on re-design of cable layout of Prinses Amalia Wind Park



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# Cable route optimization tool (II)

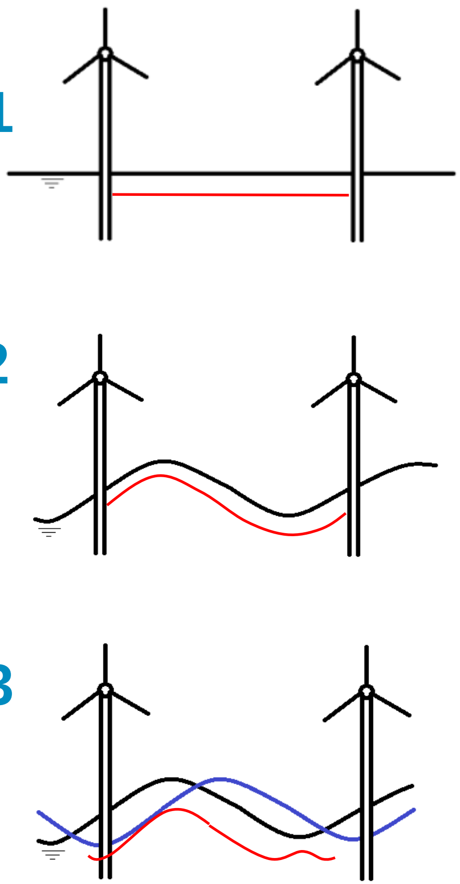
## Optimizing the cable routes both horizontally and vertically

Taking into account seabed morphodynamics, effect on risks (e.g. anchors in case of limited burial depth) and potential costs related to failure and repair

1

2

3



1. Optimization under a flat bed → 2. Optimization under a static bed

Construct distance matrix → Greedy algorithm → Genetic algorithm → Determine wind farm cable layout → 3. Optimization under a dynamic bed

3. Optimization under a dynamic bed → Development of cost function → Vertical optimization / Dijkstra's algorithm → Horizontal optimization

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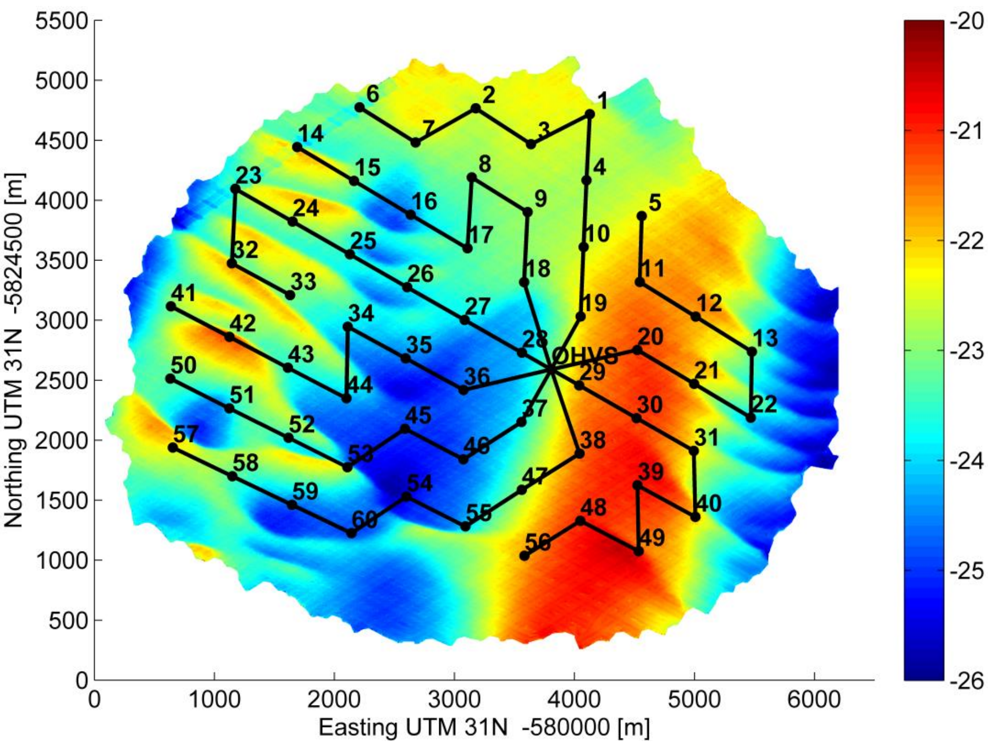
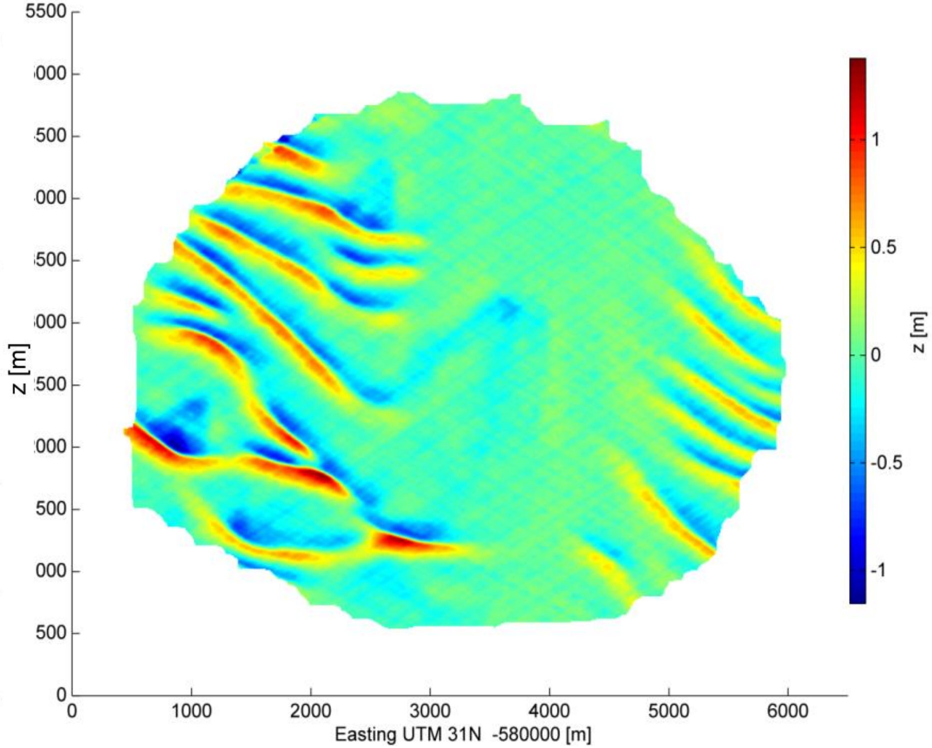
# Cable route optimization tool (III)

## Case study based on re-design of cable layout of Prinses Amalia Wind Park

2013 bathymetry




seabed changes in period 2003-2013



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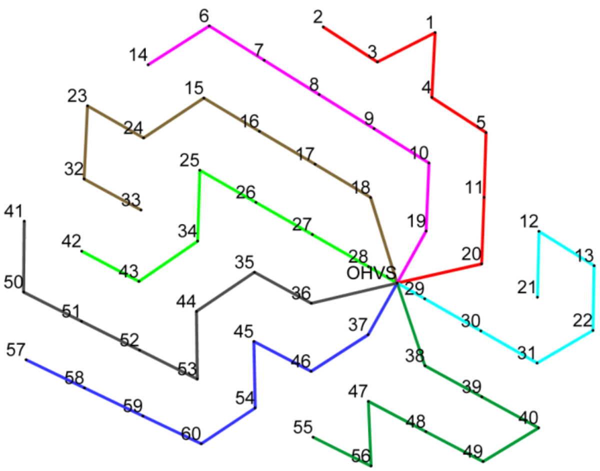
# Cable route optimization tool (IV)

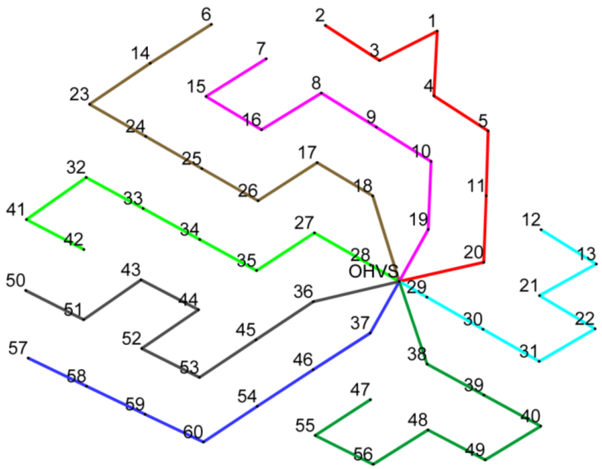
## Case study based on re-design of cable layout of Prinses Amalia Wind Park

Examples of cable routes based on different assumptions on seabed

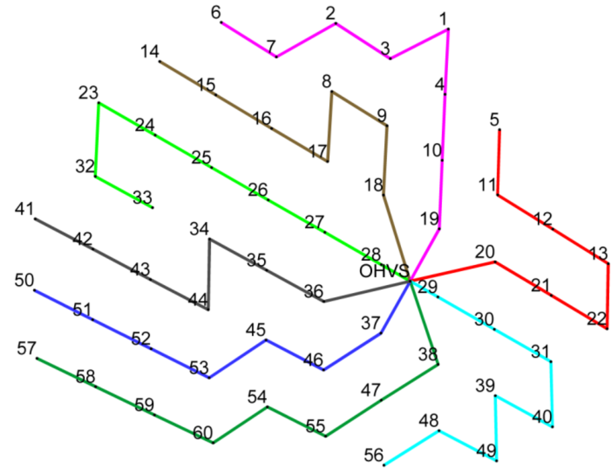
flat seabed assumption




static seabed assumption




actual layout

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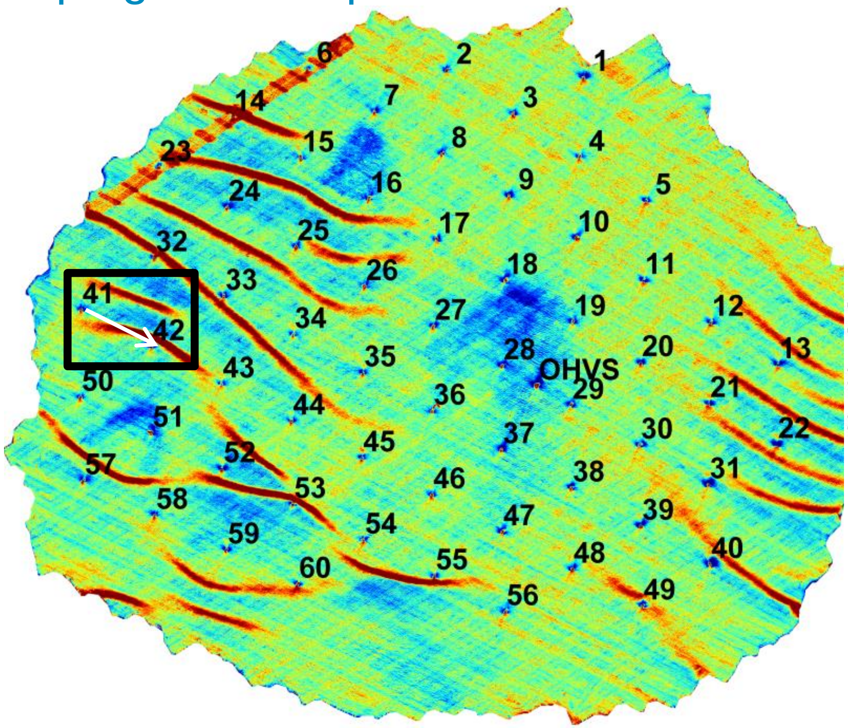
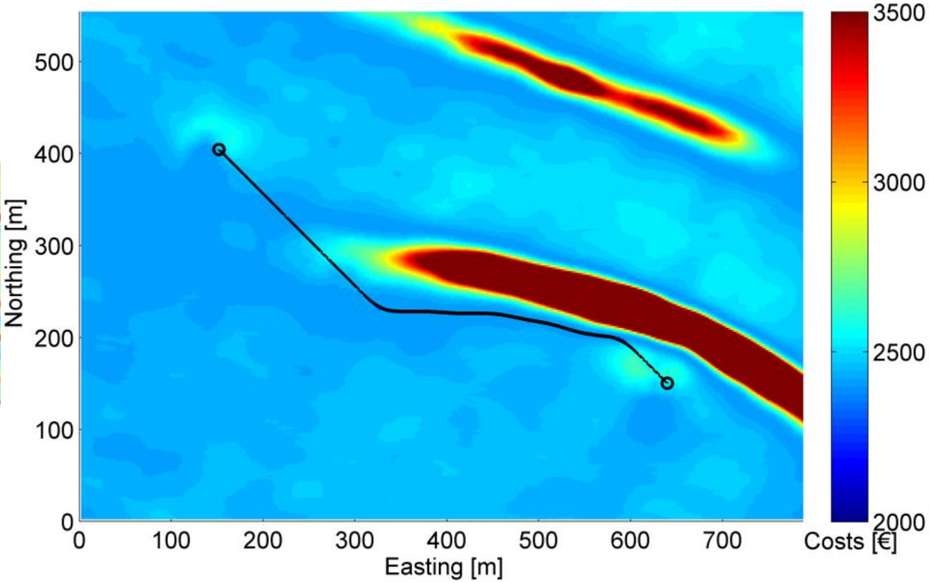
# Cable route optimization tool (V)

**Case study based on re-design of cable layout of Prinses Amalia Wind Park**

Example: horizontal micro-optimization of individual cable stretches
Optimization for dynamic seabed, avoiding areas with high costs
keeping burial depth fixed at 1.5m

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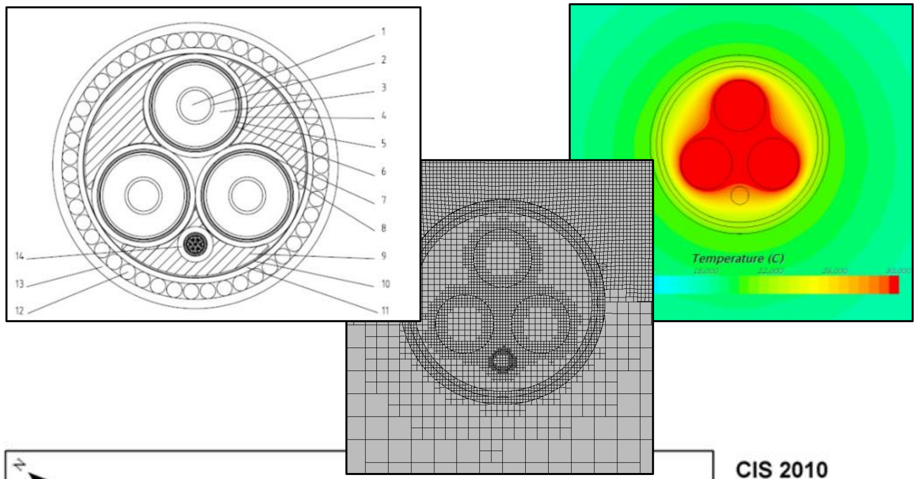
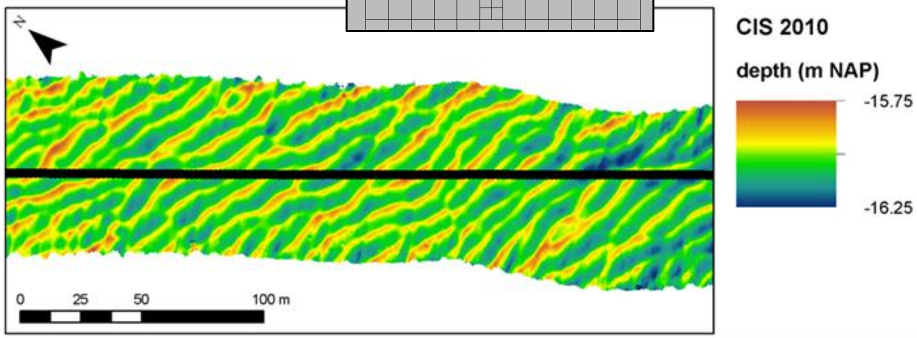
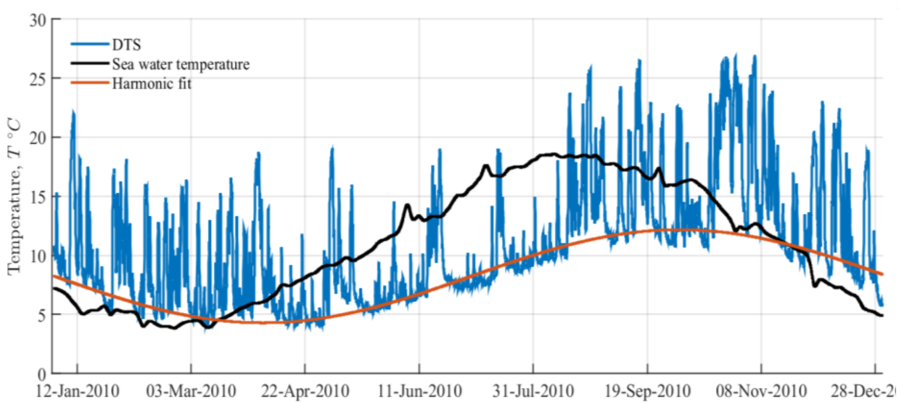
# Continuous monitoring of cable burial depth

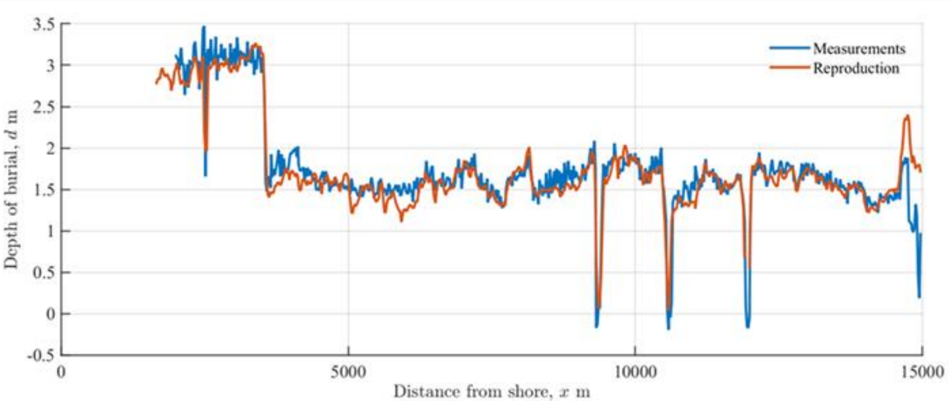
1. Real time cable burial depth monitoring
   Coupling between:
   - ➢ Distributed Temperature Sensing (DTS)
   - ➢ Power throughput
   - ➢ Water temperature
   - ➢ Morphodynamics overlying cable

2. Forecasting morphology by:
   - ➢ Data-driven Fourier analysis
   - ➢ Numerical modelling in Delft3D



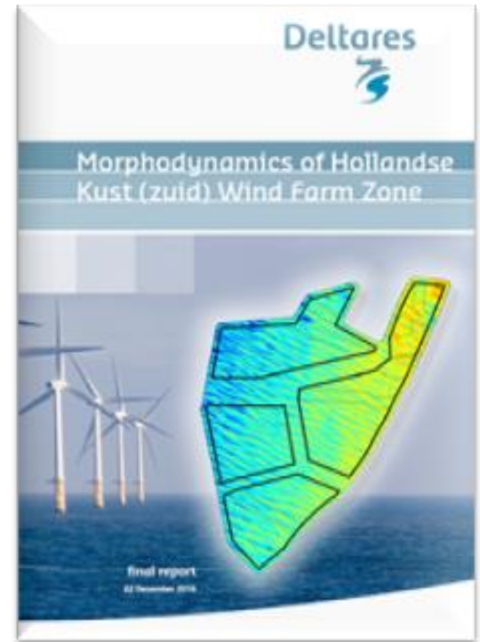
## Key take-aways

Sand waves are the dominant seabed features

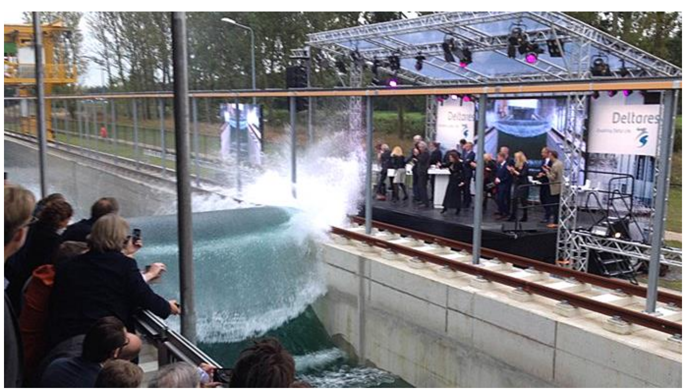
Sand waves in HKZ have a medium size and migrate with moderate speed & ~constant direction

Future seabed levels are well predictable

A sufficiently large area is available for foundations and cables, when considering morphodynamics




more information? tim.raaijmakers@deltares.nl



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