
Rijksdienst voor Ondernemend
Nederland

Deltares

# Morphodynamics and Scour Mitigation for Hollandse Kust (noord)

Presenters:

Tom Roetert - *Morphodynamics specialist*
Tim Raaijmakers - *Scour mitigation specialist*


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# Introduction to webinar team

Presenters:

Tim Raaijmakers
*Senior researcher/advisor, Programme Manager Offshore Engineering at Deltares*
*PhD researcher at TU Delft*
*Project Leader Scour and Scour Mitigation study HKN*

Tom Roetert
*Researcher/advisor Offshore Engineering at Deltares*
*Co-author of Morphodynamics and Scour Mitigation study HKN*

Moderators:

Cynthia Mors
*Senior advisor Renewable Energy, RVO.nl (NEA)*

Ben de Sonneville
*Manager Offshore Wind Energy, BLIX*

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# Objectives of the Morphodynamics and Scour Mitigation Study for Hollandse Kust (noord)

The objectives of this study are to:

- describe in detail the morphological seabed features in the wind farm zone HKN
- describe the shallow geological and sedimentological site conditions to a depth of 20m below the measured seabed level
- analyze / quantify the morphodynamics to determine future seabed levels  (2018-2058) and historic seabed levels (1945-2018)
- describe the scour conditions to be expected at HKN for typical wind farm-related structures*
- provide a state-of-the-art overview of scour mitigation measures and their applicability at HKN at these wind farm-related structures*
- provide guidance on how morphodynamics should be taken into account for the selection of the structure’s location and scour mitigation strategy

** Note that wind farm-related structure is here both interpreted as a wind turbine support structure and as an infield electricity cable. Offshore High Voltage Stations and the export cables are not considered part of the scope.*

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# Objectives of the Morphodynamics and Scour Mitigation Study for Hollandse Kust (noord)

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Part I

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Part II

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# 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
- open-source policy: “dare to share”

## Experimental facilities

Water

Subsoil

Data

**850+** employees

**40** nationalities

Offices in **Delft** and **Utrecht**

Region offices in **Singapore, Washington, Jakarta, Abu Dhabi**

# Overview 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

**Morphology & morphodynamics**

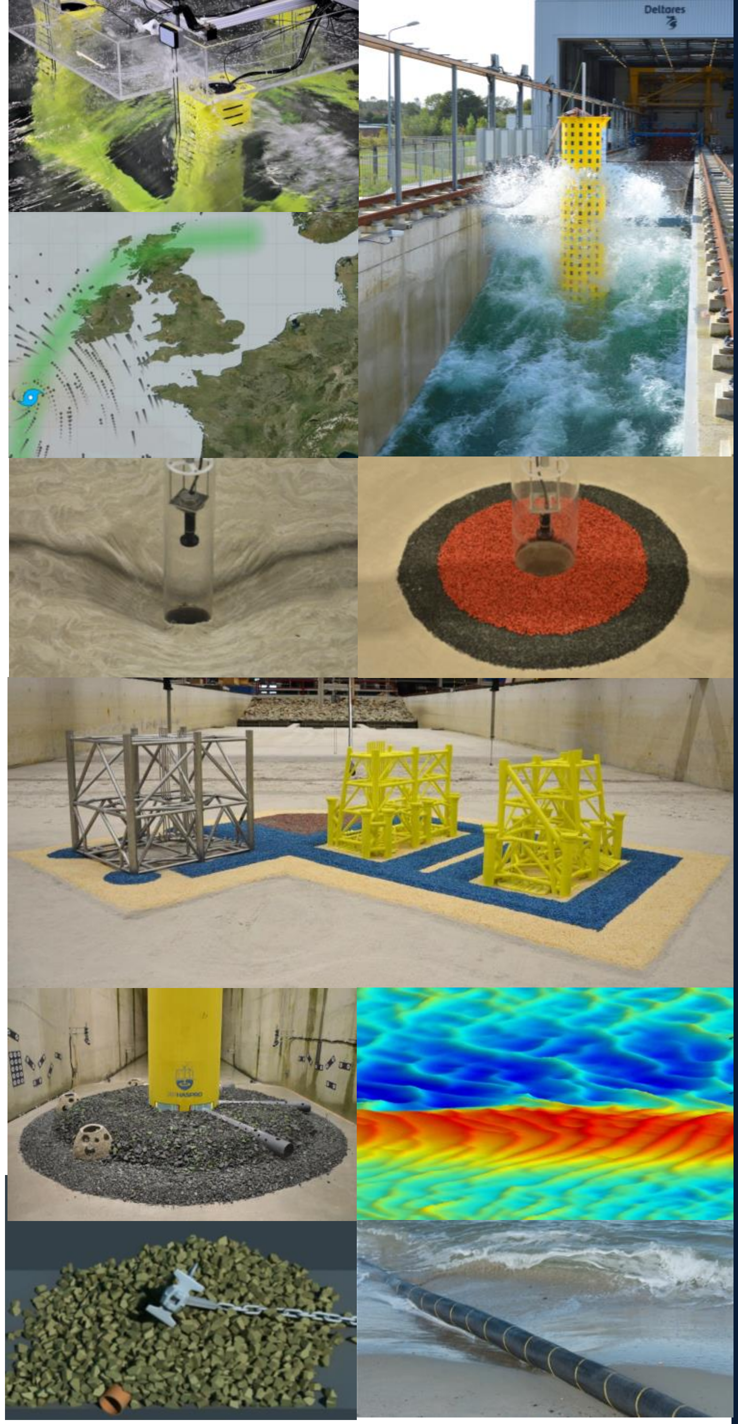
- Offshore geology, seabed characteristics
- Scour and scour protection for all types of foundations
- Bed level changes due to morphodynamics (e.g. sand waves)
- Cable routing and site selection in morphodynamic areas

**Geotechnics**

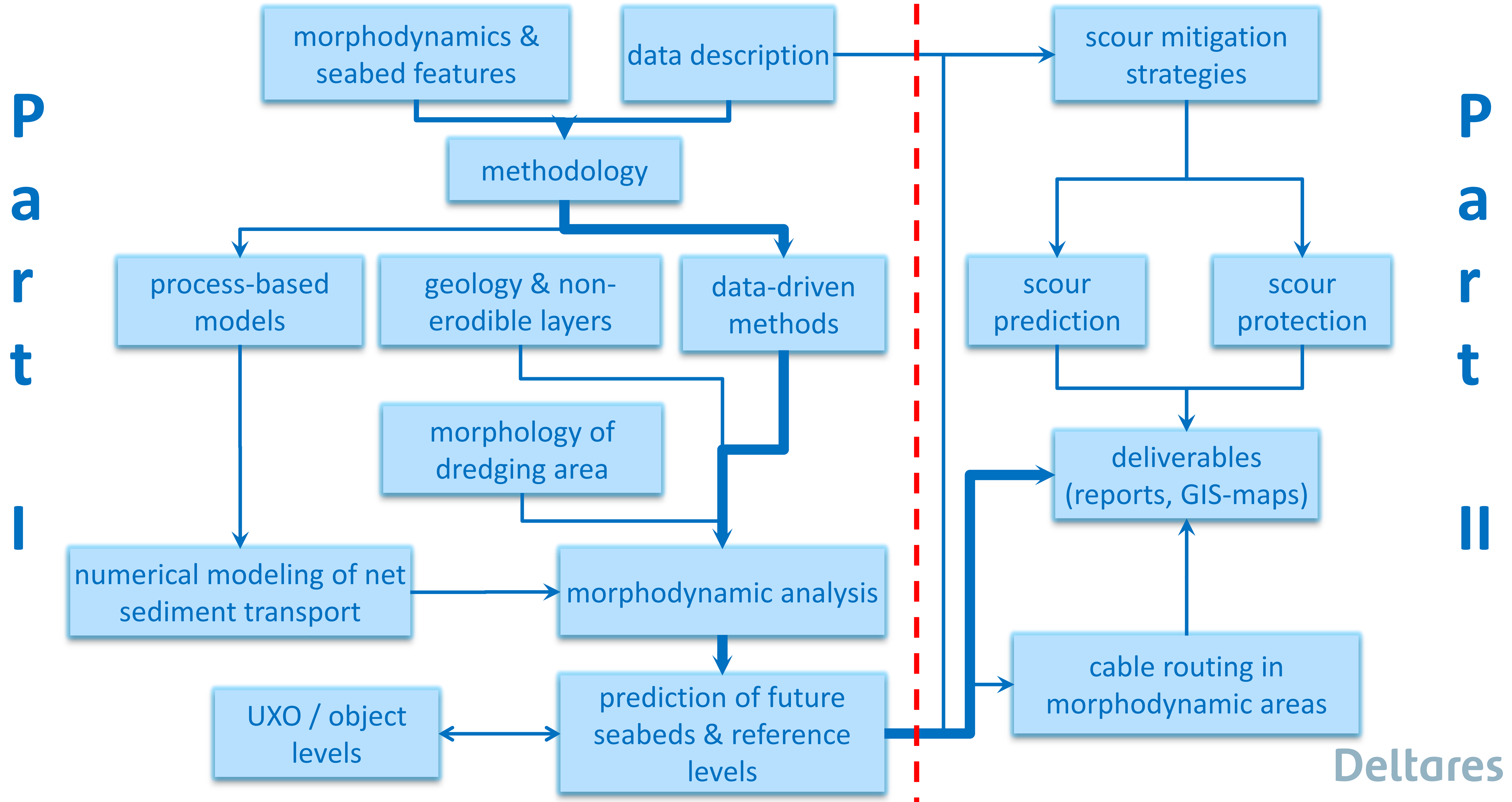
- Geotechnical design of foundations (e.g. cyclic liquefaction)
- Pile installation techniques (impact-driving, vibrating, alternatives)
- Cable burial techniques (jetting, ploughing, trenching, self-burial)
- External threats to electricity cables (anchors, fishnets, objects)

**Corrosion and biochemistry**

- Microbiologically Influenced Corrosion (MIC)
- Effectiveness of Cathodic Protection (CP) and coatings
- Effects of environmental conditions (e.g. flow, pH)



# Structure of presentation



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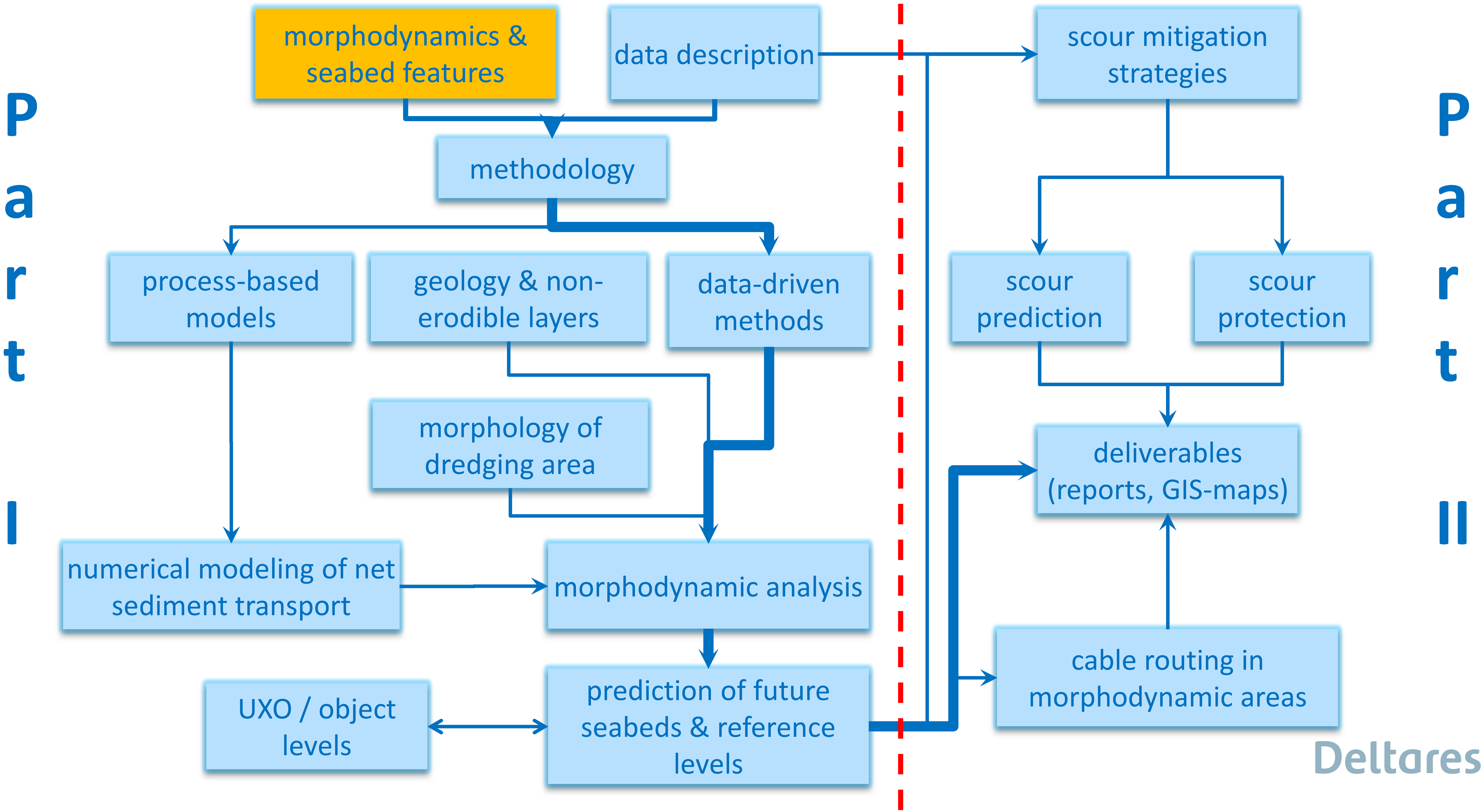
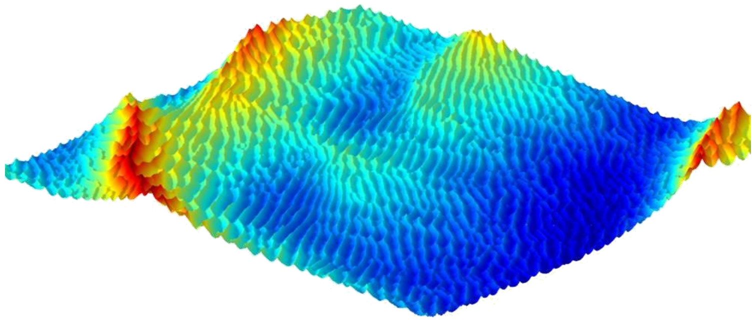


# Seabed Morphodynamics - definitions

*“**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]*



Typical offshore morphodynamic seabed features:

| | 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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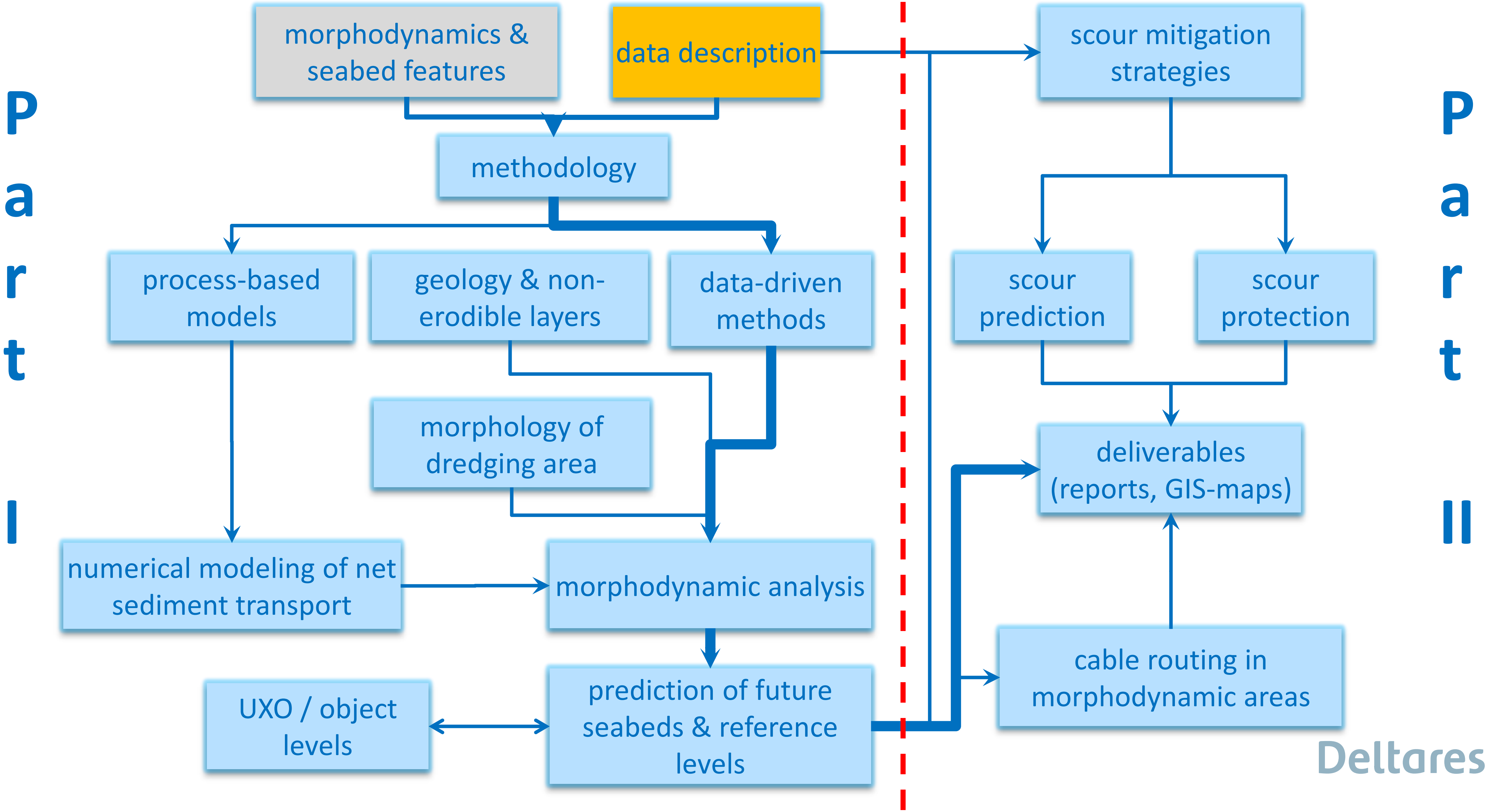


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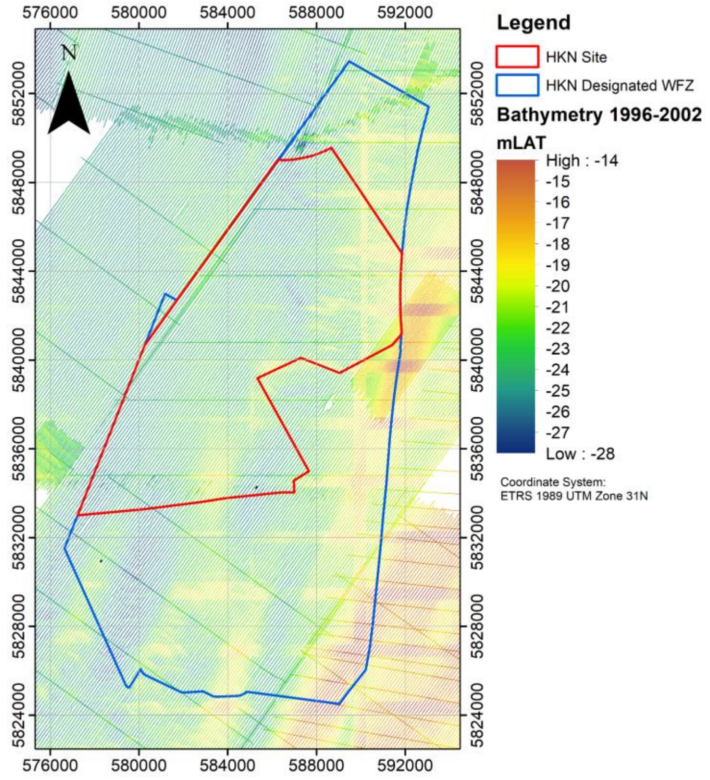
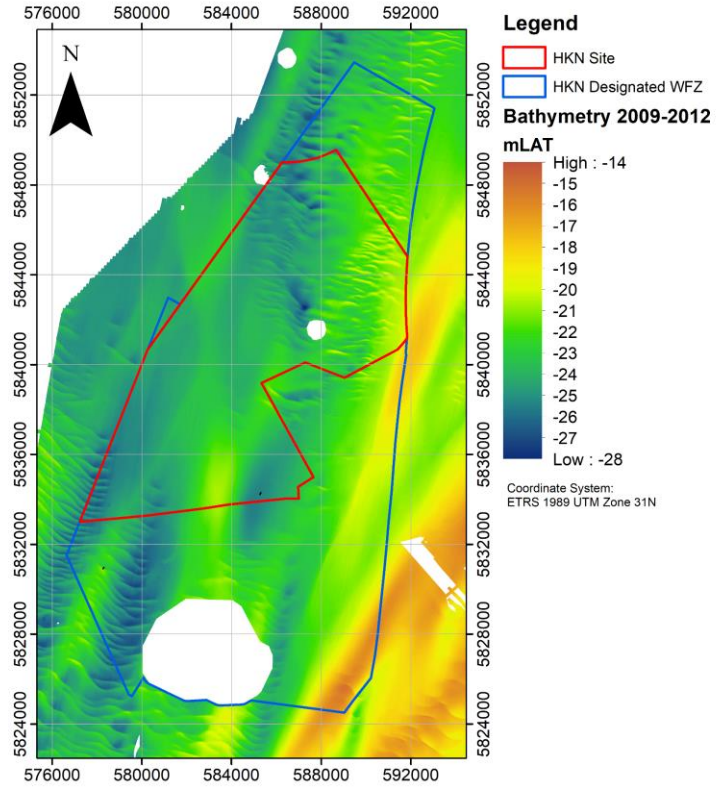
# Data description – (1996-2002) (2009-2012) (2017)

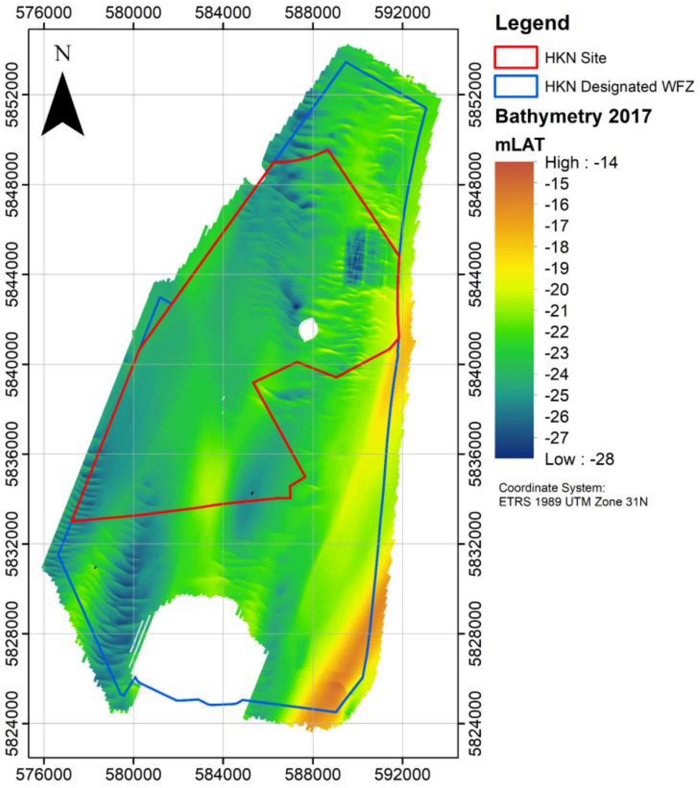
Bathymetry constructed of 6 SBES between 1996 and 2002, taken by the Netherlands Hydrographic Office of the Royal Netherlands Navy.




Bathymetry constructed of 5 MBES in 2009, 2011 and 2012, taken by the Netherlands Hydrographic Office of the Royal Netherlands Navy.




Bathymetry constructed of 1 MBES in 2017, taken by Fugro.



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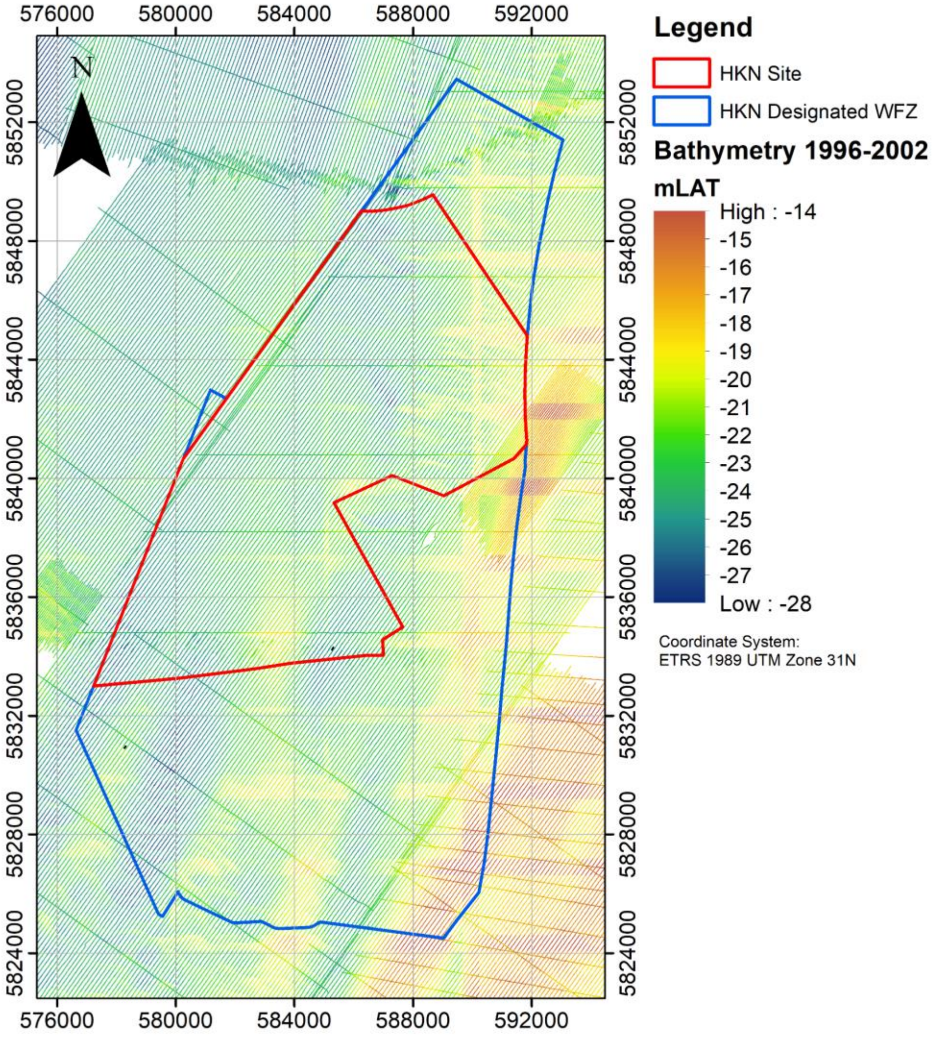


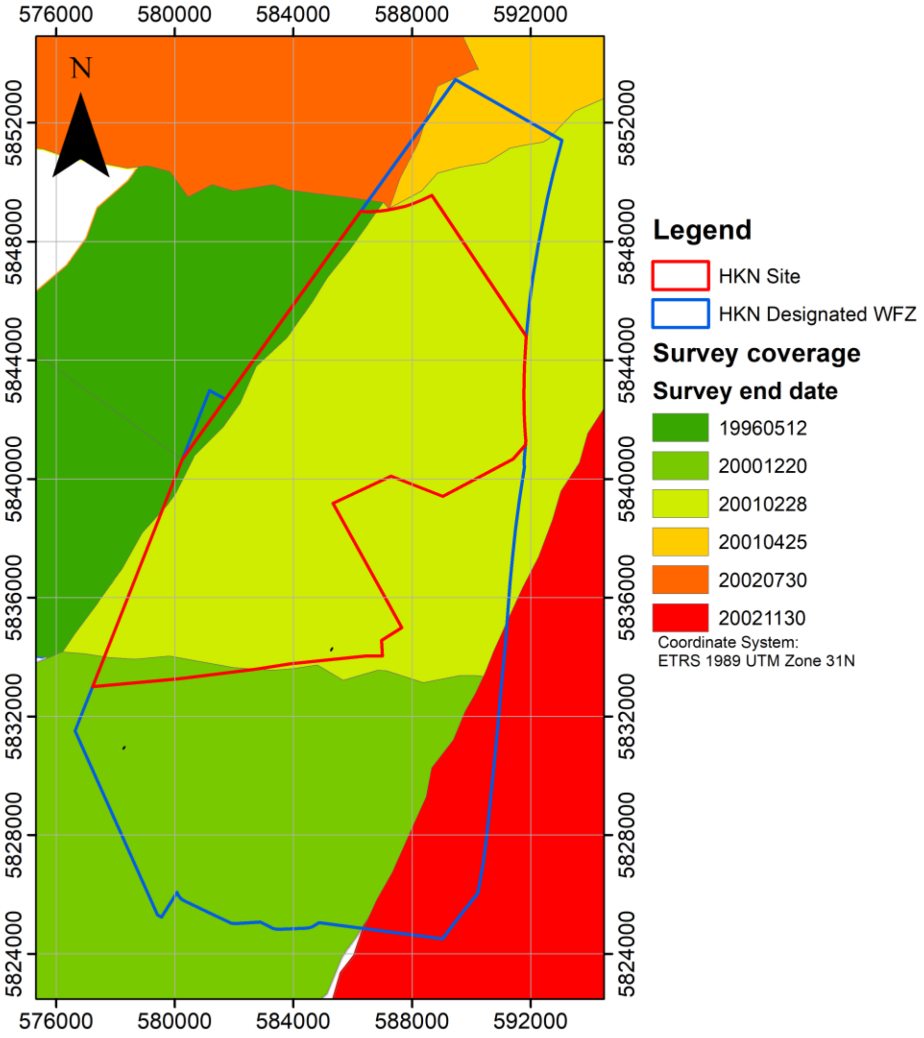

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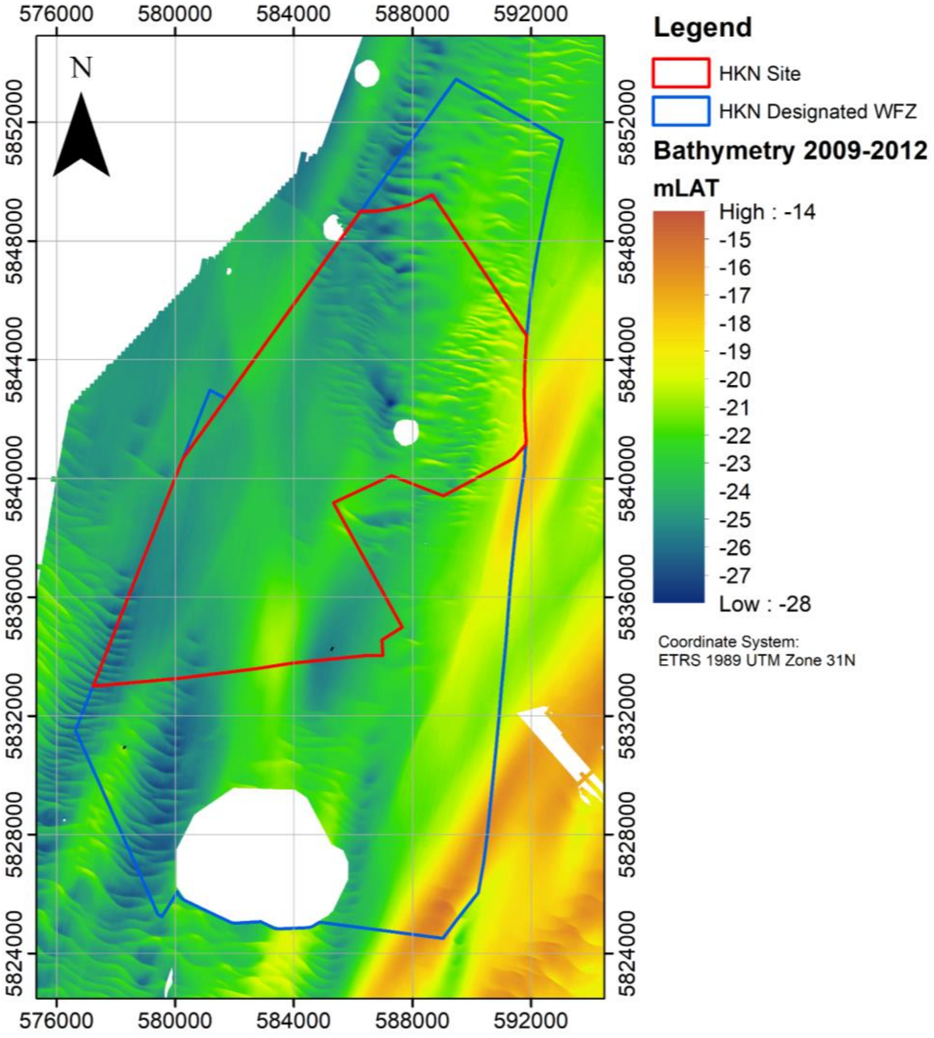


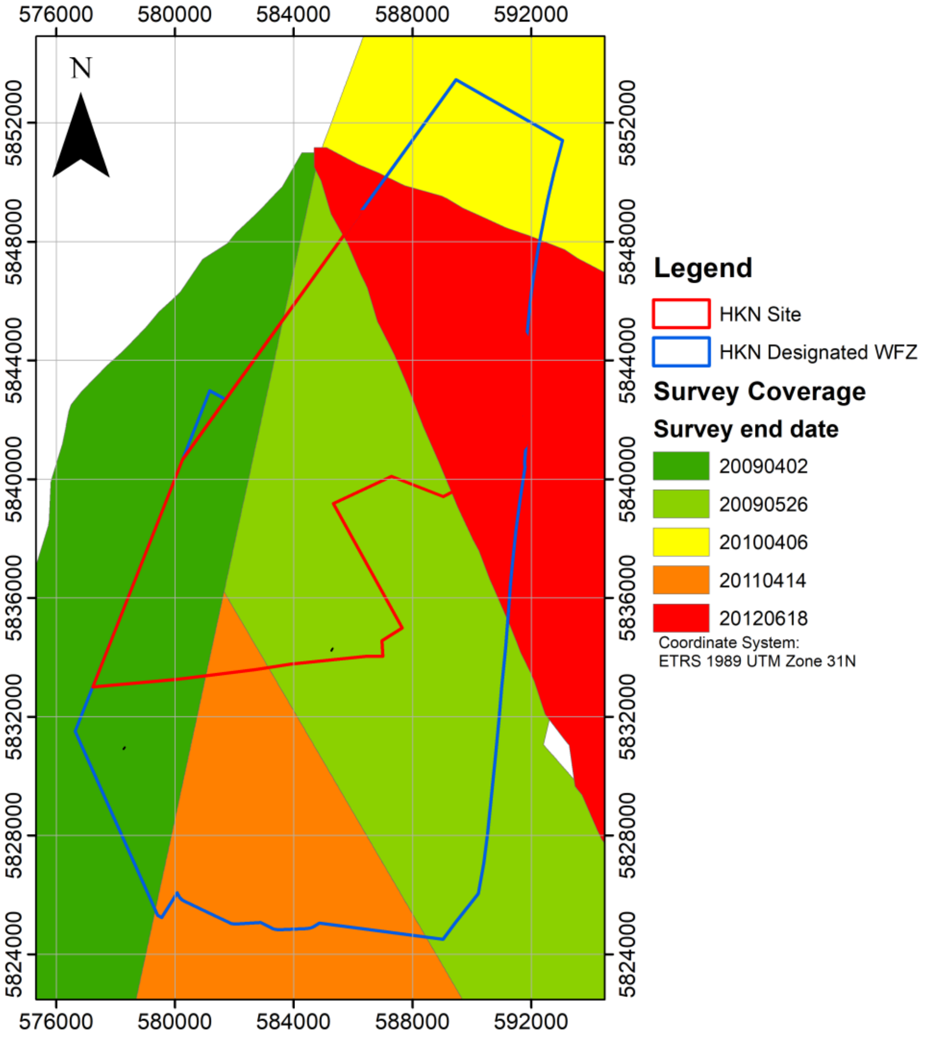

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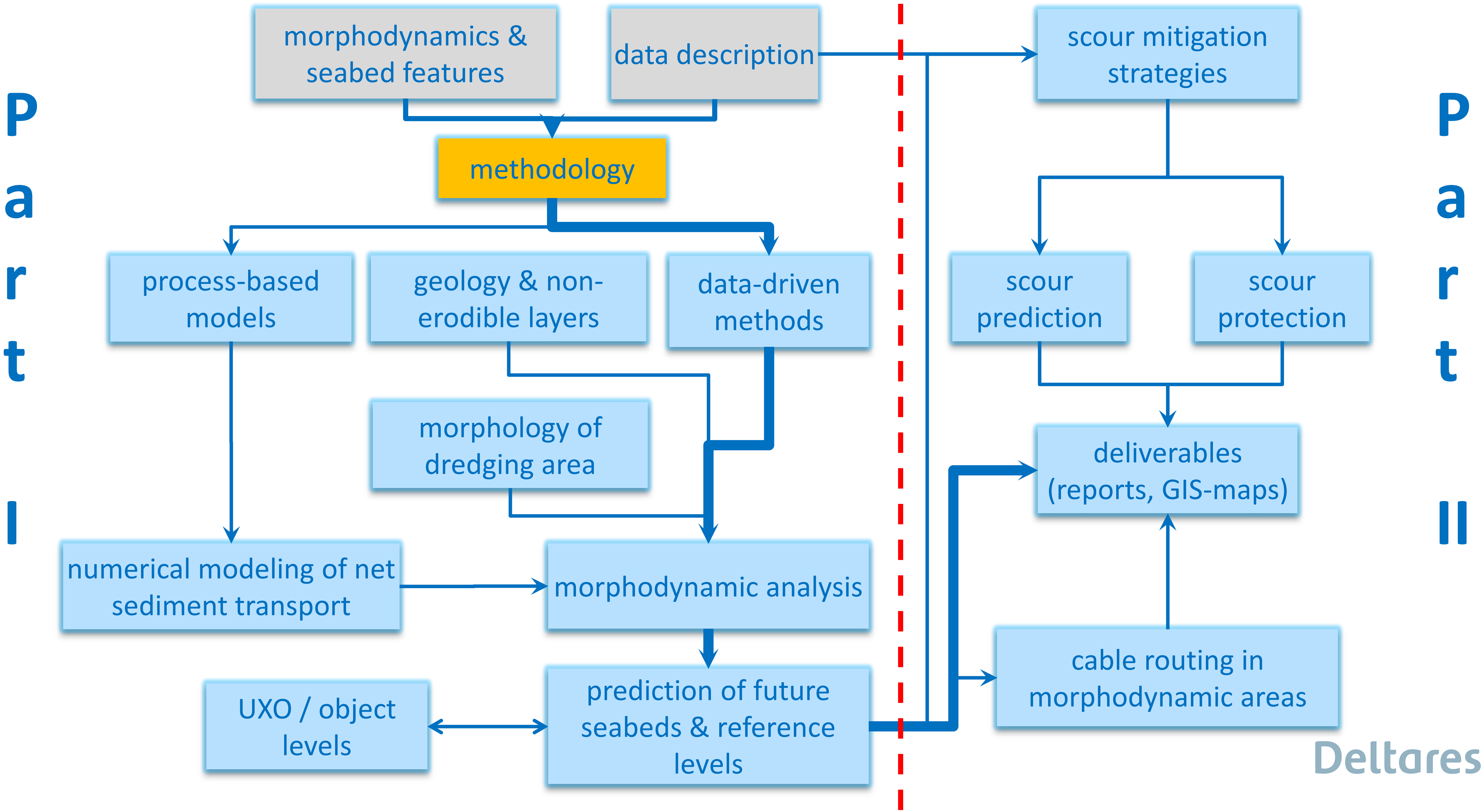


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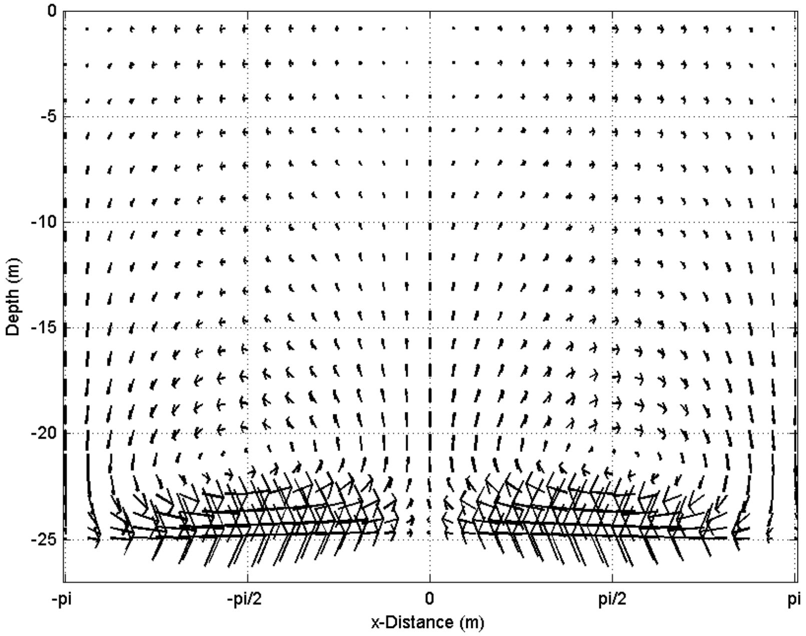
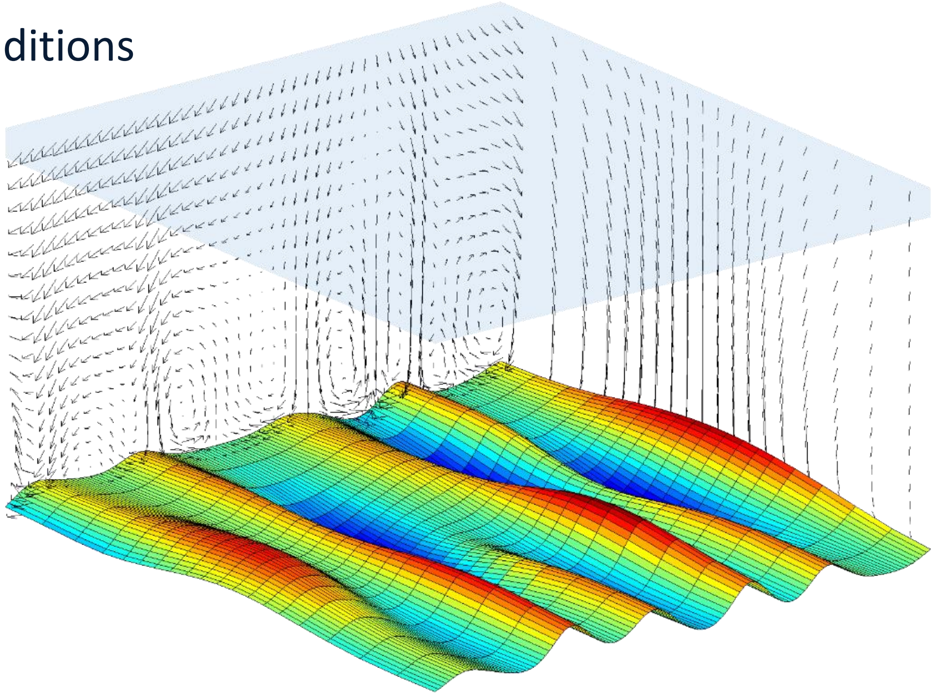
Webinar Morphodynamics and Scour Mitigation Hollandse Kust (Noord)

# 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



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# Sand Wave Morphodynamics – Analysis techniques

**Methods to investigate sand wave characteristics:**

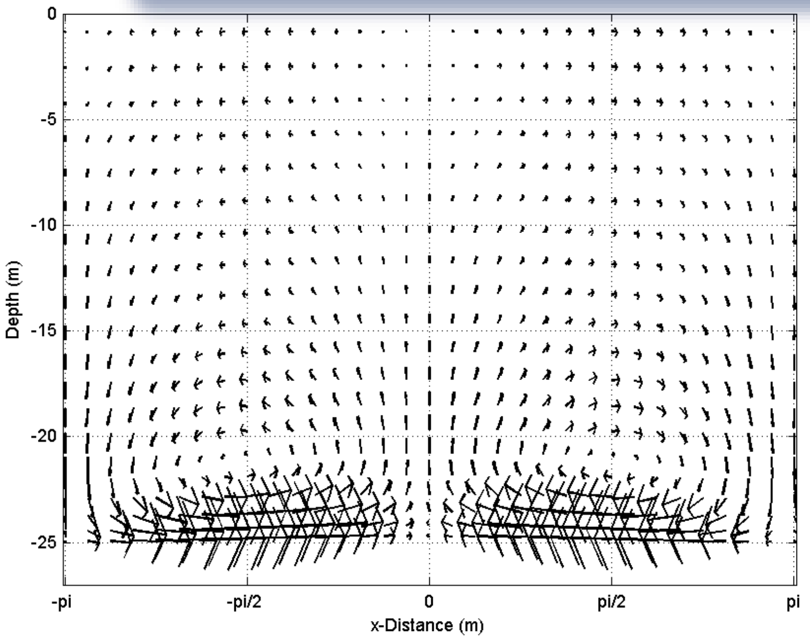
1. Data-driven analysis based on seabed surveys

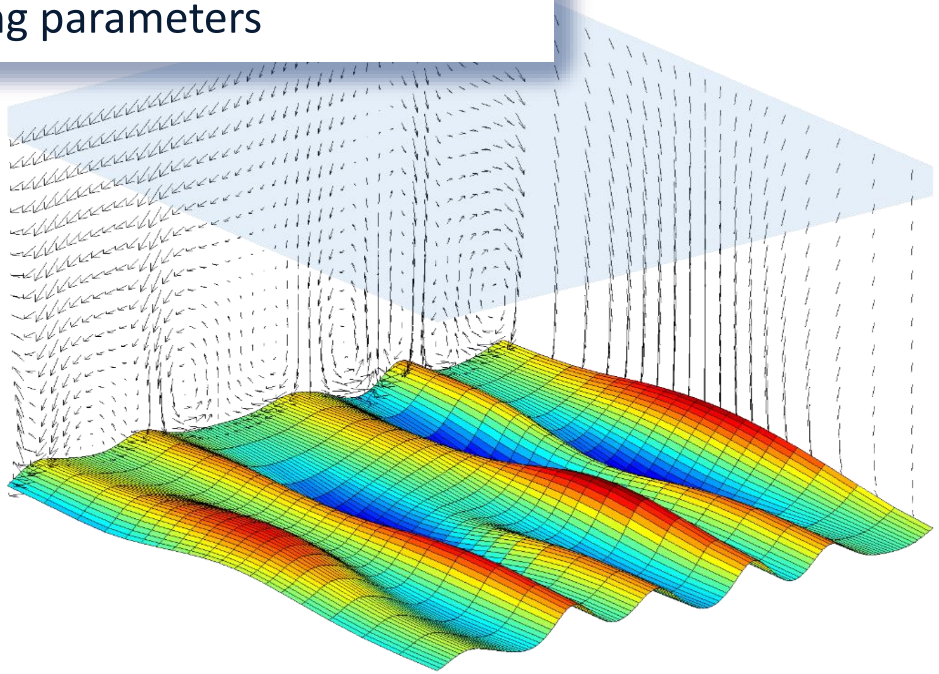
Most reliable, if data is available

➢ Preferably covering a time span of at least 10 years

2. Numerical modelling

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



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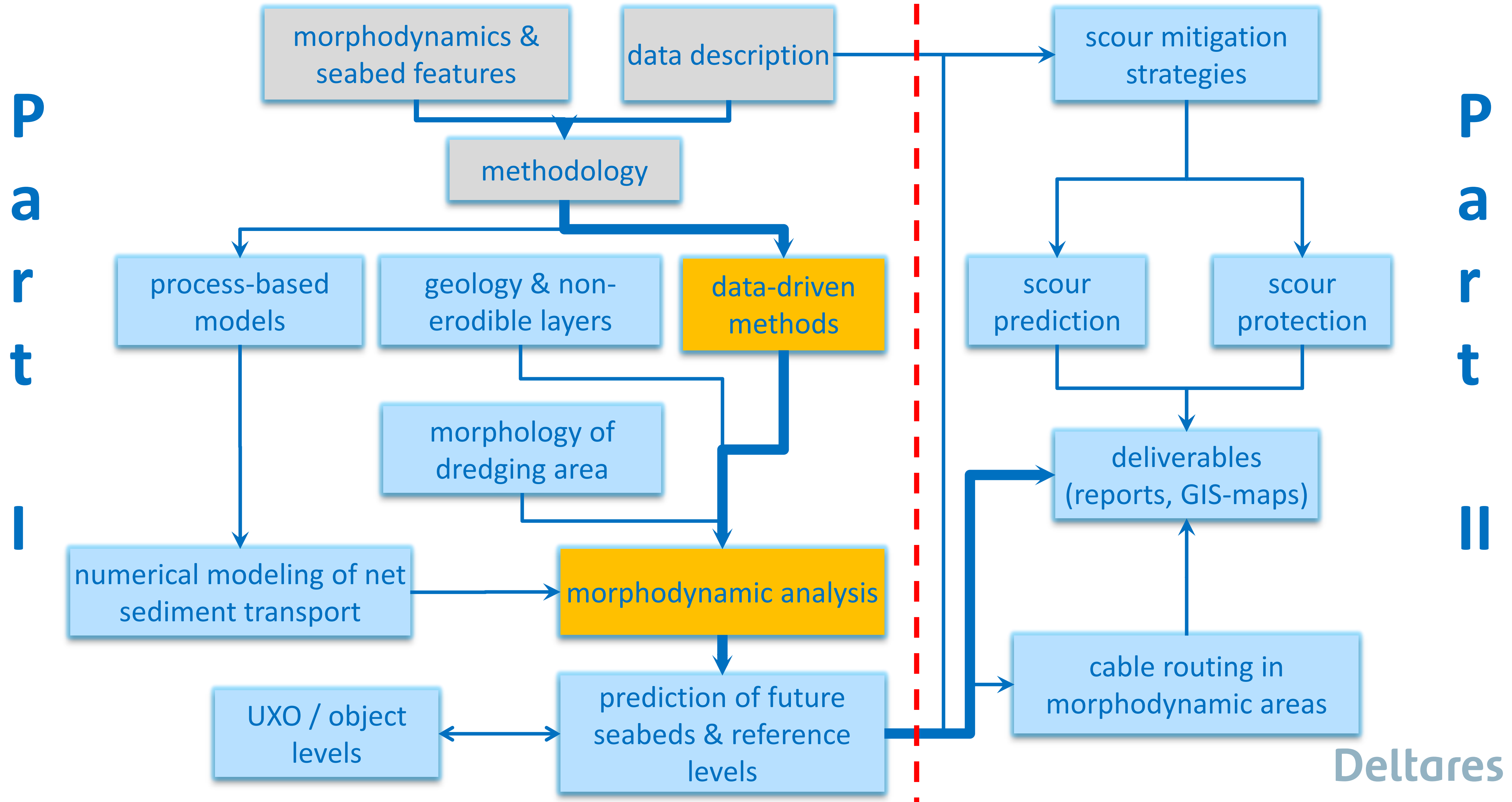

# Definitions of Bathymetrical data fields

| Short name | Description | Sand banks | Sand waves | Megaripples |
|---|---|---|---|---|
| **2017 Bathymetry** | Full measured bathymetry by Fugro in 2017 | X | X | X |
| **Large Scale Bathymetry / 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, LSBL, HSBL) | | X | |
| **Megaripple field** | Megaripple field (to determine uncertainty band) | | | X |

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# Required Design Seabed Levels

**Lowest SeaBed Level (LSBL)**

The *lowest* possible seabed level in the period 2018-2058

**Highest SeaBed Level (HSBL)**

The *highest* possible seabed level in the period 2018-2058

**Lowest Object Level (LOL)**

The *lowest* possible level of objects dropped during WWII for the period 2021-1945

(useful information for construction activities)

**Highest Object Level (HOL)**

The *highest* possible lowest level of objects dropped during WWII for the period 2021-1945

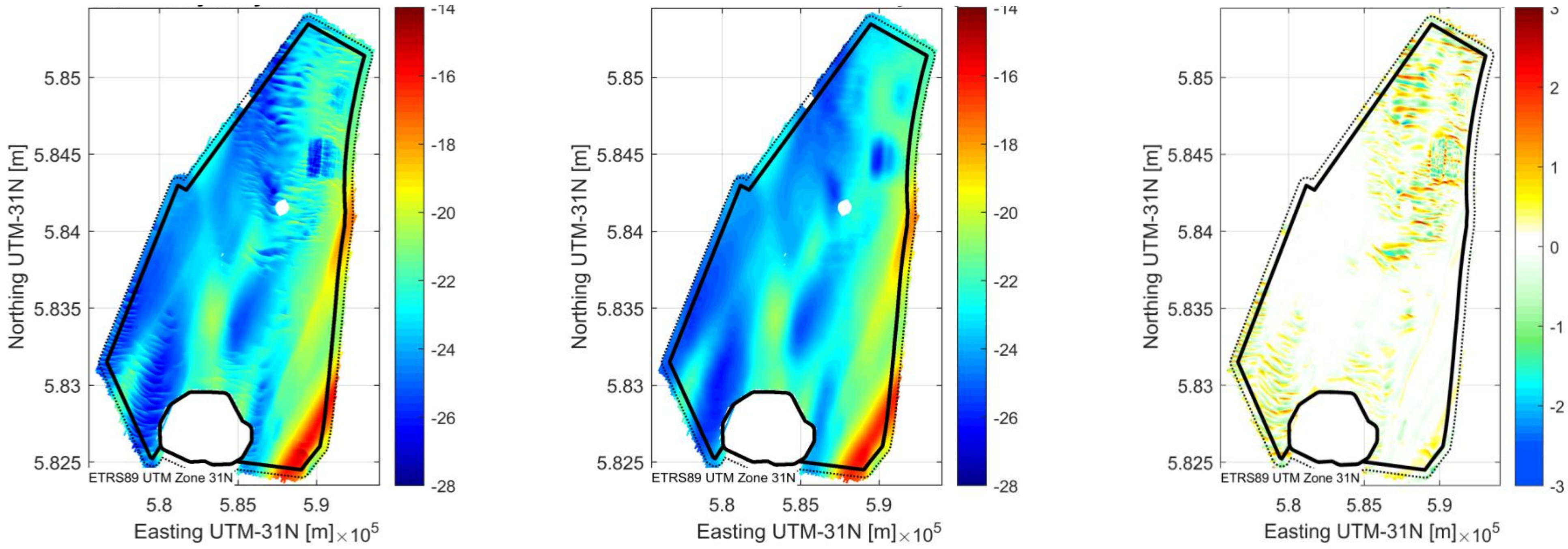
(useful information for construction activities)

*Note that all these levels are design levels which should be sufficiently conservative. Depending on the monitoring & maintenance strategy, different seabed levels can be used. Therefore, also Best-Estimate Bathymetries and Best-Estimate Object Levels are delivered.*

# Large-scale bathymetric filtering

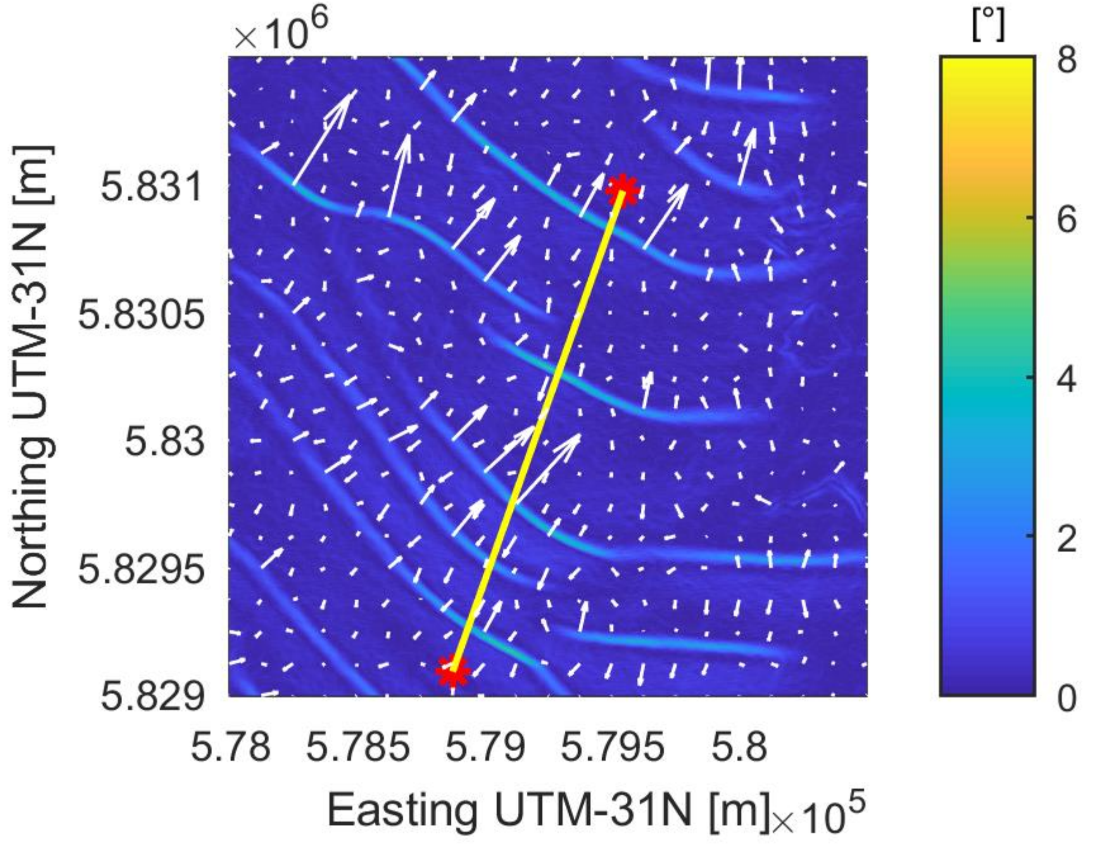
- Goal is to separate **mobile** and **static** bathymetry
- **Sand waves** have an average crest orientation around **NNE - SSW**
- For filtering it was decided to use an **ellipsoid** with the long axis under an angle of **15°N**. The filter size along the long axis was chosen at **1000m**, while the 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 static bathymetry**, while a filter size of 1000m is longer than the longest observed sand wave lengths in the HKNWFZ, ensuring that all sand waves are filtered out

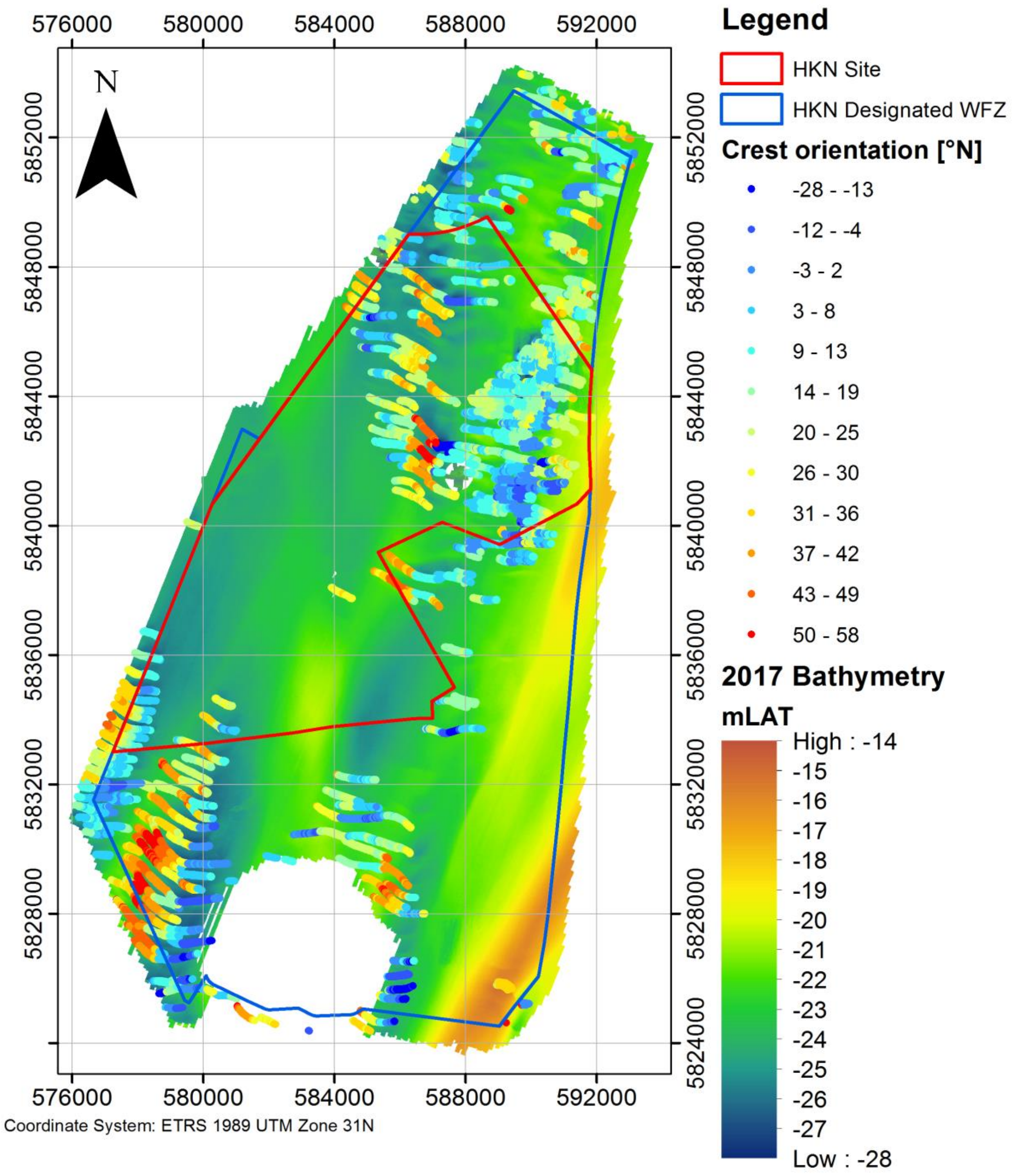
*2017 bathymetry* - *static bathymetry* = *mobile bathymetry*



# Direction of sand wave migration

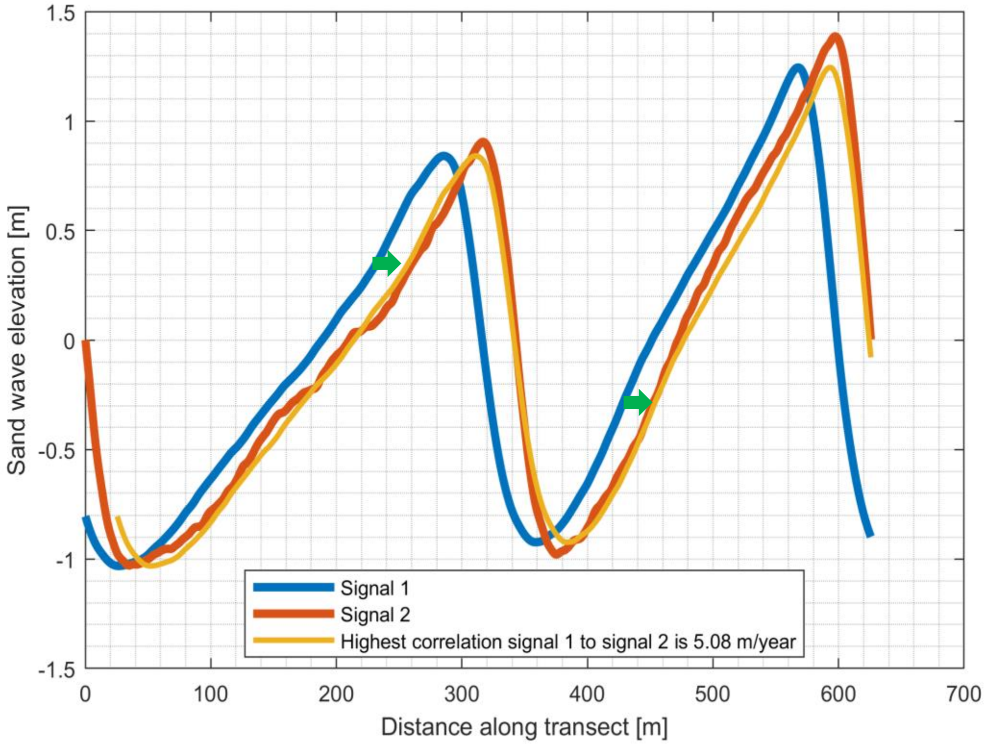
- Assumption: sand waves migrate in the direction of the steepest bed slope
- Main migration directions of approximately 18°N with variations up to about 30° around the main axis.

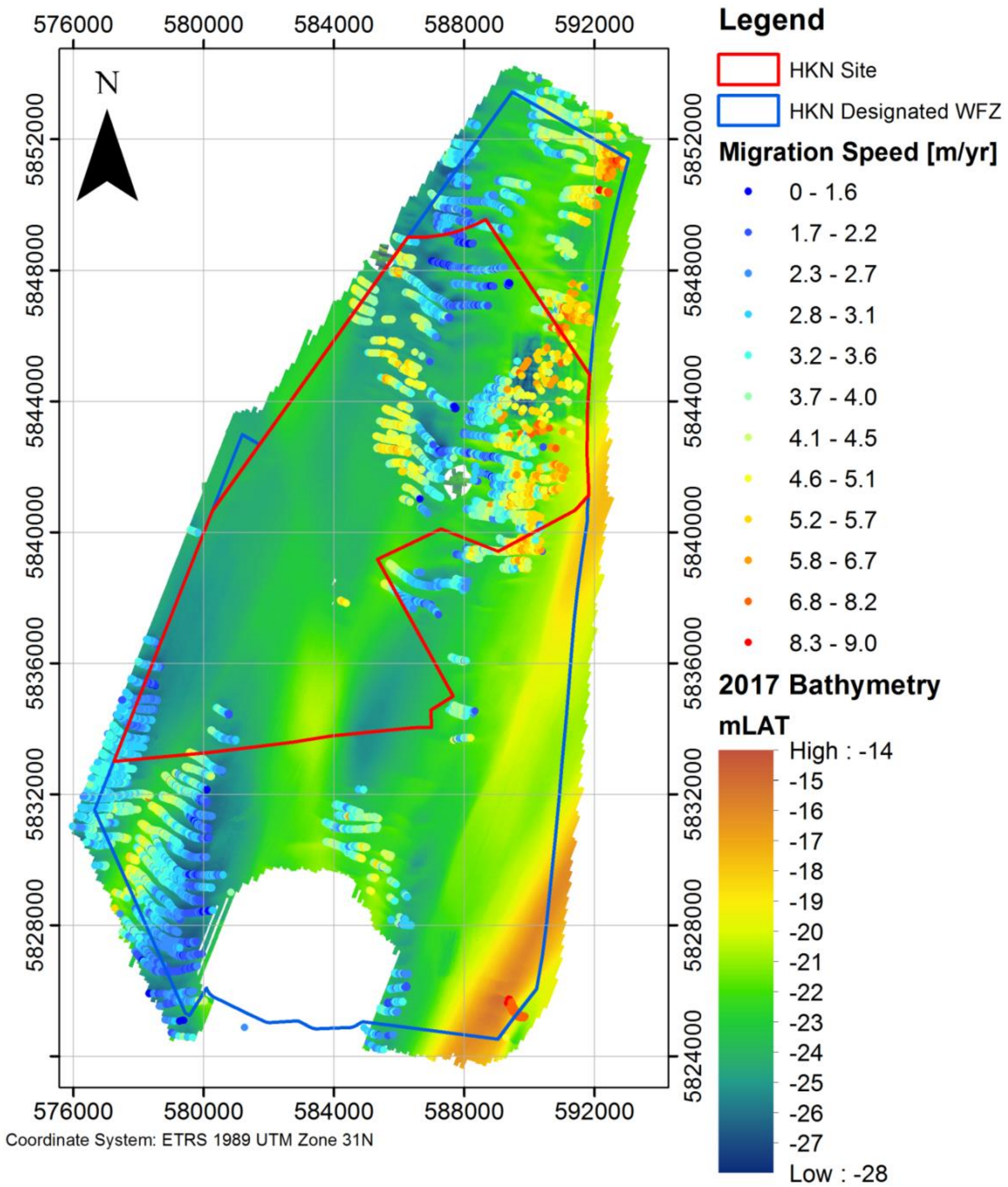


# Sand wave migration speed (I)

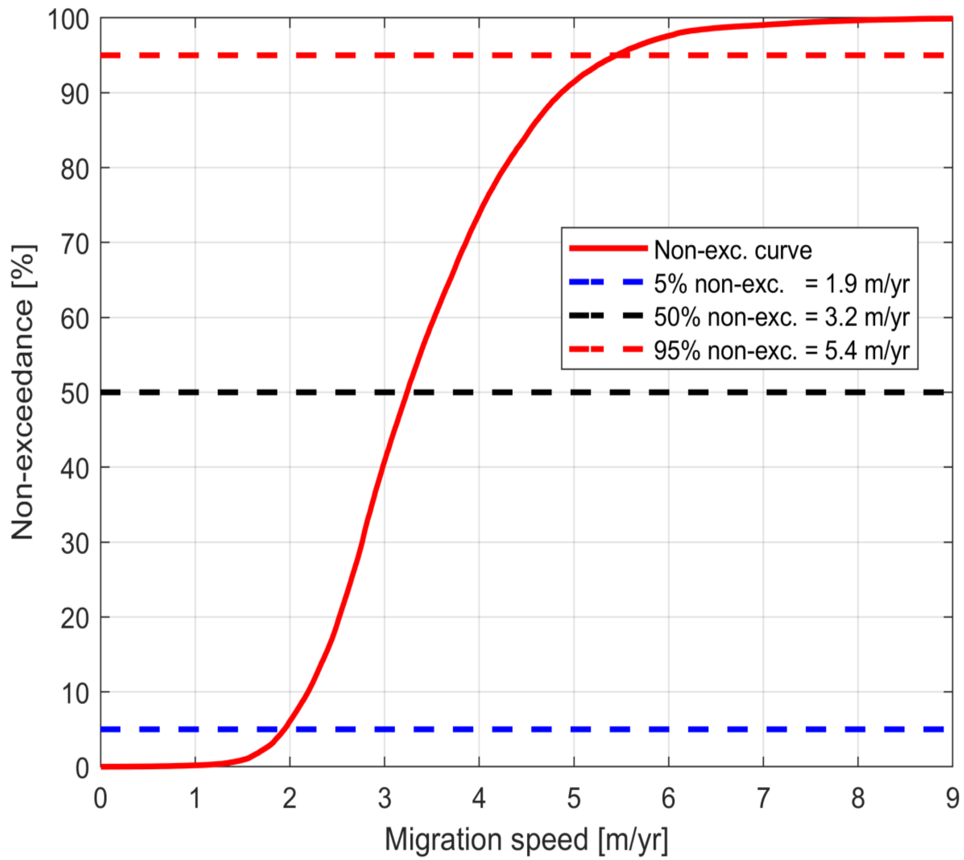
- 1D cross correlation on all individual sand waves
- Combining information per transect and per migration direction for all bathymetrical combinations

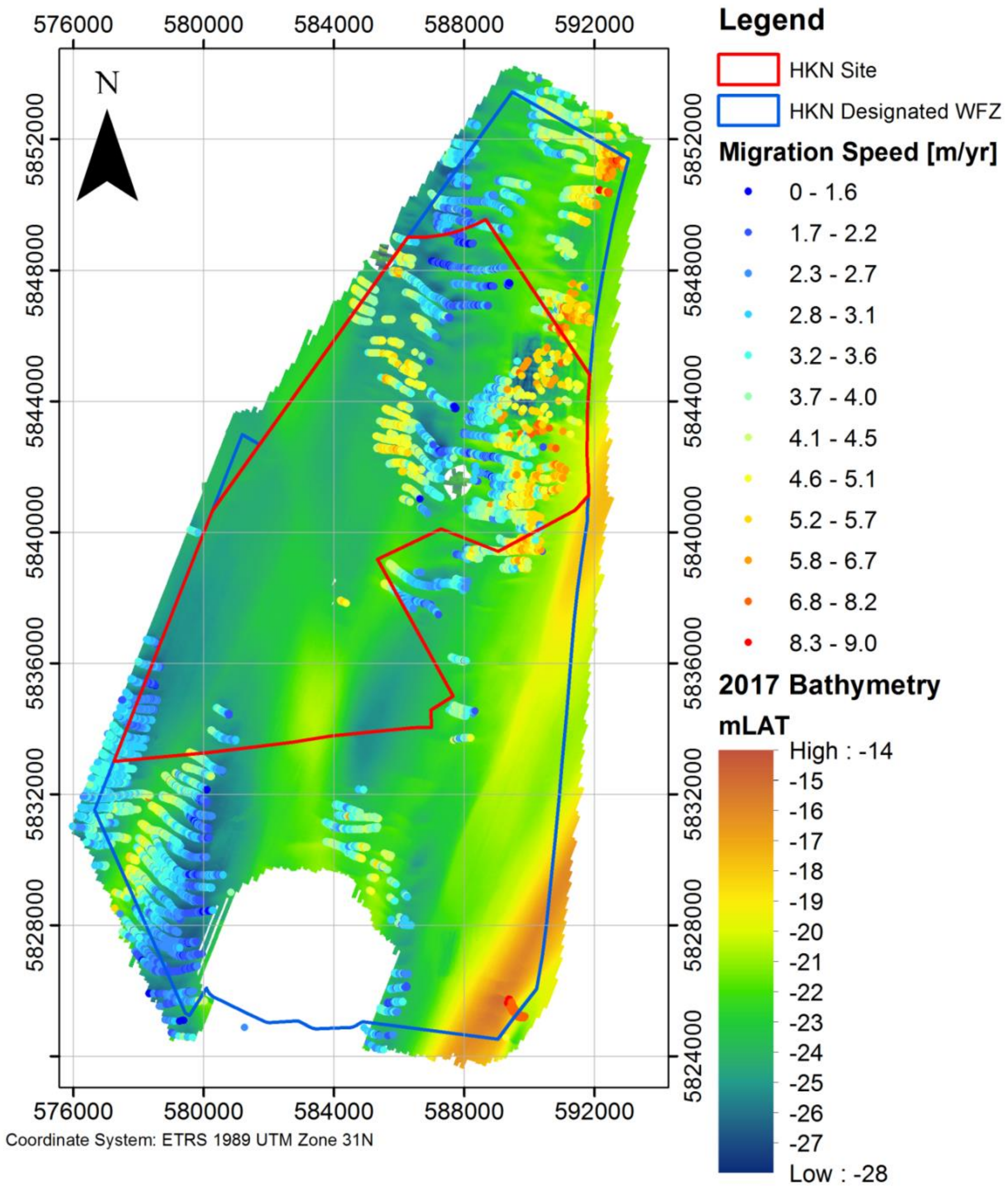


# Sand wave migration speed (II)

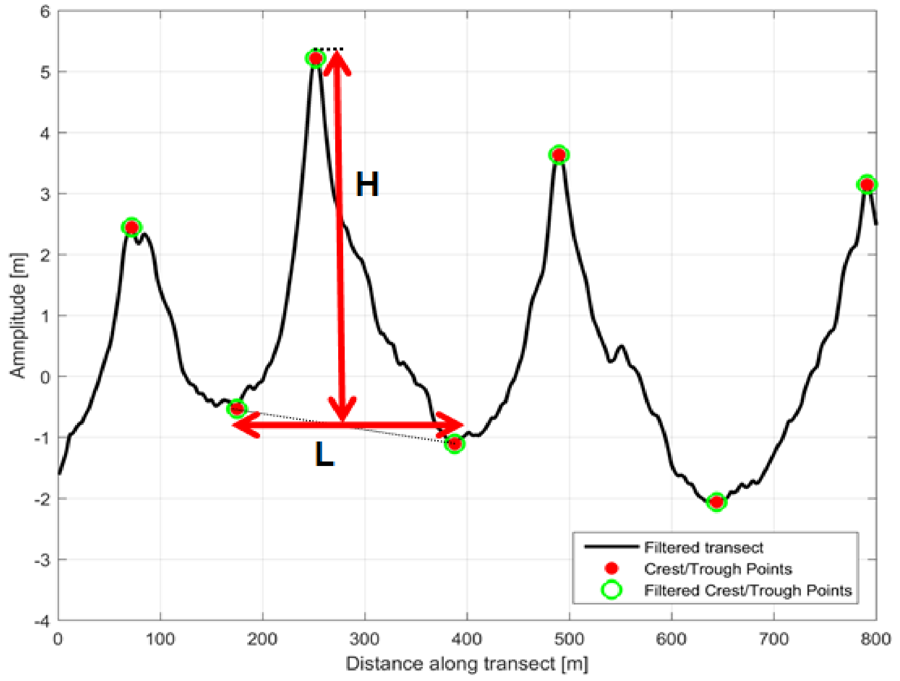
- 1D cross correlation on all individual sand waves
- Combining information per transect and per migration direction for all bathymetrical combinations



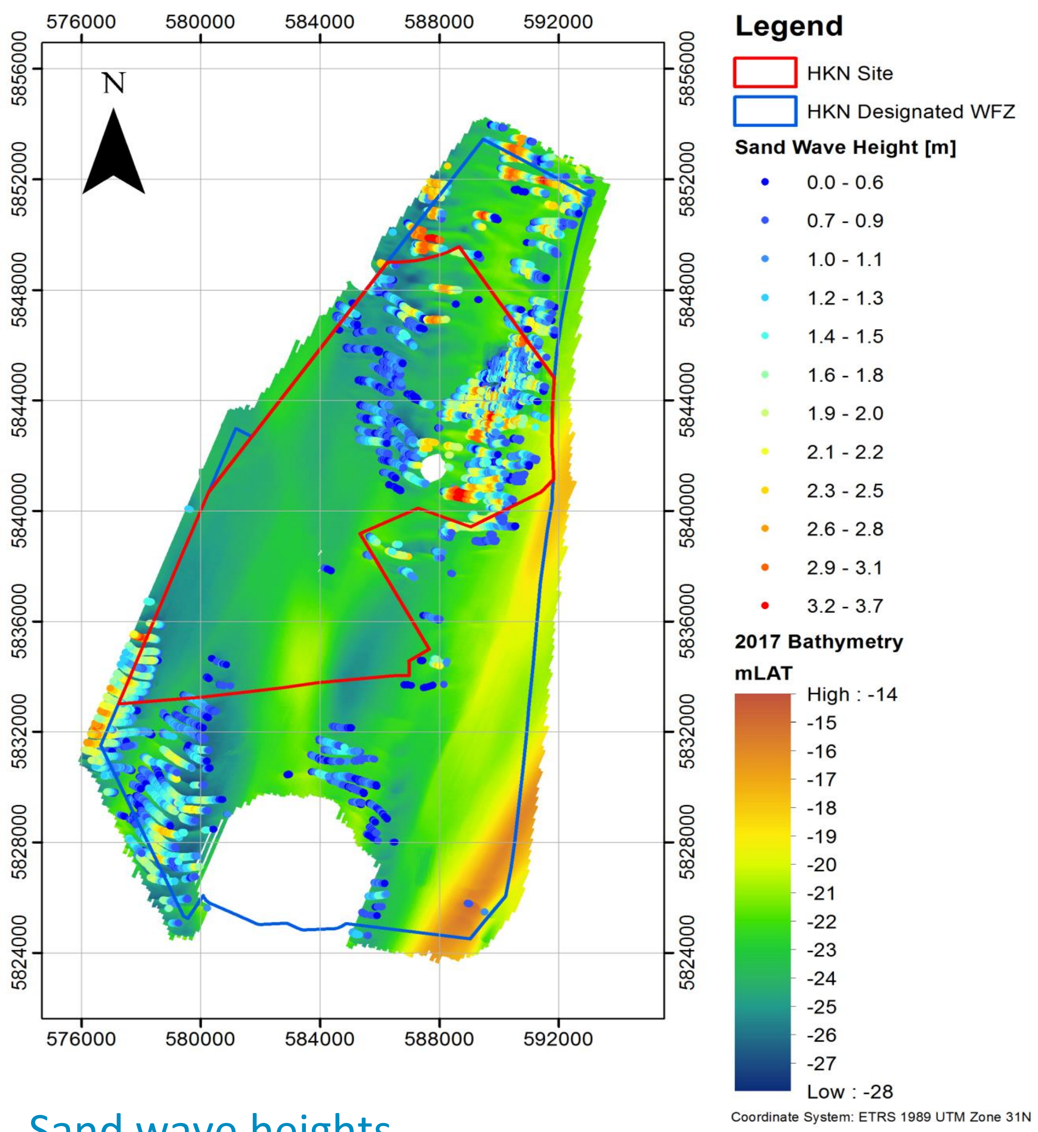



# Fourier analysis on transects (I)

- Identify crests and troughs
- Obtain statistics per sand wave such as sand wave height and length




| Sand wave property | 5% non-exceedance value | 50% non-exceedance value | 95% non-exceedance value |
|---|---|---|---|
| Sand wave height [m] | 0.8 | 1.6 | 2.9 |
| Sand wave length [m] | 190 | 380 | 690 |




Sand wave heights

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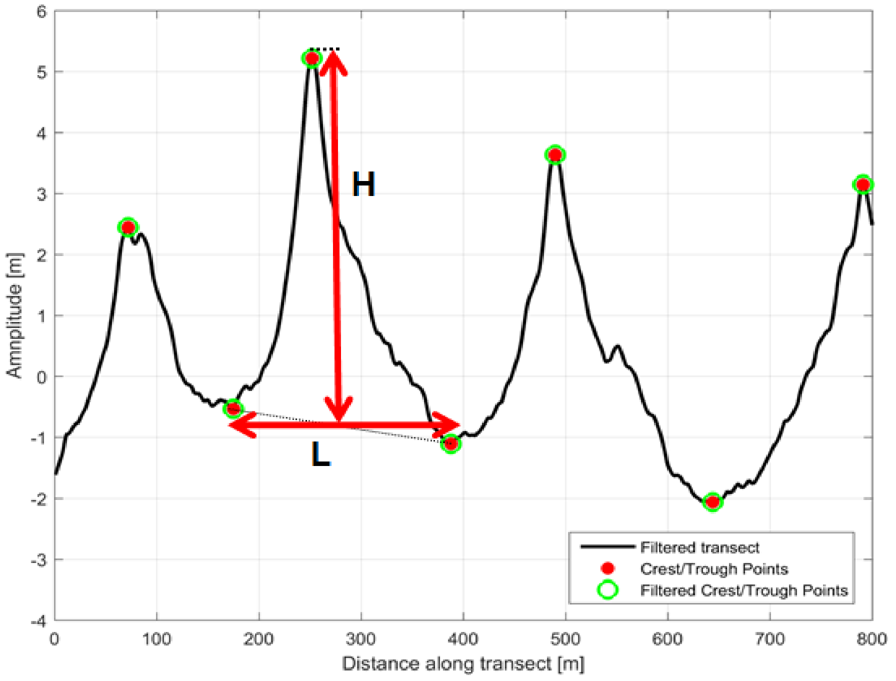


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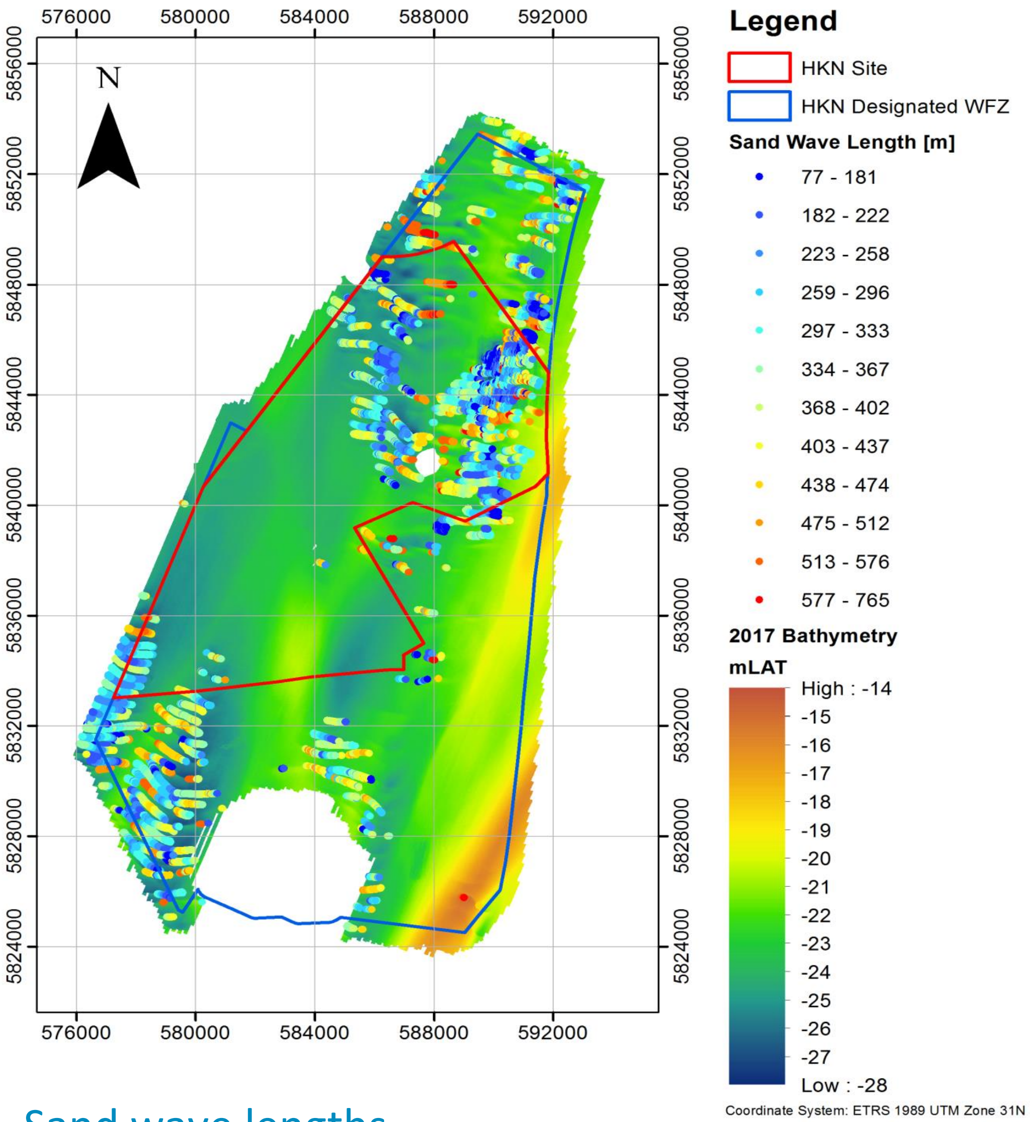
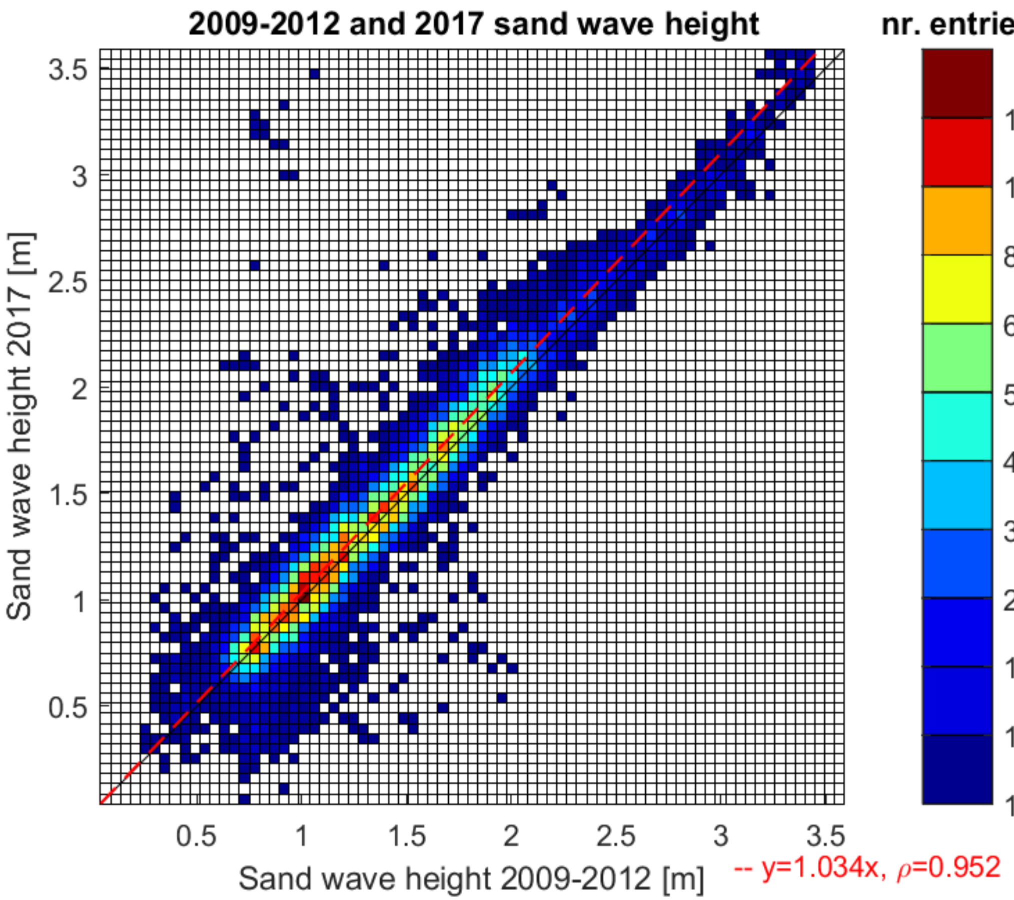
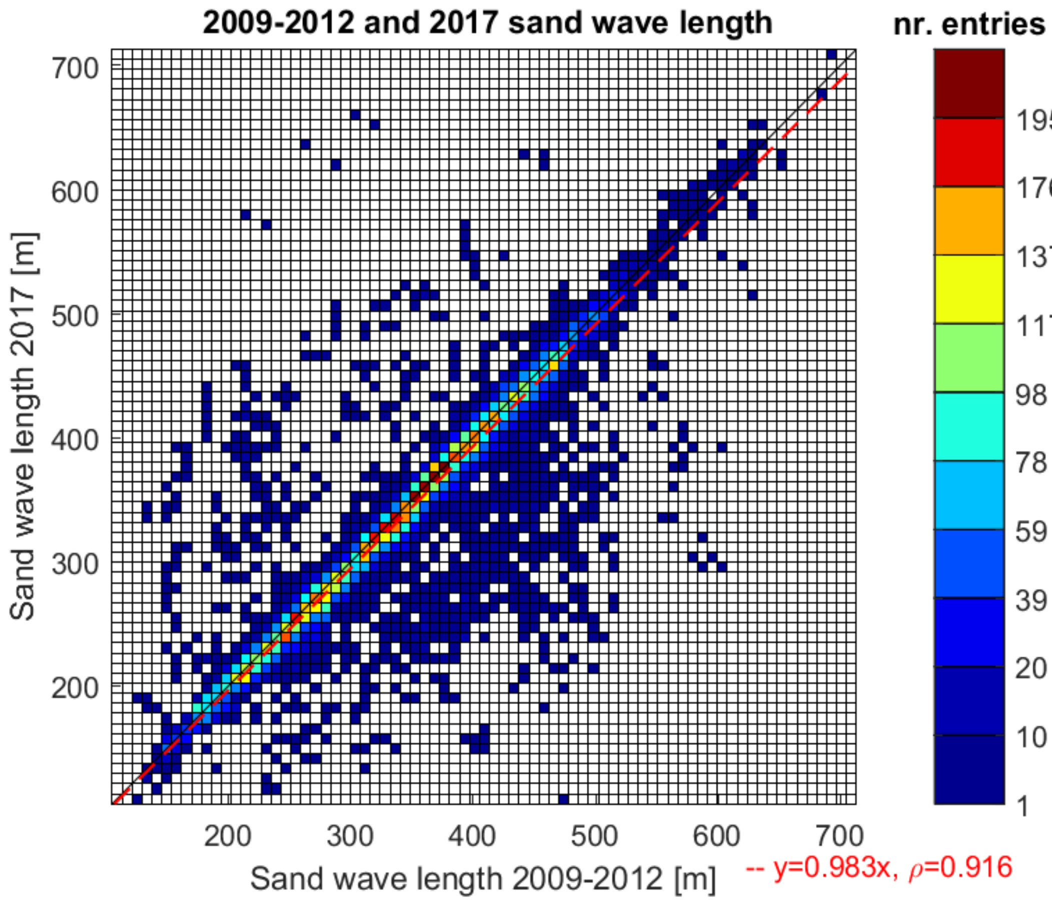



Sand wave lengths

# Fourier analysis on transects (III)

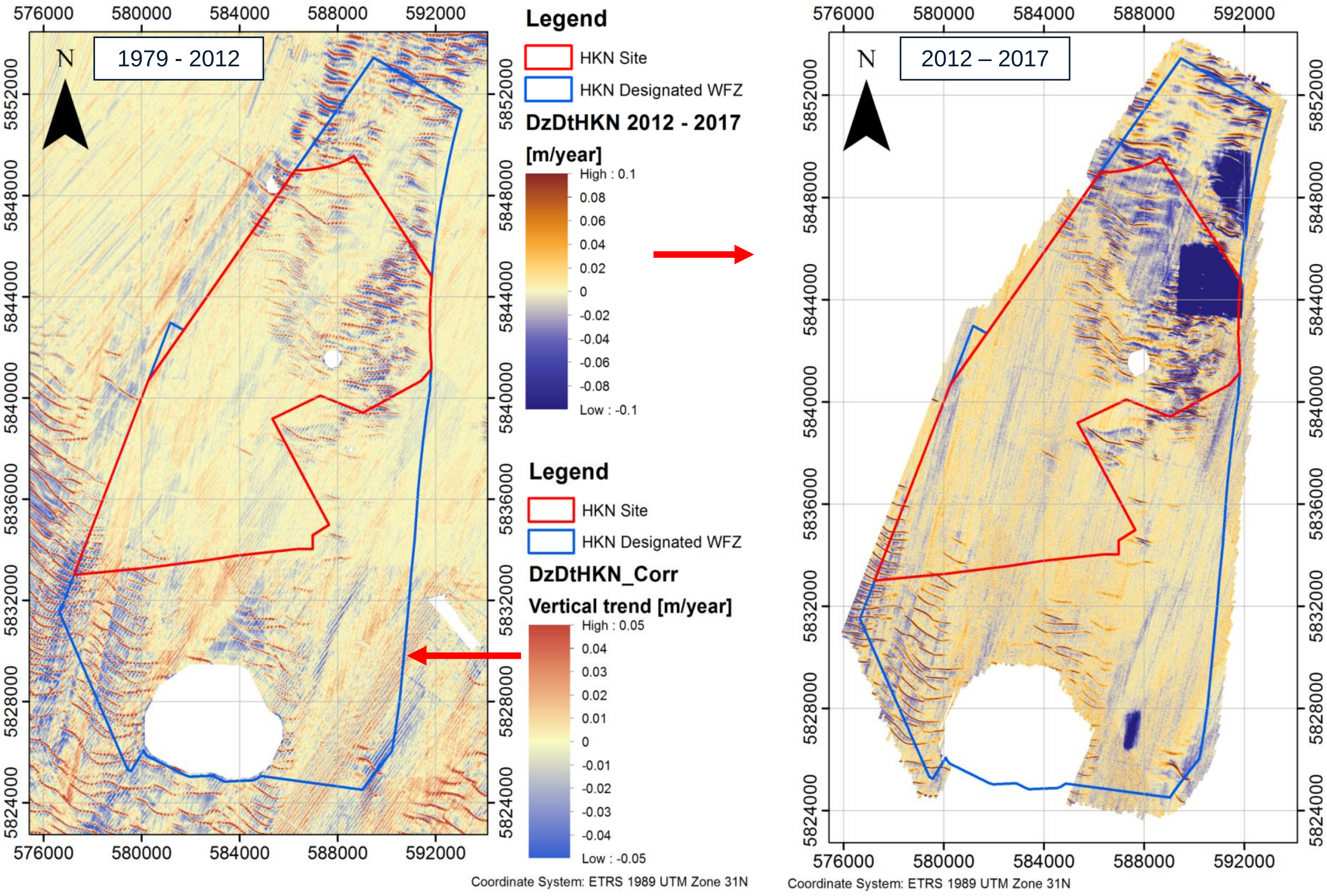
- Correlation of sand wave shapes over period 2012-2017 used to estimate retainment of sand wave shapes over time.
- High correlation for sand wave heights (0.95) and sand wave lengths (0.92)



# Large-scale seabed dynamics

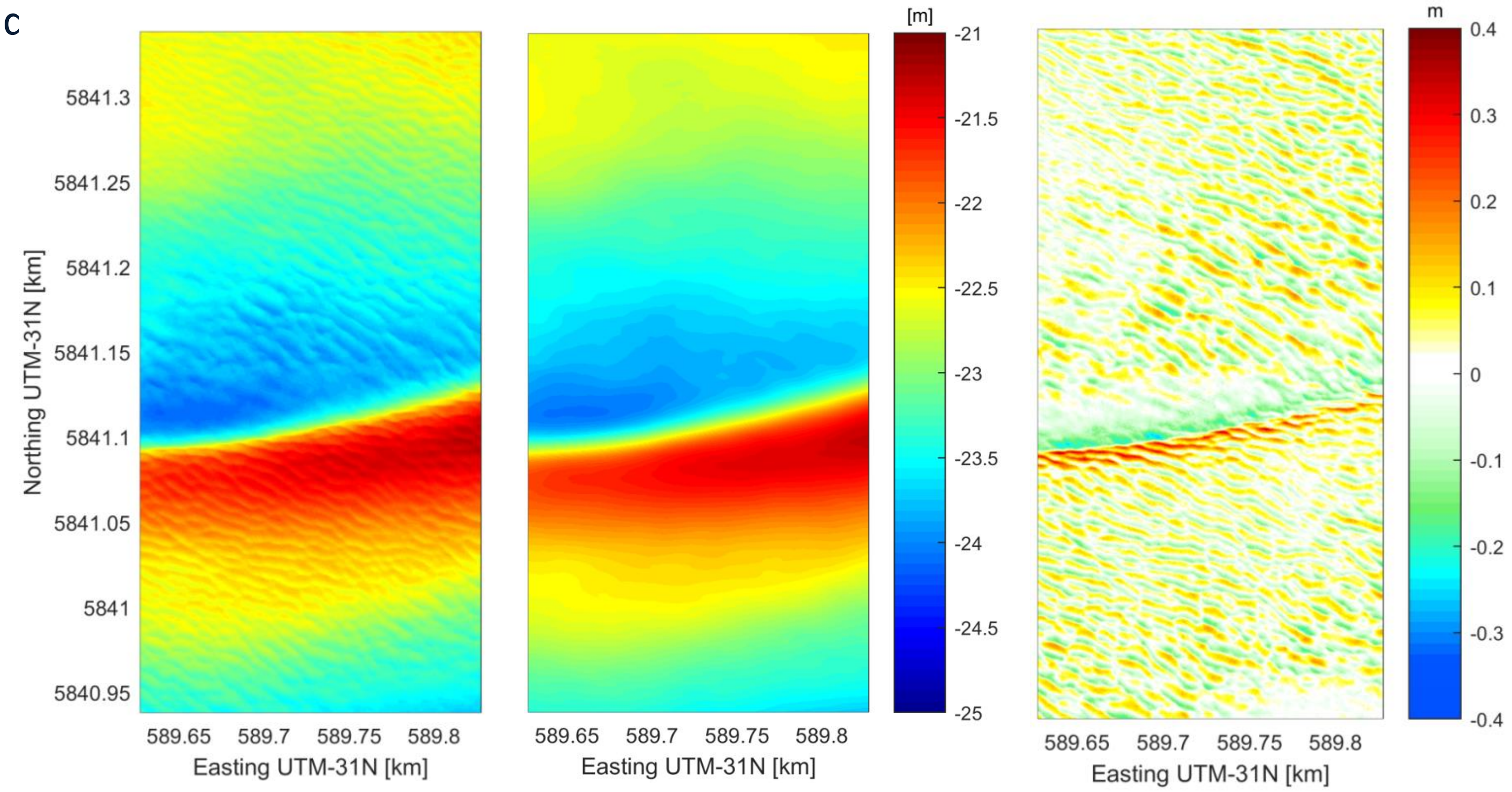
- If the filtering method is accurate and if the Static Bathymetries are indeed “static”, the differences between different years should be negligible:
- Differences are minor ~dm): no migration or growing/shrinking of sand banks can be observed.
- Assumption of static seabed over periods of decades seems valid.



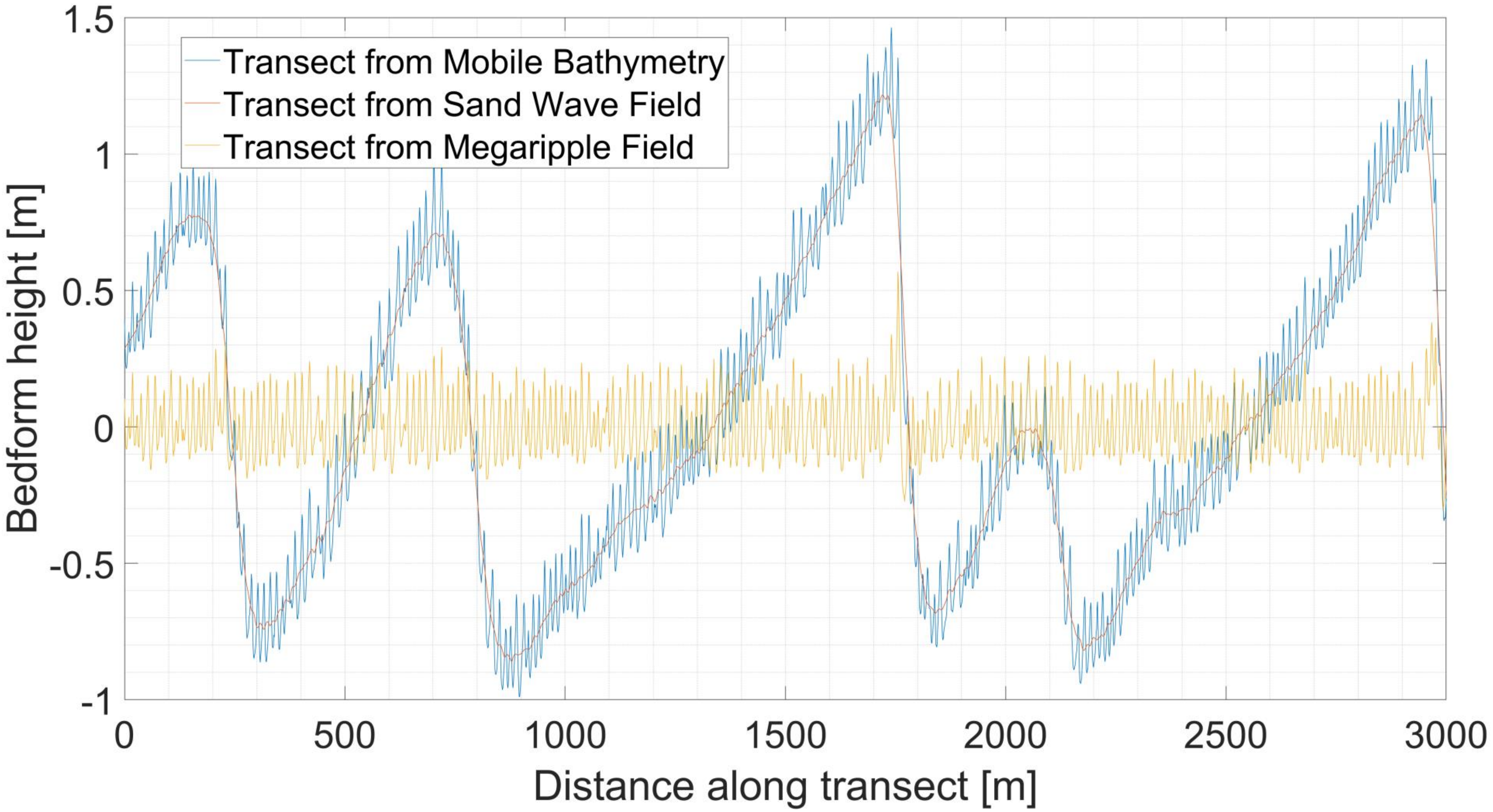
# Methodology – megaripple analysis (I)

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

- typical wavelengths of 8-20m
- rather regular megaripple pattern



# Methodology – megaripple analysis (II)

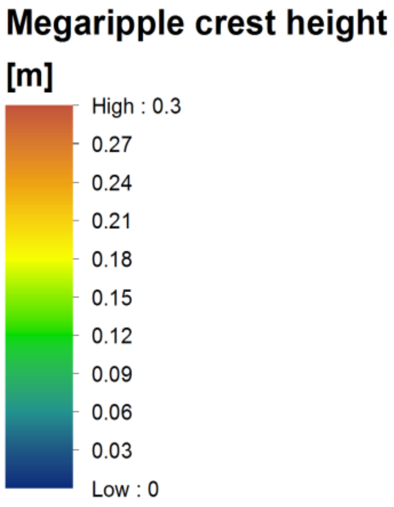


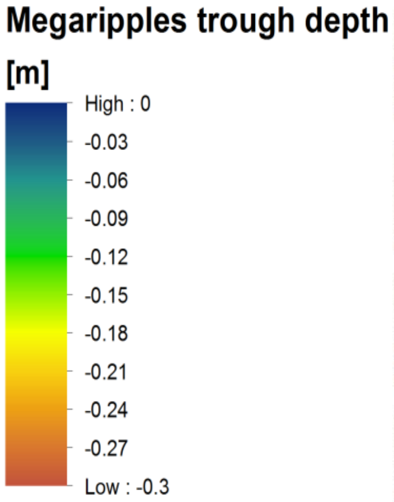
# Megaripple analysis: crest heights and trough depths

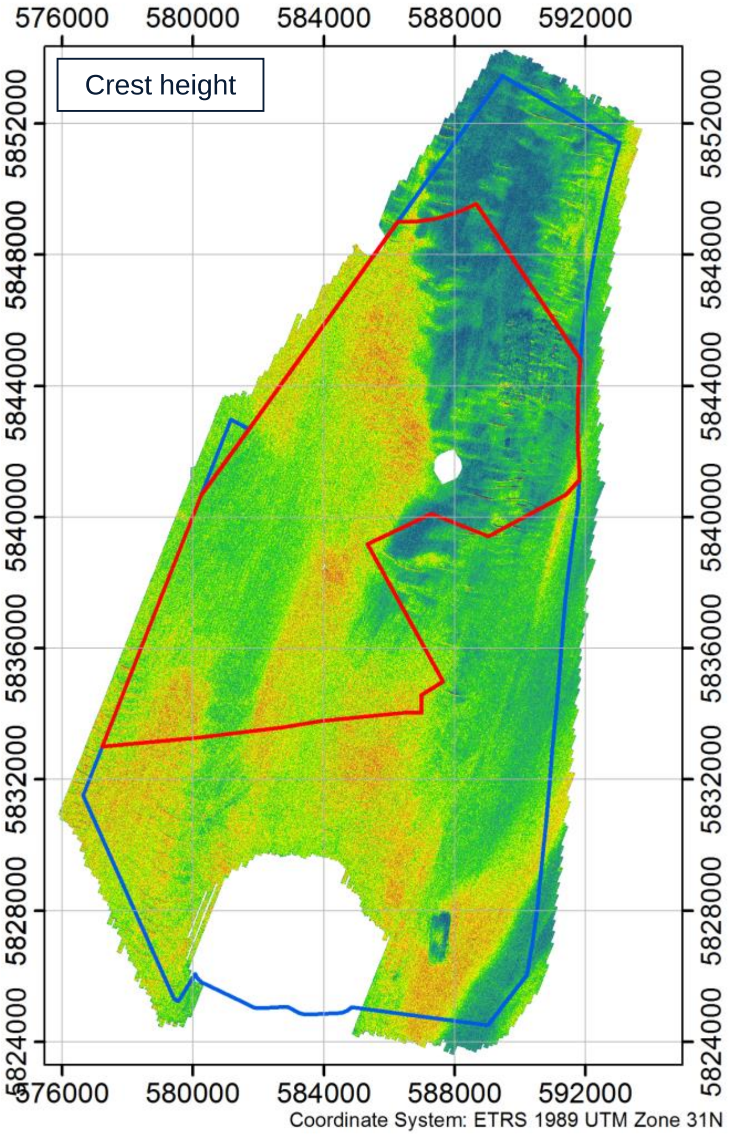
- Megaripple field analysed to determine trough depths and crest heights
- Representative values for

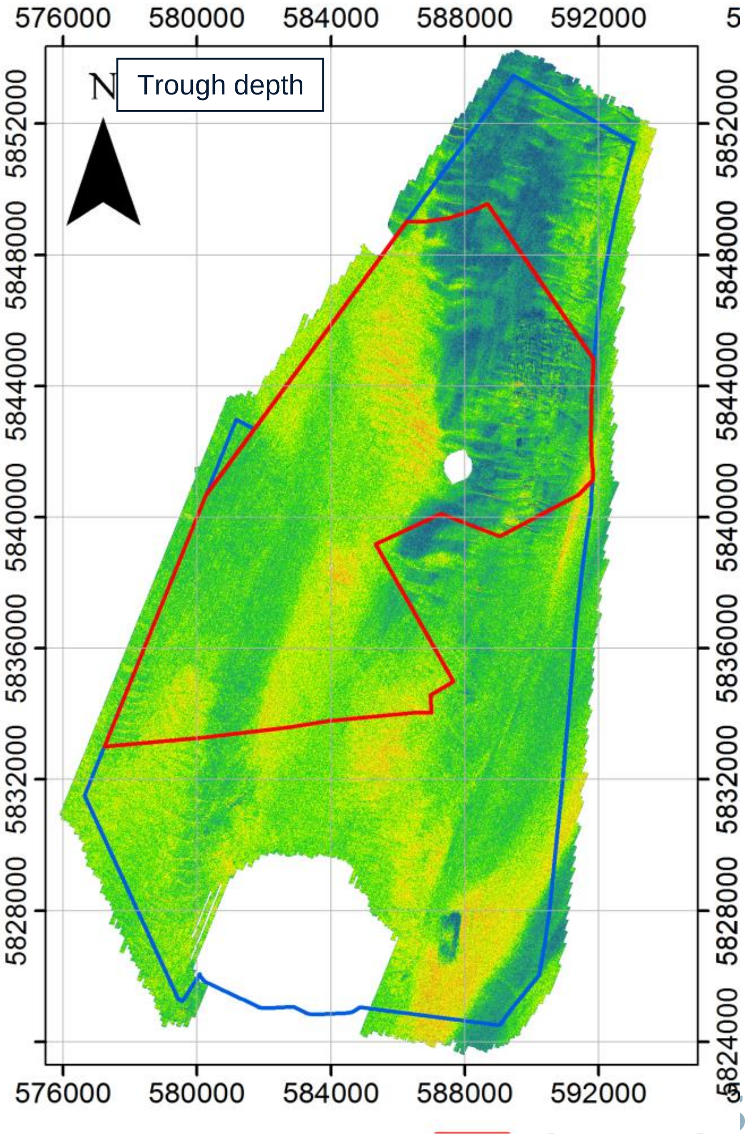
  trough depth: ~0.15m

  crest height: ~0.25m
- These values will be included in the uncertainty band



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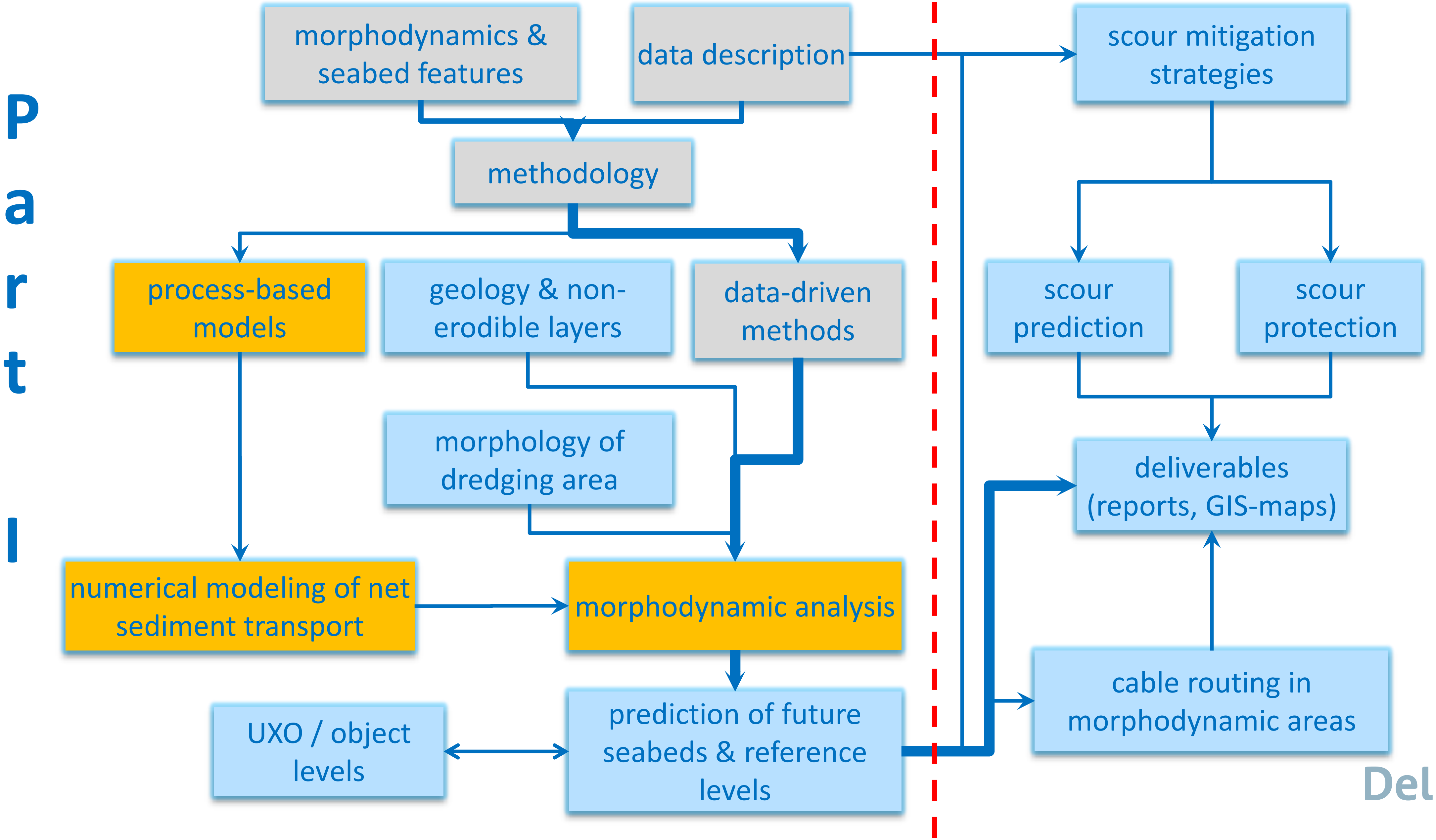


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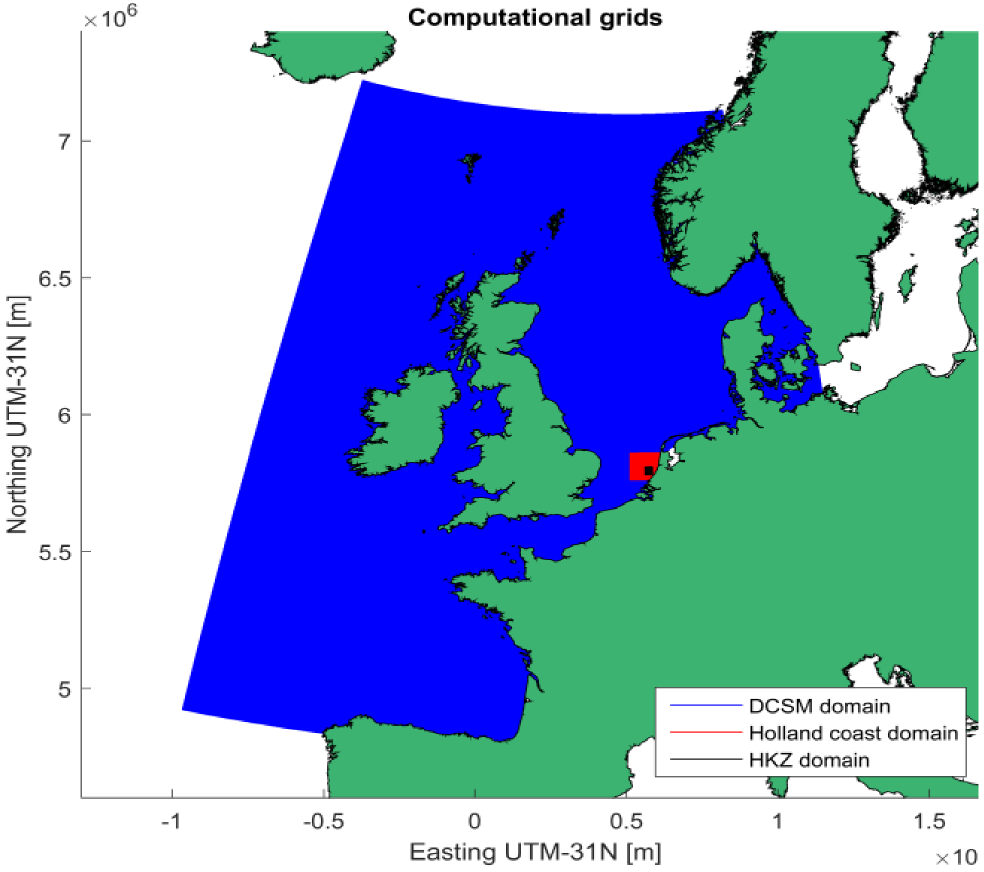
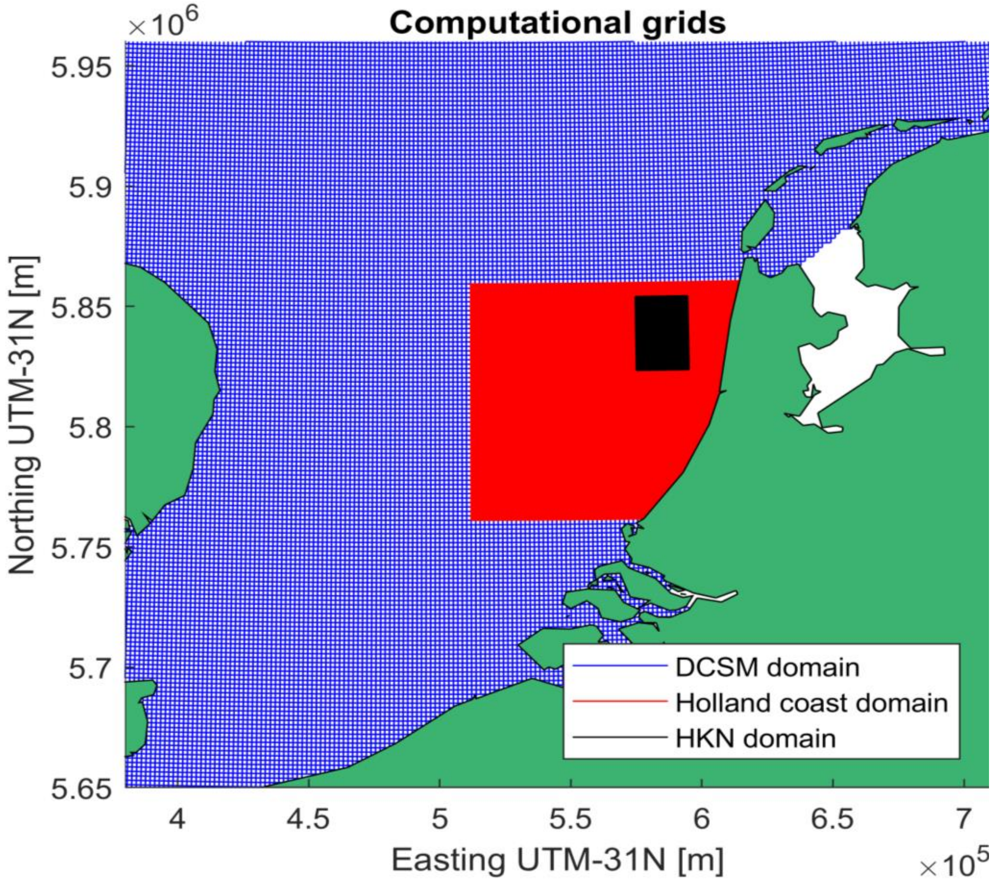
# Tidal flow and global net-sediment transport

**Numerical model setup**

- Hindcast based on available measurement data
- Boundary conditions Holland coast domain derived form Dutch Continental Shelf Model (DCSM)
- HKN domain is online coupled to the Holland Coast domain, grid resolution of 50m

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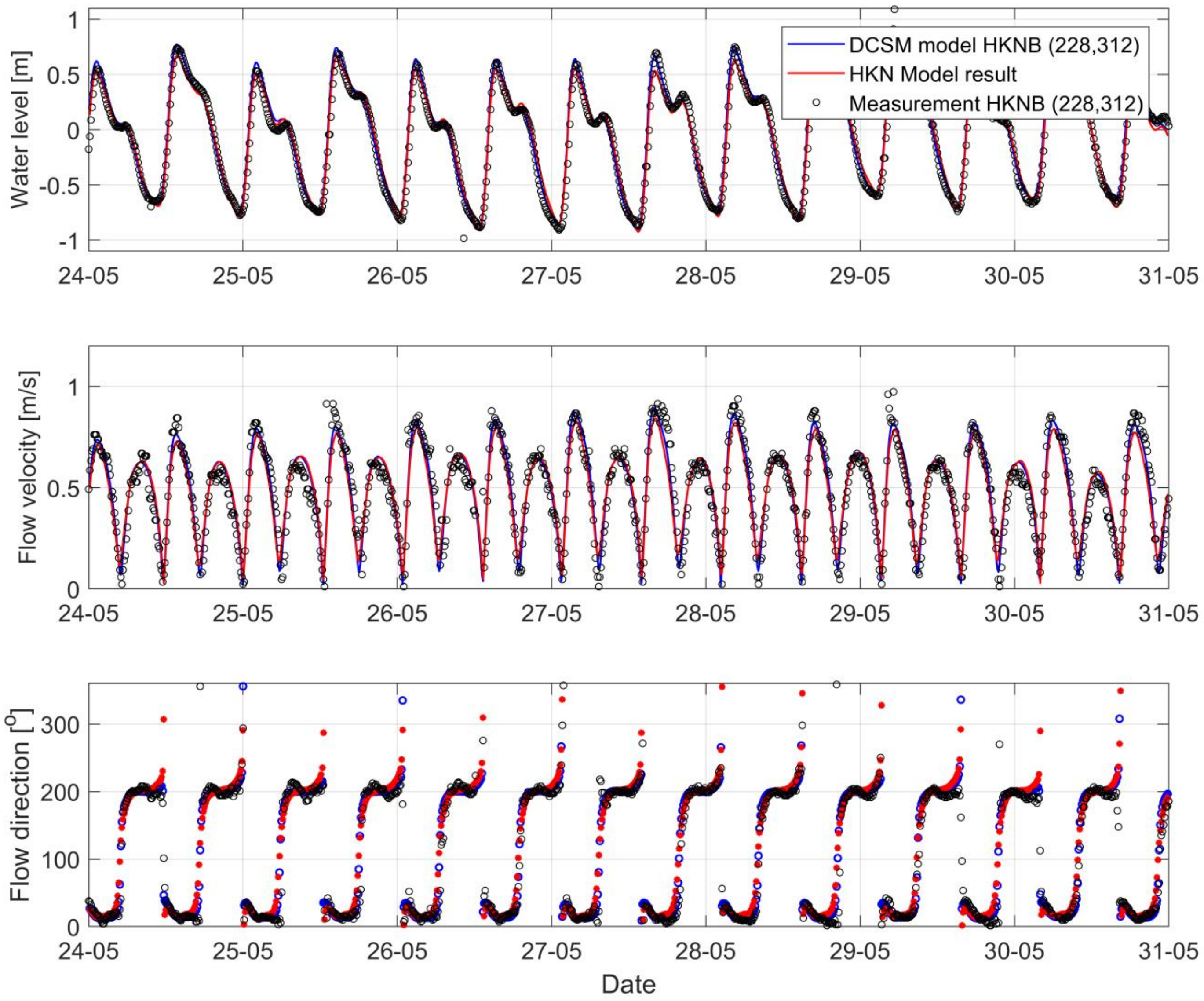
# Tidal flow and global net-sediment transport

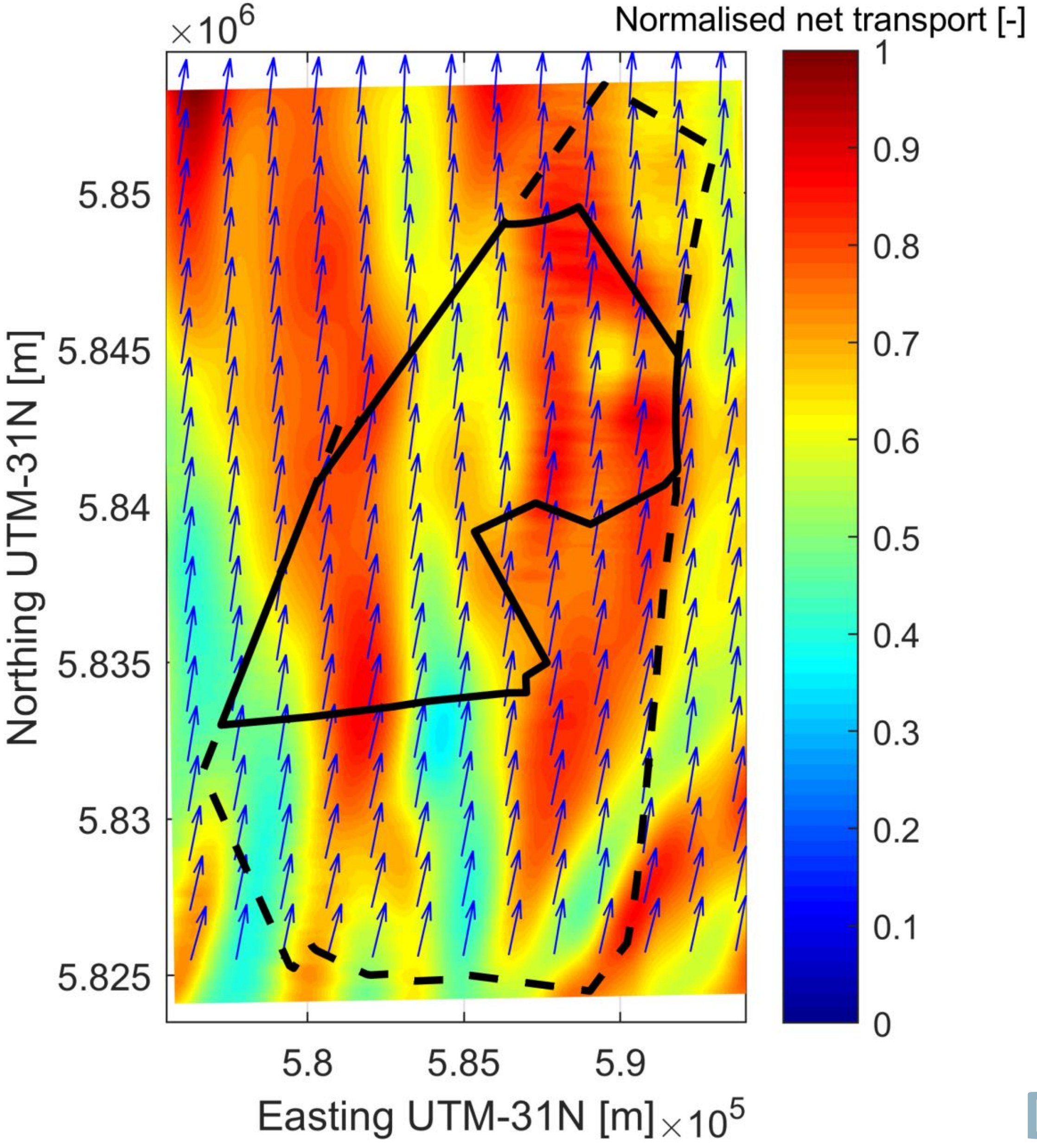
## Model validation

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



# 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: ~15°N
- Net-sediment transport influenced by underlying large-scale bathymetry. Slightly higher net transport in the Northern parts
- Very similar to migration speeds derived from data analysis

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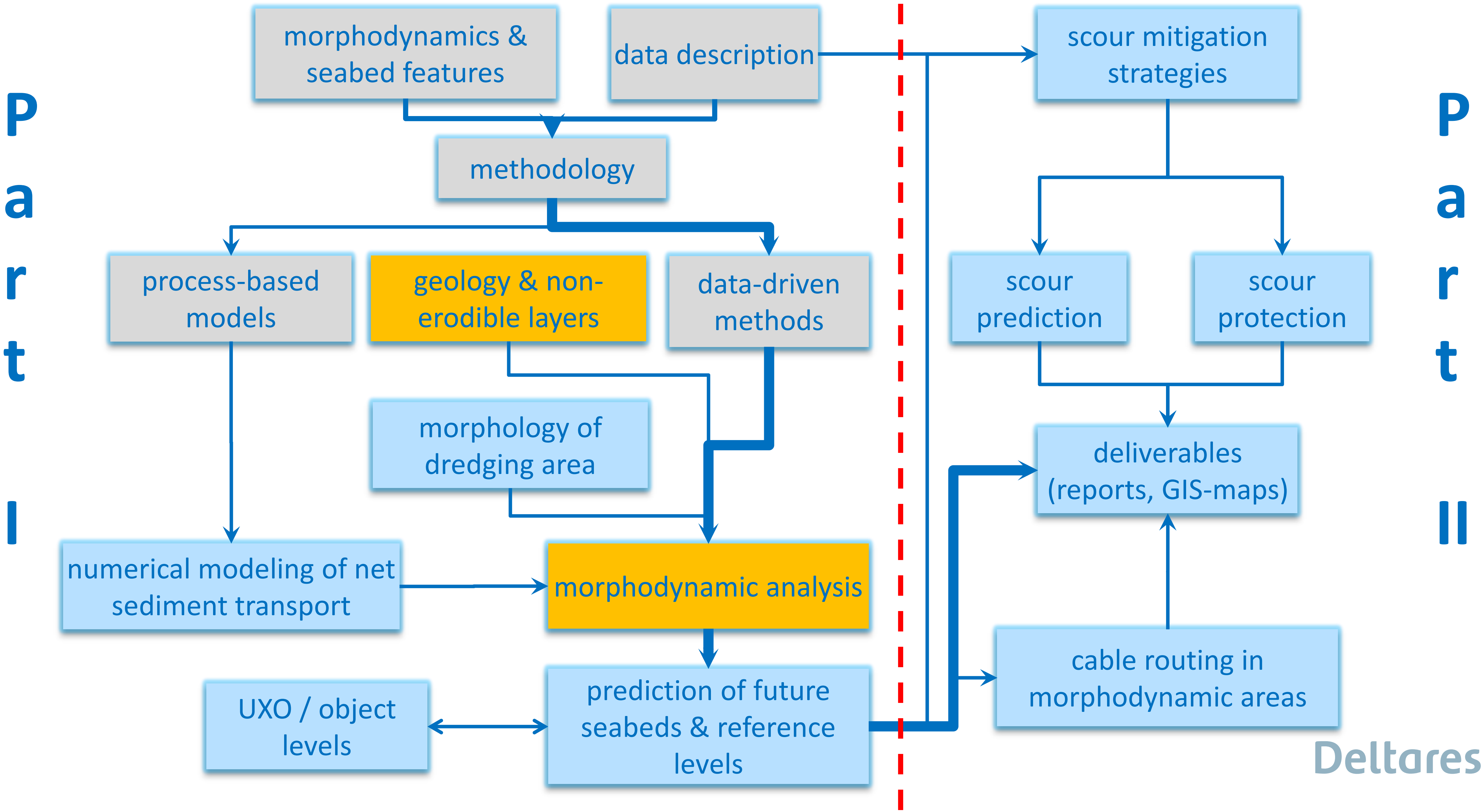
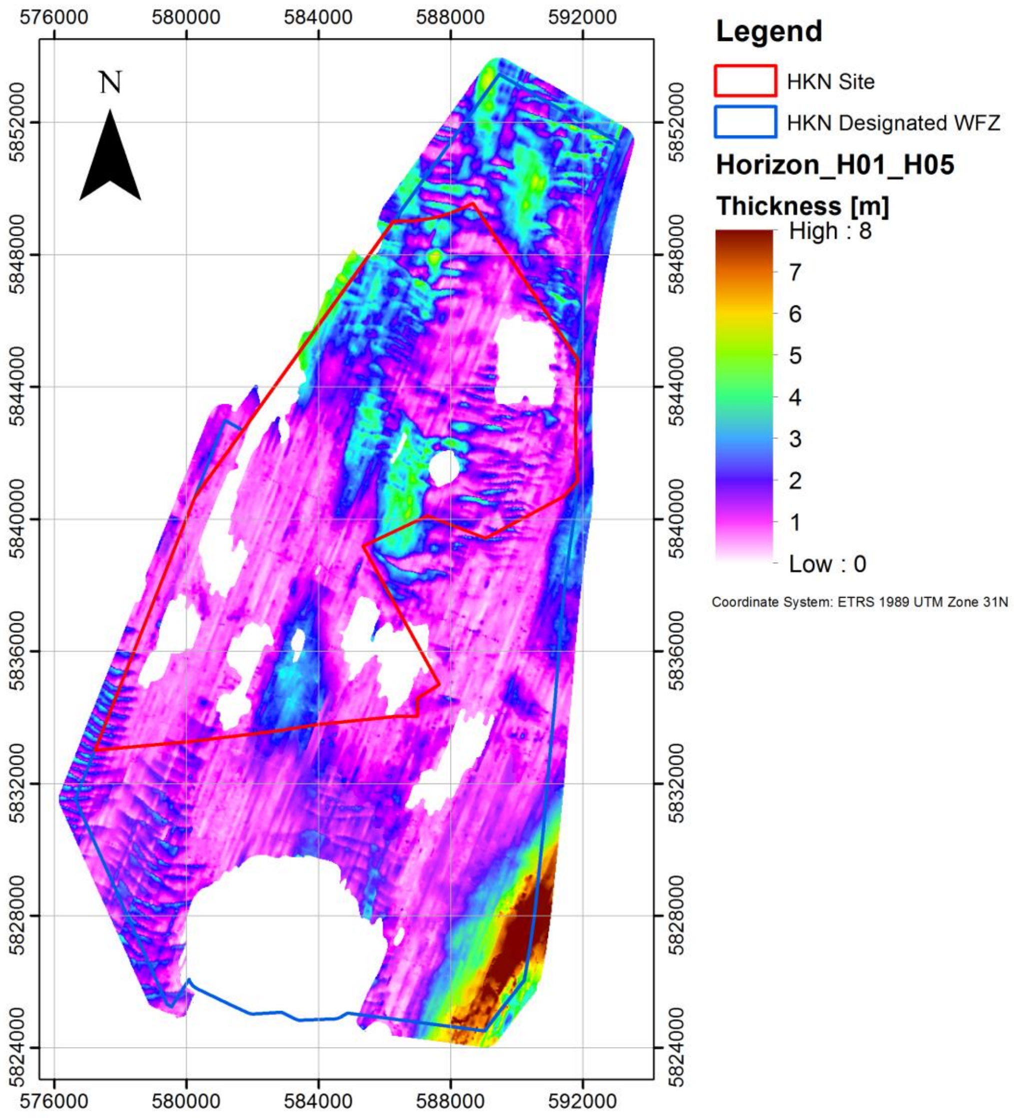


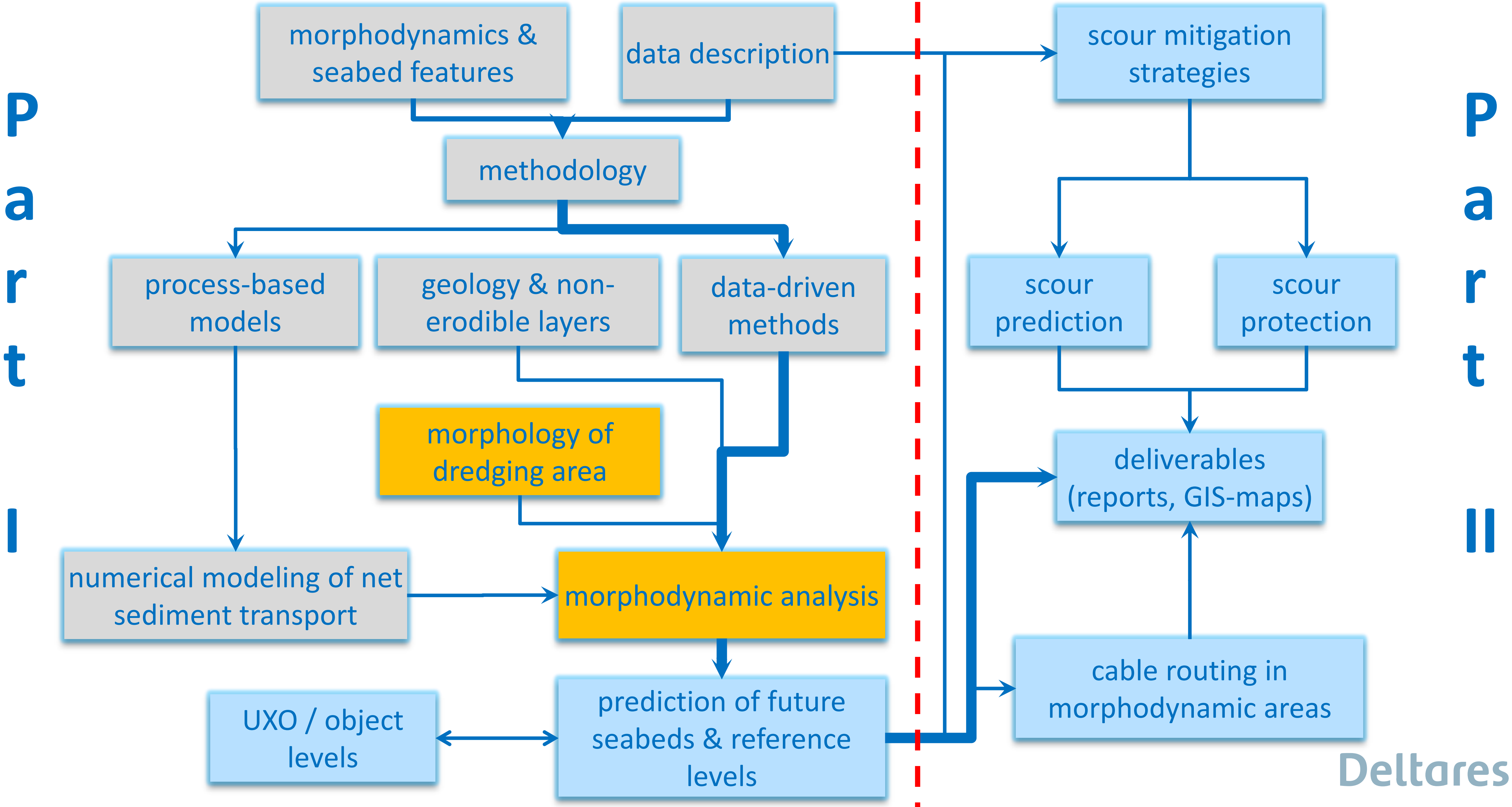
# Geological characterization - Data analysis

- 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
- Non-erodible layers => no expected influence on morphodynamics because too deep or size too limited
- Sediment grain size => large spread in grain sizes

| Unit | Thickness | Lithology |
| --- | --- | --- |
| **Southern Bight Formation** | 1-12 m typically 3 m | Fine to coarse SAND, sparse clay and silt laminae. |
| **Naaldwijk Formation** | 0-7 m | Interbedded CLAY, fine to medium SAND with locally PEAT layers. |
| **Kreftenheye and Boxtel Formation** | 0-25 m typically 5 m | Fine to coarse SAND, with gravel, locally clay, locally boulders |
| **Yarmouth Roads Formation** | 60 to 70 m | SAND, locally clay, locally boulders, occasional peat |



## Structure of presentation

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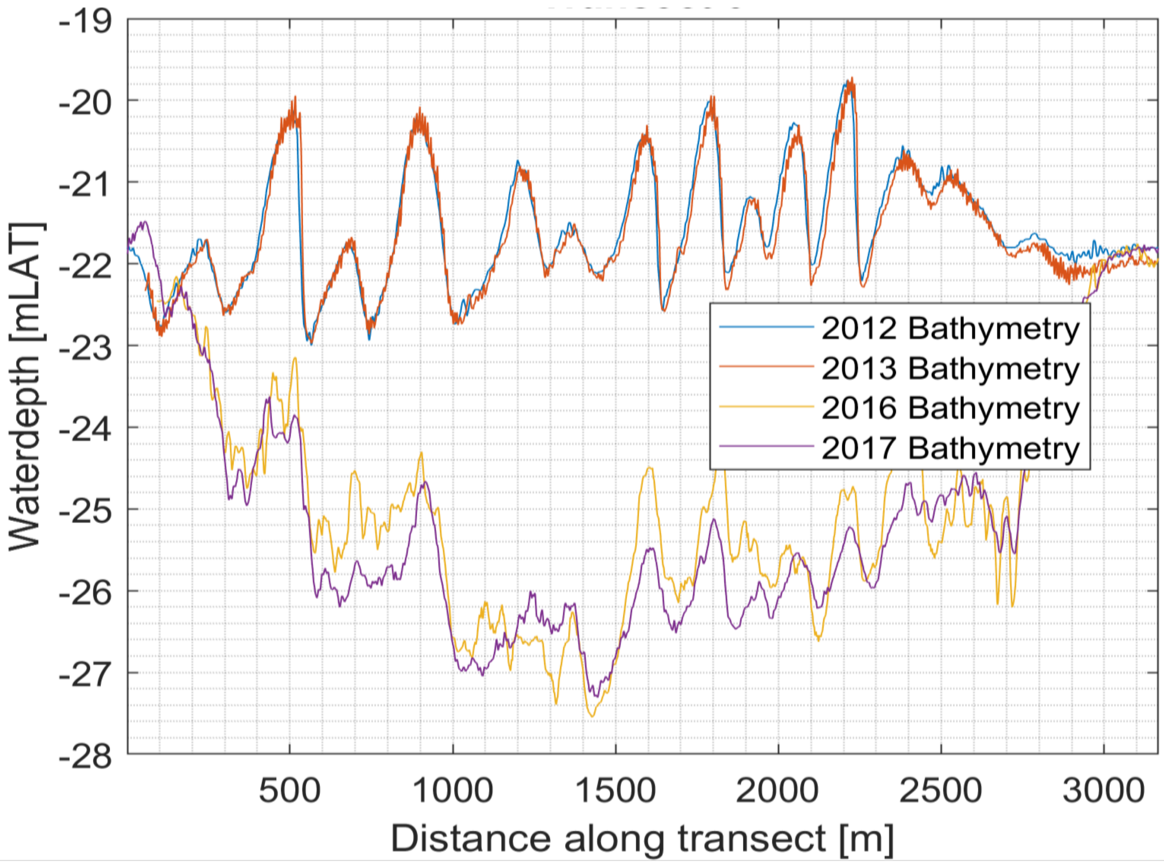
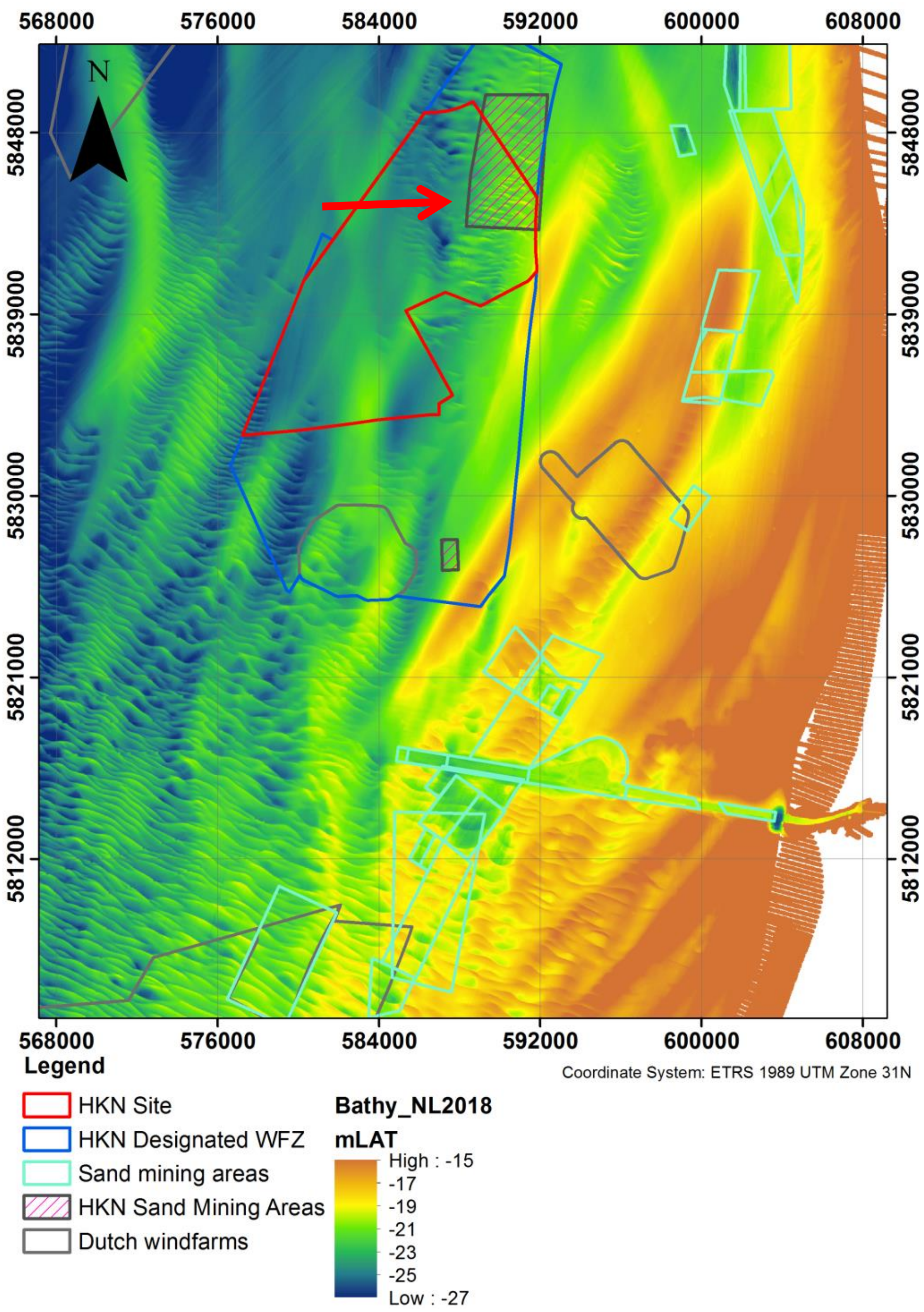
# Sand mining areas (I) – Data analysis

- Sand pits subject to infill process
- Data analysis on two areas with multiple surveys
- Analysis by comparing transects and overview figures



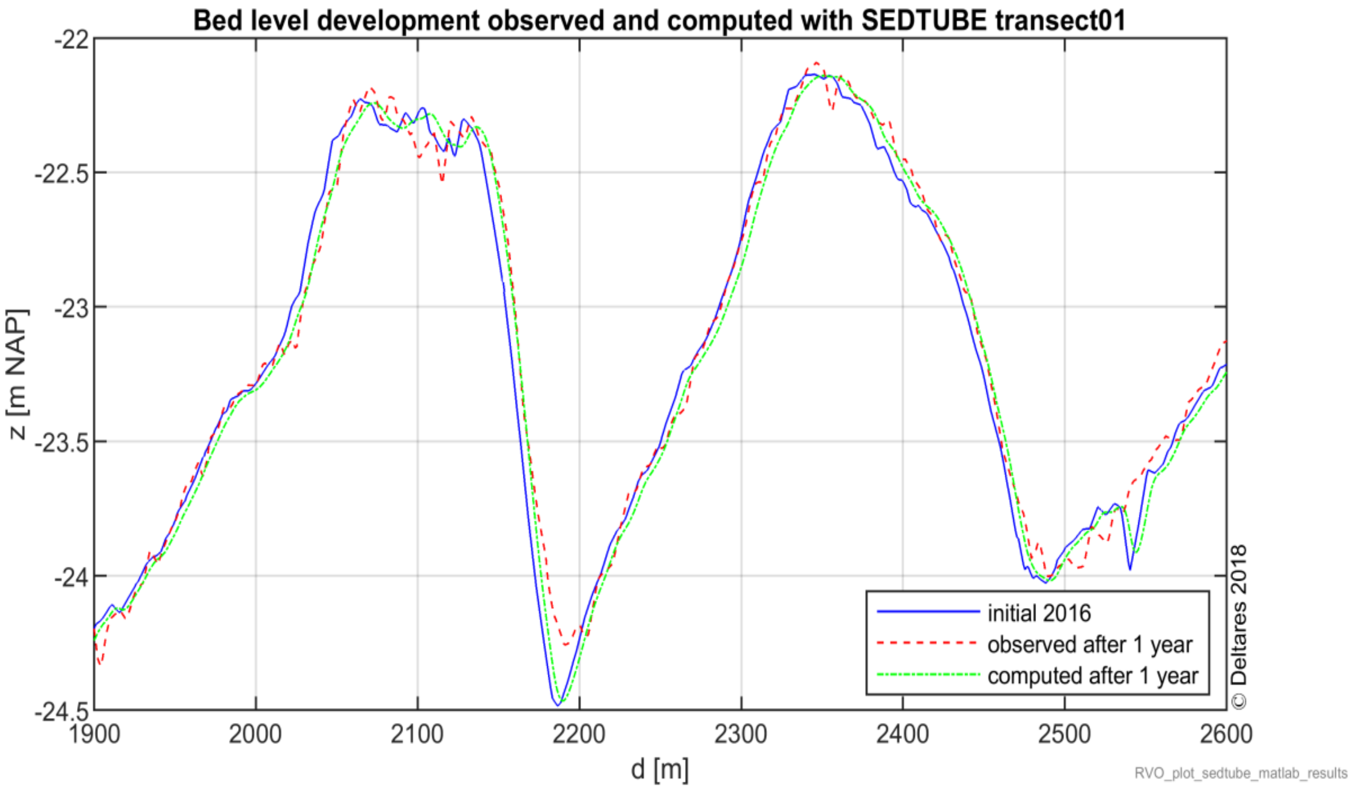



# Sand mining areas (II) – SedTube calibration

- Sand pits subject to infill process
- Future migration computed by means of SedTube model (Van Rijn, 2012)
- Backfill by means of computations of sediment transport variations in a streamtube.

$$\frac{d(bz_b)}{dt}+\left(\frac{1}{(1-p)}\rho_s\right)\frac{d(Q_s+Q_b)}{dx}=0$$

- Calibration of based on adjustment of suspended sediment transport

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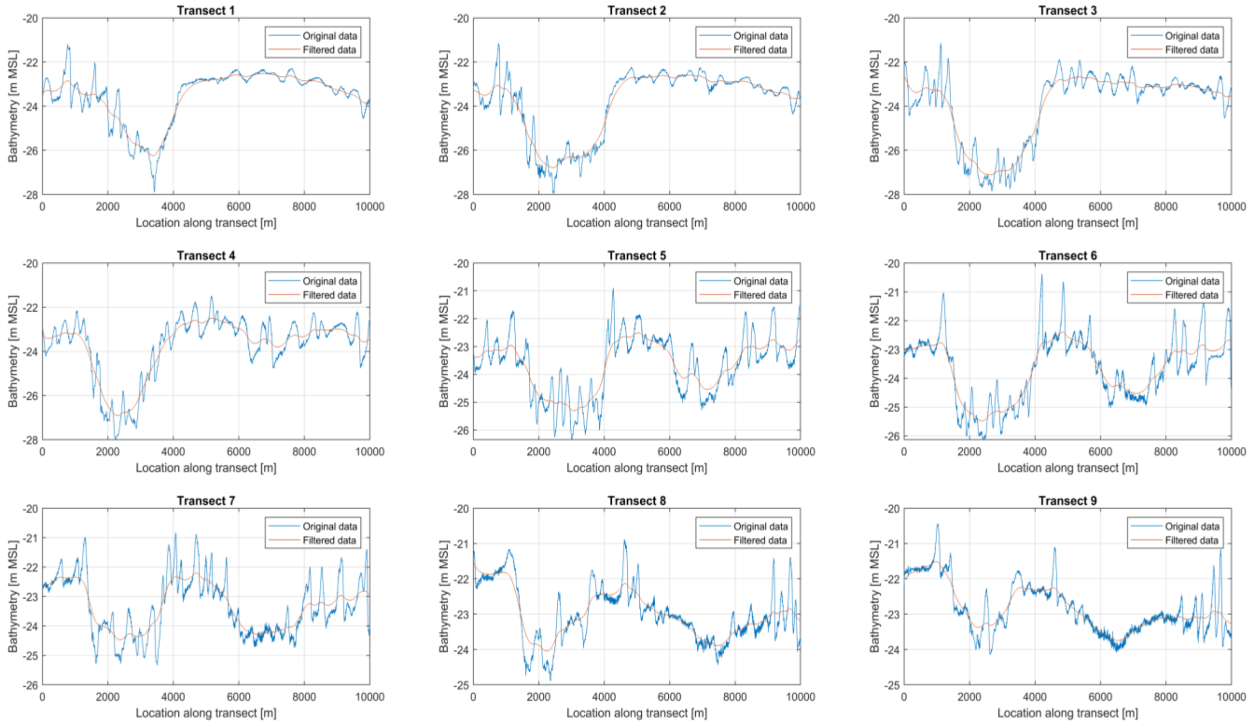
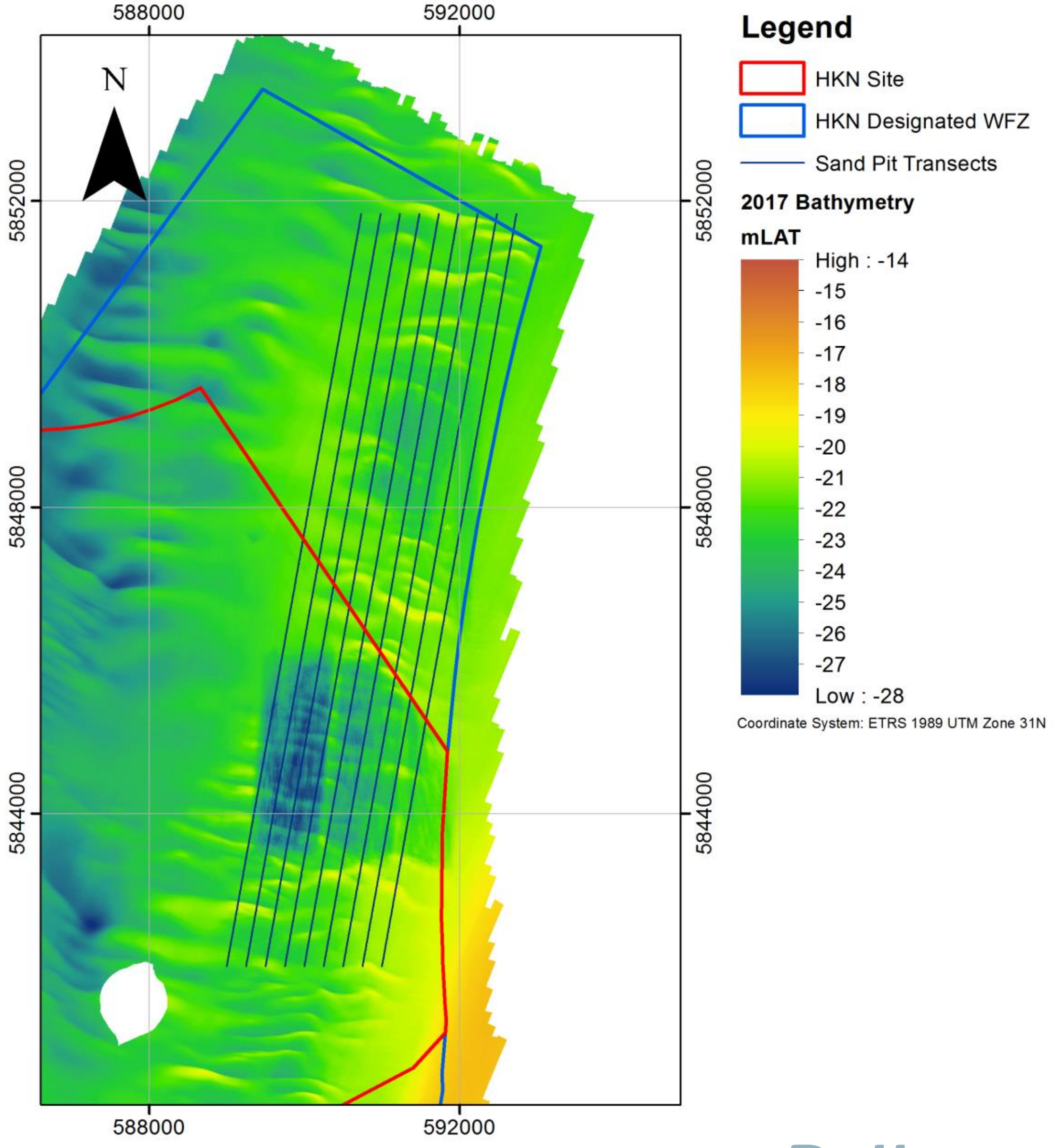
# Sand mining areas (III) – SedTube application

- Analysis along 9 south – north transects
- Transects filtered to exclude smaller bedforms
- Local Hydrodynamics from HKN metocean database (DHI, 2017)
- Analysis performed for different D50 values (150, 250, 350 and 450 μm)

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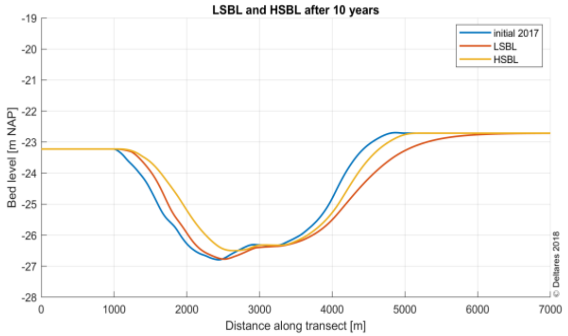
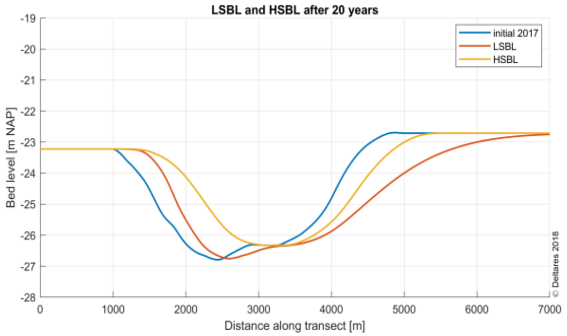
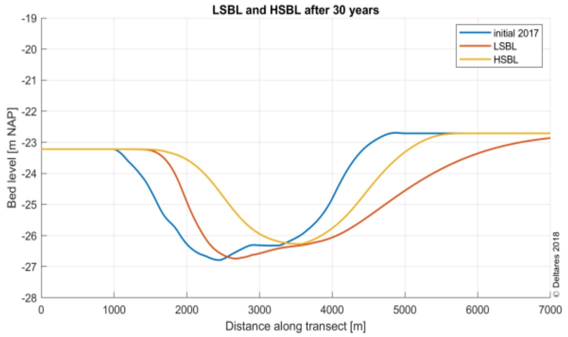
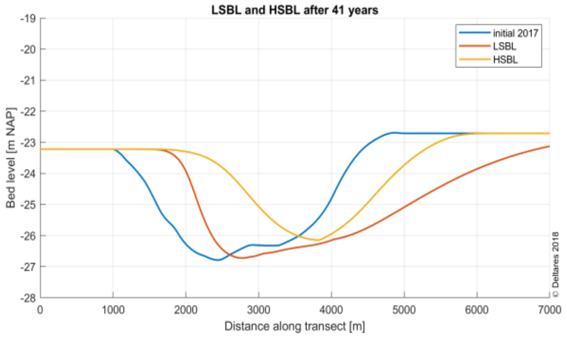
# Sand mining areas (IV) – SedTube results

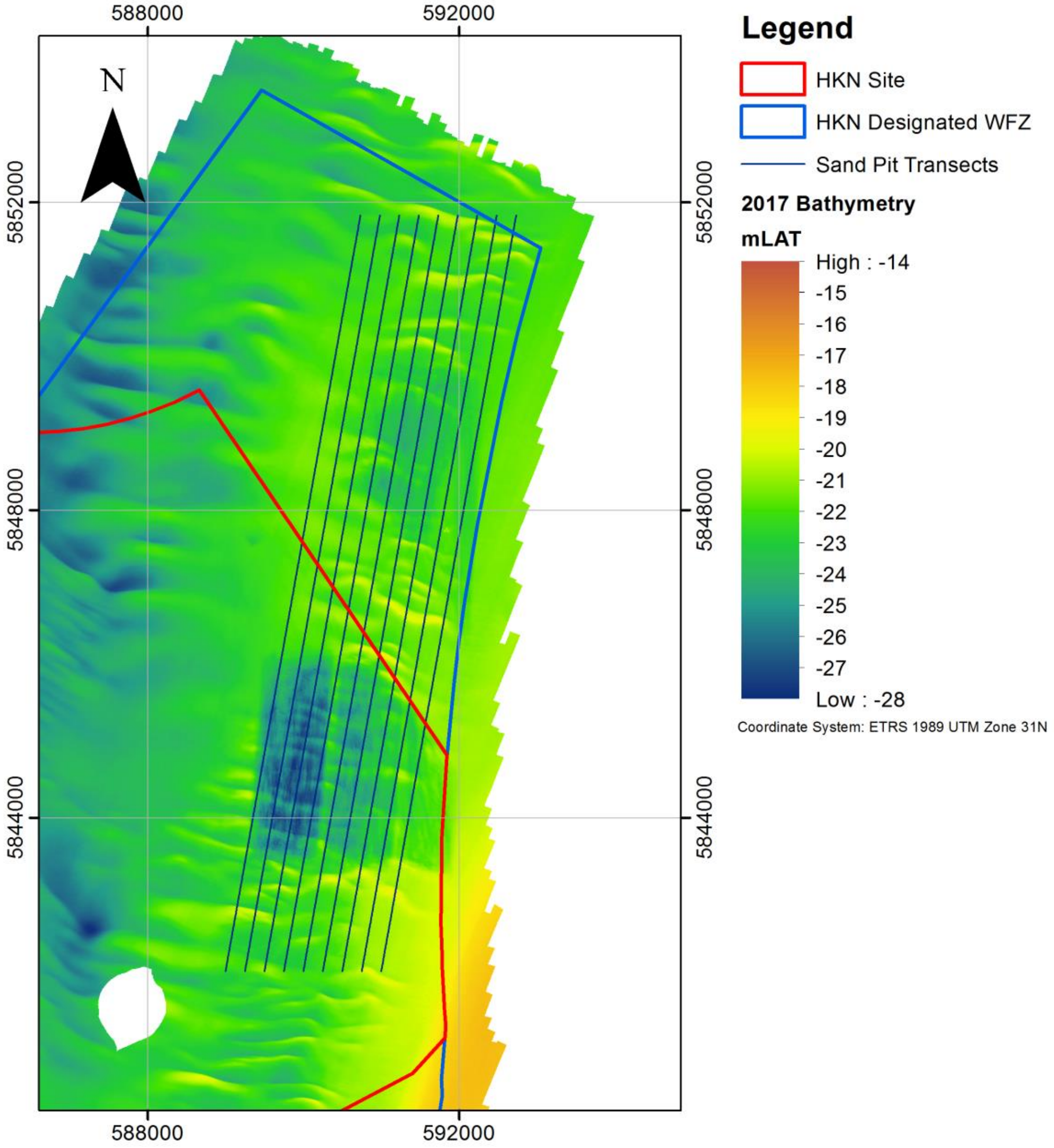
- Infill of sand mining pit over time
- Strong northward migration of pit
- Results for each D50 value are combined to yearly LSBL and HSBL per transect



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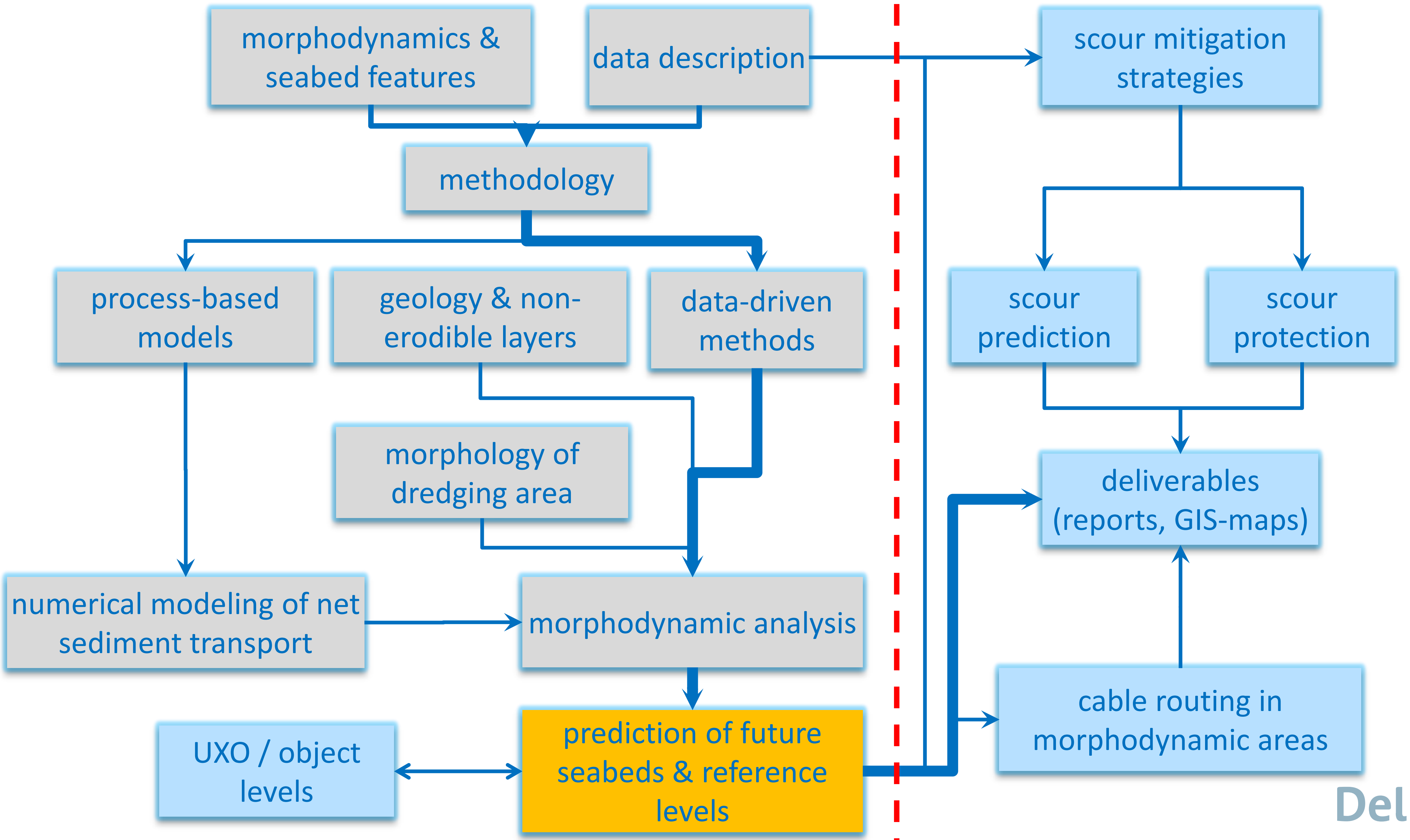
# Structure of presentation

Part I




Part II

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Webinar Morphodynamics and Scour Mitigation Hollandse Kust (Noord)

# Predicting and hindcasting bathymetries

- Extrapolation of morphodynamic trends
  - Sand wave dynamics

    3 sand wave migration directions

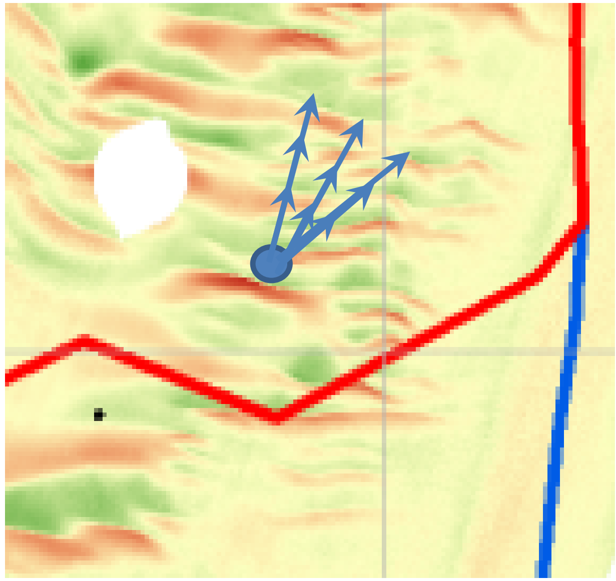
    (lower bound – best estimate – upper bound)

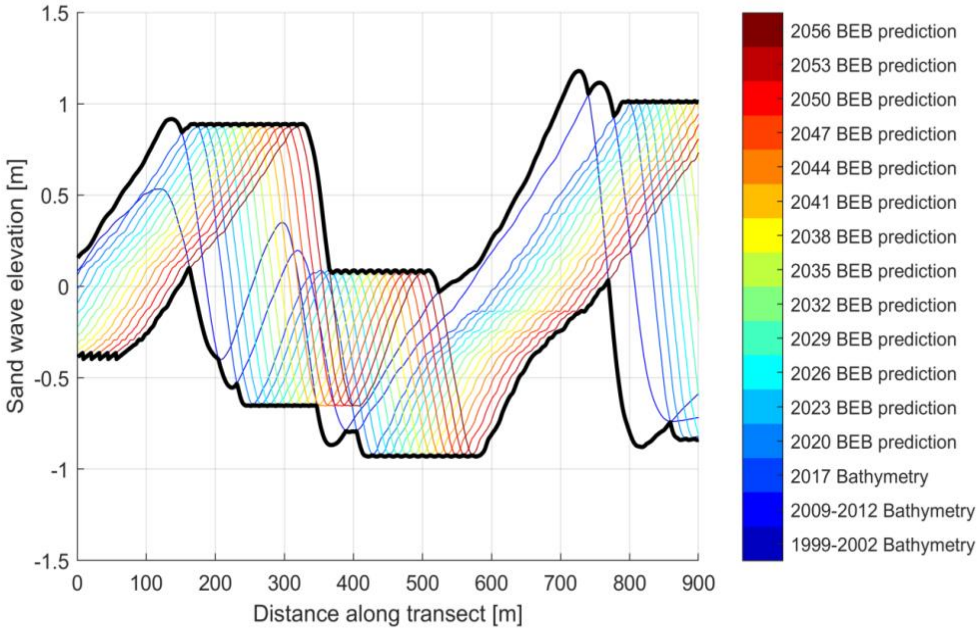
    x 3 estimates for the migration rate

    (minimum, mean and maximum migration rate)
  - Large-scale seabed dynamics
    - Sand pit evolution

- Predicted bathymetries for year 2058 are reconstructed by combining:
  - ✓ (Extrapolated) large-scale bathymetry
  - ✓ Migrated Sand Wave Field 2017 until year 2058
  - ✓ Uncertainty Band

- Hindcasted bathymetries for year 1945 are constructed by combining
  - ✓ (Extrapolated) large-scale bathymetry
  - ✓ Migrated Sand Wave Field 2012 until year 1945
  - ✓ Uncertainty Band





# Dealing with uncertainty (I)

Vertical uncertainty band consists of contributions related to:

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

| | |
|---|---|
| survey uncertainty | = 0.10m (0.25m for hindcast) |
| spatial resolution uncertainty | = 0.10m |
| uncertainty upward | = 0.20m (0.35m for hindcast) |

| | |
|---|---|
| survey uncertainty | = -0.10m (-0.25m for hindcast) |
| spatial resolution uncertainty | = -0.05m |
| uncertainty downward | = -0.15m (0.30m for hindcast) |

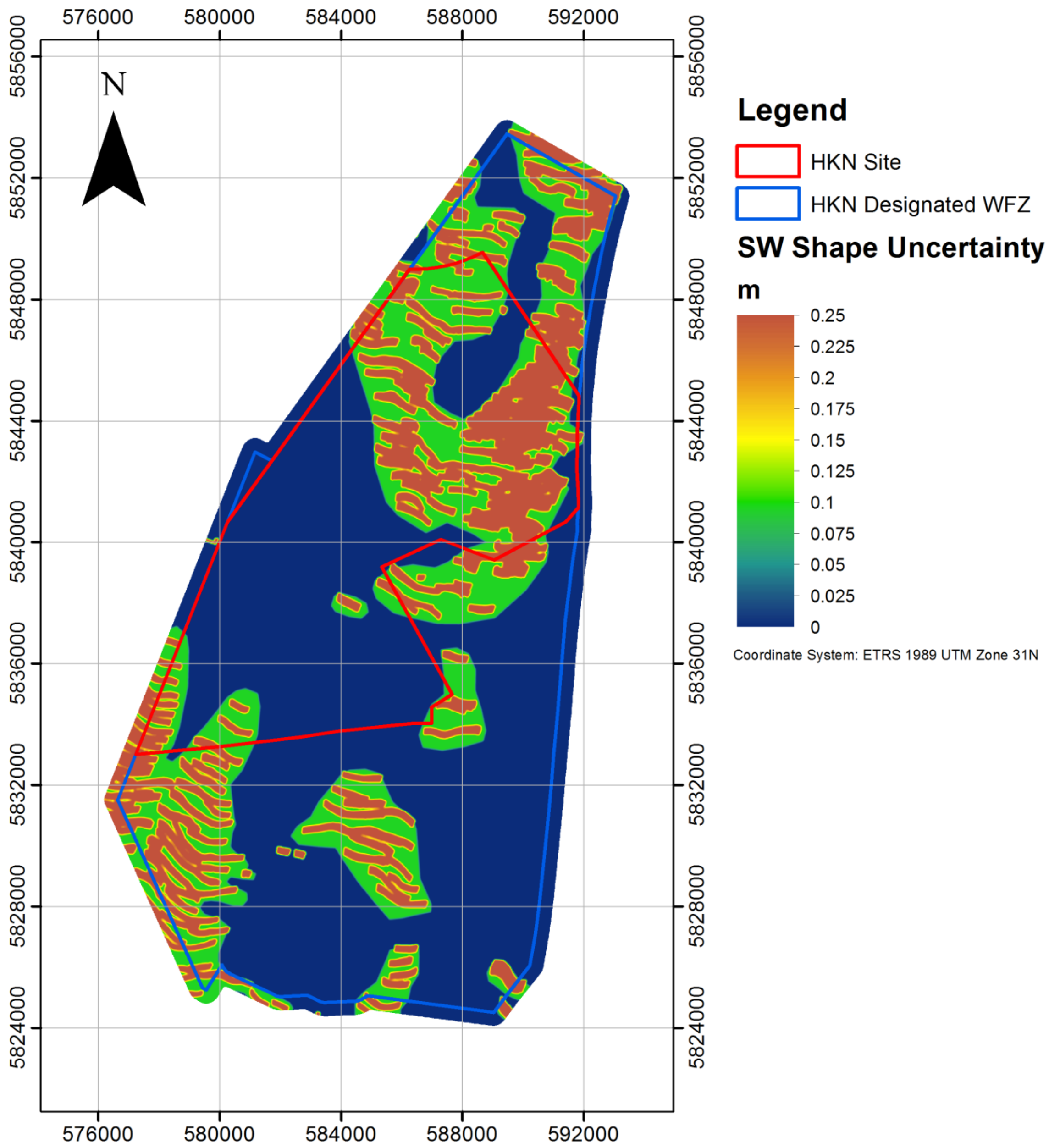
Furthermore two spatial varying uncertainties are added:

- Megaripple uncertainty
- Uncertainties in sand wave heights

# Dealing with uncertainty (II) – Sand wave shape uncertainty

Additional spatial varying uncertainty based on uncertainties in sand wave shapes

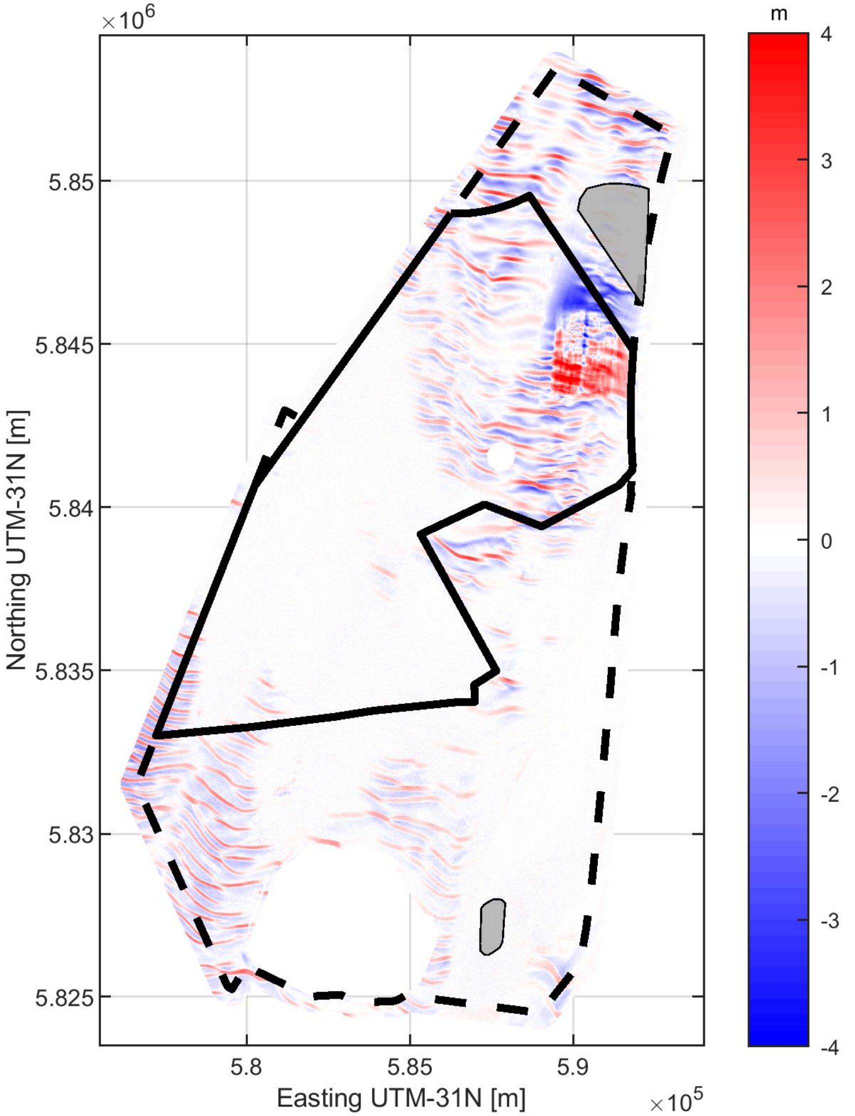
- ➢ Minor effect based on correlation of sand wave dimensions (2012-2017)
- ➢ Three different values for uncertainty:
  - 0.00m outside of sand wave fields
  - 0.10m in the sand wave fields
  - 0.25m at the sand wave crest
- ➢ Sand wave crest locations are tracked over time



# Best-Estimate Bathymetry 2058: BEB2058

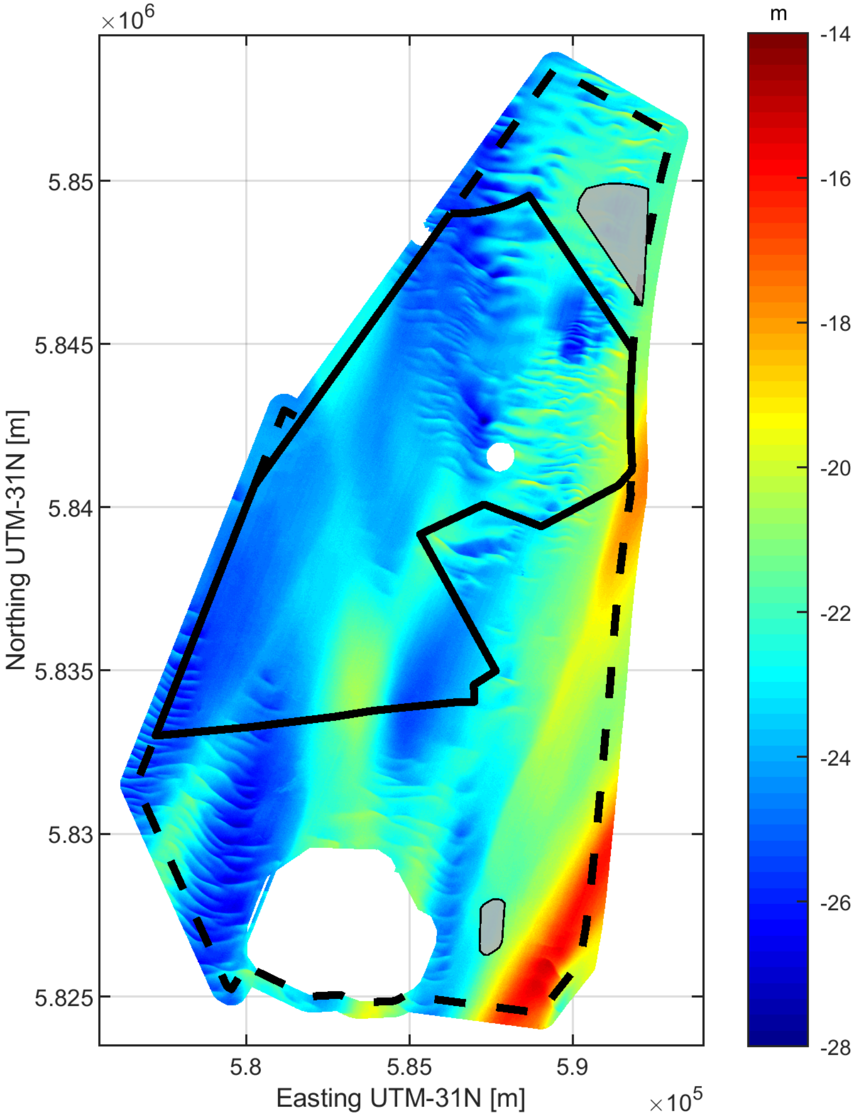
*Movie illustrating Best-estimate bathymetries*

Difference with 2017 bathymetry




combined with

Static Bathymetry: $BEB_{2058}$

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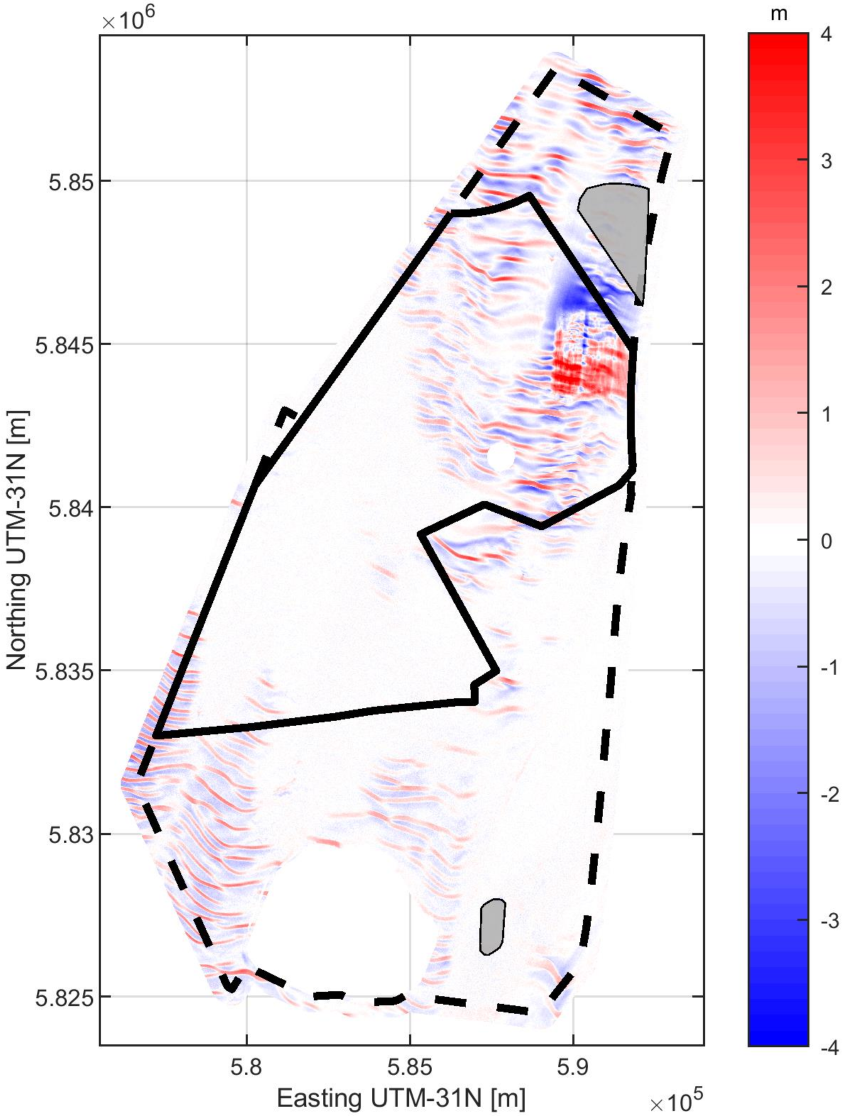
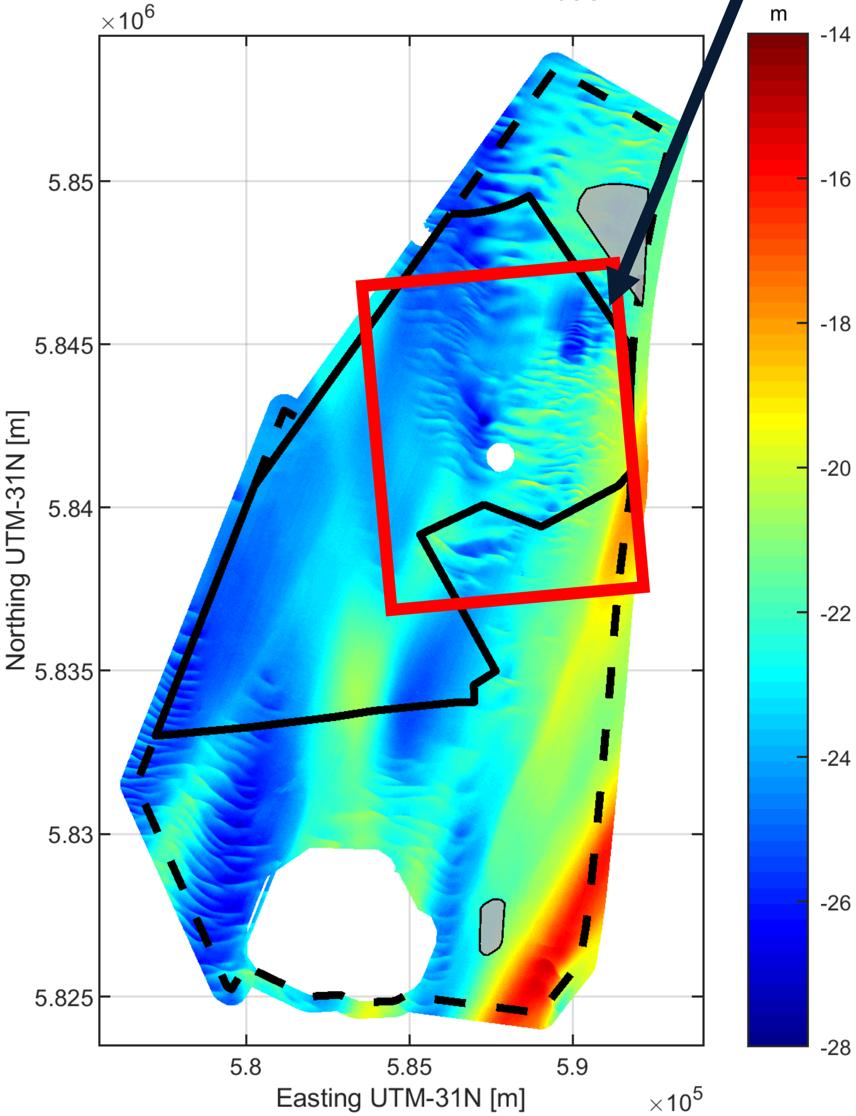
# Best-Estimate Bathymetry 2058: BEB2058

Difference with 2017 bathymetry




combined with
Static Bathymetry: $BEB_{2058}$

*Movie illustrating Best-estimate bathymetries*

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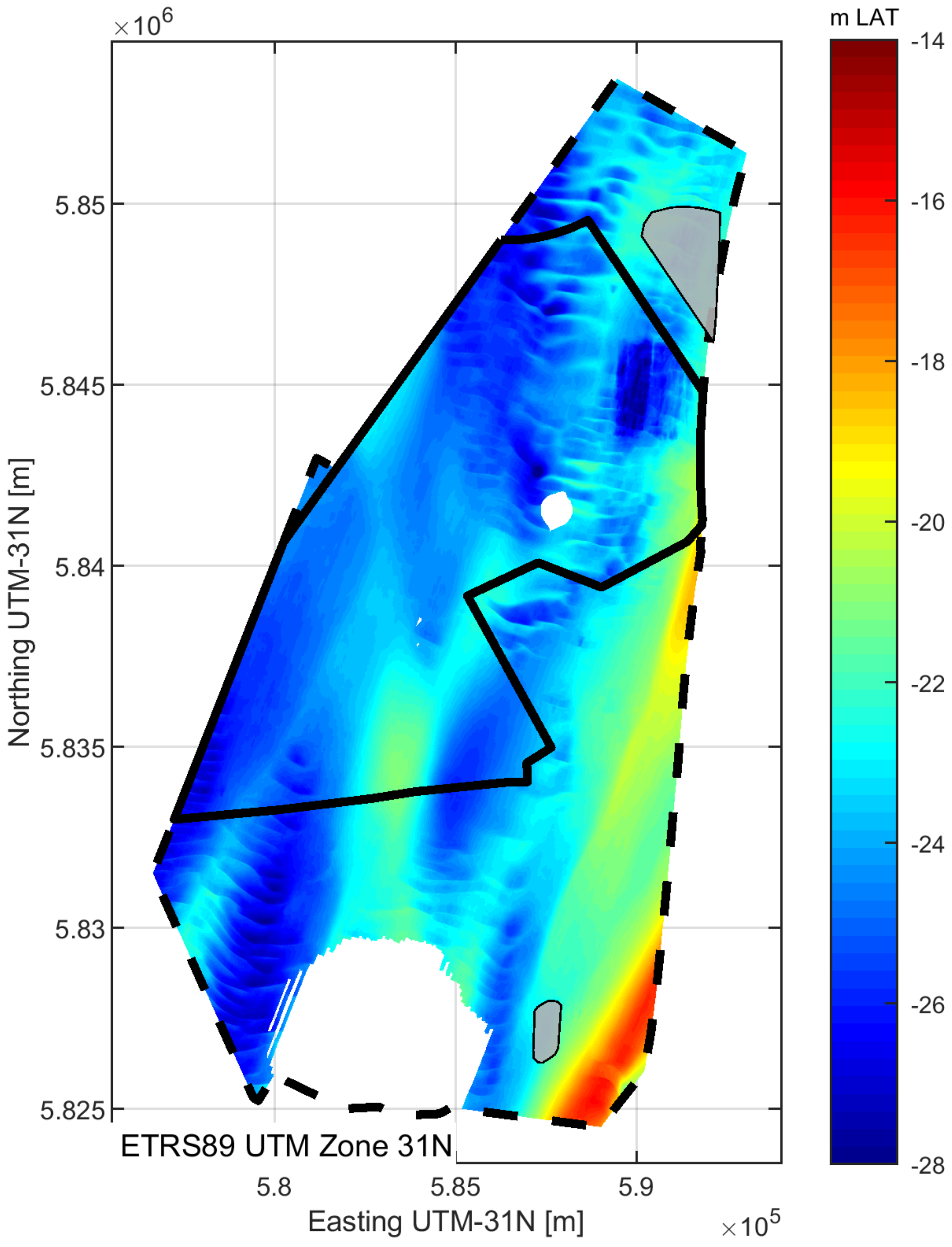
# Lowest SeaBed Level: LSBL

Lowest SeaBed Level
*The lowest possible seabed level during the lifetime of the wind parks (i.e. 2017-2058)*

+ Static Seabed Level
- Lower envelope of Sand Wave Field until 2058
- Downward uncertainty band

Lowest SeaBed Level (LSBL)

The LSBL varies between -15.8 m and -28.5 m LAT

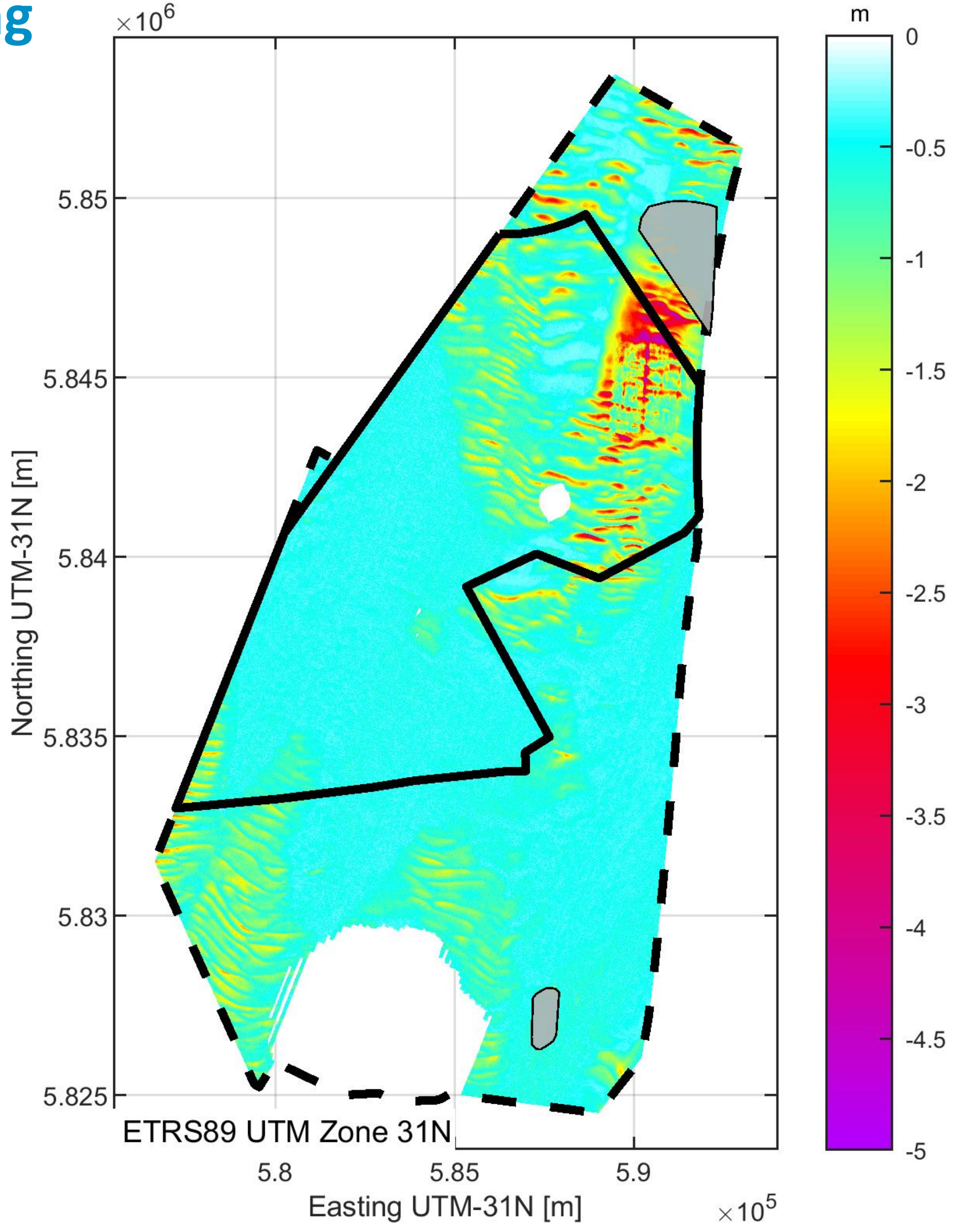


# Maximum Potential Seabed Lowering

Maximum Potential Seabed Lowering = Difference between 2017-bathymetry and LSBL

- ➢ Relatively gentle seabed lowering at stoss sides of sand waves
- ➢ Significant lowering North of the sand mining area
- ➢ 99% non-exceedance lowering of -2.6m

*Movie illustrating cumulative downward seabed movement*

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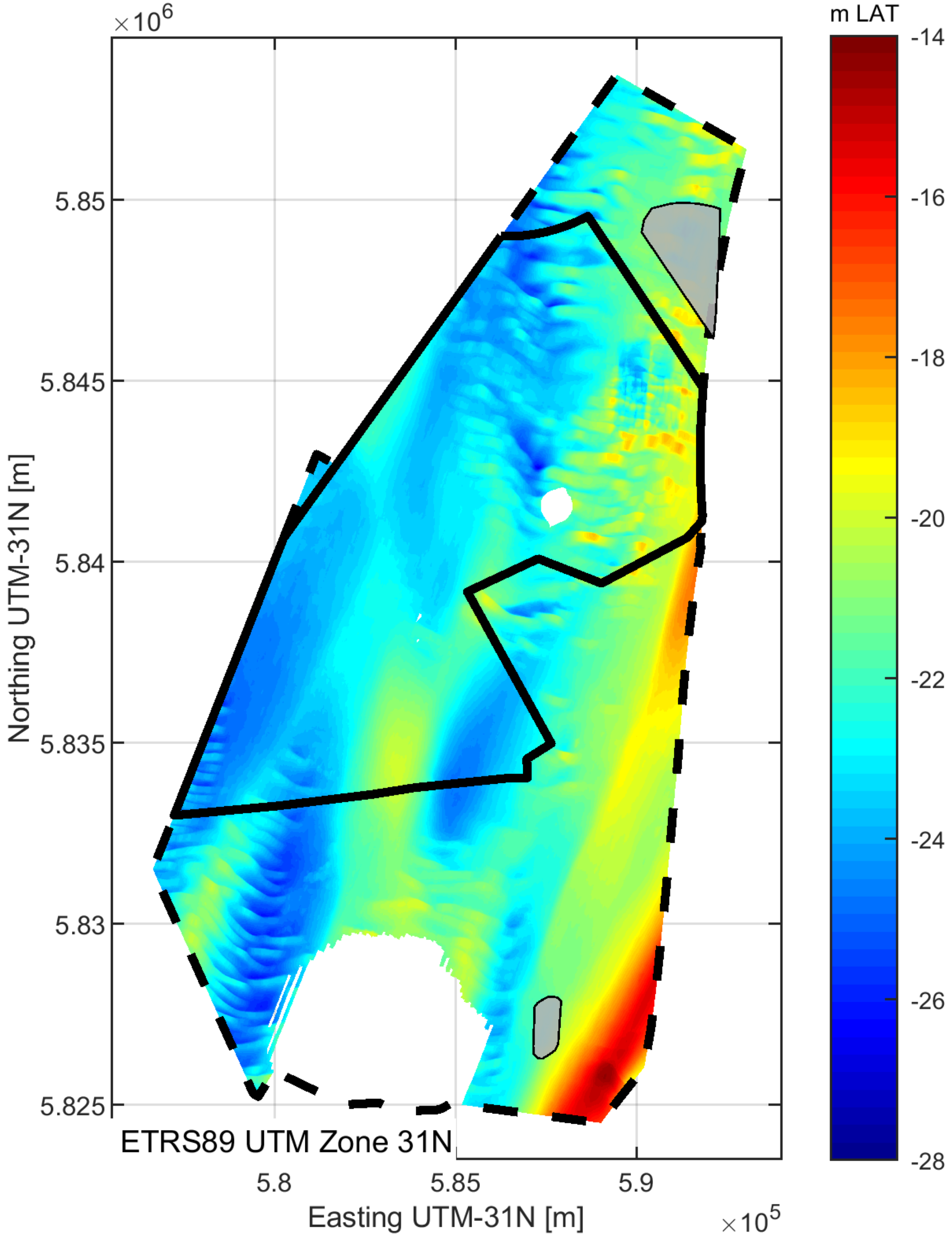
# Highest SeaBed Level: HSBL

Highest SeaBed Level
*The highest possible seabed level during the lifetime of the wind parks (i.e. 2017-2058)*

\+ Static Seabed Level
\+ Upper envelope of Sand Wave Field until 2058
\+ Upward uncertainty band
Highest SeaBed Level (HSBL)

The HSBL varies between -14.4 m and -26.8 m LAT

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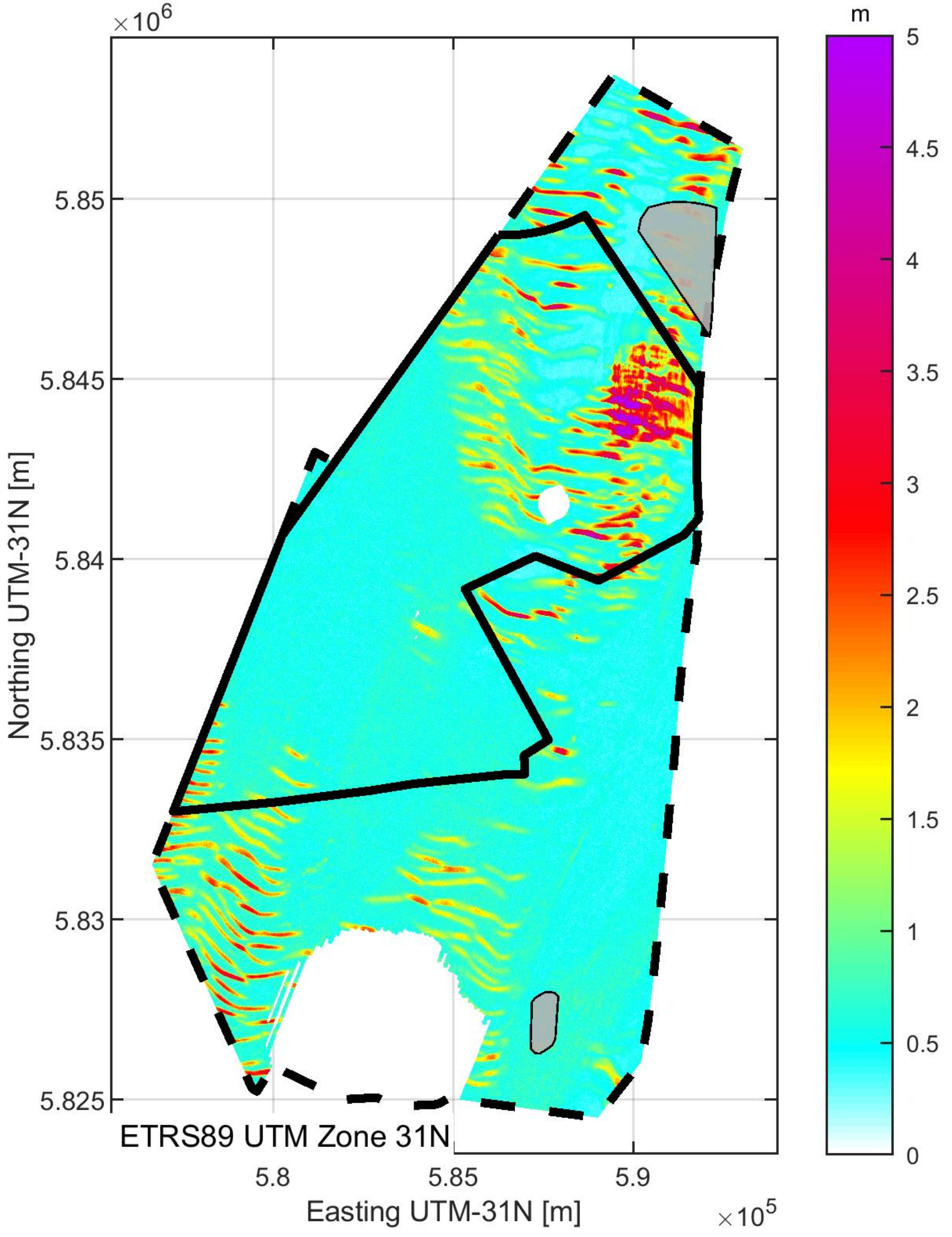
# Maximum Potential Seabed Rise

Maximum Potential Seabed Rising =
Difference between
2017-bathymetry and HSBL

- significant seabed rising but only just downstream of lee sides of sand waves
- Significant seabed rise in the sand mining pit
- 99% non-exceedance rising of 3.2m

*Movie illustrating cumulative upward seabed movement*

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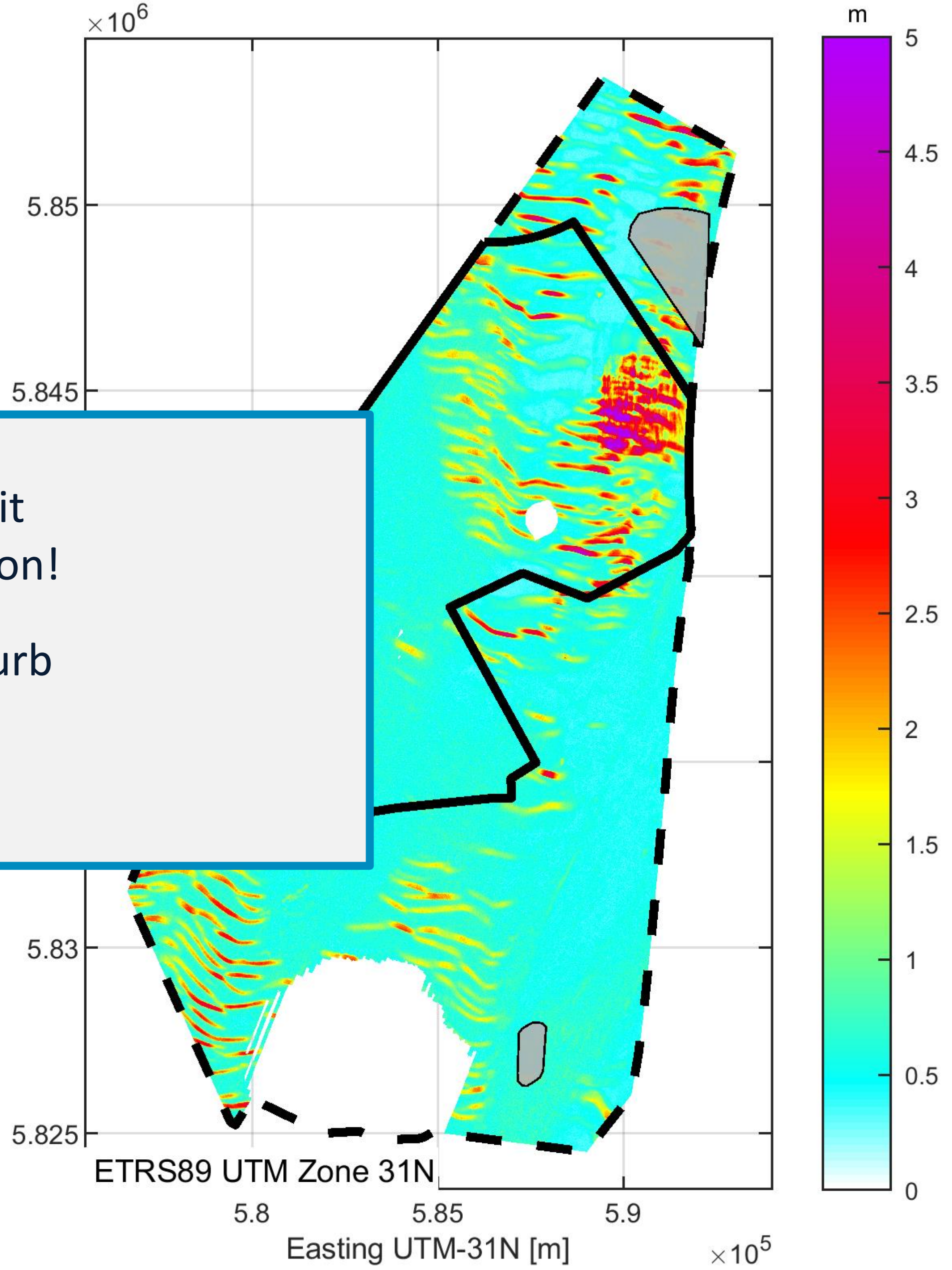
# Maximum Potential Seabed Rise

Maximum Potential Seabed Rising
=
Difference between
2017-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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Hollandse Kust (Noord)

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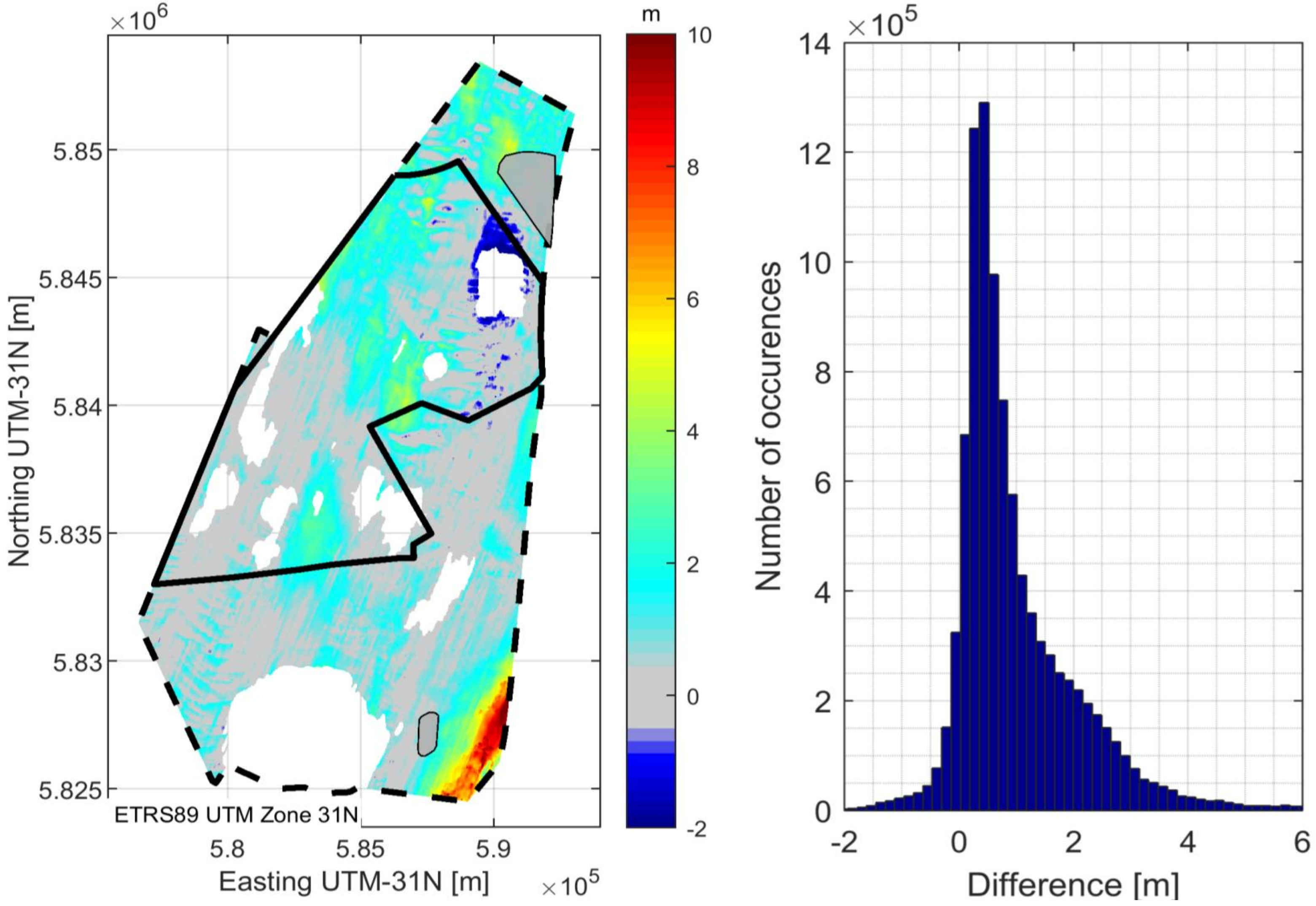
# Determining remaining layer thickness

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

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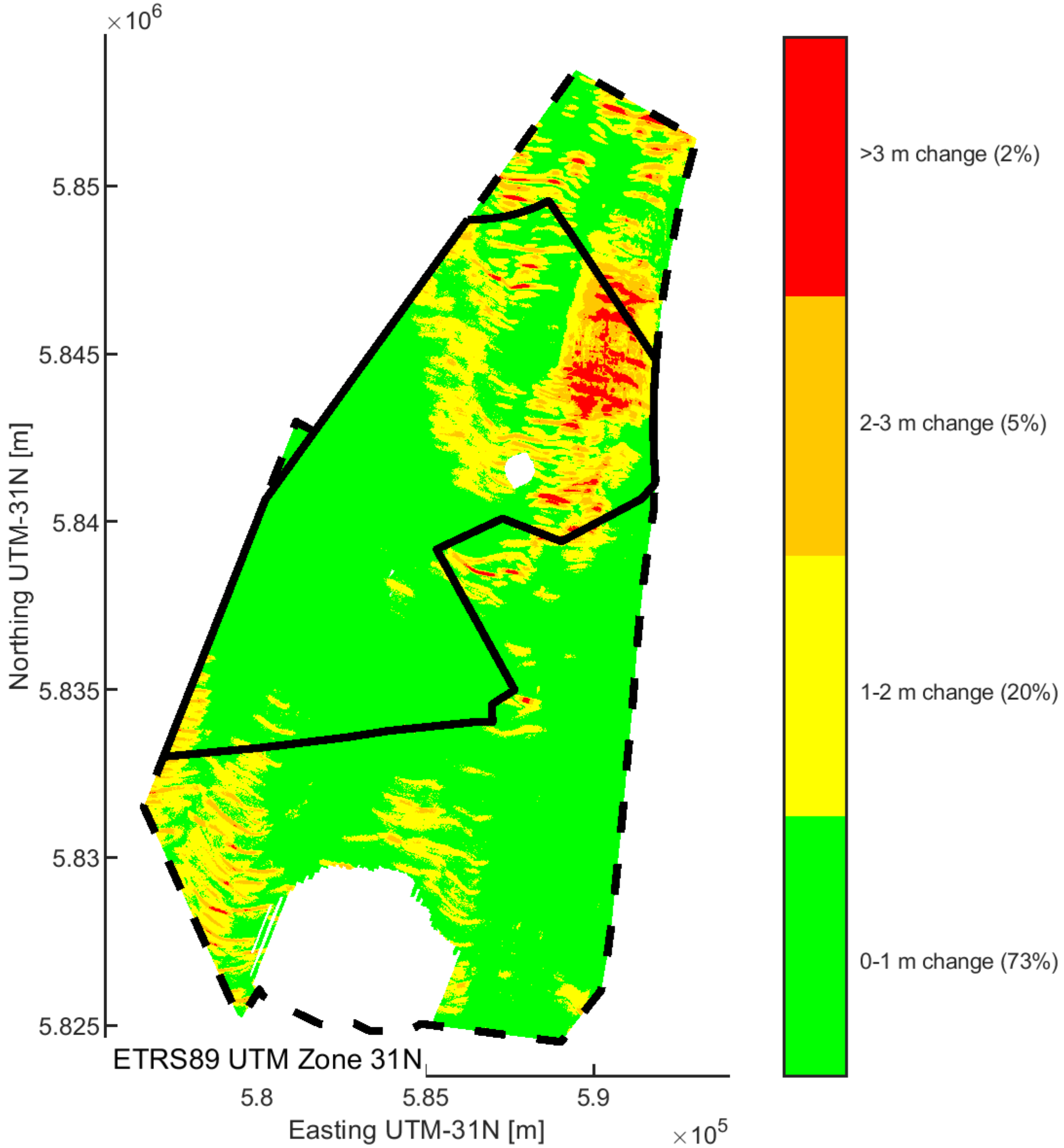
# Classification zones (I)

- Next step: translate HSBL and LSBL and corresponding seabed changes to “Classification Zones”
- 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 of zones | Bed level lowering [m] | Bed level rising [m] |
|---|---|---|
| 0-1 m change | 0 > dz ≥ -1 | 0 < dz ≤ 1 |
| 1-2 m change | -1 > dz ≥ -2 | 1 < dz ≤ 2 |
| 2-3 m change | -2 > dz ≥ -3 | 2 < dz ≤ 3 |
| >3 m change | dz < -3 | dz > 3 |

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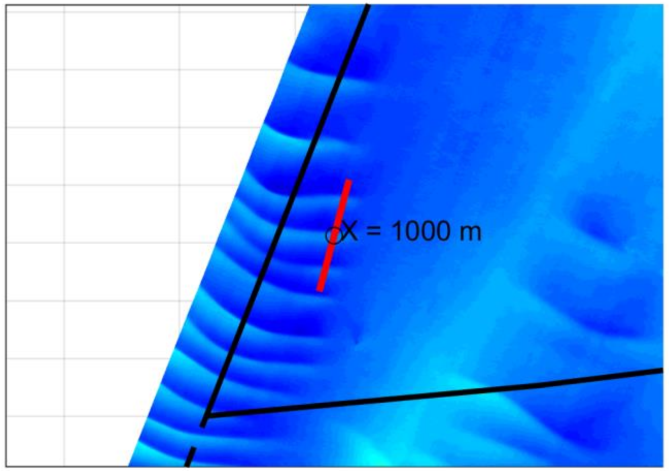
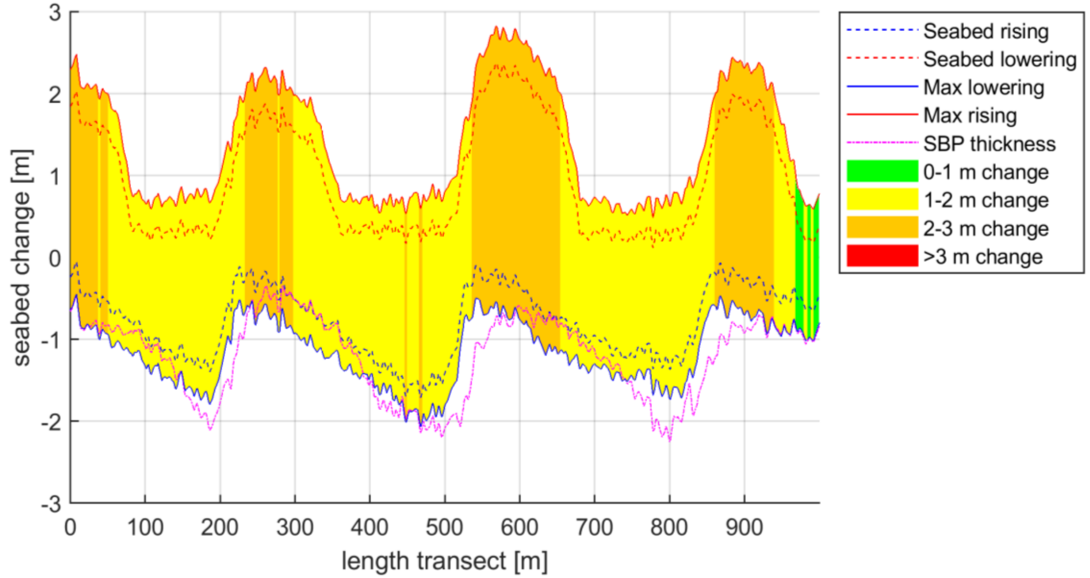
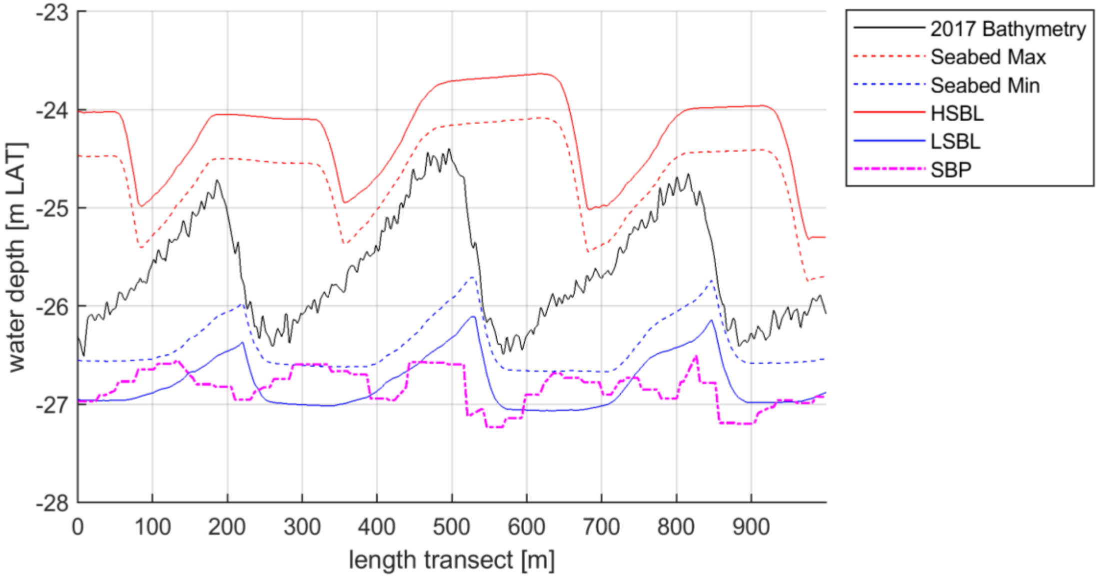
# Classification zones (II)

Example for one transect:

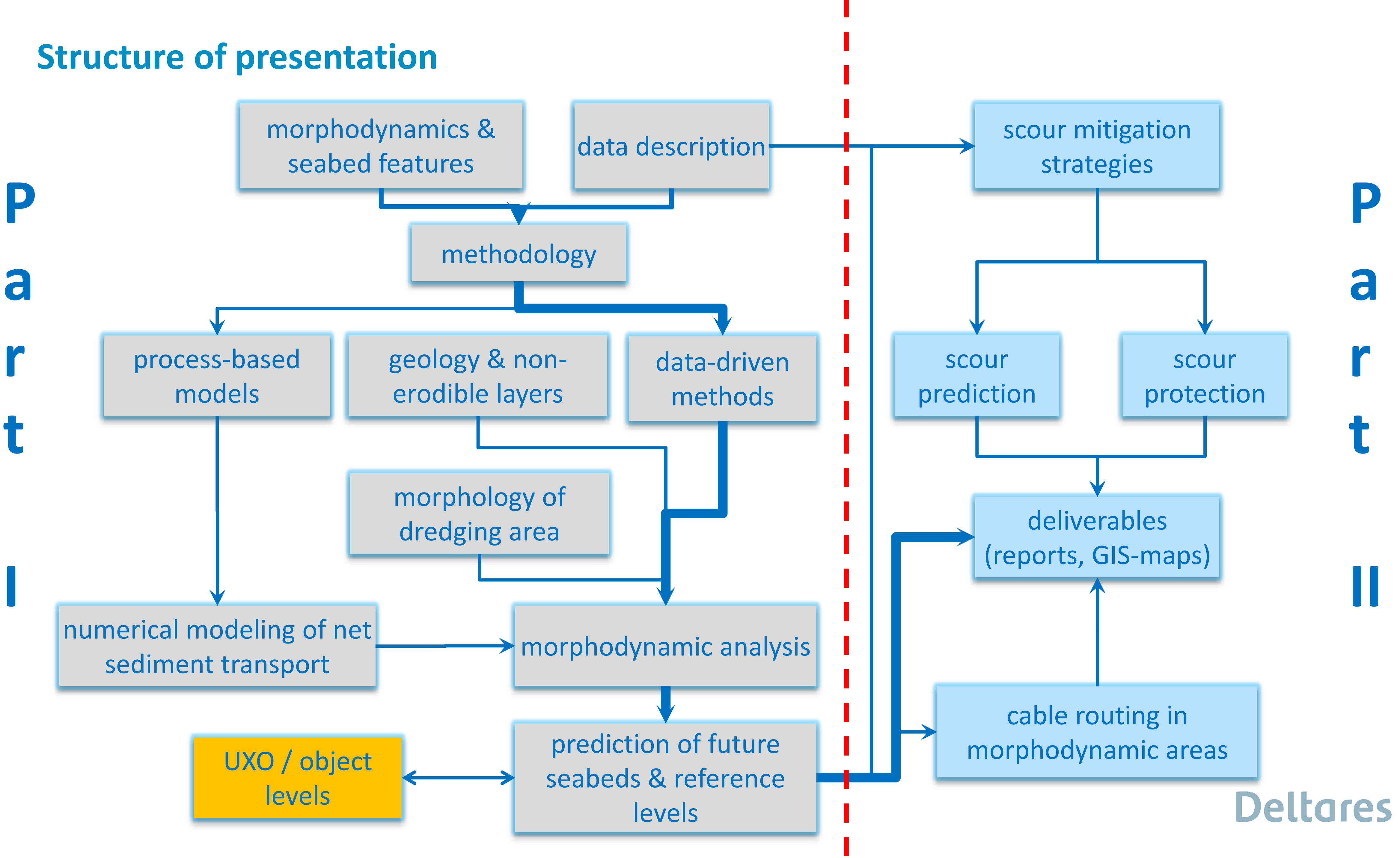
- Classification calculated for both rising and lowering seabed
- Most strict classification (rising/lowering) is used



# Structure of presentation

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# Lowest Object Level: LOL

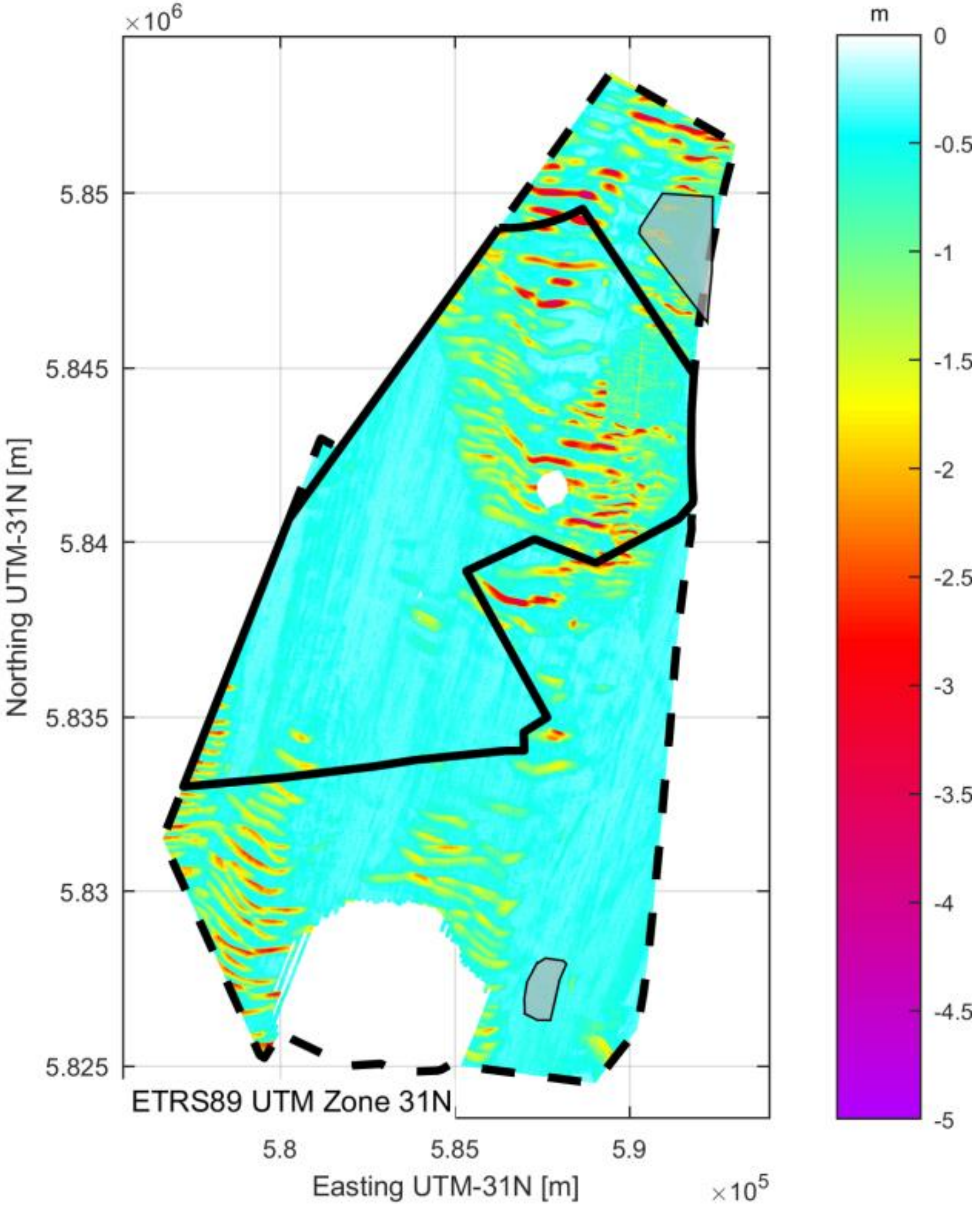
Lowest SeaBed Level
*The lowest possible seabed level during the period 2021-1945*

\+ Static Seabed Level
\- Lower envelope of Sand Wave Field until 1945
\- Downward uncertainty band

Lowest Object Level (LOL)

The LOL varies between -15.9 m and -28.7 m LAT

99% non-exceedance difference between 2017 and $LOL_{1945}$ of -2.6m

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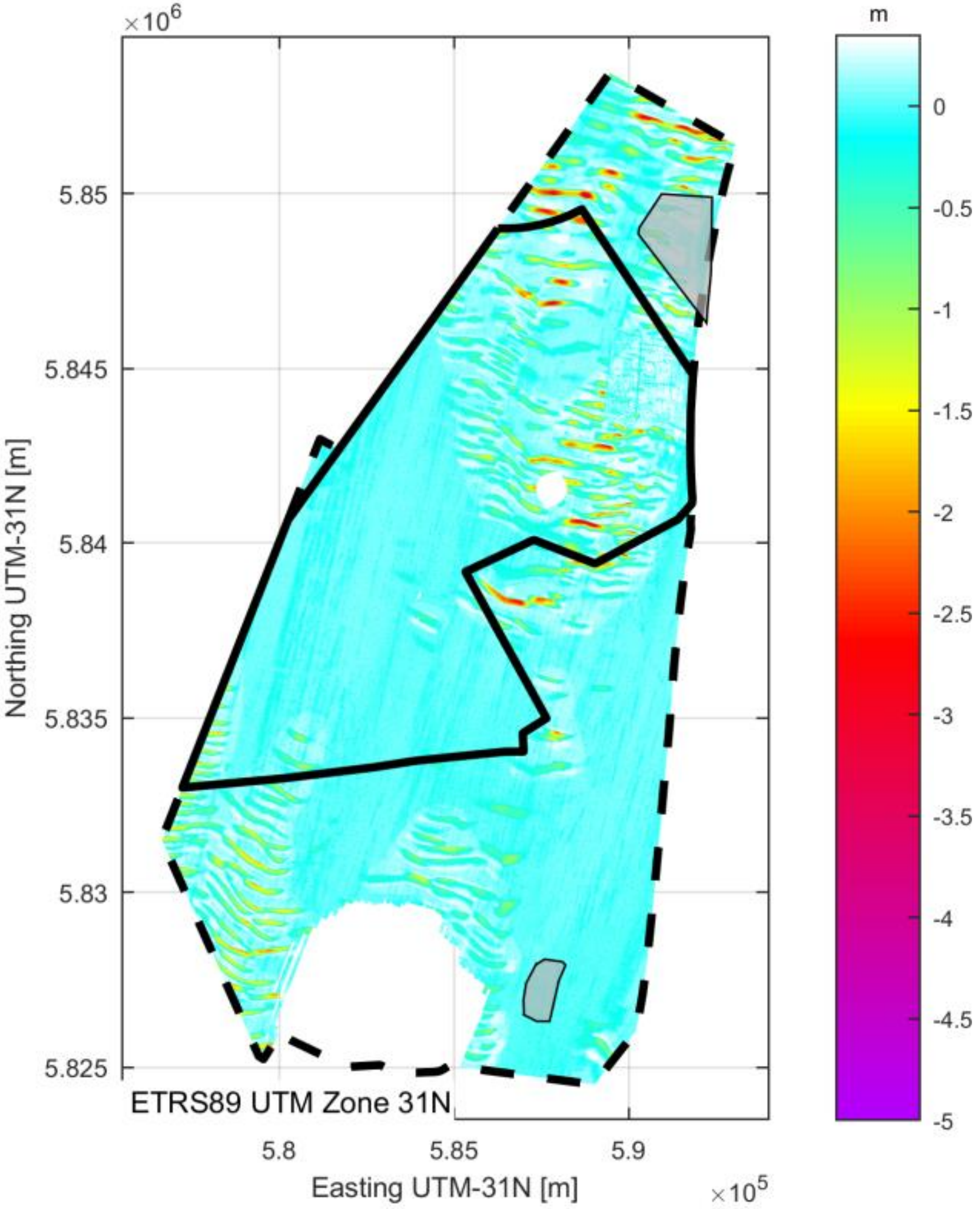
# Highest Object Level: HOL

Highest Object Level
*The highest possible object level during the period 2021-1945*

\+ Static Seabed Level
\+ Upper envelope of yearly lower envelope Sand Wave Field until 1945
<u>+ Upward uncertainty band</u>
Highest Object Level (HSBL)

The HSBL varies between -15.1 m and -27.8 m LAT

99% non-exceedance difference between 2017 and $HOL_{1945}$ of -1.6m

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# Conclusions (I)

- The bathymetry in the Hollandse Kust (noord) Wind Farm Zone (HKNWFZ) has a non-uniform morphology including a number of prominent sand banks and a partial cover of sand waves
- 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 380 m, average height of 1.6 m and typical migration speeds are in the order of 3.2 m/yr in north-northeastern direction

| | Sand wave height non-exceedance (2017) [m] | | Sand wave length non-exceedance (2017) [m] | | Migration speed [m/yr] in most frequently observed direction 15°N | |
|---|---|---|---|---|---|---|
| | 50% | 95% | 50% | 95% | 50% | 95% |
| HKNWFZ | 1.6 | 2.9 | 380 | 690 | 3.2 | 5.4 |

- 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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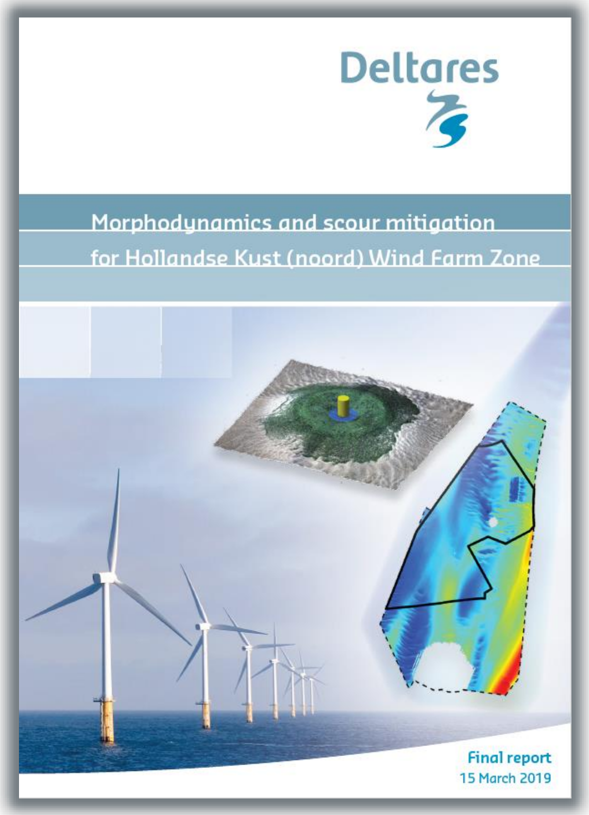
# Conclusions (II)

- Geology and numerical analysis results support findings from data analysis
- Lowest SeaBed Level (LSBL) and Highest SeaBed Level (HSBL) are determined for a bandwidth of future seabed levels
- Largest seabed changes are expected in the sand wave areas and within and north of the sand mining pit
- Classification Zones are determined based on estimated ranges for downward and upward seabed changes
- Lowest Object Level (LOL) and Highest Object Level (HOL) are determined for a bandwidth of future seabed levels

## Key take-aways

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




more information? tim.raaijmakers@deltares.nl
tom.roetert@deltares.nl

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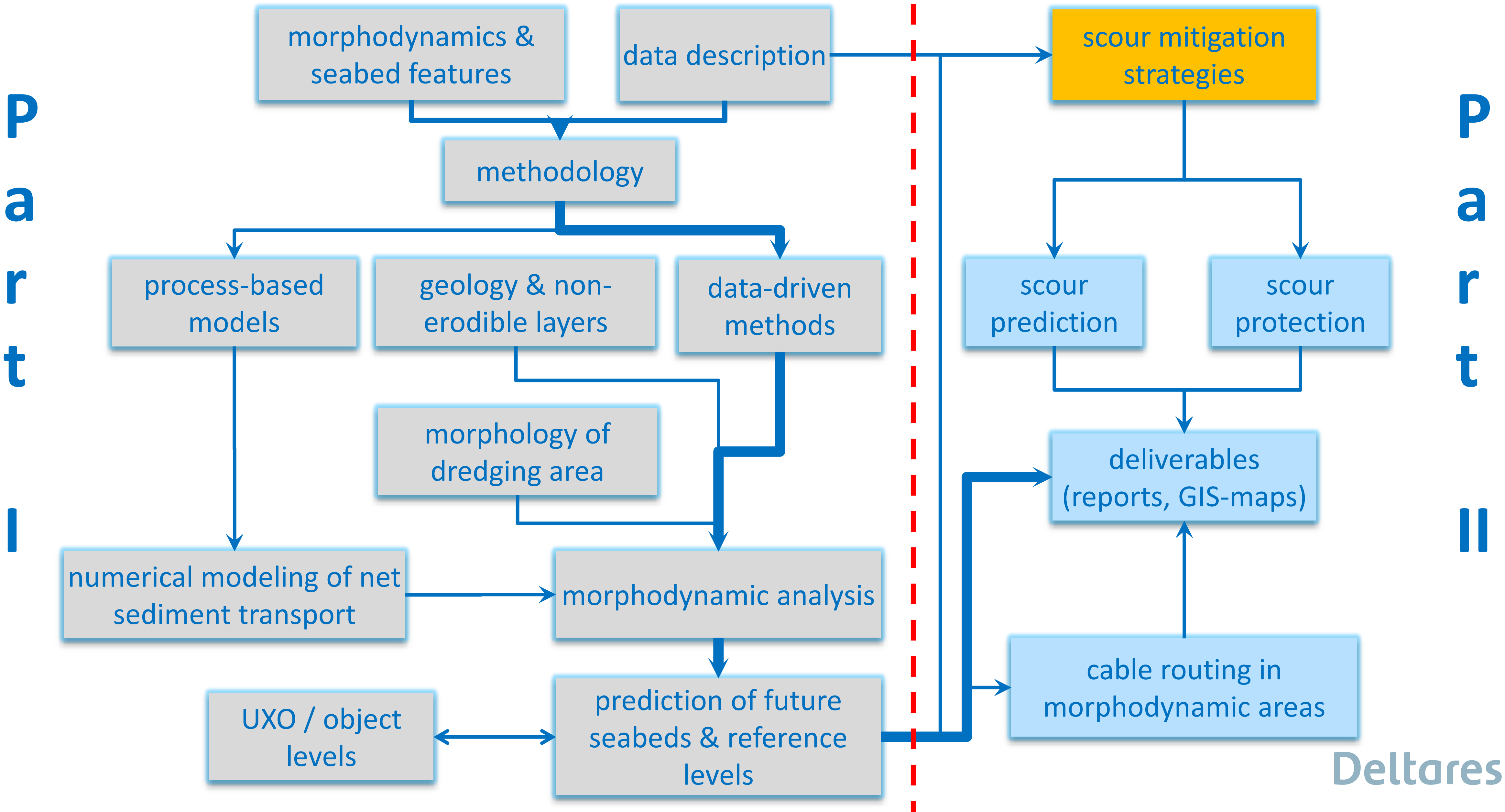
# Structure of presentation

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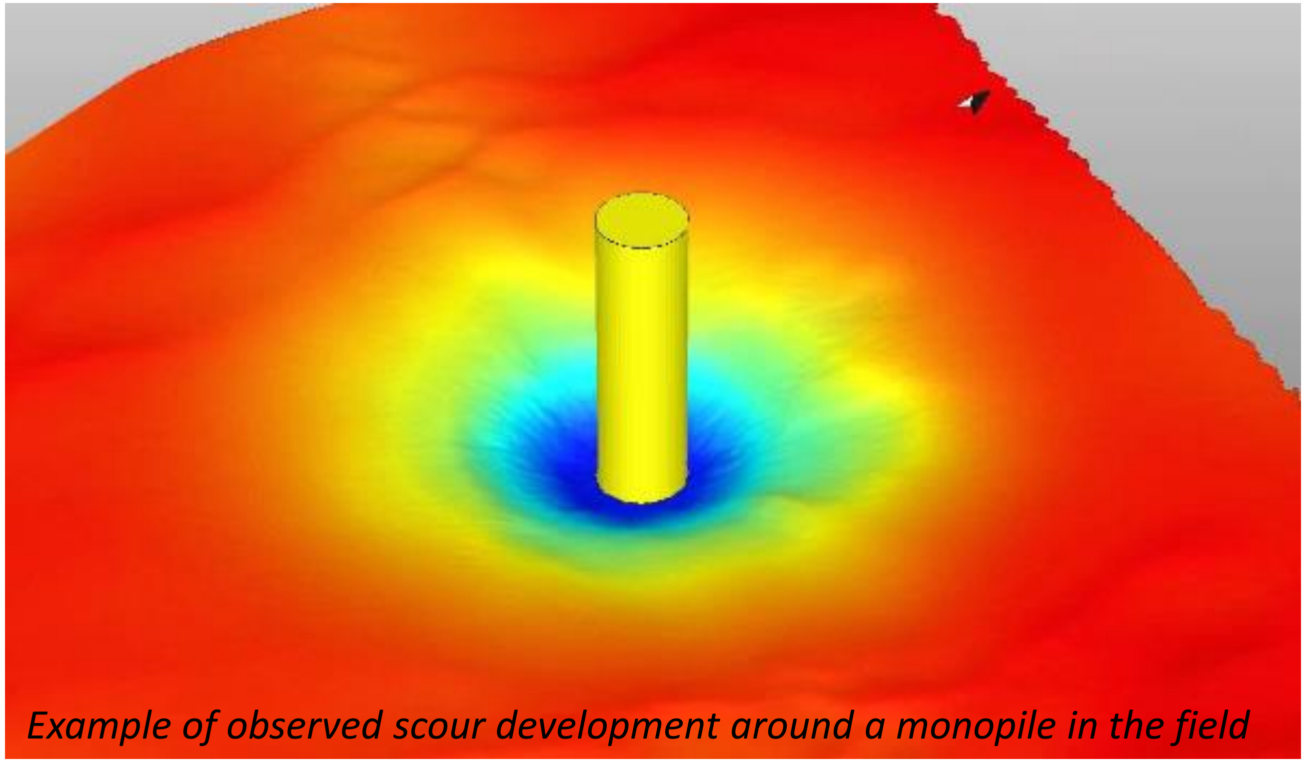
Webinar Morphodynamics and Scour Mitigation Hollandse Kust (Noord)

# What is scour and why bother?

Scour is erosion of seabed sediment around a structure caused by a local increase in sediment transport

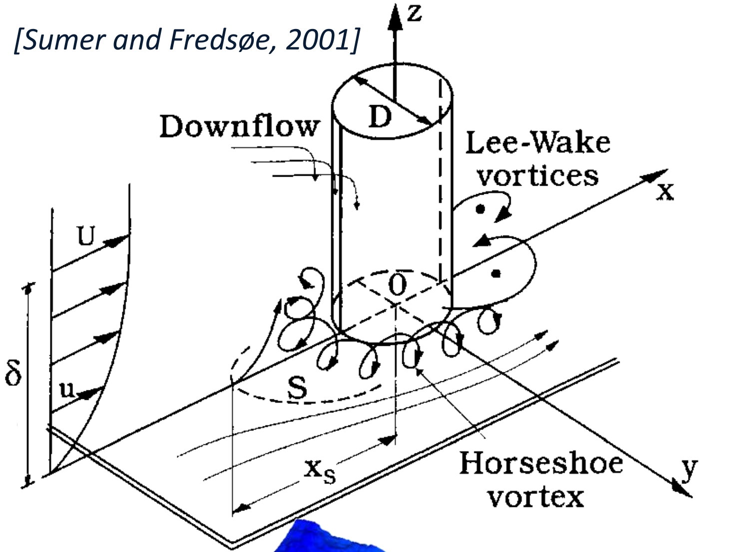
Scour:

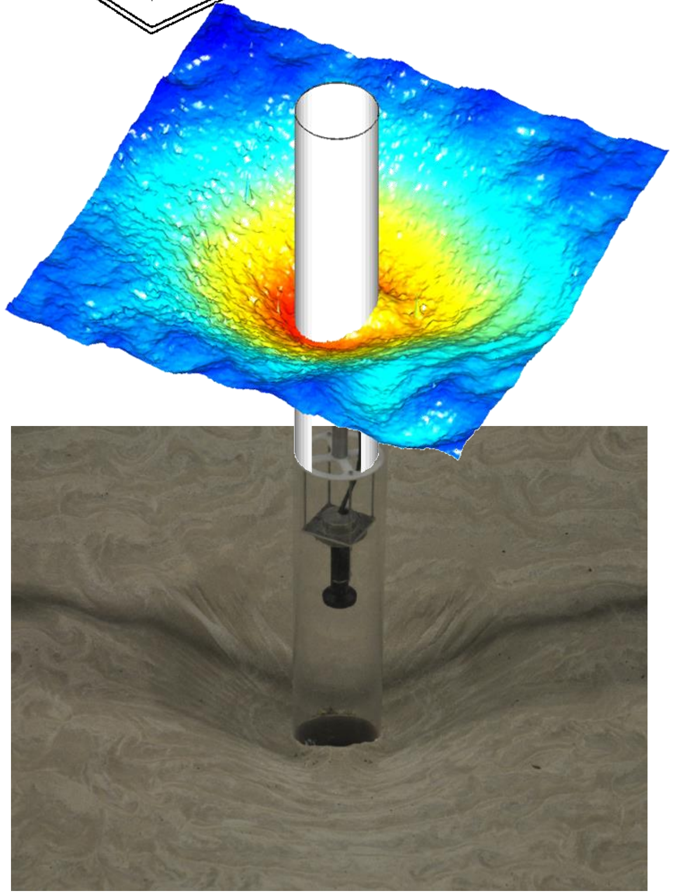
- ➢ lowers the pile fixation level, affecting the eigen frequency, reducing fatigue life (monopiles)
- ➢ causes undermining of the footings, can reduce the bearing area (GBS, suction cans, spud cans)



*Example of observed scour development around a monopile in the field*

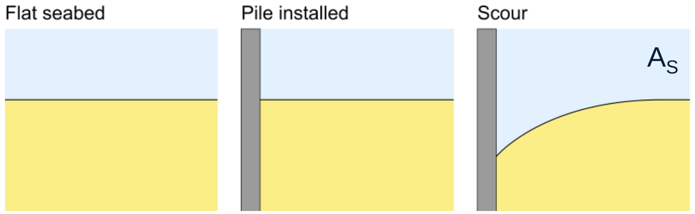
[Sumer and Fredsøe, 2001]



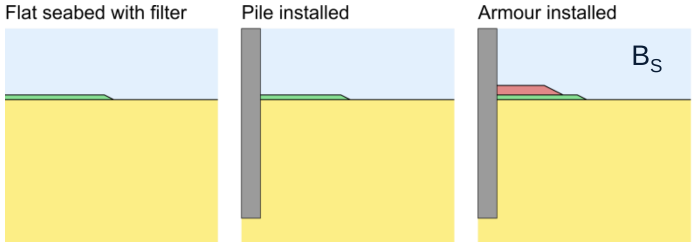



# Scour mitigation strategies excluding morphodynamics

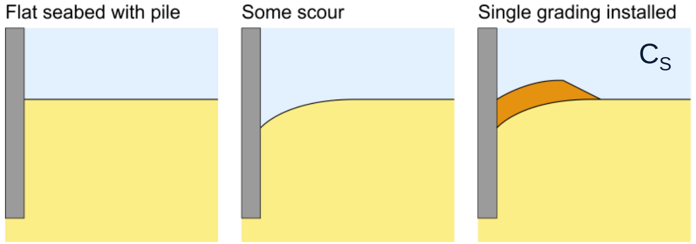
**A.** **No scour protection, allow scour development**




**B.** **Immediate scour protection, either just before or right after foundation installation**




**C.** **Monitor & React, first allow scour development and then install scour protection in scour hole**

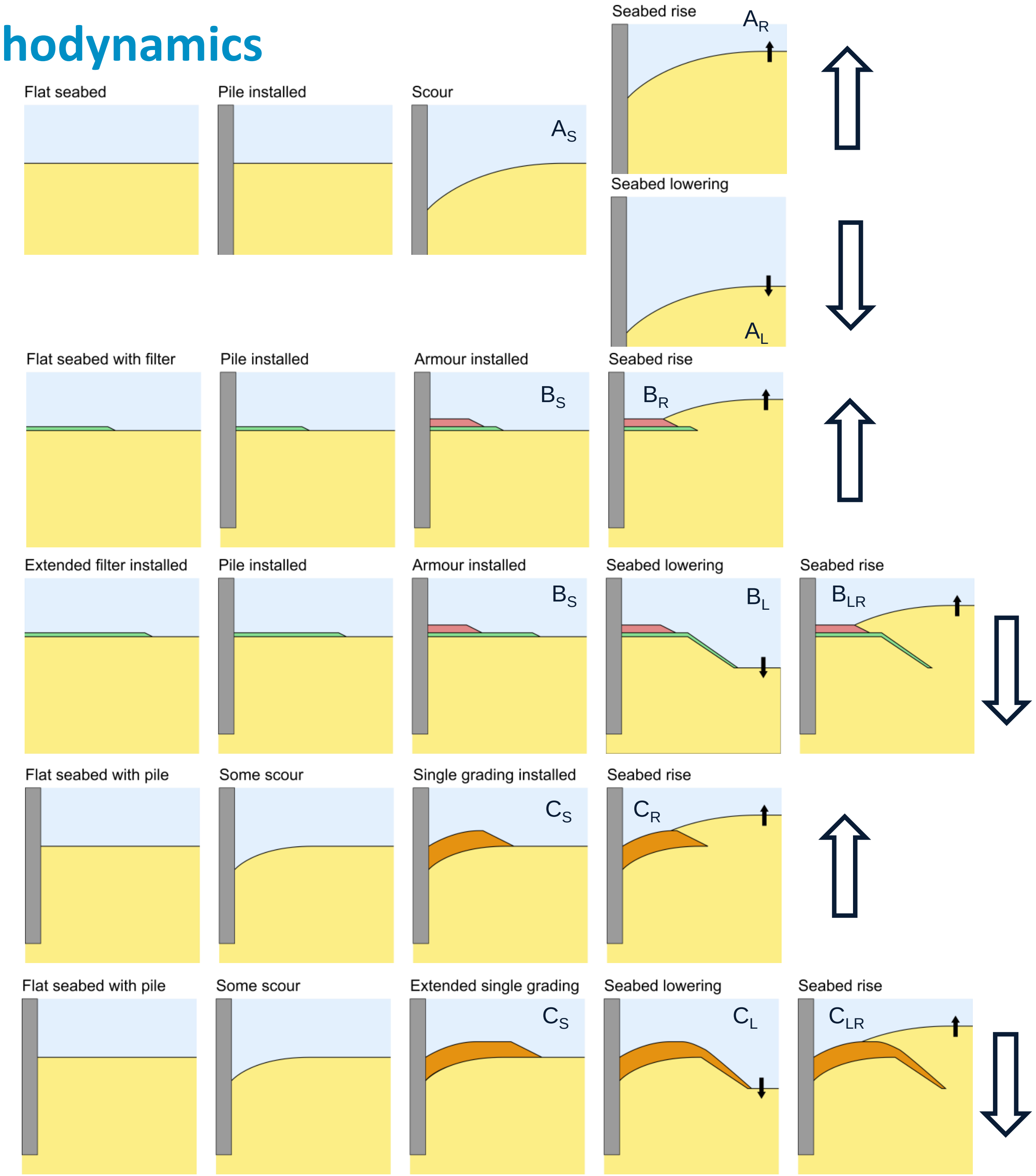


# Scour mitigation strategies including morphodynamics

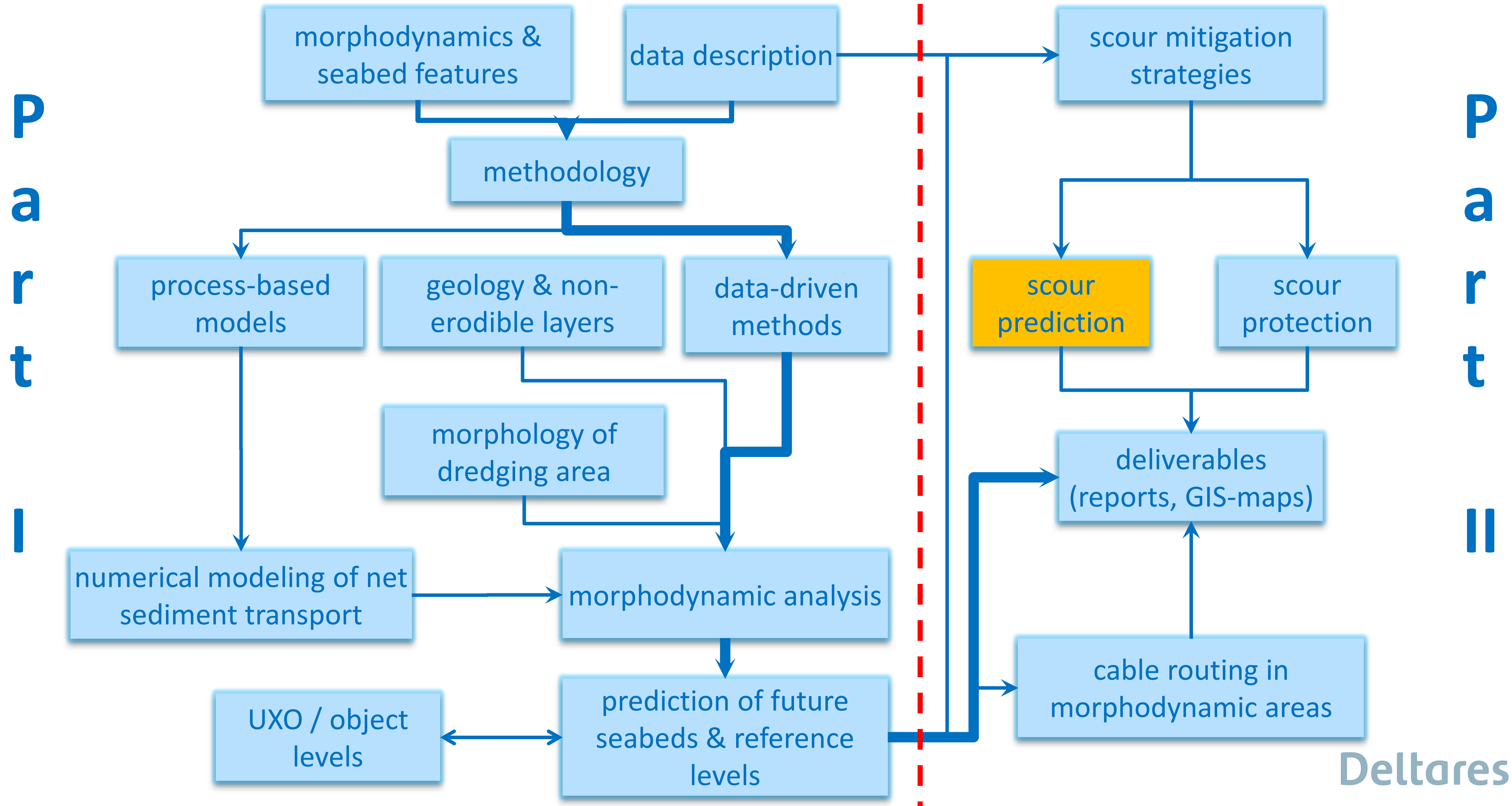
A. No scour protection, allow scour development

B. Immediate scour protection, either just before or right after foundation installation

C. Monitor & React, first allow scour development and then install scour protection in scour hole



# Structure of presentation

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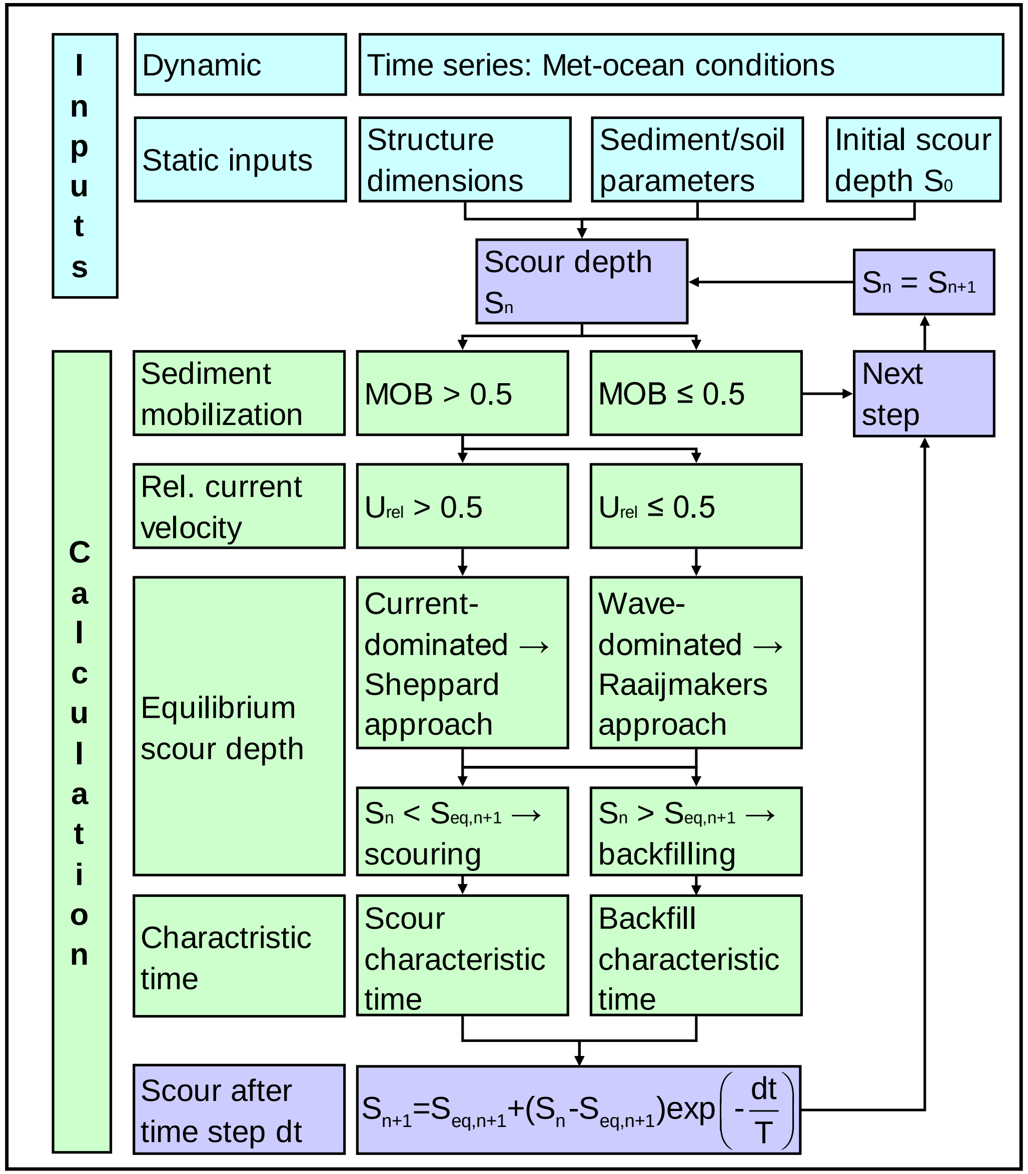
# Deltares' Scour Prediction Model

- Calculation model to predict dynamic scour development
- Every hydrodynamic condition has its own equilibirium scour depth and characteristic timescale
- Location- and structure-dependent scour prediction
- Distinguishes between wave- and current-dominated scour
- Allows for scouring and backfilling of scour hole
- Calculates years of scour development in < 1 minute
- Completely based on scale model tests and therefore required validation against field data!




Flow Chart of Deltares' Scour Prediction Model

More background information in report or webinar HKZ

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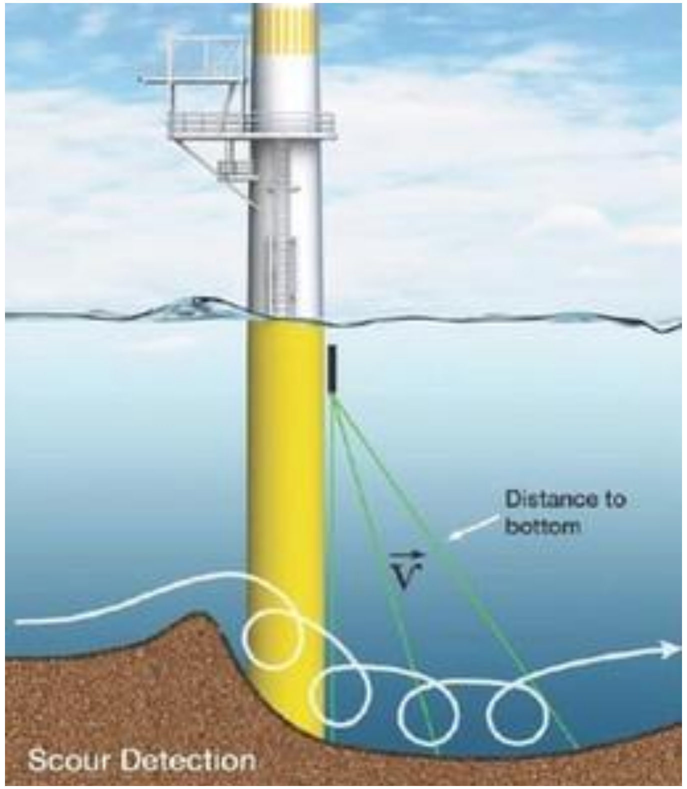
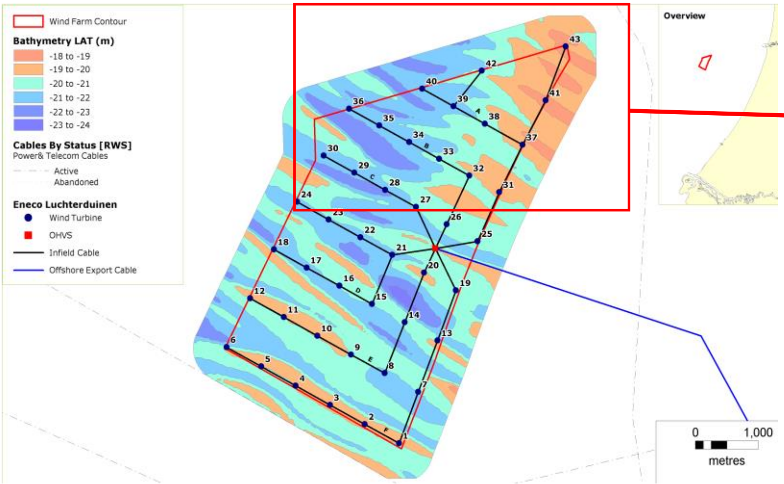
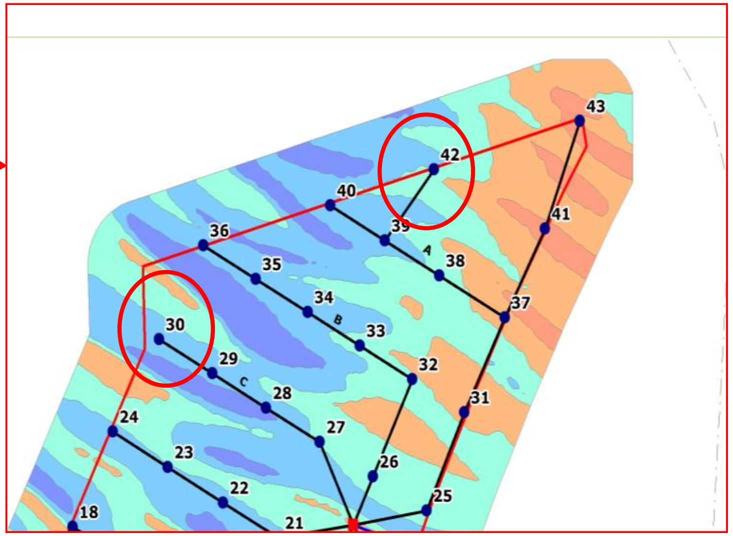
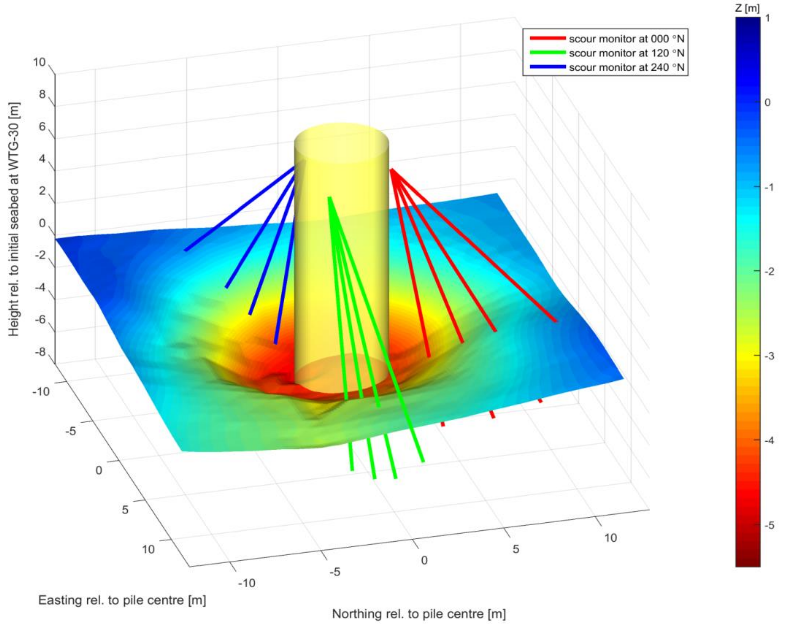
# Field Measurement Campaign in Luchterduinen to validate Scour Prediction Model

- Field measurements at 2 unprotected monopiles in Eneco Luchterduinen OWP, located just south of HKN
- To validate the equilibrium scour depths and characteristic timescales of the Deltares' Scour Prediction Model
- Simultaneous hydrodynamic data were collected as input for the Scour Prediction Model
- One year of measurements allowed for validation of the SPM for a wide range of conditions (current- and wave-dominated)



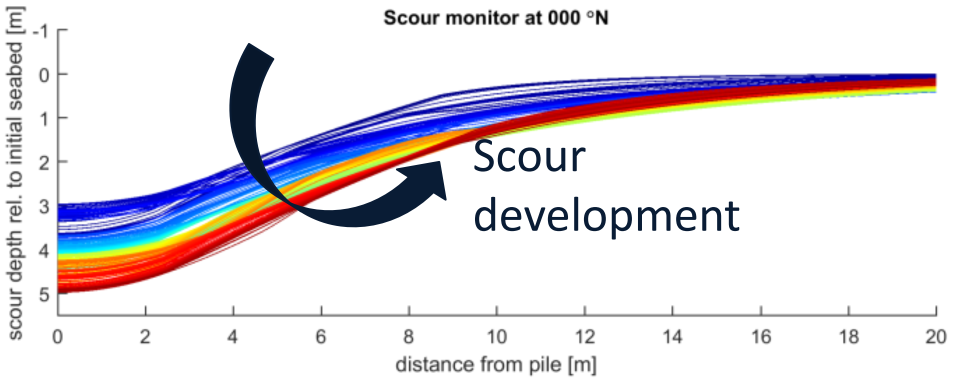



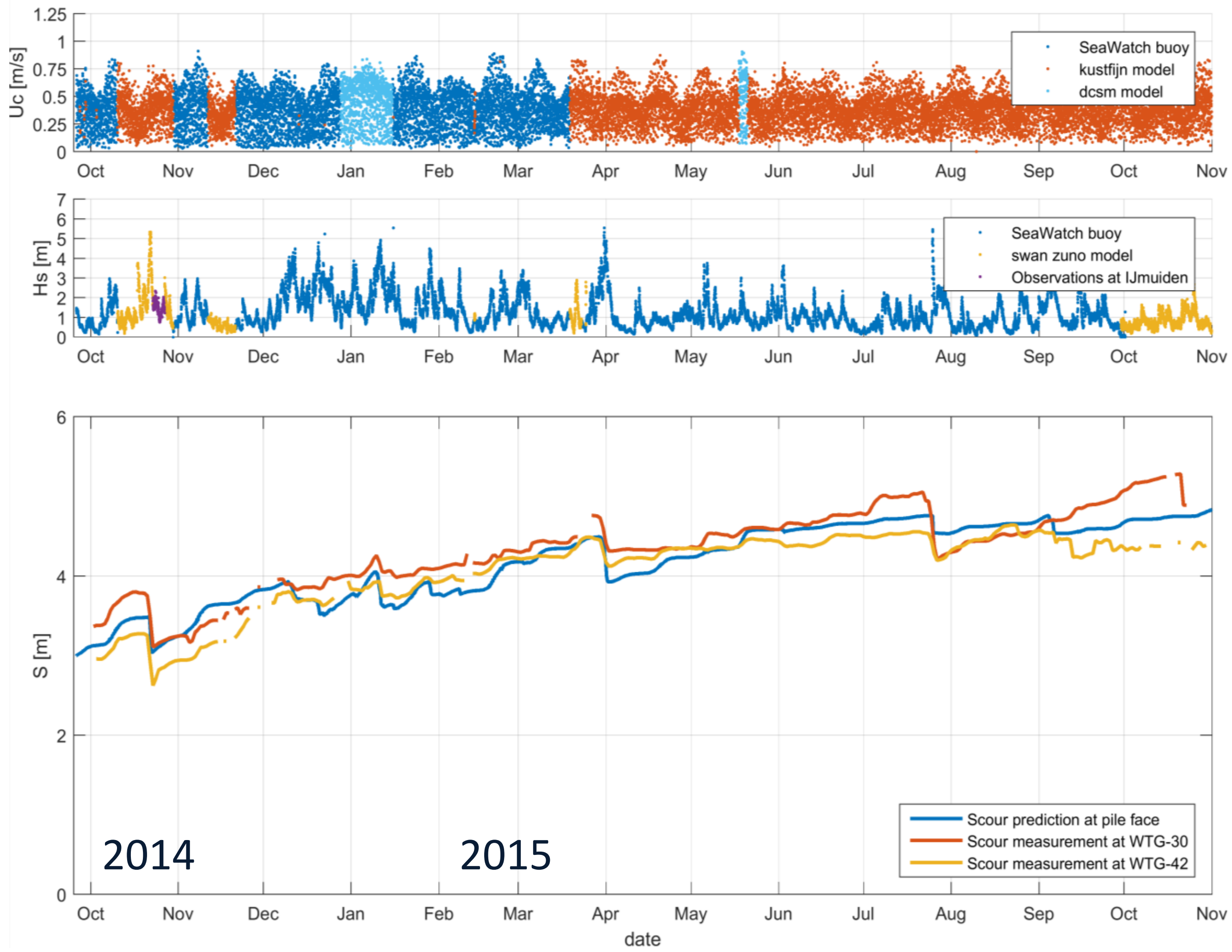



# Field Measurement Campaign in Luchterduinen to validate Scour Prediction Model

- Scour development until dynamic equilibrium takes about 1-1.5yr (in Luchterduinen)
- The scour pit was about 5-5.5m deep = 1.0-1.1*$D_{pile}$
- The dynamic scour depth will probably stabilize around 6m = 1.2*$D_{pile}$ (according to design)\
- The diameter of the scour pit was about 5*$D_{pile}$
- The side slopes were about 1:2
- The scour holes in Luchterduinen are very similar to the scour holes in the laboratory tests on scale ~1:40!

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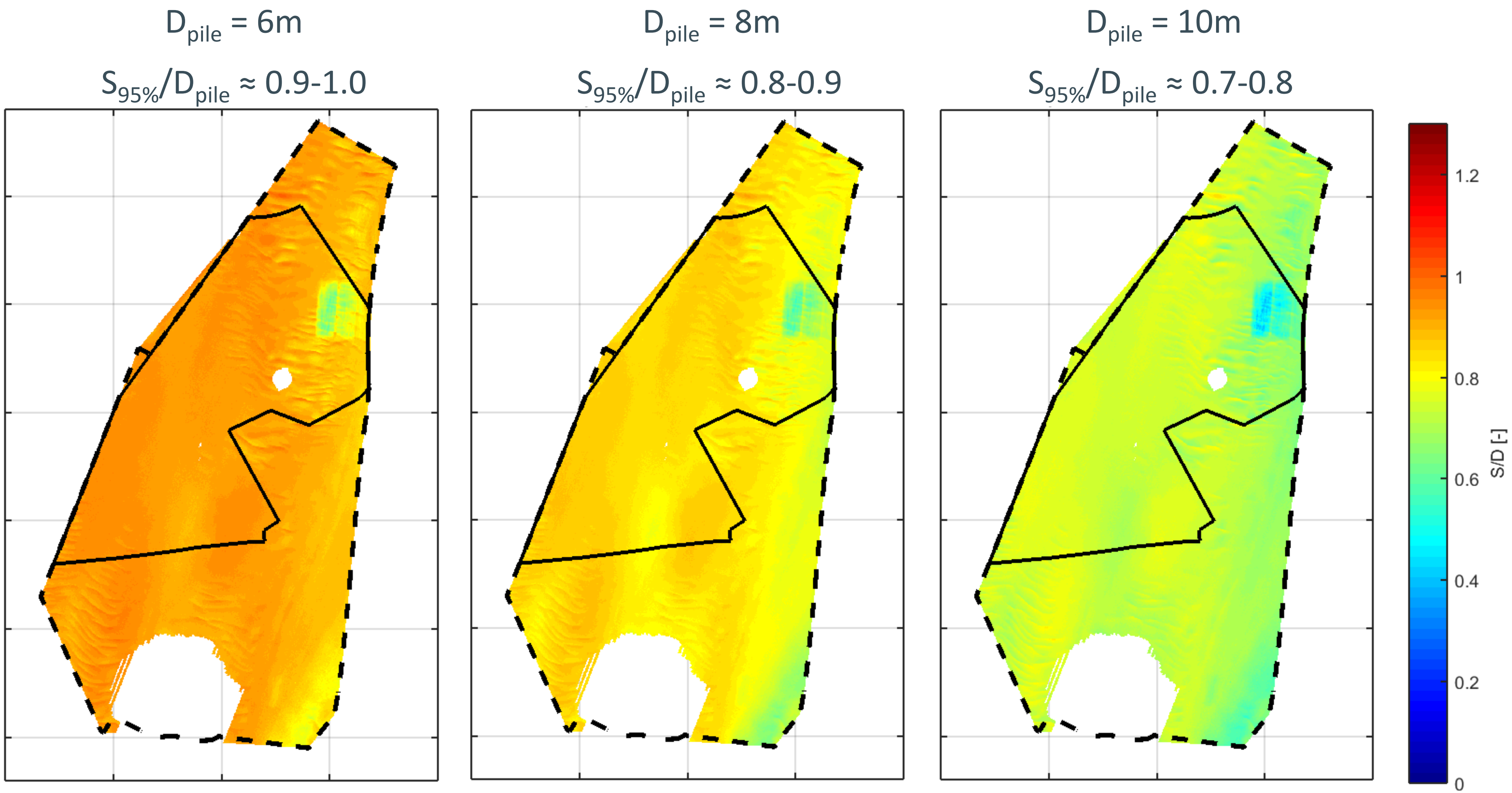
# Scour prediction for monopiles in HKNWFZ: variation in monopile diameter




- Absolute scour depth increases for increasing $D_{pile}$, but $S/D_{pile}$ reduces for increasing $D_{pile}$
- Scour depth increases at sand wave crests, where flow accelerates
- Scour depth decreases in sand mining put, where flow decelerates

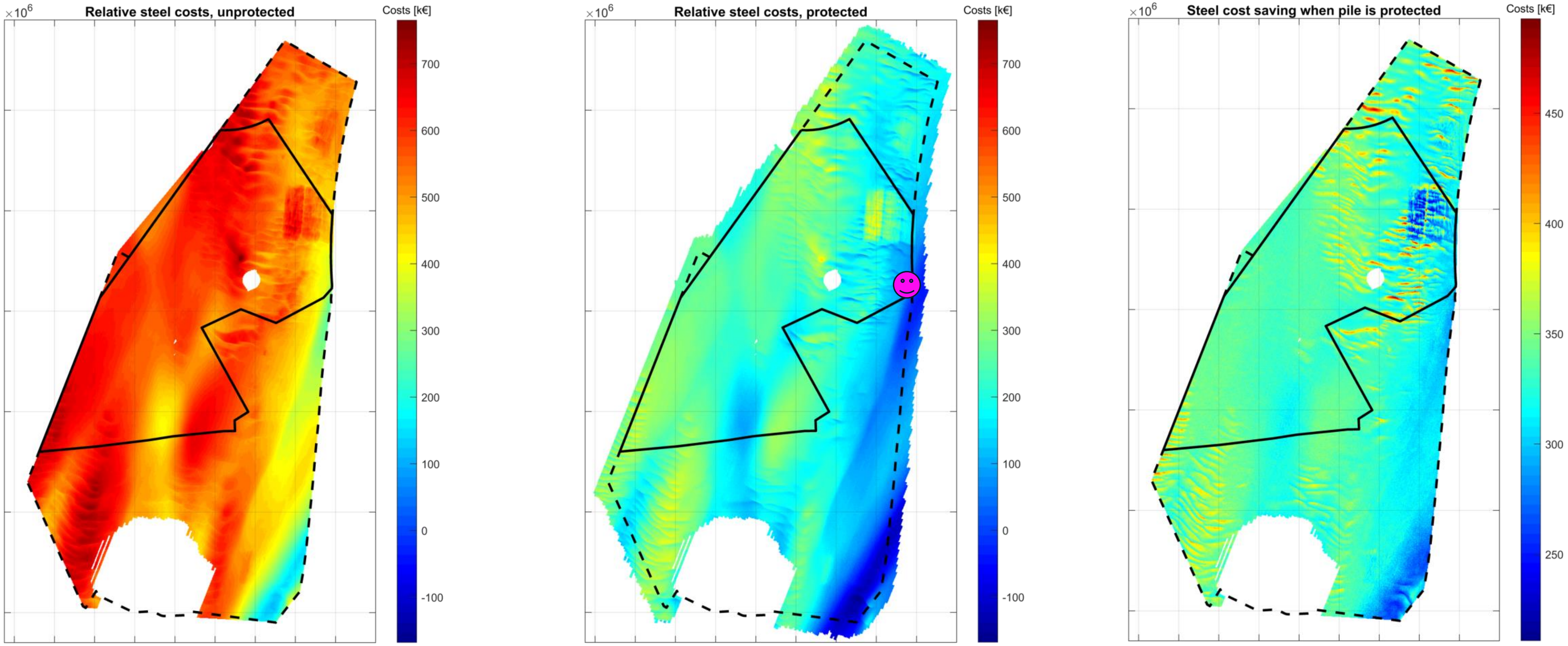
Deltares

# Example: comparing costs for steel consumption for Strategy A and B

Strategy A: unprotected
Additional steel costs compared to no scour at shallowest location

Strategy B: protected
Additional steel costs compared to shallowest location

Savings in steel costs when monopile is protected




- Assuming 20% additional steel on top of the length increase due to increased water depth + scour
- Assuming cost of primary steel to be € 2,- / kg

Deltares

# Example: comparing costs for steel consumption for Strategy A and B

Strategy A: unprotected
Additional steel costs compared to no scour at shallowest location

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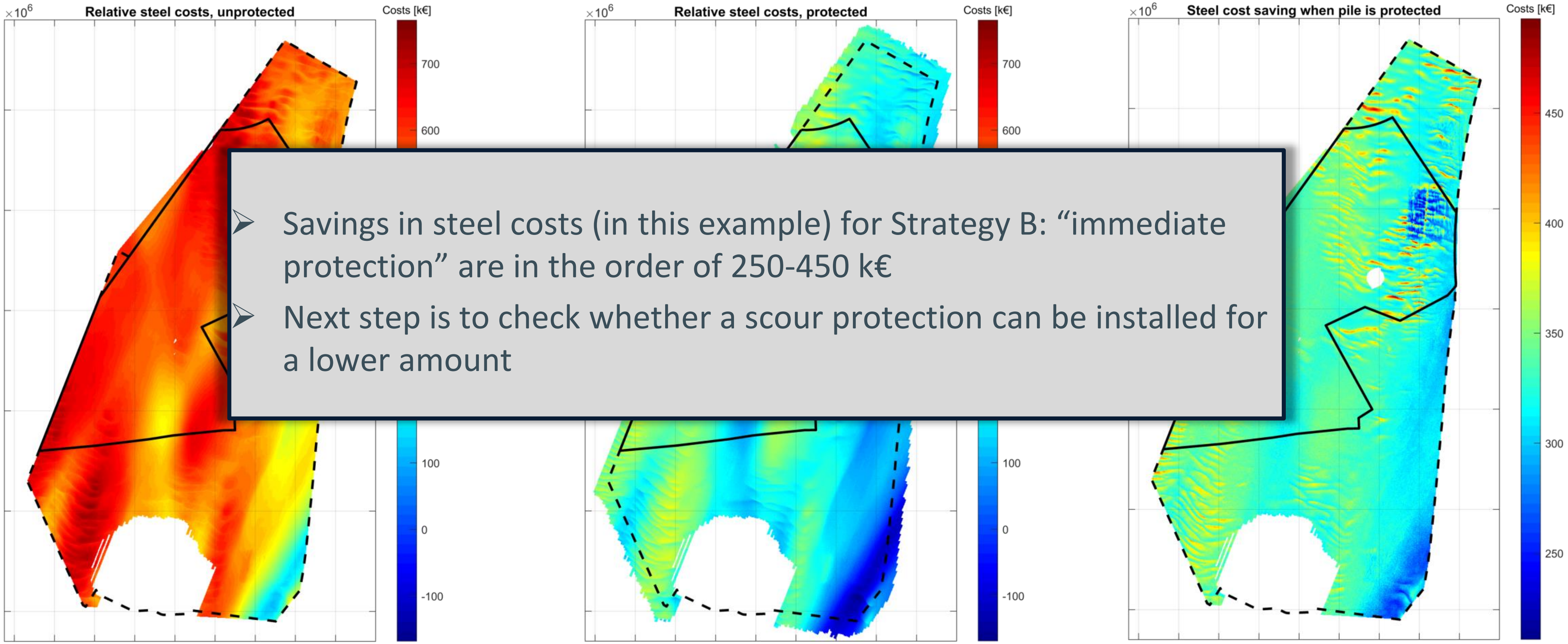


- Savings in steel costs (in this example) for Strategy B: "immediate protection" are in the order of 250-450 k€
- Next step is to check whether a scour protection can be installed for a lower amount

- Assuming 20% additional steel on top of the length increase due to increased water depth + scour
- Assuming cost of primary steel to be € 2,- / kg

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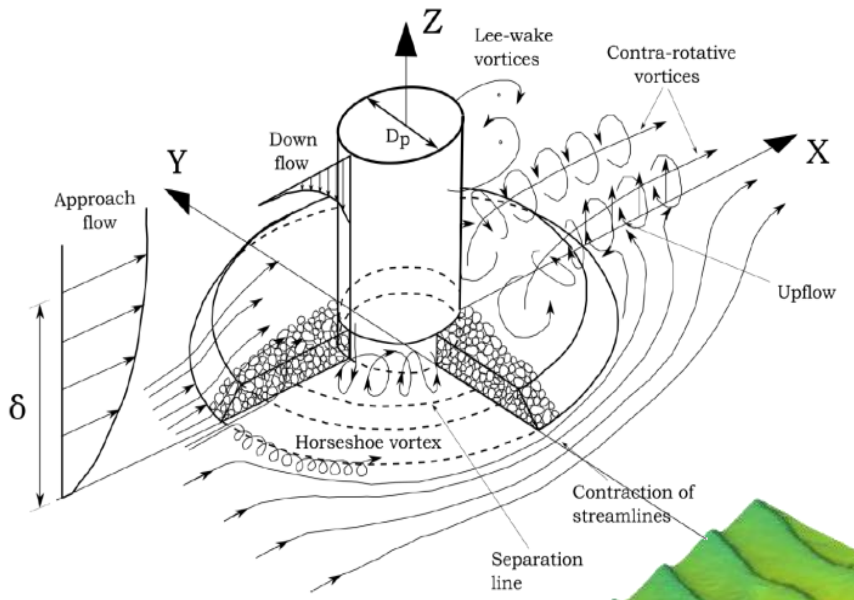
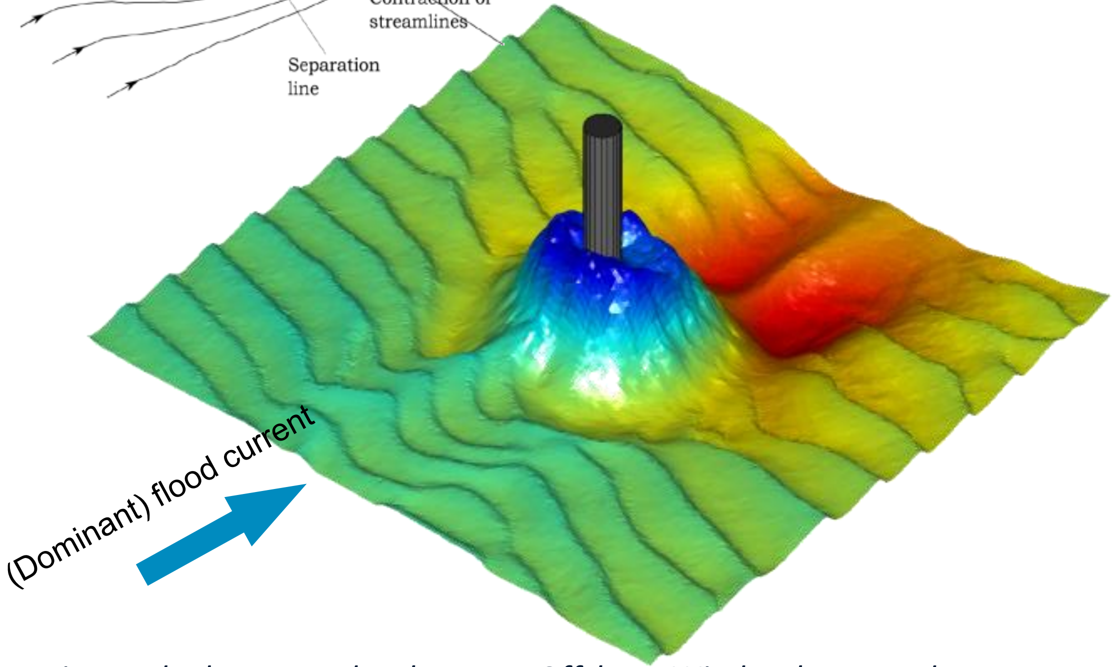
# Edge scour development




- When a scour protection is installed (Strategy B), then in HKN still scour will develop around the foundations: edge scour
- Edge scour occurs at slower time scales (order of years)
- Edge scour is mainly driven by the tidal current
- Location of deepest scour is governed by tidal asymmetry
- Depth is related to scour protection design (height above surrounding seabed, roughness and extent of scour protection



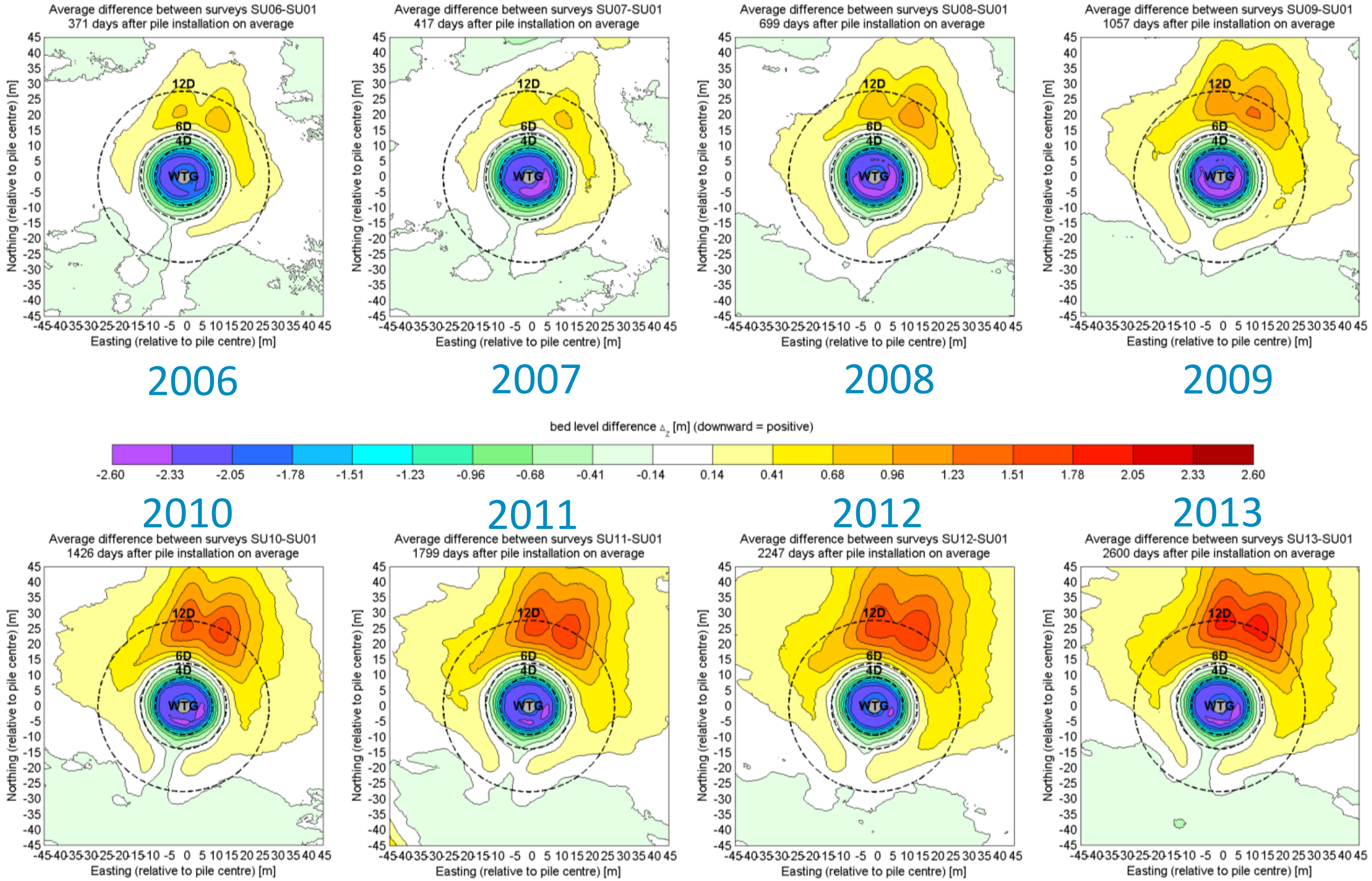


- *Deltares (2009), Evaluation of performance of scour protection and edge scour development Offshore Windpark Egmond aan Zee. Report 1200160-002-HYE-0001.*
- *Petersen T.U., Sumer, B.M., Freds¢e, J., Raaijmakers, T.C., Schouten, J.J. (2015), Edge scour at scour protections around piles in the marine environment - Laboratory and field investigation. Coastal Engineering, Vol. 106, 2015, p. 42-72*


Deltares

# Expected edge scour in HKN

- ➢ Edge scour measurements in OWP Egmond aan Zee provide useful data for HKN predictions
- ➢ For a double grading rock protection edge scour is estimated at: $S_{edge} \sim 1{*}h_{prot}$
- ➢ Deepest edge scour will occur in the NE-side of the foundation
- ➢ Edge scour can be mitigated by extending the filter layer: more falling apron material available
- ➢ Asymmetrical layouts can be considered to mitigate edge scour
- ➢ Consider favourable orientations for the cable connections

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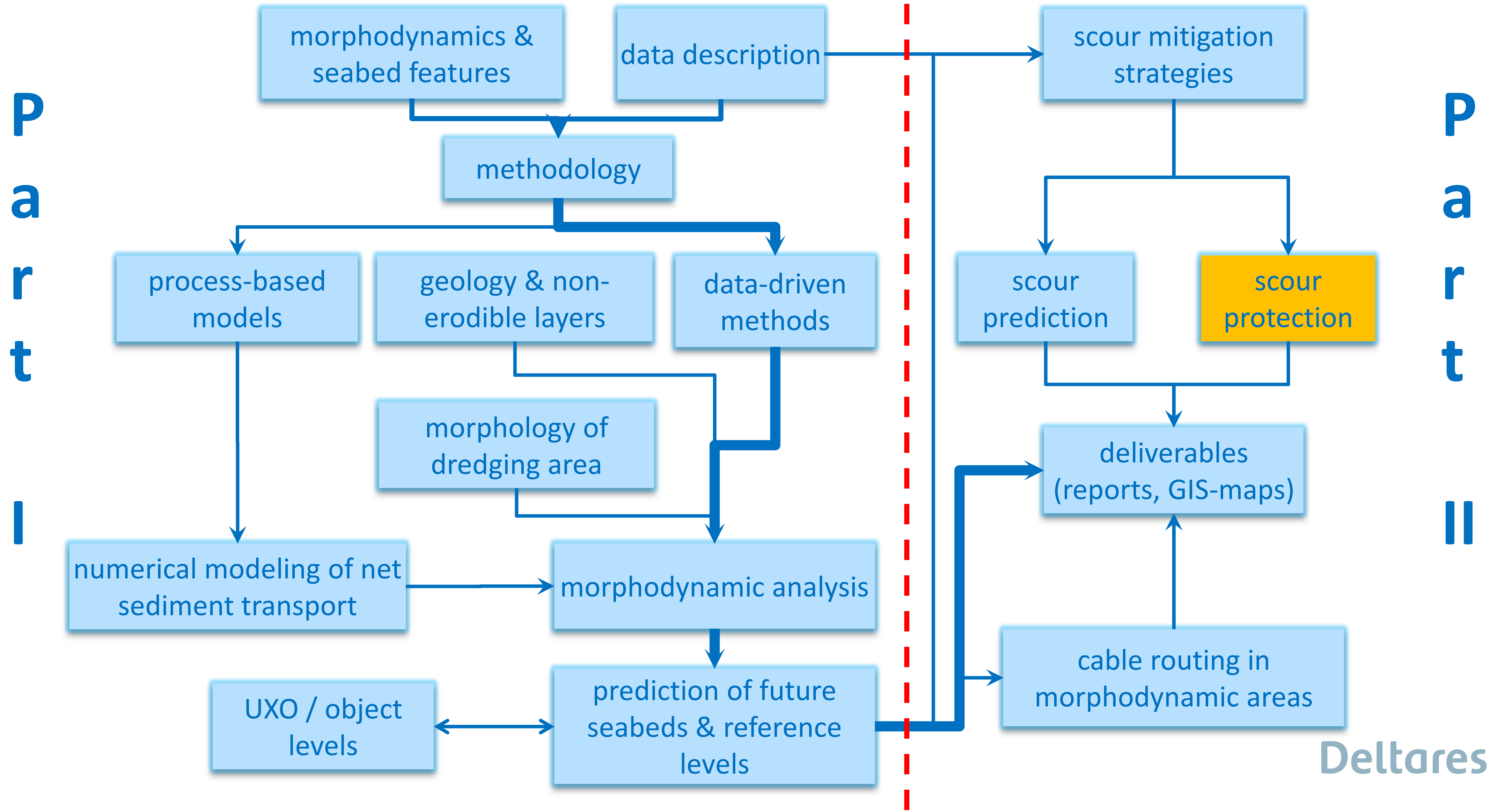
## Structure of presentation

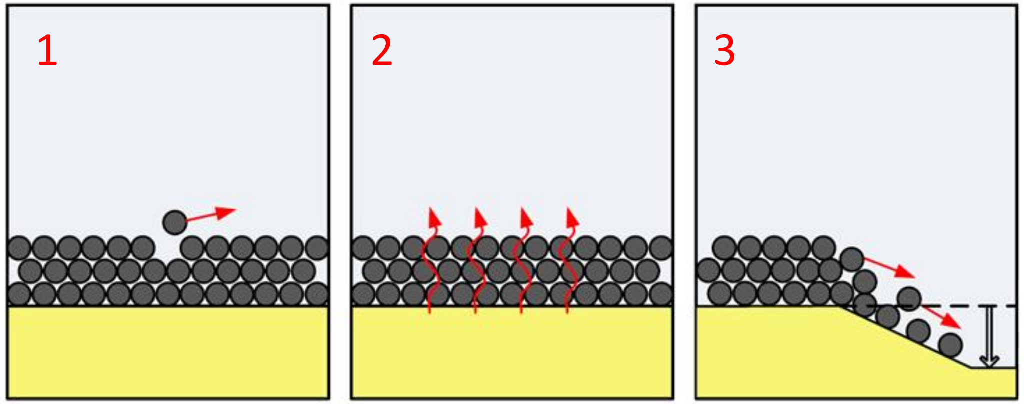



Deltares

# Requirements for a scour protection

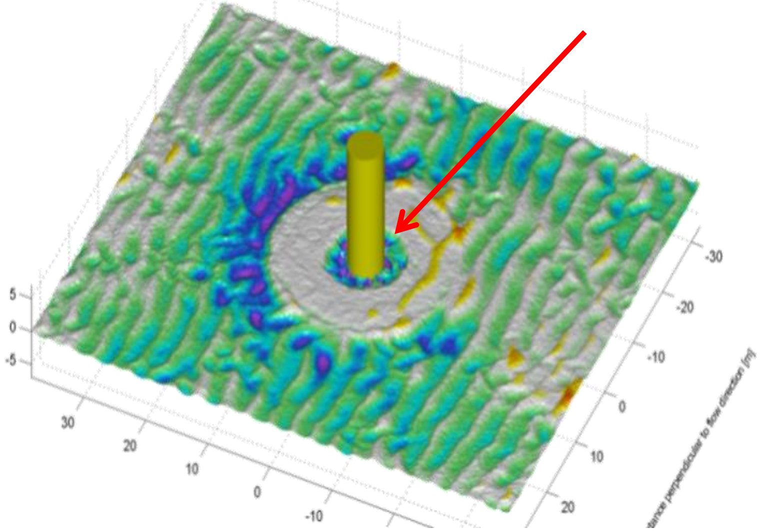
Main design requirements:

1. External stability
2. Internal stability (filter function)
3. Flexibility (performance around edge scour holes and in morphodynamic areas)
4. Ecological impact or even ecological enhancement

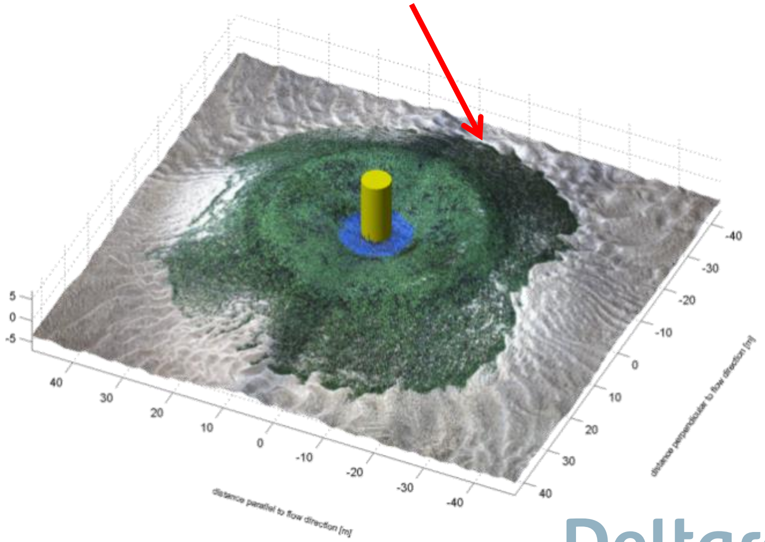



1. deformation of a scour protection related to external stability

2. lowering of the scour protection close to the pile due to winnowing



3. lowering of the edges of a scour protection due to falling apron development



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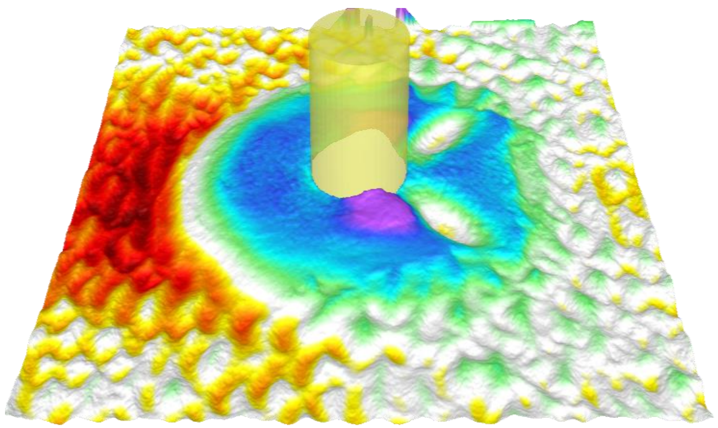
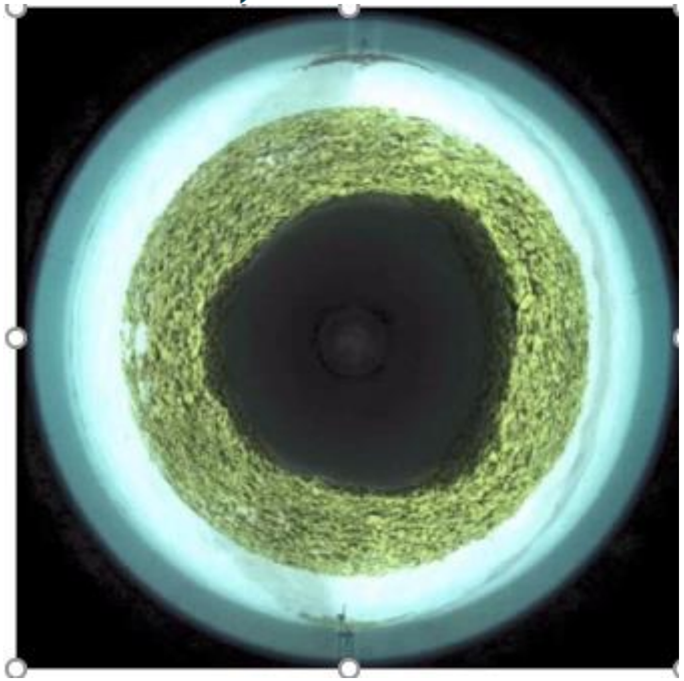
# Requirements for a scour protection

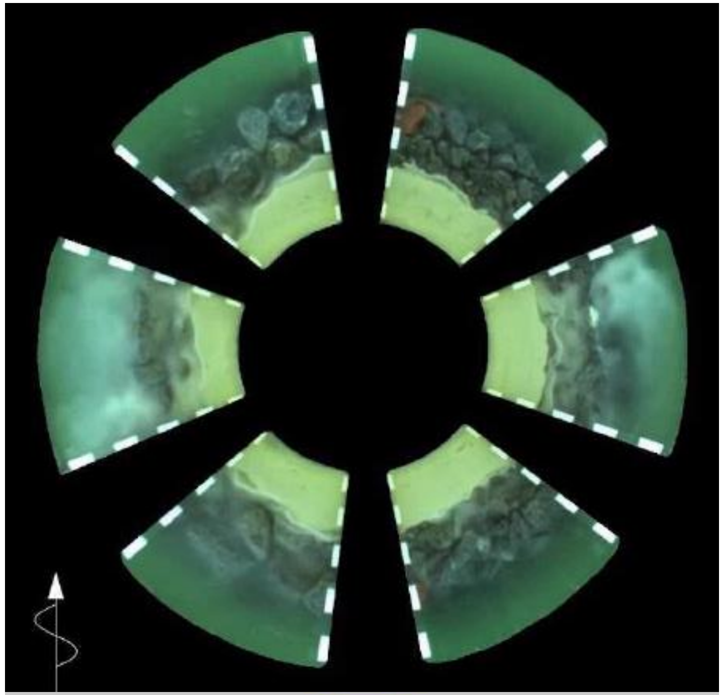
External stability

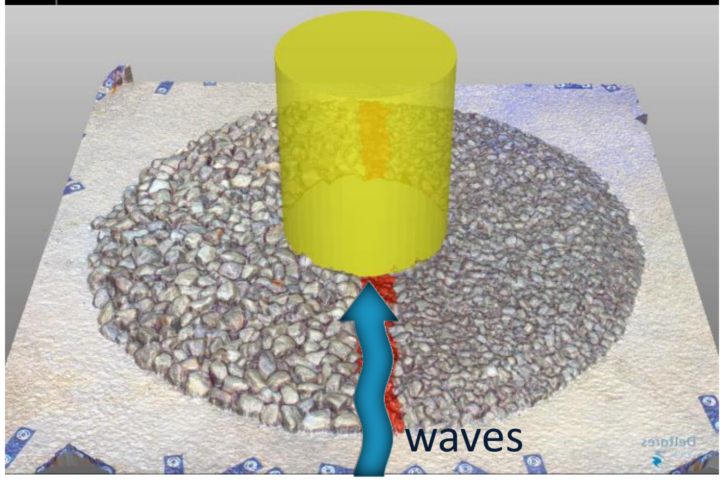


waves

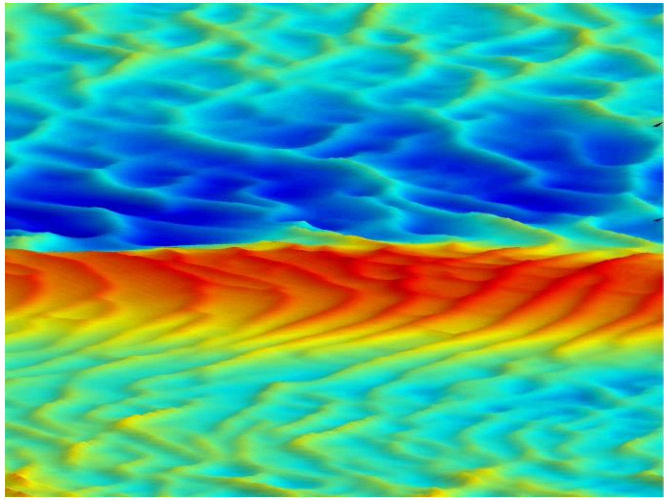


Internal stability (winnowing)

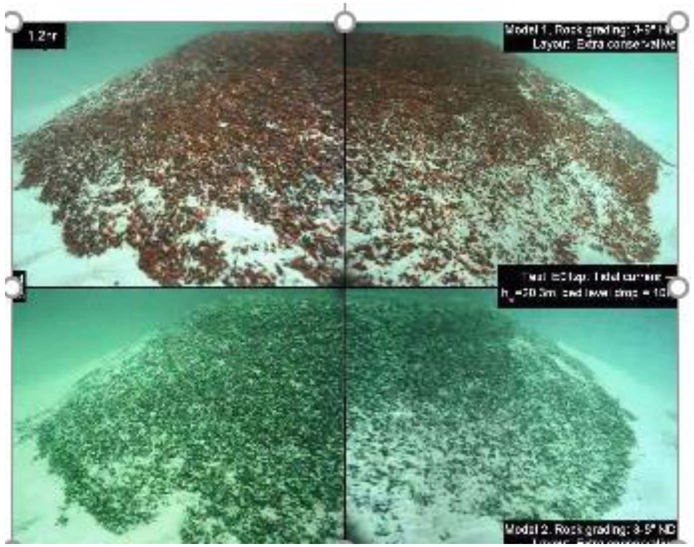




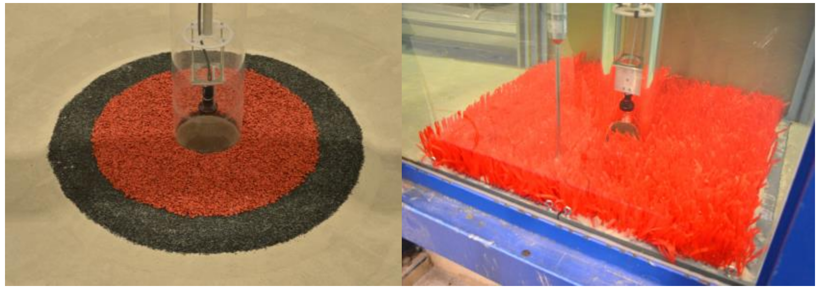

Flexibility



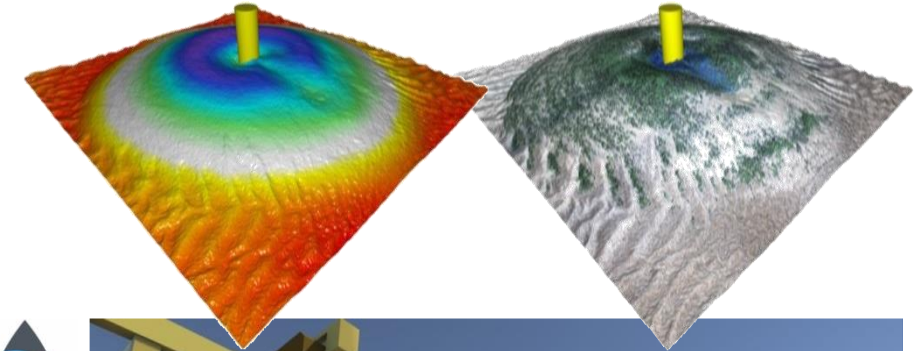
tidal current



# JIP HaSPro
# Handbook Scour and Cable Protection Methods



- Scour and cable protection methods for offshore wind support structures and cables by model tests on 3 different model scales (from small to world's largest scale)
  - ✓ Optimizing conventional rock protection
  - ✓ Innovative protection systems
  - ✓ Nature-inclusive design of scour protections
- Deriving design formulae and guidelines
- Drafting Handbook and Recommended Practice
- Project: Sept. 2016 – March 2020
- Funded by 21 participating companies and Netherlands Enterprise Agency through TKI Wind op Zee and TKI Deltatechnologie
- Remains open for new participants

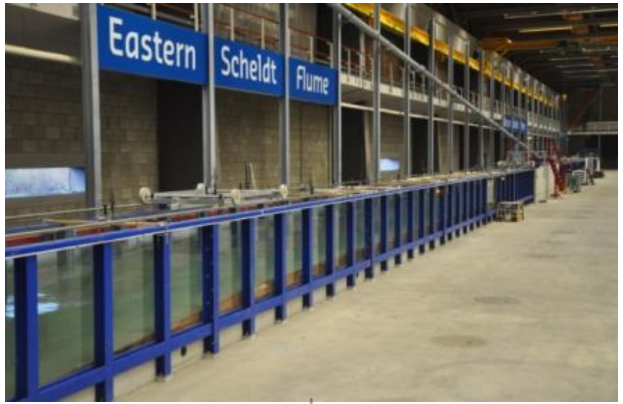


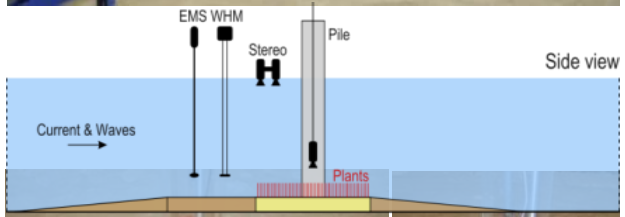
model test setup in Delta Flume

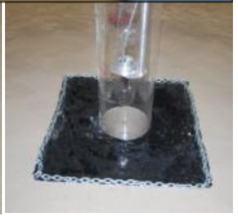
# Systematic scale model testing on three scales

### Scheldt Flume

- Model scale 1:30 to 1:50
- Tidal currents + waves
- Fast cycle times: many exploratory tests

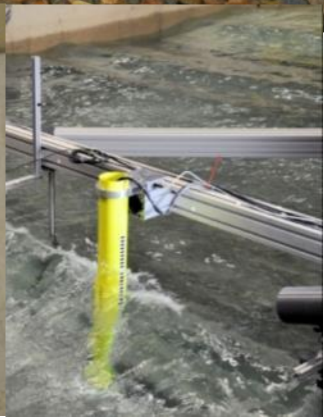


### Atlantic Basin

- Model scale 1:20 to 1:40
- Tidal currents + waves
- Wide section with mobile bed
- All governing processes are included

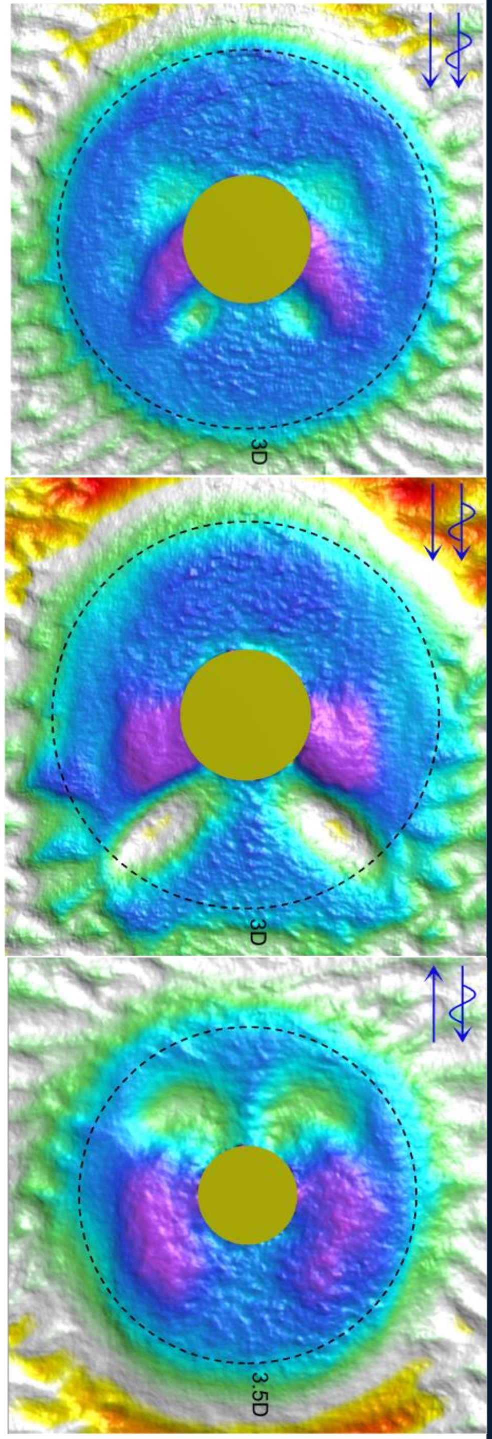


### Delta Flume

- Model scale 1:1 to 1:10
- World’s largest wave flume
- No scale effects
- Validation of smaller scale tests

# Knowledge development on rock scour protections

- Rock protections are relatively well understood
- Establishing relations between time-dependent hydraulic load and cumulative deformation
- Create unique extensive database with results on different scales for a multivariate space: *varying wave conditions, current conditions, water depth, pile diameter, rock size and grading width, rock density, protection layout, seabed lowering etc.)*
- For every test 3D-deformation patterns are recorded to derive quantitative deformation numbers and patterns
- Formulae for time-dependent 3D-deformation patterns are currently  being developed

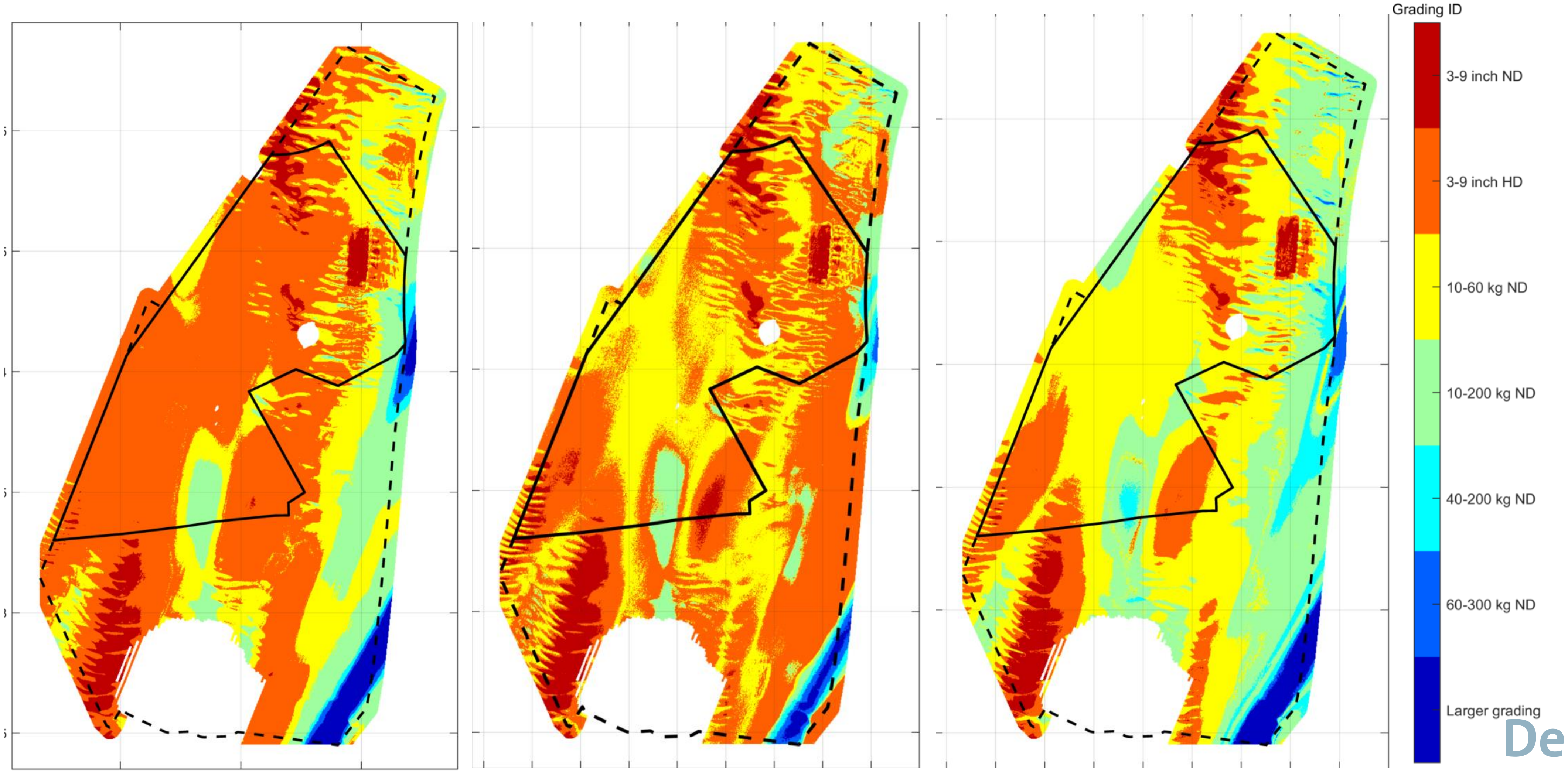



**3D-deformation patterns**

# Rock gradings with limited deformation based on Model Test Database

Rock gradings with less than 0.5m vertical deformation during the design storm, according to the Model Test Database

$D_{pile}$ = 7 m  $D_{pile}$ = 8 m  $D_{pile}$ = 9 m

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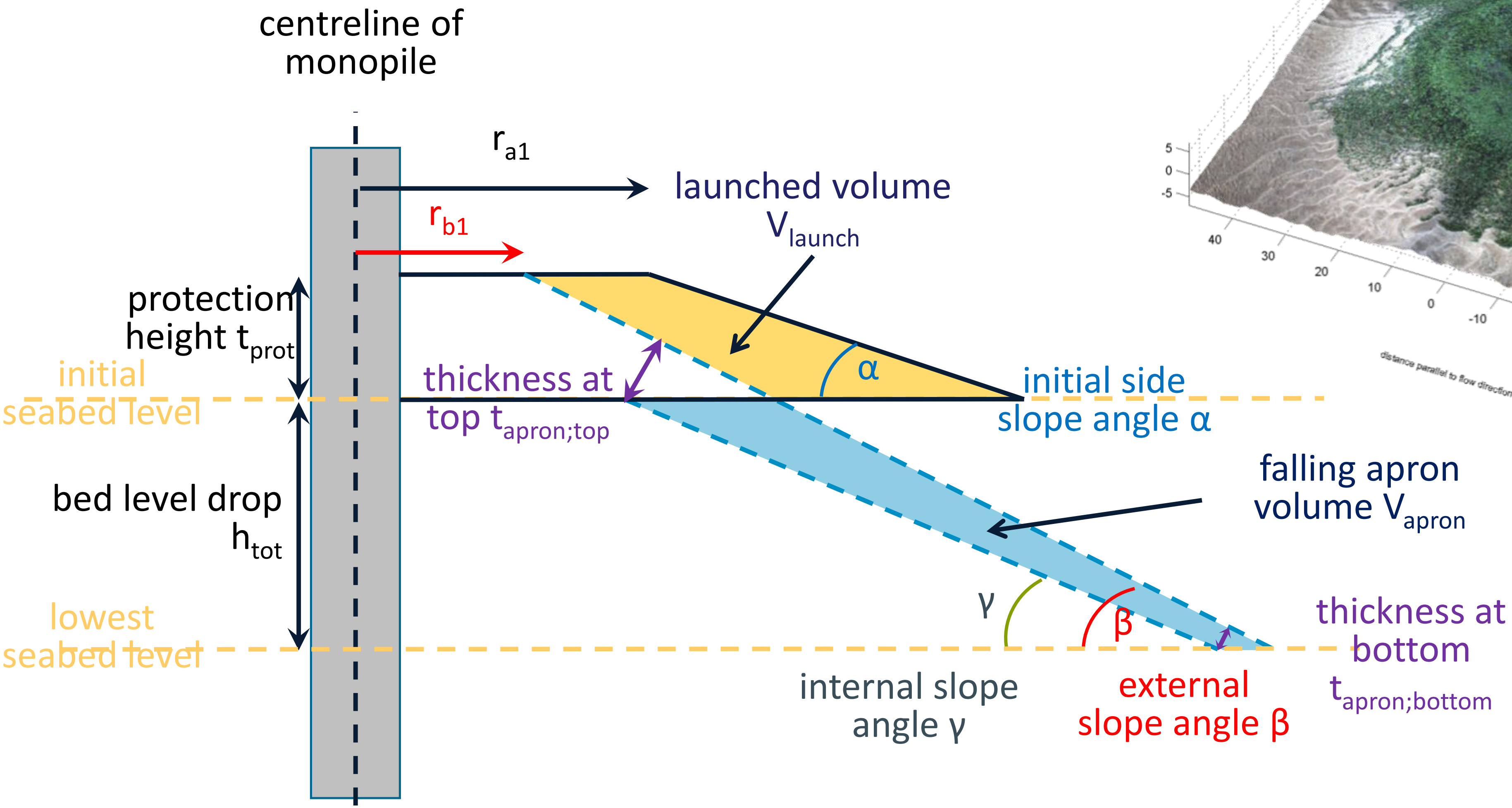
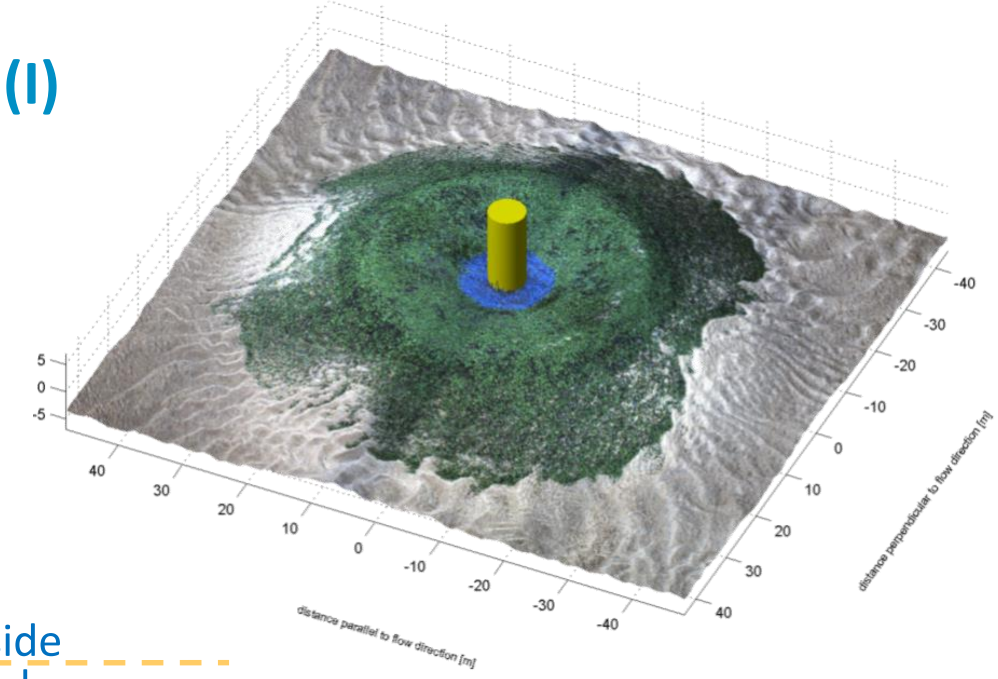
# Required falling apron volume for lowering seabed (I)

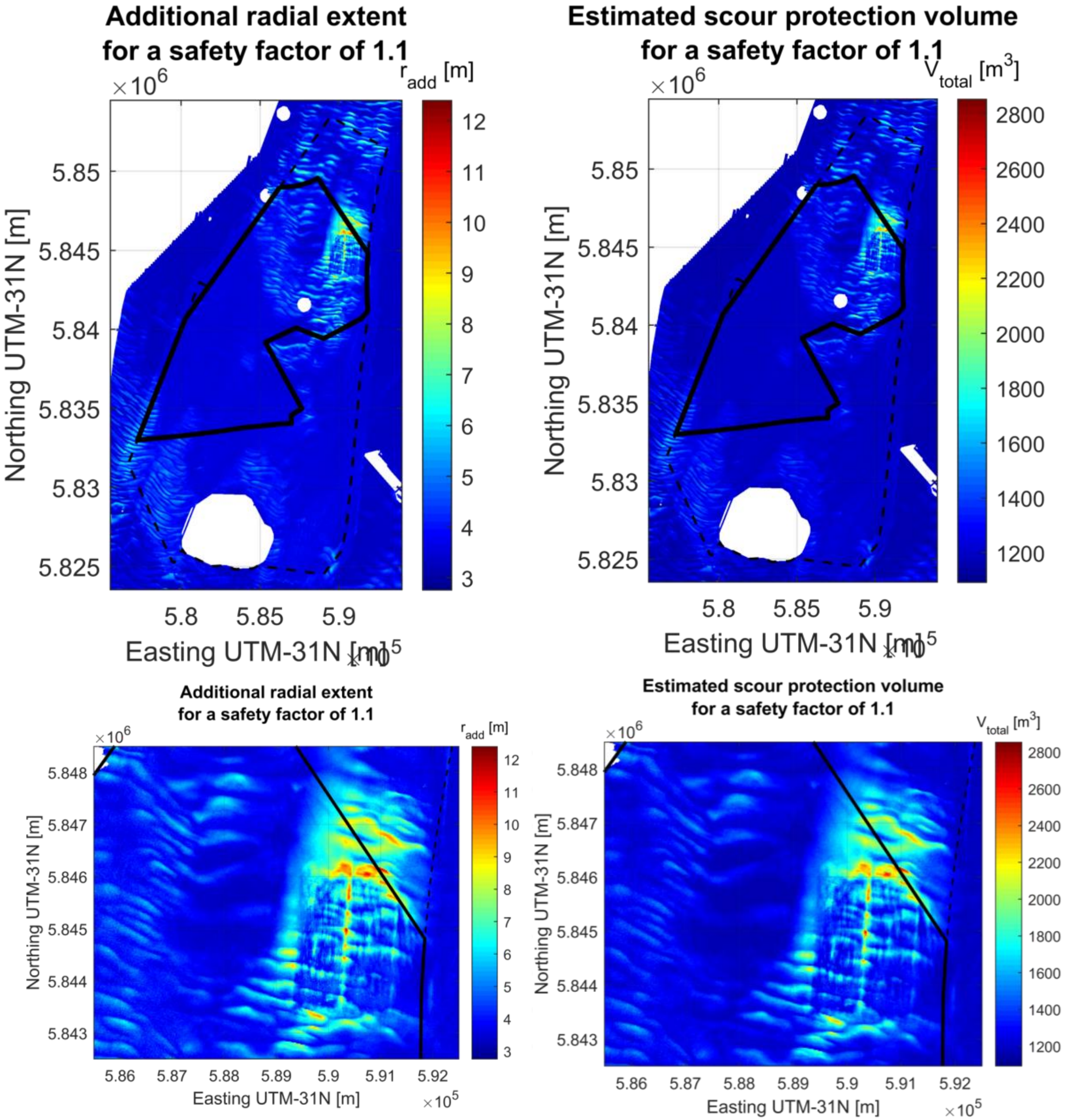


$$r_{a1} = \sqrt{r_{b1}^2 + \frac{r_{b1}t_{prot}}{\tan\beta} + \frac{t_{prot}^2}{3\tan^2\beta} - \frac{t_{prot}^2}{12\tan^2\alpha} + \frac{SF\cdot h_{tot}}{t_{prot}\sin\beta}\left(r_{b1}(t_{apron;top}+t_{apron;toe}) + \frac{h_{tot}(t_{apron;top}+2t_{apron;toe})+3t_{prot}(t_{apron;top}+t_{apron;toe})}{3\tan\beta} - \frac{t_{apron;top}^2 + t_{apron;top}t_{apron;toe}+t_{apron;toe}^2}{3\sin\beta}\right)} - \frac{t_{prot}}{2\tan\alpha}$$

# Required falling apron volume for lowering seabed (II)

Additional **radial extent** of scour protection taking into account seabed lowering and edge scour (only for NE-sector)




Additional **scour protection volume** taking into account seabed lowering and edge scour (only for NE-sector)

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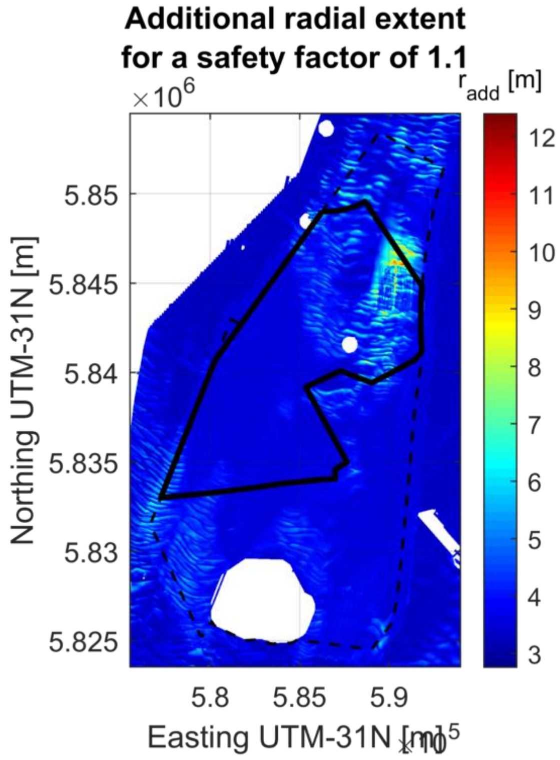
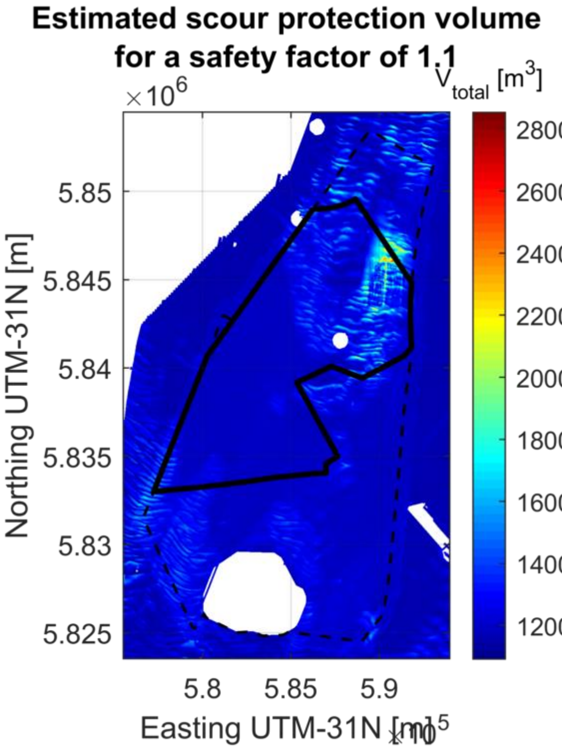
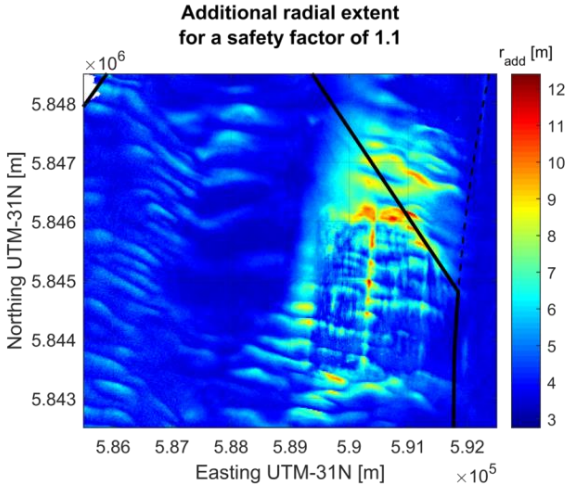
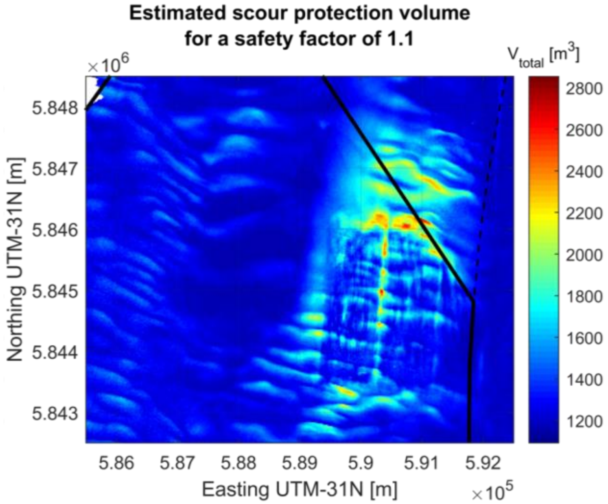
Additional **radial extent** of scour protection taking into account seabed lowering and edge scour (only for NE-sector)



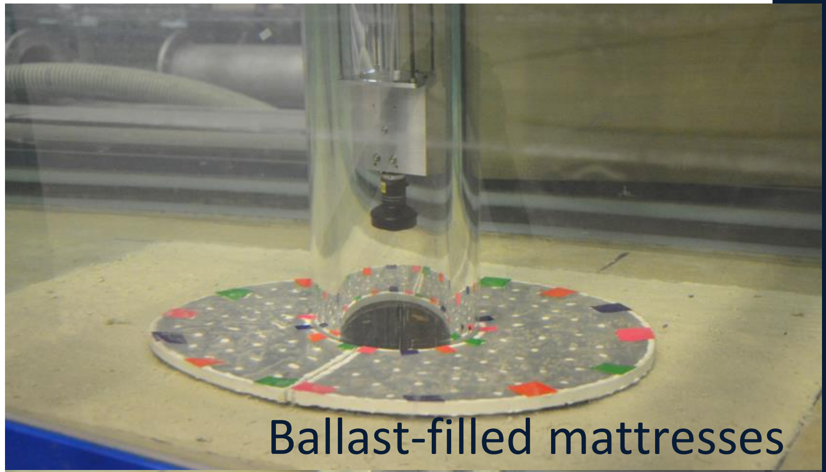

Additional **scour protection volume** taking into account seabed lowering and edge scour (only for NE-sector)

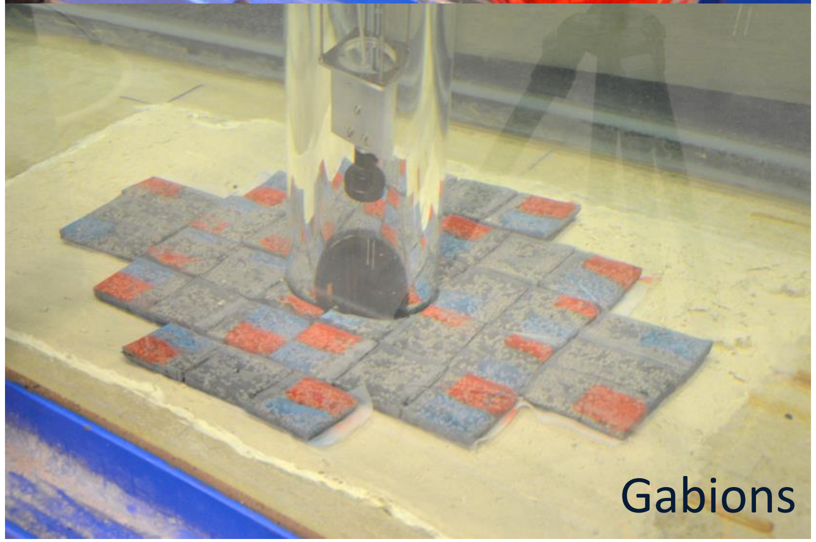
- Increase in scour protection volume is most significant on sand wave crests and NNE of the former dredging area, where largest seabed lowering is expected
- Large areas in HKN are not affected by a significant increase in protection volume related to predicted seabed lowering

# Some examples of innovative protections

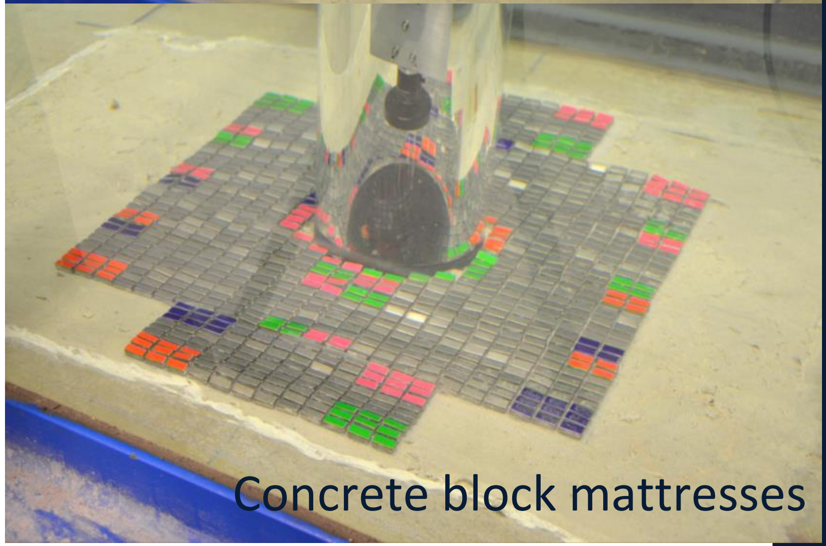

Several alternatives for rock protections can be considered: examples of test setups to investigate failure mechanisms

*Performance of alternative scour protection methods in severe wave conditions*





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# Towards eco-friendly design of wind farms

- ➢ With increasing use of offshore space by wind farms and reducing LCoE, interest is increasing to enhance ecological value of wind farms and scour + cable protections in particular
- ➢ Rock protections (hard substrates) are already rich in ecology and show a great biodiversity (compared to the surrounding sandy seabed)
- ➢ In the past years research was done on potential ways to further enhance the ecological quality of scour protections
- ➢ Two umbrella species were selected:
  1. Atlantic cod (*Godus morhua*)
  2. European flat oyster (*Ostrella edulis*)
- ➢ Focus on nature-inclusive design of scour protections targeting the umbrella species
- ➢ New “Kavelbesluit” Hollandse Kust Noord (published 9 may 2019) now contains the obligation to enhance biodiversity when constructing a wind farm…


Bureau Waardenburg Ecologie & Landschap · WAGENINGEN UNIVERSITY & RESEARCH · Deltares

*Ecological monitoring in Offshore Wind Farm*

*Lengkeek, Wouter; Didderen, K.; Teunis, M.; Driessen, F.; Coolen, J.W.P.; Bos, O.G.; Vergouwen, S.A.; Raaijmakers, T.; Vries, M.B. de; Koningsveld, M. van (2017)*

# Kavelbesluit HKN, published in Staatscourant on 9 May 2019

**STAATSCOURA**

Officiële uitgave van het Koninkrijk der Nederlanden sinds 1814.

## Kavelbesluit V windenergiegebied Hollandse Kust



### 7.8.7 Bevordering biodiversiteit

Het aanleggen en in gebruik nemen van windparken kan negatieve effecten met zich meebrengen voor biodiversiteit. Om daar op verantwoorde wijze mee om te gaan, kent dit besluit onder meer voorschriften voor mitigerende maatregelen. Daarnaast kunnen windparken in potentie ook voordelen met zich meebrengen voor een gezonde zee en behoud en duurzaam gebruik van van nature in Nederland voorkomende soorten en habitats. Naast het realiseren van bepaalde duurzame vormen van medegebruik (zie paragraaf 6.14), kan door zogeheten natuur-inclusief ontwerpen en bouwen ook direct of indirect worden bijgedragen aan behoud en duurzaam gebruik van van nature voorkomende soorten en habitats in Nederland, bijvoorbeeld doordat bepaalde organismen kunnen profiteren van de toegepaste materiale…

Een consultatie van onder meer natuurorganisaties over een eerder onderzoek[94] leverde een voorkeur op voor het nader willen uitwerken van twee richtingen: het toepassen van natuurstimulerende erosiebeschermende bestorting bij de bouw van nieuwe windparken en het introduceren van platte oesters in (nieuwe) windparken. Deze richtingen zijn tot nu toe respectievelijk nader verkend middels een onderzoek naar mogelijkheden voor het toepassen van natuurstimulerende erosiebeschermende bestorting in windparken op zee, met een focus op twee 'paraplusoorten': platte oester en kabeljauw[95] en middels twee onderzoeken naar mogelijkheden voor de ontwikkeling van platte oesterpopulaties in Nederlandse windparken op zee[96]. Het zogeheten natuur-inclusief ontwerpen en bouwen dient wel betrekking te hebben op de structuren van het windpark zelf. De erosiebescherming rondom de fundaties van het windpark zelf kan een geschikte habitat vormen, indien het aan de eisen uit het voorschrift voldoet.

De maatregelen mogen alleen voorzieningen betreffen die direct zijn gerelateerd aan de op te richten windturbines. Tegelijk worden andere benaderingen die actief bijdragen aan de hiervoor aangegeven doelstellingen niet uitgesloten. Extra installaties en eventuele voorzieningen zijn mogelijk wel vergunningplichtig op grond van de Waterwet, wanneer deze niet direct gerelateerd zijn aan de op te richten windturbines. Bij de vergunningverlening worden ook de belangen van het windpark afgewogen. De erosiebescherming rondom de fundatie van windturbinepalen kan hiervoor wel geschikte kenmerken krijgen. Voor alle toegepaste maatregelen geldt dat ze voor vergelijkbare ontwerpcondities ontworpen moeten worden als de bodembescherming, de fundering en de kabelaansluitingen. Er dient te worden aangetoond dat niet alleen de toegepaste structuren hydrodynamisch stabiel zijn, maar ook de naastgelegen bodembescherming. Tevens dient er aandacht te worden besteed aan het minimaliseren van aanzanding in de toegepaste structuren en effecten op ontgronding aan de rand van de bodembescherming (*'edge scour'*).

… bouwen van windparken op lange termijn in kaart te kunnen brengen.

[94] Van Duren, L.A., Gittenberger, A., Smaal, A.C., Van Koningsveld, M., Osinga, R., Cado van der Lelij, J.A. & De Vries, M.B. (2016). Rijke riffen in de Noordzee: verkenning naar het stimuleren van natuurlijke riffen en gebruik van kunstmatig hard substraat. Delft: Deltares; http://publications.deltares.nl/1221293_000_Eng.pdf.

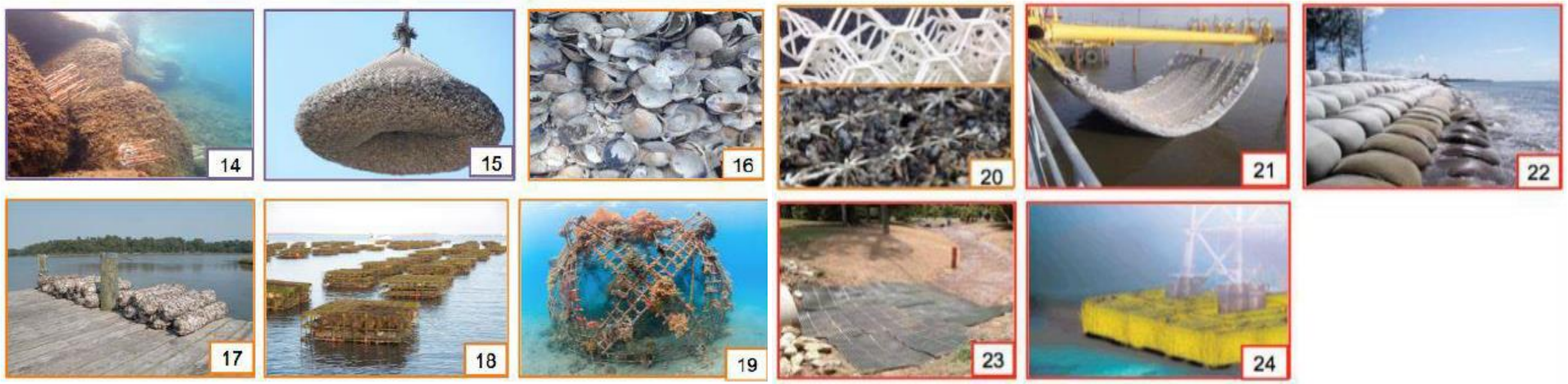
[95] http://www.buwa.nl/fileadmin/buwa_upload/Bureau_Waardenburg_rapporten/17-001_Bureau_Waardenburg_report_EcoFriendly_design_scour_protection.pdf, zie o.a. blz 19/20.

[96] http://library.wur.nl/WebQuery/wurpubs/fulltext/412950 en Kamermans, P., Van Duren, L. Kleissen, F. (2018), Flat oysters on offshore wind farms: additional locations; opportunities for the development of flat oyster populations on planned wind farms and additional locations in the Dutch section of the North Sea.

Source: https://www.rvo.nl/sites/default/files/2019/05/stcrt-2019-24545.pdf

# Catalogue of potentially eco-friendly measures

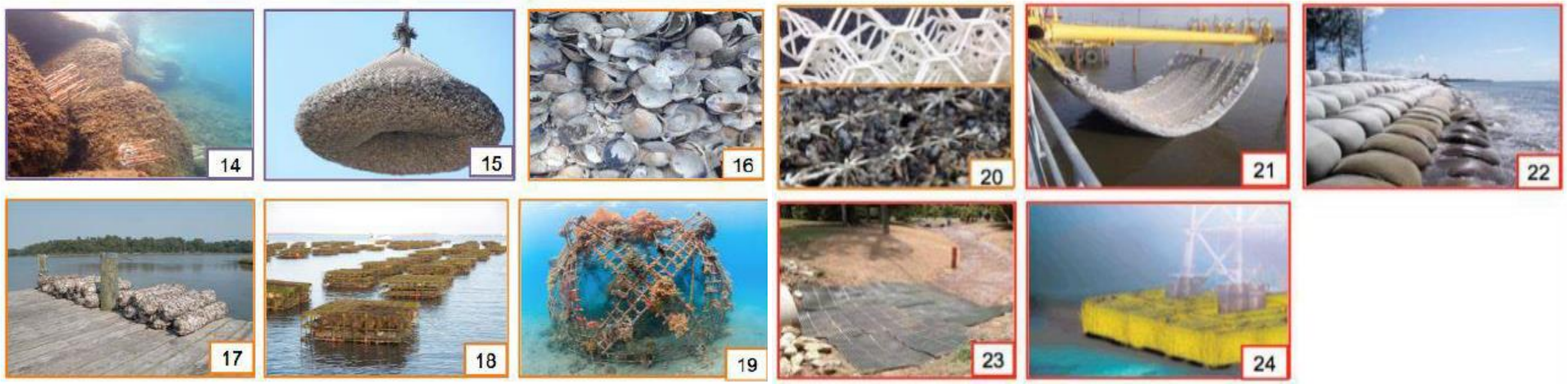

- A more complex habitat yields a more diverse biological community
- Use different type of materials and differentiate between pore sizes
- Many shapes and materials can be considered, even 3D-printed structures and artificial materials (e.g. calcareous material to allow settlement of oysters)
- But can you just modify a scour protection without harming functionality and will it actually work as intended?




*Lengkeek, Wouter; Didderen, K.; Teunis, M.; Driessen, F.; Coolen, J.W.P.; Bos, O.G.; Vergouwen, S.A.; Raaijmakers, T.; Vries, M.B. de; Koningsveld, M. van (2017)*

# Catalogue of potentially eco-friendly measures


- A more complex habitat yields a more diverse biological community
- Use different type of materials and differentiate between pore sizes
- Many shapes and materials can be considered, even 3D-printed structures and artificial materials (e.g. calcareous material to allow settlement of oysters)
- But can you just modify a scour protection without harming functionality and will it actually work as intended?
- Hydraulic aspects are being investigated in JIP HaSPro:
  - ✓ stability of ecological concepts
  - ✓ influence on surrounding protection
- Ecological functioning is tested in the field through several pilots, such as JIP ECOFRIEND




*Lengkeek, Wouter; Didderen, K.; Teunis, M.; Driessen, F.; Coolen, J.W.P.; Bos, O.G.; Vergouwen, S.A.; Raaijmakers, T.; Vries, M.B. de; Koningsveld, M. van (2017)*

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# Ecological elements

to provide shelter for (adult) fish (e.g. Atlantic cod) and crustaceans (e.g. lobster and crab)


Reef balls (by Reef Innovations)

# Natural shell material

to provide settlement area for (European flat) oysters

Oyster shells
(provided by Prins & Dingemanse, Yerseke)

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# Nature-inclusive designs tested on large-scale in JIP HaSPro

## Monopile scour protection

Rock scour protection with integrated reef balls and perforated concrete tubes

## Cable (crossing) protection

Rock berms with loose oysters and with integrated reef balls

Gabion mattresses with top layer of rock replaced by oyster shells

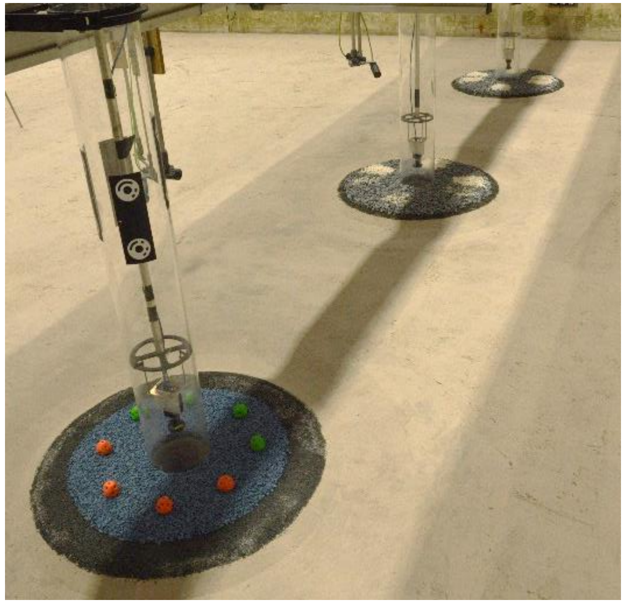
# Nature-inclusive designs tested on medium scale in JIP HaSPro

## Monopile scour protections - I

- Reef balls
- Large rock clusters (“dolmens”)
- Perforated pipes

- Scale factor ~1:30
- Wave-current conditions

## Monopile scour protections - II



- New and optimized reef elements
- Different types of shells sprinkled in scour protections

- Scale factor ~1:30
- Wave-current conditions

## Rock berms

- Oyster and mussel shells
- Schematized “living” oysters

- Scale ~1:1 (reproducing near-bed hydrodynamics)
- Regular wave and/or currents

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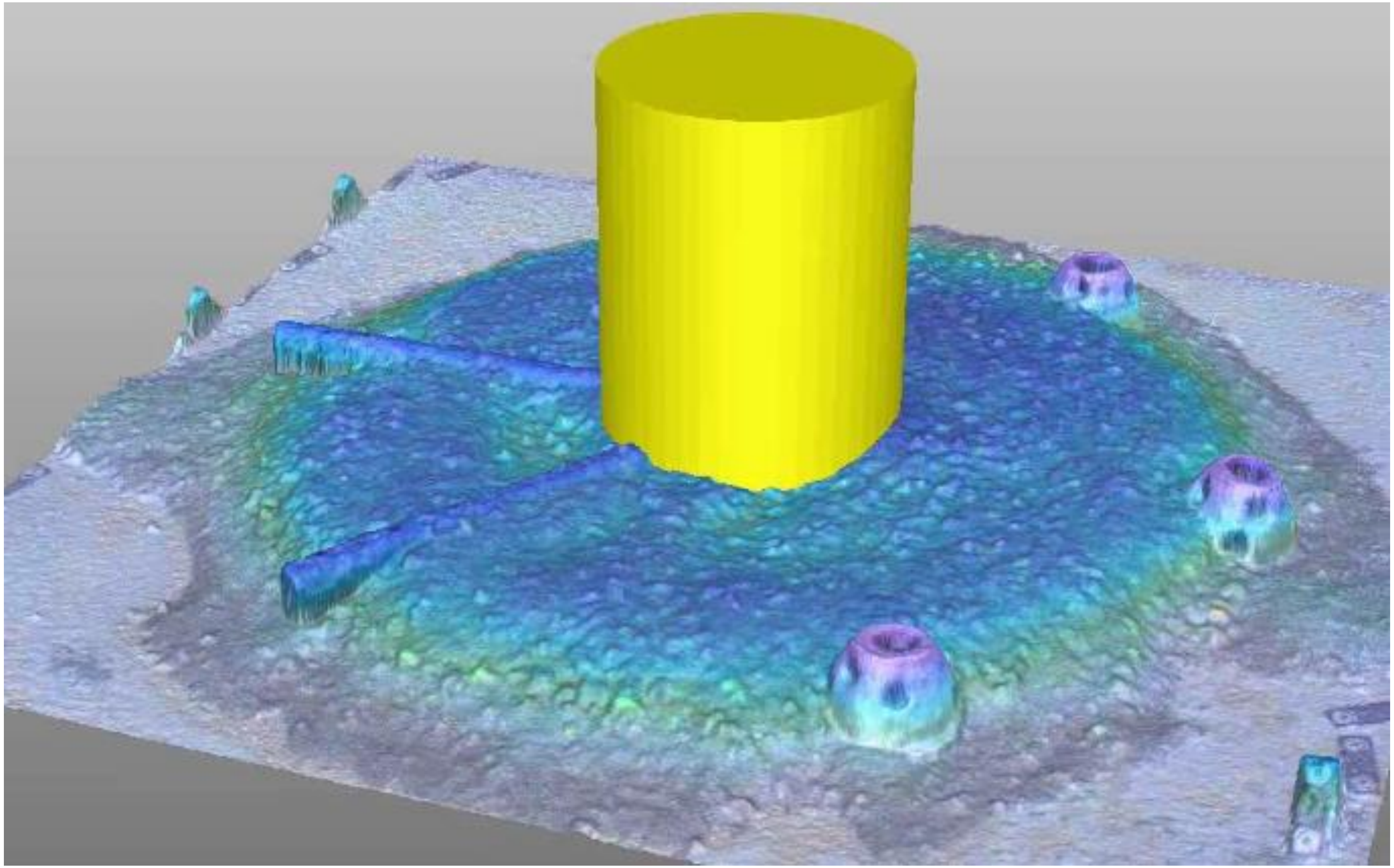
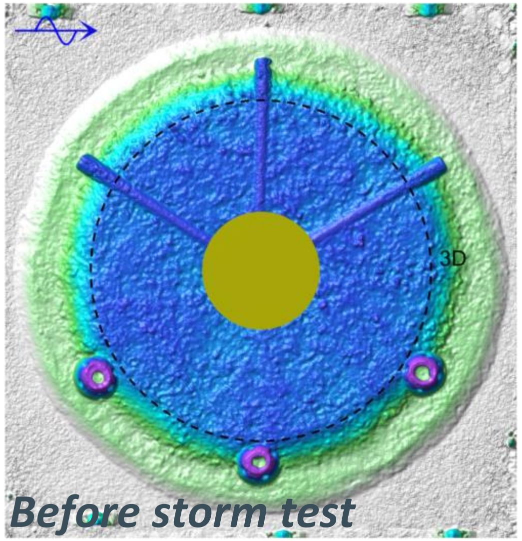
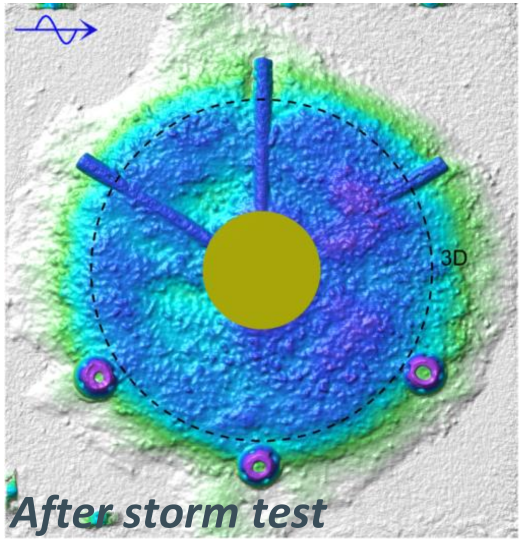
# Deformation of eco-friendly scour protection during large-scale storm test

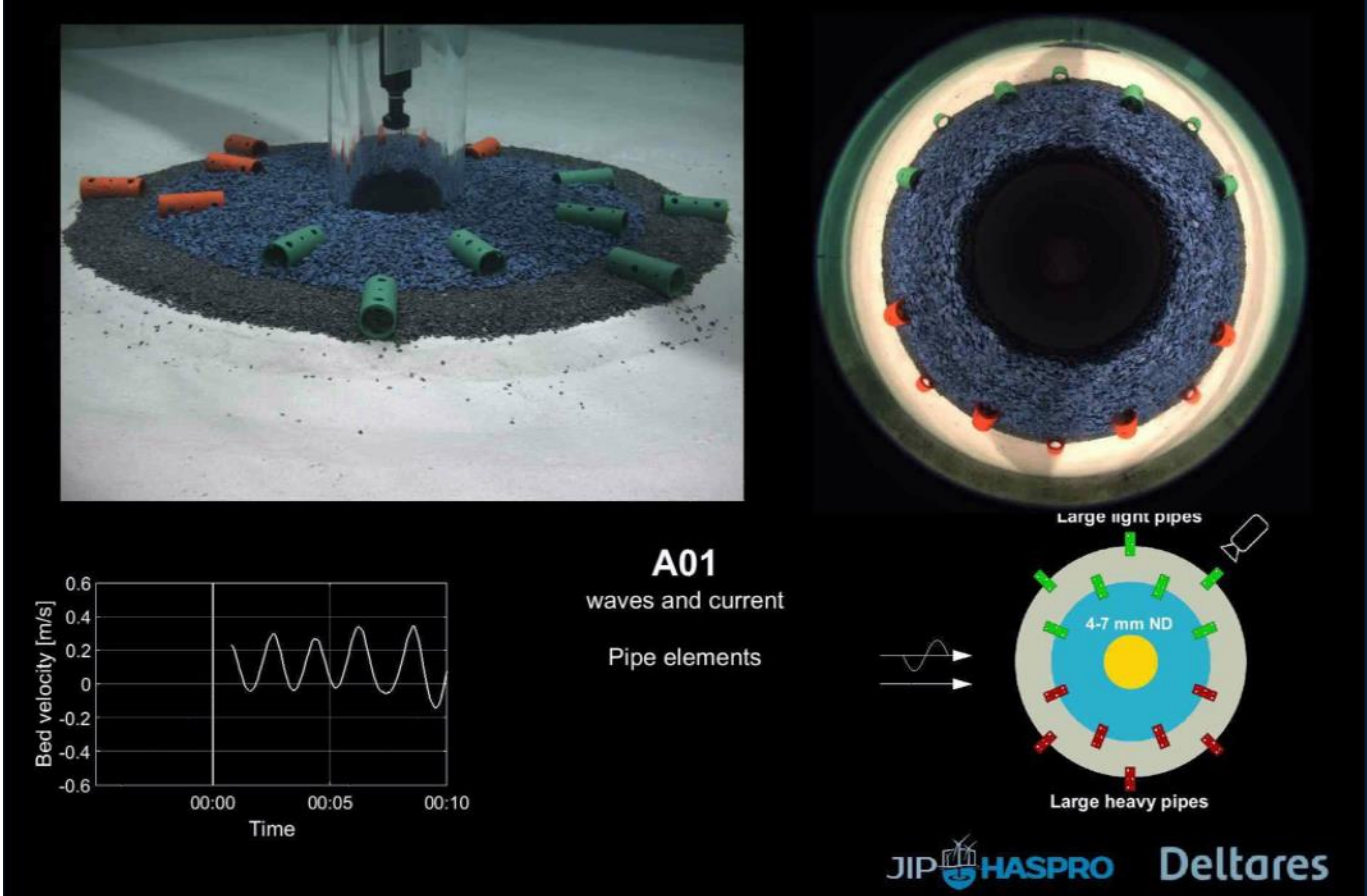
Investigating the potential consequences of interaction between eco-elements and scour protection

*3D-snapshot of combined colour image and height map*








*Performance of eco-friendly elements during storm test*

# JIP ECO-FRIEND: Eco-friendly scour protection

**Aims**

1. Develop, validate & demonstrate pilots with flat oyster restoration:
    a. Cages with living oysters (just) outside scour protection
    b. Loose shell material to provide settlement ground for larvae
2. Develop, cost-effective monitoring system to assess the effectiveness of these pilots
3. Create 70 km$^2$ of oyster reef within 5 years

**Increase insight in:**

- ➢ Effectiveness of eco-friendly designed scour protection
- ➢ Best practise to re-introduce flat oysters offshore
- ➢ Estimate feasibility of eco-friendly designs in other offshore environments

**Offshore Test Site**

GEMINI Windfarm, ~80km north of the Wadden Islands

**Project duration**

2018-2022 (duration related to annual monitoring and long-term ecological effects)

WAGENINGEN UNIVERSITY & RESEARCH

Bureau Waardenburg Ecologie & Landschap

Gemini

TKI WIND OP ZEE Topsector Energie

Sas Consultancy

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# Summary of scour protection methods: Suitability matrix for scour protections in HKN

| Scour Protection Method | $B_s$ | $B_r$ | $B_l$ | $C_s$ | $C_r$ | $C_l$ |
|---|---|---|---|---|---|---|
| Static scour protection consisting of rock | + | + | - | -- | -- | -- |
| Dynamic scour protection with two gradings of loose rock | ++ | ++ | + | - | - | - |
| Dynamic scour protection with a single grading of loose rock | + | + | + | + | + | + |
| Artificial vegetation | + | + | 0 | - | - | - |
| Concrete block mattresses | 0 | 0 | - | -- | -- | -- |
| Gabions | 0 | 0 | - | -- | -- | -- |
| Geotubes and Geocontainers | + | + | 0 | + | + | 0 |
| Rock-filled mesh bags | + | + | 0 | + | + | 0 |
| Ground Consolidators or Geohooks | 0 | 0 | 0 | + | + | 0 |
| Mattresses or rubber tyres | 0 | 0 | 0 | + | + | 0 |
| Eco-friendly scour protections | ++ | + | 0 | - | -- | - |

**Scour Mitigation Strategies**

$B_S$: Immediate scour protection, stable seabed

$B_R$: Immediate scour protection, rising seabed

$B_L$: Immediate scour protection, lowering seabed

$C_S$: Monitor & react, stable seabed

$C_R$: Monitor & react, rising seabed

$C_L$: Monitor & react, lowering seabed

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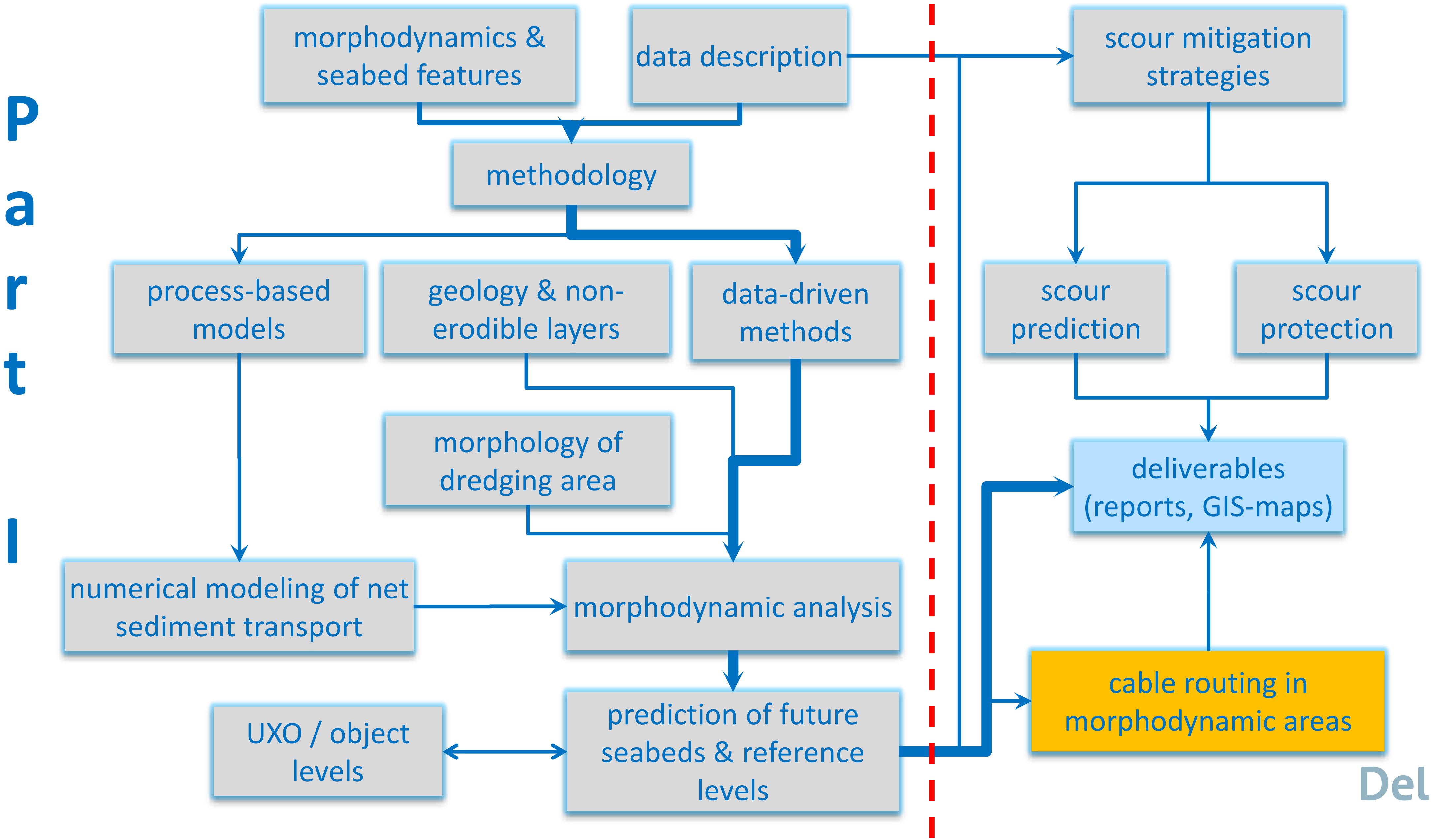
# Structure of presentation

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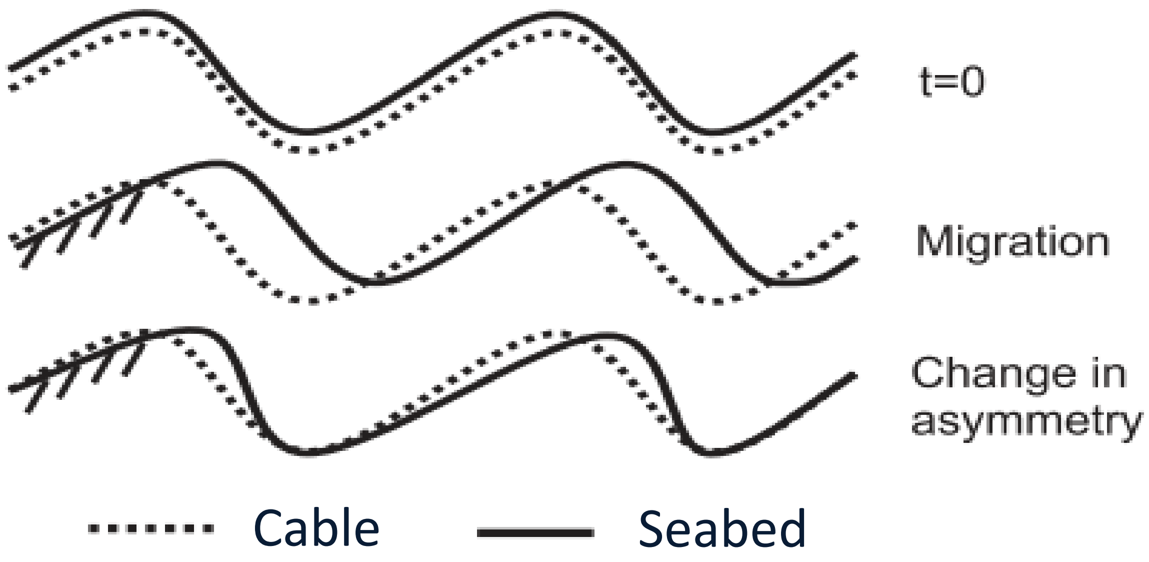
# Cable routing – current practice

- 70-80% of total value of insurance claims is related to cables
- Cable monitoring and repair require expensive marine operations
- Current methods to determine wind farm cable layouts are often based on a stable/static seabed, neglecting morphodynamics




Roetert, T.J., Raaijmakers, T.C., & Borsje, B.W. (2017). *Cable route optimization for offshore wind farms in morphodynamic areas.* Paper presented at the 27th International Ocean and Polar Engineering Conference, 25-30 June 2017, San Francisco, CA, USA.

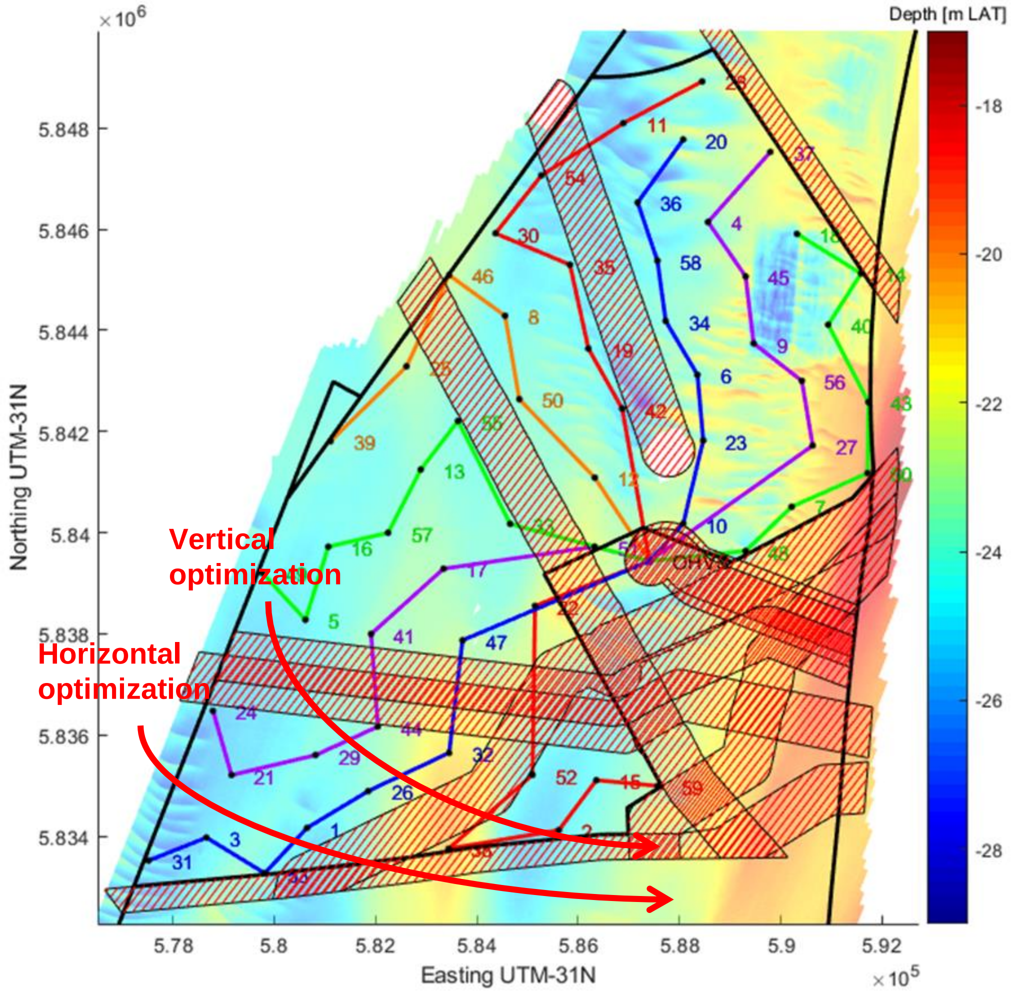
<u>Typical requirements / assumptions for cable routing:</u>

- Wind turbine capacity/yield
- Cable capacity (e.g. 33 or 66 kV), which determines number of turbines per string
- Seabed remains flat/stable
- Obstacles within the wind farm, e.g. pipelines, telecom cables and UXO’s, are to be avoided
- Constraint of not crossing cables of the wind farm itself
- Locations with unfavourable geological characteristics are to be avoided

# Cable routing optimization: stable / static seabed

**Step 1: Cable route optimization for a stable seabed**

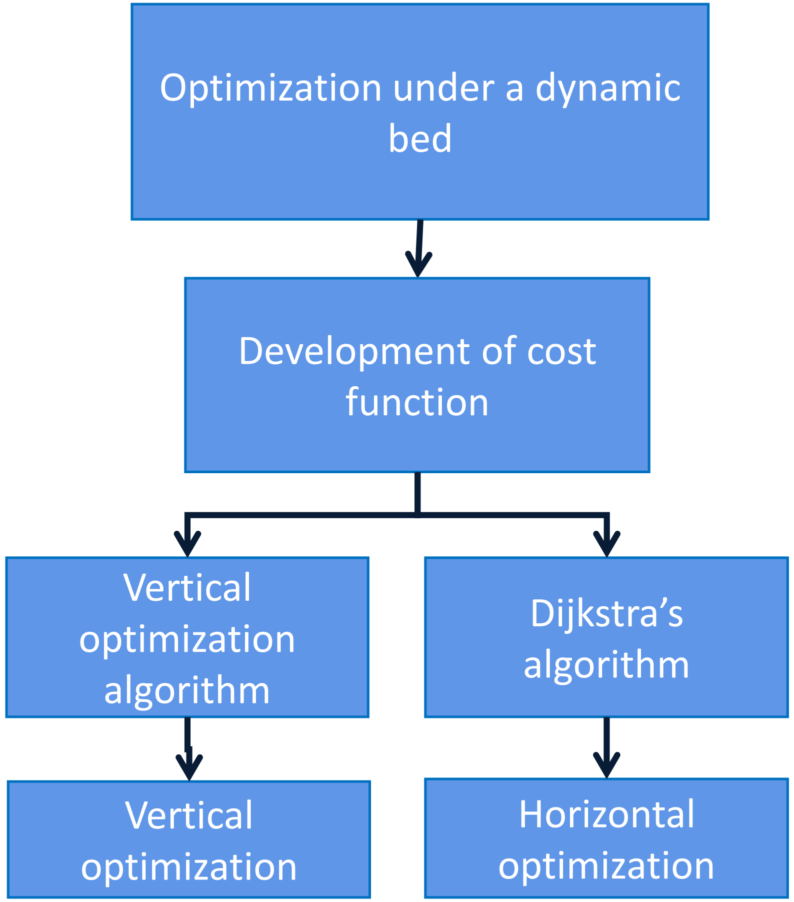
Finding optimum cable paths taking constraints into account (e.g. cable capacity, UXO’s, geology, crossings etc.)




**Step 2: Optimizing the cable routes both horizontally and vertically**

Taking into account seabed morphodynamics:

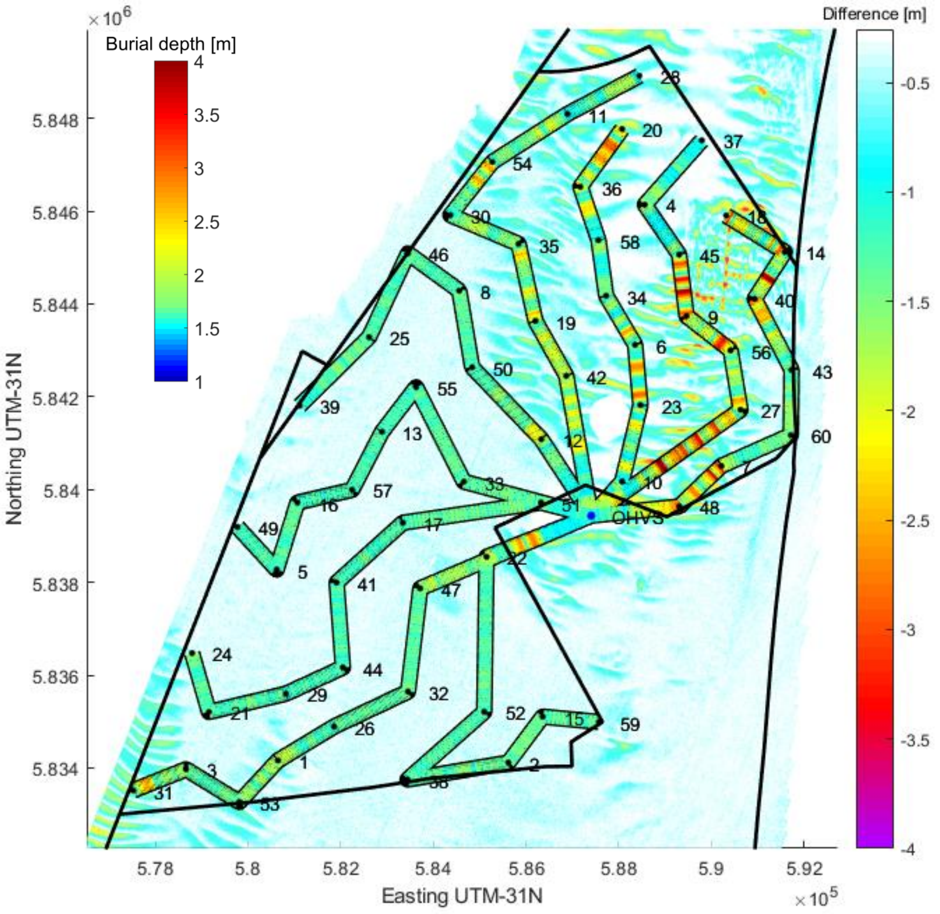
- ✓ effect on risks (e.g. anchors in case of limited burial depth) and
- ✓ potential costs (e.g. reburial of cables, repair of failed cable)



# Cable routing optimization: Vertical vs. Horizontal optimization

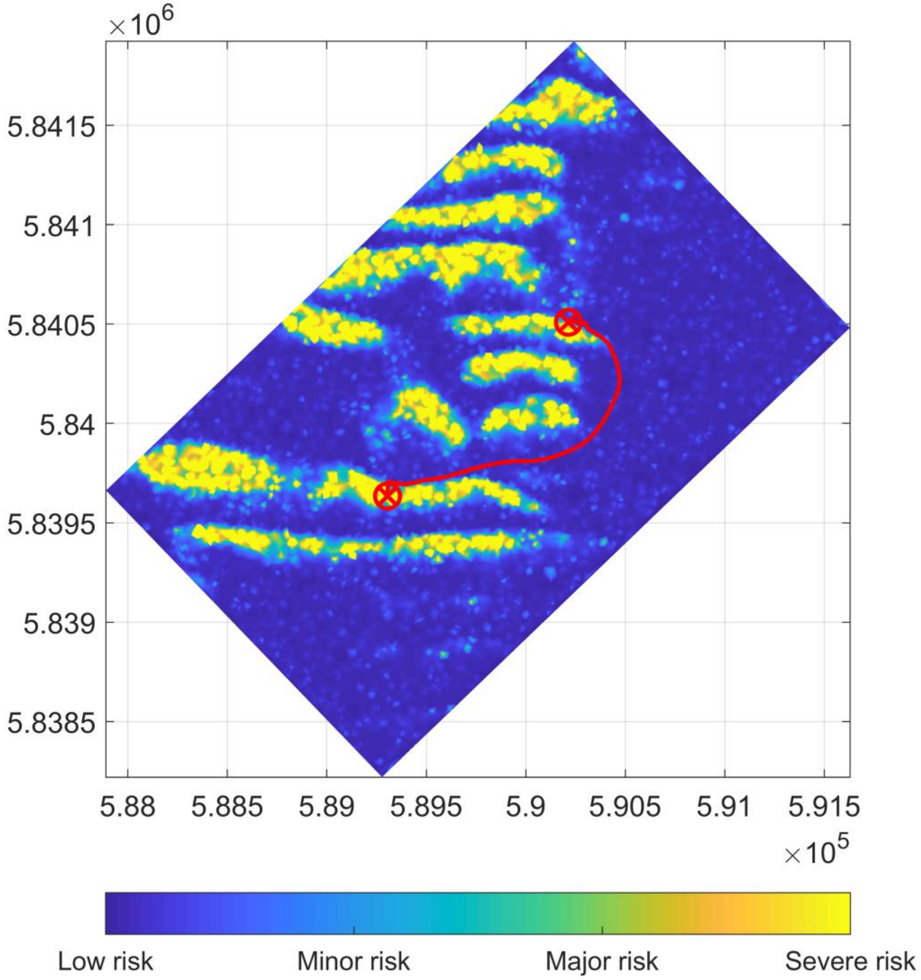
**Vertical micro-optimization of individual cable stretch modifying initial cable burial depth**

Optimization for dynamic seabed, ranging initial cable burial depth between 1.5 and 4m




**Horizontal micro-optimization of individual cable stretch using Dijkstra's shortest path algorithm**

Optimization for dynamic seabed, avoiding areas with high costs and risk related to seabed lowering, keeping initial burial depth fixed at 1.5m

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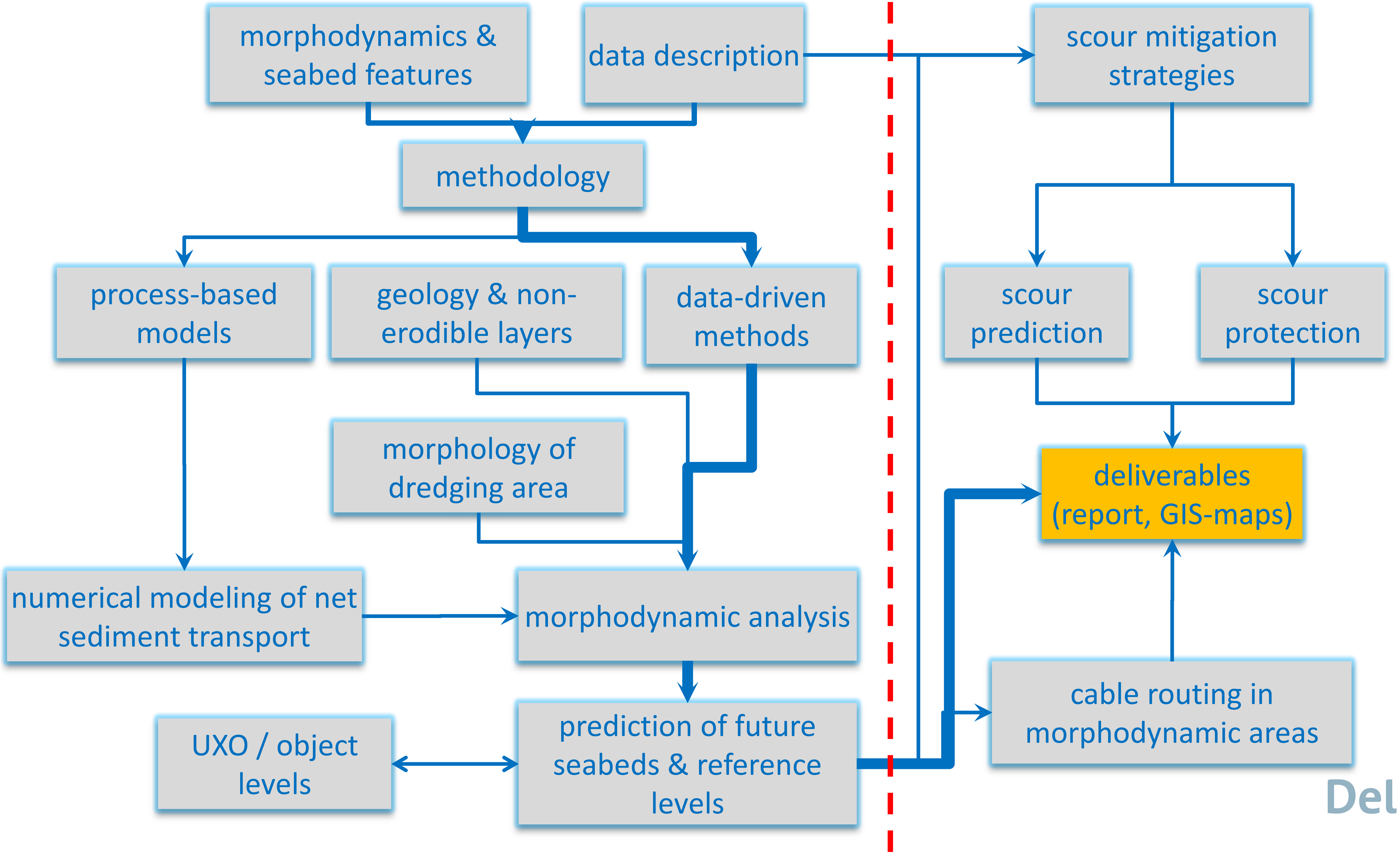
# Structure of presentation

Part I




Part II

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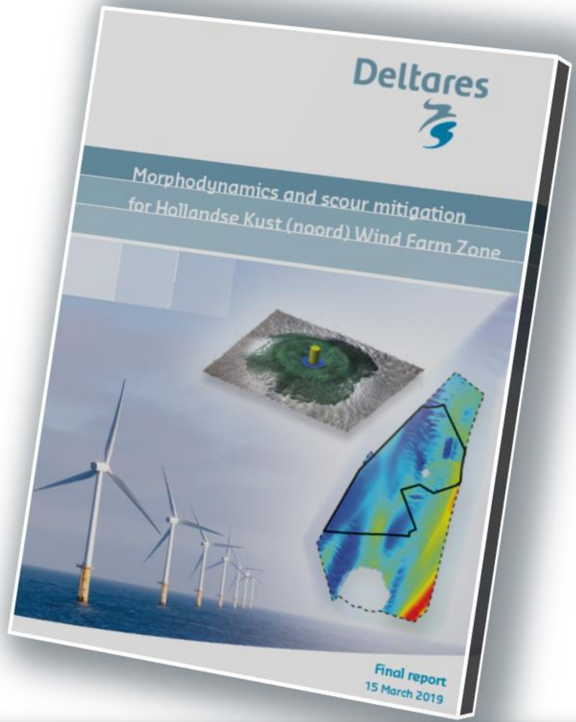
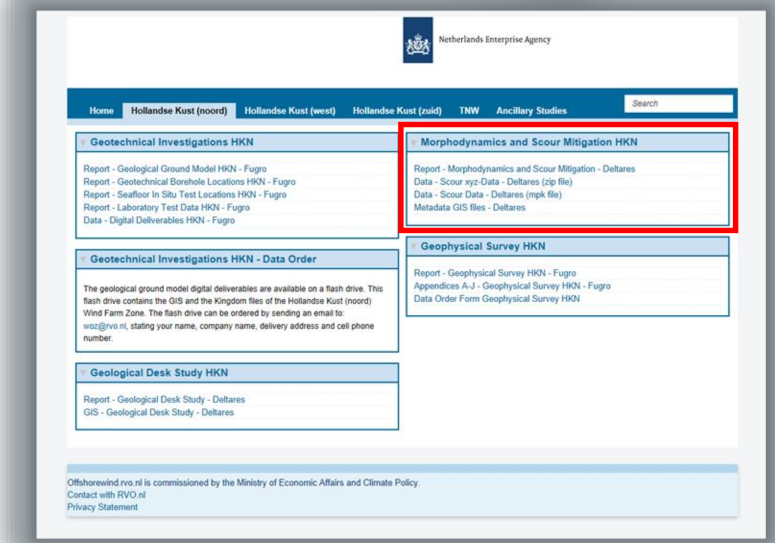
# Deliverables: report, GIS-database and webinar

Main deliverables of this study (https://offshorewind.rvo.nl/soilnh):

- Final report, dated 15 March 2019:
  https://offshorewind.rvo.nl/file/view/55040006/Report+-+Morphodynamics+and+Scour+Mitigation+-+Deltares
- GIS-database:
  for time spans of 5 year within the period of 2018-2058
  - ✓ Best Estimate Bathymetry ($BEB_{2018\text{-}2058}$)
  - ✓ Lowest SeaBed Level ($LSBL_{2018\text{-}2058}$)
  - ✓ Highest SeaBed Level ($HSBL_{2018\text{-}2058}$)
  - ✓ Best-estimate Object Level ($BEOL_{1945\text{-}2021}$)
  - ✓ Lowest Object Level ($LOL_{1945\text{-}2021}$)
  - ✓ Highest Object Level ($HOL_{1945\text{-}2021}$)
  - ✓ Classification zones for wind farm design (for 2018 -2058 only) based on:
    - seabed lowering
    - seabed rising
    - combined lowering and rising
- This webinar (23 May 2019)



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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, but e.g. to assess O&M costs

Example:
$LSBL_{2031}$ = the lowest seabed that can occur between 2018 and 2031 (lower envelope)
> Use LSBL and HSBL for design of foundations

## Key take-aways

Three scour mitigation strategies can be considered:

A. free scour development (and adjust structural design)
B. immediate scour protection
C. monitor and react (only if necessary or intended)

in combination with the morphodynamics at the location of the foundations:

S. stable seabed (less than ~1m autonomous seabed change)
L. lowering seabed
R. rising seabed

and the selected structure type, of which the following were addressed in the study:

- ✓ Monopiles
- ✓ Gravity Based Structures
- ✓ Piled Jackets
- ✓ Suction Bucket Jackets
- ✓ Jackup vessels (for temporary operations)
- ✓ Cables

Many combinations are feasible, when designed properly!

more information?

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