Netherlands Enterprise Agency

Webinar Morphological Desk Study Hollandse Kust (west) Wind Farm Zone

6 November 2020

Behzad Aziz

Rijksdienst voor Ondernemend Nederland

Deltares

Webinar Morphodynamic and Scour Mitigation desk study Hollandse Kust (west)

Tom Roetert

Hendrik Jan Riezebos

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6 November 2020

Introduction to webinar team

Presenters:

Tom Roetert

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Project Leader Morphodynamics and and Scour Mitigation study HKW

Hendrik Jan Riezebos

Senior researcher/advisor, Programme Manager Offshore Engineering at Deltares
Co-author of Morphodynamics and Scour Mitigation study HKW

Moderators:

Behzad Aziz

Advisor Renewable Energy, RVO

Ben de Sonneville

Senior Consultant Offshore Wind

Objectives of the Morphodynamic and Scour Mitigation Study for Hollandse Kust (west)

The objectives of this study are to:

- describe in detail the morphological seabed features in the wind farm zone HKW
- describe the shallow geological and sedimentological site conditions to a depth of 20m below the measured seabed level
- analyse / quantify the morphodynamics to determine future seabed levels (2019-2059) and historic seabed levels (1945-2019)
- describe the scour conditions to be expected at HKW for typical wind farm-related structures*
- provide a state-of-the-art overview of scour mitigation measures and their applicability at HKW 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 Morphodynamic and Scour Mitigation Study for Hollandse Kust (west)

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Morphodynamic assessment

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Scour and scour mitigation assessment

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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

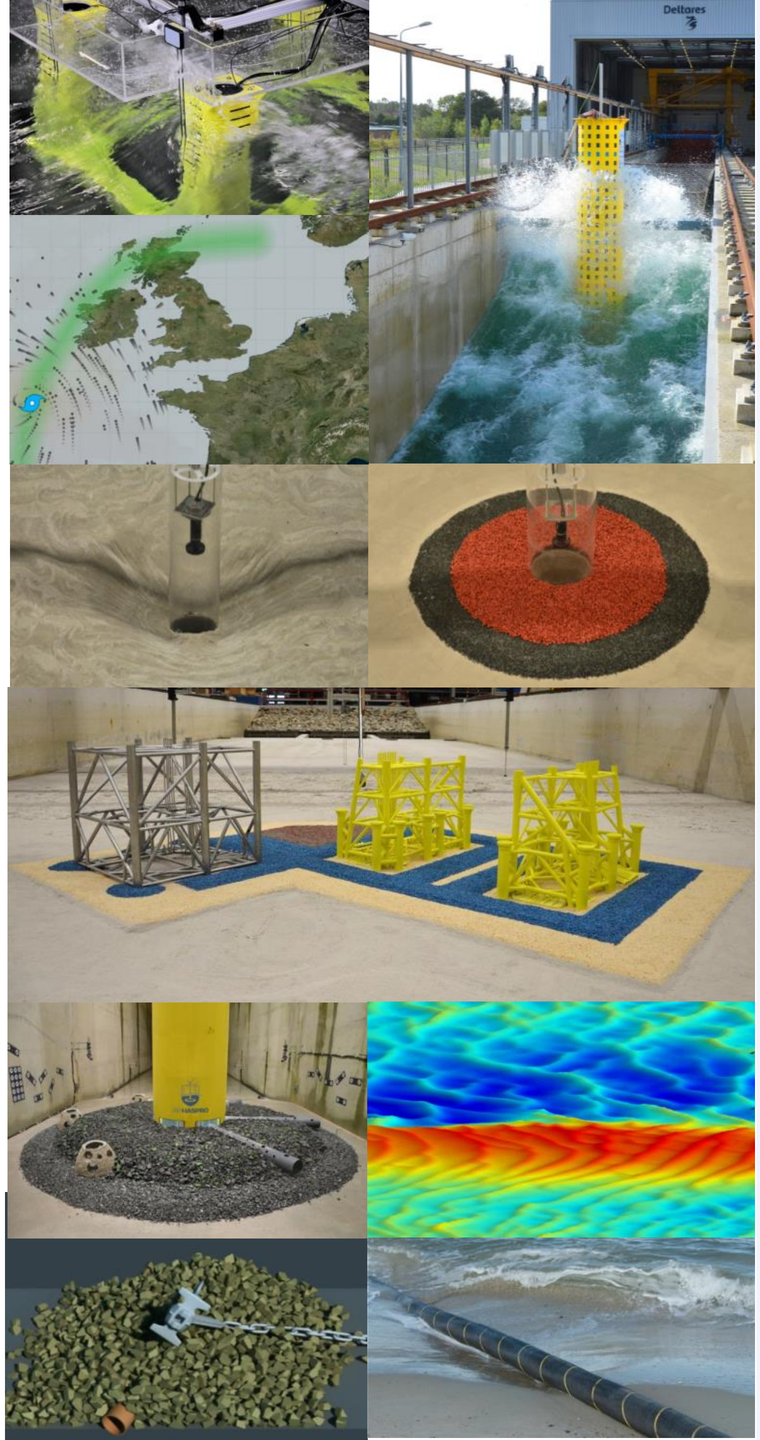
- Offshore geology, seabed characteristics
- Scour and scour protection for all types of foundations
- Bed level changes due to morphodynamics (e.g. sand waves)
- Cable routing and site selection in morphodynamic areas

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)

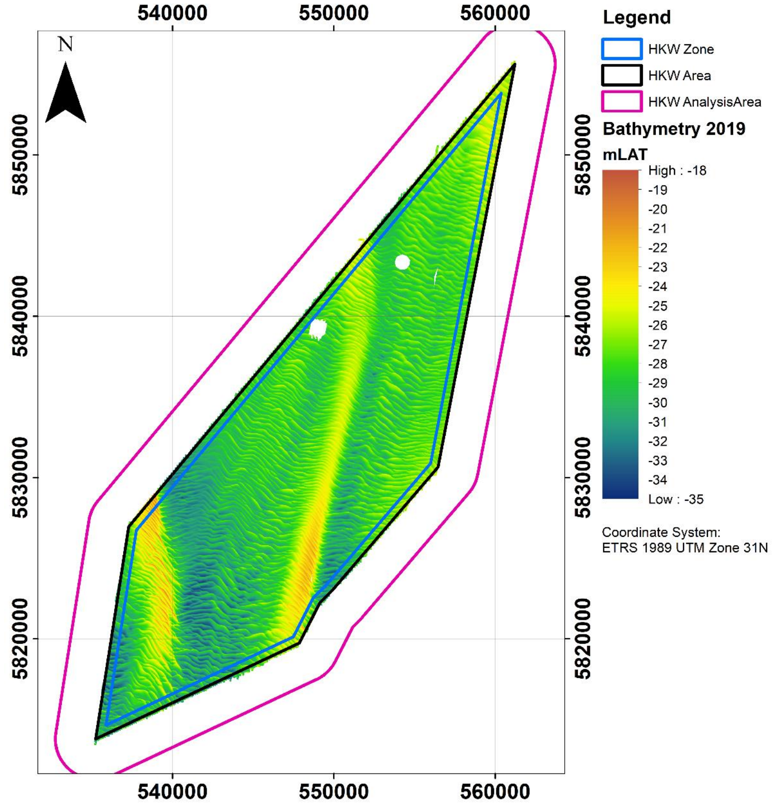
Corrosion and biochemistry

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



Structure of Morphodynamic assessment

morphodynamics & seabed features
data description
methodology
process-based models
geology & non-erodible layers
data-driven methods
analysis of Vibrocores
numerical modeling of net sediment transport
morphodynamic analysis
UXO / object levels
prediction of future seabeds & reference levels
scour mitigation in morphodynamic areas
cable routing in morphodynamic areas
deliverables (reports, GIS-maps)



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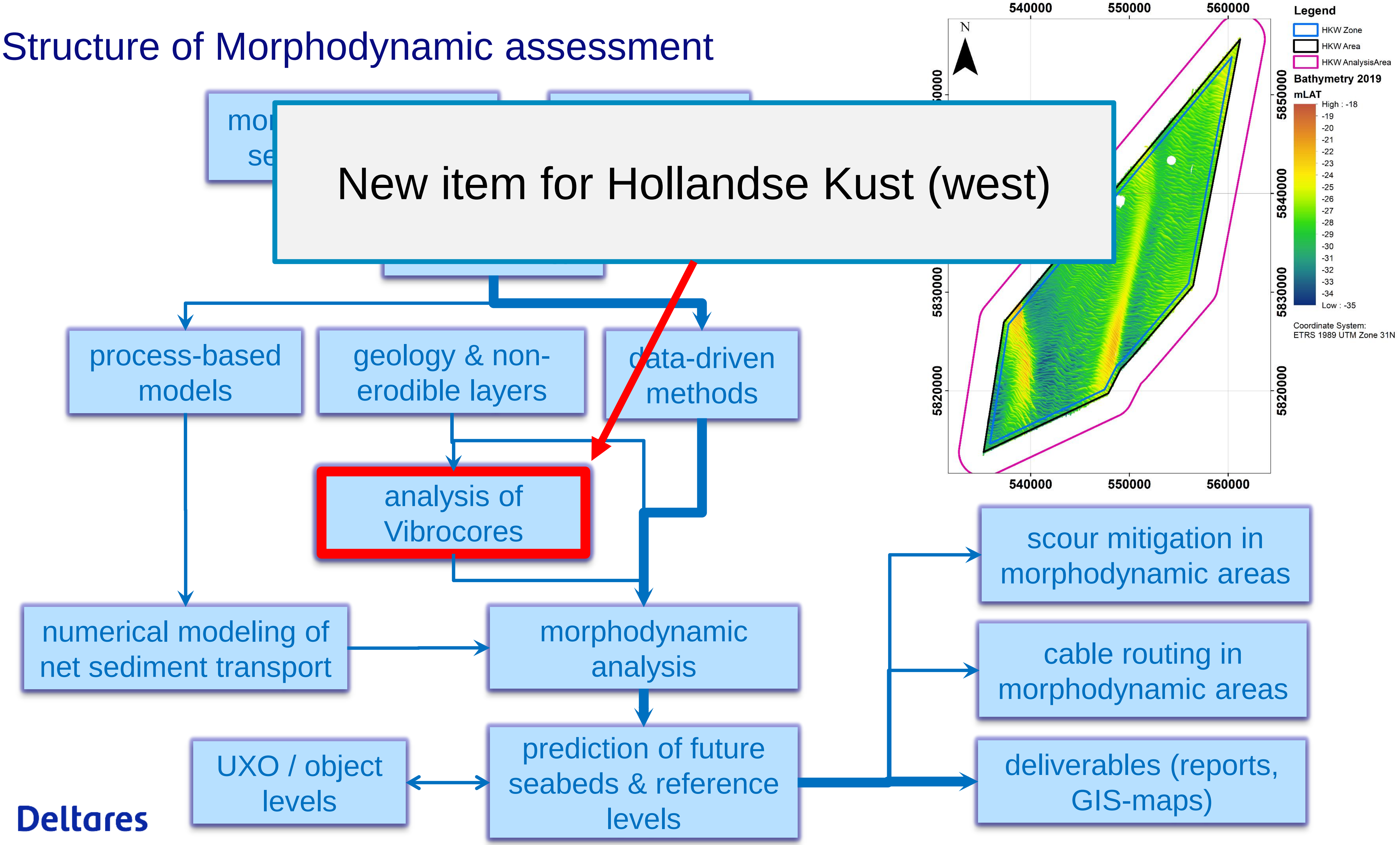

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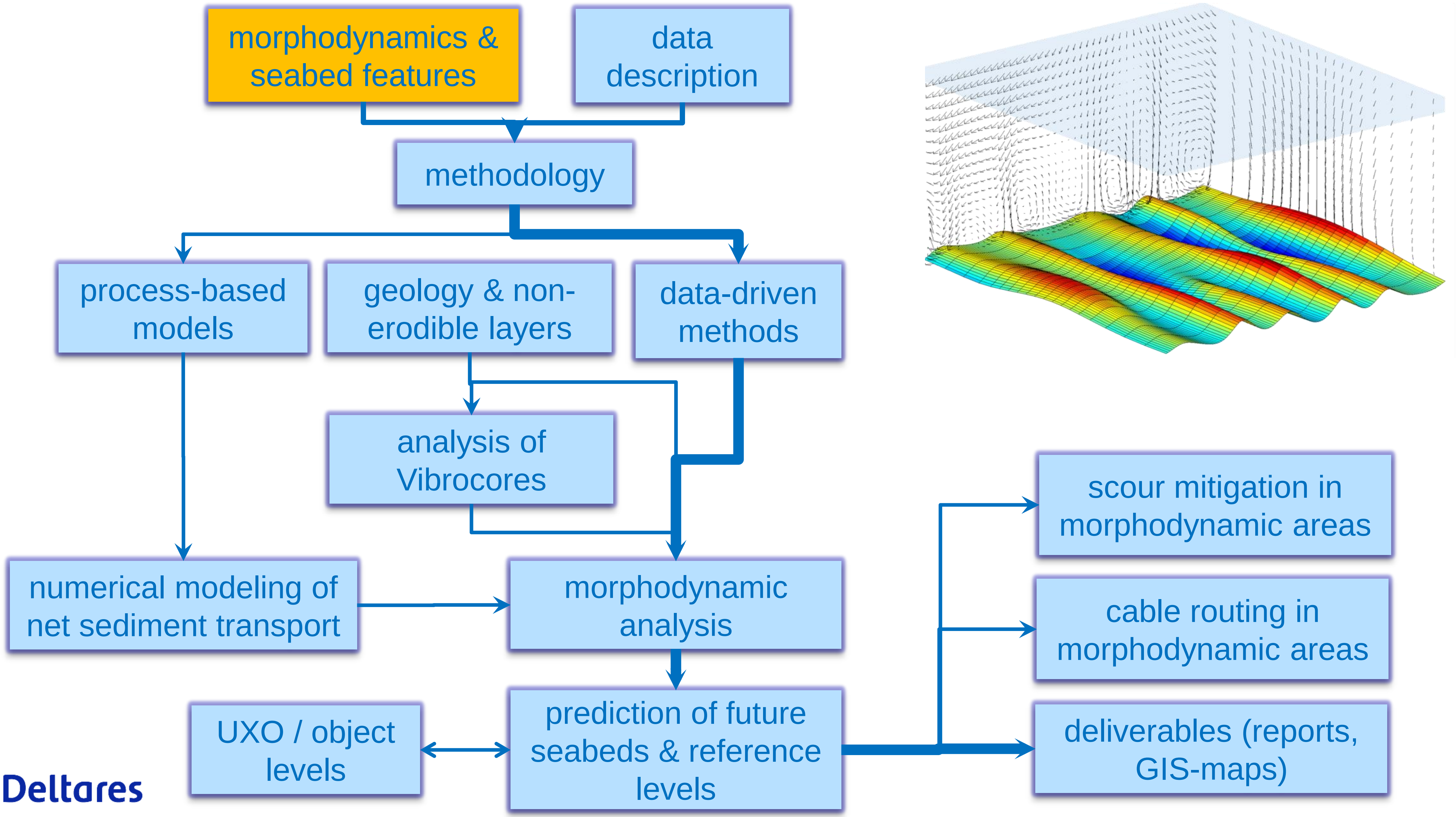

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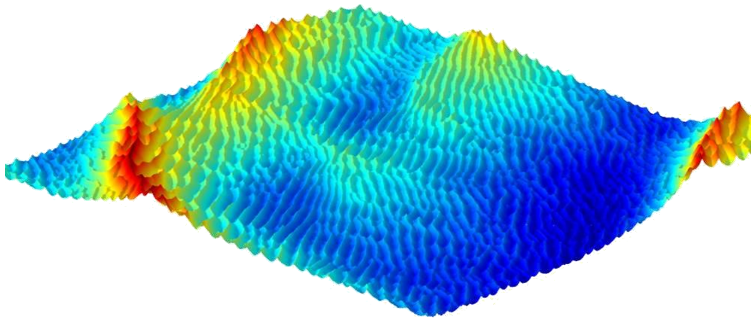
Seabed Morphodynamics - definitions

*“**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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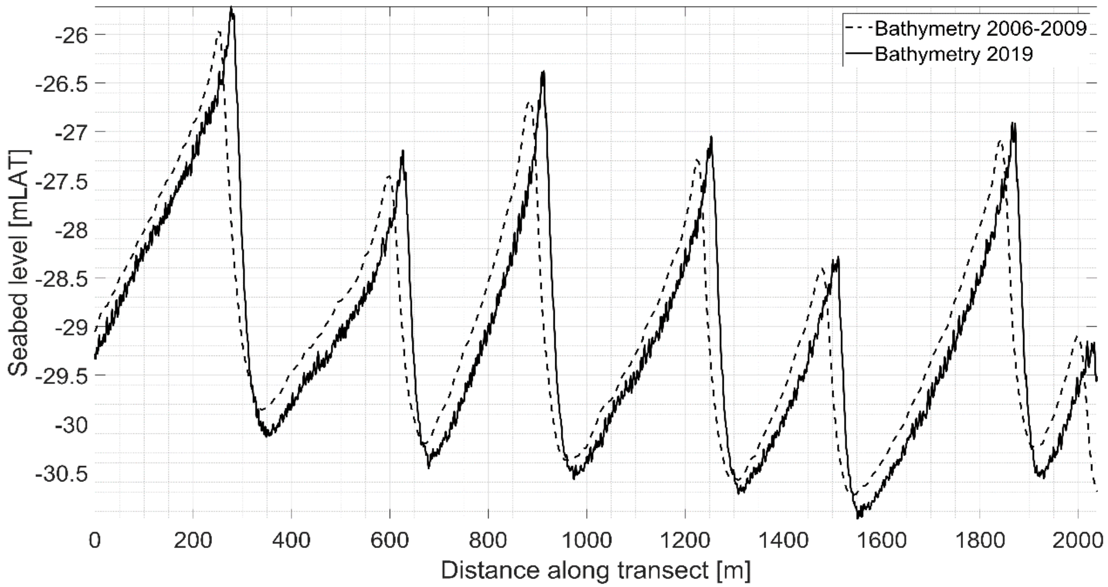
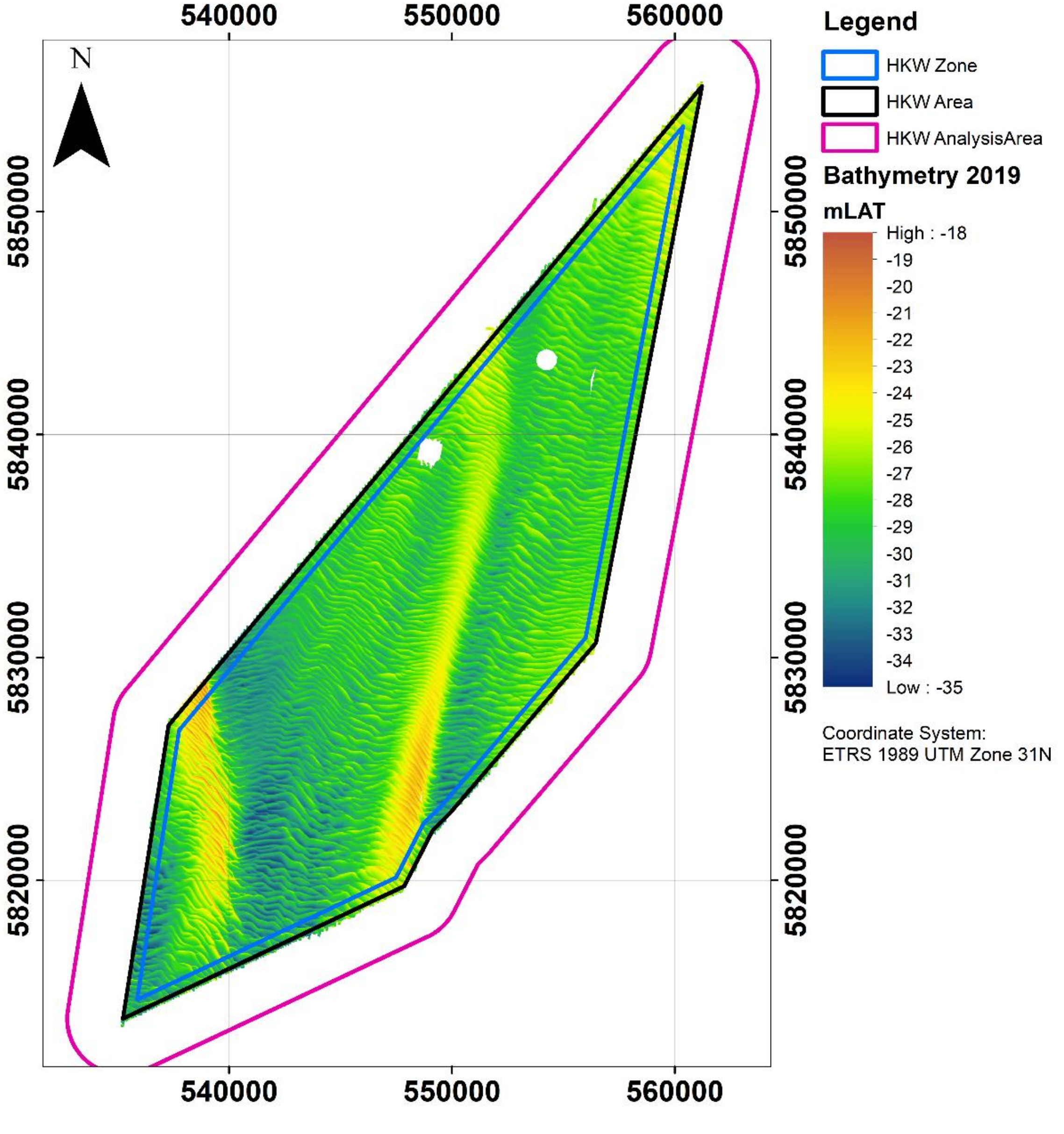
Seabed Morphodynamics – overview Hollandse Kust (west)

- Hollandse Kust (west) characterised by various bedform types
  - Two sand banks
  - Full coverage of sand waves
  - Full coverage of megaripples
- Bed level variations between -18.8 and -35.6 m LAT





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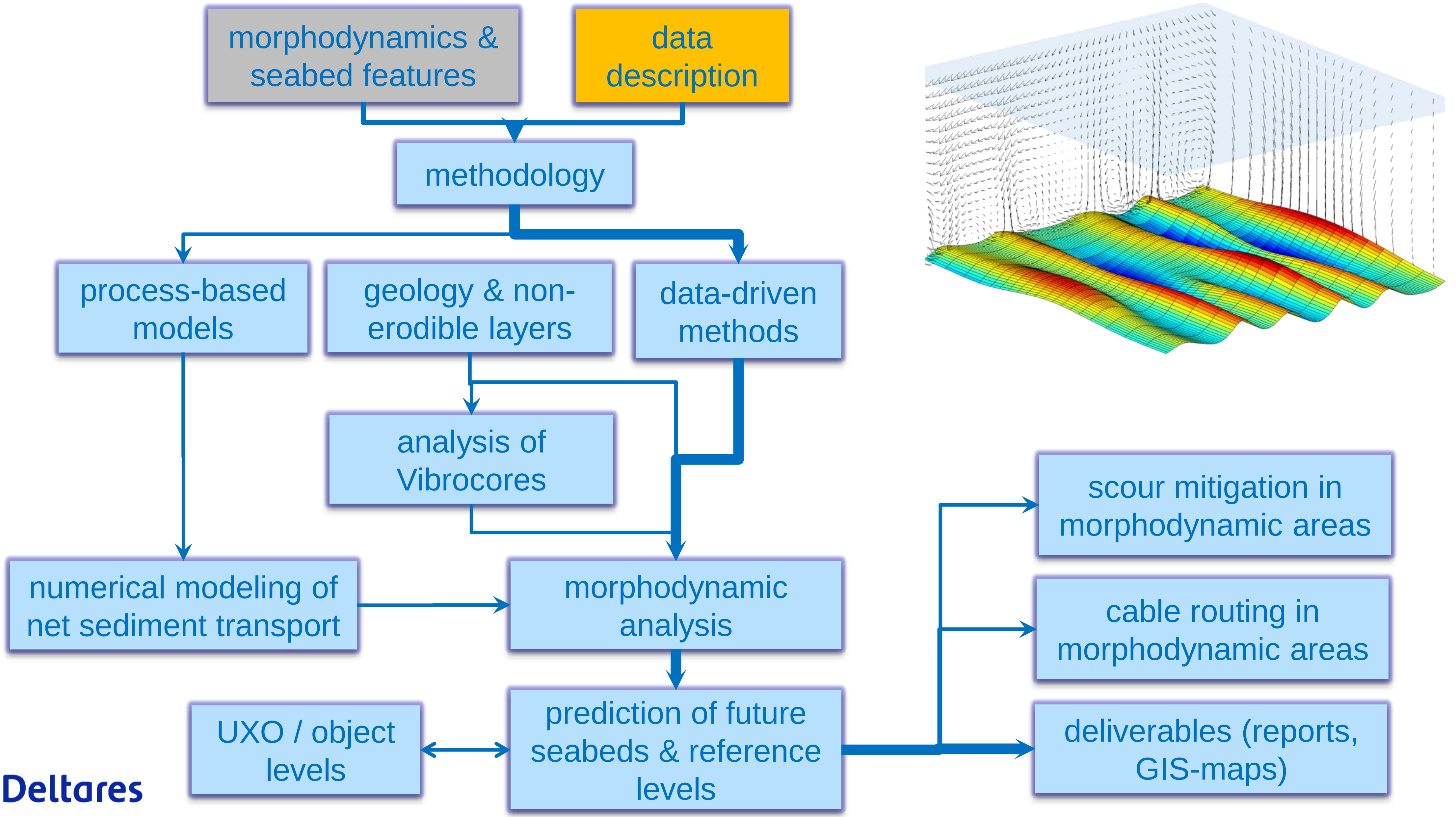
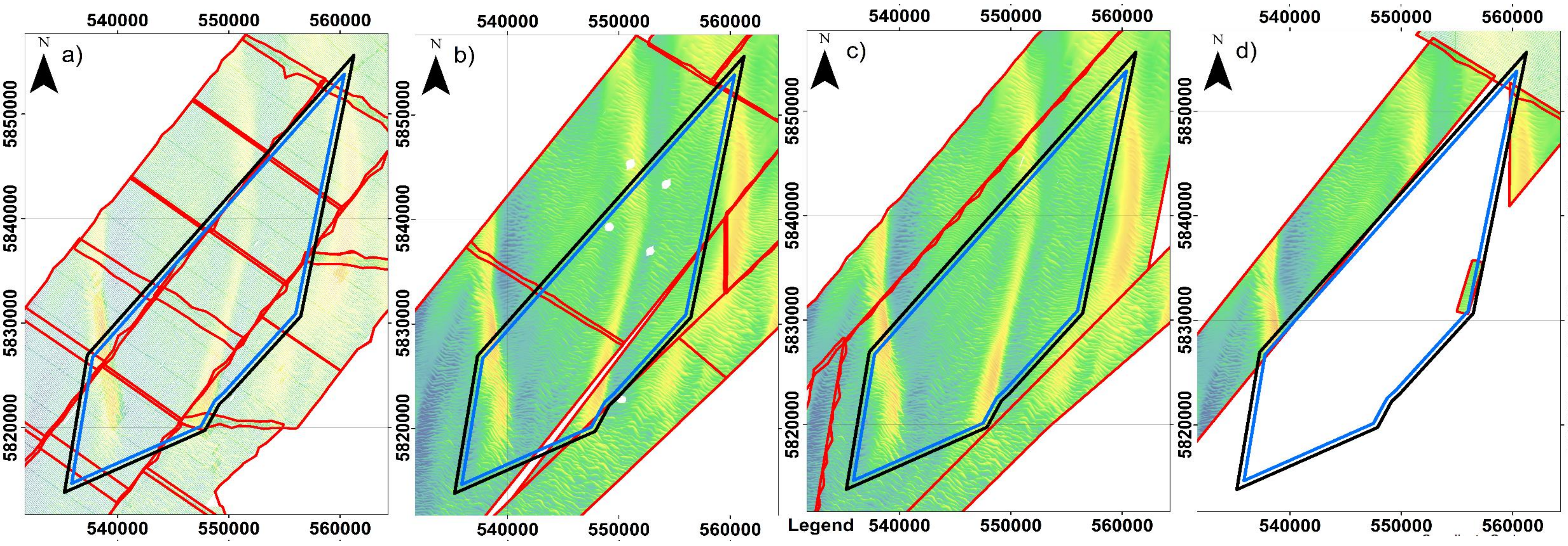


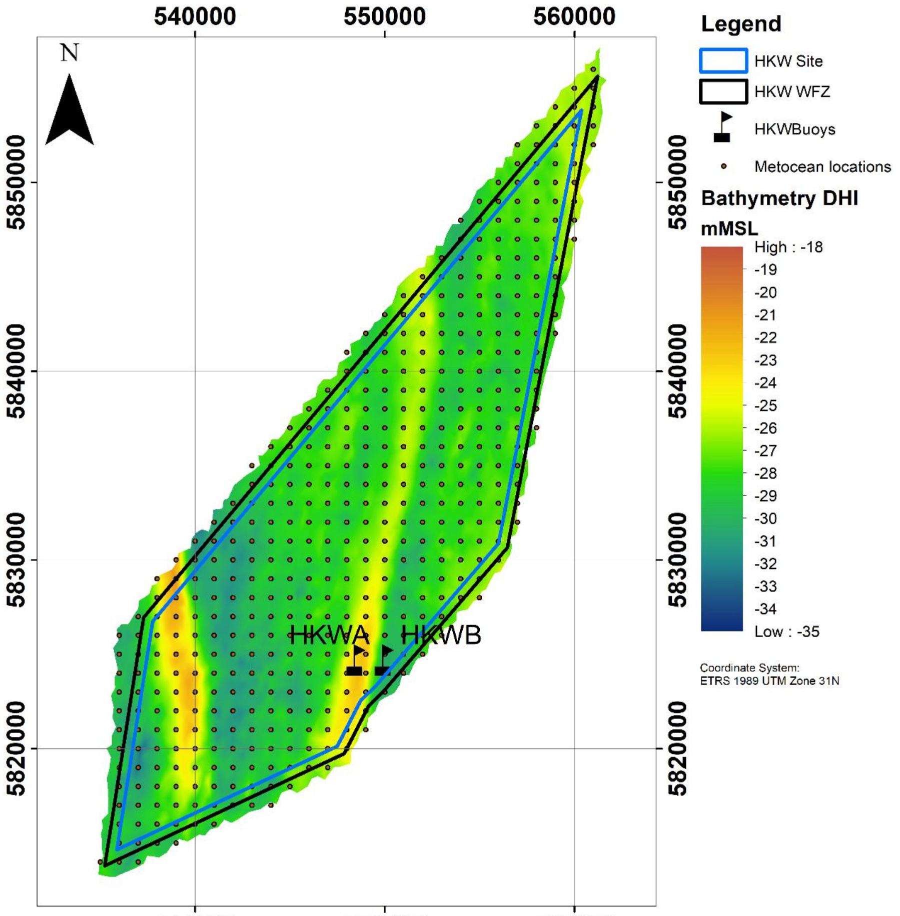
Data analysis – overview of available data (1)

- In total 37 surveys available in and around Hollandse Kust (west)
- Divided over four composite bathymetries and the 2019 Fugro dataset

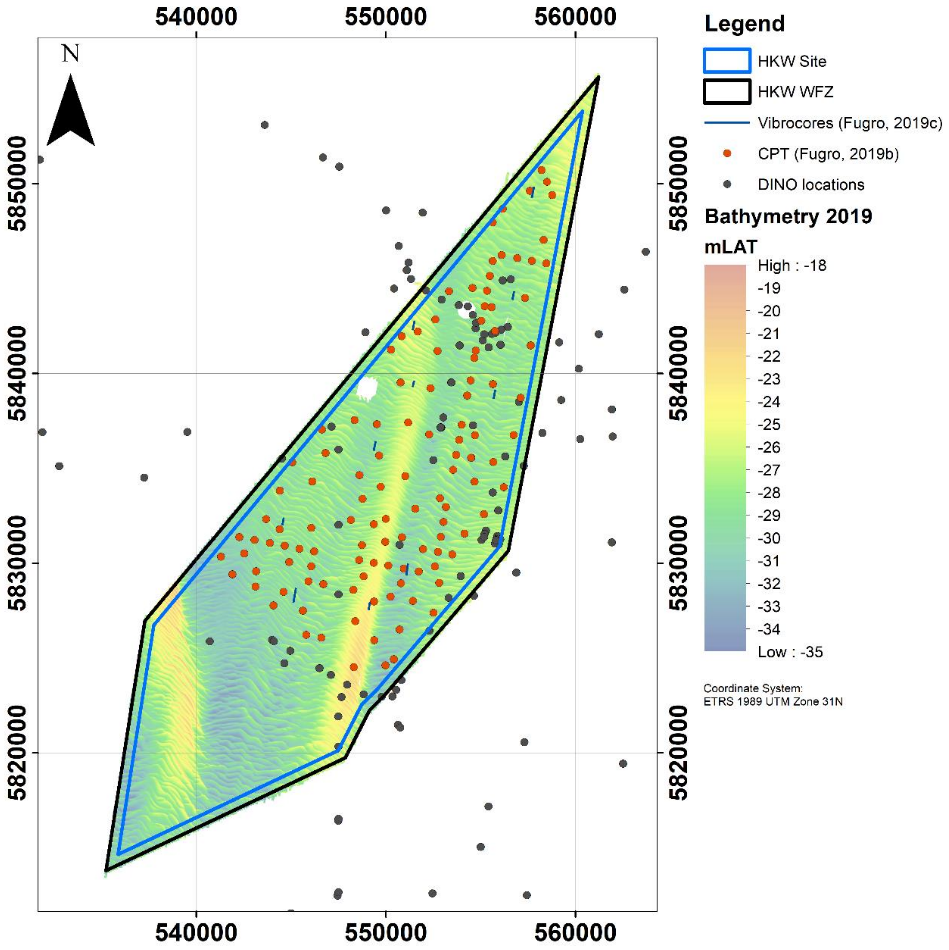


Bathymetry 1996-2002 | Bathymetry 2006-2009 | Bathymetry 2014-2015 | Individual surveys 1991-2012

Data analysis – overview of available data (2)



Hydrodynamic data



Geotechnical data

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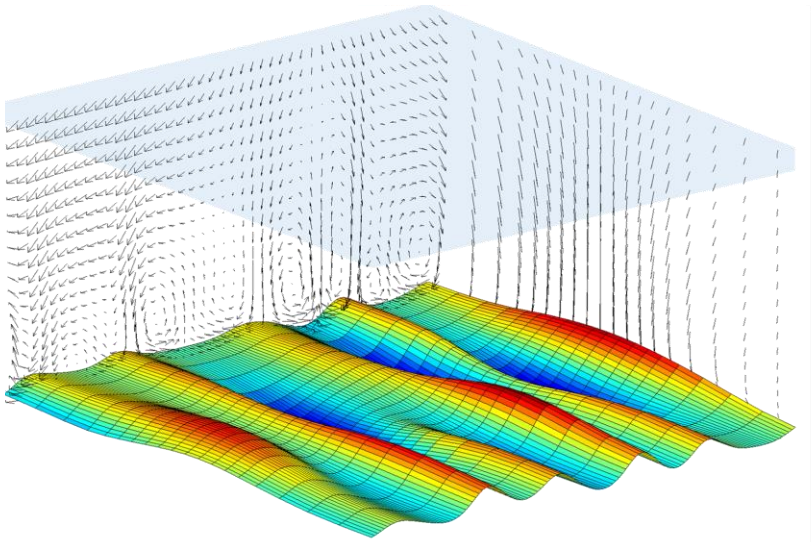
- numerical modeling of net sediment transport
- morphodynamic analysis
- UXO / object levels
- prediction of future seabeds & reference levels
- scour mitigation in morphodynamic areas
- cable routing in morphodynamic areas
- deliverables (reports, GIS-maps)



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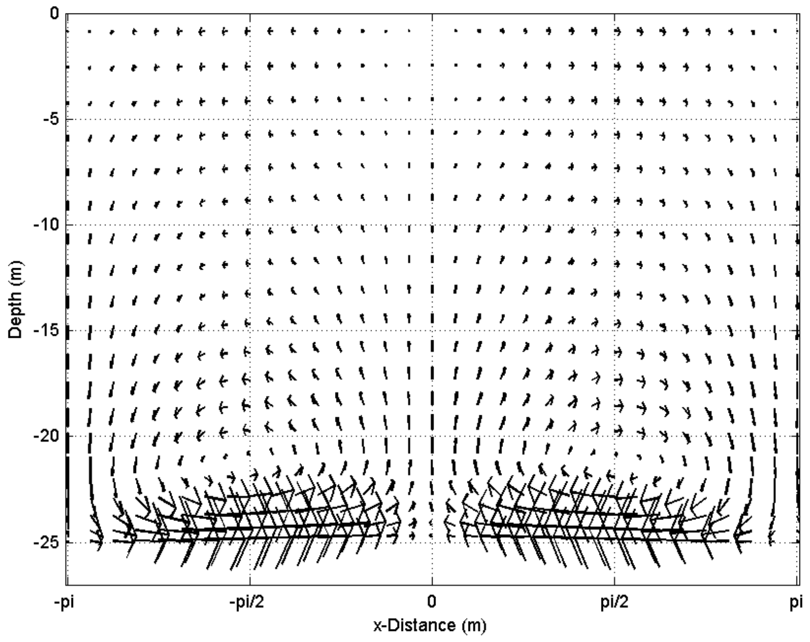
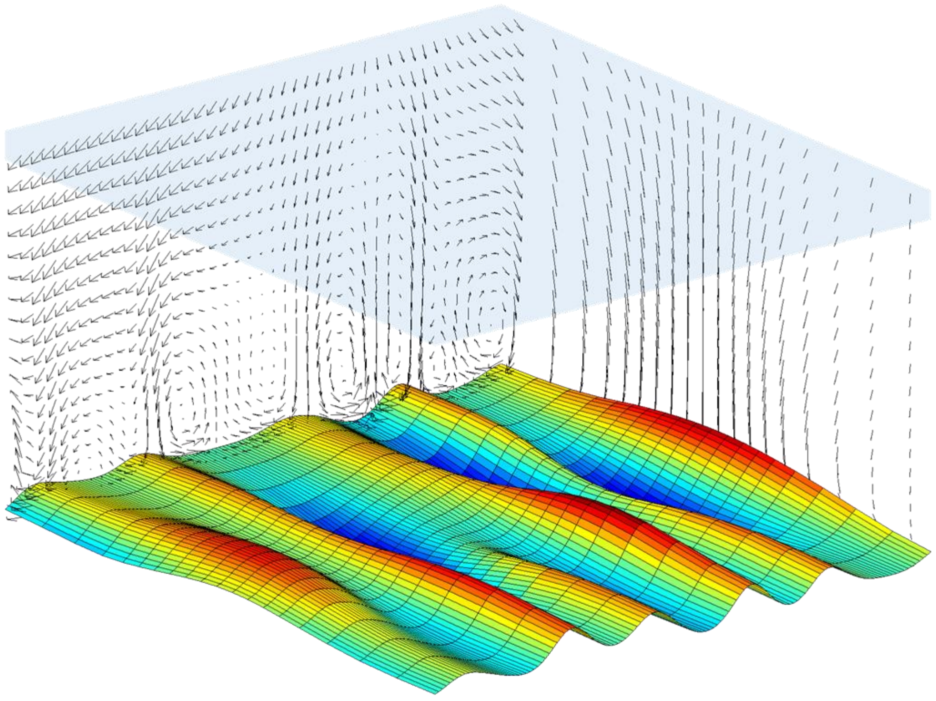
Sand Wave Morphodynamics – Analysis techniques

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





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Sand Wave Morphodynamics – Analysis techniques

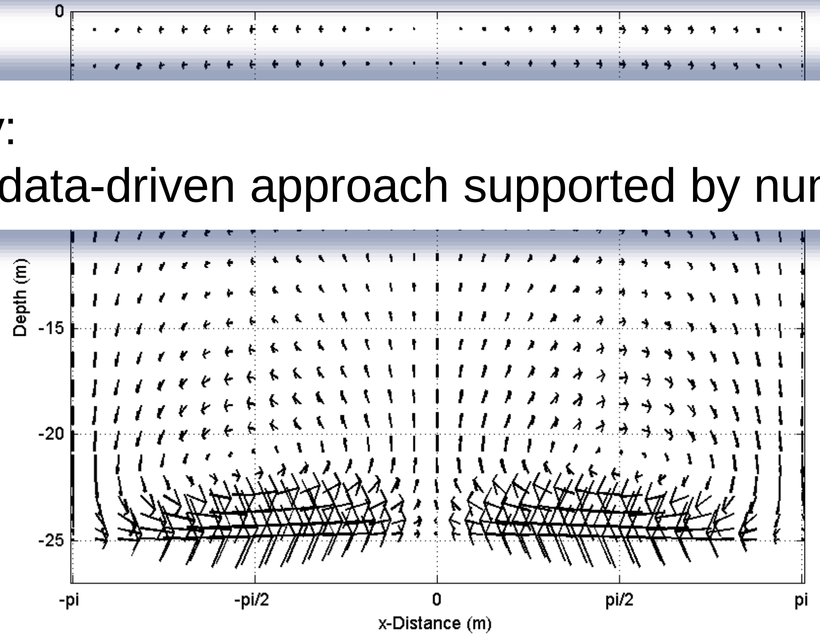
Methods to investigate sand wave characteristics:

1. Data-driven analysis based on seabed surveys

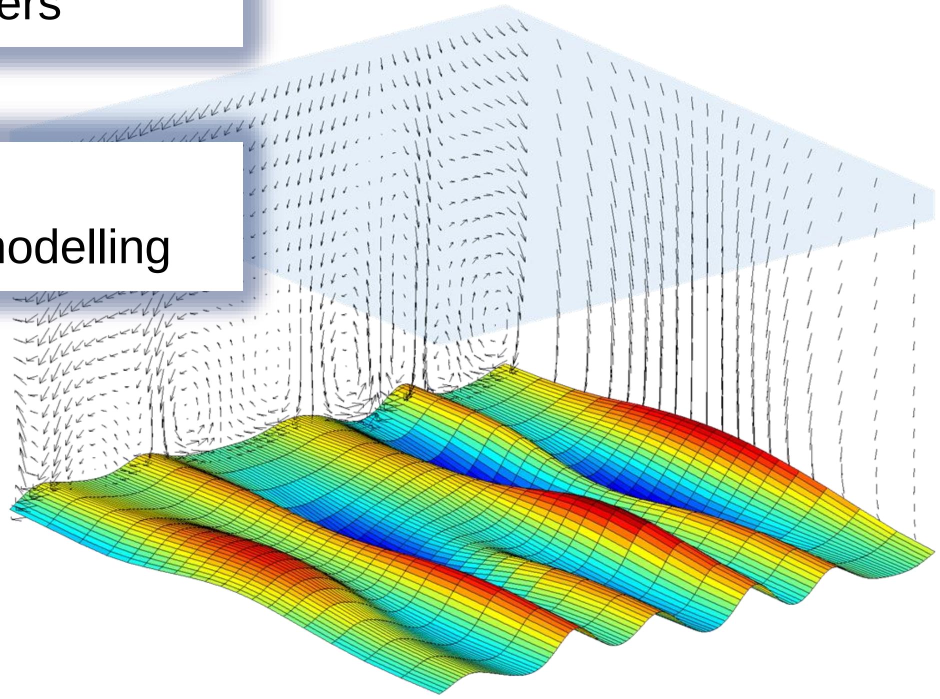
Most reliable, if data is available

2. Numerical modelling

Option if data is scarce;
useful to investigate dependencies on governing parameters



This study:
Focus on data-driven approach supported by numerical modelling



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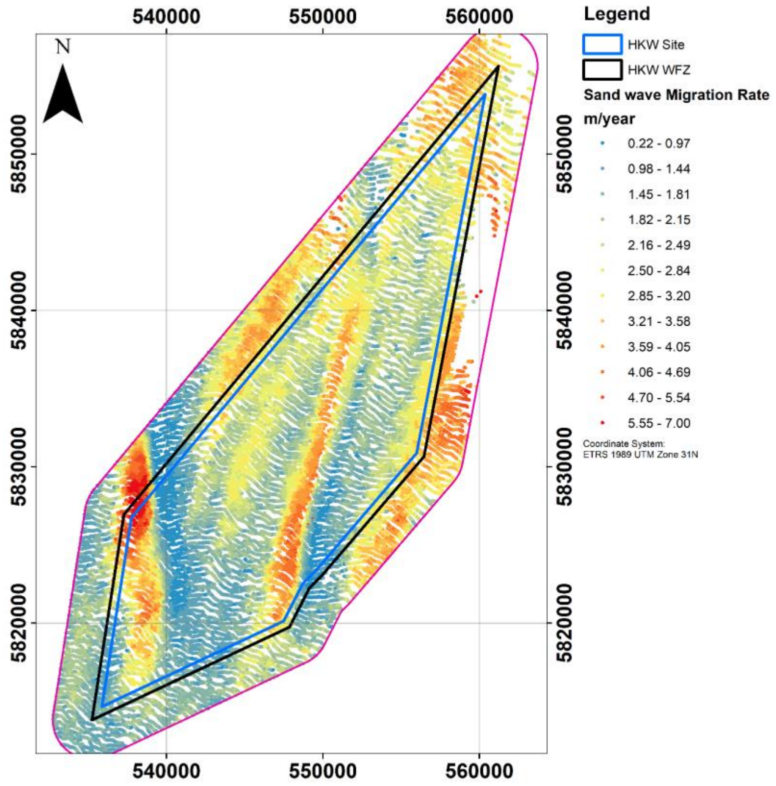

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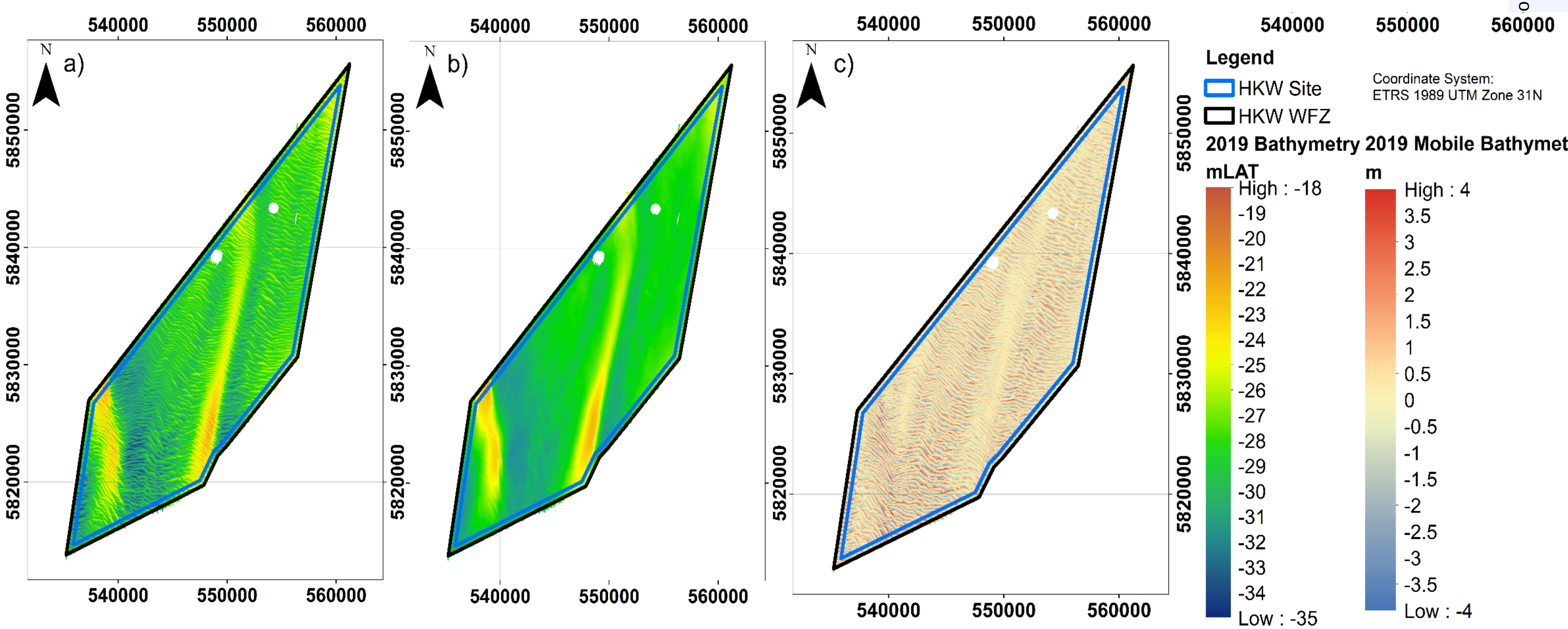
Data analysis – Separation of bedforms



2017 bathymetry - large-scale = mobile bathymetry

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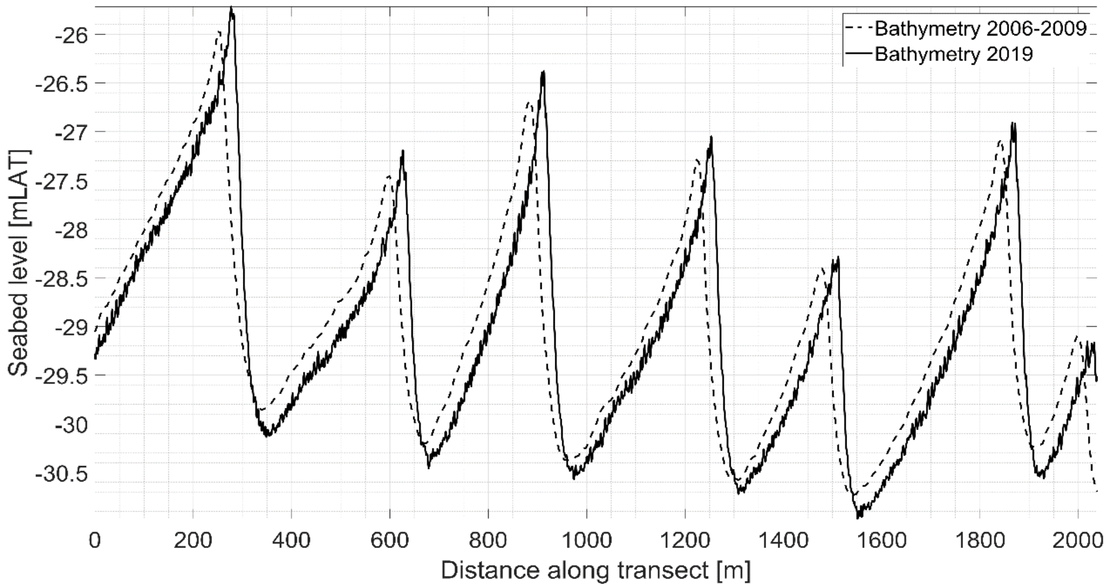
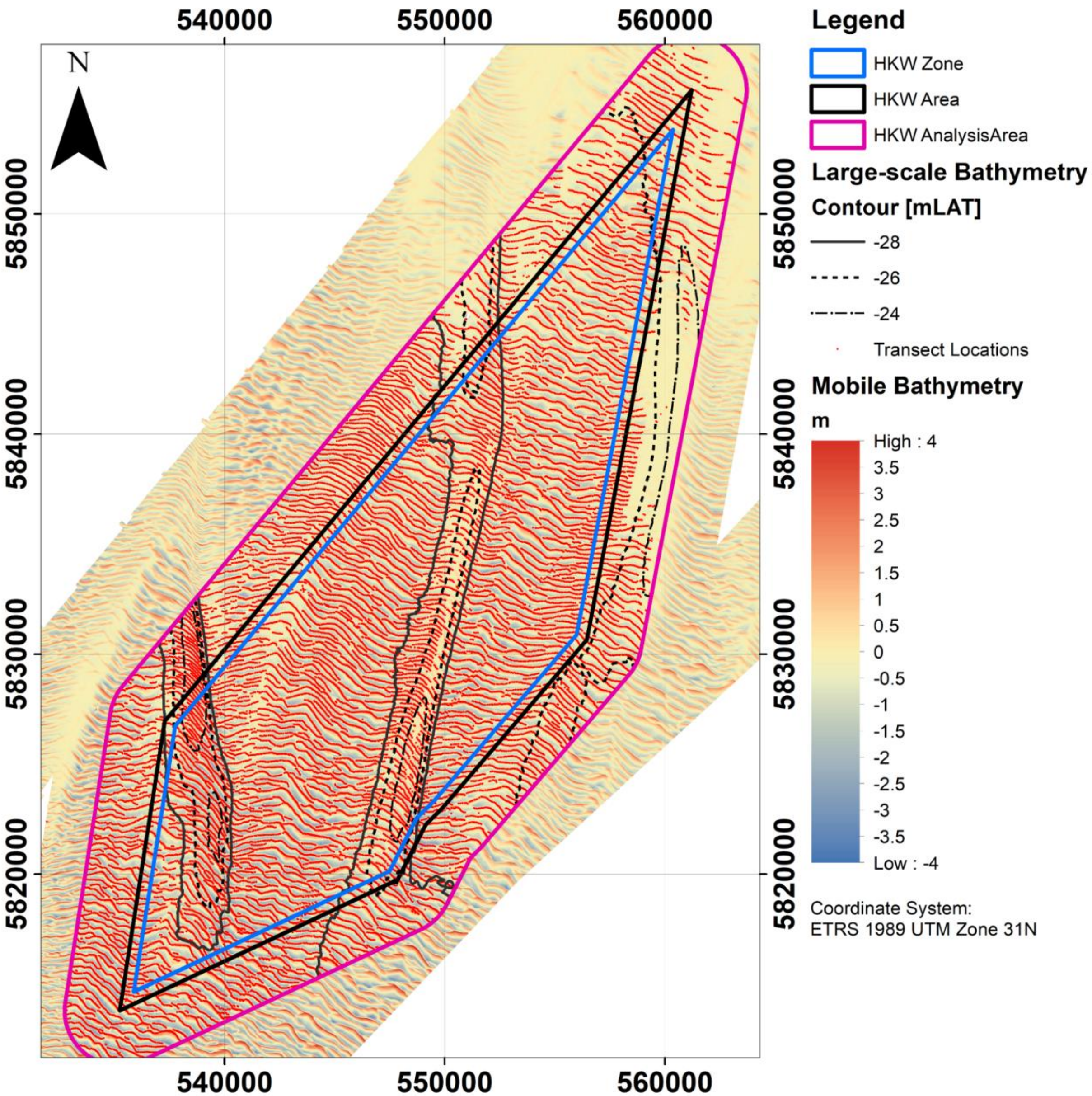
Data analysis – Selection of transects

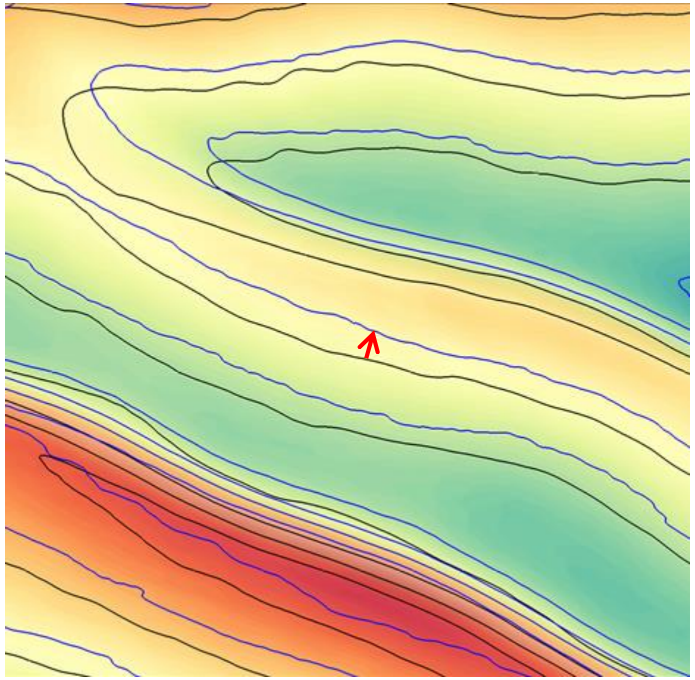
- High resolution transect selection at sand wave crests
- Spacing of 50 m between transects
- Variation in sand wave dynamics over sand waves captured

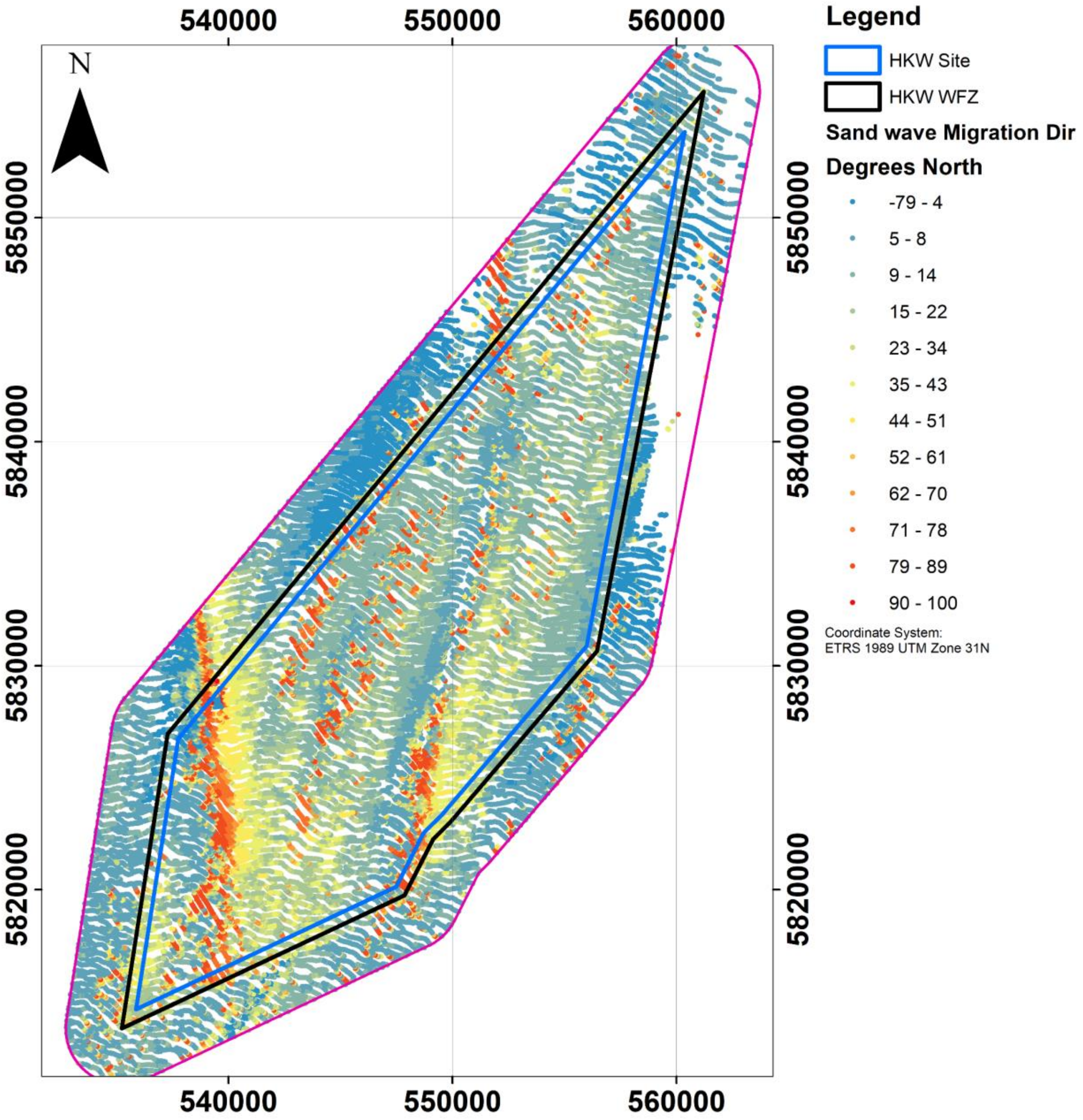




Data analysis – Sand wave migration direction

- Direction determined with use of 2D cross-correlation
- Main direction of migration approximately 10°N with spatial variations around sand banks





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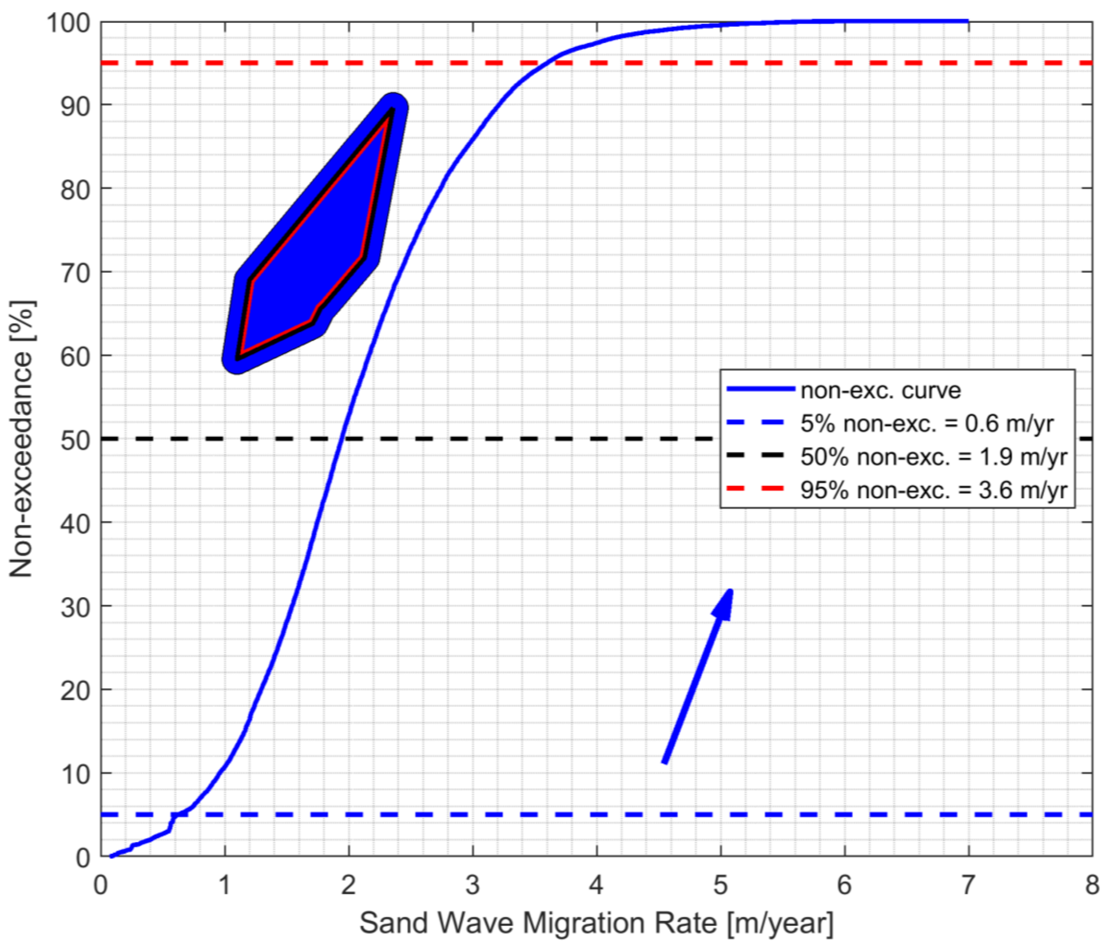
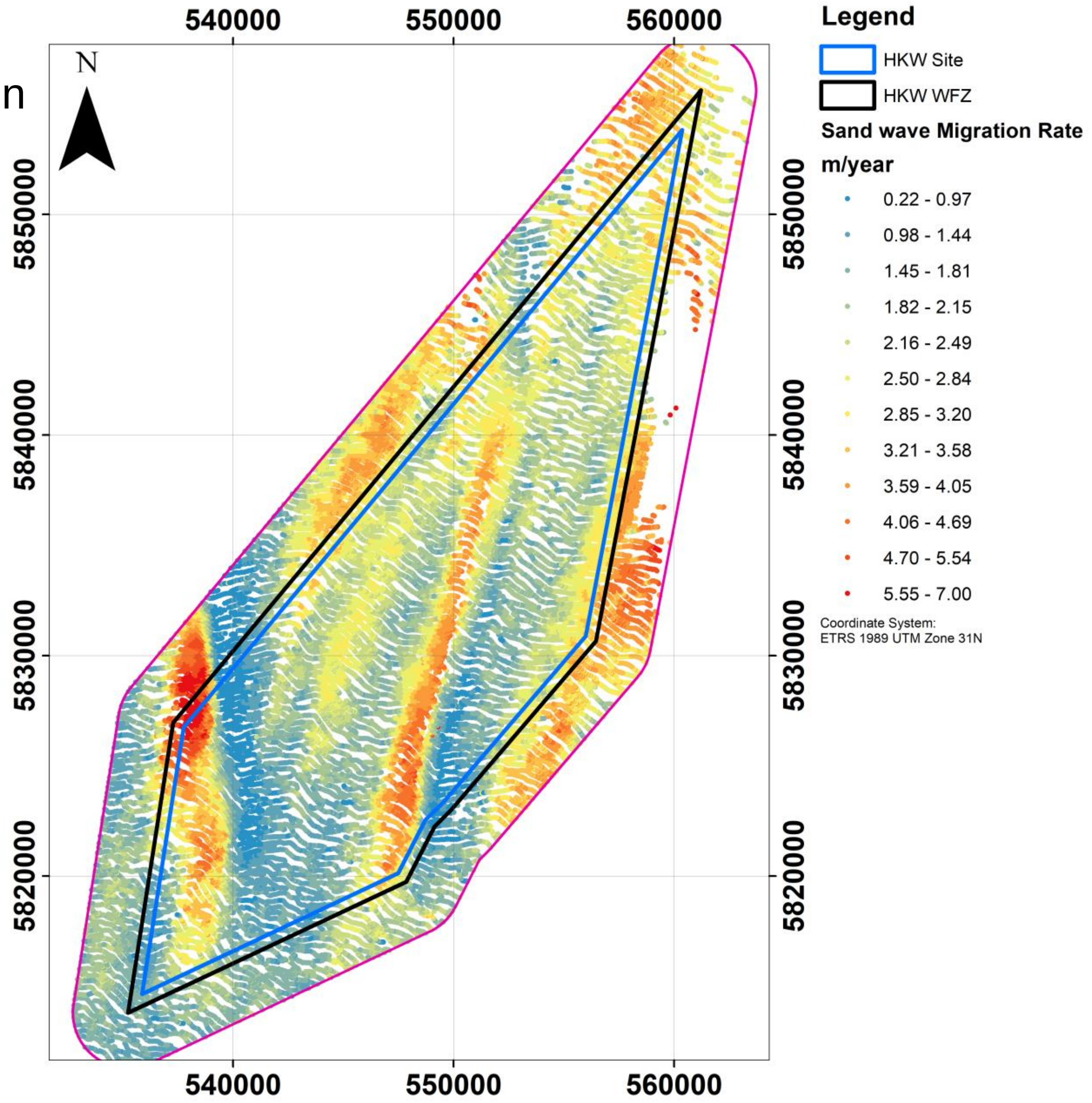
Data analysis – Sand wave migration rate

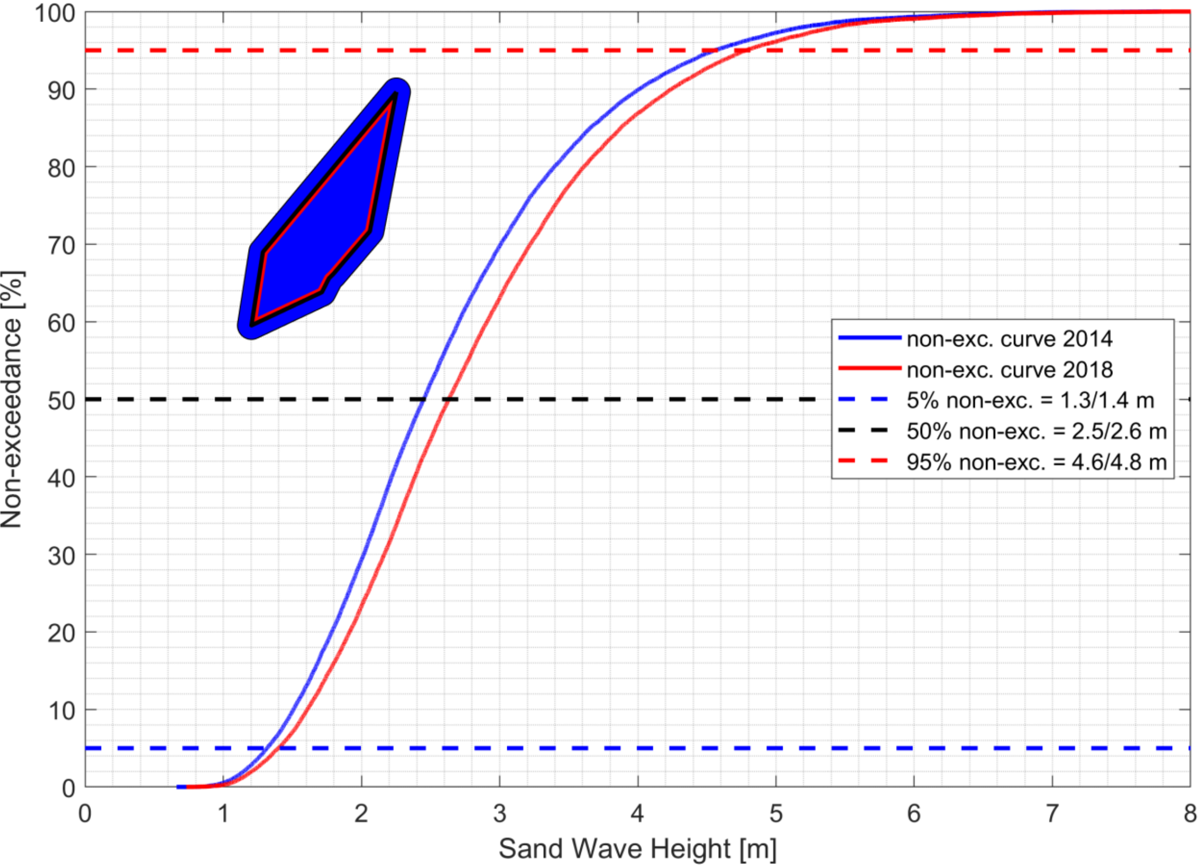
- Rate determined with use of 2D cross-correlation

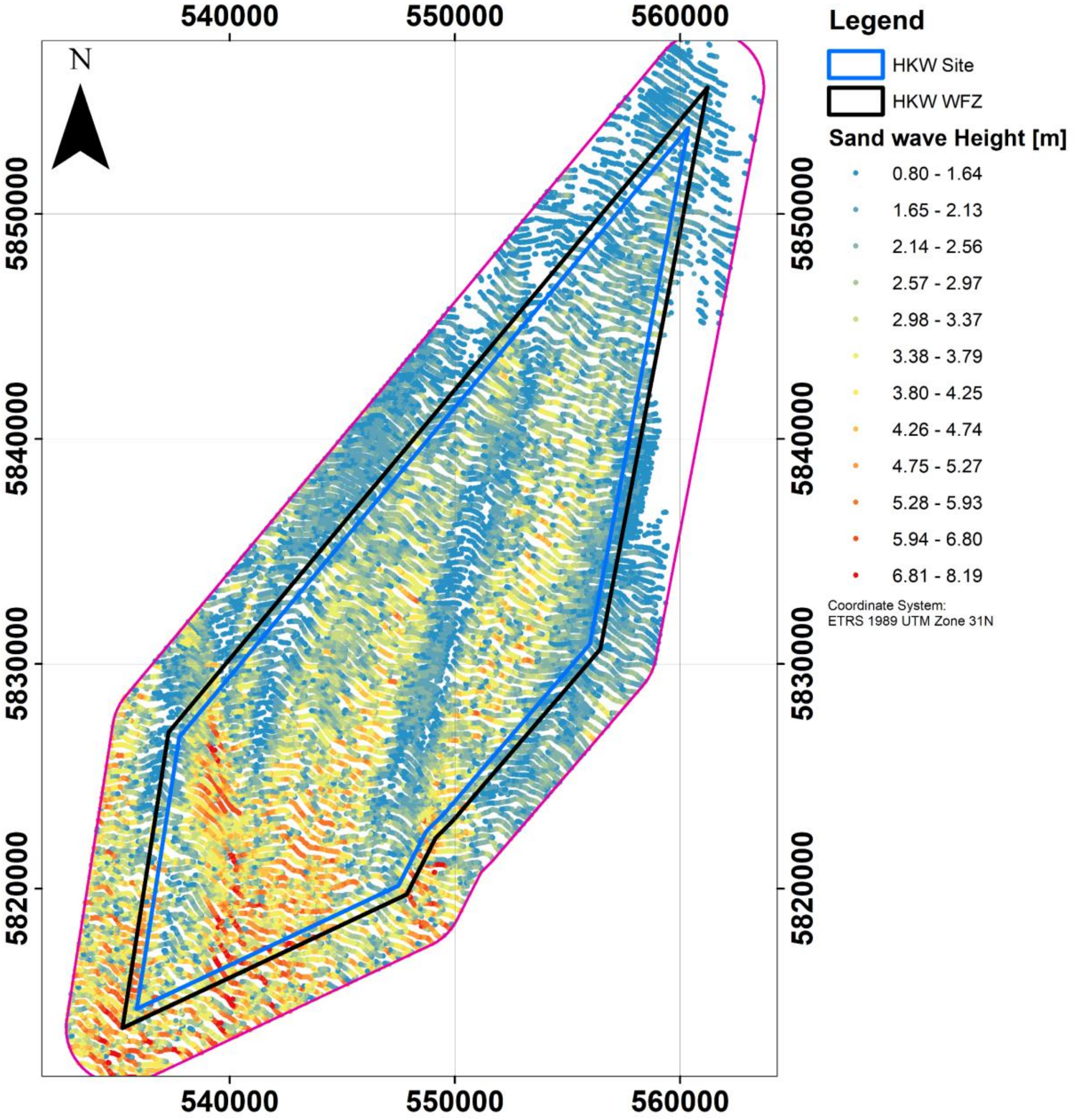




Data analysis – Sand wave height

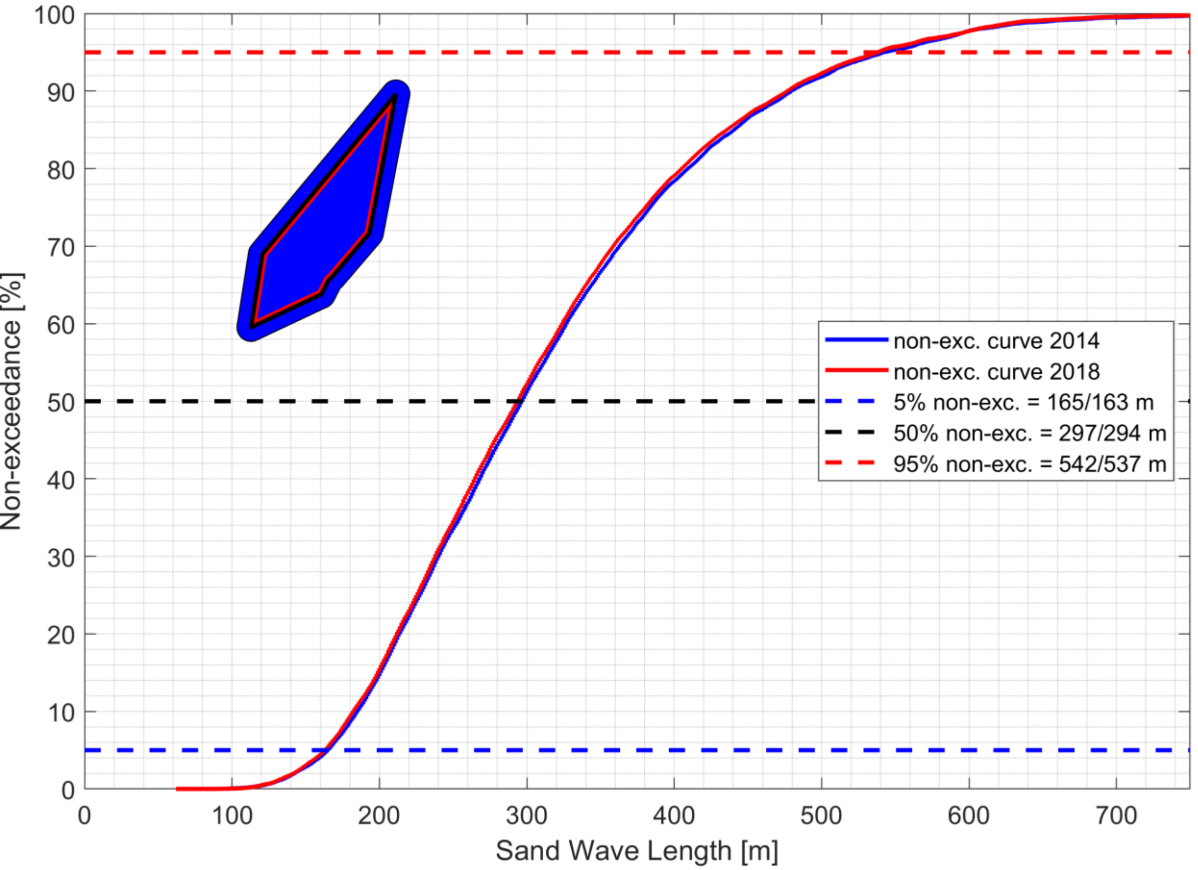
- Obtain statistics per transect with use of fourier analysis
- Tracking of crest and trough points

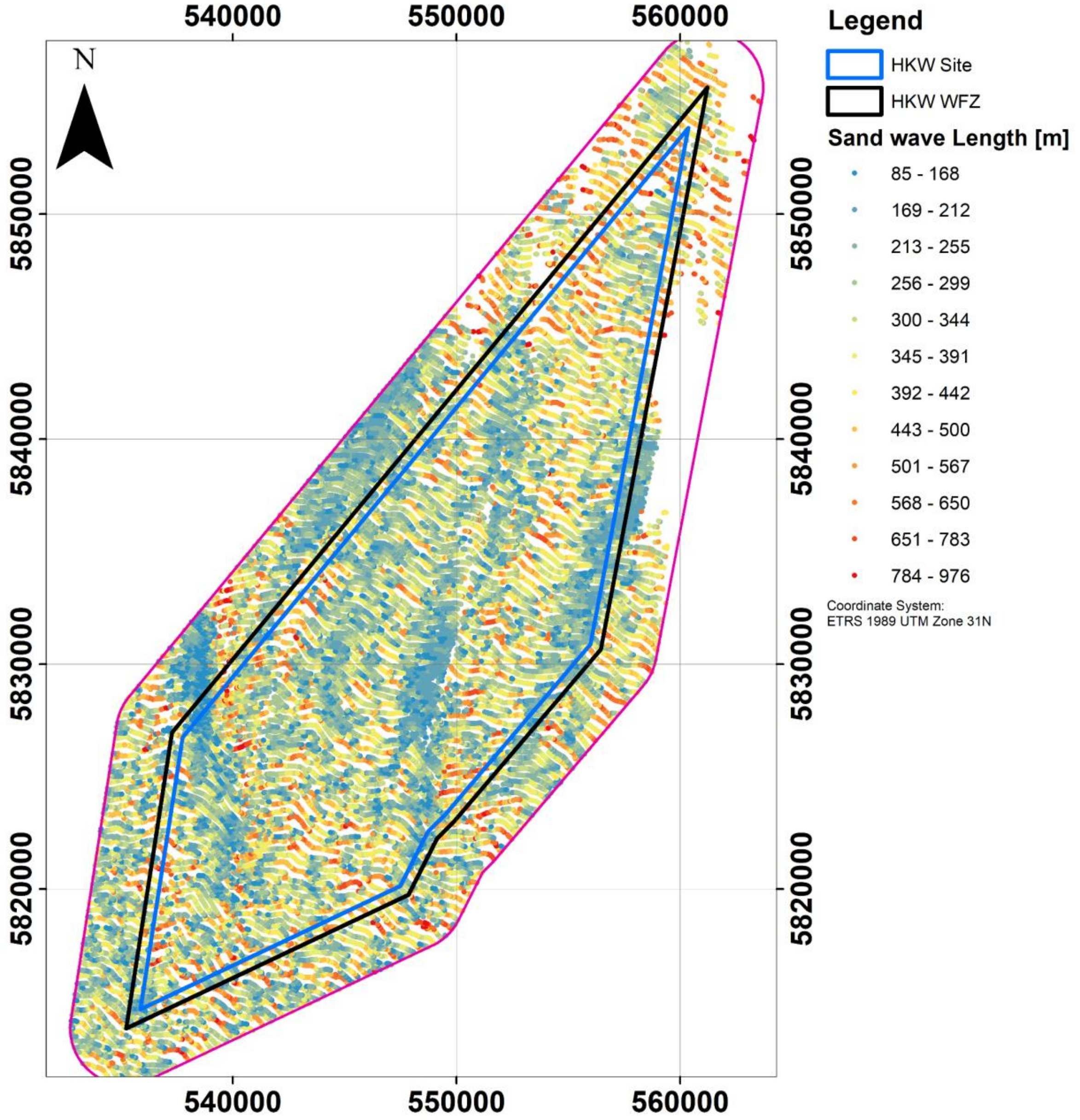




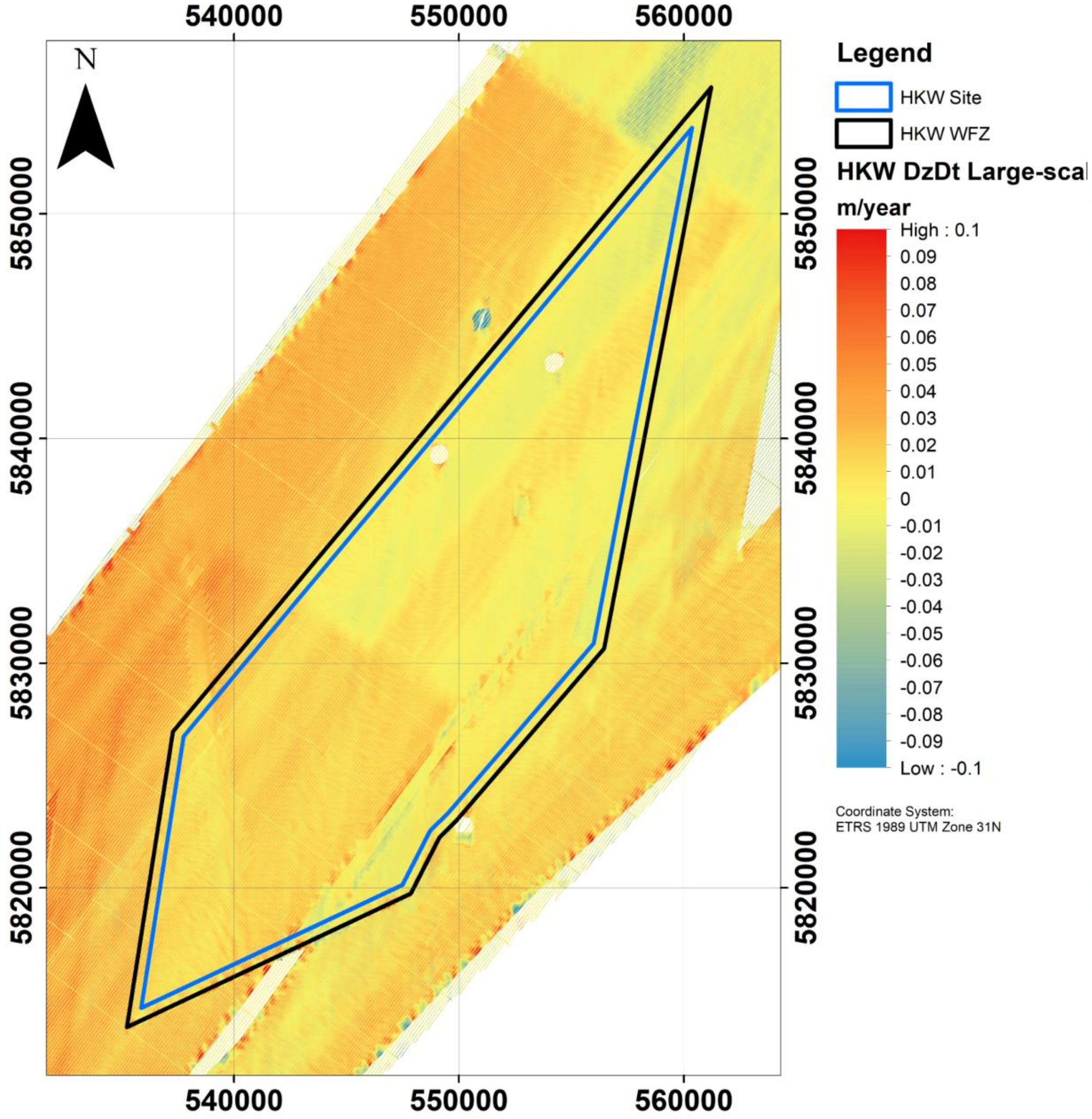
Data analysis – Sand wave length

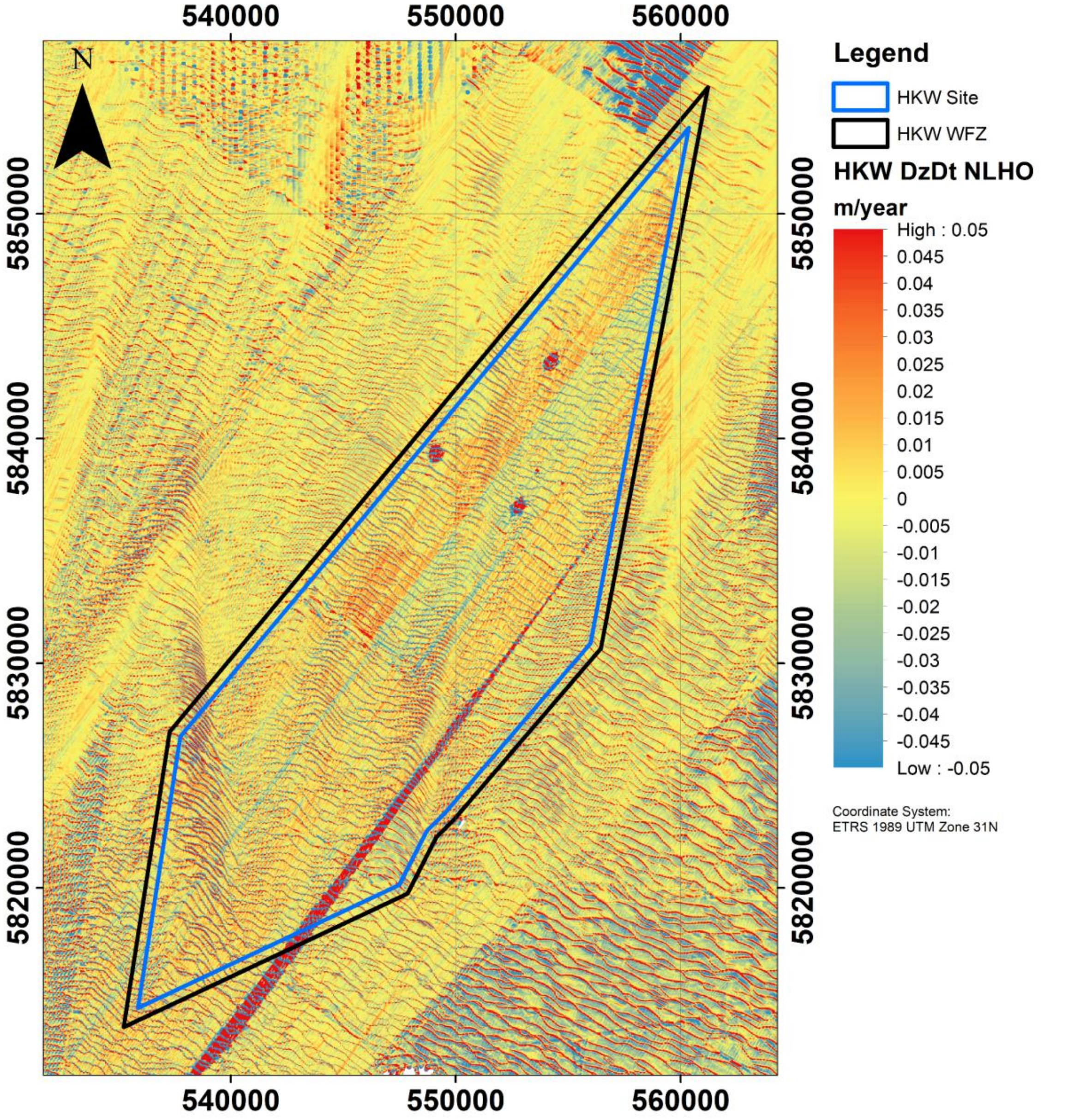
- Obtain statistics per transect with use of fourier analysis
- Tracking of crest and trough points





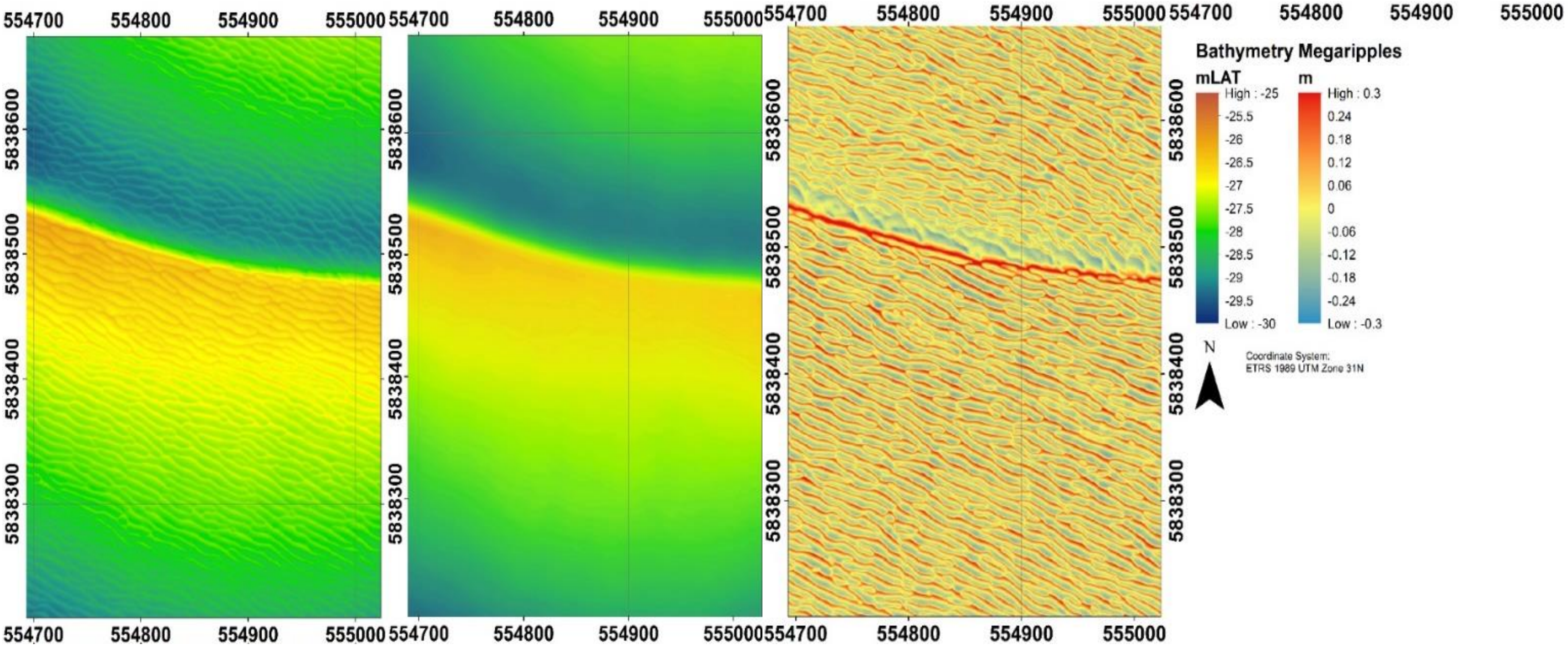
Data analysis – Large-scale seabed





Data analysis – Megaripples

- Wavelengths in the order 5-20 m – transient behavior (highly dynamic and changing dimensions over time) expected
- Rather regular pattern – heights related to date of measurement



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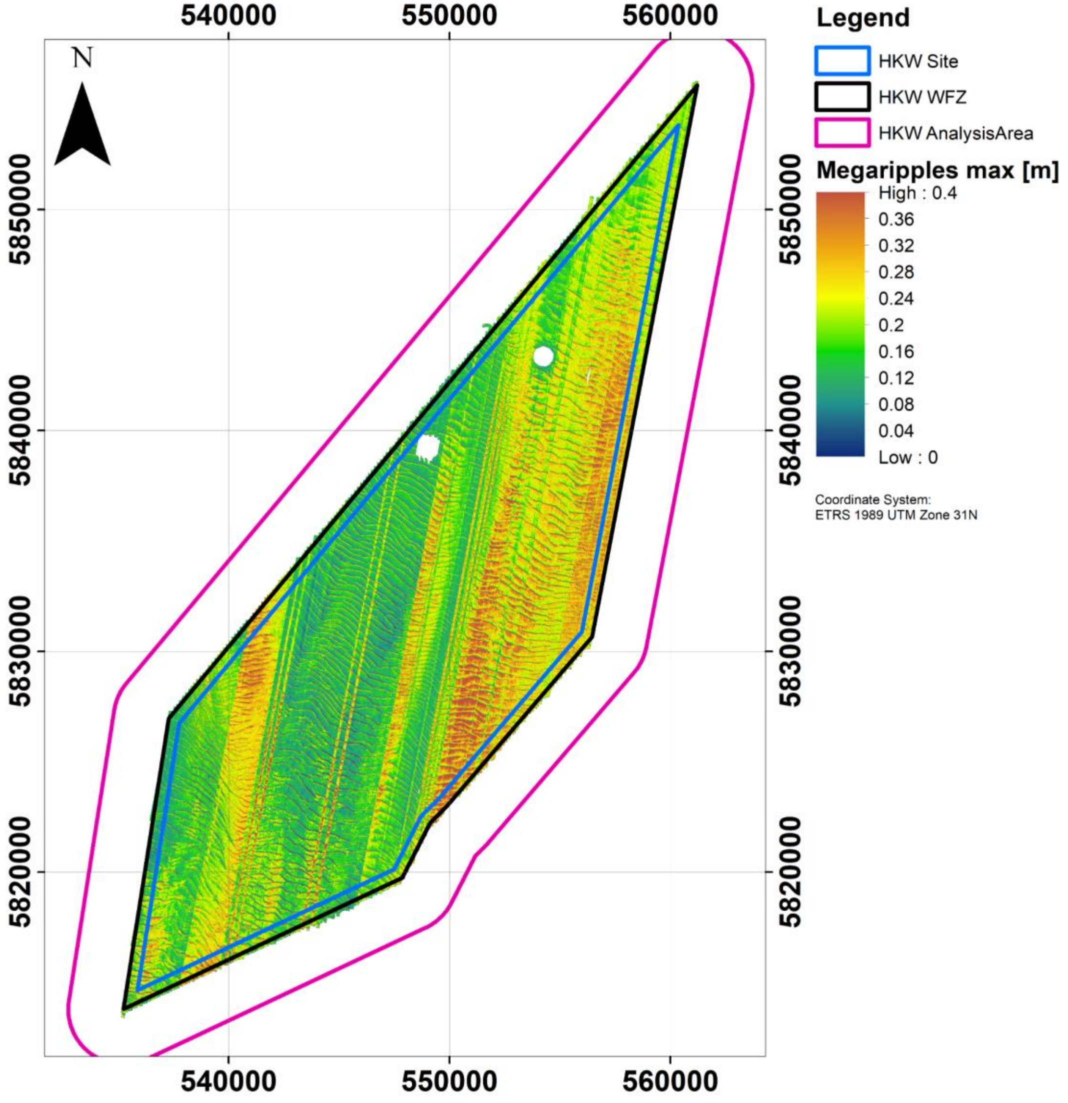
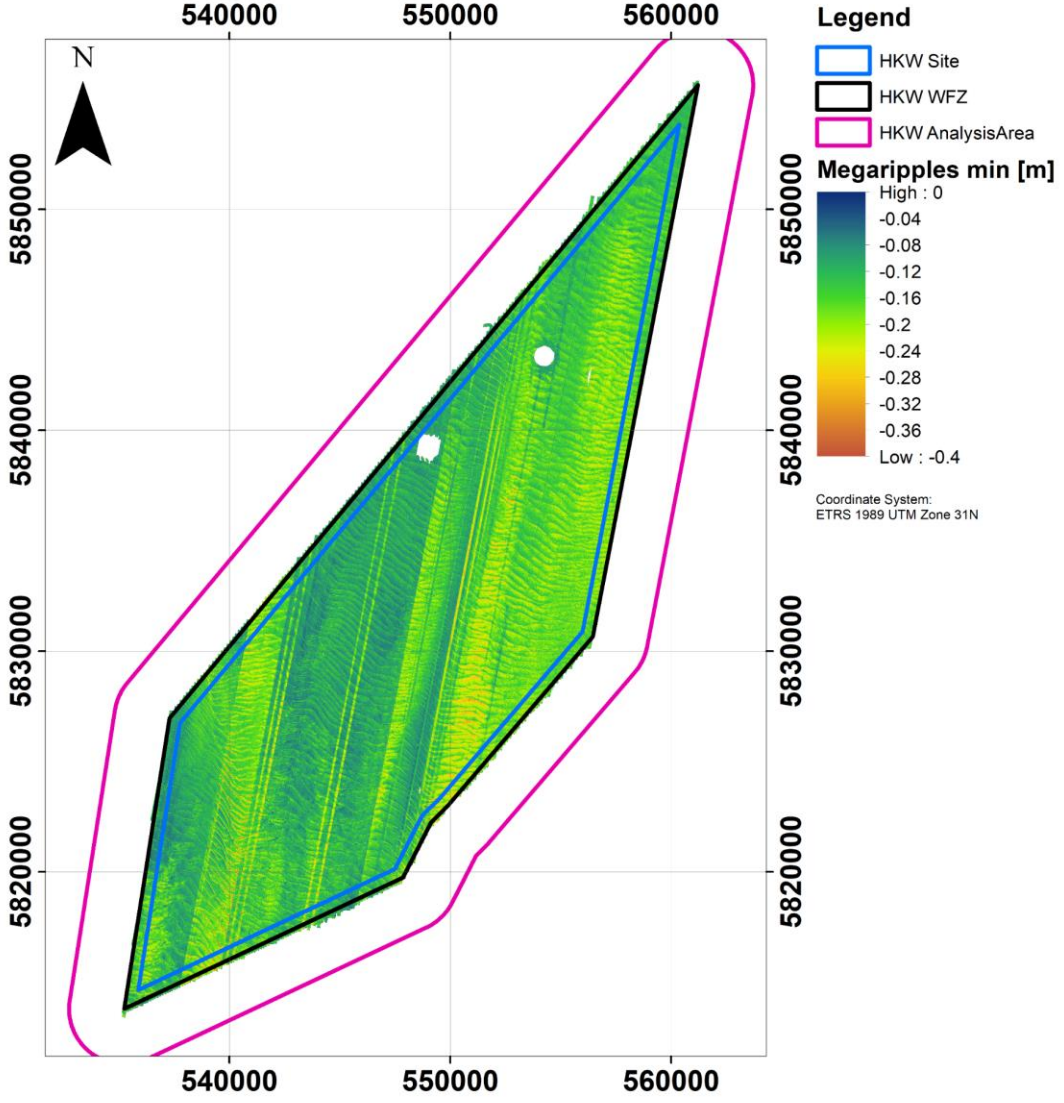
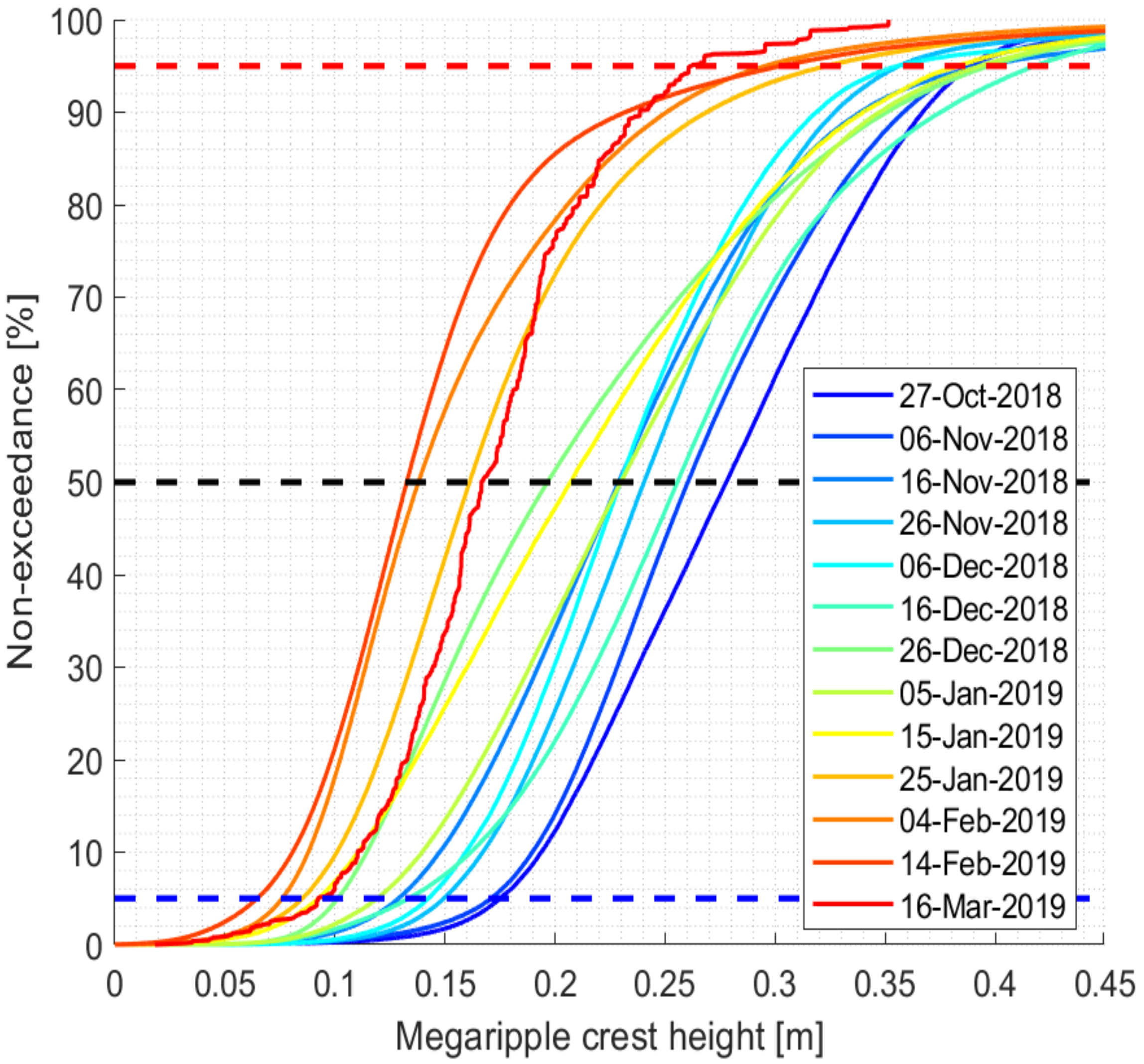
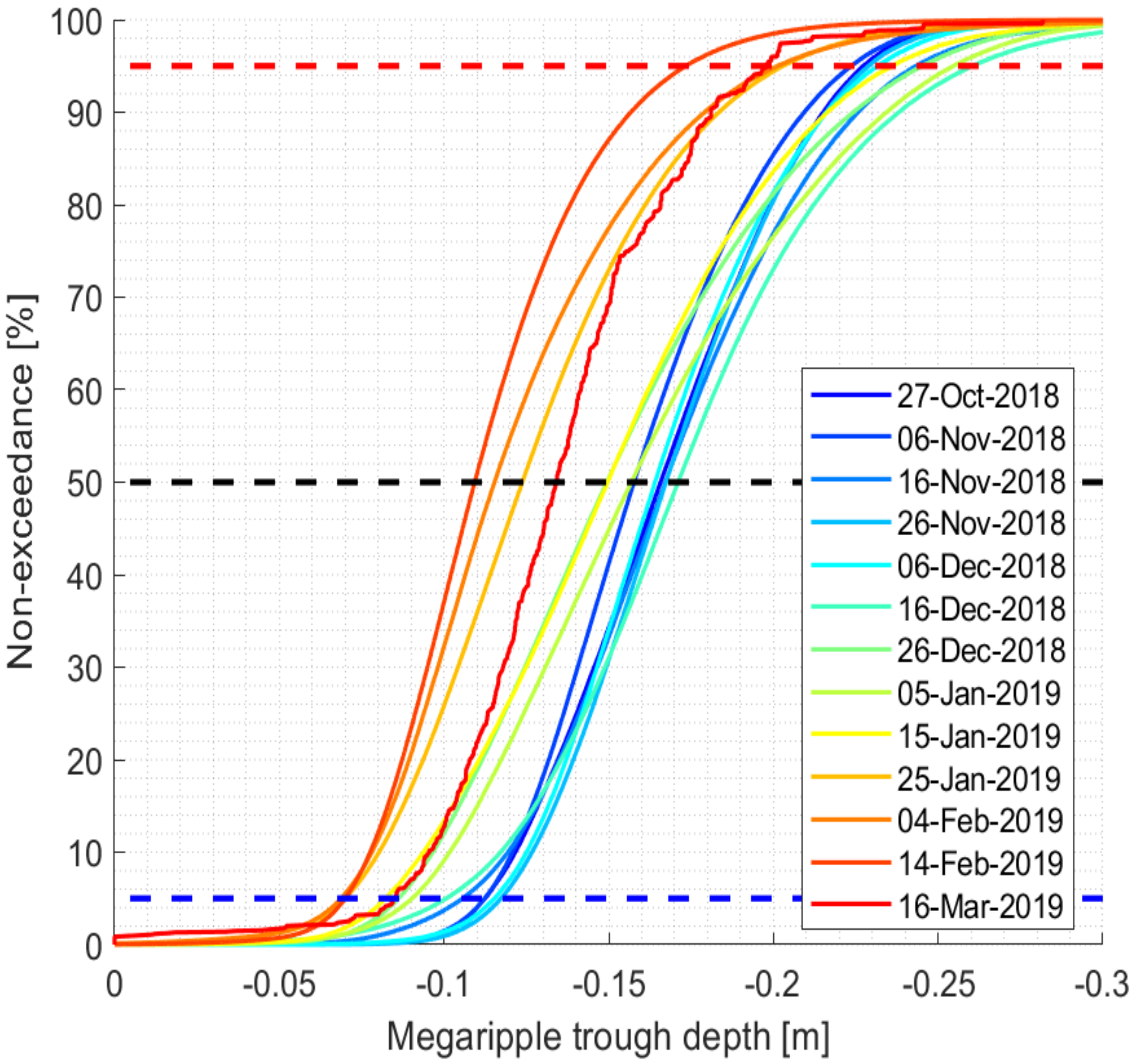
Data analysis – Megaripples - overview





Data analysis – Megaripples – Measurement dates





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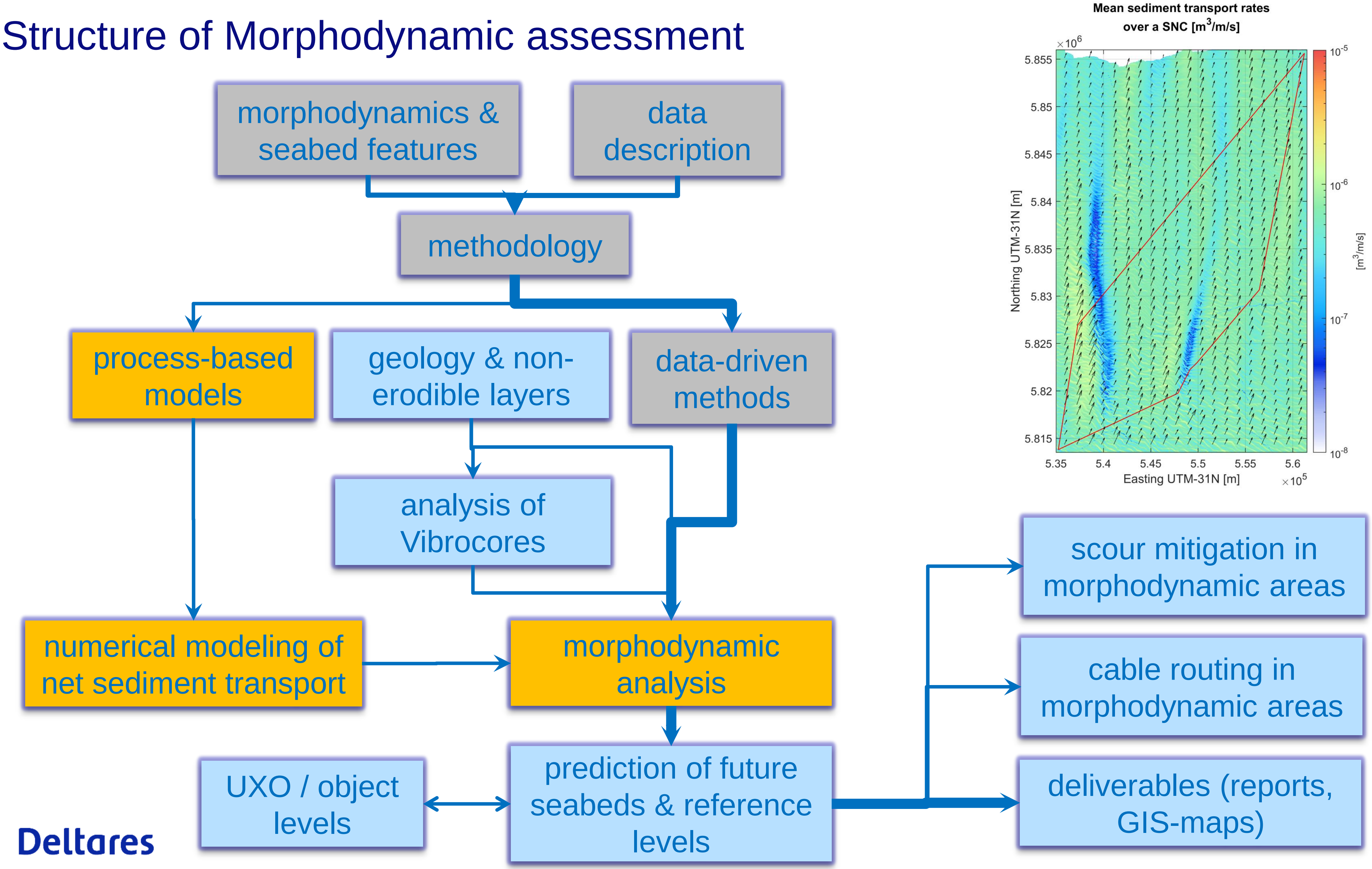
Structure of Morphodynamic assessment



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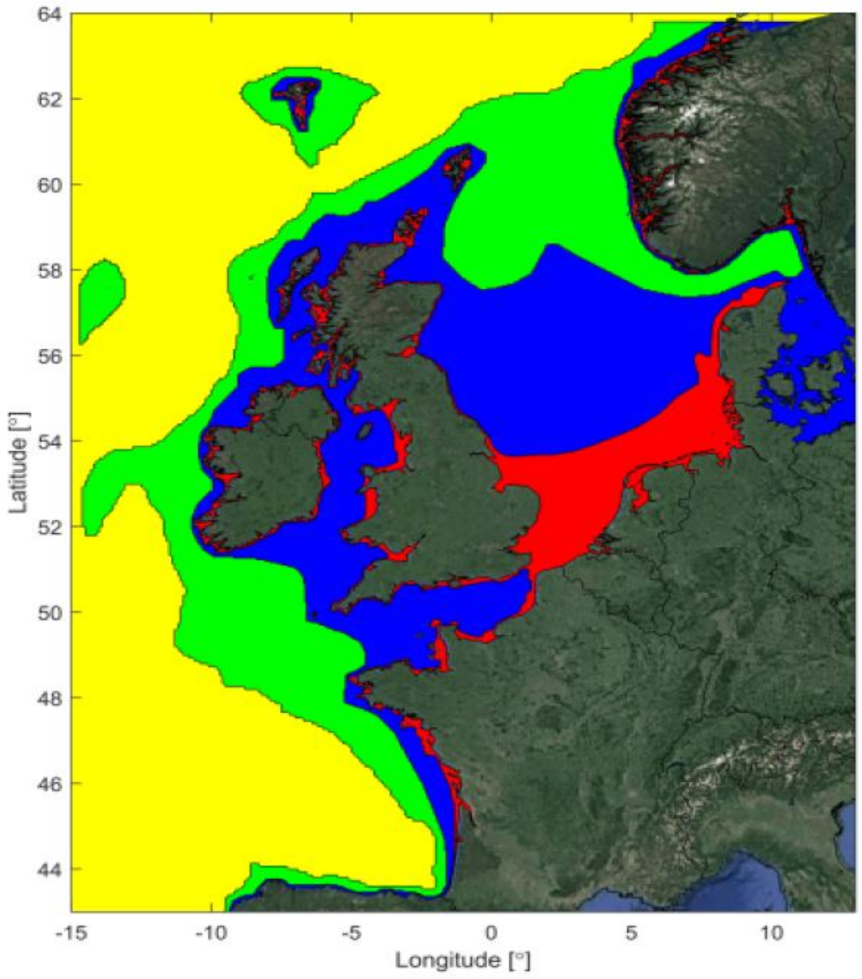
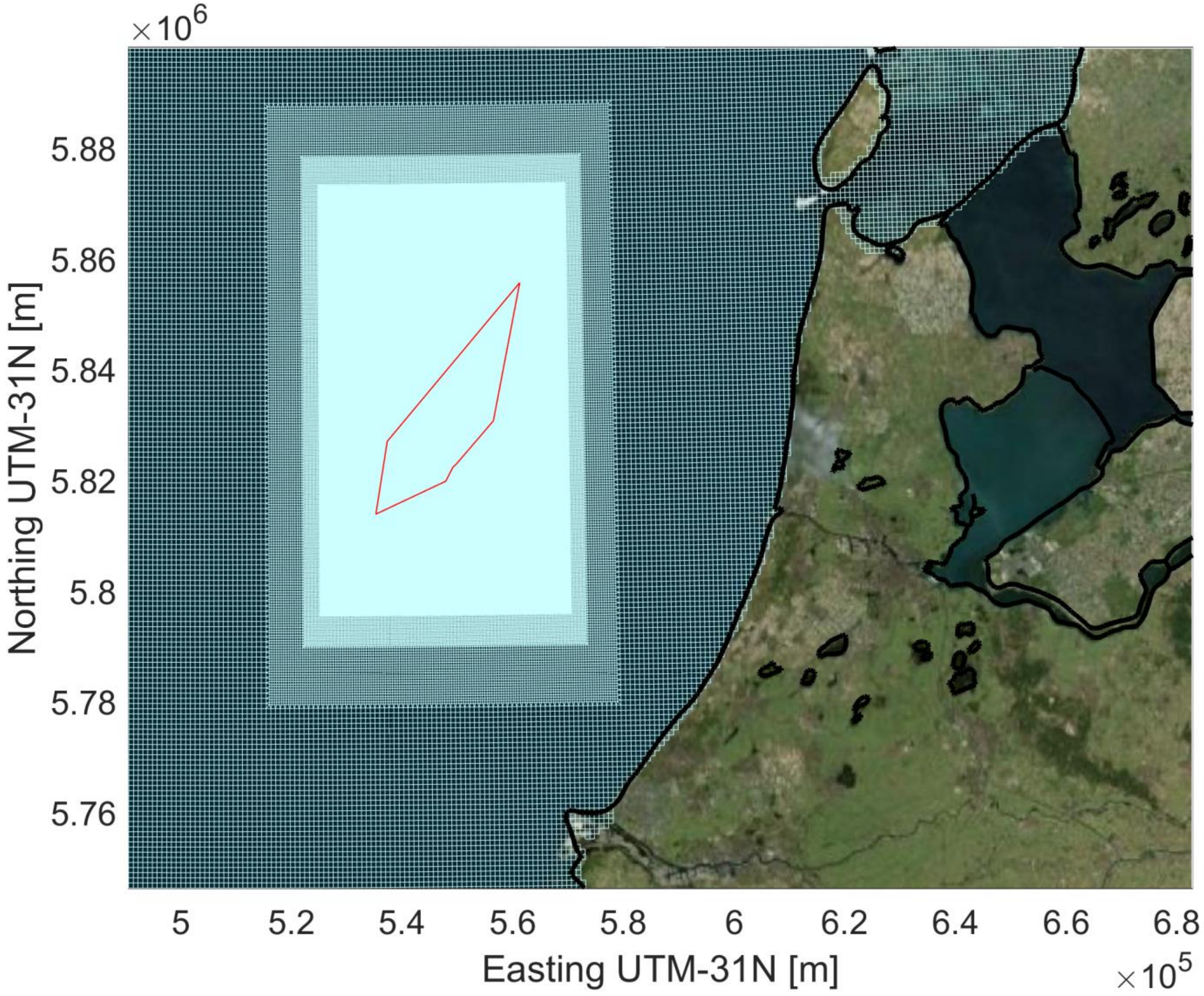
Sediment transport modelling – Grid overview





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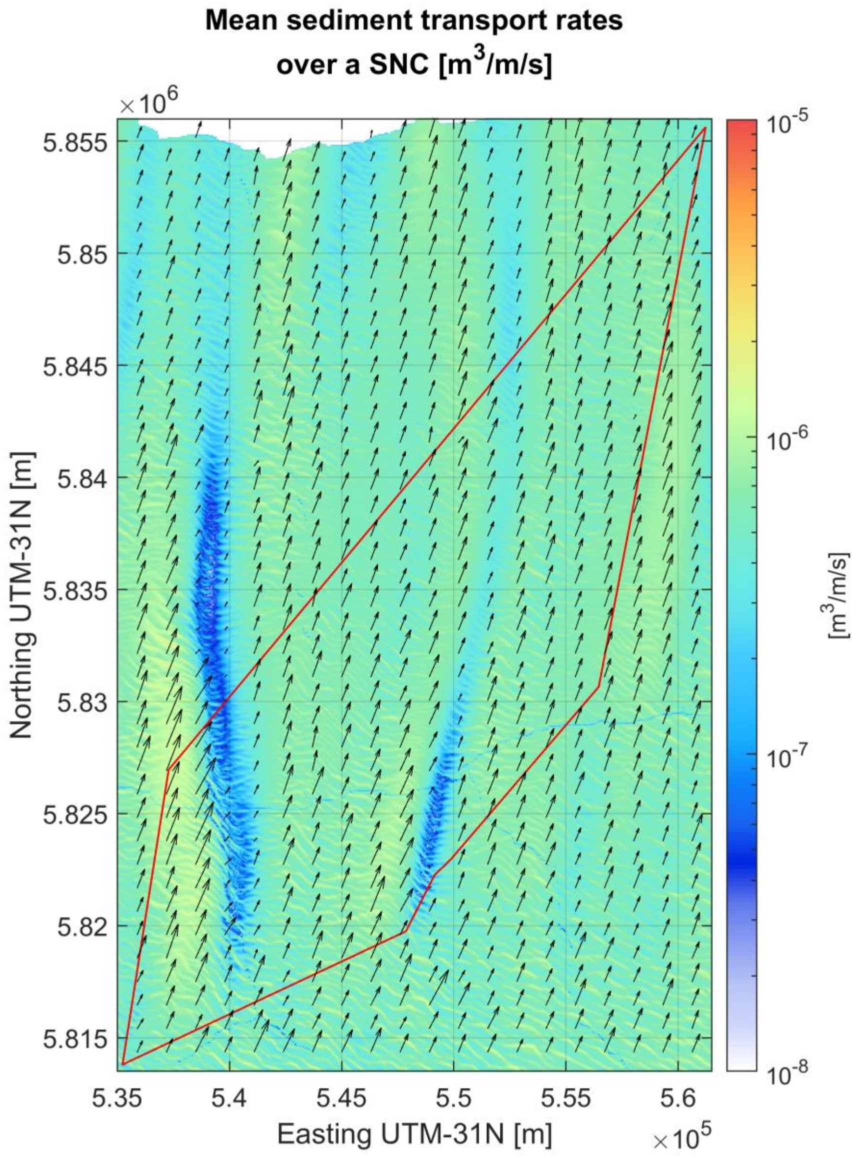
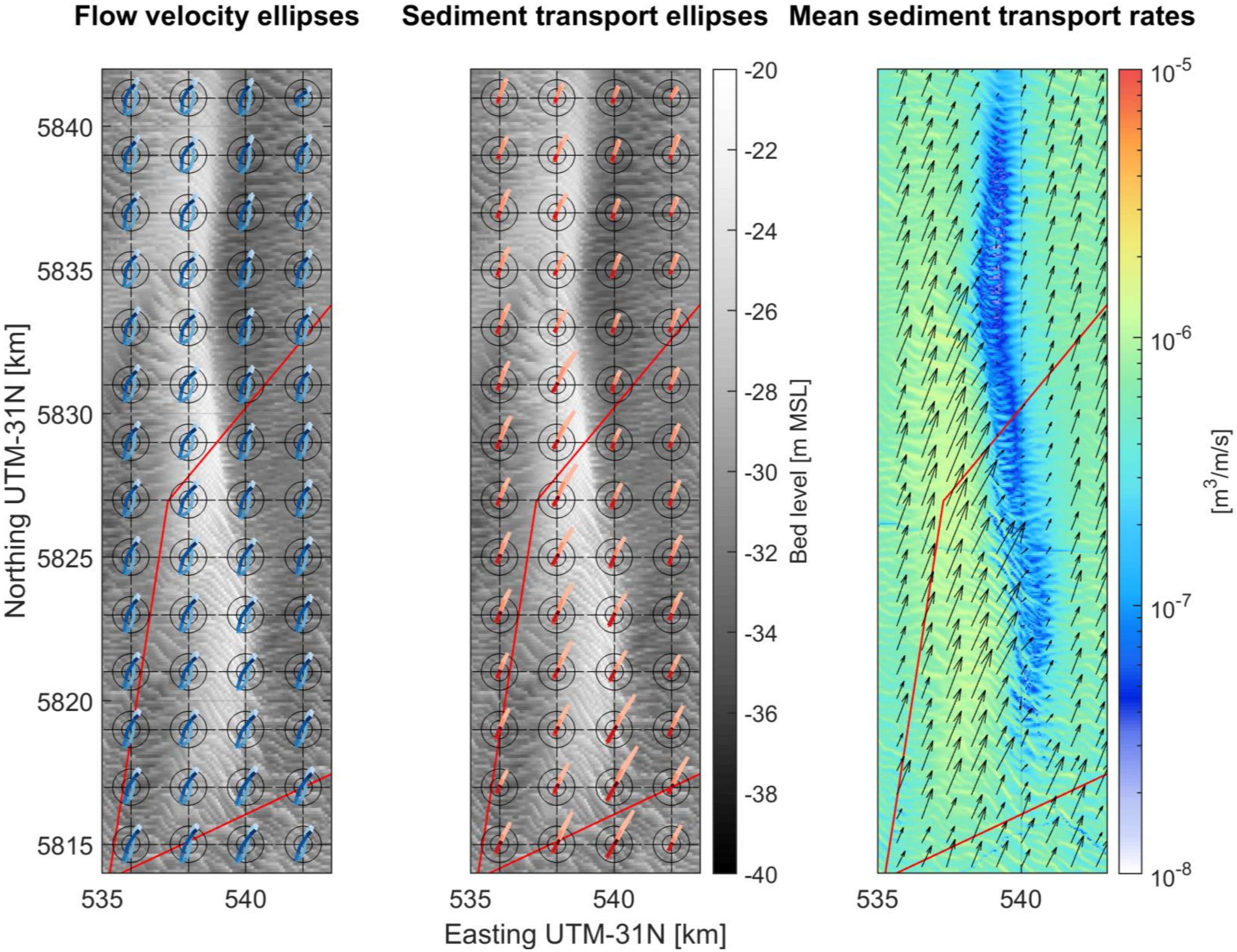
Sediment transport modelling – Transport patterns

- Transport patterns for HKW over one spring-neap cycle
- Clear influence of sand banks
- Main direction of transport ~= 10 – 20 Degrees North



Sediment transport modelling – Detailed Transport patterns



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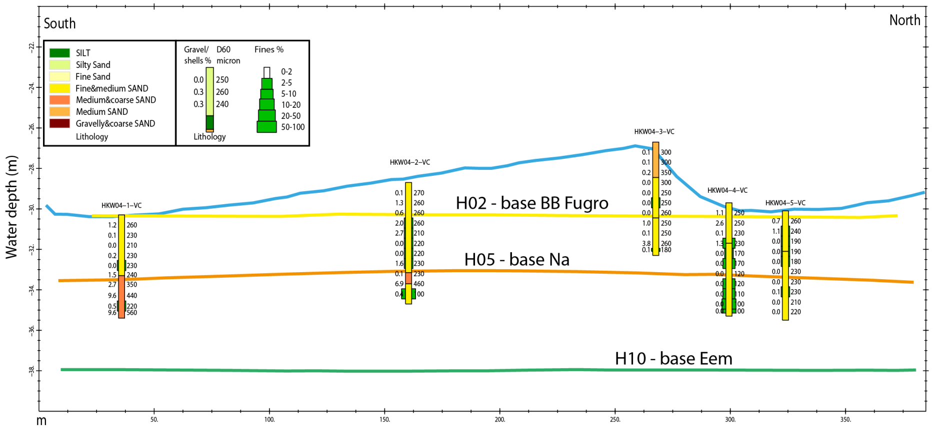

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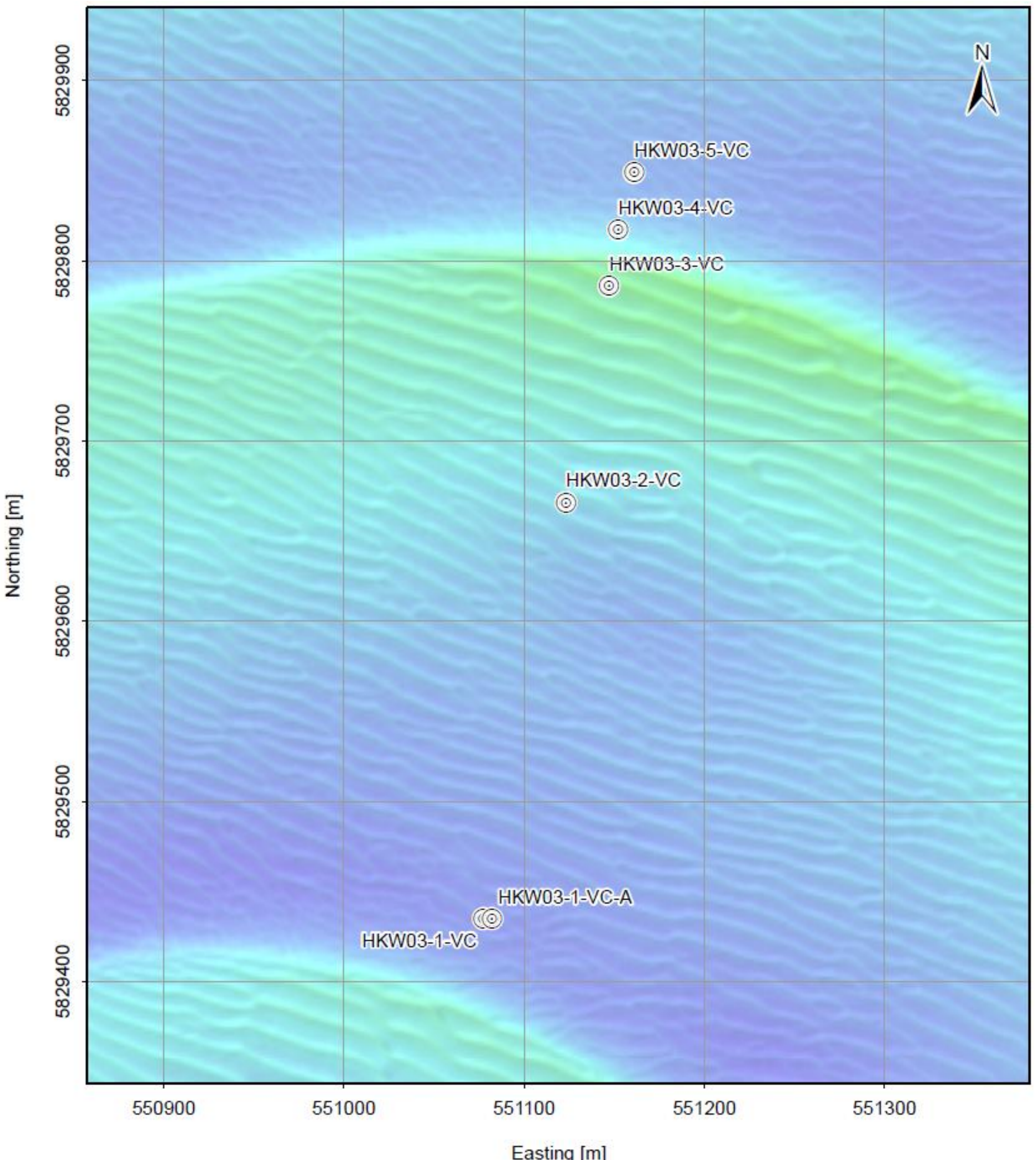
Vibrocores data

- 10 sand waves analysed distributed over HKW to capture main morphodynamic features
  - 5 Vibrocores per sandwave
- Coupled with bathymetric and seismic data
- Rather uniform distribution of sediment over sand wave
- In some cases coarser sediment at the crest
- Base of Holocene layer can in some cases be observed from the Vibrocores



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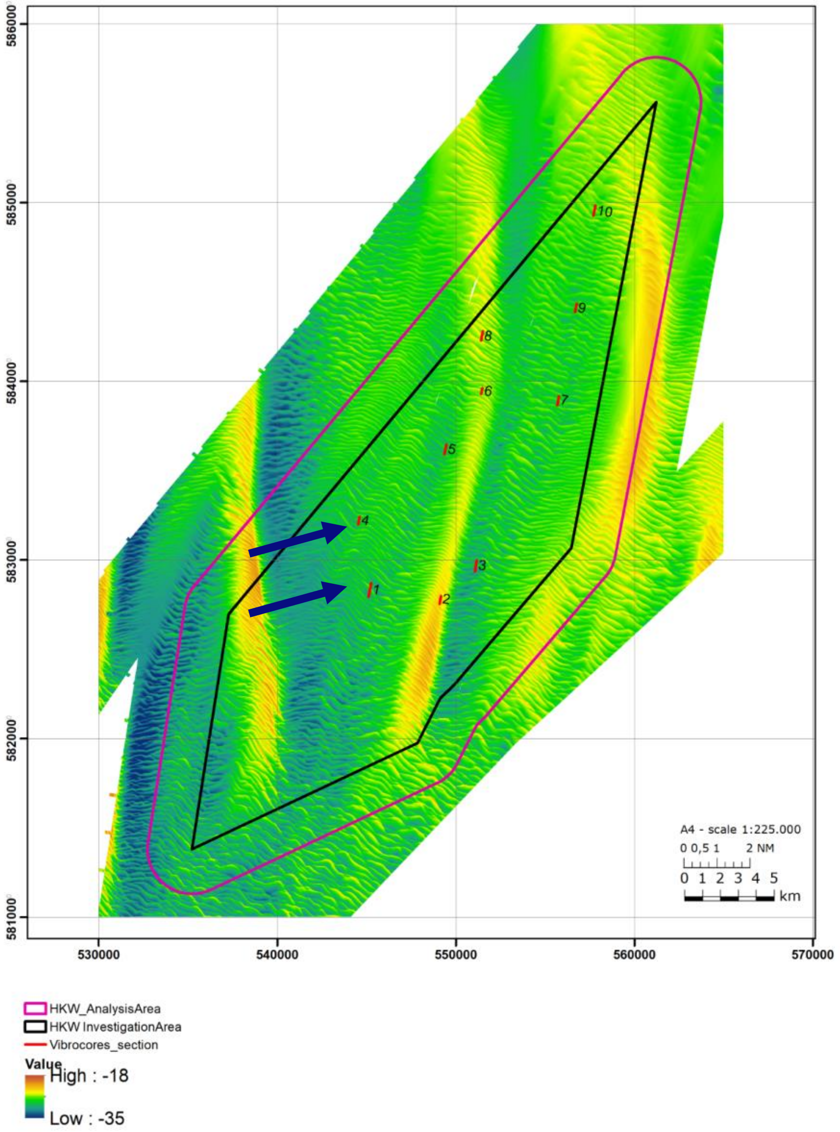
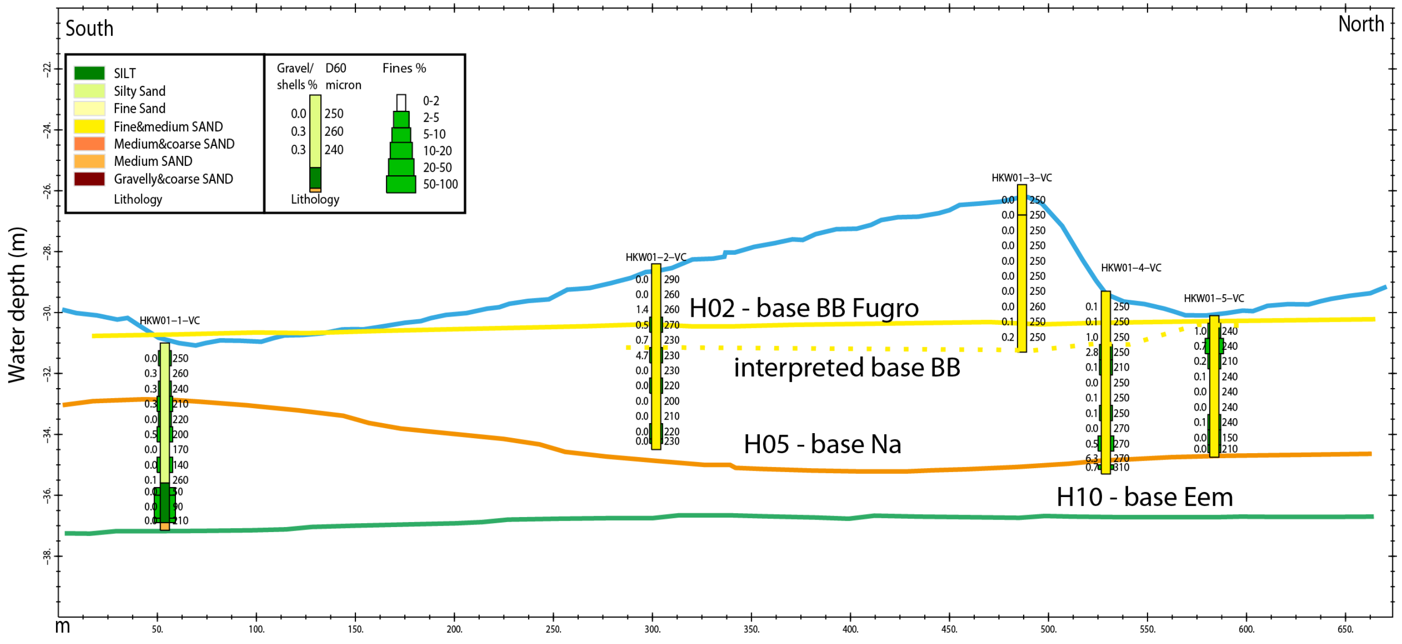
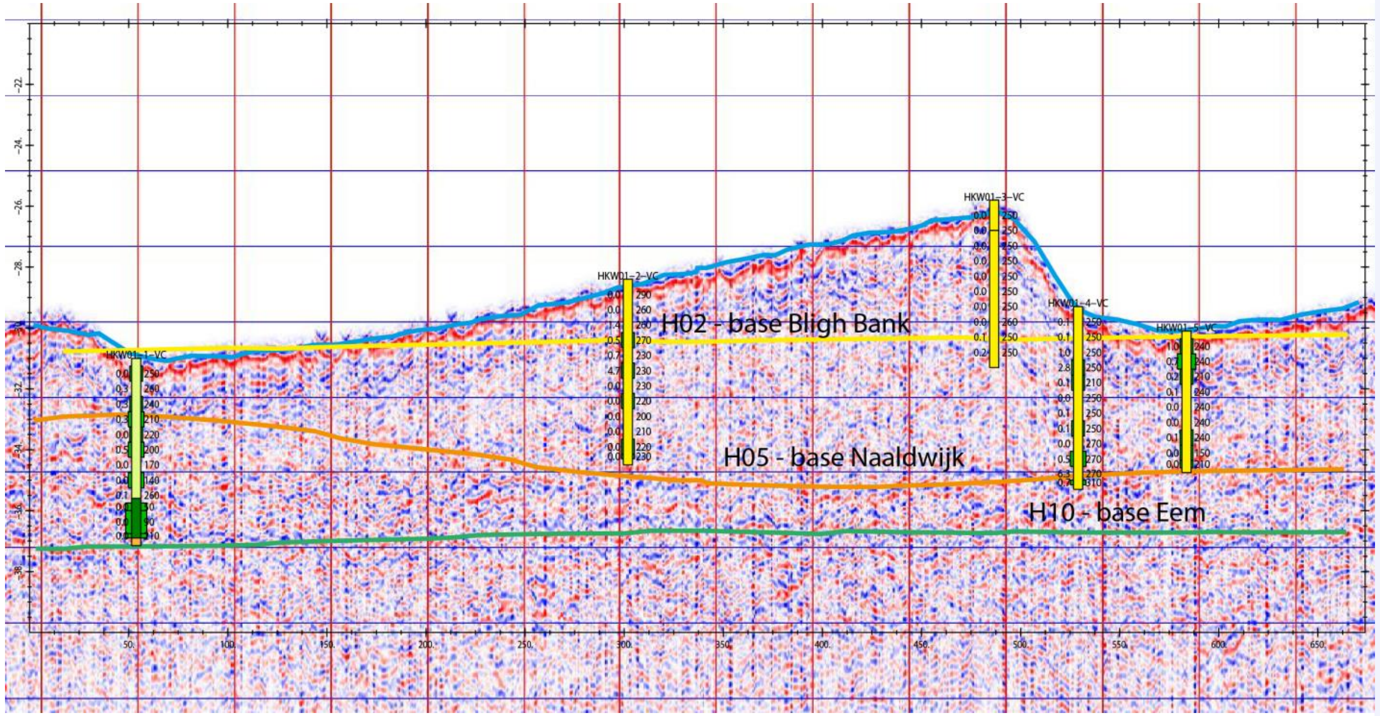
Cross-section 1







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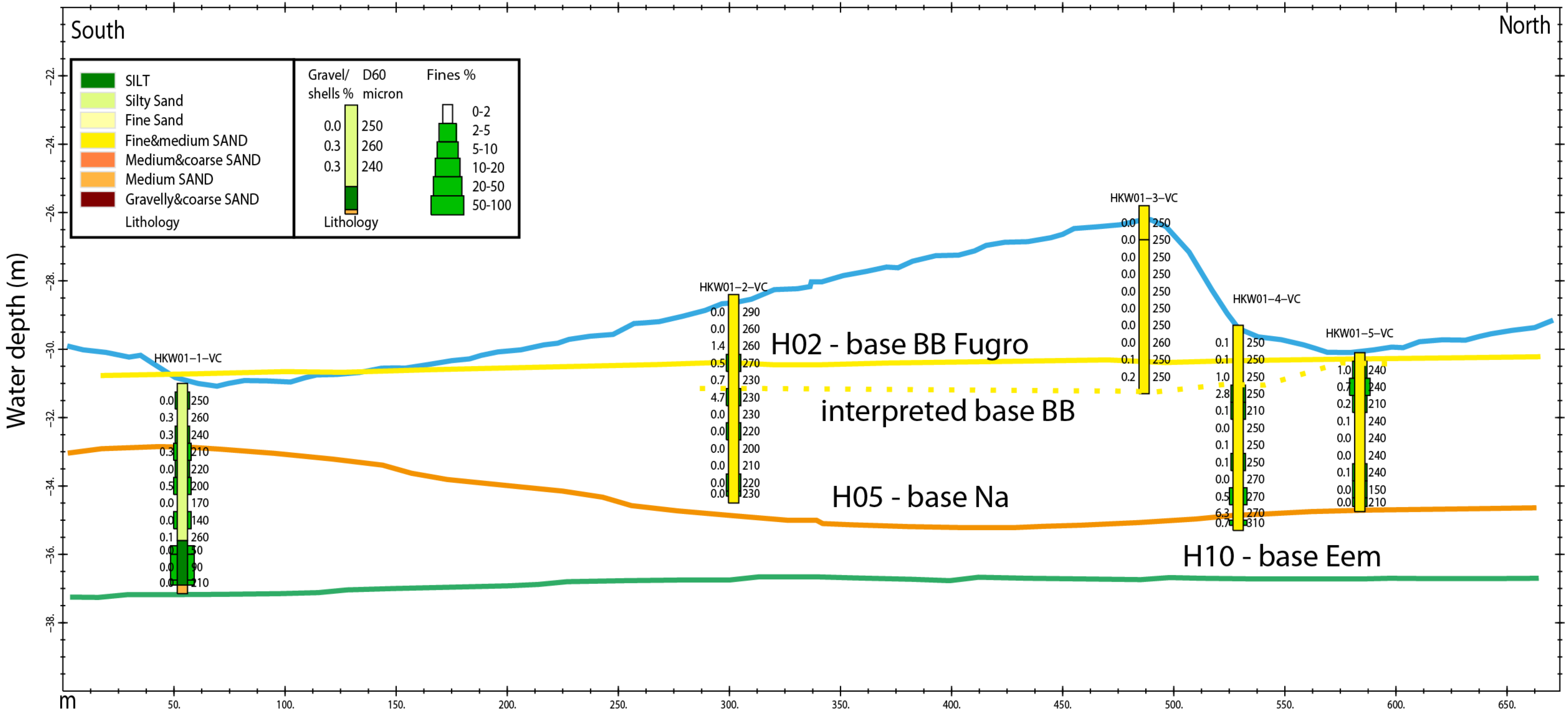
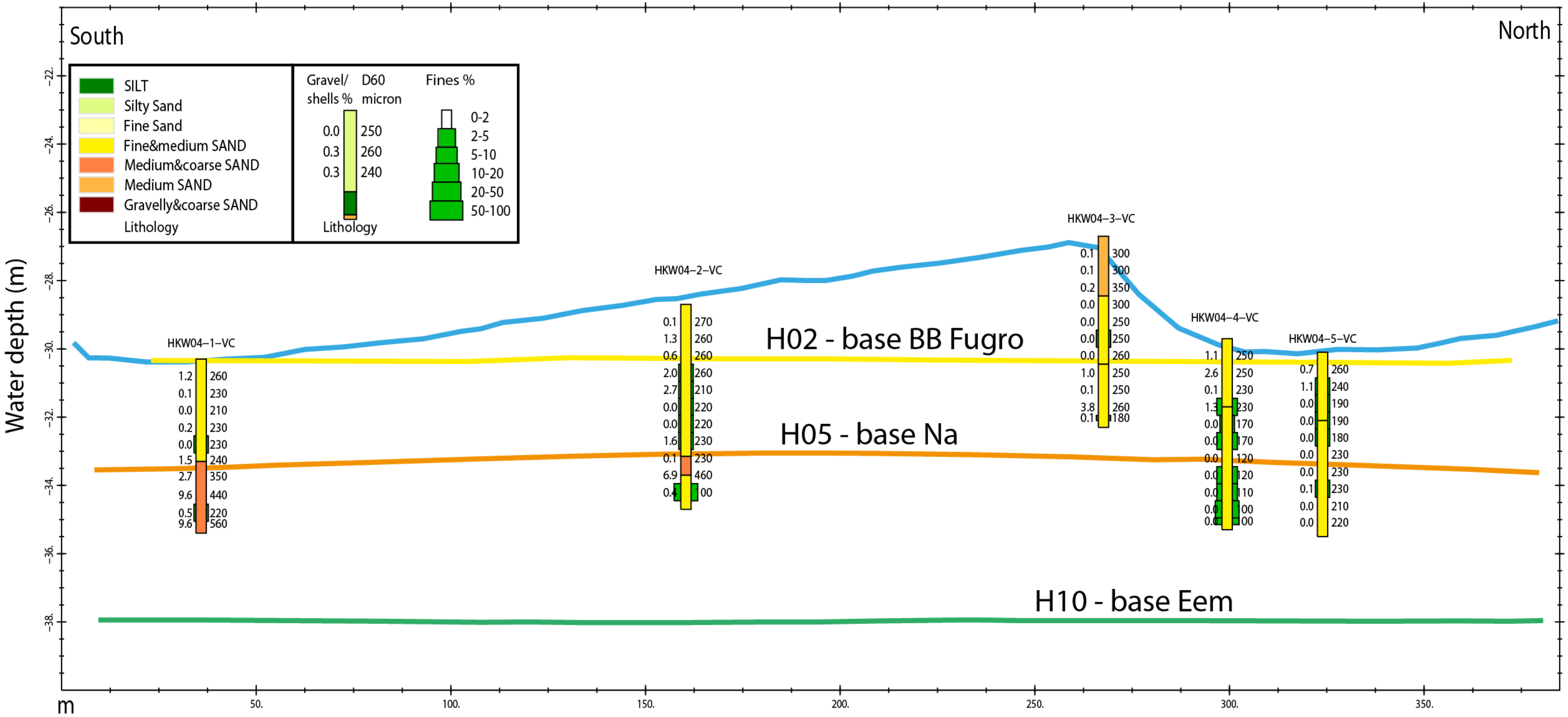


Cross-section 4



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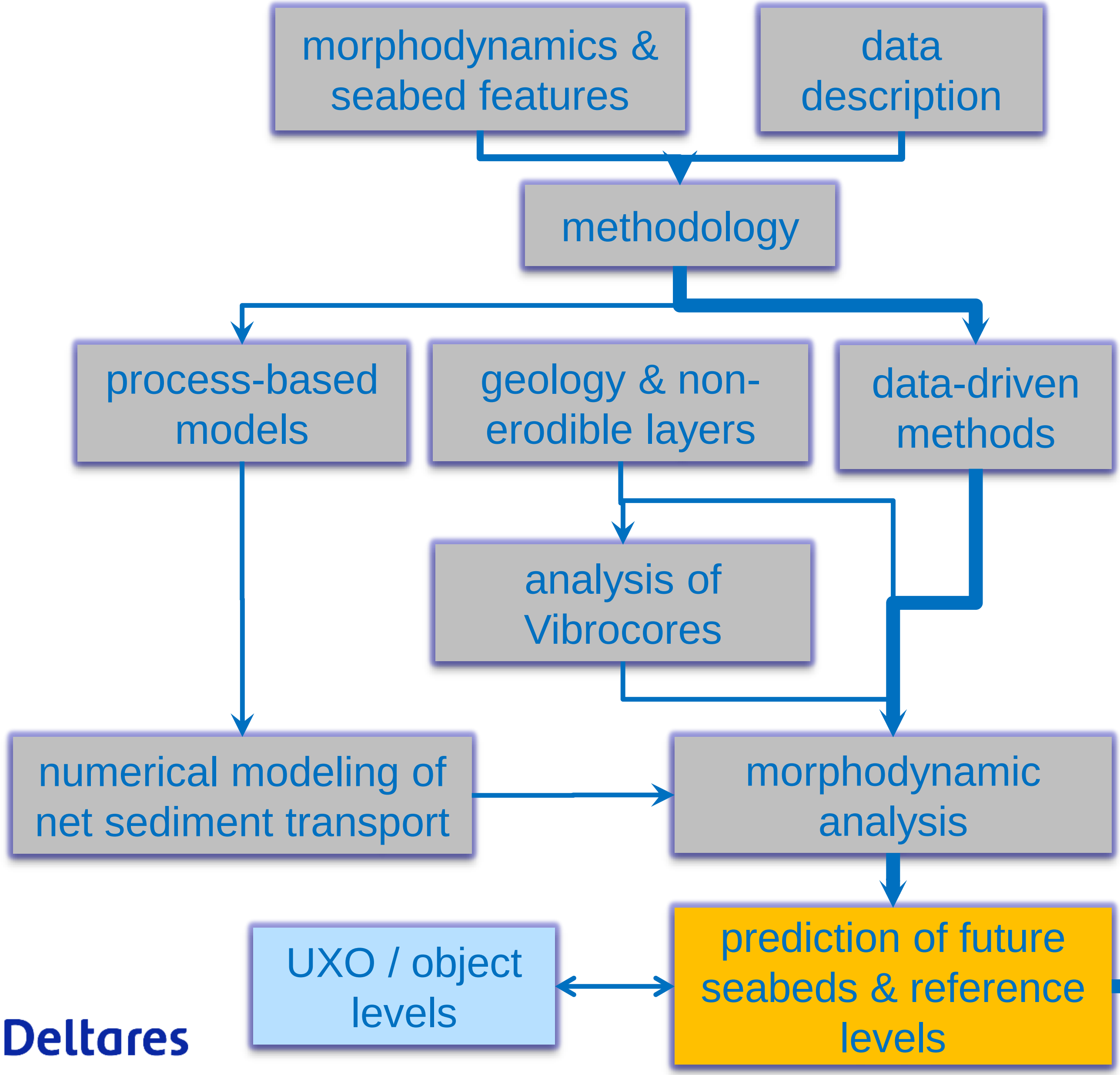

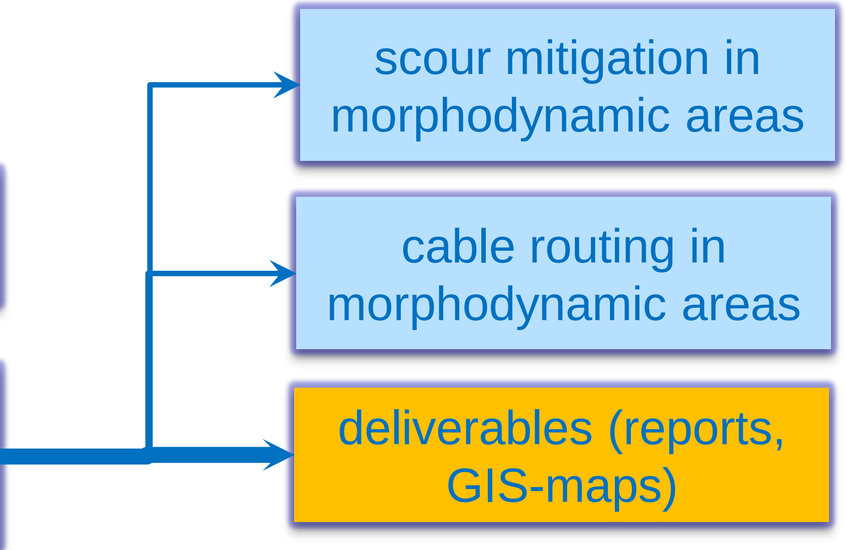

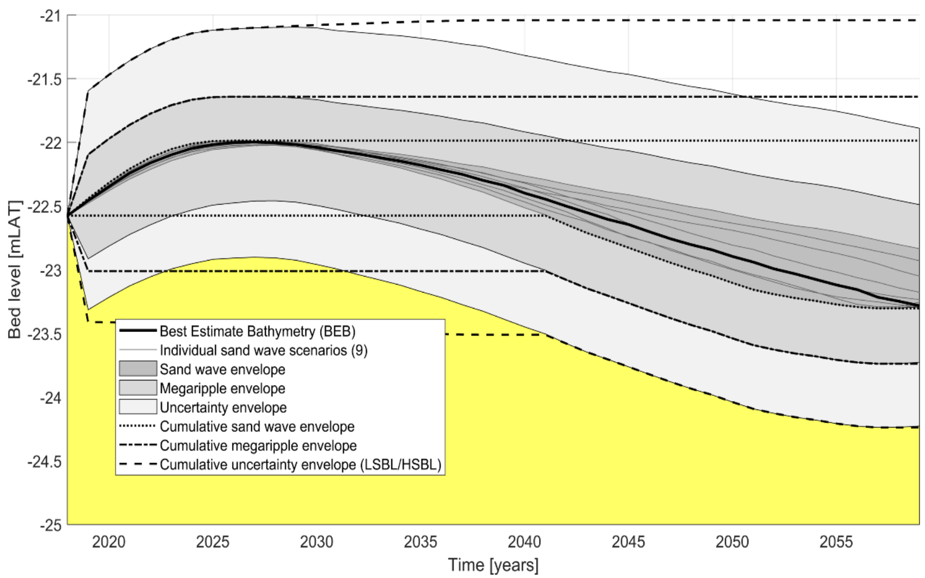

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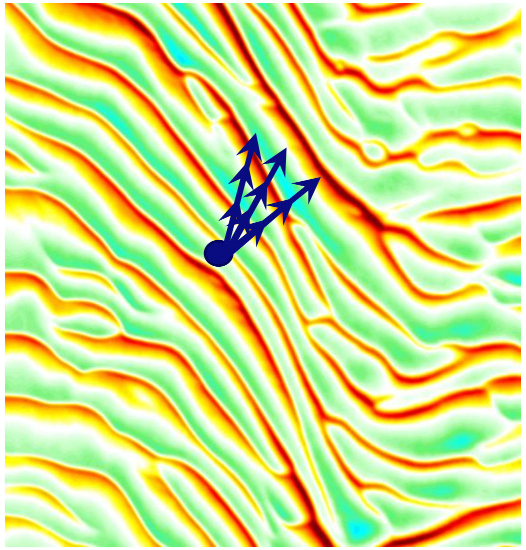
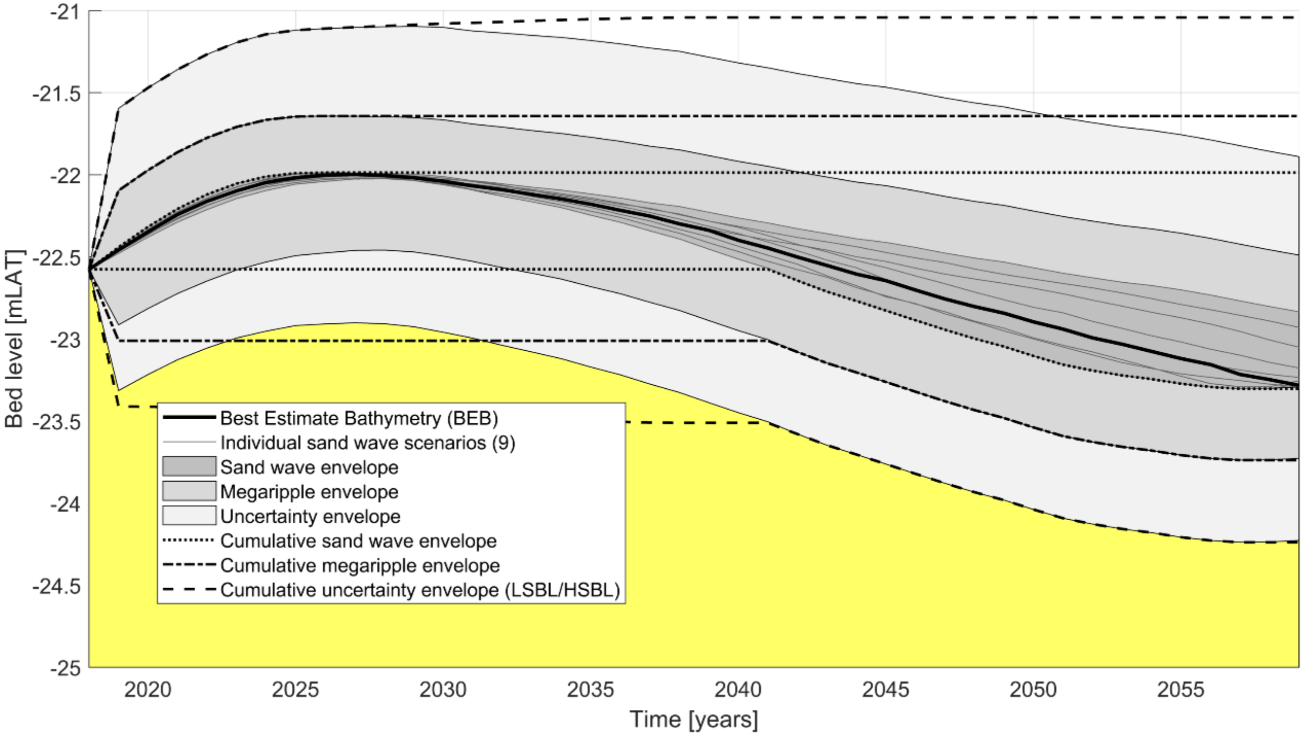
Predicting and hindcasting seabed levels



- Extrapolation of morphodynamic trends
  - Sand wave migration
  - Large-scale seabed dynamics

- Predicted bathymetries for year 2059 are reconstructed by combining:
  - ✓ (Extrapolated) Large-scale bathymetry
  - ✓ Migrated Sand Wave Field 2018/2019 until year 2059
  - ✓ Uncertainty Band
- Hindcasted bathymetries for year 1945 are constructed by combining
  - ✓ (Extrapolated) Large-scale bathymetry
  - ✓ Migrated Sand Wave Field 2018/2019 until year 1945
  - ✓ Uncertainty Band



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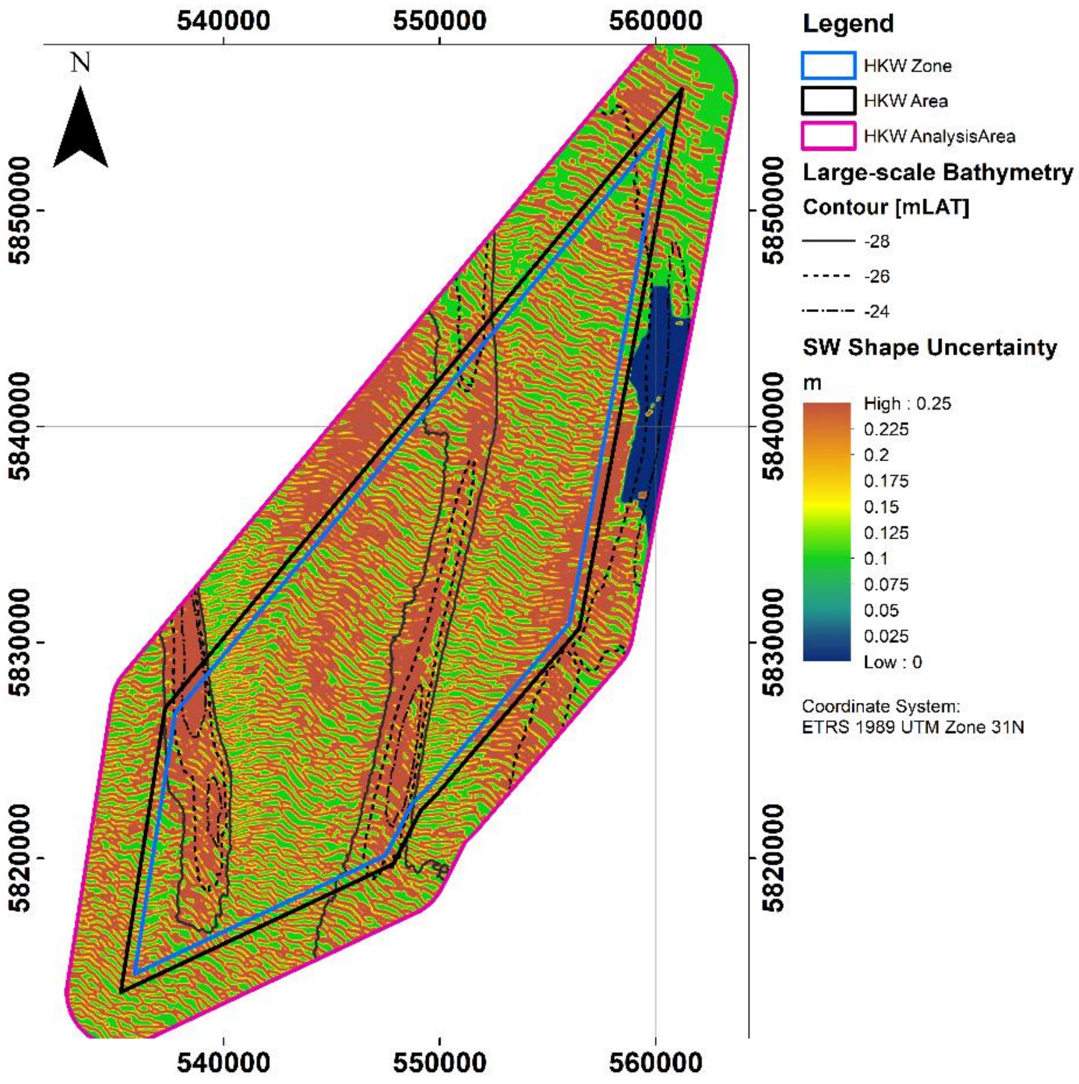
Dealing with uncertainties

Vertical uncertainty band consists of contributions related to:

- survey inaccuracies
- existence of megaripples (seasonal correction)
- spatial resolution uncertainty ('missing extreme levels')
- shape retaining bedforms

Furthermore two spatial varying uncertainties are added:

- Megaripple uncertainty
- Uncertainties in sand wave heights
  - Minor effect based on correlation of sand wave dimensions (2015-2019)
  - Sand wave crest locations are tracked over time



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Data analysis –Design Seabed Levels

Lowest SeaBed Level (LSBL)

The *lowest* seabed level in the period 2019-2059

Highest SeaBed Level (HSBL)

The *highest* seabed level in the period 2019-2059

Lowest Object Level (LOL)

The *lowest* level of objects dropped during WWII for the period 2019-1945 (useful information for construction activities)

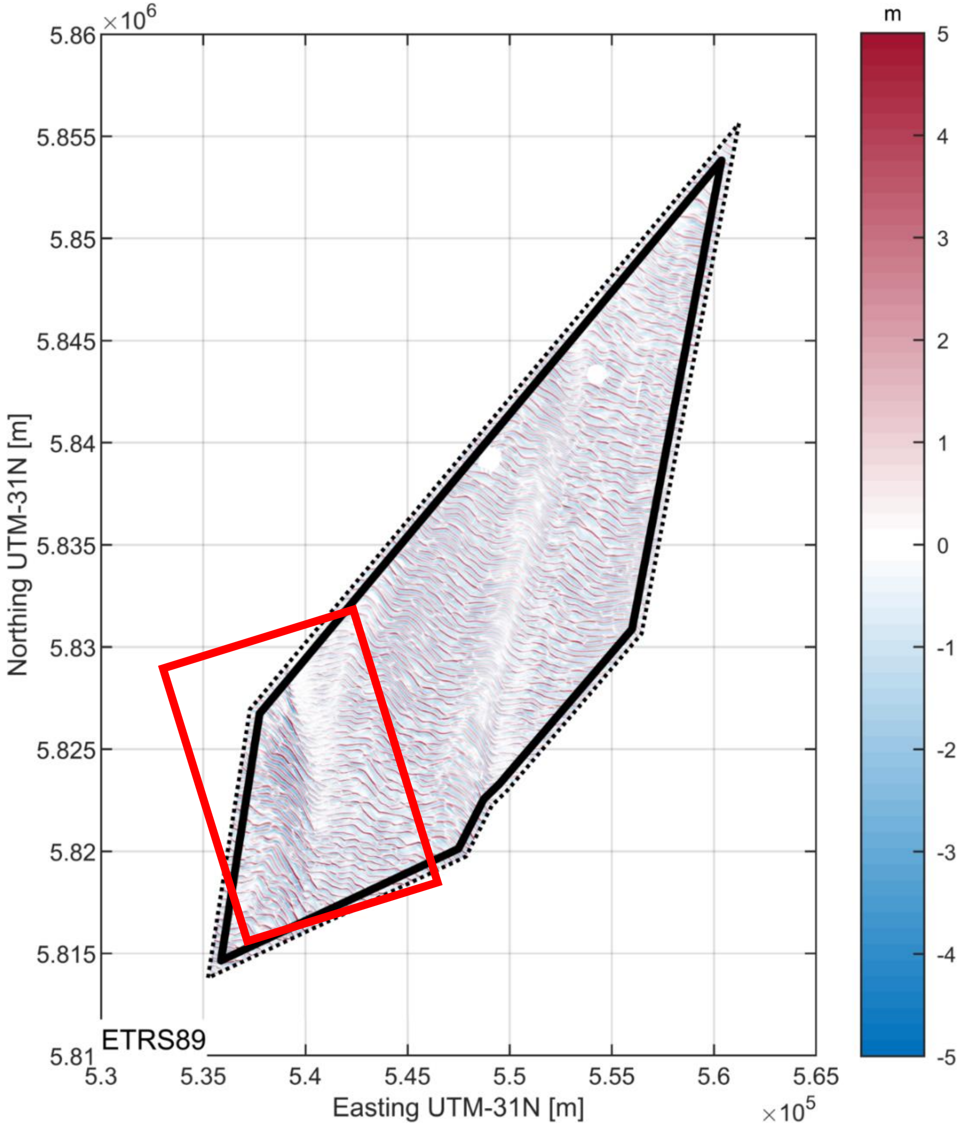
Highest Object Level (HOL)

The *highest* lowest level of objects dropped during WWII for the period 2019-1945 (useful information for construction activities)

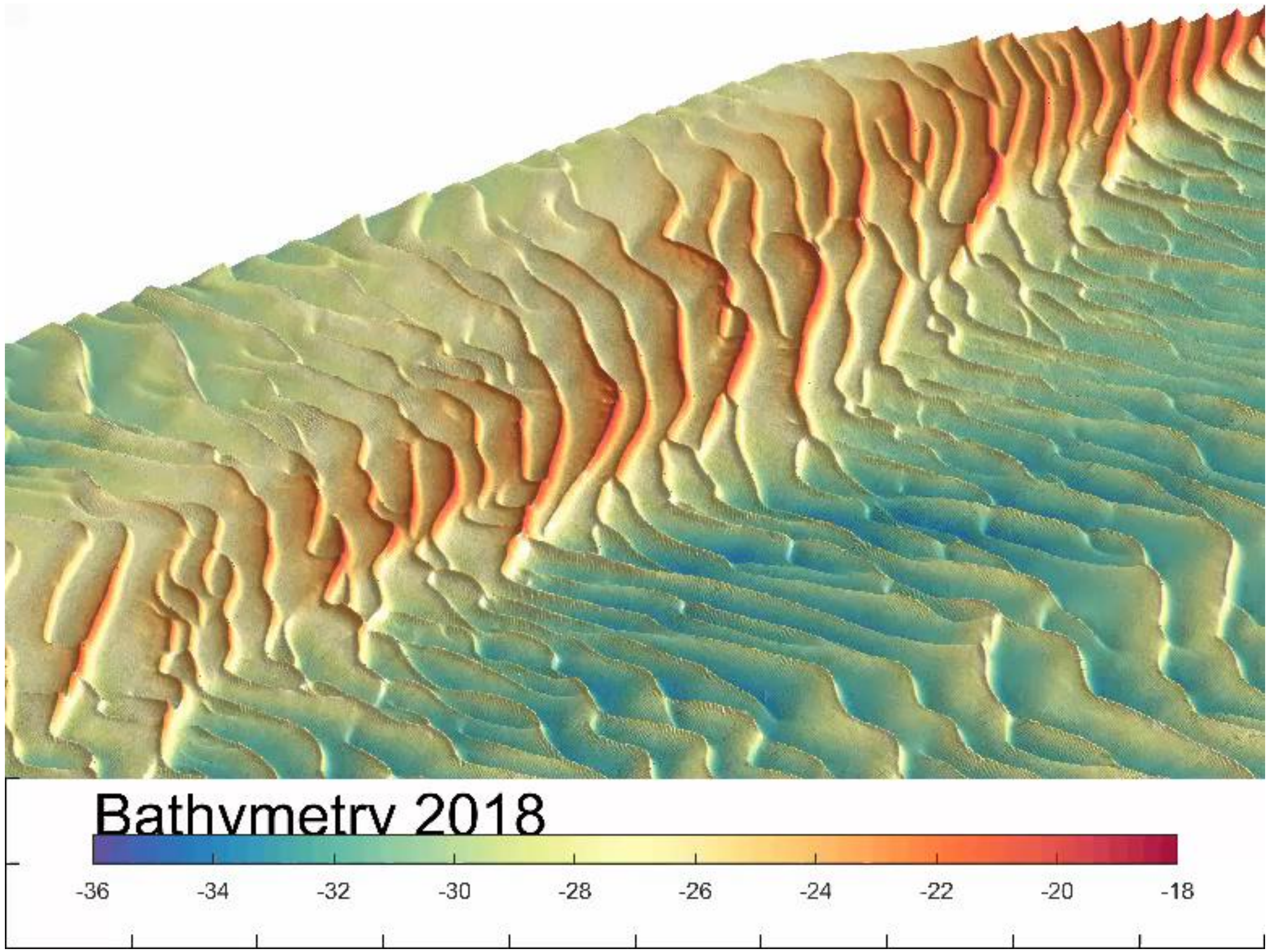
Note that all these levels are design levels which should be sufficiently conservative. Depending on the monitoring & maintenance strategy, different seabed levels can be used. Therefore, also Best-Estimate Bathymetries and Best-Estimate Object Levels are delivered.

Best-Estimate Bathymetry

Difference BEB 2059 with 2019 bathymetry

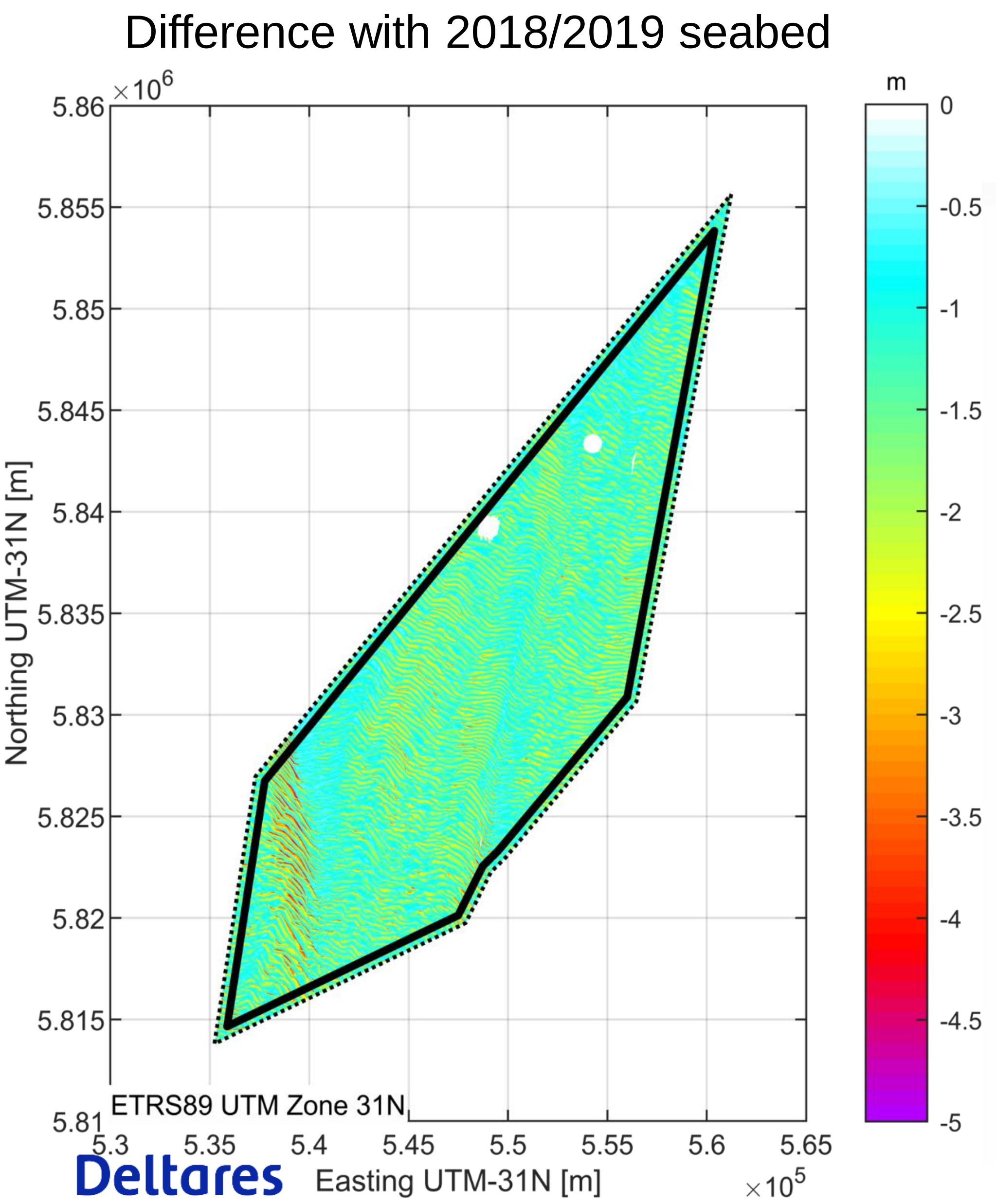


Movie illustrating Best-estimate bathymetries

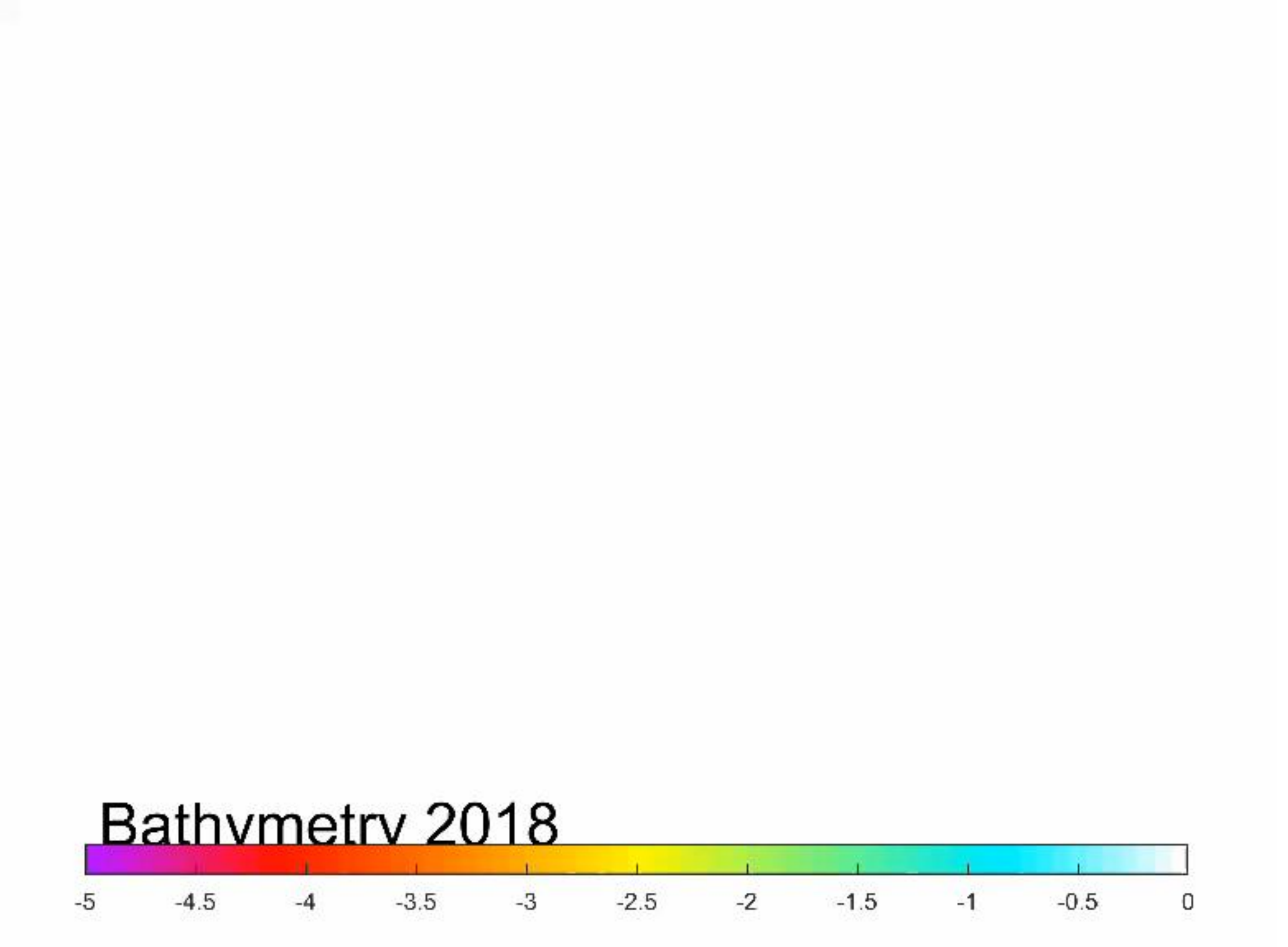


Webinar Morphodynamics and Scour Mitigation
Hollandse Kust (west)

Lowest SeaBed Level: LSBL



__Movie illustrating cumulative downward seabed movement__



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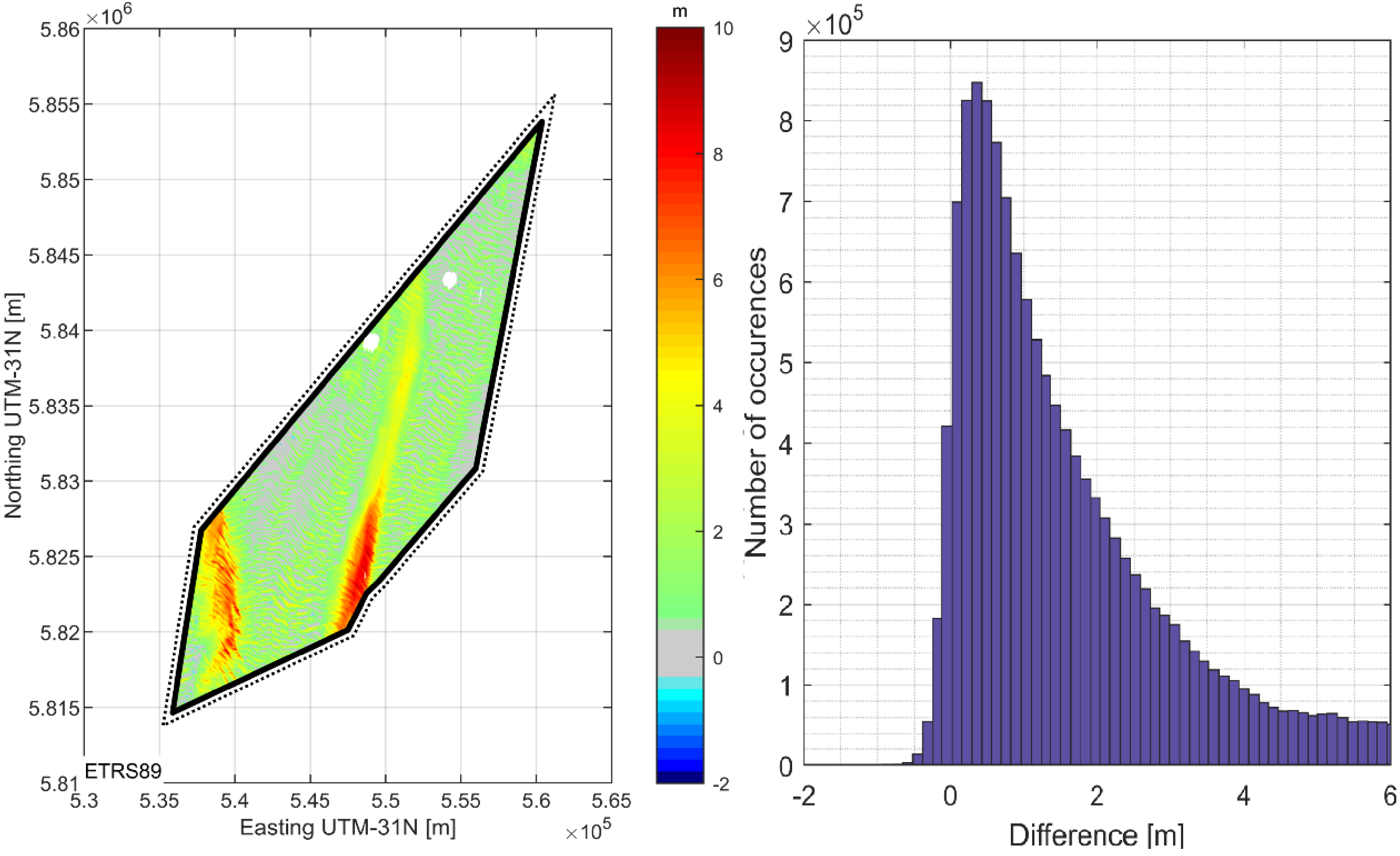
Determining remaining layer thickness

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



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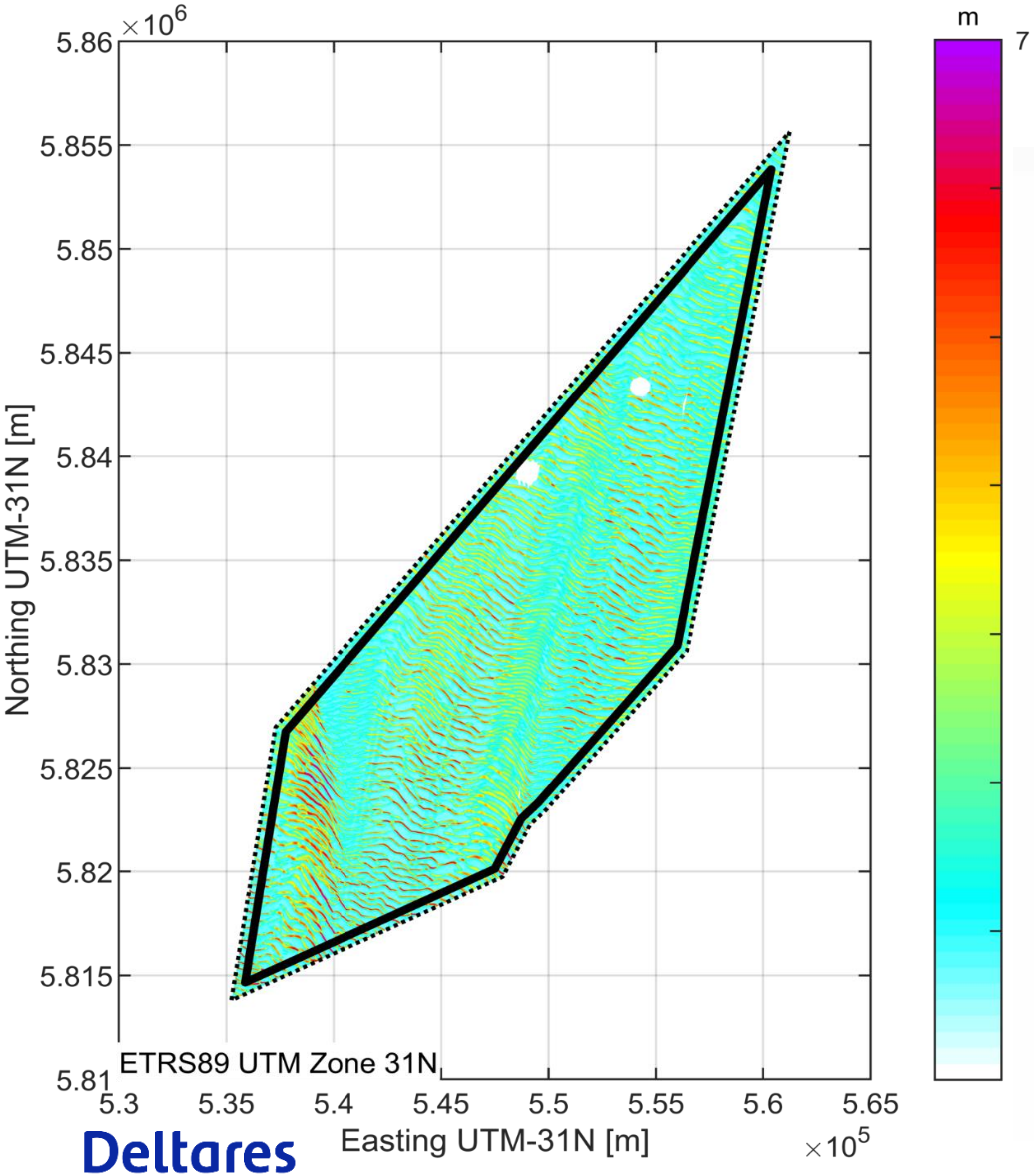
Highest SeaBed Level: HSBL

Difference with 2018/2019 seabed



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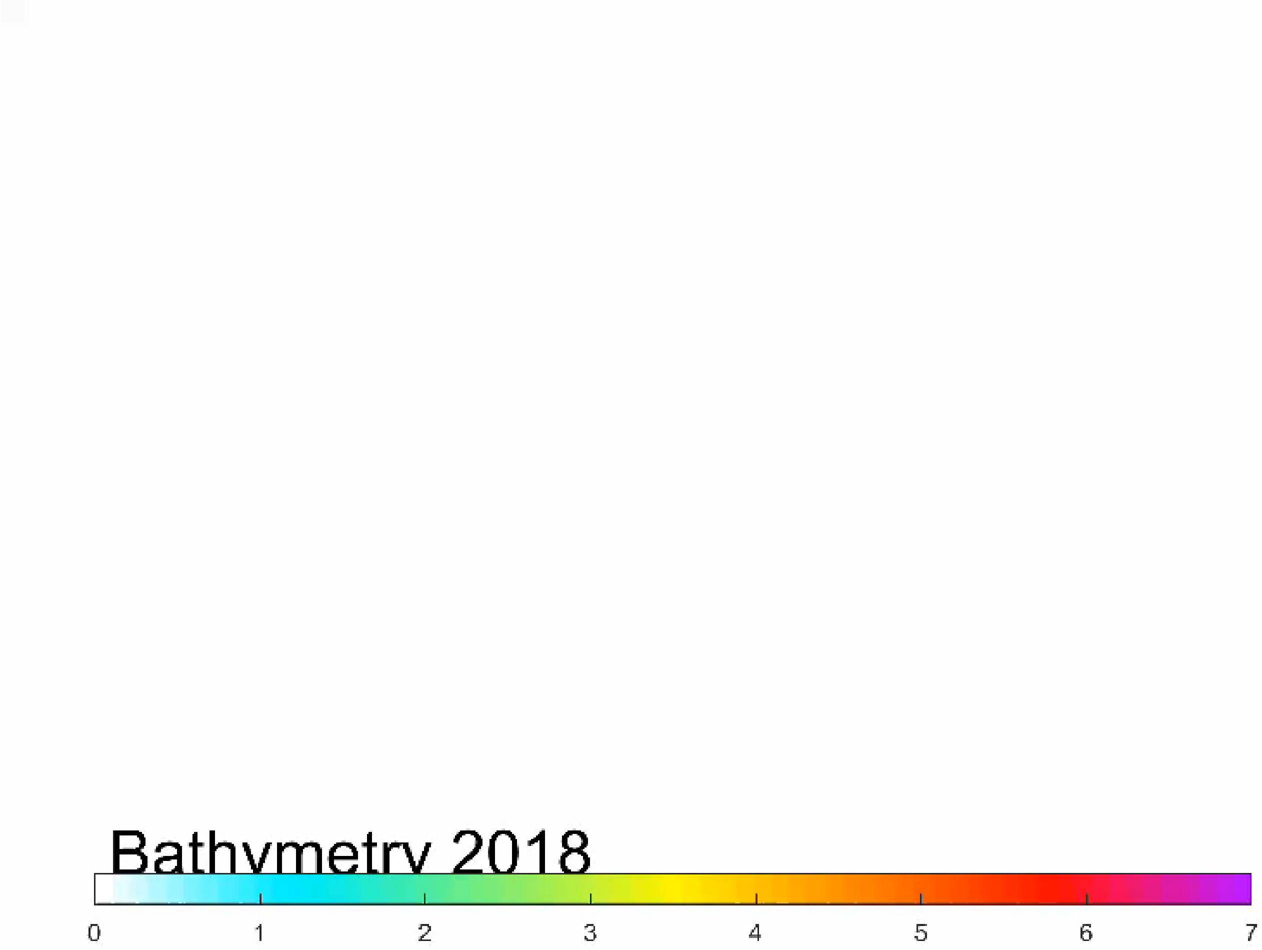
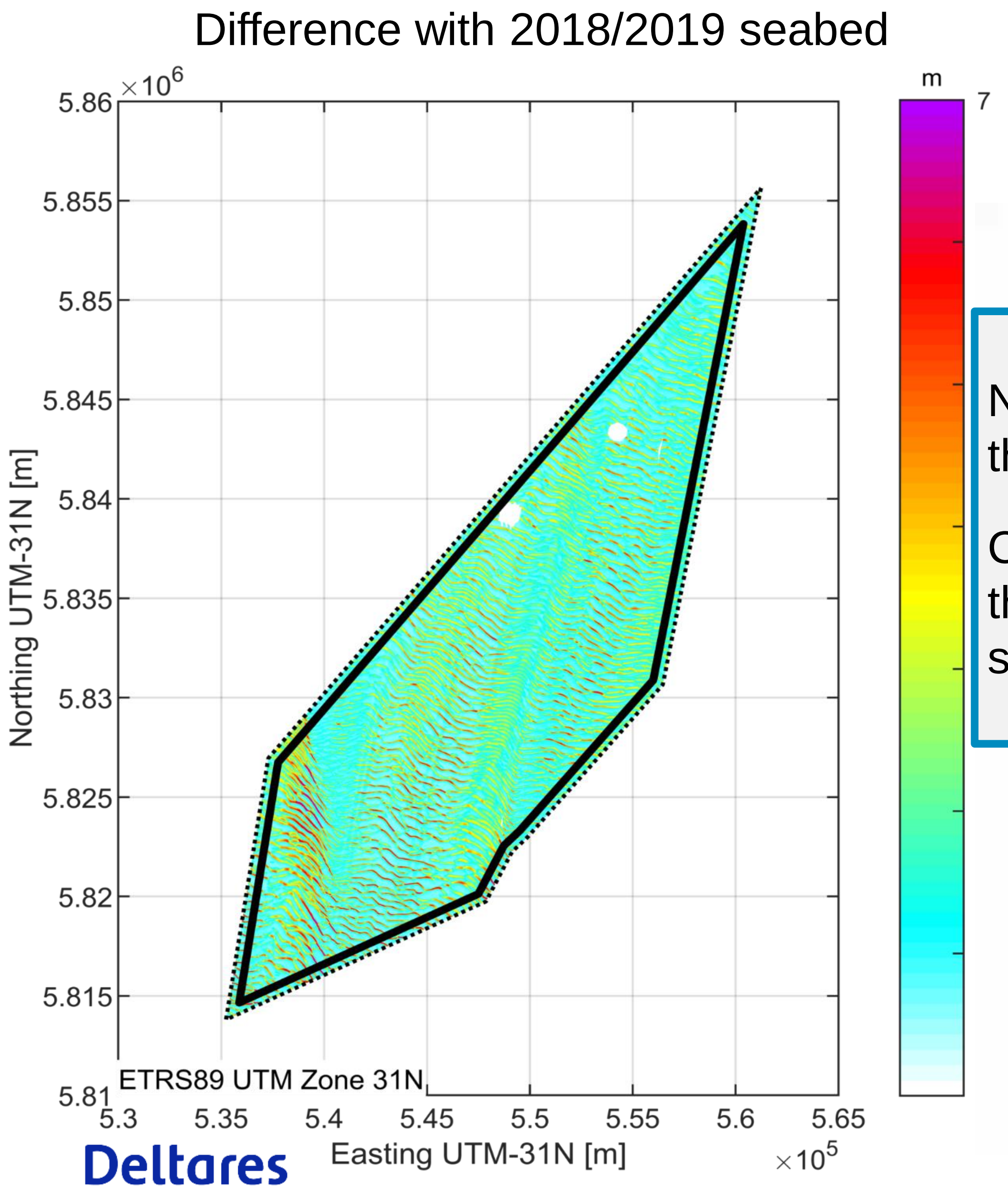
[*Movie illustrating cumulative upward seabed movement*]



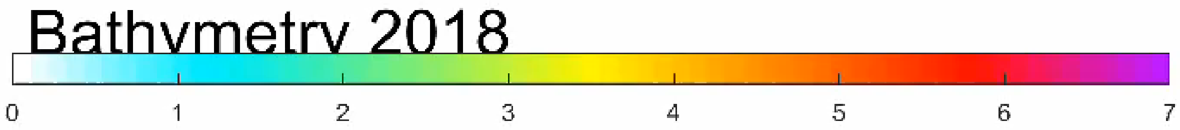
Highest SeaBed Level: HSBL



Movie illustrating cumulative upward seabed movement

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 burial by a rising seabed level.



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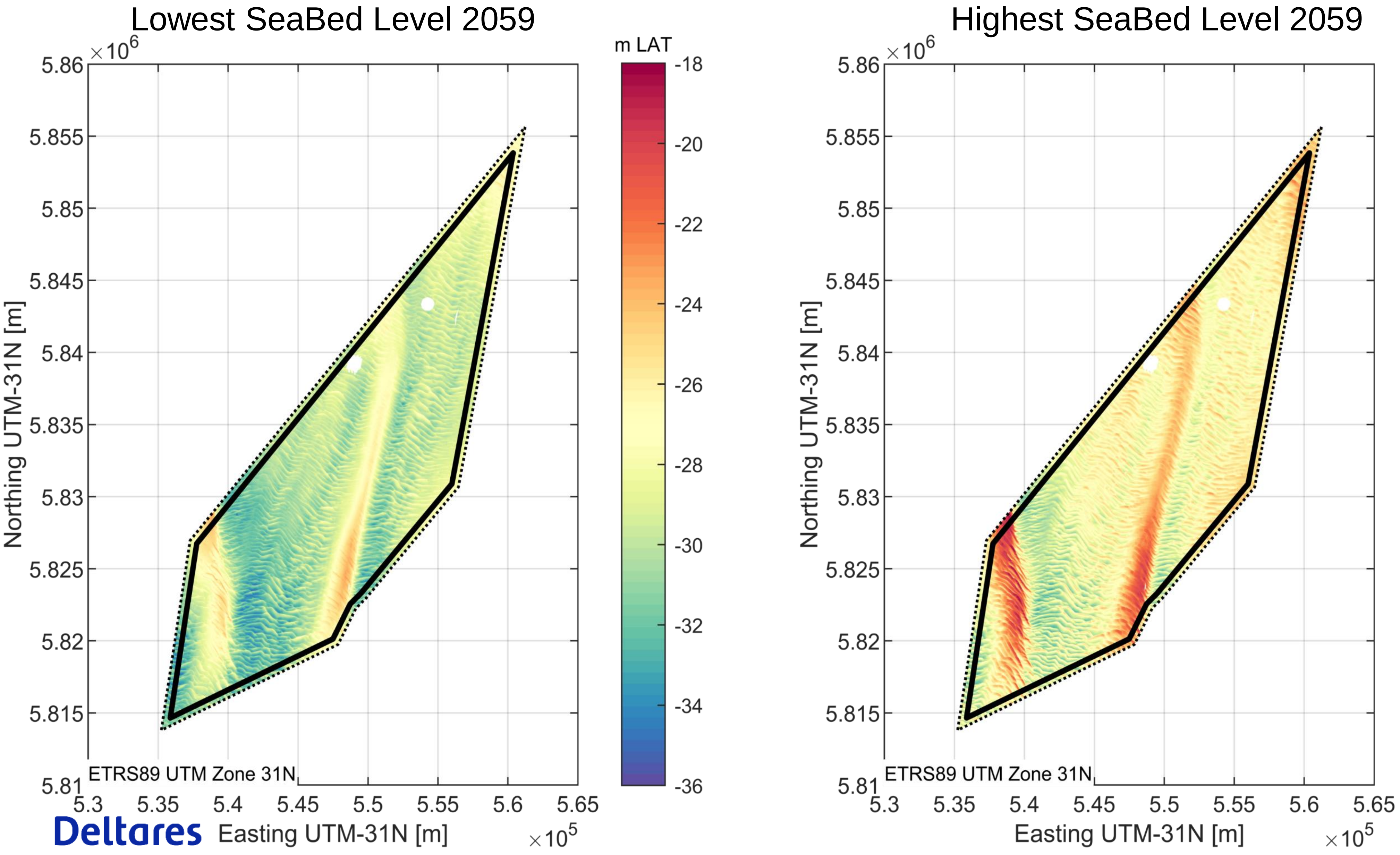
Comparison LSBL - HSBL



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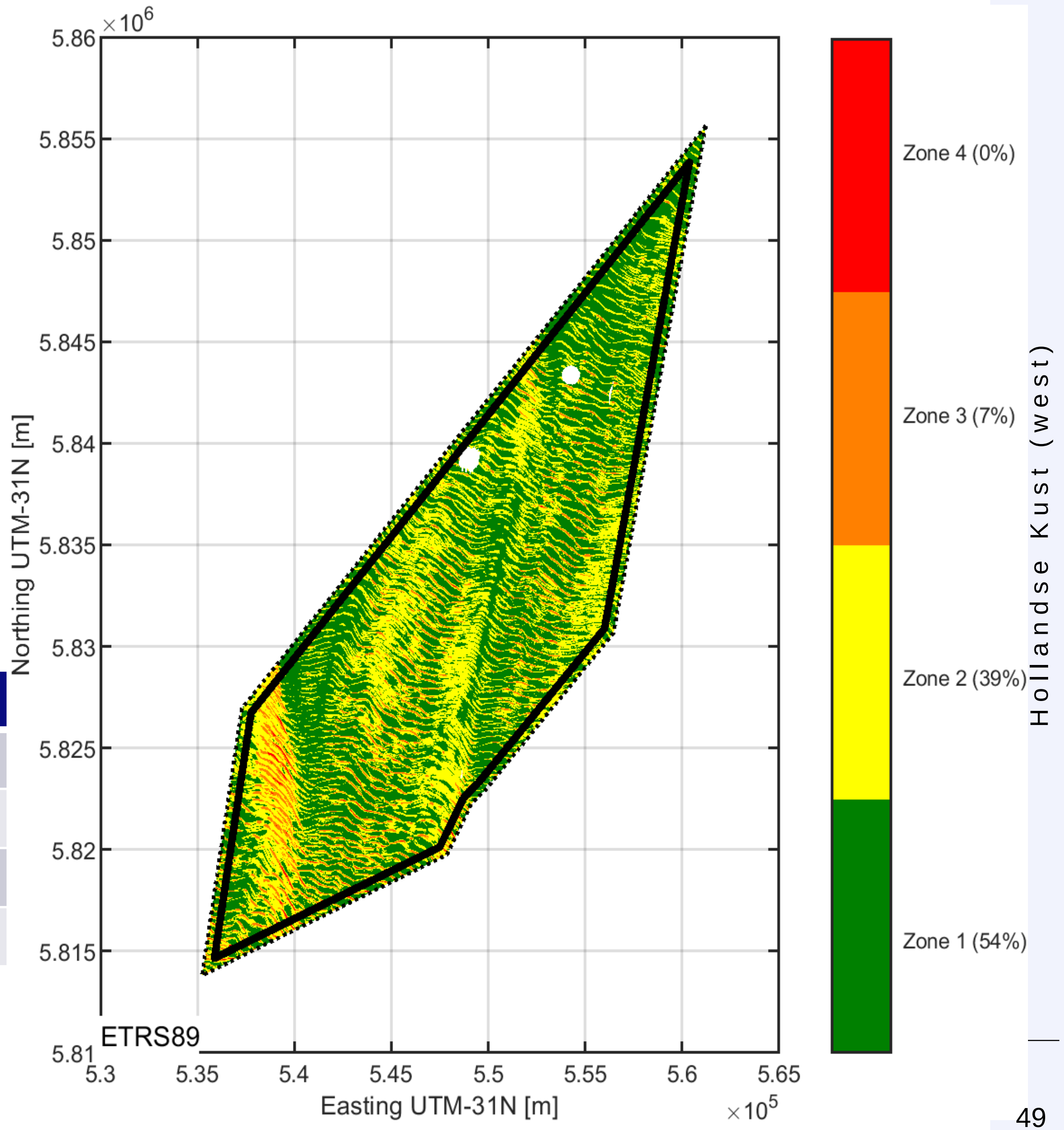
Classification zones (I)

- 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 ≥ -2	0 < dz ≤ 2
1-2 m change	-2 > dz ≥ -4	2 < dz ≤ 4
2-3 m change	-4 > dz ≥ -6	4 < dz ≤ 6
>3 m change	dz < -6	dz > 6



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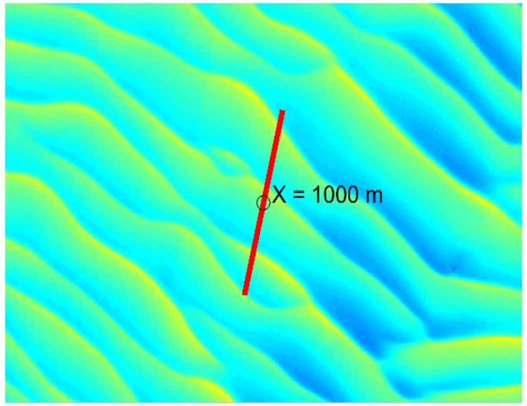
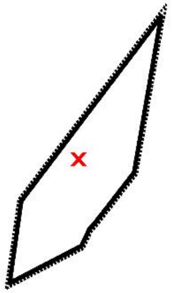
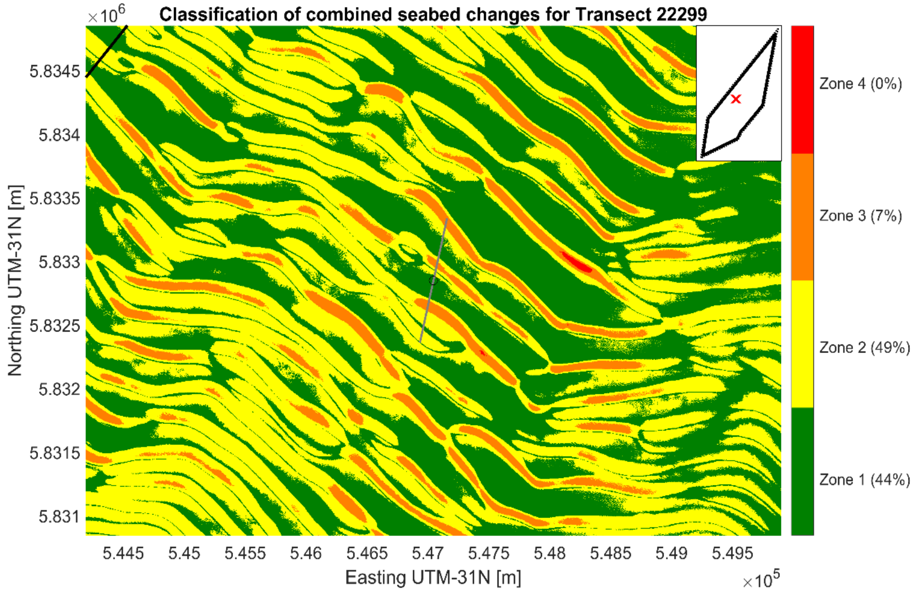
Classification zones (2)

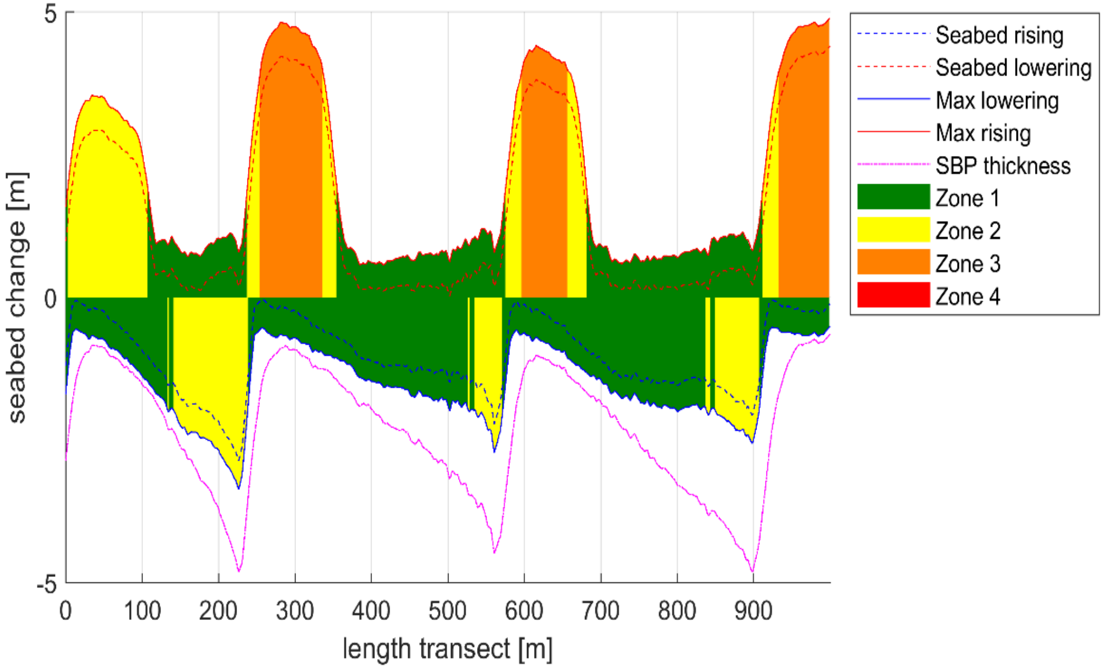
Example for one transect:

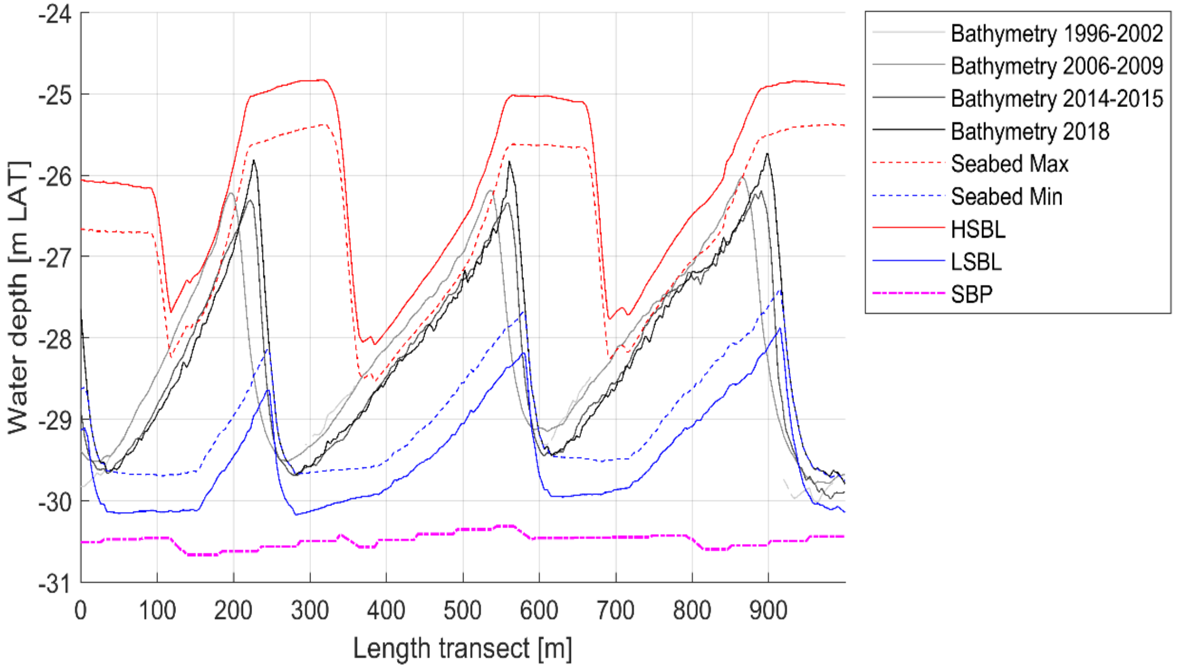
- Classification calculated for rising lowering and seabed slopes



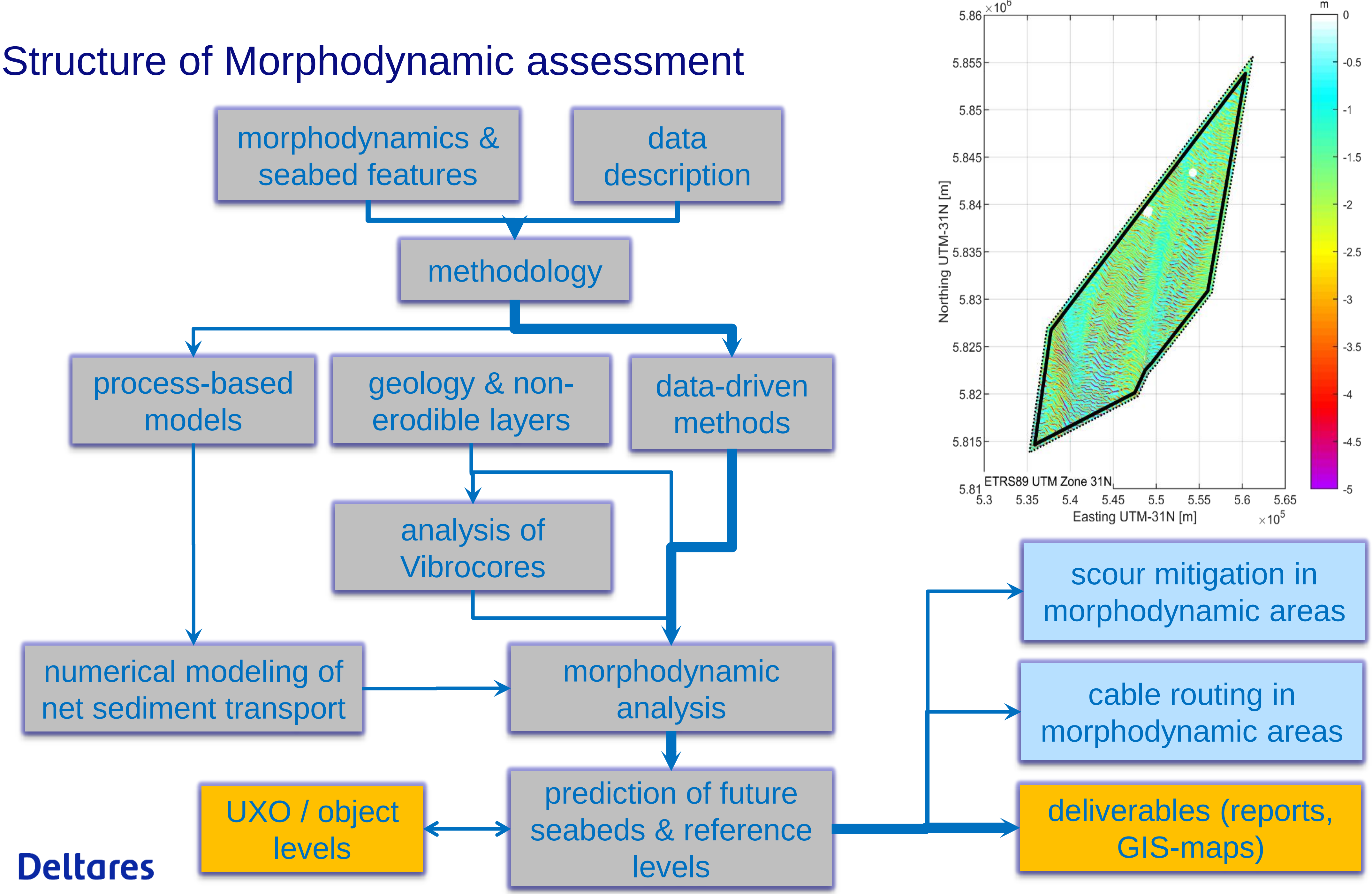








Structure of Morphodynamic assessment



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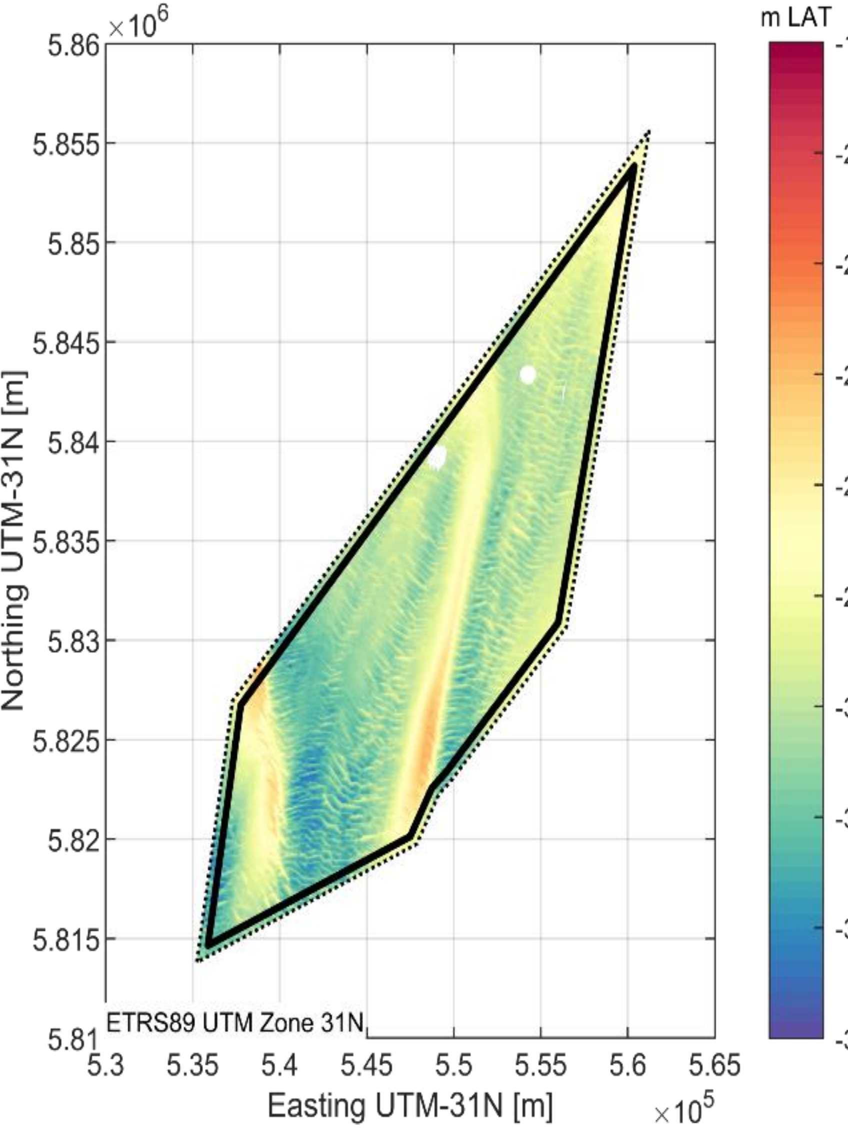
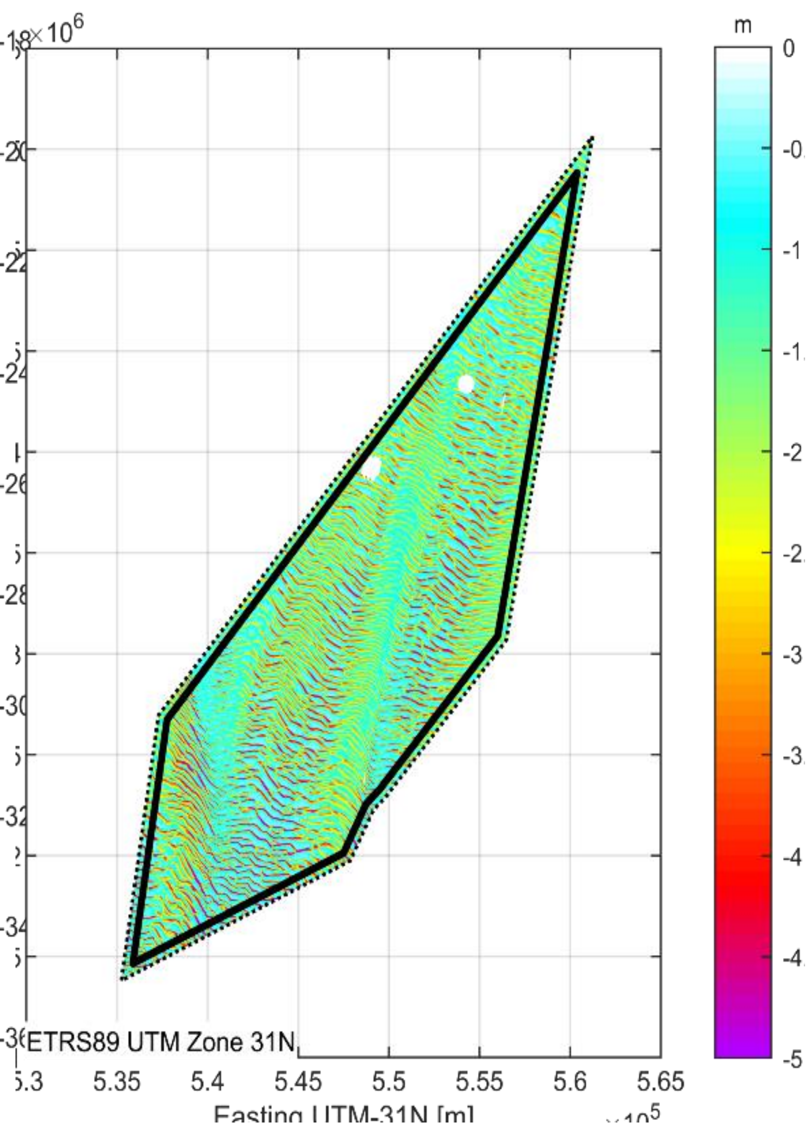
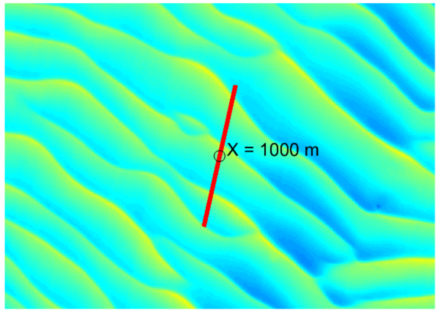
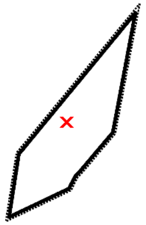
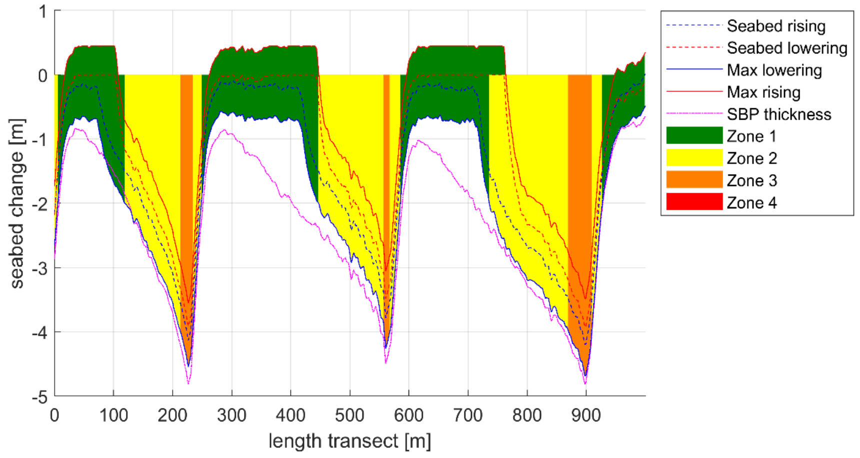
Lowest object levels

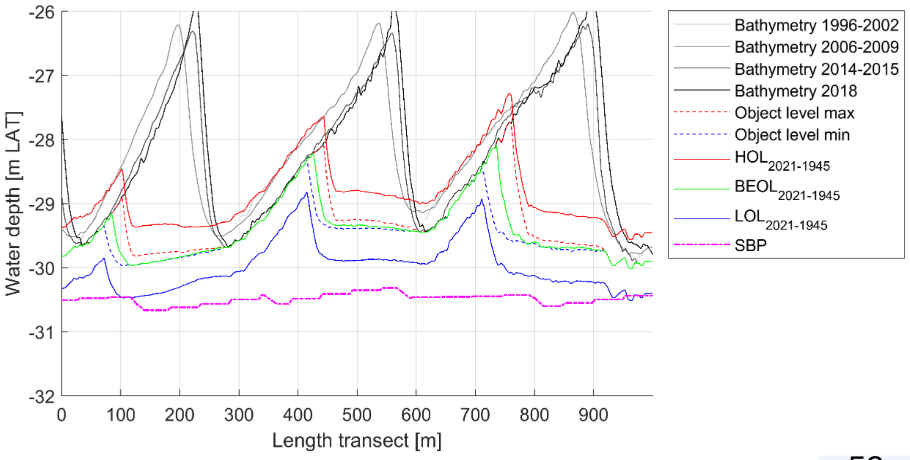












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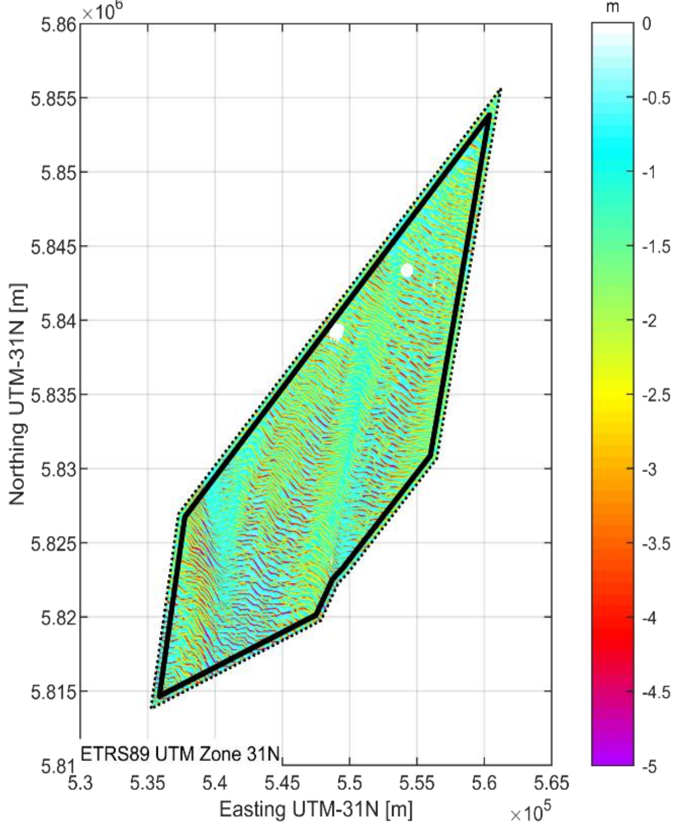
Structure of Morphodynamic assessment

- morphodynamics & seabed features
- data description
- methodology
- process-based models
- geology & non-erodible layers
- data-driven methods
- analysis of Vibrocores
- numerical modeling of net sediment transport
- morphodynamic analysis
- UXO / object levels
- prediction of future seabeds & reference levels
- scour mitigation in morphodynamic areas
- cable routing in morphodynamic areas
- deliverables (reports, GIS-maps)



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Key take-aways

- Sand waves are the dominant dynamic seabed features
- Vibrocores provide relevant insight in sand wave composition and properties of the shallowest part of the soil layering
- Sand waves in HKW have a medium size and migrate with moderate speed & ~constant direction
- Future seabed levels are relatively well predictable; largest uncertainties caused by influence of the sand banks
- A sufficiently large area with limited seabed changes is available for foundations and cables, when considering morphodynamics

Scour and scour mitigation assessment

Objectives of the Morphodynamic and Scour Mitigation Study for Hollandse Kust (west)

The objectives of this study are to:

- describe in detail the morphological seabed features in the wind farm zone HKW
- describe the shallow geological and sedimentological site conditions to a depth of 20m below the measured seabed level
- analyse / quantify the morphodynamics to determine future seabed levels (2019-2059) and historic seabed levels (1945-2019)

Morphodynamic assessment

- describe the scour conditions to be expected at HKW for typical wind farm-related structures*
- provide a state-of-the-art overview of scour mitigation measures and their applicability at HKW 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

Scour and scour mitigation assessment

** 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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Content

- Scour: background and predictions for HKW
- Dealing with scour: mitigation scenarios
- Designing a scour protection
- Cable routing in morphodynamic areas
- Key take-aways

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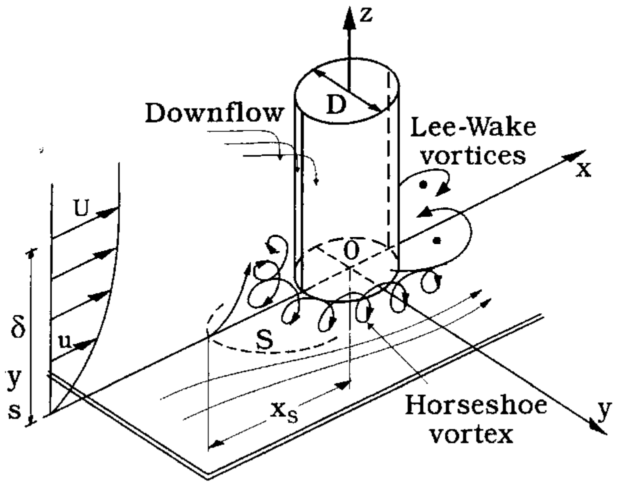
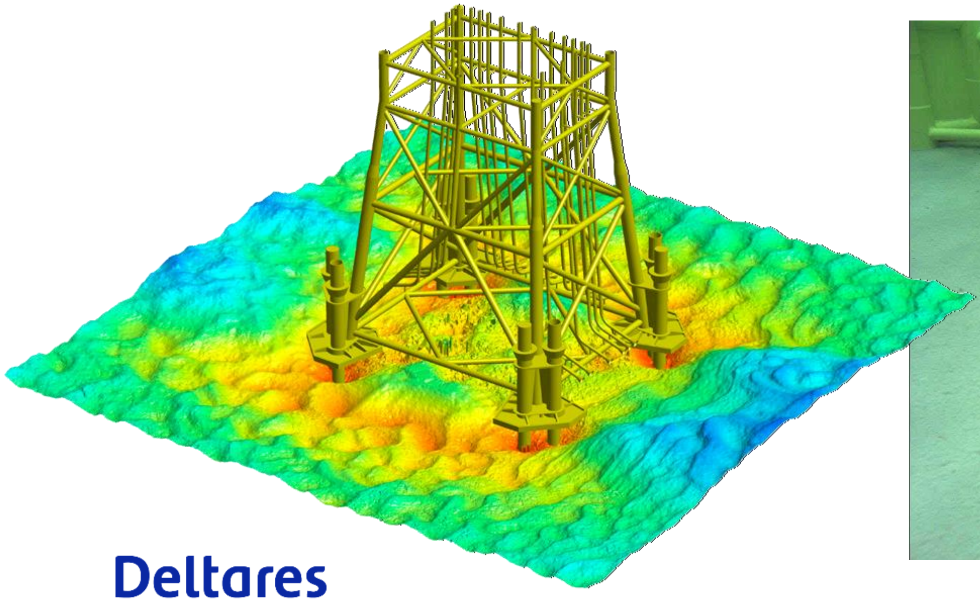
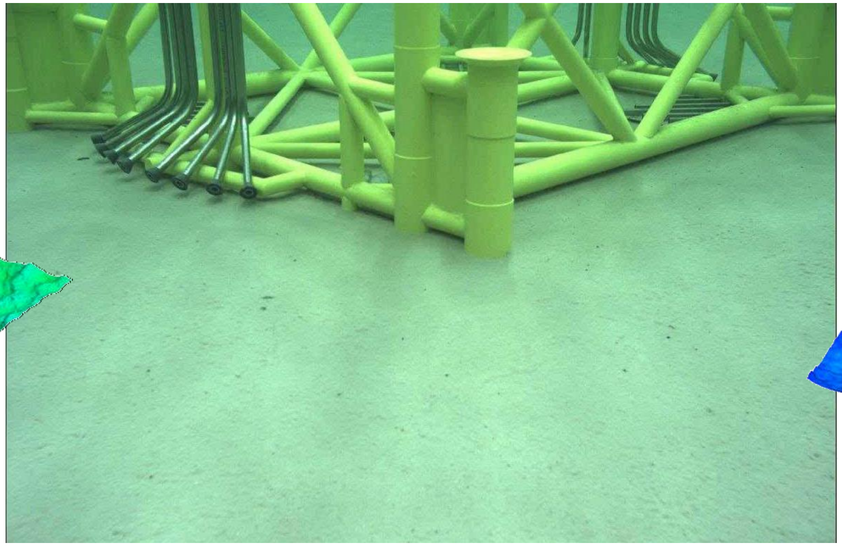
Scour: background and predictions for HKW

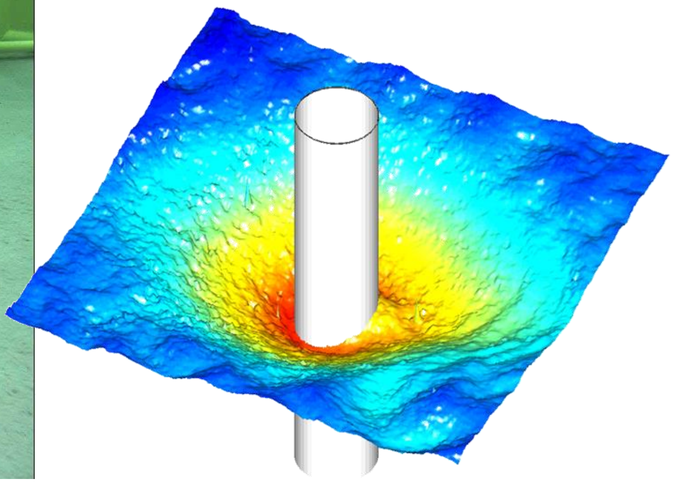
What is scour?

- Scour: erosion of seabed sediment around a structure caused by a local increase in sediment transport capacity
  - 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)









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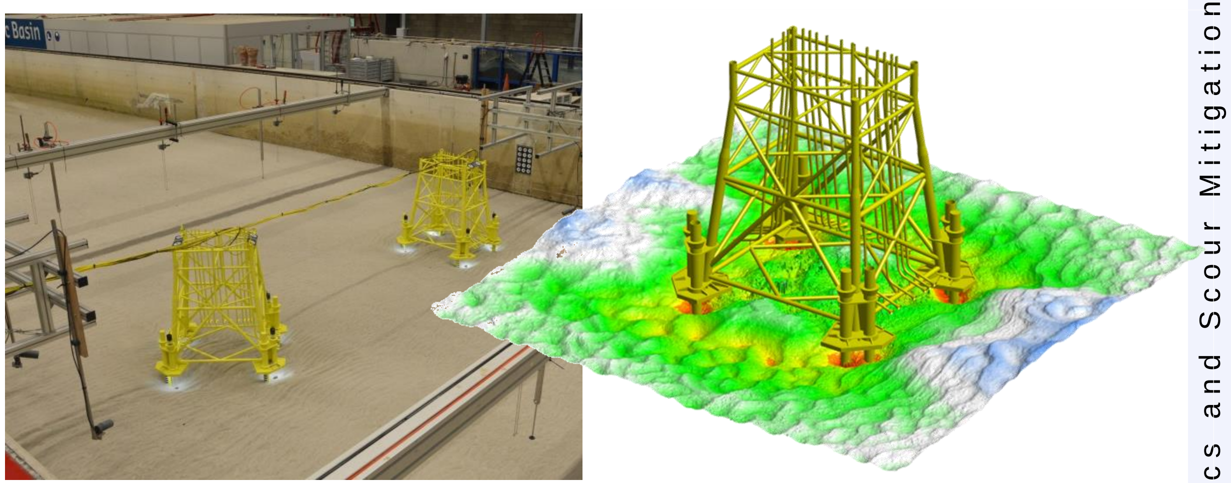
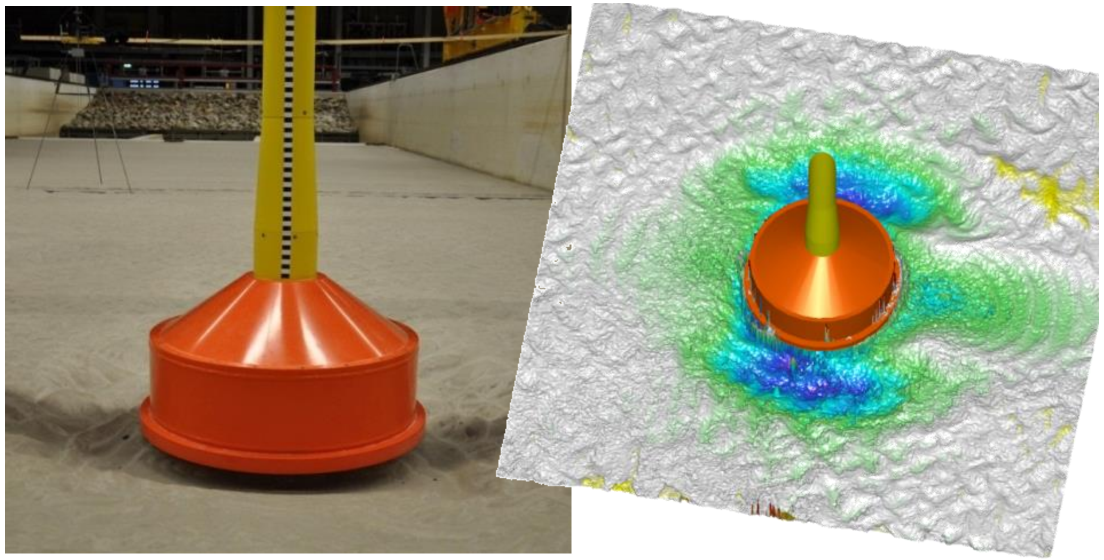
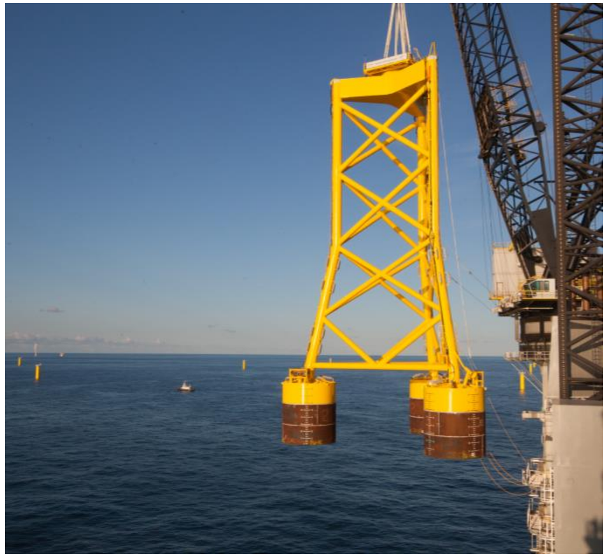
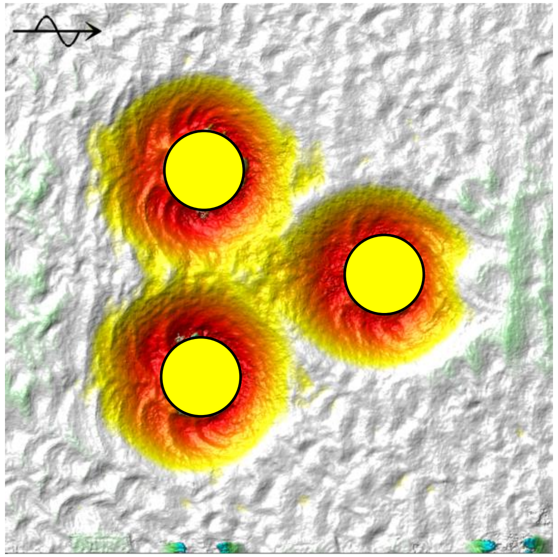
How to model scour?

- Scour prediction models (DSPM, OSCAR)
- Scale model testing
- Field validation



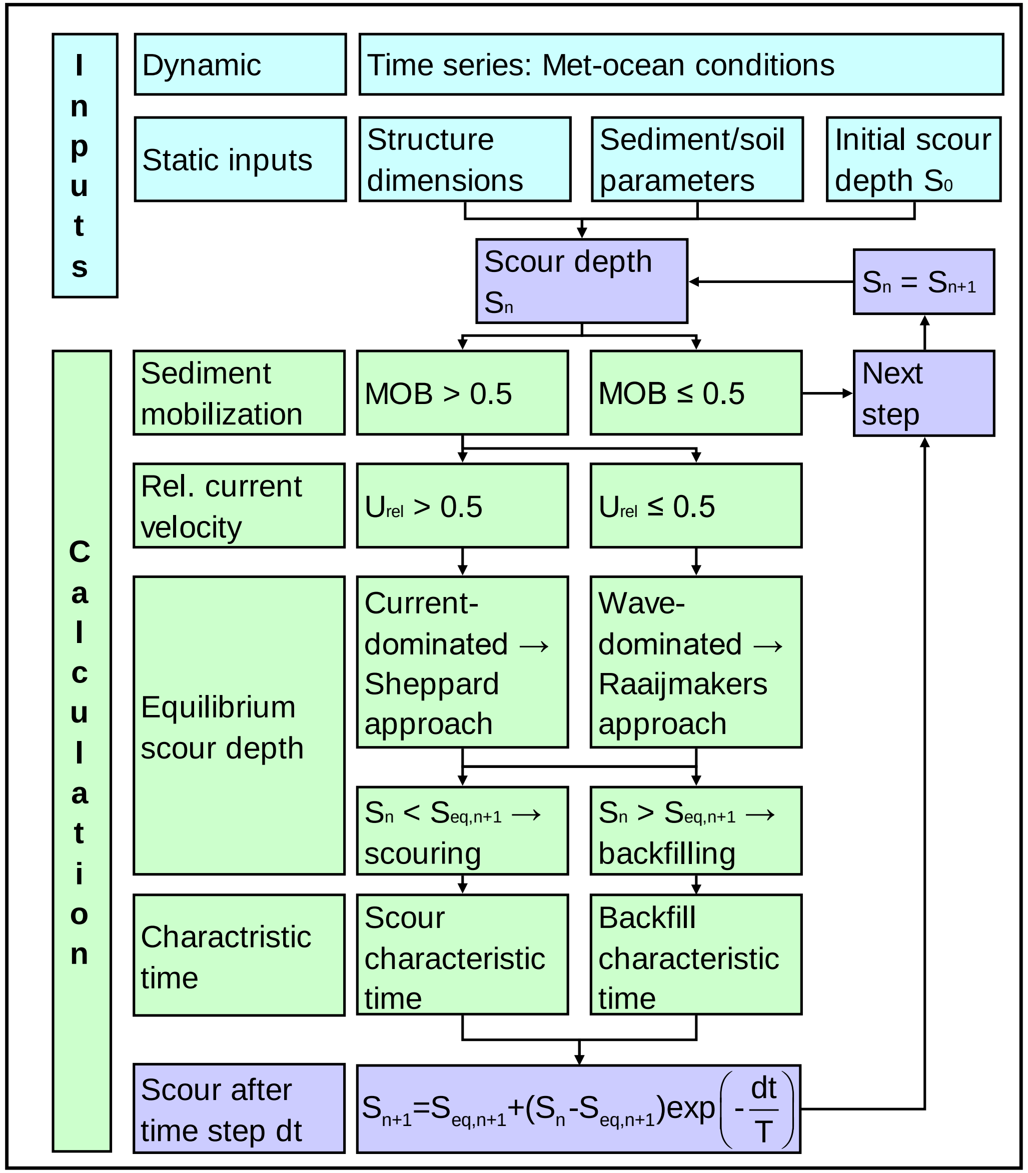






Deltares' Scour Prediction Model

- Model to predict dynamic scour development
- Location- and structure-dependent scour prediction
- Distinguish between wave- and current-dominated
- Each condition has its own equilibrium scour depth and associated characteristic timescale
- Based on laboratory test data + field validation



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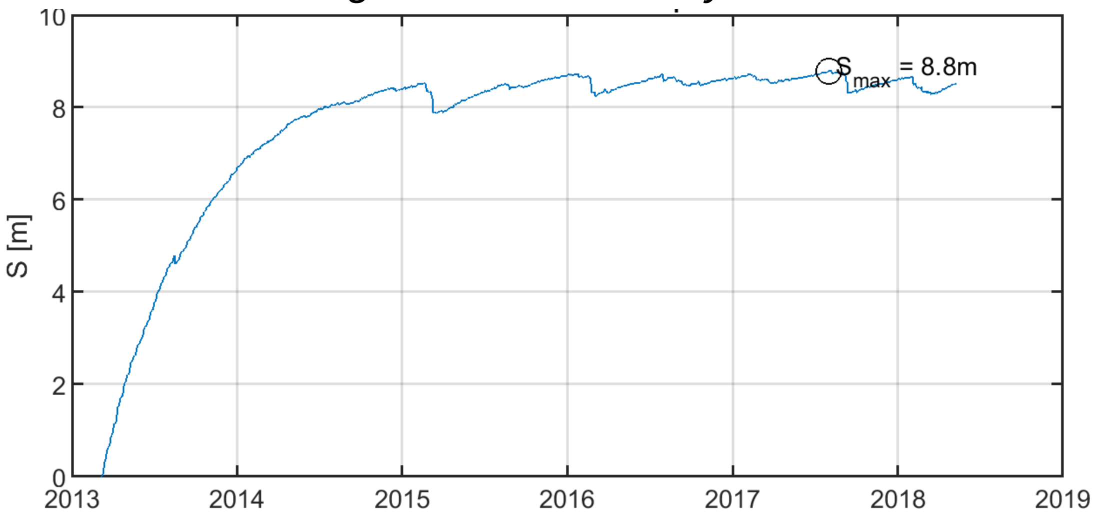
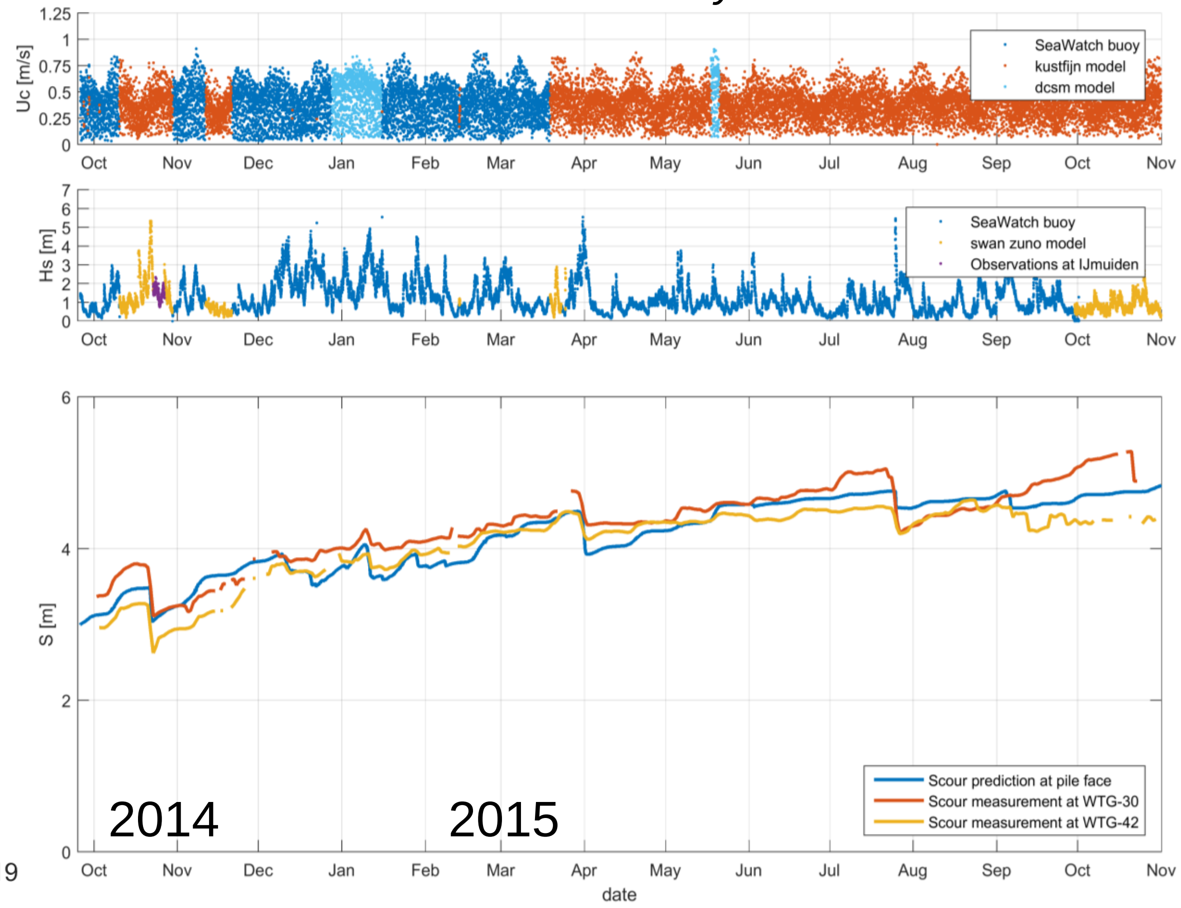
Deltares' Scour Prediction Model

- Single model prediction useful for hindcasting known conditions or *short-term* forecasting
- Monte-Carlo simulation for long-term forecasts
  - Includes variability in selected parameters
  - Provides bandwidth predictions

HKW: single realisation of 5 year hindcast



Luchterduinen OWF 1 year hindcast



Deltares' Scour Prediction Model

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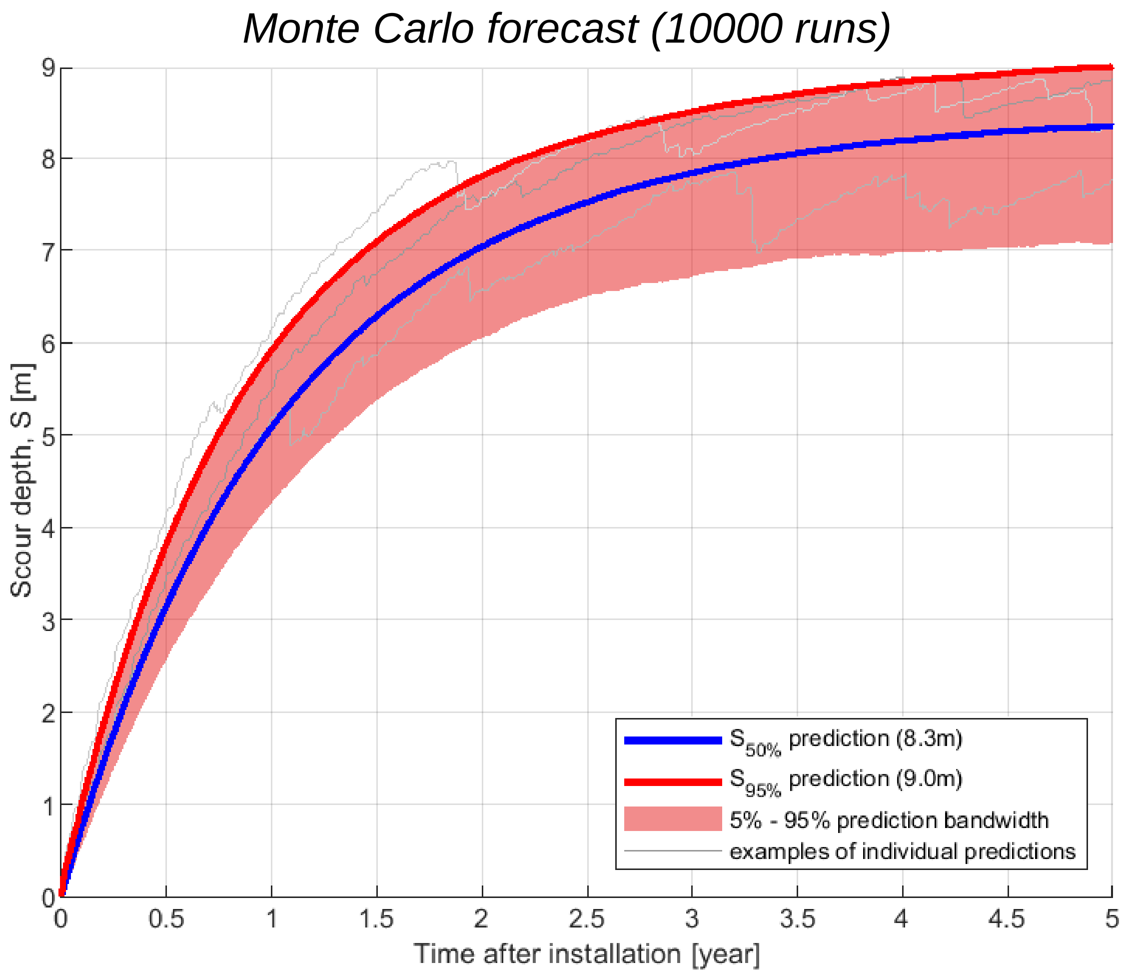
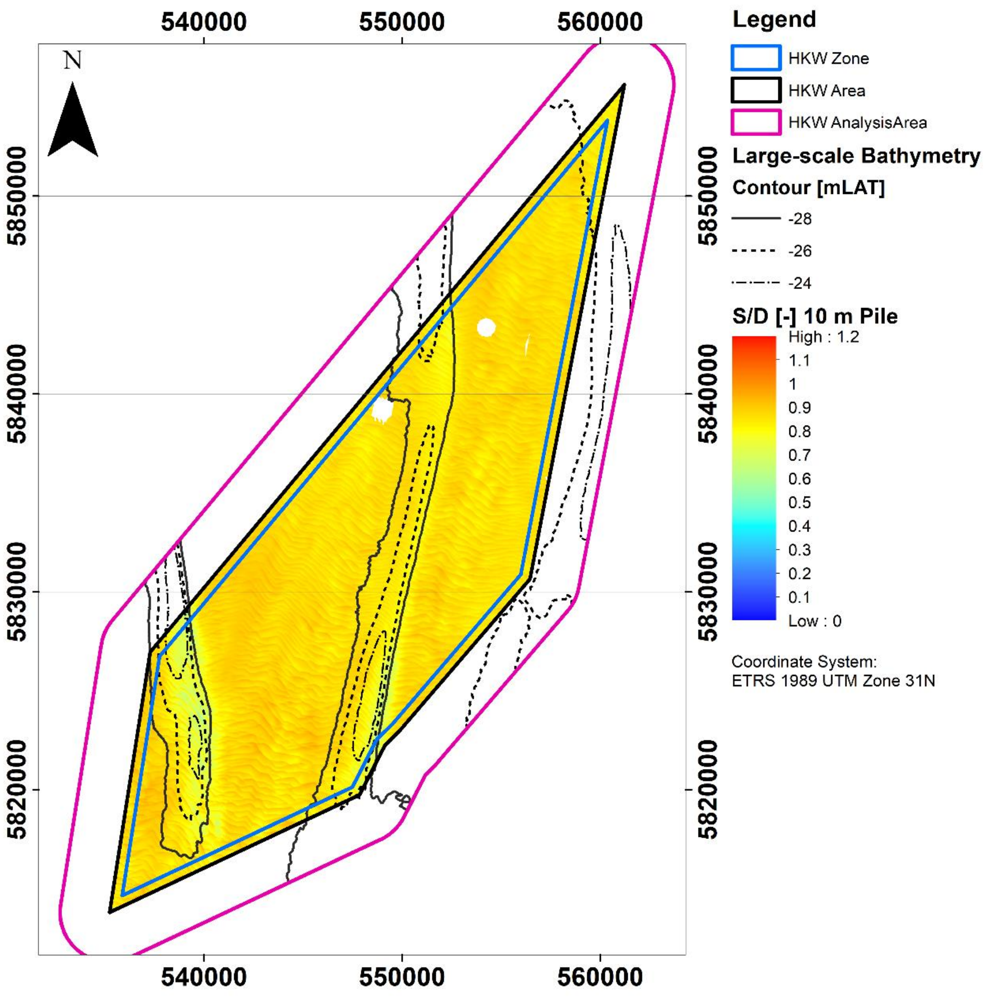


Scour predictions for HKW

- Monopiles: 0.4 – 1.1 times the pile diameter
  - Bigger piles → relatively less scour (but more in absolute sense)
  - Larger sediment → larger prediction bandwidth
- Jackets: 3 – 7 m scour
- GBS: no estimate given, scour protection advised

	d_{50} = 150 µm	d_{50} = 300 µm	d_{50} = 450 µm
D_{pile} = 8 m	5.2 m – 8.2 m (S/D = 0.7 – 1.0)	5.2 m – 8.4 m (S/D = 0.7 – 1.1)	4.9 m – 8.4 m (S/D = 0.6 – 1.1)
D_{pile} = 10 m	5.7 m – 9.7 m (S/D = 0.6 – 1.0)	5.6 m – 9.9 m (S/D = 0.6 – 1.0)	5.2 m – 9.9 m (S/D = 0.5 – 1.0)
D_{pile} = 12 m	5.9 m – 11.1 m (S/D = 0.5 – 0.9)	5.6 m – 11.3 m (S/D = 0.5 – 0.9)	5.0 m – 11.2 m (S/D = 0.4 – 0.9)



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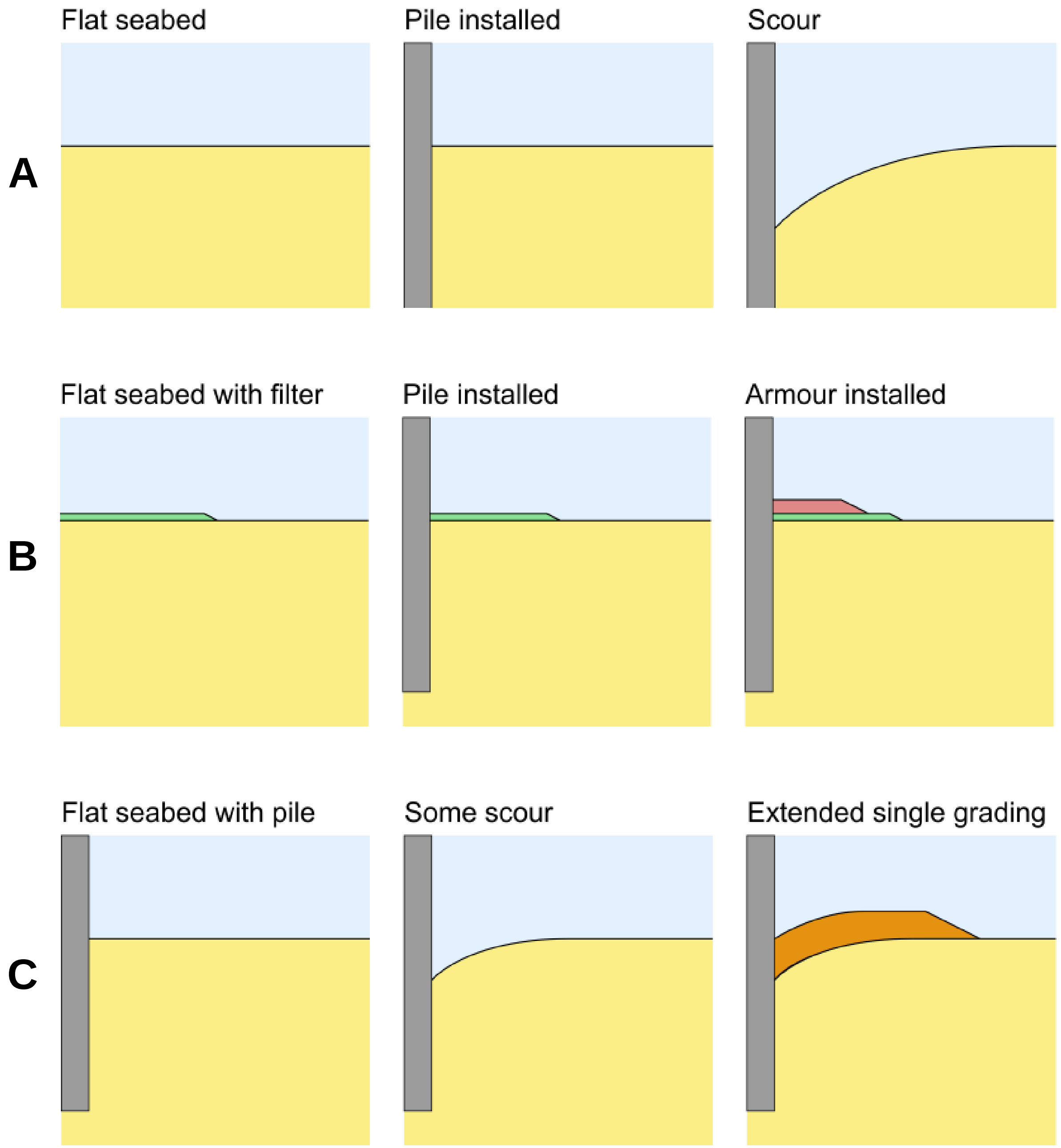
Dealing with scour: mitigation scenarios

Dealing with scour

- Entire HKW site is susceptible to scour
- Mitigation strategies:
  A. Accept scour (adjust foundation design)
  B. Apply scour protection
  C. Hybrid: monitor and react

- Note: consider other interfaces when selecting mitigation strategy, e.g.:
  - Eigenfrequency changes
  - Cable touchdown and free span
  - Corrosion protection system



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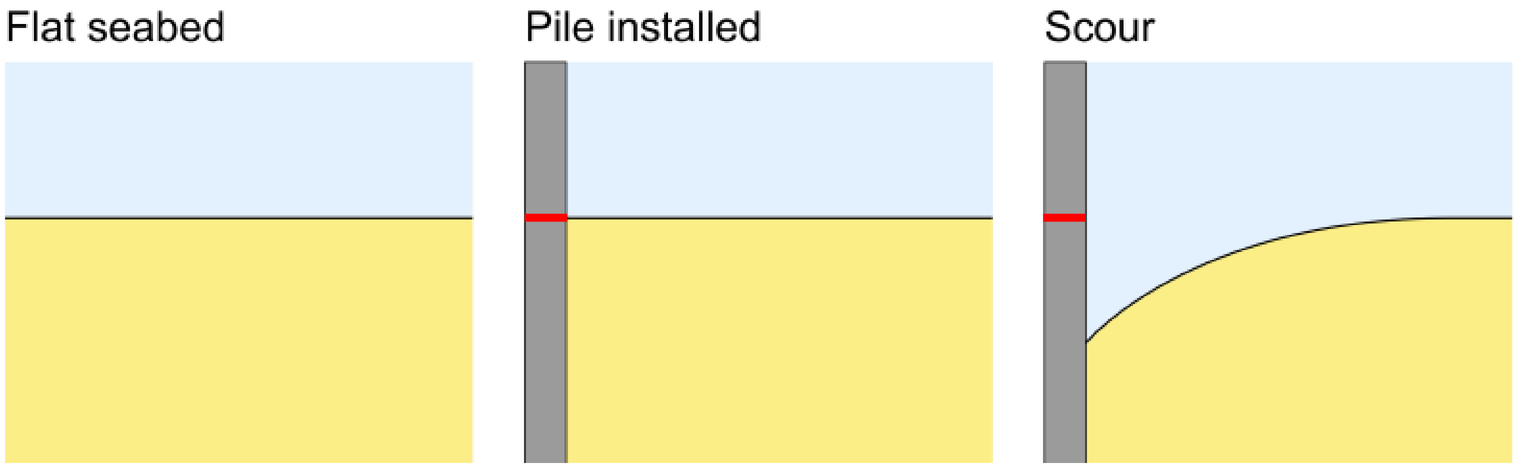
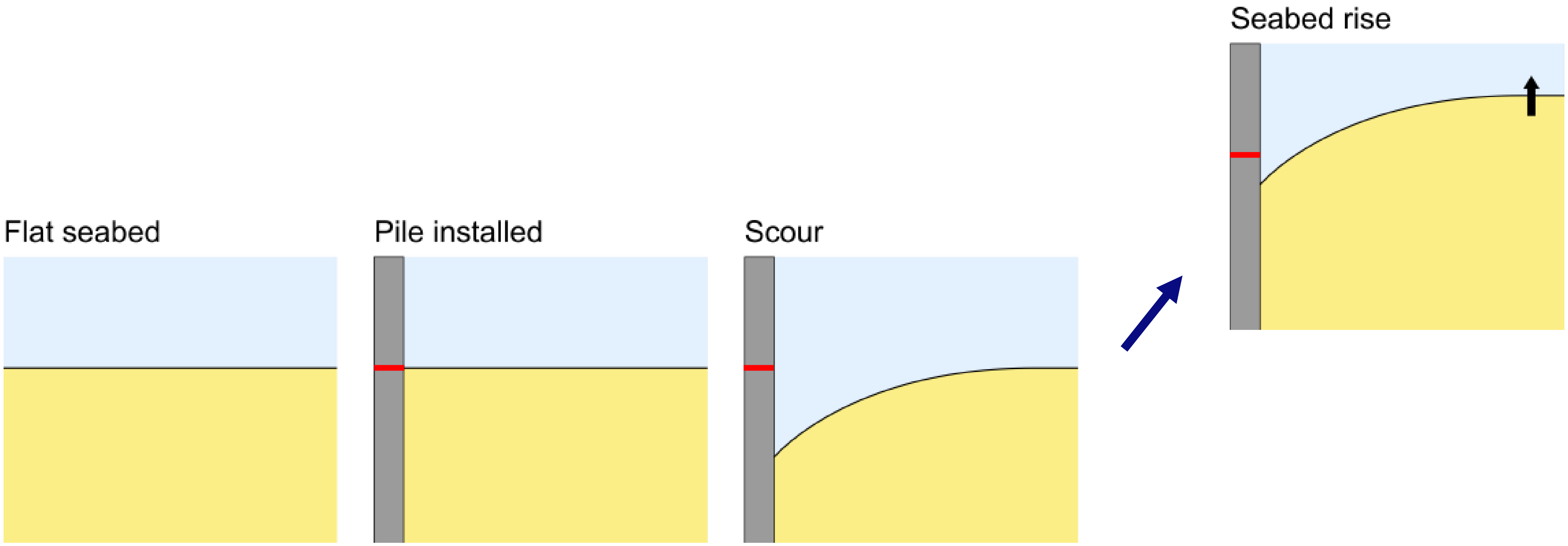
Scour & morphology in strategy A (allow scour)



** cables left out of drawings for simplicity*

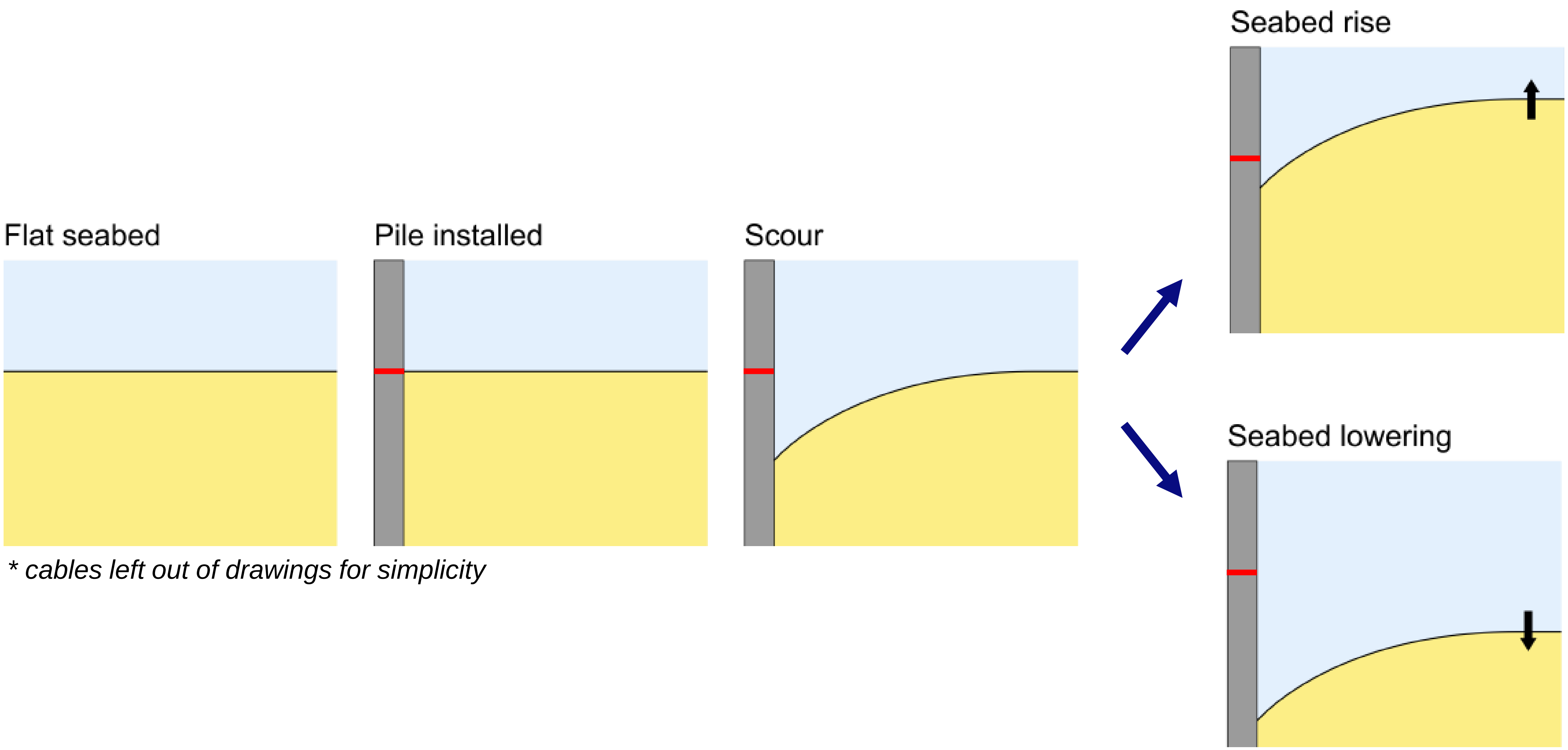
Scour & morphology in strategy A (allow scour)



** cables left out of drawings for simplicity*

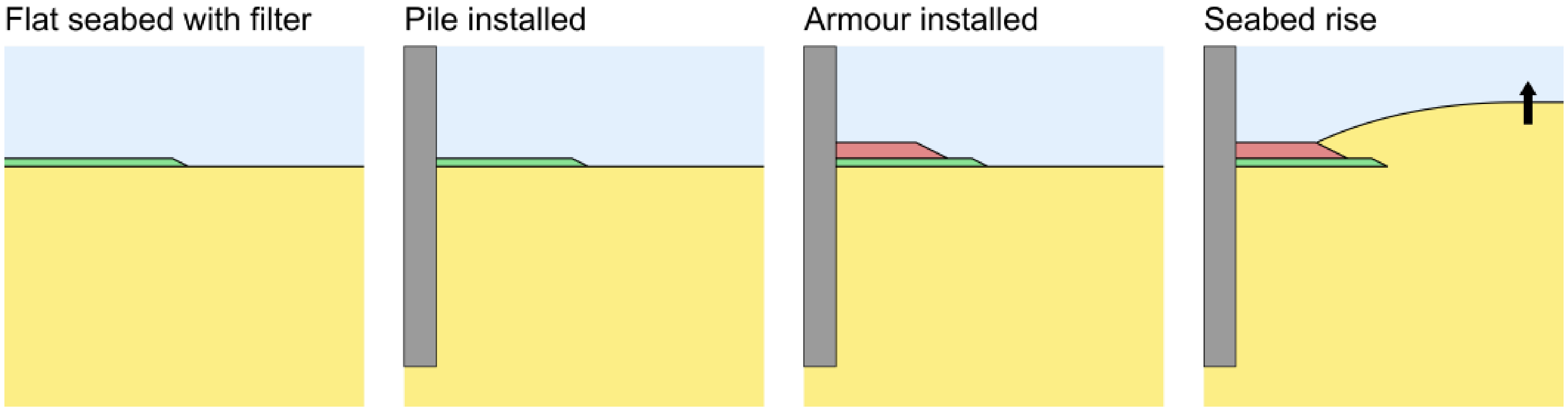
Deltares

Scour & morphology in strategy A (allow scour)



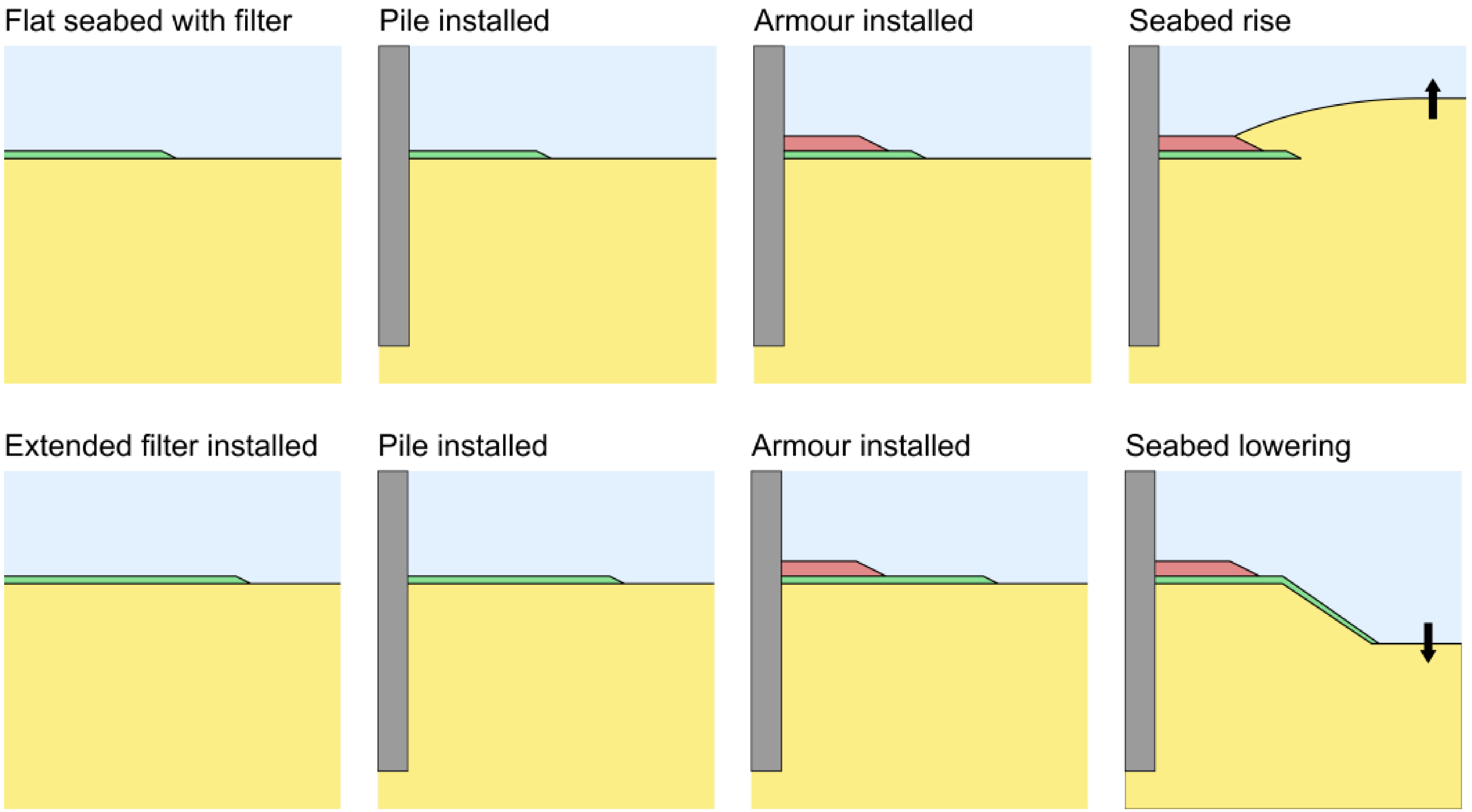
** cables left out of drawings for simplicity*

Scour & morphology in strategy B (scour protection)



** cables left out of drawings for simplicity*

Scour & morphology in strategy B (scour protection)



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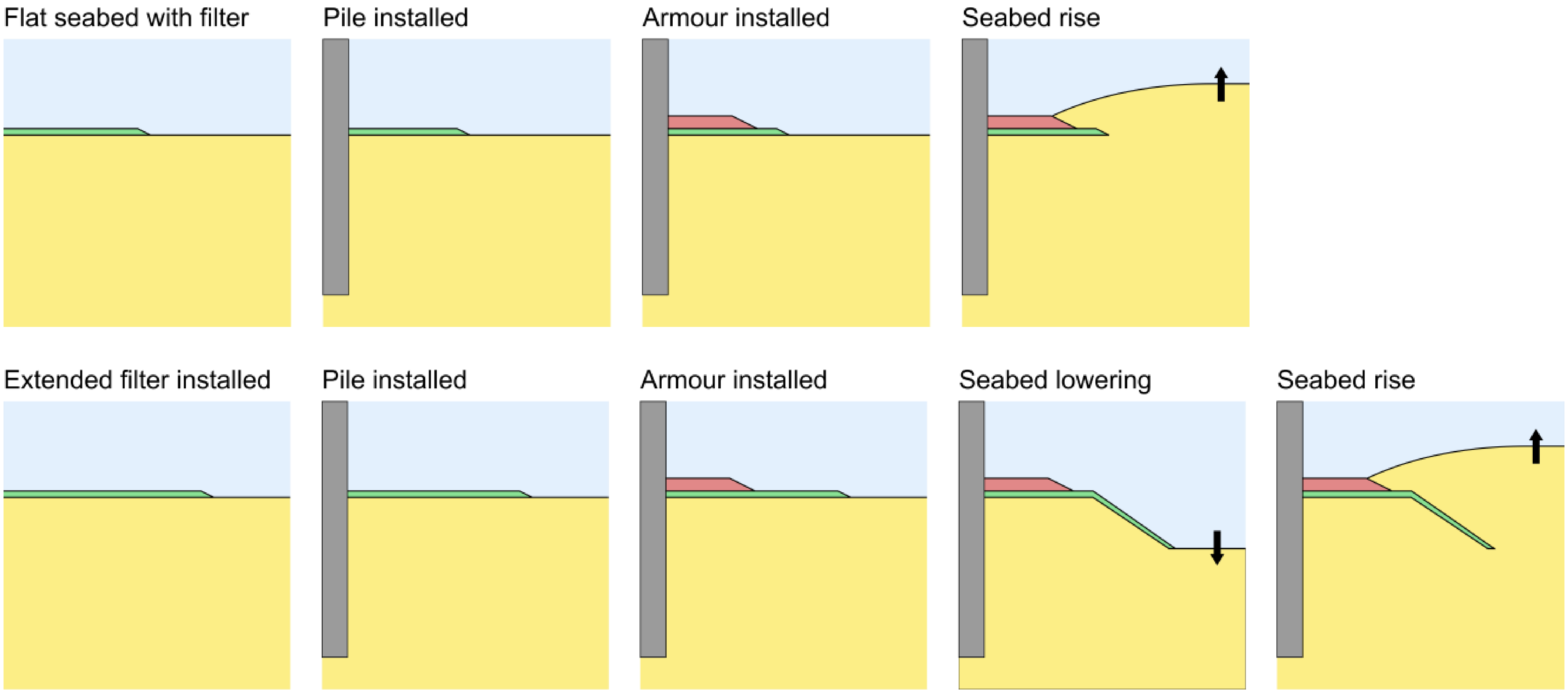
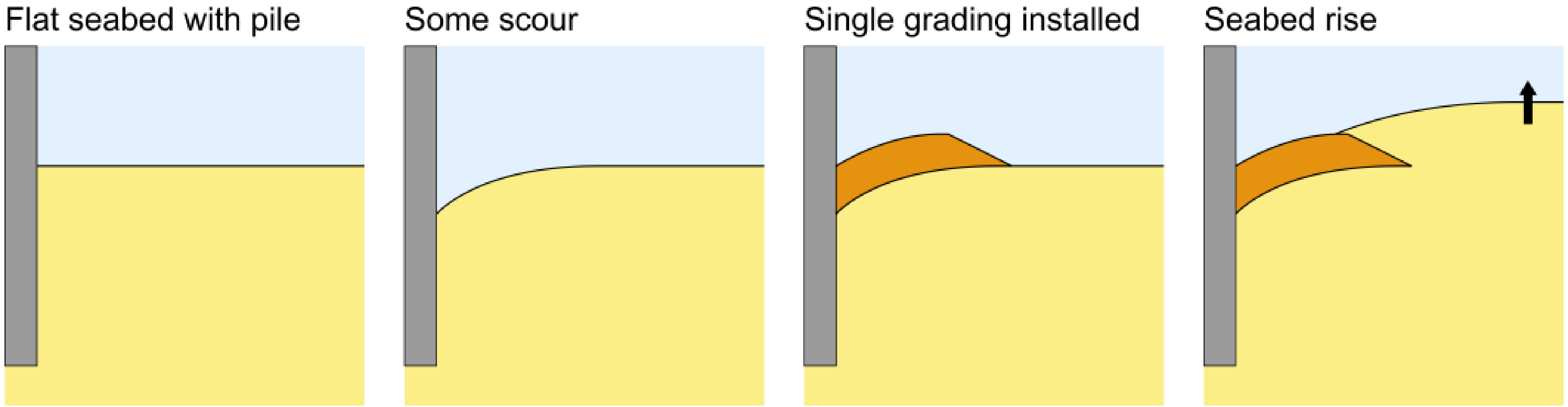
Scour & morphology in strategy B (scour protection)



Scour & morphology in strategy C (hybrid)



* cables left out of drawings for simplicity

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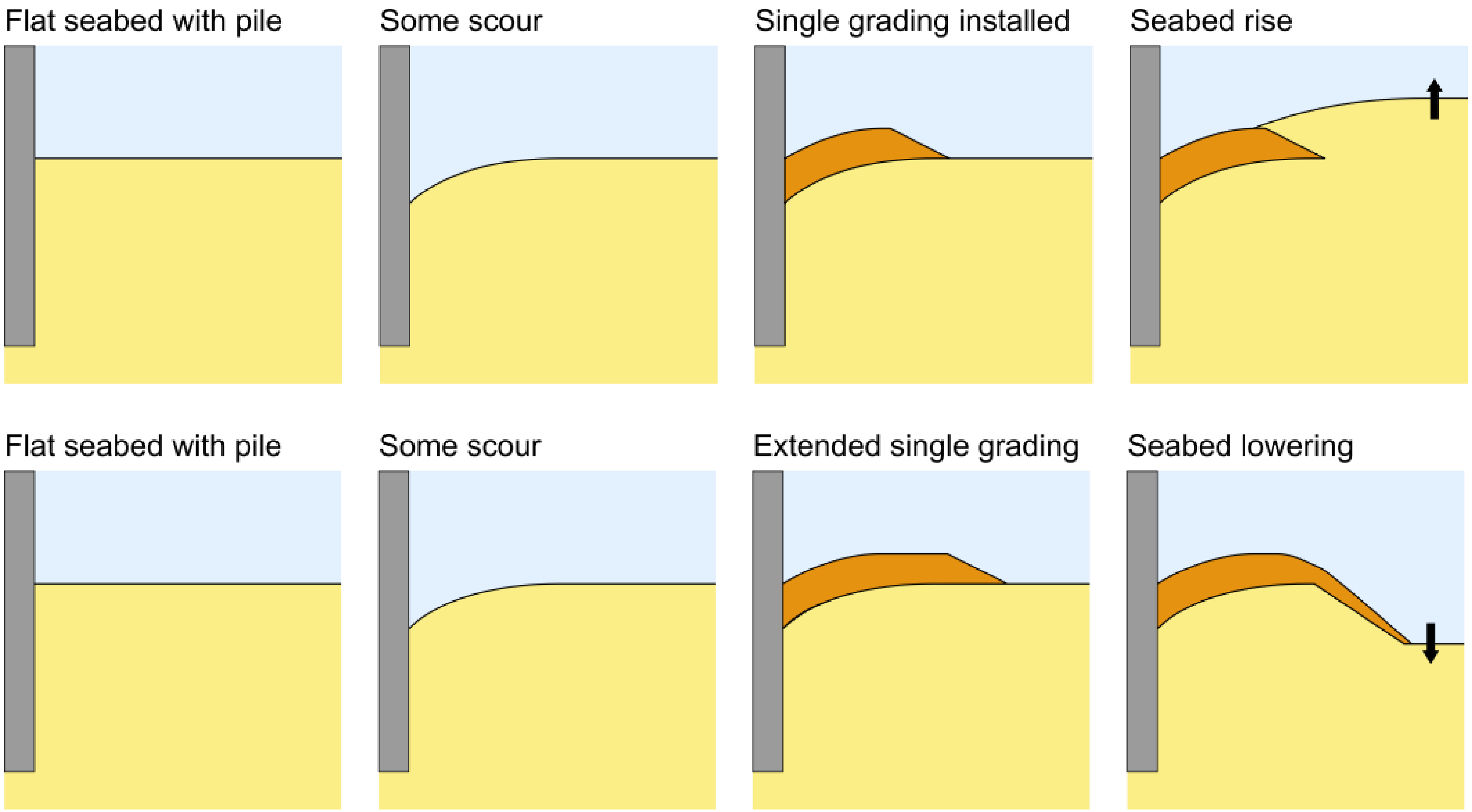
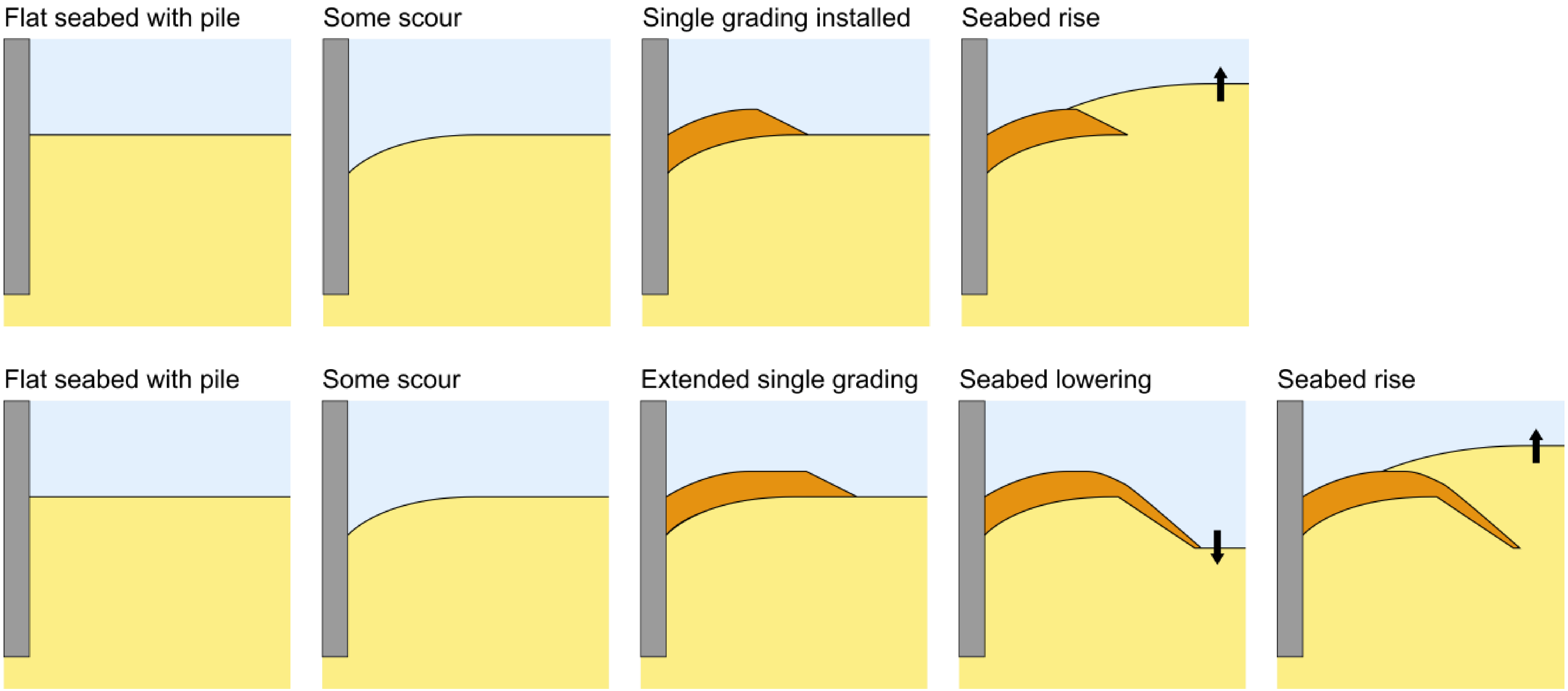
Scour & morphology in strategy C (hybrid)



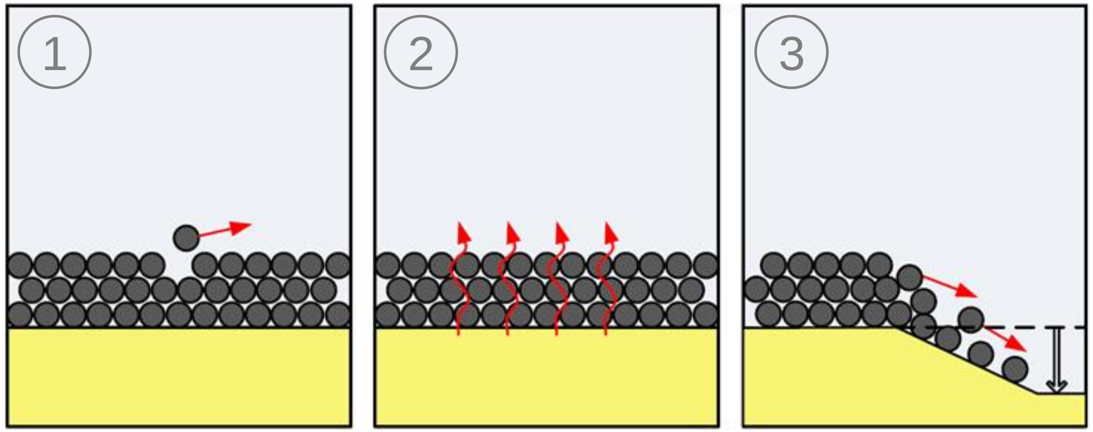
Scour & morphology in strategy C (hybrid)

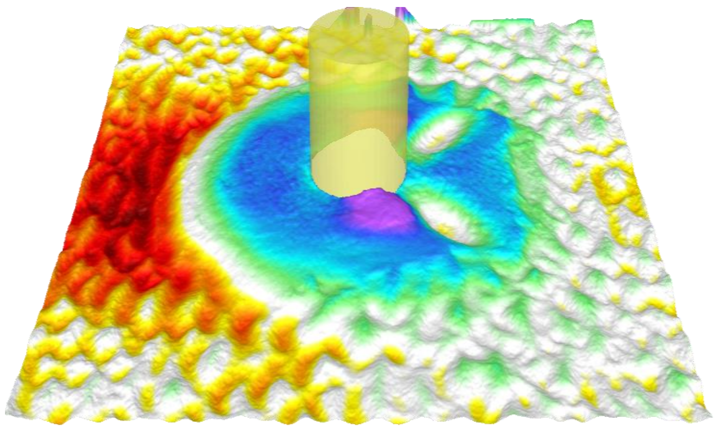


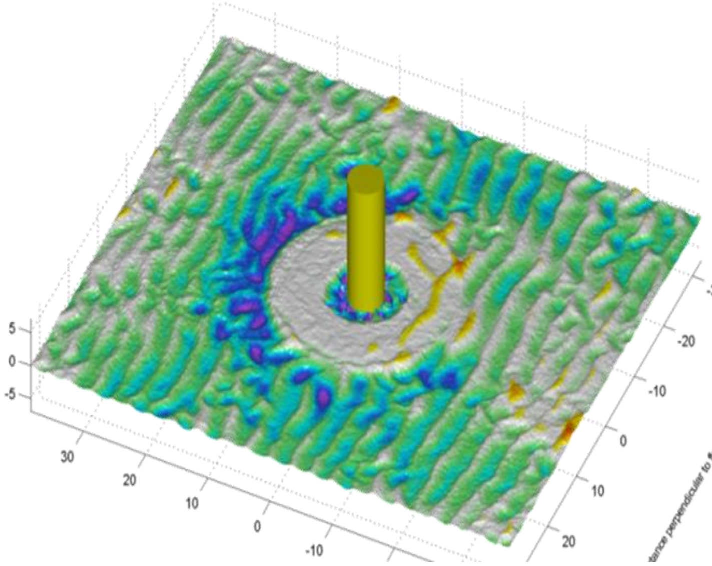
Designing a scour protection

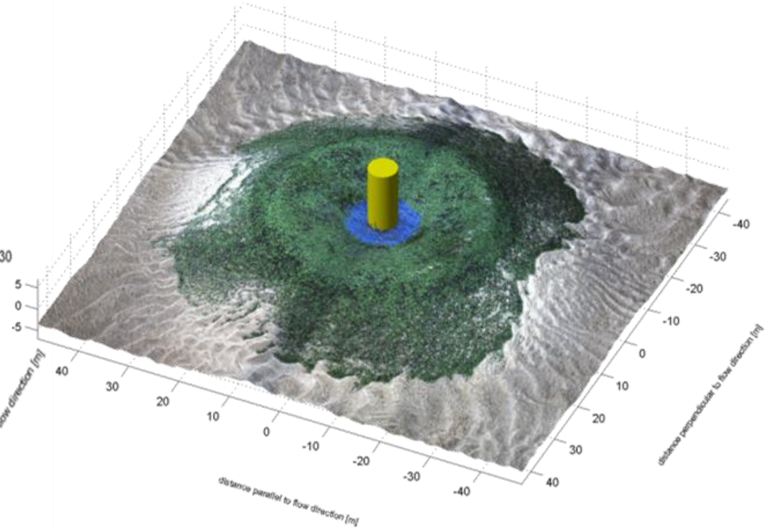
Scour protection requirements

1. External stability
2. Interface stability
3. Flexibility
4. Ecological impact / Nature Inclusive Design









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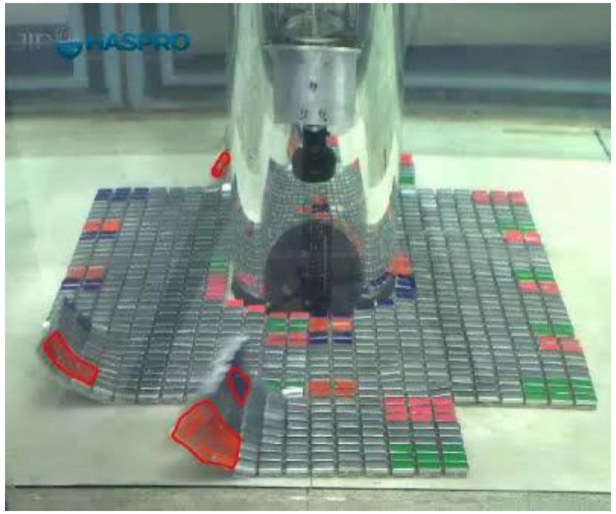
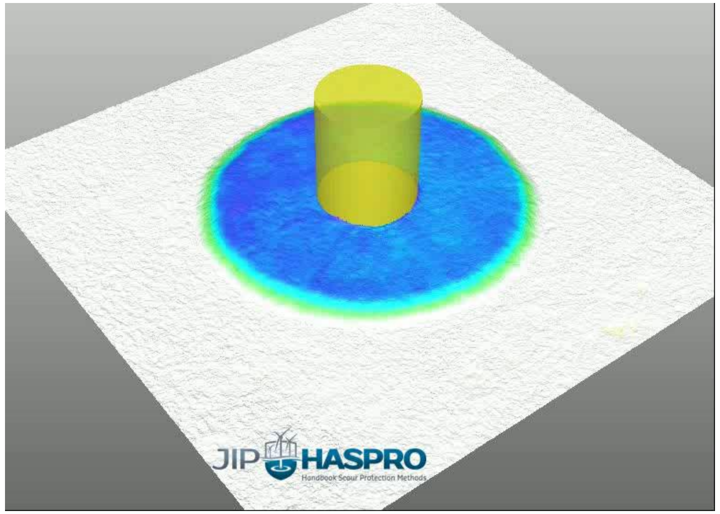
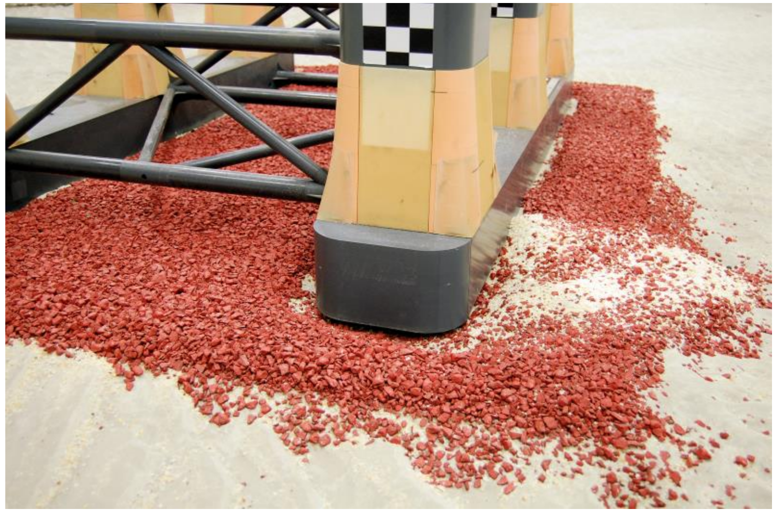
Scour protection requirements – external stability

- Design considerations:
  - Failure: gradual vs. instantaneous
  - Maintenance possible?
  - Ease of installation







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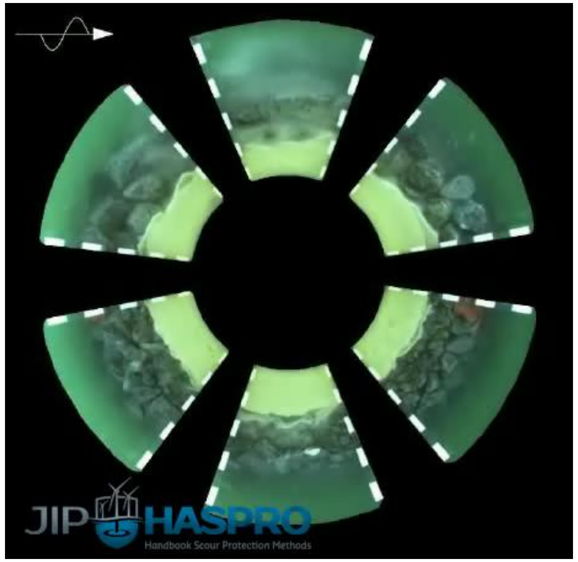
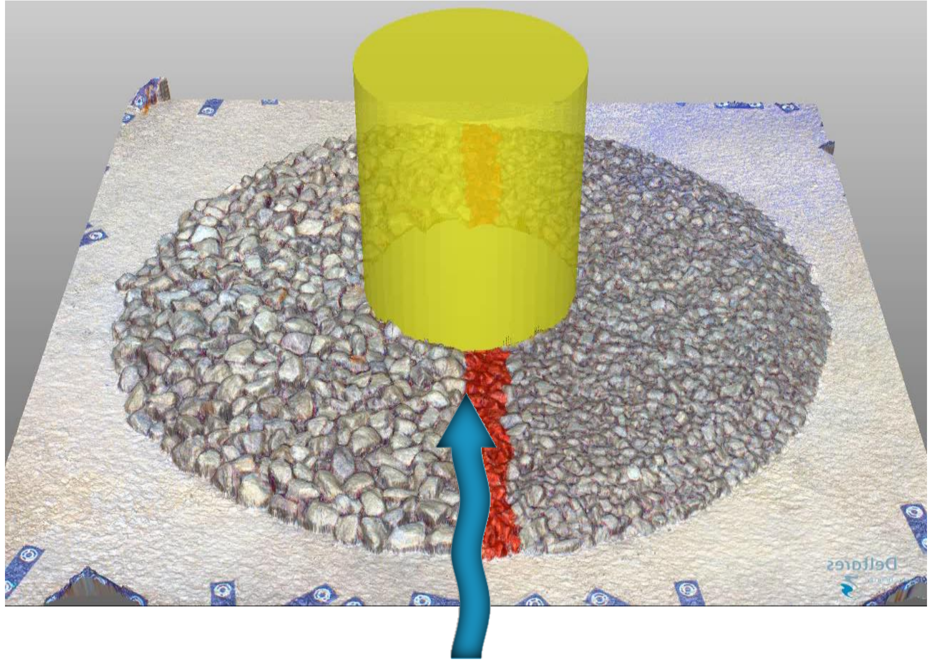
Scour protection requirements – interface stability

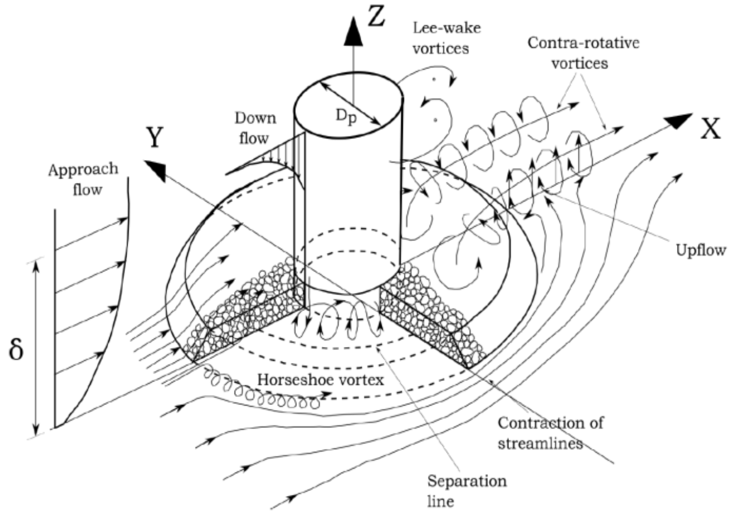
- Winnowing: sand loss through protection
- Solution: filter layer or sufficient thickness (single-grading)
- Highest potential close to structure: check connection (larger elements)
- Sometimes installation effects are mistaken for winnowing → perform as-built survey as soon as possible

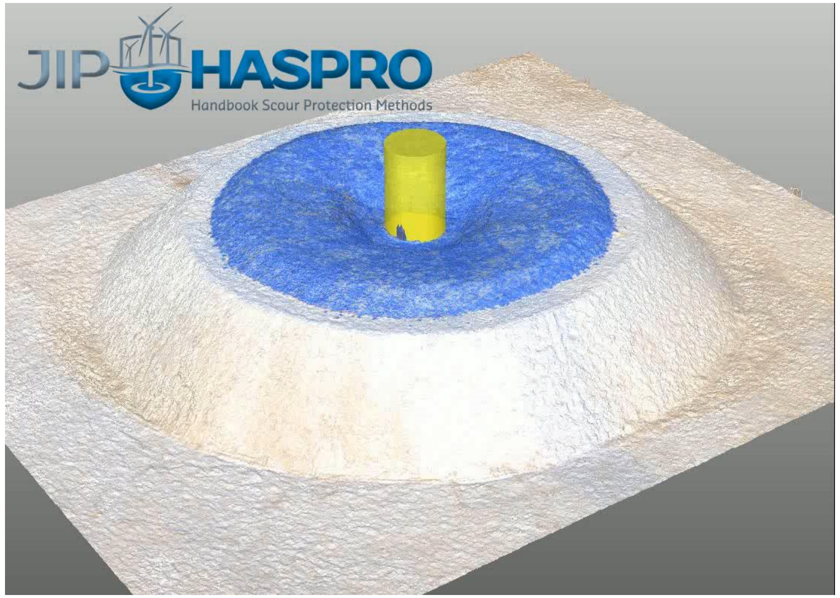


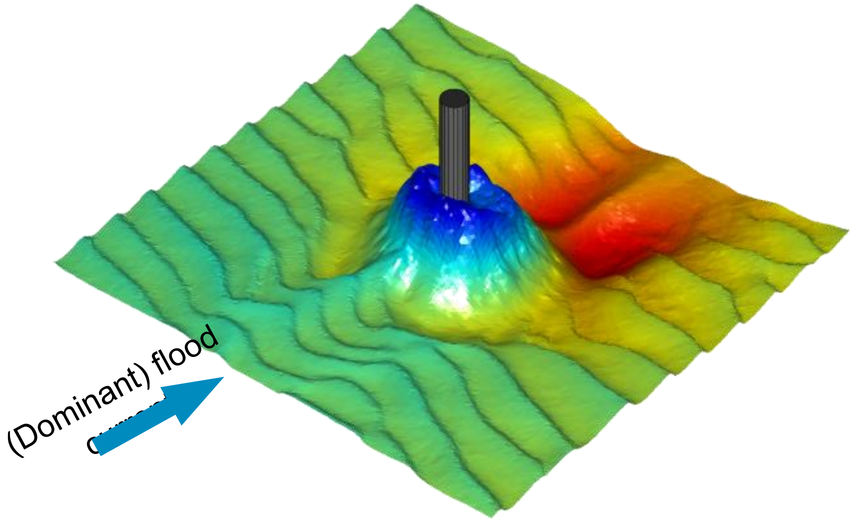


Scour protection requirements – flexibility

- Lowering due to edge scour or morphodynamics
- Typical solution: increased scour protection extent
- Loose rock: formulae exist to calculate required volume
- Watch out for instantaneous failure (e.g. sliding/rolling of elements)







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Scour protection requirements – nature inclusiveness

- Many potentially eco-friendly measures exist
- Check eco-effectiveness → not all solutions work everywhere
- Check stability → not all elements are stable in HKW
- Check impact on scour protection

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Scour protection suitability in HKW

Scour Protection Method	B_S	B_R	B_L	C_S	C_R	C_L
Statically stable, loose rock	+	+	-	--	--	--
Dynamically stable loose rock	++	++	+	-	-	-
Dynamically stable, single graded	+	+	+	+	+	+
Artificial vegetation	0	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 of rubber tyres	0	0	0	+	+	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

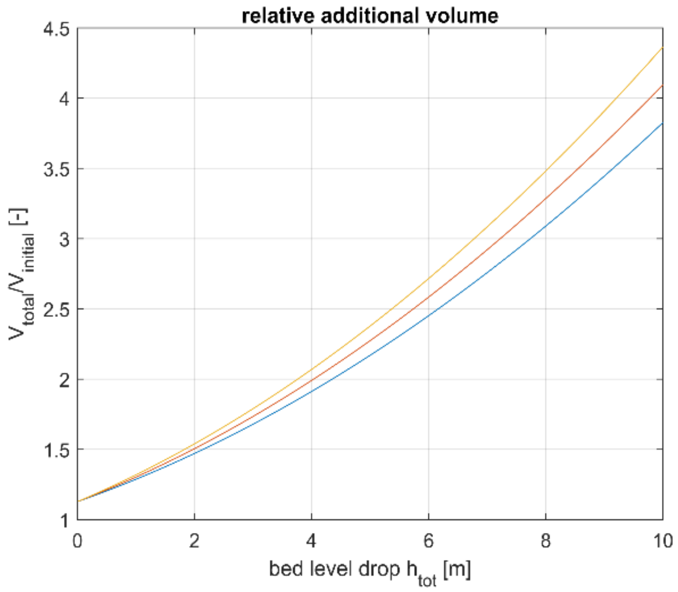
C_S: Monitor & react, stable seabed

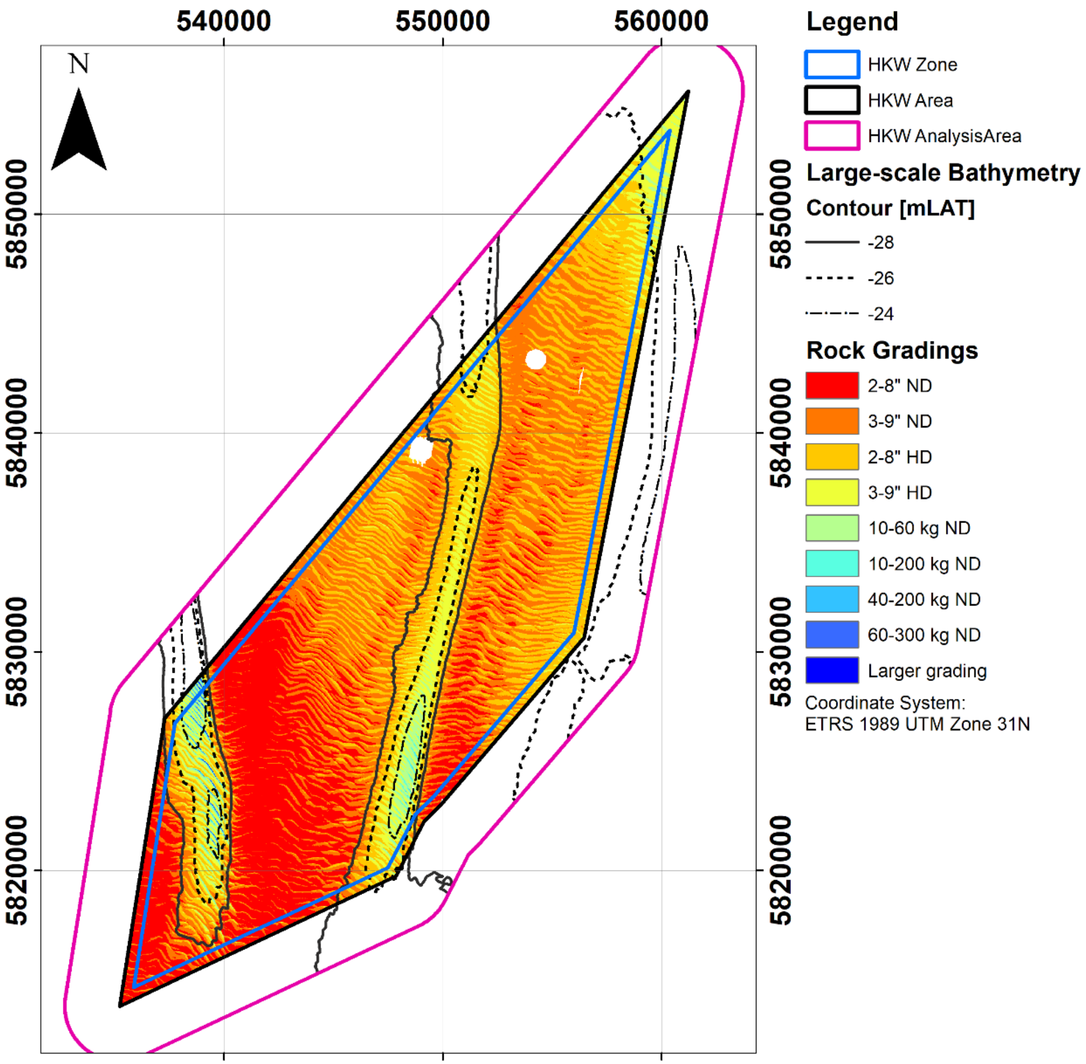
C_R: Monitor & react, rising seabed

C_L: Monitor & react, lowering seabed

Indicative loose rock scour protection layouts

- Loose rock protections most commonly applied
- Large database allows for estimating required gradings
- Dimensions depend on expected morphological bed level drop and edge scour → micro-siting of foundation can save large rock volumes





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Cable routing in morphodynamic areas

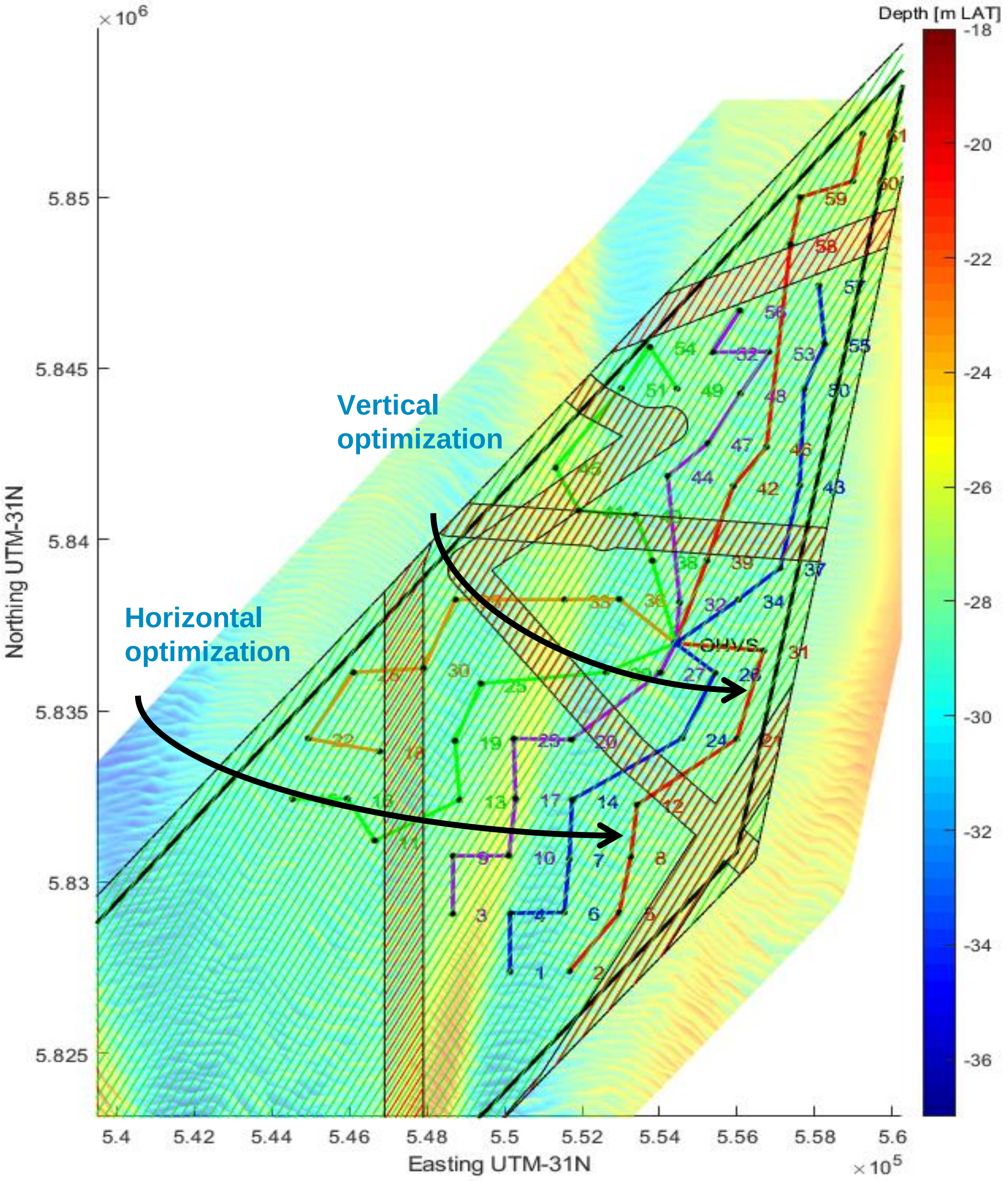
Cable routing approach

Step 1: Overall wind farm cable layout

- Power capacity (WTGs per string)
- Minimizing crossings
- Other constraints (UXOs, wrecks, wind farm boundaries)

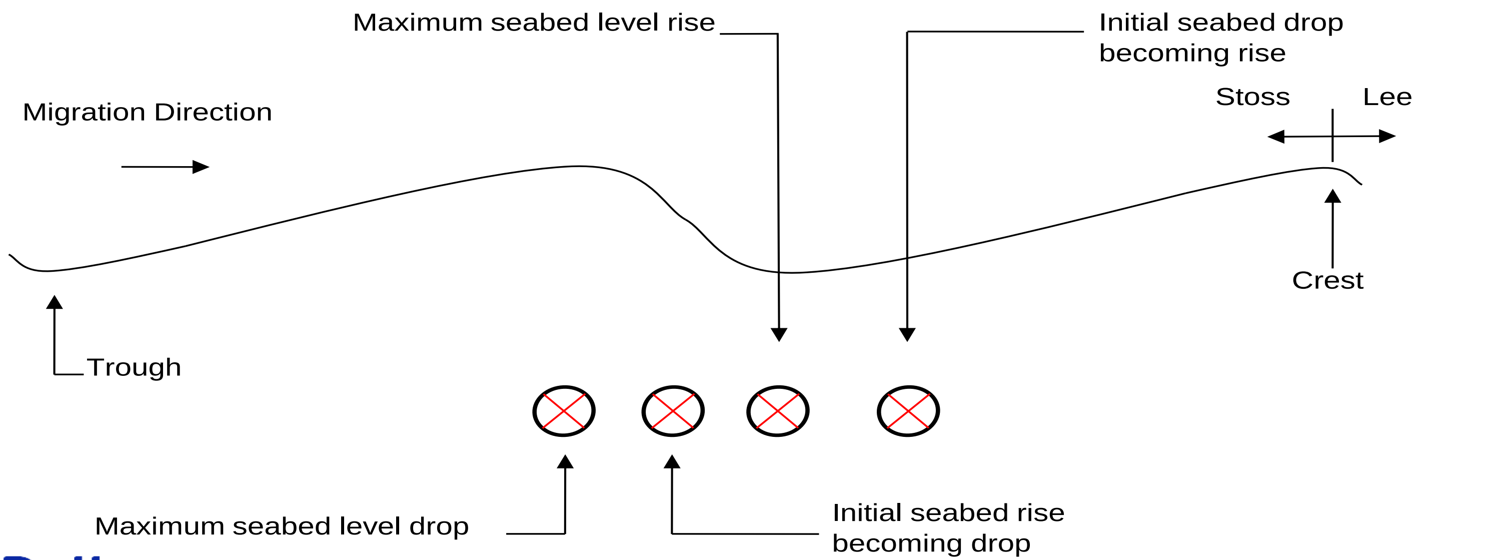
Step 2: Optimizing individual inter-array cables

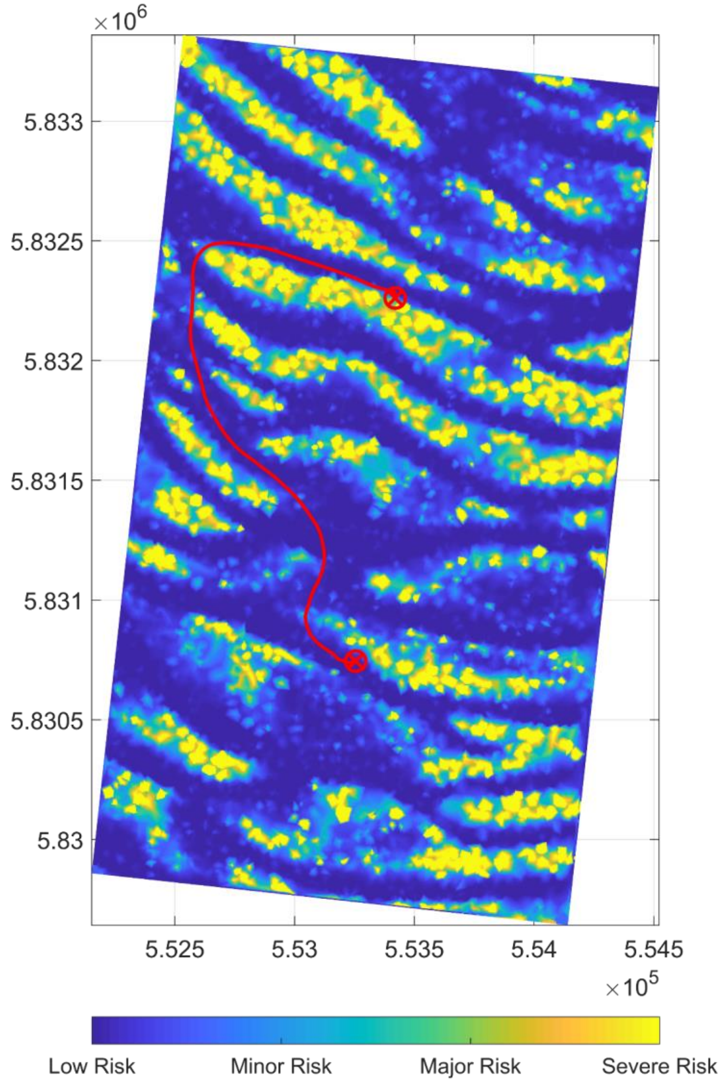
- Accounting for seabed morphodynamics
- Vertical optimization (anticipating changes in burial depth over lifetime)
- Horizontal optimization (avoiding dynamic areas)



Optimization examples

- Vertical optimization: anticipate seabed level change by using variable burial depth
- Horizontal optimization: avoid high-cost / high-risk areas
- Ultimately economic exercise (e.g. cable cost, burial restrictions)
- Rule of thumb: avoid sand wave stoss side (largest bed level drop)





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Key take-aways

Key take-aways

- The entire HKW site is susceptible to (significant) scour development
- Scour depths depend on foundation type, needs to be considered in the design
- Three scour mitigation strategies can be considered:
  - A. Accept scour (and adjust foundation design)
  - B. Apply scour protection from the beginning
  - C. Hybrid: monitor and react when needed
- Many scour protection solutions are possible (depending on the mitigation strategy)
- Scour protection design should consider seabed level change
  - Micro-siting of foundations can save large rock volumes
- Take morphological changes into account when optimizing cable routes
  - Rule of thumb: try to avoid sand wave stoss side

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