Understanding the present-day morphodynamics of Ameland Inlet - part 2

Kustgenese 2.0, product ZG-B04

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Keywords
Kustgenese 2.0; Ameland inlet; the Netherlands; coastal morphodynamics; ebb-tidal delta

Summary

The Kustgenese 2.0 program has resulted in unique high-resolution bed surveys of Ameland inlet. These measurements allow us to (1) investigate, analyse and better understand the morphodynamic changes on its ebb-tidal delta, and (2) to investigate the half-yearly changes in sediment budget. A time series of near yearly ebb-tidal delta bathymetries over the past decade, displays how initial small-scale perturbations in the central part of the ebb-tidal delta (the ebb-chute and shield systems) develop, grow, migrate and start to dominate the developments of the entire ebb-tidal delta. The realisation that small-scale perturbations result in ebb-tidal delta scale relocation of channels and shoals has important implications for the future morphodynamic modelling of the area. These morphodynamic models will have to contain sufficient resolution and detailed processes to capture such distortions.

The high-resolution multi-beam data obtained in Ameland inlet provides valuable information on the prevailing sediment transport directions. Such knowledge is essential for the future validation of our process-based sediment transport models. Based on these surveys, we are able to construct sediment transport patterns for the proximal part of the ebb-tidal delta; Borndiep is primarily ebb-dominant and Westgat flood-dominant. These transport directions correspond to the sediment transport patterns derived from the morphodynamic changes. Correspondences in repeat surveys on the ebb-tidal delta confirm that (1) bedform asymmetry is an indicator for bedform migration, and (2) coherent, consistent, bedform fields occur through the various surveys.

References

Version	Date	Author	Initials	Review	Initials	Approval	Initials
1.0	Dec. 2018	Edwin Elias		Bart Grasmeijer		Dirk-Jan Walstra	

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Samenvatting; de recente morfologische ontwikkelingen van het zeegat van Ameland – deel 2.

Achtergrond

Het Nederlandse kustbeleid streeft naar een structureel veilige, economisch sterke en aantrekkelijke kust. Dit wordt bereikt door het onderhouden van het gedeelte van de kust dat deze functies mogelijk maakt; het Kustfundament. Dit gebeurt door middel van zandsuppleties; het suppletievolume is ongeveer 12 miljoen m^3/jaar sinds 2001.

In 2020 neemt het Ministerie van Infrastructuur en Waterstaat een beslissing over een eventuele aanpassing van het suppletievolume. Het Kustgenese 2.0 programma heeft als doel hiervoor de kennis en onderbouwing te leveren. Deltares richt zich in opdracht van Rijkswaterstaat binnen het project Kustgenese 2.0 op de volgende hoofdvragen:

1. Is er een andere zeewaartse begrenzing mogelijk voor het kustfundament?
2. Wat is het benodigde suppletievolume om het kustfundament te laten meegroeien met zeespiegelstijging?

Deze twee vragen beslaan het grootste gedeelte van het onderzoek binnen het project. Een derde belangrijk onderwerp wat daarbij ook behandeld zal worden is:

3. Wat zijn de mogelijkheden voor de toepassing van grootschalige suppleties rond zeegaten?

Deze studie maakt deel uit van het deelproject ‘Systeemkennis Zeegaten’ en is een vervolg op een eerder rapport uit 2017 (Elias, 2017a). Het vergroten van onze kennis over zeegatsystemen is belangrijk om vragen te kunnen beantwoorden over de zandvraag van de getijbekkens van de Waddenzee. Deze zandvraag kan gezien worden als een belangrijke verliespost voor zand uit het kustfundament, en is daarom een belangrijke parameter om het benodigde suppletievolume te berekenen wat nodig is voor het onderhoud van het kustfundament. Daarnaast is systeemkennis van getijbekkens ook nodig om vragen te beantwoorden over de mogelijkheden van grootschalige ingrepen rondom zeegaten.

Het deelproject ‘Systeemkennis Zeegaten’ draagt dus bij aan het beantwoorden van de tweede en de derde hoofdvraag van het project Kustgenese 2.0. Dit gebeurt door een combinatie van literatuurstudies, analyse van (veld)data en modelstudies en –ontwikkeling.

De hoofdvragen van Kustgenese 2.0 zijn vertaald in meerdere onderzoeksvragen. De onderzoeksvragen waar het deelproject ‘Systeemkennis Zeegaten’ zich op richt zijn:

- SVOL-01 Wat zijn de drijvende (dominante) sedimenttransportprocessen en -mechanismen en welke bijdrage leveren ze aan de netto import of export van het bekken?
- SVOL-02 Hoe beïnvloeden de morfologische veranderingen in het bekken en op de buitendelta de processen en mechanismen die het netto transport door een zeegat bepalen? Hoe zetten deze veranderingen door in de toekomst, rekening houdend met verschillende scenario's voor ZSS?

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- SVOL-03 Wordt de grootte van de netto import of export beïnvloed door het aanbod van extra sediment in de kustzone of de buitendelta?
- SVOL-04 Wat zijn de afzonderlijke bijdragen van zand en slib aan de sedimentatie in de Waddenzee, als gevolg van de ingrepen en ZSS? En wat betekent dat voor het suppletievolume?
- INGR-01 Hoe beïnvloedden de ontwikkelingen van een buitendelta (inclusief de verandering van omvang) de sedimentuitwisselingen tussen buitendelta, bekken en aangrenzende kusten en welke consequenties en/of randvoorwaarden levert dat voor een suppletieontwerp?
- INGR-02 Is het, op basis van beschikbare kennis van het morfologisch systeem, zinvol om grootschalige suppleties op buitendeltas te overwegen?

De huidige morfologische veranderingen in het zeegat van Ameland .

De analyses uitgevoerd in deze rapportage bestaan uit 2 delen. In het eerste deel, richten we ons op de grootschalige morfologische veranderingen; het begrijpen van de huidige morfologische veranderingen op de schaal van de buitendelta. Hiervoor gebruiken we de beschikbare, gebiedsdekkende (buitendelta) bodemdata. De basis hiervoor word gevormd door de driejaarlijkse Vaklodingen. Deze metingen zijn aangevuld met de projectmetingen die door Rijkswaterstaat ten behoeve van het programma Sterkte & Belastingen Waterkeringen (SBW) zijn uitgevoerd (2006-2010) en de halfjaarlijkse metingen die vanuit het Kustgenese 2.0 project worden ingewonnen. Al deze datasets zijn op soortgelijke manier ingewonnen, verwerkt en opgeslagen. Dit geeft ons de beschikking over een dataset met hoge resolutie, in tijd en ruimte. Analyse van deze data verschaft een uniek beeld van de processen die ten grondslag liggen aan de geobserveerde morfologische veranderingen.

In dit rapport wordt een belangrijke stap gezet in het beter begrijpen van de morfologische processen die spelen binnen het zeegat van Ameland. De huidige grootschalige bodemveranderingen van de buitendelta worden gekenmerkt door de vorming, groei en migratie van initieel kleinschalige bank-geul (ebb-chute and -shield) systemen. Deze hebben het zeewaartse deel van de hoofdgeul (Akkepollegat) vervormd, weggeduwd en grotendeels dichtgedrukt. Door de afgenomen efficiëntie van deze geul is het getij-gedreven zeewaarts transport naar de rand van de buitendelta gereduceerd en domineert nu het golf-gedreven landwaarts transport. De buitenrand van de buitendelta neemt hierdoor in hoogte af en het vrijgekomen sediment wordt landwaarts afgezet. Herverdeling van dit sediment, plaatselijke kustlijnerosie door geulvorming, of juist kustlijnaanzanding door bankaanlanding heeft verstrekkende gevolgen voor het beheer van de eilandkust.

De constatering dat de huidige geobserveerde grootschalige veranderingen van de gehele buitendelta zijn geïnitieerd door kleinschalige verstoringen heeft belangrijke implicaties voor toekomstige voorspellingen en voor proces-gebaseerde modellen die hiervoor worden gebruikt. Voor lange-termijn modelering (>5 jaar) zijn lage resolutie modellen nodig om dit rekentechnisch behapbaar te maken. Dit is eigenlijk in conflict met de hoge resolutie benodigd om de verstoringen te reproduceren.

De halfjaarlijkse metingen van de buitendelta stellen ons in staat de morfologische veranderingen beter te kwantificeren, bijvoorbeeld door het opstellen van een gedetailleerde sedimentbalans. Een middellange termijn analyse gebaseerd op de 2005-2016 data geeft een netto bodemverandering van +6.5 miljoen m^3 (mcm) aanzanding. De sedimentbalansen over de periode 2016-2017 en 2017-2018 geven jaarlijkse netto veranderingen van respectievelijk +0.9 mcm en -1 mcm. Deze netto veranderingen zijn klein ten opzichte van de bruto verandering van 37-38 mcm/jaar. De halfjaarlijkse meting stelt ons in staat een eerste analyse uit te voeren over het verschil in morfologische verandering gedurende de zomer- versus winterperiode. De winterperiode vertoont hierbij significant grotere veranderingen en deze verschillen kunnen niet worden verklaard door het verschil in dekking tussen de datasets. Waarschijnlijk ligt de verklaring in de verschillen in golfenergie. Gedurende de winterperiode is er meer golfenergie aanwezig dan in de zomerperiode, waardoor in de winter de golf-gedreven transporten belangijker zijn. De beduidend grotere transporten tijdens de winterperiode leiden dan ook tot de hypothese dat golf-gedreven transporten de huidige morfologische ontwikkelingen op de buitendelta van Ameland domineren. Op zich is dat een logische conclusie, omdat er zich sinds 2005 relatief grote, ondiepe banken op de buitendelta hebben gevormd waarop golfbreking en golfgedreven sediment transporten kunnen optreden.

Het tweede deel van dit rapport richt zich op de analyse van bodemvormen. Verschillende hoge resolutie Multibeam echo-sounding -Mbes- datasets zijn ingewonnen tijdens de Kustgenese 2.0 campagne. Daarnaast zijn er verschillende aanvullende datasets beschikbaar vanuit metingen voor het onderhoud van de westkust van Ameland. Een analyse van beide Mbes datasets laat zien dat er grootschalige gebieden met bodemvormen voorkomen in de geulen Westgat en Borndiep. Op de buitendelta, geven de verschillende dataseries consistente resultaten voor hoogte, lengte en asymmetrie van de bodemvormen. Deze uitspraak geldt zowel voor de korte termijn van enkele dagen, maar ook op de langere termijn als we de Kustgenese data vergelijken met een 2012 dataset. De asymmetrie en verplaatsing van de gemeten bodemvormen zijn dan ook een indicatie voor de richting van het (bodem)transport. Op basis hiervan blijkt de uitstroom van het Borndiep richting de buitendelta eb-dominant (d.w.z. transport richting de buitendelta) en is het Westgat vloed-dominant (transport richting het Borndiep).

De metingen in het centrale deel van Borndiep, uitgevoerd door 9 raaien over 1 getij te varen, geven een minder duidelijk beeld. De herhaalde metingen laten zien dat in de keel van het Borndiep, vooral direct langs de kust van Ameland, de bodemvormen tijdens de getijcyclus in asymmetrie en migratie-richting kunnen veranderen. Deze conclusie lijkt in tegenspraak met de bodemvorm-analyse voor de vakken op de buitendelta en vergt nader onderzoek. Mogelijke oorzaken voor deze andere dynamiek zijn mogelijk een interactie met de aanwezige bestortingen of de grotere stroomsnelheden.

Een vertaling van de inzichten naar de onderzoeksvragen van Kustgenese 2.0
Met de inzichten in dit rapport kunnen we de onderzoeksvragen als volgt, gedeeltelijk, beantwoorden:

[SVOL-01] – Dit onderzoek geeft een uniek beeld van de sediment-bypassing processen op de buitendelta en draagt daarbij direct bij aan de beantwoording van de vraag. De vorming van grote banken en ondiepten op de buitendelta, heeft tot gevolg gehad dat golven in

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toenemende mate een bijdrage leveren aan opgetreden veranderingen. De banken verplaatsen zich over het algemeen oostwaarts, richting Ameland, over de buitendelta. Het onderliggende buitendelta platform vertoont een trend van verdieping langs de rand. Golven dragen hier in belangrijke mate bij aan het landwaarts verplaatsen van het sediment. Dit sediment verhoogt het landwaartse deel van Bornrif. Vanuit Bornrif kunnen banken aanlanden op de kust. De netto transporten zijn klein (orde 1 mcm) ten opzichte van de bruto veranderingen (orde 37 mcm). Het grote verschil in bruto verandering tussen de zomer- en winterperiode geeft een eerste indicatie dat golven een belangrijke rol spelen.

[SVOL-02; SVOl-03] – De geobserveerde grootschalige veranderingen van de gehele buitendelta, zijn geïnitieerd door kleinschalige verstoringen. De vorming, groei en verplaatsing van deze verstoringen heeft een rechtstreeks effect op de sedimentuitwisseling tussen buitendelta, kust en bekken. De aanlanding van banken bepaald direct de toevoer van zand naar de kust. De veranderingen in het geulenstelsel kunnen de sedimenttransporten richting het bekken beïnvloeden. Het is niet de verwachting dat onder ZSS de fundamentele processen veranderen. Als onder invloed van ZSS het bekken dieper wordt kan dit wel tot gevolg hebben dat de getijdominantie van het bekken toeneemt. Dit zou dan weer de sediment-bypassing beïnvloeden.

INGR-01, INGR-02 – Een gefundeerde uitspraak over de zin van buitendelta-suppleties is niet rechtstreeks te geven. Wel kunnen we op basis van analyse van de eb-schilden en van de verplaatsing van het Bornrif Bankje, beter begrijpen hoe zandvolumes zich over de buitendelta heen verplaatsen. Dit is een eerste belangrijke stap in het begrijpen van de effecten van grootschalige suppleties. Een belangrijke les is ook dat de huidige ontwikkelingen terug te herleiden zijn naar een initieel zeer kleine verstoring. Dit geeft aan dat grootschalig en kleinschalig gedrag niet per definitie ontkoppeld zijn.

De data en of analyses uitgevoerd in deze studie vormen onderdeel van de programma’s KPP B&O kust, Kustgenese 2.0 en EU Interreg NSR project Building with Nature, werkpakket 1.

Table 1.1 Overzicht onderzoeksvragen Kustgenese 2.0

Code	Onderzoeksvraag	Bijdrage
SVOL-01	Wat zijn de drijvende (dominante) sedimenttransportprocessen en -mechanismen en welke bijdrage leveren ze aan de netto import of export van het bekken?	JA
SVOL-02	Hoe beïnvloeden de morfologische veranderingen in het bekken en op de buitendelta de processen en mechanismen die het netto transport door een zeegat bepalen?	JA
	Hoe zetten deze veranderingen door in de toekomst, rekening houdend met verschillende scenario's voor ZSS?	NEE
SVOL-03	Wordt de grootte van de netto import of export beïnvloed door het aanbod van extra sediment in de kustzone of de buitendelta?	JA
SVOL-04	Wat zijn de afzonderlijke bijdragen van zand en slib aan de sedimentatie in de Waddenzee, als gevolg van de ingrepen en ZSS? En wat betekent dat voor het suppletievolume?	NEE
INGR-01	Hoe beïnvloedden de ontwikkelingen van een buitendelta (inclusief de verandering van omvang) de sedimentuitwisselingen tussen buitendelta, bekken en aangrenzende kusten en welke consequenties en/of randvoorwaarden levert dat voor een suppletieontwerp?	JA
INGR-02	Is het, op basis van beschikbare kennis van het morfologisch systeem, zinvol om grootschalige suppleties op buitendeltas te overwegen?	JA

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Appendices

1 Introduction

Fundamental understanding of the physical processes underlying the behaviour and development of Ameland Inlet can be obtained through numerical (process-based) modelling, and/or the detailed analysis of field data. Field-data analysis can greatly help improve knowledge of the system and processes steering the observed morphodynamic developments. In this report, we provide an overview of the present-day morphodynamic changes at Ameland inlet and an estimate of the sediment transport patterns based on these changes. In addition, we perform a detailed bedform analysis to derive sediment transport directions.

The morphodynamic behaviour of Ameland inlet shows large variations through time. These variations were described through a conceptual model of cyclic migration by e.g. Israel and Dunsbergen (1999). This conceptual model captures the observed (historic) changes in the inlet and ebb-tidal delta well. However, its predictive capability may be limited as the model does not clearly distinguish between the various time and space scales that act in the inlet system (Elias et al., submitted). A clear example is the continuous erosion of the tip of Boschplaat that cannot be explained following the proposed cyclic model.

To obtain an improved understanding of the present-day processes, we performed a detailed analysis of the morphodynamic changes. The recent bathymetric (Vaklodingen) surveys performed in 2016, 2017 and 2018 are used as prime source. High-resolution multi-beam survey data allows us to construct detailed bedform maps at various locations on the ebb-tidal delta. Estimates of the sediment transport pathways are refined through the detailed analysis of the observed bedform migration and bedform asymmetries. The analysis is summarized in an updated conceptual model describing the morphodynamic changes and the main transport pathways for the present-day Ameland Inlet.

In addition to this introduction, this report consists of 5 main chapters. Chapter 2 provides an overview of the available data used in this study. Chapter 3 describes the morphodynamic characteristics of the 2018 ebb-tidal delta and an overview of the meso-scale morphodynamic changes (2005-2017). Sediment budgets over the meso-scale (2005-2016) and present-day (2016-2017, 2017-2018) provide further indications of the magnitudes of morphodynamic change. Chapter 4 presents an analysis of bedforms that were measured using multi-beam echo sounders. Bedform asymmetries allow us to reconstruct the main sediment transport directions for selected parts of the ebb-tidal delta. In the discussion section (Chapter 5), a conceptual model summarizes the present-day morphodynamic changes and estimated sediment transport pathways of the ebb-tidal delta. Conclusions and recommendations are given in Chapter 6.

Note that the basis of this report is formed by the analysis presented in Elias (2017a,b). Where needed the relevant sections and figures are used in this report, and updated with the most recent findings obtained from ongoing Kustgenese 2.0 research.

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2 Available field data

2.1 Vaklodingen Datasets

The analysis of bathymetric changes and the construction of a detailed sediment budget are based on a series of bathymetric datasets obtained over the time-frame 2005 – 2018; see Chapter 3, for an overview and analysis of the maps. All these datasets were processed and stored using the Vaklodingen protocol, but obtained as part of various projects (see Table 2.1 for a summary). The 2005, 2008, 2011, 2014 and 2017(1) datasets form part of the regular coastal surveys. The regular coastal survey's collect data frequently (since 1986), in approximately 3-year intervals for the ebb-tidal delta and 6-year intervals for the basin. Following quality checking for measurement errors, data are combined with nearshore coastline measurements, interpolated to 20x20 m grids and stored digitally as 10x12.5 km blocks called *Vaklodingen* (De Kruif, 2001). The Vaklodingen maps for the years 2005, 2008, 2011, 2014 and 2017 form the basis of this study. For an overview of all Vaklodingen obtained since 1926 see Elias et al. (2017).

Between 2006 and 2010 additional surveys were performed on most of the ebb-tidal delta and main channels of Ameland basin in the frame work of the SBW-Waddenzee project (Zijderveld and Peters, 2008). These data were also processed and saved in a similar format as the Vaklodingen. The SBW measurements allow us to compile additional maps covering (most of) the ebb-tidal delta in the years 2006, 2007, 2009 and 2010. Combined with the Vaklodingen this allows us to analyse the yearly changes over the 2005-2011 timeframe. Note that the main channels in the basin were only surveyed in the years 2006 and 2009.

Intensified, half yearly monitoring will be performed during the Kustgenese 2.0 project. At the writing of this report bathymetries for 2016, 2017 and 2018 are present.

Table 2.1 Overview of the available bathymetric data for basin and ebb-tidal delta ETD.

Year	**Dataset**	**Coverage**		**Year**	**Dataset**	**Coverage**	
		Basin	**ETD**			**Basin**	**ETD**
2005	Vakloding	X	X	2011	Vakloding	channels	X
2006	SBW	channels	X	2014	Vakloding	X	X
2007	SBW	X	X	2016	KG2	-	X
2008	Vakloding	X	X	2017	Vakloding	Partial	X
2009	SBW	channels	X	2017	KG2	X	X
2010	SBW	channels	X	2018	KG2	-	X

2.2 High-resolution multi-beam surveys

Since 2005, regular surveys of the stone protection at NW Ameland have been made using Multi-beam echo sounding (Mbes). Table 2.2 provides a complete overview of the available datasets (also see Elias 2017). These datasets do not cover the entire ebb-tidal delta but are limited to certain parts of primarily Borndiep. Most datasets cover the area directly adjacent to the Northwest Ameland shore protection works. Especially relevant for this study is the Mbes dataset taken on 17-4-2012 that covers the central part of the Borndiep channel and the outflow into the Westgat channel (Figure 2.1).

The higher 1 m resolution grids allow us to visualize and analyze the dominant bedforms. The insert in Figure 2.1 clearly shows the presence of distinct bedforms that vary in shape and size over the channel. Such detailed maps allow for the identification of the individual bedform characteristics such as height, asymmetry and migration. Various studies point to the link between bedform morphology (size and orientation), and tidal dominance and flow magnitude. Assuming that the bedforms are still active and governed by present-day hydrodynamic conditions, the bedform distribution, arrangement, and morphology provides information about the locally dominant bottom currents and sediment transports (Boothroyd, 1985; Ashley, 1990; Lobo et al., 2000, Barnard et al, 2013, Fracassia et al. 2016).

Table 2.2 Dates of MBES surveys of Borndiep -NW Ameland

Dates of MBES surveys of Borndiep -NW ameland			
18-07-2005	18-04-2011	02-05-2013	19-01-2016
18-09-2006	29-11-2011	03-04-2014	03-03-2016
24-05-2007	17-04-2012	11-02-2015	04-07-2016
25-05-2009	18-11-2012	22-05-2015	06-12-2016
06-07-2010	12-02-2013	20-08-2015	

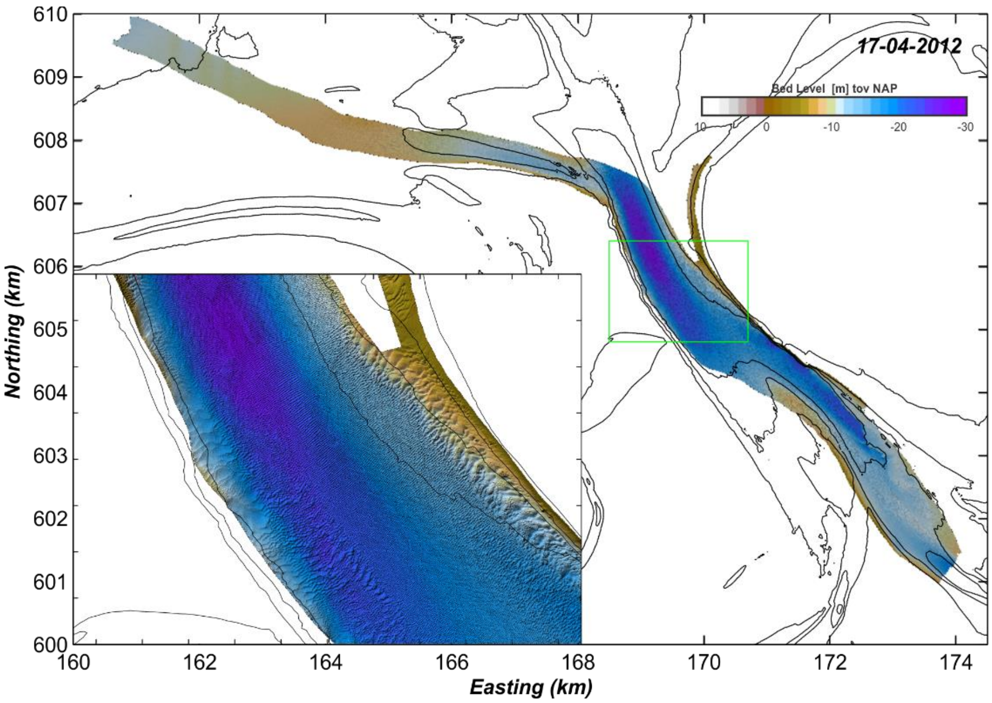


Figure 2.1 : Detailed map of MBES data taken on 17 April 2012. Insert show more details of the inlet gorge Borndiep.

Additional Mbes datasets were collected during the Kustgenese 2.0 campaigns. Mbes data was obtained at an additional 4 locations at several intervals (see Figure 2.2). The raw data were cleaned and stored. The individual datasets were sub gridded to 1 m resolution and mosaicked in single datasets. In this study we analysed the data obtained in areas A through D as summarized in Table 2.3. These data can be subdivided in 3 categories. (1) Individual measurements of the Vakken A, B, C. (2) Four repeat surveys of Vakken A, B, C on 30-8, 31-8, 04-09 and 06-09. (3) Repeat surveys of bedforms through the tidal cycle in Vak D on 07-09. In addition to these Vakken A-D detailed measurements of the frames were also made, but these were not yet analysed in the present study.

Table 2.3 Dates and locations of MBES surveys during Kustgenese 2.0.

Vak A	**Vak B**	**Vak C**	**Vak D**
30-08-2017	30-08-2017	30-08-2017	07-09-2017 7:54 - 8:26
31-08-2017	31-08-2017	31-08-2017	07-09-2017 8:36 - 9:27
02-09-2017	02-09-2017	03-09-2017	07-09-2017 9:37 - 10:17
03-09-2017	04-09-2017	04-09-2017	07-09-2017 10:24 - 11:08
04-09-2017	06-09-2017	06-09-2017	07-09-2017 11:13 - 11:52
06-09-2017			07-09-2017 11:57 - 12:31
			07-09-2017 12:37 - 13:14
			07-09-2017 13:18 - 14:13
			07-09-2017 14:15 - 14:55

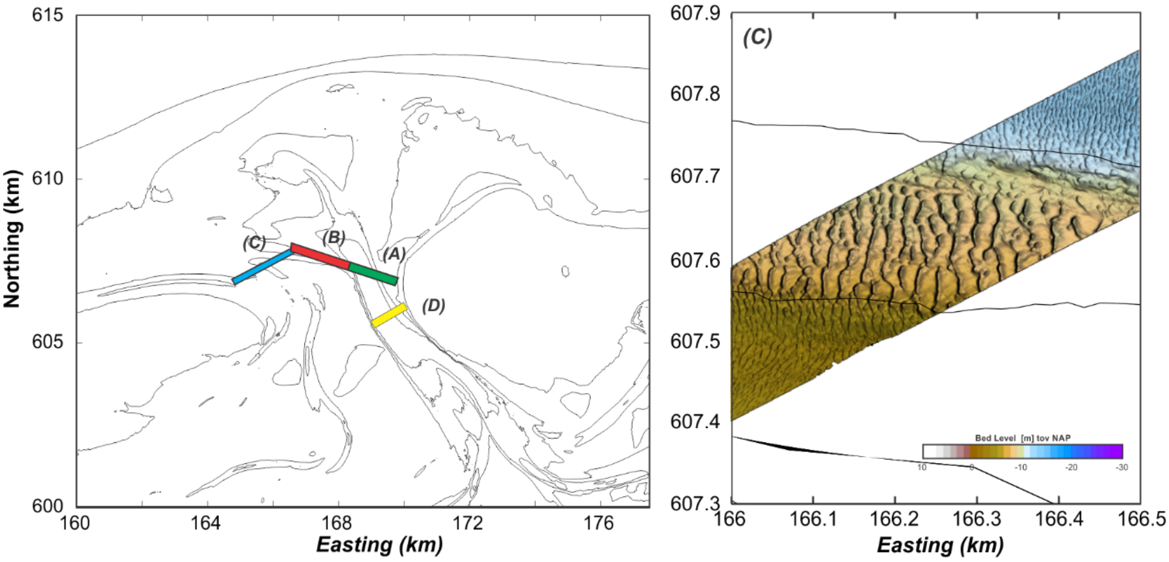


Figure 2.2 (left): Locations of the Mbes multi-beam data Vakken A-D used in this study. Right panel provides an example illustration of the bedforms present in Vak C, on the southern margin of Westgat.

3 Morphodynamics of the ebb-tidal delta

The distribution, evolution, shape and size of typical, large-scale ebb-tidal delta elements, such as ebb and flood channels, channel-margin linear bars, terminal lobes and swash-bar patterns can provide useful insights in sediment transport patterns (see e.g. Hayes, 1975; Hine, 1975; Hubbard et al., 1979; Boothroyd, 1985; Sha, 1989b; FitzGerald, 1996, Elias and van der Spek, 2018). In this section, we therefore analyse the morphodynamic changes of the present-day ebb-tidal delta starting with a description of the present-day channels and shoals (Chapter 3.1), and an analysis of the morphodynamic changes over the period 2005 - 2017 (Chapter 3.2). Estimates of the transport rates can be obtained through the detailed analysis of sediment budgets as presented in Chapter 3.3.

Note that the bathymetric figures presented all use orthogonal illumination, hill shading techniques and a factor 10 scaling of the height. By using these techniques, the bed-slope gradients are highlighted. Bed-slope gradients are an important indicator for sediment transport directions.

3.1 Present-day Channels and Shoals

Figure 3-1 provides an overview of the main channels and shoals that form Ameland Inlet. The ebb-tidal delta is based on the 2018 measurements, the basin primarily on 2017 and older measurements. In the inlet gorge, between the islands of Terschelling and Ameland, a deep main ebb-channel exists along the west coast of Ameland (Borndiep, see Figure 3-1[1]). The deepest parts of the channel exceed 25m of depth. In the basin, Borndiep connects to Dantziggat [3] that curves eastward into the basin towards the tidal divide of Ameland (Pinke Wad), through the channels Kikkertgat [4], Noorder Spruit [6] and Zuider Spruit [7]. Several smaller side channels connect to Dantziggat such as Molengat [18] near the island of Ameland, and Vaarwater vd Zwarte Haan [8].

Between Borndiep and Boschplaat, the tip of the island Terschelling, a shallow area with several small channels can be observed. This shallow area connects to the main channel Westgat [19] on the ebb-tidal delta, and the channel Boschgat [20] in the basin. A smaller channel (Oosterom [21]) is located between the Koffieboonenplaat [22] and Boschplaat. In the basin, Boschgat connects to Blauwe Balg and Nieuwe Oosterom [23,24]. The large shoal, in the middle of the inlet, between Boschgat and Borndiep is called Zeehondenplaat [25].

The ebb-tidal delta contains 3 main shoal areas and 3 named channels. The outflow from Borndiep onto the ebb-tidal delta is called Akkepollegat [2], and forms the main ebb-channel. Along the two adjacent shorelines 2 named flood channels are present: Westgat [19] and Oostgat [26]. Numerical modelling by Elias (2015) showed that hydrodynamically Oostgat does not form a distinct channel, but is formed by the connecting scour pits around the Bornrif Strandhaak and around the tip of Northwest Ameland. In this recent bathymetry, Westgat is a relative narrow channel with only a minor connection to Borndiep. Just north of Westgat two large ebb-chute and ebb-shield complexes have formed that cover most of the western part of the ebb-tidal delta [27,28]. The first ebb-chute completely covers the former shoal Kofmansbult, and the growth and north(east)ward migration of the ebb-shield has constrained flow in Akkepollegat [2]. This channel was pushed north(east)ward and the width is significantly reduced.

The largest shoal area on the ebb-tidal delta lies eastward of Akkepollegat, which is downdrift in relation to the littoral drift. This large shoal area or swash platform is named Bornrif [30]. A large, narrow swash bar, Bornrif Bankje [32], had formed along its eastern margin. This Bankje has connected to the Ameland coastline (in 2017) and volumes slowly dissolve into the coastal system. In the 2018 bathymetry the remaining remnants of this shoal are still visible as a small protrusion of the coastline, just east of the Bornrif Strandhaak. Along the coastline of Ameland the remnants of the Bornrif Strandhaak [32], a former ebb-delta shoal that attached to the coastline around 1985 are still clearly visible. This natural “zandmotor” has supplied the (downdrift) coastline with sand over the past decades.

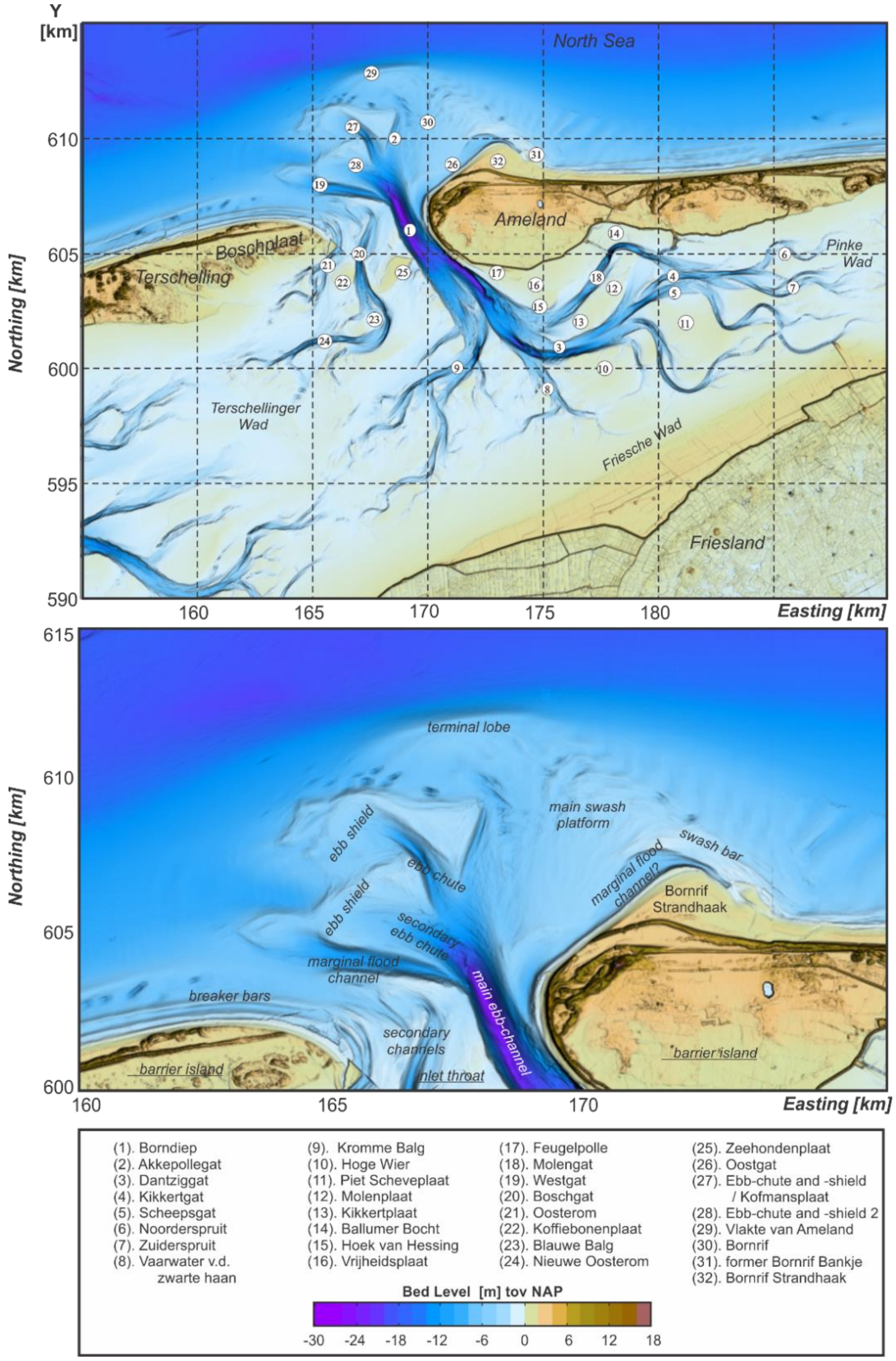


Figure 3-1 Overview of the channels and shoals that form the present day Ameland Inlet. The underlying DEM is based on the 2018 Kustgenese2 Autumn dataset (missing data and the basin are filled in with 2017 measurements).

3.2 Morphodynamic changes between 2005 and 2017

An analysis of the bathymetric changes of the ebb-tidal delta since 2005 is based on the bathymetries presented in Figure 3.2, Figure 3.3 and Figure 3.4. The choice of the 2005 bathymetry as a starting point is two-fold. Firstly, based on the analysis of the volumetric change of the ebb-tidal delta Elias (2017) indicates that inaccuracies may exist in the bathymetries prior to 2005. Secondly, the 2005 bathymetry is the last available bathymetry, prior to the ebb-chute and shield formation. Both the 2005 and 2017 bathymetries (Figure 3.2) have in common that:

(1) The inlet gorge consists of a shallow western part along the tip of Terschelling and a deep eastern part along the Ameland coastline that contains the main ebb-channel Borndiep.
(2) Borndiep has a north-westerly outflow onto the ebb-tidal delta.
(3) The main ebb-delta volume is stored north-eastward (downdrift) of Borndiep in the Bornrif shoal.
(4) In the shallow part of the inlet, smaller secondary channels occur that do not directly connect to a channel on the ebb-tidal delta.

Despite these commonalities, the details of the channels and shoals of the ebb-tidal delta show very different characteristics. One of the most noticeable differences between the two maps is the relative flat, deep, ebb-tidal delta morphology in 2005, while a clear, well-defined, main ebb-channel exists. To the east and west of the channel, shoals are present that are relatively uniform in shape. No distinct morphologic features are clearly visible. Such features exist in the 2017 bathymetry, that still shows a single large shoal area (Bornrif) to the east, but multiple ebb-chute and shield systems that dominate the western margin of the ebb-tidal delta. Figure 3.5 and Figure 3.6 show detailed representations of selected cross-sections over the 2005-2017

In order to understand the changes since 2005, we need understand how the 2005 bathymetry was formed. In Figure 3.3 and Figure 3.4, we therefore provide an overview of the measurements since 1975. A detailed analysis of these measurements is presented in Elias et al. (in press). These authors conclude that between, 1958 and 1985, Westgat increased in size and depth and likely temporarily took over as main ebb outflow from Borndiep. As a result, large volumes of sediment were also deposited along the seaward (northern) edge of Westgat, building out the (south-)western margin of the ebb-tidal delta (clearly visible in Figure 3.3). Westgat retained its size and position until 1985, but started to lose connection to Borndiep in 1989. At that time Koffiebonenplaat had migrated towards the inlet and extended to the north between Boschgat and Borndiep, forming a shallow sill between the two channels. Temporarily, Westgat and Boschgat connected directly. The constricted flow in Westgat enabled Akkepollegat to redevelop as the main outflow of Borndiep. Between 1989 and 2009 Westgat changed from an ebb-dominant channel to a flood-dominant channel again. As Westgat reduced in importance the extensive shoal deposits along its western margin could no longer be maintained. These shoals quickly reduced in height and size, and a relative deep area developed between the Kofmansbult and Boschplaat. These sediments likely contributed to the building of a large and long shoal along the western margin of Borndiep. This shoal directs flow through Borndiep seaward, and enhanced the seaward extension of Akkepollegat and the subsequent sediment deposits in front of the channel.

The shoal formation along the western margin of Borndiep facilitates some of the changes that occur since 2005. On the shoal a series of initially small ebb-chutes and -shields form (in the years 2006, 2008, 2014). A first ebb-chute formed between 2005 and 2006 as a small channel emerged just north of Westgat (Figure 3.3, 2006). As the channel grew, it pushed sediments seaward, forming a small ebb-shield onto the Kofmansbult shoal. By 2008 a second (small) ebb-chute and shield had formed that overwhelmed the first system. Migration rates of this ebb-chute are estimated from the -5.0 m and -7.5 m contours (Appendix A, Fig A-1 and A-2). In total the ebb-chute migrated over 3-km onto the ebb-tidal delta with rates varying between 167 m/year and 522 m/year. The ebb-shield development on the Kofmansbult continued to dominate the morphodynamic changes of the central-downdrift ebb-delta platform, and by 2014, the ebb-shield covered the major part of the Kofmansbult. The formation of this new ebb-shield, and the higher shoal to the north are likely contributing to the confined flow in Akkepollegat and induce a curvature of the channel around the shoal. By 2017 only a narrow, downdrift curved, channel remains. Using the -10m contour as a proxy for channel displacement we can observe a near 1.3 km eastward displacement of the tip of Akkepollegat. While the shallower part of the channel primarily rotated eastward (up to the -10 m contour), the deepest part significantly reduced in length; over 300m between 2005 and 2009 (Appendix A, Fig. A-3). The increasing length of the channel between 2014 and 2017 is related to the development of the new (third) ebb-chute. While the distal part of Akkepollegat rotates clock-wise (to the east), the proximal part, towards the inlet gorge, rotates anti-clockwise.

Sandwiched between Westgat and the second ebb-chute, a new (third) ebb-chute started to form in 2014. This ebb-chute quickly grew in size and expanded to the (north)west. The southern margin of the ebb-shield constrains the width of Westgat near the outflow to Borndiep. As a result, the channel deepened and lengthened. The 10 m contour migrated nearly 900m westward between 2011 and 2017. In front and along its northern margin the shoal formation suggest that an ebb-dominant transport prevails. It is likely that the third ebb-chute eventually connects to or merges with Westgat, forming a new main channel. This would recreate a configuration of the ebb-tidal delta as present around 1975.

Large changes were also observed on the Bornrif platform. Although the footprint of the Bornrif platform remains in place, between 2011 and 2017 the formation, migration and eventual merger of Bornrif Bankje dominated the developments. The origin of Bornrif Bankje can be traced back to the 1989-1999 timeframe. During this time period the northern ebb-delta front showed a large outbuilding and increase in shoal height at the seaward end of Akkepollegat. This outbuilding continued until 2011. It is likely that wave-breaking on this shallow shoal area resulted in downdrift sand transport along the ebb-tidal delta margin, and Bornrif Bankje slowly started to emerge on the north-east side of the ebb-tidal delta (2008-2010). The shoal continued to migrate eastward and landward (2011-2014). Migration rates based on the -5.0 m contour are between 150 and 430 m/year (Appendix A, Fig A-1). By 2014 only a small channel remained between the Bornrif Strandhaak and Bornrif Bankje. The map of 2017 shows that the tip of Bornrif Bankje finally attached to the Ameland coastline, just downdrift of the Strandhaak. Based on the morphodynamic change map (Figure 3-7) the associated volume changes are estimated at 10 million cubic meter (mcm).

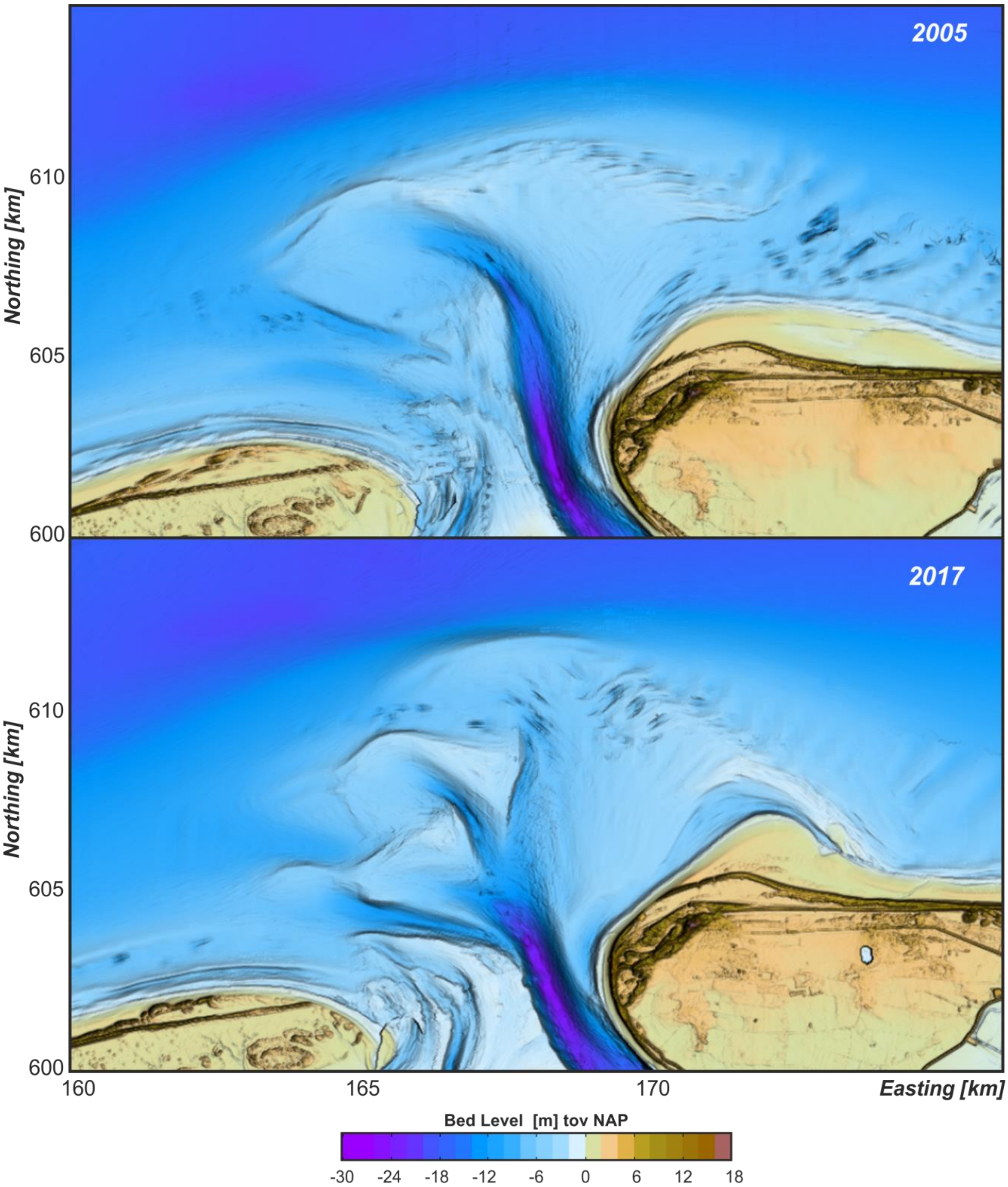


Figure 3.2 Overview plot of the 2005 and 2017 DEMs.

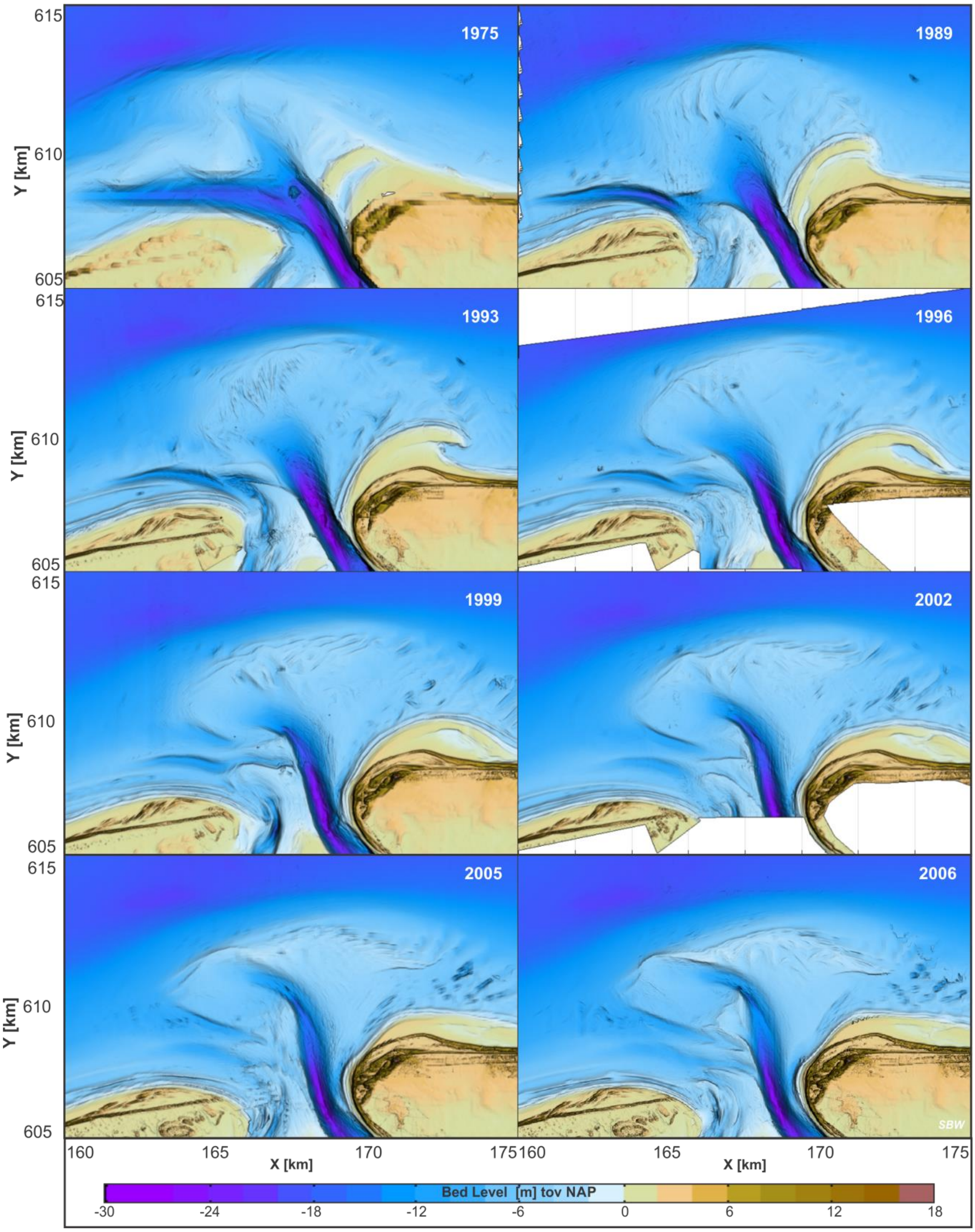


Figure 3.3 Complete DEMs of the ebb-tidal delta based on measurements over the time-frame 1975-2006.

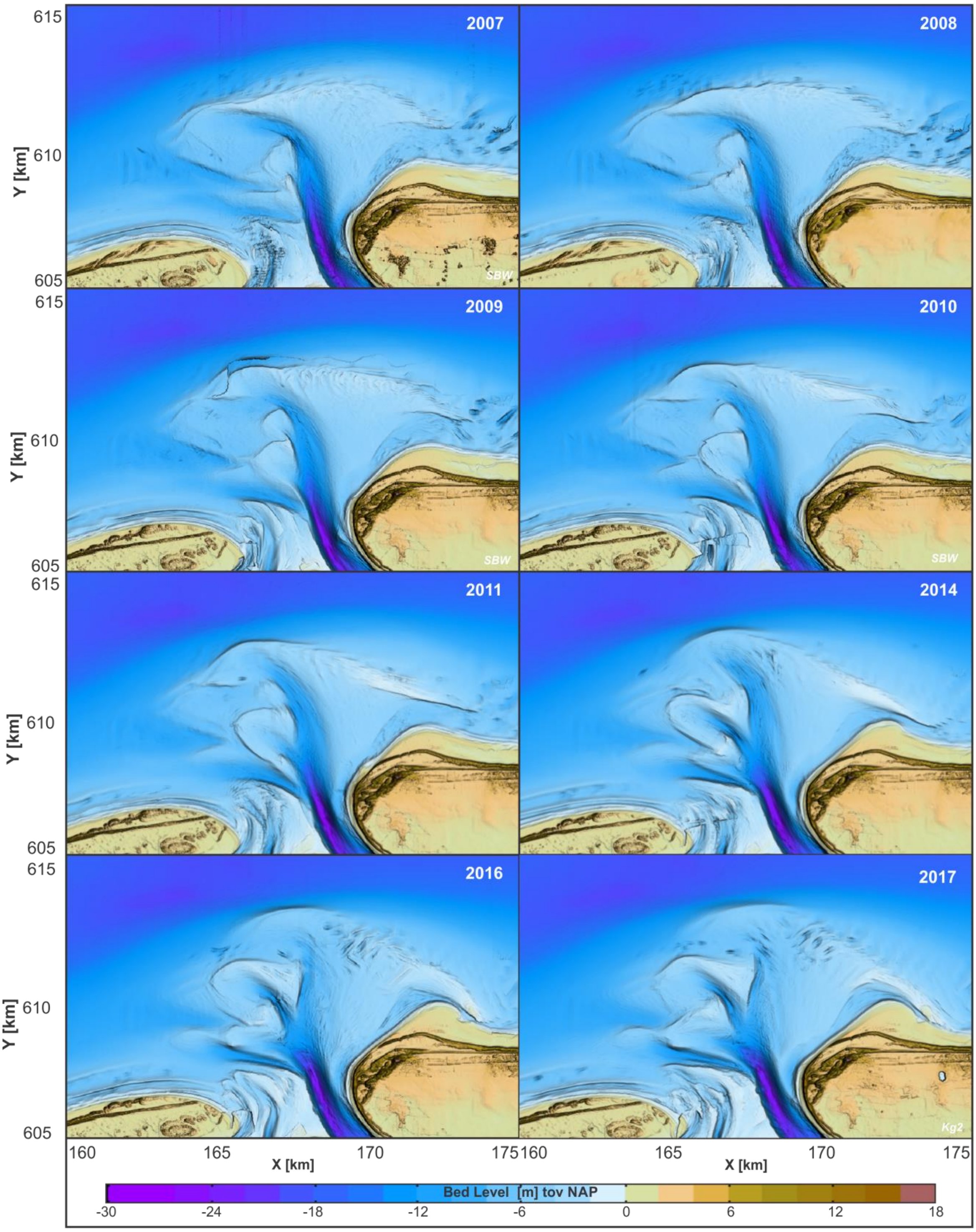


Figure 3.4 Complete DEMs of the ebb-tidal delta based on measurements over the time-frame 2007-2017.

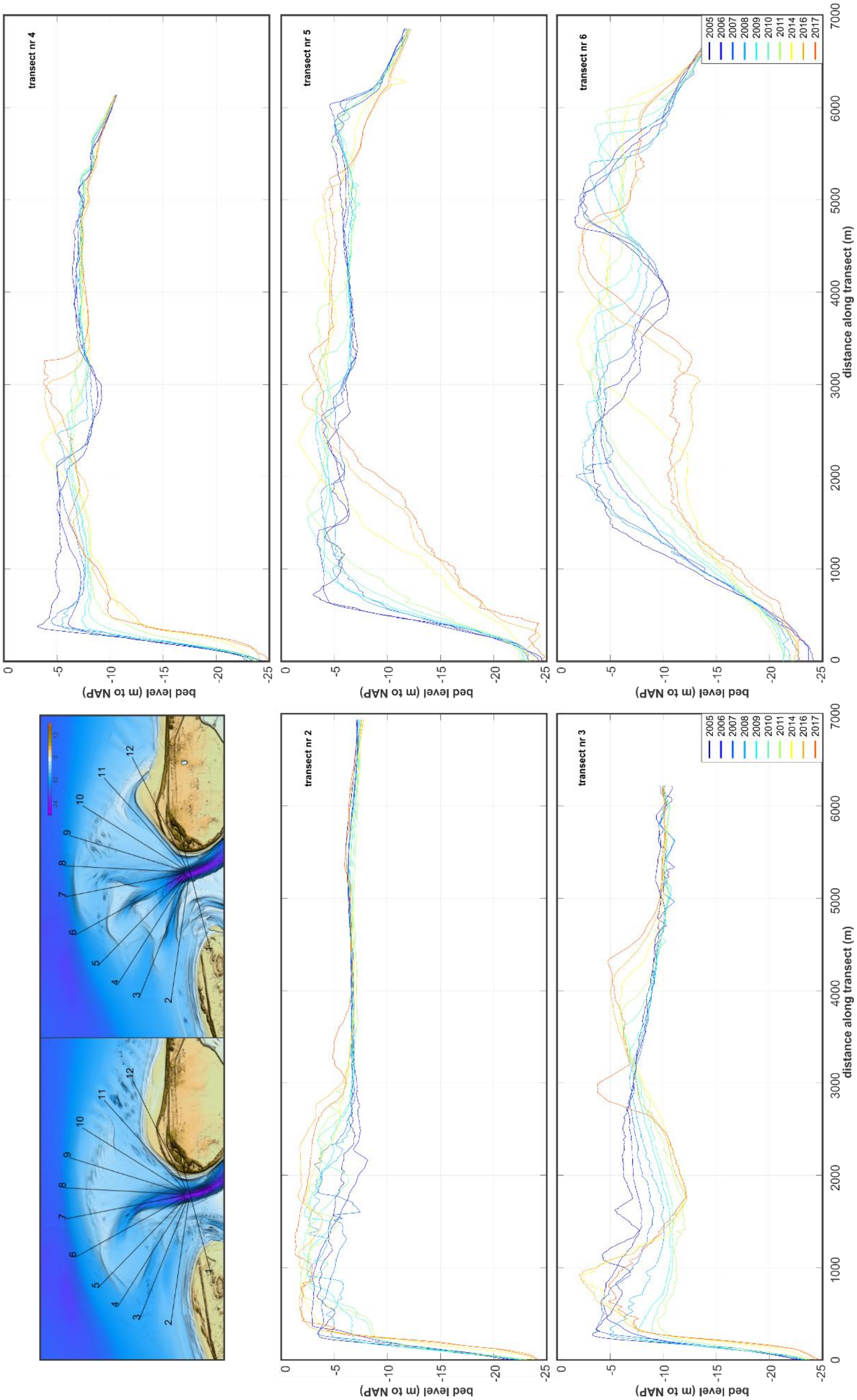


Figure 3.5 Overview of cross-sectional changes over the time-frame 2005-2017 (Profiles 1 – 6).

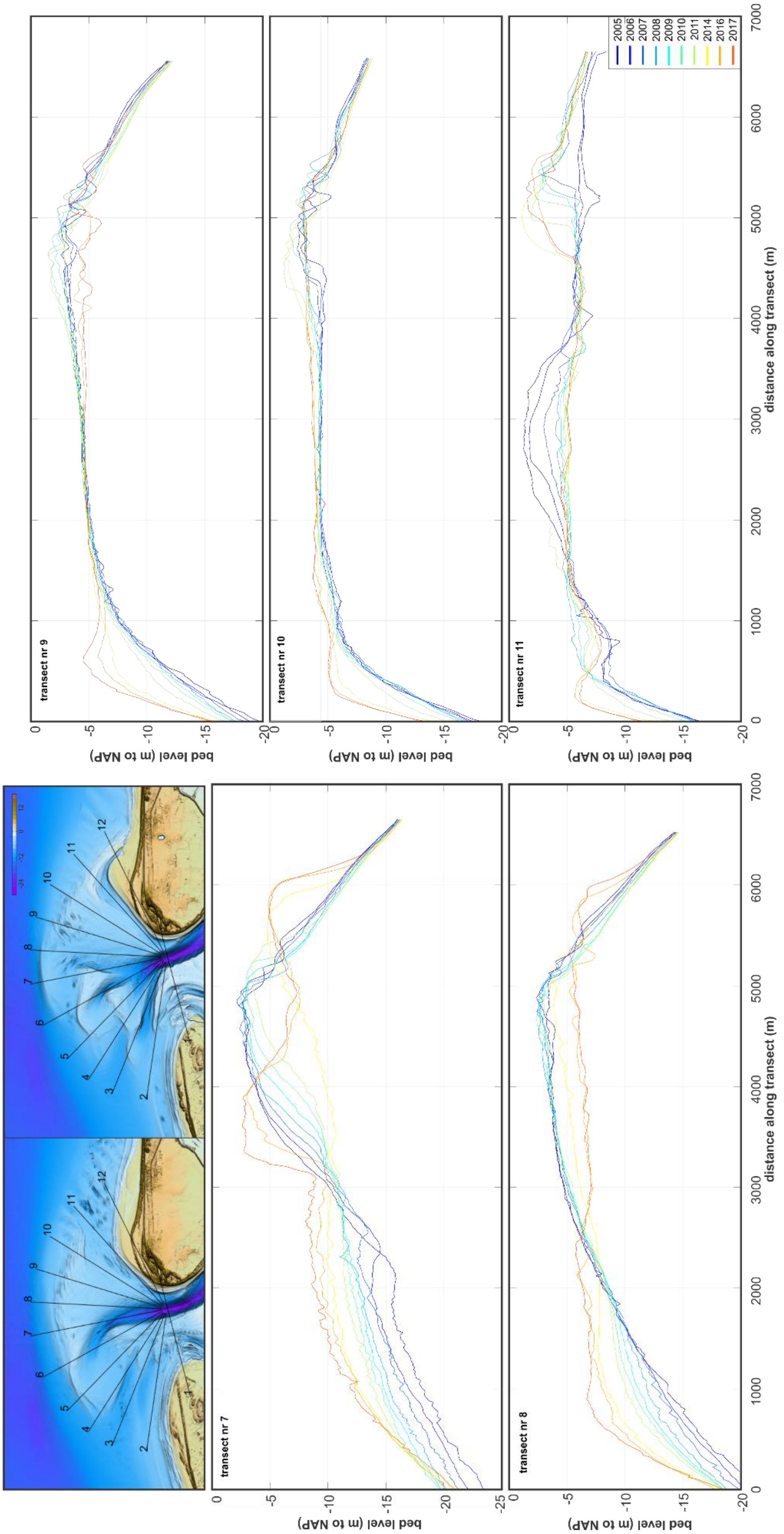


Figure 3.6 Overview of cross-sectional changes over the time-frame 2005-2017 (Profiles 7 – 11).

3.3 Sediment Budgets

3.3.1 2005 - 2016

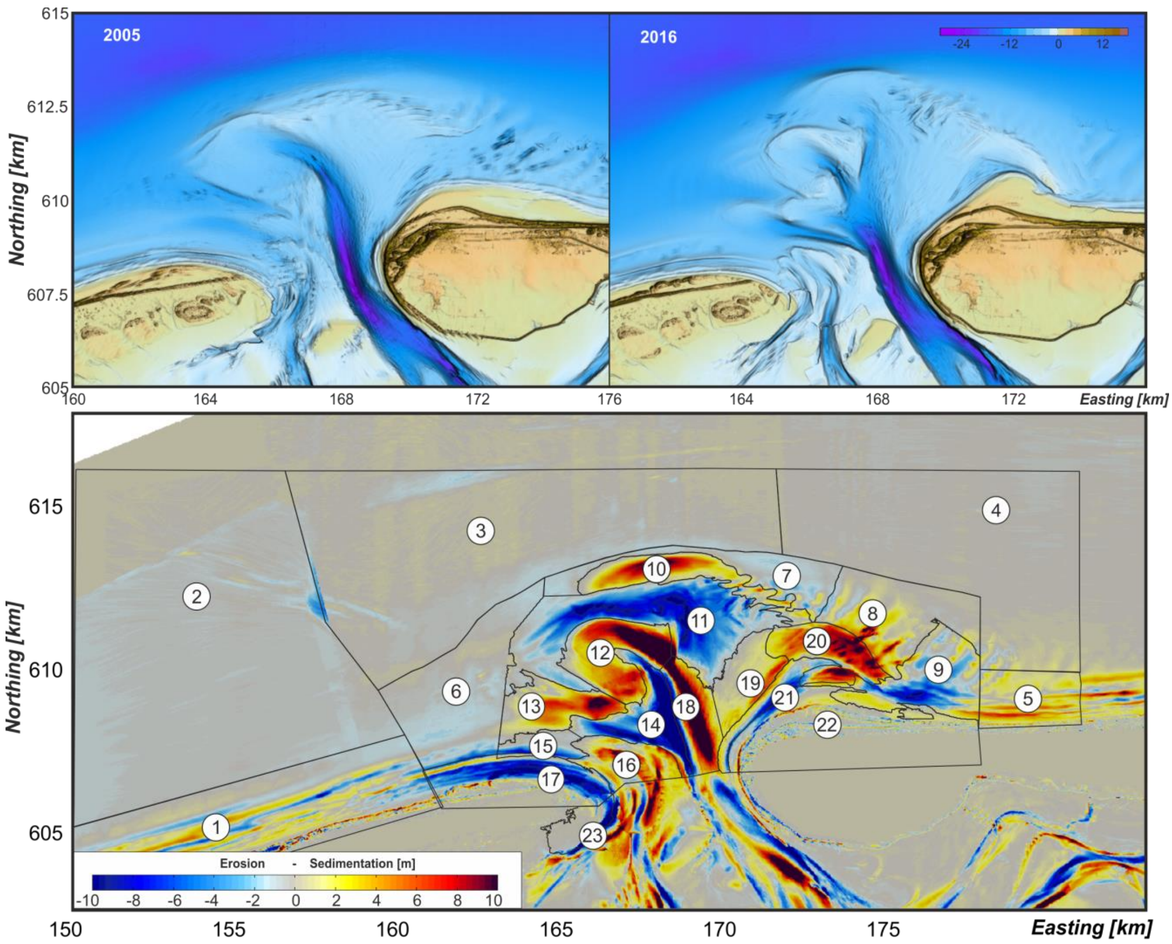
Estimates of the volumes associated with certain morphodynamic features such as channels and shoals are often difficult to make as these depend on the selection of an arbitrary reference level. In this study we use the sedimentation-erosion patterns over the period 2005-2016 as an indication of the medium-term volume changes. The numbers between square brackets [..] refer to the numbers indicated in Figure 3-7.

In total, the ebb-tidal delta and coast show a net increase in sediment volume of 7 mcm, the majority of this gain was observed along the island coastlines, to the north and south of the ebb-tidal delta. The ebb-tidal delta only gained 2 million m^3 (mcm)of sediment, but correcting for 4.7 mcm of nourishments a net loss of around 2.7 mcm would have occurred. The volume change of the ebb-tidal delta is small compared to the observed gross changes of ~200 mcm.

Erosion is observed along the adjacent coast of Terschelling, where the Boschplaat loses 5.6 mcm on its seaward side [17]. An additional loss of 3.3 mcm from is observed along the basin side [23]. A volume gain of 5.6 mcm to the east in the Boschgat area [16], suggests that sediments from Terschelling are transported cross-shore, into the inlet, at the tip of Boschplaat.

Severe erosion is observed just to the north at the location of Westgat and the ebb-chute developments. In total this area loses 17.7 mcm [14]. Part of this erosion is related to the rotation and migration of the main channel Borndiep/Akkepollegat. This migration creates accommodation space along the channels eastern (Bornrif) side. Here 12.4 mcm of sedimentation occurs [18], that is likely (partly) provided by the over 25 mcm of erosion of the delta [11]. The Bornrif shoal area shows alternating patterns of sedimentation, erosion and sedimentation. The ebb-delta front [10] gains 7.6 mcm of volume. This accretion is linked to the rotation of Akkepollegat that temporarily increased its length and resulted in a migration/outbuilding of the delta front. As a result, the deeper part of the delta migrated seaward resulting in accretion. The shallower portions of this shoal were quickly transported landward by the wave-driven transports. Resulting in a loss of 25.1 mcm [11]. Part of these sediments were transported in the form of a shoal (Bornrif Bankje) along the delta margin towards the coast of Ameland. This contributes to the 14.1 mcm of sedimentation observed here [20,8]. The deeper portion of these deposits is less easily moved and a sediment accumulation of 7.6 mcm remains [10].

The sediment accretion on the Kofmansbult due to the ebb-shield formation is estimated to be 17.8 mcm [12]. An initial 6.9 mcm accretes to the south as part of the deposits related to the third ebb-shield and the Westgat ebb-shield [13].



Poly-gons	Volume change [mcm]			Poly-gons	Volume change [mcm]		
	Wet(1)	Beach(2)	Dune(3)		Wet(1)	Beach(2)	Dune(3)
1	0,9	0,7	2,0	12	17,8	-	-
2(4)	0,4	-	-	13	6,9	-	-
3	-0,9	-	-	14	-17,7	-	-
4	1,1	-	-	15	-1,6	-	-
5	4,1	0,6	0,3	16	5,9	-	-
6	-4,9	-	-	17	-5,6	-1,5	-0,6
7	-2,5	-	-	18	12,4	-	-
8	3,8	-	-	19	3,5	-	-
9	-5,4	1,7	0,5	20	10,3	-	-
10	7,6	-	-	21	-3,3	-0,4	-
11	-25,1	-	-	22	0,2	0,2	0,1
				Total	7,6	1,3	1,9

Name	Polygons	Volume change [mcm]			
		Wet(1)	Beach(2)	Dune(3)	Total
Coast	1,2,3,4,5	5,5	1,3	2,3	9,1
ETD	6,7-22	2,1	0	-0,4	1,7
		7,6	1,3	1,9	10,8
Bornrif	8,9,19-22	9,1	1,5	0,1	10,7
Boschplaat	15,16,17	-1,4	-1,5	-0,6	-3,5
Westgat	13,14	-10,8	-	-	-10,8
Kofmansbult	12	17,8	-	- -	17,8
Borndiep	18	12,4	-	-	12,4
Bornrif (front)	11,10,7	-20,1	-	-	-20,1
		7	0	-0,5	6,5

(1). Wet = volume change for bed level <+1 NAP.
(2). Beach = volume change for bed level between +1 and + 3m NAP.
(3). Dune = volume change for bed level > +3m NAP.
(4). erosion in polygon 2 (2005-2007) is unrealistic. Therefore a zero change is assumed over this time frame.
Note that: Polygon 23 - erosion of basin side of Boschplaat = -3.3 mcm.

Figure 3-7 Observed sedimentation-erosion patterns and volume changes over the time period 2005-2016. Tables show the values for the individual polygons (left) and aggregated features (right).

3.3.2 2016 - 2017

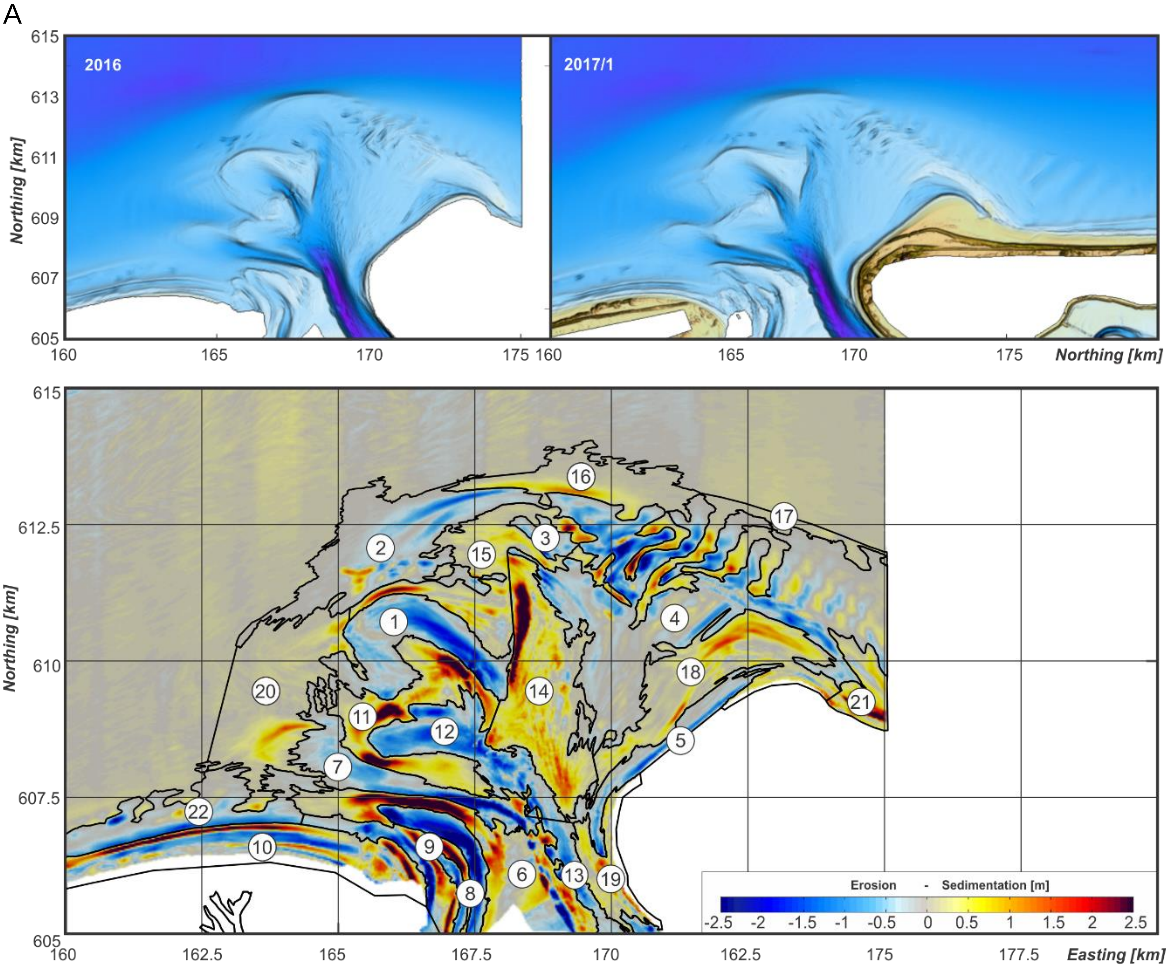
The yearly changes illustrated by the 2016 - 2017 difference map (Figure 3-8) shows height changes that are in the 1 to 2.5 m range. The sedimentation-erosion patterns are only partly similar to the longer-term changes observed in the 2005-2016 difference map.

Largest changes occur in the central part of the ebb-tidal delta around the two ebb-chute and ebb-shield systems. The erosion of polygon 12 displays the increasing size of the landward ebb-chute by 2 mcm. The nearly 2 mcm of sediments contribute to the outbuilding of the ebb-shield by 2.7 mcm [11]. Parts of the deposits are likely delivered by the 1.7 mcm erosion due to scouring of Westgat [7]. A small ebb-shield [20] facing Westgat with 0.9 mcm of accumulation, indicates the ebb-dominant character of the distal part of Westgat. The increasing depth of Westgat at least partly results from the narrowing due to the buildup of the ebb-chute to its North. A clear deeper channel is formed to the south, near Boschplaat [8] as over 2 mcm of sediments are eroded. Between this erosion and Westgat over, 2 mcm of sediments deposition occurs [6] that constrains the Westgat channel along its landward margin. With increasing ebb-dominance of the distal part of Westgat, it is possible that more flow is directed towards the south, which promoted the formation of a flood dominant channel connecting Boschgat with the open sea.

Seaward on the ebb-tidal delta, the growth of the landward ebb-shield pushes the seaward ebb-shield northward. Inducing 1.9 mcm of erosion of the ebb-chute [1] and 1.1 mcm of accretion on its ebb-shield [15]. Most accretion is however observed towards the east of the ebb-shield into Akkepollegat. Constrained flow in the distal part of Akkepollegat reduced its hydraulic efficiency and accretion is observed along most of the channel length. The erosion of the proximal eastern side of Akkepollegat and accretion along its northern embankment are clear indications that the channel is rotating clockwise. The loss of channel efficiency results in 3.4 mcm of channel accretion [14].

On the Bornrif, alternating patterns of sedimentation and erosion point to the wave-dominant character of this part of the shoals. Waves redistribute the sediments landward that appear to be migrating in large bedforms (dunes) over and along the ebb-delta margin. In total 2 mcm of net sediment erosion is observed in polygons 4, 16 and 17. Some of the sediments accumulate in Bornrif Bankje that as a whole migrates landward. The landward movement of sediments towards Ameland coast results in 1.4 mcm of sediment accumulation [18], and constricts the flow along Ameland Northwest. This automatically creates a channel along the coast, introducing 0.5 mcm of erosion in the nearshore [5].

Note that part of the erosion in polygons 2 and 3 may be related to sand mining for the nourishments at Ameland Island.



Polygons	Volume change *[mcm]*			Polygons	Volume change *[mcm]*		
	Pos.	Neg.	Total		Pos.	Neg.	Total
1	0.01	-1.95	-1.94	12	0.02	-1.95	-1.93
2	0.13	-1.11	-0.97	13	0.01	-0.63	-0.62
3	0	-0.15	-0.14	14	3.42	-0.05	3.37
4	0.48	-3.82	-3.34	15	1.31	-0.19	1.11
5	0.01	-0.55	-0.54	16	0.72	0	0.72
6	2.71	-0.61	2.1	17	0.60	0	0.6
7	0.1	-1.4	-1.31	18	1.46	-0.04	1.41
8	0.01	-2.07	-2.06	19	0.49	-0.02	0.47
9	0.97	-0.74	0.24	20	0.87	-0.01	0.86
10	1.86	-1.13	0.73	21	0.74	-0.02	0.72
11	2.76	-0.02	2.74	22	0.04	-1.37	-1.33
				Total :	18.72	-17.83	0.89

Figure 3-8 Observed sedimentation-erosion patterns and volume changes over the time period 2016-2017. Tables show the values for the individual polygons.

3.3.3 2017 – 2018

The changes during the 2017 – 2018 time-frame are illustrated in Figure 3-9 and Figure 3-10. The 2017-2018 map (Figure 3-10) shows a clear continuation of the trends observed in the 2016-2017 measurements. We observe ongoing development of the two ebb-chute and ebb-shield areas. In the landward system, erosion of the channel (3.3 mcm [9]) is near-balanced by 3.2 mcm of accumulation on its ebb-shield [8]. To the south, sediment accumulation dominates the Westgat region with a total of 1.3 mcm deposition [4]. The seaward ebb-chute shows an erosion of 2.8 mcm and 2.2 mcm of accumulation in front [6]. Along its eastern margin, sediment accumulation in the Akkepollegat region continues with a total of 4.1 mcm [7].

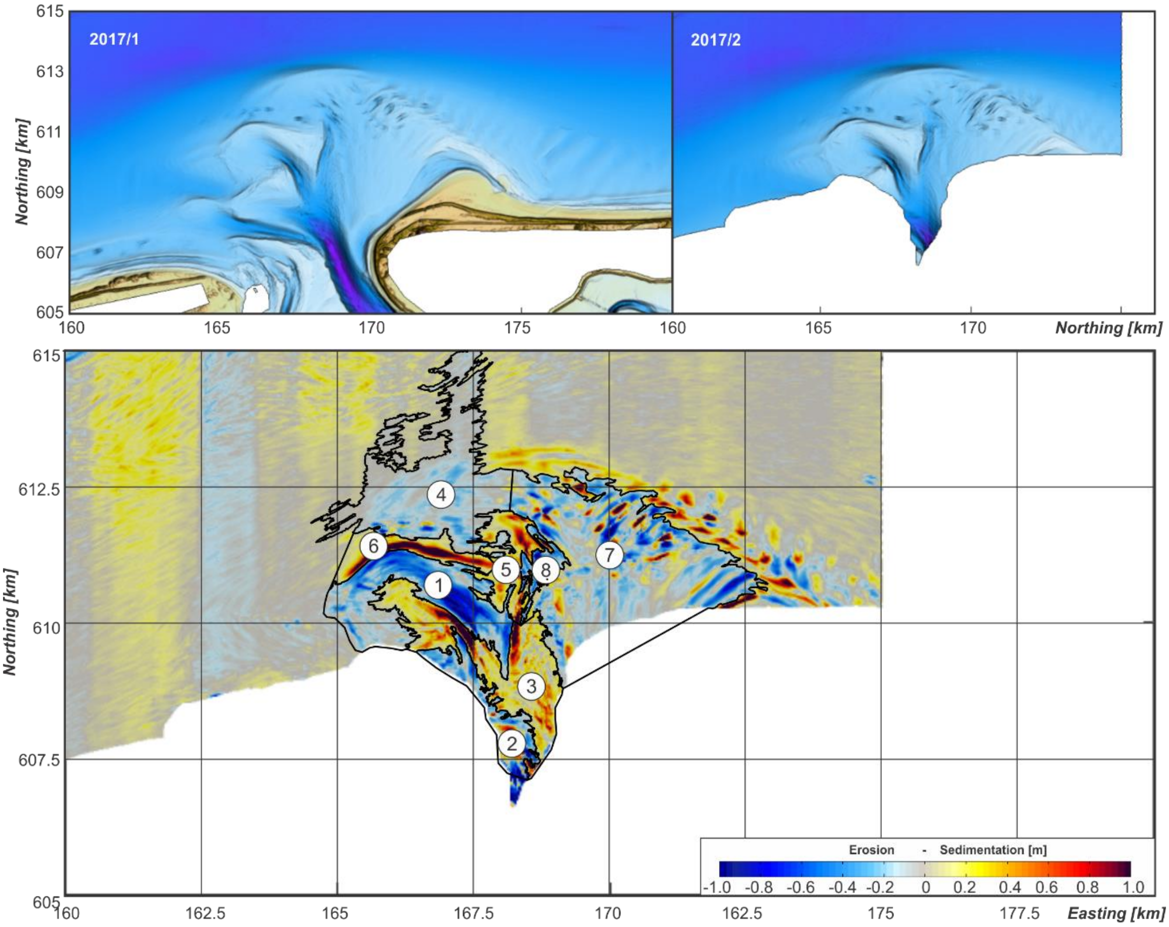
In the Boschgat region, patterns of sedimentation and erosion alternate. Adjacent to the tip of Boschplaat a total of 1.8 mcm accumulation is observed [12], and next to this area, channel formation results in 2 mcm of erosion [10]. Towards Borndiep a smaller area of 0.6 mcm of sediment accretion is observed near Zeehondenplaat [11].

The central part of Bornrif shows an erosion of 1 mcm. To the east, large bedform migration results in alternating patterns of sediment erosion and deposition. In total a loss of 1.9 mcm is observed in areas 17,19, 21. Attachment of Bornrif Bankje to the former Bornrif Strandhaak provides 1.5 mcm of sediment to this area. Landward, severe erosion of the Ameland northwest coastline occurs with a loss of 1.3 mcm in a narrow strip [15].

A comparison of the 2017 (1) and 2017 (2), spring and autumn measurements (Figure 3-9) shows that the changes between these 2 bathymetries are relatively small compared to yearly change. This difference cannot be explained by the smaller survey area alone, but indicates that the majority of the gross changes occurred between the 2017 autumn and 2018 spring measurements. The net volume change over the summer period is 0.7 mcm of erosion, as a result of 6 mcm of gross change. During the winter period, the gross changes are nearly 7 times larger with over 40 mcm of change.

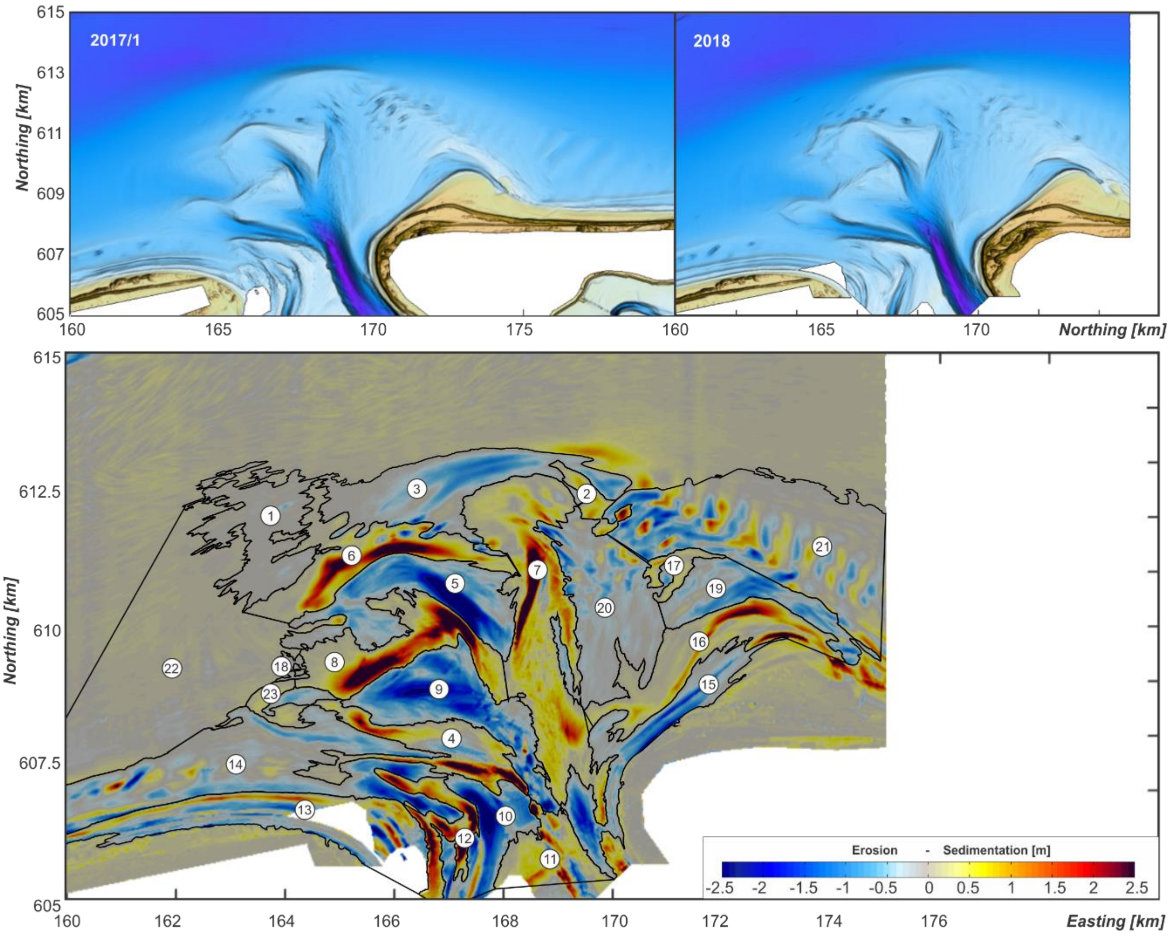
Figure 3-9 shows a similar migration rate of the ebb-shield and chute system compared to the 2017-2018 maps. The seaward ebb-chute erodes by 1 mcm, while the ebb-chute accretes by 0.6 mcm in front [6] and 0.4 mcm to the east [5]. Infilling in Akkepollegat results in 1 mcm of sediment accumulation here [3]. Erosion of the central part of Bornrif is estimated at 0.8 mcm [7], while the ebb-delta front erodes by 0.5 mcm [4].

As a pilot experiment in 2018 a large, approximately 5 mcm, nourishment is placed on the Kofmansbult. The deposition observed in Figure 3-10 polygon 6 is partly related to this nourishment. At the time of the survey 0.9 mcm was added. Based on the 2018 survey data we cannot clearly assess the impact of this nourishment, but this is clearly an aspect that needs close monitoring and further analysis.



Polygons	Volume change *[mcm]*			Polygons	Volume change *[mcm]*		
	Pos.	Neg.	Total		Pos.	Neg.	Total
1	0.01	-1.08	-1.07	5	0.37	-0.01	0.37
2	0.15	-0.29	-0.15	6	0.56	-0.00	0.56
3	1.02	-0.03	0.98	7	0.45	-1.26	-0.81
4	0.03	-0.51	-0.48	8	0.01	-0.12	-0.11
				Total :	2.60	-3.30	-0.71

Figure 3-9 Observed sedimentation-erosion patterns and volume changes over the time period 2017 spring (1) and autumn (2). Tables show the values for the individual polygons (left) and aggregated features (right).



Polygons	Volume change *[mcm]*			Polygons	Volume change *[mcm]*		
	Pos.	Neg.	Total		Pos.	Neg.	Total
1	-0.13	0	-0.12	13	-1.17	0.77	-0.41
2	0	0.28	0.28	14	-2.74	0.35	-2.4
3	-1.41	0.01	-1.4	15	-1.33	0.00	-1.33
4	-0.14	1.45	1.32	16	-0.01	1.55	1.54
5	-2.82	0.01	-2.81	17	0.00	0.11	0.11
6	-0.04	2.24	2.2	18	-0.01	0.00	-0.01
7	-0.05	4.11	4.06	19	-0.96	0.02	-0.94
8	-0.01	3.2	3.18	20	-1.03	0.08	-0.95
9	-3.29	0.04	-3.25	21	-1.86	0.97	-0.89
10	-2.07	0.09	-1.98	22	-0.19	0.50	0.31
11	-0.16	0.81	0.64	23	0.00	0.10	0.1
12	-0.01	1.78	1.76				
				Total :	-19.43	18.47	-0.99

Figure 3-10 Observed sedimentation-erosion patterns and volume changes over the time period 2017(1)-2018. Tables show the values for the individual polygons (left) and aggregated features (right). Note that in 2018 nourishment of the Kofmansbult started. A the time of the 2018 survey 0.9 mcm was added to polygon 6.

4 An analysis of Bedforms

4.1 Estimates of bedform migration

Estimates of bedform migration were obtained by selecting a single representative profile in each of the Vakken. For these profiles the peak and through locations were determined for the subsequent surveys. The profiles were visually inspected to ensure that identical peaks and troughs were selected. By selecting the corresponding peaks and troughs, the direction of migration (ebb or flood), and the mean migration rate averaged over all crests and troughs can be determined (see Table 4.1). These results were visually checked by plotting a representative part of the profile in detail.

Vak A
Figure 4-1 provides a summary of the migration of the bedforms in Borndiep, based on Vak A Profile 6. The sedimentation-erosion map (Figure 4-1, lower right panel) illustrates that migration occurs uniformly over the bedform field and the selected profile seems representative for these changes.

Three of the four surveys (30-8-2017, 31-08-2017 and 06-09-2017), show similar values for mean bedform height (0.41 - 0.43 m) and a length of 7.1 to 7.2 m. Asymmetry values are negative, which indicates an ebb-dominant transport. The third survey (4-9-2017), showed a lower mean height of 0.34 m and longer wave length of 7.4 m. Also the mean asymmetry is lower and a near equal amount of flood and ebb-dominant bedform asymmetries were observed.

Between survey 1 and 4 an average 5 m migration of the crests and 4 m migration of the troughs occurs. This migration is towards the ebb-tidal delta, which corresponds to the bedform asymmetry. The migration rate is not constant through all four surveys. Only a minor migration is observed between 30-08-2017 and 31-08-2017. The bulk of the migration occurs over the longer timespan between 31- 08-2017 and 04-09-2017. During the last 2 days (04-09-2017 and 06-09-2017) migration is again limited, but the bedform height clearly increases.

Vak B
Bedform characteristics remain constant in all 4 surveys. The mean bedform height varies around 1 m with mean wave length of 21 m. All profiles show a near similar amount of bedforms with flood-dominant asymmetry (directed towards the inlet). The bedform field is more 3D in nature compared to Vak A, which is also reflected in the sedimentation-erosion patterns.

Despite the rather complex bedform field, the migration rate as observed in the profile can be clearly identified and quantified. Based on the selected profile, the mean migration rate is 7 m for both crests and troughs. Several of the bedforms show rates exceeding 10 m. A consistent migration is observed throughout the four consecutive measurements.

Vak C
Figure 4-3 provides a summary of the migration of the bedforms in Vak C based on Profile 2.
Small variations in the bedform characteristics are observed in profile 2. The mean height varies between 0.78 and 0.91m. The main bedform length remains similar at 21 meters. The

asymmetry remains positive, although the value and number of flood dominant bedforms differs.

The vast majority of the bedforms shows a flood-dominant migration (towards Borndiep), which is consistent with the observed asymmetry. Between the surveys, average migration rates are small between 1 and 3 meters, but up to 7m of migration in flood dominant direction also occurs. Troughs migration rates seem to exceed the crest migration rates. A detailed analysis shows that part of the migration is related to changes in the peak of the bedform that may influence the calculation of the migration rate. The migration rates are constant through all four surveys indicating that the migration is a net effect and is likely not the result of the prevailing flow conditions at the time of the survey. In addition to net migration, considerable height changes of the individual bedforms are observed.

Table 4.1 Overview of migration rates determined from the trough and crest positions for Tracks 1

Profile		***Direction (nr. bf)***				***Mean migration [m]***	
		Ebb		***Flood***			
		C	***T***	***C***	***T***	***C***	***T***
A	6	20	19	0	0	4.95	3.95
B	2	1	0	19	19	-6.95	-7.24
C	2	5	1	12	16	-1.23	-3.11

nbf = number of bedforms, C – Crest, T – Through

Table 4.2 Characteristics bedforms Vak A, B, C for surveys 1 through 4.

Profile				***Bedform characteristics***			***Bedform asymmetry***		
Vak / survey		***mean depth [m]***	***nbf****	***mean length [m]***	***mean height [m]***	***max height [m]***	***mean [-]***	***nbf positive (flood)***	***nbf negative (ebb)***
A	1	-23.20	18	7.17	0.43	0.60	-0.18	16	2
	2	-23.24	18	7.17	0.42	0.63	-0.14	7	11
	3	-23.41	17	7.35	0.32	0.50	-0.07	8	9
	4	-23.27	18	7.11	0.41	0.60	-0.14	4	14
B	1	-9.62	18	21.06	1.04	1.60	0.19	16	2
	2	-9.58	18	21.00	0.99	1.51	0.08	14	4
	3	-9.69	18	20.94	0.97	1.33	0.07	14	4
	4	-9.55	18	20.72	1.06	1.59	0.14	14	4
C	1	-7.59	16	21.19	0.91	1.44	0.30	13	3
	2	-7.52	16	21.25	0.87	1.40	0.14	11	5
	3	-7.65	16	21.31	0.79	1.36	0.27	14	2
	4	-7.72	16	21.38	0.78	1.41	0.09	10	6

** nbf = number of bedforms*

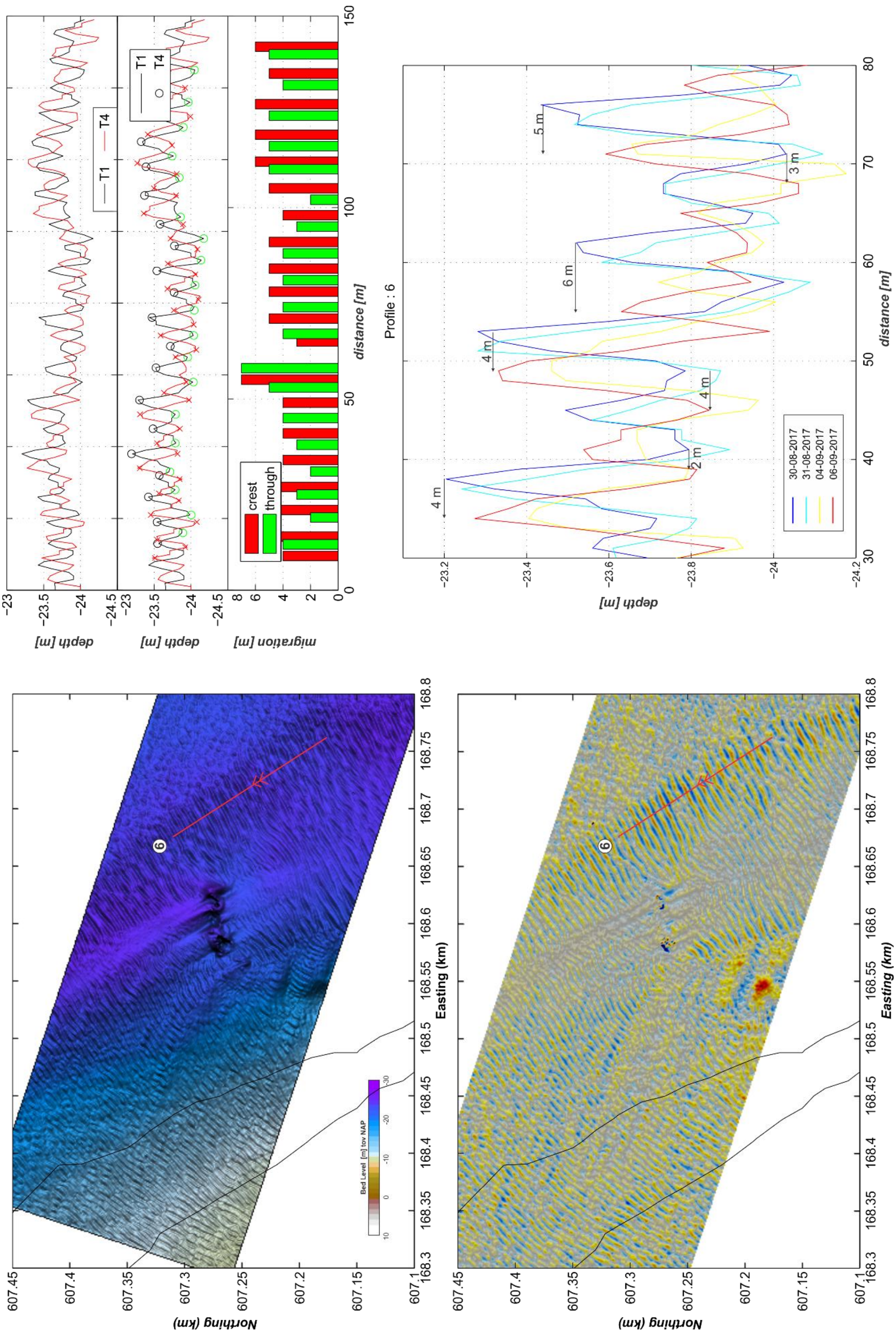


Figure 4-1: Summary plot for Migration of Vak A – Profile 2.

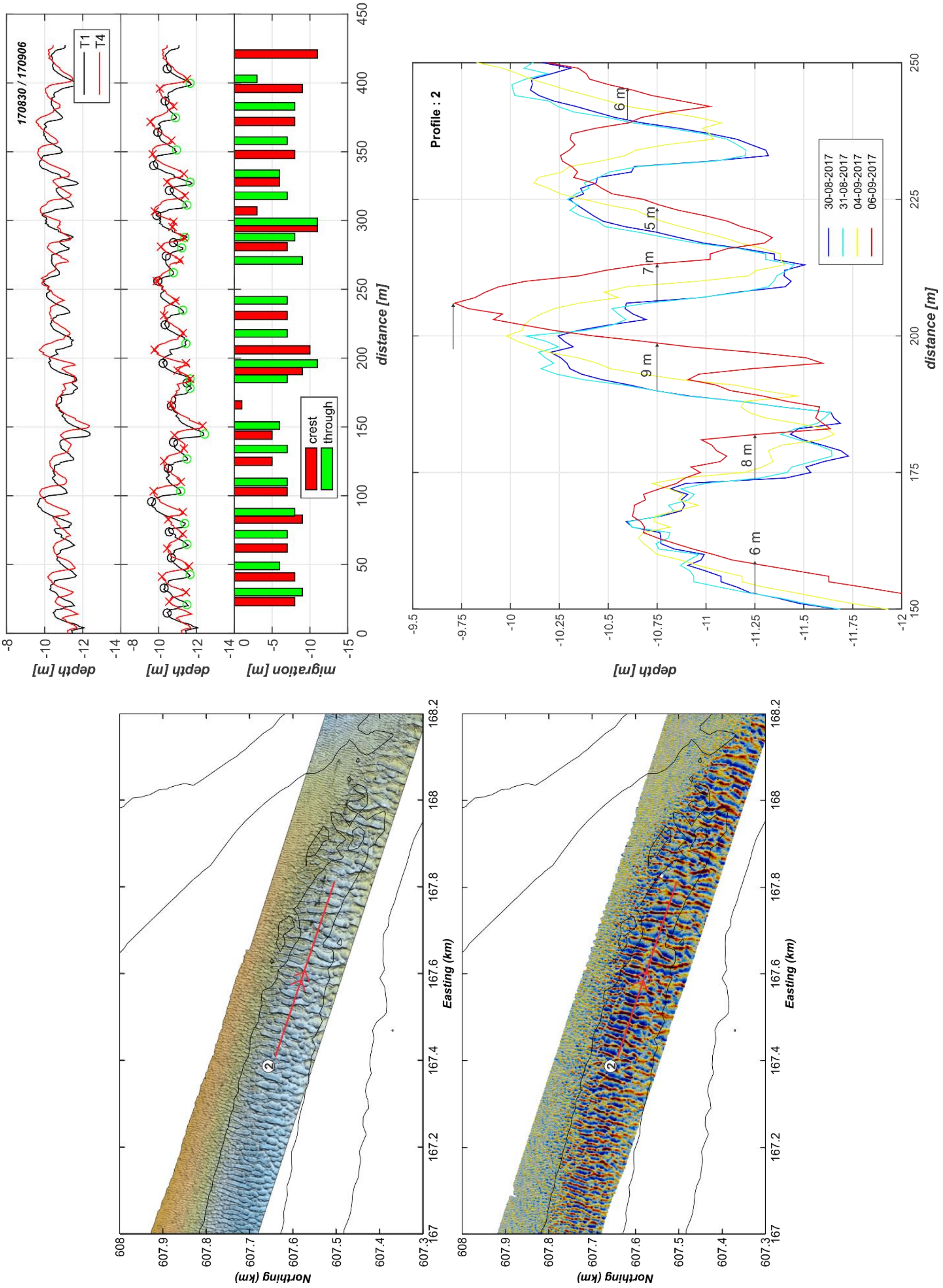


Figure 4-2: Summary plot for Migration of Vak B – Profile 2.

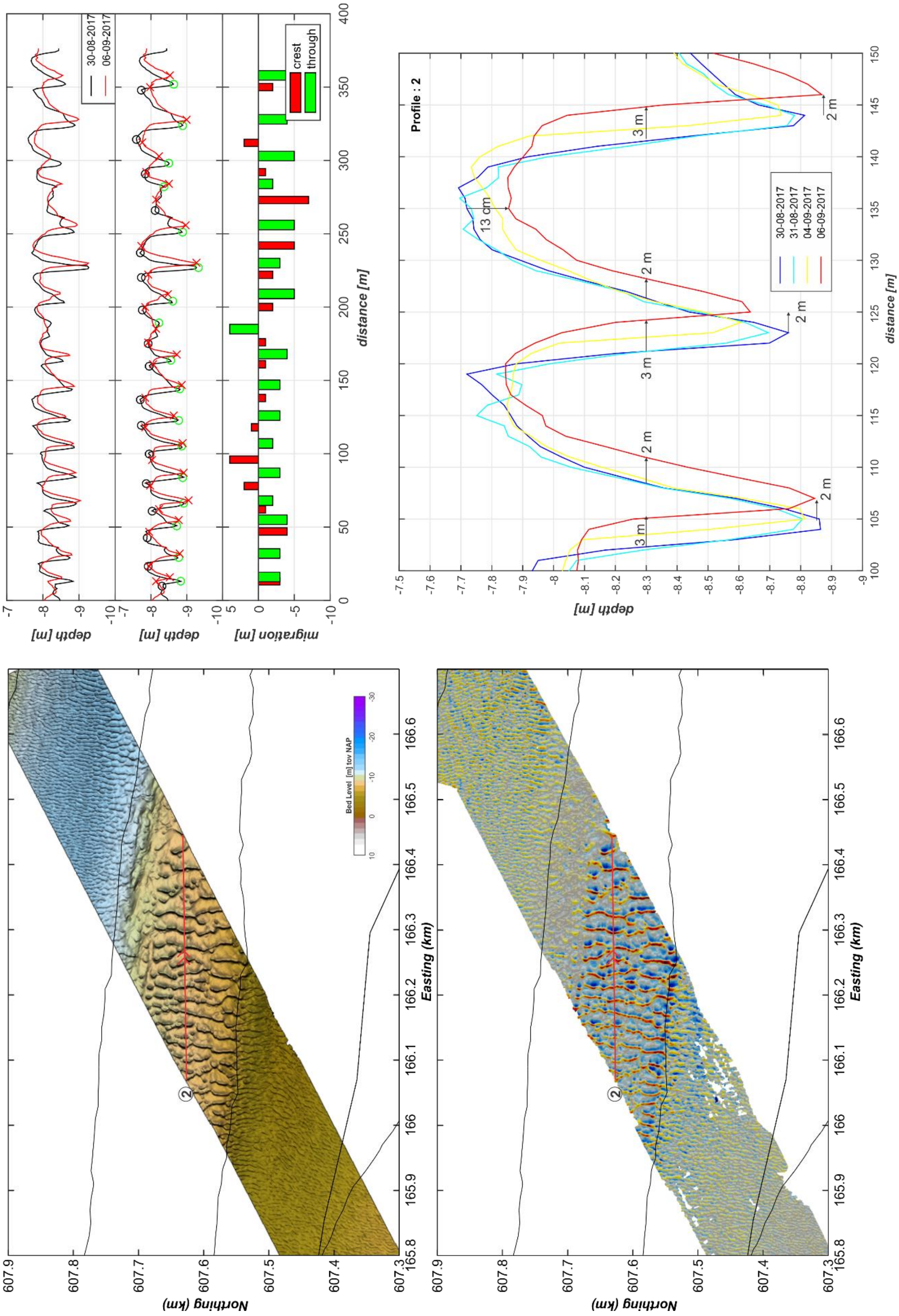


Figure 4-3: Summary plot for Migration of Vak C – Profile 2.

4.2 Multi-beam Surveys KG2: Repeat surveys in Borndiep (07-09-2018)

4.2.1 Introduction

A unique Mbes dataset was obtained in Vak D, located in the middle of the inlet throat. The multi-beam area covers an approximate 215 m wide and 1.16 km long area (Figure 4-4). Repeat surveys were performed from over a 7-hour window on 07-09-2018. In total 9 Mbes surveys were completed, covering a time frame from maximum flood- to maximum ebb velocities. An important question we aim to answer using these repeat surveys is: if and how the bedforms change size, shape or orientation over the tidal cycle. Is the asymmetry derived for these smaller bedforms representative for a long-term sediment transport pattern, or are they just a response to the local currents at the time of the measurement?

4.2.2 Bedform characteristics.

An initial analysis of the bedforms shows that larger bedforms are observed along the sides of the channel, and smaller bedforms occur in the deepest part (Figure 4-4). To characterize these bedforms, their changes and variability with the tidal velocities, 8 individual profiles were defined, perpendicular to the bedform fields, and analysed. For each profile, the peaks and troughs were determined and bedform statistics and migration calculated.

Using the Kustgenese Delft3D model (Nederhoff et al., 2018) the corresponding tidal flow velocities were computed (see Figure 4-5). The survey started at a time when flood velocities were present in Borndiep. At the location of KG2 Frame 3 these velocities are 1.7 m/s. Velocities gradually decrease to a minimum around noon. Surveys 1 through 5 cover the flooding period of the tide. Flow reversal takes place around noon (track 6). A half hour delay between the maximum water-level height versus flood-ebb reversal of the velocities is present. The ebbing phase of the tide is captured in surveys 6, 7 and 9. Peak ebb velocities with a maximum of 1.5 m/s occur around 13:30 (track 8). The peak ebb velocities of 1.5 m/s are slightly lower compared to the peak flood velocities.

The eight pre-defined profiles were used to classify the bedforms in the survey area. Figure 4-6 and Figure 4-7 summarize the profiles and identified peaks and trough’s. The calculated statistics for the beginning and end of the campaign (track 1 and 9) are summarized in Table 4.3. At the start of the experiment (track 1), the mean bedforms heights range between 0.21 to 0.65m. Larger bedforms are especially observed in profiles 8 and 9, towards the Ameland coast. In these profiles the mean heights is 0.59 to 0.65 m, with a mean wave length over 11 m. This classifies the bedforms as medium dunes. The bedform heights in profiles 2 through 7 are smaller. With mean heights varying between 0.21 and 0.39 m, these are classified as small dunes. Note that profile 4 is dominated by a large depth variation in the bathymetry with smaller bedforms superimposed on top of this fluctuation. These bedforms are small and variable which makes an exact definition of the peaks and troughs inaccurate. During this survey, all profiles have flood dominance in their bedform orientation, for both the asymmetry value and the number of bedforms. A similar analysis over track 9 (after maximum ebb) shows a distinct difference in bedform asymmetry as in profiles 7, 8 and 9, the bedform asymmetry reverses from flood-dominant to ebb-dominant.

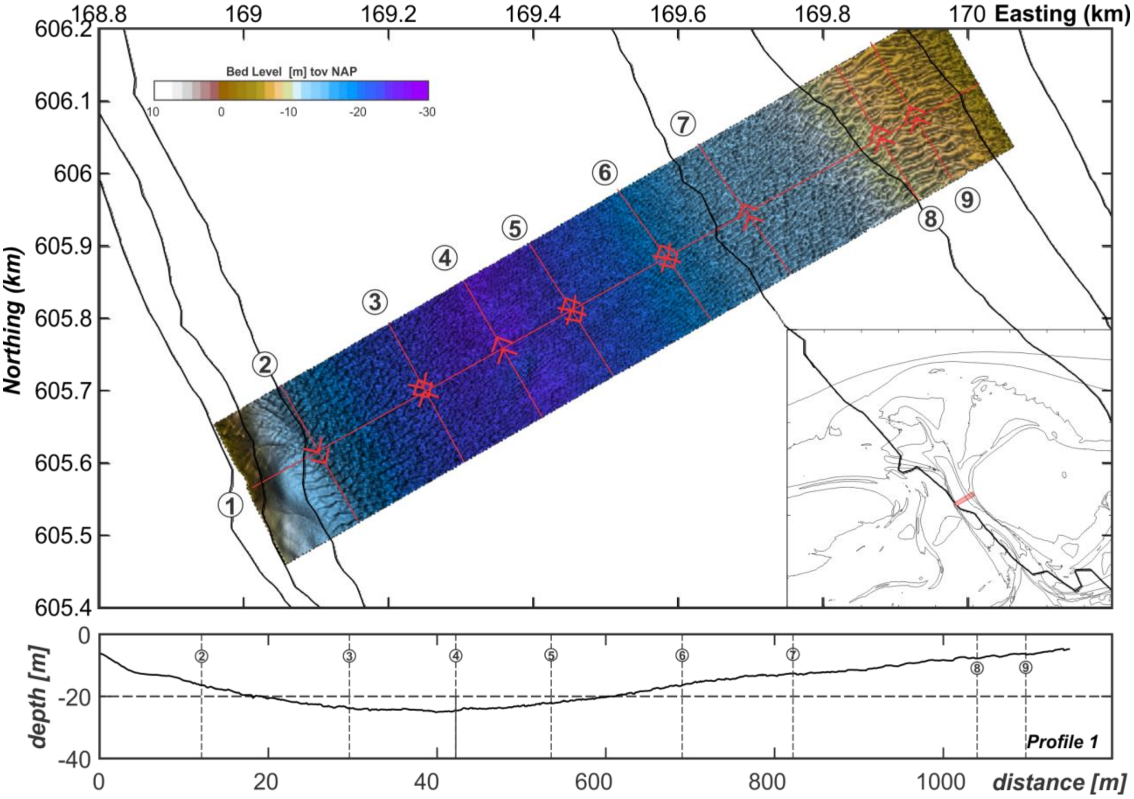


Figure 4-4: Rendering of the Mbes data obtained in Vak D on 07-09-2017 7:54/8:26 (Track 1). Red lines indicate the profiles 1-9 used in the analysis. Arrows indicate the estimated directions of bedform migration. Bottom panel: Cross-section Profile 1 and location of transects 1-8.

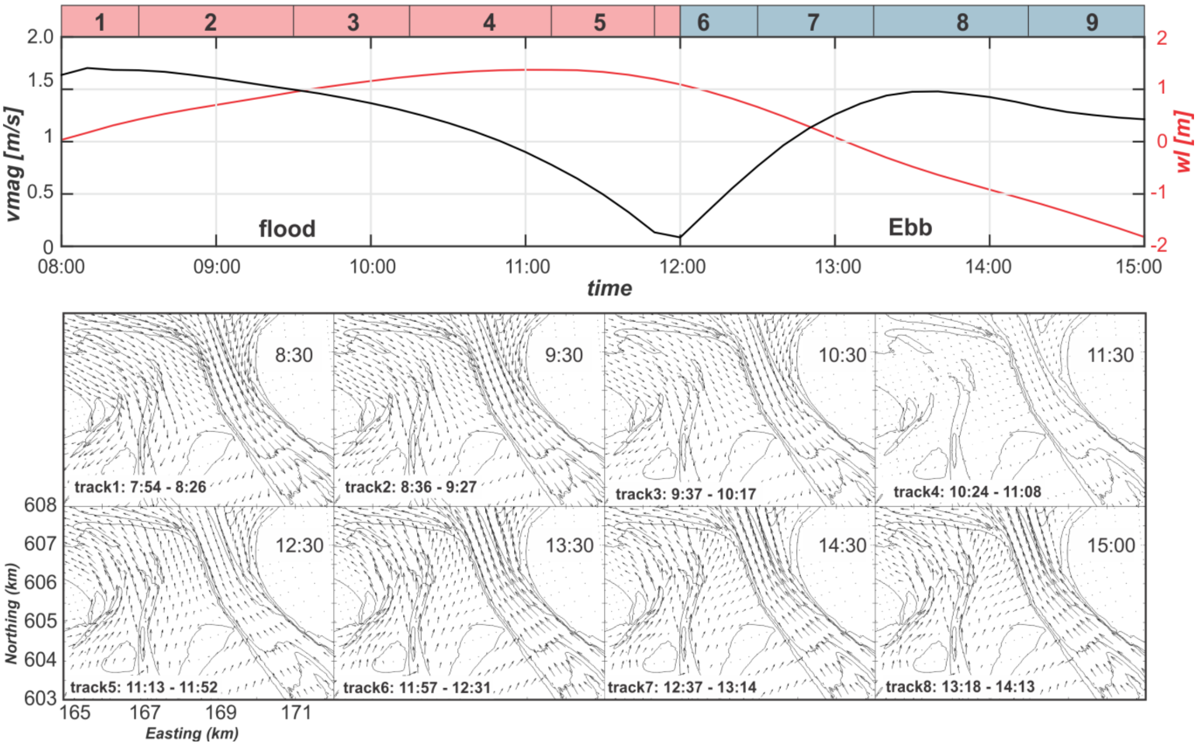


Figure 4-5 (top panel) Modelled velocity magnitude and water level computed at the location of KG2 frame 3 on 07-09-2017, Bottom panels: snap-shots of the flow fields in approximately hourly interval.

Table 4.3 Characteristics of the profiles covering Vak D (see Figure 4-4 for location), survey 07-09-2017 7:54/8:26 (track 1) and 07-09-2017 14:15/14:55 (track 9).

Profile				***Bedform characteristics***			***Bedform asymmetry***		
Track/ Profile		***mean depth [m]***	***nbf****	***mean length [m]***	***mean height [m]***	***max height [m]***	***mean [-]***	***nbf positive (flood)***	***nbf negative (ebb)***
1	2	-15.09	18	10.50	0.39	0.62	0.14	17	1
	3	-23.21	27	6.59	0.27	0.55	0.02	17	10
	4	-24.37	30	5.73	0.21	0.38	0.06	23	7
	5	-23.02	35	5.29	0.29	0.53	0.12	31	4
	6	-17.99	32	5.97	0.30	0.47	0.06	21	11
	7	-13.46	27	7.07	0.39	0.74	0.08	21	6
	8	-8.50	16	11.56	0.59	0.82	0.14	13	3
	9	-7.26	16	11.19	0.65	0.94	0.20	15	1
9	2	-15.10	18	10.56	0.42	0.66	0.10	15	3
	3	-23.23	23	7.48	0.35	0.56	-0.01	14	9
	4	-24.38	14	6.71	0.22	0.30	0.11	11	3
	5	-23.04	34	5.47	0.32	0.47	-0.03	24	10
	6	-18.00	30	6.03	0.32	0.54	-0.01	17	13
	7	-13.47	24	7.29	0.41	0.66	-0.14	6	18
	8	-8.47	17	11.12	0.48	0.69	-0.17	3	14
	9	-7.25	16	11.06	0.56	0.81	-0.13	7	9

**nbf = number of bedforms*

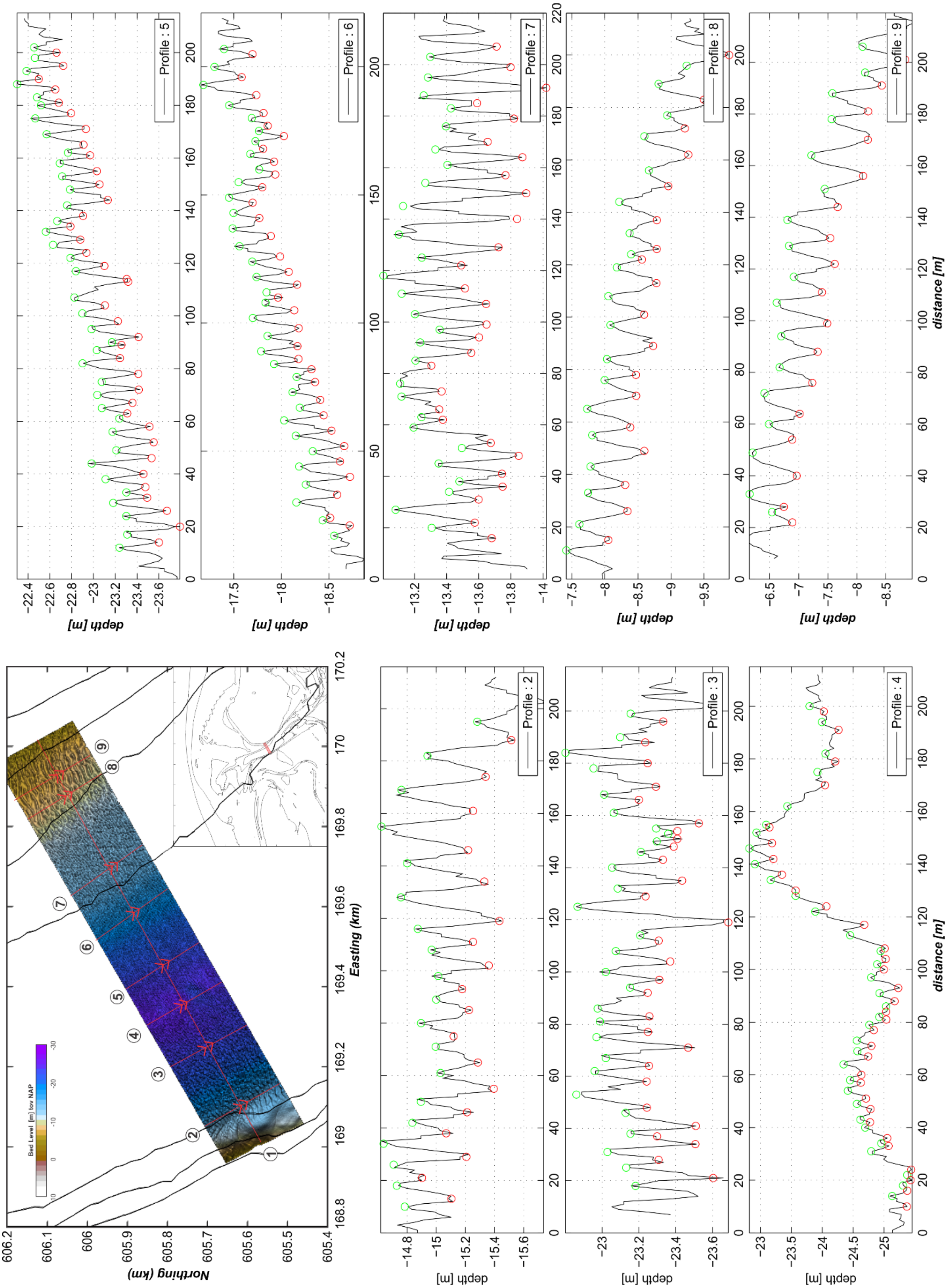


Figure 4-6: Overview of the bedforms identified in profiles 2 –98. survey 07-09-2017 7:54/8:26 (Track 1).

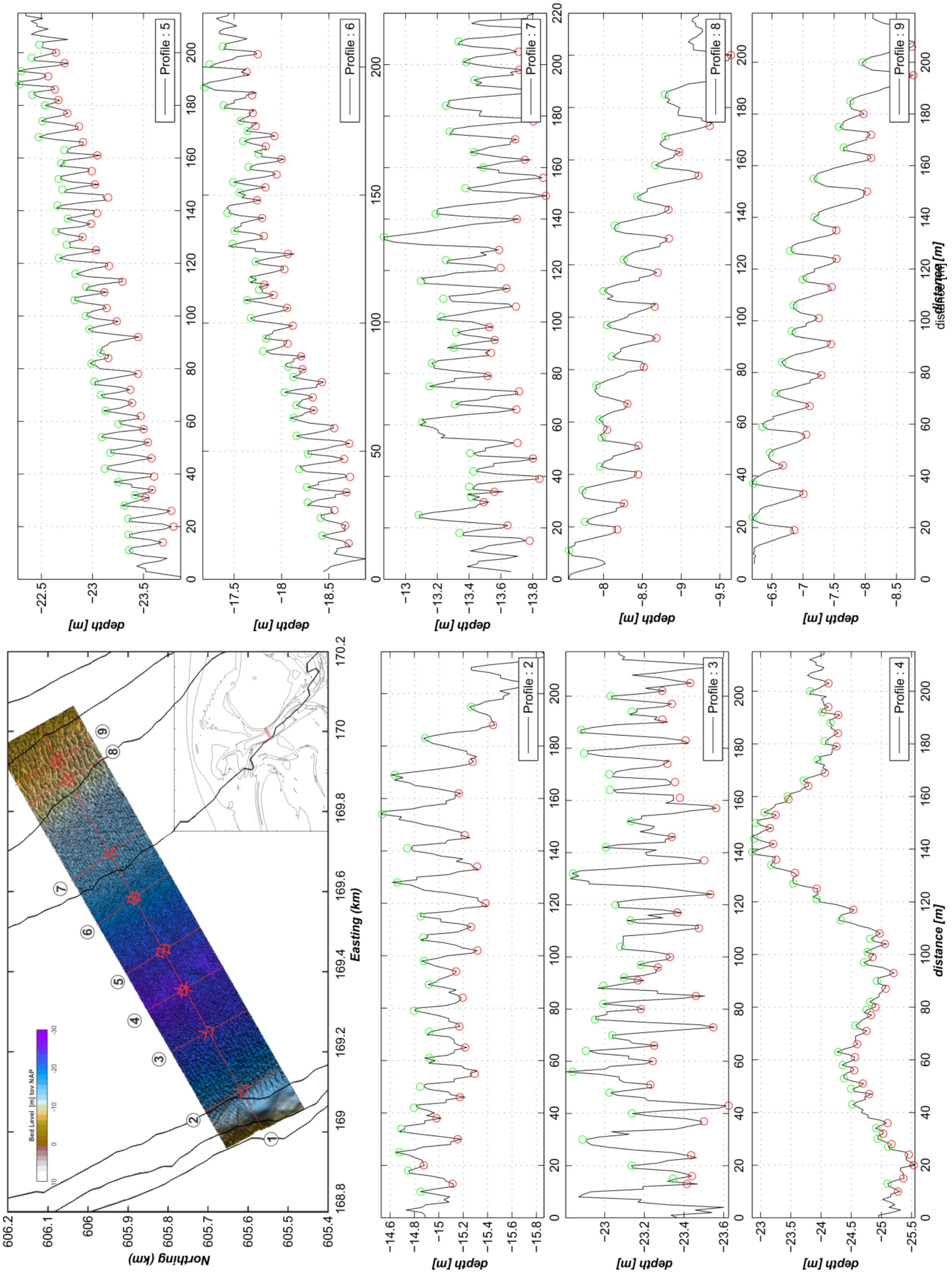


Figure 4-7: Overview of the bedforms identified in profiles 2 – 9. survey 07-09-2017 14:15/14:55 (Track 9).

4.2.3 Variability of bedform characteristics over the tidal cycle

An important question that needs to be answered is how these bedforms change over the tidal cycle. To answer this question, we have analysed the profiles 2, 6 and 8 (Appendix C, Figures C.1-3) and individual bedforms for each profile in (Figure 4-8).

Profile 2,
The four bedforms displayed in Figure 4-8, profile 2 are positioned roughly in the middle of the profile. The bedforms show limited motion through the tidal cycle, with near identical locations of the peaks and troughs. The observed vertical variations are around 10 cm. Bedforms appear to be structurally higher at track 9 (after maximum ebb) compared to track 1 (maximum flood). The observed total migration of the bedforms is limited. The troughs between the bedforms remain in place of the tide cycle, but the upper part of the profile moves with the dominant flow direction. In total this results in a near zero net displacement over the entire campaign.

A detailed analysis of the bedform statistics for each track (Table 4.4) reveals limited change (< 10%). The mean height varies between 0.37 and 0.42 m, and wave lengths vary between 9.94 and 10.61 m. In tracks 1 -7 a similar amount of ebb- and flood-dominated bedforms occur (10% and 90% respectively). Only tracks 8 and 9, after maximum ebb, show a larger amount of ebb-dominant bedforms (17 %). The asymmetry values of tracks 2-7 all show comparable values (0.21-0.26). Only tracks 1, 8 and 9, all taken during (or directly after) maximum velocities show a smaller value (0.10 – 0.14).

Bedform migration is illustrated in Appendix C, Figures C.1 and C.2. These figures reveal that over the experiment (T1-T9) no significant displacement of the bedforms occurs. The observed displacements that are in the 1 m range are mostly changes in the shape of bedform peaks and troughs, and are off the same magnitude as the sample resolution of the DEM.

Based on the behaviour of Profile 2, we must conclude that the bedforms remain consistent over the tidal cycle. The peaks of the bedforms do migrate with the ebb and flooding tide. The movements are in the order of 1 to 2 m, and height changes of peak and crest vary up to 10 cm. It must also be noted, that these variations are likely to be in the same order of magnitude as the measurement accuracy.

Profile 6,
The bedforms displayed in Figure 4-8 profile 6, show a clear migration during the tidal cycle, but little net total change. The bedform statistics show similar mean heights (0.30-0.32m) and length (around 6 m). The bedforms migrate in flood direction during tracks 1-4, remain fairly stable during track 5-7, and migrate in ebb direction during tracks 8 and 9. In total this results in a limited migration. A change in bedform asymmetry occurs (Table 4.4). In general, a clear flood -dominant asymmetry occurs through the flooding tide (> 92% of the bedforms during tracks 1 – 7). Tracks 8 and 9 both show a negative bedform asymmetry. In track 8 this still small negative asymmetry value results from a near-equal amount of ebb- and flood dominant bedforms. The larger negative value in track 9 results from a dominance of the ebb-dominant bedforms (65%).

Profile 8 (and 9),

The bedforms displayed in Figure 4-8, profile 8 show both migration and clear changes in height over the tidal cycle. During the flooding tide a clear signal is present, with down-drift migration of the bedforms (towards the basin) and well-defined (constant) bedforms. During the ebbing tide an opposite trend prevails. Bedforms show a migration in ebb-dominant direction (towards the sea), reduce in height and change shape. In total the bedforms show a flood dominant migration (towards the basin). A noticeable change is present in bedform asymmetry (Table 4.4). Overall, a flood -dominant asymmetry occurs through the flooding tide (tracks 1 – 7). Tracks 8 and 9 show a clear flood asymmetry in both values as number of bedforms (75-82%). In addition, the bedform heights reduce from around 0.66m to 0.48 m.

The time-stack image of Appendix C, Figures C.3 shows a more distinct image of how this migration occurs. Up to track 7, all profiles show similar bedforms in number and shape. These bedforms all migrated slightly in flood dominant direction. The bedform asymmetry of most bedforms is consistent with this migration. Tracks 8 and 9 show the transformation from flood-dominant to ebb-dominant bedforms. These bedforms migrate in ebb-dominant direction. As this latter migration is smaller than the migration during track 1-7, the total still results in a net flood dominant displacement. In the adjacent profile 9 (Appendix C, Figures C.4), a similar process occur. However, here the net ebb-displacement during tracks 8 and 9 exceeds the flood-displacement resulting in a net ebb-dominant movement.

In conclusion, in Borndiep:

- Bedforms migrate in ebb- and flood direction depending on the tides.
- The total net migration over the tidal cycle is limited. Migration rates vary over the tide cycle (positive and negative) and over the cross-section. Largest migration is observed along the Ameland coastline.
- Most of the bed forms retain similar height and length over the tidal cycle. The exceptions are the larger bedforms in profiles 8 and 9, which considerably reduce in height during (after) peak-ebb- and flood.
- Bedform asymmetry can reverse over the tide cycle.

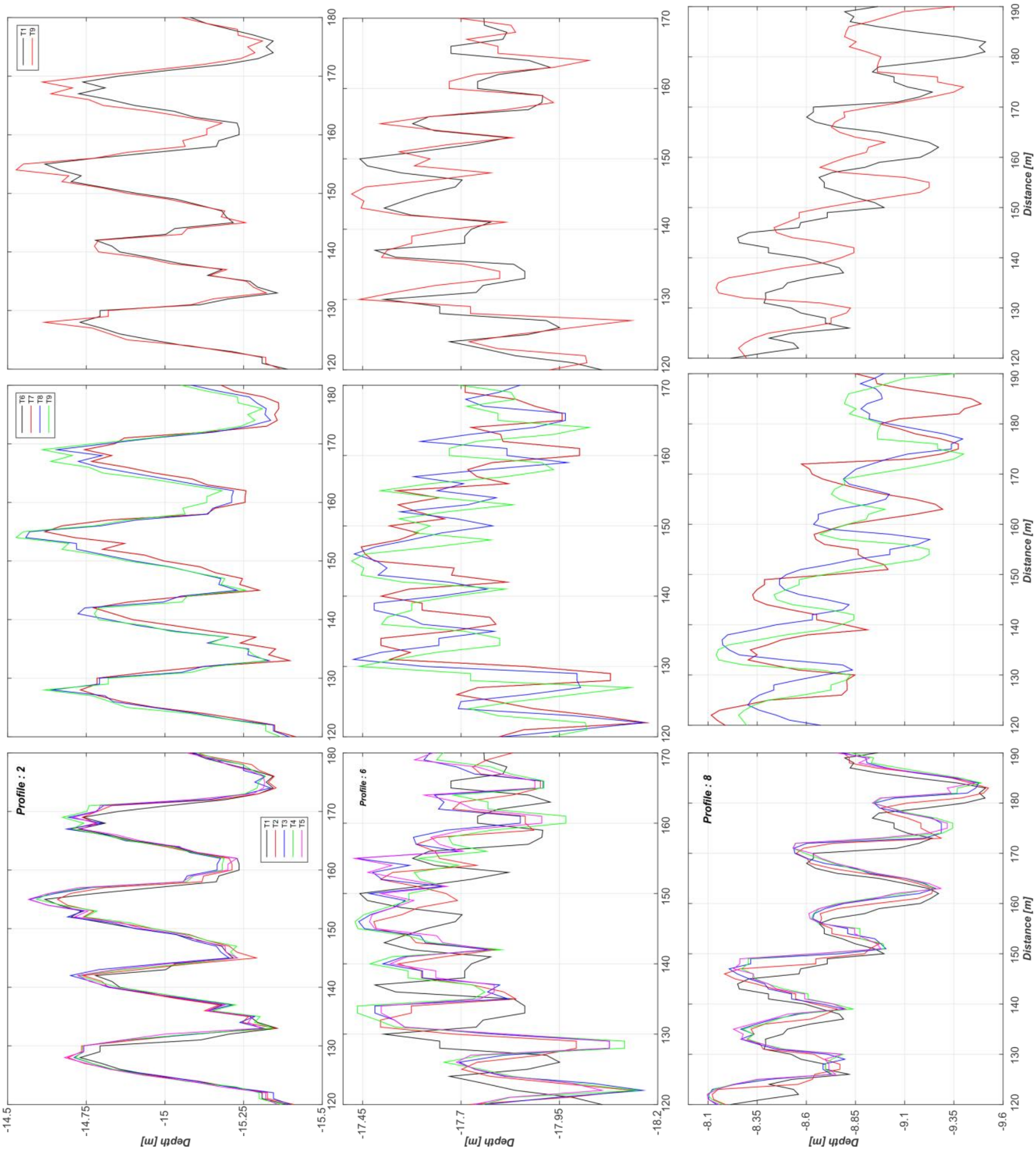


Figure 4-8: Detailed maps of individual bedform changes over the tidal cycle. From left to right, profile 2, profile 6 and profile 8. Numbers T1-8 refer to the survey tracks (see Figure 4-5). Lowest figures show the changes during the flooding tide (T1-5) and middle figures changes during the ebbing tides (T6-9), and top figgures summarize the total change (T1 and T9). See Appendix C, C1-3 for detailed figures of the complete tracks.

Table 4.4 Overview of migration rates determined from the trough and crest positions for Tracks 1, 6 and 8.

Profile				***Bedform characteristics***			***Bedform asymmetry***		
Track/ Profile		***mean depth [m]***	***nbf****	***mean length [m]***	***mean height [m]***	***max height [m]***	***mean [-]***	***nbf positive (flood)***	***nbf negative (ebb)***
2	1	-15.09	18	10.50	0.39	0.62	0.14	17	1
	2	-15.09	18	9.94	0.37	0.65	0.25	18	0
	3	-15.09	18	10.39	0.40	0.62	0.21	16	2
	4	-15.09	18	10.61	0.40	0.64	0.22	17	1
	5	-15.07	17	9.94	0.39	0.65	0.26	17	0
	6	-15.12	18	10.61	0.41	0.66	0.24	18	0
	7	-15.12	18	10.61	0.41	0.66	0.23	18	0
	8	-15.10	18	10.56	0.42	0.66	0.10	15	3
	9	-15.08	18	10.56	0.40	0.68	0.10	15	3
6	1	-17.99	32	5.97	0.30	0.47	0.06	21	11
	2	-17.98	31	6.13	0.30	0.49	0.13	29	2
	3	-17.94	29	6.17	0.31	0.50	0.16	27	2
	4	-17.98	31	6.13	0.31	0.52	0.16	29	2
	5	-17.97	28	6.29	0.32	0.52	0.22	26	2
	6	-17.98	32	5.94	0.30	0.50	0.25	31	1
	7	-17.98	30	6.07	0.31	0.50	0.22	27	3
	8	-18.00	30	6.03	0.32	0.54	-0.01	17	13
	9	-17.96	32	5.97	0.31	0.51	-0.15	11	21
8	1	-8.50	16	11.56	0.59	0.82	0.14	13	3
	2	-8.50	16	11.50	0.63	0.87	0.23	15	1
	3	-8.49	16	11.44	0.66	0.95	0.22	12	4
	4	-8.48	16	11.50	0.66	0.89	0.26	14	2
	5	-8.45	17	10.82	0.62	0.77	0.30	17	0
	6	-8.51	16	11.50	0.66	0.90	0.23	15	1
	7	-8.51	16	11.50	0.66	0.90	0.23	15	1
	8	-8.47	17	11.12	0.48	0.69	-0.17	3	14
	9	-8.47	16	11.31	0.48	0.70	-0.12	4	12

** nbf = number of bedforms*

4.3 Summary

The multi-beam surveys obtained in Ameland inlet show the presence of multiple bedform fields (see Figure 5.1 for a summary overview). Analysis of these bedform fields can provide valuable information on the prevailing sediment transport directions. Especially, multi-beam survey 17-04-2012 provides us with a detailed picture of the sediment transport directions through some of the major channels in Ameland Inlet. At the western outflow of Westgat sediments are flood dominant in the channel, transporting sediments towards Borndiep, and ebb-dominant to the south. The outflow of Borndiep towards the ebb-tidal delta is ebb-dominant. Only along the coast of Ameland a flood dominant transport prevails. However, the coastline directly faced by Borndiep is governed by ebb-dominant bedform asymmetries. In the centre of the inlet gorge, a flood-dominant transport prevails, except locally along the southern embankment a flood-dominant (basin-ward) transport is observed. Flood dominant transports are also observed onto the shoal that separates the eastern (Dantziggat) and southern (Kromme Balg) fork of Borndiep. Measurements in Kromme Balg are not present, but the three profiles leading into the channel all point to a flood-dominant transport. The majority of the profiles in the section of Borndiep that leads to Dantziggat show an ebb-dominance. The most basin ward profiles show ebb-dominant transport directed onto Kikkertplaat, and a flood dominant transport in the deepest parts of Dantziggat.

The analysis of Vakken A, B, C from the Kustgenese 2.0 Mbes surveys provides us with: (1) corresponding areas in which bedforms are present, and (2) similar bed-form asymmetries and bed form migration patterns. This correspondence illustrates that these bedform field are consistent over time and can therefore help to identify sediment transport directions and patterns on the ebb-tidal delta. These conclusions are however not completely trivial. The detailed analysis of Vak D, in which bedform characteristics are determined over the tidal cycle, indicates that bedform asymmetry and migration can depend on the local flow velocities during the survey.

Lessons learned in relation to morphodynamic modelling:

- The consistent and coherent bedform fields and asymmetries on the ebb-tidal delta provide valuable (or maybe even our only) validation datasets for the larger-scale sediment transport patterns. Such datasets cannot be easily obtained otherwise.
- The absence of distinct bedform measurements and asymmetries in the inlet gorge makes these datasets less suitable for model validation. However important lessons are learned.
  (1). Only small bedforms are present in the central part of the inlet gorge were flow velocities are large. This observation is in contrast to the numerical models that tend to predict larger bedforms in the main channels.
  (2). No clear migration of the bedforms seems to occur in the central channel over a tide cycle. This indicates that net bed-load sediment transports may be small.
  (3). Larger bedforms and migration rates are observed along the sides of the channel. This may indicate that most of the net sediment transports occur along the sides of the inlet gorge. This provides valuable concepts for model testing and analysis.

5 Discussion

The basic principles behind the ebb-tidal delta formation are simple. The classic studies of e.g. Hayes (1975, 1979), Oertel (1975) and Hubbard et al., 1979 show that the morphology of an ebb-tidal delta is formed as a balance between wave- versus tidal-energy. The ebb-currents accelerate in the narrow constriction of the inlet gorge, and a sediment laden ebb current enters the open sea. In the open sea, the tidal flow segregates, current velocities drop below the sediment transport threshold value and the sand is deposited, forming a shallow shoal called terminal lobe. Wave shoaling and breaking on these shoals tends to move these sediments landwards. The balance between the wave and tidal processes, determines the morphology of an ebb-tidal delta. Wave-dominated ebb-tidal deltas are comparatively small and pushed close to the inlet throat, whereas tide-dominated ebb-tidal deltas extend offshore. This principle holds for the large-scale of the ebb-tidal delta system, but also for the individual elements that exist on the ebb-tidal delta (such as ebb and flood channels, channel-margin linear bars, terminal lobes and swash-bar patterns). Analysis of the distribution, evolution, shape and size of these elements can provide a first indication of the sediment transport paths and directions. In this study, we therefore analysed recently obtained bathymetric maps, though 3 levels of interpretation. Firstly, we used the *Vaklodingen* maps to analyse the morphologic features present, their distribution, and shapes and sizes. Secondly, we determined the morphological changes on decadal to yearly timescales, and thirdly, we analysed bed-form characteristics of detailed *Mbes* surveys. Based on this analysis, we can better describe the sediment dynamics of the present-day Ameland inlet, and summarize these dynamics in a conceptual model (Figure 5-1).

The main channel on the ebb-tidal delta is Borndiep. In the inlet gorge this channel is governed by an ebb-dominant flow (Elias et al. 2017), and it is likely that the outflow of Borndiep has an ebb-dominant sediment transport onto the ebb-tidal delta. This transport direction is confirmed by prevailing bedforms. In 2005, most of the sediments were delivered directly to the ebb-tidal delta front, as Akkepollegat extended seaward and a large volume of sand is visible in front of the channel. Ever since, the formation of 2 ebb-chute and ebb-shield systems has dominated the developments, and sediment transport delivery to the western part of the ebb-tidal delta (Kofmansbult) has been increasingly dominant. The steep bed-slope gradients on the seaward side of these features indicate that an outbuilding due to tidally-driven sediment supply from the ebb-chutes exists. Wave breaking and related sediment transports on these ebb-shield shoals are likely to drive sediments landward and eastward. As a result, the ebb-shield shoals not only migrate seaward but also eastward. The ebb-shield outbuilding into Akkepollegat constrains the flow (and related transports) even further, contributing to the growth of the ebb-chute and shield systems. In addition, the reduced efficiency of Akkepollegat resulted in a reduced sediment supply to the ebb-tidal delta front. Initially, this front showed an outbuilding due to abundant sediment delivery, but recently we observe two trends; Firstly, a lowering of the shallow area of the ebb-delta front (roughly above -5m NAP) as wave-driven transports now dominate, the sediments are pushed landward. Secondly, in the deeper portions (roughly below -5m NAP) east of Akkepollegat, the ebb-delta front shows an outbuilding as sediments are transported eastward along the edge of the ebb-tidal delta. These transports are likely a combination of wave-driven and tidal flow and transports due to flow contraction and acceleration of the along-shore North-Sea tides around the steep slope of the ebb-tidal delta. This mechanism of shoal-by-passing along the edge of the ebb-tidal delta was also observed in the formation, migration and finally attachment of Bornrif Bankje (in 2017).

As tidally-driven sediments primarily accumulate on the western margin (distal part) of the ebb-tidal delta, and migrate along the eastern margin of the ebb-tidal delta front, the distal part of the Bornrif platform is sediment starved. Wave dominance introduces a net landward transport resulting in a lowering of the seaward part of the Bornrif shoal, and sediment accumulation towards the coast. Although this seems contradictory, the landward sediment transport introduces an increased erosion of the island coastline. This is a commonly observed phenomenon and related to the constriction and contraction of (flood) flow velocities between the coastline and advancing ebb-tidal delta. Typically for ebb-tidal delta is a dominant residual ebb-tidal velocity in the main channel, while residual flood velocities occur on either sides of the channel along the island coastlines. As the ebb-tidal delta shoal increases in height, it constricts (and traps) the flow velocities between the advancing ebb-tidal delta and the coast. As a result, often a channel forms directly along the coastline that introduces (temporarily severe) coastline erosion, but also slows the advance of the ebb-tidal delta (a perfect example of such process is the Molengat channel in Texel Inlet). The landward wave-driven sediments are transported along the coast by the tidal velocities in the channel and accumulate in the shoals that are starting to form on either side. Depending on the sediment supply, these shoals can grow to such dimensions, that they overwhelm the channel and episodically attach to the coastline (e.g. Bornrif Strandhaak), or they temporarily grow and finally dissipate when sediment supply reduces or stops due to larger-scale changes on the ebb-tidal delta. The bedforms at Ameland Northwest confirm a sediment transport that is directed towards Borndiep.

Note that in addition to the mechanisms described above, erosion of the Ameland coastline can also be driven by waves as was demonstrated in the study of Nederhoff (2017). The modelling of this study was based on a relative deep and buildout Bornrif. In such configuration waves can more easily penetrate the ebb-tidal delta and reach the coastline. Model simulations using Delft3D showed that the location of the divergence point of the (wave-dominated) sediment transport corresponds with the observed erosion hot-spot. These analysis clearly illustrate the importance of understanding processes and mechanisms in detail over a range of time and spatial scales, as different processes can drive a similar coastline response (erosion).

The processes in the south-east portion of the ebb-tidal delta (between Westgat, Boschplaat and Borndiep) are less clearly defined. The morphodynamic changes are dominated by the variability of the smaller scale channels and shoals. A clear signal however, is the ongoing erosion of the tip of Terschelling Boschplaat. Earlier studies (e.g. Elias, 2017) hypothesize that part of this erosion is related to increased wave exposure as the present-day (over the last decade) ebb-tidal delta facing Boschplaat was relatively deep. This allowed waves to propagate far onto the ebb-tidal delta, coast and into the inlet gorge, introducing larger, eastward, wave-driven transport along the coast into the inlet (Boschgat area). The sediment accumulation on the shoals between Boschplaat and Borndiep supports such hypothesis. It is likely that the future development of Westgat, will for a large part determine the future of the Boschplaat area. At the moment, bedforms indicate that Westgat is still a flood-dominant channel. However increasing sediment accumulation seaward of Westgat, provides an early indicator of a potential increase in ebb importance. With the decreased efficiency in Akkepollegat, a reorientation of the main ebb-channel is likely. If such reorientation occurs at the location of Westgat, large scale alterations of the system are to be expected. Basically, a main channel configuration as it existed around 1975 would reform, allow the western (and landward) margin of the ebb-tidal delta rebuild, providing wave sheltering for the Boschplaat region. Such change could also result in a renewed connection between Boschgat and the open sea. As Westgat becomes more ebb-dominant, flood flow is likely to be directed more to the south, promoting the formation of larger channels towards Boschgat. Increased channel erosion is visible in the recent sedimentation and erosion patterns.

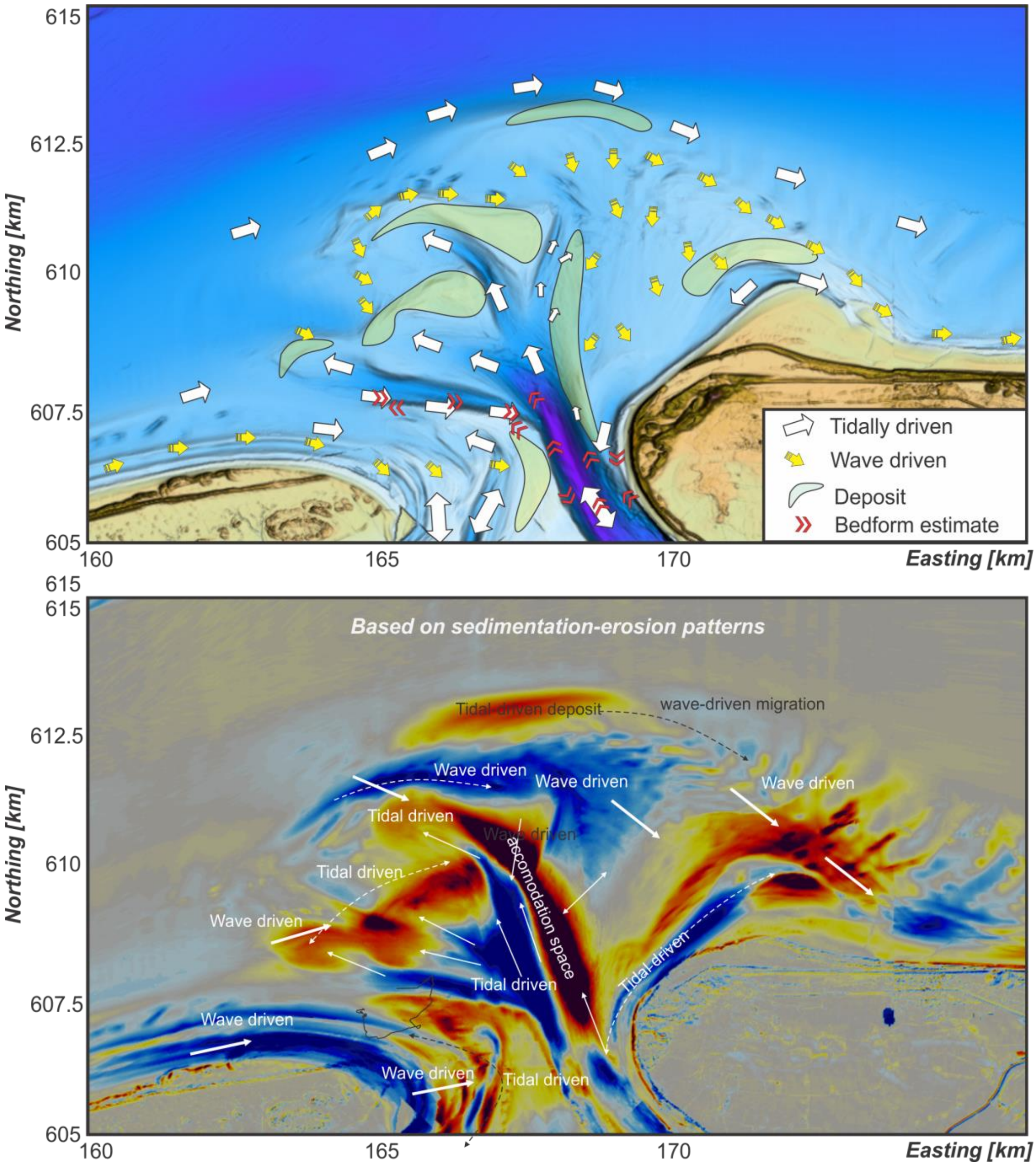


Figure 5-1: Summary of the observed sediment dynamics at Ameland inlet. Top panel: 2018 bathymetry with estimated sediment transport patterns and main sediment transport processes (waves versus tides). Bottom panel: observed morphodynamic changes over the 2005-2018 time-frame.

6 Conclusions

In this report we presented data and research undertaken in the framework of KPP – B&O Kust. Kustgenese 2.0.and the EU Interreg NSR project Building with Nature (work package 1). The combined efforts have resulted in unique data and research findings that allow us to better understand the ebb-tidal dynamics of Ameland inlet and similar systems in the Wadden Sea.

Unique high-resolution surveys are present at Ameland inlet, which allows us to investigate, analyse and better understand the morphodynamic changes on its ebb-tidal delta. Near yearly coverage of the ebb-tidal delta over the past decade, displays how initial small-scale perturbations in the central part of the ebb-tidal delta (the ebb-chute and shield systems) develop, grow, migrate and start to dominate the developments of the entire ebb-tidal delta. Only through the continuation of these frequent measurements by the Kustgenese 2.0 campaign we can fully start to understand the potential impacts on the coastal system. The realisation that small-scale perturbations result in ebb-tidal delta scale relocation of channels and shoals has important implications for the future morphodynamic modelling of the area. These morphodynamic models will have to contain sufficient resolution and detailed processes to capture such distortions.

The Kustgenese 2.0 measurements allow us to investigate the sediment budget, and quantify morphodynamic change in detail. A sediment budget of the Ameland ebb-tidal delta based on the 2005 and 2016 bathymetry shows a net change of +6.5 mcm or 0.6 mcm/year of sediment accretion. Additional sediment budgets over the 2016-2017 and 2017-2018 show yearly changes of +0.9 mcm and -1 mcm respectively. These net changes are small compared to the gross changes of 37 to 38 mcm. The half-yearly changes computed from the 2017 (1) and (2) bathymetries show significantly smaller gross changes (6 mcm). The difference in coverage, cannot explain the significant difference between the half-yearly and yearly gross change. It is hypothesized, that for the present-day ebb-tidal delta configuration, waves have a dominant impact. The observed ebb-shield and chute formation on the ebb-tidal delta has resulted in the formation of distinct, well-developed shoals. Waves and wave-breaking related sediment transport on these shoals are likely to have a large impact on the morphodynamic change. The larger changes during the more energetic winter season conditions confirm this hypothesis.

The high-resolution multi-beam data obtained in Ameland inlet show the presence of multiple bedform fields. The analysis of these bedform fields provides valuable information on the prevailing sediment transport directions. Such knowledge is essential for the future validation of our process-based sediment transport models. Based on these surveys, we are able to construct sediment transport patterns for the proximal part of the ebb-tidal delta. The most important conclusions are that Borndiep is primarily ebb-dominant and Westgat flood-dominant. These transport directions correspond to the sediment transport patterns derived from the morphodynamic changes. Correspondence in repeat surveys on the ebb-tidal delta confirm that (1) bedform asymmetry is an indicator for bedform migration, and (2) coherent, consistent, bedform fields occur continuously, as proven by the repeat surveys. The latter statement is not only based on the repeat surveys taken during the Kustgenese campaign, but also through comparison with a multi-beam survey taken in 2012. These conclusions are however not completely trivial. The detailed analysis of changes in bedform orientation in

Borndiep over the tide cycle (Vak D) shows that at this location, bedform asymmetry and migration can depend on the local flow velocities during the survey.

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A Migration rates of ebb-tidal delta contours

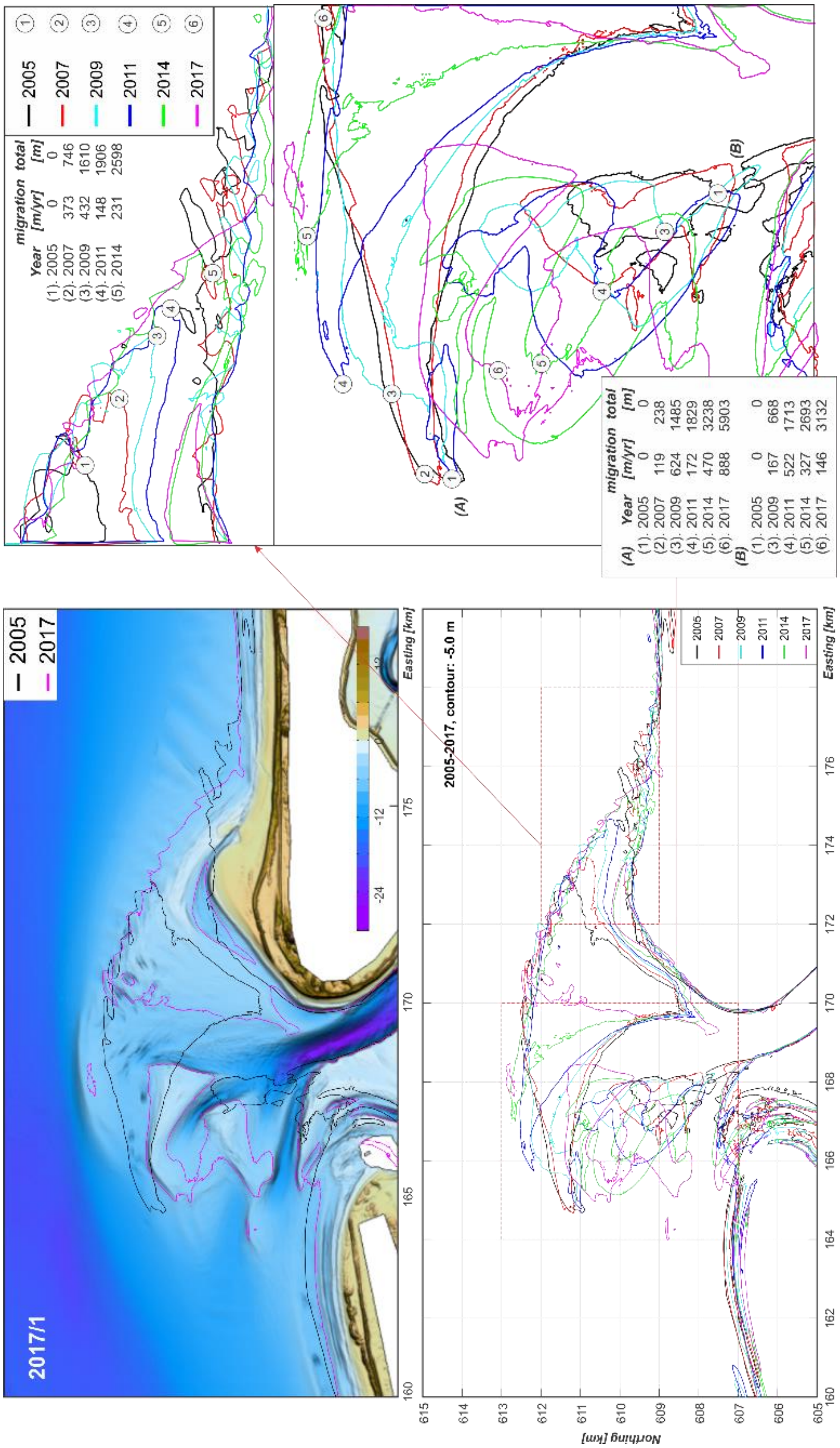

Figure A.1 Migration of the -5 m depth contour between 2005-2017.

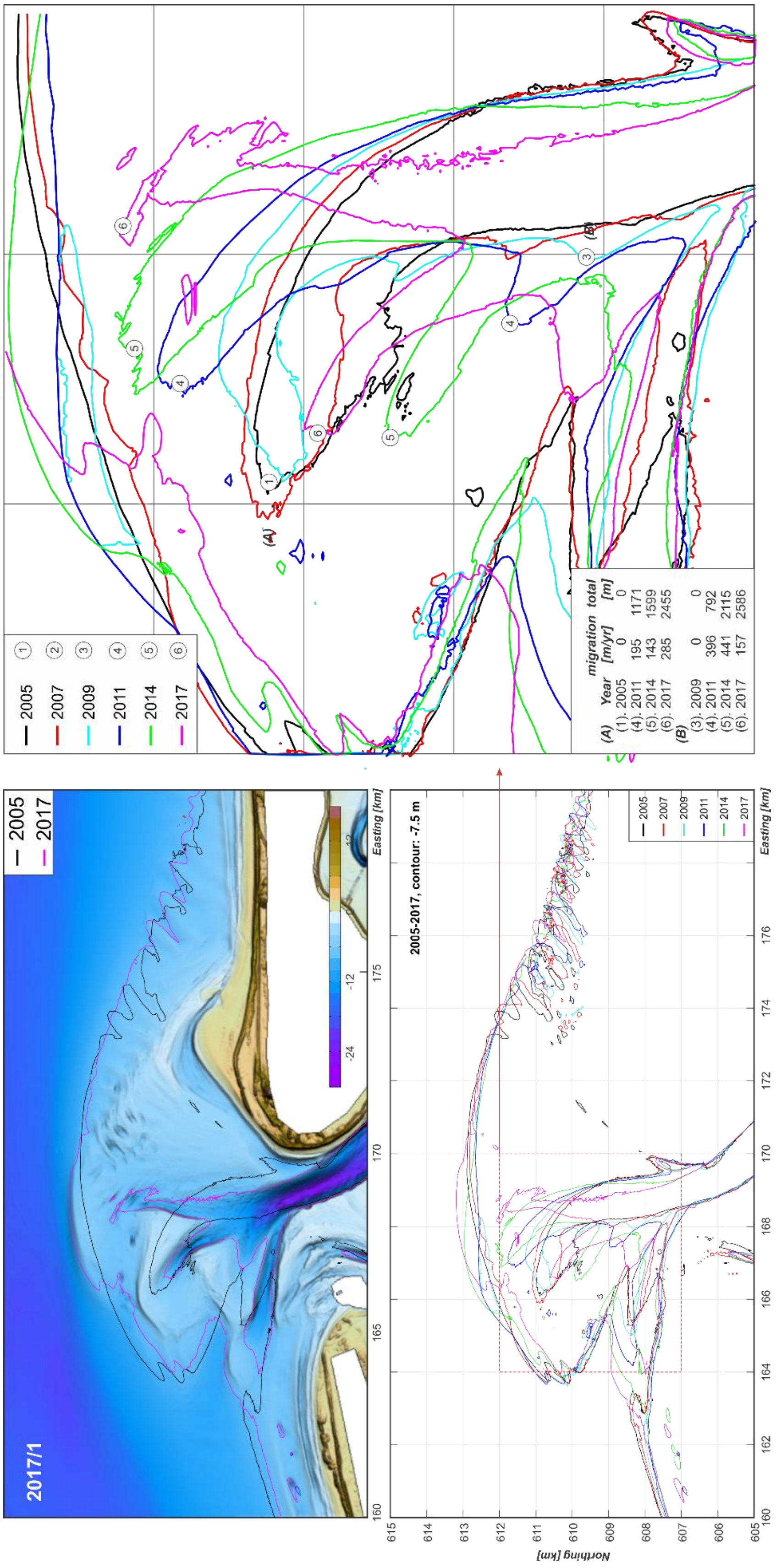

Figure A.2 Migration of the -7.5 m depth contour between 2005-2017.

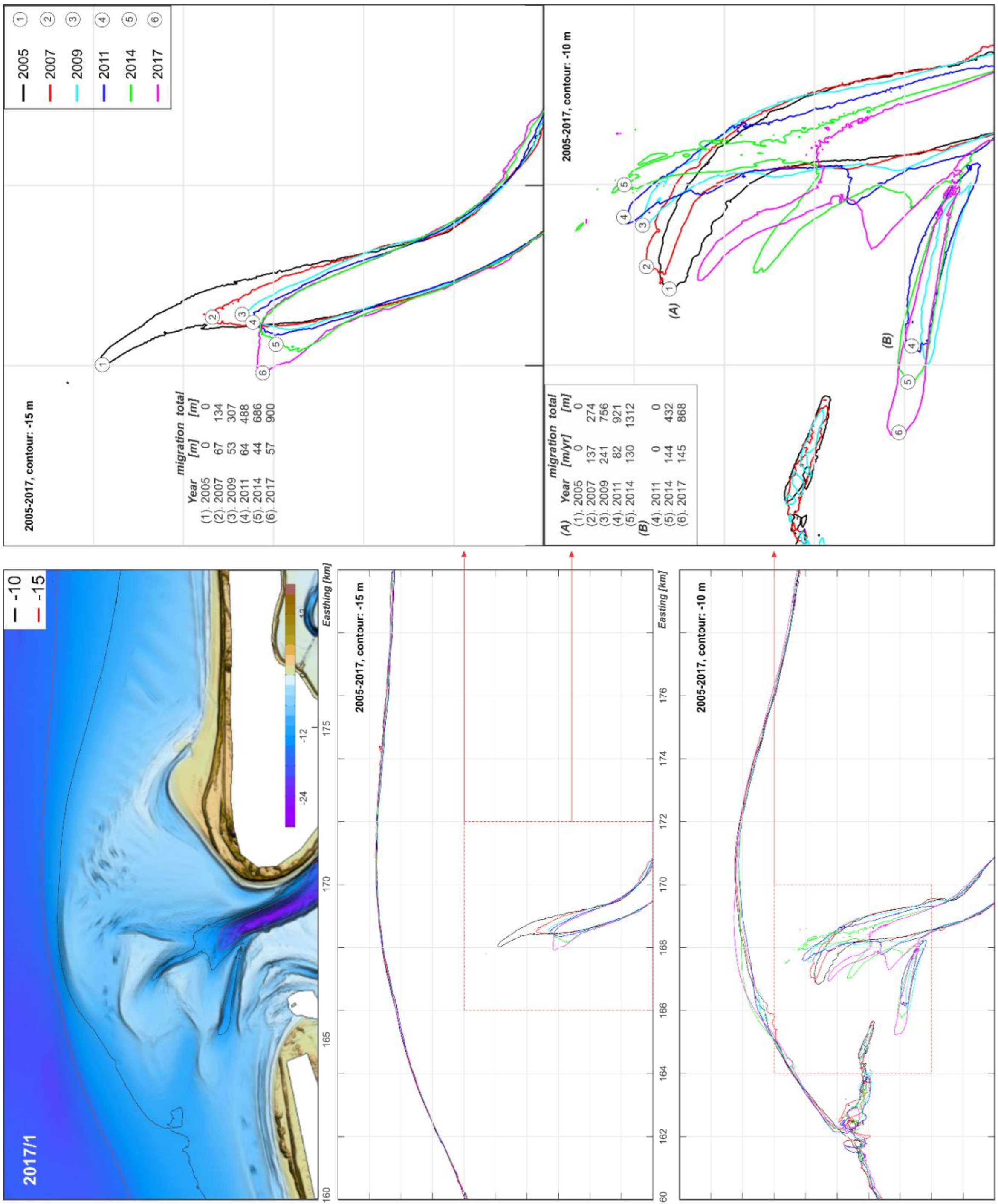

Figure A.3 Migration of the -10 and -15m depth contour between 2005-2017

B Bedform analysis: Mbes 17-04-2012

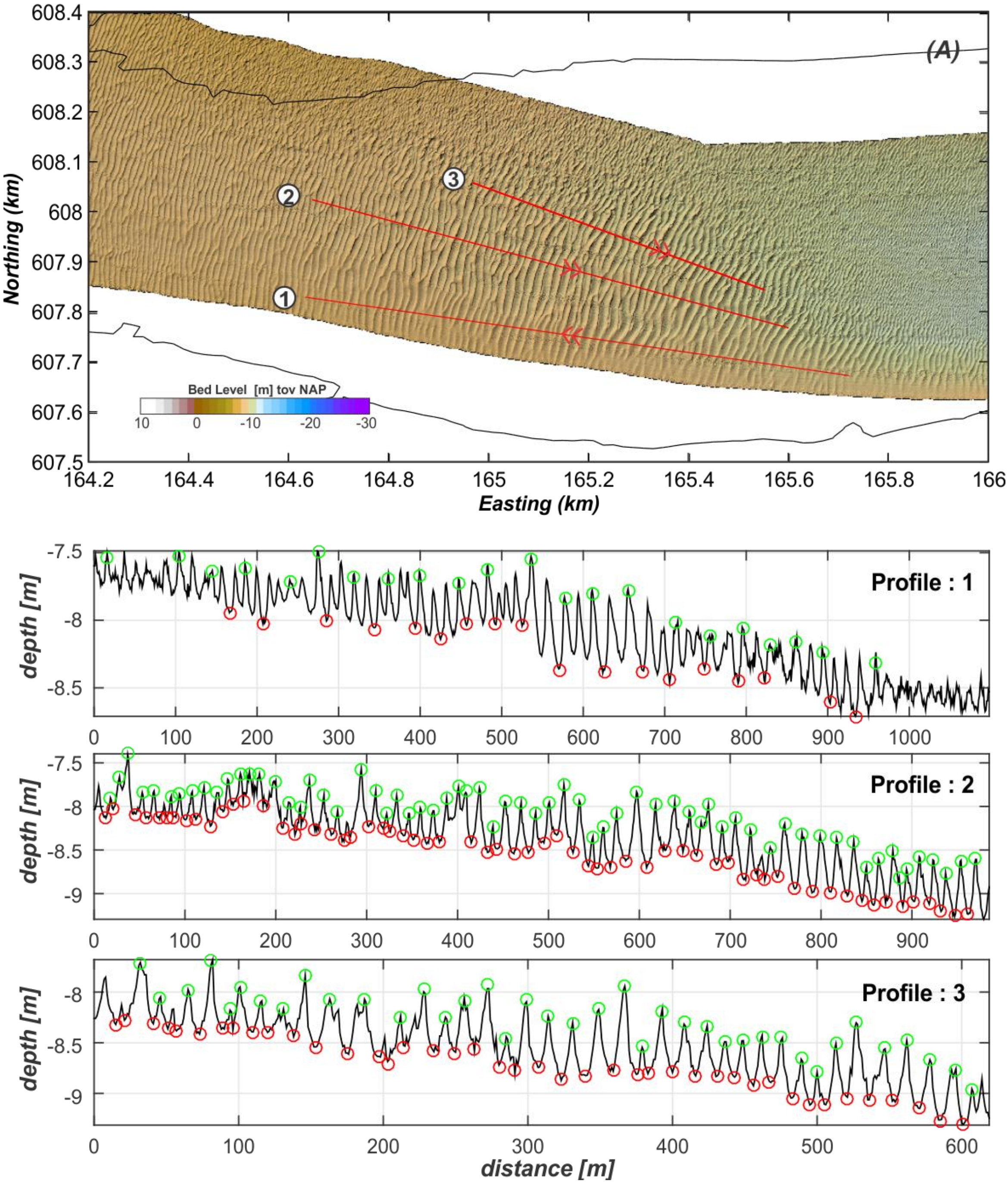

Figure B.1 Overview of bedforms observed in area A. See location Vak A in ***Error! Reference source not found.***.

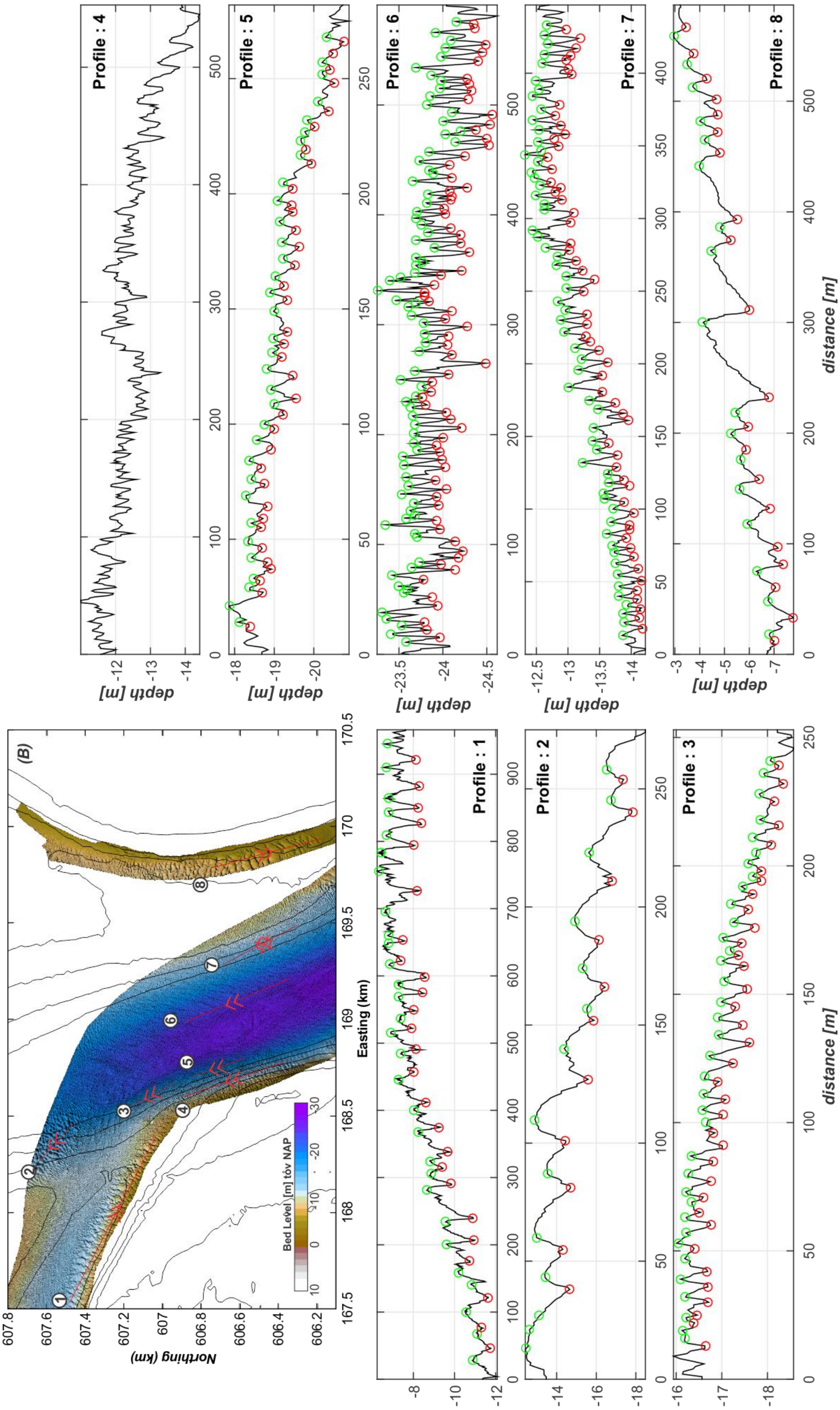

Figure B.2 Overview of bedforms observed in Vak B.

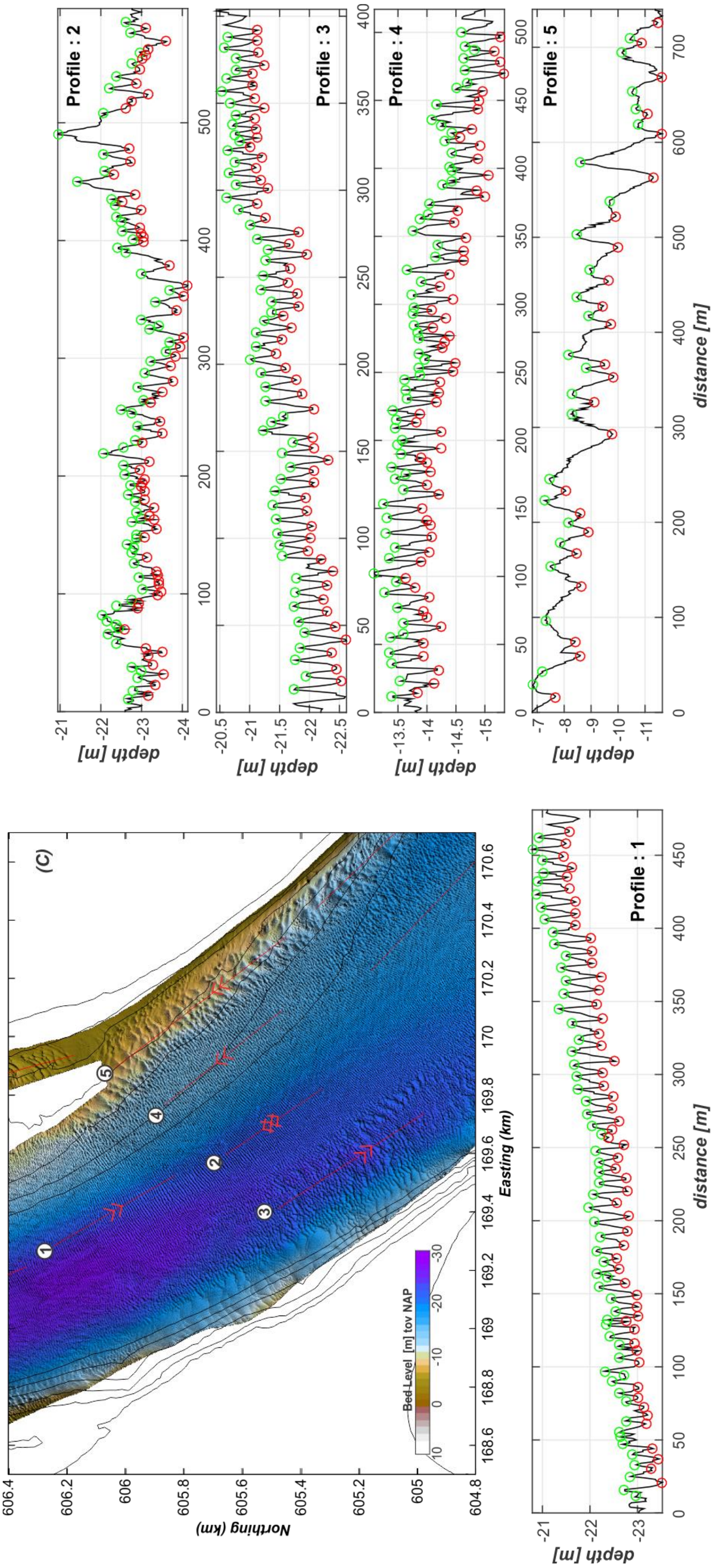

Figure B.3 Overview of bedforms observed in Vak C.

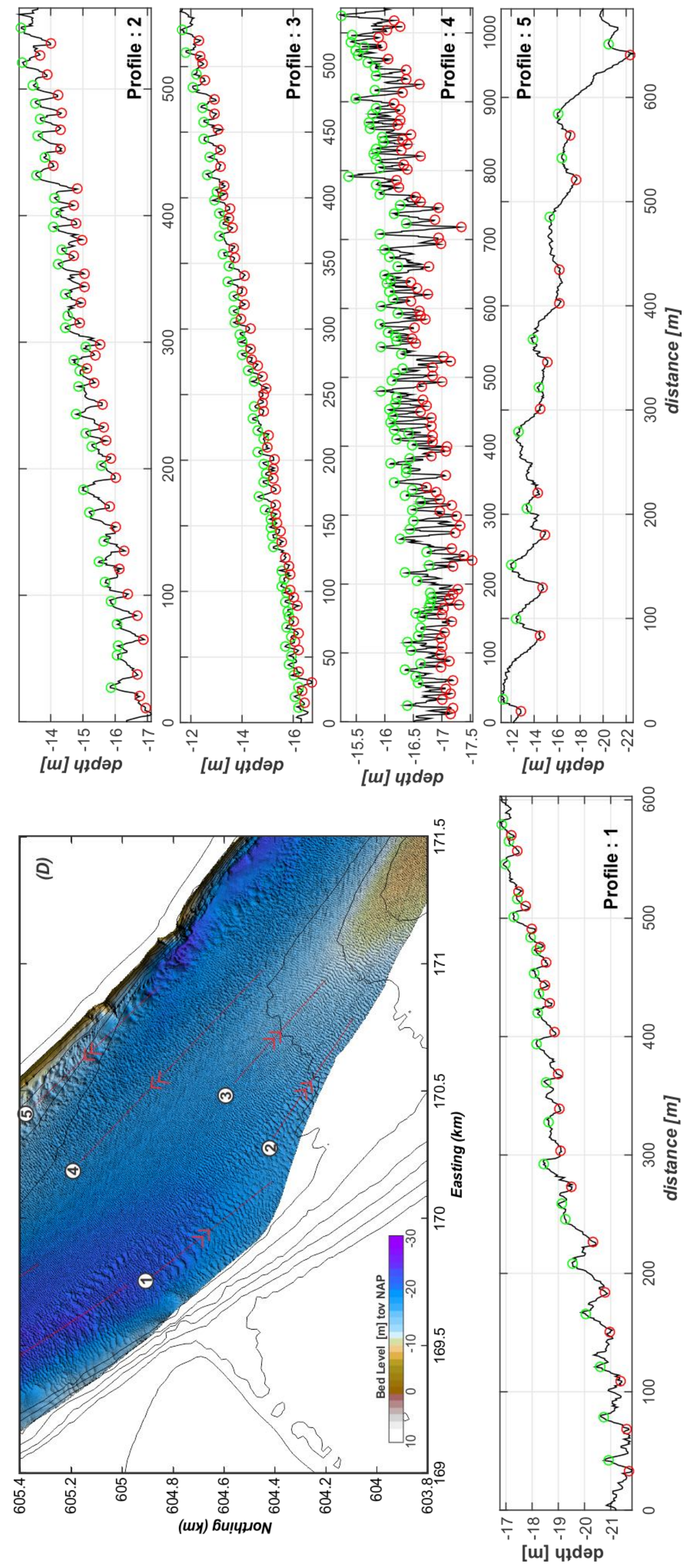

Figure B.4 Overview of bedforms observed in Vak D.

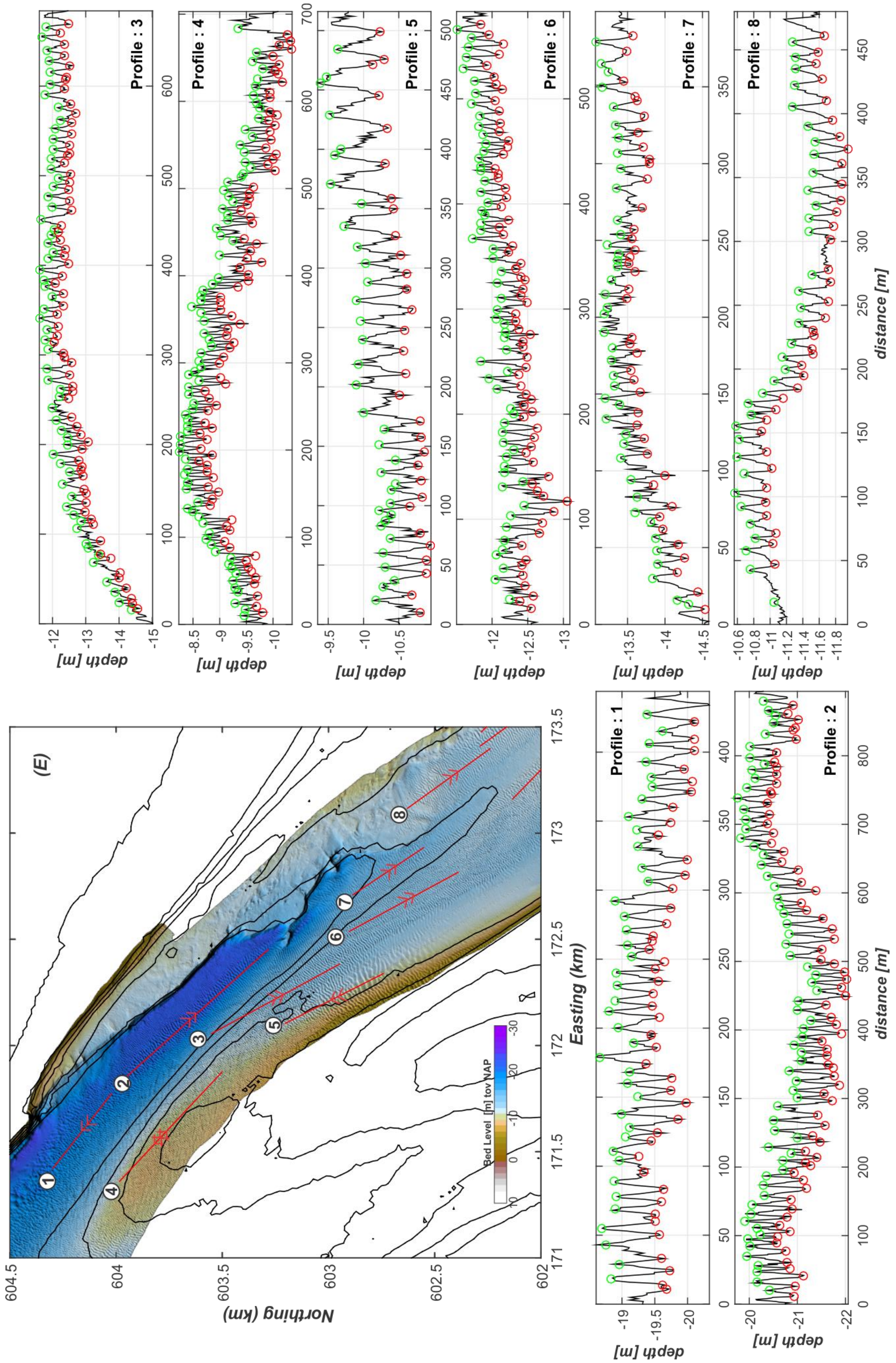

Figure B.5 Overview of bedforms observed in Vak E.

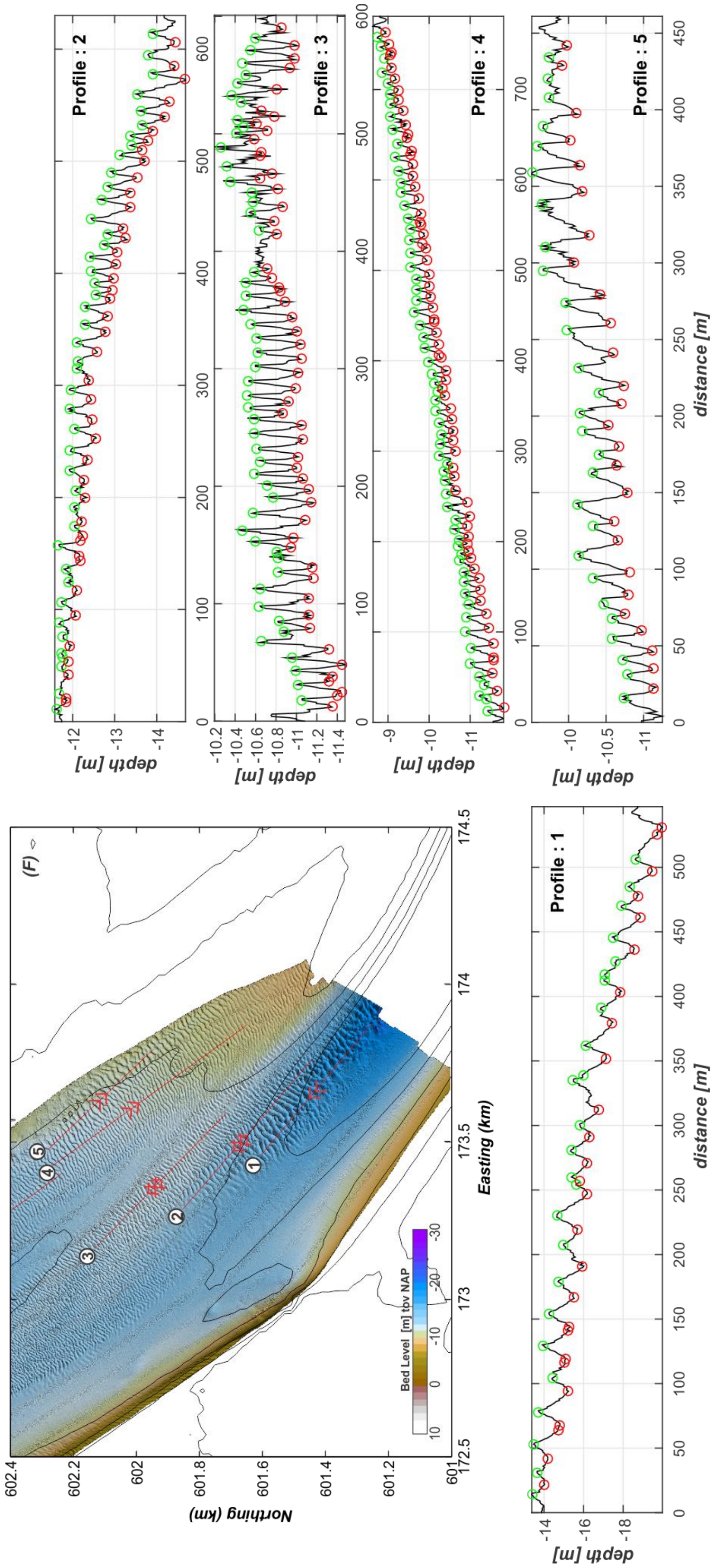

Figure B.6 Overview of bedforms observed in Vak F.

C Time-stacks, profiles Mbes survey Vak D

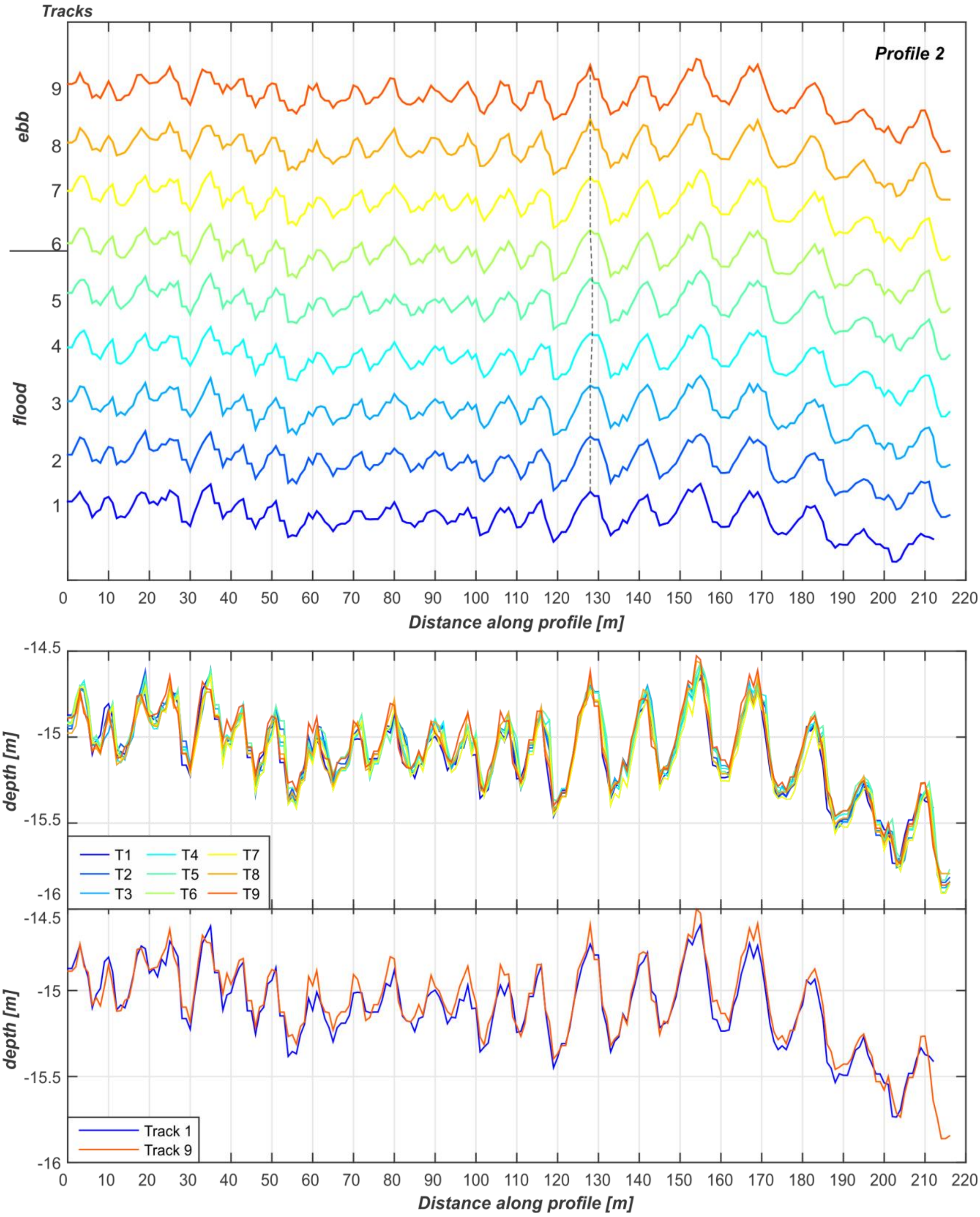

Figure C.1 Overview of bedform migration in Profiles 2. Top panel: timestack illustrating the bedforms for tracks 1-9 (from bottom to top). Middle panel: bedform cross-sectional profile for tracks 1-9, and bottom panel: bedform cross-sectional profiles for tracks 1 and 9.

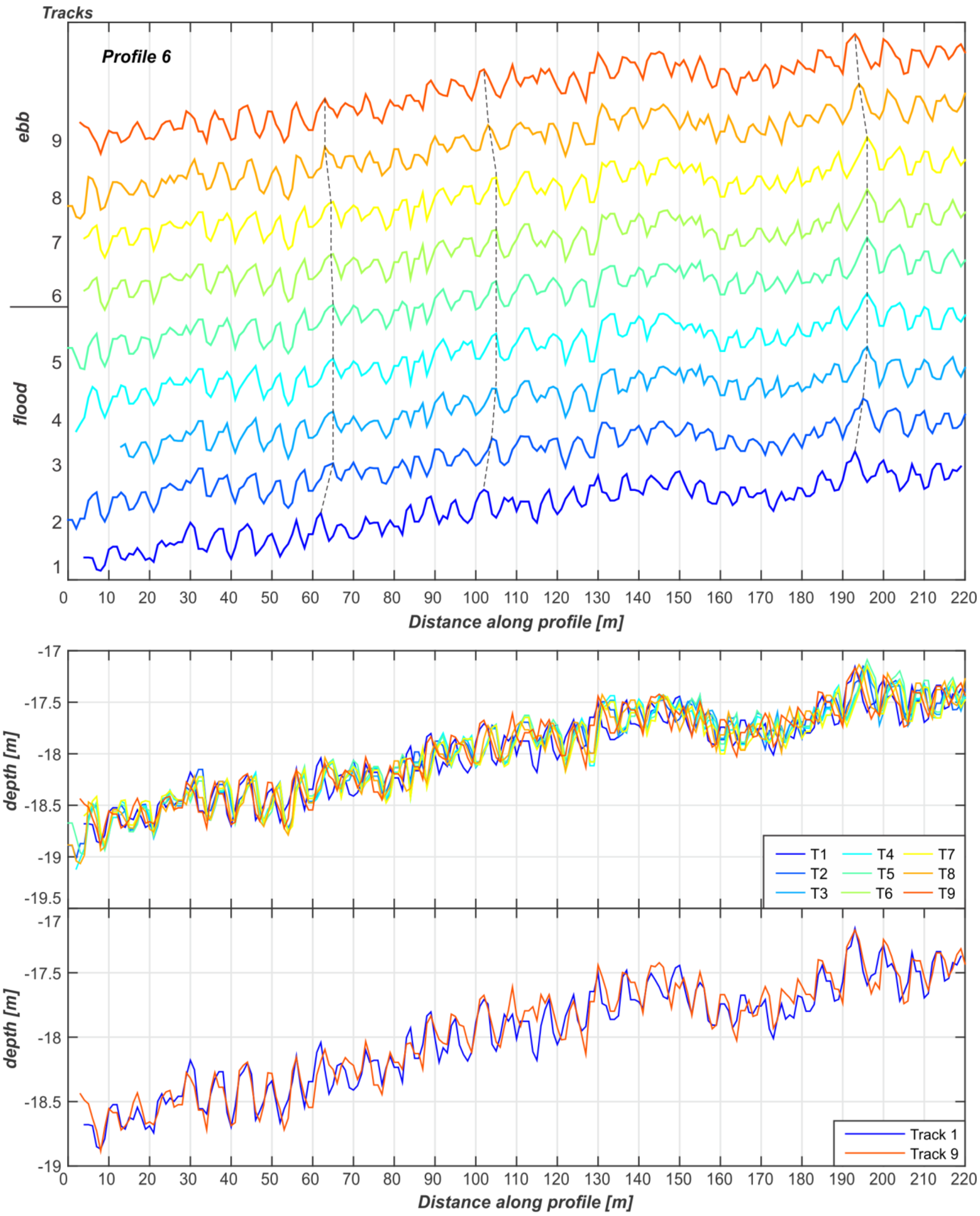

Figure C.2 Overview of bedform migration in Profiles 6. Top panel: timestack illustrating the bedforms for tracks 1-9 (from bottom to top). Middle panel: bedform cross-sectional profile for tracks 1-9, and bottom panel: bedform cross-sectional profiles for tracks 1 and 9.

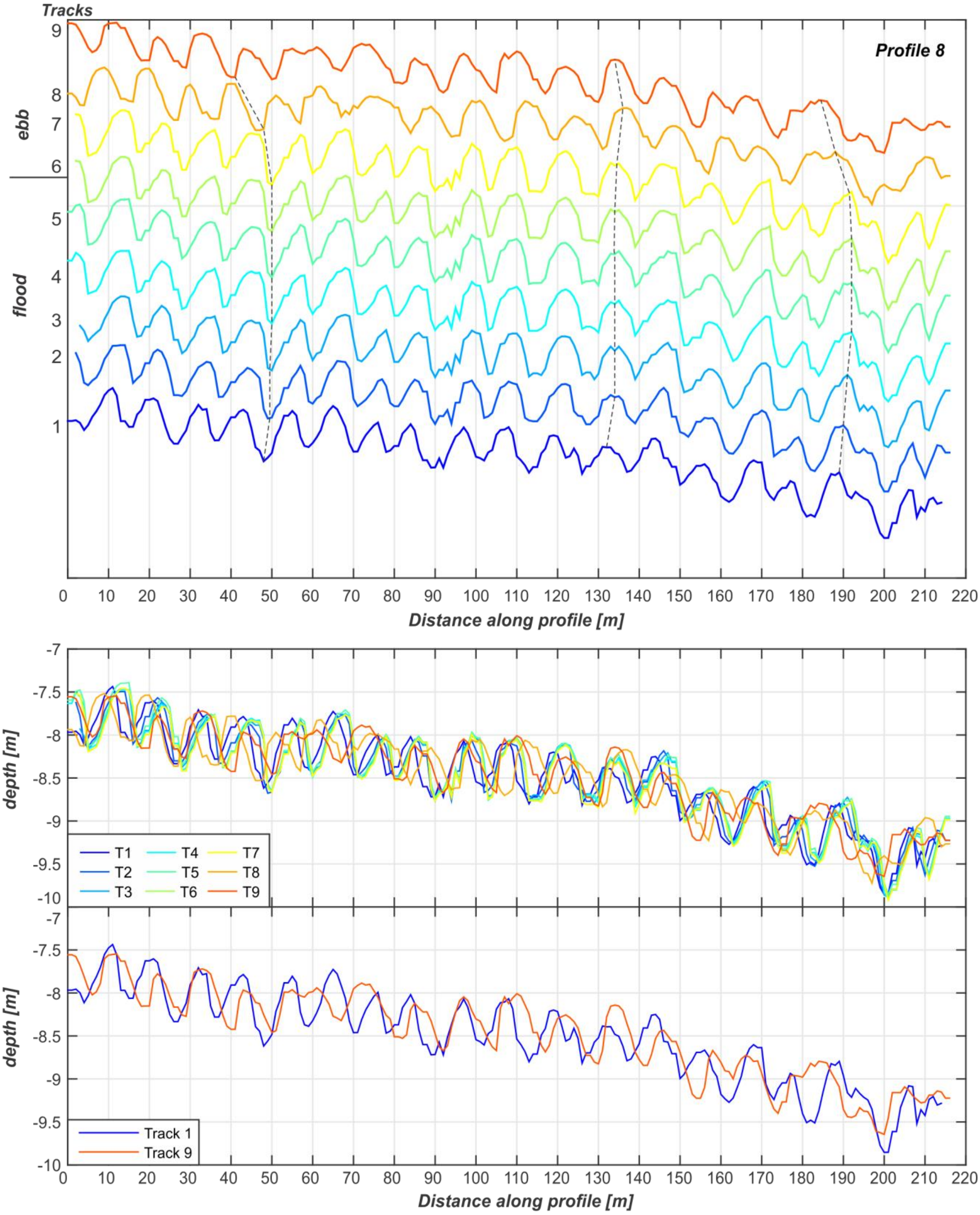

Figure C.3 Overview of bedform migration in Profile 8. Top panel: timestack illustrating the bedforms for tracks 1-9 (from bottom to top). Middle panel: bedform cross-sectional profile for tracks 1-9, and bottom panel: bedform cross-sectional profiles for tracks 1 and 9.

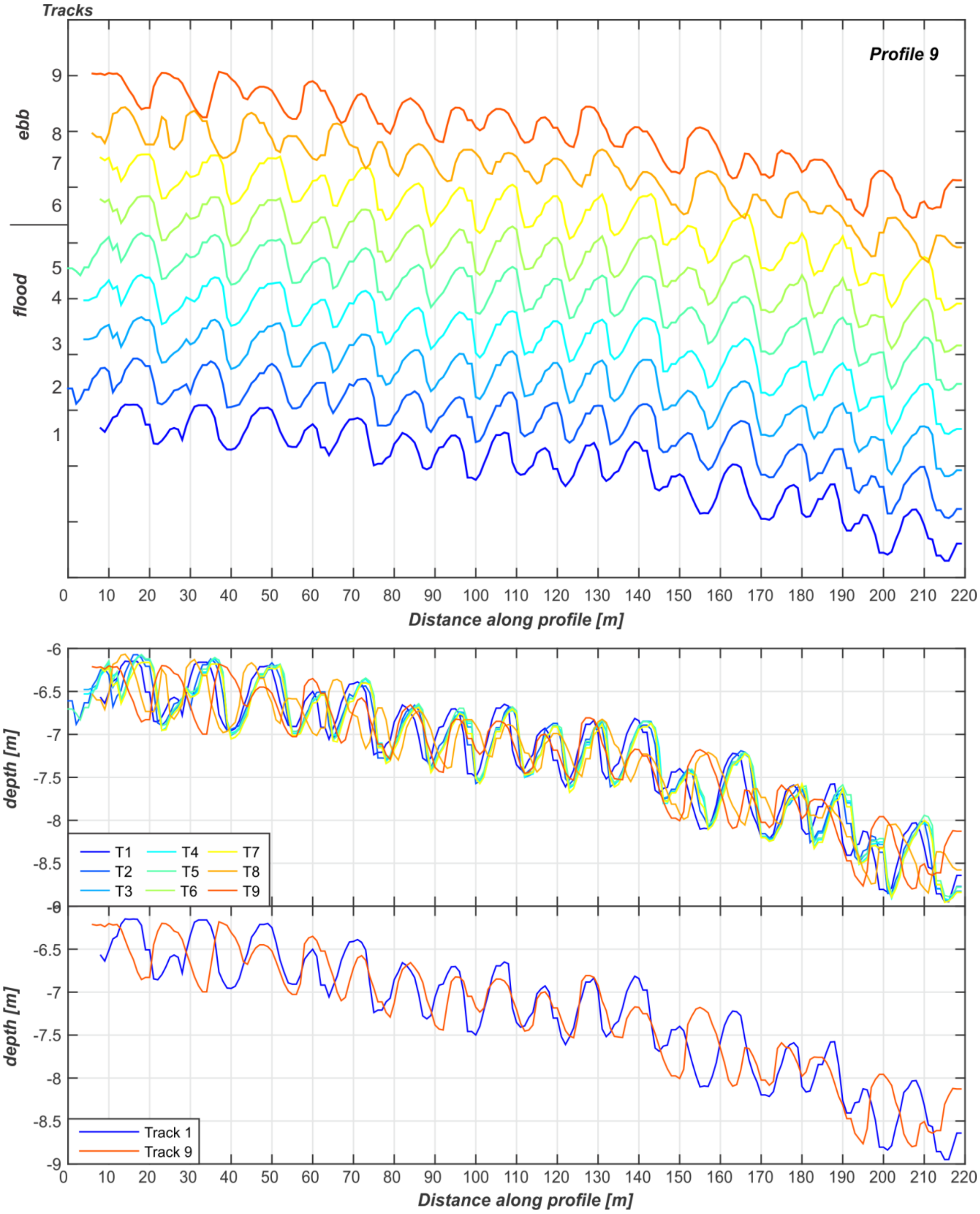

Figure C.4 Overview of bedform migration in Profile 9. Top panel: timestack illustrating the bedforms for tracks 1-9 (from bottom to top). Middle panel: bedform cross-sectional profile for tracks 1-9, and bottom panel: bedform cross-sectional profiles for tracks 1 and 9.