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Kustgenese 2.0; available measurements and bathymetric data at Ameland inlet, The Netherlands

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Rijkswaterstaat Water, Verkeer en Leefomgeving (WVL)	1220339-007	1220339-007-ZKS-0001	51

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Summary
This report provides an overview and analysis of available bathymetric and hydrodynamic data of Ameland inlet in the Netherlands. Twelve DEMs of the complete inlet system (ebb-tidal delta, basin and inlet) and eight DEMs covering the ebb-tidal delta only were constructed based on data in Vaklodingen format (sources: regular Vaklodingen, SBW and Kustgenese 2.0). Additional yearly bathymetric maps of the nearshore (Jarkus), and high-resolution multibeam data in Borndiep, suitable for bedform analysis, are presented.

Tides, wind and wave data are measured at various locations throughout the Wadden Sea and neighbouring North-sea. Most relevant for Ameland are water levels measurements at the stations Texel Noordzee, Wierumergronden, Nes and Holwerd. The long-term records of the SON (Schiermonnikoog) wave buoy correlate best to the local (SBW) wave measurements at Ameland. SBW data at 12 stations in the inlet are measured during the stormy season (September – April). Only limited measurements of flow and discharges are obtained. Discharges were only found in reports that provide the cross-section averaged results. ADCP flow measurements were obtained for 3 locations on the ebb-tidal delta (2007-2008 time frame). Spatially coherent flow and wave data over the inlet domain can be retrieved by the XBand radar and XMFit software.

All data described in this report is archived will be stored in a Kustgenese 2.0 data repository to provide easy access for the Kustgenese 2.0 researchers. This approach reduces the time to find and/or structure the data by individual researchers and allows for effective identification of errors, and redistribution of the corrected, updated, data.

References
Plan van Aanpak Kustgenese 2.0 versie januari 2017. Bijlage B bij 1220339-001-ZKS-0005-vdef-r-Offerte Kustgenese 2.0. Deltares, 27 januari 2017.

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State
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Samenvatting; beschikbare metingen en bodemdata in het zeegat van Ameland, Nederland

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 m3/jaar sinds 2000.

In 2020 neemt het Ministerie van Infrastructuur en Milieu 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?

Dit datarapport maakt deel uit van het deelproject ‘Systeemkennis Zeegaten’. 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-07 Wat zijn de drijvende (dominante) sedimenttransportprocessen en -mechanismen en welke bijdrage leveren ze aan de netto import of export van het bekken?
- SVOL-08 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?
- SVOL-09 Wordt de grootte van de netto import of export beïnvloed door het aanbod van extra sediment in de kustzone of de buitendelta?
- SVOL-10 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?

Beschikbare meet- en bodemdata in het Amelander zeegat

Deze rapportage geeft een overzicht van de bodem- en hydrodynamische data beschikbaar voor het Amelander zeegat. Op basis van verschillende datasets (opgenomen volgens het Vaklodingen protocol) is het mogelijk 12 bodemkaarten te maken van het gehele zeegata (buitendelta, keel en bekken). Daarnaast zijn er nog 8 aanvullende kaarten waarop alleen de buitendelta is opgenomen. De data die hiervoor gebruikt is komt uit de reguliere Vaklodingen, de aanvullende SBW meetcampagnes en de Kustgenese 2.0 metingen. Aanvullende bodemdata is beschikbaar voor de kustlijnen van de eilanden. De JarKus data geeft hier vrijwel jaarlijkse metingen vanaf 1965. Hoge resolutie (mutli-beam) opnamen van het Borndiep zijn beschikbaar sinds 2005. Deze data geven een goed overzicht van de bodemvormen en analyse kan een eerste inzicht verschaffen in de sediment transport patronen.

Hydrodynamische metingen van getij, wind en golven worden uitgevoerd vanuit het MWTL (Monitoring Waterstaatkundige Toestand des Lands) programma. Waterstanden worden hierin niet rechtstreeks in het zeegat ingewonnen. De metingen van de stations Texel Noordzee, Wierumergronden, Nes and Holwerd zijn hier het meest relevant. Lange termijn golfmetingen worden uitgevoerd ten westen (Eierlandse Gat) en ten oosten van het zeegat (SON). Korte termijn metingen (sinds 2007) zijn uitgevoerd in het kader van het SBW. Dit meetprogramma heeft 12 golfboeien (met wisselende databeschikbaarheid) in het zeegat. Een goede correlatie tussen de SBW metingen en de SON meetdata word gevonden in de overlappende periode. Dit leidt tot de conclusie dat SON een representatief golfklimaat geeft voor het Zeegat van Ameland.

Metingen van debiet en stroomsnelheden zijn slechts beperkt aanwezig. In het verleden zijn er wel meerdere debiet metingen (13-uurs metingen) uitgevoerd. Vanuit de bijbehorende rapportages zijn de raai gemiddelde debieten beschikbaar. De digitale data is (nog) niet beschikbaar. In het kader van het SBW programma zijn er wel op 3 locaties in het zeegat tijdseries van stroomsnelheden (ADCP metingen) opgenomen gedurende 2007-2008. Deze data is uitvoerig geanalyseerd in de SBW studies en digitaal beschikbaar. Een ruimtelijk beeld van de stromingen en golven kan worden verkregen door koppeling van de XBand radar (vuurtoren van Ameland) met het SeaDarQ software pakket. Uit eerdere studies zijn 3 perioden (2010-2012) beschikbaar en geanalyseerd.

Alle data beschreven in dit rapport is gearchiveerd en opgeslagen op de Kustgenese project schijf. Dit maakt de data makkelijk toegankelijk en beschikbaar ten behoeve van analyses en de modelering.

Een vertaling van de inzichten naar de onderzoeksvragen van Kustgenese 2.0

Dit is rapport is een inventarisatie van de beschikbare data en heeft een ondersteunende functie. Dit rapport levert dan ook geen directe bijdrage aan de onderzoeksvragen. De analyses gepresenteerd in (Elias, 2017) op basis van deze data leveren hier wel een bijdrage (zie Tabel 1 voor uitwerking).

Tabel 1: Overzicht Onderzoeksvragen Kustgenese 2

Code	Onderzoeksvraag	deze rapportage	Elias (2017)
SVOL-07	Wat zijn de drijvende (dominante) sedimenttransportprocessen en -mechanismen en welke bijdrage leveren ze aan de netto import of export van het bekken?	NEE	JA
SVOL-08	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?	NEE NEE	JA NEE
SVOL-09	Wordt de grootte van de netto import of export beïnvloed door het aanbod van extra sediment in de kustzone of de buitendelta?	NEE	JA
SVOL-10	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	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?	NEE	JA
INGR-02	Is het, op basis van beschikbare kennis van het morfologisch systeem, zinvol om grootschalige suppleties op buitendeltas te overwegen?	NEE	JA

Contents

Appendices

1 Introduction

This report provides an overview and analysis of the measurements that are available at Ameland inlet for the Kustgenese 2.0 project. This data will be archived on the Kustgenese 2.0 data repository.

The two objectives of this study are to:

1 collect and store all available data that has been collected so far (prior to the Kustgenese 2.0 project) in and around the Ameland inlet. This data will be stored in a Kustgenese 2.0 data repository to provide easy access for the Kustgenese 2.0 users. The advantage of this approach is twofold: it (a) reduces the time to find and/or structure the data by individual researchers and (b) it allows for effective identification of errors, and redistribution of the corrected, updated, data to the all Kustgenese 2.0 researchers,

2 provide “ready to use” maps and knowledge. Based on the available data we compiled complete bathymetric renderings (from here on referred to mosaic or Digital Elevation Models, DEM’s). These DEM’s can be directly implemented in the models. The renderings (figures) are built in “report quality” for future use throughout the project.

Chapter 2 of this report presents the available bathymetric data for Ameland Inlet. Based on various sources of measurements 12 complete DEMs (Digital Elevation Models) of the Ameland Inlet can be constructed, and 20 DEMs of the ebb-tidal delta. In this chapter additional bathymetric data sources include the (near) yearly JarKus measurements, and detailed multi-beam data in Borndiep (along the revetments at Ameland west). Chapter 3 presents overview of the available hydrodynamic measurements of boundary conditions (regional scale) and local measurements in the inlet. The focus of this study is on the water levels, waves, wind and currents. An additional section focusses especially on the SBW studies. During this project a field data was used to validated and calibrate numerical models on flow and waves. These studies provide a wealth of data relevant for Kustgenese 2.

Note that we do not provide a complete analysis of the field data in this report. Such analysis is presented in the report: Elias (2017).

2 A description and analysis of bathymetric data

2.1 Study Area

Figure 2.1 (names) and Figure 2.2 (definitions) provide overviews of the main channels and shoals of the present day Ameland Inlet (2017 DEM). 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 2.1 [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 [5] and Zuider Spruit [6]. Several smaller side channels connect to Dantziggat such as Molengat [7] near the island of Ameland, and Vaargeul vd Zwarte Haan [8].

Between Borndiep and the tip of the island Terschelling (called Boschplaat [18]) 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 along the southern side of the Koffieboonenplaat [22] and Boschplaat. In the basin, Boschgat connects to Blauwe Balg [23] and Nieuwe Oosterom [24]. The large shoal, in the middle of the inlet, between Boschgat and Borndiep is called Robben Eiland [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]). In the past decades, Westgat formed a pronounced channel, but in the recent 2016 bathymetry this channel is distorted by a smaller secondary ebb-chute and sill near its connection to Borndiep. In addition, a more direct connection to Boschgat seems to form along Boschplaat.

A small and a large ebb-chute [27,28] have formed on the shoal area between Westgat and Akkepollegat. A pronounced large ebb-shield now covers most of the shoal area known as Kofmansplaat [28]. The shoal area (terminal lobe) facing Akkepollegat is called Vlakte van Ameland [29].

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 [31], has formed along its eastern margin. In the 2017 bathymetry this less pronounced compared to previous years and has almost connected to the Ameland coastline. 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.

The start of a third bypassing cycle may be observed on the Kofmansbult shoal. The large ebb-shield that started to form around 2005 has migrated northward. This migration constrained flow in Akkepollegat and the channel has significantly reduced in width and recurved to a more northward direction. This shoal migration is likely to continue and eventual form a similar shoal as the Bornrif Strandhaak.

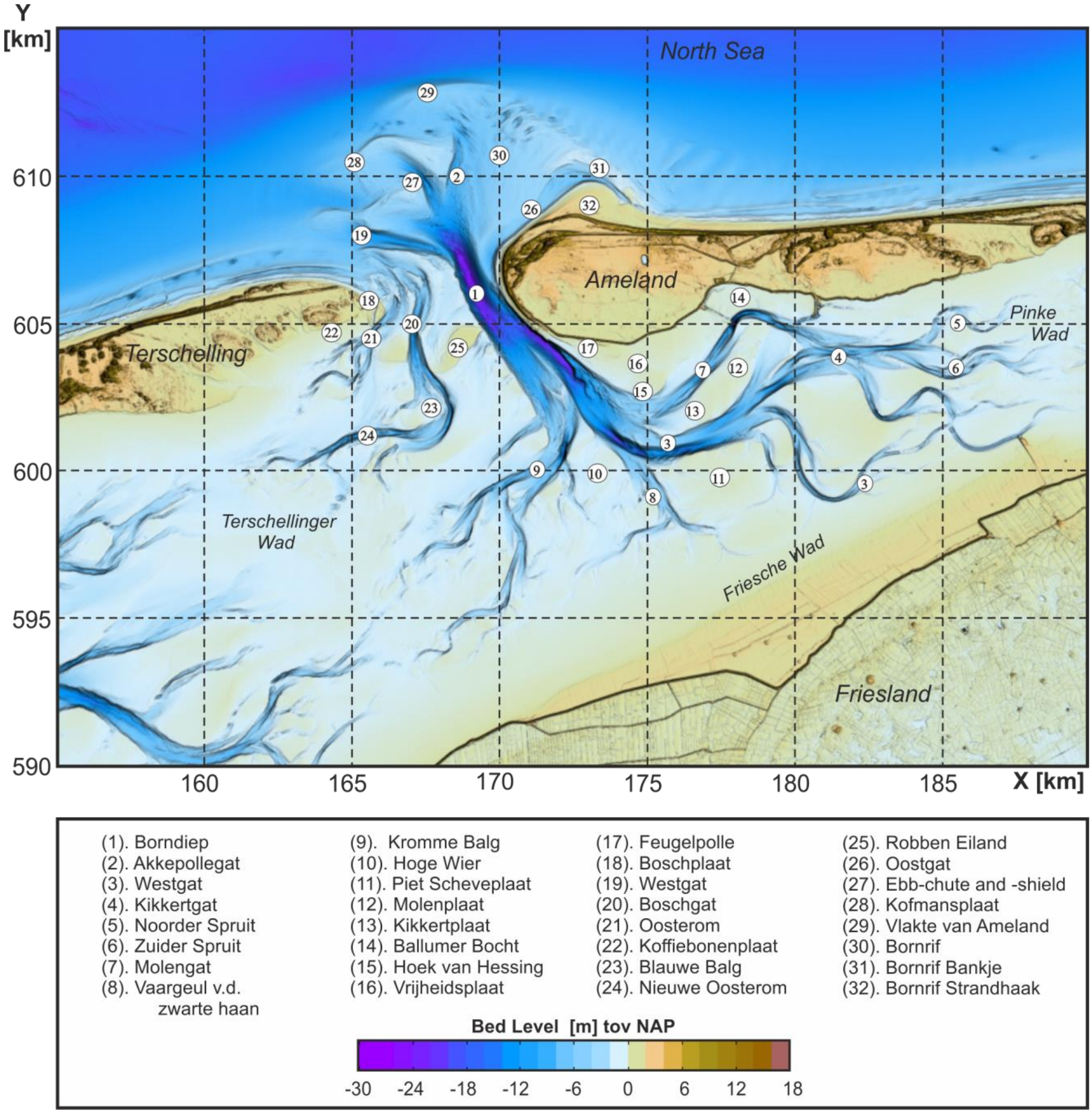


Figure 2.1 Overview of the channels and shoals that form the present day Ameland Inlet. DEM is based on the 2017 measurements of the ebb-tidal delta and main channels in the basin (obtained for the Kustgenese 2.0 project). Islands and mainland coast are based on AHN .

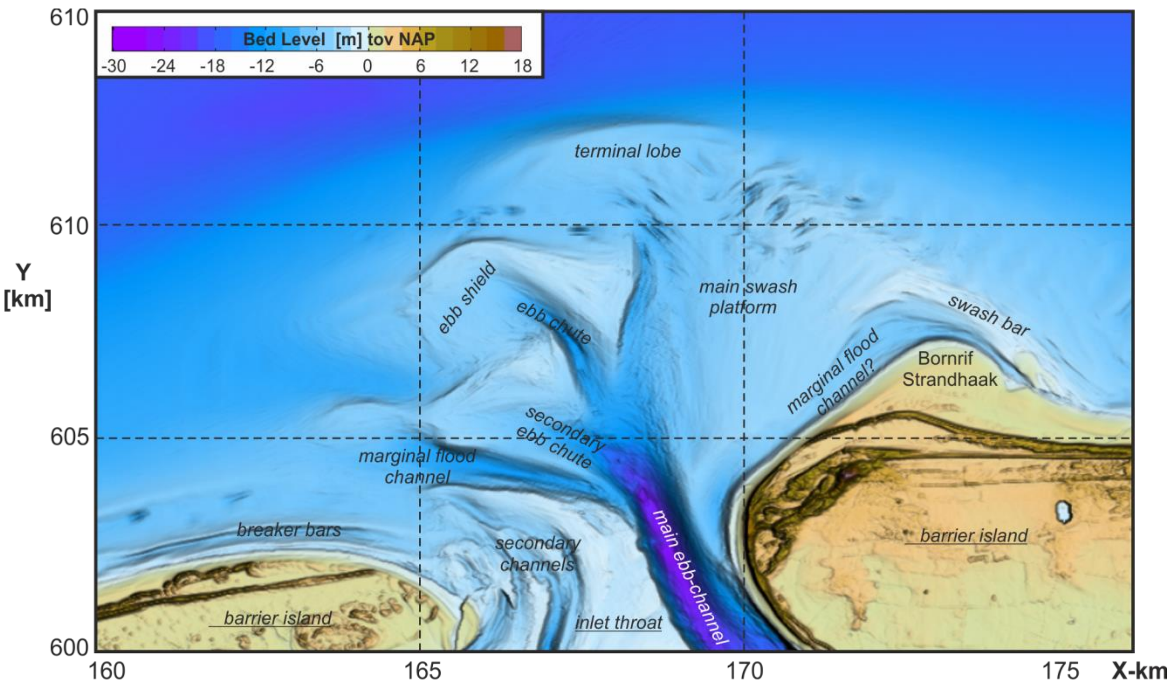


Figure 2.2 Overview of the definition of the channels and shoalson the ebb-tidal delta.

2.2 Available DEMs (Digital Elevation Models) for Ameland Inlet.

2.2.1 Data availability

Bathymetric data for Ameland inlet is available from a variety of data sources: (1) regular vaklodingen or additional datasets stored using the Vaklodingen protocol (SBW, KustGenese 2), (2) JarKus measurements, and (3) High-resoluton multibeam measurements of Borndiep.

The regular Vaklodingen, SBW and Kustgenese 2.0 measurements are all collected, processed and stored by Rijkswaterstaat using the Vaklodingen protocol. Vaklodingen are surveyed and data is interpolated on pre-designed grid that is divided in map sheets of 10 x12.5 km with a resolution of 20 m, covering the estuaries and ebb-tidal deltas up to the seaward -20 m contour. Figure 2.3 presents an overview of the Vaklodingen blocks that cover the Wadden Sea. In principal the map sheets of the individual ebb-tidal deltas are surveyed every 3-years since 1986-87. The basins are measured less frequently in 6-year intervals. Data collected prior to 1987 were originally released as paper maps and digitized in 250x250 m resolution for the Western Wadden Sea in the 1990's. Extensive descriptions of the measurements and conversion to complete maps are documented in e.g. Rakhorst (1986), Glim et al. (1988; 1990), De Boer et al. (1991), and summarized by De Kruif (2001). Maps for the Frisian Inlet were constructed during the Coastal Genesis (Kustgenese) project and stored in approximately 90x90 m resolution (Oost, 1995). A complete overview of bathymetric data collected by Rijkswaterstaat between 1965 and 2000 is given by De Kruif (2001) and in Appendix A-1.

In addition to the regular Vaklodingen, recently additional datasets were obtained in the framework of the SBW (see Chapter 3.6 for more information on the SBW project) and Kustgenese 2.0 projects. The **SBW measurements** allow us to compile ebb-tidal delta maps for the years 2006, 2007, 2009 and 2010. The main channels in the basin were only surveyed in the years 2006 and 2009. Appendix A-2, Fig A.8 and A.9 provide an overview of the original SBW bathymetric data. In combination with the regular Vaklodingen a continuous dataset of bathymetries, in yearly intervals, can be obtained for the time-frame 2005-2011.

Intensified, half yearly monitoring will be performed during the **Kustgenese 2.0** project. At the writing of this report a first bathymetry became available (2017). Additional datasets will be included on the Kustgenese 2.0 data repository as they become available. Table 2.1 provides an overview of all complete maps that were constructed during this study. Note that this bathymetry and the Kustgenese 2.0 data repository were not yet present during the analysis of the short-term processes (Elias, 2017).

The maps presented in this report are generally composed of 1 or 2 complementary surveys in order to get complete coverage of the area. Islands were filled in with data from the AHN (Algemeen Hoogtebestand Nederland). Maps with missing data along the island shores have been completed using Jarkus data or linear interpolation between the nearest available data. ***Jarkus surveys*** are executed every year since 1964, according to a grid of fixed, 800 to 1200 m long coastal transects perpendicular to coastline, with a spacing of 250 m. Since 2016 the Jarkus measurements are extended and include the entire offshore channel. The JarKus dataset can provide valuable additional insight in the behaviour of nearshore channel and shoal behaviour along the two island tips.

A third data source are multibeam measurements that have been performed regularly since 2005 along the stone protection at NW Ameland. These high-resolution dataset provide detailed images of the bedform migration and variability. Mentioned here, but not analyzed or collected are the measurements of the navigation channels in the Wadden Sea. These channels are measured with a frequency of once or twice a year (Jeuken et al, 2012).

In this Chapter the complete maps (or DEMs) are presented. See Table 2.1 for a summary. An overview of the underlying data sources is presented in Appendix A. This Appendix shows the data availability for the entire Wadden Sea as this information may be needed for the construction of larger-scale numerical models later in the project.

<u>A note on survey techiques and accuracy of the Vaklodingen.</u>
Changes in survey techniques and instruments, positioning systems and variations in correction and registration methods over time make it difficult to estimate the exact accuracy of the measurements and therefore of the maps. Wiegmann et al. (2005) and Perluka et al. (2006) estimate the vertical accuracy of Vaklodingen to range between 0.11 - 0.40 m. Storm et al. (1993) indicate that errors depend on the morphologic unit surveyed. For intertidal areas, channels and flats and channel slopes stochastic (random) errors are respectively 0.23, 0.19 and 0.39 m, and systematic errors (bias) are -0.20, -0.10 and -0.25 m. Marijs and Parée (2004) provide a detailed overview of possible measurement errors focussed on the Westerschelde datasets. These authors conclude that the Vaklodingen data contains 3 sources of error: (1) stochastic errors due to individual data outliers. Improvements in instruments, measuring techniques and protocols reduced the stochastic error from 0.48m (1969-1983), to 0.44m (1985-1989) and 0.36m (1995-present).

These errors do not seem to introduce significant bias or error when analysing the channel- and shoal behaviour. The depth change introduced by channel reallocation is significantly higher than the vertical measuring error. The recent maps (1985 onwards) presented in this study (Figure 2.4 through Figure 2.7) show coherent and consistent patterns and behaviour. However, a consistent bias or error in combination with the large area size can introduce significant volume errors in the sediment budget. Analysis of the sedimentation-erosion values (see Elias, 2017 for details) reveals that unrealistically large fluctuations in volume occur between 1989 and 2005. Elias states: “Both the ebb-tidal delta and coast show an initial reduction in volume between 1989 and 1993 (-31 mcm), an increase of nearly 60 mcm till 1999, followed by a 45 mcm reduction in the subsequent map (2002). Such fluctuations, that are for a major part related to the offshore polygons (polygons 2 and 3), are unrealistic and point to possible inaccuracies in the data. For the offshore polygons the volume change between 1989 and 1993 is therefore assumed to be zero.”

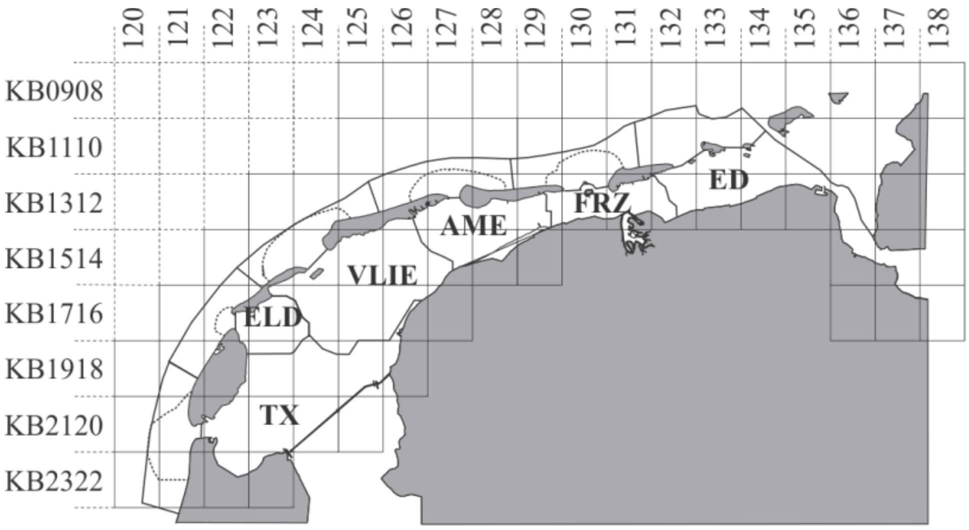


Figure 2.3 Overview of the Vaklodingen blocks that cover the Wadden Sea area.

2.2.2 An overview of DEMs collected under Vaklodingen protocol

Using the Vaklodingen datasets as a base, 20 bathymetric renderings can be constructed for Ameland inlet between 1926 and 2017 (see Table 2.1 and Figure 2.4 through Figure 2.7). Only 12 of these maps provide full coverage of ebb-tidal delta (ETD), inlet and basins ().

These maps provide a unique overview of the channel and shoal behavior in the inlet system. An analysis of the main features reveals consistent and coherent patterns. In some of the maps we do observe interpolation errors. These errors are particularly visible in: (1) the channel Westgat, that shows unrealistically steep and straight channel margins in for example the 1975 bathymetry, (2) coupling of the datasets for basin and ebb-tidal delta results in abrupt channel diversions and in the Boschgat region (see e.g. 1993, 2005), and (3) the saw-tooth bars present along the northeast side of Bornrif.

Table 2.1 Overview of the available bathymetric data.

Year	Dataset	Coverage		Year	Dataset	Coverage	
		Basin	ETD(1)			Basin	ETD
1926	Vakloding	X	X	2005	Vakloding	X	X
1948	Vakloding	X	-	2006	SBW	channels	X
1971	Vakloding	X	X	2007(2)	SBW	X	X
1975	Vakloding	X	X	2008	Vakloding	X	X
1981	Vakloding	X	X	2009	SBW	channels	X
1989	Vakloding	X	X	2010	SBW	channels	X
1993	Vakloding	X	X	2011	Vakloding	X	X
1996	Vakloding	-	X	2014	Vakloding	-	X
1999	Vakloding	X	X	2016	KG2	Partial	X
2002	Vakloding	-	X	2017(3)	Vakloding	X	X

(1) ETD = Ebb Tidal Delta.

(2) The 2007 and 2008 DEM likely contains the same information in the basin.

(3) Not officially released.

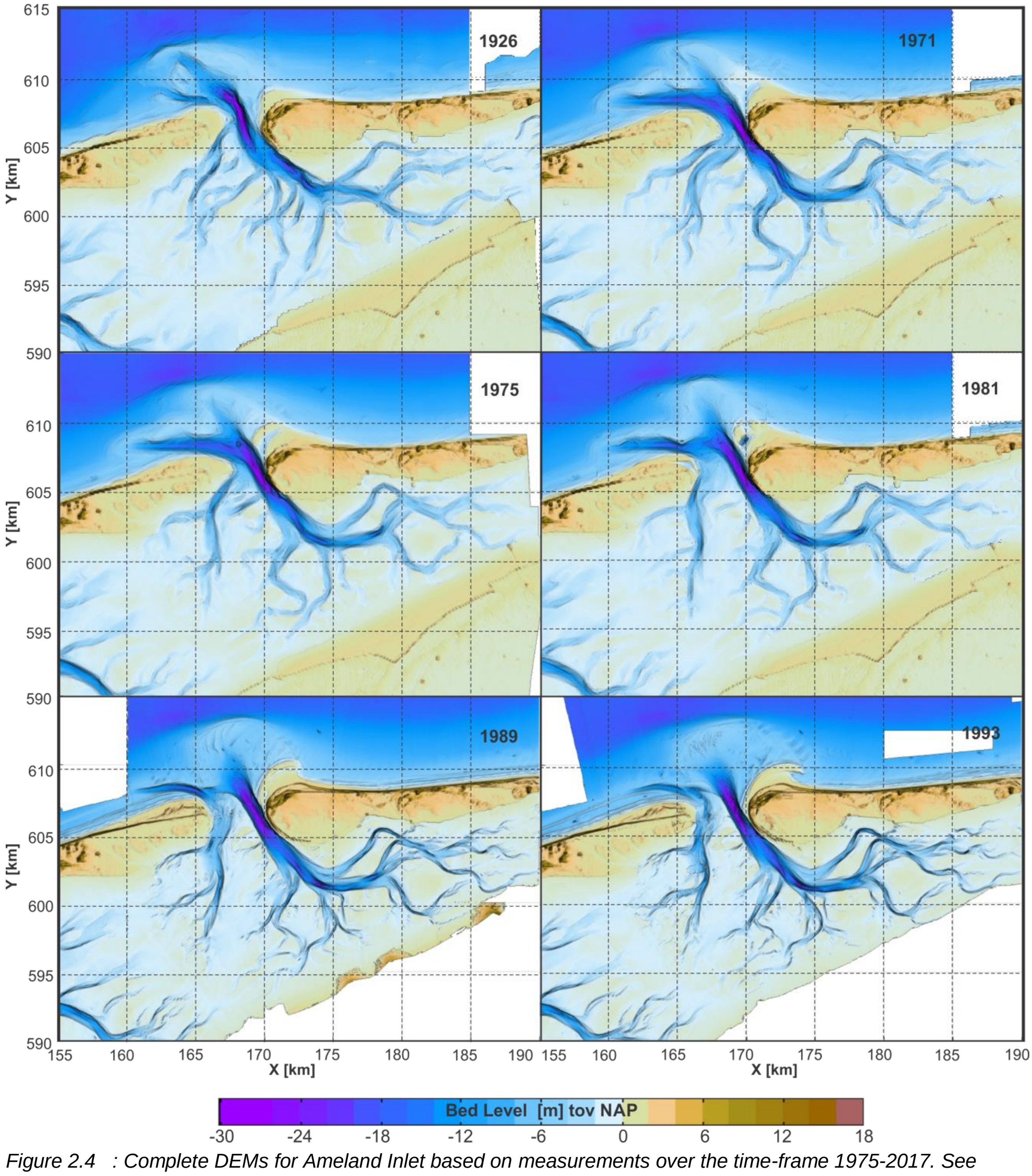


Figure 2.4 : Complete DEMs for Ameland Inlet based on measurements over the time-frame 1975-2017. See Appendix A, Figure A.1 - A.4 for data sources.

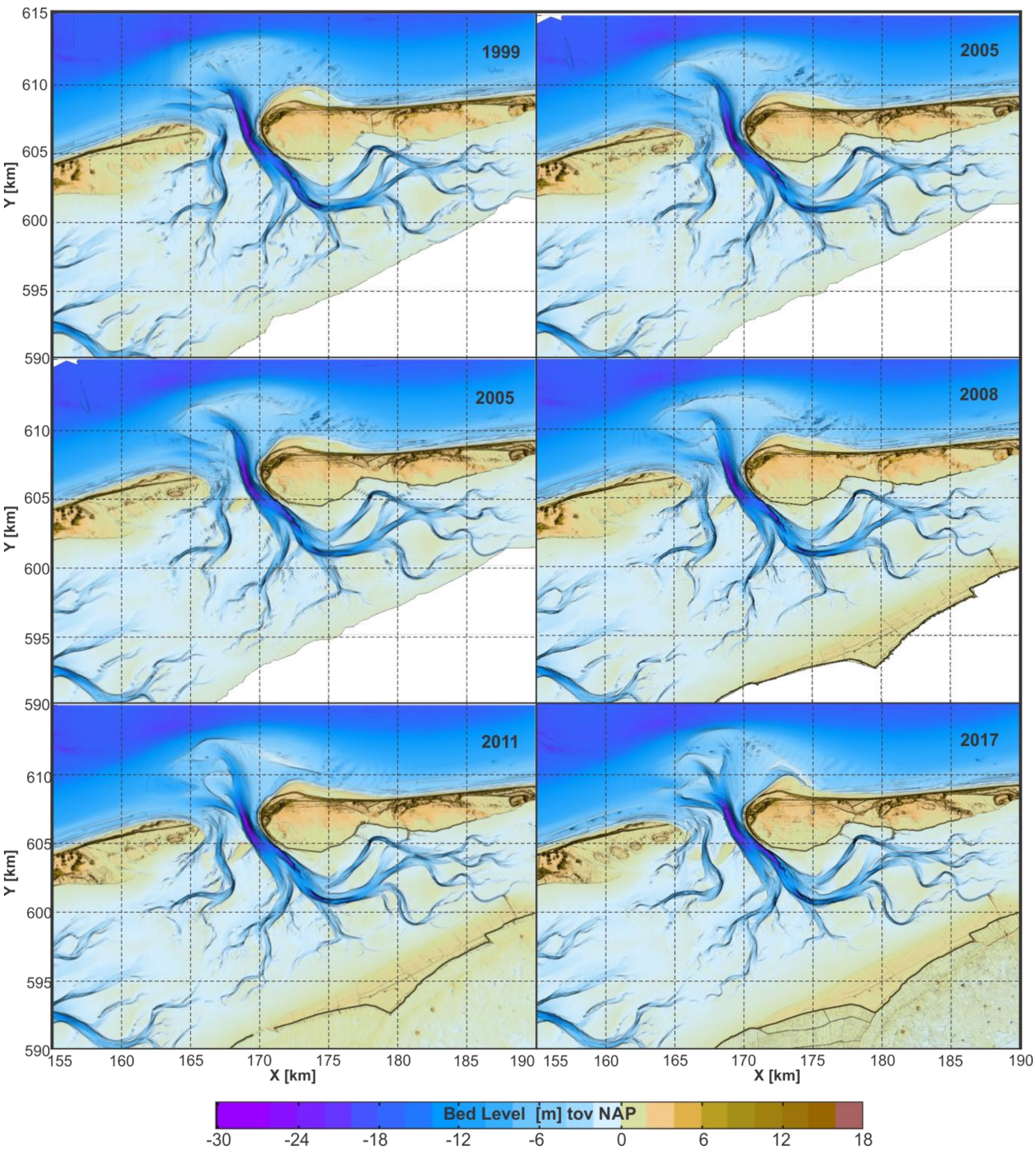


Figure 2.5 : Complete DEMs for Ameland Inlet based on measurements over the time-frame 1975-2017. See Appendix A, Figure A.5 and A.7 for data sources.

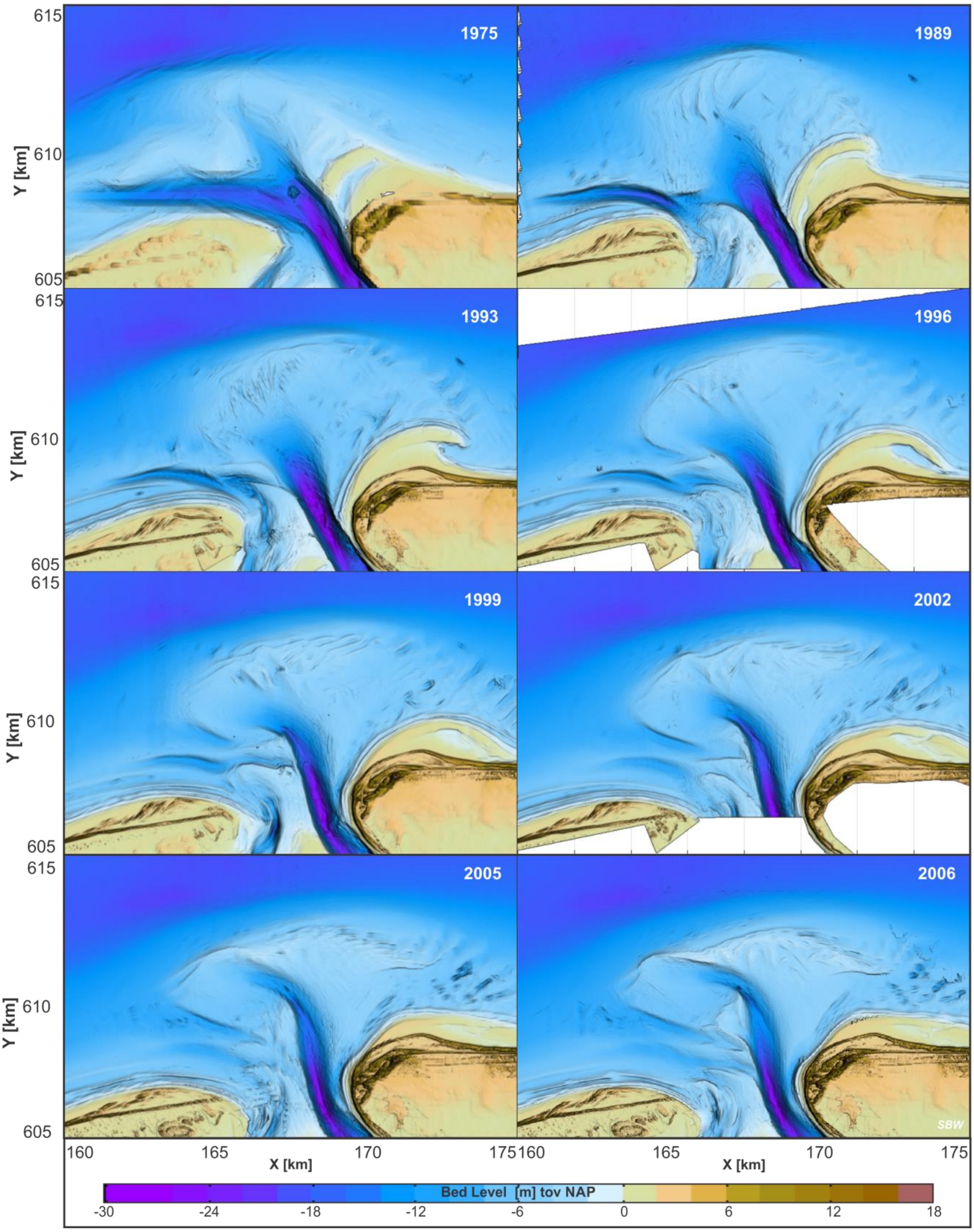


Figure 2.6 Complete DEMs of the ebb-tidal delta based on measurements over the time-frame 1975-2006.

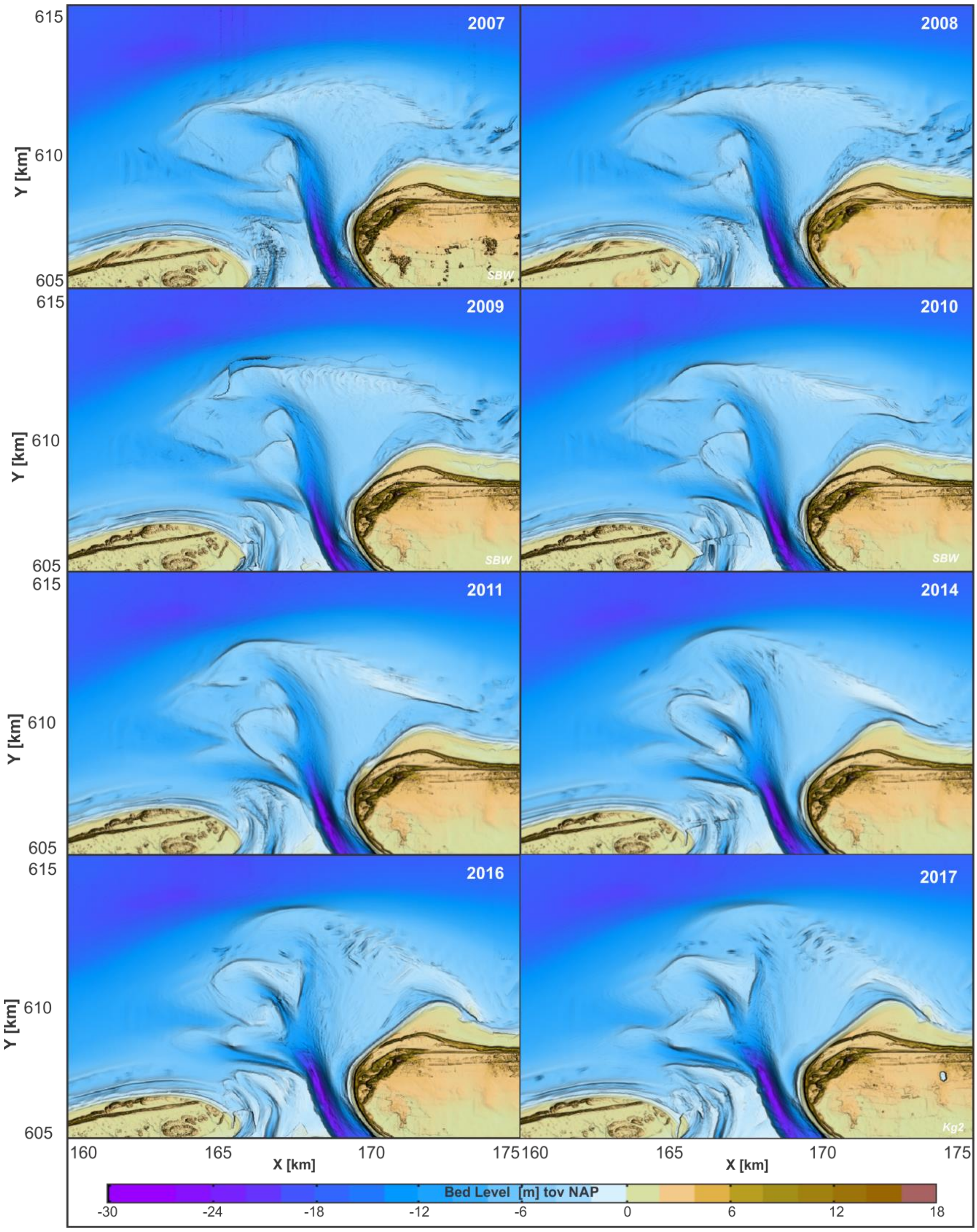


Figure 2.7 Complete DEMs of the ebb-tidal delta based on measurements over the time-frame 2007-2017.

2.3 High-resolution multibeam data for Borndiep

Since 2005 regular surveys of the stone protection at NW Ameland have been made using multi-beam echo sounding (MBES). Table 2.2 and Appendix A-3, Fig A.10 and A.11 provide an overview of the available maps.

The high resolution MBES data also contains portions of the Borndiep channel and allows for the identification of the bedforms. Figure 2.8 shows a portion of the dataset taken on 17-4-2012. Detailed images at 4 selected sites are shown in the bottom 4 panels. These images all show the presence of distinct bedforms that vary in shape and size. 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, viz. 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 provide information about the locally dominant bottom currents and sediment transports (Boothroyd & Hubbard, 1975; Hine, 1975; Boothroyd, 1985; Ashley, 1990; Lobo et al., 2000)

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[(1)]	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	

[(1)] this survey spans Borndiep and Westgat (see Figure 2.8)

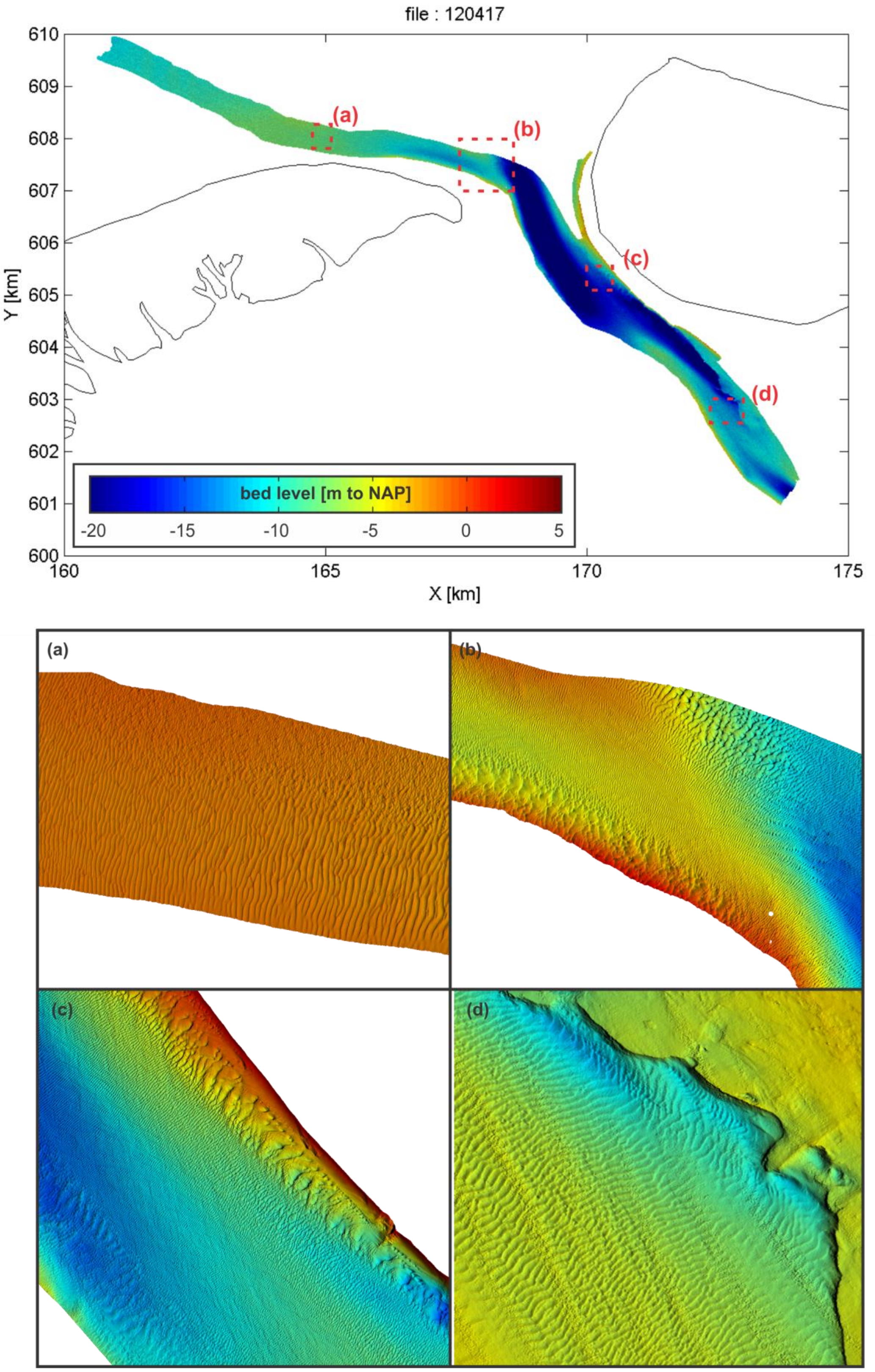


Figure 2.8 : Detailed map of MBES data taken on 17 April 2012. Top panel: overview of total transect, bottom 4 panels show a snapshot of the bedforms present.

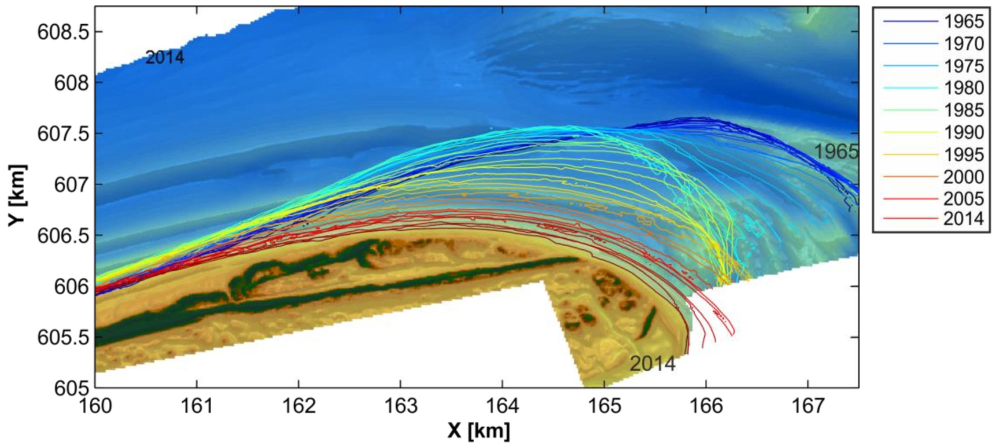
2.4 JarKus measurements

Jarkus surveys are executed every year since 1964, according to a grid of fixed, 800 to 1200 m long coastal transects perpendicular to coastline, with a spacing of 250 m. An overview of the available JarKus data is presented in Appendix A-1. Although the JarKus measurements are limited to a narrow strip along the coastline, their frequent reoccurrence can provide valuable insight in the yearly variability of the nearshore area.

Figure 2.9 provides an overview of selected data for the eastern tip of Terschelling, illustrating the ongoing retreat of the Boschplaat. Recent analysis by Elias (2017) indicates that the present day erosion of the Boschplaat may result from an increasing depth of the ebb-tidal delta and the resulting increase in wave energy in the Boschplaat and Boschgat region.

One of the most renowned morphodynamic features of the Ameland ebb-tidal delta is the Bornrif Strandhaak. As part of sediment-by-passing process, periodically large volumes of sand migrate over the ebb-tidal delta and eventually attach to the Ameland coastline. A visualisation of the JarKus measurements over the 1965-2011 timeframe illustrates this attachment process (Figure 2.10 and Figure 2.11).

The ebb-delta shoal is first visible around 1970, and connects to the Ameland coast between 1985 and 1989. After attachment, a large volume of sand migrates into the basin, but most reshapes into the form of an eastward, cuspate shaped, spit or in Dutch called “strandhaak”. The eastern tip of the shoal quickly migrates eastward, eventually connecting to the Ameland coast around (1989-1995). Sediments for this eastward extension are supplied by erosion of its seaward side. After attachment, a small lagoon is formed and the process of erosion of the spit front and eastward extension continues. In 2011 the spit had extended eastward over a length of 8 km. While the shoal merged with the coastline in the following decades, a new shoal (Bornrif Bankje) formed offshore. The initial formation of this Bornrif Bankje most likely originates between 1999 and 2002 as the ebb-tidal delta front slightly migrates onshore thereby increasing in height, forming a shallow shoal facing Akkepollegat. Between 1999 and 2005 this shallow area develops a long linear bar along the Northeast side of Borndiep. This shoal continues to migrate towards the Ameland coast and is nearly attached in the 2016 survey. Shoal attachment is likely to occur eastward of the original strandhaak.



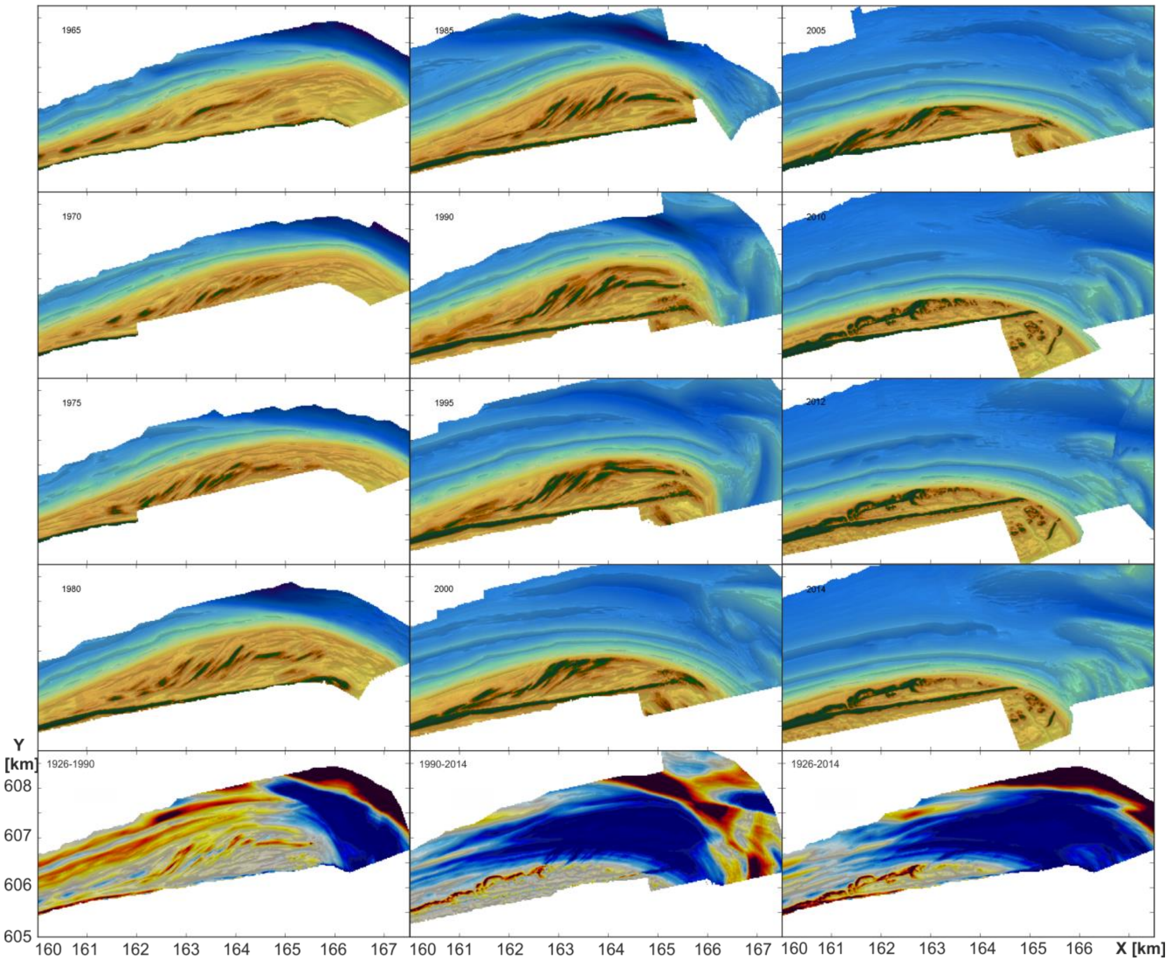


Figure 2.9 An overview of selected JarKus data for the Boschplaat. Top panel illustrates the coastline retreat (0m contour) since 1965 Based on original figures presented in Elias (2013).

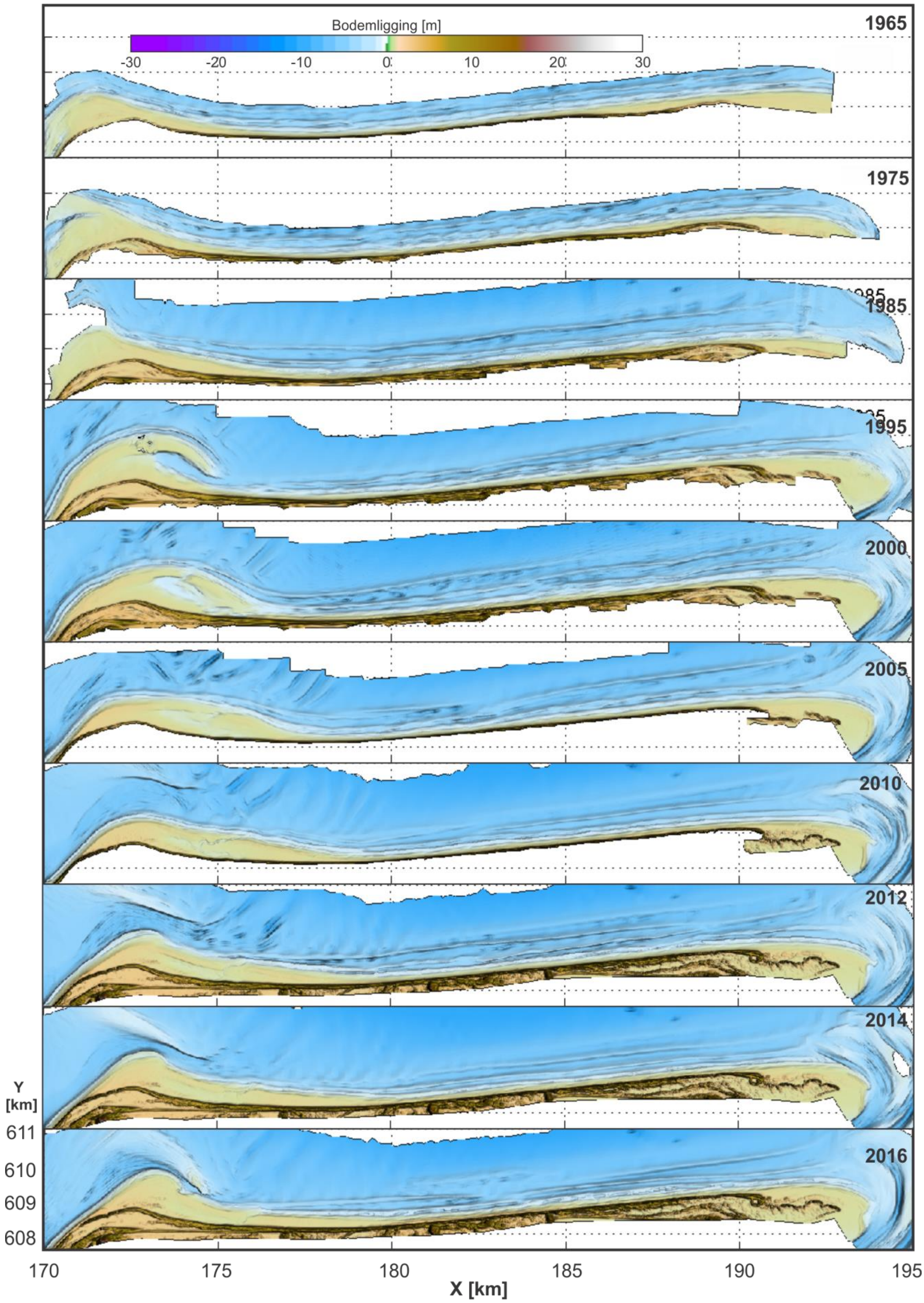


Figure 2.10 *An overview of selected JarKus data for the Coastline of Ameland (1965-2016)..*

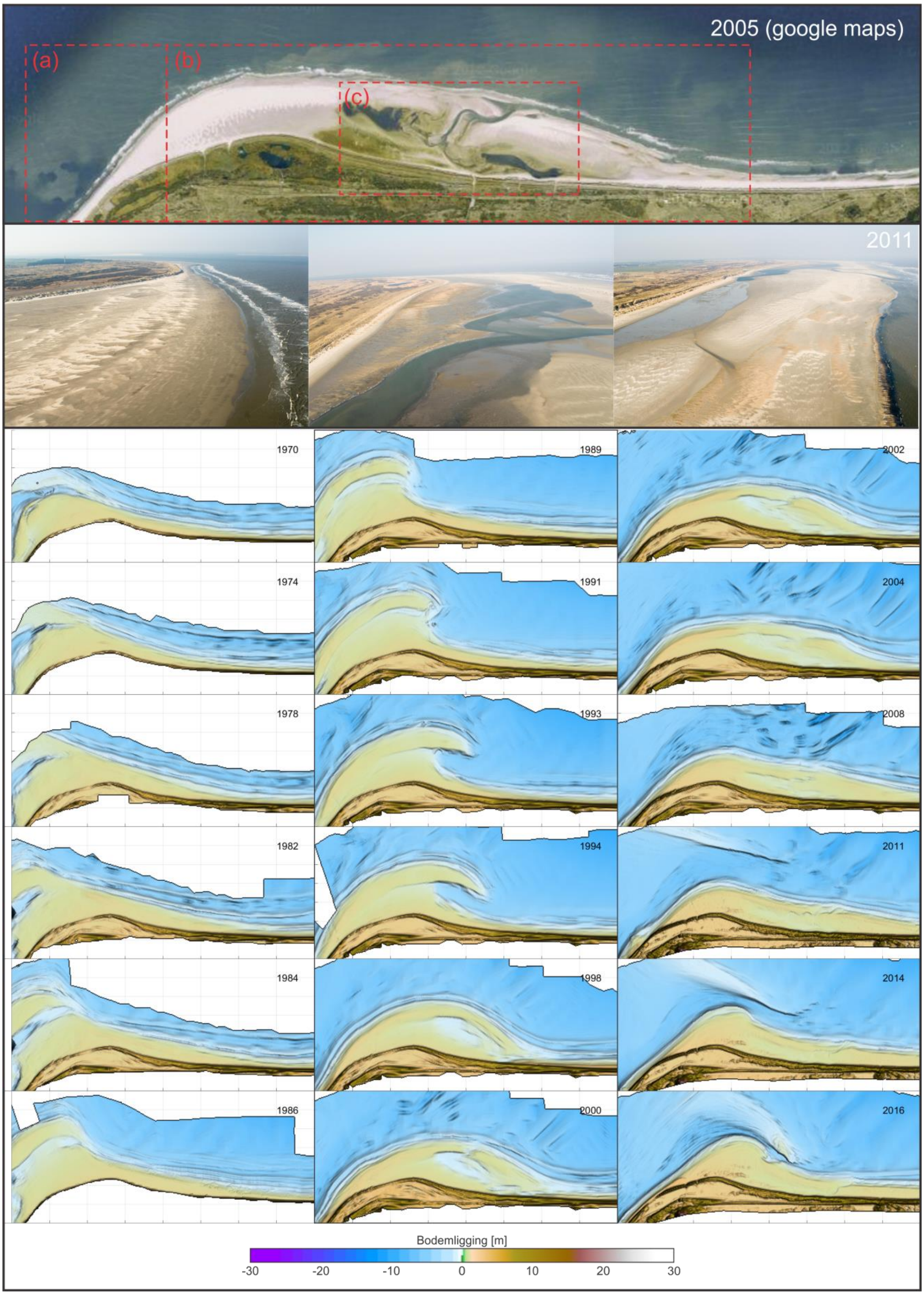


Figure 2.11 Attachment and merger of the Bornrif Strandhaak based on the JarKus gridded data (1970-2016). In the recent bathymetries (2001-2016) the formation and migration of Bornrif Bankje is also visible.

3 Hydrodynamics

3.1 Introduction

Tides, waves and wind are capable of transporting large quantities of sand back and forth that are an order of magnitude larger than the net displacement of sand. Sediment transport measurements in these highly energetic environments are not trivial tasks. To measure the gross (or net) contribution of the sediment transport directly, with sufficient resolution in time and space is virtually impossible, and forms one of the major limitations in our present knowledge. To obtain understanding of the sediment transport we need to resort to a combination of measurements and numerical modelling.

Point measurements of flow of sediment transport by itself is valuable, but they are also essential to calibrate and validate the numerical models. Validated model results can help us understand the point measurements, and when reproduced with sufficient accuracy, the model results provide synoptic data, in space and time, over the entire inlet domain. In order to successfully simulate the sediment transports the models need detailed boundary conditions for the main forcing processes (e.g. tides and waves), and time series of local measurements to validate the model.

In this section we present an overview of the data present to drive the model (Chapter 3.2). This data be subdivided in (regional scale) long-term measuring campaigns such as performed through MWTL (Monitoring Waterstaatkundige Toestand des Lands), stored in the RWS database DONAR and available through MATROOS (http://noos.matroos.rws.nl). Chapter 3.2 describes the available water level measurements, Chapter 3.3 focusses on waves, wind stations and data ae described in Chapter 3.4. Estimates of discharges and velocities in Borndiep are presented in Chapter 3.5. A special dataset concerns the radar data collected at the Ameland light house (Chapter 3.6). By using special software (SeaDarQ) the radar images can provide spatial observations of wave length, dominant wave direction, wave period and (by means of the dispersion relation) also current magnitude, current direction and water depth. The data provide a snapshot of the sea state for an approximate 7.5 km from the lighthouse which basically covers the entire ebb-tidal delta domain (see e.g. Swinkels et al., 2012). The analysis of 2017 radar data is part of the Kustgenese project and will not be repeated here. In Chapter 3.3.3. we provide a brief overview of the analyzed data within the SBW framework.

In addition to the long-term datasets, detailed measurements were made during the SBW measuring campaigns. SBW stands for the ”Strength and Loading of Water Defenses” Program, filling in the knowledge gaps in the periodic safety assessment of the primary flood defenses. One of the research topics within SBW is the penetration of North Sea waves into the tidal inlet systems of the Wadden Sea, with an aim is to improve the numerical wave model SWAN (Booij et al., 1999) on this point. In addition to extensive wave measurements at various locations in the Wadden Sea, additional measurements (such as bathymetry and currents) were made. In Chapter 3.7. we present an overview of the most relevant SBW studies and datasets for Kustgenese 2.

3.2 Water levels

Water levels are measured at various locations in and around the Wadden Sea (Figure 3.1). A data inventory presented by Jeuken et al. (2012) indicates that 23 stations are present in the MWTL program with long-term records. The longest records date back to 1879 (e.g. Den Helder), but most stations have data since 1970 (see Table 3.2). All data are stored on DONAR (Data Opslag Natte Areaal Rijkswaterstaat) and various data parameters are present through water base or MATROOS, most relevant for this study are the 10-minute interval data. Table 3.2 provides an overview of the data retrieved for 26 (active) stations in the Wadden Sea and nearby North Sea. All data are stored as Netcdf and mat files on the Kustgenese project disk. For an additional 11 (inactive) stations data was retrieved (Table 3.2, bottom).

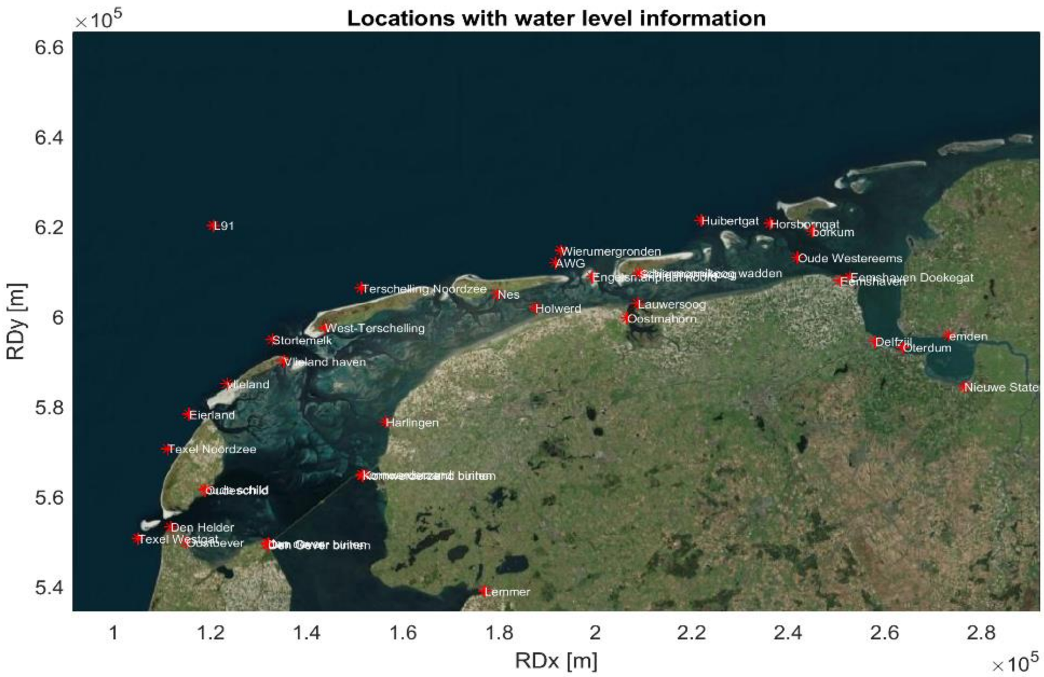


Figure 3.1 : Overview of the relevant stations for waterlevels near Ameland Inlet, based on Waterbase data.

In addition to the long-term records 10 additional stations with records dating back to 2007 are present (see Figure 3.2). Most of these short-term records were recorded for the SBW project (2004-2016). The data records can be retrieved through MATROOS (http://noos.matroos.rws.nl). Wierumerwad 2 and Uithuizenwad 2 are 2 additional water level stations added to MATROOS from the SBW measurements. All data will be stored in matlab and netcdf format on the Kustgenese 2.0 data repository.

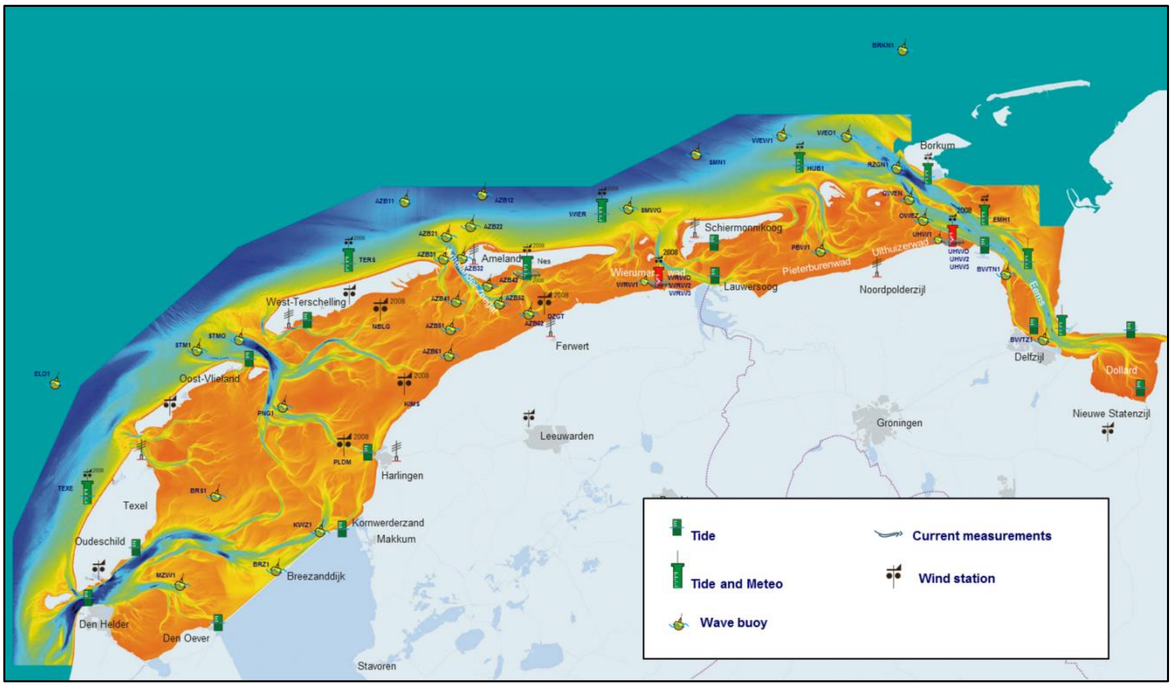


Figure 3.2 Overview of the locations of water levels, wind and wave measurement locations during the SBW measurement campaign (based on an overview plot for the year 2008-2009).

No long-term records are available directly seaward of Ameland inlet. The closest, nearby stations for the north-sea waterlevels are Terschelling NoordZee (TNZ), located just westward of the inlet at Terschelling (Oosterend), and the station Wierumergronden (WIER) located to the east on the ebb-tidal delta of the Frisian Inlet. In the basin two stations are present in the harbours of Nes (NES) and Holwerd. A quick analysis of the tidal record for TNZ, using the t_tide software package (Pawlowicz et al., 2002), reveals that the M2 constituent with an amplitude of 0.86 m is the dominant water level component (Table 3.1). Distortion of the M2 tide results in a significant asymmetry (M4 amplitude is 0.08 m) and faster rise than fall of the tide. A considerable spring neap variation (S2 amplitude is 0.24 m) results in an increase of the tidal range to 2.0 m during spring tide and a drop to about 1.0 m during neap.

Table 3.1 Overview 10 main constituents for Station Terschelling North Sea (based on 2016 data).

Constituent		*Amplitude*	*Phase*
Name	ϕ	*[m]*	*[deg]*
M2	28.98	0.86	234.07
S2	30.00	0.24	296.12
N2	28.44	0.15	211.71
O1	13.94	0.10	206.38
M4	57.97	0.08	330.04
K1	15.04	0.07	0.53
L2	29.53	0.07	237.37
K2	30.08	0.07	295.26
MU2	27.97	0.06	321.76
MS4	59.98	0.05	42.08
SSA	0.08	0.05	233.59
M6	86.95	0.05	60.42

Comparing the tidal signal with the full measurement timeseries reveals the importance of the non tidal components to the water levels (Figure 3.3). It is well-known that meteorological distortion due to air pressure and wind-generated set-up or set-down can reach significant heights along the Dutch coast. At TNZ, set-ups can exceed 1.5 m during major storm events (see Figure 3.3, bottom). In the Wadden Sea, with its complex bathymetry, set-up-gradients can drive complicated residual flow fields, generate shore-parallel velocities and throughflow between adjacent basins (Duran-Matute et al., 2014). In addition, the volume of water stored in the Wadden Sea due to the larger set-up can considerably enlarge the outflow velocities in the inlets following the storm events, thereby affecting channel dimensions, the ebb-tidal delta development and adjacent beaches (Elias, 2006).

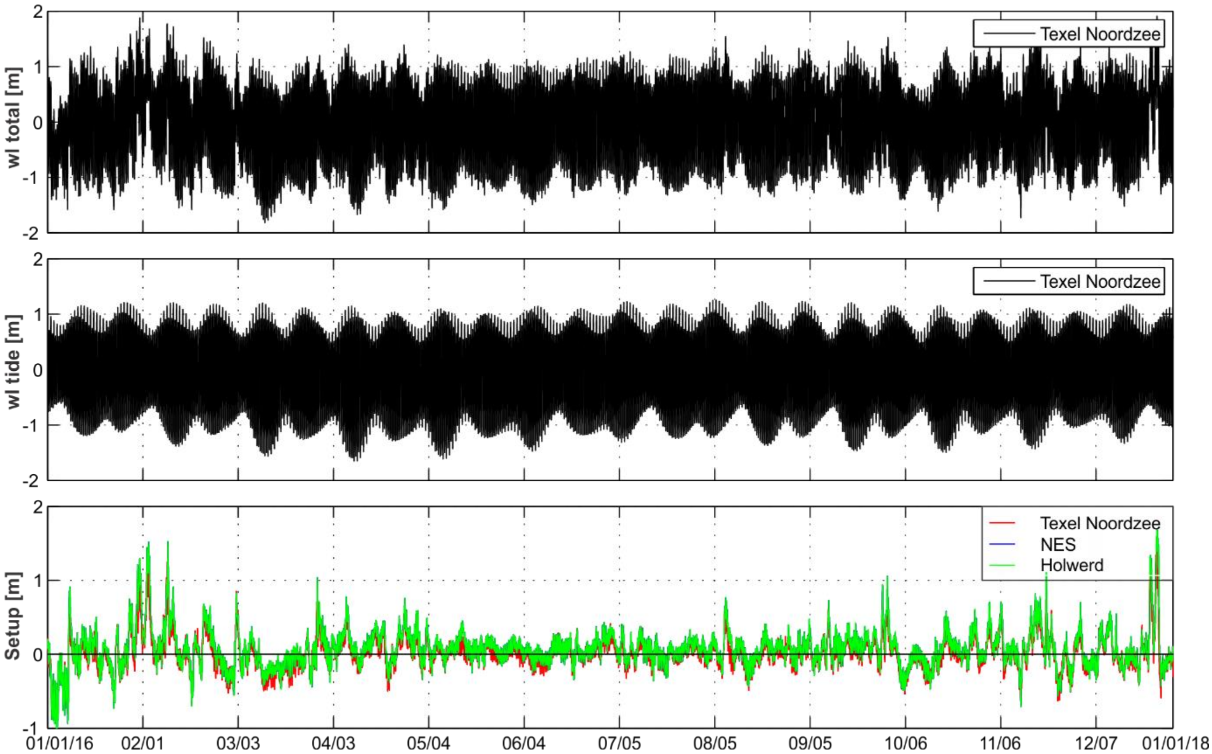


Figure 3.3   Figure 3.3Overview of water level measurements at station Terschelling NoordZee -TNZ (top), an estimate of the tidal water levels based on t_tide analysis of TNZ, and the computed setup at stations TNZ, NES and Holwerd.

Table 3.2 Overiew of waterlevel stations in and around the Wadden Sea.

Station	Start date	End date	X [m]	Y [m]	Instrument type	Source
Long term records						
Delfzijl	01-Jan-1879	present	258000	594430	VL	WB,M
Den Helder	01-Jan-1932	present	111850	553230		WB,M
Den Oever buiten	01-Jan-1921	present	132030	549440		WB,M
Eemshaven	29-Dec-1978	present			VL	WB,M
Harlingen	01-Sep-1935	present				WB,M
Holwerd	01-Jan-1971	present	187550	601850	RW	WB,M
Huibertgat	01-Jan-1973	present	221990	621330	VL	WB,M
Kornwerderzand buiten	01-Sep-1932	present	154610	583416		WB,M
Lauwersoog	01-Jan-1971	present	208850	602790	VL	WB,M
Nes	01-Jan-1971	present	179707	604916	VL	WB,M
Nieuwe Statenzijl	01-Jan-1979	present			RW	WB,M
Oudeschild	01-Jan-1971	present				WB,M
Schiermonnikoog	01-Jan-1971	present			VL	WB,M
Terschelling Noordzee	01-Mar-1989	present	151400	606250	VL	WB,M
Texel Noordzee	01-Jun-1989	present				WB,M
Vlieland haven	01-Nov-1943	present	135280	590000		WB,M
West-Terschelling	01-Feb-1928	present	143870	597420		WB,M
Wierumergronden	01-Jan-1981	present	192882	614562	VL	WB,M
Wieremerwad 2	??	present	200000	602587	ES	WB,M
Uithuizenwad 2	??	present	245500	609810	ES	WB,M
AWG	01-Jan-09	present	192348	612796		WB,M
L91	02-Jun-09	present	127168	625717		WB,M
Q11	02-Feb-09	present				WB,M
borkum	01-Jan-07	present				WB,M
emden	21-Jan-09	present				WB,M
K13A	-	present	10268	583416		WB,M
Inactive stations						
vlieland	08-Oct-07	09-Okt-07				
Eemshaven Doekegat	01-Jan-83	01-Jan-87				
Eierland	01-Jan-81	01-Feb-83				
Engelsmanplaat Noord	01-Jan-81	01-Dec-92				
Horsborngat	01-Jan-81	30-Dec-87				
Oostmahorn	01-Jan-32	25-May-69				
Oostoever	01-Jan-71	01-Jan-81				
Oterdum	01-Jan-83	01-Jan-87				
Oude Westereems	01-Jan-81	01-Jan-84				
Stortemelk	01-Jan-81	24-Nov-81				
Texel Westgat	01-Jan-74	10-Feb-81				

Instrument type: VL – Vlotterniveaumeter
RW – Radac Waveguide
ES – Etrometa Stappenaak

Source data: (WB) Waterbase - https://waterinfo.rws.nl/#!/kaart/waterhoogte-t-o-v-nap/,
(M) MATROOS - http://noos.matroos.rws.nl/

3.3 Waves

Long-term (since 1979) wave data is available through permanent measurements at various (9) locations in and along the Wadden Sea and coast (Figure 3.4 and Table 3.3). Most stations in the Wadden Sea are no longer active. Near Ameland the 3 closest stations are Eierlandse Gat (ELD) to the southwest, Schiemonnikoog Noord (SON) to the east, and the L9 platform further seaward (Northwest). These stations measure a variety of parameters. Bulk parameters most relevant for Kustgenese are: (1) Wave height, (2) Mean and Peak wave period (Tm02, Tp), (3) Wave direction, and (4) Wave directional spreading.

On the ebb-tidal deltas, waves redistribute the sediments and contribute to the sediment bypassing mechanism. In order to capture these processes accurately detailed wave measurements are essential. At Ameland inlet, detailed wave measurements at multiple locations have been taken since 2007 (Figure 3.5). Initially these measurements were part of the SBW project (Zijderveld & Peters, 2008), but measurements have been continued since. The wave buoys are only installed in the stormy season, from September/October till April. See Chapter 4 for more details on the SBW measurements. Also during Kustgenese the deployment at the Ameland Inlet will be continued in similar configuration.

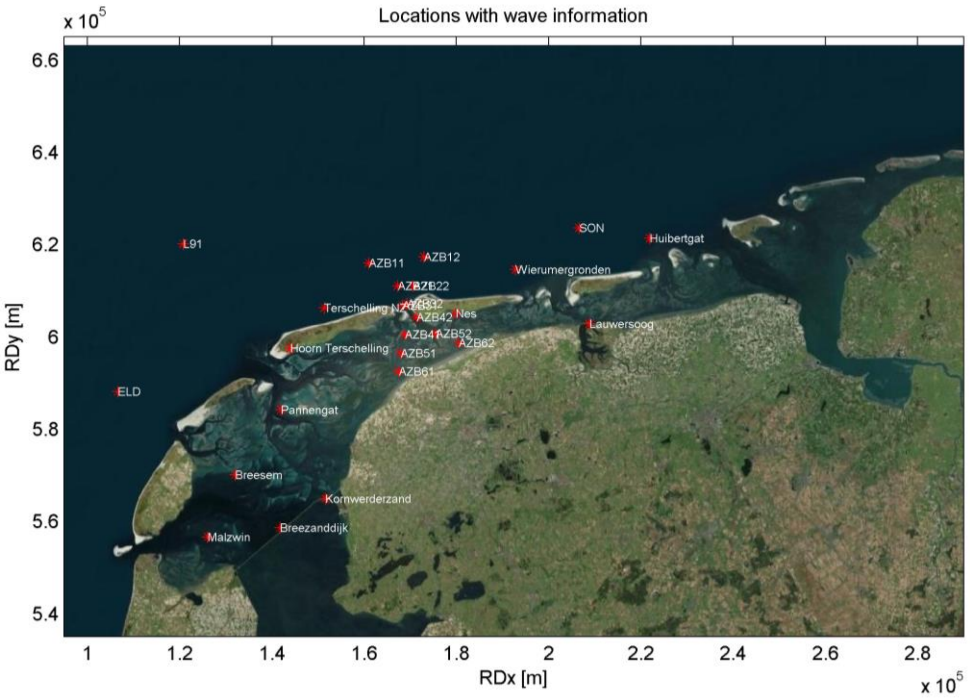


Figure 3.4 Overview of all locations with wave records.

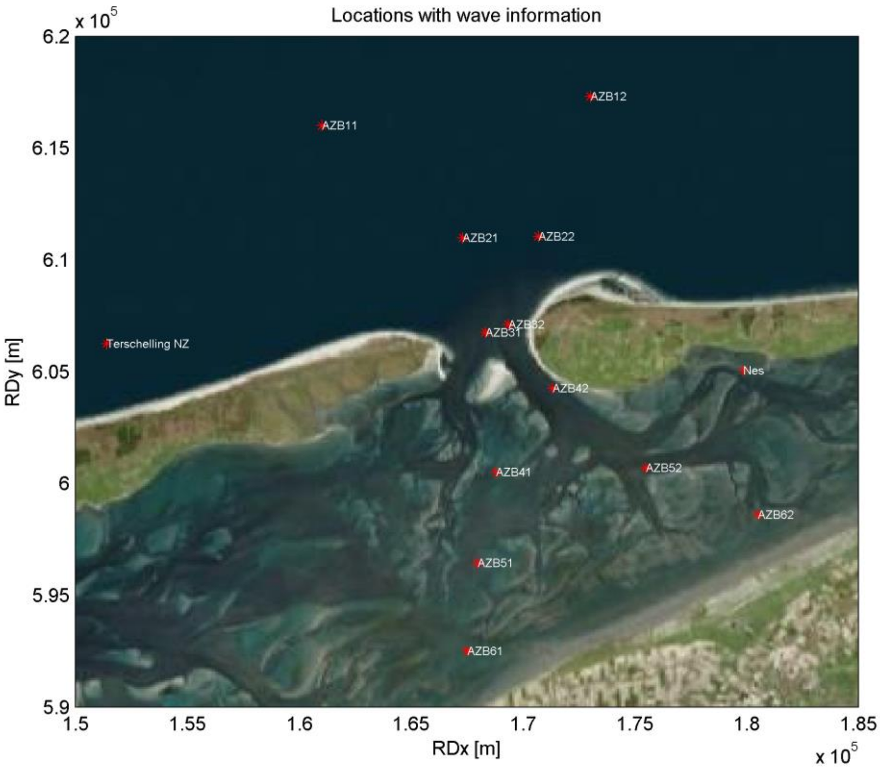


Figure 3.5 Details of the wave buoys in Ameland inlet (bottom).

Table 3.3 Overview of stations and start date measurements

Station	Type	X [m]	Y[m]	Bed level [m]
Eierlandse Gat	DWR	107000	588000	- 27
Schiermonnikoog (SON)	DWR	208000	622000	- 19
Stortemelk	DWR	128930	592767	- 13.3
Malzwin	DWR	126000	556500	- 4
Pannengat	DWR	141900	584100	- 4.15
Breesem	DWR	132000	570000	- 1.2
Breezanddijk	WR	141650	558500	- 5.2
Kornwerderzand	WR	148216	564347	- 6.5
Nes	radac	179810	604920	
Overview of wave stations in Amelander Inlet				
AZB11	DWR	161006	616004	-18.1
AZB21	DWR	167307	610978	-9.1
AZB31	DWR	168318	606745	-3.5
AZB41	DWR	168792	600501	-0.9
AZB51	WR	167963	596444	+0.8
AZB61	WR	167500	592500	-0.5
AZB12	DWR	173011	617304	-21.0
AZB22	WR	170688	611040	-3.3
AZB32	DWR	169349	607115	-10.7
AZB42	DWR	171319	604249	-16.7
AZB52	DWR	175490	600699	-12.2
AZB62	WR	180506	598604	-2.3

DWR = Directional Waverider (buoy); WR=Waverider (buoy); radac is type of downward looking radar.

Data availability:

DWR (directional wave rider buoys):

- wave parameters based on wave spectrum 0.03 – 0.5 Hz
- 1D wave energy spectrum
- wave direction spectrum
- wave direction spreading spectrum

WR (non-directional wave rider buoys):

- wave parameters based on wave spectrum 0.03 – 0.5 Hz
- 1D wave energy spectrum

The offshore wave climate at Ameland shows a mean wave significant wave height of 1.37 m with a corresponding peak wave period of 7.2 s. Analysis of the measurements over the period 2007-2017, reveals that the wave climate mainly consists of local wind-generated waves in the shallow North Sea basin (Figure 3.6 and Figure 3.7c). The wave climate is fairly mild. Typically, waves are below 2 m (83% of the record), only during severe storms significant wave heights can occasionally reach heights between 4.5 and 9.1 m (less than 1 % of the record). Roughly 33% of the wave directions lie between west-southwest and north-northwest (235° – 305°). Most waves (62%) are from directions between north-northwest and east (305° – 90°). The remaining 4% is offshore directed and do not significantly contribute to the sediment transports. Waves from the easterly direction (0°-360°) are smaller due to the sheltering by the mainland (offshore directed) and occur less frequently. Wave periods (T1/3) typically vary between 3 to 6 seconds for lower wave conditions (89 % of the measurements). For typical storm waves (Hsig= 2-3 m) a mean wave period of 6,0 s occurs increasing to 7.6 s for severe storms (Hsig > 4m). Contributions of swell are minor. Wave periods over 9 seconds are only measured occasionally (0,1% of the record). The differences between the wave-roses of the two Ameland stations illustrate the important wave reduction effect of the ebb-tidal delta. As a result of wave-breaking on the ebb-tidal delta shoals the wave heights in the nearshore (inlet) Ameland station reduced to 1,0 m while wave directions are constrained almost entirely to the north-westerly quadrant (in line with the main channel).

Due to the relative short record of observations at the Ameland buoys and missing data early summer, when the buoys are out of the water for maintenance, it is not possible to create a long-term representative wave climate for these buoys. Such a climate needs to be based on either the Eierlandse Gat or SON buoy. Comparing the wave direction and wave heights between ELD-AME and SON-AME (Figure 3.8) illustrates that SON best resembles the Ameland wave record with a close correlation in height and direction. For future wave climate schematizations it is recommended to use the SON data as basis.

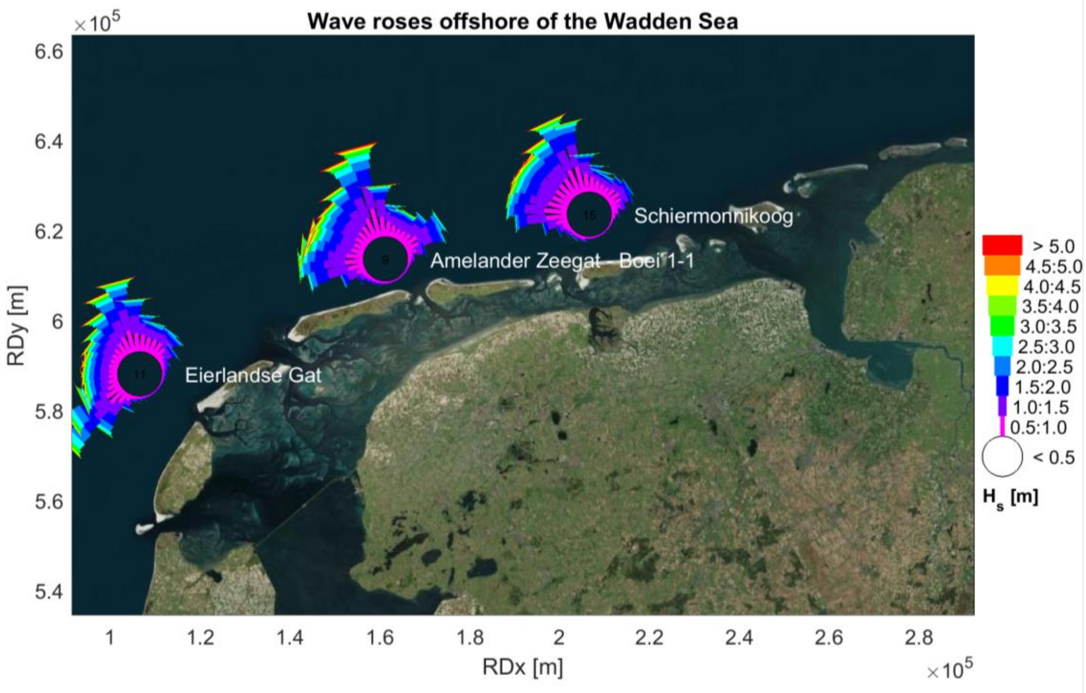


Figure 3.6 Wave roses and locations for stations Eierlandse Gat, Amelander Zeegat and Schiermonnikoog.

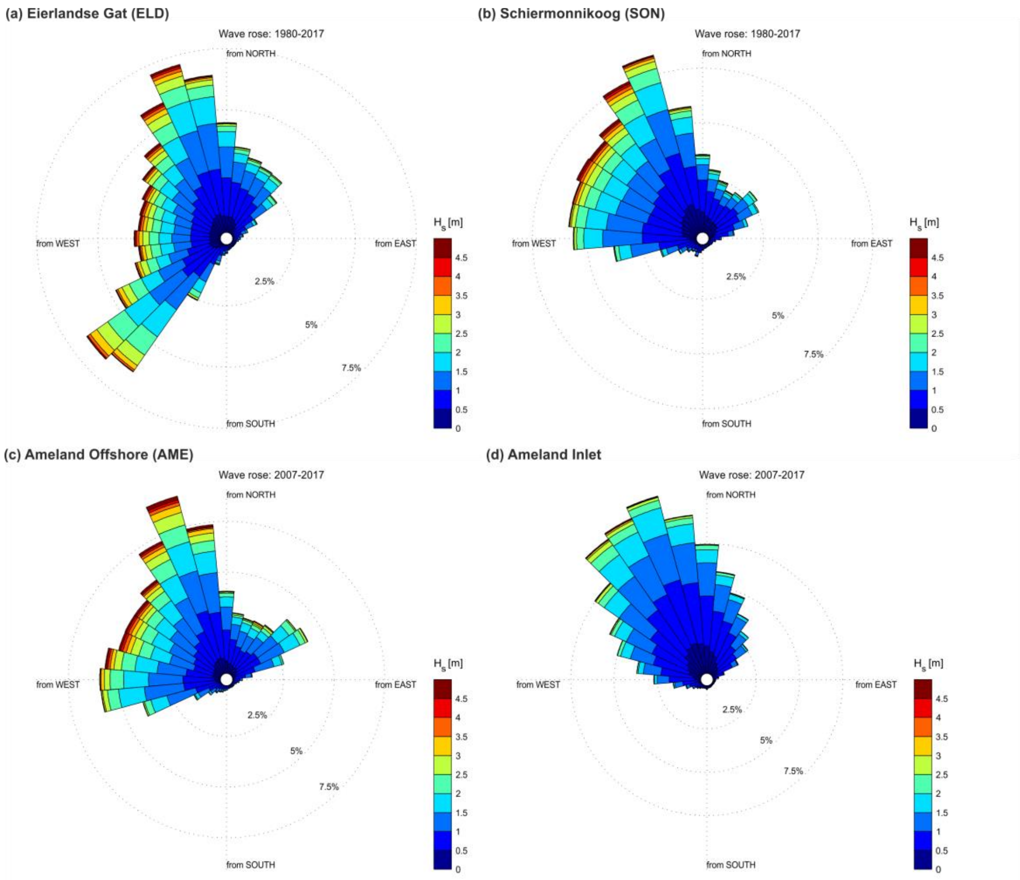


Figure 3.7 Detailled wave roses for stations (a) Eierlandse Gat (ELD), (b) Schiermonnikoog (SON), and the Ameland offshore (AME) and Ameland Inlet..

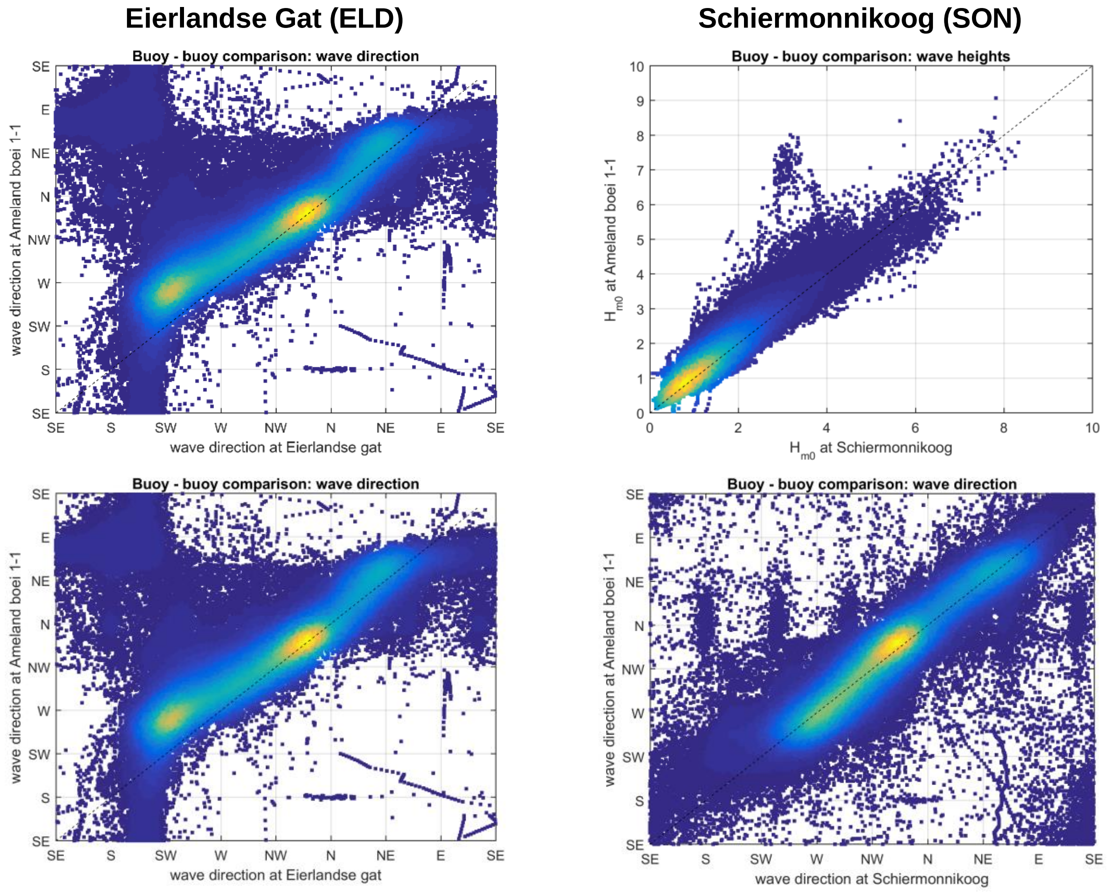


Figure 3.8 *Comparison of wave direction (left column) and wave height (right column) between ELD – AME (top panels) and SON – AME (bottom panels).*

3.4 Wind stations

Limited knowledge is present on the importance of the wind and wind-driven flow on the ebb-tidal delta and in the inlet gorge. Depending on the wind speed and direction a considerable setup can be generated in the North Sea which is important to include in the analysis of the Ameland Inlet. In the Wadden Sea, we can expect the wind to be important for mixing and estuarine circulations, and in shallow areas wind is effective in generating large currents and tidal flat degeneration by locally generated waves. Also the eastward migration of the tidal divides in the Wadden Sea may for a major part be related to the prevailing wind direction (de Boer et al, 1991, FitzGerald et al., 1984; Van Veen et al., 2005).

Figure 3.10 provides an overview of the stations present in the North Sea (top panel) and in the Wadden Sea (bottom panel). The observed wind speed and direction (U10 [m/s]) can be obtained as 10 minute averages from the Matroos database from RWS. Most relevant stations for Ameland that can be downloaded from MATROOS are L91, Hoorn Terschelling, AWG, Huibertgat and Lauwersoog. These time series generally span the period since 1970-present.

In addition to MATROOS wind data for 35 stations is also available through the KNMI (http://projects.knmi.nl/klimatologie/uurgegevens/selectie.cgi). Through the KNMI website the hourly data for e.g. temperature, sun, cloudiness, visibility, air pressure, wind speed and rainfall can be obtained.

A brief analysis of the wind measurements taken at the nearby AWG station (see Figure 3.9) show a mean wind velocity of 4.9 m/s from a south-southwesterly direction (200°). This nearshore wind velocity is considerably smaller compared to the averaged measured velocities of 5.7 m/s at the offshore (L9) location. A noticeable difference is present between the dominant wind and wave directions. The largest and most frequent winds occur from the Southwest, a direction hardly present in the wave record due to the sheltering of the mainland.

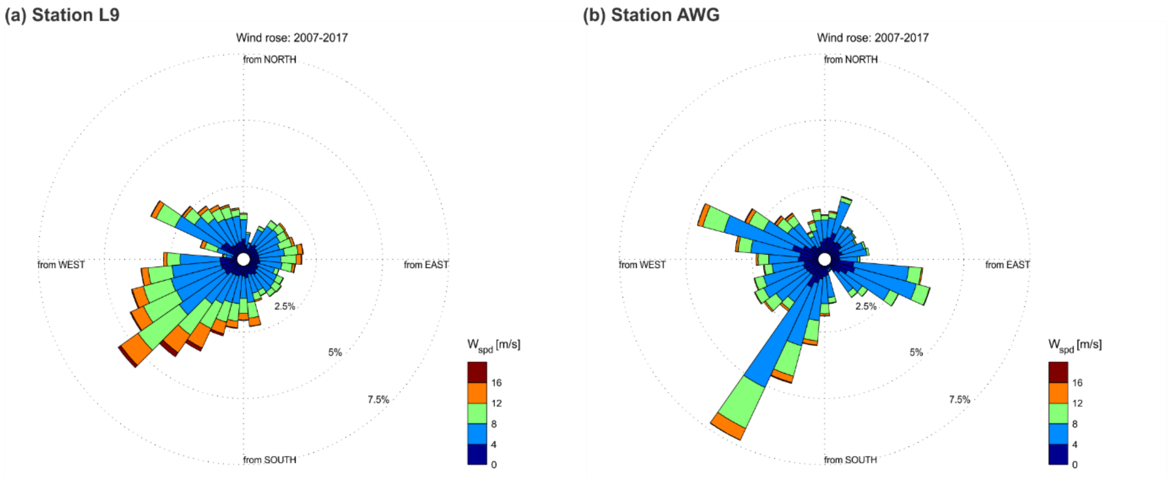
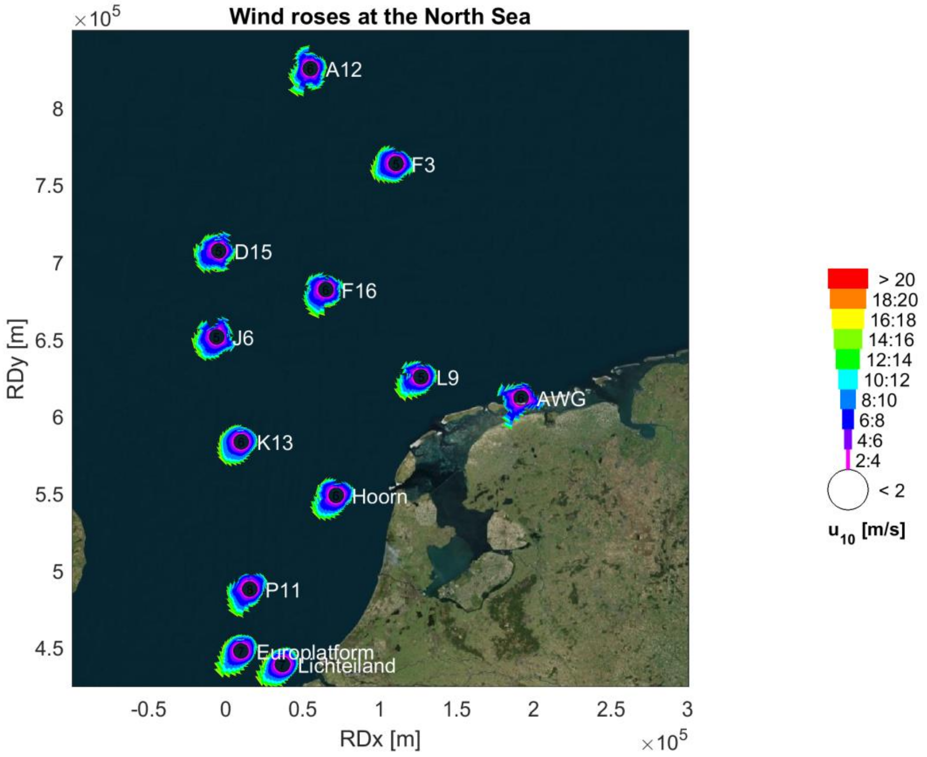


Figure 3.9 Details of the wind roses for stations (a) L9 (offshore) and (b) AWG (Ameland).

Note that in addition to the point observations, data from the HIRLAM wind model is available. HIRLAM (High Resolution Limited Area Model) is a weather prediction model and contains among others spatial wind and pressure fields on approximate 11 x 11 km^2 grids in 3-hourly interval.



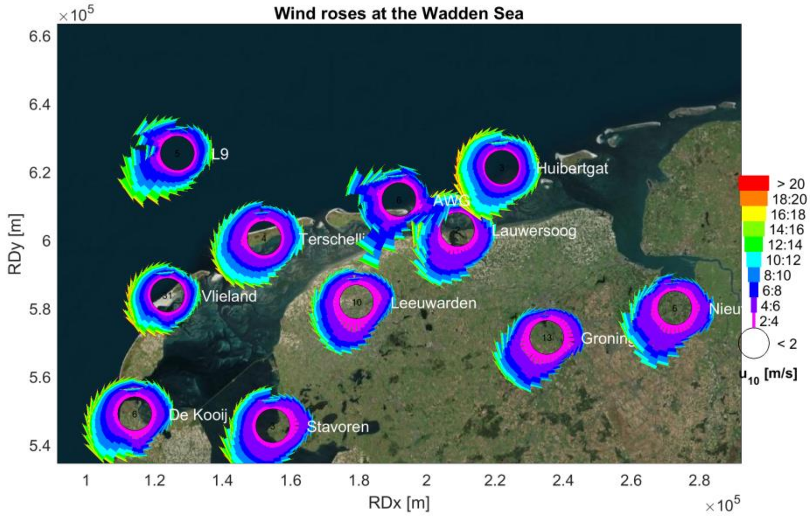


Figure 3.10 Overview of the wind roses based on the stations in the North Sea (top) and details of the stations near the Wadden Sea (bottom).

3.5 Discharges and Velocities in Ameland Inlet

3.5.1 Discharges in the Inlet (Borndiep)

In the inlet gorge Borndiep, the semi-diurnal tidal movement is the main driving force behind the horizontal water flow through the inlet. The most recent discharge measurement was executed in 2001 (Briek et al. 2003) and show on average ebb- and flood volumes through the inlet of c. 400 million m3. The peak ebb- and flood-tidal velocities are around 1 m/s in the central Borndiep channel. All available discharge measurements are summarized in Table 2. The values presented in this table are based on Israel (1998) as in this study all measurements (with the exception of the year 1937) were recalculated to a mean tide using a coherent method (Van Sijp, 1989). The oldest available measurement (1937) has a similar value to the 2001 measurement.

A comprehensive study of ebb and flood volumes was presented by Studiedienst Hoorn (1973). In this report 109 flood and 110 ebb tides obtained from roving ship measurements (taken over the time frame 1968 -1971) and continuously operating current stations (1971) were analyzed. The average discharge value during this time frame is significantly higher compared to the more recent measurements (1996, 1999, 2001). Both the 1999 and 2001 measurement indicate that a small residual ebb dominance prevails that is less than 10 % of the ebb and flood volumes.

Table 3.4 Overview of measured ebb and flood volumes in Borndiep based on 13-hours measurements.

Survey year	**dates**	**Average Tidal Ampl. [m]**	**Measured Discharge [10^6 m^3]**			**Mean Discharge [10^6 m^3]**			**Reference**
			Flood	Ebb	Nett	Flood	Ebb	Nett	
1937	-	-	-	-	-	406	-431	-25	Beckering Vinkers (1943)
1968 – 1973	109 flood 110 ebb tides	1.95	-	-	-	518	-494	24	Studiedienst Hoorn (1973)
1996			502	-450	52	448	-395	53	Hut (1997)
1999	26-10-1999 04:00-18:00		542	-573	-31	416	-454	-38	Visser (1999)
2001	22-01-2001 05:30-18:30		557	-547	10	407	-418	-11	Briek et al (2003).

Flow and discharge measurements at Ameland inlet were obtained previously during the Kust2005 Research Program of RWS, and more recently during the SBW project. An overview of discharge measurements is presented in de Fockert (2008) and Table 3.4. For a selected number of (recent) measurements the underlying reports and documents have been retrieved. A first analysis of these reports shows that most of these allow for the reconstruction of the tidal volumes. The underlying data has not yet been retrieved.

(1) Beckering Vinkers, 1943. De waterbeweging in het borndiep. Report 73.3. Rijkswaterstaat, Studiedienst Hoorn. pp:34.

(2) Barsingerhom, S., Briek, J., Huizinga, M.A., Hut, J., Noordstra, P. (2003). Meting Bornrif/Borndiep september 1996. Project Strobodi. Report 98.006. Rijkswaterstaat, directie Noord-Nederland, Delftzijl: pp: 89

(3) Briek, J., Huizinga, M.A., Hut, J., Noordstra, P. (1998). Meting Borndiep september 1997. Project Strobodi. Report 98.005. Rijkswaterstaat, directie Noord-Nederland, Delftzijl: pp: 45

(4) de Visser, R. (1999). Amelander Zeegat 99. Debietmetingen en Morfologische ontwikkelingen. RIK 48, Ingenieursbureau S.D. Kamminga BV, Zoetermeer.

(5) Briek, J., Huizinga, M.A., Hut, J., (2003). Stroommeting Zeegat van Ameland 2001. RIKZ-report 2003-169, RWS Noord-Nederland, Delftzijl.

Additional velocity and discharge measurements:
Buiteveld R. (1990). Meetverslag debietrneting Dantziggat 1990. Rijkswaterstaat, directie Friesland. Report ANW 90.30: 12 pp.

3.5.2 SBW ADCP measurements.

Detailed velocity measurements on the ebb-tidal delta and main inlet channel were obtained during the SBW project by placing 3 Acoustic Doppler Velocity Profilers (ADCP's) in Ameland inlet (Figure 3.11, 3.12 and Table 3.5). ADCP locations 1 and 4 were measured at intervals (bins) of 0.5m and 10-minute time intervals. The ADCP location 5, located on a tidal flat, was measured with 0.05m depth bins and a similar time interval of 10 minutes. Details of the measurements and collection can be found in (Aqua Vision, 2008).

Table 3.5 Locations and depths of Amelander Zeegat ADCP measurements (based on de Graaf, 2009)

	Easting (m, RD)	**Northing (m, RD)**	**Water depth**	**Description of location**
ADCP-loc1	161300	616000	18.6	approx. 12km offshore of the Amelander Zeegat in deep water
ADCP-loc4	171150	604400	17.3	in the centre of the main tidal channel of the Amelander Zeegat, just South of Ameland. See also its location in Figure 3.7.
ADCP-loc5	168800	600300	1.0	on top of a tidal flat, with exposure during low water

Current measurements at a total of three locations were collected by RWS in the Amelander Zeegat in the framework of the SBW project. The full current measuring campaign lasted from November 2007 to May 2008. Only the data at location 1 is available for the entire time frame.

De Graaf (2009) describes the steps that were followed in previous studies to process the ADCP data:

1 Import the data in WinADCP (software package from RD Instruments®) and export the current magnitudes and directions for all bins in ASCII format;
2 Import the ASCII data in ADCPview (Deltares' ADCP viewing and analysis tool) and make animations of the vertical current profiles;
3 review the quality of the measurements and convert the current profiles to depth-averaged currents by averaging all bins except for the upper 5 bins as these show

irregularities (related to reflection of the sound waves at the surface and possibly waves) and interpolating the lowest bin to 0m/s at the seabed;
4 the depth-averaged currents for locations 1 and 4 (not location 5 as this station had no recordings during low water) were analysed by means of harmonic analysis, resulting in sets of harmonic constituents and time-series of current predictions.

De Graaf (2009) summarizes the main characteristics of the processed data as follows:

Location 1:
- relatively strong current magnitudes of up to 1m/s
- coast parallel two-directional currents, with flood currents directed towards the East to East-Northeast and ebb currents directed to the West to West- Southwest
- currents observed in the bins are uniform over the water depth, indicating a logarithmic current profile
- good quality of measurements

Location 4:
- relatively strong current magnitudes of up to 2m/s at the surface
- two-directional currents, with flood currents directed towards the Southeast to South-Southeast and ebb currents directed to the Northwest to North- Northwest
- currents show a steep vertical gradient with relatively high velocities near the surface and relatively low velocities near the bed. This steep current profile may be explained by spiral flow effects in the curved channel around Ameland, enhanced friction on the flow as a result of the channel edge, density or wind effects.
- good quality of measurements during most parts of the measurement period

Location 5:
- exposure of ADCP during low water with no readings, and during high water:
- measurements show large degree of scatter, although tidal influence is still apparent with flood currents in south-westerly directions and ebb currents in north-easterly directions. The scatter may be related to the effects of wind and waves, but also to measurement errors (i.e. reflection of acoustic waves against surface) as a result of the limited depth.
- relatively low current magnitudes of up to 0.6m/s
- poor quality of measurements

An additional dataset is available for the 2011-2012 timeframe (Figure 3.12). This dataset constist of two station locations. Station AZG03 is located seaward in Akkepollegat. Here velocities are measured over an approximately 2-week timeframe. Velocities in Borndiep, are measured for the entire month of January 2011 and for a near 4-month timeframe in 2012. The two ADCP stations are located in Borndiep. Largest velocities are measured at the AZG03 station with magnitudes of 1.8 m/s during spring tide, while during neap the velocities reduce to 1 m/s. Seaward a considerable reduction of the velocities occurs. Velocities at AZG02 are generally between 20% and 50% smaller.

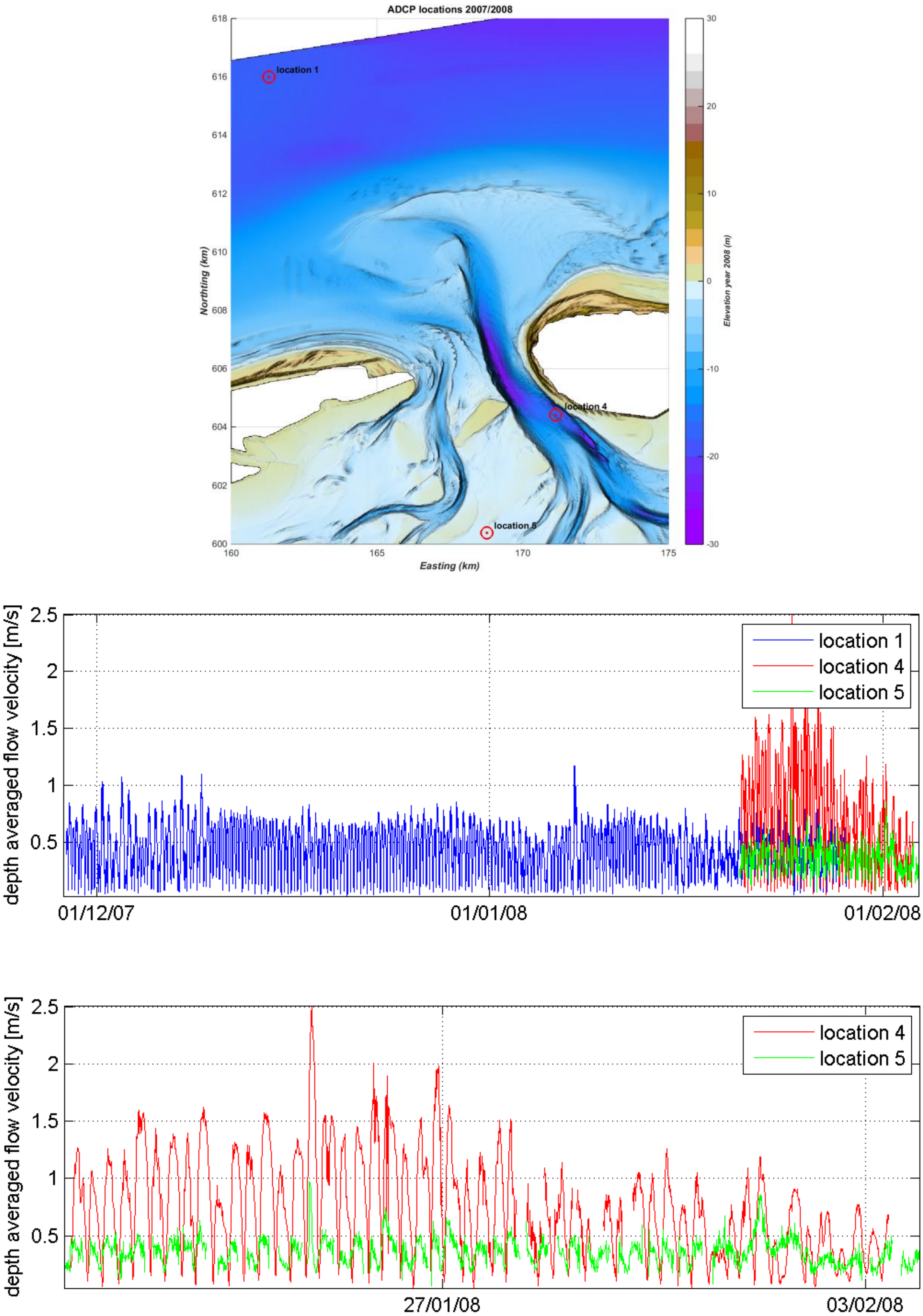


Figure 3.11 Top panel: Locations of the 3 ADCP deployments during 2007-2008. Bottom panels: a snapshot of the depth-averaged velocity magnitude at ADCP stations 1, 4 and 5, illustrating the data availability for the 2007-2008 timeframe.

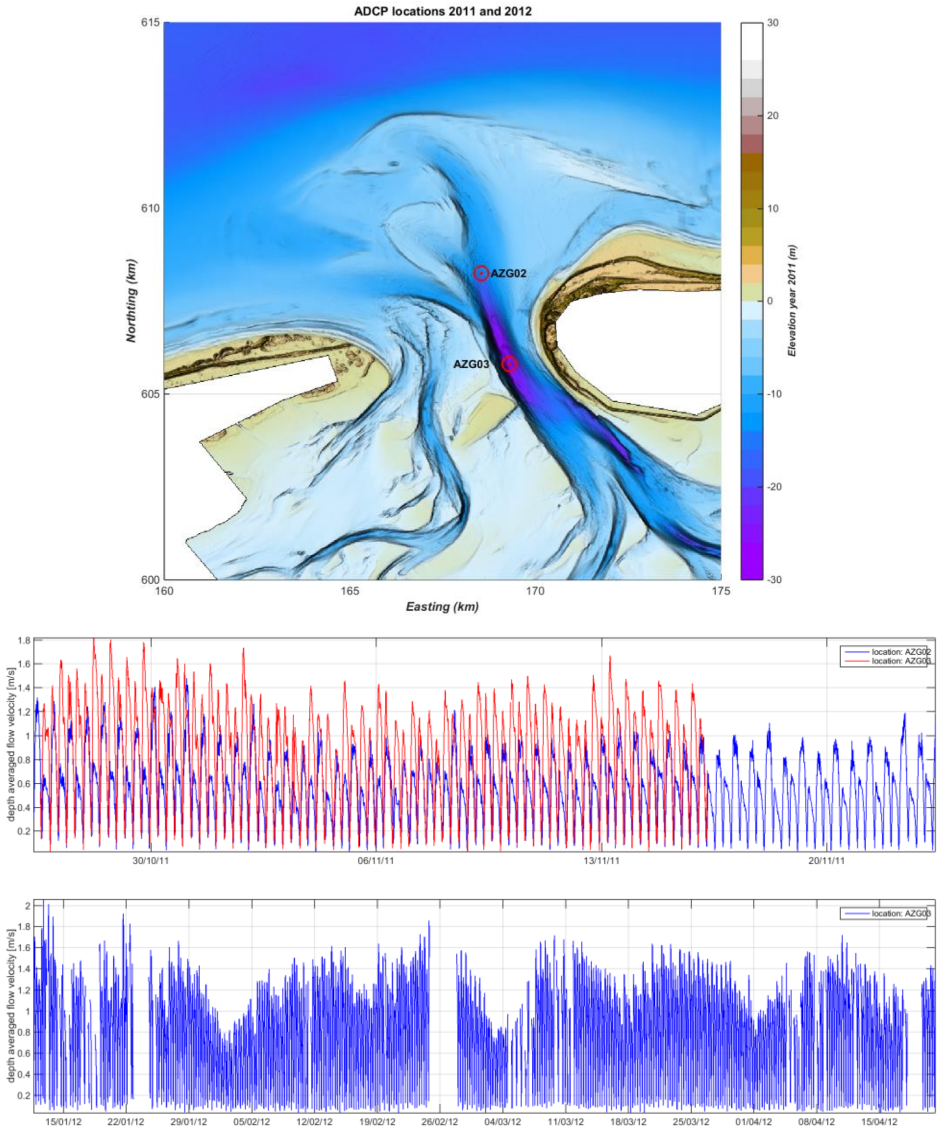


Figure 3.12 Top panel: Locations of the 3 ADCP deployments during 2011-2012 campaigns. Bottom panels: A snapshot of the depth-averaged velocity magnitude at ADCP stations AZG02 and 03, illustrating the data availability for the 2011-2012 timeframe.

3.6 Velocity fields based on SeaDarQ radar (a summary of SBW reports)

The radar data of Ameland is part of the SBW measuring campaign. In addition to time-series at the individual ADCP locations, estimates of the flow fields can be obtained from the X-band rader images obtained at the Ameland lighthouse (Figure 3.13). These images have been collected since 2010. Through the use of special software (SeaDarQ) the radar images (Figure 3.14) can provide spatial observations of wave length, dominant wave direction, wave period and (by means of the dispersion relation) also current magnitude, current direction and water depth (Figure 3.15 and Figure 3.16). The data provide a snapshot of the sea state for an approximate 7.5 km from the lighthouse which basically covers the entire ebb-tidal delta domain. See e.g. Swinkels et al. (2012) for details.

Figure 3.13 Location and approximate range of the lighthouse of Ameland (left) and lighthouse with marine radar mounted on its top (right). From: Swinkels et al. (20??)

As part of the Kustgenese 2.0 project a detailed analysis of the recent (2017) Sea DarQ radar data will be made. In addition, data for three consecutive periods, January 2010, October, 2010 and April, 2012 are already analysed and available through various SBW projects (see Table 3.6 and next sections).

Table 3.6 Overview of data and settings for SeaDarQ.

Period	Period	SeaDarQ settings	rangeCell [m]	cubeSize [m]
January 2010	27/01/2010 17h40–28/01/2010 09h00	settings 1	7.5	960
	27/01/2010 19h20–28/01/2010 09h50	settings 2	7.5	960
October 2010	18/10/2010 23h20–24/10/2010 09h30	settings 2	15.0	1920
April 2012	13/04/2012 22h30–17/04/2012 13h00	settings 3	15.0	1920
ADCP data	11/01/2012 17h20–21/04/2012 06h40	-	-	-

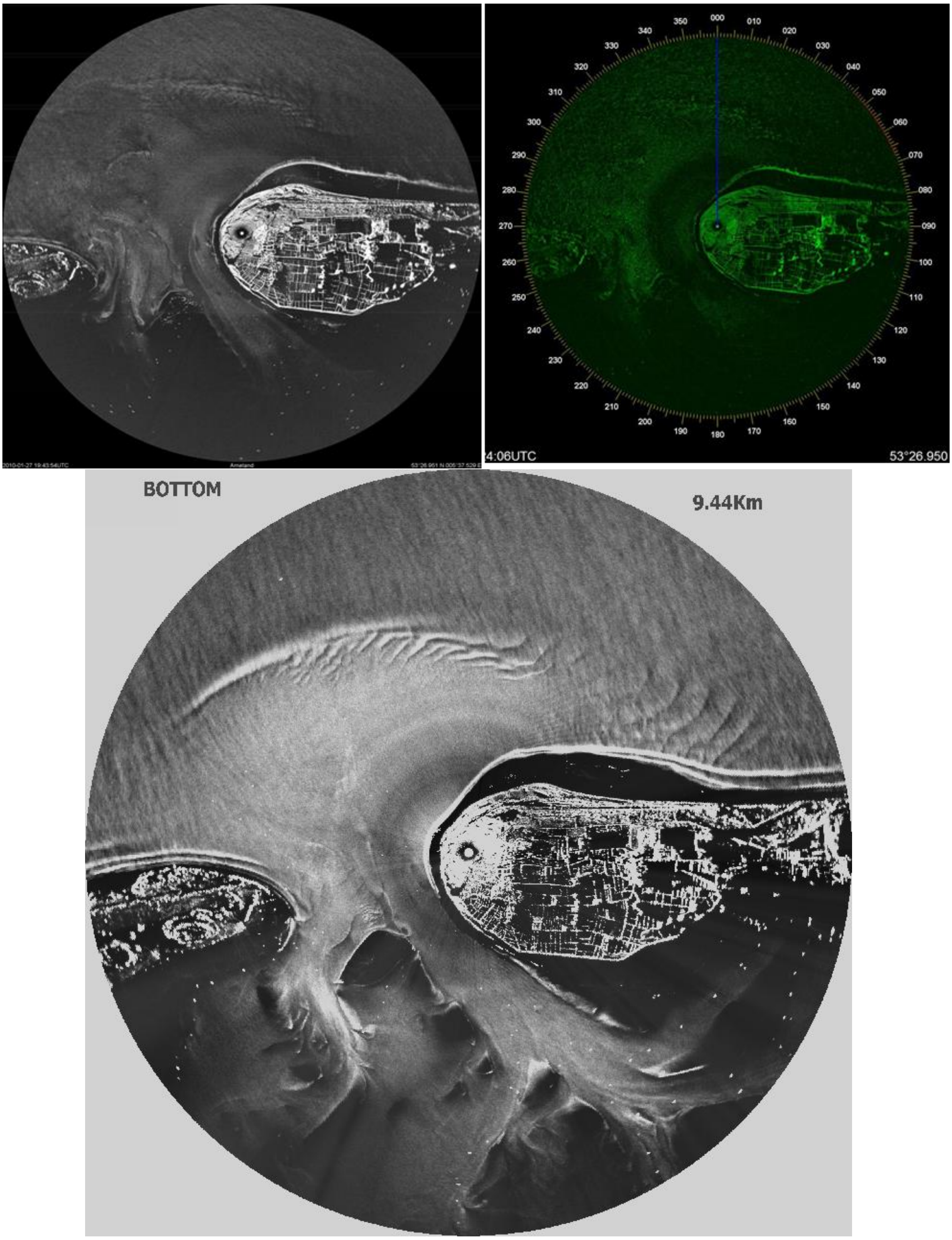


Figure 3.14 Unprocessed radar image (upper left) and snapshot (upper right, average of 8 images) at the Amelander tidal inlet (from Swinkels 2010). Bottom panel: processed snapshot showing the bathymetric features of Ameland inlet (from Gautier et al. 2014)

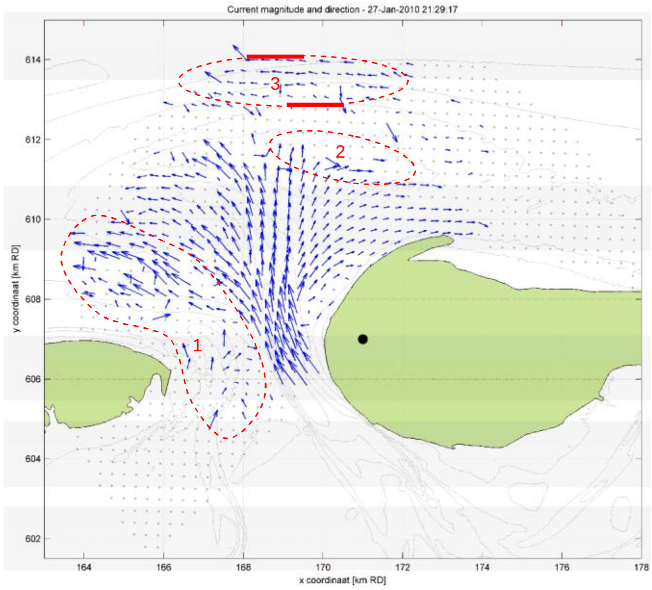


Figure 3.15 Example of SeaDarQ current field with indication of areas with high occurrence of outliers (from Swinkels, 2010).

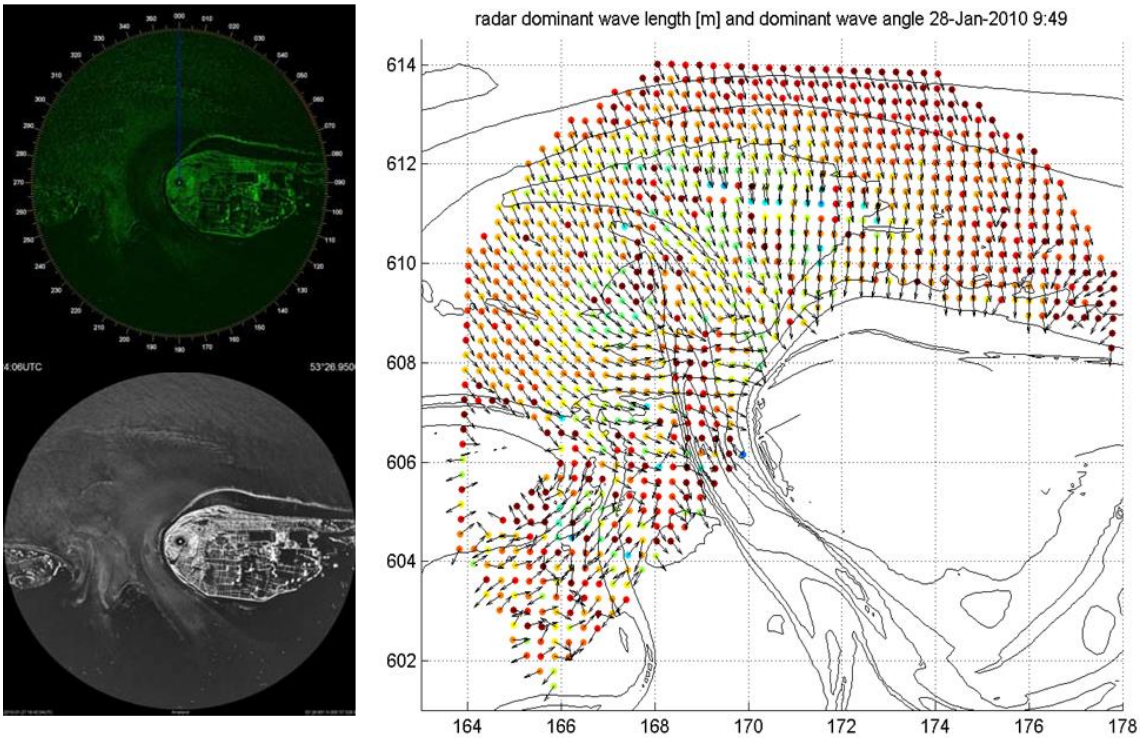


Figure 3.16 left panels: Radar image and snapshot Amelander Zeegat (from SeadarQ); right: Scatter plot of processed dominant wave length and wave direction (from Gautier and van der Westhuysen, 2010).

3.7 An overview of SBW available data/events:

Detailed model simulations of the Wadden Sea and the Ameland inlet were conducted in the SBW projects. These projects focussed on specific events and calibration and validation datasets. The reports contain a wealth of data descriptions that may be useful for the Kustgenese project. In this section a brief overview of the most relevant studies and underlying data are presented.

3.7.1 General water level modelling of the Dutch Wadden Sea.

<u>Project:</u>
De Graaf, R. (2009).SBW Wadden Sea, water level modelling. Calibration hydrodynamic model. Deltares project 1200114-005. Deltares, Delft.

<u>Summary of available data:</u>
The main objectives of this study are to (1). determine whether the setup of the 2008 version of the Wadden Sea model can be improved or updated, and (2) assess and improve the ability of the Wadden Sea model to accurately compute tide induced water levels and currents in the Wadden Sea (no wind modelling), by updating the schematization and calibration against water level and current measurements. The data in this report focusses on the 2008 and 2009 time frames with a focus on a storm hindcast 31 January 2008, and a winter hindcast (2008 – 2009). For the model calibration the waterlevels were compared against measured time-series and sets of harmonic constituents at 6 stations (see Figure 3.17 for an example). Validation of the currents was based on 3 ADCP measurements taken in the Ameland inlet. These measurements were previously described in section 3.3.2.

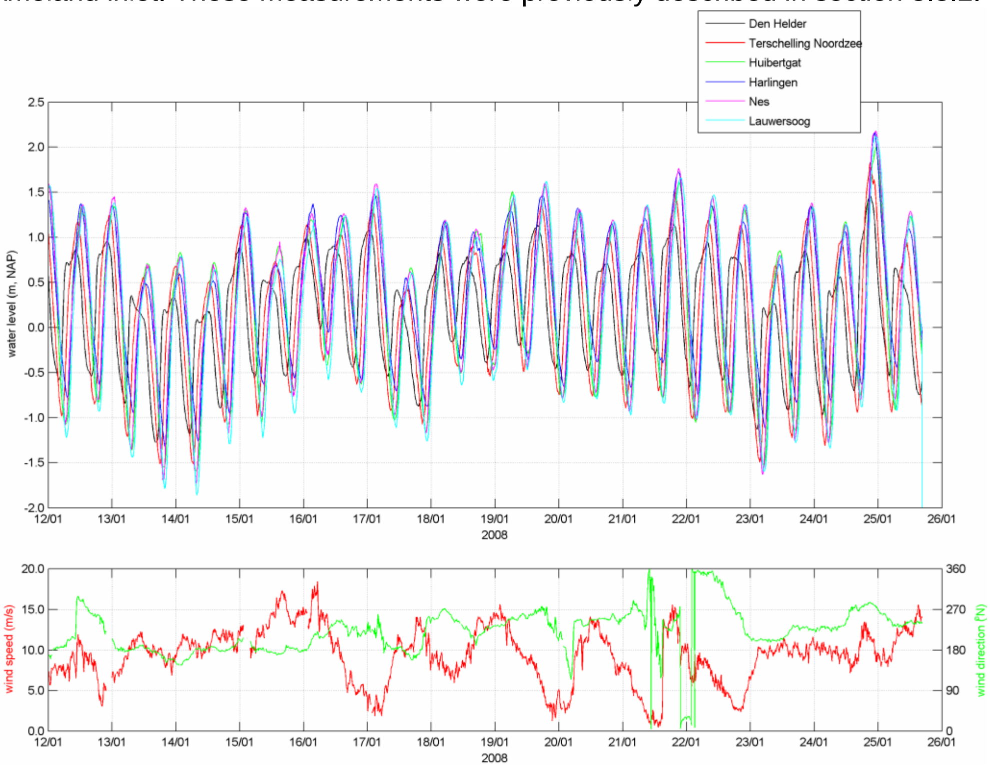


Figure 3.17 Observed water levels for 6 stations in the Wadden Sea for a period of 2 weeks in January 2008. The lower plot shows the simultaneous wind speeds and directions. From de Graaf (2009).

3.7.2 Moderate storm event of January 2010.

Project:
Swinkels, C. (2010): Storm hindcast January 2010 – Analysis of the application of radar current data for hindcast purposes. Deltares report 1202119-001.

Summary of available data:

Swinkels (2010) presents an analysis and comparison of Delft3D modelling and the X-band radar images for a moderate storm event (27-01-2010 – 28-01-2010). In addition to the radar images waterlevels are available for the stations Terschelling Noordzee, Huibertgat, Den Helder, Nes, Schiermonnikoog and Lauwersoog (MATROOS database). Wind speeds and directions are present for Hoorn / Terschelling, Huibertgat and Lauwersoog. Wave boundary conditions for the SON and ELD (Schiermonnikoog and Eilerlandse Gat) wave buoys were used. Bathymetry is based on 2007/2008 Vaklodingen and Lidar. The tidal channels and ebb-tidal delta were based on the 2009 SBW data. Waves were validated using 12 wave buoys placed on the ebb-tidal delta. The same time frame was analysed by Gautier and van der Westhuysen (2010) with the focus on wave propagation under the influence of currents. See. See Figure 3.19, Figure 3.18and Table 3.7 for a snapshot of the available data. The coherent datasets available for this time frame make this an interesting test case for model testing in the Kustgenese project.

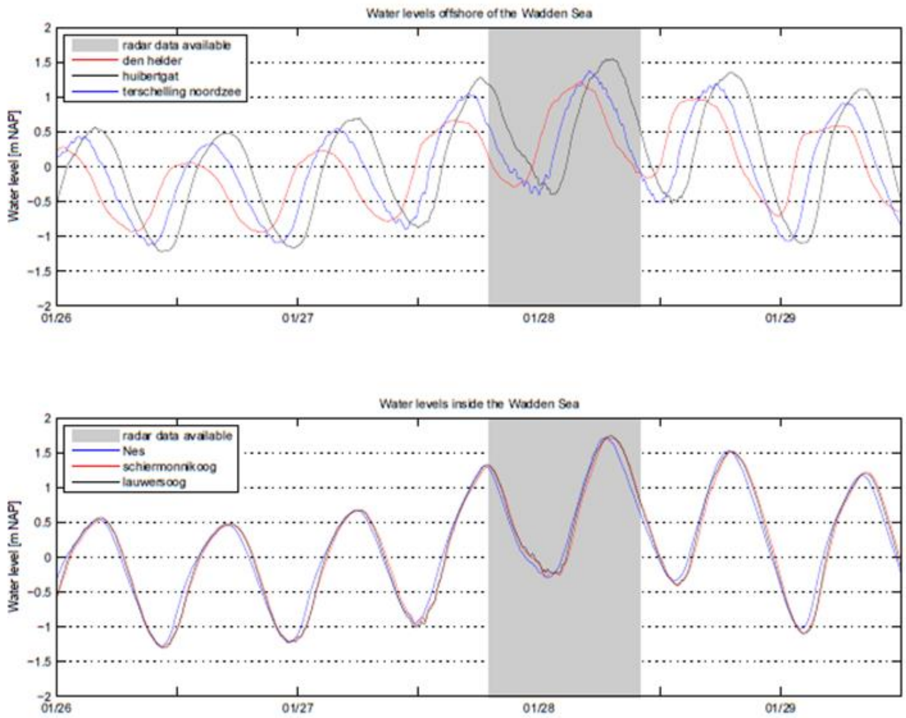


Figure 3.18 : Observed water levels at different water level stations during the January 2010 storm event (From Swinkels et al. 2010).

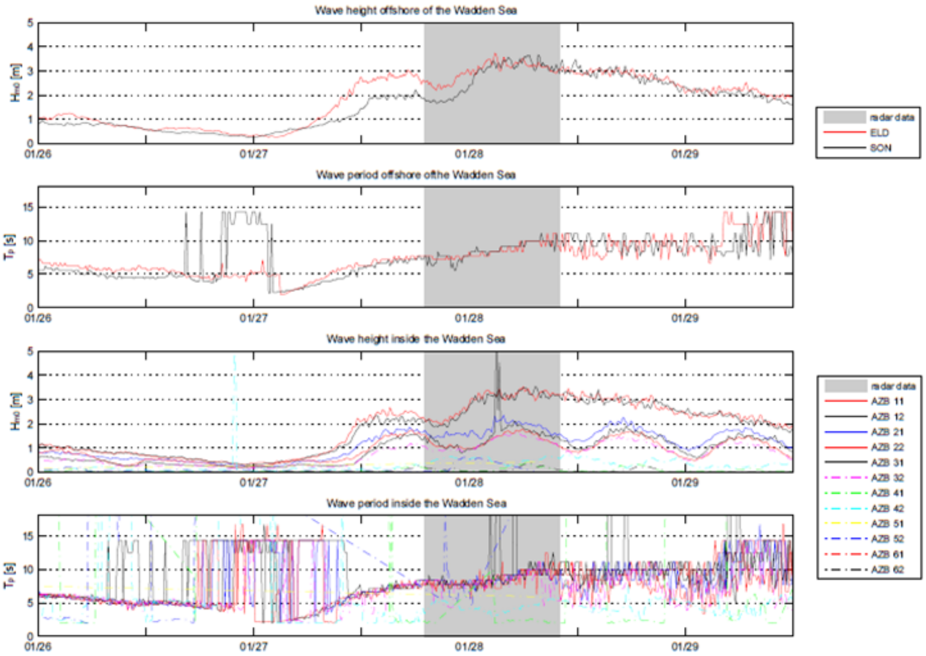


Figure 3.19 Measured wave heights Hm0 and peak periods Tp at different wave buoys during the January 2010 storm event (From Swinkels et al. 2010).

Table 3.7 Overview of the available observation locations for waves, wind and water levels for the January 2010 storm event (from Gautier and van der Westhuysen, 2010).

buoy	X [m RD]	Y [m RD]	bed level [m +NAP]	parameter	input data	validation data
AZB11	161006.	616004.	-18.1	waves+dir		v
AZB21	167307.	610978.	-9.1	waves+dir		v
AZB31	168318.	606745.	-3.5	waves+dir		v
AZB41	168792.	600501.	-0.9	waves+dir		v
AZB51	167963.	596444.	+0.8	waves		
AZB61	167500.	592500.	-0.5	waves		
AZB12	173011.	617304.	-21.0	waves+dir		v
AZB22	170688.	611040.	-3.3	waves		v
AZB32	169349.	607115.	-10.7	waves+dir		v
AZB42	171319.	604249.	-16.7	waves+dir		v
AZB52	175490.	600699.	-12.2	waves+dir		
AZB62	180506.	598604.	-2.3	waves		v
SON	206608*	623565*	-20	waves+dir	v	
ELD	106603*	588068*	-27	waves+dir	v	
Nes	179841**	605047**	-5.8	water level	v	
Terschelling NZ	151400.	606250.		water level		
Terschelling NZ	151400.	606250.		wind	v	
Wierumergronden	192882.	614562.		wind	v	
Hoorn Terschelling	143957**	597502**		wind		
Huibertgat	221990.	621330.		wind	v	
Lauwersoog	208850.	602790.		wind		

3.7.3 Swan hindcasts for December 2013 extreme storm event.

Project:
Gautier, G., Camarena, A., van Nieuwkoop, J., (2014). SWAN hindcasts Wadden Sea, December 2013. Tidal inlet of Ameland and eastern Wadden Sea. Deltares project 1209433-007, Deltares, Delft.

Summary of available data:
The aim of this project was to assess the SWAN model performance in stationary mode for the Sinterklaasstorm (December 5/6, 2013) which is one of the most severe storms (in terms of water levels and wind velocities) for which proper wave observations are available in the Wadden Sea (see Figure 3.21 for a snapshot of the measurements). Data of time series (wind, water levels, waves) was received from the Servicedesk Data of Rijkswaterstaat. The bathymetry data was taken from the OpenEarthTools database in which vaklodingen datasets are stored for a series of years (http://opendap.deltares.nl/thredds/dodsC/opendap/rijkswaterstaat/vaklodingen).

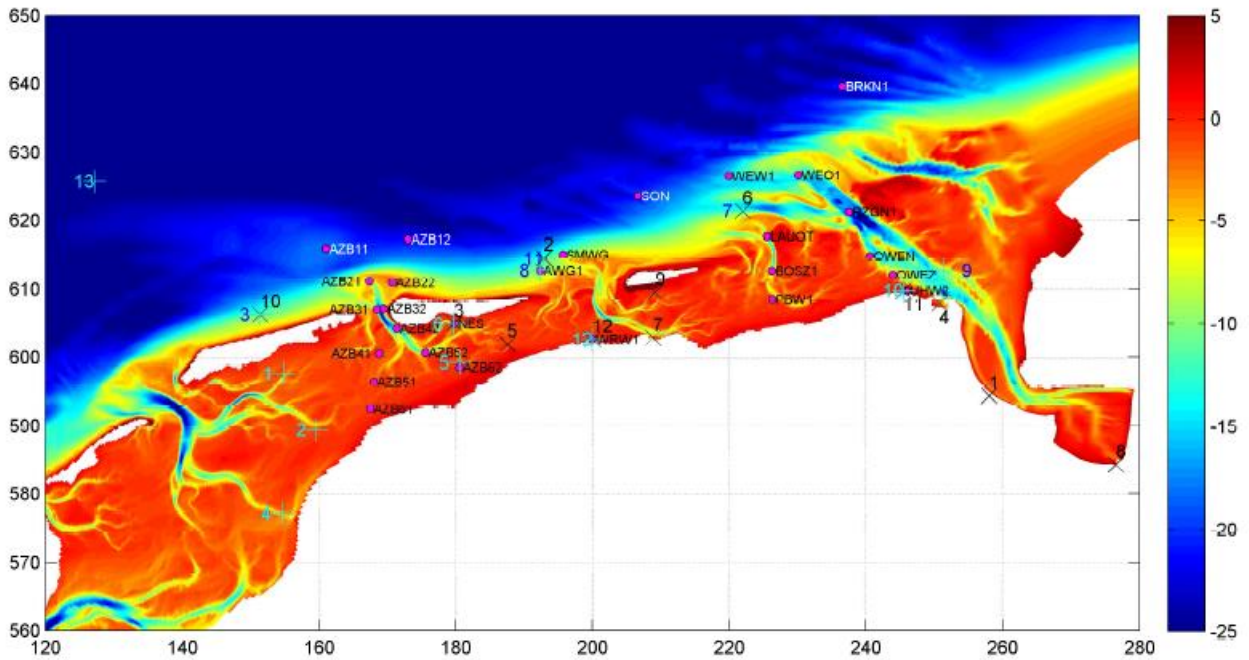


Figure 3.20 Overview of the wave buoys present at Ameland Inlet and the Eastern Wadden Sea (see Table 3.6 for locations). From Gautier et al. (2014).

This study mentions that 32 wave instruments are present near the inlet of Ameland and the eastern Wadden Sea. Just west of Ameland they are located in two transects of six buoys each from the relatively deep North Sea to the shallow foreshore of the Friesland coast. There are a few offshore buoys (Eierlandse Gat (ELD), Schiermonnikoog Noord (SON), Borkum Noord (BRKN)) which are normally used for boundary conditions and a few individual buoys like Nes, AWG-platform, Wierumerwad and Schiermonnikoog Westgat.

However, not all instruments functioned well during this storm. Locations that were used as boundary condition in previous hindcasts (SON and ELD) failed. Also the waveriders at the shallow locations Uithuizerwad and Wierumerwad gave no data, but the step gauge and downward looking radar did at these two locations. Furthermore there is no data for AZB21 in the Amelander Zeegat. The wave data consists of wave variance spectra and – if available – mean direction and directional spread as a function of frequency, all with a 10 minute time interval. The frequency domain of the directional wave riders is 0.03 – 0.5 Hz, whereas the non-directional waveriders provide spectra for frequencies from 0.01 to 1 Hz.

Water level observations are available from thirteen locations on the Wadden Sea and North Sea. The time step is 10 minutes. Wind observations are available from twelve locations on the Wadden Sea and North Sea.

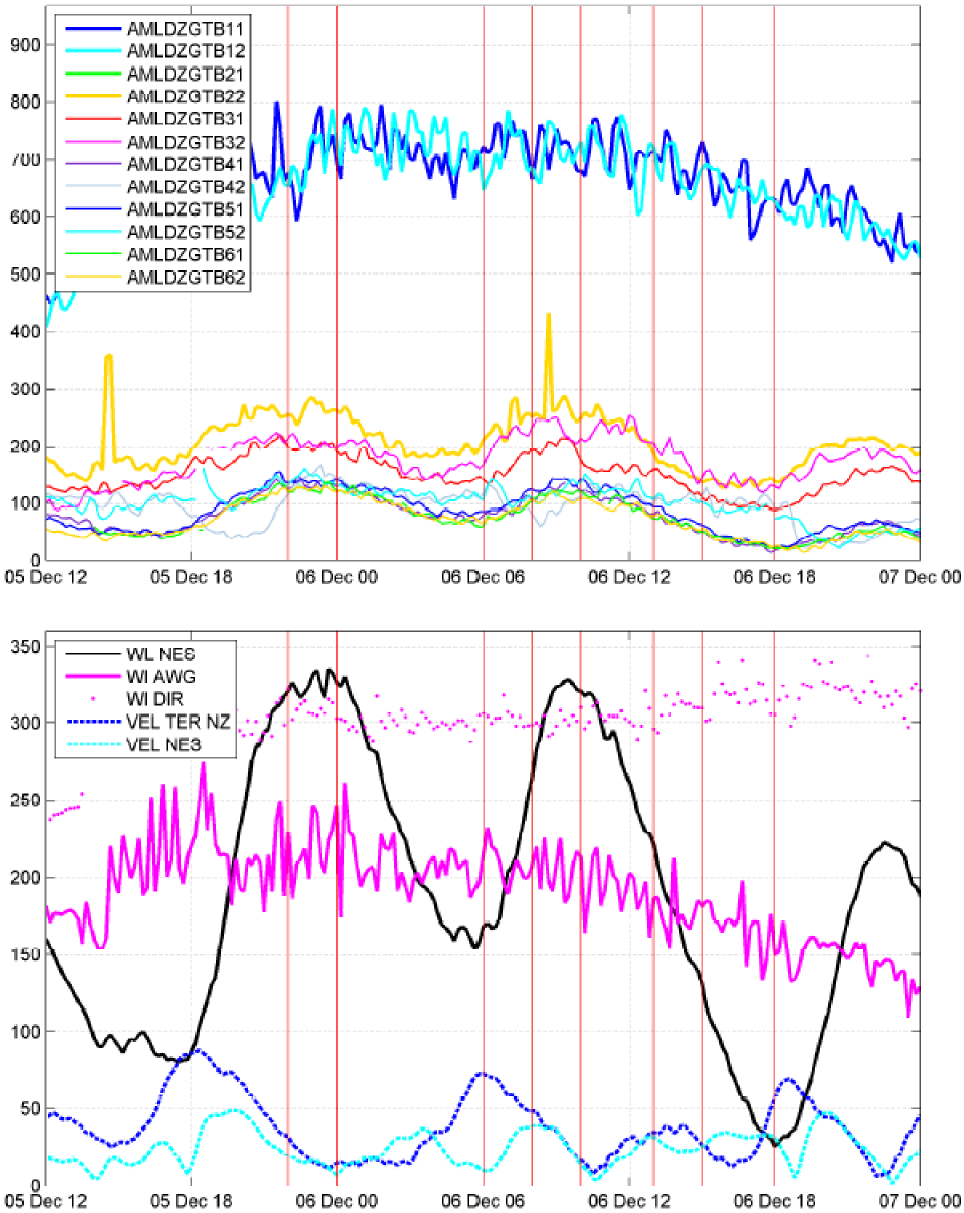


Figure 3.21 Selected snapshot of the wave measurements (top) and water levels at the Ameland inlet for the Sinterklaas storm (from Gautier 2014).

3.7.4 A summary of additional SBW reports at Deltares.

A wealth of information on processes in Ameland Inlet is contained in the SBW studies. Below is a reference list of the studies conducted at Deltares.

Deltares (2007): Storm hindcasts for Wadden Sea. Hindcasts in inlet systems of Ameland and Norderney and Lunenburg Bay. WL | Delft Hydraulics report H4918.20, September 2007

Deltares (2008): Verification of water levels during storm events in the Wadden Sea. Deltares report H5107-31, November 2008

Deltares (2009): SBW Wadden Sea, water level modelling, Study on improvement of wind input. Deltares report 1200114.005, September 2009

Deltares (2009): SBW Wadden Sea, water level modelling, Calibration of the hydrodynamic model. Deltares report 1200114.005, September 2009

Deltares (2009): SBW Wadden Sea, water level modelling, Study on sensitivity of applying spatially varying bed characteristics. Deltares report 1200114.005, December 2009

Deltares (2009). Evaluatie van de nieuwe bodem V61-04 voor het Kuststrookmodel. Deltares report 1200103-023, Spee, E., Vatvani, D. December 2009.

Deltares (2009): SBW Wadden Sea, wave hindcast of the storm of 31 January 2008. Deltares report 1200114-005, December 2009

Deltares (2010): Storm hindcast January 2010 – Analysis of the application of radar current data for hindcast purposes. Deltares report 1202119-001

Deltares (2010). Wave propagation under influence of currents - Hindcasts of Port Phillip Bay Heads and Amelander Zeegat. Deltares Report 1202119-003

Deltares (2010). SWAN calibration and validation for HBC2011. Deltares report 1200103- 020

Deltares (2011): SBW Wadden Sea, Water level modelling of storm events in the Wadden Sea. Deltares report 1204199.003, December 2011.

Deltares. (2011). ”Comparison SWAN, PHAROS and radar wave observations.” Deltares report 1204199-002-HYE-0009 dd 24 November 2011.

Deltares (2012). SBW – Hydraulische Belastingen, Onderzoek t.b.v. het Wettelijk Toets Instrumentarium, Projectplan 2012, Deltares report 1206011-007-HYE-0001, Groeneweg, J., A. Smale, A. van Dongeren, A. Luijendijk, S. Caires. February 2012

Deltares (2012): SBW Waves: quantifying uncertainties of SWAN results. Investigation of SWIVT cases. Deltares report 1206011-002.

Deltares. 2012. ”Water level modelling of storm events in the Wadden Sea.” Deltares report 1204199-003-HYE-0007 dd 10 January 2012.

Note that this list does not provide a full overview of all SBW reports.

4 Summary of Available data

This report provides an overview and analysis of the measurements that are available at Ameland inlet for the Kustgenese 2.0 project (Table 4.1). This data will be archived on the Kustgenese 2.0 data repository.

The focus of the data analysis is on the bathymetric data. By using the available data in Vaklodingen format we have created 12 bathymetric renderings of the complete inlet system of ebb-tidal delta, inlet and basin. An additional 8 DEMs cover the ebb-tidal delta only. All maps haven been archived as mat files on the project disk. Coastline position are obtained yearly since 1965 in the Jarkus datasets. Additional high-resolution multibeam data are available for portions of the Borndiep channel. This data allows for the identification of bedforms and sediment transport directions

Tides, wind and wave data are measured at various locations throughout the Wadden Sea and neighbouring North-sea. Most relevant for water levels are the measurements at the stations Texel Noordzee, Wierumergronden, Nes and Holwerd. These stations allow for the identification of the tidal and non-tidal contributions to the waterlevels. An additional 23 stations throughout the Wadden Sea provide detailed time-series for model calibration and validation. Not available are long-term measurements of water levels directly in the inlet or on the ebb-tidal delta.

Long-term records of waves are only present to the west (Eierlandse Gat) and east (Schiermonnikoog) of the inlet. A correlation analysis between local (short-term) measurements offshore off Ameland and the SON wave data reveals the best correlation. It is advised to use the SON records as representative for the Ameland wave climate. Local wave measurements are present at Ameland although these measurements are only conducted during the storm months (September – April).

Only limited data on flow and discharges are present. Various 24-hour discharge measurements were performed, but only the reported values for averaged discharges over the cross-section have been retrieved. Time-series of flow observations are present for 3 locations on the ebb-tidal delta over selected time-frames in the years 2007 and 2008. Spatially coherent flow and wave data over the inlet domain can be retrieved by the XBand radar and SeaDarQ software. Three selected time-frames have been analysed with mixed results on obtained accuracy.

Table 4.1 A summary of relevant measurements for Ameland Inlet

Parameter	Time Frame	Descriptions	Format Available
Bathymetry	1926, 1971, 1975, 1981, 1989, 1993, 1999 2005, 2007, 2008 2011, 2017,	Complete DEM Ameland Inlet (ebb-tidal delta, basin and inlet)	Mat(1), Dep (2)
	2002, 2006, 2009, 2010, 2014, 2016	DEM ebb-tidal delta only	Mat, Dep
	1965-2017	JarKus, yearly coastline data	Mat, Netcdf
Bedforms	2005 - 2016	High-resolution multibeam for bedform analysis	Mat(1)
Waterlevels	Long-term datasets (various start dates).	Texel Noordzee, Wierumer-gronden, Nes and Holwerd	Mat
Waves	Long-term records (1979-present)	Schiermonnikoog (SON)	Mat
	Short-term records (2007 – present, varying length for each station)	12 stations covering ebb-tidal delta and basin	Mat
Wind	1970 – present	AWG - windstation	Mat
Discharges	Various (1937-2001)	Based on literature	Table
Currents	2007-2008	ADCP data for buoys: 1, 4 and 5	Mat
	2011-2012	ADCP data for buoys: 1, 4 and 5	Mat
Radar Data	2010, 2012 (selected time frames)	Processed data of flow and wave measurements (Not ready to use).	Mat

(1). Mat format contains the data in a structure X, Y, dep. https://waterinfo.rws.nl/ - !/nav/publiek/

(2). DEP format contains the data in the form of a Delft3D depth file. All data gridded on a square 20x20m Grid.

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Beckering Vinkers, 1943. De waterbeweging in het Borndiep. Report 73.3. Rijkswaterstaat, Studiedienst Hoorn. pp:34.

Briek, J., Huizinga, M.A., Hut, J., Noordstra, P. (1998). Meting Borndiep september 1997. Project Strobodi. Report 98.005. Rijkswaterstaat, directie Noord-Nederland, Delftzijl: pp: 45

Briek, J., Huizinga, M.A., Hut, J., (2003). Stroommeting Zeegat van Ameland 2001. RIKZ-report 2003-169, RWS Noord-Nederland, Delftzijl.

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A Bathymetric data

A.1 Overview available Vaklodingen and Jarkus data

Vaklodingen and Jarkus data are collected and stored by Rijkswaterstaat. Yearly, Deltares requests a copy of this data, reformats it to a standardized format (Netcdf) and the data is stored in the openearth database. This database can be accessed at:
https://svn.oss.deltares.nl/repos/openearthrawdata/trunk/rijkswaterstaat/vaklodingen/

The Netcdf data forms the basis of the DEMs used in this study.

The Vaklodingen are stored in a block format (see section 2.2.1. for details. The Jarkus data is stored in two formats. The profile data grouped into regions called Kustvakken. For this study the kustvakken Ameland (3) and Terschelling (4) are used. Each of the kustvakken contains the individual data for the Jarkus transects. An addition JarKus grid following the Vaklodingen blocks is also build. The Jarkus transect data can be obtained through:
https://svn.oss.deltares.nl/repos/openearthrawdata/trunk/rijkswaterstaat/jarkus/

The Jarkus grid data through:
https://svn.oss.deltares.nl/repos/openearthrawdata/trunk/rijkswaterstaat/jarkus/raw/grid/

In this appendix (Figures A-1 through A-7) overviews of the data coverage in the Wadden region are presented.

For more information on Vaklodingen and Jarkus data see:

de Kruif, A.C., 2001. Bodemdieptegegevens van het Nederlandse kustsysteem; Beschikbare digitale data en een overzicht van aanvullende analoge data. Report RIKZ/2001.041, Rijkswaterstaat, National Centre for Coastal and Marine Management RIKZ, The Hague, 34 pp. (in Dutch).

Accuracy for depth measurements:
Wiegmann, N., 2002. Onderzoek naar efficiency verbetering kustlodingen Rijkswaterstaat Meetkundige Dienst, rapport MD-GAM-2002-49. pdf
Accuracy for elevation measurements: [Graaf, H.J.C. de e.a., 2003. Inwinning 'droge' JARKUS profielen langs Nederlandse kust. pdf

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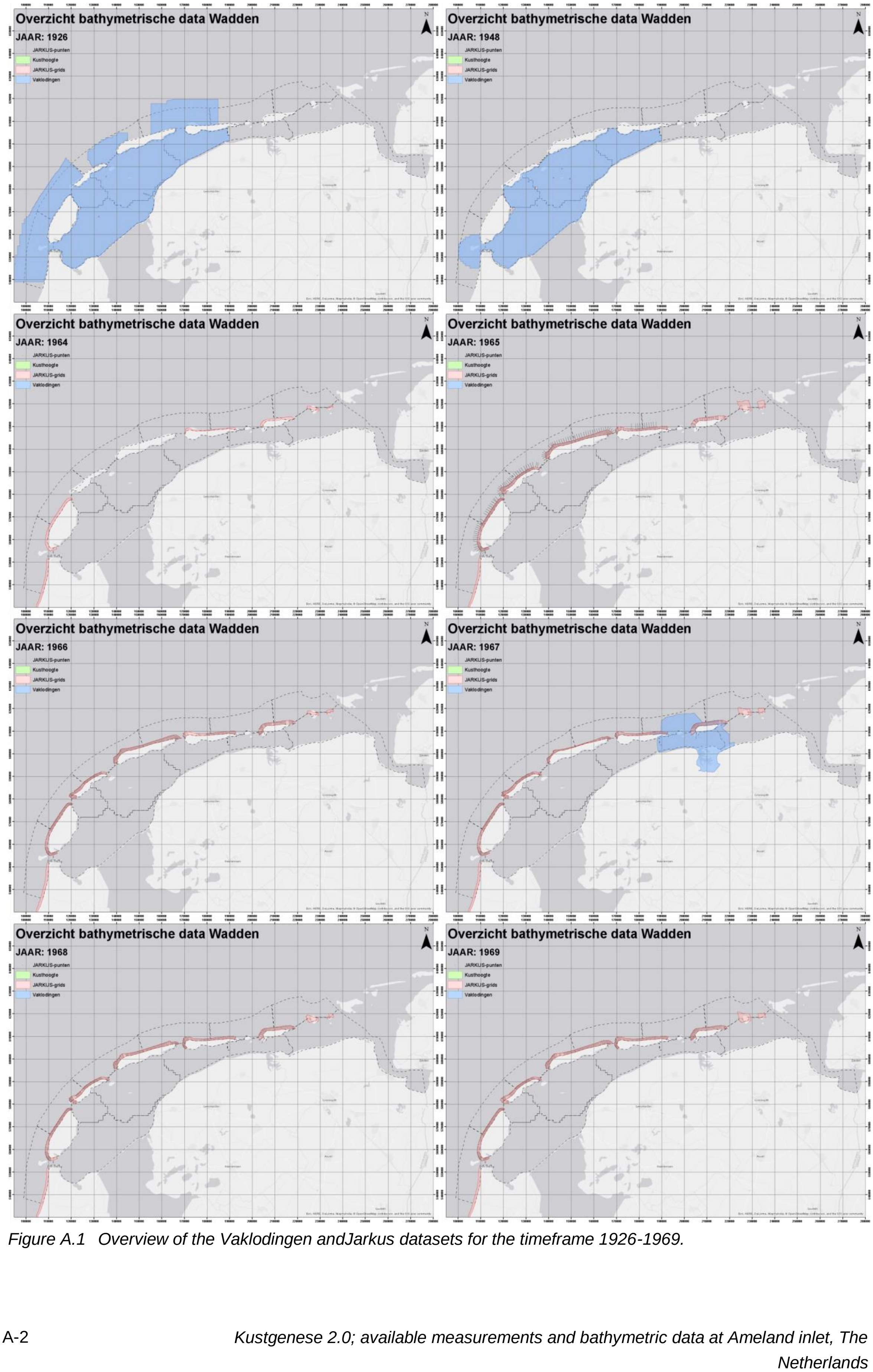

Figure A.1 Overview of the Vaklodingen andJarkus datasets for the timeframe 1926-1969.

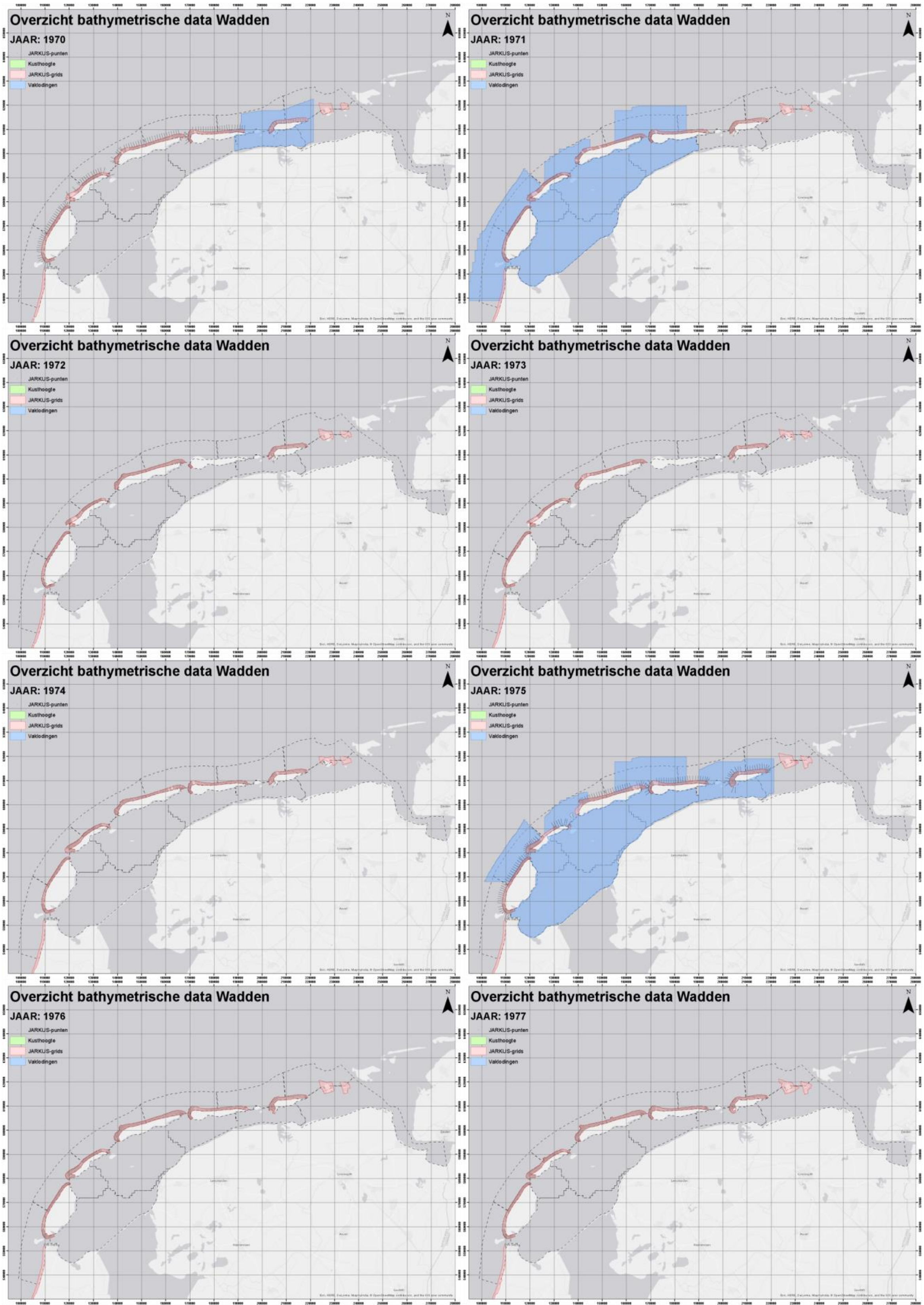

Figure A.2 Overview of the Vaklodingen and Jarkus datasets for the timeframe 1970-1977.

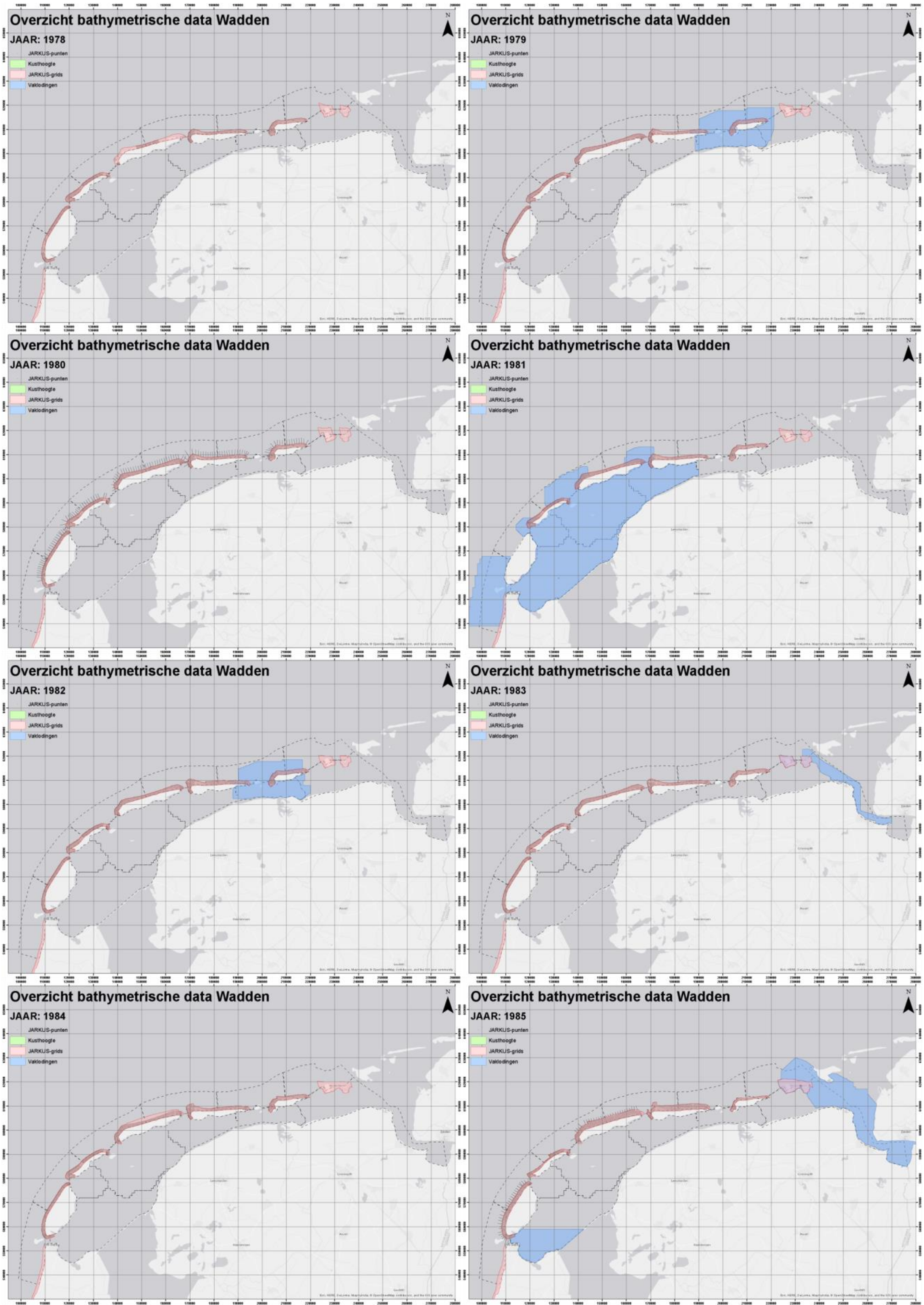

Figure A.3 Overview of the Vaklodingen and Jarkus datasets for the timeframe 1978-1985

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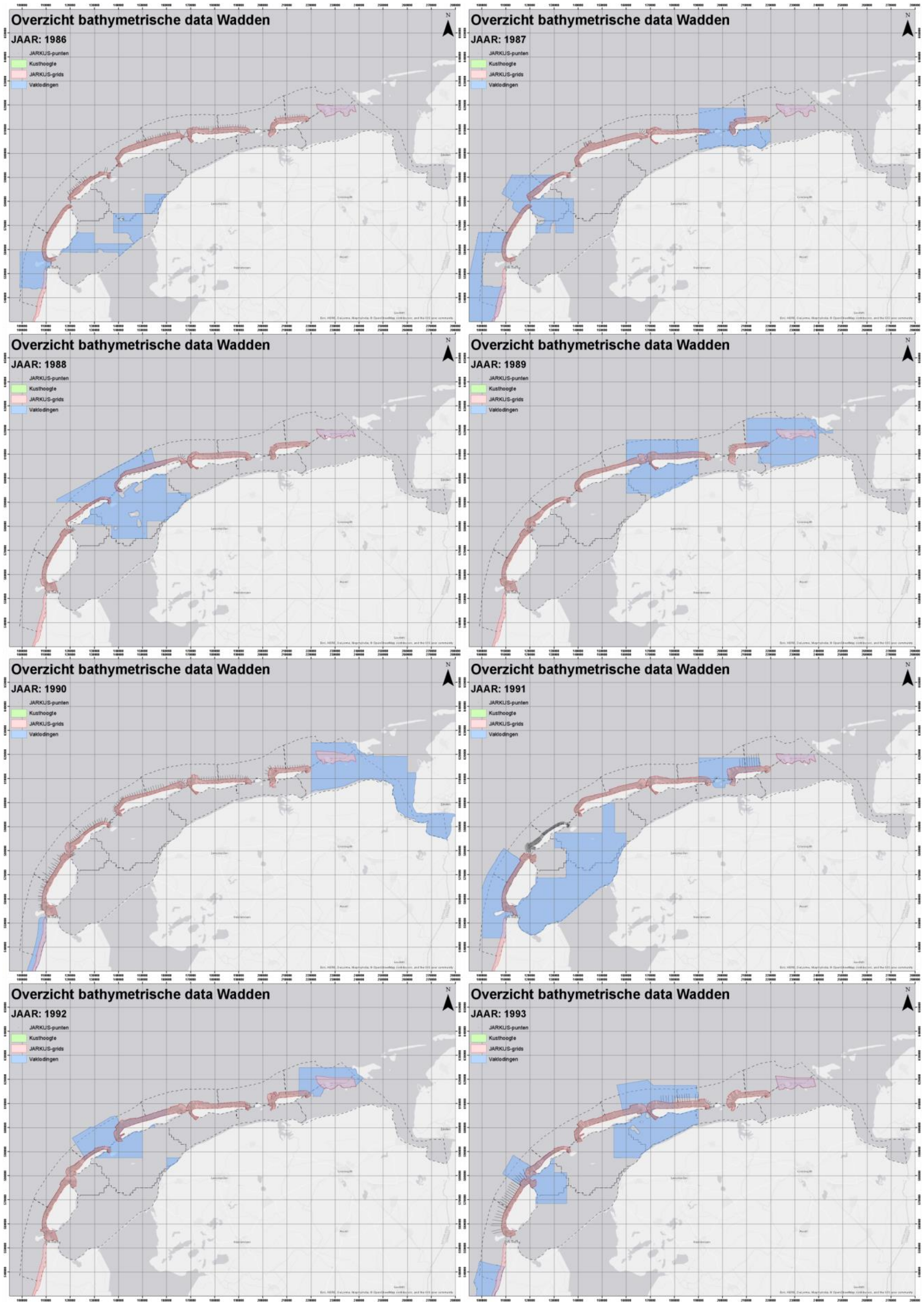

Figure A.4 Overview of the Vaklodingen and Jarkus datasets for the timeframe 1986-1993

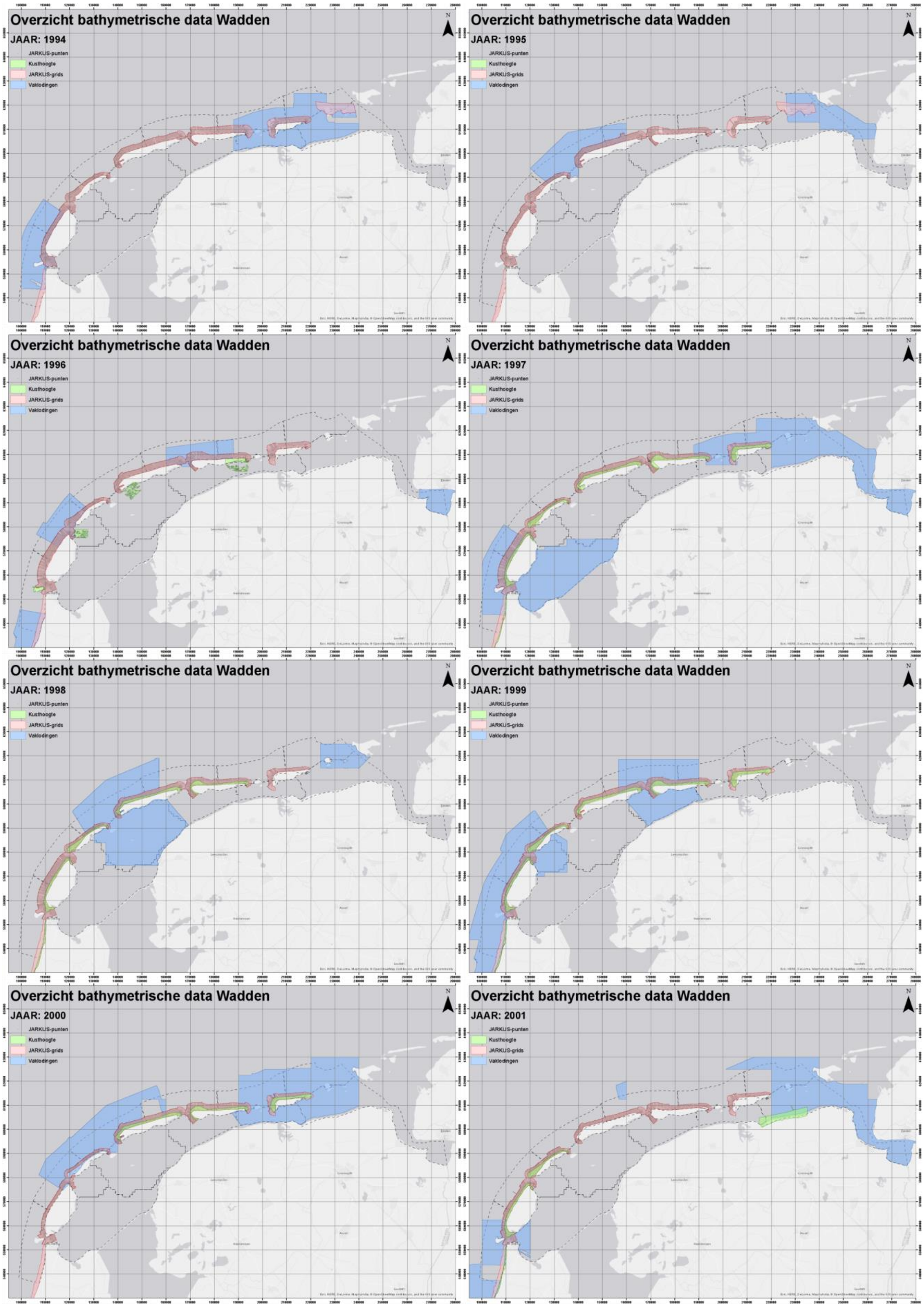

Figure A.5 Overview of the Vaklodingen and Jarkus datasets for the timeframe 1994-2001

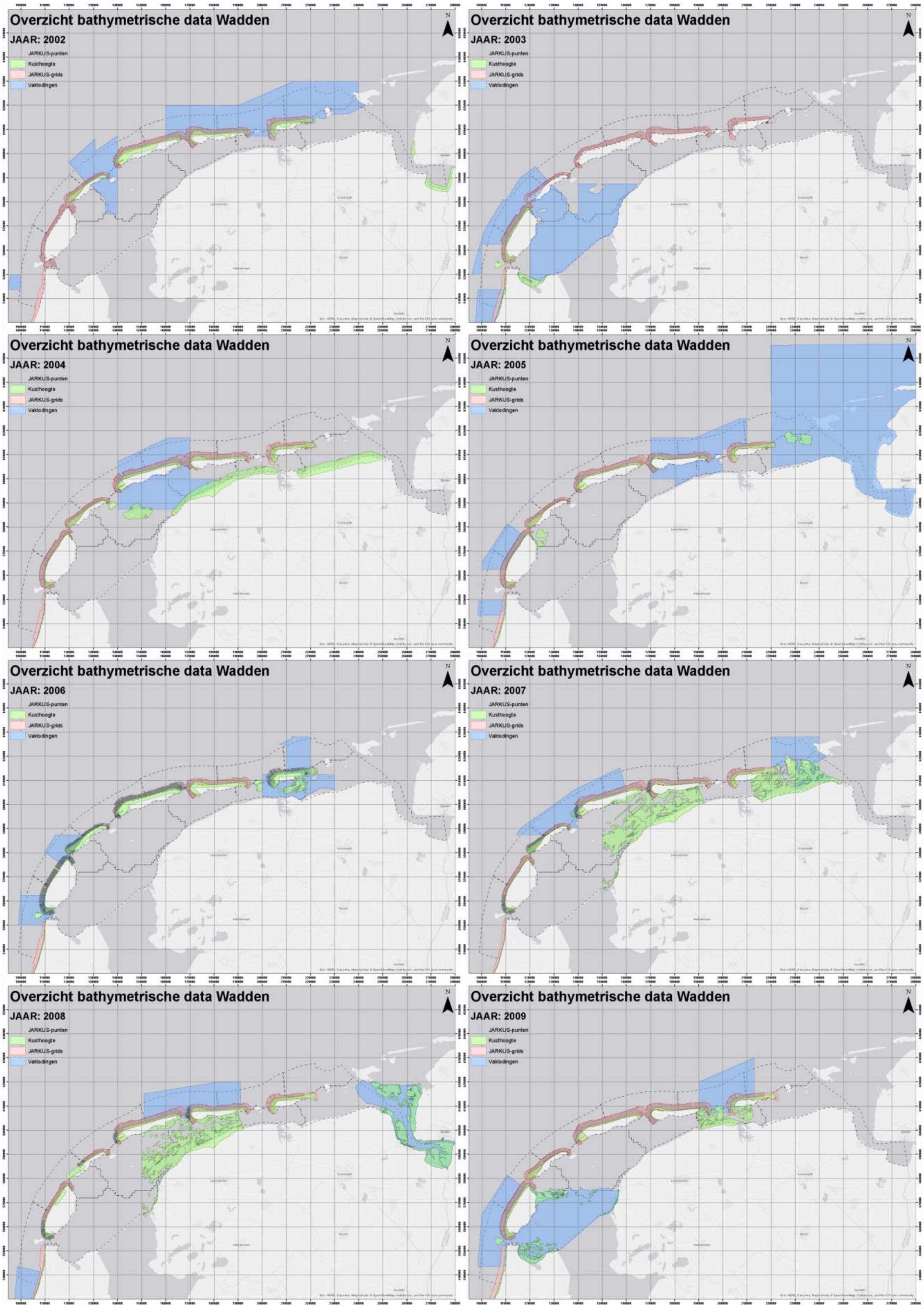

Figure A.6 Overview of the Vaklodingen and Jarkus datasets for the timeframe 2002-2009

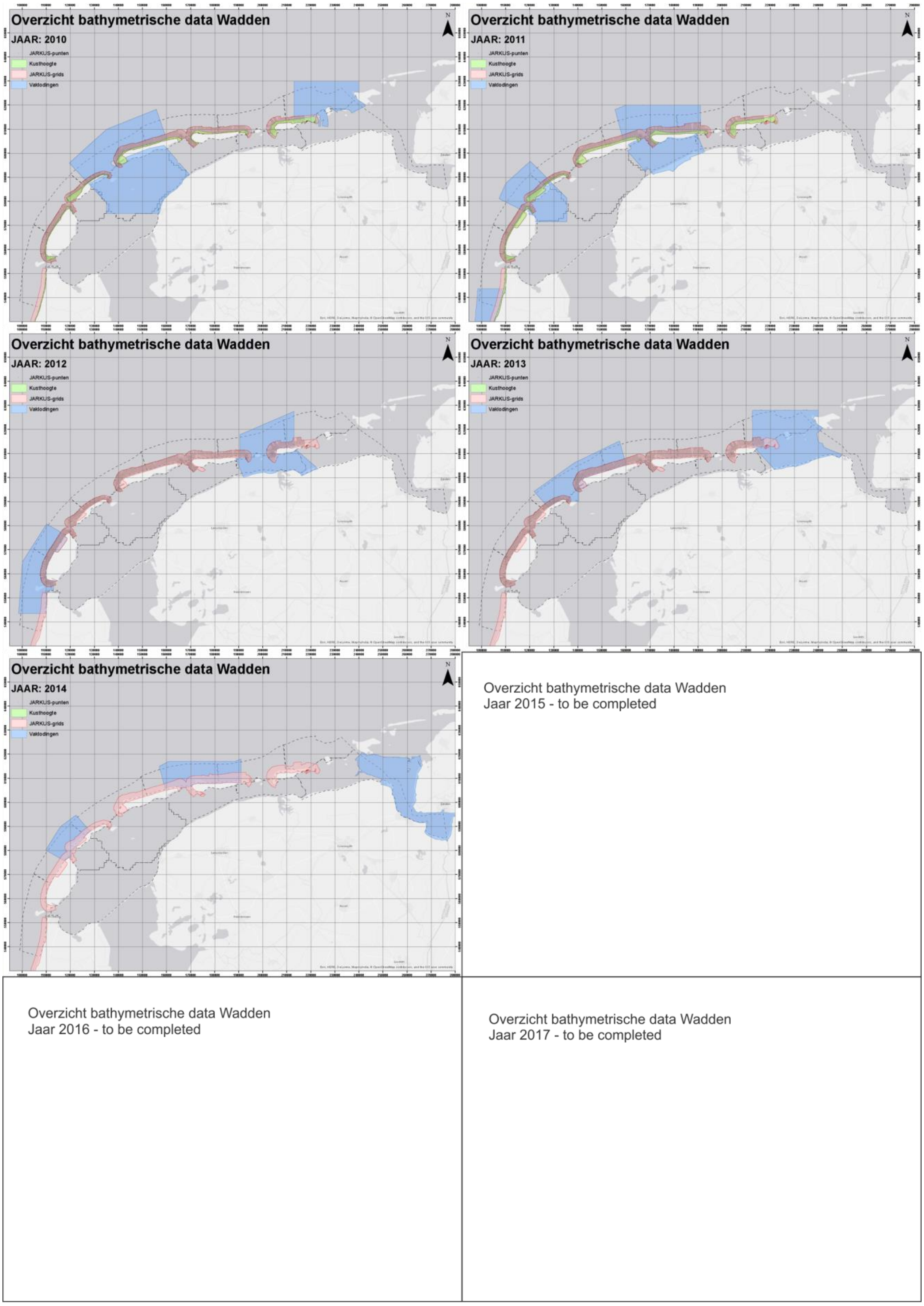

Figure A.7 Overview of the Vaklodingen and Jarkus datasets for the timeframe 2010-2014

A.2 SBW measurements

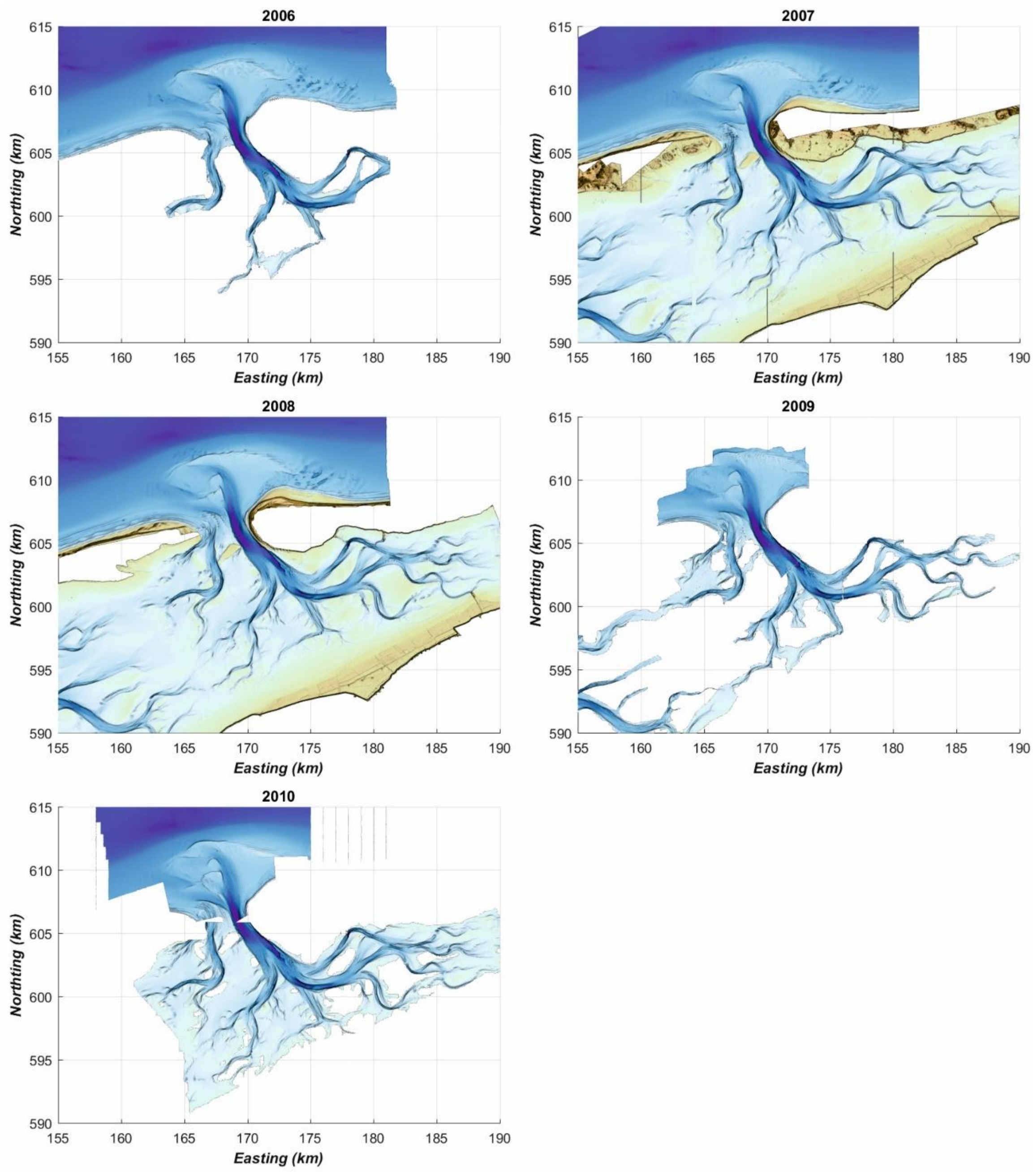

Figure A.8 Overview of the bathymetric data collected during the SBW project.

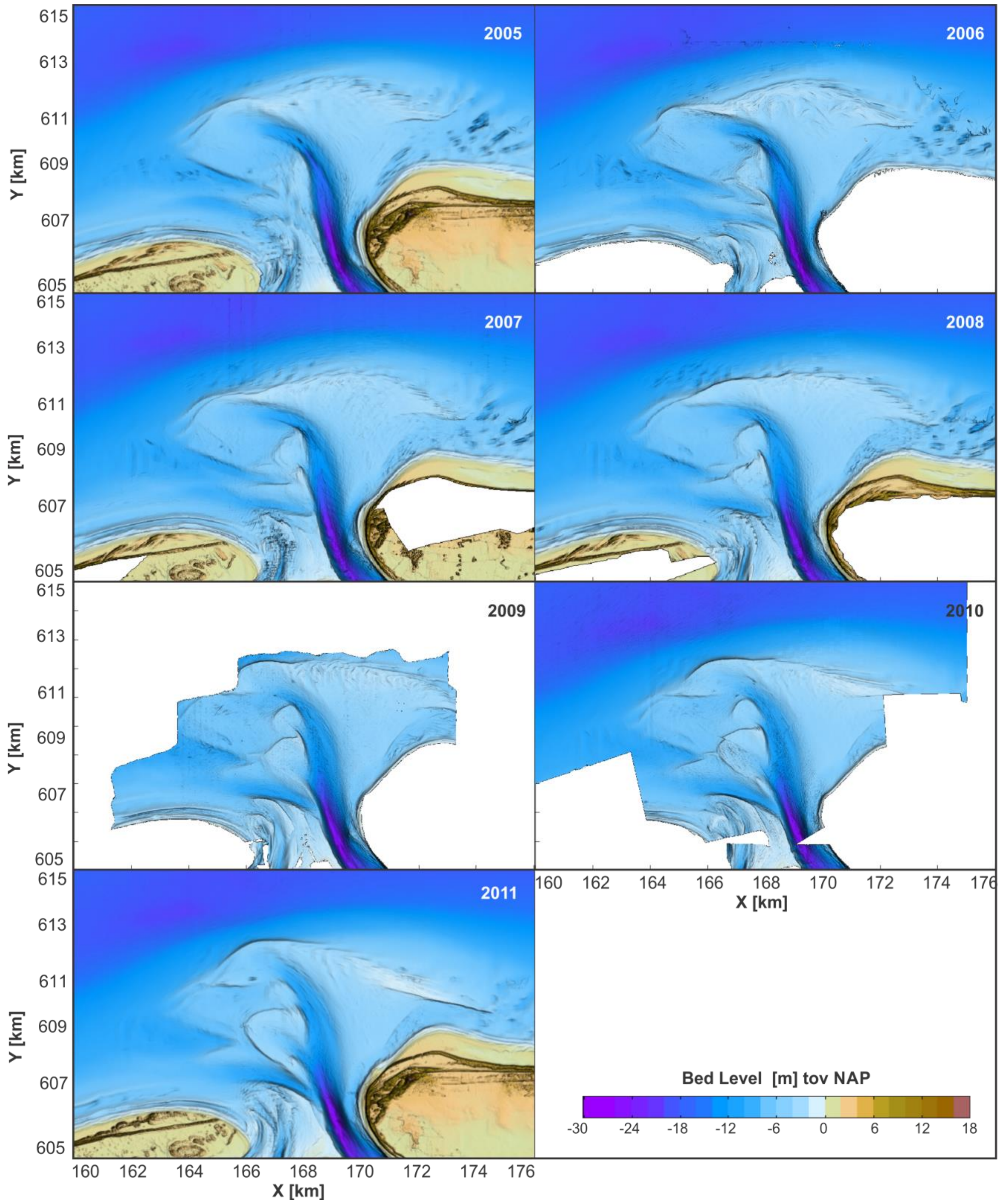

Figure A.9 Detailed overview of bathymetric changes over the time-frame 2005-2011. DEM's based on Vaklodingen (2005 and 2011) and SBW measurements for the years 2006, 2007, 2008, 2009 and 2010.

A.3 Multibeam Borndiep

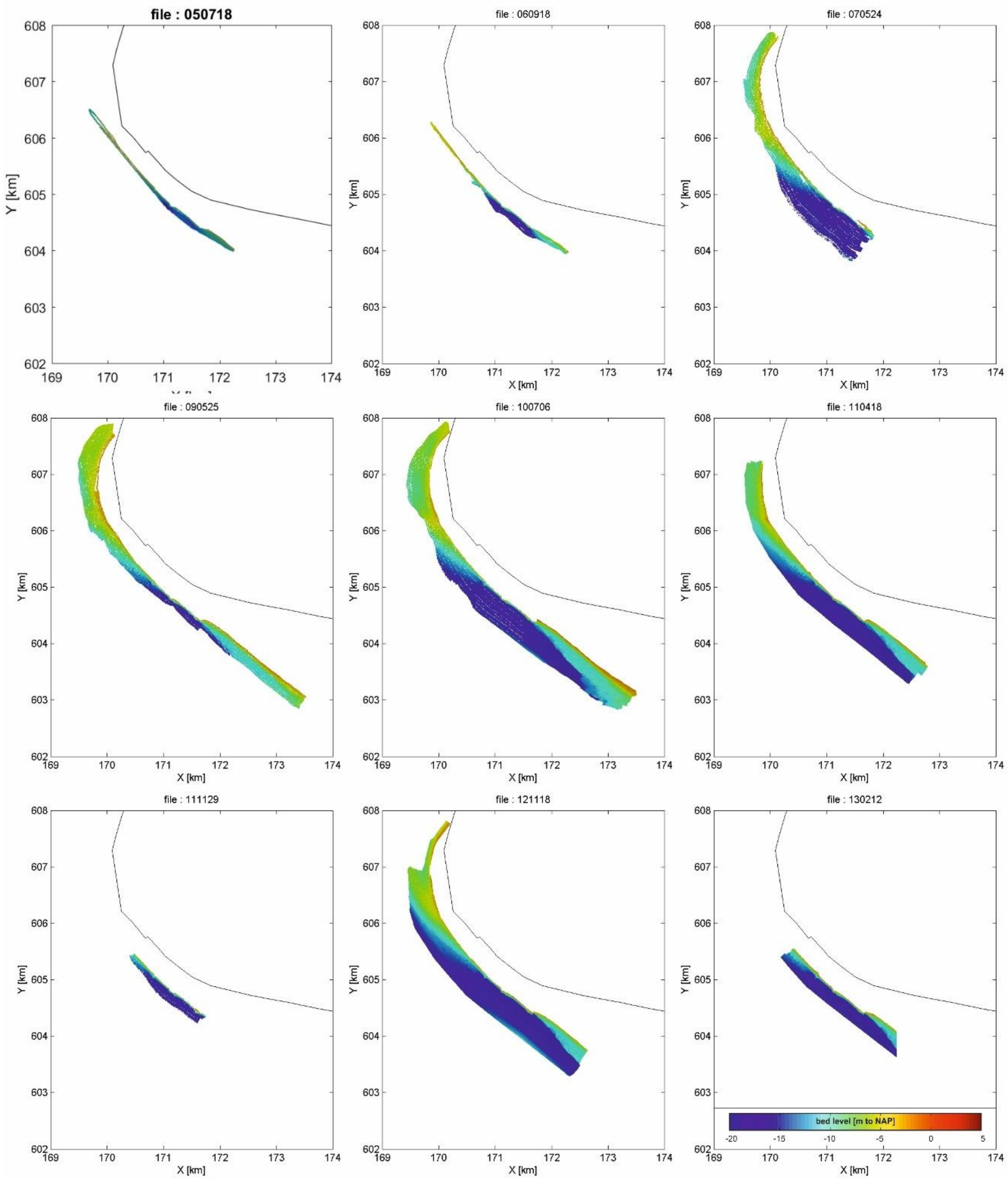

Figure A.10 Overview (1of 2) of multibeam data Borndiep (Ameland SW).

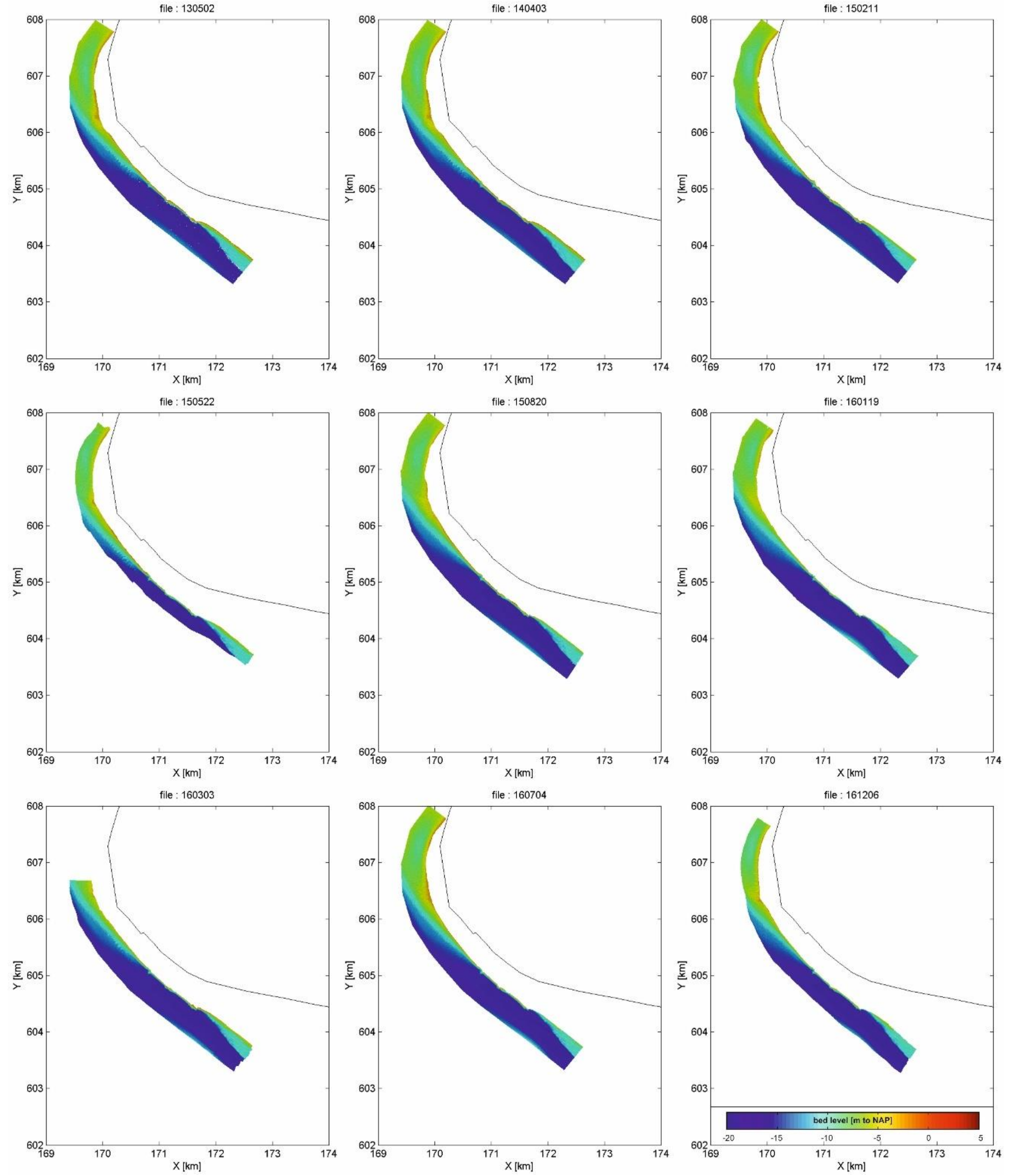

Figure A.11 Overview (2 of 2) of multibeam data Borndiep (Ameland SW).

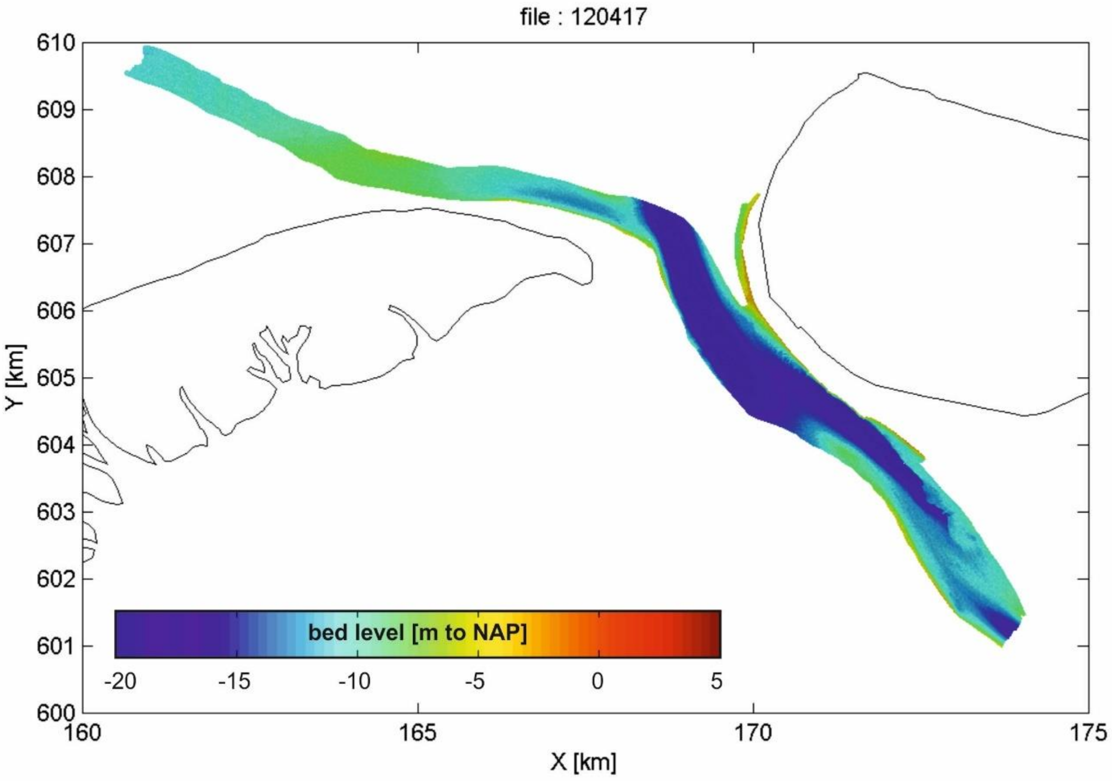

Figure A.12 Detailled map of data file 120417. Multibeam survey of Borndiep, long transect including part of Dantziggat and Westgat.