VALIDATION OF DUNE EROSION MODEL XBEACH

Development of 'BOI Sandy Coasts'

Rijkswaterstaat

MARCH 21, 2022

Project details

Project	"Ontwikkeling BOI instrumentarium zandige waterkeringen" *Development of instrument for assessment, design and management of sandy coastal defences*
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Keywords	XBeach, BOI, sandy coasts, dunes, dune erosion, flood safety assessment, field validation

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Document history

Version	Date	Status	Remarks
0.1	20-05-2021	Working version	*Progress update* General outline of main report + draft reports for 2 field validation cases (Appendix 1 and Appendix 2)
1.0	09-07-2021	Draft version	Draft version for external review *Note: some open items remaining; those will be finished shortly*
1.1	26-11-2021	Draft version	Updated draft version based on external review *Note: version 1.x of the validation report is based on the* ***initial BOI-settings*** *(Deltares, 2021a). Based on the results and recommendations in this report the BOI-settings have been recalibrated.*
2.0	02-12-2021	Draft version	Draft version for (2nd) external review *Note: Revised report based on new* ***recalibrated BOI-settings*** *and new XBeach release (BOI-version, Phase 1). Incl. field case 'Egmond aan Zee'. Also, feedback from the 1st external review has been processed.*
3.0	21-03-2022	Final version	Final version *Note: feedback from the 2nd external review has been processed.*

CONTENTS

SAMENVATTING (NL)

Dit rapport beschrijft de aanpak, resultaten en conclusies van de validatiestudie die is uitgevoerd om de meest actuele BOI-versie van het model XBeach (release '*XBeach BOI Phase1, rev. 5867*'), in combinatie met de (her)gekalibreerde BOI-standaardinstellingen (Deltares/Arcadis, 2021a), te valideren op basis van veldmetingen.

Deze studie maakt deel uit van de eerste fase van het project 'BOI Zandige Waterkeringen', dat gericht is op het ontwikkelen van een vernieuwd instrumentarium voor het beoordelen, ontwerpen en beheren van duinwaterkeringen langs de Nederlandse kust. Het hoofddoel van de studie die is gepresenteerd in dit rapport is het valideren van de BOI-versie van XBeach en het verkrijgen van inzicht in de nauwkeurigheid van het model met betrekking tot hydrodynamische processen, morfodynamische processen en de toepasbaarheid van het model bij zowel reguliere als extreme stormen. Specifieke aandacht is besteed aan de gemodelleerde infragravity golven vanwege hun grote invloed op de hoeveelheid duinerosie tijdens stormen.

Voor de validatiestudie zijn negen **Nederlandse en internationale studies met veldmetingen tijdens stormcondities** geselecteerd; dit is gedaan op basis van de beschikbaarheid van relevante meetgegevens en de representativiteit van de lokale situatie (profielvorm, korrelgrootte, stormcondities en hoeveelheid duinerosie). Voor elk van de geselecteerde cases zijn één of meerdere dwarsprofielen beschouwd waarvoor (1D) XBeach modellen zijn opgesteld op basis van de huidige status van de in ontwikkeling zijnde BOI-specifieke richtlijnen (zie ook Deltares, 2021a,b,d). De resultaten van 1D modelsimulaties zijn geanalyseerd ten behoeve van de validatie van XBeach, met oog voor zowel hydrodynamische als morfodynamische processen.

In totaal zijn (9+57=) 66 dwarsprofielen geanalyseerd voor een kwantitatieve vergelijking tussen de modelresultaten en de beschikbare meetgegevens.

Op basis van de cases met **hydrodynamische veldmetingen** (9 profielen) is geconcludeerd dat de BOI-versie van XBeach (1D) goed in staat is om (onder stormcondities) gemeten nearshore golven en waterstanden te reproduceren. Met name ook de gemodelleerde infragravity (IG) golven vertonen sterke gelijkenissen met de beschikbare meetgegevens. De systematische fout, ofwel *bias*, van de IG golfhoogte varieert tussen -0,04 en 0,18 m, met een bijbehorende relatieve *bias* tussen -0,04 en 0,22. Dit wordt gezien als een goede basis voor het uitvoeren van simulaties met duinafslag.

In relatie tot bovenstaande is ook geconcludeerd dat de nieuw geïmplementeerde modelparameter αE functioneert zoals beoogd. Deze parameter is geïntroduceerd om een betere consistentie tussen 1D en 2DH modelsimulaties te verkrijgen door het effect van golfrichtingsspreiding op de generatie van infragravity golven na te bootsen; zie Deltares/Arcadis (2020). De kleine *bias* van de IG golfhoogte is grotendeels te danken aan deze αE implementatie.

Op basis van de cases met **morfodynamische veldmetingen** (57 profielen) is geconcludeerd dat de BOI-versie van XBeach (1D) ook goed in staat is om profielveranderingen en duinerosie door stormen te reproduceren. Met name de gemiddelde *bias* van de gemodelleerde duinerosievolumes is bemoedigend klein: 0,9 m^3/m, met een bijbehorende *relatieve bias* van 0,03. Daarbij is een gemiddelde standaardafwijking, *RMSE*, vastgesteld van 10 m^3/m (absoluut), met een bijbehorende scatter index van 0,24 (relatief).

De resultaten van deze validatiestudie geven vertrouwen dat de huidige BOI-versie van XBeach, in combinatie met de gekalibreerde BOI-standaardinstellingen, geschikt is als kernmodel voor het, nog in ontwikkeling zijnde, nieuwe beoordelings- en ontwerpinstrumentarium voor zandige waterkeringen.

SUMMARY

This report describes the approach, results, and conclusions of a study that aims at validating the performance of the latest BOI-version of the XBeach model (release '*XBeach BOI Phase1, rev. 5867*'), in combination with the (re)calibrated BOI parameter settings (Deltares/Arcadis, 2021a), based on a series of field validation cases.

This study is part of the first phase of the project 'BOI Sandy Coasts', which aims at developing a renewed framework and toolkit for assessing, designing and maintaining dunes as part of the flood defences along the Dutch coast. The main objective of the work, presented in this report, is to validate the BOI-version of XBeach and to gain insight into the accuracy of the model regarding hydrodynamical processes, morphodynamical processes and the applicability for both regular and extreme storm conditions. Specific attention is given to the modelled infragravity wave height because of their large contribution to dune erosion and the calculated dune erosion during a storm event.

For the validation study a series of **Dutch and international field cases** was selected based on availability of data and representativeness of the local situation (profile, grain size, storm conditions, erosion volumes). For each of the selected cases one or more coastal transects are considered for which (1D) XBeach models are set up in accordance with the recently developed BOI-specific guidelines for the setup of a consistent dune assessment model (partly still work-in-progress); see Deltares (2021a,b,d). The results of 1D model simulations are analysed for the validation of XBeach in terms of both hydrodynamic and morphodynamic processes.

In total, (9+57=) 66 transects are considered for a quantitative comparison between model results and observational data.

From the **hydrodynamic field cases** (9 transects), it is concluded that the 1D BOI-version of XBeach is well capable of reproducing measured nearshore waves and water levels during storm events. Particularly, (also) the modelled infragravity (IG) wave heights show good resemblance with the measurement data of the available field cases. The bias of the IG wave height ranges between -0.04 and 0.18 m, with an associated relative bias between -0.04 and 0.22. This is qualified as a solid basis for morphodynamic model simulations for the purpose of estimating dune erosion volumes.

Associated with this, it is concluded that the newly implemented model parameter αE functions as intended. This parameter was introduced to obtain better consistency between 1D and 2DH model simulations by mimicking the effect of wave directional spreading on infragravity wave generation in 1D models; see Deltares/Arcadis (2020). The small bias in modelled infragravity wave height is thanks to the well calibrated setting of αE.

From the **morphodynamic field cases** (57 transects), it is concluded that the 1D BOI-version of XBeach is well capable of reproducing observed nearshore bed level changes and dune erosion during storm events. In particular, the overall bias of the modelled dune erosion volumes is encouragingly small: 0.9 m^3/m; with a corresponding relative bias of 0.03. The overall RMSE is 10 m^3/m (absolute), with a corresponding scatter index of 0.24 (relative).

The results of this field validation study provide confidence in the applicability of the latest BOI-version of XBeach, in combination with the (re)calibrated BOI-settings, as the computational core of the new BOI framework for dunes and sandy flood defences.

1 INTRODUCTION

1.1 Project 'BOI Sandy Coasts'

1.1.1 Background and context

Project background

The Netherlands is protected from flooding from the North Sea by a system of dunes, dikes and storm surge barriers. The largest part of the Dutch coastline consists of dunes and sandy beaches. This sandy barrier is of national importance since 27% of the country is located below mean sea level. Flood risk management is therefore strongly embedded in the national laws. The Dutch Water Act states that all primary flood defences should be assessed periodically to verify that their probability of failure does not exceed the prescribed legal standards.

Specific regulations and guidelines are developed for each type of flood defence (dunes, dikes, etc.) as part of the National Assessment Framework, currently called (*in Dutch*): 'het Wettelijke Beoordelingsinstrumentarium' or WBI. The Dutch government is responsible for developing and continuously updating this framework and all required models and tools. The successor of WBI is called 'het Beoordelings- en Ontwerpintrumentarium' or BOI (Assessment and Design Instrument).

The methodology for assessing the state of the dunes was developed in the 1980s. This led to a formal guideline for the assessment of (the degree of flood protection by) dunes (Technische Adviescommissie voor de Waterkeringen, 1984). This guideline was last updated in 2006, by including an additional factor to account for the effect of the peak wave period on dune erosion. The resulting 'Technical Report Dune Erosion (TRDA2006)' is in fact still the current basis of the procedure for the assessment of the flood safety levels of the dunes, as part of the WBI framework.

In a joint assignment of the Directorate-General for Water and Soil ('Directoraal-Generaal Water en Bodem', DGWB) of the ministry of Infrastructure and Water Management, Rijkswaterstaat, the Foundation for Applied Water Research ('Stichting Toegepast Onderzoek Waterbeheer', STOWA) and all Dutch regional authorities for coastal management, Rijkswaterstaat has been commissioned to implement a project that aims at revising the framework for assessing, designing and managing (i.e. maintenance, permitting) the dunes along the Dutch coast. This includes both an update of the computational methodology (model, tools) as well as a revision of all relevant guidelines and regulations for end-users.

One of the core activities of the project is a (phased) replacement of the currently used (empirical) dune erosion model, Duros+, by the state-of-the-art numerical model XBeach. The main justifications for this assignment are [1] recently discovered (additional) omissions in the Duros+ model, [2] the (expected) more reliable estimates of dune failure probabilities when using a process-based model (XBeach), and [3] other limitations of Duros+ related to the assessment, design and day-to-day management of sandy flood defences.

Long-term ambition: new framework for assessment of sandy and hybrid flood defences

The anticipated development of a new assessment framework for dunes is part of a broader ambition. The main objective on the longer term is to provide a consistent set of tools, guidelines and regulations that can be applied to all Dutch coastal areas with sandy and hybrid flood defences, including spatially complex areas, in order to accurately determine the probability of flooding of the hinterland. In order to achieve this ambition without major (unexplainable) trend breakages in the results of the periodic dune assessments, an action plan has been drafted in which different ambition levels and associated development phases are described. The phased approach leads to a step-by-step increase in the applicability and usability of the new assessment framework:

1. Development phase 1 – Development of a new 1D assessment tool for dunes (XBeach)
2. Development phase 2 – Broadening of applicability of the assessment tool: 1D approach
3. Development phase 3 – Broadening of applicability of the assessment tool: 2DH approach
4. Development phase 4 – Full probabilistic approach for assessments and design

The current project relates to the first development phase. The aim of this development phase is to develop a reliable, traceable and well-supported set of tools and guidelines for the assessment, design and day-to-day management of dunes along the Dutch coast, with specific focus on setting up a validated 1D assessment tool for fully sandy coasts (without coastal structures and without strong curvature of the coast, yet). This forms a solid basis for intended future developments in subsequent phases of the longer-term development plan; see Figure 1-1.

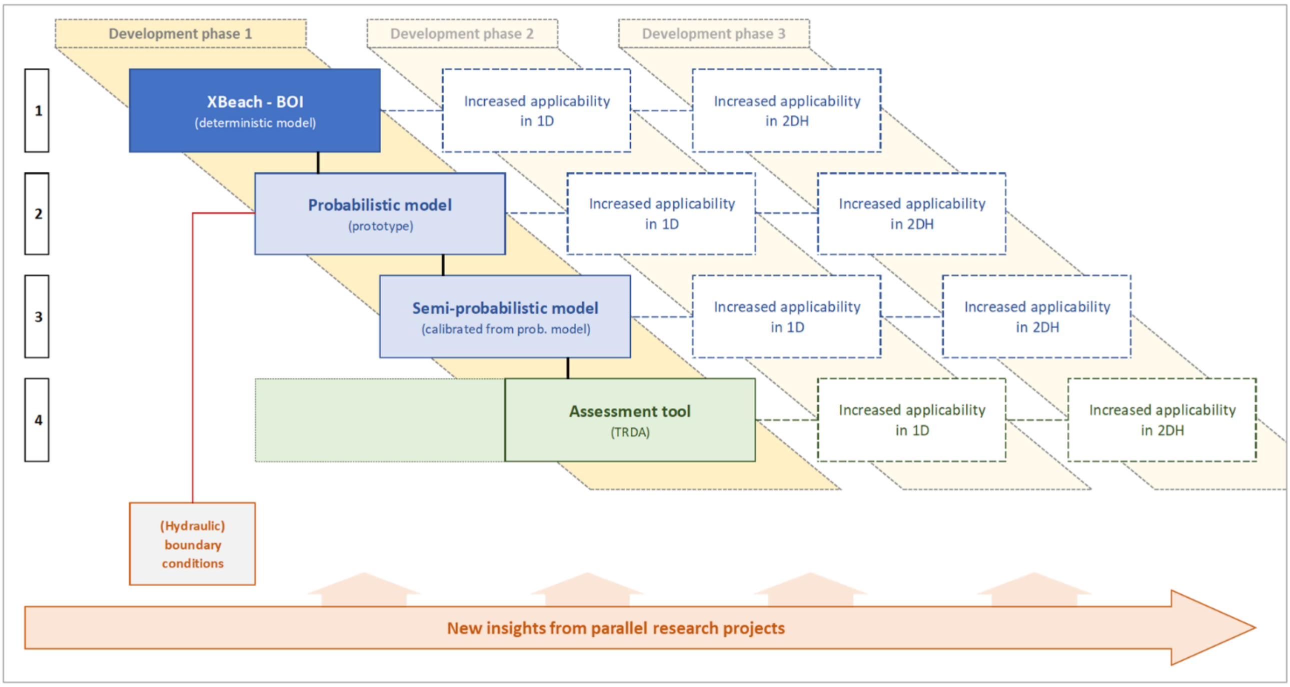

Figure 1-1 Overview of the long-term development plan for the revision of the formal national framework for assessing and designing sandy types of flood protection. The first development phase relates to the scope of the current project.

Preparatory studies (Phase 0): starting point for the current project

Prior to the start of the current project, a series of studies has been executed under supervision of Rijkswaterstaat. In the so-called Phase 0 project, a renewed version of XBeach was developed in which several model improvements have been implemented for 1D applications. The model was also calibrated for application along the Dutch coast using flume-scale experiments, resulting in de so-called BOI-version of XBeach (Deltares, 2021a). This version of XBeach forms the basis for any further developments during subsequent phases, including the activities in the current project.

During Phase 0 also special attention has been paid on topics such as wave spreading and sediment size effects in the XBeach model (Deltares/Arcadis, 2020), reduction of the calculation time (Deltares, 2021b), scaling of dimensional parameters (Deltares, 2021c), boundary condition guidelines (Deltares, 2020) and functional requirements for the future user interface in MorphAn (Rijkswaterstaat, 2021).

Current project: development of a renewed assessment tool for dunes

The first phase of the anticipated series of (future) developments for a new assessment framework for sandy and hybrid flood defences has been incorporated in one project, which is executed by Rijkswaterstaat, Deltares and Arcadis. This project aims at the replacement of the empirical dune erosion model Duros+ by the physics-based numerical model XBeach and the revision of relevant methodologies and (assessment) guidelines. This development will clear the path to make better estimates of the flood risk probability of sandy flood defences possible. The resulting tools and guidelines also provide better support for decision making related to coastal and dune management, spatial development plans and/or permitting processes.

The main features of the work in the current project are:

1. Developing a 1D assessment tool for dunes along the Dutch coast, based on a semi-probabilistic calculation method for XBeach, and implement this in the existing software tool MorphAn.
   The main substantive steps in the project:
   - Step 1.1 – Validating the new XBeach core model;
   - Step 1.2 – (Further) development of a probabilistic shell (prototype);
   - Step 1.3 – Defining and adjusting a semi-probabilistic model;
   - Step 1.4 – Determining the (overarching) assessment tool (incl. renewed methodology).
2. Providing relevant background reports and technical guidelines for the new assessment framework, in consultation with Deltares, Rijkswaterstaat and other stakeholders.

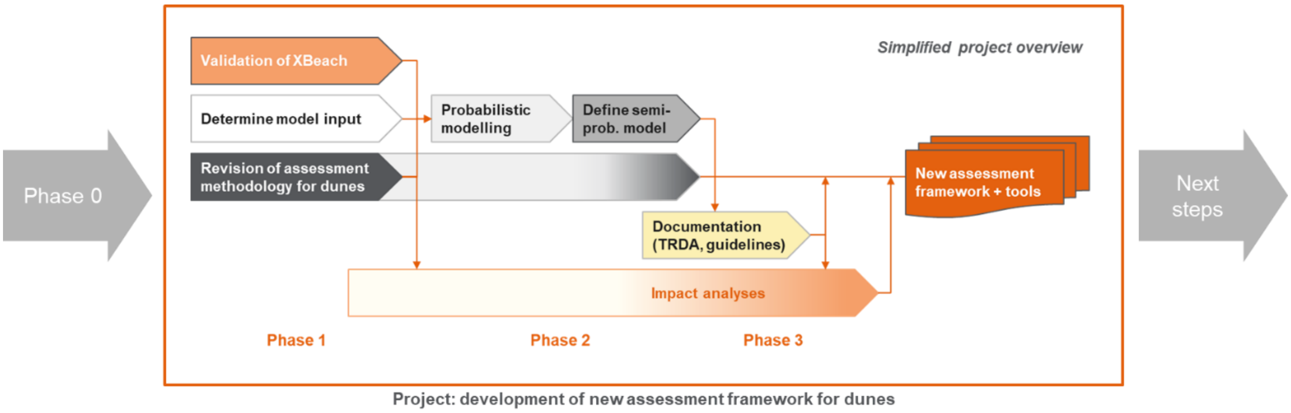

Figure 1-2 Simplified overview of the scope of the project.

The execution of the above-mentioned steps and other related activities is divided into **three subsequent project phases**. Figure 1-2 shows a schematic overview of the core activities of the project and the associated project phasing. The diagram also shows that the deliverables of the prior Phase 0 project are used as input for this project, and that the output of this project is aimed to be input for next stages of the longer-term development plan (as mentioned above).

Objectives of the project

The main objective for this project is to develop **a reliable, traceable and well-supported set of tools** that can be used for both assessing, designing and managing dunes as primary flood protection.

A secondary objective of Rijkswaterstaat is beneficial use this project to **increase, transfer and safeguard expert knowledge** about the development of tools and assessment frameworks for sandy coasts, in particular to give a knowledge boost to coastal management tasks such as permitting processes.

In addition to these core objectives, it is also a specific goal during this project to optimize communication and **collaboration with relevant stakeholders**, such as the national and regional authorities for coastal and dune management. The new framework should be the result of a joint effort of all parties involved.

Coherence with BOI programme

The development of the new assessment methodology for dunes and all associated tools is part of the BOI programme, which aims to develop a renewed integral framework for assessment and design of all types of flood defences that seamlessly connects to the current Dutch flood risk probability approach. The BOI framework is the anticipated successor and combination of WBI2017 (tools and guidelines for assessments) and OI2014 (tools and guidelines for design). The result of the BOI programme will be a renewed set of tools, databases, methodologies, guidelines and regulations that should be used for the periodic formal assessments of the flood defences and the design of any new measures.

1.1.2 Overview of subprojects / tasks

As shown in Figure 1-2, the current project consists of multiple interconnected core activities that jointly contribute to the final set of tools and guidelines for the renewed assessment framework for dunes. The project consists of three subsequent project phases and for each phase a list of activities and deliverables is defined. As an example, the first project phase primarily consists of three parallel but related core activities or **subprojects**:

- **[1]** Validation of XBeach,
- **[2]** Development of probabilistic model, and
- **[3]** Revision of assessment methodology.

Each of these subprojects consist of a series of underlying **tasks**. The results of all activities are delivered as part of a report or product, either per subproject or per task, depending on the specific scope.

Apart from the activities within the subprojects, phase 1 also comprises some smaller additional tasks, such as a first quantitative impact analyses in which new developments are compared to the tools/models/methods of the currently used formal national framework.

An overview of all related subprojects and associated tasks for this project is presented in Table 1-1.

Table 1-1 Overview of different core activities (subprojects) and tasks per project phase.

Phase	Core activities / subprojects	Task ID
Phase 1	**1.1 Validation XBeach model**	
	Validation hydrodynamics *(IG waves)*	# 04
	Validation more frequent storm events	# 05
	Validation morphodynamics *(dune erosion)*	# 06
	Robustness tests Xbeach	# 07
	1.2 Development probabilistic model	
	Determine stochastics and distributions	# 08
	Add post-processing routines (i.e. *model uncertainties*)	# 09
	Setup & testing of probabilistic model	# 10
	1.4 Revision assessment methodology	
	Further elaboration of concepts and methodology	# 11a
	(Re)definition of failure function	# 11b
	Support / other	
	Workshop for end-users	# 12
Phase 2	**1.2 Development probabilistic model**	
	Setup & testing of probabilistic model	# 13
	1.3 Development semi-probabilistic method	
	Run calculation with probabilistic model	# 14
	Set input for semi-prob model	# 15
	Set addition for model uncertainties	# 16
	Validation of semi-probabilistic model	# 17
	1.4 Revision assessment methodology	
	Further elaboration of concepts and methodology	# 18
	Background report 'description of model input'	# 19
	User guideline for dune assessment	# 20
	Technical Report Dune Erosion (*draft*)	# 21
	Support / other	
	Workshop(s) for end-users	# 22
Phase 3	**1.4 Revision assessment methodology**	
	Technical Report Dune Erosion (definitief)	# 23
	1.5 Impact analyses for new assessment tools	
	Impact analyses (arithmetical)	# 24
	Impact analyses (administrative)	# 25
	Support / other	
	Workshop(s) for end-users	# 26

1.2 Description of current subproject

1.2.1 Current subproject: validation of BOI-version XBeach

This report describes the results of three tasks related to the validation of the new calibrated BOI-version of the XBeach model (Deltares, 2021a; Deltares/Arcadis, 2021a), as part of the subproject ‘validation of XBeach’. These tasks are presented in Table 1-2[1]: validation of the hydrodynamic processes (#04), validation of the morphodynamic responses (#06) and validation of the model for more regularly occurring storm events (#05).

The validation cases for hydrodynamics (task #04) and morphodynamics (task #06) *ideally* are based on field cases in which the impact of extreme (normative) storm conditions was measured. However, these conditions are very rare in practice and have never (yet) occurred in the Dutch context. Therefore, for validation of the model with regards to the Dutch normative storm conditions, international (outside the North Sea area) validation cases of extreme events are combined in this report with case studies in the North Sea area during less extreme conditions. However, it should be noted that the number of available and/or usable field cases is limited. As a consequence, *in practice*, no strict distinction is made between validations of extreme events (tasks #04 and #06) and more frequent events (task #05); this is discussed in more detail in the report.

It has been decided to combine the outcome of the three validation tasks in one report. Although the focus of each validation task is slightly different, the *joint* results and conclusions are most relevant in order to verify the accuracy and usability of XBeach as core model for the new BOI assessment framework.

Table 1-2 The subproject with associated tasks as described in this report: validation of XBeach model. Note that task #07 (robustness tests) is not included in this report; this task is included in the report of subproject ‘development of probabilistic model’.

Phase	Subproject / tasks *(in this report)*	Task ID
Phase 1	**1.1 Validation XBeach model**	
	Validation hydrodynamics *(IG waves)*	# 04
	Validation morphodynamics *(dune erosion)*	# 06
	Validation more frequent storm events	# 05
	Robustness tests Xbeach	# 07

Validation of hydrodynamics (infragravity waves)

This task focuses on the validation of the hydrodynamics of the BOI-version of XBeach in 1D, with specific attention to the accuracy of the modelled infragravity waves ('long waves'). The starting point of this validation is a BOI-specific version of the XBeach model that has been developed and calibrated prior to this project, in the so-called Phase 0 project. In this version, for example, improvements have been made to model the infragravity waves, in field conditions, in a more consistent manner. Proposed model settings for this version of XBeach have been derived based on data from laboratory tests and numerical model experiments. In this task, the resulting model is validated based on available field measurements. A primary focus point is the validation of the simulated characteristics of the infragravity waves, since these have a demonstrable large impact on dune erosion. Relevant characteristics of the infragravity waves are the (low frequency) wave height along the profile and the resulting maximum and (wave group) averaged water levels near the dune front.

Validation of morphodynamics (dune erosion)

This task focuses on the validation of the morphodynamics of the BOI-version of XBeach in 1D, with specific attention to the accuracy of the calculated amount of dune erosion. In this case, the validation is also based on the calibrated XBeach-version with BOI-settings that has been developed in the preceding phases of the project[2]. The primary focus of this task is on indicators related to dune erosion that are relevant for assessing, designing or managing dunes as part of a flood defence system: the erosion volume (total, or above a reference level), the distance of dune front retreat (at a reference level) and the shape of the erosion-deposition profile.

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[1] *The fourth task in Table 1-2, ‘#07 - robustness tests for XBeach’ (in grey), is not included in this report. For convenience (readability), it is decided to include a description of approach and results of the robustness tests in a separate report that focusses on the development of the probabilistic model.*

[2] *During the execution of this study, it was decided to recalibrate the BOI-settings for XBeach based on recommendations from a first round of field validations; see section 2.3.1 for further details. This report describes the validation of the* ***recalibrated BOI-settings****.*

Validation of more frequent storms

The third validation task focusses on the hydrodynamics and morphodynamics in cases with less energetic storm conditions; this in contrast to the focus on extreme conditions in the previously mentioned tasks. This validation for more frequently occurring storms is intended to test the usability of the specific BOI-version of XBeach, with calibrated settings and basic model setup, for other practical applications for policy makers, coastal/dune managers and/or regional water authorities. Examples of other applications of the model are assessments related to coastal or dune management, maintenance policy or permitting processes. Therefore, it is useful to assess the performance of XBeach for storm events with a probability of exceedance from once per year to ca. 1/50 per year. In practice, many of the available field cases are within this range.

1.2.2 Objectives of this subproject

The subproject ‘validation of XBeach’, described in this report, aims to validate the performance of the calibrated BOI-version of XBeach[3] (in 1D), based on field measurements. A well-validated model is of utmost importance for the further development of the safety assessment methodology as part of the new BOI framework for dunes along the Dutch Coast.

The main objectives of this subproject are:

- Gaining insight into – and quantify – the accuracy of the modelled hydrodynamic processes and the infragravity wave characteristics in the BOI-version of XBeach (1D); based on field measurements.
- Gaining insight into – and quantify – the accuracy of the modelled morphodynamic processes and the resulting amount of dune erosion in the BOI-version of XBeach (1D); based on field measurements.
- Gaining insight into – and quantify – the accuracy of in the BOI-version of XBeach (1D) for 'regular' storm events; based on field measurements.
- [Indirectly] Gaining and increasing support for the use of XBeach as the computational core of the new assessment and design framework for dunes and sandy coasts.

This validation report describes and discusses the approach, the data analyses and the modelling results of the work that has been performed for the validation of XBeach for real-world cases.

1.3 Outline of report

This document aims at providing relevant insights on the performance of the BOI-version of XBeach on prototype scale (real-world) and validating the model based on field measurement data. After this introductory chapter, this report is structured as follows: **Chapter 2** describes the applied approach for this subproject, including an overview of available field cases, relevant details on the general model setup and used definitions of performance indicators that are used to quantify and compare the modelled and observed data.

In **Chapter 3** the main results from each of the individual field cases are summarized. Distinction has been made between the validation of the *hydrodynamical processes* in XBeach, with specific focus on the infragravity waves, and the validation of the *morphodynamical processes*, with specific focus on dune erosion. The overall observations and (joint) conclusions across the different field cases are further discussed in **Chapter 4**. The discussions in this chapter are divided into three main themes: [1] representativeness of the field validation cases, [2] performance of the BOI-version of XBeach, and [3] overall model uncertainties.

Chapter 5 provides a summary of the general approach in this subproject and describes the main conclusions and observations from the performed analyses of field validation data and model simulations. This provides the necessary ingredients for the overall model validation of XBeach for the purpose of the new assessment framework for dunes along the Dutch coast.

A detailed description of modelling approach, results and discussion for each of the individual field cases is provided in the **Appendices** attached to this document. The main conclusions and observations from these individual cases are included in the main report.

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[3] *This subproject specifically focusses on the validation of the BOI-version of XBeach, with calibrated BOI-settings, for the purpose of carrying out dune assessments along the Dutch coast with the new formal national BOI framework. For this, the most relevant aspects of the model, related to dune erosion during normative conditions, are validated based on field cases.*

2 APPROACH

This chapter describes the approach applied for the subproject 'validation of XBeach'. First, the general study approach is summarized, followed by an overview of the available field validation cases. Then, the overall model setup that has been applied for all the field cases is discussed. Lastly, the most relevant definitions of performance indicators for both the hydrodynamical and the morphodynamical validations are presented.

2.1 General approach

The BOI-version of the (1D) XBeach model is validated based on a series of field validation cases. The validation has been performed in two subsequent steps: [1] a validation of the modelled **hydrodynamic** processes, and [2] a validation of the modelled **morphodynamic** processes.

First, the hydrodynamic behaviour of XBeach 1D is validated by comparing the result of the model simulations with measured data for three different field measurement campaigns. In these validation cases, sediment transport and morphology are not included in the model simulations; by omitting bed level changes it is ensured that spatial and temporal changes in the model output are a result of hydrodynamic processes only instead of also being influenced by a changing bed level. It should be noted that generally little bed level change was observed during these events in reality, and therefore that omitting bed level change in the model is an appropriate simplification. The primary focus of the hydrodynamical validation is on the modelled (characteristics of) infragravity waves, which are an important driving force for dune erosion.

Secondly, when satisfying results are obtained from the hydrodynamical validation cases, the morphodynamic behaviour of the XBeach model is validated using one field case that has been used for the hydrodynamic validation as well and six other field cases. The primary focus of these validations is on the model performance related to dune erosion; indicated by for example the dune erosion volumes and/or the retreat distance of the dune face or characteristic erosion point. Based on the results of these cases, it is assessed whether the current BOI-version of XBeach is capable to simulate realistic (observed) dune erosion volumes.

A secondary point of attention for the validation studies is the capability of the BOI-version of XBeach to produce satisfactory results for different storm intensities; ranging from extreme/normative storm conditions (related for flood safety assessments) to more regular / higher frequent storm events (relevant for issues related to coastal/dune management). A clear distinction between 'extreme' and 'regular' has not been defined for the purpose of this study. The number of available field cases is too limited to classify each of them in one of both categories. Based on the discussions of the case results and an analyses of the representativeness of the field cases for different applications, an overall conclusion will be provided regarding the performance of the model for a range of different storm intensities.

2.2 Overview of field validation cases

In total, nine field validation datasets are available with data on either or both hydro- or morphodynamics of a storm. From the field experiments, 3 cases with 9 profiles are available for the hydrodynamic validation and seven cases with 67 profiles for the morphodynamics validation. Table 2-1 and Table 2-2 provide an overview of these cases. The cases cover a variety of wave and water level conditions, profiles shapes and grain sizes, as explained below. This variation is strongly related to the variation in geographical location of the case studies: most locations are at several locations along the North Sea coast, but case 2 is along the French Atlantic coast and case 4 along the East coast of the USA. An overview of the locations of the cases is shown in Figure 2-1. Each case comprises 1 to 30 cross-shore profiles for which validation data are available and a 1D BOI-XBeach simulation is set up. As far as possible, the chosen profiles are at a more-or-less alongshore uniform location to limit processes in the alongshore direction that affect the 1D validation results. For the morphodynamic validation, case 8 ('Holland 1953') could only be used for a general validation (focus on the order of magnitude of dune erosion) due to limitations in available data, but this is still valuable since this storm resulted in the largest recorded dune erosion volumes along the Dutch coast.

In the appendices of this report, each individual field case is described in more detail. This comprises a case description, the model setup, the validation results, case-specific discussion points and conclusions.

Figure 2-1 Overview map of the location of all field validation cases. *Source base map: ESRI world street map.*

Table 2-1 Overview of the validation case study and characteristics.

Case		Number of profiles	Type	Profile shape characteristics	Remarks
Nr.	**Name**				
1	**Schiermonnikoog (NL)**	1	Hydro	Long gentle Wadden profile with bars	No dunes; overwash conditions
2	**Saint Trojan (France)**	1	Hydro	Long. Average beach slope, ~1:180 slope to long, gentle shelf	Very long swell waves; high infragravity waves
3	**Flemish Coast (Belgium)**	15	Morpho	Short. Average beach slope, steeper slope (~1:45 - 1:65) to very shallow flat shelf	High surge level, but minor dune erosion
4	**Fire Island, NY (USA)**	6	Morpho	Long, steep and with bar, low dunes (2-6 m)	Extreme wave conditions leading to dune erosion, overwash and dune breaching
5	**Vedersoe (Denmark)**	2	Morpho	Steepest beach, nearshore slope of Holland coast. Short	Two profiles with different erosion volume, incl. the largest observed erosion volume in this study
6	**Langeoog (Germany)**	6	Morpho	Gentle Wadden profile	Profiles with and without beach nourishment. Little dune erosion
7	**Holland 1976 storm (NL)**	30	Morpho	Long Holland profile	Profile shape varies due to bars and channels
8	**Holland 1953 storm (NL)**	1	Morpho	Holland reference profile	Indicative due to limited data. Significant dune erosion
9	**Egmond aan Zee (NL)**	7	Hydro + morpho	Holland profile with 2 bars and relatively steep beach	Little dune erosion (winter storm)

Table 2-2 Overview of the storm conditions and representative median grain sizes in all validation case studies. The storm conditions are the offshore (deep water) storm peak conditions as imposed in the XBeach simulation.

Case		Date of storm	Storm conditions			D_{50} [μm]
Nr.	**Name**		**WL** [m +MSL]	**H_s** [m]	**T_p** [s]	
1	**Schiermonnikoog (NL)**	10 - 11 January 2015	2.7	7.1	13	200
2	**Saint Trojan (France)**	2 - 3 February 2017	2.0	7.5	16.5	200
3	**Flemish Coast (Belgium)**	5 - 6 December 2013	3.67	3.8	8	216 - 308
4	**Fire Island, NY (USA)**	29 October 2012	2.2	10	16	400
5	**Vedersoe (Denmark)**	8 - 9 January 2005	3.00	6.6	13	250
6	**Langeoog (Germany)**	5 - 6 December 2013	3.95	7	15	250
7	**Holland 1976 storm (NL)**	3 - 4 January 1976	2.99	6.1	10.8	174 - 246
8	**Holland 1953 storm (NL)**	31 Jan. - 1 Feb. 1953	3.96	7.3	14	225
9	**Egmond aan Zee (NL)**	8 - 9 January 2019	2.08	5.2	14	250

Wave and water level conditions

The maximum water levels of the storms in the different field cases range from about 2 to 4 m above MSL and the maximum significant wave heights (H_s), offshore between approximately 4 and 10 m (Table 2-2). Validation case 3 ('Flemish coast, Belgium') and 6 ('Langeoog, Germany') both represent the Sint Nicholas Storm in 2013, but the water level and wave conditions are different due to the different locations and associated spatial characteristics.

To get an overview of how extreme the storms in all validation cases are in an absolute and relative sense, Figure 2-2 and Figure 2-3 give an indication of the return period of respectively the maximum water level and H_s during the storm of each case if the storm would have occurred along the Dutch coast. Note that the return period of the water level and H_s for the same storm are different and that similar conditions have a different return period at different locations along the Dutch coast. The spreading in the return period between different locations along the coast is especially large for H_s.

Four types of storm characteristics can be discriminated in the field cases:

1. ***Storms with high waves*** *(but low maximum water levels)*
   The Fire Island case (case 4) has a storm surge level corresponding to a return period of roughly one year along the Dutch coast, but hurricane Sandy in 2012 resulted in waves that would have a wave height return period of at least a thousand years. Storm Kurt hitting the coast at Saint Trojan in 2017 (case 2) resulted in the second highest return periods for the offshore wave height of 7.5 m, while the observed maximum water levels were quite common from a Dutch perspective. Although the return period of the H_s of case 2 is not much longer than for some other cases, the infragravity wave height for this case was quite extreme from a Dutch perspective, with nearshore long wave heights of 1.5 - 2 m high.

2. ***Storms with high peak water levels*** *(and varying wave heights)*
   In 1953, a combination of high spring tide and a severe storm at the North Sea resulted in the highest water levels in the past decades and consequently large floodings in the Netherlands. The corresponding field case 8 ('Holland 1953') has a maximum water level of about MSL + 4 m, with a return period of multiple hundreds up to a few thousand years, and wave heights with a wide range in return periods of about ten to thousands of years.
   The Sint Nicholas Storm in 2013 resulted in only slightly lower storm water levels and waves at the German Wadden Island Langeoog, which hence would have similar return periods as case 6 if it occurred along the Dutch coast. The same storm resulted slightly lower but still high maximum water levels of MSL + 3.7 m along the Belgian coast in Case 3, corresponding to a return period of a few hundreds of years for the Dutch coast, but in this case, the maximum H_s of 3.8 m is relatively low, which generally occurs at least a few times per year along the Dutch coast.

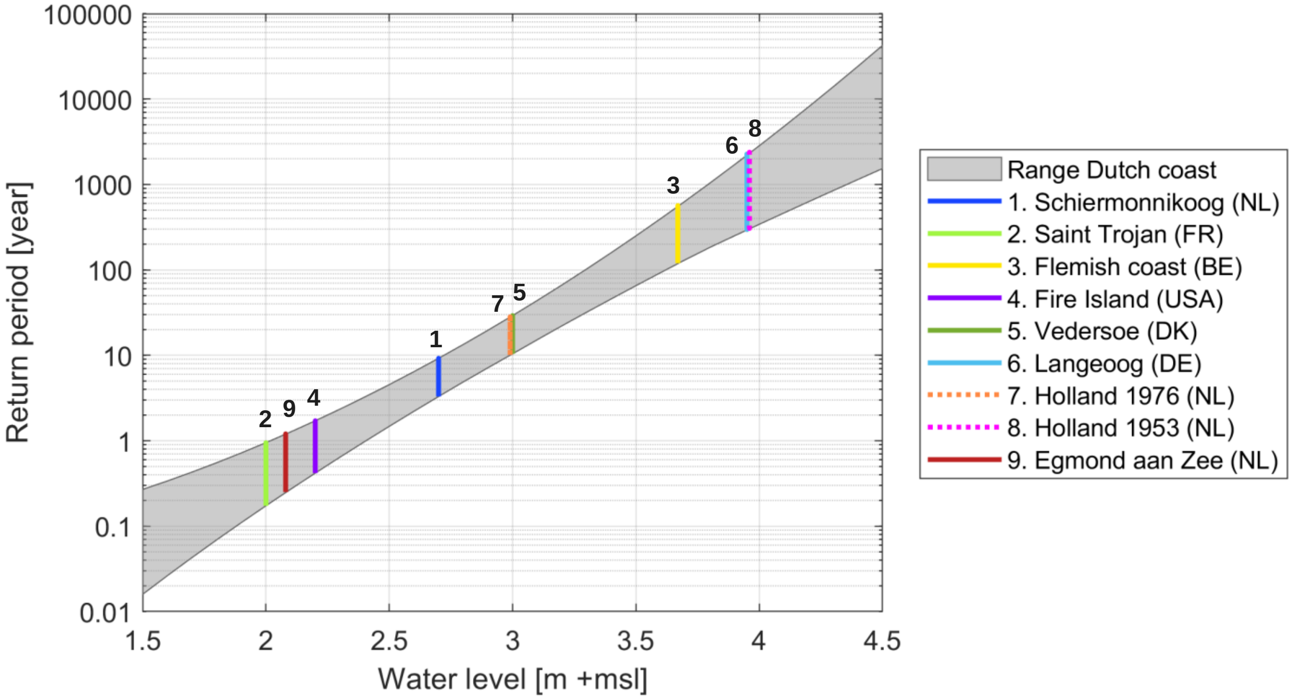

Figure 2-2 Indication of the return period of the field case storms (thick vertical lines) if the maximum storm surge level would have occurred in the Netherlands. The grey area shows the range in the return periods as function of the storm surge level for the Dutch coast based on statistical datasets conform WBI2017 (WL | Delft, Alkyon and TU Delft, 2007). To increase the visibility of overlapping cases, some cases are displayed as dotted line.

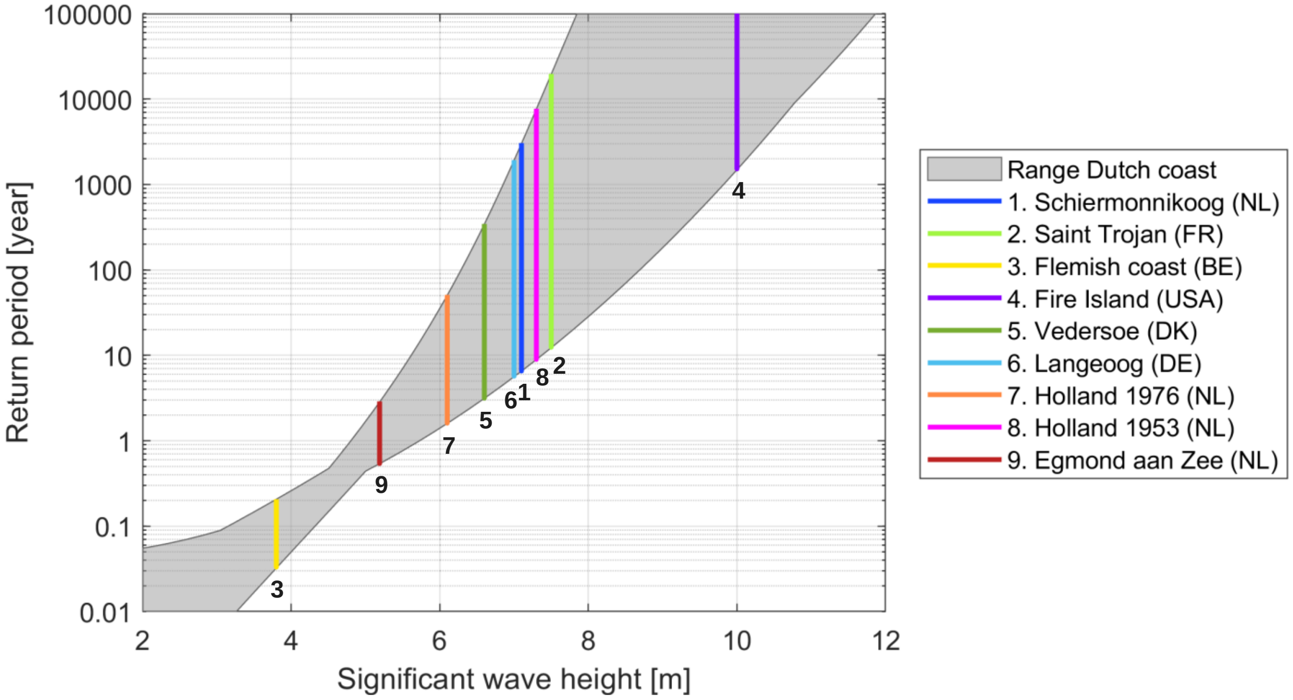

Figure 2-3 Indication of the return period of the field case storms (thick vertical lines) if the maximum significant wave height (H_s) would have occurred in the Netherlands. The grey area shows the range in the return periods as function of H_s for the Dutch coast based on statistical datasets conform WBI2017 (WL | Delft, Alkyon and TU Delft, 2007).

3. ***Storms with moderately high peak water levels and high waves***
   Validation case 1 (‘Schiermonnikoog’), 5 (‘Vedersoe’) and 7 (‘Holland 1976’) have a maximum H_s between about 6 m and 7 m, which corresponds along the Dutch coast to a return period of several years at Eierlandse Gat (between the Wadden Islands Vlieland and Texel) to several tens or even thousands of years at Hoek van Holland (southern end of the Holland coast). The maximum water level during the storms in these three cases is MSL + 2.7 m and MSL + 3.0 m, respectively, which corresponds with a return period in (the lower end of) the same range as for the wave height: 10 years and a few tens of years, respectively, along the Dutch coast.

4. ***Frequently occurring storms with moderate peak water levels and moderate waves***
   Validation case 9 (‘Egmond aan Zee’) represents a typical storm with a return period of about 1 year for both the maximum H_s and peak water level.

Profile shape

The shape (and length) of the cross-shore profiles in all cases varies, as visualized in Figure 2-4. The shape of the profile is important because it directly affects the hydrodynamics and thereby the dune erosion volumes. In the figure, the reference profiles for the Holland and Wadden coast are shown as reference. The Holland reference profile is characterized by a dune with a 1:3 slope, a beach with a 1:20 slope between the dune foot and MSL and gentle beach slope of 1:70 between MSL and low water (MSL -3 m), followed by a 1:180 slope to deep water. The Wadden reference profile is more gentle, with a small berm at MSL +2 m, a beachslope of 1:70 up to MSL -3 m and a foreshore slope of 1:500 to deep water.

The profiles of case 1 (‘Schiermonnikoog’) and case 6 (‘Langeoog’) are similar to the Wadden coast reference profiles with a gently sloping beach and a very gently sloping, shallow nearshore. On the other hand, the profiles of case 7 (‘Holland 1976’) and case 8 (‘Holland 1953’) resemble the Holland coast reference profile with a relatively steep beach and nearshore in the first few km’s (with some variation in the 1976 profiles related to local sand banks and channels).

The profiles of the Egmond aan Zee case (case 9) resemble a Holland coast profile, but with two bars and (consequently) on average a slightly steeper beach. The profile of French case nr. 2 (‘Saint Trojan’) lies between the Wadden and Holland coast reference profile. It starts with a relatively gentle beach (~1:70), then becomes as steep as the Holland coast profile (~1:180) and below MSL -8 m it reaches the continental shelf which is very long and flat (~1:700). The profiles of case 4 (‘Fire Island’) resembles the steep profile of the Holland reference profile above MSL (1:20 slope), but then continues with a relatively steep slope of ~1:40 to the bar around 400 m seaward of the waterline. Seaward of the bar, the profile continues with a relatively steep nearshore slope of ~1:125 to at least MSL -15 m and then gradually flattens. The steepness of these profiles might be related to the presence of relatively coarse sediment (Table 2-2). The profiles of the Danish case (case 5) have the steepest beach of all cases (~1:15), are quite short and have a slope similar to the Holland coast reference profile below about MSL -4 m.

Finally, despite their proximity to the Dutch coast, the profiles of case 3 (‘Belgium’) do not clearly resemble either the Holland or Wadden reference profile. The Belgian profiles (case 3) have an average beach slope above MSL but become steeper below MSL up to about MSL -8 m (on average ~1:45 to ~1:65) and then continue at about this depth along the shelf. Just like the Danish profiles, the Belgian profiles are relatively short.

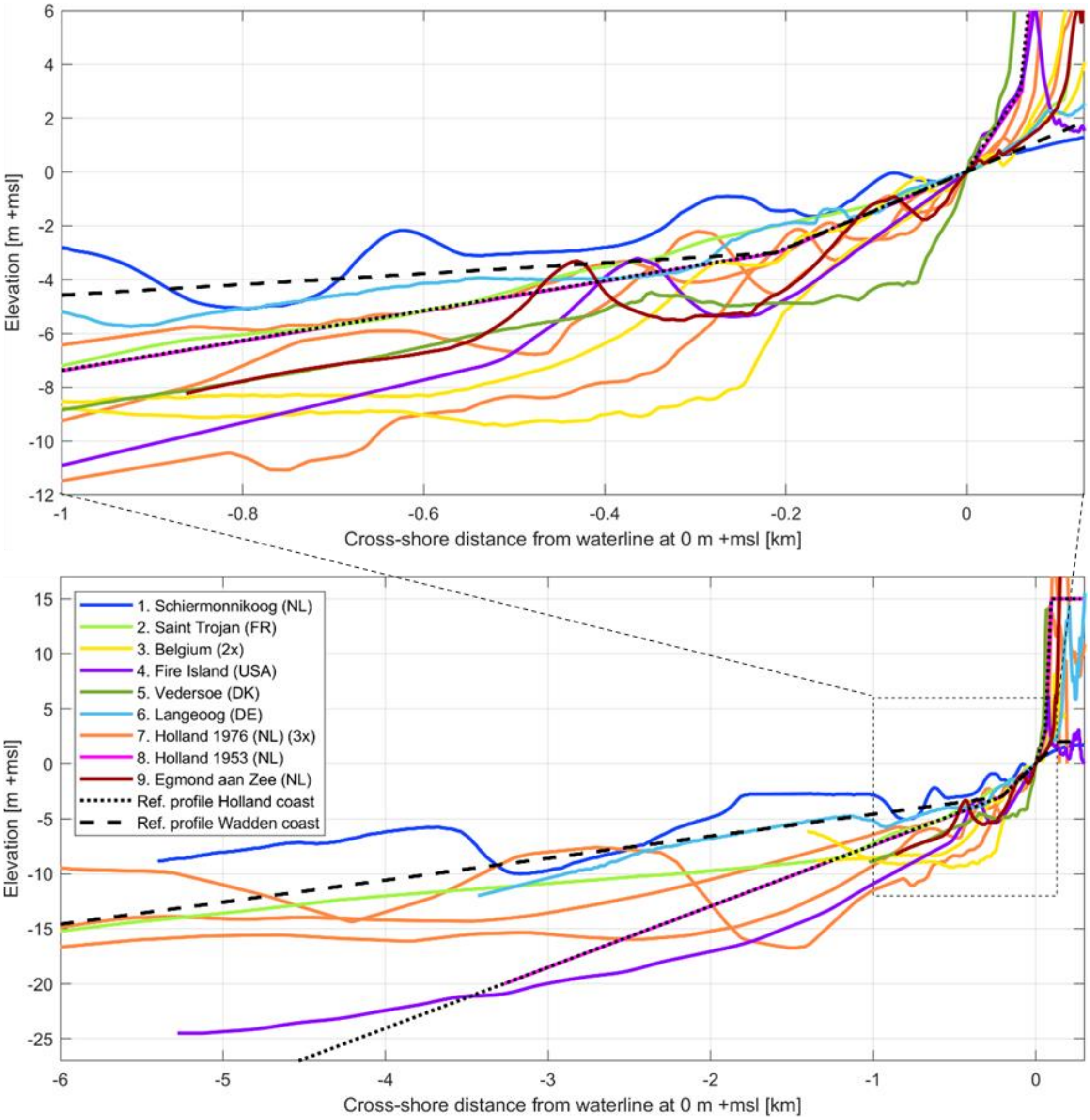

Figure 2-4 Overview of the pre-storm profile shapes for all field validation cases. The top figure zooms in on the first km in the bottom figure. For cases with multiple profiles, only a selection of representative profiles is shown.

Representative grain size

All cases consider sandy beaches and dunes. For each profile in the validation cases, a representative median grain size - the D_{50} - is given in Table 2-2. The D_{50} is a (uniform) input parameter in XBeach. In most cases, the D_{50} corresponds to fine sand (175-250 µm). The Fire Island coast and a few profiles along the Flemish coast and consist of medium sand (250-400 µm). Especially the average D_{50} of 400 µm of Fire Island is quite coarse compared to the Dutch coast. The smallest D_{50} of the field cases is found for some profiles along the Holland coast (1976 storm case).

For most profiles, only limited data are publicly available on the grain size distribution and even less information is available about the data collection, processing and measurement methods that also influence the D_{50}. As described in more detail in the appendices, the D_{50} for Schiermonnikoog (where no dunes are present), Saint Trojan, Fire Island, Langeoog and Egmond aan Zee is based on samples on the beach, while the D_{50} for Vedersoe, Holland 1976, Holland 1953 and probably also the Flemish coast is based on samples in the dunes. Generally, the sediment at the beach tends to be somewhat coarser than in the dunes that are formed by aeolian transport of sand from the beach.

Aside from the D_{50}, the D_{90} is an input parameter of XBeach too, although this parameter has less impact on the morphodynamics. For Schiermonnikoog the D_{90} is measured to be 300 µm and the corings at Fire Island show that for these profiles $D_{90} = 1.5 * D_{50}$. For all other profiles, no data on the D_{90} is available and the general rule of thumb $D_{90} = 1.5 * D_{50}$ is used.

2.3 Model set-up

2.3.1 BOI-settings

For all validation cases, the official release of XBeach version '*Release BOI-phase1-5867'* has been used. This model version is used in combination with the so-called BOI-settings for XBeach These settings include both hydrodynamic and morphodynamic model parameters that have been calibrated based on lab- and flume- experiments and field cases.

The calibration of the BOI-settings is explained in full detail in a separate calibration report: Deltares/Arcadis (2021a).

Calibration and validation process

The calibration and validation process in this project consisted of several steps. A first version of the BOI-settings consisted of parameter settings that were calibrated using lab- and flume experiments (Deltares, 2021a). These initial BOI-settings were used for a first round of validation with data from field measurements. Based on that validation some recommendations were made for further finetuning (recalibration) of the morphodynamic parameters *facAs*, *wetslp* and αD_{50} (see previous version of this report[4]). Based on these recommendations a new set of parameter settings is derived using the lab-/flume- experiments *plus* a selection of data from the field cases[5]: the **recalibrated BOI-settings** (Deltares/Arcadis, 2021a). These settings as used for the field validation of XBeach-BOI, as described in this report.

Table 2-3 shows all (non-default) relevant XBeach parameter settings that are used for the validation case, including the calibrated BOI-specific parameter settings.

The relevant calibration parameters were initially selected and calibrated using lab-scale experiments. The 'Boers' and 'GLOBEX' experiments were applied in the optimization of the hydrodynamic parameters (*gamma, gamma2* and *alpha*), and the morphodynamic parameters (*facSk, facAs, wetslp* and *beta*) were derived from larger-scale flume experiments. The model is not calibrated on bed friction and the wave breaking formulation '*Roelvink_daly',* and wave form formulation '*vanthiel'* are being used, as explained in Part 1 of the calibration report (Deltares/Arcadis, 2021a).

In addition, in this project a new parameter had been introduced as part of the BOI-settings: αD_{50}. This parameter is an enhancement factor to increase (or decrease) the grain size sensitivity of XBeach through the sediment transport formulas; this affects the morphodynamic processes but not the hydrodynamics. A first introduction of the parameter was provided in Deltares/Arcadis (2020). However, during the calibration process a new improved implementation[6] of αD_{50} has been developed. The final implementation and calibration of αD_{50} is described in more detail in Deltares/Arcadis(2021b). Parameter αD_{50} is calibrated based on (a very limited amount of) flume experiments and a selection of the available field cases. The (final) setting that is considered for this validation process: αD_{50} = 0.4.

Besides the calibrated parameters, some general XBeach parameters are defined in Table 2-3 for all validation cases. One of these parameters is the reduction factor αE, which is set to a value of 0.3, based on Deltares/Arcadis (2020). More information and details on the implementation of αE can be found in that report as well. In short, this parameter was introduced to obtain better consistency between 1D and 2DH model simulations by mimicking the effect of wave directional spreading on infragravity wave generation in 1D. The parameter should only be used in 1D models, not in 2DH.

For all parameter settings that are not included in Table 2-3, the default XBeach settings are used, such as *epsi* = -1 and *single_dir* = 0; except for case-specific input such as the boundary conditions and grid-related parameters. A complete overview of the applied (default) XBeach settings – related to the used version of XBeach – is given at the end of the report (page 59). *Morfac* is set to 1 in all cases, because the focus in this validation is on the (calibrated) BOI settings and hence the potential negative effect on the morphological results of parameters that could be used to decrease the computational time - such as *morfac* - is minimized*.* Moreover, *random* = 0 has been used for all validation cases, and the left and right boundary (keyword *left* and *right*) are set to 'wall' since the cases are validated in 1D.

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[4] *The approach, the results, and the recommendation of the first round of field validation (using the 'old' BOI-settings) are described in a previous draft version of this report (v1.1). This (outdated) draft version is not released, but it is included, as support information for the recalibration study, in an appendix of the (renewed) calibration report, Deltares/Arcadis (2021a).*

[5] *In the calibration report (Deltares/Arcadis, 2021a) more details are provided on the selection of addition calibration data from the available field cases. Only a small subset of the entire dataset of field data is used for calibration, such that validation is still possible.*

[6] *During the project, several implementations of* αD_{50} *have been tested. In the report of Deltares/Arcadis (2020) an older version of the implementation of* αD_{50} *has been presented; in which the 'meaning' of the parameter itself slightly differs from the new implementation. Hence the parameter values and their resulting behavior cannot be compared one-to-one. A more detailed description of the new* αD_{50} *implementation will be included in the final version of the calibration report (work-in-progress).*

Table 2-3 Overview of the XBeach BOI-settings for flow, wave breaking, sediment transport and morphology, and general XBeach 1D model settings used for the validation based on the field cases. More information on these settings is provided in the calibration report (Deltares/Arcadis, 2021a).

Type parameter	Keyword/parameter	BOI parameter value
Flow	bedfriction	Manning
	bedfriccoef	0.02
Wave breaking	beta**	0.08
	break	Roelvink Daly
	gamma*	0.46
	gamma2*	0.34
	alpha*	1.38
	DeltaHmin	0.1
Sediment transport and morphology	form	VanThiel_VanRijn
	waveform	VanThiel
	facSk**	0.15
	facAs**	0.20
	wetslp**	0.15
	oldTsmin	0
	dtLimTs	5
General	alfad50 (αD_{50}) **	0.4
	wbcEvarreduce (αE) *	0.3
	wbcScaleEnergy	1
	wbcRemoveStokes	1
	fixedavaltime	0
	nTrepAvaltime	1.0
	Hswitch	0
	snells	1
	nuhfac	0
	CFL	0.95
	eps	0.005
	eps_sd	0.5

***** *BOI calibration parameter hydrodynamics*

*** BOI calibration parameter morphodynamics*

2.3.2 Case-specific settings

In general, for all validation cases, it is attempted to use the most realistic boundary conditions and grid to reduce the effect of the case-specific model input on the error between measured and modelled hydro- and morphodynamics and focus on the validation of the BOI XBeach setup itself. For each profile the local representative grain size (D_{50} and D_{90}) is used, preferably characteristic values for the first dune row, where the sand that is eroded from. If the D_{50} of the dunes is unknown, the D_{50} of the beach is used. And, if the D_{90} is unknown, the relationship $D_{90} = 1.5 \times D_{50}$ is used.

Grid setup

For each profile in each validation case, a 1D XBeach grid is set-up with a spatially varying resolution. The minimum grid resolution is 1 m in the dunes (above an elevation of MSL + 3 m) and the maximum grid resolution at the deepest point of the profile depends on the offshore wave period. A relatively fine grid resolution is used (up to max. 40 grid points per wavelength, following the recommendations of Deltares (2021b). At the offshore boundary, the imposed waves should be in deep water for the entire run to ensure correct calculation of the infragravity wave height at the boundary. Deltares (2021d) showed that this is the case if the depth at the model boundary is at least three times the offshore significant wave height *and* the wave celerity ratio is smaller than 0.9. This is checked using the characteristics of the imposed waves (the maximum H_s and maximum T_p), the imposed minimum water level and the bed level at the offshore boundary. If the bed level at the offshore boundary is too shallow, the profile is extended to deep water with additional data (if available) and/or manually extended with a 1:10 or 1:50 slope, as prescribed in Deltares (2020).

Boundary conditions

For each validation case profile, the offshore water levels at deep water are based on available measured (/hindcast) time series for the storm at about the same water depth as the offshore boundary, as far as available. The temporal resolution of the available data determines the time interval of this input. In case open water is present at the landward side (i.e. for the Schiermonnikoog case), a measured water level time series is imposed on the landward boundary of the model.

The wave boundary condition type depends on the type of available data. In general, a JONSWAP spectrum is imposed with time-varying significant wave heights (H_s), peak wave periods (T_p) and wave directional spreading coefficients (*s*), and a default fixed peak enhancement factor (*gammajsp*) of 3.3. If data on directional wave spreading are unavailable, s = 6 (approx. 30°) is used. For case 2 and 4, wave boundary conditions in the form of 2D wave spectra are available. These spectra are imposed directly without conversion to a JONSWAP spectrum to get as close to the actual situation as possible. In both cases, waves at the offshore boundary are imposed perpendicular to the coast. In case of a profile oriented east-west (*alfa* = 0), this means that *thetamin* = -90, *thetamax* = +90 and *dtheta* = 180 are used (unless described otherwise in the case model setup) to ensure that all wave energy is in the same bin centred perpendicular to the coast.

2.4 Performance indicators for validation

2.4.1 Validation of hydrodynamics

In the validation of the hydrodynamics, at first the spatial pattern in modelled and measured water levels and short and long wave heights is compared visually. Next, the modelled time series of the water level and the significant short and long wave heights are compared to the measured time series at the measurement locations.

In this validation report, short waves or gravity waves are waves within the 0.05-1 Hz frequency domain, and long waves or infragravity waves in the 0.005-0.05 Hz domain. In the Saint Trojan case, no upper limit for the long waves is applied in the measurements and hence for this case, the long wave height include very low frequency waves as well.

The goodness of fit (GoF) of these three hydrodynamic variables is quantified by four GoF indicators (or model performance statistics or skill scores):

- The **Root Mean Squared Error** (*RMSE*)

  $$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(f_{model,i} - f_{meas.,i}\right)^2}$$

  Low values indicate a good performance; zero means perfect prediction.

- The **Scatter Index** (*SCI*)

  $$sci = \frac{RMSE}{\max\left(\overline{f}_{meas}, rmsm\right)}$$

  with

  $$rmsm = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(f_{meas.,i}\right)^2}$$

  The Scatter Index is the RMSE (in the numerator) relative to the mean value of the measured signal (in the denominator). Low values (close to zero) indicate a good performance. To prevent relative low values of the mean causing high values of *sci*, the RMSE is divided by the maximum value of the mean measured values and the root mean squared mean of the measured values.

- The **Bias**

  $$Bias = \frac{1}{N}\sum_{i=1}^{N}\left(f_{model.,i} - f_{meas.,i}\right)$$

  The bias is the systematic error. Low values (close to zero) indicate a good performance.

- The **Relative Bias** (Rel. Bias)

  $$Rel.Bias = \frac{Bias}{\max\left(\overline{f}_{meas}, rmsm\right)}$$

  The relative bias is the systematic error relative to the mean. Low values indicate a good performance. To prevent relative low values of the mean causing high values of *sci*, the RMSE is divided by the maximum value of the mean measured values and the root mean squared mean of the measured values.

2.4.2 Validation of morphodynamics

In the validation of the morphodynamics, two quantitative measures of dune erosion are used to compare the measured and modelled situation: the dune erosion volume and the dune retreat distance. The absolute as well as the relative differences (percentage of measured value) between measured and modelled dune erosion are analysed per case. For the overall goodness of fit of the modelled dune erosion versus the measured dune erosion, the same indicators as for the validation of the hydrodynamics are used: the root mean squared error (RMSE), the scatter index (SCI), the bias and the relative bias. These are calculated with the equations given in section 2.4.1, except that the denominator is simplified for the SCI and relative bias from $\max(\overline{f}_{meas}, rmsm)$ to respectively the $rmsm$ of the measured values and the mean measured value ($\overline{f}_{meas}$).

The dune erosion volume [m^3/m] is calculated as the erosion area above the maximum storm surge level imposed on the offshore boundary (Figure 2-5). Only the erosion volume up to the first crossing of the pre- and post-storm profile is included, which generally means that only the erosion volume at the seaward side of the first dune row is included.
The dune retreat distance [m] in this report is defined as the horizontal distance between the pre- and post-storm profile at 1 m above maximum storm surge level (Figure 2-5), unless indicated otherwise for a case. This representative elevation roughly corresponds to the elevation of the new dune foot and/or the largest dune erosion distance.

Besides the quantitative measures, the profile modelled post-storm profile shape is qualitatively compared to the measured profile. In this case, the focus is on the shape and size of the deposition profile below the eroded dune and other clear changes in profile shape and associated net sediment transport trends.

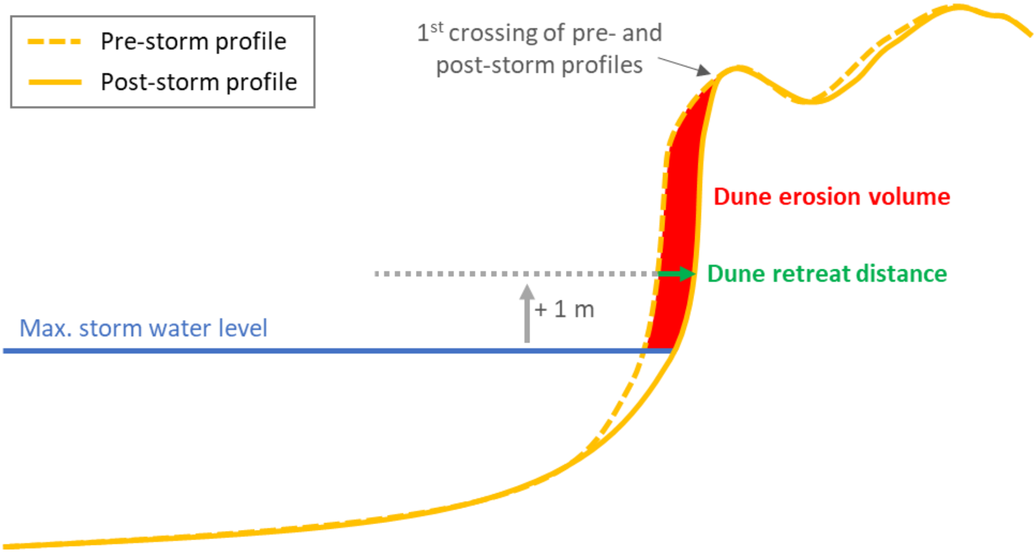


Figure 2-5 Schematic dune erosion profile with the definition of the dune erosion volume and dune retreat distance.

3 MAIN RESULTS OF FIELD CASES

This chapter gives an overview of the main results of the two field cases focusing on the **hydrodynamics**, followed by the six cases focusing on the **morphodynamics**. This is mainly a summary of relevant results and observations that are described in more detail, per individual field case, in the separate appendices at the end of this report.

3.1 Validation of hydrodynamics

The hydrodynamics in the BOI-version of XBeach are validated based on measurements along a coastal transect at Schiermonnikoog in the Netherlands (case 1), measurements along a transect in the area of Saint Trojan in France (case 2) and measurements along seven profiles at the beach near Egmond aan Zee in the Netherlands (case 9). Detailed descriptions of the individual cases, including approach, results, discussion and conclusions are presented in more detail in Appendix 1, 2 and 9 of this report. A short summary of the results and main discussion points per case is provided in the next sections. These summaries refer to Table 3-1 for the overall goodness-of-fit indicators for all three cases and elaborate on the most notable values in this table.

From these field validation cases, it is concluded that the 1D BOI-version of XBeach is well capable of reproducing measured hydrodynamic conditions at the beach and dune foot during storm events. In particular, the modelled infragravity (IG) wave heights that are important for dune erosion show good resemblance with the measurement data in all cases: the overall biases in the IG wave height are only a few cm. *This also suggests that the newly implemented* αE *parameter – that is added to mimic the effect of wave directional spreading on IG-wave generation in 1D, to get more consistency between 1D and 2DH simulations (see Deltares/Arcadis, 2020) – functions well.*

Table 3-1 Overall goodness-of-fit (GoF) indicators for the modelled water depth and short (HF: high frequency) and long (LF: low frequency) wave height compared to the measurements for all hydrodynamic cases: case 1 (Schiermonnikoog, NL), case 2 (Saint Trojan, FR) and case 9 (Egmond aan Zee, NL). Colours indicate relative GoF between the locations (greener = better fit). For case 1, the GoF for all measurement locations across the island tail as well as those on the beach only (most relevant for dune erosion) are shown.

Case	Locations	Period	Water depth [m] *				$H_{mo\,hf}$ [m]				$H_{mo\,lf}$ [m]			
			RMSE	sci	bias	rel. bias	RMSE	sci	bias	rel. bias	RMSE	sci	bias	rel. bias
1	All	Entire period	0.13	0.14	0.07	0.07	0.12	0.29	0.05	0.11	0.07	0.28	0.04	0.15
		Storm peak	0.14	0.12	0.09	0.08	0.13	0.25	0.06	0.12	0.07	0.25	0.04	0.13
	Beach (P1-P5)	Entire period	0.16	0.17	0.14	0.15	0.14	0.31	0.13	0.27	0.08	0.29	0.06	0.22
		Storm peak	0.18	0.15	0.17	0.14	0.17	0.29	0.15	0.25	0.09	0.26	0.06	0.17
2	Beach (all PT's)	Entire period	0.17	0.12	0.11	0.07	0.24	0.33	0.22	0.29	0.24	0.28	-0.04	-0.04
		Storm peak	0.18	0.11	0.09	0.06	0.24	0.28	0.22	0.26	0.29	0.23	0.18	0.14
9	Beach (all PT's)	Entire period	0.59	0.28	-0.45	-0.21	0.36	0.42	-0.04	-0.05	0.15	0.27	-0.01	-0.02

* *Water level [m +NAP] for case 9.*

** *In case 1 and 9, the LF waves are only infragravity waves (0.005-0.05 Hz), while in case 2 no lower limit is used and hence infragravity and very low frequency waves are included.*

From the field validation cases, it is concluded that the 1D BOI-version of XBeach is well capable of reproducing measured nearshore hydrodynamic conditions during storm events:
Particularly relevant in relation to dune erosion, it is concluded that the modelled infragravity (IG) wave heights generally show good resemblance with the measurement data for all available field cases. The determined bias ranges between -0.04 and 0.18 m, while the relative bias ranges between -0.04 and 0.22.

3.1.1 Case 1: Schiermonnikoog, NL

Along a cross-shore profile at the tail of barrier island Schiermonnikoog, ten pressure transducers (PT's) have been installed during a storm in 2015 (Figure 3-1). The PT's are located on the beach above MSL and across the island tail. No dunes are present: during the storm, overwash occurs. The water depths and short and long wave height time series derived from the PT's are compared to the hydrodynamics at the corresponding locations in the 1D XBeach simulation that is forced at the offshore boundary with the measured offshore hydrodynamics of the storm.

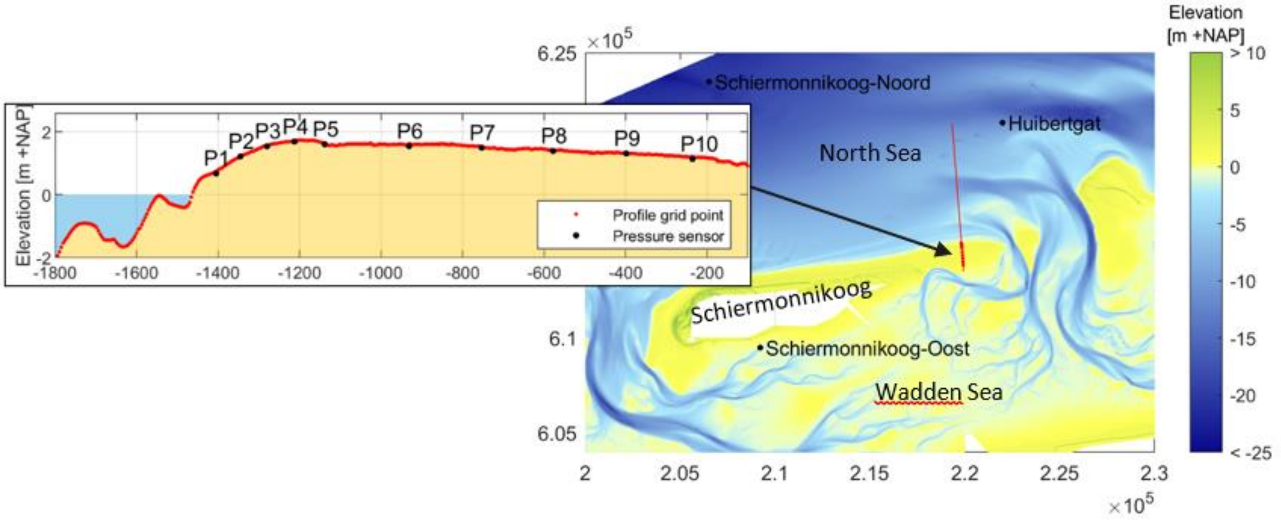


Figure 3-1 Overview of the measurement locations at Schiermonnikoog.

Overall, the fit between the measured and modelled water depths and wave heights is very good at the beach (PT 1-5) as well as across the island tail (PT 6-10). Figure 3-2 shows an example of a time series which showcases that the XBeach results closely follow the measured hydrodynamics (for variation in the time series between locations: see appendix 1). This can also be concluded from the comparisons in Figure 3-3 and the overall goodness-of-fit (GoF) indicators summarized in Table 3-1. The good fit for the infragravity wave height indicates that the newly implemented αE parameter works fine, even for the directional spread of less than 30° during the storm peak.

Some deviations between measurements and model results are observed: an overestimation of mainly the short wave heights and a slight overestimation in the water depth by the model, especially at the beach (P1-P5); see bias in Table 3-1. The deviations could to some extent be explained by case-specific model input inaccuracies. For example, some morphological changes were observed during the 3 months of the field campaign. The observed water depths were corrected for these changes by a linear interpolation of the bed level at the begin and end of the field campaign, while the XBeach water depth at the beach is based on only the bed level at the end of the campaign (closest to the storm period). These assumptions in the bed level inherently resulted a small offset in the water depths and consequently in the wave heights. Since the morphological changes were very limited landward of the beach crest, this could explain the spatial variation in the GoF. For more details on spatial variations in the goodness of fit is referred to Appendix 1.

Besides the case-specific model input, the difference in modelled and measured wave heights are also partly related to the value of the *gamma* wave breaking parameter in the BOI settings, which was calibrated for steeper coastal profiles than those of this case study. However, this hydrodynamic validation case gives insufficient reason to adjust the *gamma* value, because the hydrodynamic offsets are relatively small and could already partly be ascribed to input inaccuracies.

Table 3-2 Overall goodness-of-fit (GoF) indicators for case 2 (Schiermonnikoog, NL); this is a subset of the data in Table 3-1.

Case	Locations	Period	Water depth [m]				$H_{mo\,hf}$ [m]				$H_{mo\,lf}$ [m]			
			RMSE	sci	bias	rel. bias	RMSE	sci	bias	rel. bias	RMSE	sci	bias	rel. bias
1.	All	Entire period	0.13	0.14	0.07	0.07	0.12	0.29	0.05	0.11	0.07	0.28	0.04	0.15
		Storm peak	0.14	0.12	0.09	0.08	0.13	0.25	0.06	0.12	0.07	0.25	0.04	0.13
	Beach (P1-P5)	Entire period	0.16	0.17	0.14	0.15	0.14	0.31	0.13	0.27	0.08	0.29	0.06	0.22
		Storm peak	0.18	0.15	0.17	0.14	0.17	0.29	0.15	0.25	0.09	0.26	0.06	0.17

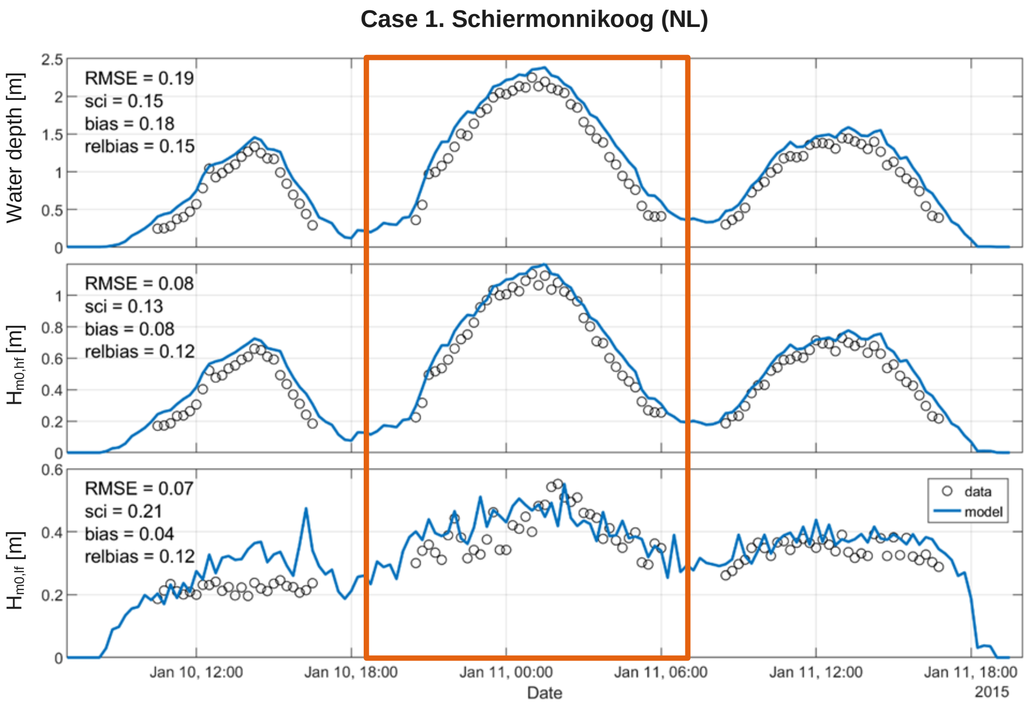


Figure 3-2 Example of a time series of measured and modelled water depth, short and long wave height for the case 1 (Schiermonnikoog, NL) for P1 at the beach at a similar water depth as in Figure 3-5 for case 2. For all other time series, see appendix 1. The orange box indicates the storm peak period. The long waves are only infragravity (IG) waves between 0.005-0.05 Hz.

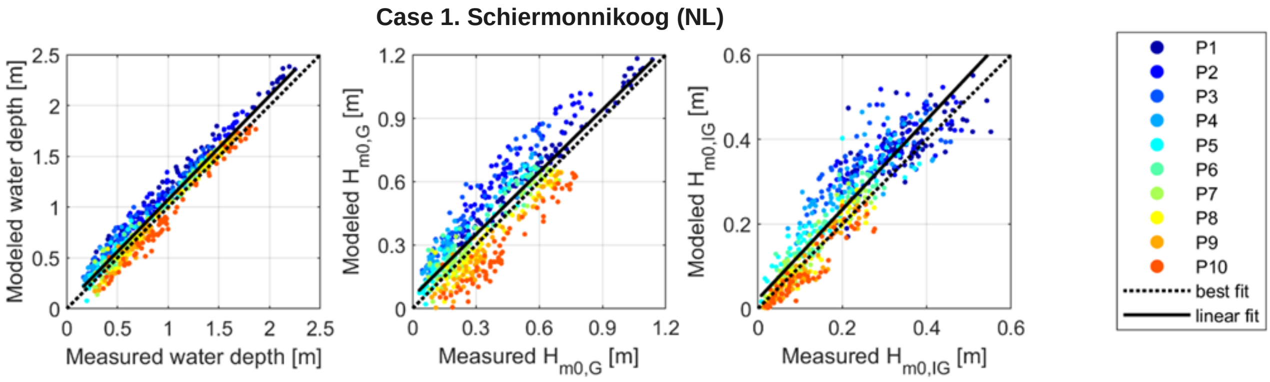


Figure 3-3 Scatter plot of the modelled versus measured water depth (left), spectral significant wave height (H_{m0}) of short waves (G) (middle) and long waves (right) for all measurement locations at Schiermonnikoog. The long waves are infragravity (IG) waves between 0.005-0.05 Hz. The dashed line here indicates a perfect 1:1 relationship; the solid black line represents the linear data fit.

3.1.2 Case 2: Saint Trojan, France

Along a cross-shore profile at the beach near Saint Trojan (France), eight pressure transducers (PT’s) have been installed during a storm in 2017 with high infragravity waves. Four of the PT’s are located at the beach below MSL and the others in the area above MSL up to the dune foot. The water depths and short and long wave height time series derived from the PT’s are compared to the hydrodynamics at the corresponding locations in the 1D XBeach simulation that is forced at the offshore boundary with the measured offshore hydrodynamics of the storm.

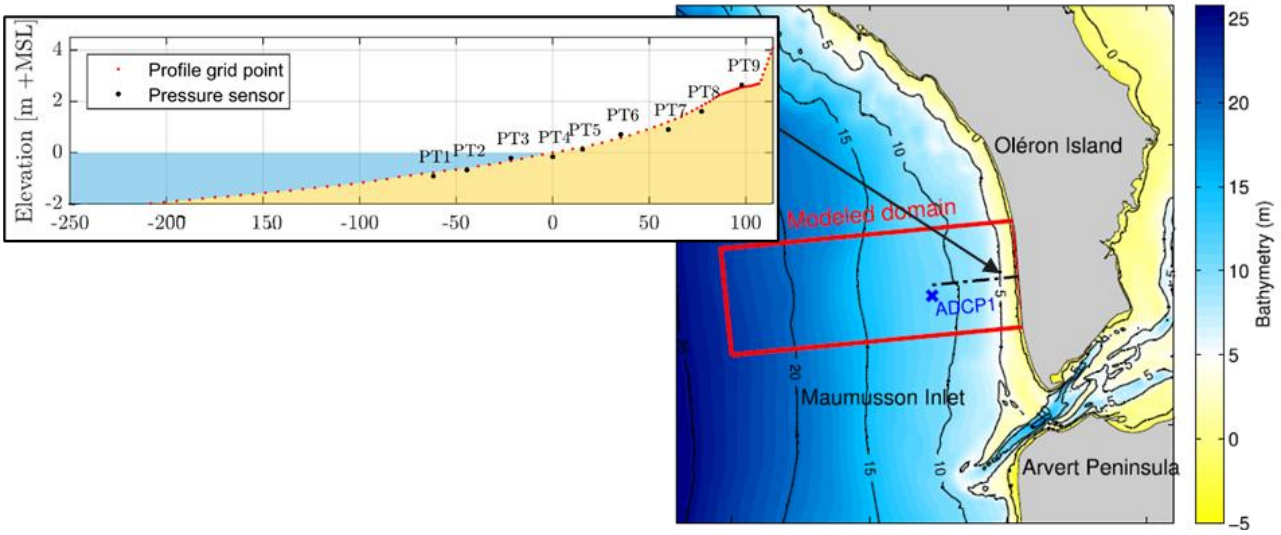


Figure 3-4 Overview of the measurement locations at Saint Trojan.

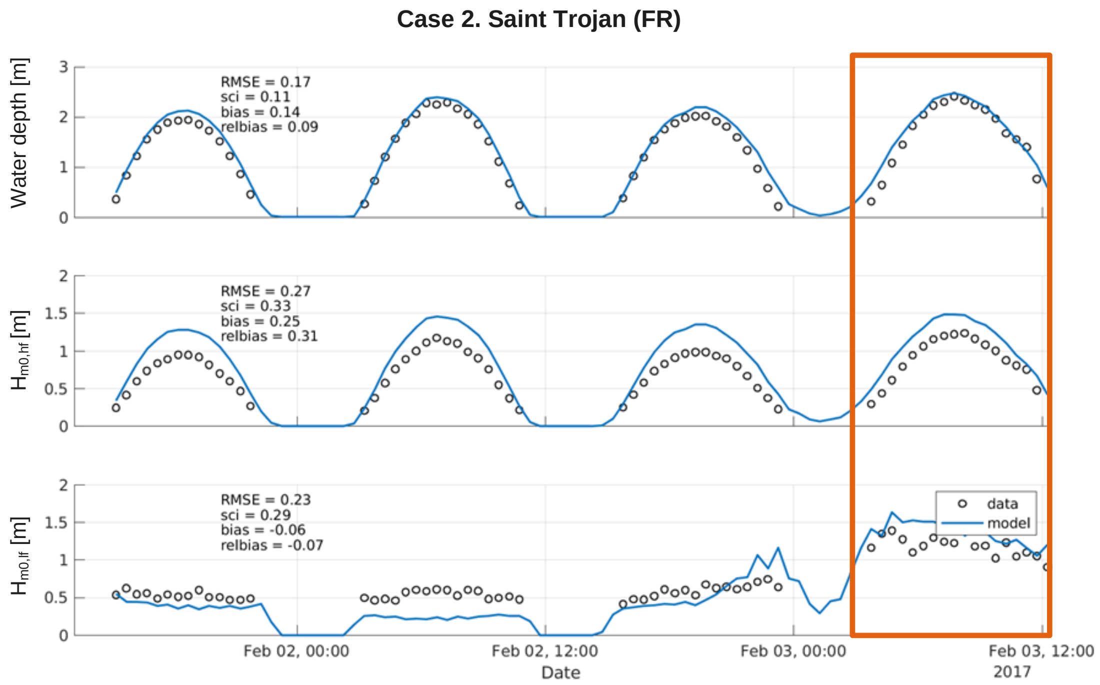
Overall, the fit between the measured and modelled water depths and wave heights at the beach of Saint Trojan in France is good, also for the high infragravity waves. Figure 3-5 shows an example of a time series which showcases that the XBeach results closely follow the measured hydrodynamics (for variation in the time series between locations: see appendix 2). This can also be concluded from the comparisons in Figure 3-6 and the overall goodness-of-fit (GoF) indicators summarized in Table 3-1. Note that the range in measured and modelled values is larger in case 2 than in case 1, especially for the long wave height, but that the trends in the comparison and the GoF indicator values are very similar.

Some deviations between measurements and model results are observed in both cases: an overestimation of on average 0.22 m of short wave heights by the model and an overestimation of on average 0.1 m in the water depth (see bias in Table 3-1). The deviations could to some extent be explained by case-specific model input inaccuracies. Inaccuracies in offshore water depth input could have contributed to the small overestimation of the water depths by XBeach, and inaccuracies in the directional wave spreading input could explain the underestimation of the long wave height during the second modelled tidal cycle. For more details on spatial variations in the goodness of fit is referred to Appendix 2.

Besides the case-specific model input, the difference in modelled and measured wave heights are also partly related to the value of the *gamma* wave breaking parameter in the BOI settings, which was calibrated for steeper coastal profiles than this case study. However, this hydrodynamic validation case gives insufficient reason to adjust the *gamma* value for the Dutch coast, because the relatively small offset could already partly be ascribed to input inaccuracies and a specific *gamma* value that works best for relatively mildly sloping cases such as in this case.

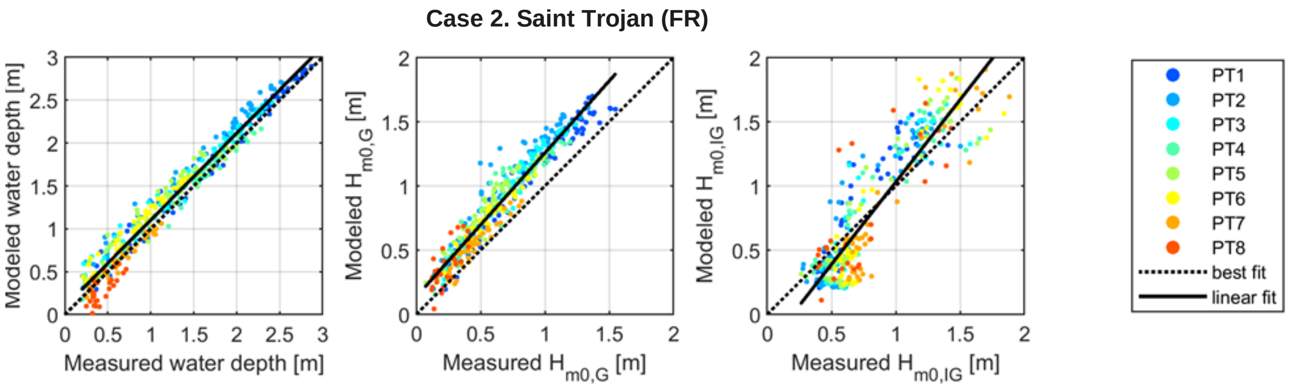
Table 3-3 Overall goodness-of-fit (GoF) indicators for case 2 (Saint Trojan, France); this is a subset of the data in Table 3-1.

Case	**Locations**	**Period**	**Water depth [m]**				$H_{mo\,hf}$ **[m]**				$H_{mo\,lf}$ **[m]**			
			RMSE	sci	bias	rel. bias	RMSE	sci	bias	rel. bias	RMSE	sci	bias	rel. bias
2.	Beach (all PT’s)	Entire period	0.17	0.12	0.11	0.07	0.24	0.33	0.22	0.29	0.24	0.28	-0.04	-0.04
		Storm peak	0.18	0.11	0.09	0.06	0.24	0.28	0.22	0.26	0.29	0.23	0.18	0.14



Case 2. Saint Trojan (FR)

Figure 3-5 Example of a time series of measured and modelled water depth, short and long wave height for case 2 (Saint Trojan, FR) for PT3 at the beach at a similar water depth as in Figure 3-2 for case 1. For all other time series, see appendix 2. The orange box indicates the storm peak period. The long waves do not have a lower limit and hence include IG waves and very low frequency (VLF) waves.



Case 2. Saint Trojan (FR)

Figure 3-6 Scatter plot of the modelled versus measured water depth (left), spectral significant wave height (H_{m0}) of short waves (G) (middle) and long waves (right) for all measurement locations at Saint Trojan, France. The long waves do not have a lower limit and hence include IG waves and very low frequency (VLF) waves. The dashed line here indicates a perfect 1:1 relationship; the solid black line represents the linear data fit.

3.1.3 Case 9: Egmond aan Zee, NL

Near Egmond aan Zee (the Netherlands) along a 3 km long stretch of the coastline measurements have been performed during a winter storm in January 2019 (see Figure 3-7). Along seven different cross-shore profiles combinations of two pressure sensors (PT's) have been installed to measure nearshore hydrodynamics (water levels and wave conditions). The landward sensors were located at different levels above high tide water level and were only temporarily inundated during high water during the storm, while most seaward sensors were inundated for substantially longer periods of time during the storm. The water levels and short and long wave height time series derived from the PT's are compared to the hydrodynamics at the corresponding locations in the 1D XBeach simulation that is forced at the offshore boundary with the measured offshore hydrodynamic conditions related to the storm.

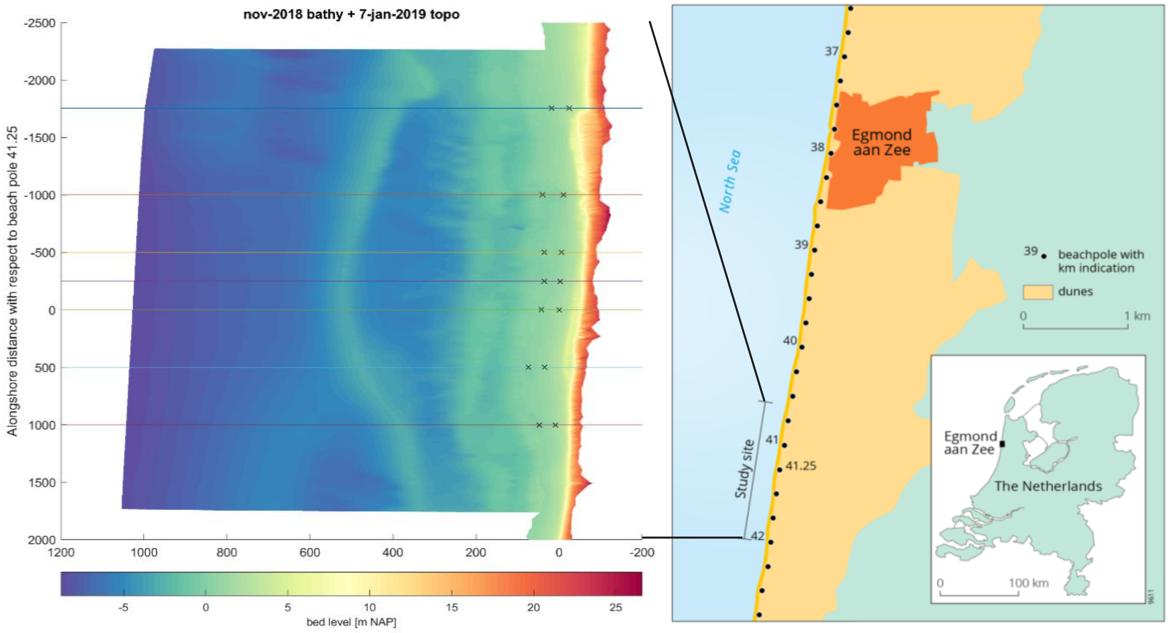


Figure 3-7 Overview of the location of the cross-shore profiles near Egmond aan Zee that are used in the hydrodynamic validation. The origin of the local coordinate system used (left panel) is at beach pole 41.25. The cross-sections are referred to by their local y-coordinate. Right panel is adopted from Ruessink et al. (2019).

The patterns in the time series of the water level and short and long wave heights in the XBeach simulations are in line with the measurements, as shown in Figure 3-8 for the infragravity wave height (see appendix 9 for the other time series). However, the modelled water level in XBeach is on average lower than in the measurements for most sensors, with a bias of -0.45 m and RMSE of 0.59 m, which is shown in Figure 3-9 and summarized in Table 3-1. The modelled short- and infragravity wave heights correspond well with observations for most of the sensors, despite the underestimated water levels. Additional relevant figures and tables for this specific field case are presented in Appendix 9.

The difference in modelled and observed water levels most probably is caused primarily by inaccuracies in (processing of) the observational data, instead of model inaccuracies. The field data show relatively large alongshore water levels variations for the different observation points that are highly unlikely since these will induce strong (unrealistic) currents and which probably would have affected the waves as well. However, the wave data does not show a similar alongshore variation. Also, the comparison with the model results hints at an error in the measurements instead of the model: the measured wave heights are well captured by the model for different sensors along the beach (short wave bias = -0.04 m), which would probably not have been the case when modelled water depths were incorrect (as wave heights are determined by depth-induced breaking). Furthermore, some sensors along a profile show a decrease in water level towards the coast, which also indicates that the measured water level at least one of the sensors probably is incorrect.

Table 3-4 Overall goodness-of-fit (GoF) indicators for case 3 (Egmond aan Zee, NL); this is a subset of the data in Table 3-1.

Case	**Locations**	**Period**	**Water depth [m]**				**$H_{mo\,hf}$ [m]**				**$H_{mo\,lf}$ [m]**			
			RMSE	sci	bias	rel. bias	RMSE	sci	bias	rel. bias	RMSE	sci	bias	rel. bias
9.	Beach (all PT's)	Entire period	0.59	0.28	-0.45	-0.21	0.36	0.42	-0.04	-0.05	0.15	0.27	-0.01	-0.02

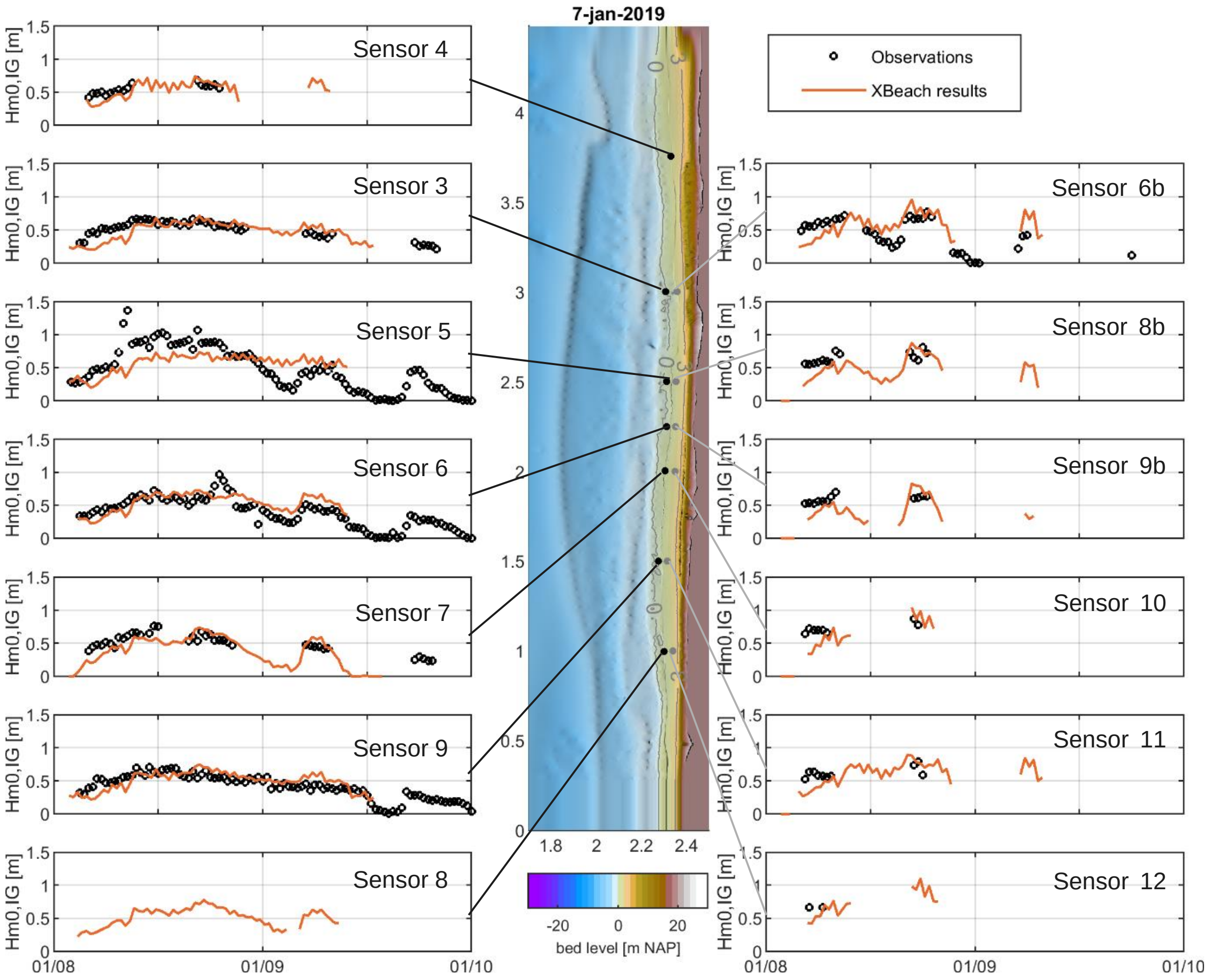


Figure 3-8 Timeseries of measured and modelled infragravity wave heights for all pressure sensors in the Egmond aan Zee case. The panel in the middle shows the location of the pressure sensors, and the surrounding subpanels follow the order from North to South (top to bottom) and from sea (left) to the beach (right). Time series of water level and short wave height are presented in Appendix 9.

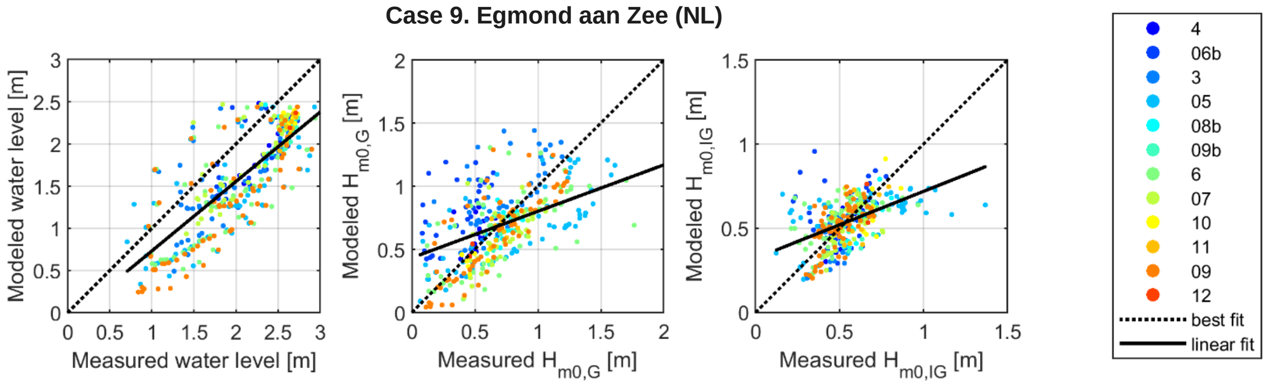


Figure 3-9 Scatter plot of the modelled versus measured water level (left), spectral significant wave height (Hm0) of short waves (G) (middle) and infragravity waves (IG) (right) for all pressure transducers near Egmond aan Zee. The long waves are only infragravity (IG) waves between 0.005-0.05 Hz. The dashed line here indicates a perfect 1:1 relationship; the solid black line represents the linear data fit.

A small overall bias is found of -0.04 m is found for the short wave height at the beach, which indicates that short wave breaking is simulated correctly. Although, the scatter is relatively large compared to the other hydrodynamic cases. The latter is mainly related to a few sensors with some outliers and an offset that are probably related to measurement inaccuracies. In the other hydrodynamic field cases it was shown that an adjustment of parameter *gamma* might improve the model results (for mildly sloping profiles); however, from the results in this case that recommendation is not necessary: *gamma* seems to be properly calibrated for this case. This is probably related to the fact that the cross-shore profiles at Egmond closely resemble a typical profile of the Holland Coast, for which *gamma* has been calibrated.

Focussing on the infragravity wave height, the derived goodness-of-fit parameters (Table 3-1) show that the IG-waves are reproduced well; also compared to the other hydrodynamic cases. A small overall bias is found of -0.01 m and a relative bias of -0.02; which is encouraging. This also indicates that the newly implemented parameter αE, that mimics the effect of wave directional spreading on IG-wave generation in a 1D model, performs as intended. Without this implementation the modelled IG-waves would have been overestimated compared to both data and a 2DH model.

The scatter plots in Figure 3-9 as well as the goodness-of-fit (GoF) parameters in Table 3-1 show that the data scatter in this validation case is larger than for the other hydrodynamic cases.

For the short waves a RMSE of 0.36 is found and a scatter index of 0.42. For the infragravity waves the RMSE = 0.15 and scatter index = 0.27. When studying Figure 3-9 it is found that the GoF parameters for the short waves are affected by the data of sensors 5 and 6 (underestimation by model) and sensor 6b (overestimation by model). The short wave data of sensors 5 and 6 however show remarkable spikes indicating that the measurement results might be corrupted. At sensor 6b a structural tendency for low short wave height is found in the data compared to nearby other sensors, which is remarkable, but possibly caused by bed level changes in the nearshore zone. The differences between model and data for these sensors affect the scatter index substantially. Similarly, the scatter index of the infragravity waves seems to be largely affected by sensor 5 data; also here remarkable data spikes are found (see Figure 3-9). It is found that the correlation between observations and model results would have been better when outliers and unrealistic offsets are being filtered out.

In general, while considering the presence of some data inconsistencies, the 1D XBeach models performed reasonably well in terms of nearshore hydrodynamics during this storm event. There is no need for specific recommendations to further improve the BOI settings for the model.

3.2 Validation of morphodynamics (dune erosion)

The morphodynamics in the BOI XBeach model are validated by means of seven validation cases (case 3 - case 9) with available measurement data for 67 profiles in total (of which 57 were usable for quantitative comparisons). All cases are described in detail in separate appendices. For each profile, the post-storm profile and the amount of dune erosion based on the available measurements and XBeach simulation are compared. Dune erosion is quantitatively compared in terms of dune erosion volume and retreat distance, while the profile shape is qualitatively compared. Figure 3-10 and Annex B give an overview of all measured versus modelled dune erosion volumes and retreat distances for all profiles in all morphological validation cases.

The dune erosion volumes in the validation cases were mostly a few m^3/m for the Belgian profiles (case 3) and Egmond aan Zee (case 9) to a few tens of m^3/m for among others the Holland coast in 1976 (case 7). The largest erosion volumes occurred in the Holland 1953 storm case (case 8) and the two Danish profiles (case 5), while the largest change in the profile shape occurred due to the hurricane at Fire Island that resulted in dune breaching and overwash in multiple profiles. The corresponding retreat distances of all cases vary from a few meters up to 20 - 30 m.

From the field validation cases, it is concluded that the 1D BOI-version of XBeach, in general, is reasonably well capable of reproducing observed nearshore bed level changes and dune erosion during storm events. Figure 3-10 shows that the 1D BOI XBeach model resulted in dune erosion volumes and retreat distances that are roughly in the same order of magnitude as measured and that generally are close to the measurements. The overall goodness of fit is quantified in Table 3-5. The number of profiles for which the dune erosion volume is underestimated by XBeach (28x) balances the number of profiles for which the dune erosion volume is overestimated (29x). The bias of the dune erosion volume is 0.9 m^3/m (overestimation) and the bias relative to the mean of the measured values is 3% (Table 3-5). The dune erosion volumes are scattered around the 1:1 line with an overall RMSE of 10 m^3/m, corresponding to a scatter index of 24% (Table 3-5).

Generally, the profile shape is reproduced quite reasonable and the occurrence of dune breaching and overwash is correctly modelled for hurricane conditions at Fire Island. However, a difference between observed and modelled dune erosion is that the post-storm dune foot is located somewhat higher in XBeach than in the measurements for case 6 (Langeoog, Germany) and 7 (Holland coast, 1976 storm). Hence, multiple profiles with a too high XBeach dune erosion volume have an underestimation of the dune retreat distance, as discussed per individual case below and in the discussion section. As a result, a larger number of profiles shows an underestimation by XBeach for the dune retreat distance than an overestimation and the retreat distance had a bias of -1.5 m and a relative bias of -21%, as discussed in the discussion section 4.2.3.

The full individual results, per field case, are presented in more detail in the appendices of this report. A short summary of the results and main discussion points per case is provided in the next sections.

Table 3-5 Goodness of fit indicators for dune erosion for all profiles of all morphological cases together.

	RMSE	Scatter index	Bias	Relative bias
Dune erosion volume [m^3/m]	10.0	0.24	0.9	0.03
Dune retreat distance [m]	3.3	0.37	-1.5	-0.21

From the field validation cases, it is concluded that the 1D BOI-version of XBeach is well capable of reproducing observed nearshore bed level changes and dune erosion during storm events:
The overall bias of the modelled dune erosion volumes is encouragingly small, 0.9 m^3/m, with a corresponding relative bias of 0.03. The overall RMSE is 10 m^3/m (absolute), with a corresponding scatter index of 0.24 (relative).

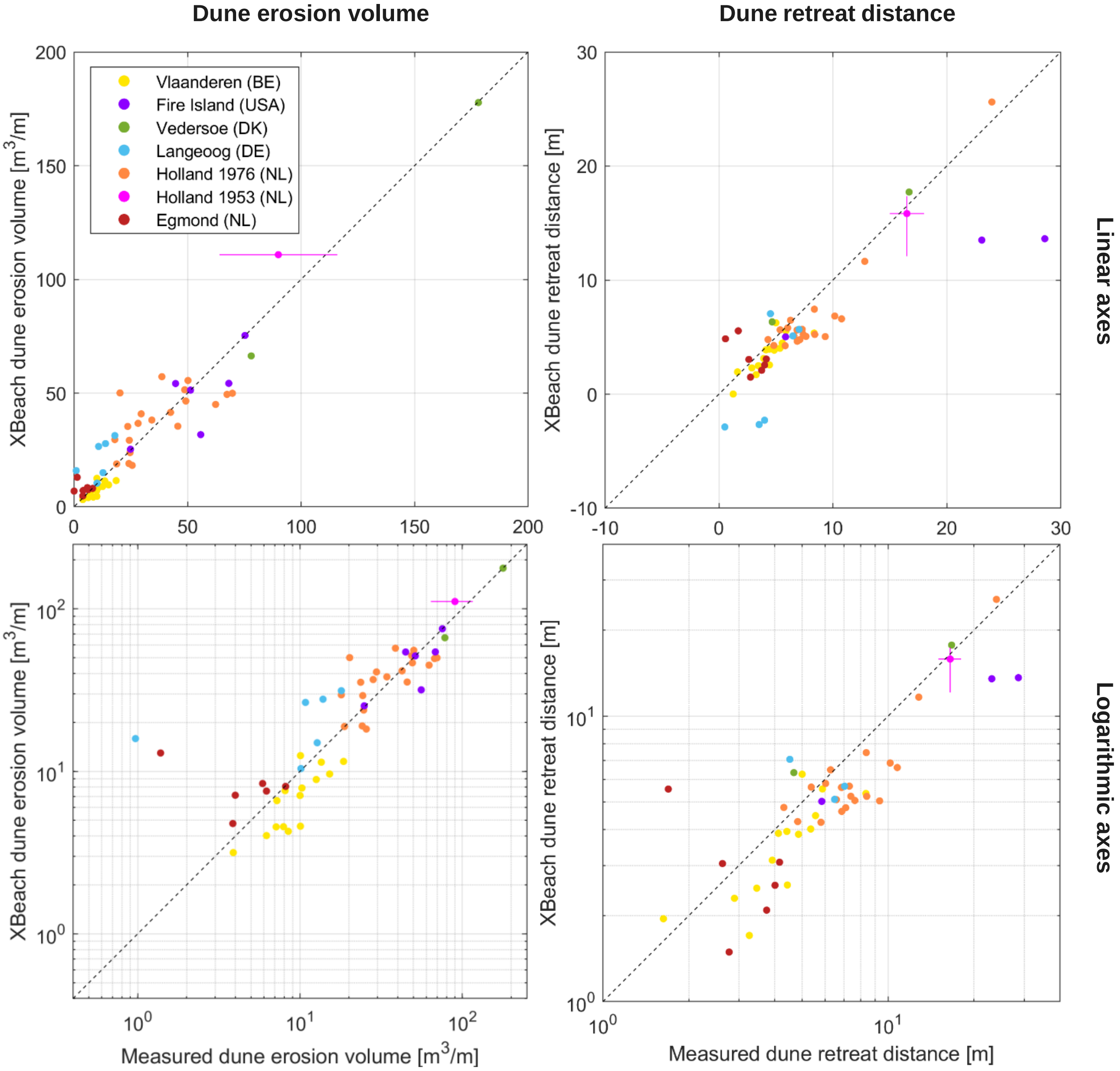


Figure 3-10 Overview of measured and modelled dune erosion volume above maximum storm surge level (left) and dune retreat distance (right) in all morphodynamics field cases. Linear axes on top, same figure with logarithmic axes at the bottom (without values <0.4). For Holland 1953, an uncertainty band is shown as pink lines since no exact observed dune erosion values are known (horizontal lines show the value range) and the elevation at which the retreat distance is measured is uncertain (vertical line gives XBeach values at different elevations). Note that the retreat distance is measured at different elevations for different cases. The dashed line indicates a perfect 1:1 relationship.

3.2.1 Case 3: Flemish coast, Belgium

Dune erosion amounts in case 3 were relatively small, but well reproduced by XBeach. The dune erosion due to the Saint Nicholas storm in 2013 along the shallow and gently sloping Belgian coast was limited to on average 10 m^3/m (min. 4 m^3/m, max. 19 m^3/m) for the 15 profiles that are analysed (Figure C-31 for locations), and the retreat distance to 4.3 m (min. 1.2 m, max. 8.4 m) at one meter above storm surge level. In the XBeach simulations, the dune erosion volume and retreat rate were smaller in most profiles; respectively 3 m^3/m and 0.9 m on average, as is visible in Figure 3-10. Note that the difference of 0.9 m in the retreat distance is smaller than the horizontal model resolution of 1 m. As the observed erosion is small, the relative difference between observed and modelled erosion volumes and retreat distance is on average -27% and -22% respectively. If also the dune erosion volume below the maximum storm surge level is taken into account, this difference is closer to zero.

The post-storm storm profile shape produced by XBeach for this case is realistic. Figure 3-12 shows an example of a pre- and post-storm profile for a profile with erosion volumes and retreat distances closest to the average of the 15 profiles. The shape of the XBeach beach and dune post-storm profile closely resembles the measured profile. The dune erosion starts below the maximum storm surge level, generally around TAW[7] + 5.5 m, in both the measured and XBeach profiles. Smoothening of the dune cliffs after the storm by machinery before the post-storm profile measurements could have contributed to some small differences between measured and modelled profiles. A small deposition berm below the eroded dune is present in the XBeach post-storm profiles, which is often smaller or even absent in the measured profiles. This could be related to alongshore processes that are not incorporated in the 1D XBeach model. Below the deposition berm, the XBeach profiles remain quite stable: the bars do not show strong migration and no unexpected profile shape changes occur. As far as the measured profiles reach, this is in line with the measurements.

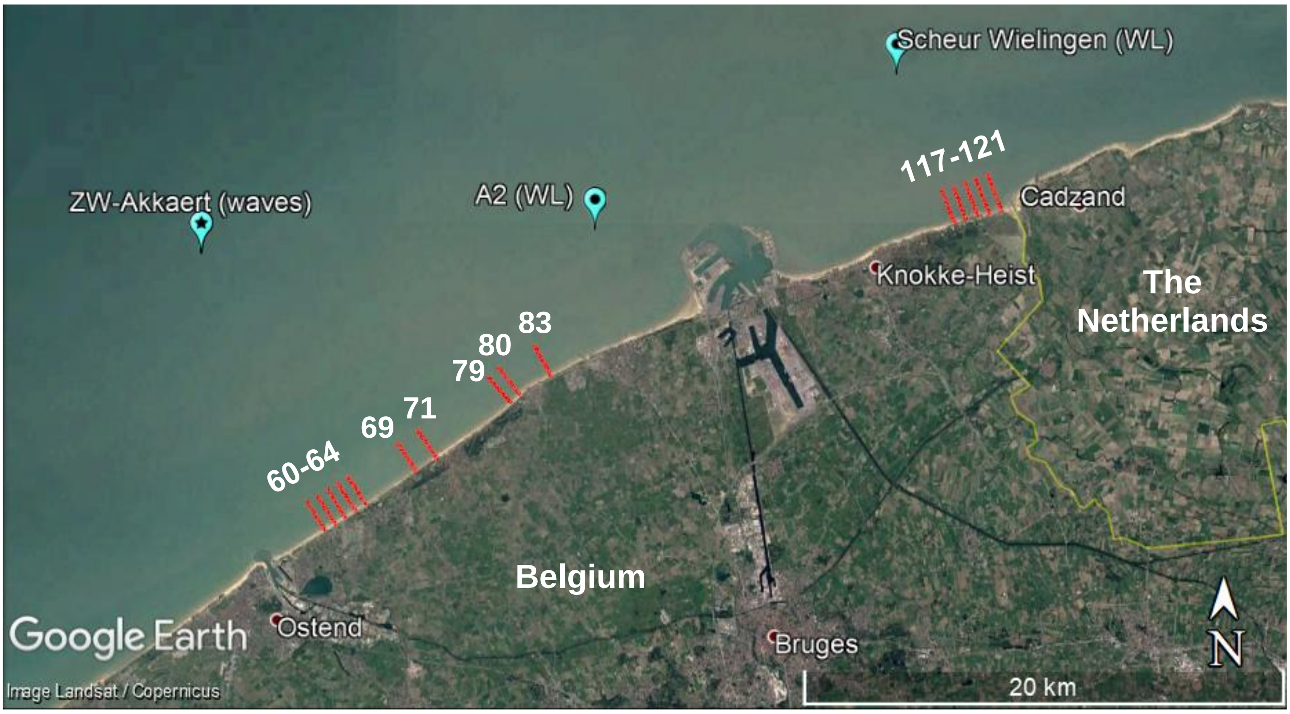


Figure 3-11 Overview of the location of the cross-shore profiles along the Flemish coast in Belgium that are used in the morphological validation.

The dune erosion volume and retreat distances varied somewhat alongshore between the profiles in both the measurements as the XBeach simulations. This can be related to among others variation in the initial profiles and grain size variation. Figure 3-13 shows the relation between the applied D_{50}-values and the measured and modelled dune erosion. The trend in the measured and modelled dune erosion volumes and retreat distances are similar, although the data is scattered and the underestimation by the model results in a bias. The dune erosion volume does not show a clear relation with the grain size, and the retreat distances a decrease with increasing D_{50}. Overall, the similar trend in Figure 3-13 indicates that the current degree of grain size dependence in de model (with $\alpha D_{50} = 0.4$) is fine.

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[7] *TAW = 'Tweede Algemene Waterpassing', the local reference level for elevations in Belgium, corresponding with the average sea level in Oostende during low tide. TAW ≈ MSL - 2.33 m.*

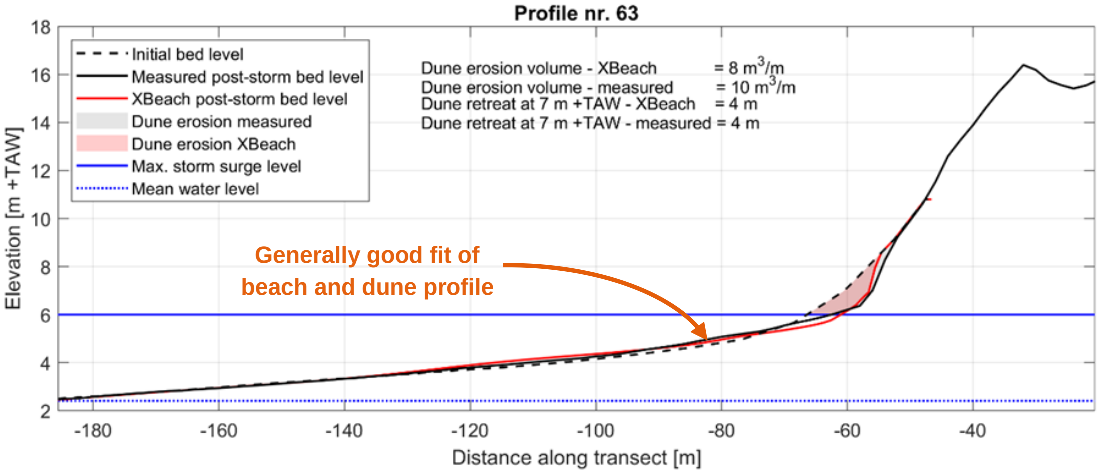

Figure 3-12 Example of a cross-shore transect of case 3 (Flemish coast, Belgium) before and after the Saint Nicholas storm according to the measurements and XBeach 1D simulation, including dune erosion volumes and retreat distances. This profile has dune erosion volumes and retreat distances close to the average of all 15 profiles in this case. Note: TAW ≈ MSL -2.33 m.

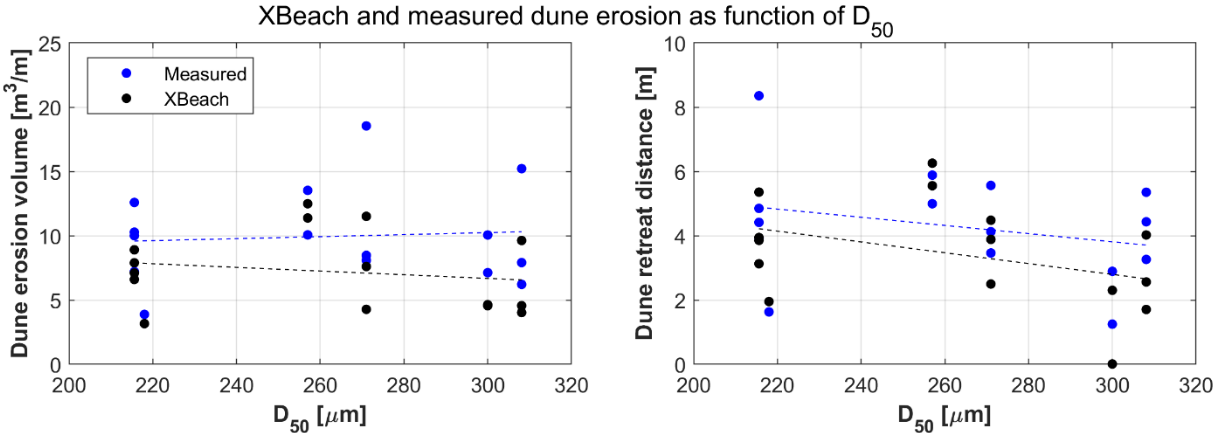

Figure 3-13 Grain size dependence of dune erosion along the Belgian coast (case 3): modelled XBeach (black dots) and measured (blue dots) dune erosion volumes and retreat distances as function of the D_{50}. The dashed lines are linear trendlines.

3.2.2 Case 4: Fire Island, New York, USA

Case 4 is an outlier regarding the local conditions: the profiles are relatively steep, with low dunes and a very coarse grain size, compared to the Dutch coast (D_{50} = 400 µm). Moreover, the hurricane storm conditions resulted in very high waves of 10 m high and much dune erosion. During this storm, the dunes in 3 of the 6 profiles (Figure 3-14 for locations) breached and vanished (inundation regime), while overwash occurred in another profile where the dune was not entirely eroded (overwash regime), and the last two profiles with higher dunes only experienced dune front retreat (collision regime). All profiles are shown in Figure 3-15.

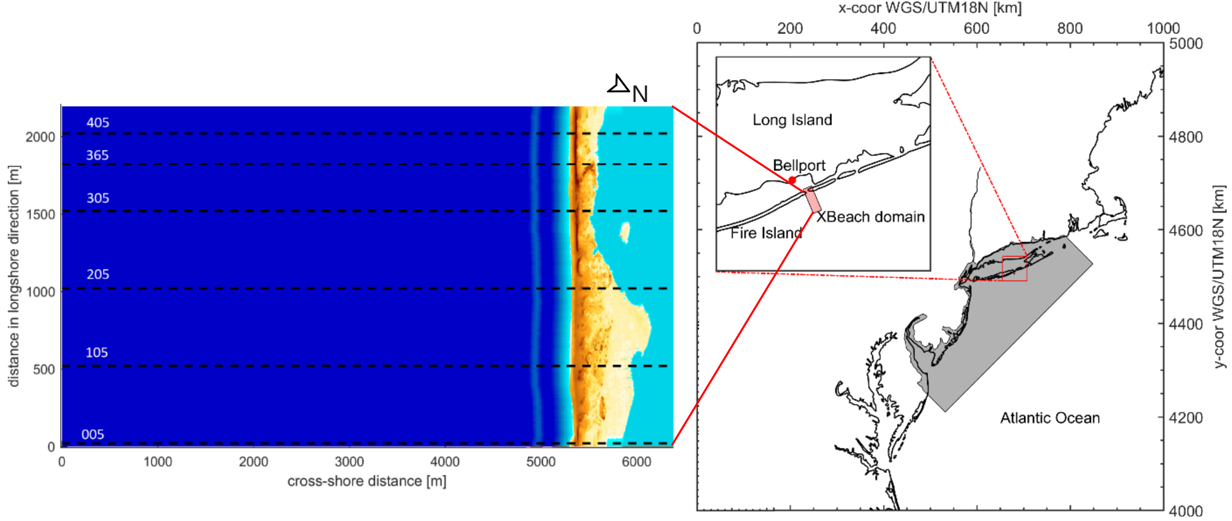

Figure 3-14 Overview of the location of the cross-shore profiles at Fire Island that are used in the morphological validation.

The *occurrence* of breaching and overwash is correctly modelled by XBeach, and the corresponding dune erosion volumes are reproduced reasonably well. For transects 005, 105 and 205, measurements show that the dune is completely eroded by the storm, which is also predicted by the model (Figure 3-15D, E and F). Since the dune above the maximum storm surge level is eroded completely in both the measured profiles as the XBeach simulation, erosion volumes are similar. In the overwash profile 305, the lowering of the dune crest is well captured by the model, but the dune retreat – and therefore the dune erosion volume - is underestimated (Figure 3-15C).

In addition, XBeach showed that it is also able to capture the erosion of the coarse-grained dunes for the two profiles with higher initial dunes. For one of the profiles, the post-storm dune profile is almost exactly the same as measured, while the erosion is underestimated by XBeach for the other profile (Figure 3-15A and B). Nonetheless, the post-storm profile shape shows good resemblance with the observations. The post-storm profiles of XBeach are similar for both profiles as expected based on the similarity in their initial profiles and boundary conditions, but in the measurements one of the profiles showed stronger erosion. The reason for this is unknown, but probably is related to factors that are not included in XBeach, such as local geotechnical variations in dune strength or uncertainties in the initial profile.

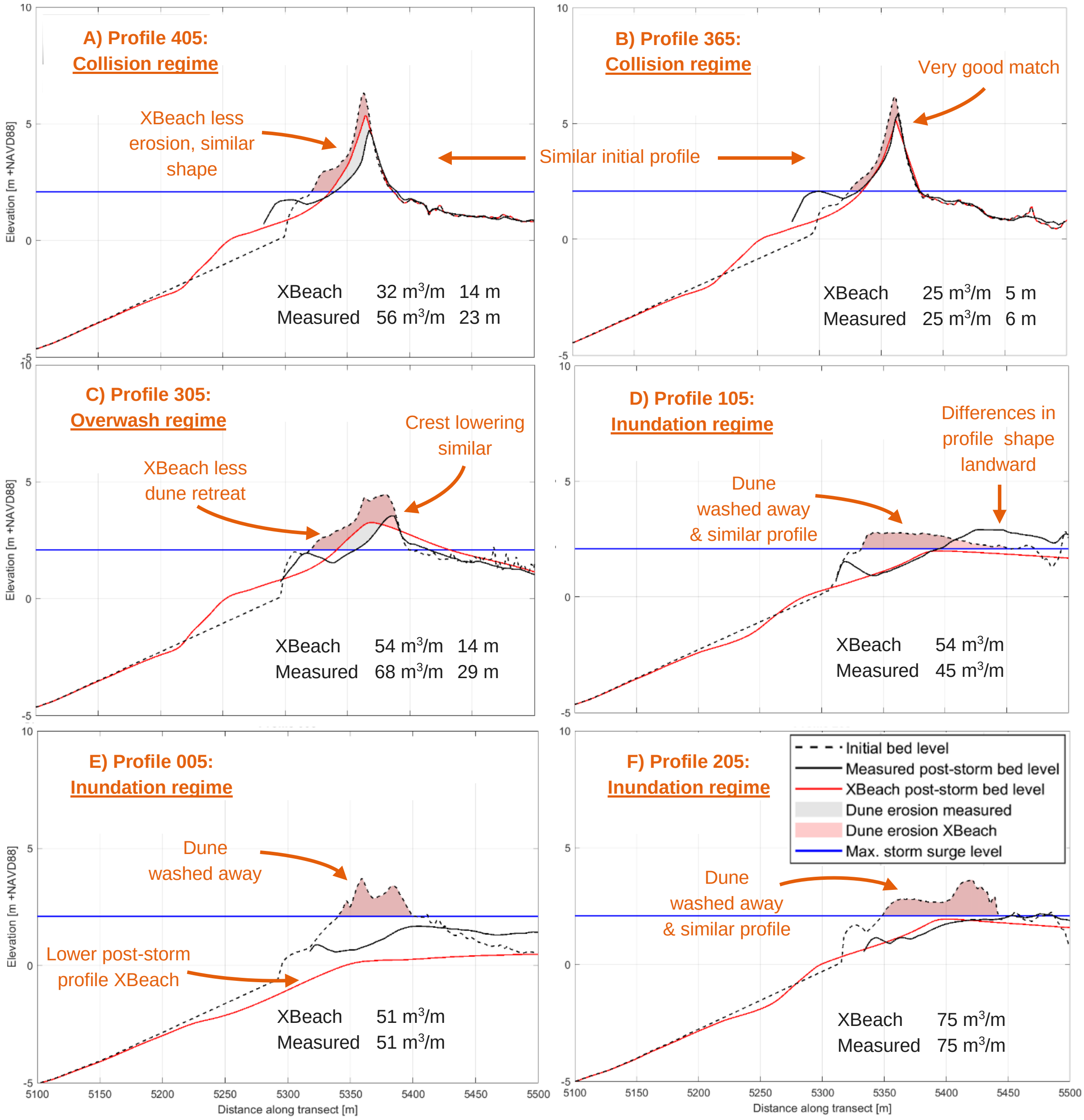

Figure 3-15 Overview of the six cross-shore transects of case 4 (Fire Island, USA) before and after the hurricane according to the measurements and XBeach 1D simulations, including dune erosion volumes and retreat distances (if applicable).

3.2.3 Case 5: Vedersoe, Denmark

Case 5 (Vedersoe, Denmark) is a good example of a case in which relatively large amounts of dune erosion are very well reproduced with XBeach, as is visible in Figure 3-17. The location of the two profiles is shown in Figure 3-16. The 30 m wide berm high on the beach in profile 2 (right in Figure 3-17) resulted in significantly less erosion above the storm surge level in both the 'measurements' and XBeach compared to profile 1 (left in Figure 3-17). In both cases, dune erosion starts below the maximum storm surge level, generally around MSL +1 m, in both the measured and XBeach profiles. Overall, this case not only shows that XBeach is capable of producing realistic dune erosion volumes and retreat rates in a case with much dune erosion, but also that its response to different profiles is correctly simulated.

It should be noted that for both profiles, the actual measurements of the pre-storm profile only reach up to about MSL +5 m, and the profile above is approximated. Hence, the erosion volumes are a reasonable estimation rather than real observations. This did not affect the dune retreat distance that is measured at MSL +5 m.

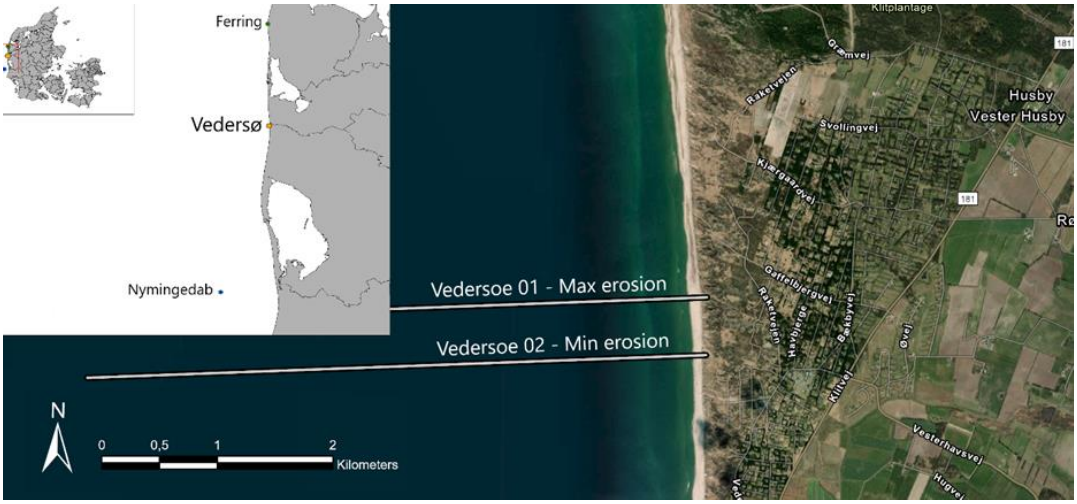

Figure 3-16 Overview of the location of the cross-shore profiles near Vedersoe (Denmark) that are used in the morphological validation. Adapted from Kystdirektoratet (2021).

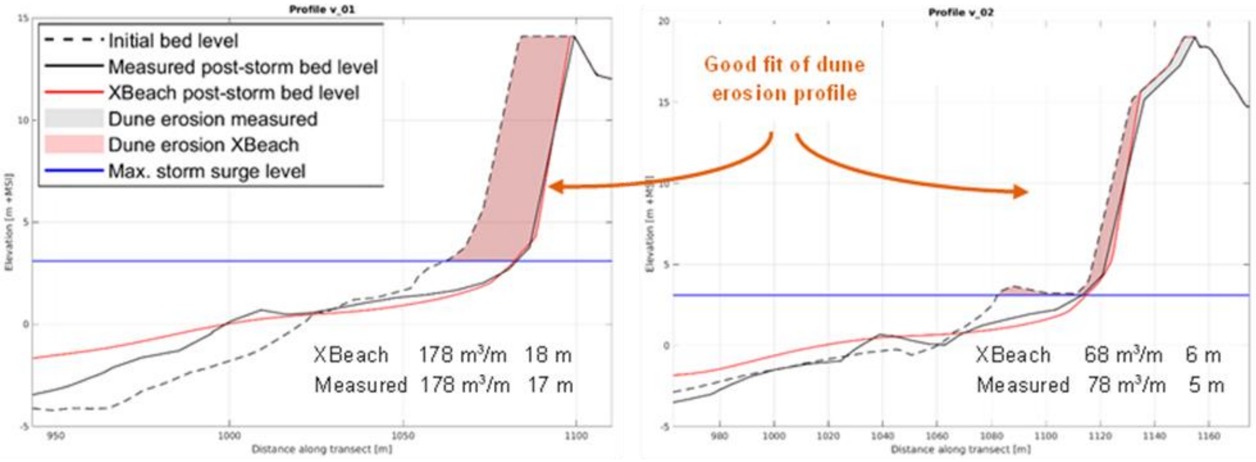

Figure 3-17 The two cross-shore transects of case 5 (Vedersoe, Denmark) before and after the storm according to the measurements and XBeach 1D simulation (applying 250 µm), including dune erosion volumes and retreat distances.

A point of discussion in this case is the representative grain size, which is in the range of 200-400 µm based on Saye and Pye (2006) and Clemmensen et al. (2006). In the XBeach model, a best-estimate grain size of 250 µm is used as substantiated in the model setup in appendix 5. The results are compared to a similar simulation with a minimum and maximum D_{50} of 200 and 400 µm. Overall, the D_{50} of 250 µm results in dune erosion values closest to the measured volumes. The maximum D_{50} of 400 µm results in underestimation of dune erosion (-43 m^3/m for profile 01, -36 m^3/m for profile 02), while the minimum D_{50} of 200 µm results in overestimation of dune erosion (+22 m^3/m for profile 01, +3 m^3/m for profile 02). Hence, the uncertainty in dune erosion volume related to the grain size is up to a few tens of percentages.

3.2.4 Case 6: Langeoog, Germany

Case 6 is an example with relatively little dune erosion that was not very well reproduced by XBeach compared to the other cases. At the Wadden Island Langeoog in Germany, 6 profiles close to each other were used for the validation. A beach nourishment was present in 3 of the 6 profiles. The location of the profiles is shown in Figure 3-18.

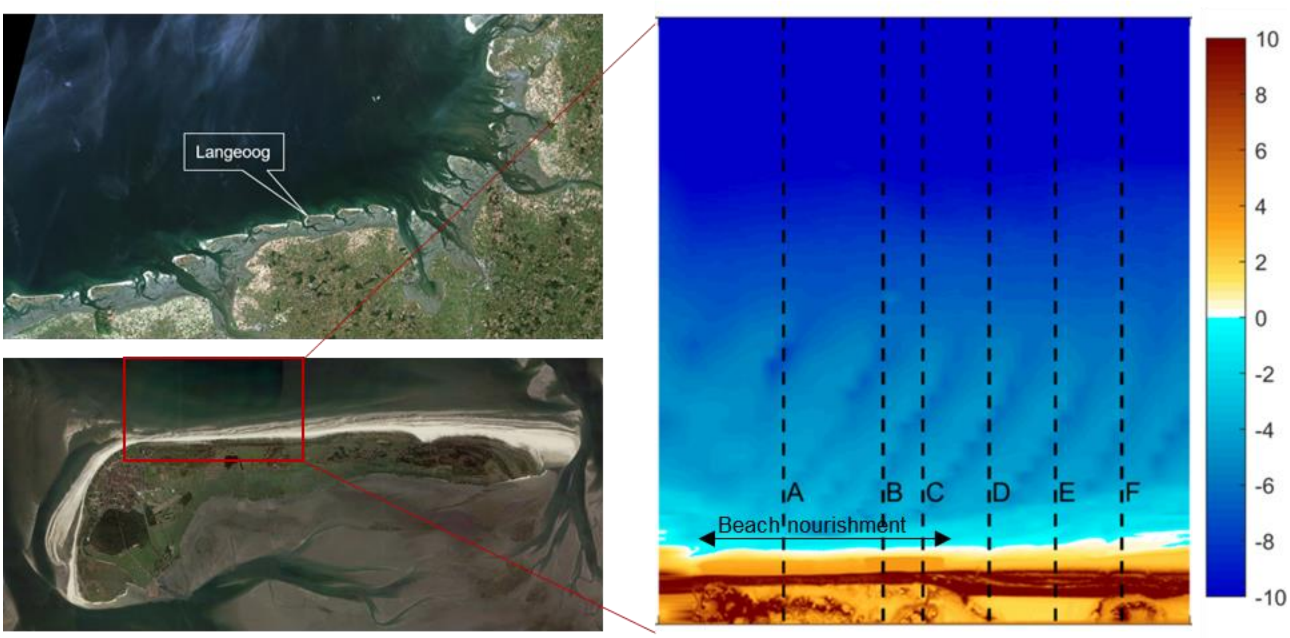

Figure 3-18 Overview of the location of the cross-shore profiles at Langeoog (Germany) that are used in the morphological validation. Adopted from Hillman et al. (2021).

An example of a modelled and measured cross-shore profile through the nourishment is shown at the left in Figure 3-19. The erosion of the nourishment is smaller in XBeach than in the measured profiles, but the profile shape is similar. Erosion of the dune is limited in both the measurements and XBeach, but occurs much higher in XBeach (starting about MSL + 2 m) than in the measurements. In line with the erosion higher in the dune, the dune foot in XBeach was elevated during the storm, probably due to deposition of eroded dune sediment, more than in the measured profiles. This stronger elevation of the dune foot resulted in negative dune retreat distance at MSL + 5 m. In the three profiles without a nourishment, slightly more dune erosion occurs, which is again observed higher in the profile in the XBeach simulations (see right side of Figure 3-19 for an example). In these cases, the dune retreat distances at MSL + 5 m show smaller errors.

The difference in erosion volume for the profile with nourishment is largest for the profile shown at the left in Figure 3-19: 15 m^3/m. For the other profiles with nourishment this difference is only 0 to 2 m^3/m. For the profiles without nourishment, the difference is 13 to 16 m^3/m (overestimation of a factor two due to the small measured erosion volumes), but much closer to zero if erosion below the storm surge level is also included. Overall, the Langeoog profiles are among the profiles with the largest absolute as well as relative differences in dune erosion of all morphological profiles in this field validation report: XBeach performed worst for this case.

The difference in the post-storm nourishment elevation may partly be due to the timing of the pre-storm profile: the pre-storm profile was measured just after the nourishment, about two months before the storm, and hence probably overestimates the actual pre-storm bed level that is used as model input. As a consequence, the hydraulic forcing on the dune in XBeach is off, and eroded dune sediment stays higher in the profile than in reality, resulting in differences in the post-storm profile.

Another point of discussion in this case is that alongshore processes seem to play an important role in the morphodynamics (including dune erosion) at the Langeoog case. For example, the local presence of the nourishment results in alongshore gradients. In the measurements, there does not seem to be a sediment balance in each cross-section: sediment seems to be lost in alongshore direction. The oblique wave attack during the storm – which is not included in the 1D model - probably resulted in a substantial longshore transport towards the East. Since these alongshore processes are not included in the 1D XBeach model, the model could not exactly reproduce the measured post-storm profile.

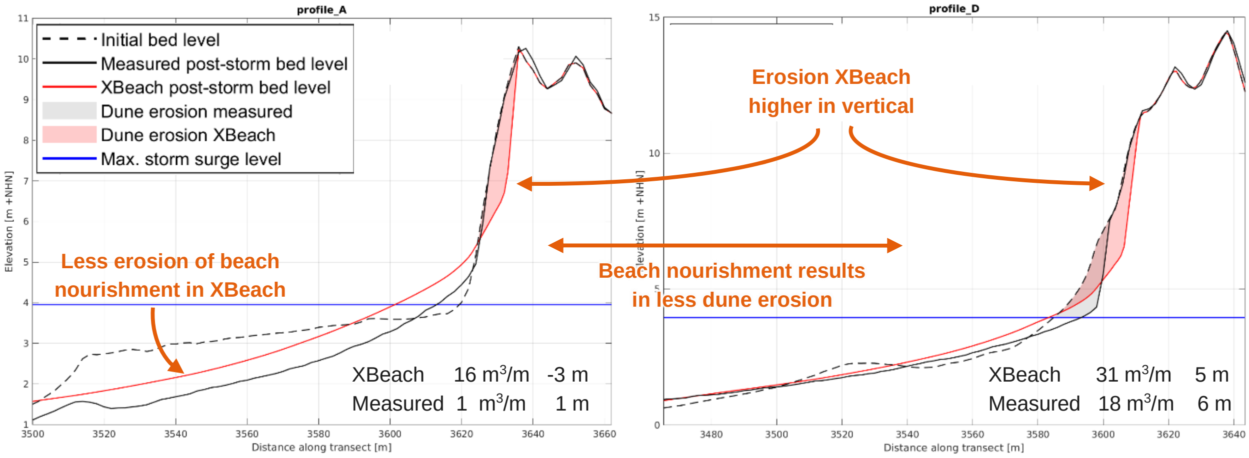

Figure 3-19 Two examples of cross-shore transects of case 6 (Langeoog, Germany) before and after the Saint Nicholas Storm according to the measurements and XBeach 1D simulation, including dune erosion volumes and retreat distances. Left: Profile A with a beach nourishment, right: Profile D without beach nourishment.

3.2.5 Case 7: Holland coast (NL), 1976 storm

The storm in 1976 in case 7 resulted in dune erosion volumes of several tens of m^3/m along the coast of Holland that were quite well reproduced by XBeach. In total 30 pre- and post-storm profiles of the Holland coast were analysed. The location of all profiles considered in this case is shown in Figure 3-20. Pre-storm profiles were extended at the landward and seaward side with JarKus-data, and post-storm profiles were extended into the dunes with a 1:1 slope. Ten profiles were only visually analysed and not included in the dune erosion volume and retreat distance calculations, because the post-storm profile was not measured past the new dune foot (break in the profile slope) resulting in unacceptably large uncertainties in the post-storm profile.

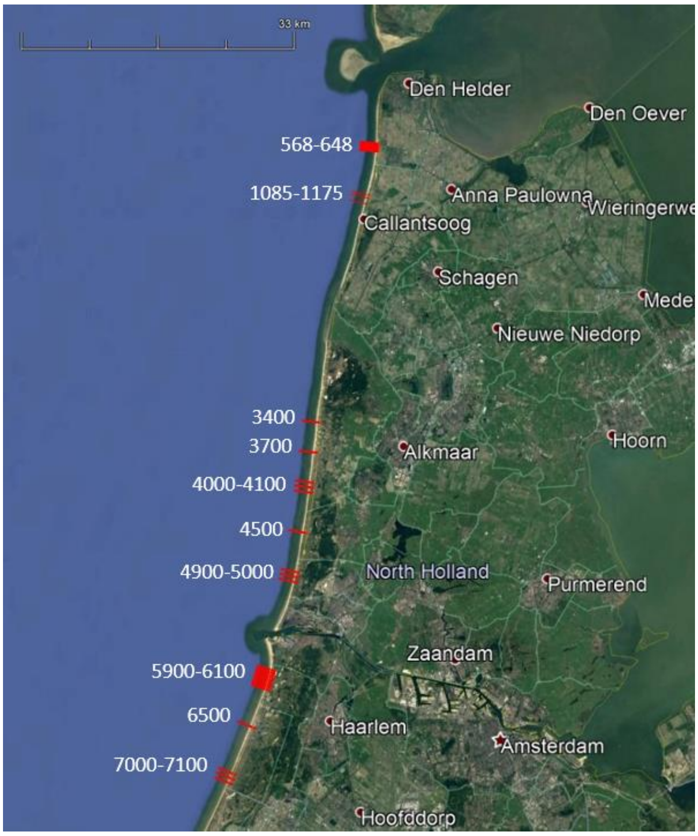

Figure 3-20 Overview of the location of the cross-shore profiles along the Holland coast (1976 storm case) that are used in the morphological validation.

Overall, the dune erosion volumes above maximum storm surge level were overestimated by XBeach by 13% on average (1.37 m^3/m with a std.dev. of 12 m^3/m) and the retreat distances at NAP + 4 m were underestimated by XBeach by -19% (-1.5 m) on average, as is also visible in Figure 3-10. The number of profiles for which the dune erosion volume is overestimated by XBeach is in balance with the number of profiles with an underestimation.

Figure 3-21 shows three examples of erosion profiles in case 7: one with a good match, one for which XBeach has a larger dune erosion volume than based on the measurements, and one for which XBeach has a smaller dune erosion volume. Regarding the profile shape, the lowest point where dune erosion starts is generally the same in the modelled and measured post-storm profile, but the XBeach post-storm dune front seems slightly steeper than in the measurements and the level of the bottom of the steep dune face in the almost all XBeach post-storm profiles is located somewhat higher in the vertical than in the measured post-storm profile. The latter is a main cause for the underestimation of the dune retreat distances at 1 m above the maximum storm surge level that is observed for most profiles. Therefore, the dune erosion volume is considered to be a more robust indicator for the model performance for the purpose dune safety assessment.

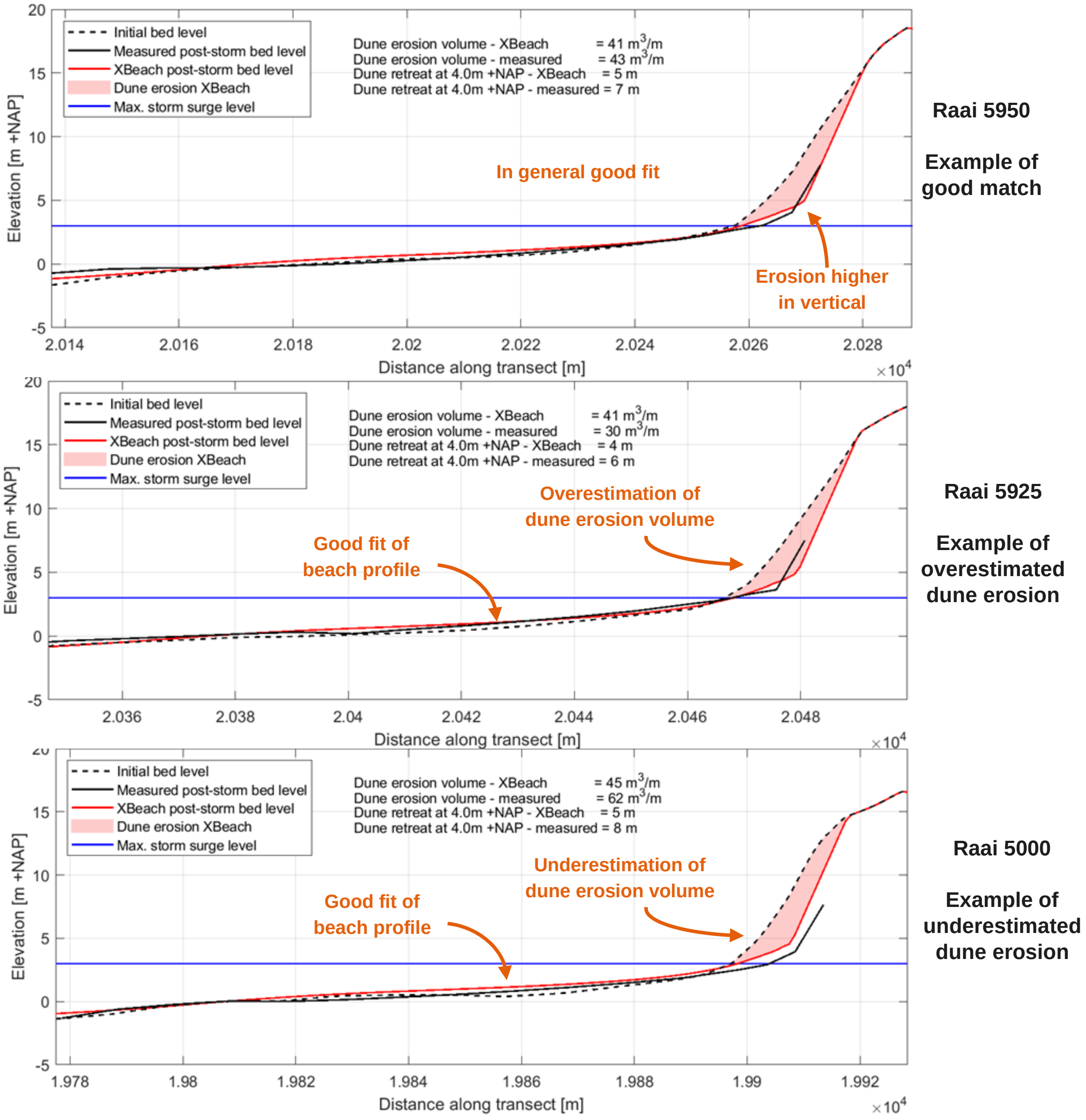

Figure 3-21 Three typical examples of cross-shore transects of case 7 (Holland, 1976) before and after the storm according to the measurements and XBeach 1D simulation, including dune erosion volumes and retreat distances: a profile with a good fit (top), a profile with a larger dune erosion volume in XBeach (middle) and a profile with a smaller dune erosion volume in XBeach (bottom).

Overall, taking the uncertainties related to the profiles (especially the extrapolation of the measured post-storm profiles) and the simplifications in the boundary conditions (same forcing used for all profiles) into account, the BOI 1D XBeach model performs well regarding the dune erosion: the volumes are not highly biased if compared to the measured profiles.

Along the coast, the grain size varies, and hence different D_{50}-values are used for the different profiles. Figure 3-22 shows the relation between the applied D_{50}-values and the measured and modelled dune erosion. Surprisingly, the ‘measured’ dune erosion volumes seem to increase on average with the D_{50}, although the scatter is large. The dune retreat distances tend to decrease on average with increasing D_{50}, as expected. Both trends are also visible in the XBeach dune erosion results, despite a small difference in the slope. This similar trend in Figure 3-22 indicates that the current degree of grain size dependence in de model (with $\alpha D_{50} = 0.4$) is fine for this field case.

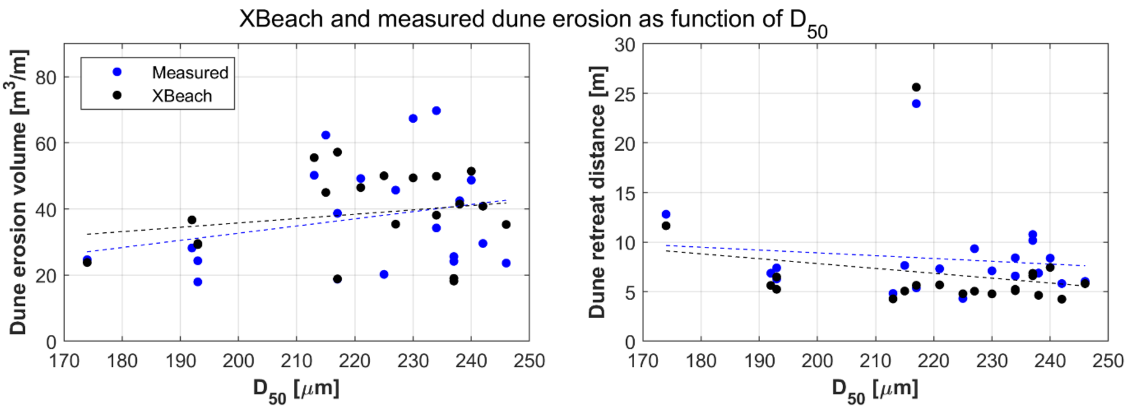

Figure 3-22 Grain size dependence of dune erosion along the Holland coast (case 7): modelled XBeach (black dots) and measured (blue dots) dune erosion volumes and retreat distances as function of the D_{50}. The dashed lines are linear trendlines.

3.2.6 Case 8: Holland coast (NL), 1953 storm

Validation case 8 differs from the other validation cases, since it is a more indicative/general validation with the focus on the order of magnitude of dune erosion due to large limitations in available data. However, it is still a valuable case, because the 1953 storm resulted in the largest recorded dune erosion volumes along the Dutch coast. In this case, a 1D BOI XBeach model is set up for the reference profile of the Holland coast with an average D_{50} of 225 µm. The hydrodynamic boundary conditions representative for the Holland coast between Hoek van Holland-Scheveningen were derived from a combination of reanalysis data (ERA5-data) and literature. No pre- and post-storm profiles were available, so the XBeach dune erosion is compared to a few numbers reported in literature.

Overall, the dune erosion for the reference Holland profile matched very well with the reported numbers (Figure 3-23). The dune erosion volume in the XBeach simulation was 111 m^3/m. This is within the reported range in observed dune erosion volumes of 64 - 116 m^3/m (mean of 90 m^3/m plus and minus std.dev. of 26 m^3/m) for the Dutch coast (Van Thiel and De Vries, 2009). The XBeach dune retreat distance is compared to an approximated change in dune foot location due to the 1953 storm of 15-18 m for Hoek van Holland-Scheveningen, which is derived from a figure with alongshore variations in dunefoot positions over multiple decades in Ruessink & Jeuken (2002). Since the elevation of the dune foot is not reported, the dune retreat distance in XBeach is measured at three different elevations, resulting in a retreat distance of 12, 16 and 17 m. This is very close to or within the range derived from literature.

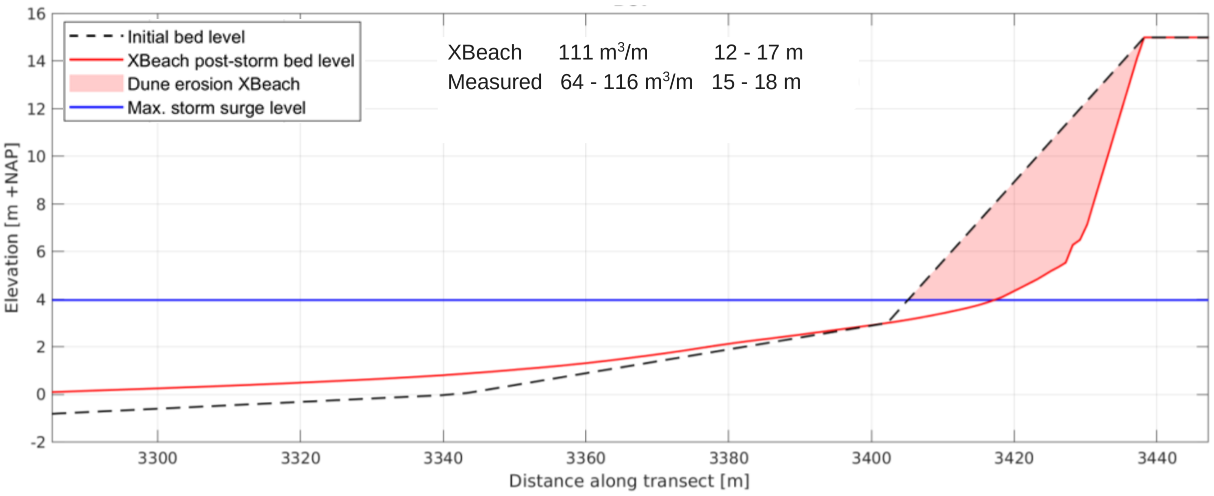

Figure 3-23 Representative cross-shore transect of the Holland coast in case 8 before and after the 1953 storm according to the XBeach 1D simulation, including dune erosion volumes and retreat distances.

3.2.7 Case 9: Egmond aan Zee, NL

Near Egmond aan Zee (the Netherlands) along a 3 km long stretch of the coastline measurements have been performed during a winter storm in January 2019 (see Figure 3-24). For seven different cross-shore profiles the amount of dune erosion during storm has been derived by measuring pre- and post-storm profile height (bed level). These measurements supplement to the hydrodynamic measurements, as described in section 3.1.3. During the measurement period the amount of observed dune erosion near Egmond was limited to a few m^3/m (near the dune foot).

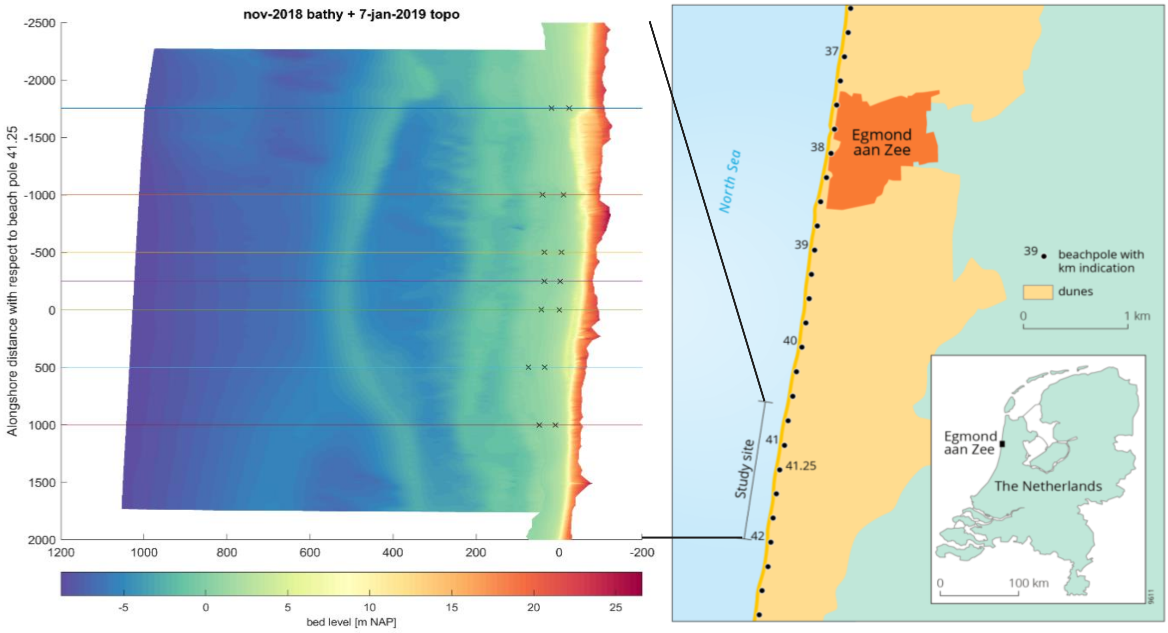

Figure 3-24 Overview of the location of the cross-shore profiles near Egmond aan Zee that are used in the morphological validation. The origin of the local coordinate system used (left panel) is at beach pole 41.25. The cross-sections are referred to by their local y-coordinate. Right panel adopted from Ruessink et al. (2019).

For this field case it is found that the modelled dune erosion volumes near Egmond are well in line with the observed dune erosion. The observed and modelled post-storm dune erosion profiles are similar and the absolute difference in dune erosion is small on average; except for the two northern profiles where a slight overestimation by XBeach is found. The relative differences between modelled and observed, however, are quite large for this specific case: on average ~30%. This is explained by the fact that only small absolute erosion values are considered in this case: max. 3 m^3/m (volume) and 4 m (dune retreat distance). Here it also should be noted that the measured retreat distances (in the order of meters) are close to the model resolution near the dune front (1 m) and hence are at the limit of the model's finest level of detail.

For the two northern profiles larger differences are found between modelled and observed erosion volumes and dune retreat distances: XBeach results in erosion volumes of 7-13 m^3/m and retreat distances of 5-6 m; compared to small dune erosion (resp. ~1 m^3/m and ~1 m) in the measured profiles. These absolute differences automatically result in extremely large relative differences. These differences are primarily related to alongshore processes during the storm (which as not modelled in a 1D model). In the measured profiles it is noted that net sedimentation is found at the beach (near NAP level), which results in (extra) wave damping and less erosion; the model does not capture this.

In general, it is noted that reliable information on the initial situation (in terms of bathymetry and topography) becomes increasingly more important when considering small dune erosion volumes. Specifically in this case it is concluded that bed level changes between the measurement of the initial bathymetry (two months before the storm) and the start of the storm could have contributed to (some of) the differences between modelled and measured data.

The **overall conclusion** from the morphodynamic validation – also considering the explainable differences for the northern transects – is that XBeach is sufficiently well capable of simulating dune erosion for more frequent storm event during which only limited erosion is found. This allows for applications other than dune safety assessments for normative conditions.

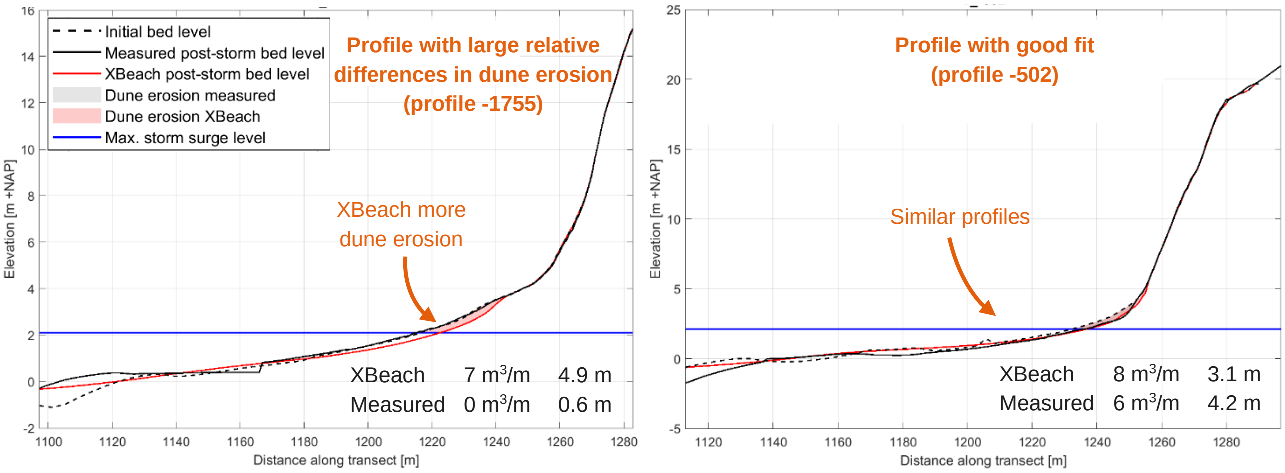

Figure 3-25 Examples of cross-shore transects of case 9 (Egmond aan Zee, NL) before and after the winter storm according to the measurements and XBeach 1D simulation, including dune erosion volumes and retreat distances. Left: profile with large relative differences in dune erosion between measured and modelled, right: profile with a relatively good fit. The kink in the measured post-storm profile at the left (around x = 1165 m) is due to merging of post storm bathymetry and topography.

4 DISCUSSION

This chapter discusses the model results of the field validation cases. In contrast to Chapter 3, this chapter focusses on describing and (if possible) explaining the most notable overall observations from all cases. The discussion section aims at identifying the relevant joint conclusions across all field cases in order to validate the BOI-version of XBeach for both hydrodynamic processes and morphodynamic processes. First, the representativeness of the field cases is discussed. Next, the overall performance of the model is analyses in more detail. And lastly, model uncertainties are discussed. The latter will, in addition to the final version and setting of the XBeach model itself, form an explicit input for the subproject ‘development of the probabilistic model XBeach’.

4.1 Representativeness of field validation cases

Variety of hydrodynamic field validation cases

For the validation of the hydrodynamics, the number of available validation cases is limited to three out of nine, with two cases with measurements along one cross-shore profile (Case 1: Schiermonnikoog, NL and Case 2: Saint Trojan, France) and one case with two measurements along seven profiles (Case 9: Egmond aan Zee, NL). Both profiles of case 1 and case 2 are representative of the Wadden coast due to their long profiles with a gentle slope and relatively shallow nearshore. Case 9 represents the steeper Holland coast, where storm conditions are generally less energetic than along the Wadden coast.

For the hydrodynamic validation, the focus is on the infragravity waves, because of its importance for dune erosion and because it is not calibrated on the lab scale. For this, the wave conditions during the storm are most important. Both case 1 and 2 have a high offshore significant wave height (over 7 m offshore). Especially in the French case (case 2), very high swell waves of 7 to 10 m were measured offshore, which resulted in very high nearshore long waves of 1.5 - 2 m. The Egmond aan Zee case represents a frequently occurring storm with offshore significant wave height of 5 m. Since the storm characteristics of the hydrodynamic validation cases cover low as well as high storm waves, they are considered representative for this purpose.

Variety of morphodynamic field validation cases

For the validation of the morphodynamics with the focus on dune erosion, seven of the nine field validation cases could be used, with in total 67 cross-shore profiles. Despite the lack of field measurements for normative conditions, these cases are still representative for different types of storm conditions: 1 case represent a frequently occurring storm with moderately high maximum water levels and waves (case ‘Egmond aan Zee’), 3 of the 6 cases represent storms with moderately high maximum water levels and high waves (case ‘Schiermonnikoog’, ‘Vedersoe’ and ‘Holland 1976’), 2 represent storms with very high maximum water levels (case ‘Holland 1953’, ‘Langeoog’ and ‘Belgium’) and 1 represents a storm with very high waves (Fire Island case).

Moreover, different types of profiles are covered, from more gentle Wadden coast type of profiles (such as the Langeoog case) to steeper Holland coast type of profiles (such as the Holland 1953 and 1976 storm cases). The Fire Island and Vedersoe case and to a lesser extent the Belgian case stand out due to their steeper slope in the 100-200 m in front of the dunes, which is less representative for the Dutch coast. The Fire Island case also is an outlier considering the low dunes that in 4 of the 6 profiles breached or experienced overwash.

Finally, the grain size is also important for dune erosion and hence the morphodynamics validation of the BOI-version of XBeach. Special attention goes to the BOI-setting αD_{50} (see Section 4.2.3) that has more impact the more the D_{50} deviates from 225 µm. In the calibration data, the variation in D_{50} was very limited, but in the field validation cases, the variation in grainsizes is larger. The D_{50} ranges from 174 µm along the Holland coast (a profile in the 1976 case) to even 400 µm in the Fire Island case, with most profiles having a D_{50} between 200 and 250 µm. Note that a D_{50} of 400 µm is not representative for a natural Dutch situation, but it is nevertheless important to have insight in the performance of XBeach for more extreme grain sizes regarding coastal design purposes.

Extreme versus more frequent storm events

As explained in Section 1.2.1, the validation of the hydrodynamics and morphodynamics in the BOI-version of XBeach in task #04 and #06 of phase 1 of the project is ideally based on field cases in which the impact of extreme (normative) storm conditions on the Dutch sandy coast was measured, while for task #05 more frequent events are considered. However, extreme storm conditions as well as available and usable field measurements are rare. Therefore, interpreted extrapolation from a limited number of less extreme cases and/or cases in another (international) setting is required.

Seven field cases for frequent to not-so-frequent and severe storm events were available for the Dutch coast or a comparable setting along the North Sea. This includes the ‘Egmond aan Zee’ case with a return period of roughly one year and three cases (‘Flemish Coast’, ‘Holland Coast (1953)’ and ‘Langeoog’) with high storm water levels with return periods of over a hundred up to maximal a few thousand years for the Dutch coast (as explained in Section 2.2). This is complemented with two field cases with conditions that were more extreme in a Dutch context regarding the wave heights: the French case (‘Saint Trojan’), with relatively high infragravity waves during a storm, and the Fire Island case (New York, USA), with hurricane conditions.

Due to both the limited number of total cases, and the lack of reliable field data for Dutch cases with extreme storm conditions, it was decided to make no strict distinction between extreme and regular storm cases for the purpose of the model validations. On the positive note, as described in Section 2.2, the cases altogether represent a broad variety of characteristics in terms of storm conditions, profile shape, grain size as well as geographical location. Thereby, no substantial performance differences have been identified for different *types* of cases. From this, it is concluded that the validation cases, as a group, show that the BOI-version of XBeach is capable of simulating the impact of storm conditions (dune erosion) for a broad range of input conditions (i.e. regular to extreme storms), for profiles that are typically found along the Dutch coast.

4.2 Performance of the BOI-version of XBeach (in 1D)

Below, the performance of the 1D BOI-version of XBeach will be discussed based on the validation results as summarized in Chapter 3. The goodness of fit between the field measurements and the XBeach results is determined by the model performance itself, the quality of the model input and the quality of the field data for comparison. Although the focus in the next paragraphs 4.2.2 and 4.2.3 is on the model (settings) itself, it cannot entirely be separated from the inaccuracy that is inherent to the validation data. Moreover, the required assumptions for a 1D model generally do not entirely hold in a field case, introducing another potential source of error. The uncertainties in the data and limitations of a 1D model are discussed in paragraph 4.2.1 in more detail.

4.2.1 Impact of model setup and data

Uncertainties in model input and field data

For each case, the potential inaccuracies in the data are discussed in the appendices and Chapter 3. Uncertainties can occur in the model input – the initial bed level, hydraulic boundary conditions and grain size – as well as the field data to compare with such as the water level and post-storm bed level.

In the hydrodynamic cases, a static bed level is used in the simulations to be able to discriminate between effects due to hydrodynamic and morphodynamic processes. In general, this assumption holds for all three cases, but some slight bed level changes in the period between the pre-storm bed level measurements and the storm and maybe also during the storm were observed, at least at the beach in the Schiermonnikoog case. In this case, the measured water level was already converted to the ‘measured’ water depth by using a linear interpolation of the pre- and post-storm bed level, which inherently resulted in a slight offset with the water depths in XBeach based on the static bed level. The small offset in the water depth could also have resulted in small offsets in wave characteristics, which could not be quantified.

Moreover, for the hydrodynamic analysis of the Egmond aan Zee case, offsets in the water level of on average 45 cm were observed between the modelled and observed water level (but remarkably also between adjacent observation points), while the offset in the $H_{m0,\,HF}$ en $H_{m0\ IG}$ are only 1 cm and 4 cm on average. This suggests that the main error source is in the processing of the field data to derive the measured water levels. Hence, the water level offsets of this case are considered not to be representative for the model (in)accuracy itself.

In the morphodynamics cases, the pre- and post-storm bed level did not always cover the entire reach of interest. In the Vedersoe and Holland 1976 case, extrapolation of respectively the pre- and post-storm profiles was needed, introducing an uncertainty in the dune erosion rates. In most other cases, the seaward end of the profile did not run down to the closure depth, so the sediment balance along the transect could not properly be compared. In the Holland 1953 case, no bed level profiles were available at all and only the reference profile and some indicative numbers from literature could be used for dune erosion comparison.

Besides the extent of the profiles, the timing of the measurements could also introduce bed level change discrepancies that are inherently not included in the XBeach results. For example, the pre-storm profiles of Langeoog and Egmond aan Zee were measured about two months before the storm: the bed level probably changed between this moment and the start of the storm, but this was not included in XBeach. For Egmond, where only small dune erosion volumes were measured, an accurate initial bed level is even more important. The same holds for bed level changes after the storm, but before the post-storm measurements, such as potential removal of the erosion cliffs by machinery in the Belgian case.

For the hydraulic boundary conditions, it is attempted to stay as close as possible to the actual storm conditions for example by applying 2D spectra if available. However, in all cases some inaccuracies arise by differences in location (and water depth) between the measurement location and the XBeach offshore boundary location, the conversion of one statistic to another (e.g. $T_p = 1.2 * T_{mean}$) and using hindcast hydraulic conditions (e.g. for Vedersoe and Holland 1976 storm case).

Finally, the grain size influences the dune erosion in XBeach, but in all cases, limited data is available about the representative grain size of the dunes (and beach). In the 1D BOI XBeach-version, one D_{50} and D_{90} are used as input, while in reality, the grain size varies along the cross-shore profile: a grain size measured on the beach may give an overestimation of the grain size of the dunes. For example, for Vedersoe a reported D_{50} of 250 µm has been used, but also a coarser D_{50} of 400 µm is found in literature (which seems to be a bit odd in this context). Using the latter, however, also results in model results that substantially differ from the measured profile changes.

It is difficult to quantify the effect of these inaccuracies in the data on the validation outcomes. However, it is assumed that overall, no consistent bias is introduced by these inaccuracies since these vary from case to case and can result in both over- and underestimations. Taking this into account, the overall, general trends observed in the validation cases together could be assigned to the performance of the model itself.

Limitations of 1D modelling approach

In this validation, all XBeach simulations have a 1D setup, which has some limitations when comparing the results with field data. *It should be noted that these limitations also apply when this 1D model setup is implemented as part of the renewed dune safety assessment.*

Firstly, alongshore processes and gradients are not taken into account, while in reality the situation is at least somewhat alongshore non-uniform. Especially in the Langeoog case, net losses of sediment were observed at the beach that were not observed in XBeach, which is at least partly caused by alongshore sediment transport gradients.

Secondly, oblique wave attack is not resolved properly in the current 1D model. The mean wave direction in the XBeach simulations is forced to be shore-normal, also if it is known that waves approach under an angle. This probably also has impact on the dune erosion, especially in cases with alongshore non-uniformity.

Thirdly, directional wave spreading is recently implemented in the 1D BOI-version of the XBeach model in a quasi-2DH approach by using an αE (‘*wbcEvarreduce*’) of 0.3; see Deltares/Arcadis (2020). The calibration of the parameter is based on inter-model comparisons for a limited number of representative Dutch cases. Therefor the wider applicability was rather uncertain on forehand. However, the field validation cases (especially the hydrodynamic cases) suggest that the current parameter setting works as intended. In this validation study no further sensitivity analyses have been performed to test the model performances for different settings of the parameter.

Finally, the accuracy of predicting small dune erosion volumes and retreat distance is limited by the grid cell size of the higher part of the beach and in the dunes. For BOI, the smallest grid cells are 1 m wide at the upper part of the beach and in the dunes for BOI. Hence, dune retreat distance differences of >> 1 m are captured well by this model, but cases with measured retreat distances of around 1 m (such as some Egmond aan Zee profiles) are inherently difficult to reproduce and generally result in larger relative differences between measured and modelled. Note that this does not specifically relate to the 1D setup, but the numerical modelling approach in general.

4.2.2 Performance related to hydrodynamics

Overall performance (model accuracy)

The hydrodynamic validation cases ‘Schiermonnikoog (NL)’, ‘Saint Trojan (FR)’ and ‘Egmond aan Zee (NL)’ showed a good overall performance of the nearshore hydrodynamics in the 1D BOI-version of XBeach, given the fact that XBeach was not calibrated specifically for these individual field cases. A uniform model setup with pre-calibrated settings was used and tested for all field cases.

In particular, also the modelled nearshore infragravity wave heights showed good resemblance in each of the cases; which is important because these IG waves have a large impact on dune erosion.

Moreover, some deviations in water depths and short and long wave heights are found that cause scatter in the results; but these could partly be explained by inconsistencies in the case-specific model input. Although not studied in full detail, it is also concluded that the newly introduced αE *(‘wbcEvarreduce’)* parameter to mimic the effect of directional wave spreading on infragravity wave generation in 1D functions as intended, since the overall biases in the infragravity wave heights of only a few cm (while large overestimations were found with older versions of the 1D model implementation without αE).

Recommendations regarding parameter setting for *gamma*

Regarding the BOI-settings, a hydrodynamic model parameter that is still subject to some discussion is the *gamma* parameter (wave breaking threshold). From the (limited number of) hydrodynamic field cases an indication is found that the optimal setting of *gamma* might be case-specific: more specifically profile slope dependent. The calibrated setting (0.46) is close to the *gamma* value of 0.45 that Wesselman et al. (2017) use as an appropriate value for gentle shoreface slopes. However, an even smaller value seems to (slightly) improve the resulting hydrodynamic parameters for the Schiermonnikoog and Saint Trojan case; both *with gently sloping shorefaces*. For the Egmond aan Zee case *with a steeper shoreface*, the small biases for the wave heights (only a few cm on average) suggest that the current *gamma* value is appropriate for this case. A smaller *gamma* – for this case –most likely would result in larger negative biases.

The number of available field cases, with different foreshore slopes, is too small to derive – for example – an optimized slope-dependent setting for *gamma*. Therefore, it is concluded that – for BOI purposes – the current (calibrated, and spatially constant) value for *gamma* is the best possible setting; given the (limited) availability of calibration and validation data for this specific topic. This setting results in good (quantitative) resemblance between observational data and model results. In addition to that, it is also recommended to further study the relationship between foreshore slope and the optimal *gamma* setting in a parallel research study.

4.2.3 Performance related to morphodynamics

Overall performance (model accuracy)

In general, the morphodynamic validation field cases show a satisfactory overall model performance regarding the morphodynamic processes (including dune erosion) in the 1D BOI-version of XBeach. On average, the dune erosion volumes calculated by XBeach show limited bias compared to the measurements (bias = 0.9 m^3/m, rel. bias = 3%), with an equal number of profiles with over- and underestimation and scatter index of 24%. See Table 3-5 in section 3.2.

Based on the (quantitative) goodness-of-fit parameters as well as on a more qualitative visual assessment of the modelled profile shapes, it is concluded that the model is reasonably well capable of reproducing the observations. Especially for a broadly applicable process-based dune erosion model.

XBeach versus Duros+

A further performance qualification for the modelled morphodynamics and dune erosion is given by comparing the XBeach results with results of the empirical dune erosion Duros+ (that is currently used for formal dune safety assessments in the Netherlands). A preliminary comparison between both models is described in a separate report: Deltares/Arcadis (2021b). This report shows that XBeach outperforms Duros+ when considering all the available field cases. Both the overall (relative) bias and the RMSE and scatter index are substantially larger for Duros+. It is concluded that XBeach is less biased and less scattered. Also, the applicability range of XBeach is much larger than of Duros+, because of the difference between a process-based approach and an empirical approach.

Performance for individual field cases

The Vedersoe (Denmark) case is a good example of a case in which a relatively *large* amount of dune erosion (two profiles with the highest erosion volumes in this validation study) is very well reproduced by XBeach. It not only shows that XBeach can produce realistic dune erosion volumes and retreat rates in a case with significant dune erosion, but also that its response to different types of profiles is correctly simulated: a berm on the beach, in one profile, resulted in significantly less erosion above storm surge level compared to a similar profile without a beach berm.

For *small* dune erosion volumes, the performance differs between the individual cases. The post-storm profiles at Langeoog (Germany) are relatively poorly reproduced by XBeach compared to the other cases, with larger dune erosion volumes located higher in the vertical in XBeach than in the measured profiles. This is opposite to (and more pronounced than) the profiles along the Flemish coast (Belgium) with similar dune erosion volumes. Together, this resulted in the observed spread in the dune erosion volumes for especially the lower volumes for which more cases are available.

Moreover, the Fire Island case showed that XBeach was correctly able to calculate the same *type* of post-storm profile compared to the measurements for extreme (hurricane) conditions: either post-storm profiles as a result of breaching or overwash or profiles as a result of dune erosion (non-breaching). So, for a transect where no breaching was observed, XBeach also did not result in breaching, and visa-versa. The corresponding dune erosion volumes above storm surge level were reproduced quite well (mean difference of -7%), but the exact *shape* of the post-storm profile and corresponding erosion volumes however did not always match very well. Even then, the fact that the model can correctly predict overwash and breaching of dunes is a key advancement of the XBeach model over the current empirical model used for formal dune safety assessments (DUROS+).

Profile shape in relation to dune retreat distances

The dune erosion volumes were generally well reproduced by XBeach with a relative bias of only 3%, but the dune retreat distances did show an underestimation of 21% by XBeach. Partly this is related to the chosen definition of 'retreat distance' (see below). And to a large extent it is (also) related to the calculated (dune) profile shape and the distribution of eroded sediment along the profile. The reproduction of post-storm profile shapes is considered to be one of the hardest aspects of dune erosion modelling. Some scatter here is inevitable. Fortunately, for the purpose of the BOI project it is more important to get reliable estimates of the dune erosion volumes.

In some cases, it is found that the observed pre- and post-storm profiles do not have a closed sediment balance (net loss (erosion) or net gain (sedimentation) of profile volume is found). This is caused by alongshore processes that occur in the field. These processes – by definition – cannot be reproduced with a 1D model approach.

In this study it is also found that in some cases (i.e. the Holland 1976 storm case and the Langeoog case) the modelled dune foot height (transition point between steep dune face and beach slope) differs from the observed data. In these cases, the modelled dune foot is located well above maximum storm surge level. Since no unique or notably different characteristics are found for these cases, in terms of profile shape, offshore boundary conditions or grain sizes, compared to the other cases, the exact reason for the simulated high levels of the post-storm dune foot is not fully understood. It might be related to large (overestimated) water level setup and/or (enhanced) infragravity wave dynamics close to the dune foot. But another explanation can be that the near-dune profile shape is affected by alongshore processes which are (by definition) not accounted for in the 1D models.

Inaccuracies in the modelled post-storm profile shape, and for example the dune foot level, tend to lead to overall underestimation of the determined dune retreat distance, while the (associated) dune erosion volumes are well represented or even overestimated by XBeach. This is also shown in the goodness-of-fit parameters, which show an overall negative bias for retreat distance, while the bias for erosion volume is small. This indicates that the definition of the dune retreat distance itself affects the comparison between two different profiles / profile shapes. A dune retreat distance measured at storm surge level gives different results than a retreat distance measured in terms of the difference between two erosion points. In this study fixed vertical levels are defined (per case) to calculate the retreat distances.

Despite the relatively high post-storm dune foot *in some cases* and/or other profile shape related points of attention, it is found that XBeach in general is well capable of simulating post-storm profiles that resemble the measured profiles; especially for the purpose of the BOI-project.

Differences in sediment compaction

In flume experiments, which form the basis of calibration for most of the existing dune erosion models, it was observed that measured erosion and deposition volumes were not equally balanced in reality; even in a simple 1D flume setup. This is the result of differences in compaction of the sediment. Less compacted dune sediment has a larger volume than when it is eroded, deposited and compacted by wave action. The volume of dune sand after erosion, deposition and compaction can be in the order of 10% smaller than the volume of the original dune sand.

A complicating factor here is that actual differences in sediment compaction are not easily measured, directly. In an ideal situation these volume differences due to compaction should be compensated for in numerical models. In reality, no compensation for sediment (de)compaction is included in this type of models, so either a compensation should be applied (as post-processing step) or the compaction effect should be accounted for indirectly as part of the model calibration.

For the existing (process-based) model DurosTA (Steetzel, 1993), it was suggested to apply a correction factor of 12% on the simulated erosion volume (as a post-processing step) to compensate for volume differences due to compaction. DurosTA was calibrated primarily on profile shape rather than erosion volume. For XBeach-BOI it is decided not to apply a post-processing stap for this, but rather account for the compaction effect indirectly by calibration. Therefore, the dune erosion volume was one of the primary indicators for the calibration of the XBeach BOI-settings. The consequence of this approach is that the erosion volumes are modelled well (because of calibration), at the cost of a potentially less accurate shape/extent of the deposition-part of the post-storm profile. This could be an additional explanation of the larger deposition volume in the XBeach profiles than measured in especially the profiles of case 3 (Flemisch coast) and case 5 (Vedersoe).

Grain size sensitivity

The impact of sediment grain sizes on the amount of dune erosion is a continuous point of discussion; also because the grain size sensitivity of XBeach originally was relatively low compared to other models. Therefore, the new parameter αD_{50} was implemented and calibrated recently. An αD_{50} value larger than 0 *enhances* the calculated grain size sensitivity of the model (which is relatively small originally for $\alpha D_{50}=0$). Due to this parameter grain sizes smaller than 225 µm will lead to more dune erosion (compared to the original model) and grain sizes larger than 225 µm result in less dune erosion. This validation study is based on the (recalibrated) parameter setting $\alpha D_{50} = 0.4$. The calibration process is described in Deltares/Arcadis (2021a).

As part of this validation study the relation between D_{50} and simulated dune erosion volumes was analyses for all considered profiles of both the Belgian case (with D_{50} in the range 216-308 µm) and the Holland 1976 storm case (with D_{50} in the range 174-246 µm). Although the effect of grain size could not be isolated in the field validation data and the D_{50} input data might be somewhat inaccurate (unknown), these analyses are useful to gain insight in the grain size dependency of the model in relation to dune erosion for field applications. It was found that for the Holland 1976 storm case – on average – no clear dependency is found between dune erosion volumes and D_{50} in both the measured and the modelled data. The trends are similar. For the Belgian case – remarkably – a slight increase is found in erosion volume for increasing D_{50}; while the model shows a slight decrease. In both cases the scatter, however, is relatively large.

One of the difficulties here is that the effect of the grain size on dune erosion volumes cannot be isolated in field cases, because other profile-specific aspects influence the erosion volumes as well. The observational data *suggest* that the effect of grain size itself on dune erosion is minor compared to other factors in a natural environment.

Overall, it is concluded that the resemblance between modelled and observed relationship between D_{50} and erosion volume is quite good; suggesting that the recalibrated setting for αD_{50} (0.4) is acceptable.

Another more general discussion regarding the grain size sensitivity, is which grain size should be used as input for a model setup. An average D_{50} for the first dune seems appropriate and is used in the validation cases if available, because the focus is on dune erosion, and eroded dune sediment in front of the dune foot will be a main source of transported sediment during an extreme storm. However, this value generally is smaller than at the beach or nearshore. Even if the impact of using a single D_{50} representative for the dunes is negligible, the question remains whether enough reliable data are available to determine this representative grain size for the Dutch coast for application in the new BOI framework. In the currently used dune safety assessment framework, a grain size dataset is used (prescribed) that is based on measurements in 1982. Since then, the Dutch coastline has been intensively nourished and hence an update of the grain size dataset of the Dutch coast is desired. The use of an updated dataset as part of the new BOI framework is considered to be at least as important as (the accuracy of) the grain size dependency of the XBeach model.

5 CONCLUSION AND RECOMMENDATIONS

5.1 Summary

This report describes the approach, results and conclusions of a series of field validations of the new BOI-version of the XBeach model. The report is one of the key deliverables of the first phase of the project 'BOI Sandy Coasts'. The overall project aims at developing a renewed framework and toolkit for assessing, designing and maintaining dunes as part of the flood defences along the Dutch coast. In this subproject (*validation of XBeach*) a series of different field cases is studied in order to validate the performance of the calibrated BOI-version of XBeach. A well-validated model in combination with an explicable definition of the model uncertainty (in terms of bias and spreading) forms the basis for all subsequent development steps in this project.

The main objective of the work, presented in this report, is to validate the BOI-version of XBeach and to gain insight into the accuracy of the model regarding hydrodynamical processes, morphodynamical processes and the applicability for both regular and extreme storm conditions. Specific attention is given to the modelled infragravity waves and the calculated dune erosion during a storm event.

The validation study is based on a series of field measurement campaigns from which measurements or observations are available of nearshore hydrodynamics (specifically: infragravity waves) and/or bed level changes (specifically: dune erosion) during storms events. The field cases were selected based on relevance and availability of data. This resulted in a list of both national and international field cases:

▪ Schiermonnikoog (NL)	[Hydro]
▪ Saint Trojan (France)	[Hydro]
▪ Flemish Coast (Belgium)	[Morpho]
▪ Fire Island, New York (USA)	[Morpho]
▪ Vedersoe (Denmark)	[Morpho]
▪ Langeoog (Germany)	[Morpho]
▪ Holland Coast – 1976 (NL)	[Morpho]
▪ Holland Coast – 1953 (NL)	[Morpho]
▪ Egmond aan Zee (NL)	[Hydro & Morpho]

For each of these cases one or more coastal transects are considered for which a 1D XBeach model is set up. The model setup is based on measured data when available and hindcast datasets when needed and is finalized based on the *interim* BOI guidelines for model setup; see Chapter 2. The results of 1D model simulations (Chapter 3) are analysed for the validation of XBeach in terms of either hydrodynamics or morphodynamics (Chapter 4). The main conclusions are summarized on next section.

5.2 Conclusions

A summary of the main conclusions from the validation study is presented below.

At first, the conclusions related to the overall model performance in the field validation cases:

- **Hydrodynamic processes / infragravity waves**
  - The validation of hydrodynamic processes (and especially infragravity waves) is based on three available field cases: two cases with a gentle foreshore and extreme to moderate storm conditions with offshore wave heights over 7 m, and one case with a steeper foreshore and frequently occurring storm conditions with offshore wave heights over 5 m.
  - From the hydrodynamic field cases, it is concluded that the BOI-version of XBeach (1D) is well capable of reproducing measured nearshore waves and water levels during storm events. Particularly, (also) the modelled infragravity (IG) wave heights show good resemblance with the observational data: the bias of the IG wave height ranges between -0.04 and 0.18 m, with an associated relative bias between -4% and 22%. *See section 3.1 and Table 3-1.*
- **Morphodynamic processes / dune erosion**
  - The validation of morphodynamic processes (and especially dune erosion) is based on seven available field cases, at different locations in Belgium, Germany, Denmark, the US and the Netherlands.

    - From the morphodynamic field cases, it is concluded that the BOI-version of XBeach (1D) is well capable of reproducing observed nearshore bed level changes and especially dune erosion volumes during storm events. In particular, the overall bias of the modelled dune erosion volumes is encouragingly small: 0.9 m^3/m; with a corresponding relative bias of 3%. The overall RMSE is 10 m^3/m (absolute), with a corresponding scatter index of 0.24 (relative). *See section 3.2 and Table 3-5.*
    - The overall bias of the modelled dune retreat distances is -1.5 m, with a corresponding relative bias of -21% (underestimation by XBeach). *See Table 3-5.*
    - In some field cases it is observed that the modelled post-storm dune foot level – the transition point from the steep dune face to the beach – is located well above the maximum (offshore) storm surge level and above the observed dune foot levels. *More details are provided in section 4.2.3.*
    - The Fire Island case showed that XBeach is well capable of predict when (i.e., in which situation) overwash and breaching of dunes occurs. This is a key advancement of the XBeach model over the current model used in the dune safety assessment (DUROS+). *More details are provided in section 3.2.2.*
- **Extreme/normative versus frequently occurring storm events**
    - The set of field cases, altogether, represent a broad variety of situations in terms of hydraulic boundary conditions, but also profile shapes and grain sizes. No clear distinction can be made between cases with extreme storm conditions and regular storm conditions; most cases are somewhere in-between.
    - From the limited but mixed set of field validations cases it is *cautiously* concluded that the BOI-version of XBeach is capable of reproducing observed dune erosion volumes for a wide range of storm conditions, from regular to extreme storms.
    - The relative error (scatter index) of modelled dune erosion volumes seems to be larger for field cases with small erosion volumes compared to cases with larger erosion volumes. These small erosion volumes can be the result of either relatively mild conditions (high-frequent storm events) and/or the result of a specific profile shape (for example, wide beach in front of dune).

Some additional, minor remarks related to the usability of the field validation cases:

- **Uncertainties in model input and field data for comparison**
  It should be noted that many of the validation cases – to greater or lesser extent – are subject to uncertainties in the required model input data. Lack of available data sometimes requires using second-best estimates or schematized input for a validation run with the model. Uncertainties are associated with all types of input and comparison data:
    - Uncertainties in bed level (pre- and post-storm data)
    - Uncertainties in hydraulic data for boundary conditions (storm characteristics) and comparison
    - Uncertainties in grain size (representative averages for dune/beach)

- **Limitations of 1D approach**
  It should be noted that a 1D XBeach model setup is considered in all cases, corresponding to the anticipated model setup for the BOI assessment framework (development phase 1). The application of a 1D approach has obvious limitations for real-world applications. In some of the cases, it is obvious from the measured data that alongshore processes have influenced the bed level changes during a storm event. For example, a clear net loss of sediment from that location. A 1D model is – by definition – not capable of reproducing this, resulting in differences between modelled and measured bed level data. Other (possible) limitations of a 1D approach relate to grid cell size at the beach and in the dunes, and the limited possibilities of a 1D model to ‘deal with’ oblique wave attack and/or wave directional spreading.

The results of this field validation study provide confidence in the applicability of the latest BOI-version of XBeach, in combination with the (re)calibrated BOI-settings, as the computational core of the new BOI framework for dunes and sandy flood defences along the Dutch coastline.

In addition to the conclusions, it is noted that parallel to this study also a (separately reported) **model comparison** has been made between XBeach and the empirical dune erosion model Duros+ that is currently used for formal dune safety assessments; see Deltares/Arcadis (2021c). From this comparison it is concluded that XBeach on average provides much better results than Duros+ for the different field validation cases. Both the (relative) bias and the RMSE/scatter index is substantially lower for XBeach.

5.3 Next steps and recommendations

Based on the field validation cases several relevant topics were addressed that [1] will be further elaborated in next phases of the current BOI-project or [2] can be considered as recommendations for (future) research and/or additional studies outside the scope of the current BOI-project.

Next steps in project

- As input for the probabilistic model of XBeach a stochastic variable ‘model uncertainty’ will be defined. A post-processing routine will be used to ‘add’ model uncertainty to the original XBeach model result. The quantitative definition of the ‘model uncertainty’ will primarily be based on the results of the field validation cases (i.e. modelled versus observed dune erosion volumes).

Recommended next steps outside project

- It is strongly recommended to continuously collect, process, and analyse additional field (and/or lab) measurement data for dune erosion events during storms along sandy coasts. Additional field (and/or lab) data will further strengthen the overall validation of the XBeach-BOI model and new data might be useful to fill in some of the still existing fundamental knowledge gaps.
- Further research is recommended to obtain better understanding on the simulated dune erosion profile shape, focussing on the (calculated) high dune foot levels (above max. storm surge level) in some of the field cases in relation to the dune retreat distance and the impact of sediment compaction on the volume of deposited eroded dune sediment.
- Further research is recommended on optimization of the *gamma* (wave breaking threshold) parameter value; for example, by deriving a relationship between optimal *gamma* setting and the characteristic profile slope.
- Fundamental research is recommended on the impact of grain sizes (D_{50}) on the amount of dune erosion during storm events, based on both laboratory and field experiments.
- Further research is recommended on the dune breaching behaviour in XBeach: the current validation study only focussed on the *occurrence* of a breach, but also the profile shape during and after the breach is relevant to predict the magnitude of flooding and/or the amount of dune erosion in a more landward second dune row.
- It is recommended to update the existing database(s) with grain size data for the entire sandy Dutch coastline.

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A OVERVIEW OF DEFAULT XBEACH SETTINGS

Overview of the default parameter settings of XBeach; associated with release '*XBeach BOI Phase1, rev. 5867*'.

Category	Keyword	Default value	Keyword	Default value
Physical processes	cyclic	0	vegetation	0
	swave	1	setbathy	0
	lwave	1	viscosity	1
	flow	1	advection	1
	gwflow	0	wind	0
	ships	0		
Model time parameters	dtset	.0000	maxdtfac	50.0000
Physical constants	rho	1025.0000	depthscale	1.0000
	g	9.8100		
Initial conditions	zsinitfile	None specified		
Wave boundary condition parameters	taper	100.0000	lateralwave	neumann
	nmax	.8000		
Wave-spectrum boundary condition parameters	fcutoff	.0000	Tm01switch	0
	trepfac	.0100	nspectrumloc	1
	sprdthr	.0800		
Flow boundary condition parameters	front	abs_1d	highcomp	0
	back	abs_1d	freewave	0
	ARC	1	epsi	-1.0000
	order	2.0000		
Tide boundary conditions	paulrevere	Land		
Discharge boundary conditions	disch_loc_file	None specified	ndischarge	0
	disch_timeseries_file	None specified	ntdischarge	0
Wave breaking parameters	gammax	2.0000	fwfile	None specified
	n	10.0000	fwcutoff	1000.0000
	delta	.0000	breakerdelay	1.0000
	fw	.0000		
Roller parameters	roller	1	rfb	0
Wave-current interaction parameters	wci	0	hwcimax	100.0000
	hwci	0.1000	cats	4.0000
Flow parameters	maxcf	.0400	smag	1
	nuh	0.100		
Coriolis force parameters	wearth	0.0417	lat	.0000
Sediment transport parameters	sws *	1	smax *	-1.0000
	lws *	1	bdslpeffmag *	roelvink_total
	BRfac *	1.0000	bdslpeffini *	none
	facua *	.1750	bdslpeffdir *	none
	Tbfac *	1.0000	reposeangle *	30.0000
	turb *	bore_averaged	tsfac *	.1000
	turbadv *	None	Tsmin *	.5000
	sus *	1	facDc *	1.0000

	bed *	1	lwt *	0
	bulk *	0	betad *	1.0000
	facs1 *	.1500	fallvelred *	0
	z0 *	.0060	dilatancy *	0
Bed composition parameters	ngd	1	dzg1 *	.1000
	nd	3	dzg2 *	.1000
	por	.4000	dzg3 *	.1000
	rhos	2650.0000	sedcal *	1.0000
	dzg *	.1000	ucrcal *	1.0000
Morphology parameters	morfacopt *	1	dzmax *	0.0500
	dryslp *	1.0000	struct *	0
Wave numerics parameters	scheme	warmbeam	oldhmin	0
Flow numerics parameters	umin	0.000	secorder	0
Sediment transport numerics parameters	thetanum *	1.0000 *	cmax *	.1000 *
Bed update numerics parameters	frac_dz *	.7000 *	split *	1.0100
	nd_var *	2	merge *	.0100 *

**for morphological runs only (for which sedtrans=1, morphology=1 and avalanching=1 instead of 0)*

B OVERVIEW OF MEASURED AND MODELLED DATA

Overview of measured and modelled dune erosion volumes and retreat distances, for all morphological field cases.

Case nr.	Case location	D50 [µm]	Profile nr.	Erosion volume above max. storm water level		Retreat distance (reference level differs)	
				XBeach [m^3]	Measured [m^3]	XBeach [m]	Measured [m]
3	Flemish coast, Belgium	215.6	**60**	9	13	5.4	8.4
3	Flemish coast, Belgium	215.6	**61**	7	7	3.9	4.9
3	Flemish coast, Belgium	215.6	**62**	7	10	3.1	3.9
3	Flemish coast, Belgium	215.6	**63**	8	10	3.9	4.4
3	Flemish coast, Belgium	308.1	**64**	5	8	2.6	4.4
3	Flemish coast, Belgium	308.1	**69**	10	15	4.0	5.4
3	Flemish coast, Belgium	308.1	**71**	4	6	1.7	3.3
3	Flemish coast, Belgium	300	**79**	5	10	2.3	2.9
3	Flemish coast, Belgium	300	**80**	5	7	0.0	1.2
3	Flemish coast, Belgium	218	**83**	3	4	2.0	1.6
3	Flemish coast, Belgium	257	**117**	11	14	5.6	5.9
3	Flemish coast, Belgium	257	**118**	12	10	6.3	5.0
3	Flemish coast, Belgium	271	**119**	8	8	3.9	4.1
3	Flemish coast, Belgium	271	**120**	12	19	4.5	5.6
3	Flemish coast, Belgium	271	**121**	4	8	2.5	3.5
4	Fire Island, New York, USA	400	**5**	51	51	NaN	NaN
4	Fire Island, New York, USA	400	**105**	54	45	NaN	NaN
4	Fire Island, New York, USA	400	**205**	75	75	NaN	NaN
4	Fire Island, New York, USA	400	**305**	54	68	13.6	28.6
4	Fire Island, New York, USA	400	**365**	25	25	5.0	5.9
4	Fire Island, New York, USA	400	**405**	32	56	13.5	23.1
5	Vedersoe, Denmark	250	**1**	178	178	17.7	16.7
5	Vedersoe, Denmark	250	**2**	66	78	6.3	4.7
6	Langeoog, Germany	250	**A**	16	1	-2.9	0.5
6	Langeoog, Germany	250	**B**	15	13	-2.7	3.5
6	Langeoog, Germany	250	**C**	10	10	-2.3	4.0
6	Langeoog, Germany	250	**D**	31	18	5.1	6.5
6	Langeoog, Germany	250	**E**	28	14	5.7	7.0
6	Langeoog, Germany	250	**F**	27	11	7.1	4.5
7	Holland 1976, NL	217	**648**	19	19	25.6	24.0
7	Holland 1976, NL	237	**3400**	19	24	6.8	10.2
7	Holland 1976, NL	240	**4000**	51	49	7.4	8.4
7	Holland 1976, NL	237	**4050**	18	26	6.6	10.8
7	Holland 1976, NL	234	**4100**	38	34	5.1	6.6
7	Holland 1976, NL	227	**4500**	35	46	5.0	9.3
7	Holland 1976, NL	215	**5000**	45	62	5.1	7.6
7	Holland 1976, NL	246	**5900**	35	24	5.8	6.0

7	Holland 1976, NL	242	**5925**	41	30	4.2	5.8
7	Holland 1976, NL	238	**5950**	41	43	4.6	6.9
7	Holland 1976, NL	234	**5975**	50	70	5.2	8.4
7	Holland 1976, NL	230	**6000**	49	67	4.8	7.1
7	Holland 1976, NL	225	**6025**	50	20	4.8	4.3
7	Holland 1976, NL	221	**6050**	46	49	5.7	7.3
7	Holland 1976, NL	217	**6075**	57	39	5.6	5.4
7	Holland 1976, NL	213	**6100**	56	50	4.3	4.8
7	Holland 1976, NL	174	**6500**	24	25	11.6	12.8
7	Holland 1976, NL	192	**7000**	37	28	5.6	6.9
7	Holland 1976, NL	193	**7050**	29	24	5.2	7.4
7	Holland 1976, NL	193	**7100**	30	18	6.5	6.3
8	Holland 1953, NL	225	**Repr. profile**	111	90	12.1	15-18
						15.8	
						17.4	
9	Egmond aan Zee, NL	250	**-1755**	7	0	4.9	0.6
9	Egmond aan Zee, NL	250	**-1001**	13	1	5.6	1.7
9	Egmond aan Zee, NL	250	**-502**	8	6	3.1	4.2
9	Egmond aan Zee, NL	250	**-249**	8	8	2.1	3.7
9	Egmond aan Zee, NL	250	**0**	5	4	1.5	2.8
9	Egmond aan Zee, NL	250	**499**	7	4	3.0	2.6
9	Egmond aan Zee, NL	250	**1001**	8	6	2.6	4.0