



departement  
Mobiliteit en  
Openbare Werken

# Scientific support regarding hydrodynamics and sand transport in the coastal zone

HINDCAST OF THE MORPHOLOGICAL IMPACT OF THE 5-6 DECEMBER 2013 STORM  
USING XBEACH



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WL Rapporten

# **Scientific support regarding hydrodynamics and sand transport in the coastal zone**

Hindcast of the morphological impact  
of the 5-6 December 2013 storm using XBeach

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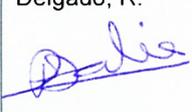
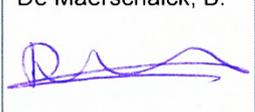
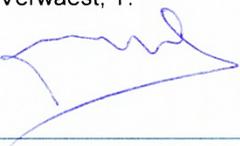
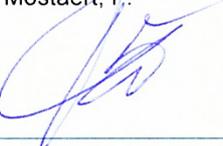
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Abstract

A storm occurred in the North Sea on 5-6 December 2013 (also known as the Sinterklaasstorm) which generated high surge levels and moderately high wave heights along the Belgian coast, resulting in beach and dune erosion. Measurements of beach profile change along 122 cross-shore survey transects were compared with the numerical model XBeach. First, a novel configuration for XBeach was developed that takes into account the effects of wave directional spreading since XBeach cannot resolve directionally spreading of long waves in 1D mode (which is generally used to predict cross-shore profile change). The effect of wave directional spreading on hydrodynamics and sediment transport is investigated using idealized and realistic simulations. Idealized simulations show that the near-shore long wave field is more energetic in 1D than in an equivalent 2D model with an alongshore-uniform bathymetry. Realistic storm scenarios show that this leads to predicted erosion volumes that are 25-57% higher than in the 2D model. Sparse 2D models with 5 to 8 alongshore grid cells provide a reasonable approximation (both for hydrodynamics and sediment transport) of the full 2D model (with 50 alongshore grid cells) at a lower computational cost. The December 2013 storm was therefore simulated using a sparse 2D model with 5 grid cells in the alongshore direction. Good agreement with measured erosion volumes was found when using a recently established set of calibration values provided by Deltares. Default calibration values from an older version of XBeach lead to an overestimation of the erosion volumes, as does the use of a 1D model instead of a sparse 2D model. The sensitivity of the predicted erosion volumes to increased surge levels and wave heights was also investigated.

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# 1. Introduction

## 1.1 The assignment

In the frame of the project “Wetenschappelijke bijstand hydrodynamica en zanddynamica in de kustzone” (“Scientific support for hydrodynamics and sand dynamics in the coastal zone”) executed by IMDC for Flanders Hydraulics Research (tender WL/09/23), tools are being developed in order to help answering morphology-related questions for Flanders Hydraulics Research itself and the relevant governmental services. One of these questions is the performance of the the XBeach model for near-shore morphodynamics, which is tested by conducting a hindcast of the “Sinterklaasstorm” of 5 and 6 December 2013.

## 1.2 Aim of the study

A storm occurred during 5 and 6 December 2013 in the North Sea and is known “Storm Xaver” or “Sinterklaasstorm” (Saint Nicholas storm). Generating a storm surge of up to 6.19 m TAW in Ostend (the highest surge level since 1953), combined with significant wave heights of over 3 m, the storm caused noticeable morphological changes on the Belgian coast (Oceanografisch Meteorologisch Station, 2014). 122 cross-shore profiles were surveyed 2-4 days before the storm. These were compared to an airborne lidar survey executed 4 days after the storm to provide a dataset of beach profile change along the entire Belgian coastline (~67 km).

The XBeach model (Roelvink *et al.*, 2009) was developed with the aim of predicting shoreface, beach and dune system response to storm impacts. Its possibilities have been studied at Flanders Hydraulics Research in terms of its general capabilities (Zimmermann *et al.*, 2011) and to model long-term morphological evolution (Zimmermann *et al.*, 2015). In this report, the XBeach model is used to hindcast the morphological impact of the December 2013 storm.

## 1.3 Overview of the study

Table 1-1 lists the reports written in the frame of this project.

Table 1-1 : Overview of reports

Reference WL / IMDC	Title
Literature review	
WL2010R744_30_2 / I/RA/11355/10.144/MIM	Literature review of physical processes
WL2011R744_30_3 / I/RA/11355/10.156/NZI	Literature review of models
WL2011R744_30_4 / I/RA/11355/10.157/JDW	Literature review of data
Blankenberge case	
WL2011R744_30_7 / I/RA/11355/11.055/NZI	Simplified Blankenberge case : Comparison of Delft3D and XBeach results
WL2012R744_30_18	Update of the sediment budget for the nearshore of Blankenberge-Zeebrugge
WL2012R744_30_17 / I/RA/11355/12.098/NZI/	Calibration of the Oostende-Knokke hydrodynamic and sediment transport model (OKNO)

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WL2012A744_30_12 / I/RA/11355/12.048/NZI	Effect of a beach nourishment on the sedimentation of the entrance channel of the port of Blankenberge : Application of a simplified model for the Blankenberge area
WL2012R744_30_11 / I/RA/11355/12.049/lwa/NZI	Longshore modelling : realistic Blankenberge case
WL2013R00_063 / I/RA/11355/13.221/NZI	Toegankelijkheid haven Blankenberge: Optimalisatie van de haveningang
WL2013R13_105 / I/RA/11355/13.222/LWA/NZI	Energy atolls along the Belgian coast: Effects on currents, coastal morphology and coastal protection
<b>Knokke case</b>	
WL2015R12_107_1 / I/RA/11355/13.219/NZI	Inschatting van de morfologische impact van strandsuppleties te Knokke op het Zwin en de Baai van Heist
WL2015R12_107_2 / I/RA/11355/15.143/NZI/	Literature review coastal zone Zeebrugge - Zwin
WL2015R12_107_3 / I/RA/11355/14.175/LWA/NZI	Long term morphological model of the Belgian shelf: Calibration
WL2015R12_107_5 / I/RA/11355/15.145/NZI/	Advies suppletie Knokke – Effect op de morfologie van het Zwin en van de Baai van Heist: XBeach - modellering
<b>Cross-shore modelling</b>	
WL2015R00_072_13 / I/RA/11355/12.050/MIM/NZI	Evaluation of XBeach for long term cross-shore modelling
WL2015R00_072_6 / I/RA/11355/15.144/NZI/	Inventarisatie randvoorwaarden en morfologische impact Sinterklaasstorm (6 december 2013)
WL2015R12_107_4 / I/RA/11355/15.134/THL	Hindcast of the morphological impact of the 5-6 December 2013 storm using XBeach
<b>Lessons learnt</b>	
WL2015R00_072_19 / I/RA/11355/12.051/NZI/	Modelling tools and methodologies

## 2. Model input

### 2.1. The December 2013 storm

A storm occurred during 5 and 6 December 2013 in the North Sea and is known as Storm Xaver or “Sinterklaasstorm” (Saint Nicholas storm). A detailed description of the meteorological conditions during the storm around Belgium is given by Oceanografisch Meteorologisch Station (2014). The storm was the result of a low-pressure system that formed between Iceland and the British Isles and migrated eastward across southern Norway into the Baltic sea (Figure 2-1). The core system reached a minimum barometric pressure of 961 hPa but remained far from the Belgian coast; the minimum atmospheric pressure in Belgium was 1012 hPa. Wind speeds reached 8-9 Bft in the Belgian coastal waters (Figure 2-2). The storm also affected other countries along the North Sea. In the United Kingdom, for example, the storm caused the highest still water levels on record at several tide gauges, overtopping of gravel ridges, and erosion of coastal dunes and cliffs that was equivalent to roughly 10 years of ‘normal’ shoreline retreat at the Suffolk coast (Spencer *et al.*, 2015).

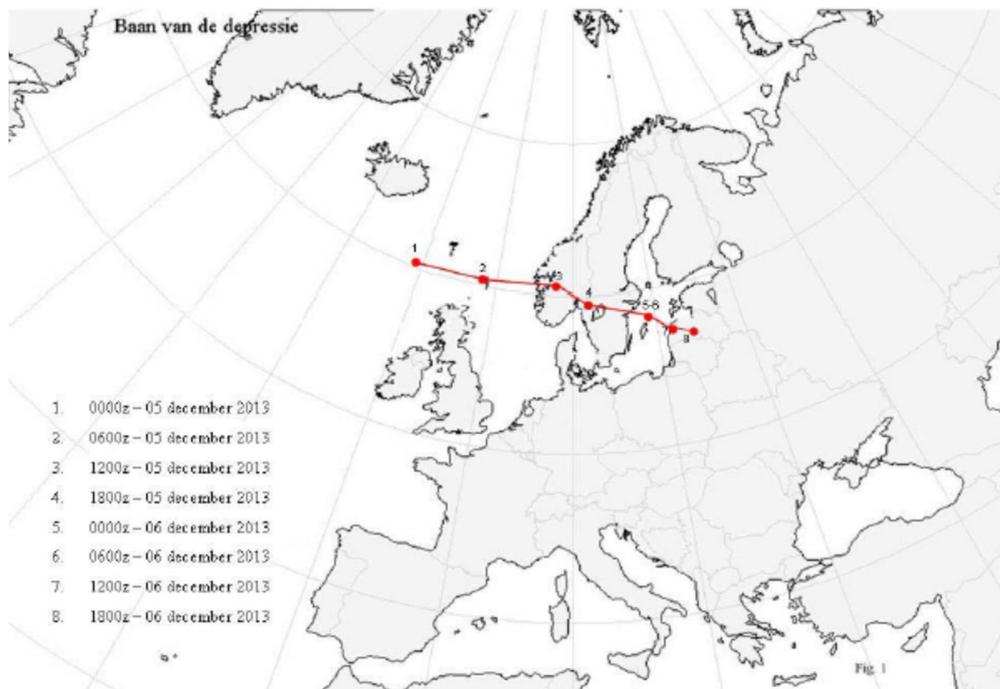


Figure 2-1: Cyclone track of the December 2013 storm  
(source: Oceanografisch Meteorologisch Station, 2014)

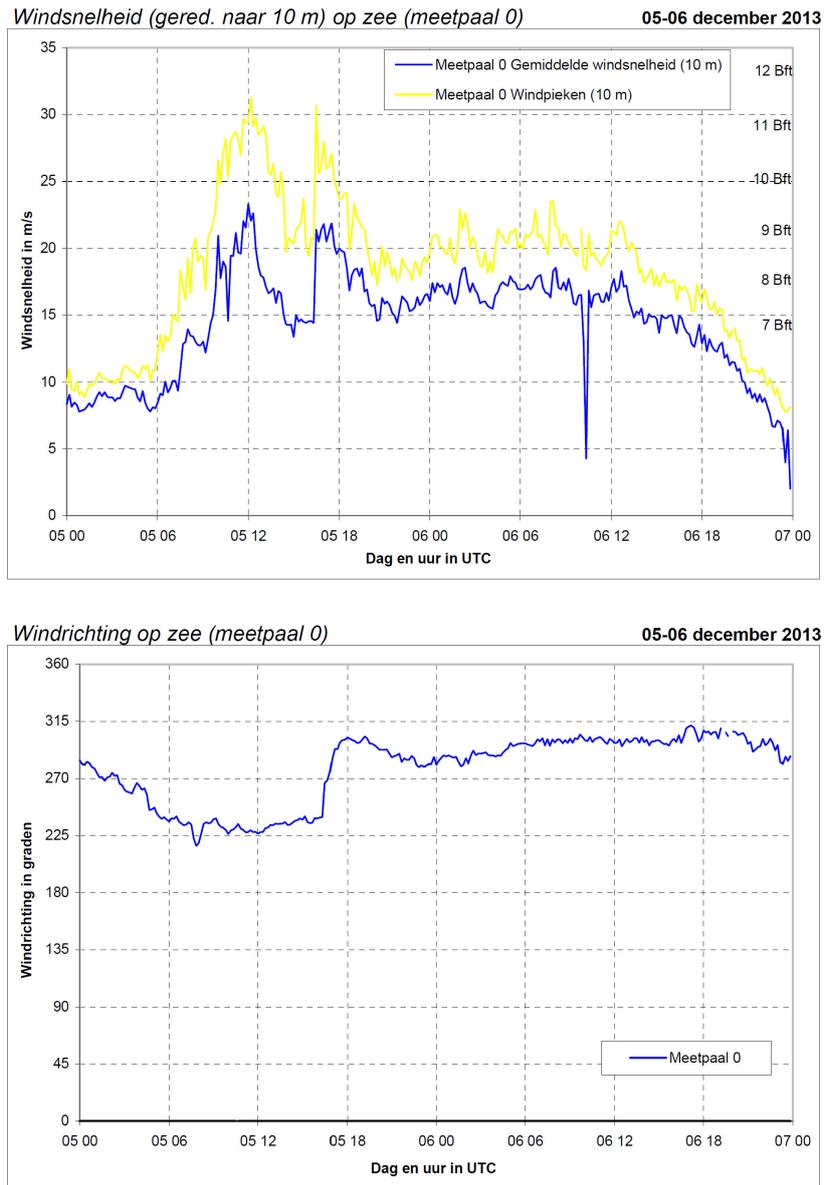


Figure 2-2: Wind speed (top) and wind direction (bottom) at sea, at measurement platform 0 (Wandelaar) (source: Oceanografisch Meteorologisch Station, 2014). Measurement locations are shown in Figure 2-4.

The strong winds (9-10 Bft) in the northern North Sea generated a surge toward the Belgian coastline. A maximum water level of 6.19 m TAW was measured by the float tide gauge (5 minute average) in the port of Ostend (Oceanografisch Meteorologisch Station, 2014) which was the highest level since 1953 (estimated return period approx. 40 years, IMDC, 2005). Water level measurements, significant wave heights and peak wave periods measured at three locations during the storm are displayed in Figure 2-3. Water levels were elevated during two tidal cycles. Measured near-shore wave heights were elevated during 3 tidal cycles and reached 2.7 m, with peaks up to 3 m. Offshore wave heights reached approximately 3.5 m, which corresponds to a return period on the order of one year on the Belgian coast (IMDC, 2005). The storm hindcast simulations were executed over a period of 78 hours (6 tidal cycles) from 2013-12-04 19:30 until 2013-12-07 23:30 (dashed vertical lines, Figure 2-3).

In conclusion, the December 2013 storm was associated with a low pressure system that remained relatively far from Belgium. Due to the wind speed and direction, the effect on the hydrodynamics near the Belgian coast was a high surge level, combined with a moderately high wave climate.

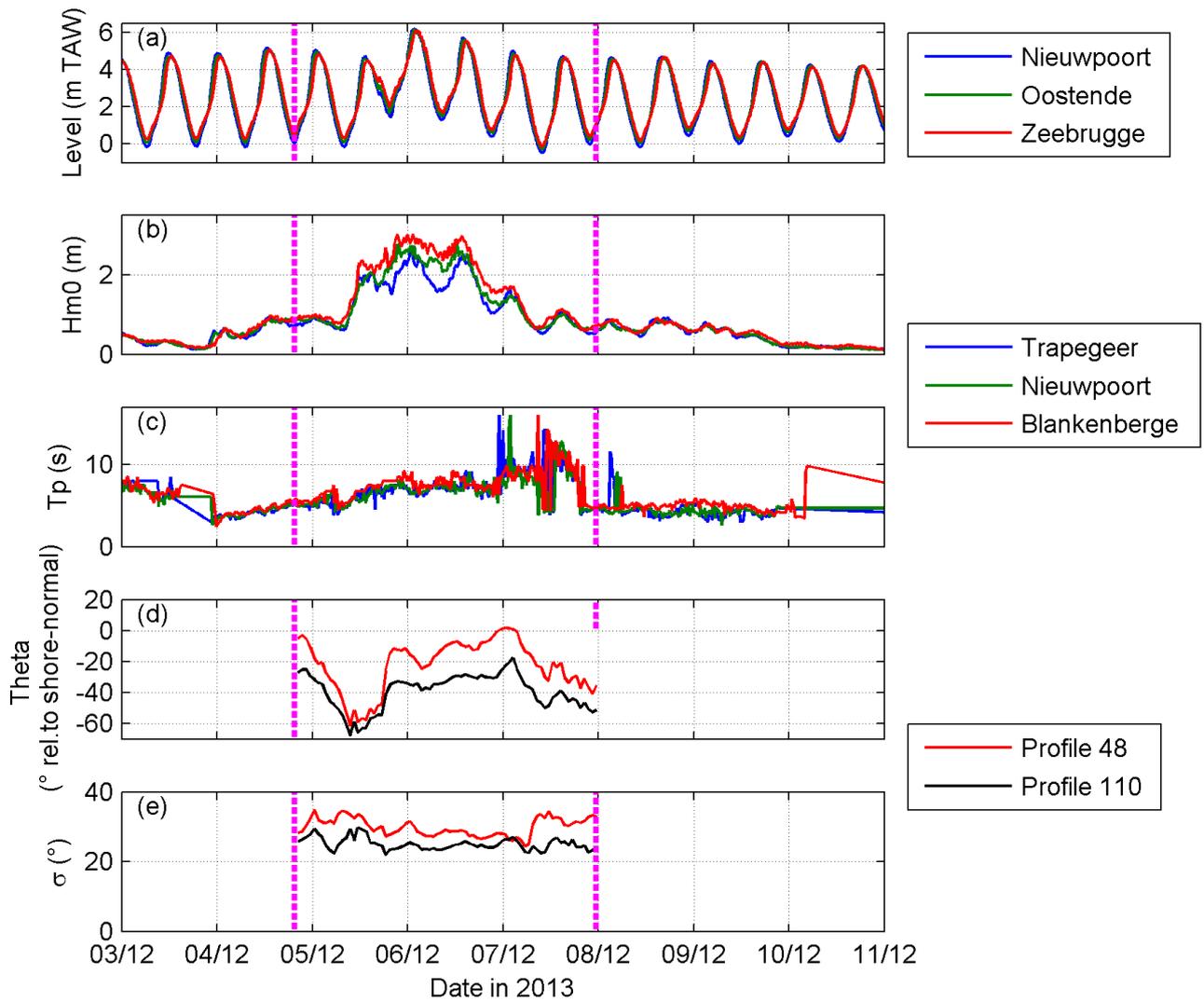


Figure 2-3: Hydrodynamic conditions recorded during the December 2013 storm.  
(a) Water level; (b) significant wave height; (c) peak wave period;  
(d) Incident wave angle (from SWAN model); (e) Directional spreading width.  
Vertical dashed lines indicate the start and stop times for the hindcast simulations.  
Measurement locations are shown in Figure 2-4.

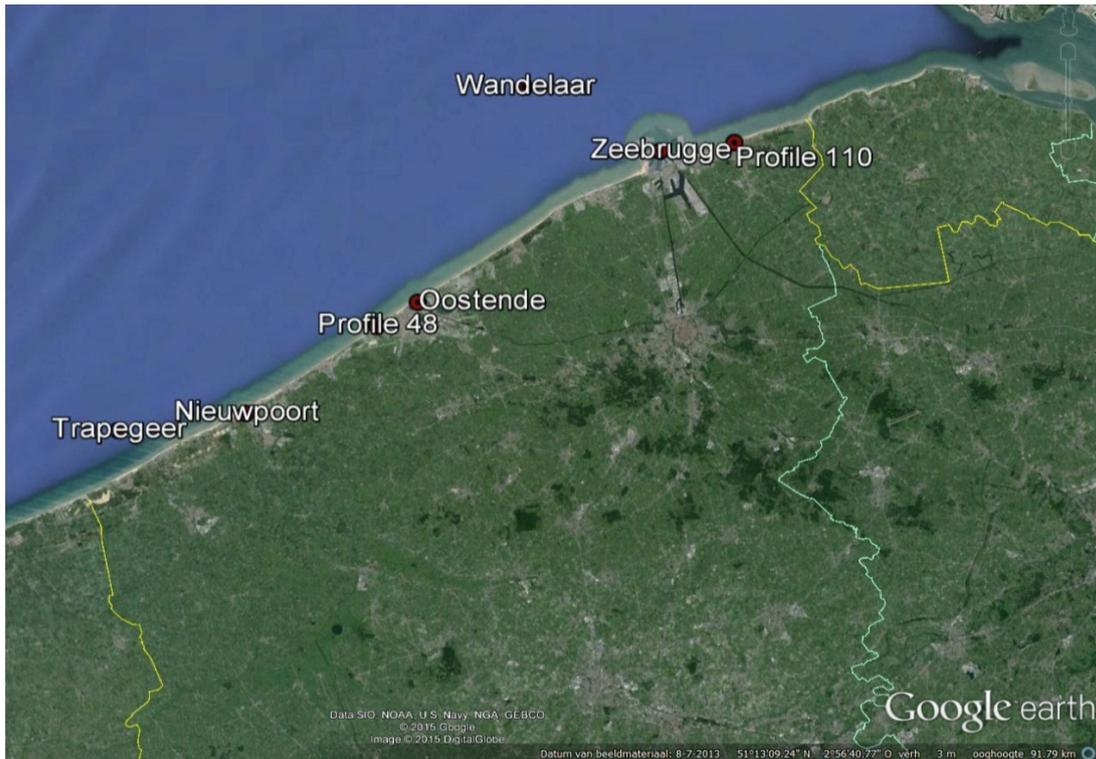


Figure 2-4: Map indicating the location of all measurement stations.  
Data SIO, NOAA, U.S. Navy, NGA, Gebco, Google.

## 2.2. Topo-bathymetric dataset

### 2.2.1. Pre-storm beach survey

On 2-4 December 2013 (2-4 days before the storm), 122 cross-shore profiles were surveyed with a 2 to 15 m cross-shore resolution using a GPS survey station along the entire Belgian coastline (typical alongshore spacing 500m). Data were made available by the Coastal Division of the Flemish Government. The location of all profiles is shown in Appendix A. The profiles were surveyed from the toe of the dyke or dune until approximately the low-tide shoreline and were combined with existing DEM data for elevations of the dyke and dune areas.

12 profiles were excluded from the XBeach modelling, leaving 110 modelled profiles. The excluded profiles, along with the reason for their exclusion, is given in Table 2-1. In most cases, the exclusion is due to the profile being located adjacent a harbour structure. In this case, the wave and current field cannot be modelled in XBeach without detailed 2D modelling, which was not considered within this study.

Table 2-1: Excluded profiles

Profile number	Reason for exclusion
1	Incomplete survey data (profile near Belgian-French border)
4-5	Dune toe protection structure west of De Panne. No detailed information on the exact geometry of the hard structure was available.
55	Profile located adjacent to Oostende harbour breakwater
87	Profile located adjacent to Blankenberge harbour jetty
98-102	Profile located right next to Zeebrugge harbour breakwater
122	Incomplete survey data (profile next to Belgian-Dutch border)

### 2.2.2. Post-storm beach survey

An airborne LiDAR survey of the intertidal beach along the complete coast was conducted on 10 December 2013 (4 days after the storm).

### 2.2.3. Shoreface surveys

The foreshore (the area seaward of the low-tide shoreline) was surveyed using single-beam surveys conducted in June-July 2013 (pre-storm) and May 2014 (post-storm). The foreshore surveys were typically conducted as single-beam surveys in cross-shore transects with 100 m alongshore spacing.

### 2.2.4. Combined profiles

The pre-storm beach and foreshore surveys and the post-storm beach and foreshore surveys were combined to form a single set of 122 pre-and post-storm profiles along the transect lines of the pre-storm beach surveys. The profiles extended from the dyke or dune up to approximately 1500 m from the dune or dyke toe. The bottom elevation of the offshore boundary was generally located in the range from at -5m TAW).

The post-storm foreshore survey was executed 10 months after the pre-storm survey, so foreshore bed level changes cannot be attributed solely to the Sinterklaasstorm. Therefore, bed level changes were only investigated on the intertidal beach. It is noted that the differences in the foreshore survey of resp. June/July 2013 and May 2014 are within measuring accuracy (differences generally less than 10cm).

## 2.3. Hydrodynamic model input data

### 2.3.1. Water levels

Water levels were obtained from the tide gauges of Nieuwpoort, Oostende and Zeebrugge. During the storm, the three gauges recorded similar water levels (differences at HW around 10cm) but with a small time lag due to the propagation of the tidal wave along the coastline (Figure 2-3). No spatial interpolation was performed between the three tide gauges. Instead, the water level time series at the nearest tide gauge was used as the offshore water level boundary condition of the XBeach model for each profile:

- The Nieuwpoort tide gauge was used for profile 1-39.
- The Oostende tide gauge was used for profile 40-83.
- The Zeebrugge tide gauge was used for profile 84-122.

### 2.3.2. Wave conditions

Directional wave spectra were recorded offshore by two directional wave buoys in deep water (Akkaert, Westhinder<sup>1</sup>). Non-directional wave spectra were recorded by six wave buoys located near the shoreline (Trapegeer, Nieuwpoort, Oostende, Blankenberge A2, Scheur van Wielingen,) and one directional buoy (Bol van Heist). SWAN, a third-generation spectral wave model (Booij *et al.*, 1999), was used to transform the directional wave data to the near-shore and to supply directional wave spectra as the boundary condition of the Xbeach model at the offshore boundary (-5 m TAW, ~1500 m from the dyke toe).

Two instances of the SWAN model were run, one for the eastern section of the Belgian coast and one for the western section. The western SWAN model instance used directional wave spectra from the Akkaert wave buoy as the offshore boundary condition and provided spectral wave data at the offshore boundary of the beach profiles for the profiles west of Oostende (profile 1-55). The eastern SWAN model instance used directional wave spectra from the Westhinder buoy as the offshore boundary condition and supplied spectral wave data at the offshore boundary of the profiles east of Oostende (profiles 56-122). The SWAN models used spatially uniform wind fields for wind-driven wave growth within the model domain and supplied output wave spectra every hour.

After running the SWAN models based on the offshore wave data, the output spectral wave heights were corrected using the information from the near-shore buoys. For each hourly output of the SWAN model, the

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<sup>1</sup> Locations of the wave buoys is given at [www.meetnetvlaamsebanken.be](http://www.meetnetvlaamsebanken.be)

significant wave height at the nearshore buoy locations was calculated and compared to the significant wave height measured by the near-shore wave buoy. The SWAN spectra were then corrected so that at each time step, the wave height of SWAN was equal to the wave height of the buoy. These correction factors were applied to the modelled wave spectra for nearby beach profiles. These “corrected spectra” thus provide a wave height that is based on the measured wave height of the near-shore wave buoy, along with a directional and frequency spectrum that is obtained from the offshore directional buoys and the SWAN model.

The directional wave spectrum from the SWAN models at the near-shore boundary is determined by the wave directionality at the offshore boundary and by the directionality of the locally-generated wind waves, and is influenced by refraction by the bathymetry throughout the model domain. Since a spatially uniform wind field was supplied for the SWAN model, the directional spreading of the waves at the near-shore points may be underestimated.

## 2.4. Sediment composition

For each profile, a single median diameter ( $d_{50}$ ) was used. Cross-shore or vertical variability in bed composition was thus not taken into account. Grain diameter values are based on sample measurements by laboratorium ‘de Vlieger’ and by VITO that are reported in the guidelines for the 2007 coastal safety assessment (IMDC, 2008). Beach nourishments with a median grain diameter of approximately 300  $\mu\text{m}$  were performed at certain profiles after 2008. At these profiles,  $d_{50}$  was set to 300  $\mu\text{m}$ . The median grain diameter that was used in XBeach for each profile is listed in Table 2-2.

Table 2-2: Median grain diameters used in the XBeach model

Profile	Beach section	$d_{50}$ ( $\mu\text{m}$ )
1-6	1-12	179.3
7-9	13-18	300.0
10	19-20	179.3
11-13	21-26	300.0
14-20	27-41	240.5
21-27	42-56	198.2
28-30	57-59	184.7
31-32	60-65	220.0
33-34	66-73	184.7
35	74-79	300.0
36-39	80-88	219.8
40-49	89-105	219.4
50-55	106-117	300.0
56-63	118-133	215.6
64-78	134-167	308.1
79-82	168-177	300.0
83-102	178-219	218.0
103-105	220-224	286.0
106-118	225-249	257.0
119-122	250-256	271.0

## 3. XBeach model setup

### 3.1. The XBeach model

XBeach is a public-domain model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the near-shore area, supported by a consortium of UNESCO-IHE, Deltares, Delft University of Technology, and the University of Miami (Roelvink *et al.*, 2009). An overview of the capabilities of XBeach is given in reports WL2010R744\_30\_3 and WL2012R744\_30\_13 (Zimmermann *et al.*, 2011, 2015). The XBeach version v1.21.3657 ('Groundhog Day' release<sup>2</sup>) was used for all modelling within this report.

The storm was simulated over a period of 78 hours (273600 seconds or 6 tidal cycles) from 2013-12-04 19:30 until 2013-12-07 23:30 (dashed vertical lines, Figure 2-3). A comprehensive list of all model input parameters for the basic model setup (setup 0) is given in Appendix B.

### 3.2. Model grid

The XBeach model grid uses a variable cross-shore grid spacing that ranged from 20 m in the offshore region to 2m on the intertidal beach and dune area. The exact grid spacing was determined automatically using the XBeach Matlab toolbox, which chooses the grid spacing to optimize the CFL criterion. The total number of cross-shore grid rows ( $n_x$ ) was on the order of 170 for all profiles.

Following the findings on directional wave spreading in 1D and 2D model configurations that are presented in Chapter 4, five grid rows ( $n_y = 5$ ) with a grid spacing of 200 m were used in the alongshore direction of the model, with an alongshore uniform bathymetry.

The evolution of short waves across the near-shore is modelled in XBeach using a spectral wave model. 28 directional bins ranging from  $-70^\circ$  to  $+70^\circ$  from shore-normal and a bin width of  $5^\circ$  were used to describe the directional distribution of the short waves.

### 3.3. Physical processes

The default configuration of XBeach was used to model hydrodynamics:

- Infragravity (long) waves are modelled using a (phase-resolving) non-linear shallow water equation solver
- Short wave propagation is modelled using a spectral wave model.
- Sediment transport was using the formulation of van Thiel-Van Rijn formulation.

The following functions of XBeach were not used:

- Non-hydrostatic flow
- Groundwater flow
- Quasi-3D effects
- Short-wave runup

No morphological acceleration (*morfac*) was used. Preliminary testing showed that predicted sediment transport volumes deviated from the no-morfac case for morfac as low as 2. This is likely due to the combination of a large tidal range and a shallow beach slope, which can result in unrealistic (cross shore) current velocities when the tidal cycle is artificially sped up using morphological acceleration.

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<sup>2</sup> Since all XBeach releases are named after a popular holiday that occurs around the date of the release, "Groundhog day" presumably refers to the American holiday, not the movie.

### 3.4. Boundary conditions

A weakly absorbing boundary condition was used at the seaward boundary of the flow model (the XBeach default). The water level was supplied by the tide gauge measurements (§2.3.1) and the wave input from the SWAN model (§2.3.2) output at the offshore point of each profile. Neumann (no-gradient) boundary conditions were used as the lateral boundary conditions.

### 3.5. Calibration values

A number of semi-empirical parameters are used within XBeach to describe various processes. Two sets of calibration values were used within this study (Table 3-1). The first set of calibration values, the Groundhog Day (GHD) calibration set, contains the default values used in the Groundhog Day release of XBeach. Most of these calibration values were also the default values in earlier versions of XBeach.

The second set of calibration values is the WTI (Wettelijk Toetsinstrumentarium) calibration set, which was provided by Deltares, determined using an extensive calibration of XBeach based on a large database of laboratory and field measurements (van Geer *et al.*, 2015).

For the parameters other than those listed in Table 3-1, the default values were used. These are the same in the GHD and WTI calibration sets. An extensive list of all calibration values is listed in Appendix B.

Table 3-1: Calibration values for the Groundhog Day (GHD) calibration set and the “Wettelijk Toetsinstrumentarium” (WTI) calibration set

Parameter name used in XBeach	Description	GHD	WTI
fw	Bed friction factor (for waves)	0.000	0.000
cf	Bed friction factor (for flow)	0.003	0.001
gammax	Parameter for depth-induced breaking: maximum ratio Hrms/hh	2.000	2.364
beta	Breaker slope coefficient in roller model	0.100	0.138
wetslp	Critical avalanching slope under water	0.300	0.260
alpha	Wave dissipation coefficient	1.000	1.262
facSk	Calibration factor for wave skewness effect on sediment transport	0.100	0.375
facAs	Calibration factor for wave asymmetry effect on sediment transport	0.100	0.123
gamma	Breaker parameter in Baldock or Roelvink formulation	0.550	0.541

## 4. Modelling methodology: the effect of wave directional spreading in XBeach 1D and 2D

### 4.1. Introduction

The morphological response of beach and dune systems to coastal storms often shows significant alongshore variability (De Winter *et al.*, 2015) and modelling is increasingly performed in 2D mode (e.g., Abanades *et al.*, 2014; Lindemer *et al.*, 2010; McCall *et al.*, 2010). However, 1D cross-shore models are still commonly used, e.g. for larger timescales or when no detailed 2D bathymetry is available (e.g., Pender & Karunaratna, 2013). The 1D approach neglects alongshore variability in sediment transport due to alongshore differences in the bathymetry, but also due to alongshore variation in wave run-up due to wave directional spreading.

Wave directional spreading is known to affect wave runup (Guza & Feddersen, 2012), wave overtopping (Hiraishi & Maruyama, 1998; Suzuki *et al.*, 2014), and near-shore infragravity wave energy (Van Dongeren *et al.*, 2003). Reniers *et al.* (2004) also found that directional spreading of infragravity waves has an effect on alongshore rip spacing. Van Thiel De Vries *et al.* (2010) found that storm-induced beach profile change is affected by wave directional spreading as well.

The directionality of the wave field is expressed by the two-dimensional spectrum  $S(f, \theta)$  where  $f$  is the frequency and  $\theta$  is the wave direction angle. The directional distribution of wave energy at a given frequency  $f$  is then (Kuik *et al.*, 1988):

$$D_f(\theta) = \frac{E(f, \theta)}{\int_0^{2\pi} E(f, \theta) d\theta} \quad (1)$$

In general, the directional distribution can be different for each frequency. In this report, the directional distribution is calculated at the most energetic frequency and the subscript  $f$  is subsequently dropped. The directional width  $\sigma$ , a measure of directional spreading, is defined following Kuik *et al.* (1988):

$$\sigma = \frac{180^\circ}{\pi} \sqrt{2(1 - m_1)} \quad (2)$$

where

$$m_1 = \sqrt{a_1^2 + b_1^2} \quad (3)$$

$$a_1 = \int_{0^\circ}^{2\pi} \cos(\theta) D(\theta) d\theta \quad (4)$$

$$b_1 = \int_0^{2\pi} \sin(\theta) D(\theta) d\theta \quad (5)$$

A typical form of the directional distribution is (Longuet-Higgins *et al.*, 1963; Mitsuyasu *et al.*, 1975):

$$D(\theta) = D_0 \cos^{2s} \left( \frac{\theta - \theta_0}{2} \right) \quad (6)$$

where  $D_0$  is a normalization constant and  $s$  is the directional spreading parameter.  $s$  and  $\sigma$  are related by

$$\sigma = \frac{180}{\pi} \sqrt{\frac{2}{s+1}} \quad (7)$$

Another definition of the directional distribution is

$$D(\theta) = K \cos^m(\theta - \theta_0) \quad (8)$$

Distributions (6) and (8) are highly similar for  $s = 2m + 1$ .

The XBeach model uses a dual approach to model near-shore waves. Short waves (gravity waves) are modelled using a time-varying wave-action balance, similar to the HISWA model (Holthuijsen *et al.*, 1989). Within this spectral model, several frequency and directional bins can be incorporated to account for the effect of directional spreading. Long (infragravity) waves and mean flows are modelled using the shallow water equations. As a result, the possible long wave modes that are allowed within a model domain depend on the domain geometry (grid spacing and alongshore and cross-shore domain size). For example, edge waves, which constitute a significant fraction of the total near-shore wave energy in the near-shore (Herbers & Elgar, 1995; Herbers *et al.*, 1994; Huntley *et al.*, 1981), only exist as solutions of a two-dimensional flow field, and can therefore not be generated in a one-dimensional model domain (Svendsen, 2006).

In summary, directional wave spreading, both in the short and long wave band, is likely to have an effect on near-shore sediment transport. In XBeach, directional spreading in the long wave band can only be resolved using a 2D model setup. It is therefore hypothesized that in cases where directional spreading is important, a 2D model setup, which resolves wave directional spreading, yields different sediment transport predictions than an equivalent 1D model. This hypothesis was investigated using XBeach model runs, first using idealized simulations that focus on hydrodynamics (§4.2) and then using realistic storm cases that focus on sediment transport (§4.3).

## 4.2. Idealized case simulations

A first set of simulations were conducted to investigate the effect of directional spreading, focusing on hydrodynamics. In the first instance, the simulations were run with a fixed bed level (sediment transport disabled) to calculate hydrodynamic parameters. The simulations were then repeated with sediment transport enabled to illustrate the impact on sediment transport and beach profile change.

When directionally spread waves are specified at the model offshore boundary, this impacts both the short and long wave generation in the model. Even though a 2D wave field is not possible in a 1D model domain, specifying a directional spreading still impacts the long wave field in a 1D model because of the way that long waves are generated following Van Dongeren *et al.* (2003). Therefore, the effect of “directional spreading” in this section refers to both long and short wave directional spreading, unless specified otherwise.

The pre-storm profile number 48 (Mariakerke) of the December 2013 storm dataset was used as the bathymetry (Figure 4-1a). The offshore boundary conditions were schematised for this exercise, and consisted of a constant water level of +4m TAW and shore-normal incident waves with a JONSWAP spectrum with  $H_{m0} = 3.0$  m,  $T_p = 8$  s. The GHD calibration parameters (Table 3-1) were used for all runs since the WTI parameters were not yet available when the simulations were conducted. The modelled period was 4 hours.

Runs that included directional spreading had a directional distribution following equation (6) with  $s = 12$  ( $\sigma = 22,5^\circ$ ), a representative value for short-crested waves observed in nature (Goda, 2010). For the runs with directional spreading, the directional spectrum was discretized by the spectral model using 28 directional bins with bin widths of  $5^\circ$  ranging between  $-70^\circ$  and  $+70^\circ$  degrees relative to shore-normal.

Table 4-1: Overview of idealized runs to investigate directional spreading

Case	Ny	dy	Along-shore Length of the domain	Directional spreading?	Erosion Volume Shore-normal wave condition	Erosion Volume Shore-oblique wave condition (25°)
1D_NOSPREAD_0	0	/	/	No	-5.36 m <sup>3</sup> /m	-0.75 m <sup>3</sup> /m
2D_NOSPREAD_50	50	20 m	1000m	No	-4.63 m <sup>3</sup> /m	-0.76 m <sup>3</sup> /m
1D_SPREAD_0	0	/	/	Yes	-4.05 m <sup>3</sup> /m	-3.53 m <sup>3</sup> /m
2D_SPREAD_5	5	200 m	1000m	Yes	-2.62 m <sup>3</sup> /m	-2.62 m <sup>3</sup> /m
2D_SPREAD_8	8	125 m	1000m	Yes	-2.31 m <sup>3</sup> /m	-2.39 m <sup>3</sup> /m
2D_SPREAD_50	50	20 m	1000m	Yes	-1.57 m <sup>3</sup> /m	-2.08 m <sup>3</sup> /m
2D_SPREAD_150	150	20 m	3000m	Yes	-1.73 m <sup>3</sup> /m	-2.23 m <sup>3</sup> /m

7 different simulations were performed (summarized in Table 4-1). 2 simulations were run in 1D ('superfast'<sup>3</sup>) mode (ny = 0, where ny is the number of alongshore grid rows): a simulation that included wave directional spreading (1D\_SPREAD\_0) and a simulation that did not include spreading (1D\_NOSPREAD\_0). Furthermore, four 2D simulations were performed over a domain with an alongshore width of 1000 m and an alongshore uniform bathymetry. 2D\_SPREAD\_50 and 2D\_NOSPREAD\_50 were simulations with and without directional spreading, respectively, that used 50 grid rows in the alongshore (ny = 50) with a grid spacing of dy = 20 m. 2D\_SPREAD\_5 is an additional 2D simulation with directional spreading, but with 5 alongshore grid rows (ny = 5, dy = 200 m). 2D\_SPREAD\_8 is similar but with 8 alongshore grid rows (ny = 8, dy = 125 m). Finally, a fifth 2D simulation was performed over a domain with an alongshore width of 3000 m, an alongshore uniform bathymetry, 150 grid rows in the alongshore and a grid spacing of dy = 20 m, in order to test if the alongshore domain width of 1000 m is sufficient.

The following parameters were calculated from the XBeach output:

- $\bar{\eta}$  (m), the mean water level (including wave setup)
- $\sigma_{\text{short}}$  (°), the directional spreading width of the short waves.
- $H_{\text{rms,IG}}$ , the rms (root mean square) wave height of the infragravity wave field, defined as  $\sqrt{8}\bar{\eta}_{\text{rms}}$ , where  $\eta_{\text{rms}}$  is the rms of the free surface elevation. This is proportional to the square root of the potential energy of the waves.
- $u_{\text{rms,IG}}$ , the rms cross-shore velocity of the infragravity wave field. This is proportional to the square root of the kinetic energy of the cross-shore wave motions.
- $v_{\text{rms,IG}}$ , the rms alongshore velocity of the infragravity wave field. This is proportional to the square root of the kinetic energy of the alongshore wave motions.

The first hour of the model time series were considered to be ramp-up of the wave field and were not taken into account for the calculation of mean and rms values. In the calculation of  $u_{\text{rms,IG}}$  and  $v_{\text{rms,IG}}$ , the mean value was subtracted out before calculating the rms value to remove mean currents such as the undertow.  $\sigma_{\text{short}}$  (°) was calculated using equations (2)-(5) from the XBeach model output of  $D(\theta)$ .

Model results for all cases are displayed in Figure 4-1. Figure 4-2 - Figure 4-4 show the same graphs as Figure 4-1 but only for a subset of the cases, in order to facilitate the comparison. First, the behaviour of the short wave directional spreading width  $\sigma_{\text{short}}$  is investigated (Figure 4-1b). The evolution of  $\sigma_{\text{short}}$  is nearly identical for all run cases, indicating that differences in sediment transport (see below) are not caused by differences in the wave spreading in the short wave band. The spreading width shows the expected behaviour:  $\sigma_{\text{short}}$  decreases as the water depth decreases toward the shoreline as waves that propagate in a shore-oblique direction refract toward shore-normal.

<sup>3</sup> 'Superfast' is the internal reference to the default 1D mode of XBeach. In this mode, calculations are performed on one row of cells. Alongshore gradients and fluxes are not calculated or taken into account into the equations.

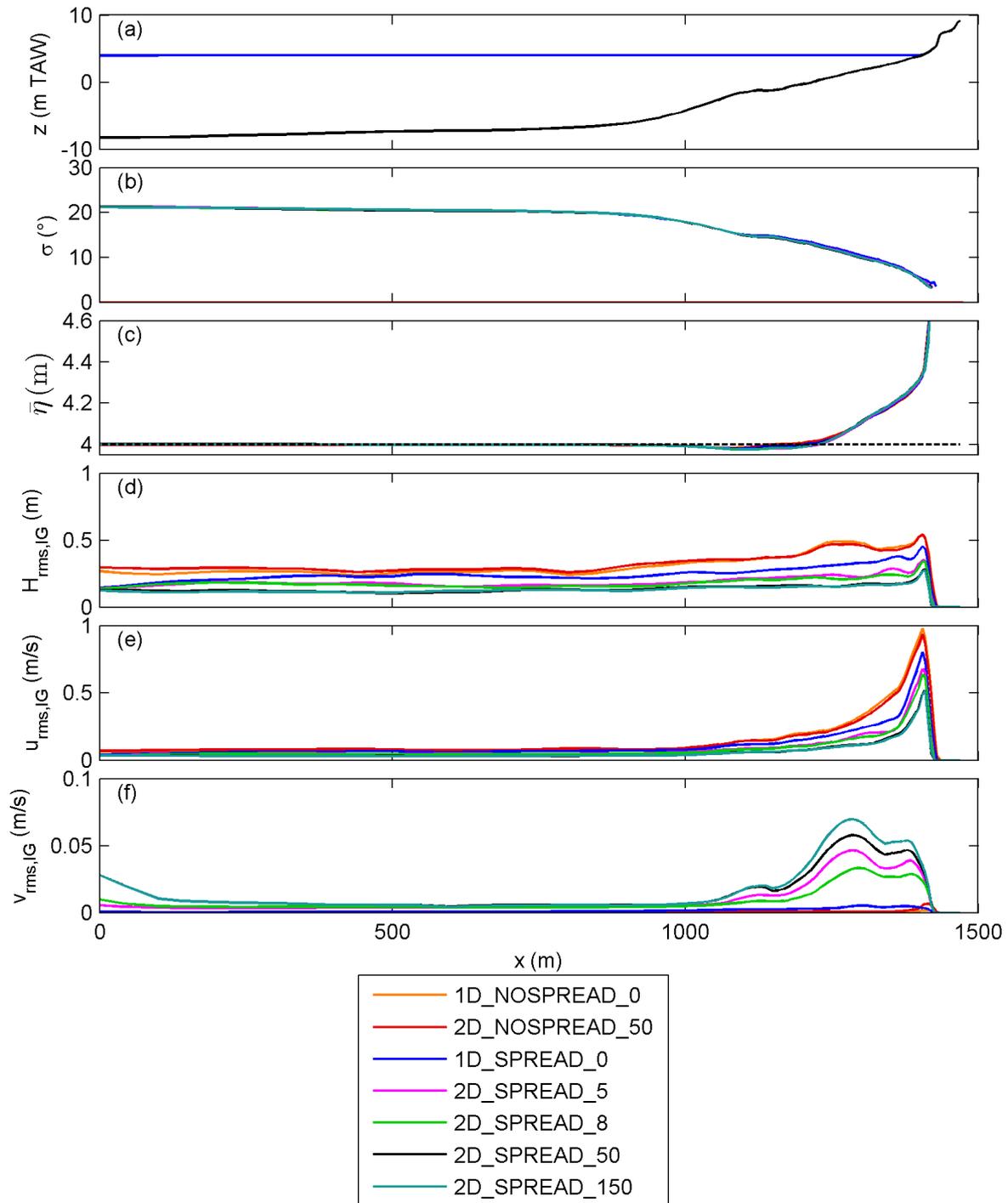


Figure 4-1: Model results for fixed bed model simulations with shore-normal wave incidence (all cases). (a) Still water level (blue) and beach profile (black). (b) Short wave directional spreading  $\sigma$  (note that this value is zero for 1D\_NOSPREAD\_0 and 2D\_NOSPREAD\_50). (c) Mean waterlevel including wave setup  $\bar{\eta}$ . (d) RMS infragravity wave height. (e) RMS infragravity cross-shore velocity. (f) RMS infragravity alongshore velocity.

Secondly, the 1D and 2D cases in which the model is forced with waves with no directional spreading are analysed (Figure 4-2, 1D\_NOSPREAD\_0, orange curves, and 2D\_NOSPREAD\_50, red curves). For these cases, XBeach configurations in 1D and 2D yield results that are nearly identical for all parameters.

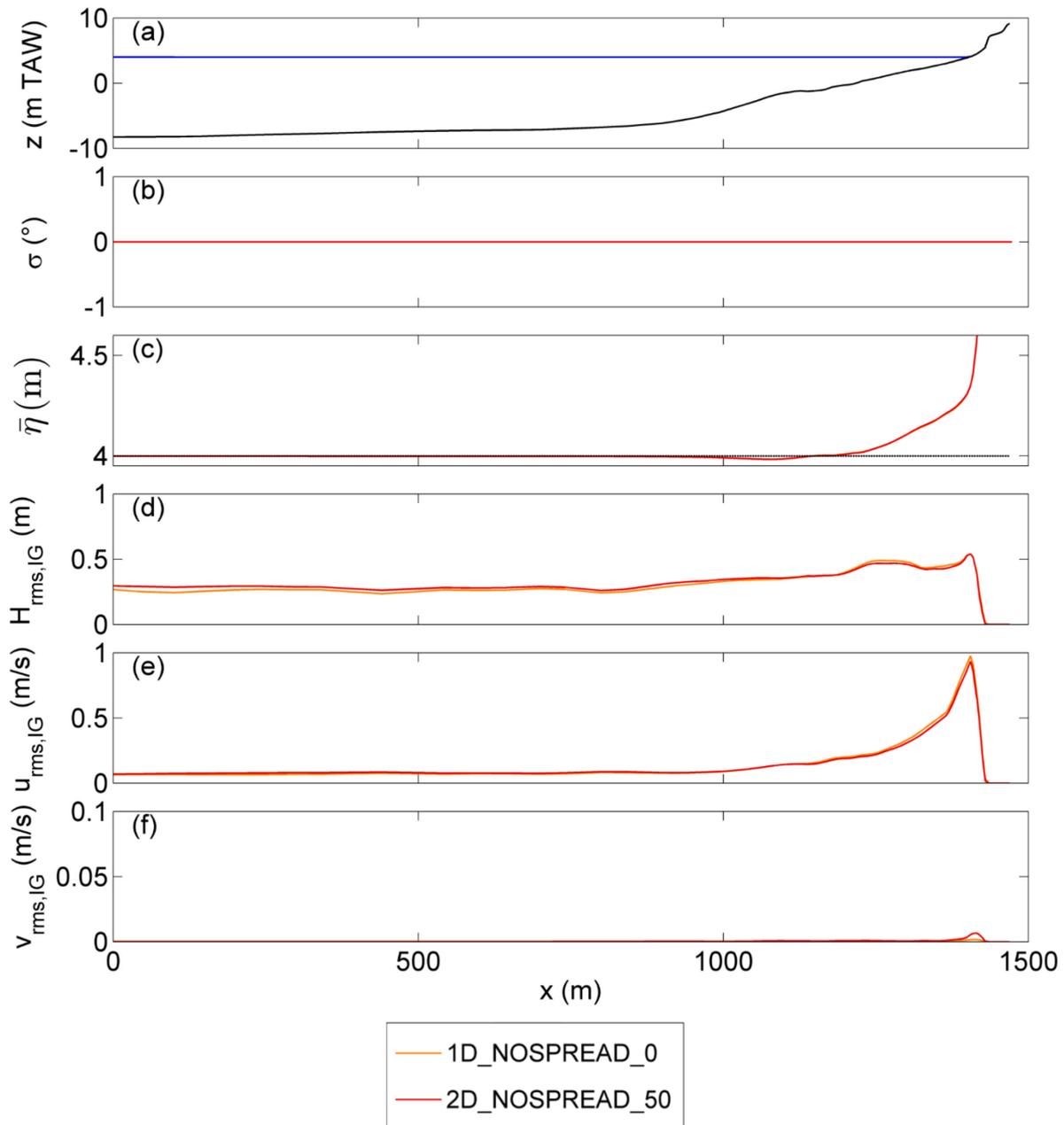


Figure 4-2: Model results for fixed bed model simulations with shore-normal wave incidence (no-spreading cases only). (a) Still water level (blue) and beach profile (black). (b) Short wave directional spreading  $\sigma$ . (c) Mean waterlevel including wave setup  $\bar{\eta}$ . (d) RMS infragravity wave height. (e) RMS infragravity cross-shore velocity. (f) RMS infragravity alongshore velocity.

Next, the effect of directional spreading is investigated, starting with the 2D runs with  $n_y = 50$ , as this geometry is assumed to be the most realistic and detailed representation of the near-shore wave field (Figure 4-3). The wave setup (Figure 4-1c) is nearly identical for the case with wave spreading (2D\_SPREAD\_50, black curves) and the case with no spreading (2D\_NOSPREAD\_50, red curves). This is due to the fact that wave setup is caused by gradients in the short-wave radiation stress  $\frac{\partial S_{xx}}{\partial x}$  and because the short wave field is simulated in the same way by the spectral model for both cases. The infragravity wave height, however, is roughly a factor 2 smaller for the spreading case than for the no-spreading case. This finding is in agreement with results of Van Dongeren *et al.* (2003) and van Thiel De Vries *et al.* (2010). Similarly, the RMS cross-shore infragravity velocity (Figure 4-1d) is reduced by a factor 2 for the directional spreading case. The RMS alongshore infragravity velocity field (Figure 4-1e) is near zero when no directional spreading is present. The alongshore velocity is larger for the case of directional spreading, but still an order of magnitude smaller than cross-shore velocities. In summary, the

modelled near-shore infragravity wave field is less energetic when directional spreading is present at the offshore boundary condition.

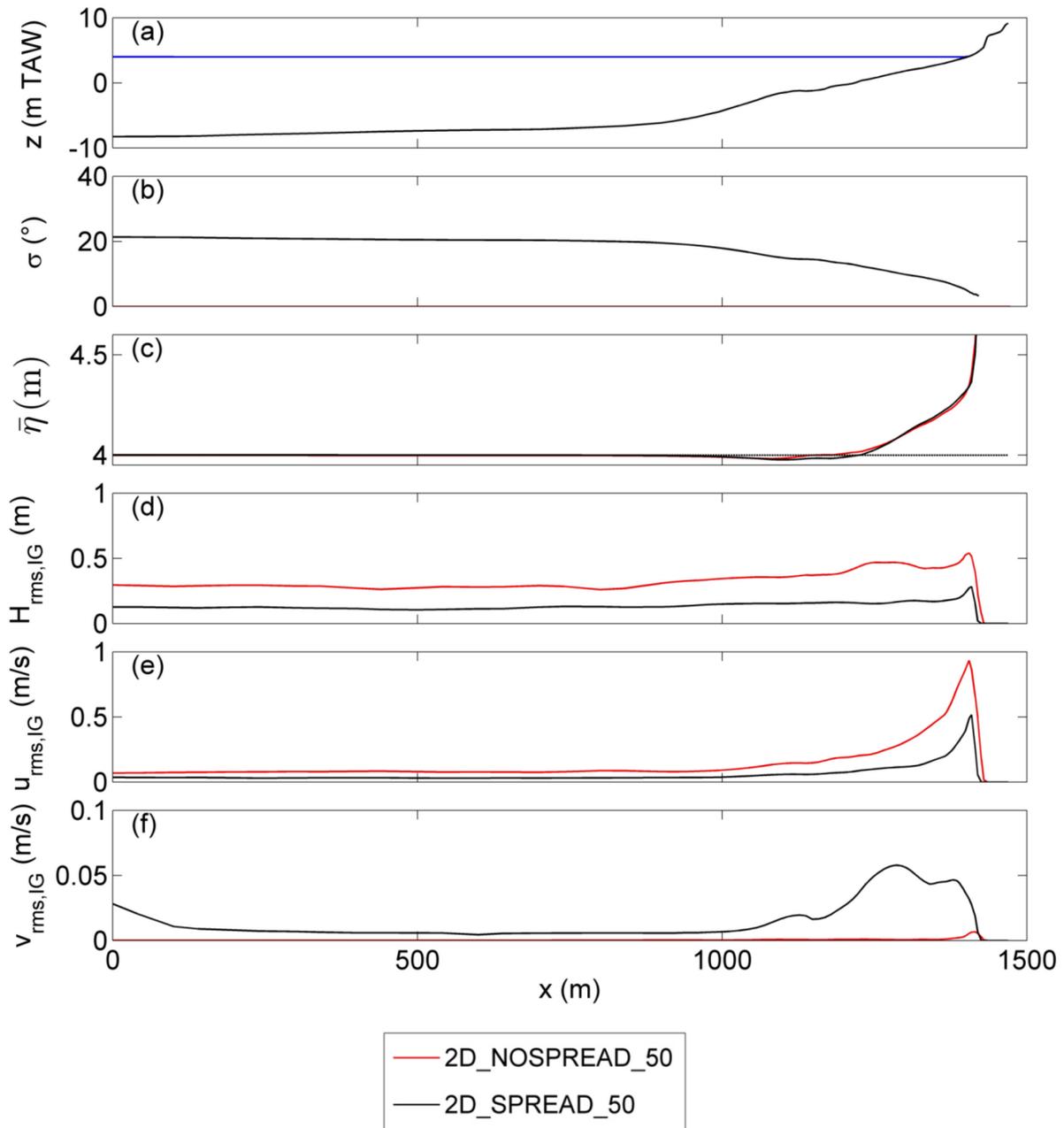


Figure 4-3: Model results for fixed bed model simulations with shore-normal wave incidence ( $n_y = 50$  cases only). (a) Still water level (blue) and beach profile (black). (b) Short wave directional spreading  $\sigma$ . (c) Mean waterlevel including wave setup  $\bar{\eta}$ . (d) RMS infragravity wave height. (e) RMS infragravity cross-shore velocity. (f) RMS infragravity alongshore velocity.

Looking at the different configurations with directional spreading in Figure 4-4, the one-dimensional simulation that includes directional spreading (1D\_SPREAD\_0, blue curves) shows a surf zone infragravity field that is less energetic than the case with no directional spreading, but more energetic than the two-dimensional case. The two-dimensional simulations with a limited number of alongshore grid rows (2D\_SPREAD\_5, 2D\_SPREAD\_8) display a surf zone that is still more energetic than the full 2D simulation, but already shows significant improvement over the one-dimensional case.

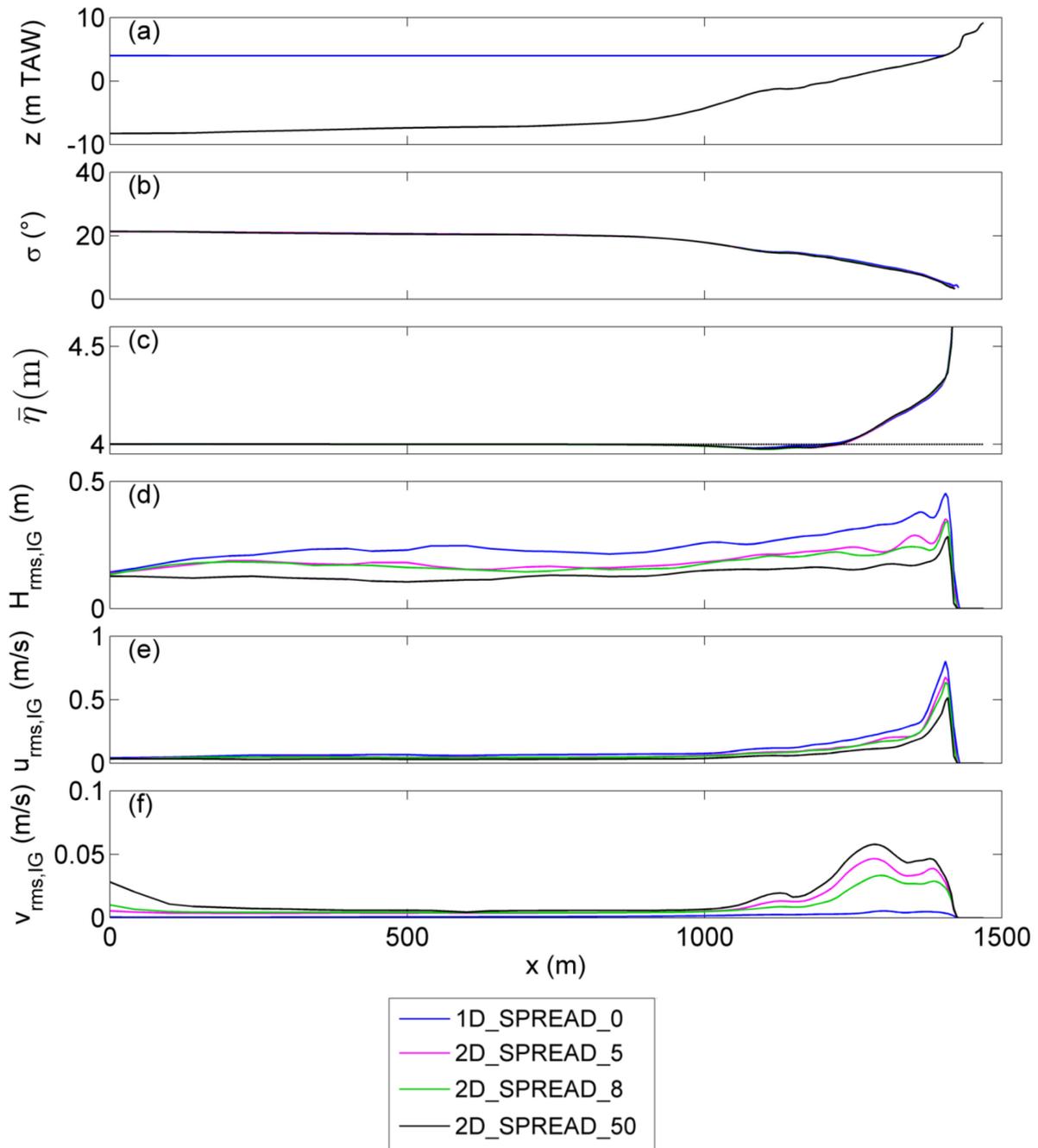


Figure 4-4: Model results for fixed bed model simulations with shore-normal wave incidence (cases with wave spreading only). (a) Still water level (blue) and beach profile (black). (b) Short wave directional spreading  $\sigma$ . (c) Mean waterlevel including wave setup.

The effect of the difference in long wave energy on sediment transport is displayed in Figure 4-5 and Table 4-1. As expected, simulations with a more energetic long wave field display more erosion. The erosion volume (calculated as the volume change landward of  $x = 1391$  m, the pivot point between erosion and deposition) of the full 2D case with spreading is less than half of the volume for the 1D case with spreading. The 2D cases with a limited number of grid rows (2D\_SPREAD\_5, 2D\_SPREAD\_8) again form an improvement over the 1D case in approximating the full 2D solution. The run 2D\_SPREAD\_150 (with a domain width of 3000 m) shows results for the hydrodynamics that are in close agreement with the run 2D\_SPREAD\_50 (domain width 1000 m). The difference in erosion volume is small but not negligible. It is concluded that a domain width of 1000 m provides results that are reasonably accurate.

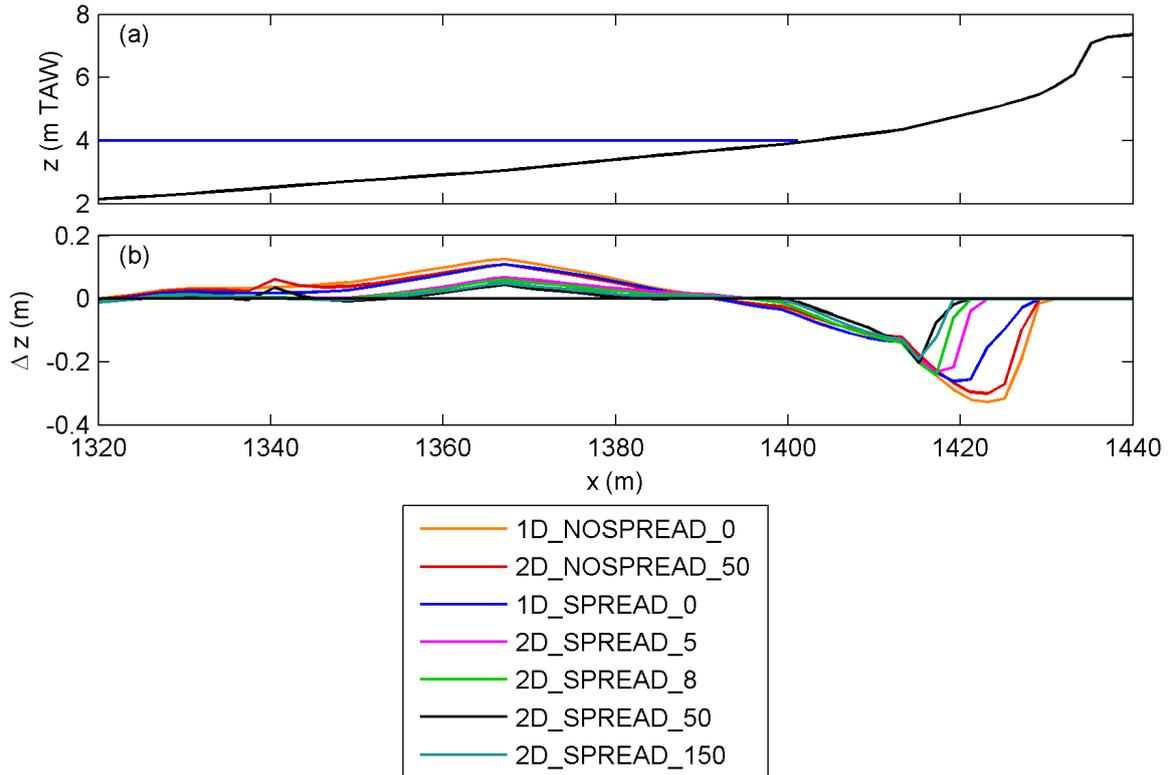


Figure 4-5: Model results for hydrodynamics-focused model simulations with shore-normal wave incidence  
(a) Still water level (blue) and beach profile (black). (b) Bed level change (m).

The simulations were then repeated with shore-oblique waves with a wave incidence angle of 25° relative to shore-normal. Results are displayed in Figure 4-6. The results are consistent with the findings of the shore-normal simulations, except for the following things:

- The wave setup (Figure 4-6c) is much smaller for the no-spreading cases, both in 1D and 2D. This result can be expected from physical arguments, since the lack of directional spreading means that less wave energy is directed in the shore-normal direction. As a result, the erosion volumes are also smaller.
- The near-shore infragravity wave field is no longer near-identical for the no-spreading cases in 1D and 2D. The wave field is more energetic in the 2D case than in the 1D case.
- There is still a difference in near-shore infragravity wave energy between the 1D and 2D cases with directional spreading, but it is smaller than in the shore-normal case. As a result, the erosion volumes also differ less.

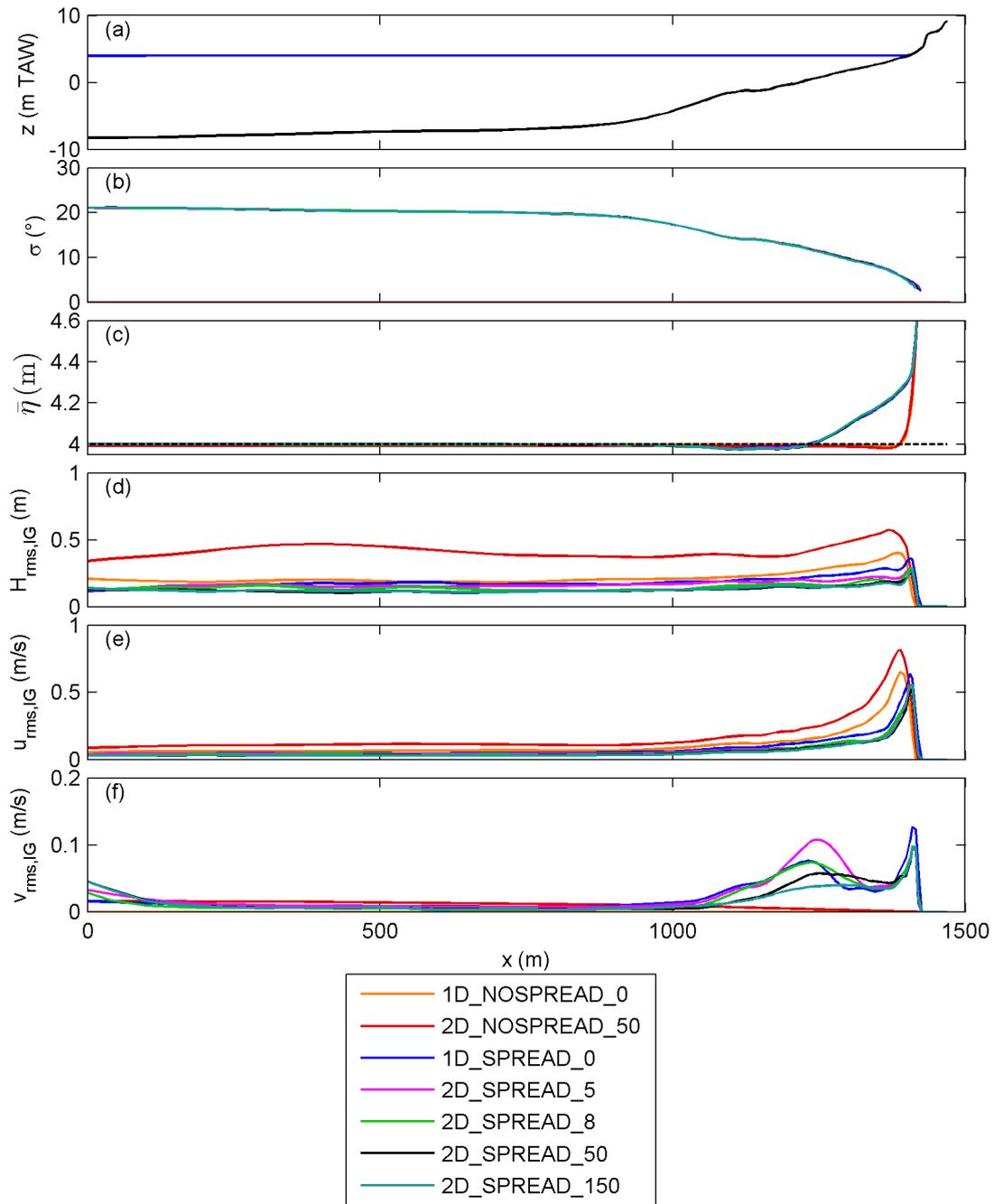


Figure 4-6: Model results for fixed bed simulations with shore-oblique wave incidence.  
(a) Still water level (blue) and beach profile (black). (b) Short wave directional spreading  $\sigma$ . (c) Wave setup  $\bar{\eta}$ .  
(d) RMS infragravity wave height. (e) RMS infragravity cross-shore velocity.  
(f) RMS infragravity alongshore velocity.

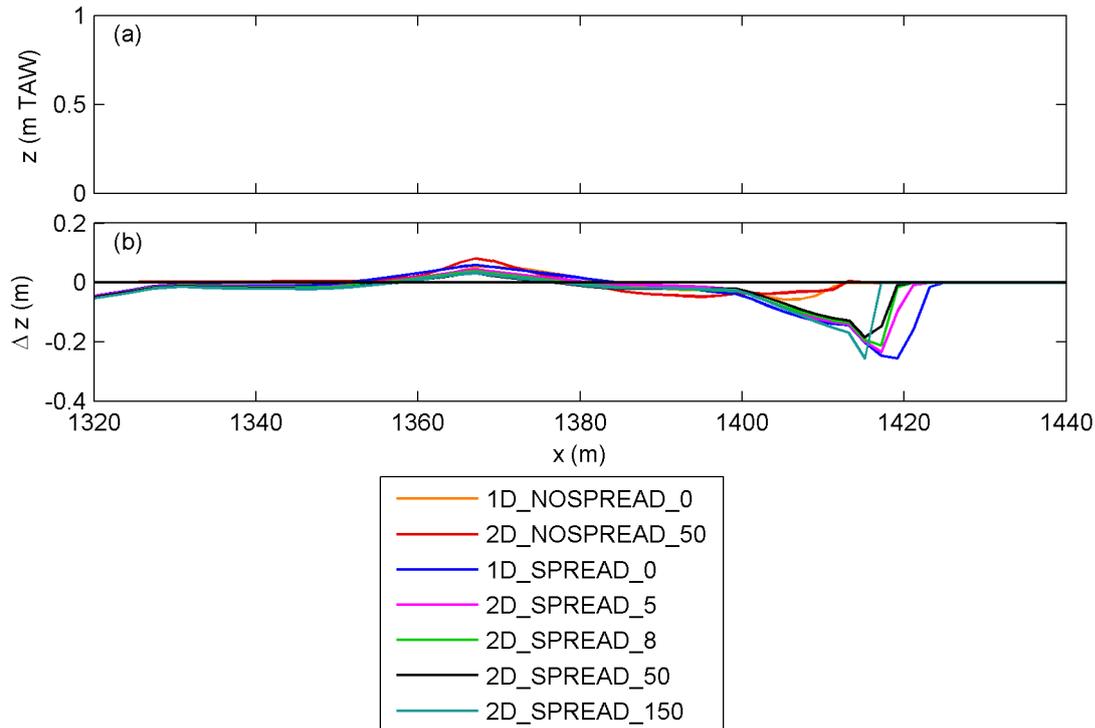


Figure 4-7: Model results for hydrodynamics-focused model simulations with shore-oblique wave incidence. (a) Still water level (blue) and beach profile (black). (b) Bed level change (m).

### 4.3. Storm case simulations

The previous section discussed simulations under simplified conditions such as a constant offshore wave height and constant water level. Simulation results indicated that for cases with wave directional spreading, the modelled infragravity wave field in the surf zone is more energetic when a 1D model is used, resulting in a higher predicted erosion volume compared to a 2D model. 2D model configurations with a limited number of alongshore grid rows incorporate part of the effect of directional spreading but do not fully replicate the full 2D solution. Depending on the desired accuracy and the computation capabilities, such ‘sparse 2D’ models may provide an acceptable compromise by accounting for part of the directional spreading effect, at a lower computational cost than a full 2D model. This section further explores this notion by modelling the full December 2013 storm over 6 different profiles and with time-varying water level and wave condition time series that correspond to the conditions measured during the December 2013 storm. Since the wave conditions are based on measured time series (and SWAN-modelling), the wave incidence angle is not shore-normal.

Six profiles (profiles 48, 60, 65, 110, 114, and 119) were chosen that have a good geographical coverage of the Belgian coastline and for diversity in the beach profile shape and erosion type (beach erosion vs. dune erosion). No profiles west of Middelkerke (profile numbers 39 and below) were included because the beach was locally reworked by bulldozers to remove beach scarps between the end of the storm and the post-storm survey, so that measured erosion volumes are not as reliable as the profiles east of Middelkerke. Introductory analysis of the measurements showed that the beach profile response on most sections was that sediment was removed landward of the +5m TAW contour and deposited seaward of the +5m TAW contour (see also section 5.1.1). The erosion volume was therefore calculated as the sediment volume change (per unit alongshore width) of the profile landward of the +5m contour. Pre-storm profiles for the 6 transects are shown in Figure 4-8.

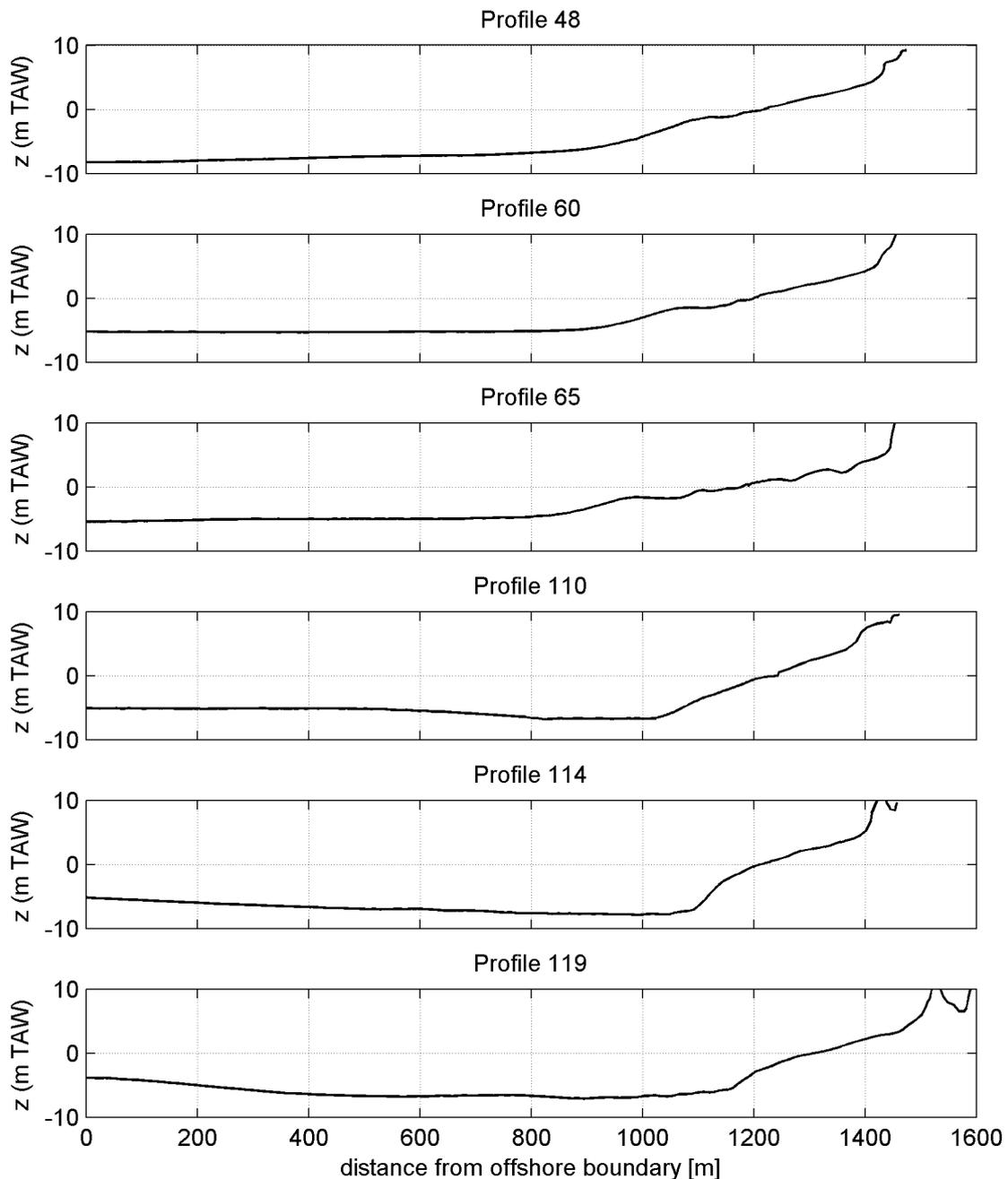


Figure 4-8: Pre-storm profiles for profiles 48, 60, 65, 110, 114, and 119

Model simulations were performed with a 1D model and three 2D models with 5, 8 and 50 alongshore grid rows and an alongshore domain width of 1000 m. In addition, simulations were conducted with a “wide” 2D model with a domain width of 2400 m and 120 grid cells, in order to test if the 1000 m – width models were sufficiently wide in the alongshore. All simulations were performed with the WTI calibration parameters. Modelled and measured erosion volumes are displayed in Figure 4-9 and listed in Table 4-2. The measured and predicted pre- and post-storm profiles from the 2D model with  $n_y = 50$  are displayed in Appendix C.

The emphasis of this section is to compare the different model results against each other, rather than to compare the model results with the measured erosion volume. After all, the agreement between modelled and measured erosion volumes is highly dependent on the calibration factors used (see §0), whereas the difference between the different model setups is purely due to the physics captured by the different models. If the model user assumes that the 1D model provides a good representation of an alongshore-uniform 2D model domain, then the predicted erosion volumes from the 1D model should be in close agreement to the 2D model for all profiles.

First, the “basic” 2D simulation with 1000 m domain width and  $\Delta y = 20$  m ( $n_y = 50$ ) is compared with the “wide” 2D simulation with 2400 m domain with and  $\Delta y = 20$  m ( $n_y = 120$ ) to assess whether an alongshore domain width of 1000 m is sufficient. The difference in erosion volumes predicted by the basic and wide 2D models is relatively small (6% difference on average). Keeping in mind that the wide 2D model is 140% more computationally expensive than the “basic” 2D model, the “basic” 2D model with a 1000 m domain width is deemed sufficiently accurate (the wide 2D model had a typical computation time of 23 hours on 2 processors, and the “basic 2D” model had a typical computation time of 10 hours on 2 processors).

Comparing the “basic” 2D model ( $n_y = 50$ ) with the 1D model, predicted erosion volumes by the 1D model are considerably higher than the 2D model (Figure 4-9). The overestimation by the 1D model compared to the 2D model ranges between 25% and 57%. The lightweight model with  $n_y = 8$  predicts erosion volumes that differ by up to 10% from the 2D configuration. The lightweight model with  $n_y = 5$  predicts erosion volumes that differ by 15% from the 2D configuration.

Comparing the model results to the measured erosion volumes, the 1D model appears to be in better agreement with measurements for profiles 48 and 60, whereas the 2D models display a better agreement for the other 4 profiles. Model-data agreement, however, depends on many factors such as model calibration, how well the true bathymetry is represented by the alongshore-uniform profile, whether the local wave and flow boundary conditions are a good representation of the true local conditions during the storm, et cetera. For this reason, the model-data agreement was investigated (for the 1D and 2D models) for the full dataset of 110 measured profiles in §5.3. Only the sparse 2D model ( $n_y = 5$ ) and the 1D model were calculated for all 110 profiles; the full 2D model and the sparse 2D ( $n_y = 8$ ) were not due to the prohibitive computational cost. For the entire dataset, erosion volumes predicted by the sparse 2D model are in substantially better agreement with measurements than predictions by the 1D model, which generally overestimates the measured erosion volume.

In conclusion, simulations of 6 example profiles show that a 1D XBeach model may predict erosion volumes that are different by over 50% compared to a 2D model with an alongshore uniform bathymetry. Lightweight 2D models with  $n_y = 5$  or  $n_y = 8$  predict erosion volumes that are relatively close to the predictions of the full 2D model. Which of the two lightweight models is ultimately recommended ( $n_y = 5$  or 8) is dependent on the level of accuracy and computational effort desired by the model user (the  $n_y = 8$  simulations had a typical runtime of 2 hours on 2 processors, the  $n_y = 5$  simulations roughly 1.5 hours). Many other uncertainties are still present in models of beach profile change and the error for erosion predictions is in many cases larger than 15%. Since the  $n_y = 5$  setup yields results that are typically different by less than 15% compared to the full 2D model, this configuration is chosen for the modelling of the December 2013 storm (Chapter 5).

Table 4-2: Erosion volumes for profiles 48, 60, 65, 110, 114, and 119 for different numbers of along-shore grid rows.

Profile	Measurements	2D, $n_y = 50$	Wide 2D, $n_y = 120$	2D, $n_y = 8$	2D, $n_y = 5$	1D, $n_y = 0$
48	20.2 m <sup>3</sup>	12.7 m <sup>3</sup>	13.0 m <sup>3</sup>	13.5 m <sup>3</sup>	14.3 m <sup>3</sup>	18.6 m <sup>3</sup>
60	14.5 m <sup>3</sup>	10.1 m <sup>3</sup>	10.4 m <sup>3</sup>	10.4 m <sup>3</sup>	10.5 m <sup>3</sup>	14.2 m <sup>3</sup>
65	9.7 m <sup>3</sup>	8.7 m <sup>3</sup>	9.0 m <sup>3</sup>	9.4 m <sup>3</sup>	10.1 m <sup>3</sup>	13.7 m <sup>3</sup>
110	18.3 m <sup>3</sup>	20.4 m <sup>3</sup>	22.4 m <sup>3</sup>	22.6 m <sup>3</sup>	22.2 m <sup>3</sup>	26.1 m <sup>3</sup>
114	14.9 m <sup>3</sup>	13.6 m <sup>3</sup>	14.2 m <sup>3</sup>	13.4 m <sup>3</sup>	13.6 m <sup>3</sup>	17.8 m <sup>3</sup>
119	12.4 m <sup>3</sup>	14.5 m <sup>3</sup>	16.5 m <sup>3</sup>	15.1 m <sup>3</sup>	14.8 m <sup>3</sup>	18.0 m <sup>3</sup>

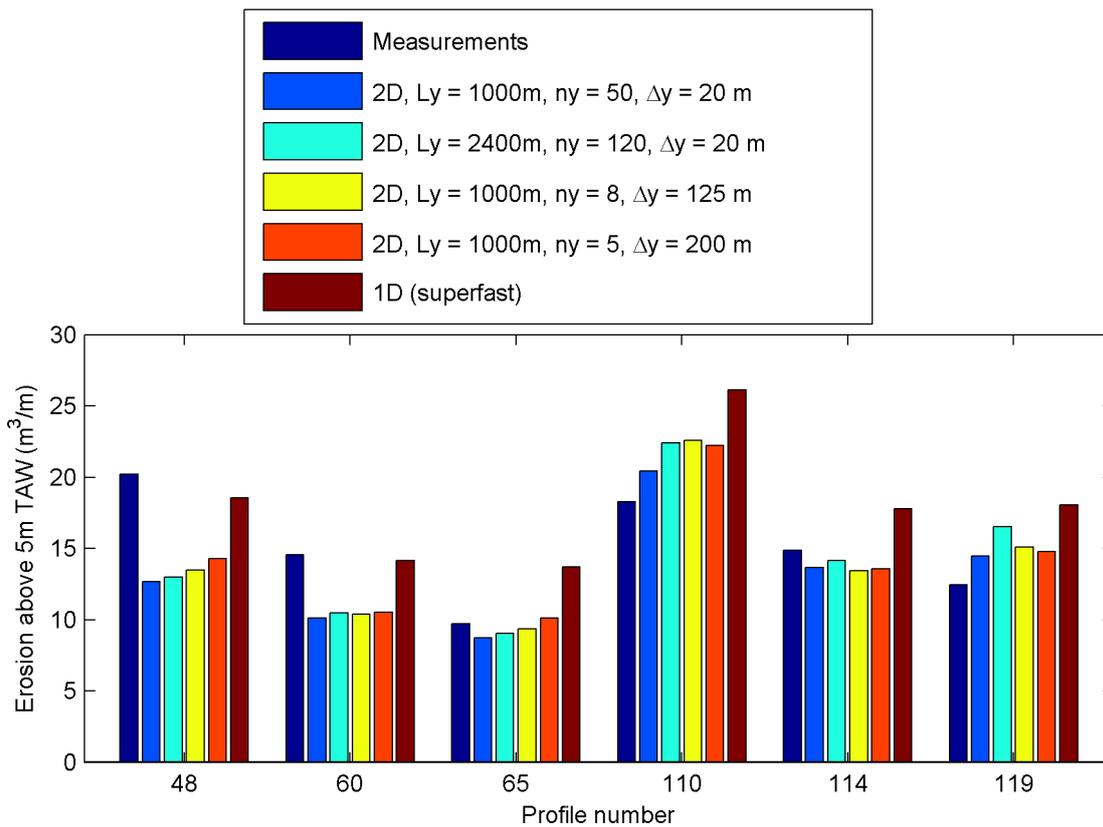


Figure 4-9: Erosion volumes for profiles 48, 60, 65, 110, 114, and 119 for different numbers of along-shore grid rows.

#### 4.4. Conclusions

Directional wave spreading, both in the gravity and the infragravity band, has an effect on near-shore hydrodynamics and morphodynamics. The numerical model XBeach models short waves using a spectral approach (where the wave directional distribution is discretized using direction bins) and long waves using a shallow water equation solver (phase-resolving approach). XBeach is commonly used in 1D and in 2DH mode, but a 1D cross-shore cannot resolve alongshore variability, e.g. due to edge waves or directionally spread infragravity waves.

XBeach simulations that focus on hydrodynamics show that for a 2D case, the near-shore long wave energy decreases when directional spreading is included, in agreement with findings of Van Dongeren *et al.* (2003). A 1D simulation that includes directional spreading has a near-shore infragravity wave field that is more energetic than the equivalent 2D simulation, indicating that directional spreading effects are not resolved accurately. As a result, simulations with no directional spreading or cases where directional spreading is not accurately resolved predict higher beach erosion volumes than the case where directional spreading is correctly resolved. Sparse 2D models with 5 or 8 alongshore grid rows display wave energy levels that approximate the 2D solution.

Simulations of a realistic storm case over 6 different beach profiles show that erosion volume predictions are up to 50% larger in a 1D simulation than a 2D simulation. Sparse 2D models result in predicted volumes that differ by up to 10% ( $n_y = 8$ ) or 15% ( $n_y = 5$ ) from the full 2D model. Based on these simulations, a new methodology for modelling the December 2013 storm is proposed: to use an alongshore-uniform beach profile with  $n_y = 5$  and alongshore grid spacing  $\Delta y = 200$  m (total domain width 1000 m).

## 5. December 2013 storm hindcast results

Results of the hindcast of the December 2013 storm are presented in this chapter. The following setups were calculated:

- Setup 0: The “standard” setup with the WTI calibration parameters and the sparse 2D approach ( $n_y = 5$ ).
- Setup 1: Using the same sparse 2D approach ( $n_y = 5$ ) and the GHD calibration parameters
- Setup 2: Using a true 1D simulation ( $n_y = 0$ ), and the WTI calibration parameters (setup 2a) or the GHD calibration parameters (setup 2b).
- Setup 3: Same settings as the standard setup (setup 0) but with a water level that was raised by 0.25 m, to test the sensitivity of erosion volumes on storm surge levels.
- Setup 4: Same settings as the standard setup (setup 0) but with offshore wave heights increased by 10%, to test the sensitivity of erosion volumes on wave heights.

### 5.1. Setup 0: Standard setup

Results for all profiles for setup 0 are displayed in Appendix D. The following two sections first illustrate the impact of the storm and the behaviour of the XBeach model for a few key profiles, and then give an overview of the erosion along the entire Belgian coast, including an assessment of the model-data agreement for the full dataset.

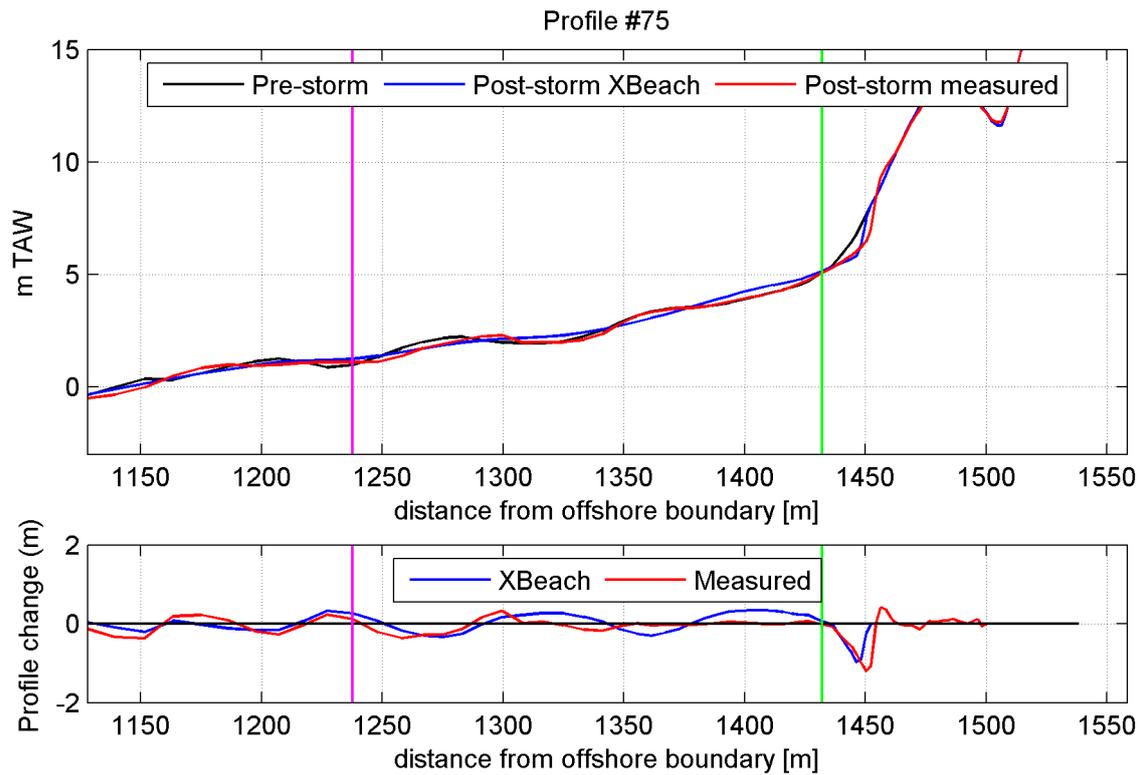
#### 5.1.1. Individual profile results

##### Profile 75

Results of profile number 75 (west of De Haan), are shown in Figure 5-1. A post-storm aerial picture of the location of profile 75 is displayed in Figure 5-2. The pre- and post-storm surveys of the intertidal beach (landward of the magenta vertical line) were conducted 3 days before and 4 days after the storm, respectively. On the foreshore (seaward of the magenta vertical line), however, the pre- and post-storm data was taken 10 months apart, and profile change can thus not be attributed to the December 2013 storm. For this reason, model-data agreement descriptors were only calculated for the section that was surveyed right before and after the storm (landward of the magenta line).

The measured pre- and post-storm profile displays a pivot point around the +5m TAW contour (green vertical line in Figure 5-2), with sand being removed landward of the +5m TAW contour (erosion) and deposited seaward of the +5m TAW contour. For this reason, erosion volumes were defined as the volume change (per unit alongshore width) landward of the +5 m contour line. Focusing on the measured (blue curve) and modelled (red curve) post-storm profile, sediment was removed landward of the +5 m contour line for both profiles, resulting in scarping of the dune (which is also visible in the aerial picture). The model slightly underpredicts the amount of dune scarping, resulting in a smaller predicted erosion volume. The dune scarping is controlled to a large extent by the parameters *wetslp* and *dryslp*, the critical slopes for avalanching below and above water. The aerial picture suggests that the dune fences and vegetation may have provided additional stability to the dune, highlighting the challenges in correctly representing the true beach state in the numerical model.

The eroded sediment was largely deposited between the seaward edge of the intertidal beach (purple line) and the +5m contour. A number of intertidal bars or humps are visible between  $x = 1250$  m and  $x = 1400$  m. The movement of these bar-like features during the storm is not well predicted by XBeach, which generally tends to flatten and/or move the bar features,. The Brier Skill Score (Roelvink *et al.*, 2009) of the model is fairly small (0.07), in part due to the ‘double penalty effect’ of the moved bar features (Bosboom & Reniers, 2014; Bosboom *et al.*, 2014). The bed level change on the intertidal beach is often quite subtle (typically less than 20-30 cm) and less important for practical (e.g. safety) purposes than the erosion volume further landward. For this reason, the assessment of the model-data agreement will focus on the erosion volumes landward of the +5m TAW contour. For profile 75, the XBeach profile change prediction landward of the +5m contour is better than the profile change prediction of entire surveyed beach (for example, the BSS score of the section landward of the +5m contour is 0.51, much higher than the BSS for the entire surveyed beach).



BSS = 0.07

Xbeach: Above 5 m TAW:  $-7.99 \text{ m}^3/\text{m}$ . Below 5m TAW:  $9.57 \text{ m}^3/\text{m}$ .

Measured: Above 5 m TAW:  $-9.15 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-8.69 \text{ m}^3/\text{m}$ .

Figure 5-1: XBeach profile results for profile 72, setup 0.

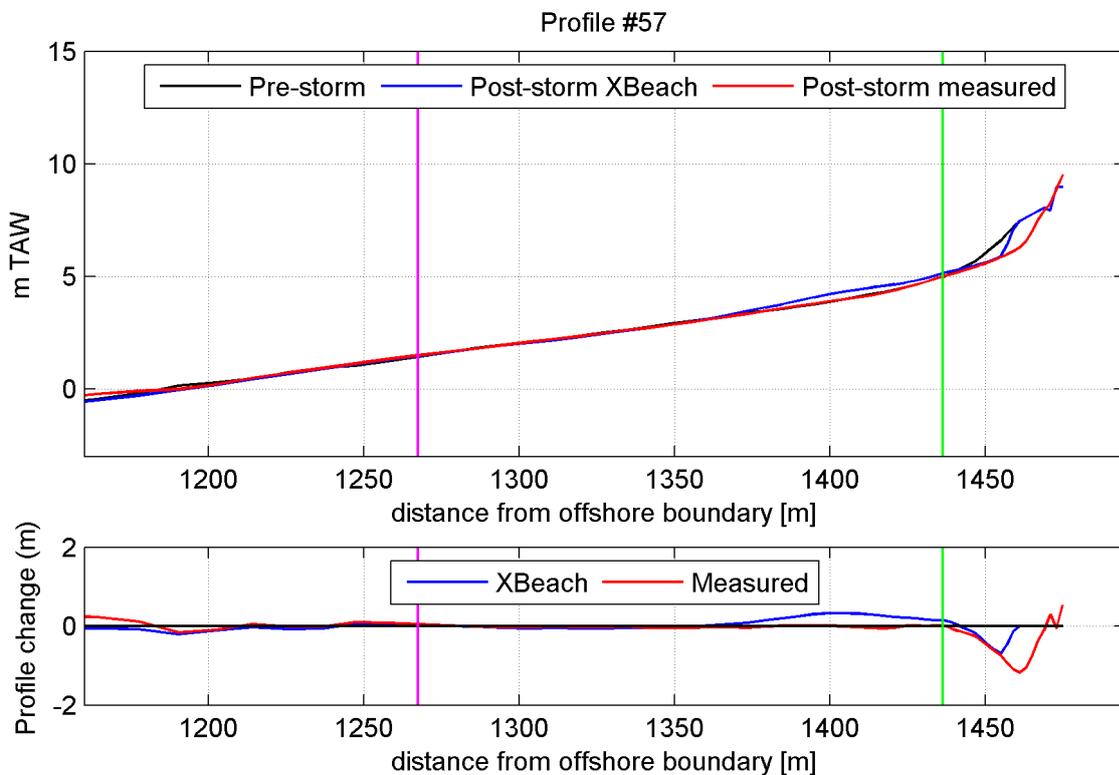


Figure 5-2: Post-storm areal picture taken at the (approximate) location of profile 75.

### Profile 57

A second profile that is discussed is profile 57, east of Ostend (Figure 5-3, Figure 5-4). Again, a pivot point between erosion and deposition is visible at the +5m contour (green vertical line). For this profile, the measured erosion profile is roughly three times higher the predicted volume. The explanation for this is that profile 57 is located downdrift from the harbour jetties of the Ostend harbour when waves are coming from the left of shore-normal, as was the case during the December 2013 storm (Figure 2-3). Near the harbour structure, the beach profile change during the storm was not only affected by cross-shore processes (as is typically the case during a storm) but also by alongshore processes: the harbour blocks the alongshore sediment transport, causing additional erosion along the downdrift beaches. A full 2D model, which takes into account alongshore bathymetry variations and the harbour structure, would be better suited at this location.

In the overview of all profiles, discussed in section 5.1.2, the profiles downdrift of the harbours of Oostende (profiles 56-59), Blankenberge (profiles 88-89) and Zeebrugge (profile 103) all display higher measured erosion volumes than the model predictions.



BSS = 0.05

Xbeach: Above 5 m TAW:  $-5.62 \text{ m}^3/\text{m}$ . Below 5m TAW:  $12.91 \text{ m}^3/\text{m}$ .

Measured: Above 5 m TAW:  $-16.20 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-1.73 \text{ m}^3/\text{m}$ .

Figure 5-3: XBeach profile results for profile 57, setup 0

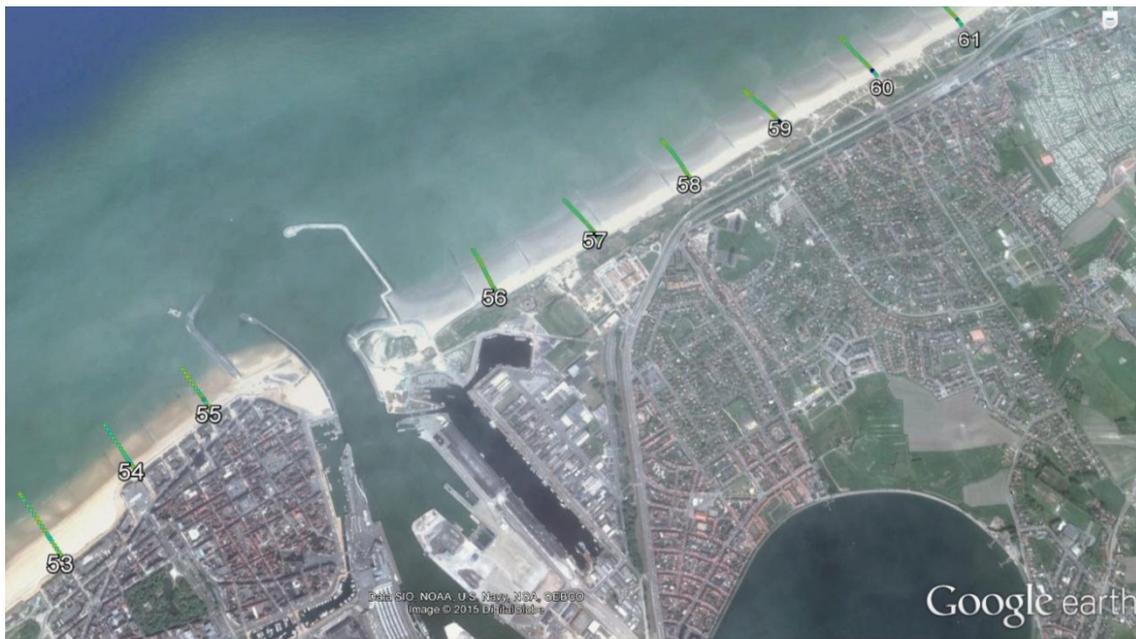


Figure 5-4: Satellite image of the location of profile 57

### 5.1.2. Combined results for all profiles

In order to provide a general overview of results across the entire coastline of Belgium, Figure 5-5 displays erosion volumes across all beach profiles. The exact location of all profiles is displayed in 7. Appendix A. Figure 5-6 displays the same results as a scatter plot between modelled and measured volume changes.

The average measured erosion volume is  $8.21 \text{ m}^3/\text{m}$ , the average predicted volume is  $7.71 \text{ m}^3/\text{m}$ , resulting in a of  $0.50 \text{ m}^3/\text{m}$ . The general magnitude of the erosion is well-predicted by the model, as well as the spatial variation of the erosion volume (correlation between measured and modelled erosion volumes  $r = 0.67$ ). The root mean square error (rmse) between measured and modelled erosion volumes is  $4.39 \text{ m}^3/\text{m}$ . Error metrics for setup 0, as well as for the other model setups, are summarized in Table 5-1. It is noted that this result was obtained using the standard (WTI) calibration parameters and that no case-specific model calibration was performed. The model-data agreement is roughly similar for profiles 1-40 and profiles 41-122, indicating that the effect of sediment displacement by bulldozers on profiles 1-40 was rather limited.

The difference between the measured and predicted erosion volumes varies from profile to profile. Some of the largest differences between predicted and measured volumes are found in the profiles located downdrift of the harbours of Ostend (profiles 56-59), Blankenberge (profiles 88-90) and Zeebrugge (profile 103). This is due to alongshore sediment transport gradients which are not captured by a model with alongshore uniform bathymetry. A 2D modelling approach may be more appropriate in these areas.

An additional area where the disagreement between modelled and measured erosion volumes is relatively large is the area of profile 79-82. This is the area around Wenduine (Figure 5-7), a known erosional hotspot due to the presence of an abrupt change in shoreline orientation. The effect of the shoreline orientation change is not captured by the present pseudo-1D model, but could again be resolved by a full 2D model with an alongshore-varying bathymetry. The profiles that were identified as having a 2D geometry are indicated in red in Figure 5-6.

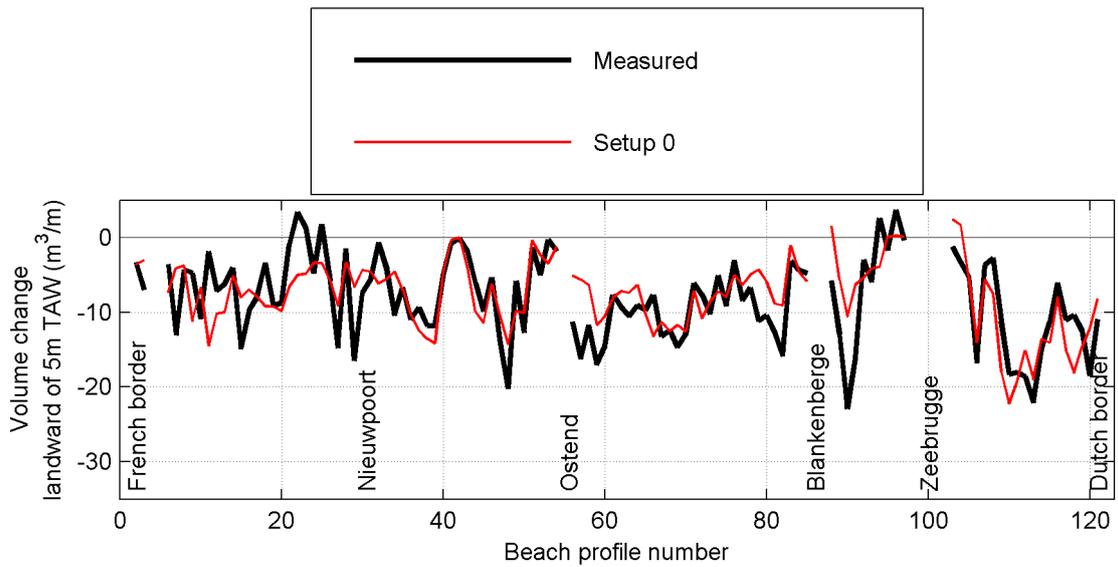


Figure 5-5: Erosion volumes landward of the +5m TAW contour for setup 0.

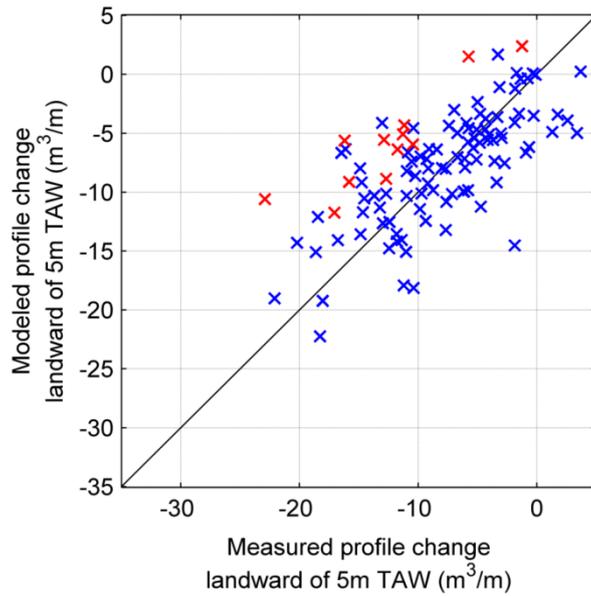


Figure 5-6. Modelled versus measured profile change for setup 0.  
Profiles that are located in a beach area with a 2D geometry are located in red.  
Black line indicates the line of 1:1 agreement.

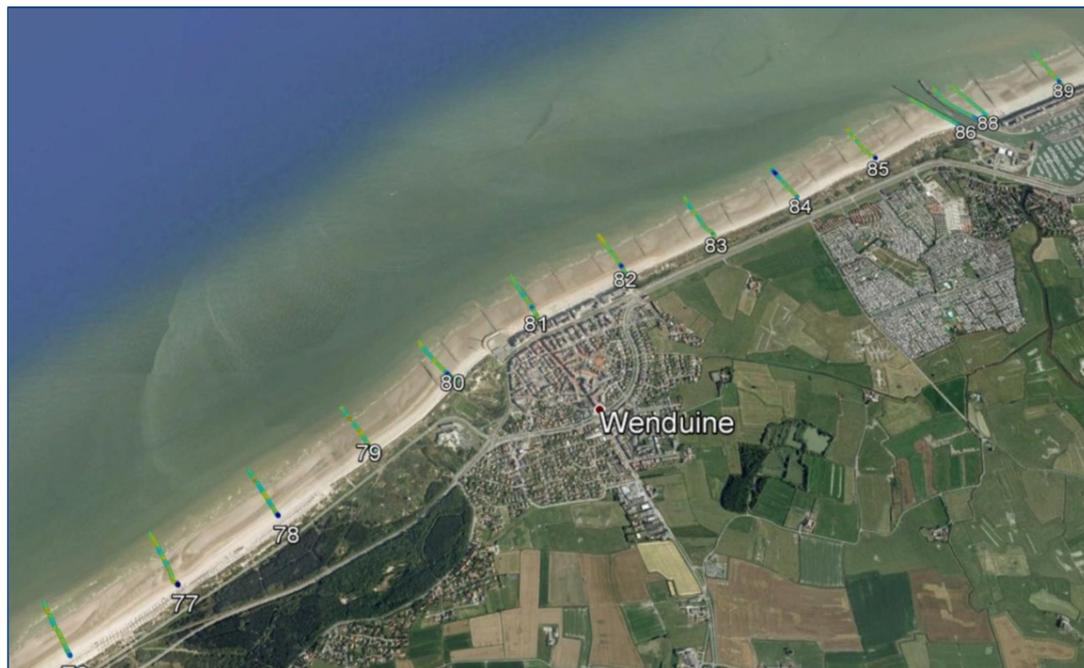


Figure 5-7: Location of the beach profiles near Wenduine

Table 5-1: Summary of predicted erosion volumes and error metrics (bias, root mean square error *rmse*, and correlation coefficient *r*) for the different model setups. Error metrics are not given for Setup 3 and 4 because they do not model the same storm conditions (water levels, wave heights) as the measured storm.

Setup	Bias (m <sup>3</sup> /m)	rmse (m <sup>3</sup> /m)	<i>r</i>	Mean predicted erosion volume (m <sup>3</sup> /m)
Setup 0	-0.50	4.39	0.67	7.71
Setup 1	5.85	7.58	0.70	14.06
Setup 2a	4.06	6.54	0.59	12.27
Setup 2b	8.66	10.12	0.66	16.87
Setup 3				10.50
Setup 4				8.47

## 5.2. Setup 1: GHD calibration parameters

In order to quantify the difference due to the new WTI calibration parameters, the same simulations as setup 0 were executed with the GHD calibration parameters, the default parameters of XBeach in the Groundhog Day version (Table 3-1). Using the GHD calibration parameters results in predicted erosion volumes that are higher than the simulations with the WTI calibration parameters (average erosion volume of 14.06 m<sup>3</sup>/m compared to 7.71 m<sup>3</sup>/m for setup 0). Error metrics (Table 5-1) show that model-data agreement for setup 1 is substantially worse than for setup 0, both in terms of bias and of rmse, since erosion volumes are overpredicted compared to the measurements. The spatial correlation  $r$ , however, is slightly better for setup 1 than for setup 0.

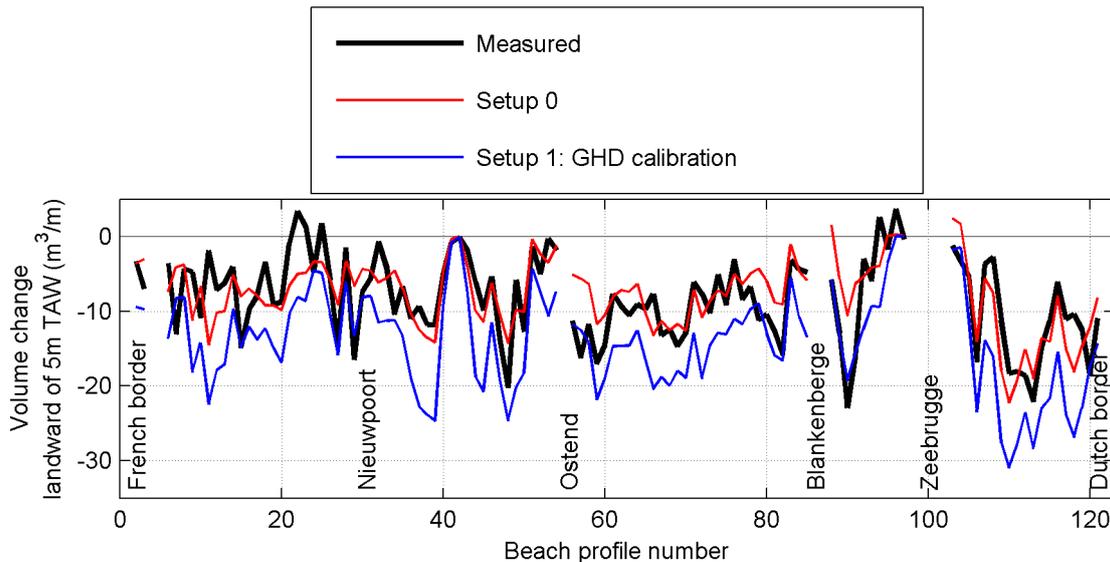


Figure 5-8: Erosion volumes landward of the +5m TAW contour for setup 0 and 1.

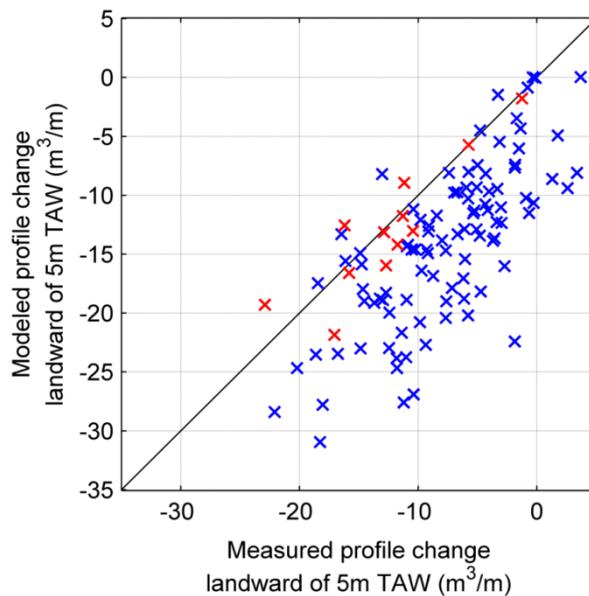


Figure 5-9: Modelled versus measured profile change for setup 1.  
Profiles that are located in a beach area with a 2D geometry are located in red.  
Black line indicates the line of 1:1 agreement.

### 5.3. Setup 2: 1D simulations

Simulation were also performed in 1D mode ( $n_y = 0$ ) in order to quantify the difference between sparse 2D ( $n_y = 5$ , see section 4.2-4.3) and 1D for the entire dataset. 1D runs were done both with the WTI calibration parameters (Setup 2a) and with the GHD calibration parameters (Setup 2b). For both setup 2a and setup 2b, the predicted erosion volumes are larger than for the sparse 2D configurations (setup 0 and setup 1). Error metrics (Table 5-1) show that the 1D simulations perform worse than the sparse 2D counterparts, in terms of bias, rmse and spatial correlation.

Compared to setup 0 (the basic setup), the error made by using the old (GHD) calibration parameters (setup 1) instead of the new and improved (WTI) calibration parameters is slightly larger than the error by calculating in 1D (setup 2a) instead of in sparse 2D mode, but the errors are of the same order of magnitude. The error made by using both the old calibration parameters *and* calculating in 1D mode (setup 2b) is the largest.

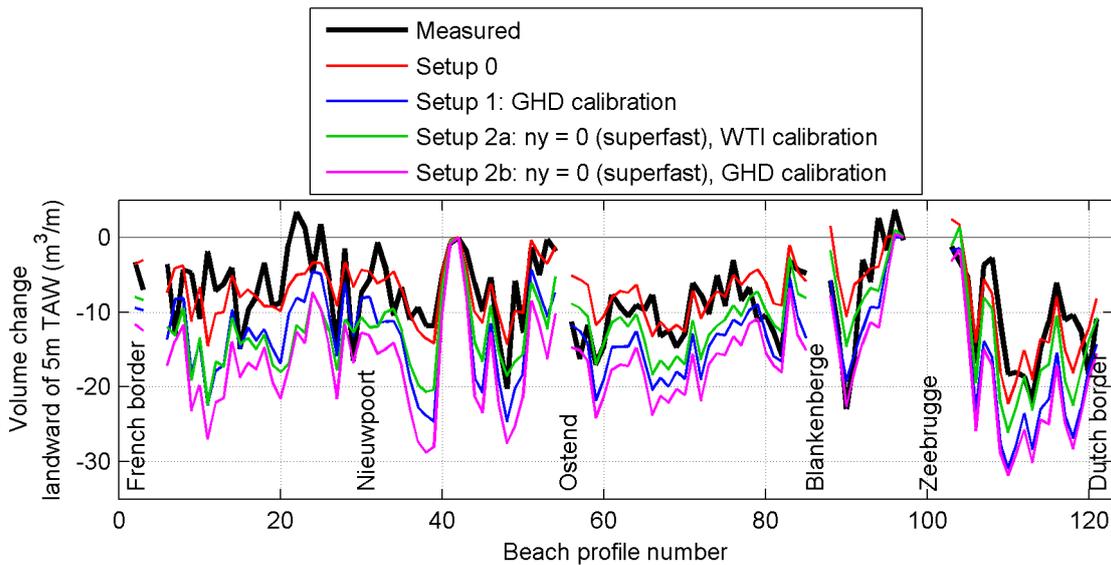


Figure 5-10: Erosion volumes landward of the +5m TAW contour for setup 0, 1, 2a and 2b.

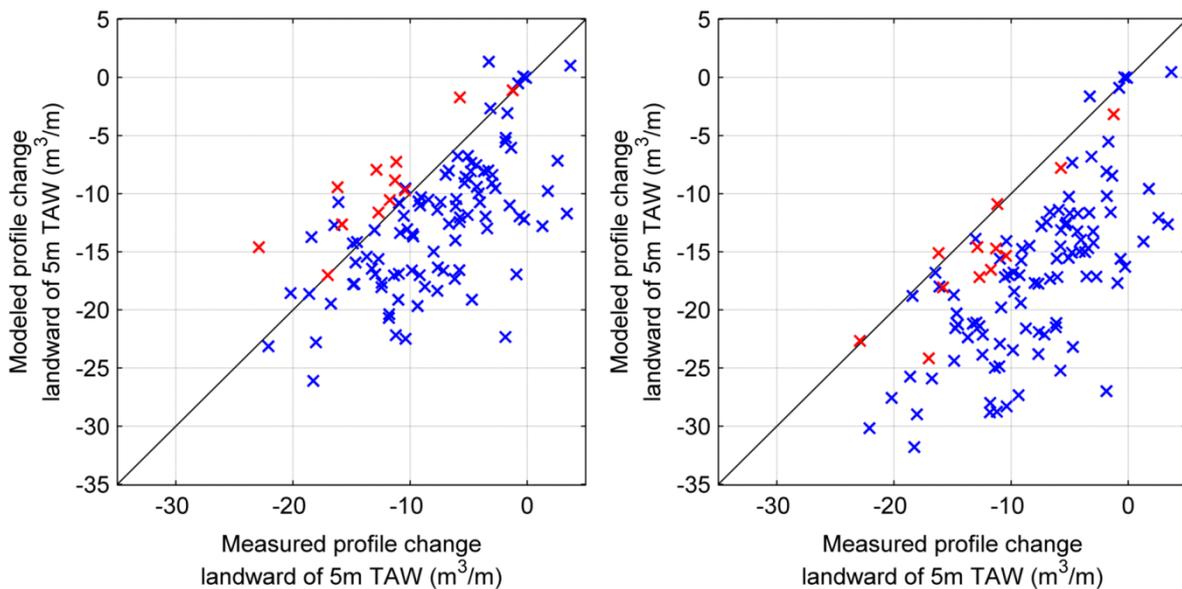


Figure 5-11: Modelled versus measured profile change for setup 2a (left) and setup 2b (right). Profiles that are located in a beach area with a 2D geometry are located in red. Black line indicates the line of 1:1 agreement.

### 5.4. Setup 3: Raised water level

The sensitivity of beach erosion volumes to the water level was examined by running the simulations with a sea level that was raised by 0.25 m. This sensitivity analysis can be used to estimate the impacts of storms with a higher surge level than the December 2013, or for assessing the effect of future sea level rise on storm-induced beach erosion. The raise in water level was added for the entire time series (high waters and low waters, from before the storm until after the storm) and not just for the peak of the storm surge.

On average, the predicted erosion volume is 10.50 m<sup>3</sup>/m, which is 2.79 m<sup>3</sup>/m (or 36%) higher than the default setup 0. The difference in erosion volume, however, is not constant for the different profiles.

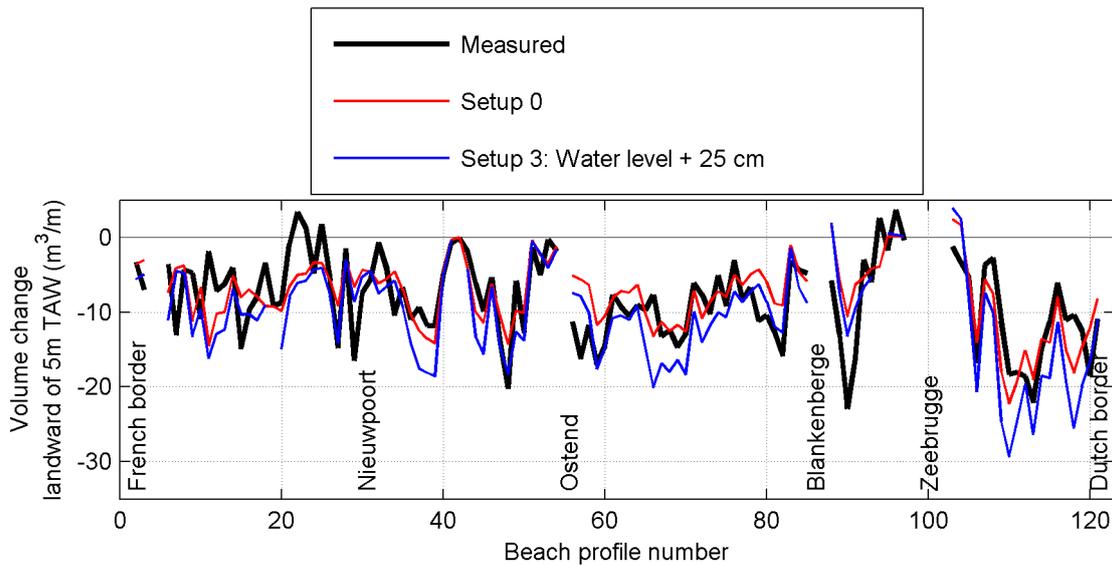


Figure 5-12: Erosion volumes landward of the +5m TAW contour for setup 0 and 3

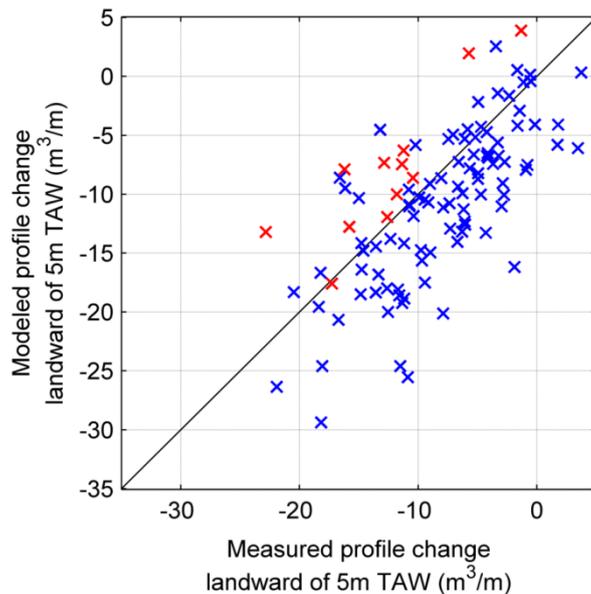


Figure 5-13: Modelled versus measured profile change for setup 3.  
Profiles that are located in a beach area with a 2D geometry are located in red.  
Black line indicates the line of 1:1 agreement.

### 5.5. Setup 4: Increased wave height

Finally, the simulations were repeated with the measured water level (same as in Setup 0), but with the wave height imposed at the offshore model boundary increased by 10%. As with the previous setup, the increased wave height leads to increased erosion predictions. The average predicted erosion volume is 8.47 m<sup>3</sup>/m which is 0.76 m<sup>3</sup>/m or 9.8% higher than setup 0. The proportional increase in erosion volume (9.8%) is thus nearly identical to the increase in wave height (10%).

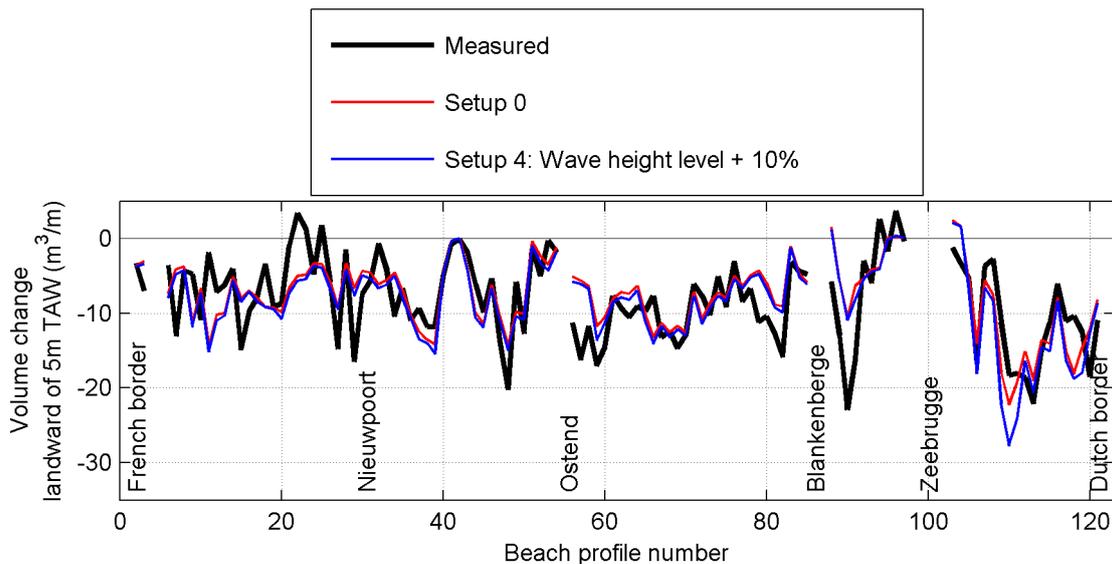


Figure 5-14: Erosion volumes landward of the +5m TAW contour for setup 0 and 4

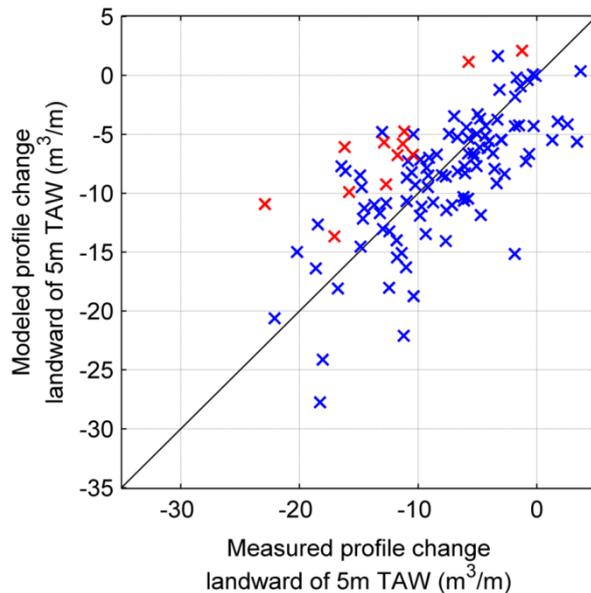


Figure 5-15: Modelled versus measured profile change for setup 4.  
Profiles that are located in a beach area with a 2D geometry are located in red.  
Black line indicates the line of 1:1 agreement.

## 6. Conclusions

The North Sea storm of 5-6 December 2013 generated high surge levels (approx. 40-year return period) and moderately high wave heights (approx. 1 year return period) along the Belgian coast. As a result, beach and dune erosion on the order of 8 m<sup>3</sup>/m occurred along the coastline. A pre- and post-storm survey campaign of 122 cross-shore transects along the intertidal beach and dune provided a valuable dataset to assess the skill of morphodynamics model in predicting storm impact.

This report presented a hindcast of the storm using the XBeach numerical model. First, the behaviour of XBeach with regards to wave directional spreading was investigated, using both idealized and realistic model runs. The idealized model runs, which focused on the hydrodynamics, showed that XBeach in 1D has a more energetic long wave band than an equivalent model in 2D (with an alongshore uniform bathymetry over a length of 1km) because the 1D model is unable to resolve wave directional spreading in the long wave band. Realistic simulations of the December 2013 storm for 6 profiles shows that this leads to beach erosion predictions that are 25-57% higher than the 2D model. Sparse 2D models, with 5 or 8 alongshore grid rows with a resolution of respectively 200 and 125m, provide sufficient degrees of freedom to allow for alongshore-nonuniform wave motions and provide a reasonable approximation of a full 2D model with 50 alongshore grid rows covering the same beach length of 1km. Erosion volume predictions for the 6 profiles considered differed from the full 2D model by up to 10% for the sparse model with 8 alongshore grid rows, and by up to 15% for the sparse model with 5 grid rows. The models with 5 or 8 grid cells have therefore not yet grid-converged, in the sense that there is a non-negligible error as a result of the grid resolution. However, since the inaccuracy of beach morphology models is often more than 20%, the sparse model with 5 alongshore grid rows was considered to provide a good compromise in terms of accuracy and computational efficiency and was chosen as the preferred configuration for the hindcast of the December 2013 storm. However, if computationally feasible, it is advised to aim for a model with the least numerical error, i.e. increase the alongshore resolution so the solution becomes grid-converged. Model tests also show that a uniform beach of 1 km gives comparable results to a 3 km beach, indicating that a 1km width model is sufficient to capture the effects of the directional spreading well.

The hindcast of the storm was performed for different configuration and calibration settings of the XBeach model, in order to test the model sensitivity of the model to these changes. The basic model setup (setup 0), with the recently established WTI calibration parameters and the sparse 2D geometry (5 alongshore grid rows) provides good agreement with measured erosion volumes, even with no additional tuning of the calibration or forcing parameters (bias of 0.5 m<sup>3</sup>/m, rmse of 4.4 m<sup>3</sup>/m). The locations where model-data agreement is the least satisfactory are typically located downdrift of harbours and near changes in the coastline orientation (Wenduine). In this case, the assumption of an alongshore-uniform bathymetry and sediment transport is no longer valid and a full 2D model setup (taking into account alongshore variability in coastline orientation, bathymetry and harbour structures) is necessary.

Using the default calibration values of the 2013 Groundhog Day version of XBeach leads to an overprediction of the measured erosion volumes. The newly established WTI calibration (for which the December 2013 storm was not included in the calibration dataset) thus provides an improvement over the old calibration factors for this test case. The full dataset of 122 profiles was also calculated for XBeach in 1D mode. The 1D models also overestimate the erosion volumes compared to the measured dataset. The error made by using the old calibration factor (bias = 7.58 m<sup>3</sup>/m) is of the same order as the error made by using a 1D model setup (bias = 6.54 m<sup>3</sup>/m), with the former resulting in the larger error.

The model was also run with an elevated water level and with an increased wave height. Increasing the water level by 25 cm throughout the entire model run duration (78 hours) resulted in an erosion volume increase by 2.79 m<sup>3</sup>/m (or 36%); increasing the wave height by 10% throughout the model run resulted in an increase by 0.76 m<sup>3</sup>/m or 9.8%. However, this number lies within the same range as the estimated numerical error due to the choice for a coarse alongshore resolution. For these kinds of sensitivity analyses it is advised to increase the alongshore grid resolution.

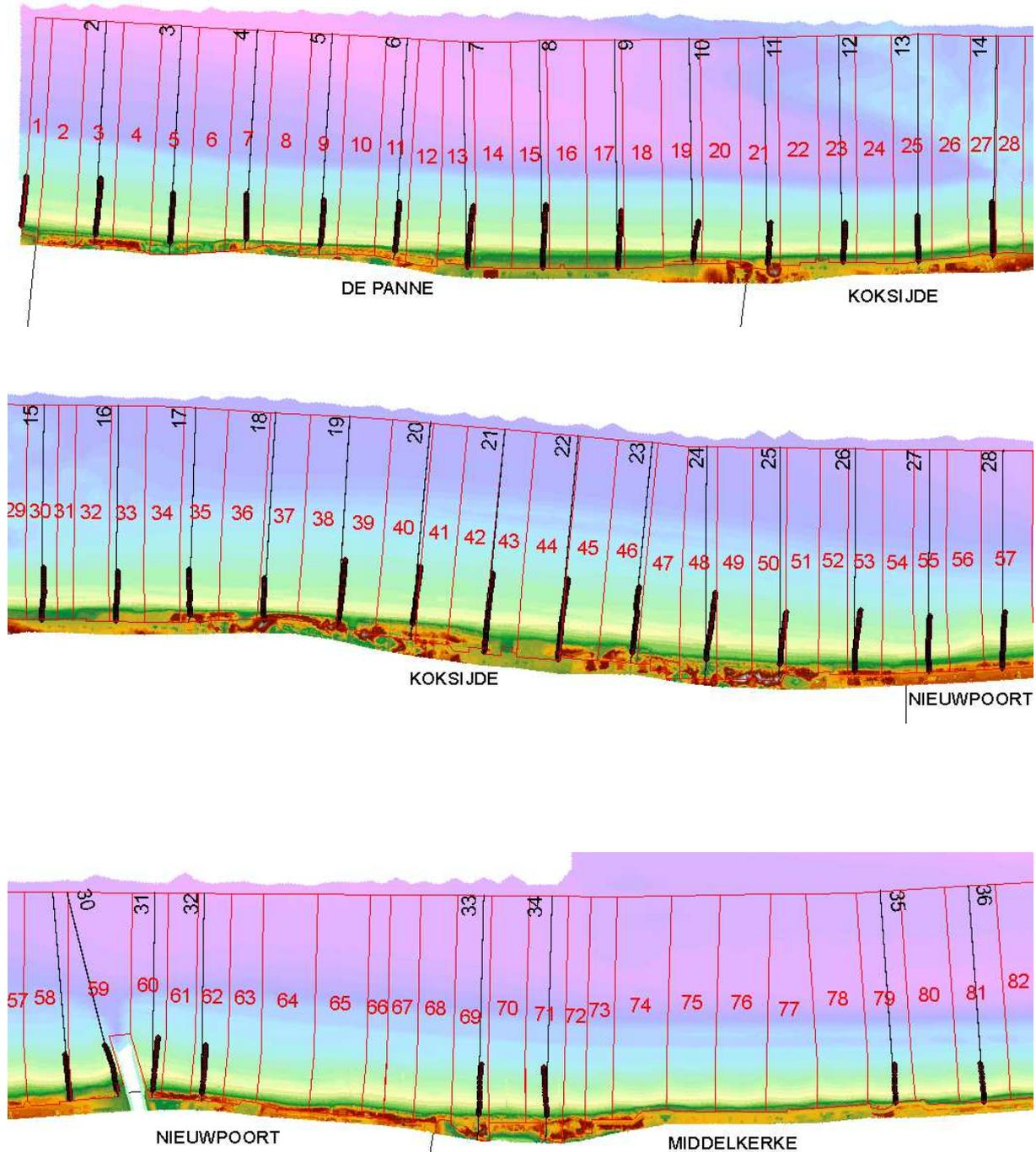
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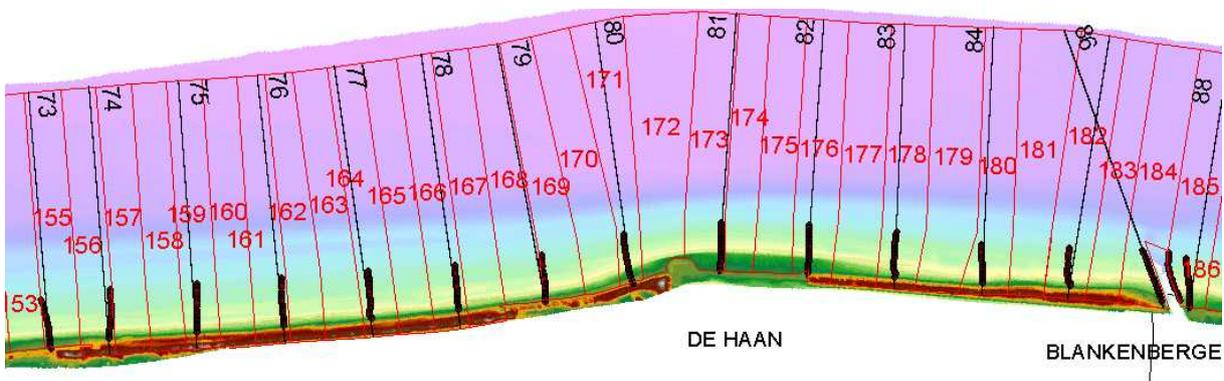
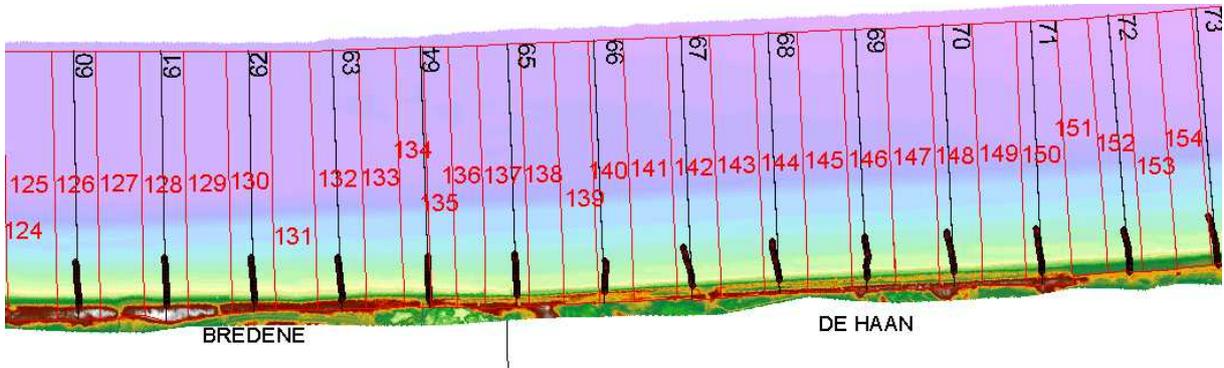
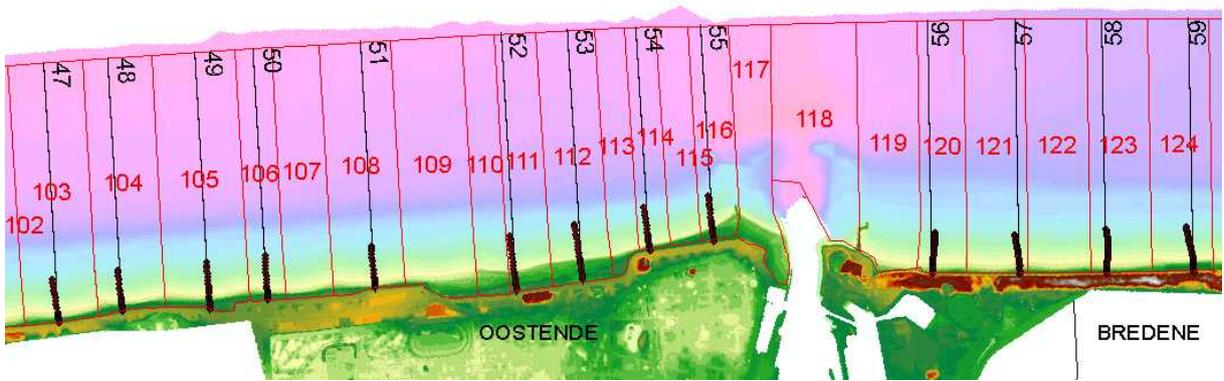
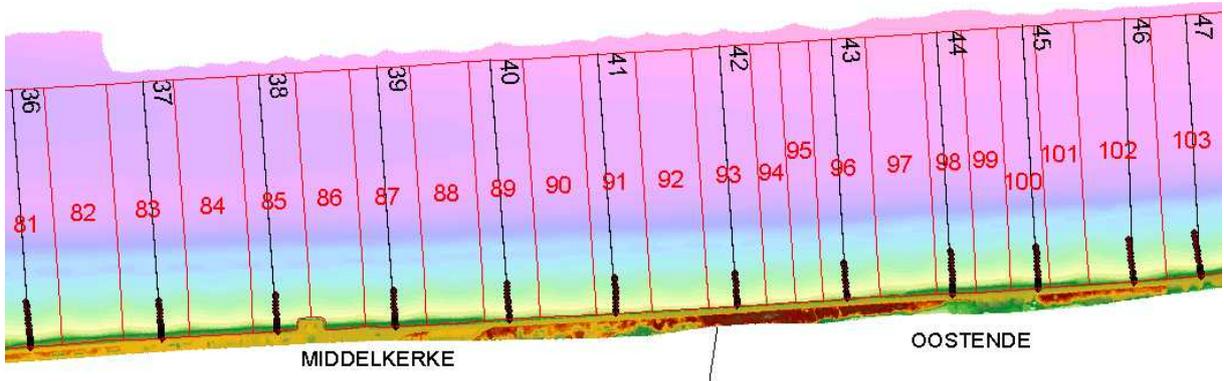
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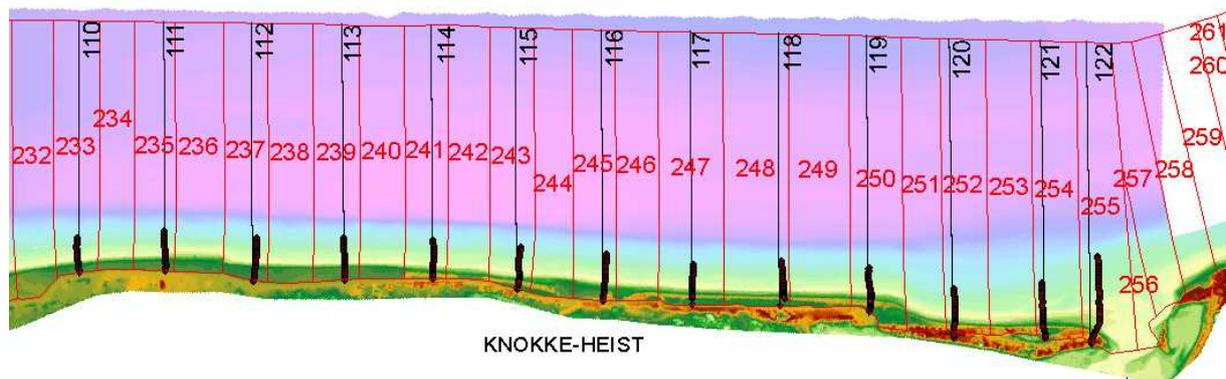
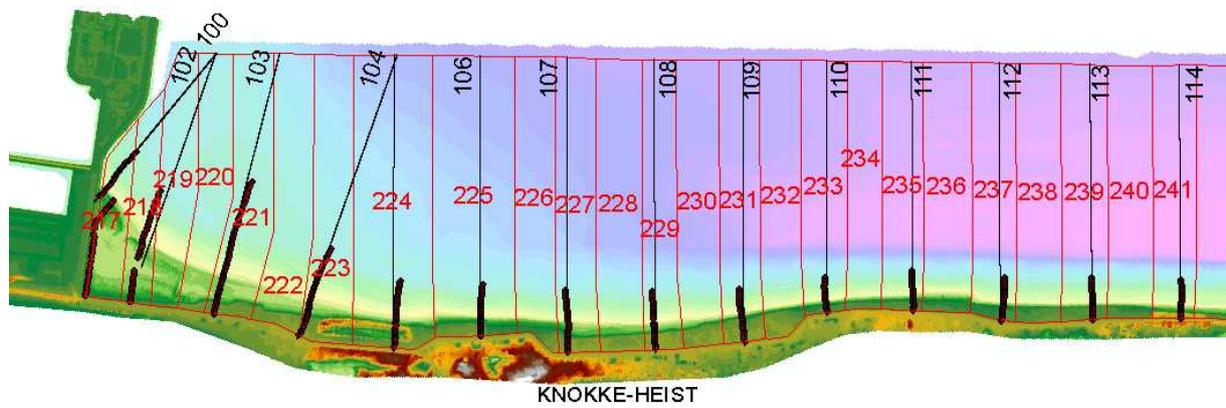
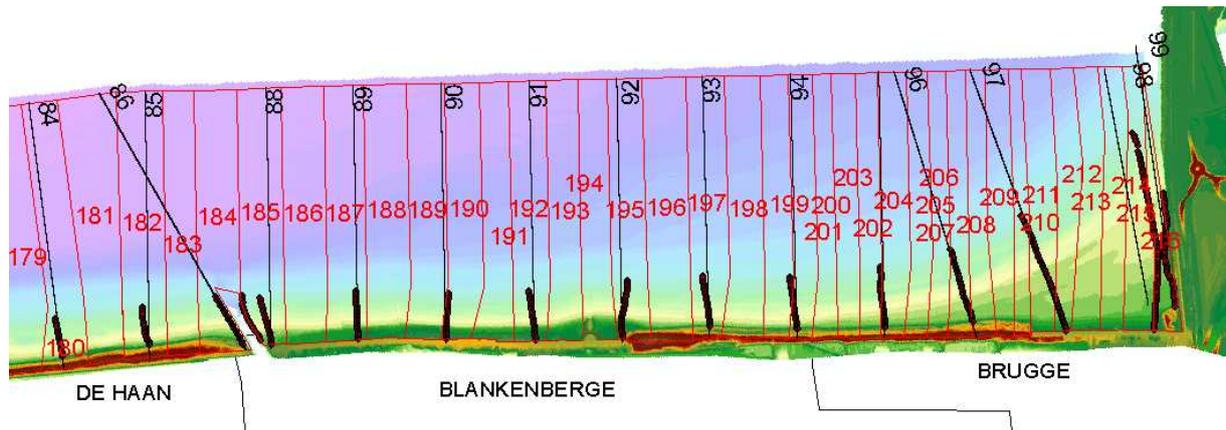
## Appendix A Location of survey transects

Location of the survey transects (black lines and numbering) and the section polygons and numbers as defined by Coastal Division (red).



Scientific support regarding hydrodynamics and sand transport in the coastal zone:  
 Hindcast of the morphological impact of the 5-6 December 2013 storm using XBeach





## Appendix B List of XBeach model parameters used

The following list of model parameters was used for XBeach in the standard setup (setup 0) for profile 2.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% XBeach parameter settings input file                                %%
%%                                                                    %%
%% date:      03-Feb-2015 14:51:31                                    %%
%% function:  xb_write_params                                        %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Bed composition parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

D50      = 0.000179
D90      = 0.000269

%% Flow parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

cf       = 0.001000

%% General
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

jetfac   = 0
tidelen  = 1201

%% Grid parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

depfile  = bed.dep
posdwn   = 0
nx       = 158
ny       = 5
alfa     = 296.947232
vardx    = 1
xfile    = x.grd
yfile    = y.grd
xori     = 0
yori     = 0
thetamin = -70
thetamax = 70
dtheta   = 5
thetanaut = 0

%% Initial conditions
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

zs0      = 0

%% Model time
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

tstop    = 273598

%% Morphology parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Scientific support regarding hydrodynamics and sand transport in the coastal zone:  
Hindcast of the morphological impact of the 5-6 December 2013 storm using XBeach

---

```
wetslp      = 0.260000
struct      = 1
ne_layer    = nebed.dep

%%% Roller parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

beta        = 0.138000

%%% Sediment transport parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

facSk       = 0.375000
facAs       = 0.123000

%%% Tide boundary conditions
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

zs0file     = tide.txt
tideloc     = 1

%%% Wave boundary condition parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

instat      = swan

%%% Wave breaking parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

gamma       = 0.541000
alpha       = 1.262000
gammax      = 2.364000
fw          = 0

%%% Wave-spectrum boundary condition parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

bcfile      = swanfiles.txt

%%% Output variables
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

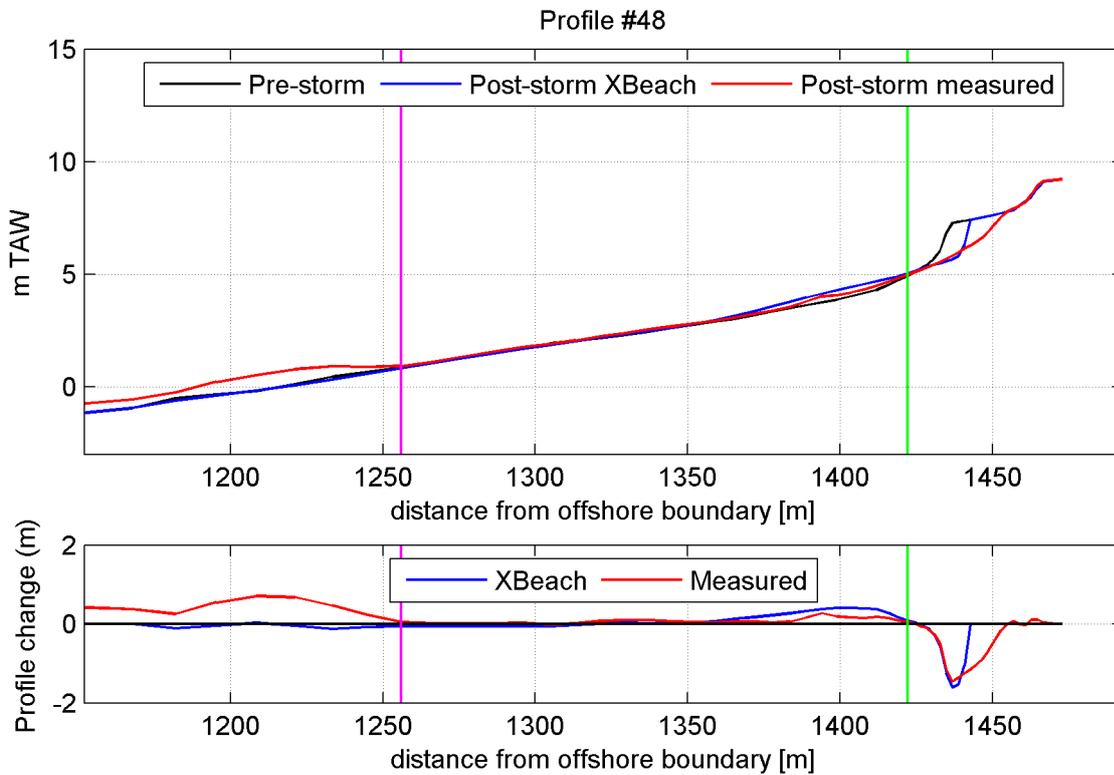
tintm       = 3600
tintp       = 3600
tint        = 3600

nmeanvar    = 6
zs
zs0
zb
zb0
x
sedero

nvar        = 1
zb
```

## Appendix C Profiles used for storm simulations (§4.3)

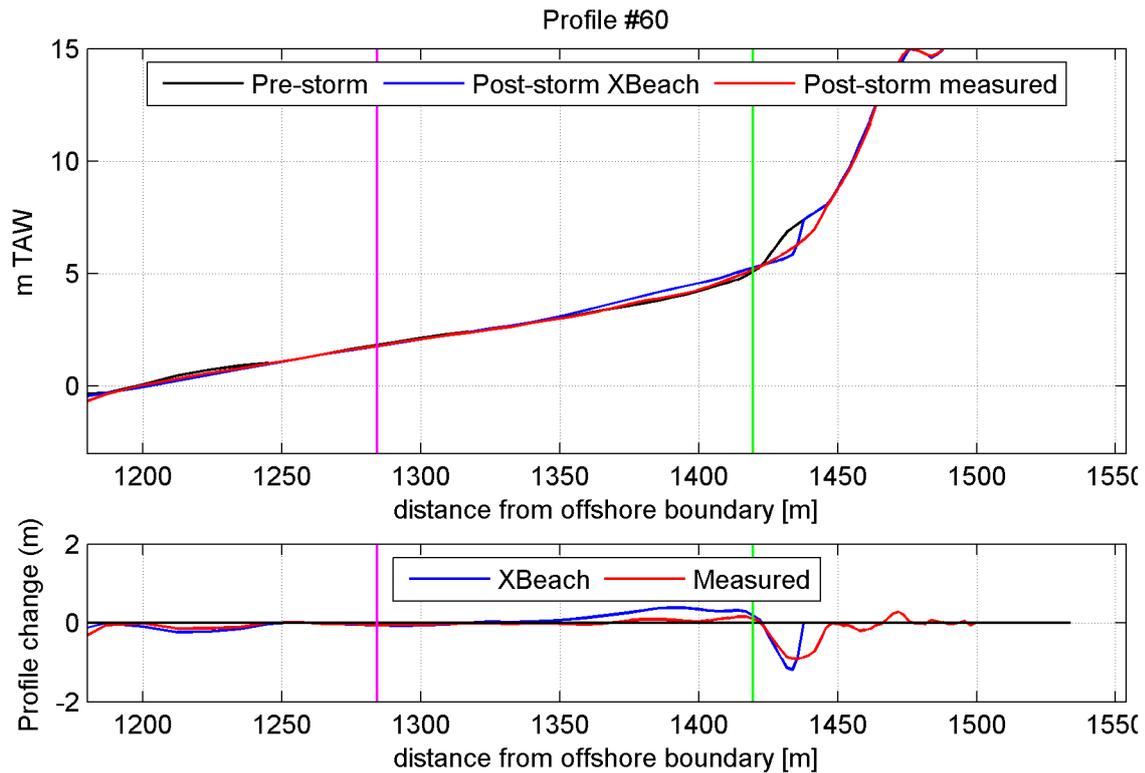
The following figures show the measured pre- and post-storm profiles as well as the post-storm profiles from the 2D XBeach simulation (ny = 50) for the 6 profiles simulated in §4.3.



BSS = 0.57

Xbeach: Above 5 m TAW:  $-12.69 \text{ m}^3/\text{m}$ . Below 5m TAW:  $15.03 \text{ m}^3/\text{m}$ .

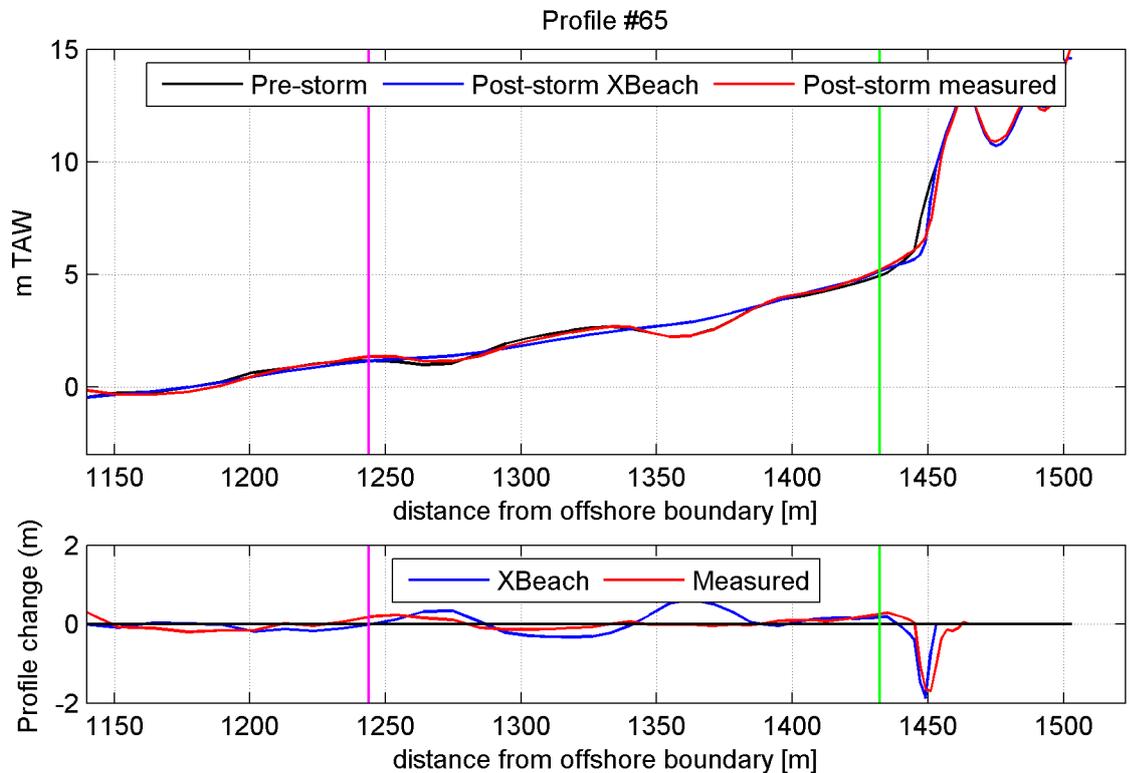
Measured: Above 5 m TAW:  $-20.21 \text{ m}^3/\text{m}$ . Below 5m TAW:  $11.68 \text{ m}^3/\text{m}$ .



BSS = 0.25

Xbeach: Above 5 m TAW:  $-10.10 \text{ m}^3/\text{m}$ . Below 5m TAW:  $18.12 \text{ m}^3/\text{m}$ .

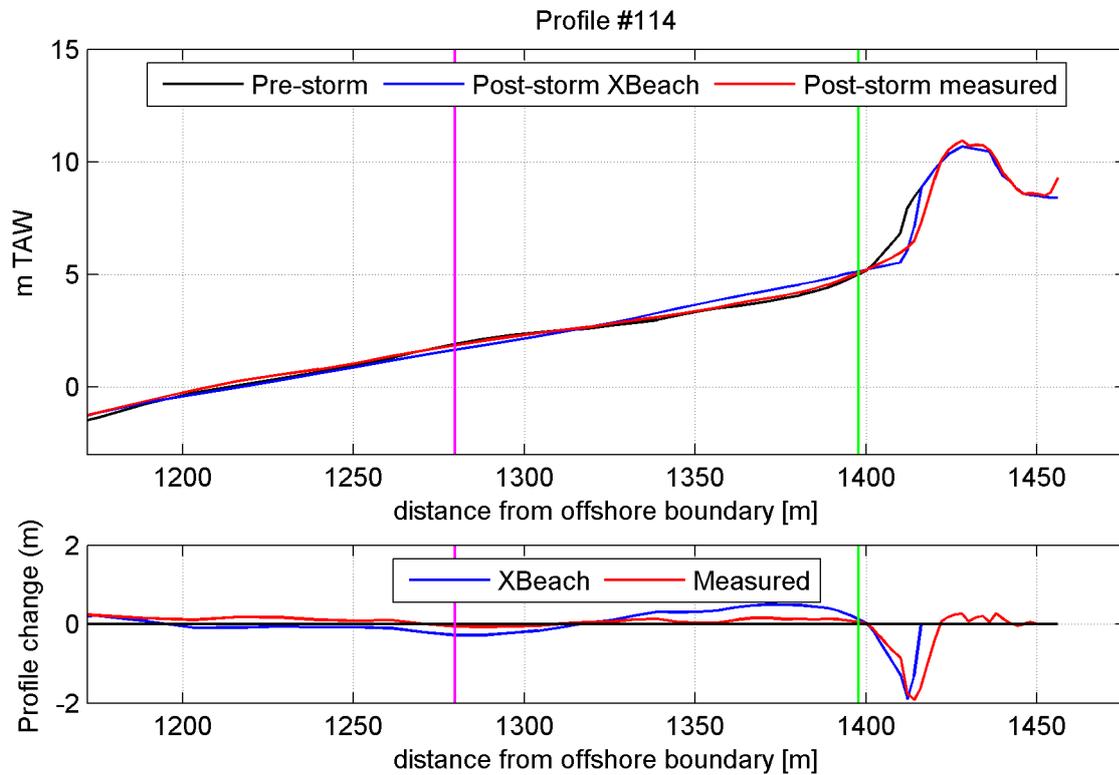
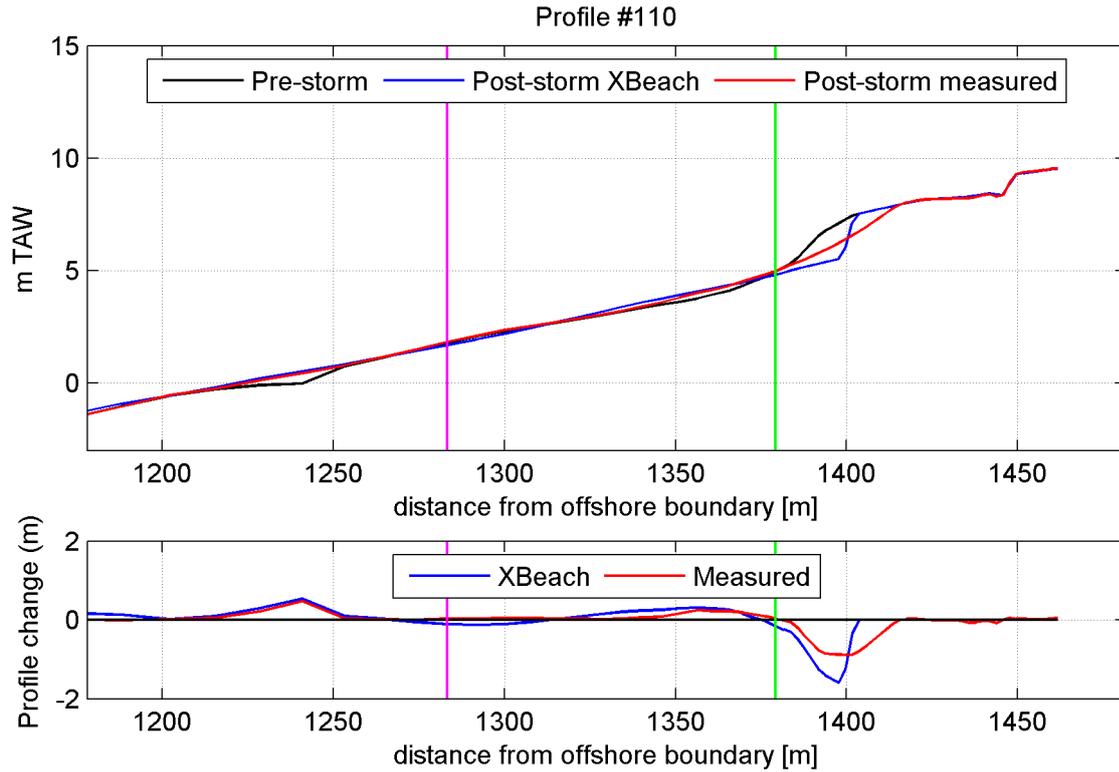
Measured: Above 5 m TAW:  $-14.54 \text{ m}^3/\text{m}$ . Below 5m TAW:  $2.06 \text{ m}^3/\text{m}$ .

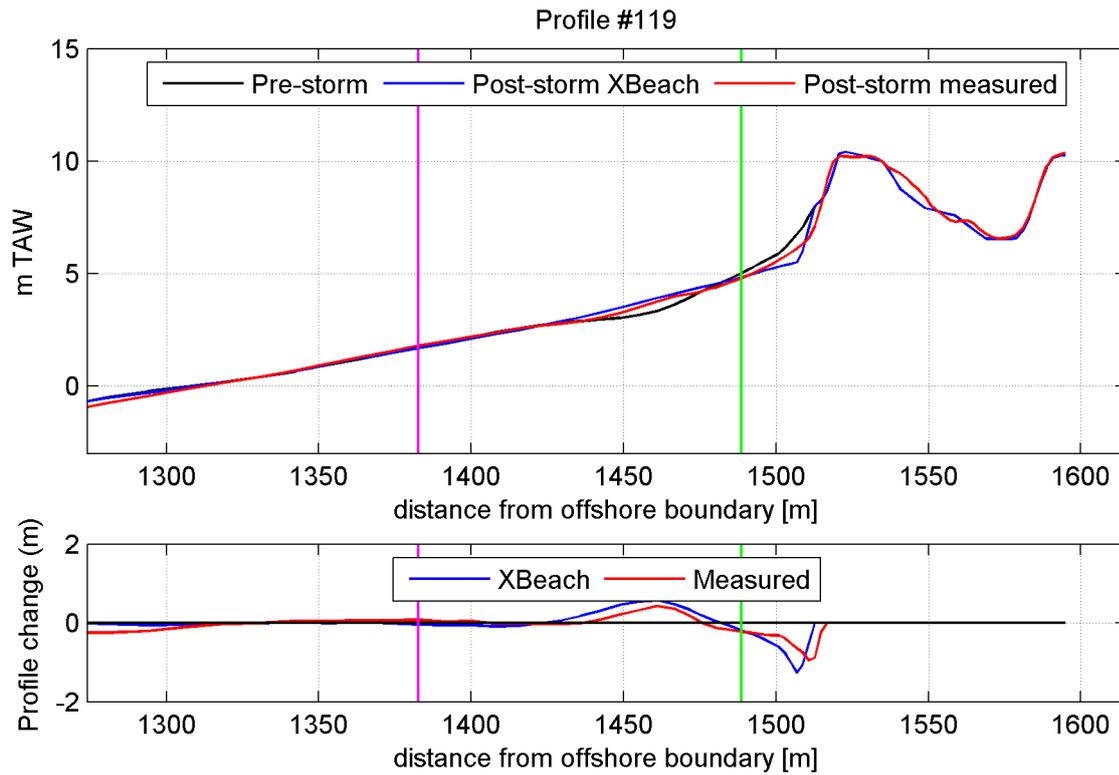


BSS = 0.04

Xbeach: Above 5 m TAW:  $-8.73 \text{ m}^3/\text{m}$ . Below 5m TAW:  $16.22 \text{ m}^3/\text{m}$ .

Measured: Above 5 m TAW:  $-9.72 \text{ m}^3/\text{m}$ . Below 5m TAW:  $5.55 \text{ m}^3/\text{m}$ .



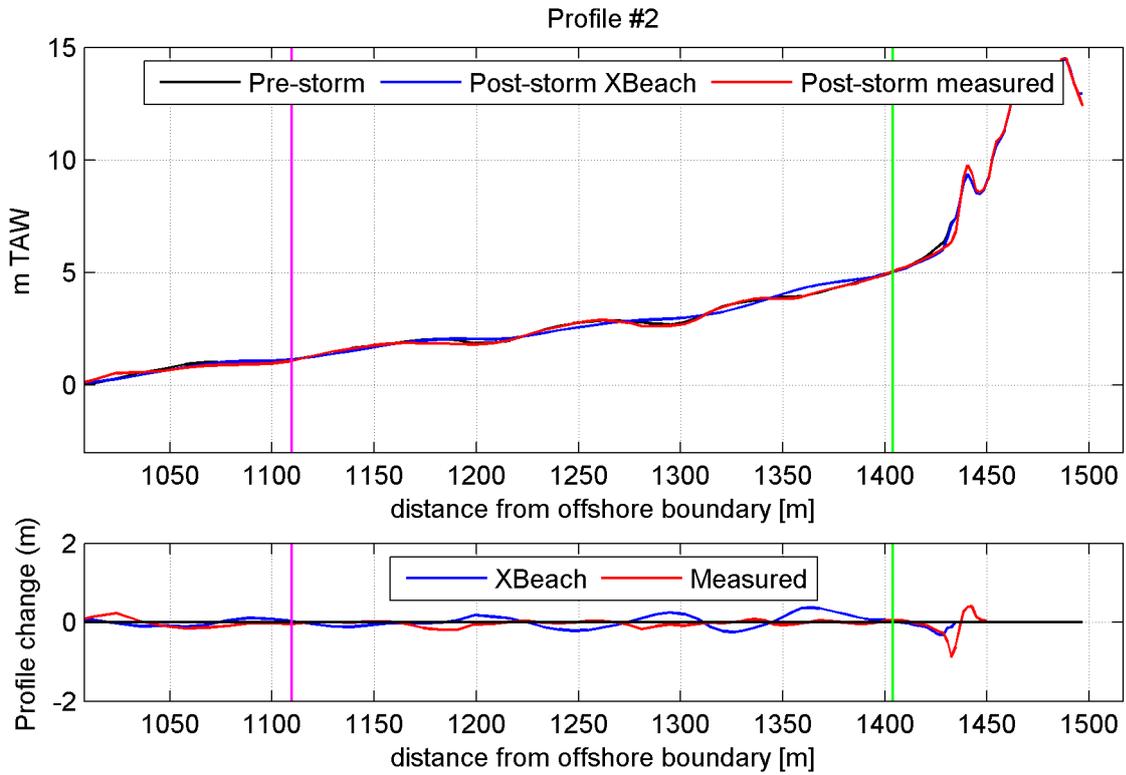


BSS = 0.41

Xbeach: Above 5 m TAW:  $-14.45 \text{ m}^3/\text{m}$ . Below 5m TAW:  $14.91 \text{ m}^3/\text{m}$ .

Measured: Above 5 m TAW:  $-12.45 \text{ m}^3/\text{m}$ . Below 5m TAW:  $7.82 \text{ m}^3/\text{m}$ .

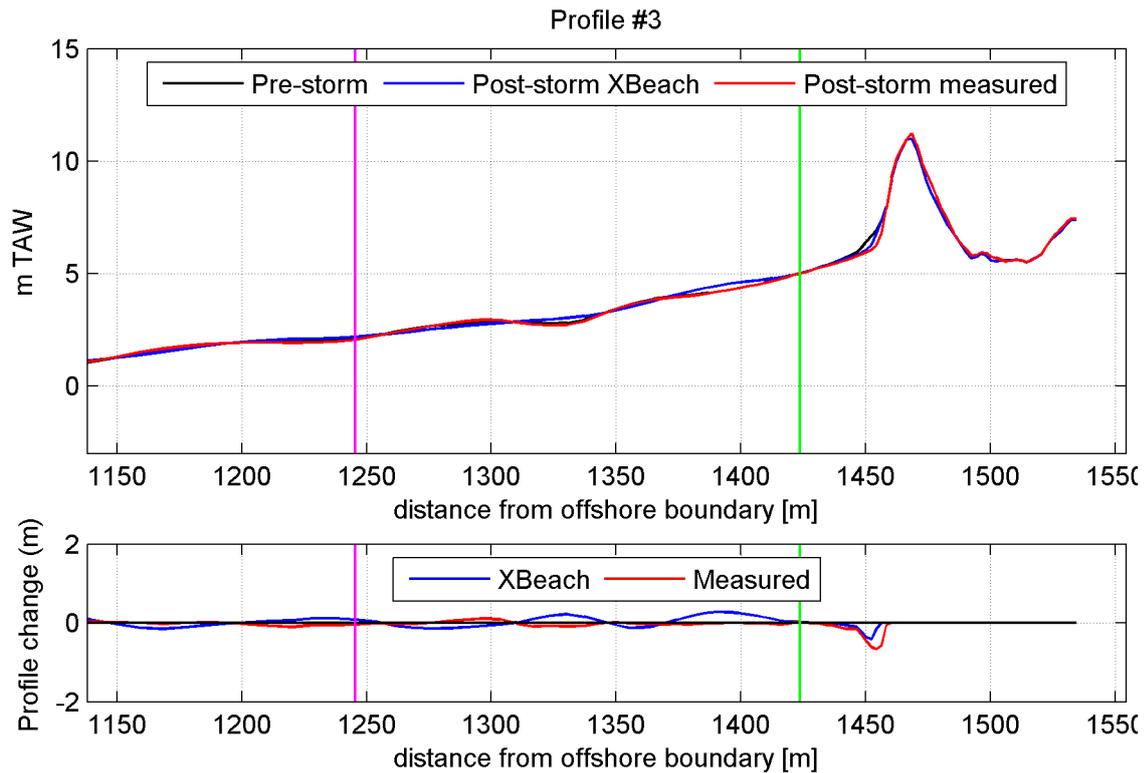
## Appendix D Results for all profiles for Setup 0 (§5.1)



BSS = -1.44

Xbeach: Above 5 m TAW:  $-3.61 \text{ m}^3/\text{m}$ . Below 5m TAW:  $5.92 \text{ m}^3/\text{m}$ .

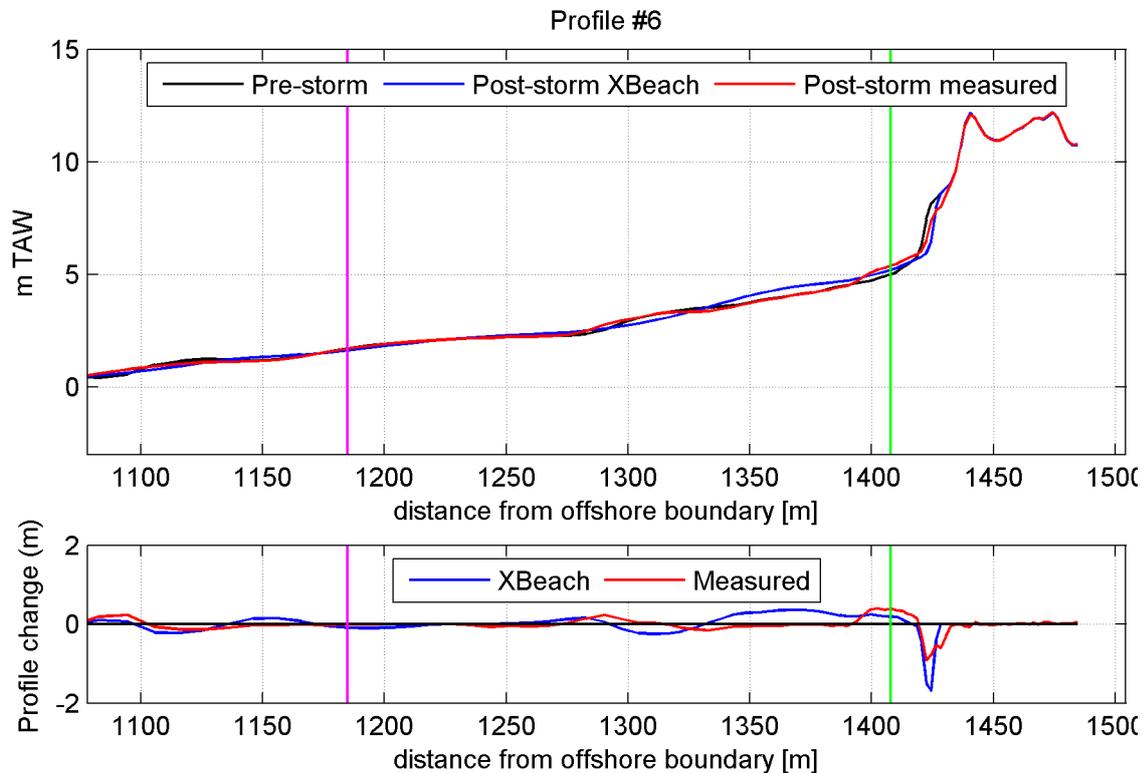
Measured: Above 5 m TAW:  $-3.33 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-8.72 \text{ m}^3/\text{m}$ .



BSS = -0.82

Xbeach: Above 5 m TAW:  $-3.02 \text{ m}^3/\text{m}$ . Below 5m TAW:  $7.37 \text{ m}^3/\text{m}$ .

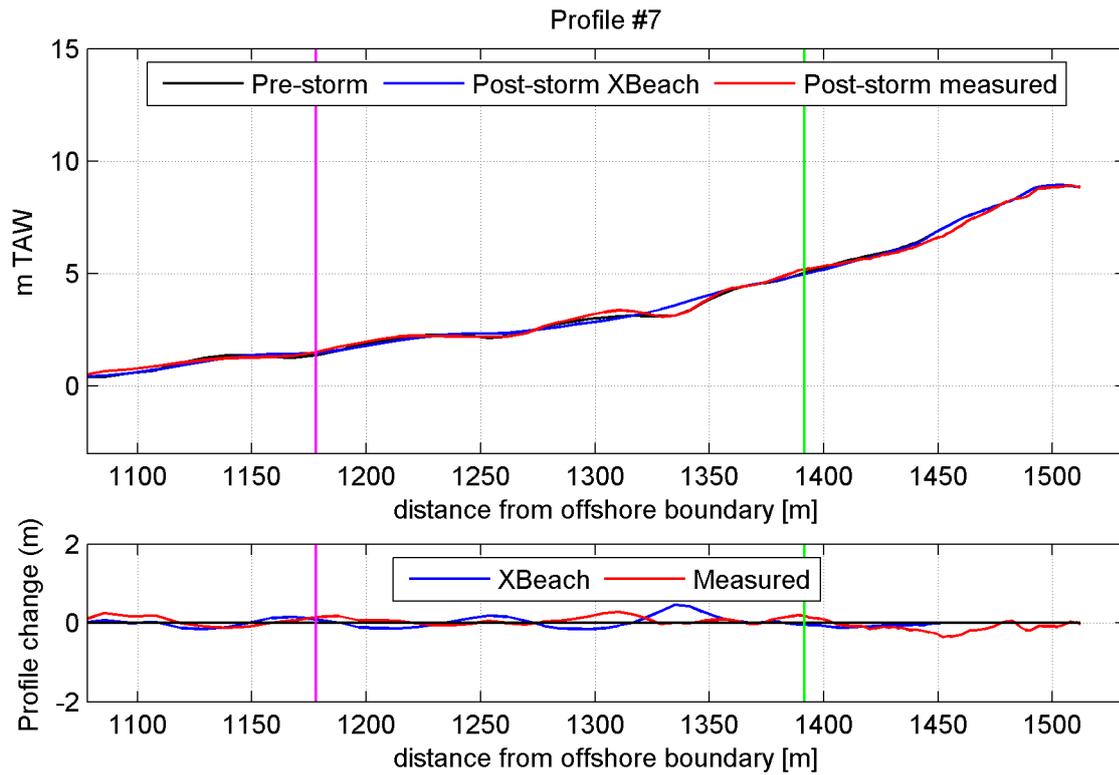
Measured: Above 5 m TAW:  $-6.97 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-1.79 \text{ m}^3/\text{m}$ .



BSS = -0.53

Xbeach: Above 5 m TAW:  $-7.36 \text{ m}^3/\text{m}$ . Below 5m TAW:  $13.71 \text{ m}^3/\text{m}$ .

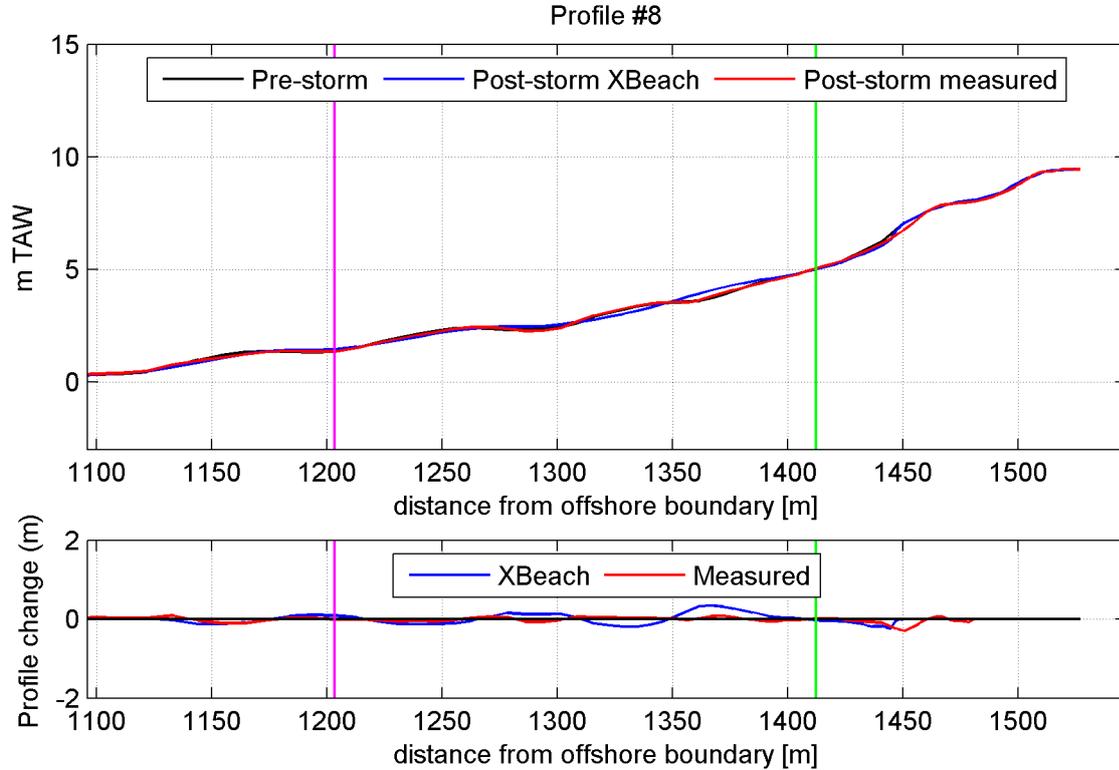
Measured: Above 5 m TAW:  $-3.57 \text{ m}^3/\text{m}$ . Below 5m TAW:  $2.60 \text{ m}^3/\text{m}$ .



BSS = -1.14

Xbeach: Above 5 m TAW:  $-4.12 \text{ m}^3/\text{m}$ . Below 5m TAW:  $6.88 \text{ m}^3/\text{m}$ .

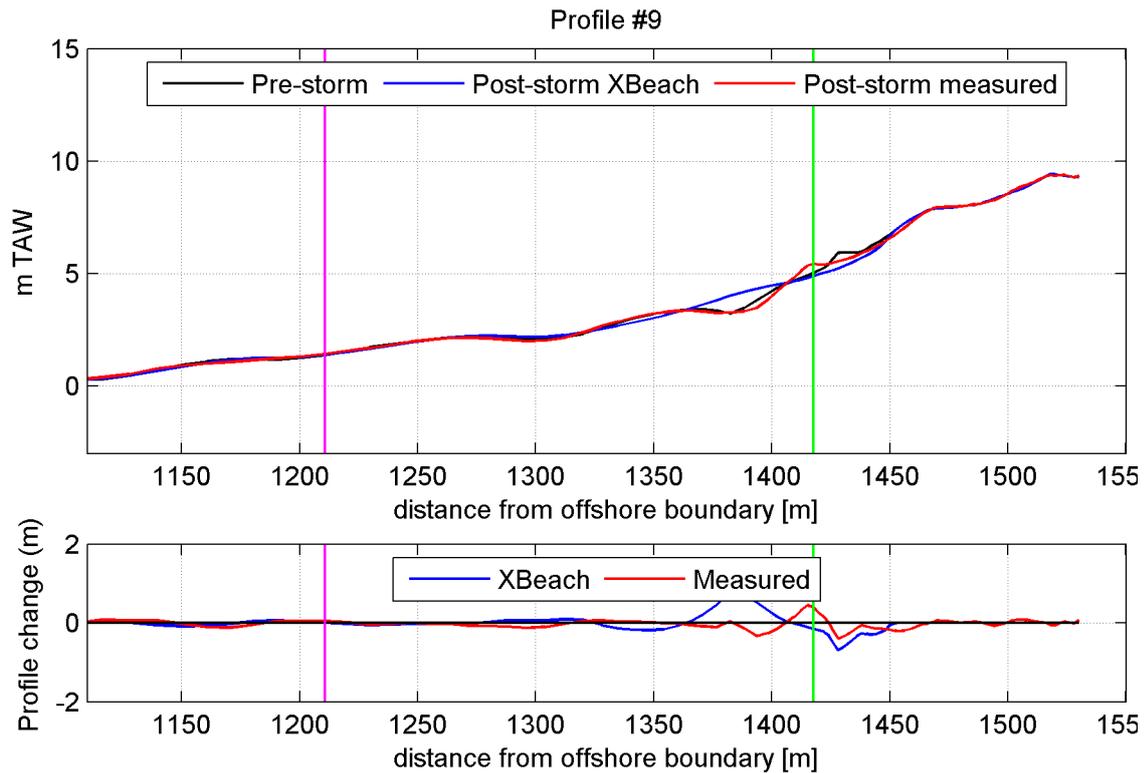
Measured: Above 5 m TAW:  $-13.04 \text{ m}^3/\text{m}$ . Below 5m TAW:  $13.45 \text{ m}^3/\text{m}$ .



BSS = -3.18

Xbeach: Above 5 m TAW:  $-3.77 \text{ m}^3/\text{m}$ . Below 5m TAW:  $6.14 \text{ m}^3/\text{m}$ .

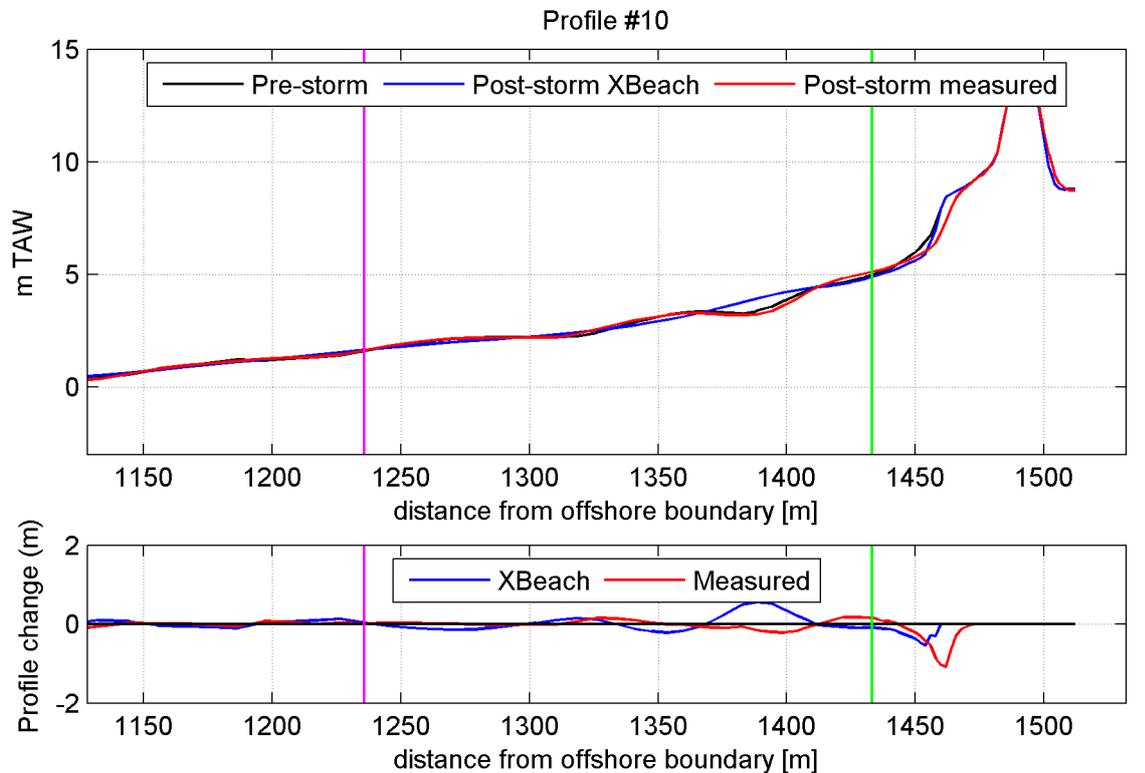
Measured: Above 5 m TAW:  $-4.30 \text{ m}^3/\text{m}$ . Below 5m TAW:  $0.49 \text{ m}^3/\text{m}$ .



BSS = -3.48

Xbeach: Above 5 m TAW:  $-11.23 \text{ m}^3/\text{m}$ . Below 5m TAW:  $12.54 \text{ m}^3/\text{m}$ .

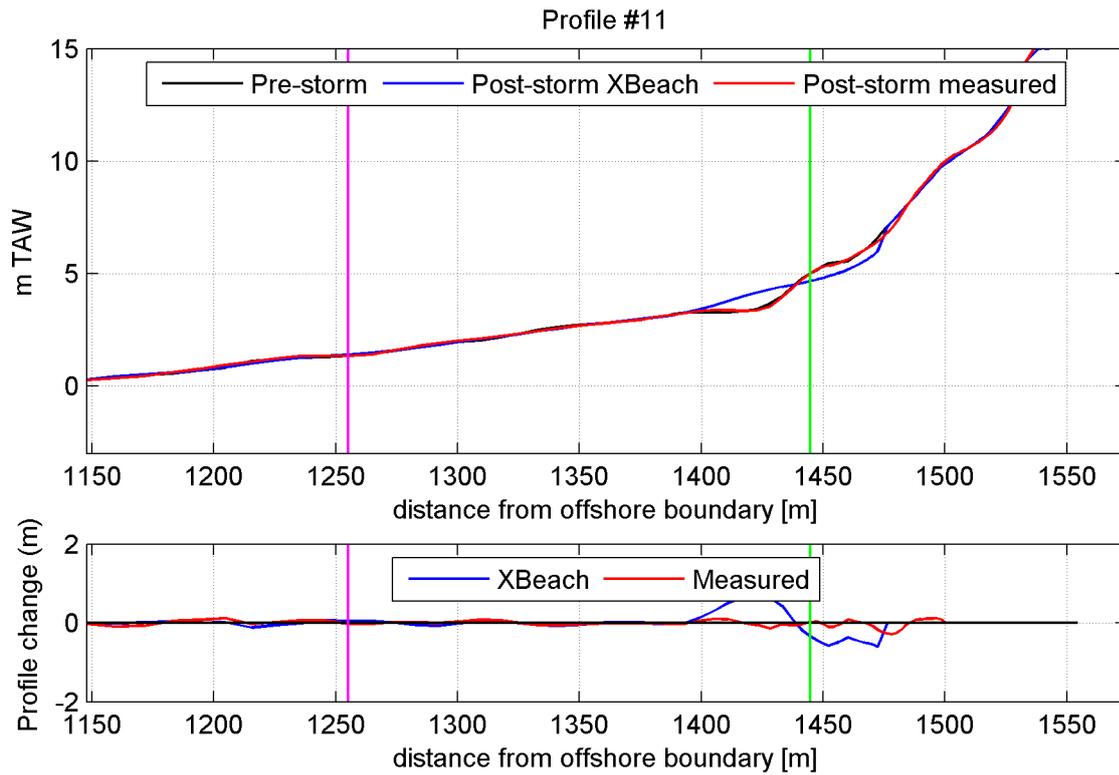
Measured: Above 5 m TAW:  $-4.73 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-5.41 \text{ m}^3/\text{m}$ .



BSS = -1.06

Xbeach: Above 5 m TAW:  $-6.63 \text{ m}^3/\text{m}$ . Below 5m TAW:  $5.81 \text{ m}^3/\text{m}$ .

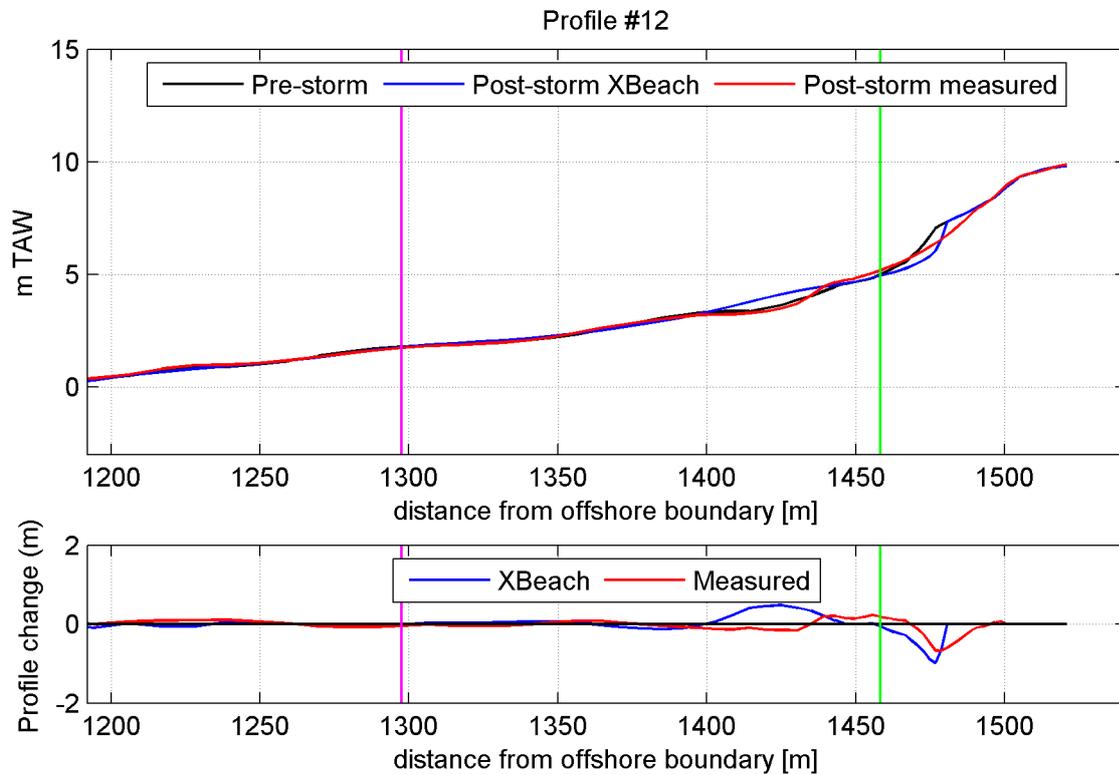
Measured: Above 5 m TAW:  $-10.85 \text{ m}^3/\text{m}$ . Below 5m TAW:  $0.91 \text{ m}^3/\text{m}$ .



BSS = -12.96

Xbeach: Above 5 m TAW:  $-14.53 \text{ m}^3/\text{m}$ . Below 5m TAW:  $16.54 \text{ m}^3/\text{m}$ .

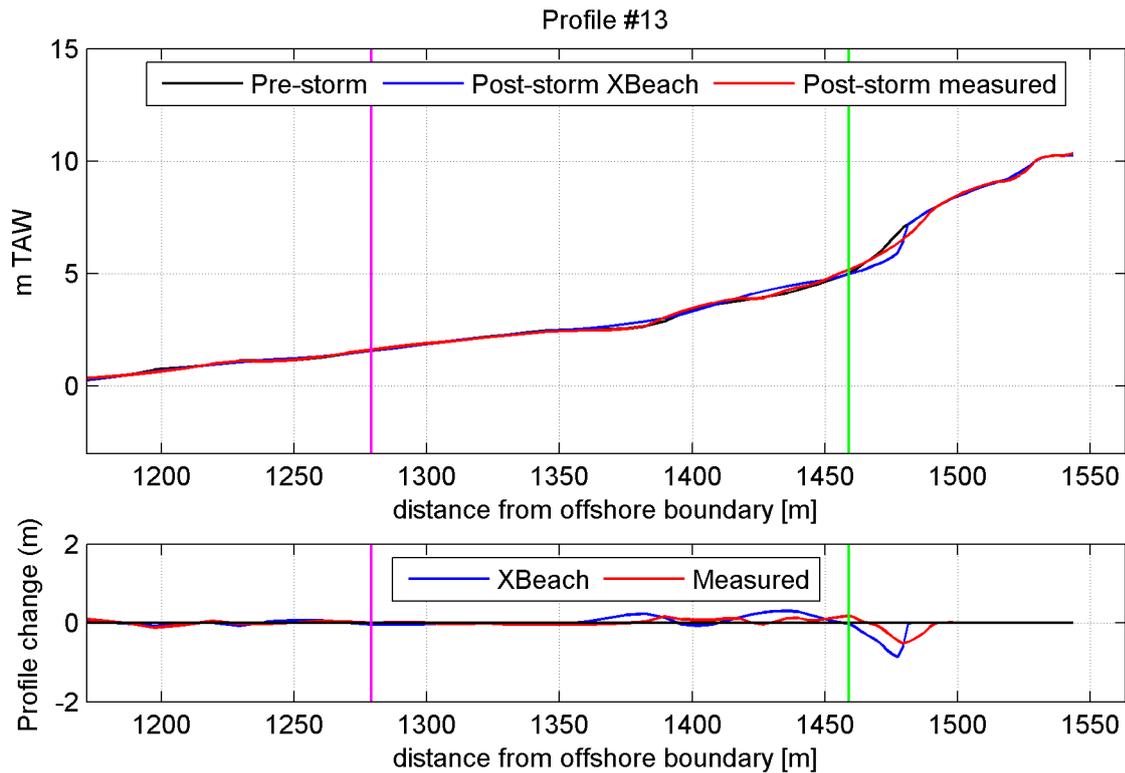
Measured: Above 5 m TAW:  $-1.86 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-0.38 \text{ m}^3/\text{m}$ .



BSS = -1.33

Xbeach: Above 5 m TAW:  $-10.16 \text{ m}^3/\text{m}$ . Below 5m TAW:  $13.32 \text{ m}^3/\text{m}$ .

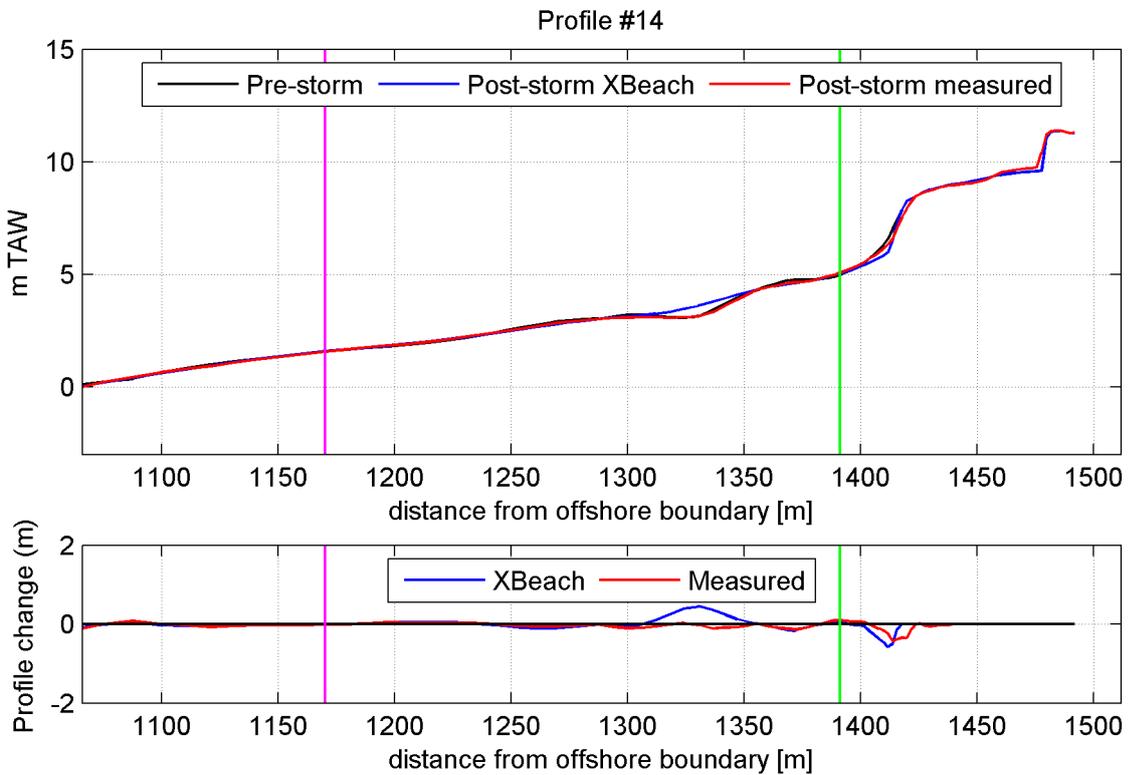
Measured: Above 5 m TAW:  $-7.16 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-1.10 \text{ m}^3/\text{m}$ .



BSS = -0.76

Xbeach: Above 5 m TAW:  $-9.95 \text{ m}^3/\text{m}$ . Below 5m TAW:  $11.04 \text{ m}^3/\text{m}$ .

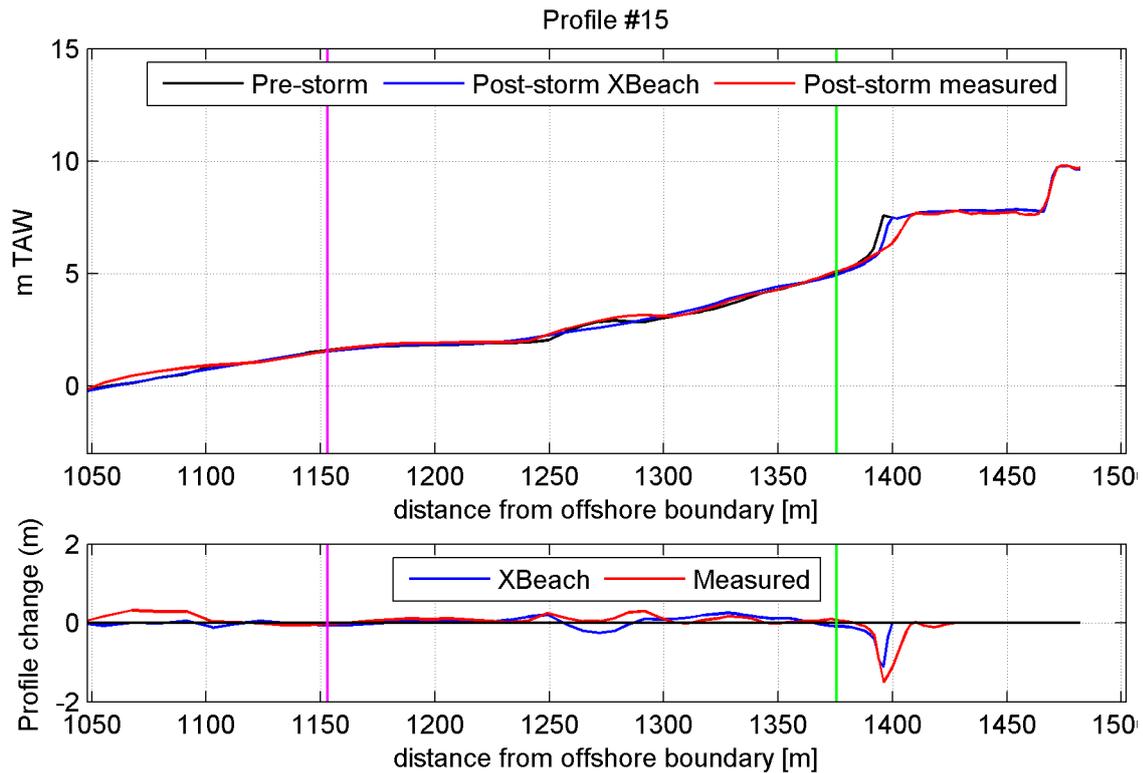
Measured: Above 5 m TAW:  $-6.19 \text{ m}^3/\text{m}$ . Below 5m TAW:  $4.61 \text{ m}^3/\text{m}$ .



BSS = -1.91

Xbeach: Above 5 m TAW:  $-5.10 \text{ m}^3/\text{m}$ . Below 5m TAW:  $7.16 \text{ m}^3/\text{m}$ .

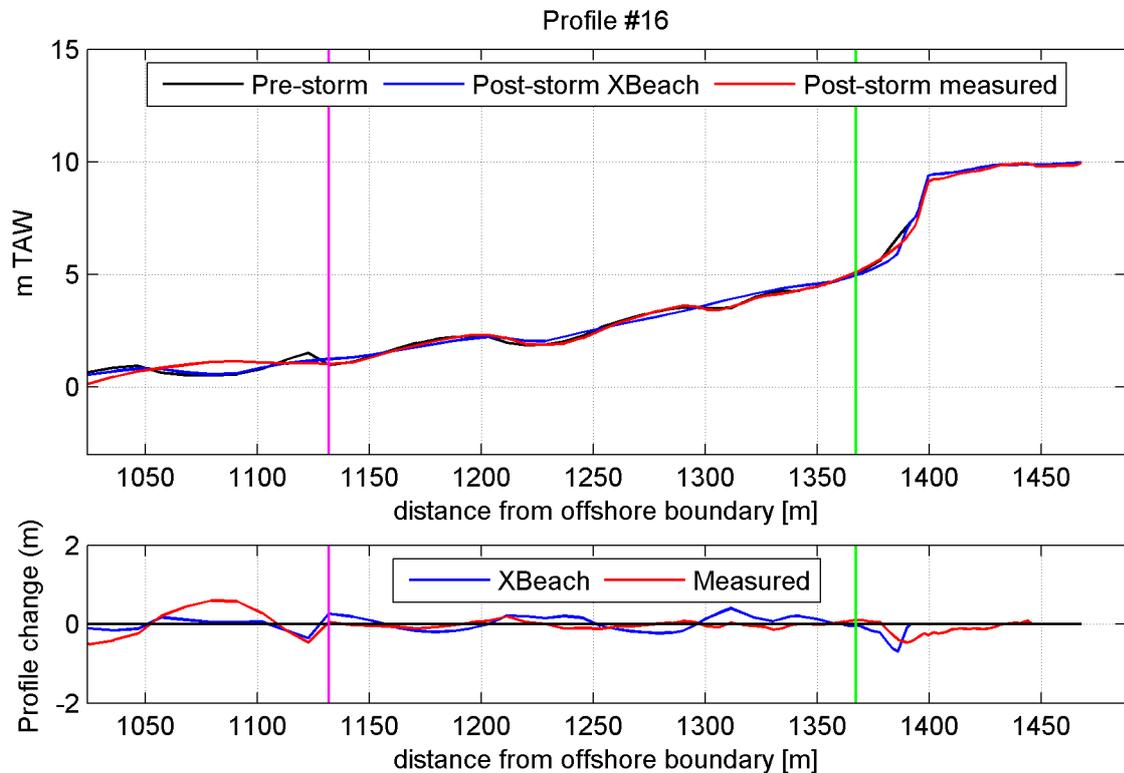
Measured: Above 5 m TAW:  $-4.04 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-5.17 \text{ m}^3/\text{m}$ .



BSS = 0.37

Xbeach: Above 5 m TAW:  $-7.98 \text{ m}^3/\text{m}$ . Below 5m TAW:  $9.43 \text{ m}^3/\text{m}$ .

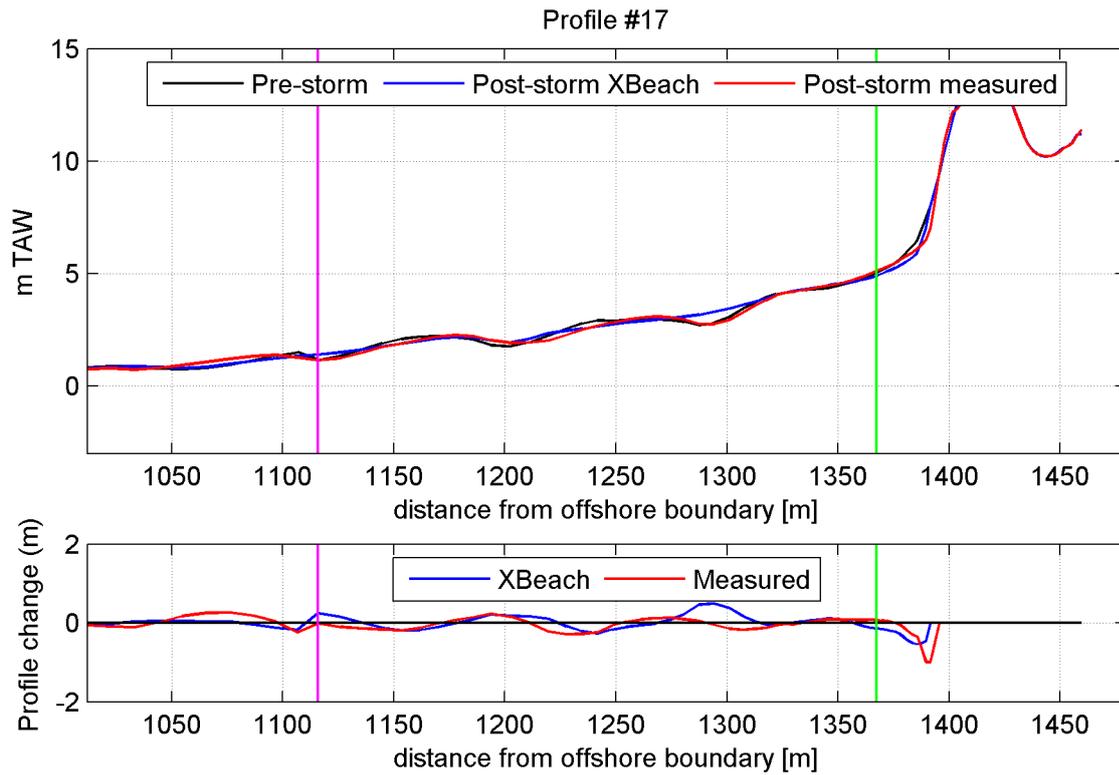
Measured: Above 5 m TAW:  $-14.90 \text{ m}^3/\text{m}$ . Below 5m TAW:  $19.05 \text{ m}^3/\text{m}$ .



BSS = -1.54

Xbeach: Above 5 m TAW:  $-6.97 \text{ m}^3/\text{m}$ . Below 5m TAW:  $9.57 \text{ m}^3/\text{m}$ .

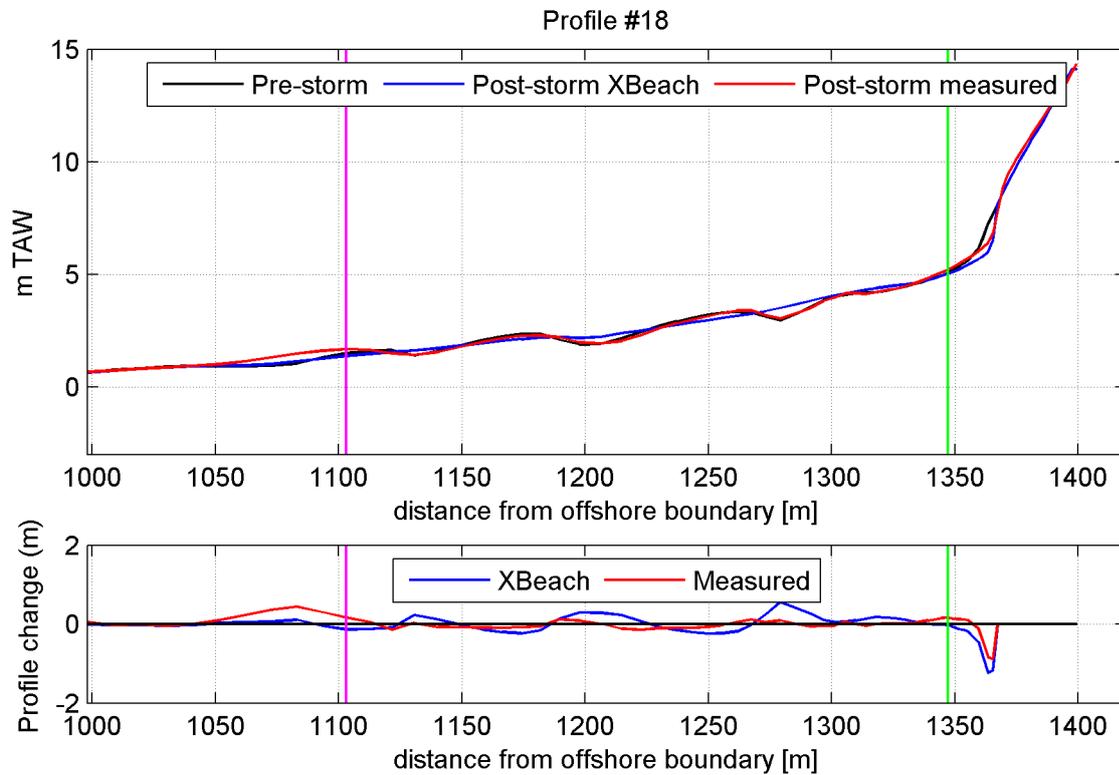
Measured: Above 5 m TAW:  $-9.81 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-4.00 \text{ m}^3/\text{m}$ .



BSS = -0.24

Xbeach: Above 5 m TAW:  $-7.95 \text{ m}^3/\text{m}$ . Below 5m TAW:  $9.89 \text{ m}^3/\text{m}$ .

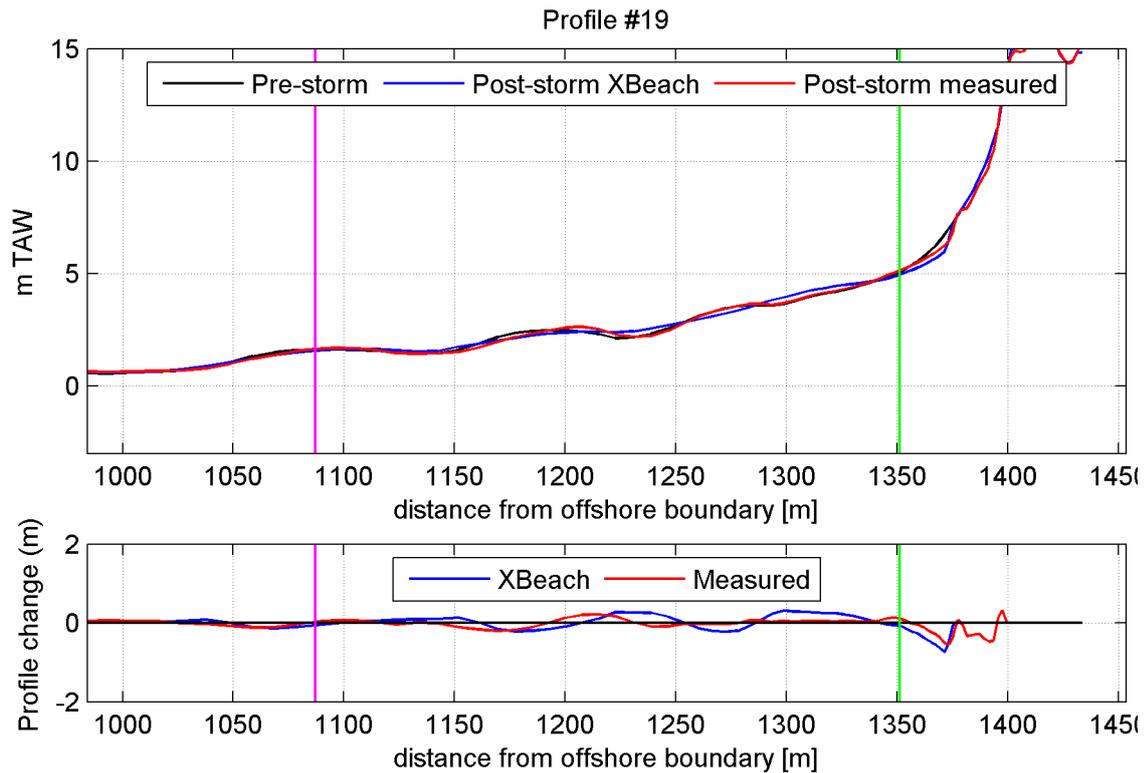
Measured: Above 5 m TAW:  $-8.00 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-8.13 \text{ m}^3/\text{m}$ .



BSS = -1.06

Xbeach: Above 5 m TAW:  $-9.18 \text{ m}^3/\text{m}$ . Below 5m TAW:  $9.78 \text{ m}^3/\text{m}$ .

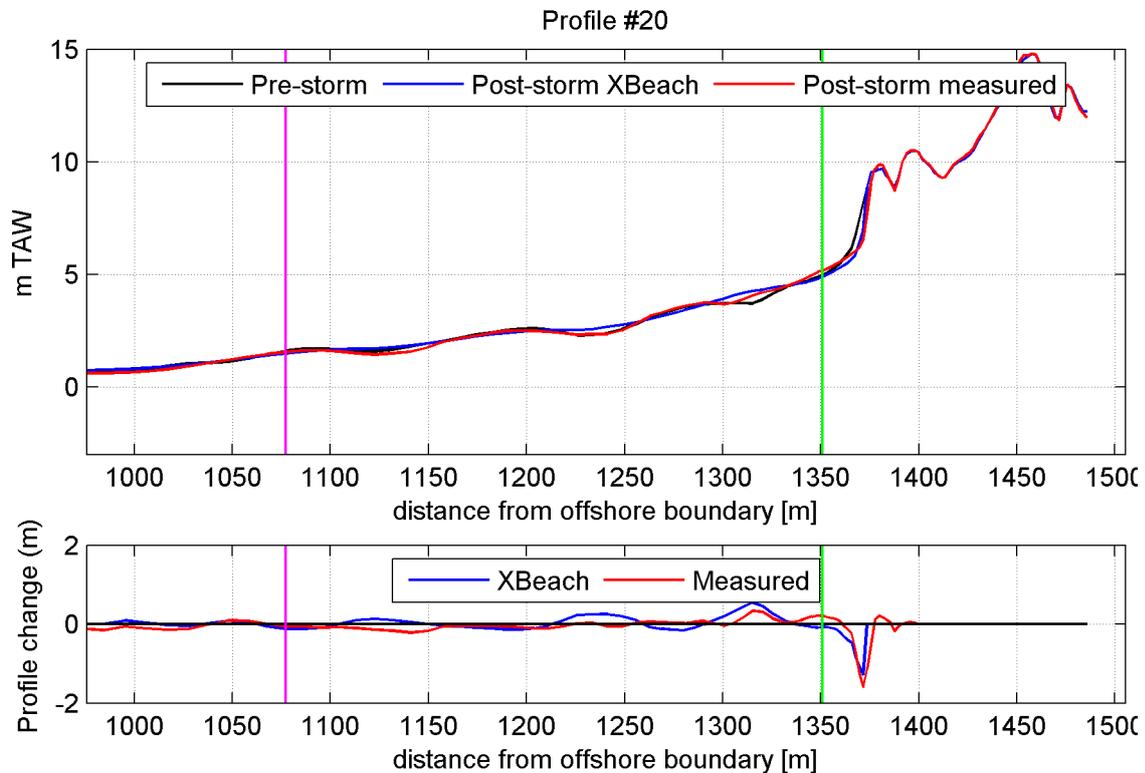
Measured: Above 5 m TAW:  $-3.39 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-3.19 \text{ m}^3/\text{m}$ .



BSS = -0.61

Xbeach: Above 5 m TAW:  $-9.26 \text{ m}^3/\text{m}$ . Below 5m TAW:  $12.38 \text{ m}^3/\text{m}$ .

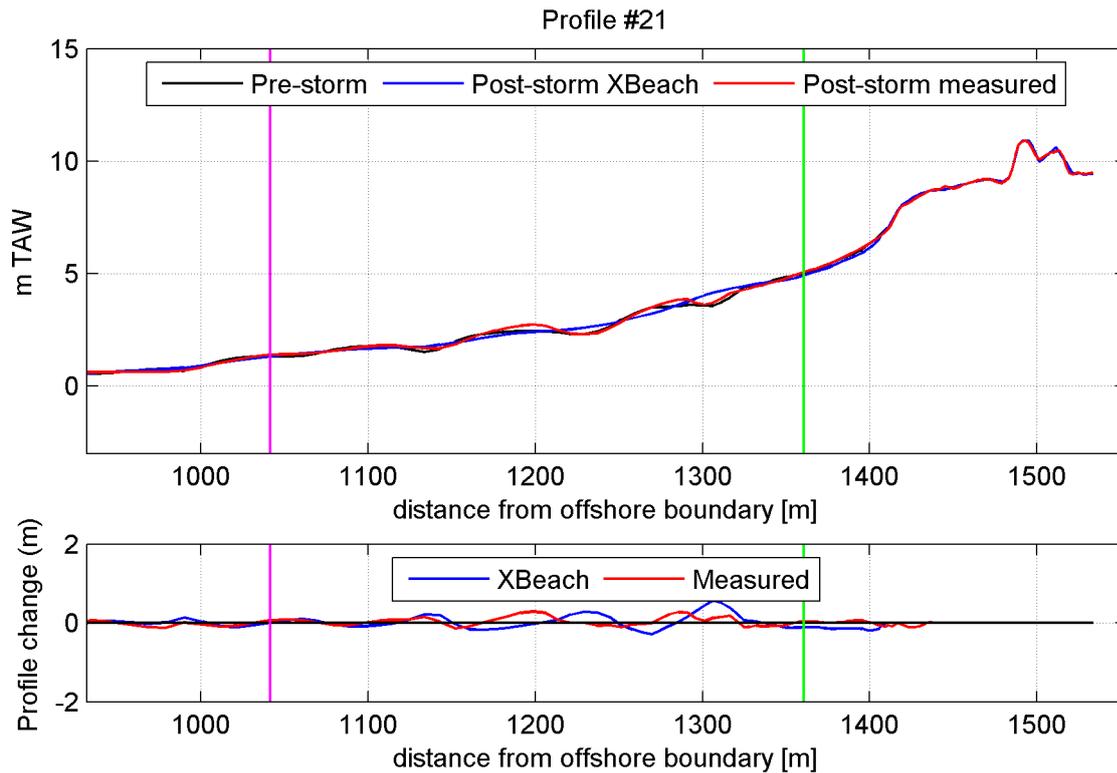
Measured: Above 5 m TAW:  $-9.18 \text{ m}^3/\text{m}$ . Below 5m TAW:  $2.06 \text{ m}^3/\text{m}$ .



BSS = 0.22

Xbeach: Above 5 m TAW:  $-9.83 \text{ m}^3/\text{m}$ . Below 5m TAW:  $12.46 \text{ m}^3/\text{m}$ .

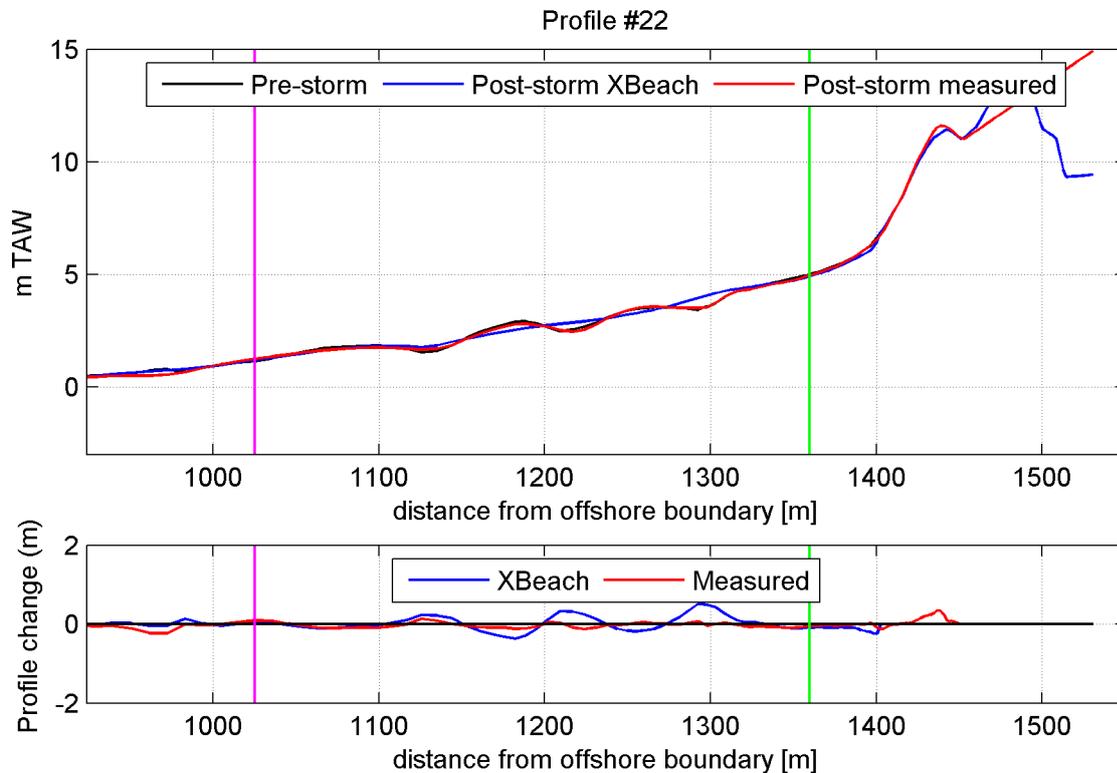
Measured: Above 5 m TAW:  $-8.74 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-4.88 \text{ m}^3/\text{m}$ .



BSS = -1.73

Xbeach: Above 5 m TAW:  $-6.64 \text{ m}^3/\text{m}$ . Below 5m TAW:  $11.31 \text{ m}^3/\text{m}$ .

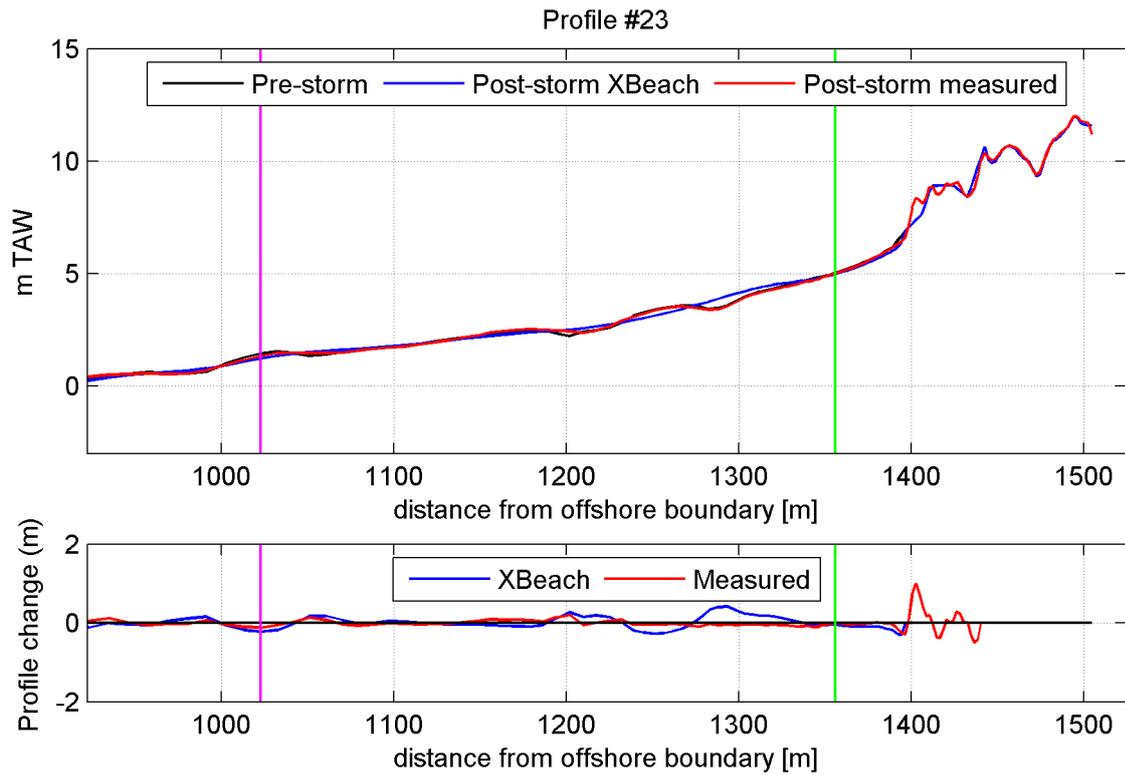
Measured: Above 5 m TAW:  $-0.92 \text{ m}^3/\text{m}$ . Below 5m TAW:  $14.59 \text{ m}^3/\text{m}$ .



BSS = -3.36

Xbeach: Above 5 m TAW:  $-4.98 \text{ m}^3/\text{m}$ . Below 5m TAW:  $8.24 \text{ m}^3/\text{m}$ .

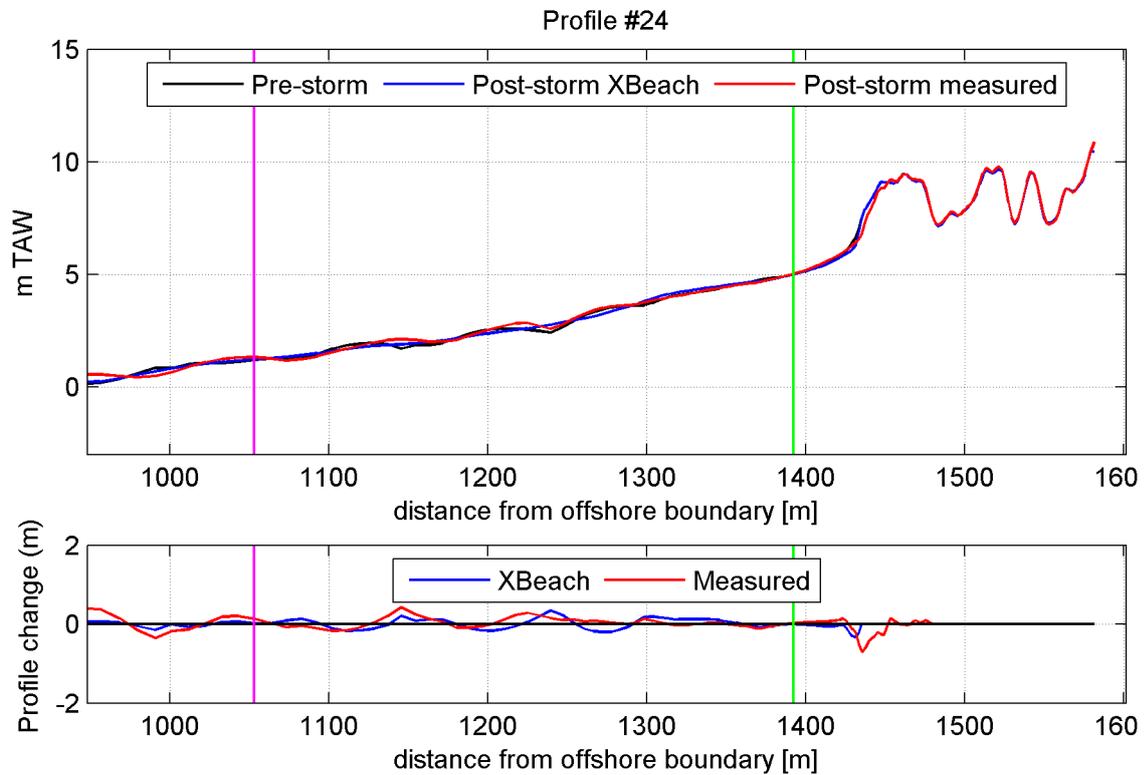
Measured: Above 5 m TAW:  $3.38 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-9.34 \text{ m}^3/\text{m}$ .



BSS = -0.86

Xbeach: Above 5 m TAW:  $-4.89 \text{ m}^3/\text{m}$ . Below 5m TAW:  $9.68 \text{ m}^3/\text{m}$ .

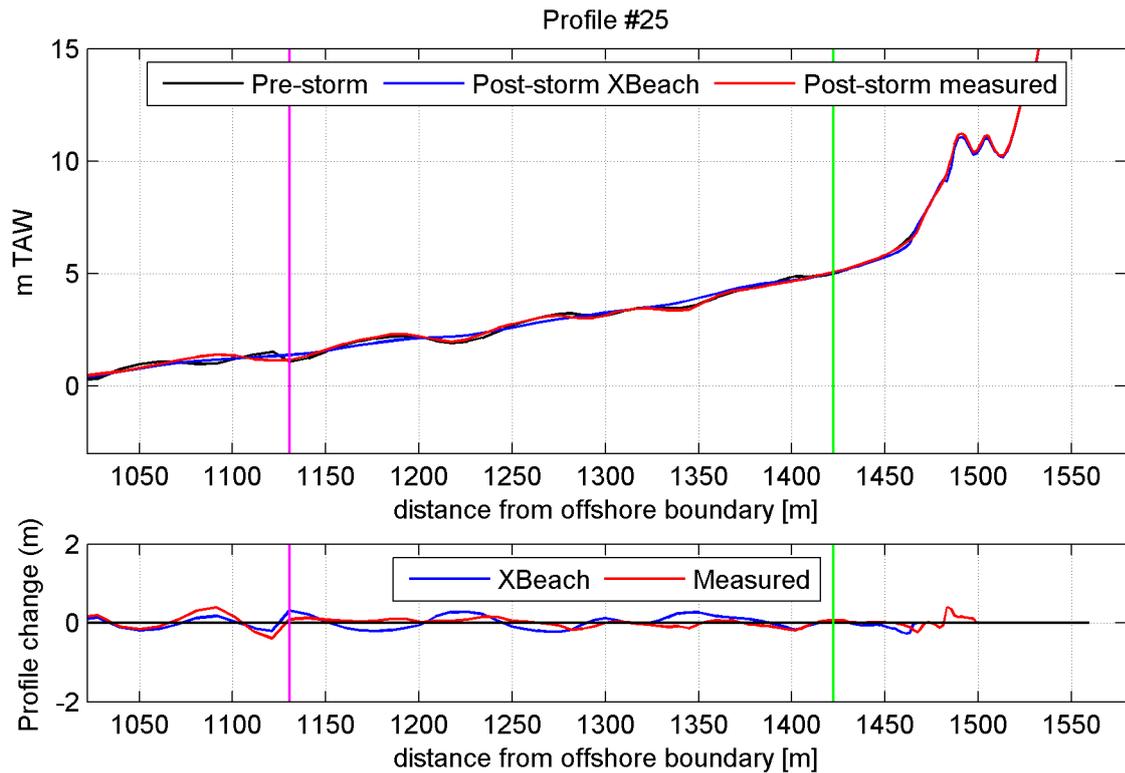
Measured: Above 5 m TAW:  $1.29 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-1.23 \text{ m}^3/\text{m}$ .



BSS = -0.07

Xbeach: Above 5 m TAW:  $-3.35 \text{ m}^3/\text{m}$ . Below 5m TAW:  $5.91 \text{ m}^3/\text{m}$ .

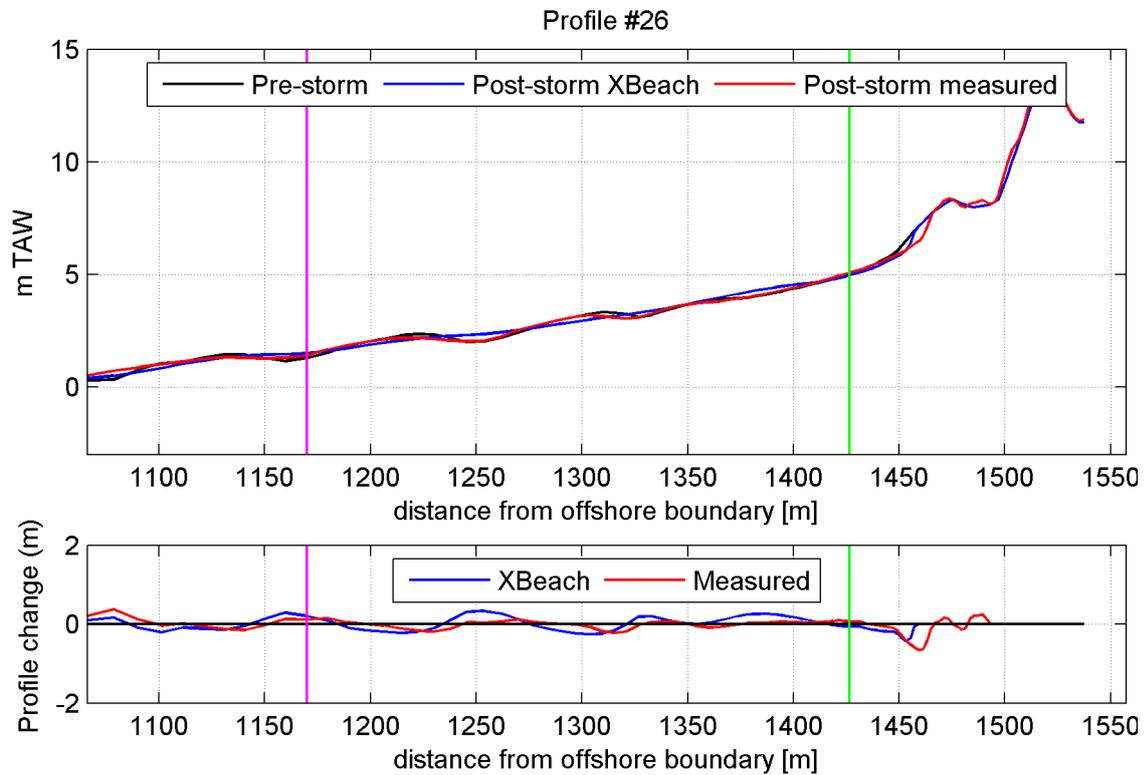
Measured: Above 5 m TAW:  $-4.79 \text{ m}^3/\text{m}$ . Below 5m TAW:  $13.72 \text{ m}^3/\text{m}$ .



BSS = -1.82

Xbeach: Above 5 m TAW:  $-3.43 \text{ m}^3/\text{m}$ . Below 5m TAW:  $7.09 \text{ m}^3/\text{m}$ .

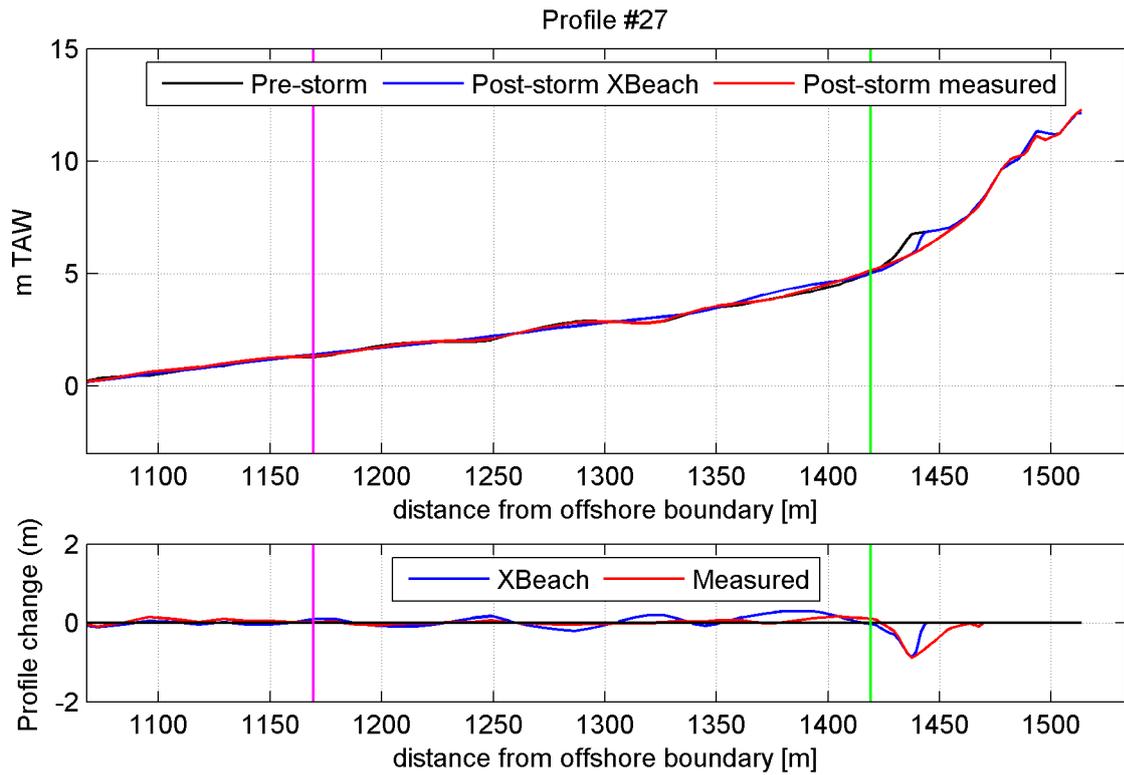
Measured: Above 5 m TAW:  $1.76 \text{ m}^3/\text{m}$ . Below 5m TAW:  $2.29 \text{ m}^3/\text{m}$ .



BSS = -0.45

Xbeach: Above 5 m TAW:  $-5.76 \text{ m}^3/\text{m}$ . Below 5m TAW:  $7.85 \text{ m}^3/\text{m}$ .

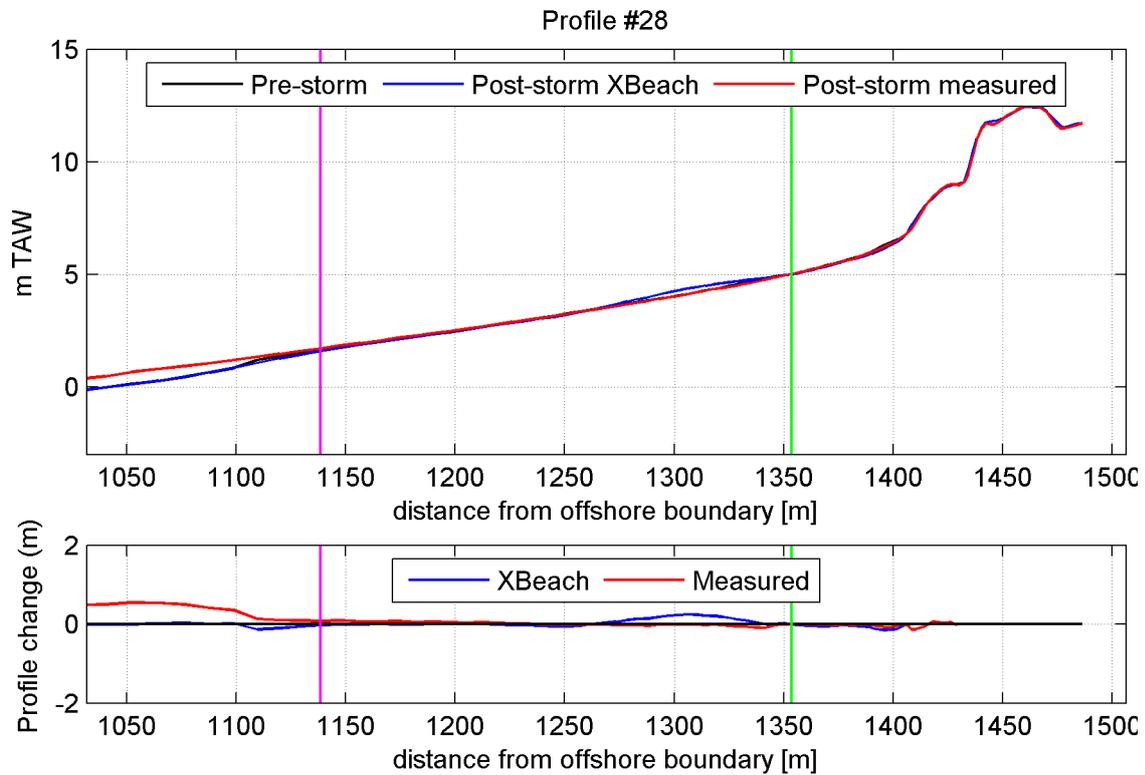
Measured: Above 5 m TAW:  $-5.79 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-1.52 \text{ m}^3/\text{m}$ .



BSS = 0.28

Xbeach: Above 5 m TAW:  $-9.18 \text{ m}^3/\text{m}$ . Below 5m TAW:  $12.72 \text{ m}^3/\text{m}$ .

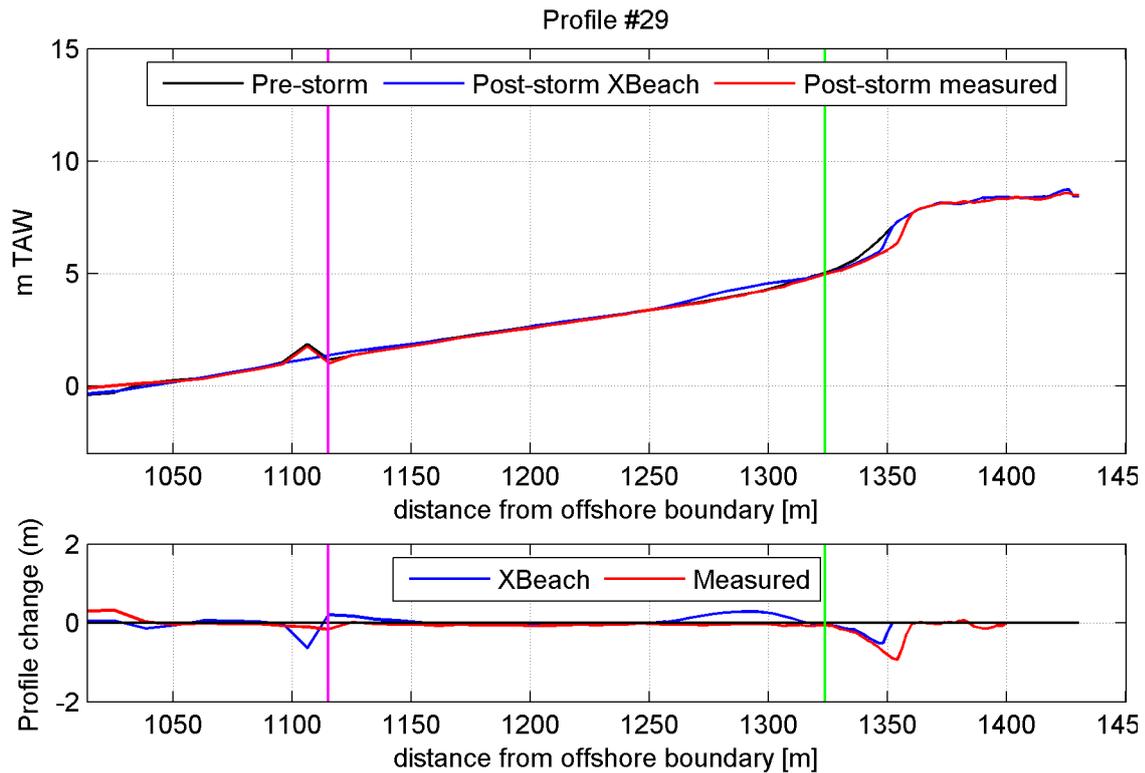
Measured: Above 5 m TAW:  $-14.76 \text{ m}^3/\text{m}$ . Below 5m TAW:  $5.04 \text{ m}^3/\text{m}$ .



BSS = -4.10

Xbeach: Above 5 m TAW:  $-3.34 \text{ m}^3/\text{m}$ . Below 5m TAW:  $9.69 \text{ m}^3/\text{m}$ .

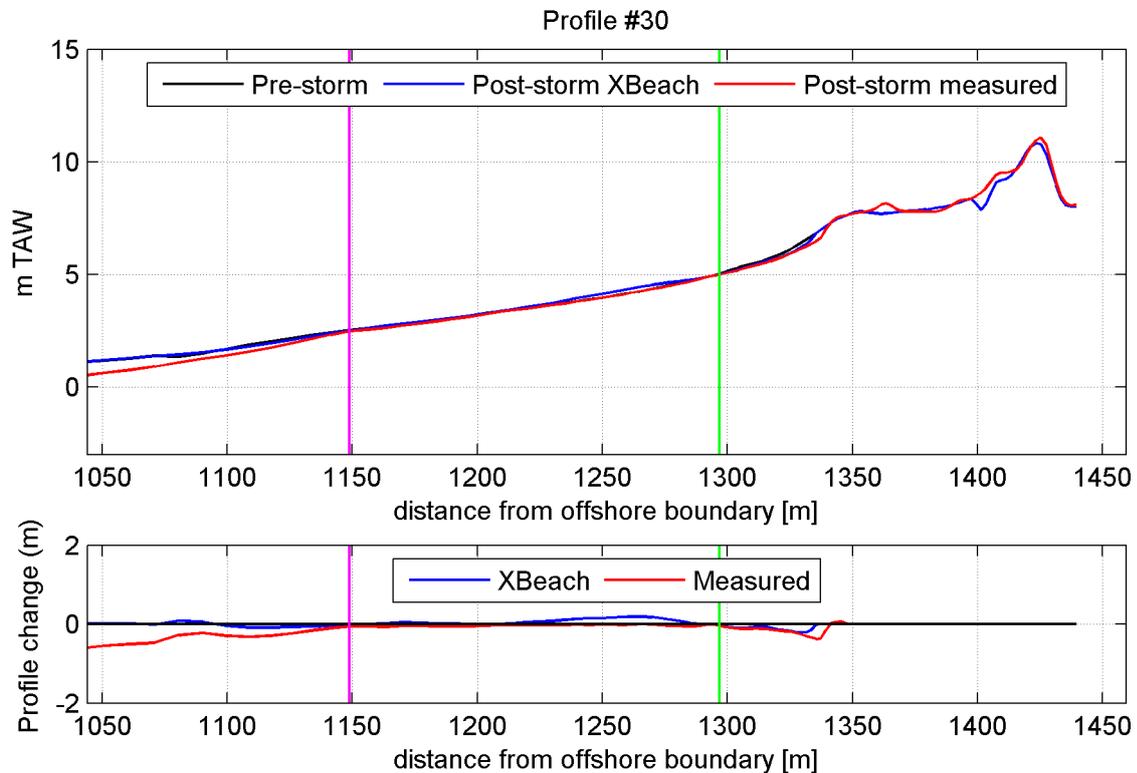
Measured: Above 5 m TAW:  $-1.51 \text{ m}^3/\text{m}$ . Below 5m TAW:  $2.38 \text{ m}^3/\text{m}$ .



BSS = -0.01

Xbeach: Above 5 m TAW:  $-6.67 \text{ m}^3/\text{m}$ . Below 5m TAW:  $13.62 \text{ m}^3/\text{m}$ .

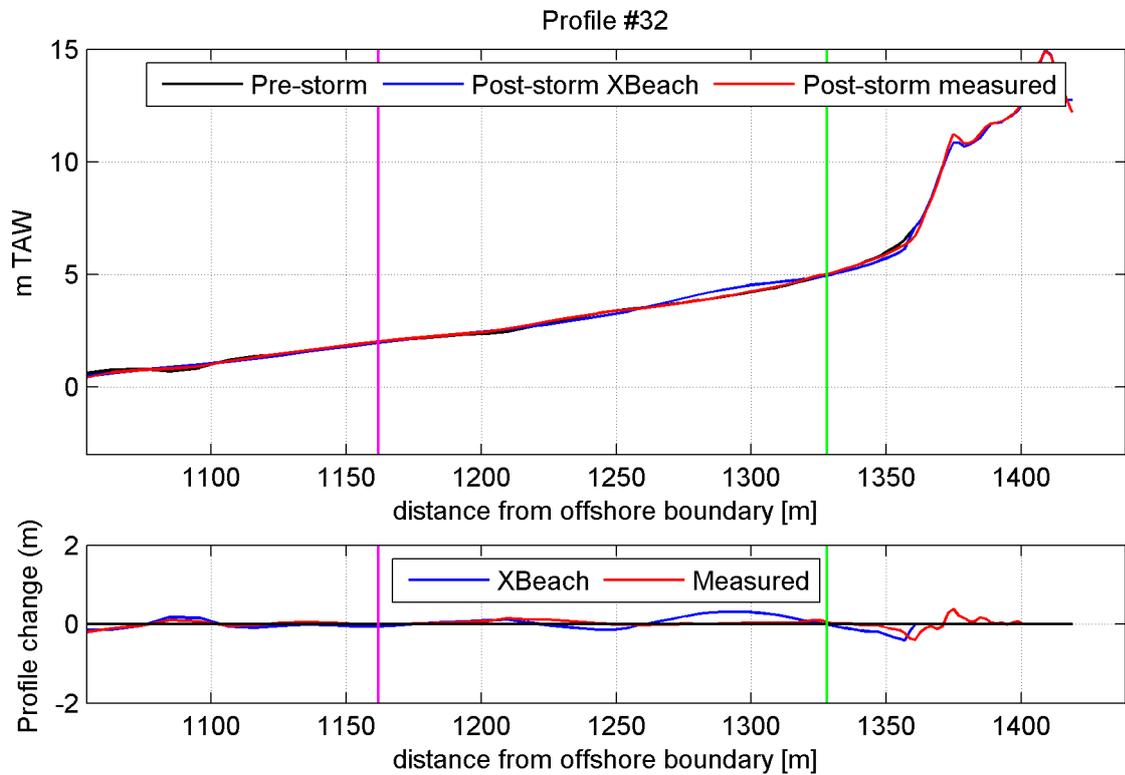
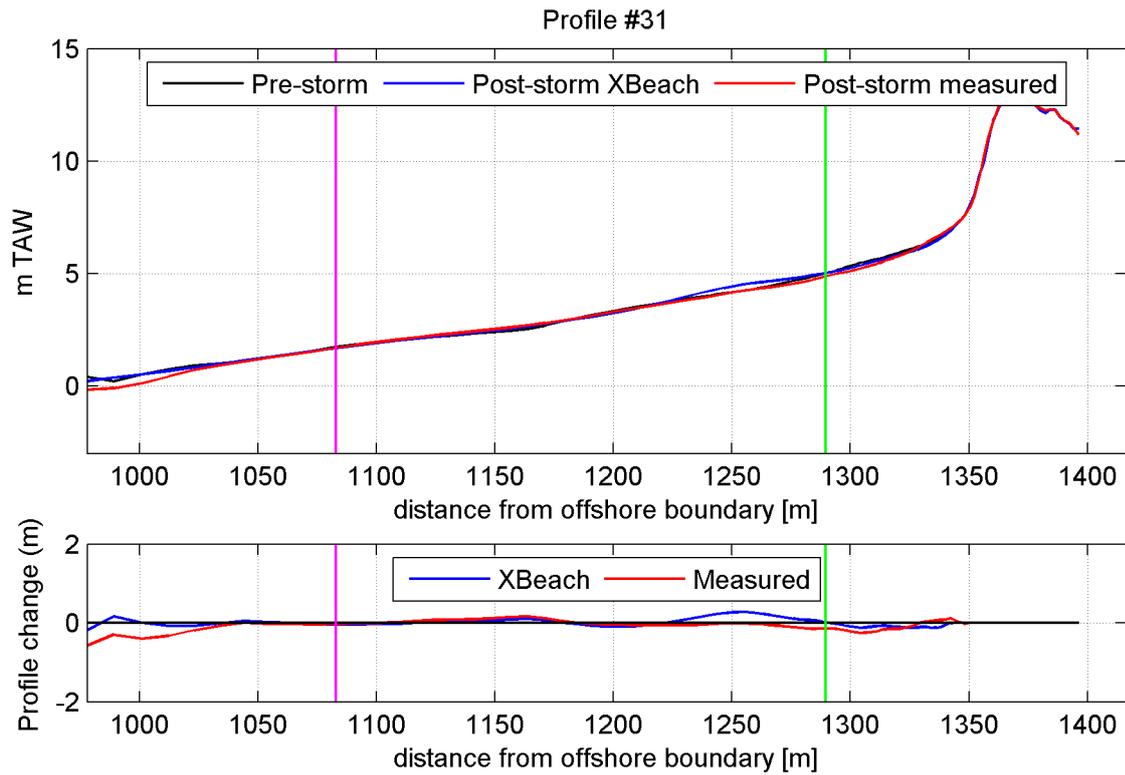
Measured: Above 5 m TAW:  $-16.47 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-9.62 \text{ m}^3/\text{m}$ .

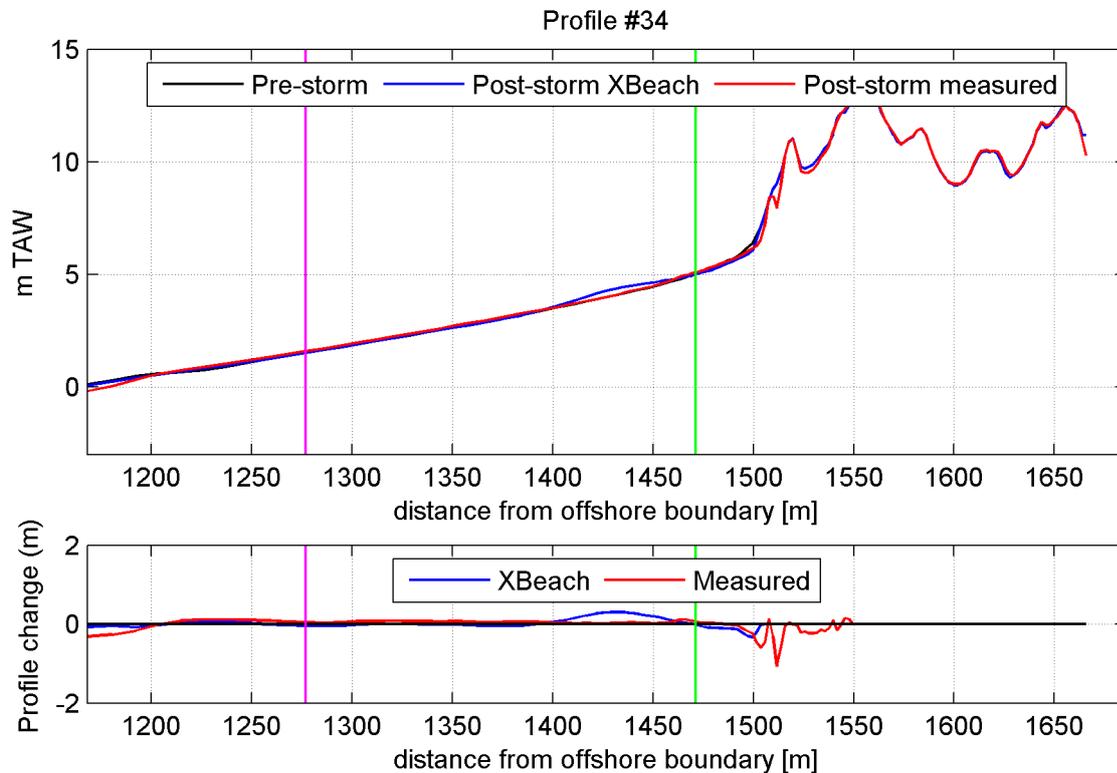
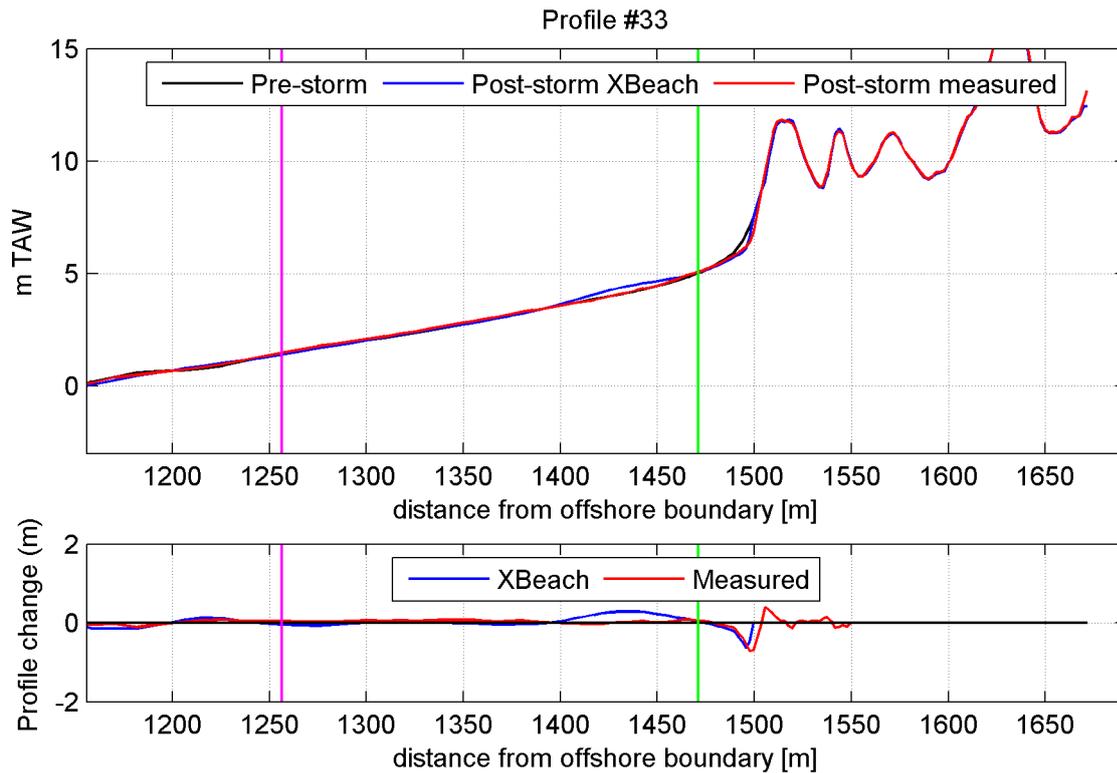


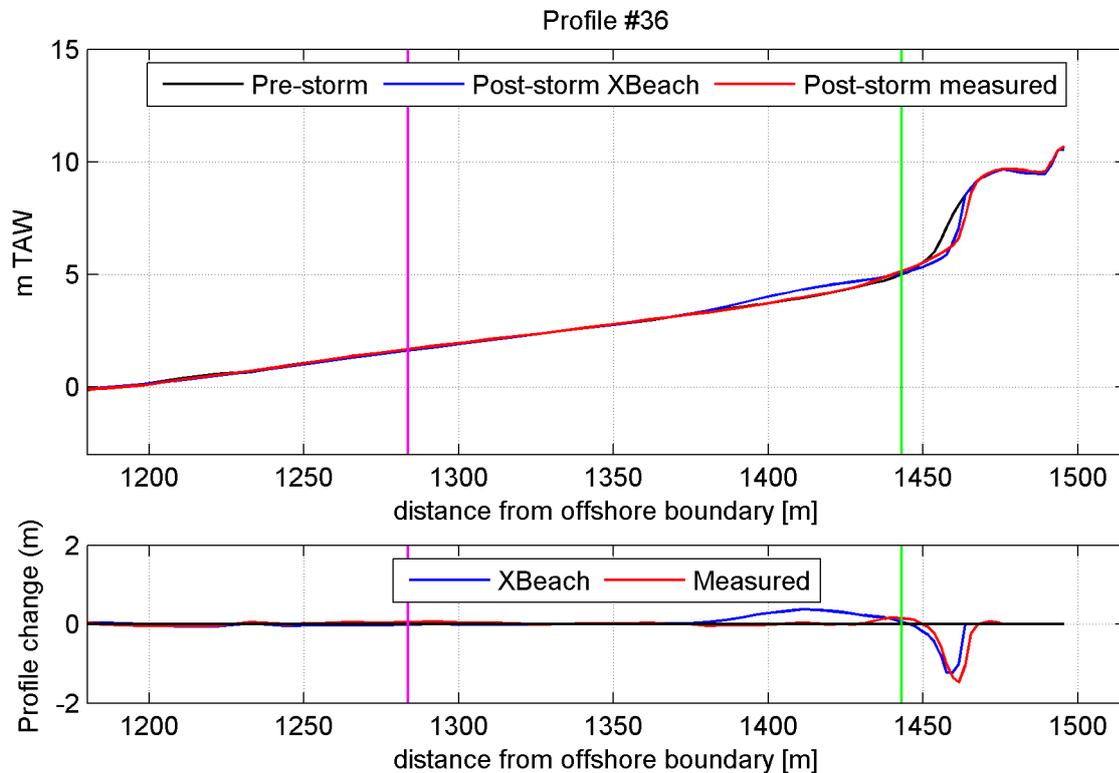
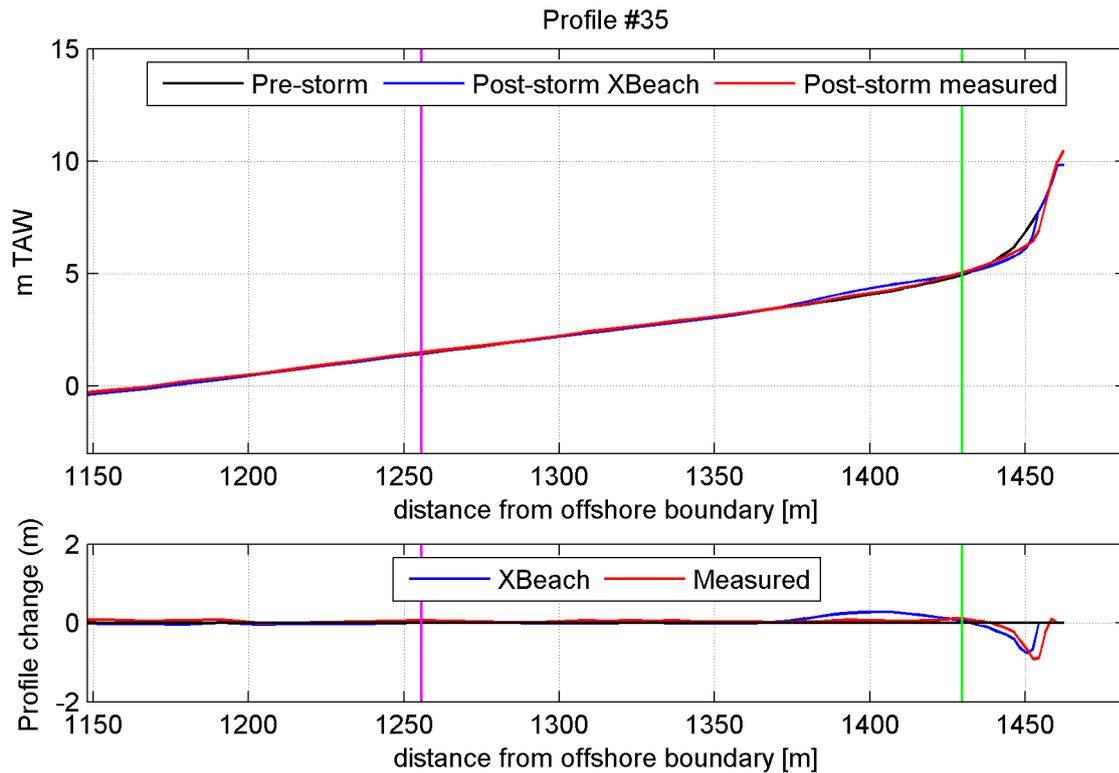
BSS = -0.31

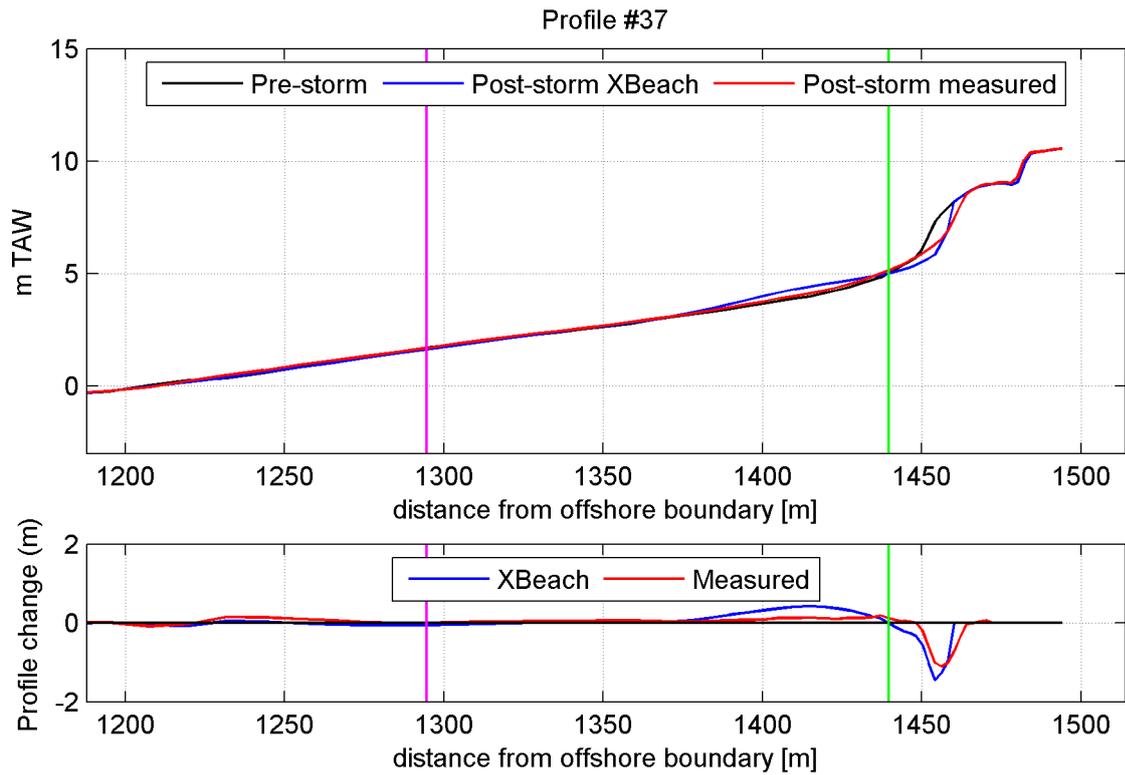
Xbeach: Above 5 m TAW:  $-4.36 \text{ m}^3/\text{m}$ . Below 5m TAW:  $9.51 \text{ m}^3/\text{m}$ .

Measured: Above 5 m TAW:  $-7.41 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-4.83 \text{ m}^3/\text{m}$ .





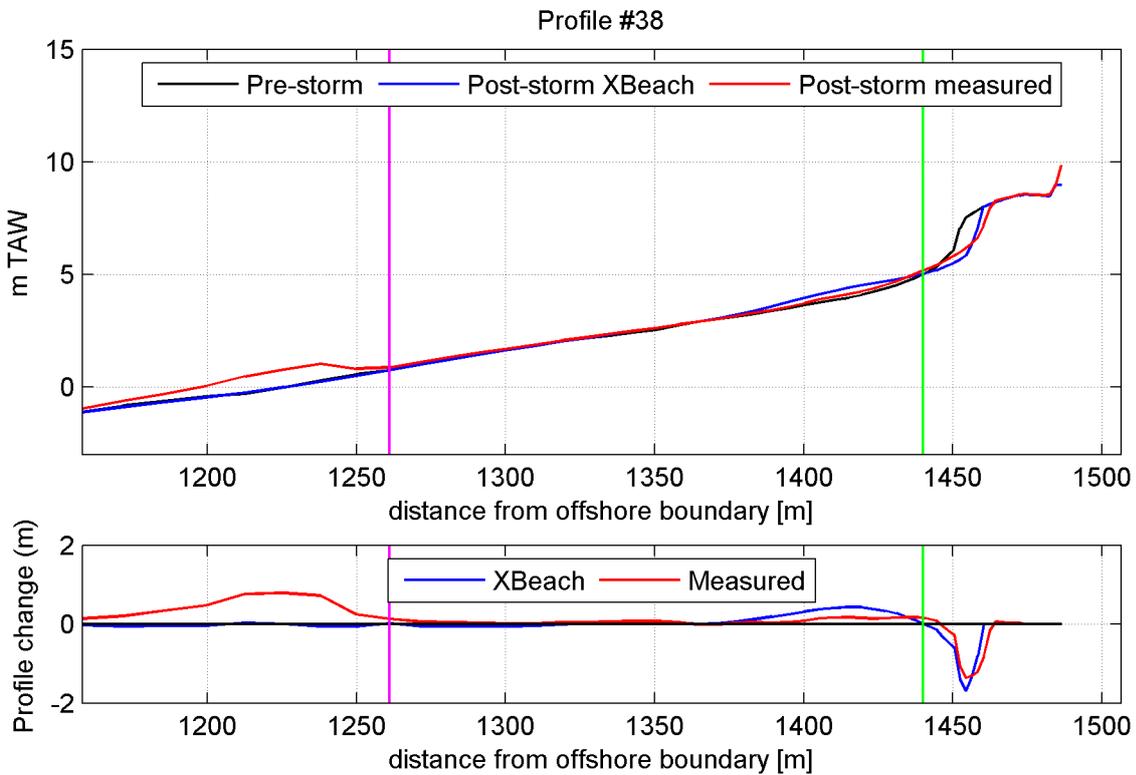




BSS = 0.40

Xbeach: Above 5 m TAW:  $-12.44 \text{ m}^3/\text{m}$ . Below 5m TAW:  $17.56 \text{ m}^3/\text{m}$ .

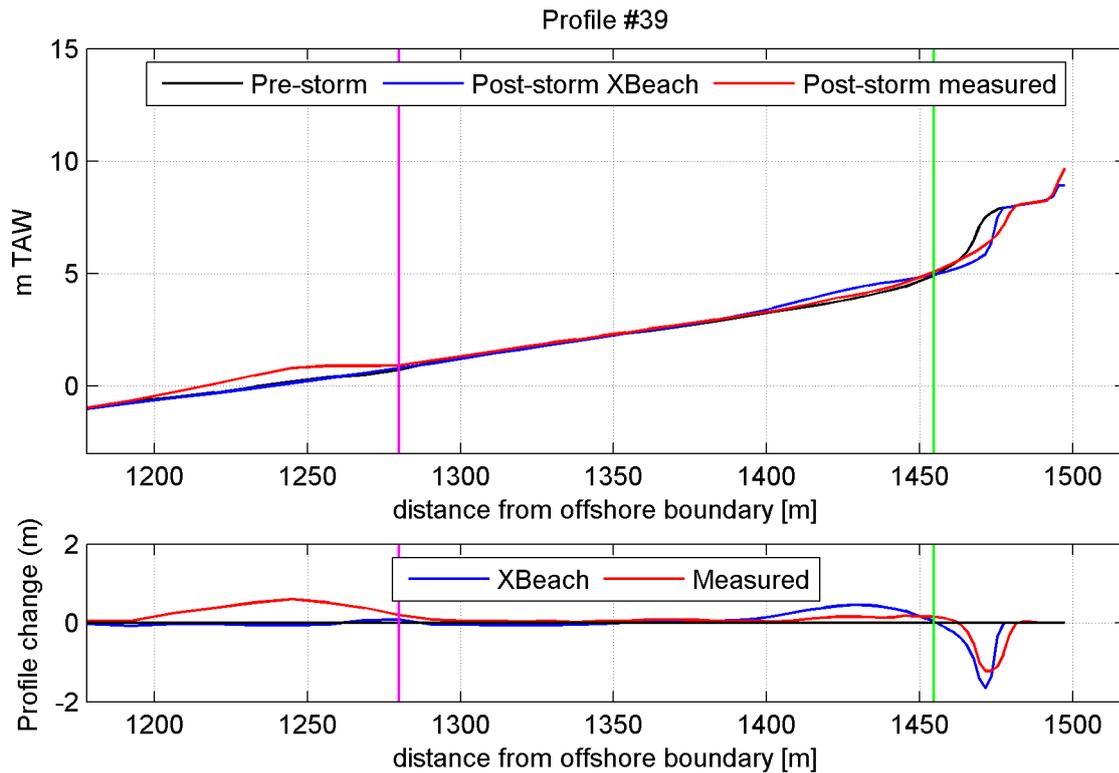
Measured: Above 5 m TAW:  $-9.36 \text{ m}^3/\text{m}$ . Below 5m TAW:  $9.69 \text{ m}^3/\text{m}$ .



BSS = 0.63

Xbeach: Above 5 m TAW:  $-13.55 \text{ m}^3/\text{m}$ . Below 5m TAW:  $16.59 \text{ m}^3/\text{m}$ .

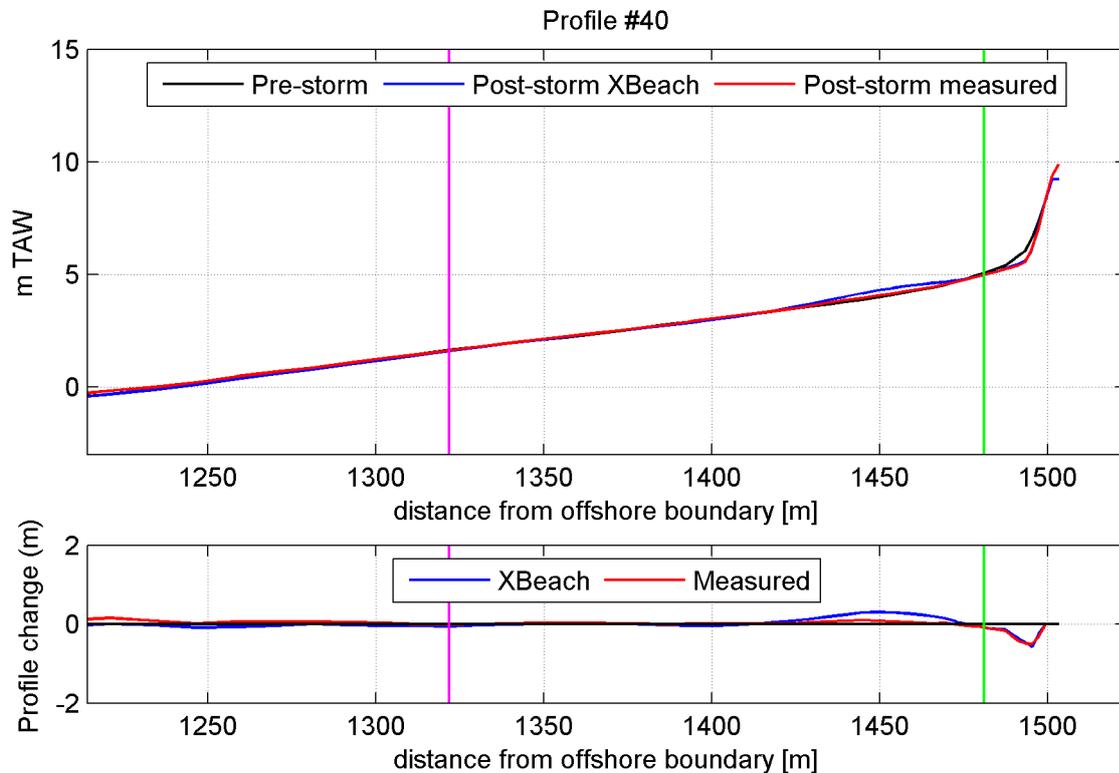
Measured: Above 5 m TAW:  $-11.82 \text{ m}^3/\text{m}$ . Below 5m TAW:  $12.30 \text{ m}^3/\text{m}$ .



BSS = 0.42

Xbeach: Above 5 m TAW:  $-14.19 \text{ m}^3/\text{m}$ . Below 5m TAW:  $17.32 \text{ m}^3/\text{m}$ .

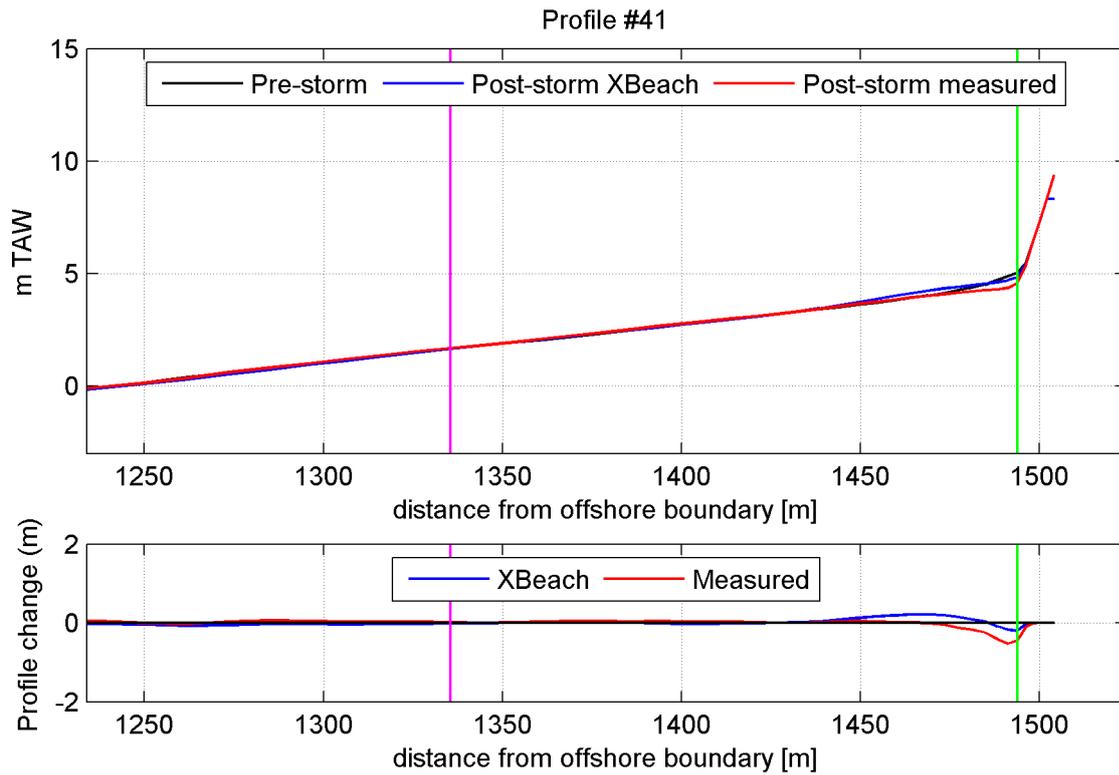
Measured: Above 5 m TAW:  $-11.79 \text{ m}^3/\text{m}$ . Below 5m TAW:  $14.12 \text{ m}^3/\text{m}$ .



BSS = 0.28

Xbeach: Above 5 m TAW:  $-4.69 \text{ m}^3/\text{m}$ . Below 5m TAW:  $10.15 \text{ m}^3/\text{m}$ .

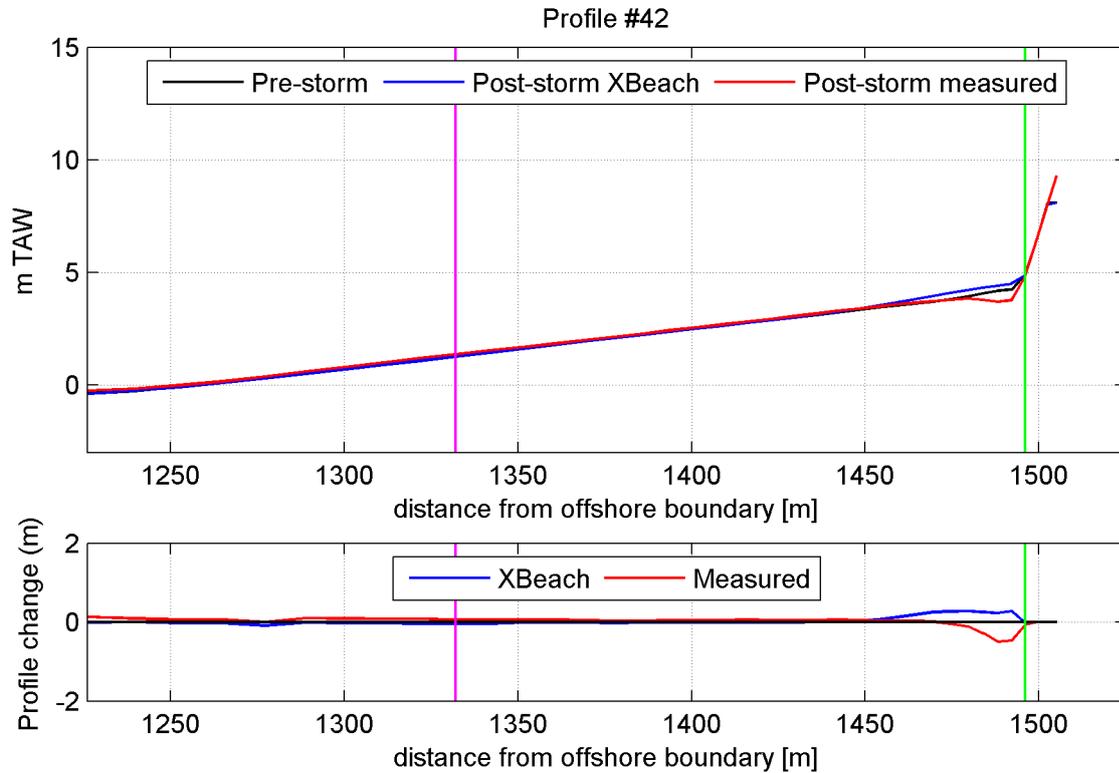
Measured: Above 5 m TAW:  $-5.07 \text{ m}^3/\text{m}$ . Below 5m TAW:  $3.86 \text{ m}^3/\text{m}$ .



BSS = -0.15

Xbeach: Above 5 m TAW:  $-0.33 \text{ m}^3/\text{m}$ . Below 5m TAW:  $6.37 \text{ m}^3/\text{m}$ .

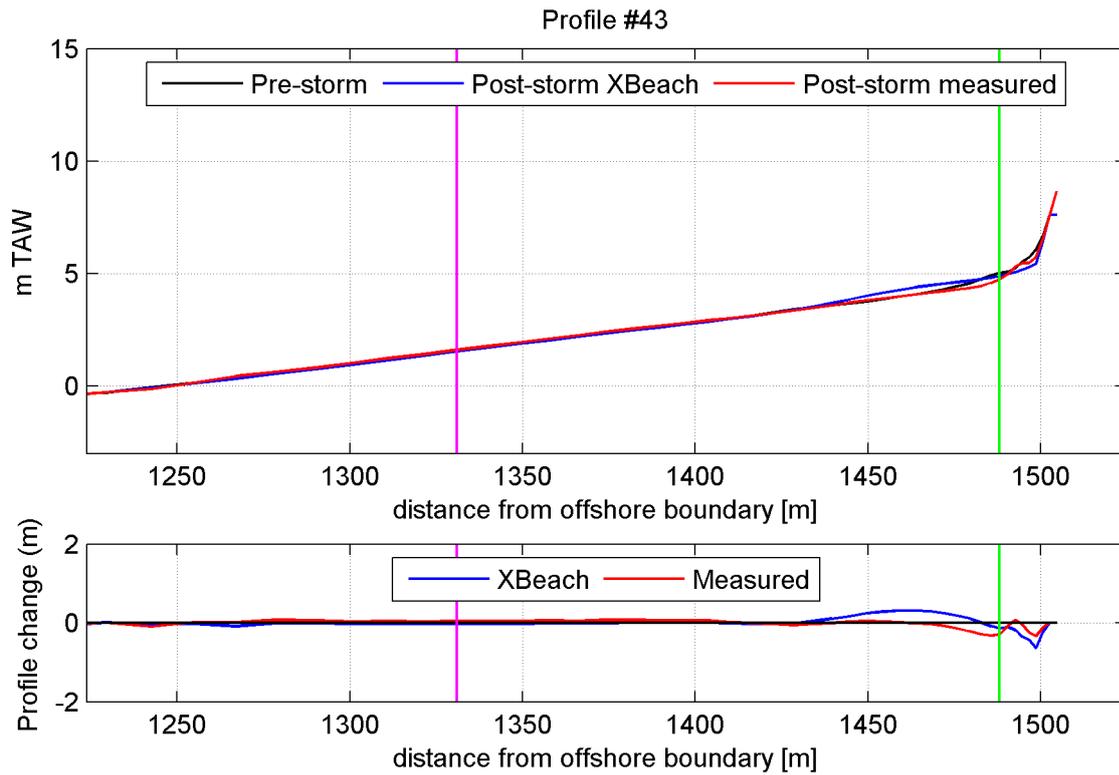
Measured: Above 5 m TAW:  $-0.78 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-2.05 \text{ m}^3/\text{m}$ .



BSS = -1.93

Xbeach: Above 5 m TAW:  $-0.04 \text{ m}^3/\text{m}$ . Below 5m TAW:  $8.17 \text{ m}^3/\text{m}$ .

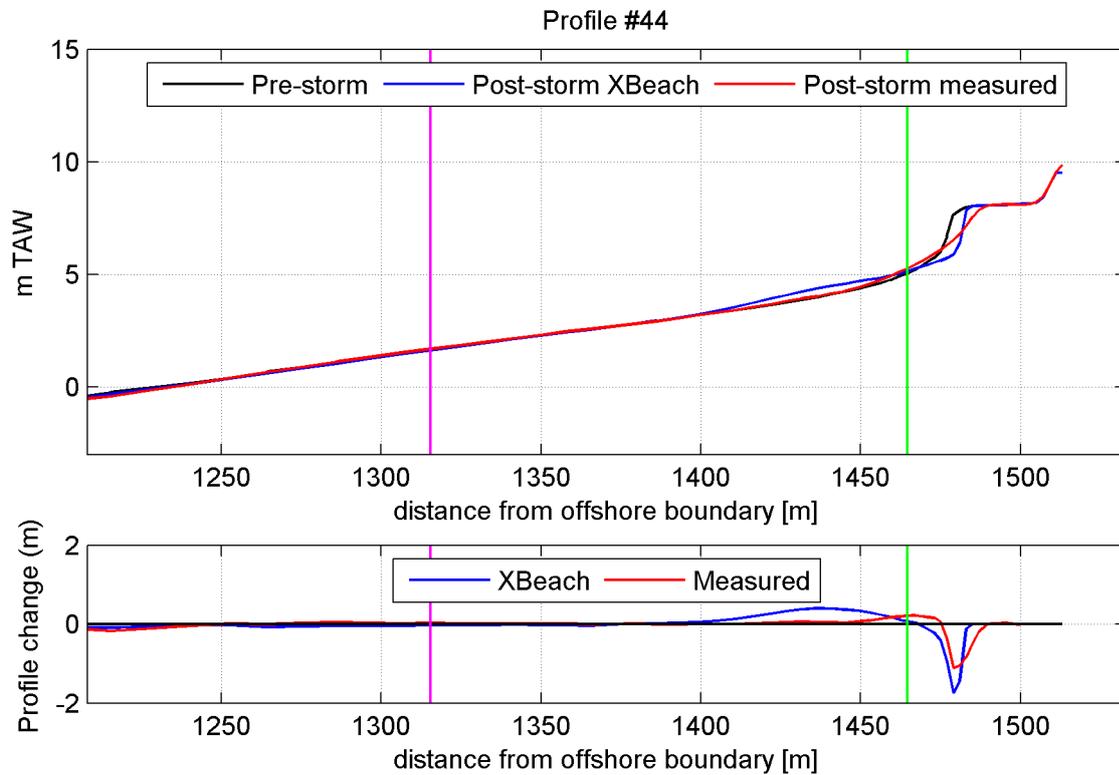
Measured: Above 5 m TAW:  $-0.11 \text{ m}^3/\text{m}$ . Below 5m TAW:  $0.87 \text{ m}^3/\text{m}$ .



BSS = -1.68

Xbeach: Above 5 m TAW:  $-4.10 \text{ m}^3/\text{m}$ . Below 5m TAW:  $8.99 \text{ m}^3/\text{m}$ .

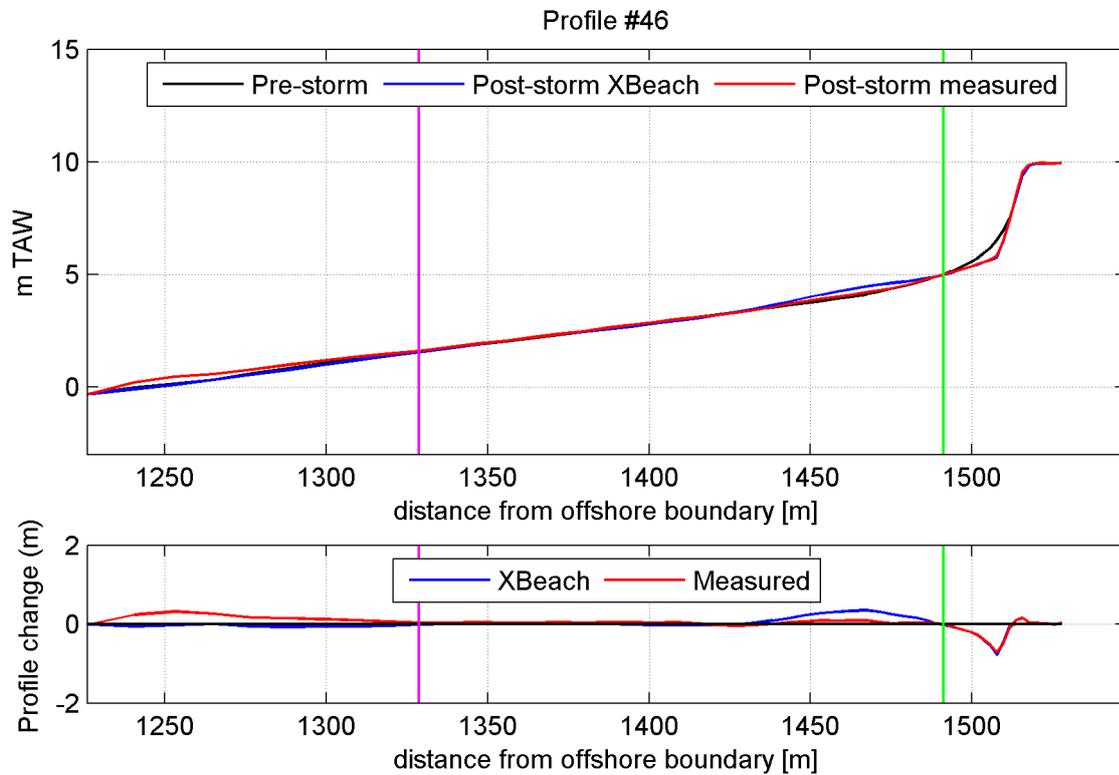
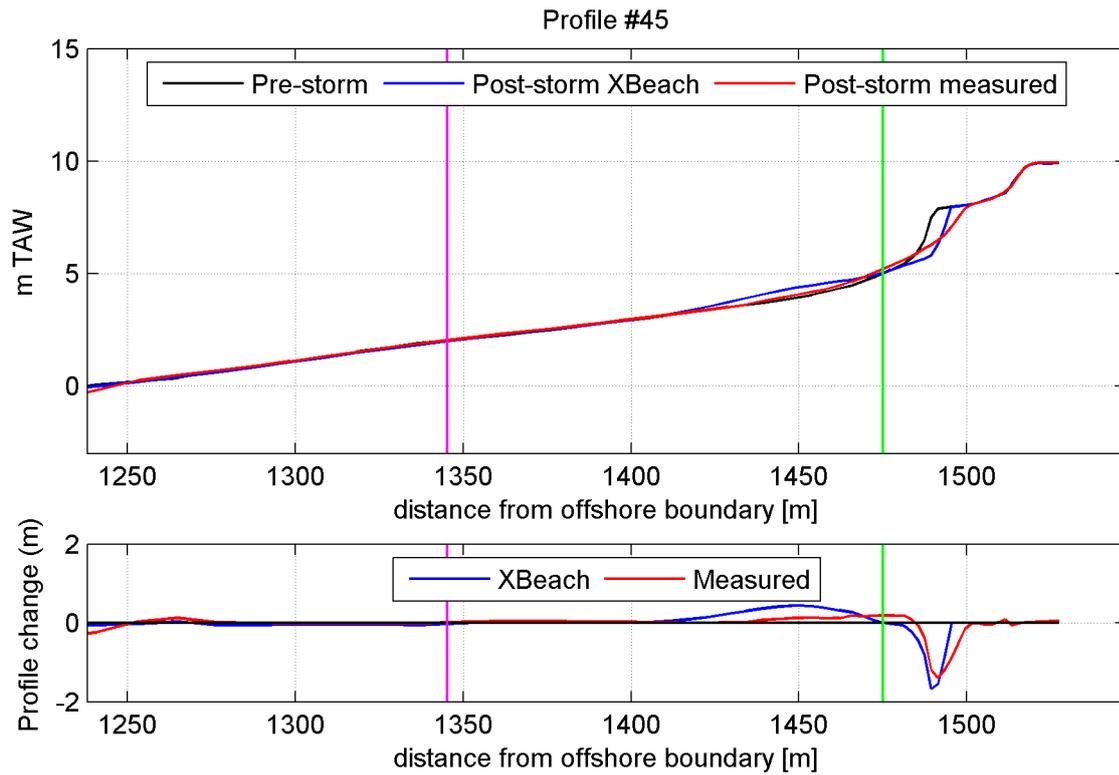
Measured: Above 5 m TAW:  $-1.86 \text{ m}^3/\text{m}$ . Below 5m TAW:  $0.64 \text{ m}^3/\text{m}$ .

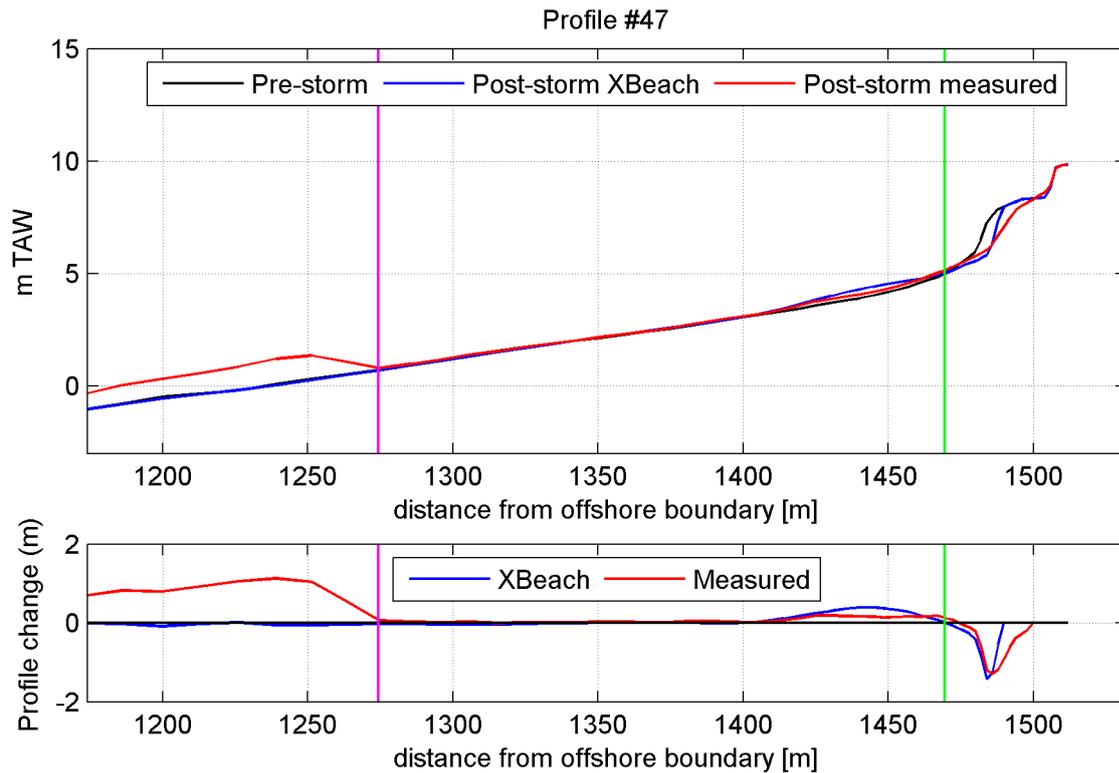


BSS = -0.05

Xbeach: Above 5 m TAW:  $-9.95 \text{ m}^3/\text{m}$ . Below 5m TAW:  $15.95 \text{ m}^3/\text{m}$ .

Measured: Above 5 m TAW:  $-6.14 \text{ m}^3/\text{m}$ . Below 5m TAW:  $4.62 \text{ m}^3/\text{m}$ .

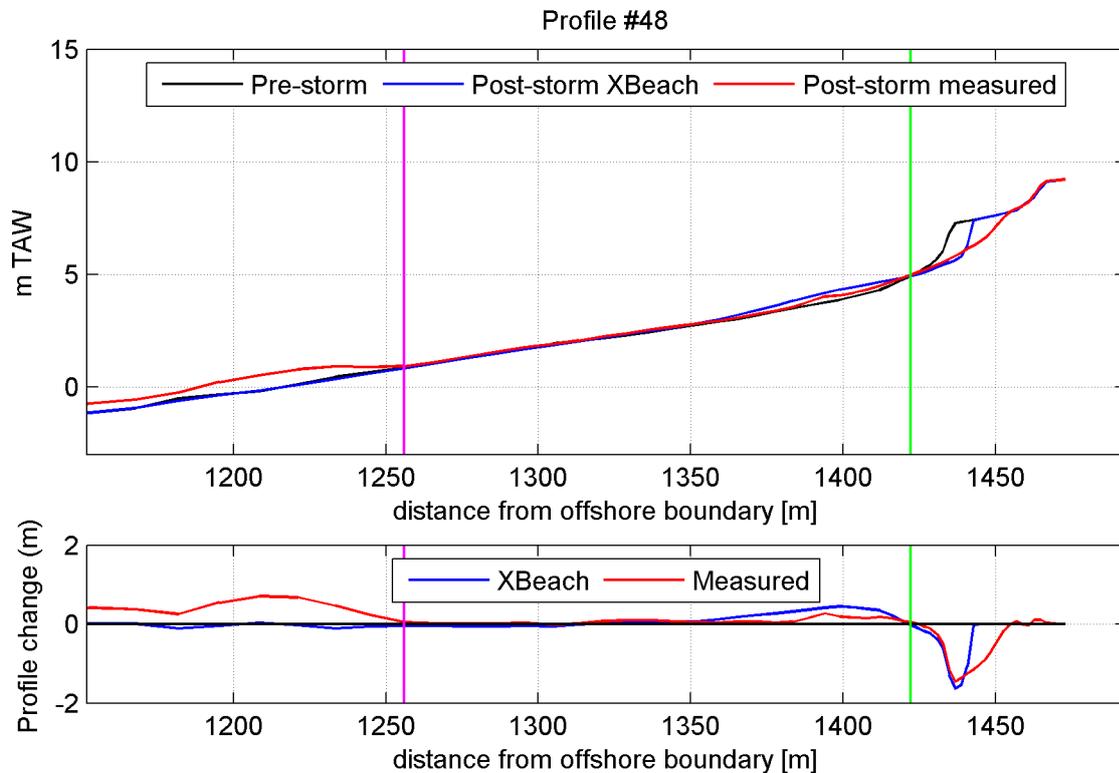




BSS = 0.61

Xbeach: Above 5 m TAW:  $-10.31 \text{ m}^3/\text{m}$ . Below 5m TAW:  $13.97 \text{ m}^3/\text{m}$ .

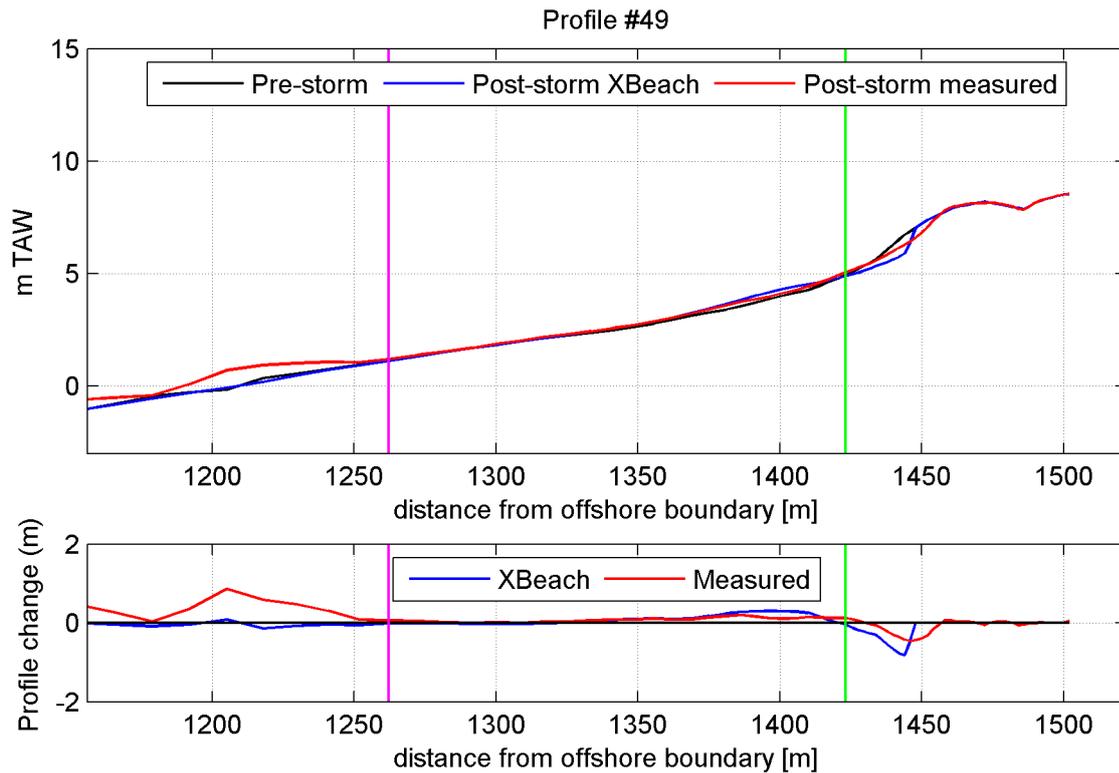
Measured: Above 5 m TAW:  $-13.70 \text{ m}^3/\text{m}$ . Below 5m TAW:  $12.28 \text{ m}^3/\text{m}$ .



BSS = 0.55

Xbeach: Above 5 m TAW:  $-14.29 \text{ m}^3/\text{m}$ . Below 5m TAW:  $18.16 \text{ m}^3/\text{m}$ .

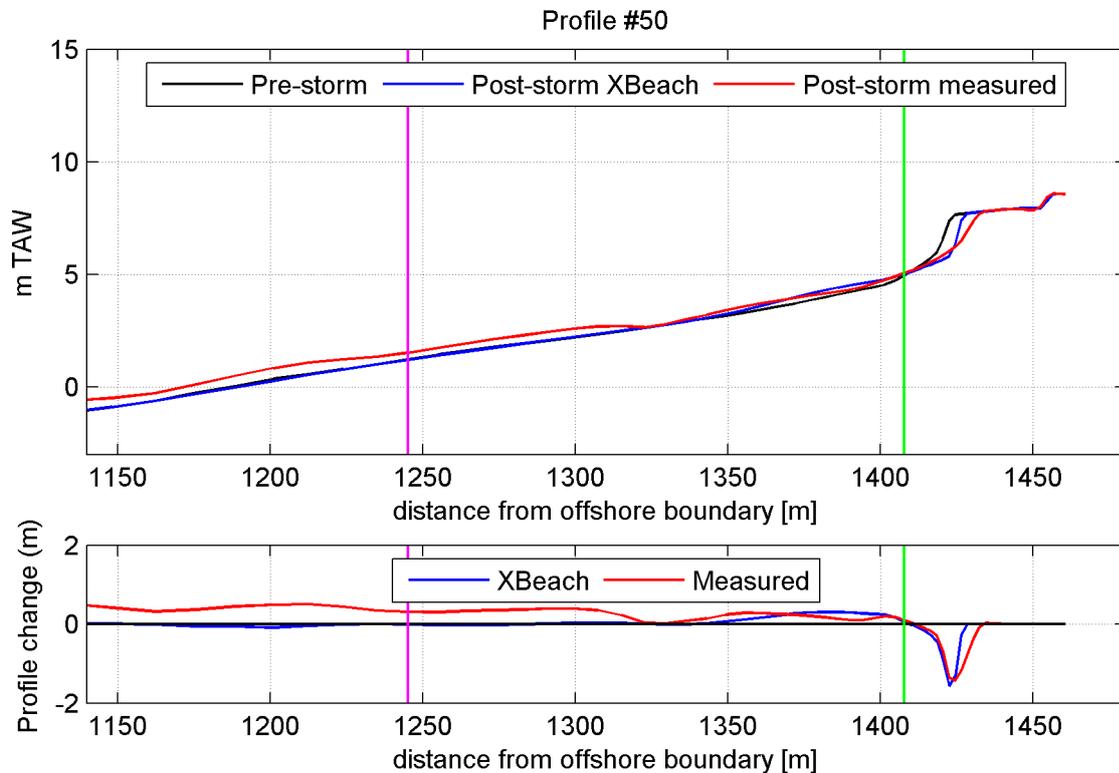
Measured: Above 5 m TAW:  $-20.21 \text{ m}^3/\text{m}$ . Below 5m TAW:  $11.68 \text{ m}^3/\text{m}$ .



BSS = 0.01

Xbeach: Above 5 m TAW:  $-9.83 \text{ m}^3/\text{m}$ . Below 5m TAW:  $14.28 \text{ m}^3/\text{m}$ .

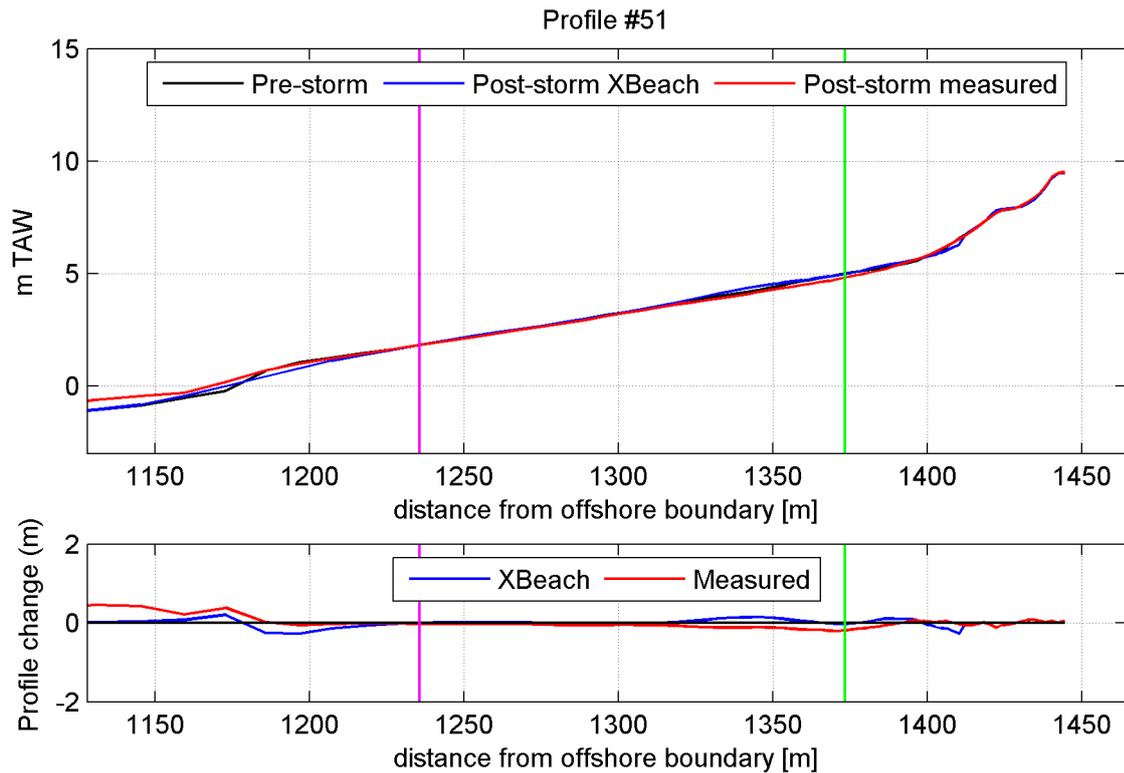
Measured: Above 5 m TAW:  $-5.80 \text{ m}^3/\text{m}$ . Below 5m TAW:  $12.73 \text{ m}^3/\text{m}$ .



BSS = 0.47

Xbeach: Above 5 m TAW:  $-10.14 \text{ m}^3/\text{m}$ . Below 5m TAW:  $13.31 \text{ m}^3/\text{m}$ .

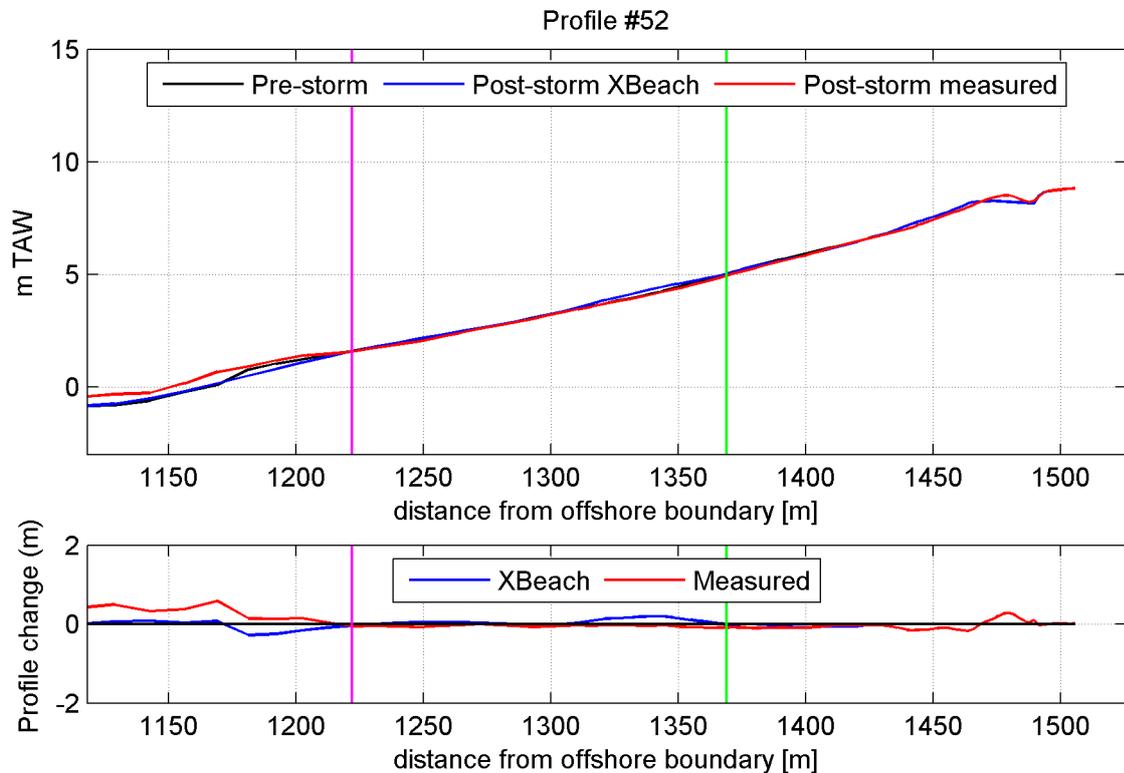
Measured: Above 5 m TAW:  $-12.71 \text{ m}^3/\text{m}$ . Below 5m TAW:  $39.26 \text{ m}^3/\text{m}$ .



BSS = -1.29

Xbeach: Above 5 m TAW:  $-0.38 \text{ m}^3/\text{m}$ . Below 5m TAW:  $4.08 \text{ m}^3/\text{m}$ .

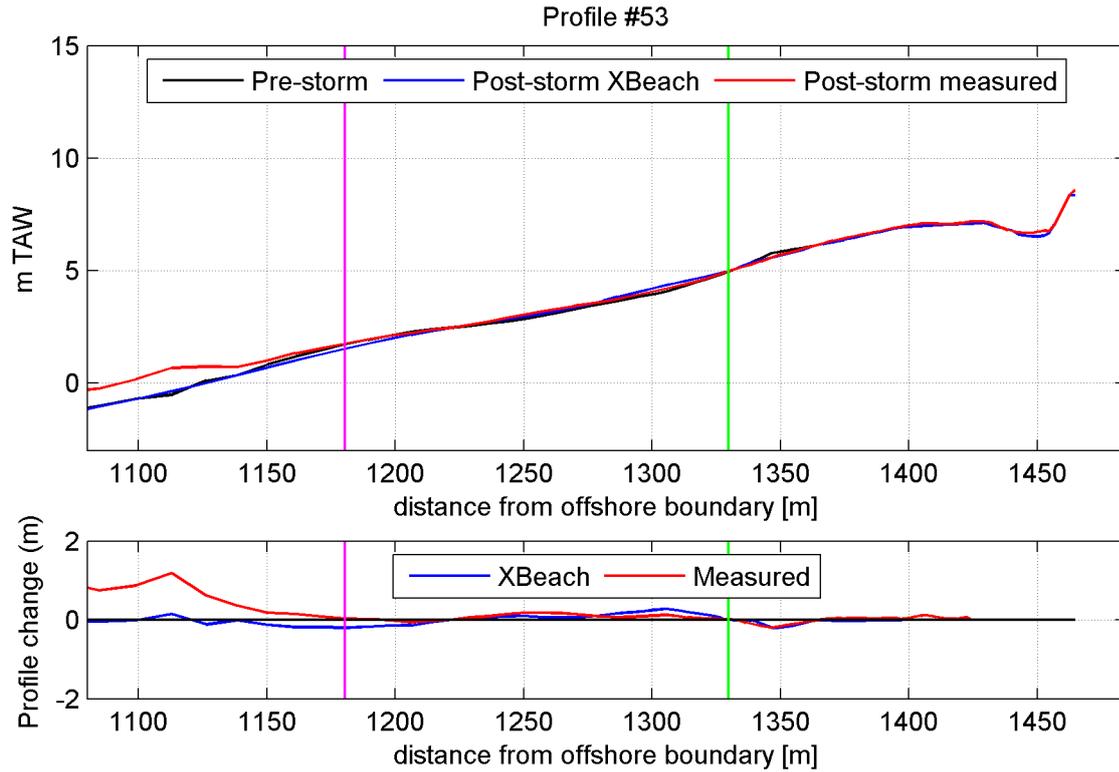
Measured: Above 5 m TAW:  $-1.38 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-10.59 \text{ m}^3/\text{m}$ .



BSS = -0.95

Xbeach: Above 5 m TAW:  $-2.35 \text{ m}^3/\text{m}$ . Below 5m TAW:  $8.85 \text{ m}^3/\text{m}$ .

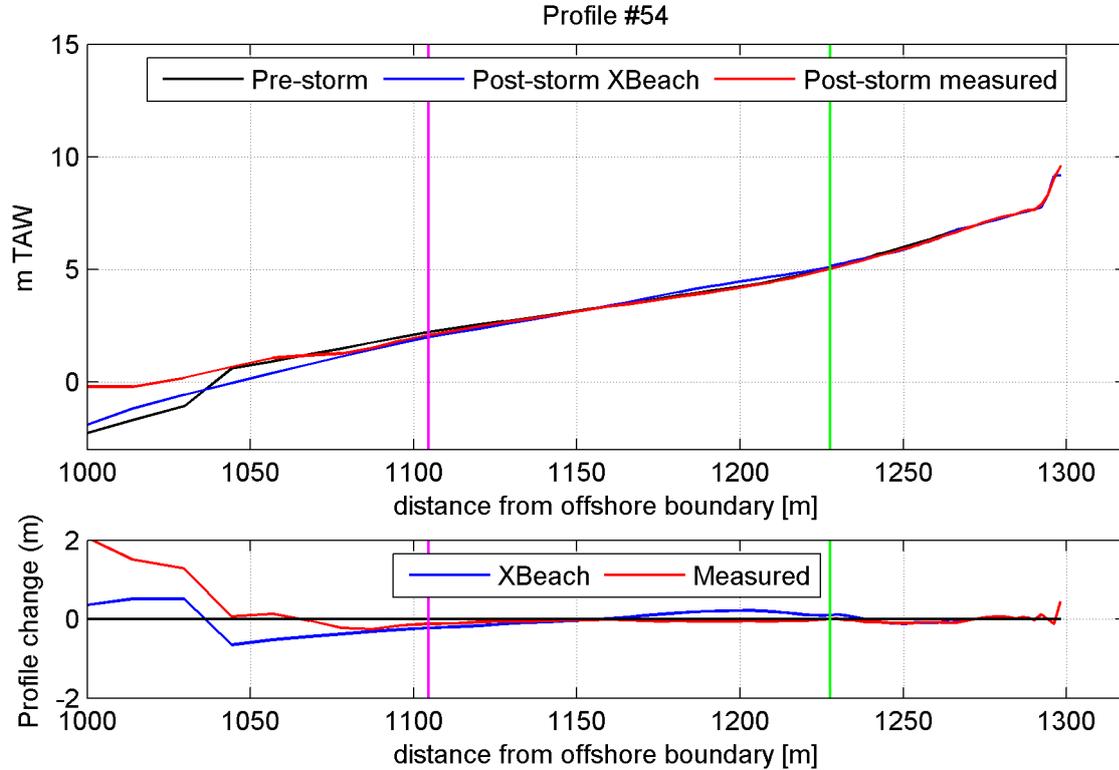
Measured: Above 5 m TAW:  $-5.00 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-6.73 \text{ m}^3/\text{m}$ .



BSS = 0.01

Xbeach: Above 5 m TAW:  $-3.52 \text{ m}^3/\text{m}$ . Below 5m TAW:  $8.11 \text{ m}^3/\text{m}$ .

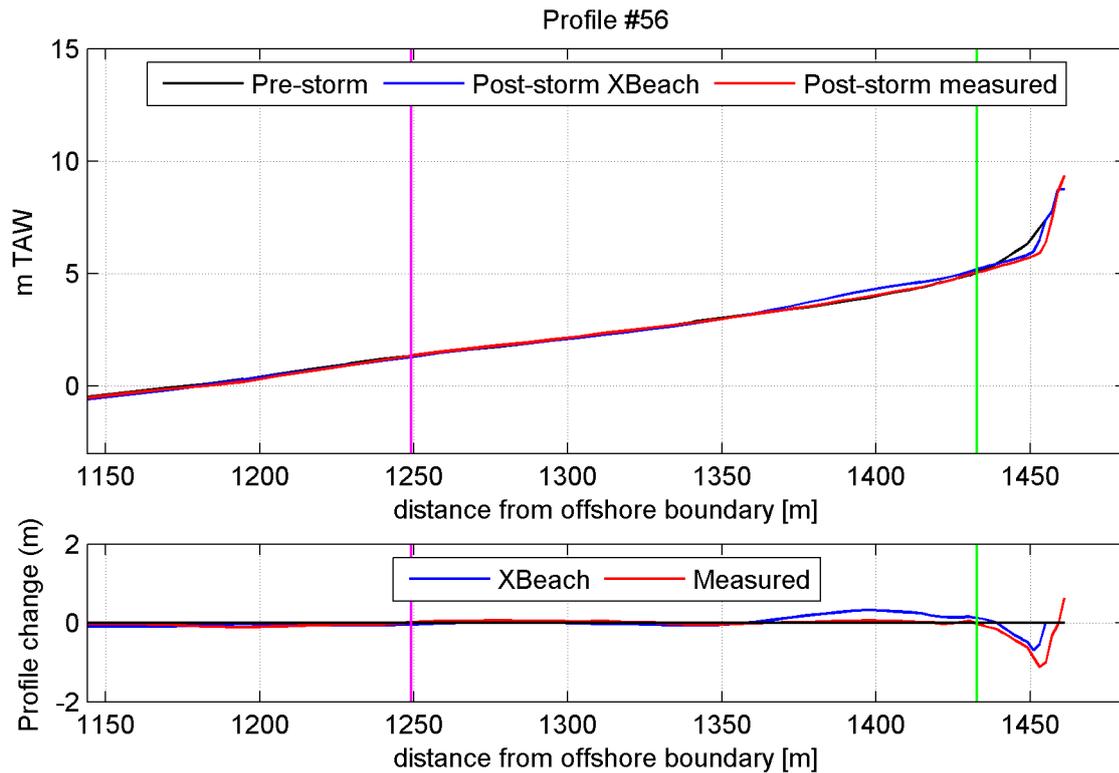
Measured: Above 5 m TAW:  $-0.27 \text{ m}^3/\text{m}$ . Below 5m TAW:  $10.58 \text{ m}^3/\text{m}$ .



BSS = -2.81

Xbeach: Above 5 m TAW:  $-1.22 \text{ m}^3/\text{m}$ . Below 5m TAW:  $4.03 \text{ m}^3/\text{m}$ .

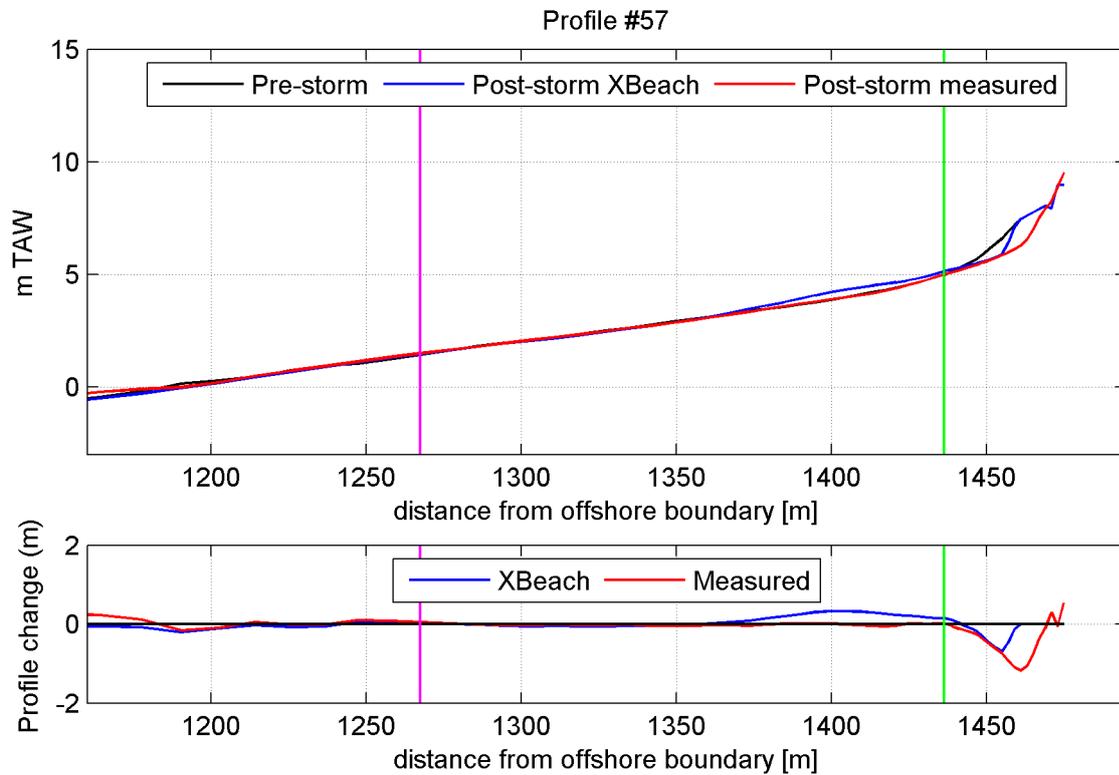
Measured: Above 5 m TAW:  $-1.83 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-6.13 \text{ m}^3/\text{m}$ .



BSS = 0.27

Xbeach: Above 5 m TAW:  $-5.09 \text{ m}^3/\text{m}$ . Below 5m TAW:  $13.51 \text{ m}^3/\text{m}$ .

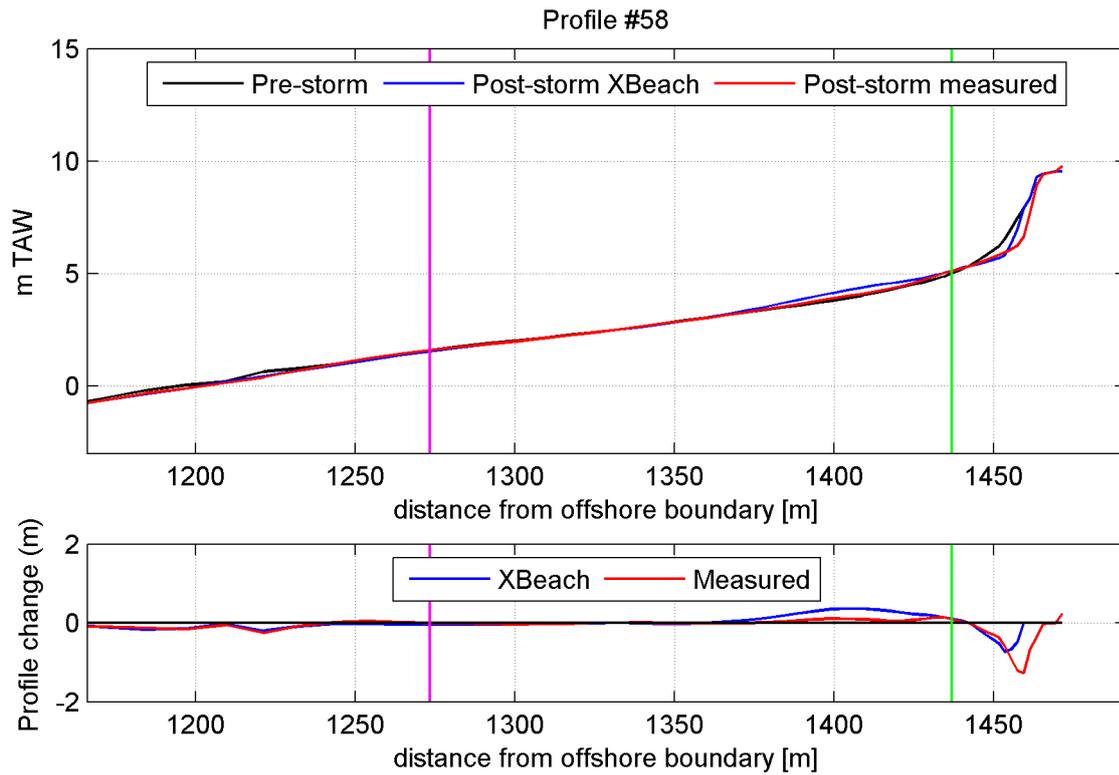
Measured: Above 5 m TAW:  $-11.30 \text{ m}^3/\text{m}$ . Below 5m TAW:  $4.30 \text{ m}^3/\text{m}$ .



BSS = 0.05

Xbeach: Above 5 m TAW:  $-5.62 \text{ m}^3/\text{m}$ . Below 5m TAW:  $12.91 \text{ m}^3/\text{m}$ .

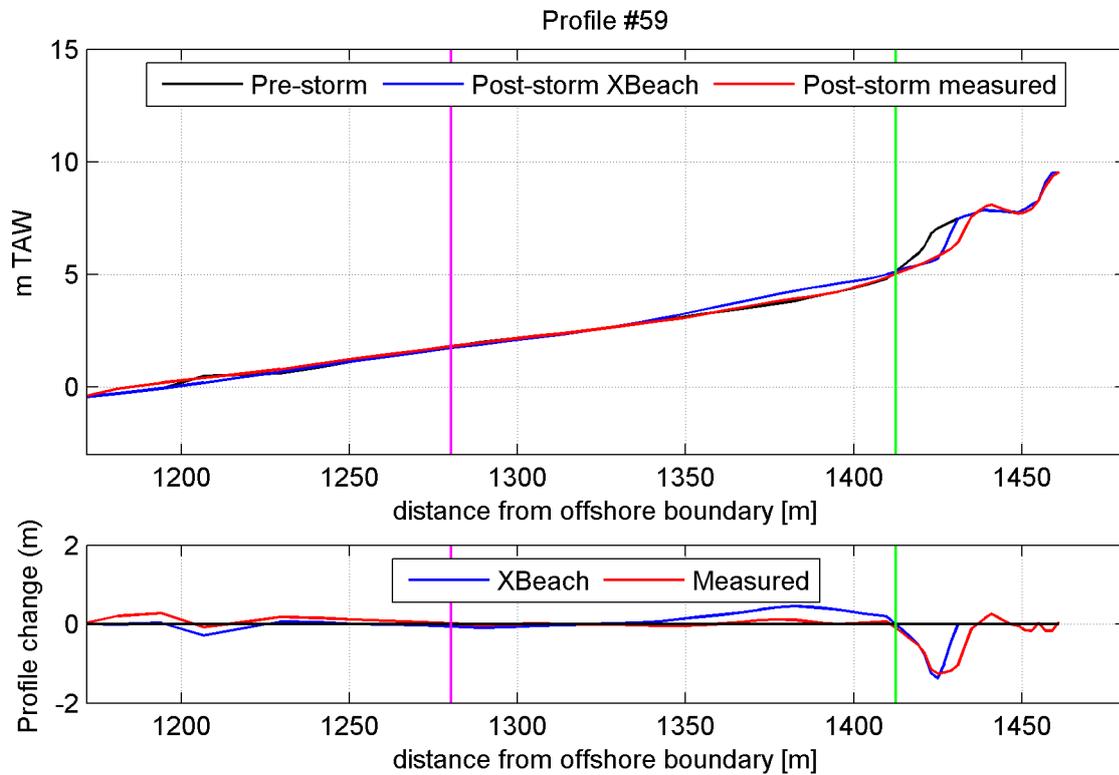
Measured: Above 5 m TAW:  $-16.20 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-1.73 \text{ m}^3/\text{m}$ .



BSS = 0.24

Xbeach: Above 5 m TAW:  $-6.37 \text{ m}^3/\text{m}$ . Below 5m TAW:  $14.80 \text{ m}^3/\text{m}$ .

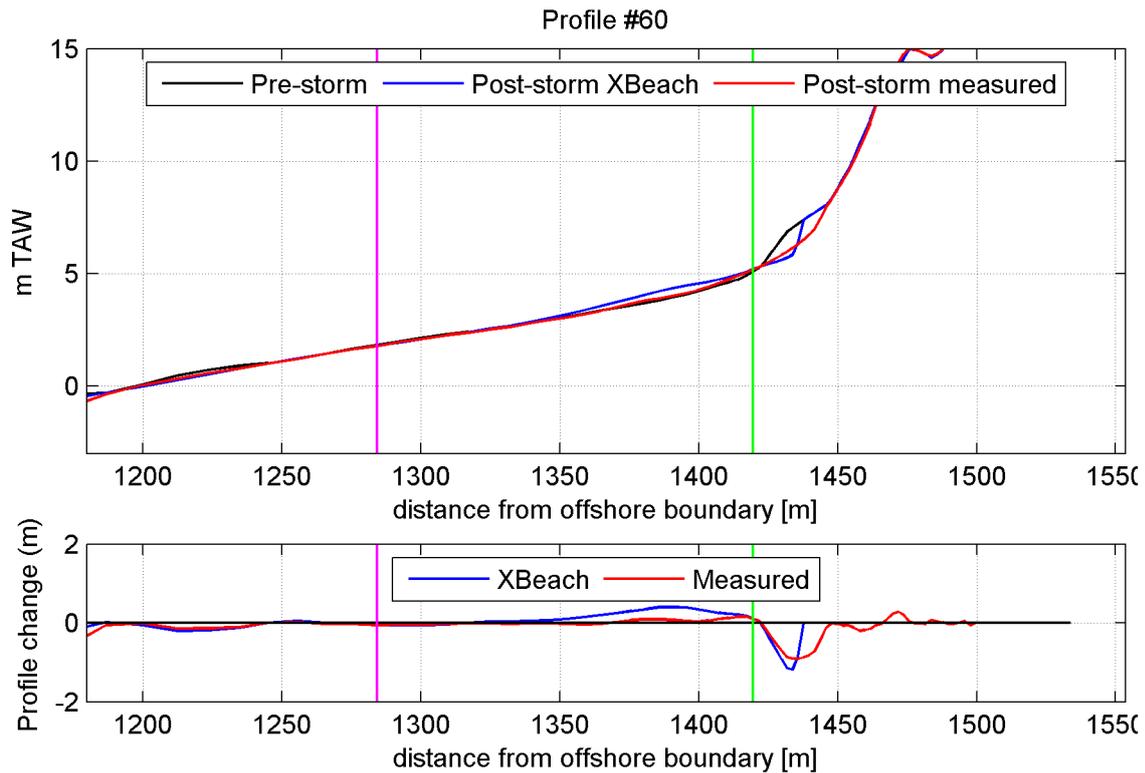
Measured: Above 5 m TAW:  $-11.74 \text{ m}^3/\text{m}$ . Below 5m TAW:  $3.59 \text{ m}^3/\text{m}$ .



BSS = 0.43

Xbeach: Above 5 m TAW:  $-11.74 \text{ m}^3/\text{m}$ . Below 5m TAW:  $18.62 \text{ m}^3/\text{m}$ .

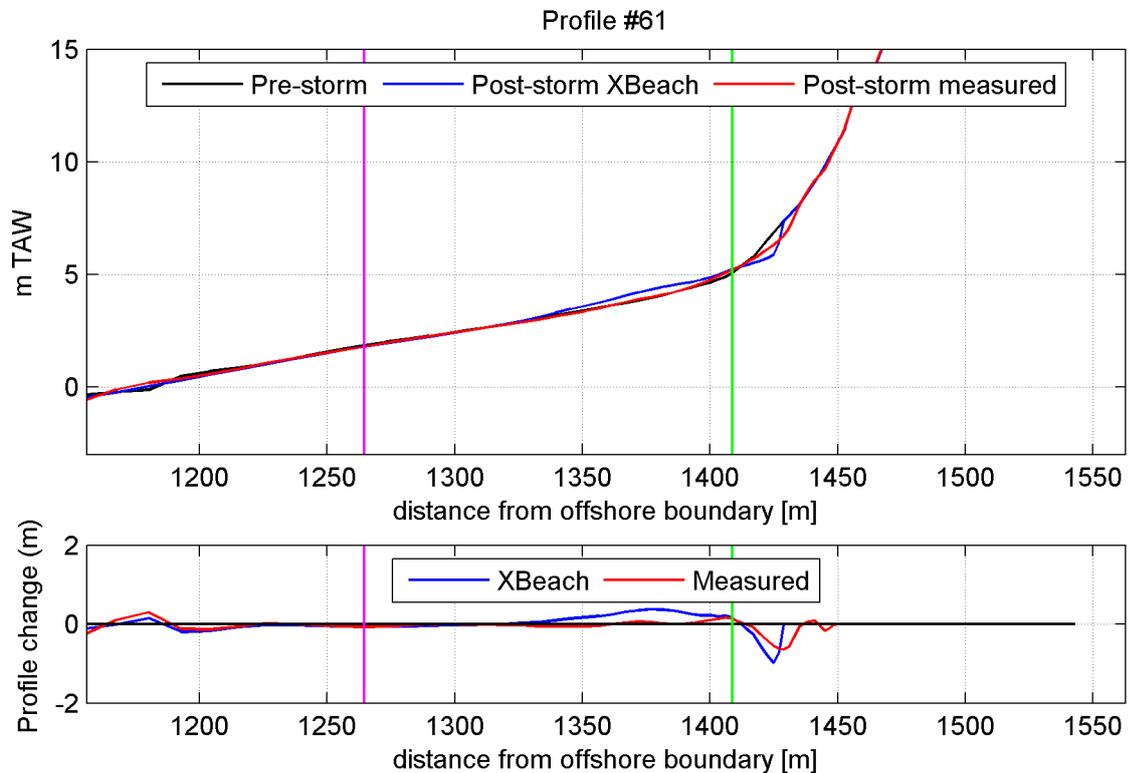
Measured: Above 5 m TAW:  $-17.06 \text{ m}^3/\text{m}$ . Below 5m TAW:  $1.98 \text{ m}^3/\text{m}$ .



BSS = 0.23

Xbeach: Above 5 m TAW:  $-10.53 \text{ m}^3/\text{m}$ . Below 5m TAW:  $18.35 \text{ m}^3/\text{m}$ .

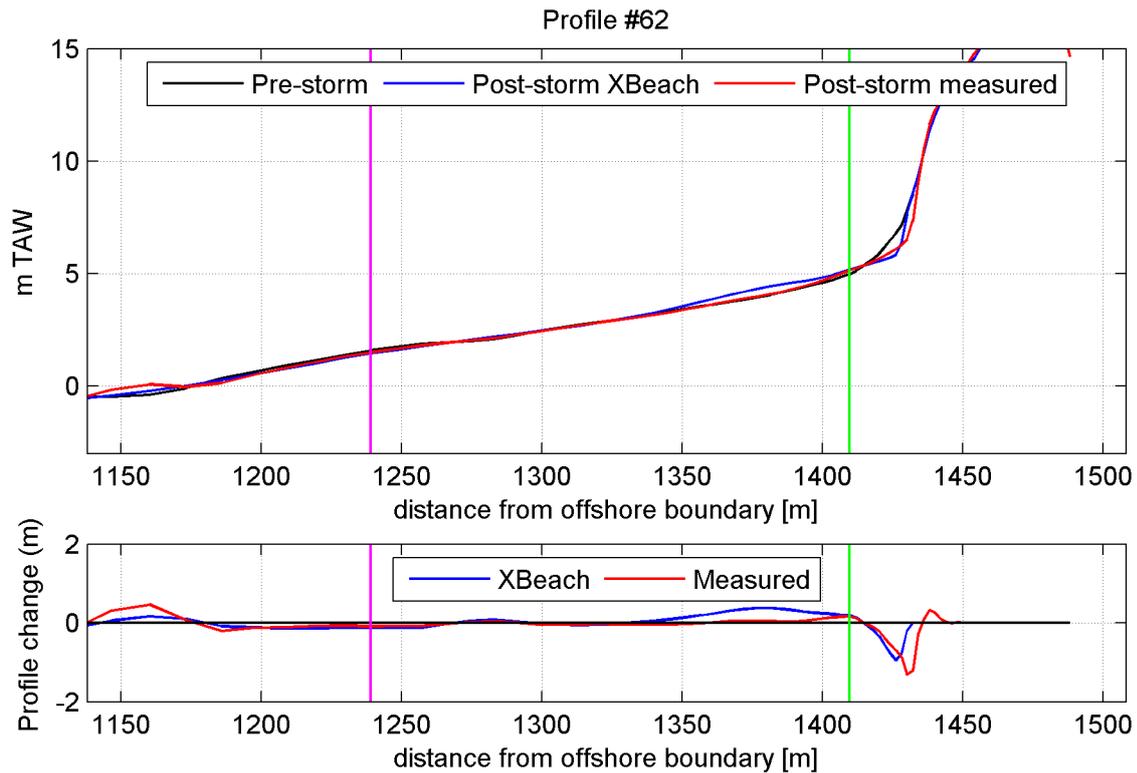
Measured: Above 5 m TAW:  $-14.54 \text{ m}^3/\text{m}$ . Below 5m TAW:  $2.06 \text{ m}^3/\text{m}$ .



BSS = -0.69

Xbeach: Above 5 m TAW:  $-8.03 \text{ m}^3/\text{m}$ . Below 5m TAW:  $16.30 \text{ m}^3/\text{m}$ .

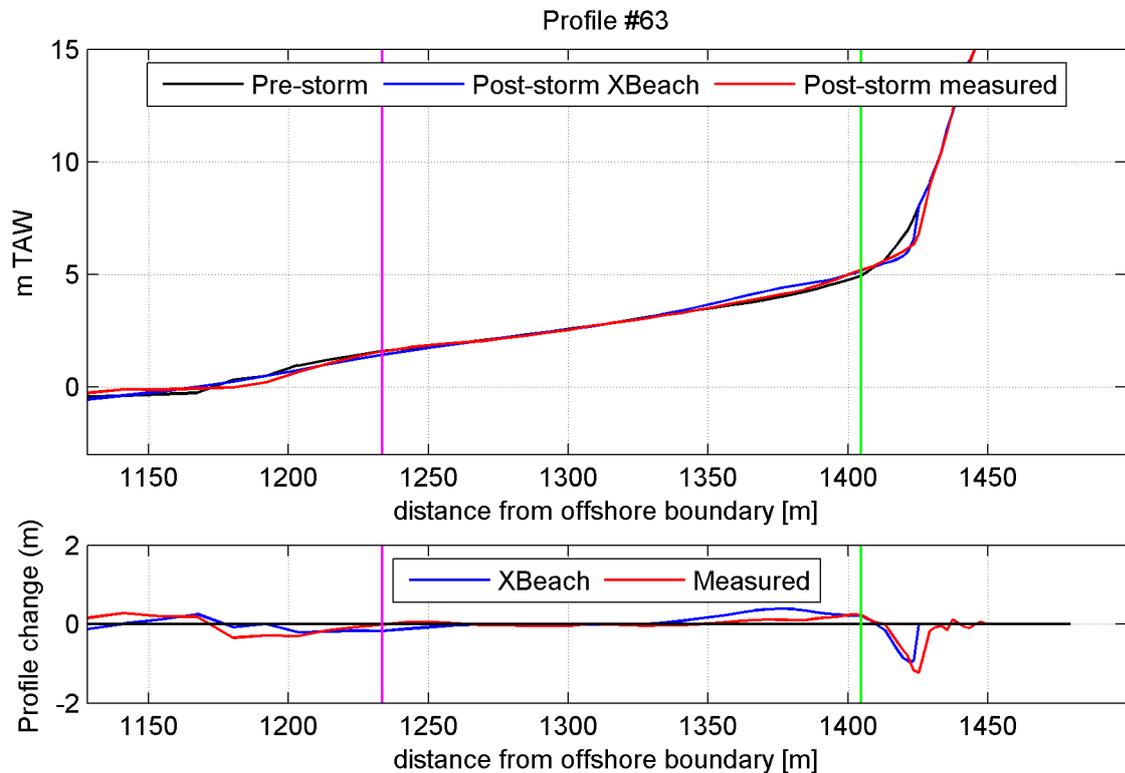
Measured: Above 5 m TAW:  $-7.68 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-0.45 \text{ m}^3/\text{m}$ .



BSS = 0.08

Xbeach: Above 5 m TAW:  $-7.19 \text{ m}^3/\text{m}$ . Below 5m TAW:  $14.84 \text{ m}^3/\text{m}$ .

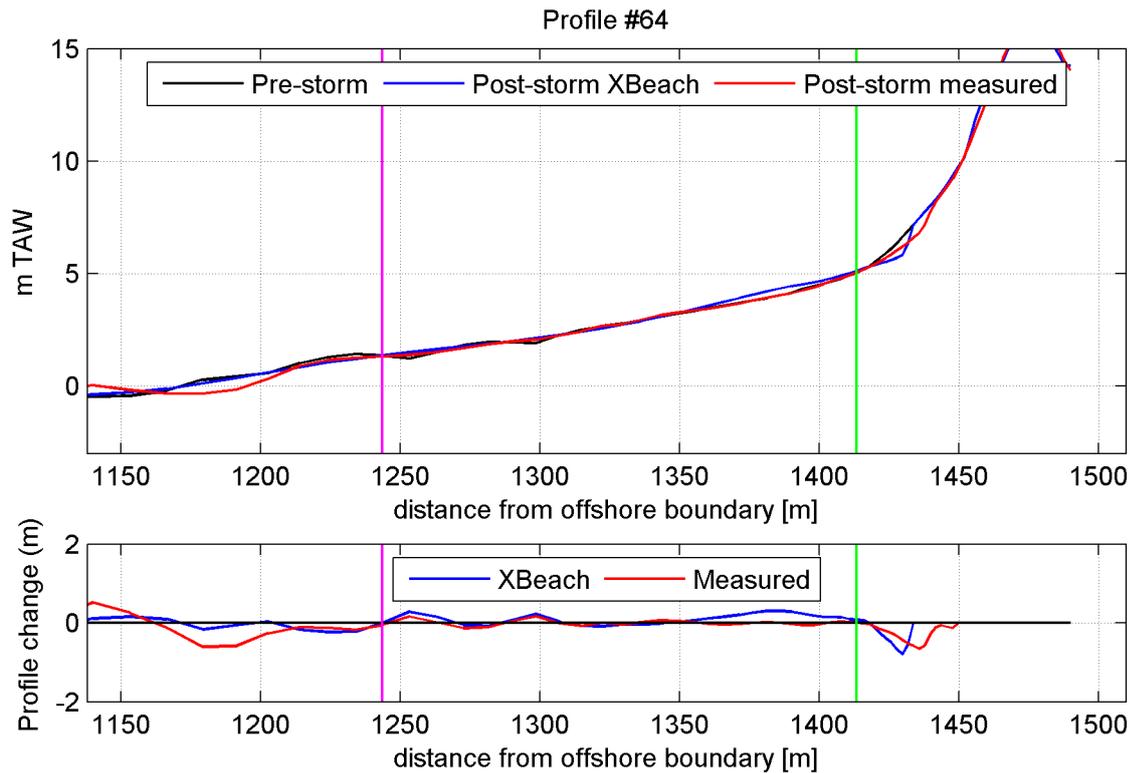
Measured: Above 5 m TAW:  $-9.29 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-0.47 \text{ m}^3/\text{m}$ .



BSS = 0.30

Xbeach: Above 5 m TAW:  $-7.41 \text{ m}^3/\text{m}$ . Below 5m TAW:  $14.56 \text{ m}^3/\text{m}$ .

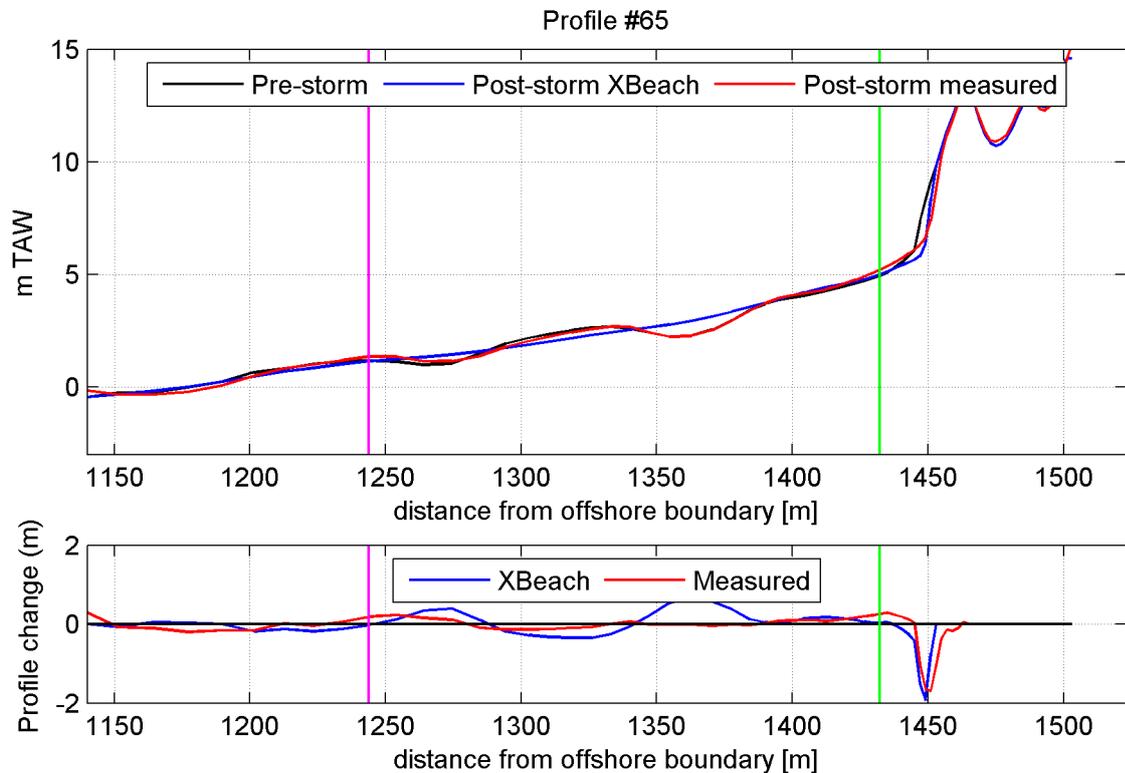
Measured: Above 5 m TAW:  $-10.55 \text{ m}^3/\text{m}$ . Below 5m TAW:  $5.52 \text{ m}^3/\text{m}$ .



BSS = -0.38

Xbeach: Above 5 m TAW:  $-6.33 \text{ m}^3/\text{m}$ . Below 5m TAW:  $15.70 \text{ m}^3/\text{m}$ .

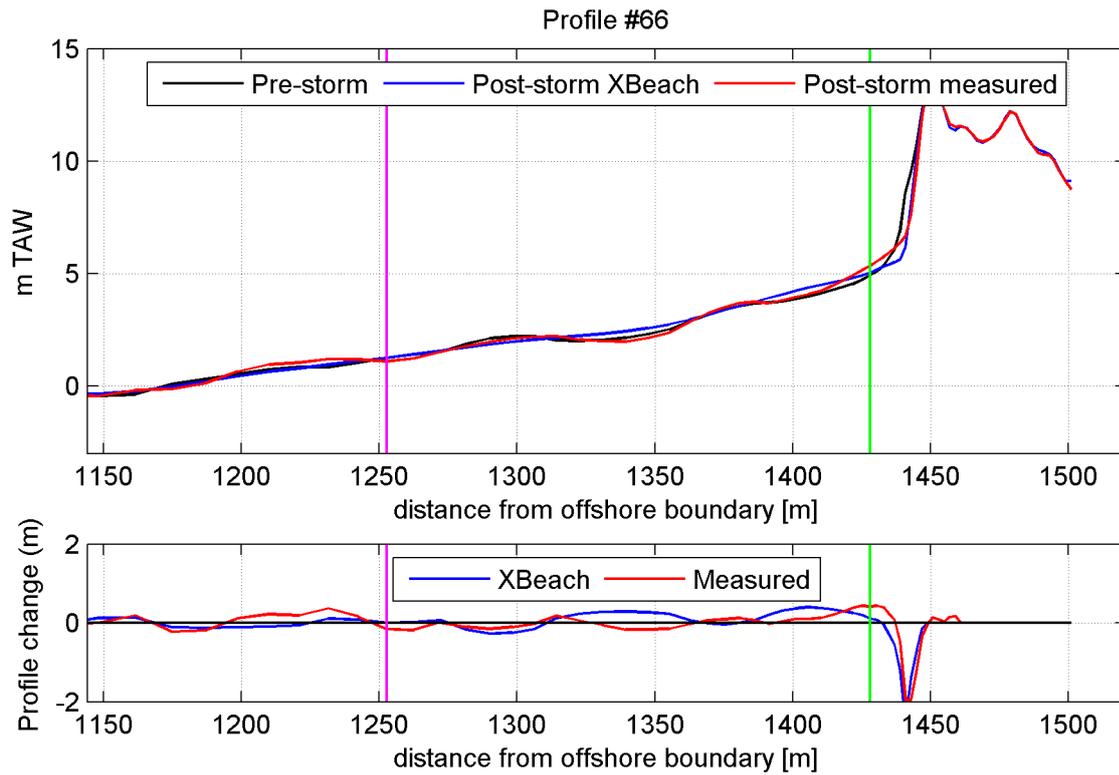
Measured: Above 5 m TAW:  $-9.08 \text{ m}^3/\text{m}$ . Below 5m TAW:  $0.41 \text{ m}^3/\text{m}$ .



BSS = -0.11

Xbeach: Above 5 m TAW:  $-10.12 \text{ m}^3/\text{m}$ . Below 5m TAW:  $19.02 \text{ m}^3/\text{m}$ .

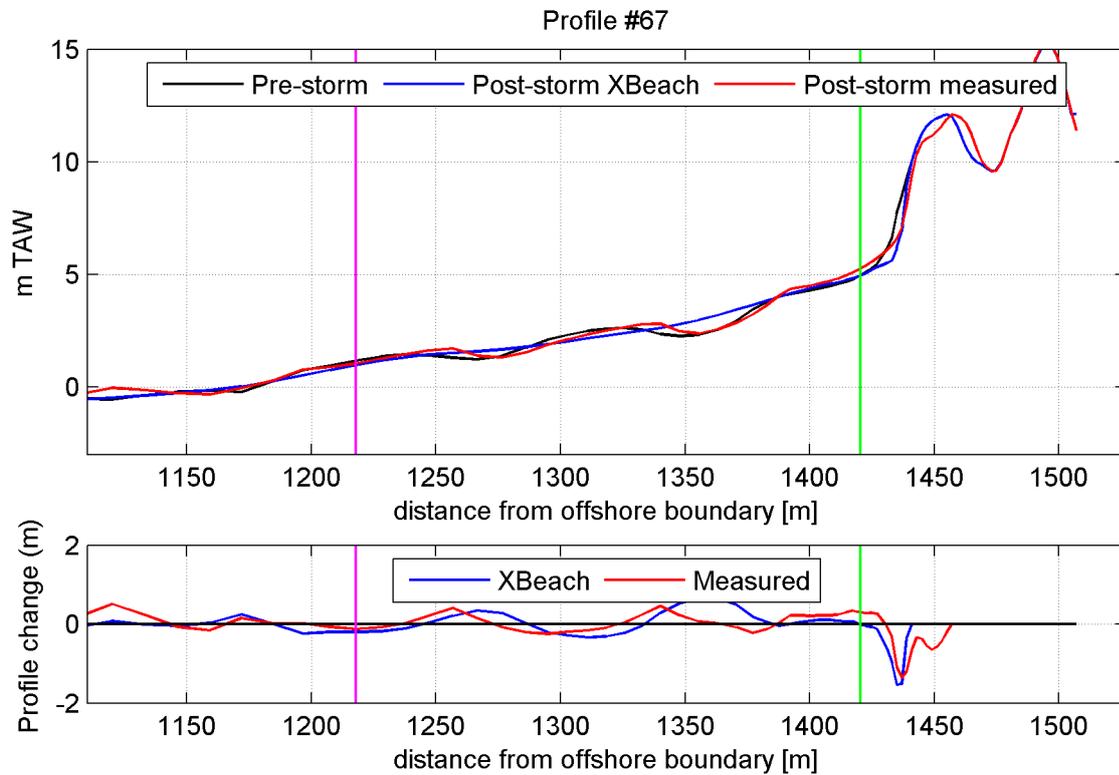
Measured: Above 5 m TAW:  $-9.72 \text{ m}^3/\text{m}$ . Below 5m TAW:  $5.55 \text{ m}^3/\text{m}$ .



BSS = 0.42

Xbeach: Above 5 m TAW:  $-13.22 \text{ m}^3/\text{m}$ . Below 5m TAW:  $17.87 \text{ m}^3/\text{m}$ .

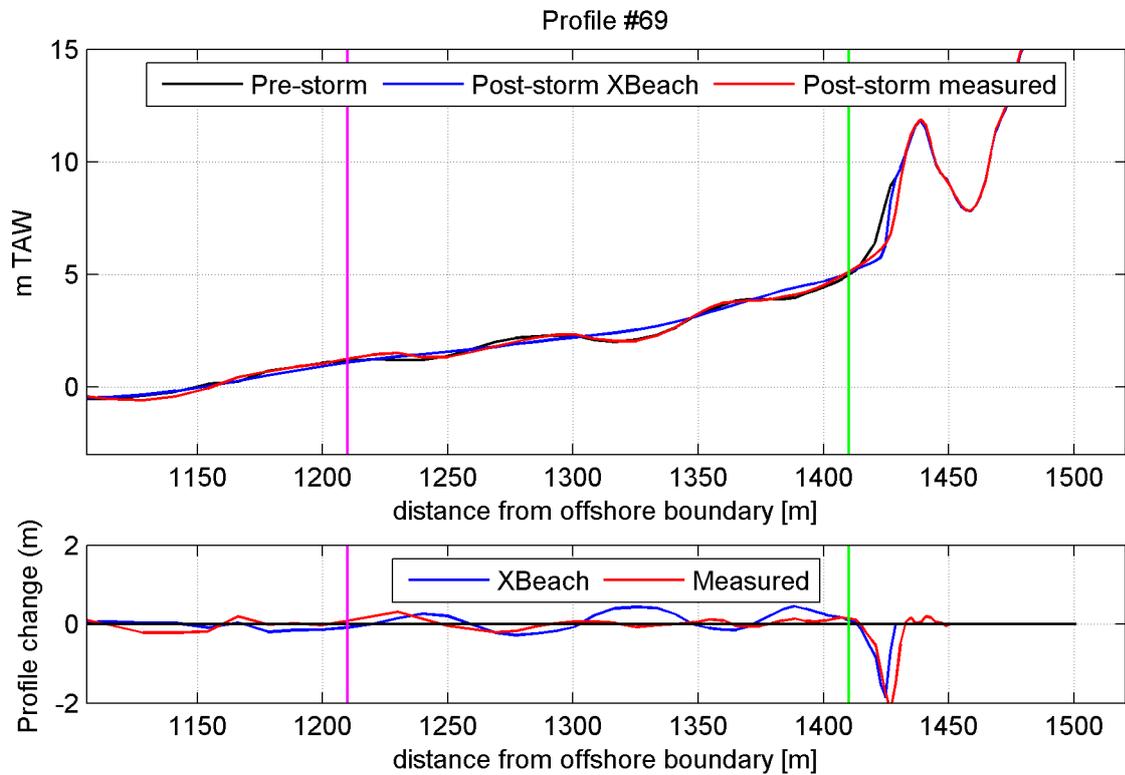
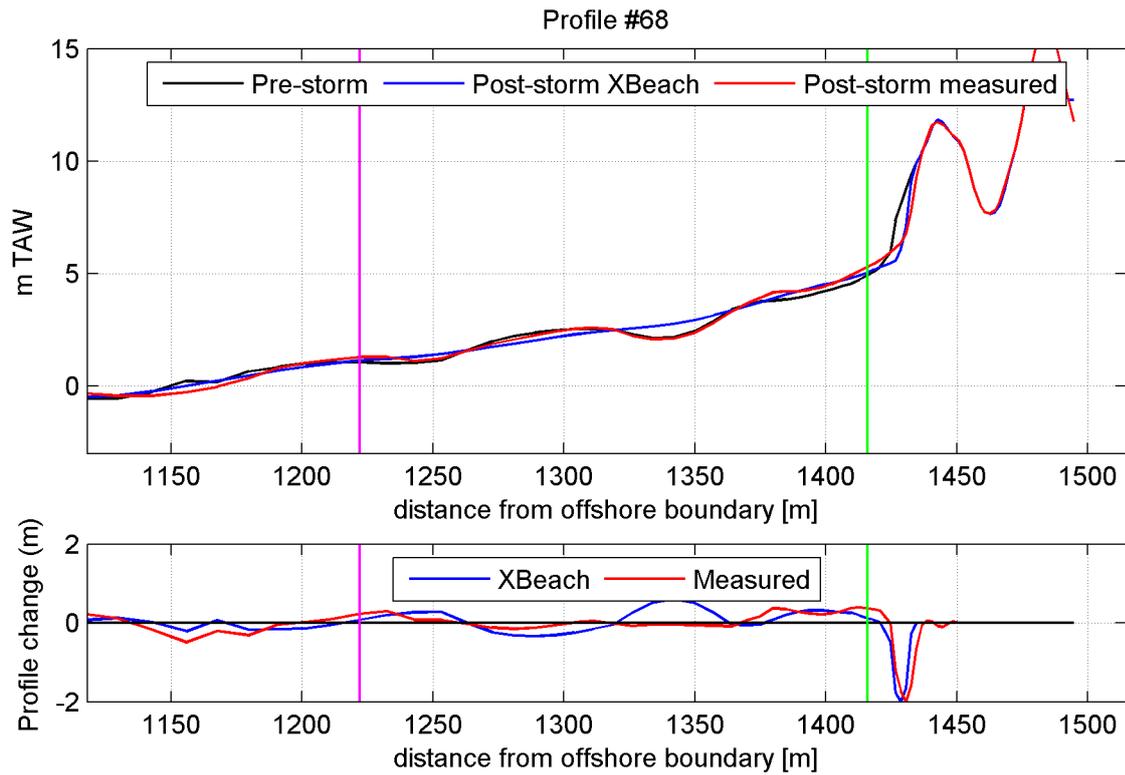
Measured: Above 5 m TAW:  $-7.68 \text{ m}^3/\text{m}$ . Below 5m TAW:  $0.71 \text{ m}^3/\text{m}$ .

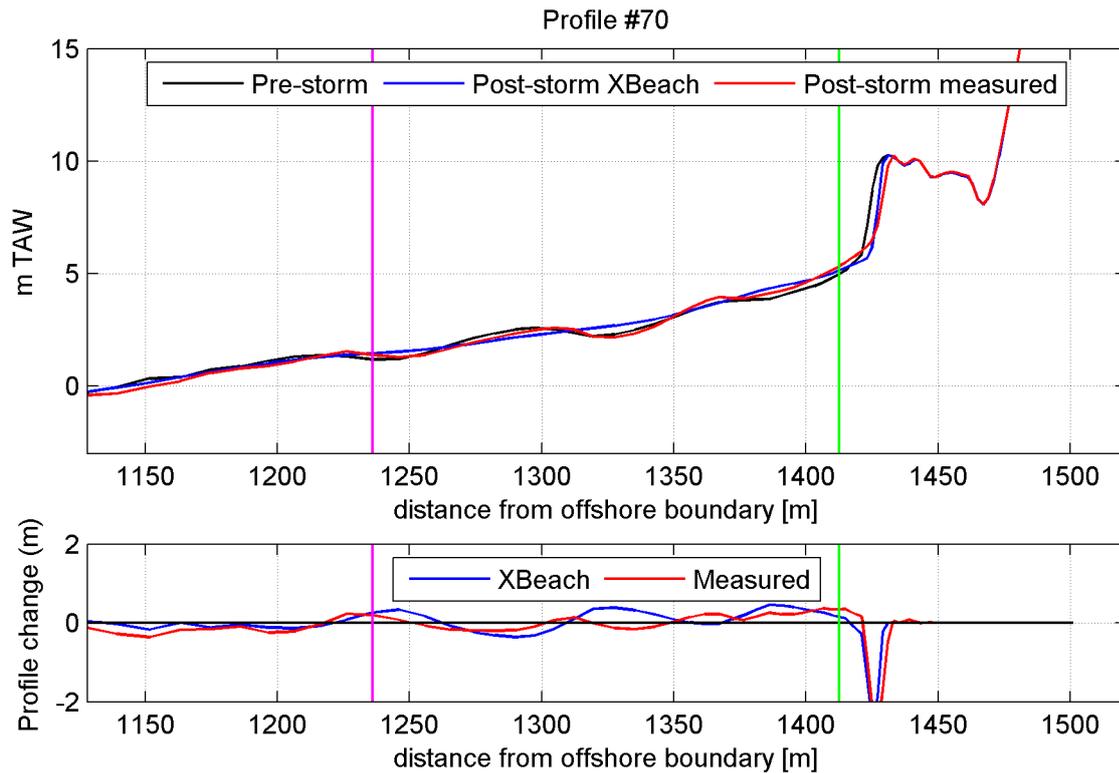


BSS = -0.10

Xbeach: Above 5 m TAW:  $-11.31 \text{ m}^3/\text{m}$ . Below 5m TAW:  $16.78 \text{ m}^3/\text{m}$ .

Measured: Above 5 m TAW:  $-13.23 \text{ m}^3/\text{m}$ . Below 5m TAW:  $10.78 \text{ m}^3/\text{m}$ .

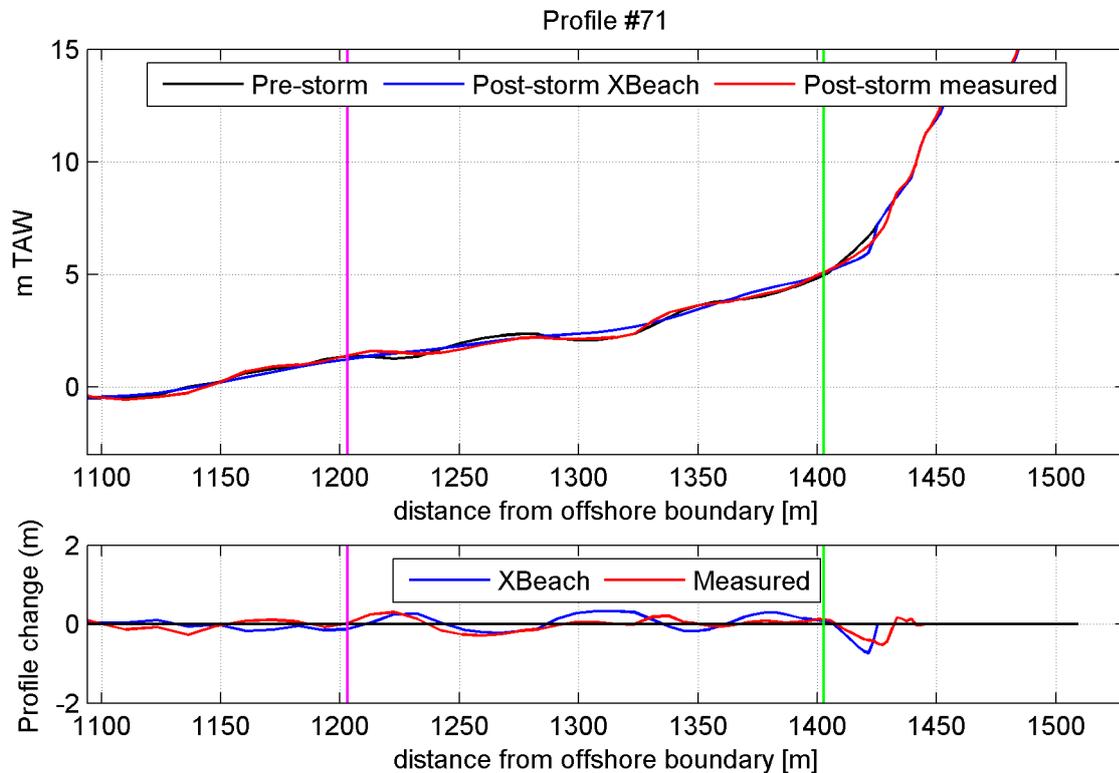




BSS = 0.54

Xbeach: Above 5 m TAW:  $-12.64 \text{ m}^3/\text{m}$ . Below 5m TAW:  $19.03 \text{ m}^3/\text{m}$ .

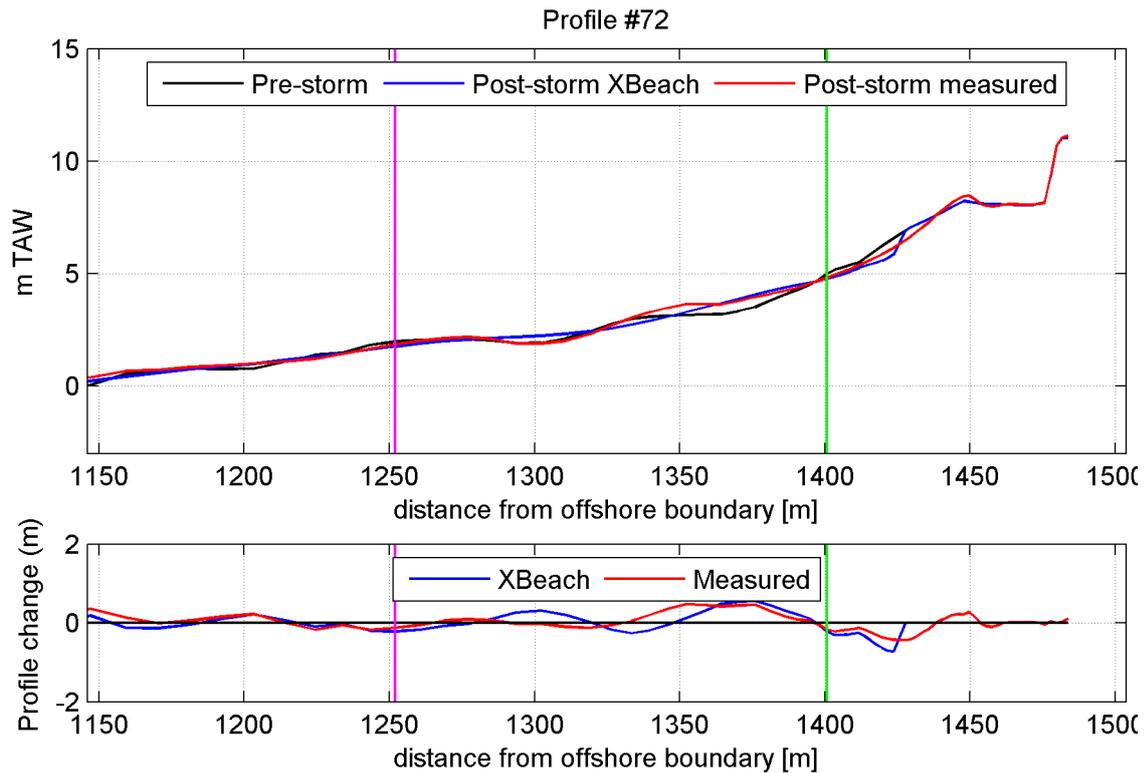
Measured: Above 5 m TAW:  $-12.98 \text{ m}^3/\text{m}$ . Below 5m TAW:  $6.06 \text{ m}^3/\text{m}$ .



BSS = -0.08

Xbeach: Above 5 m TAW:  $-7.16 \text{ m}^3/\text{m}$ . Below 5m TAW:  $14.42 \text{ m}^3/\text{m}$ .

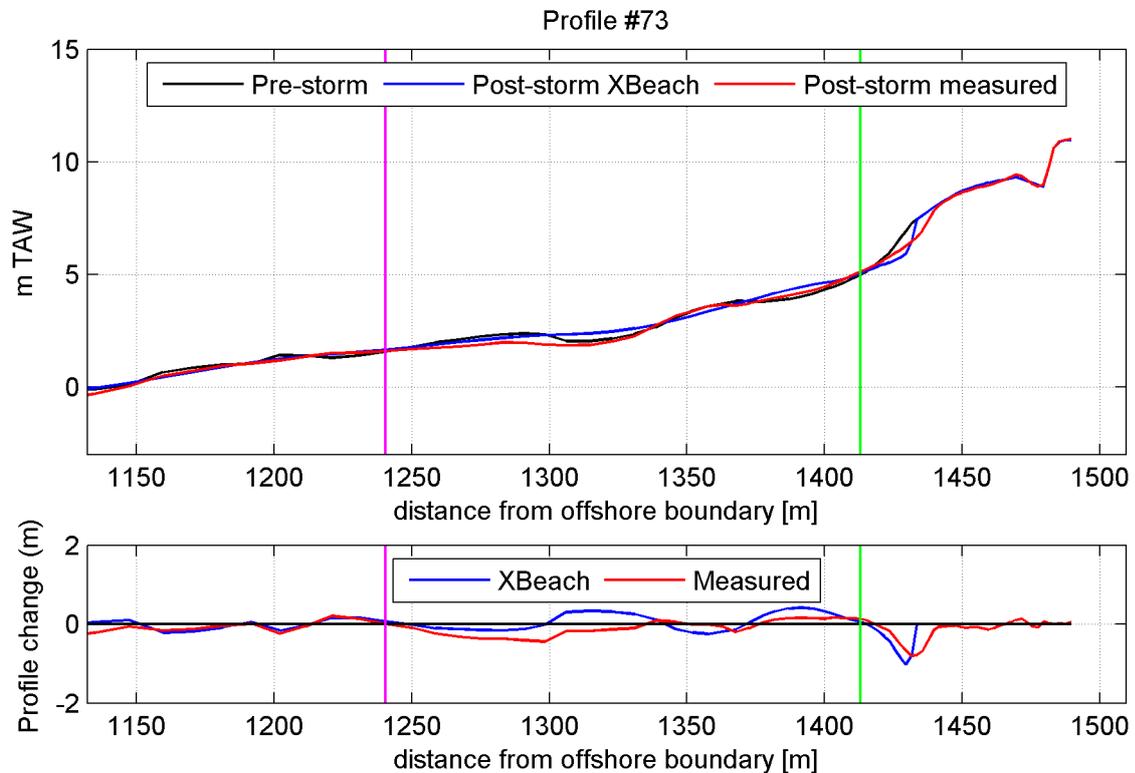
Measured: Above 5 m TAW:  $-6.11 \text{ m}^3/\text{m}$ . Below 5m TAW:  $1.72 \text{ m}^3/\text{m}$ .



BSS = 0.21

Xbeach: Above 5 m TAW:  $-10.83 \text{ m}^3/\text{m}$ . Below 5m TAW:  $16.01 \text{ m}^3/\text{m}$ .

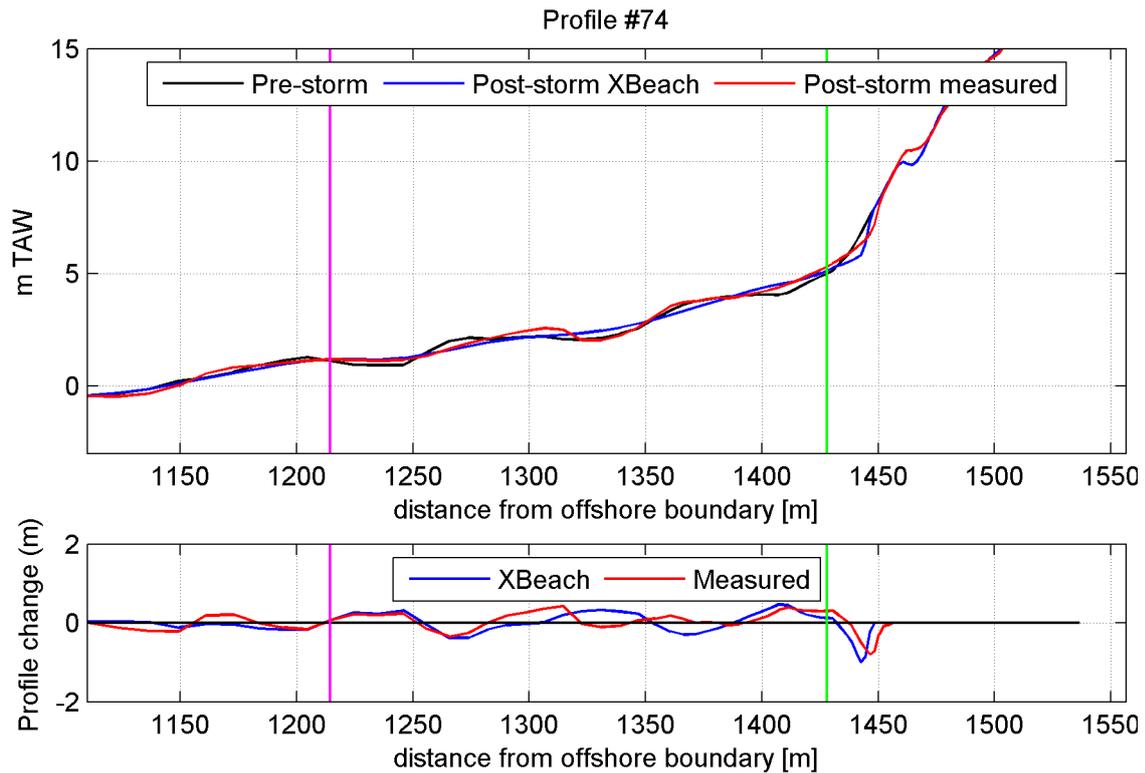
Measured: Above 5 m TAW:  $-7.63 \text{ m}^3/\text{m}$ . Below 5m TAW:  $17.75 \text{ m}^3/\text{m}$ .



BSS = -0.14

Xbeach: Above 5 m TAW:  $-8.63 \text{ m}^3/\text{m}$ . Below 5m TAW:  $11.61 \text{ m}^3/\text{m}$ .

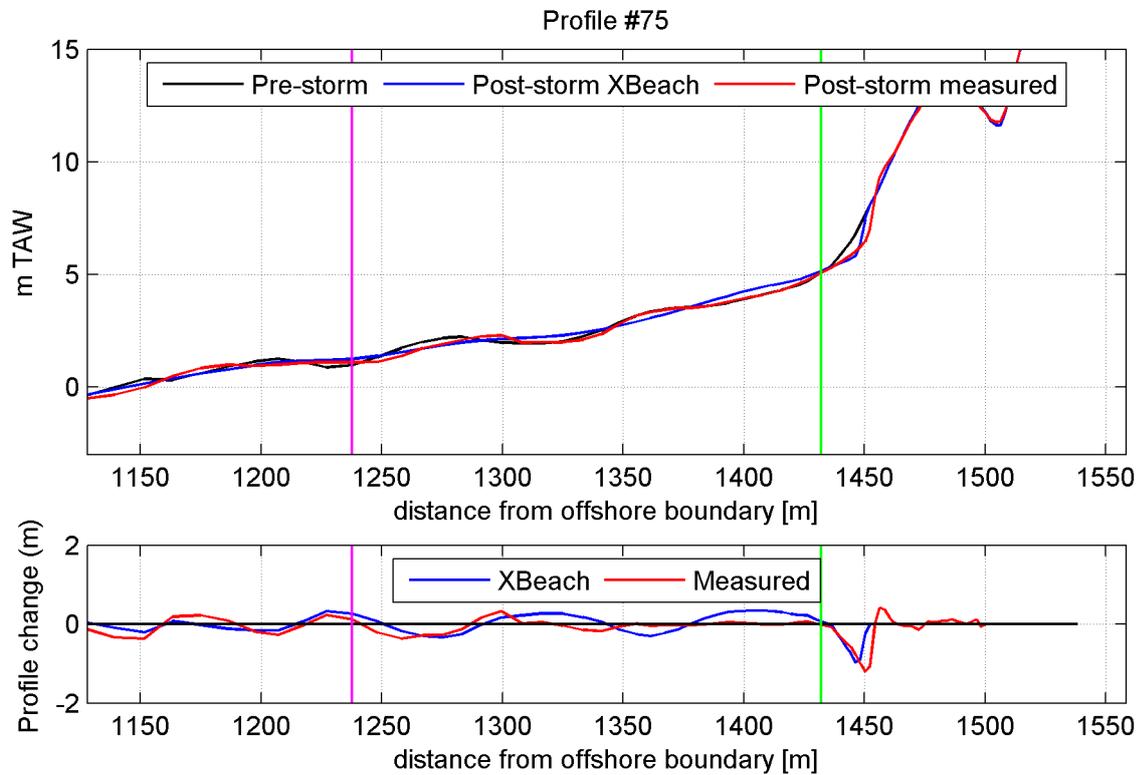
Measured: Above 5 m TAW:  $-10.24 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-18.27 \text{ m}^3/\text{m}$ .



BSS = 0.02

Xbeach: Above 5 m TAW:  $-7.23 \text{ m}^3/\text{m}$ . Below 5m TAW:  $14.60 \text{ m}^3/\text{m}$ .

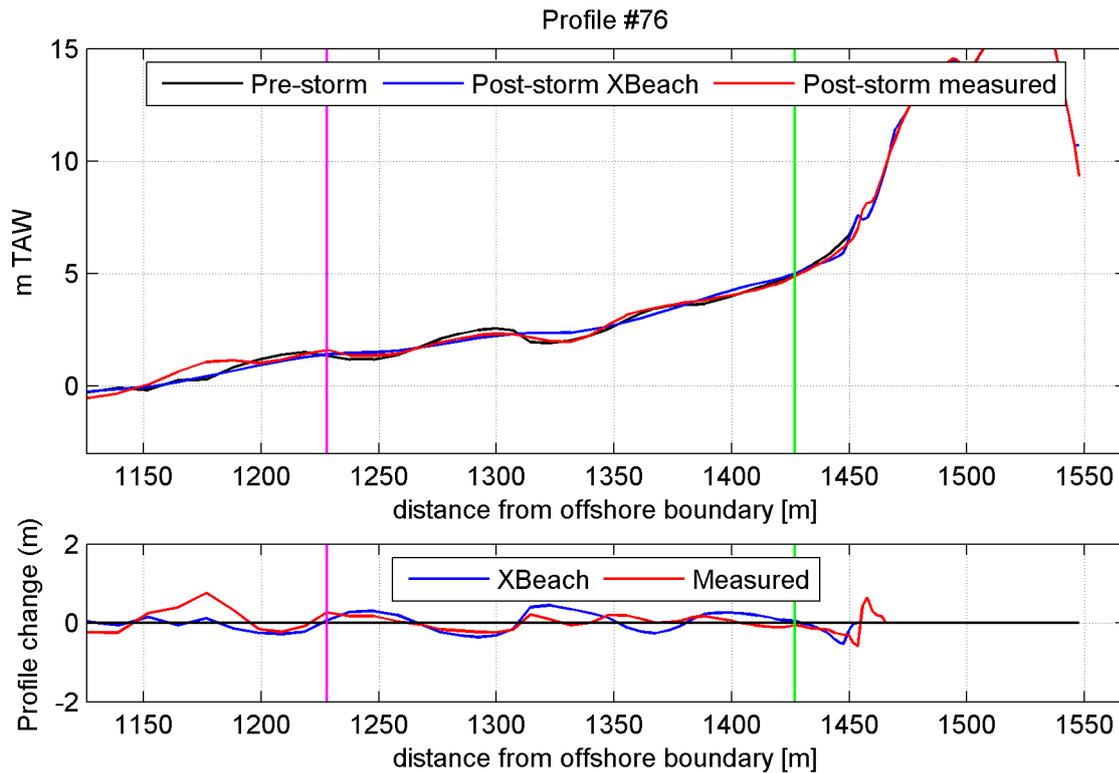
Measured: Above 5 m TAW:  $-5.09 \text{ m}^3/\text{m}$ . Below 5m TAW:  $19.97 \text{ m}^3/\text{m}$ .



BSS = 0.07

Xbeach: Above 5 m TAW:  $-7.99 \text{ m}^3/\text{m}$ . Below 5m TAW:  $9.57 \text{ m}^3/\text{m}$ .

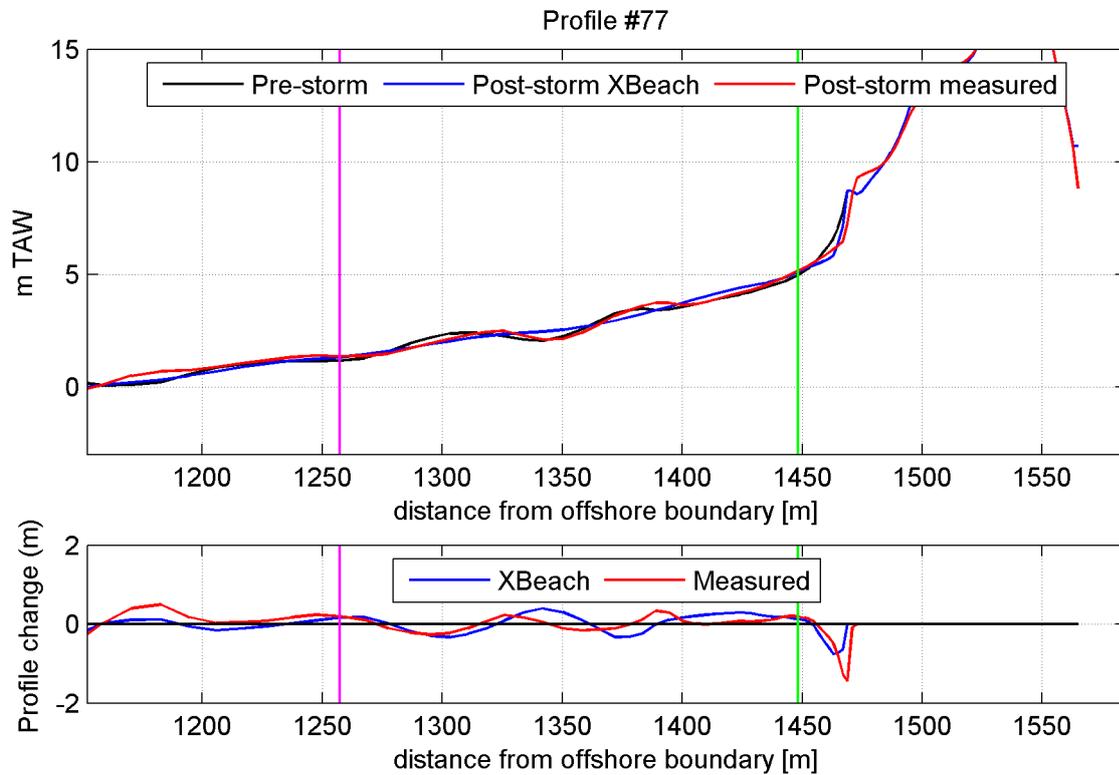
Measured: Above 5 m TAW:  $-9.15 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-8.69 \text{ m}^3/\text{m}$ .



BSS = -0.44

Xbeach: Above 5 m TAW:  $-5.02 \text{ m}^3/\text{m}$ . Below 5m TAW:  $13.24 \text{ m}^3/\text{m}$ .

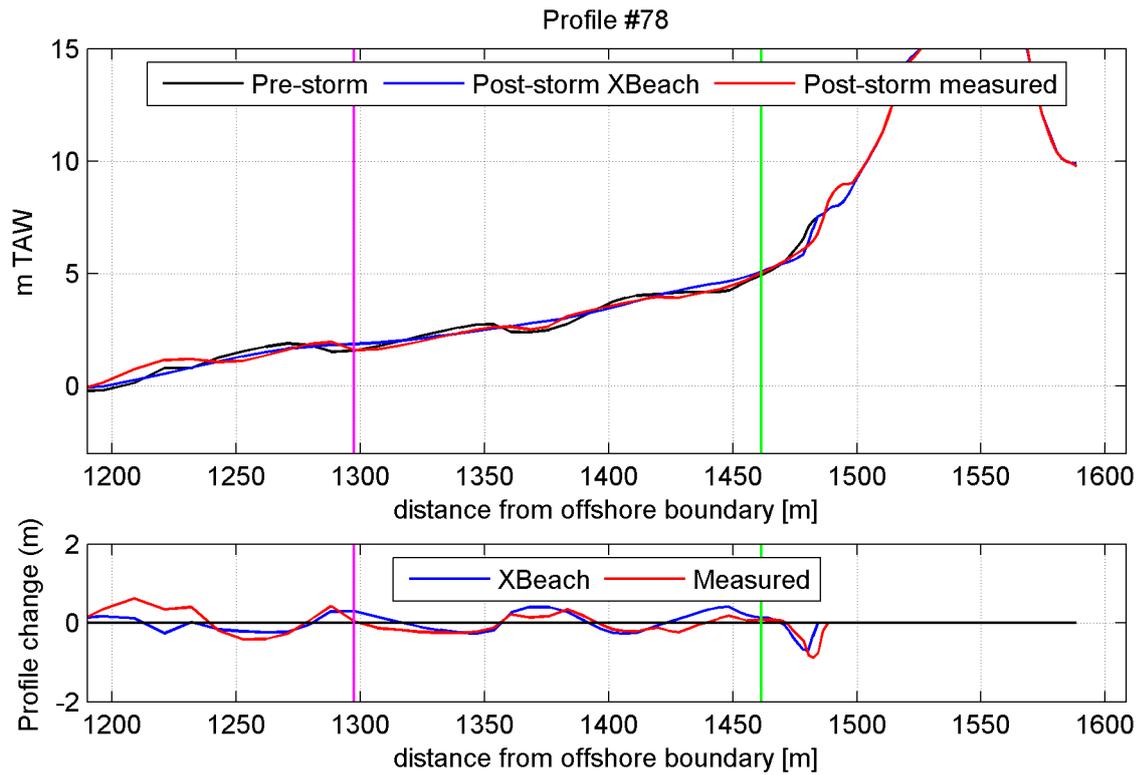
Measured: Above 5 m TAW:  $-3.03 \text{ m}^3/\text{m}$ . Below 5m TAW:  $3.70 \text{ m}^3/\text{m}$ .



BSS = 0.08

Xbeach: Above 5 m TAW:  $-6.38 \text{ m}^3/\text{m}$ . Below 5m TAW:  $9.27 \text{ m}^3/\text{m}$ .

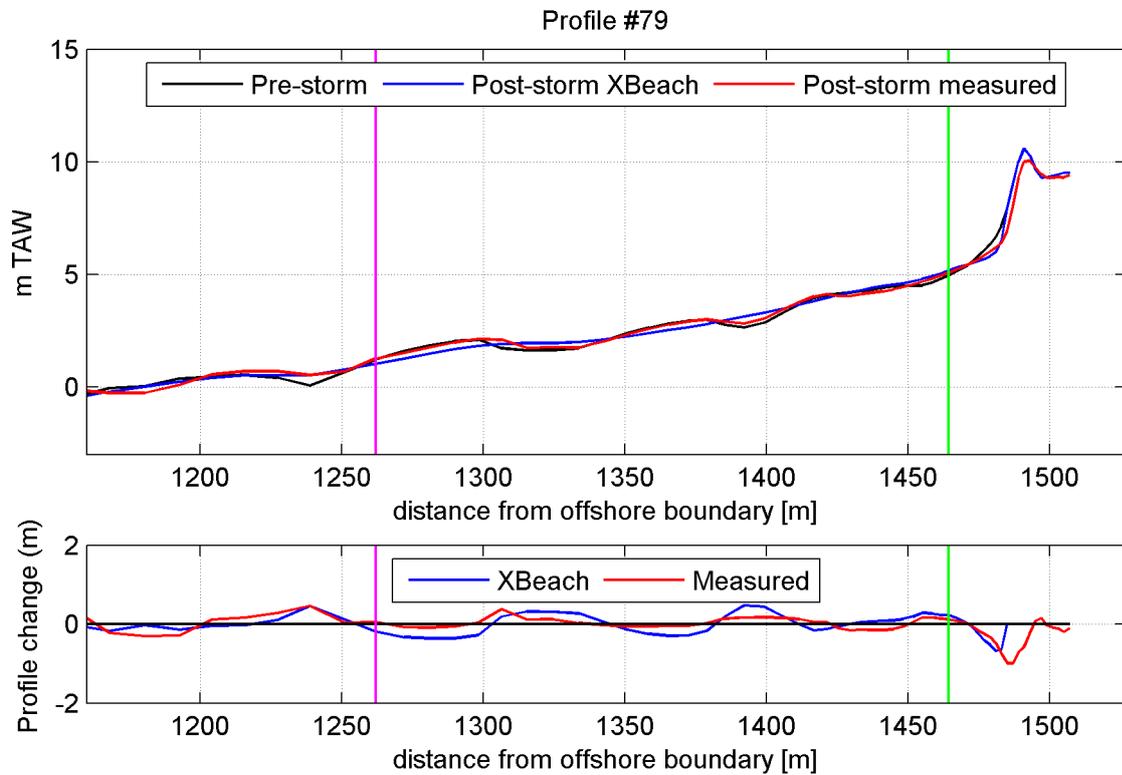
Measured: Above 5 m TAW:  $-8.43 \text{ m}^3/\text{m}$ . Below 5m TAW:  $2.94 \text{ m}^3/\text{m}$ .



BSS = 0.27

Xbeach: Above 5 m TAW:  $-4.97 \text{ m}^3/\text{m}$ . Below 5m TAW:  $9.41 \text{ m}^3/\text{m}$ .

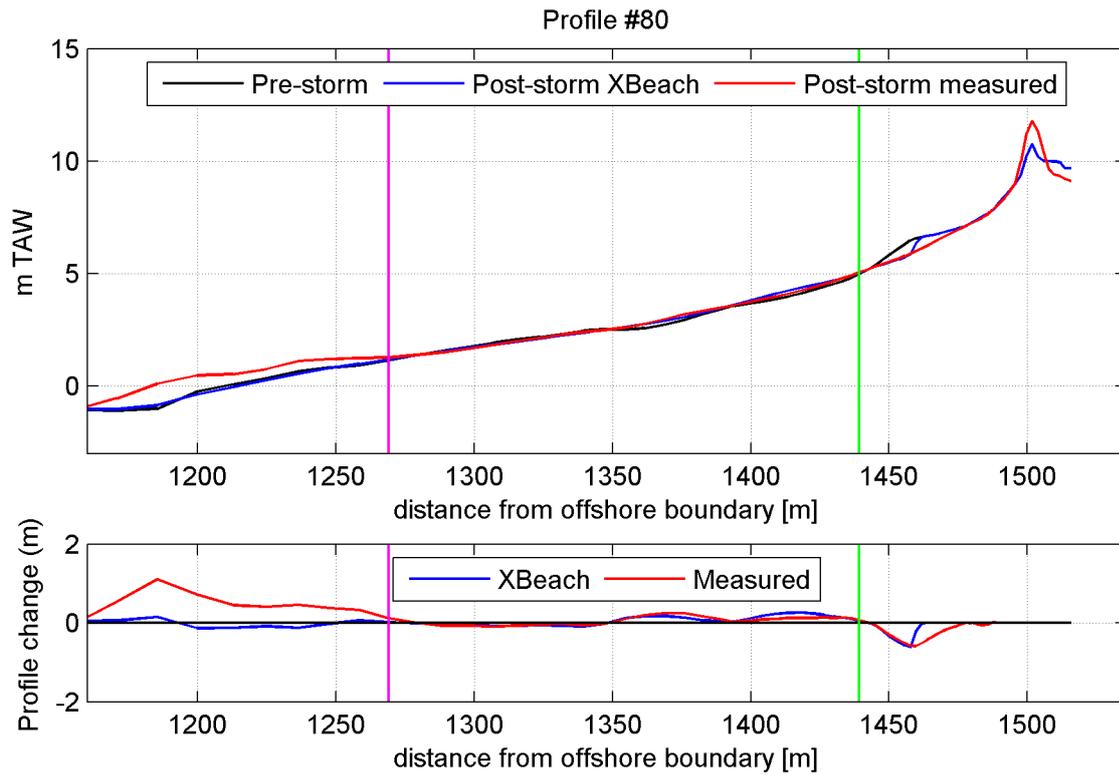
Measured: Above 5 m TAW:  $-6.70 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-7.71 \text{ m}^3/\text{m}$ .



BSS = -0.33

Xbeach: Above 5 m TAW:  $-4.32 \text{ m}^3/\text{m}$ . Below 5m TAW:  $1.84 \text{ m}^3/\text{m}$ .

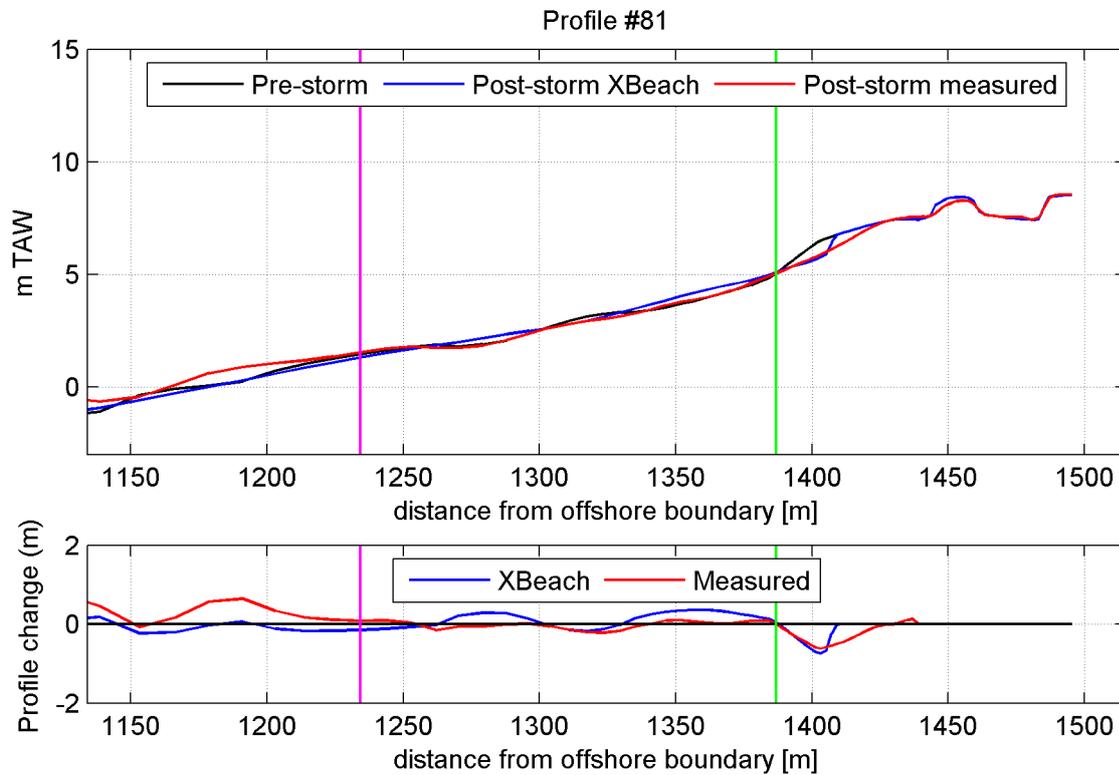
Measured: Above 5 m TAW:  $-11.18 \text{ m}^3/\text{m}$ . Below 5m TAW:  $6.62 \text{ m}^3/\text{m}$ .



BSS = 0.64

Xbeach: Above 5 m TAW:  $-5.95 \text{ m}^3/\text{m}$ . Below 5m TAW:  $9.09 \text{ m}^3/\text{m}$ .

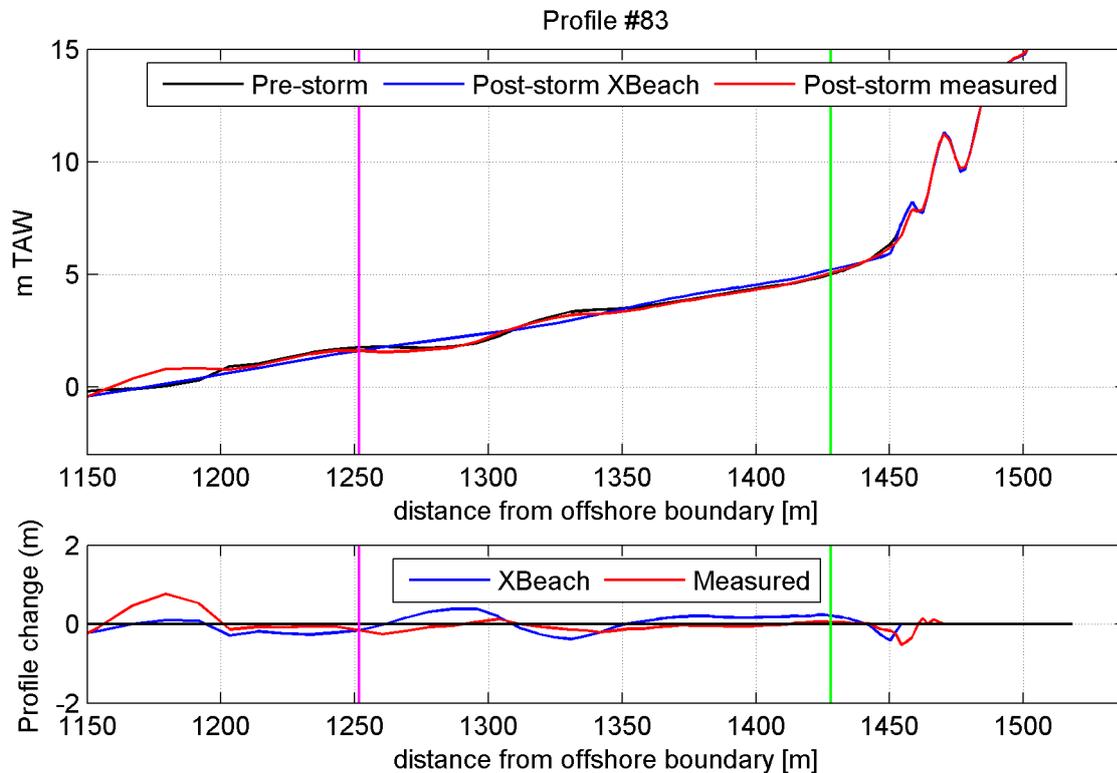
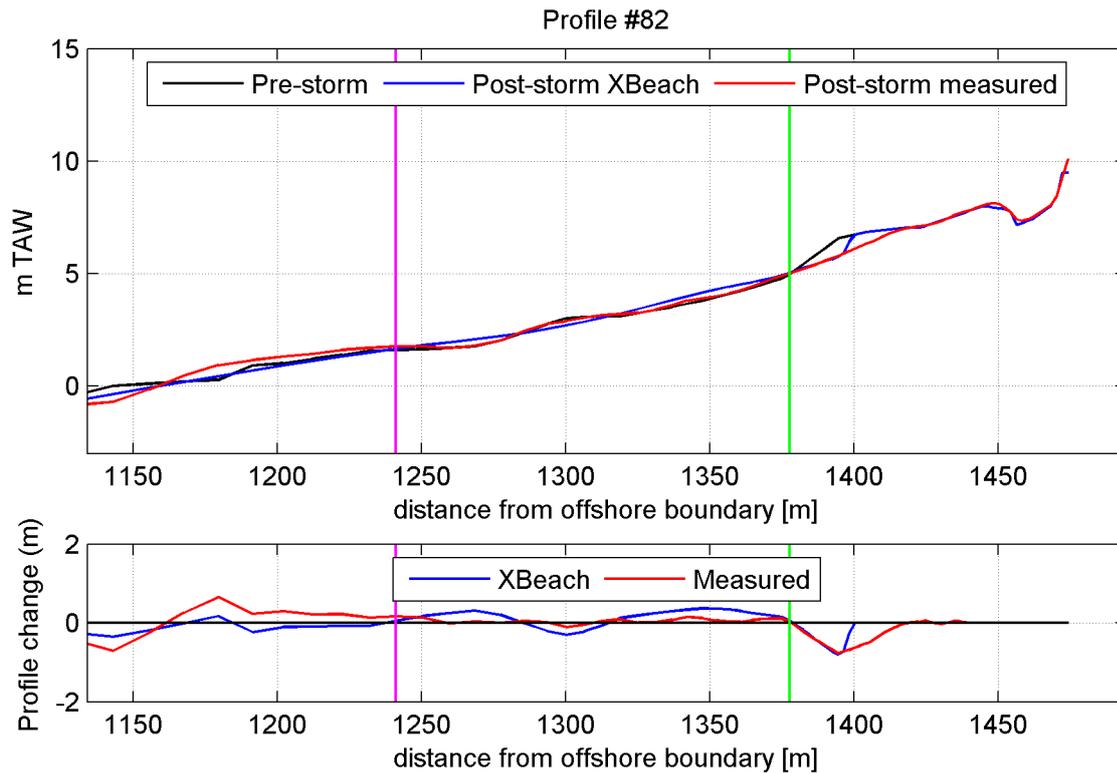
Measured: Above 5 m TAW:  $-10.44 \text{ m}^3/\text{m}$ . Below 5m TAW:  $8.82 \text{ m}^3/\text{m}$ .

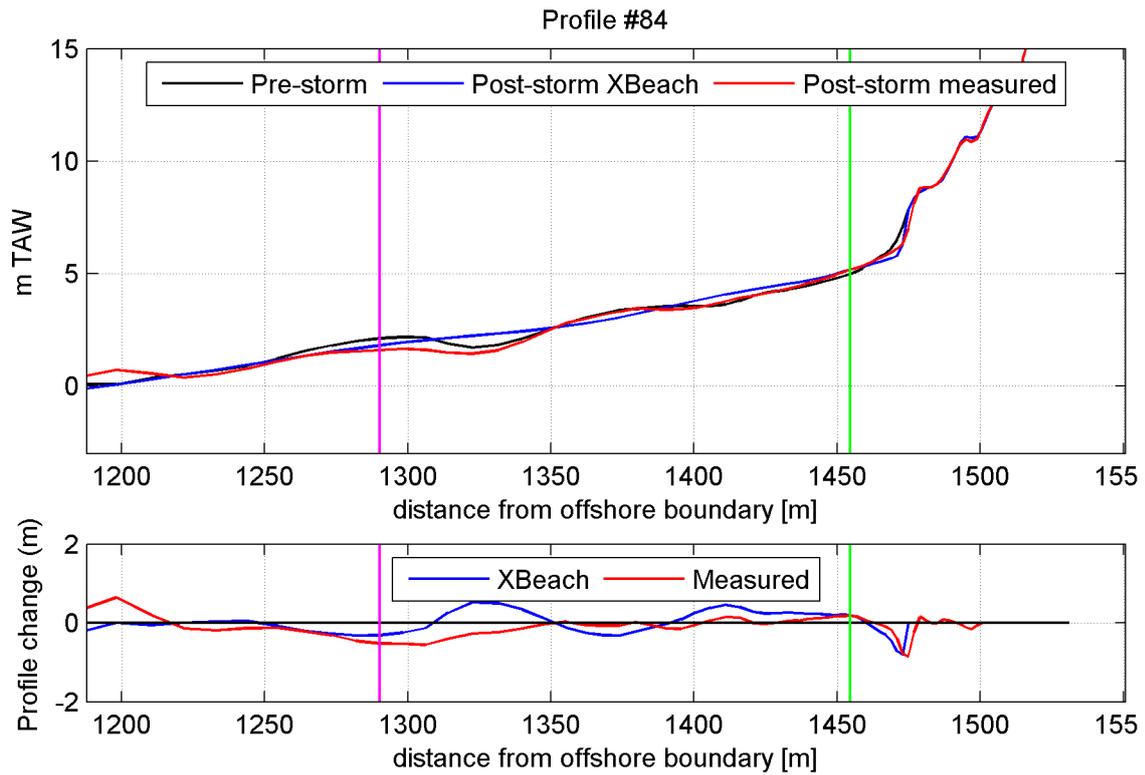


BSS = -0.17

Xbeach: Above 5 m TAW:  $-8.87 \text{ m}^3/\text{m}$ . Below 5m TAW:  $16.26 \text{ m}^3/\text{m}$ .

Measured: Above 5 m TAW:  $-12.70 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-3.25 \text{ m}^3/\text{m}$ .

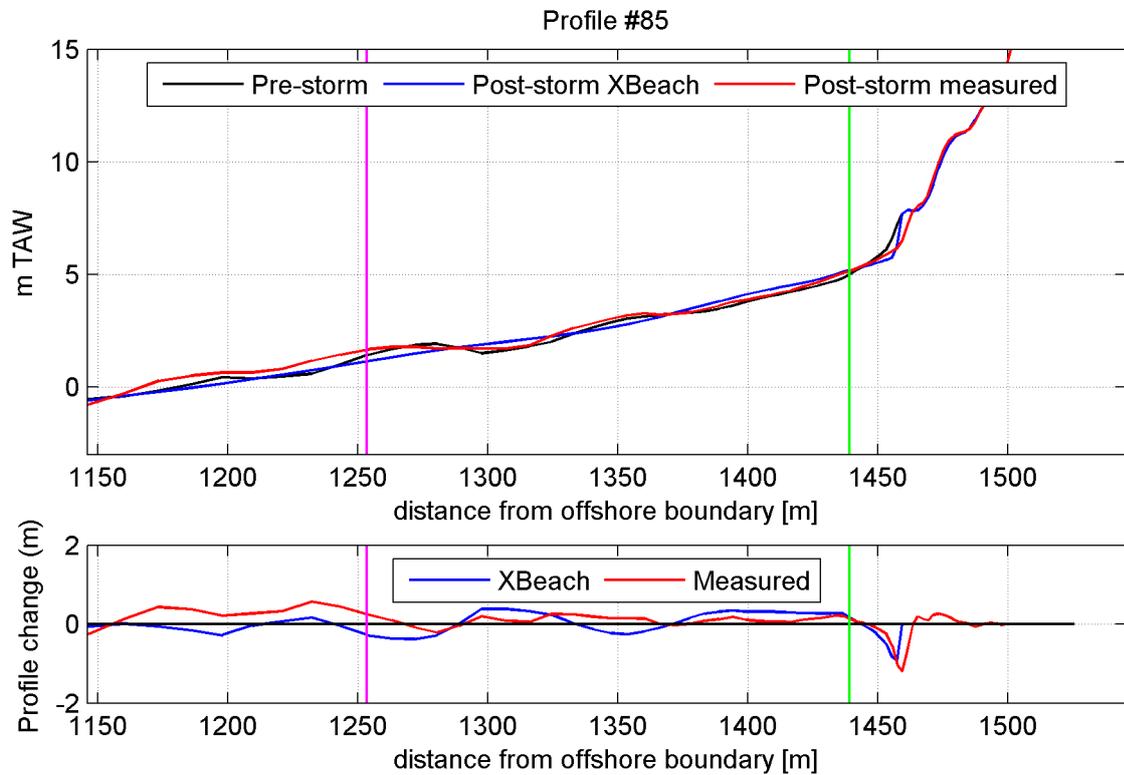




BSS = -0.97

Xbeach: Above 5 m TAW:  $-4.67 \text{ m}^3/\text{m}$ . Below 5m TAW:  $18.76 \text{ m}^3/\text{m}$ .

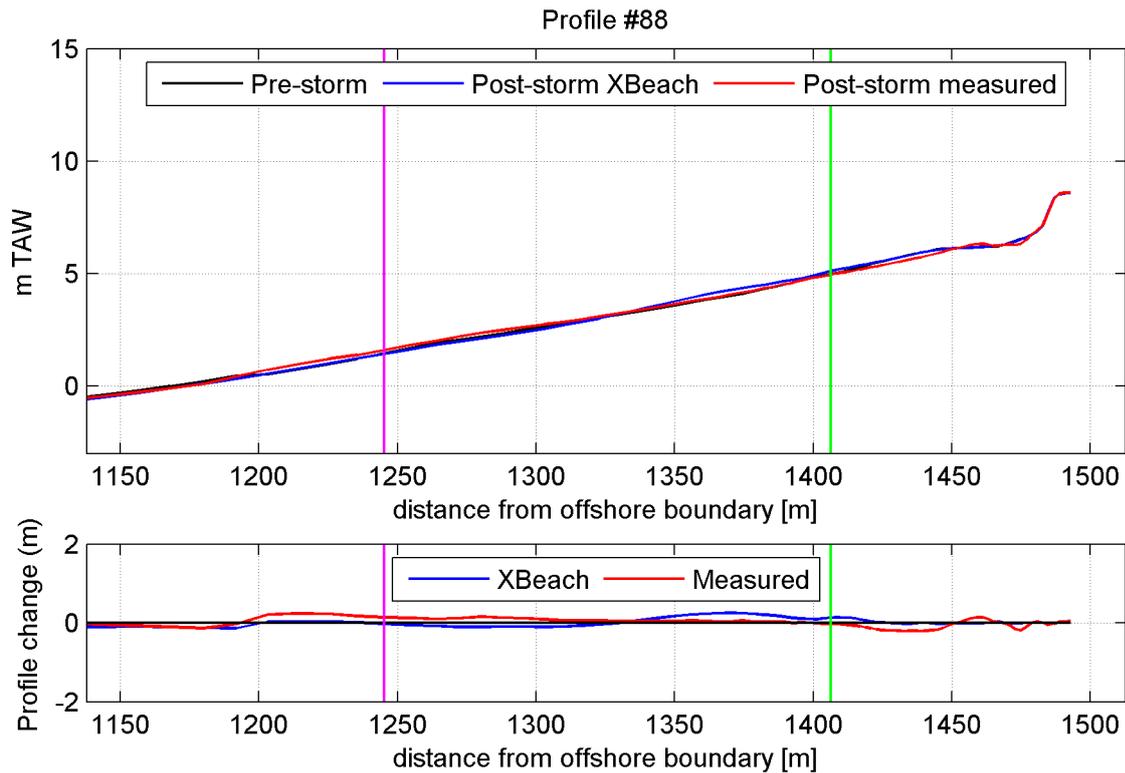
Measured: Above 5 m TAW:  $-4.34 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-18.53 \text{ m}^3/\text{m}$ .



BSS = -0.46

Xbeach: Above 5 m TAW:  $-5.82 \text{ m}^3/\text{m}$ . Below 5m TAW:  $14.47 \text{ m}^3/\text{m}$ .

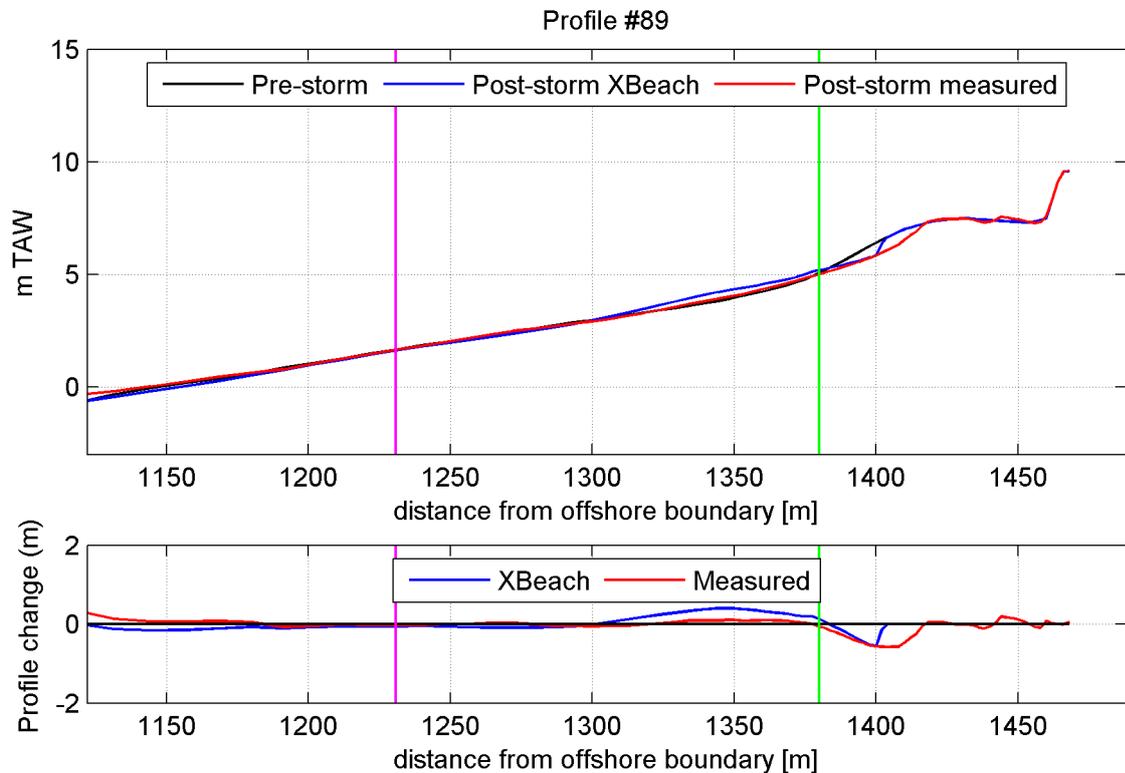
Measured: Above 5 m TAW:  $-4.81 \text{ m}^3/\text{m}$ . Below 5m TAW:  $17.66 \text{ m}^3/\text{m}$ .



BSS = -1.53

Xbeach: Above 5 m TAW: 1.51 m<sup>3</sup>/m. Below 5m TAW: 5.94 m<sup>3</sup>/m.

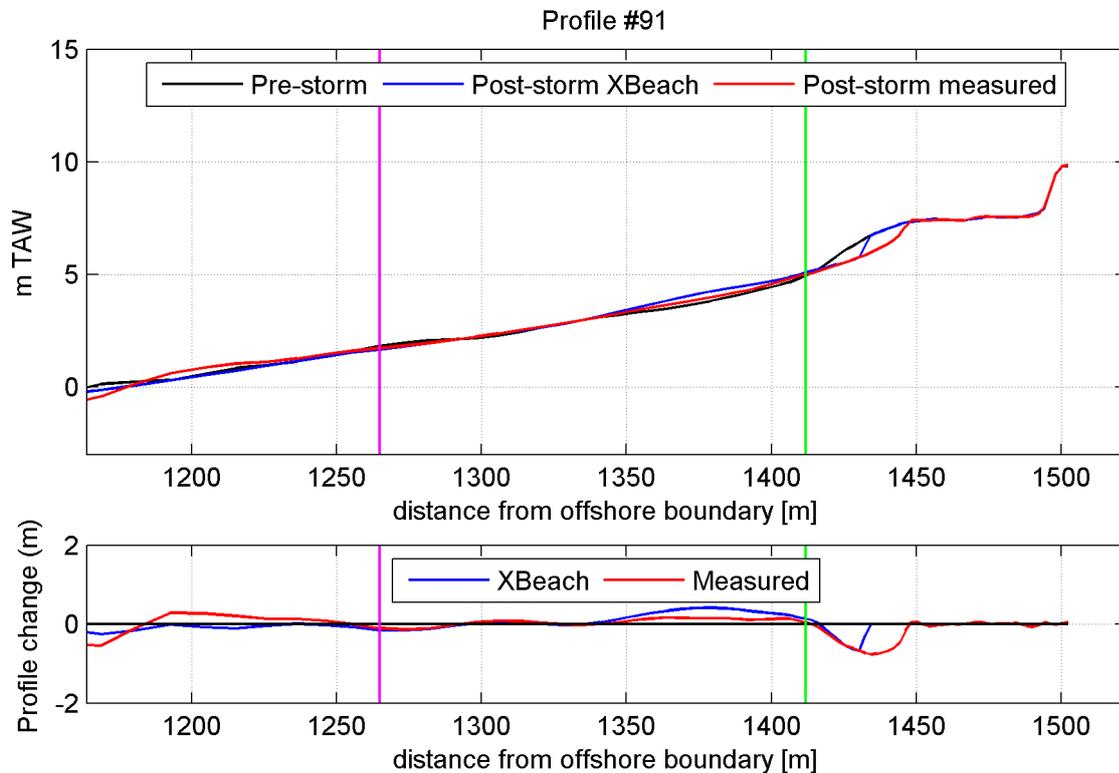
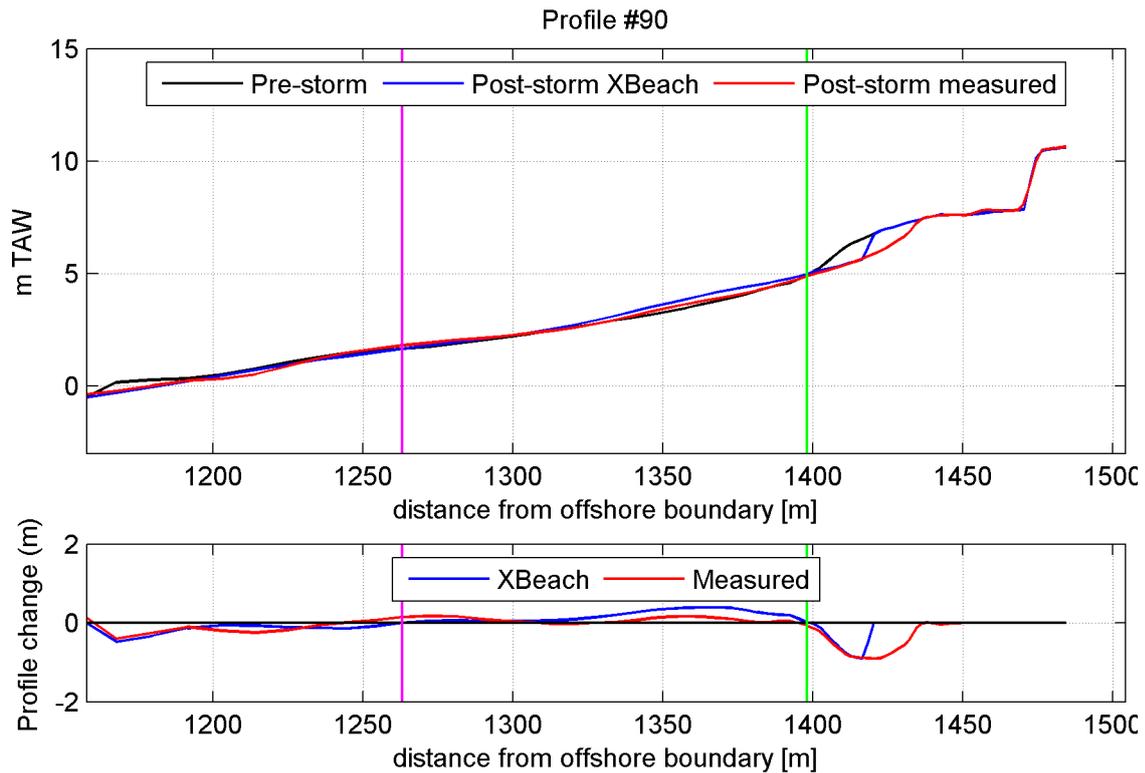
Measured: Above 5 m TAW: -5.75 m<sup>3</sup>/m. Below 5m TAW: 11.44 m<sup>3</sup>/m.

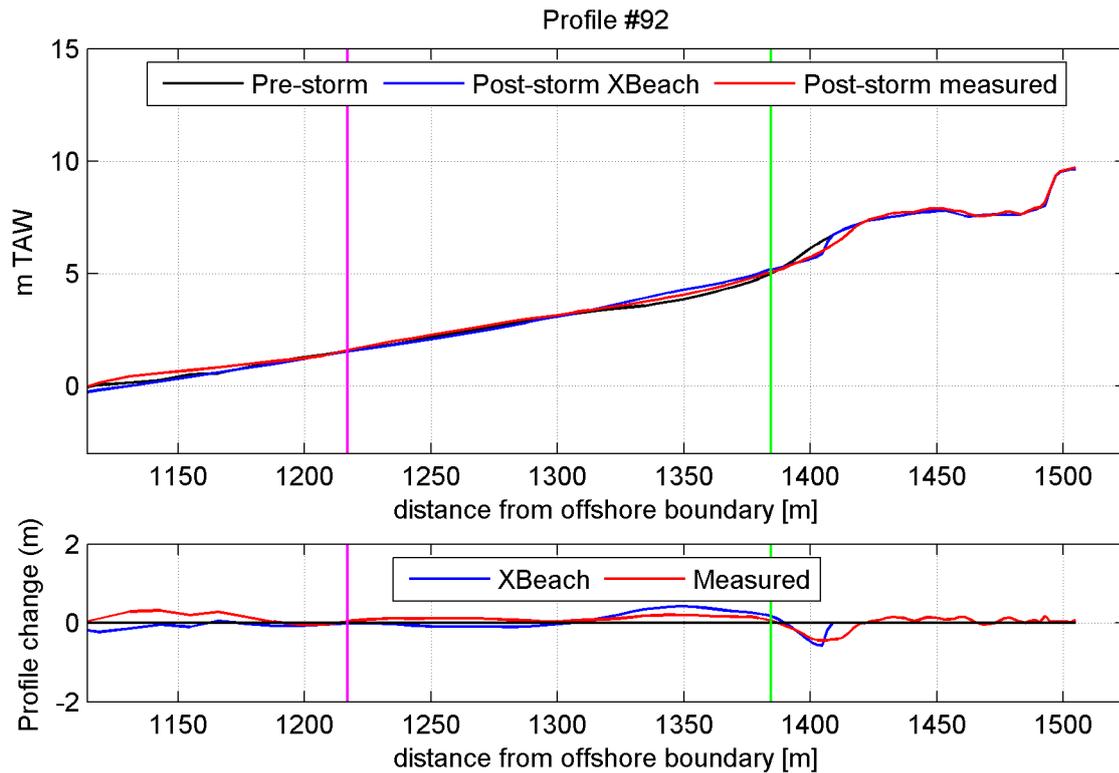


BSS = -0.10

Xbeach: Above 5 m TAW: -5.55 m<sup>3</sup>/m. Below 5m TAW: 15.58 m<sup>3</sup>/m.

Measured: Above 5 m TAW: -12.88 m<sup>3</sup>/m. Below 5m TAW: 2.99 m<sup>3</sup>/m.

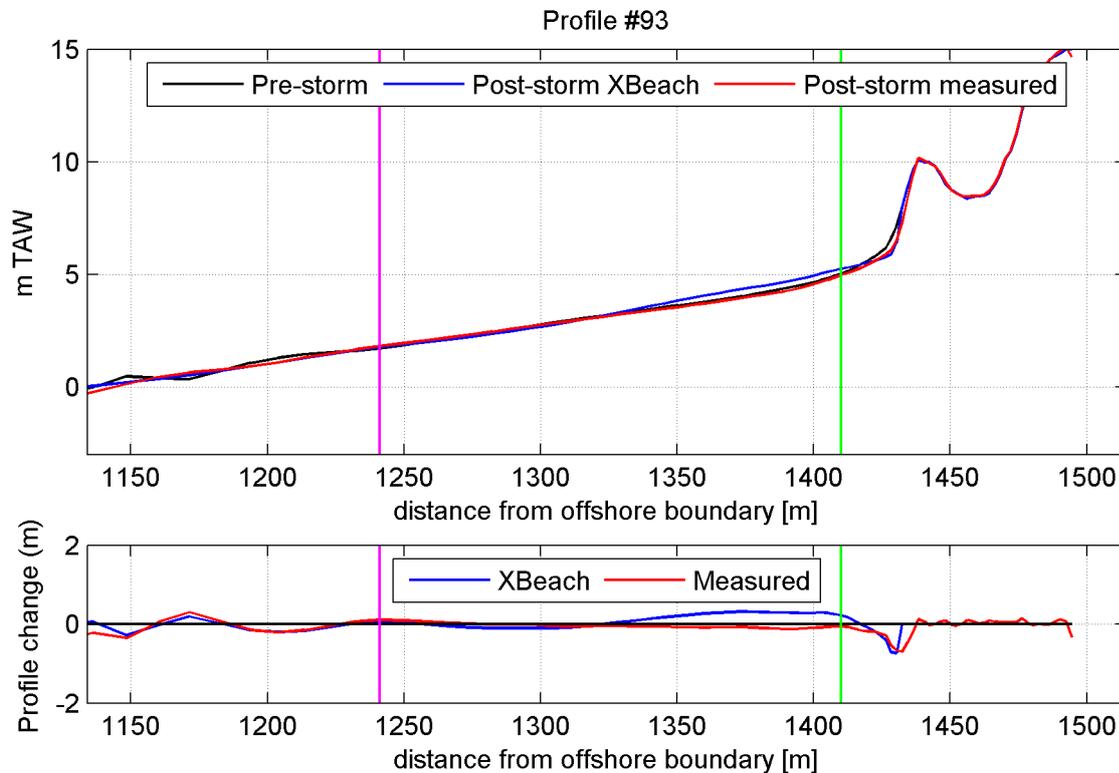




BSS = 0.03

Xbeach: Above 5 m TAW:  $-5.40 \text{ m}^3/\text{m}$ . Below 5m TAW:  $16.06 \text{ m}^3/\text{m}$ .

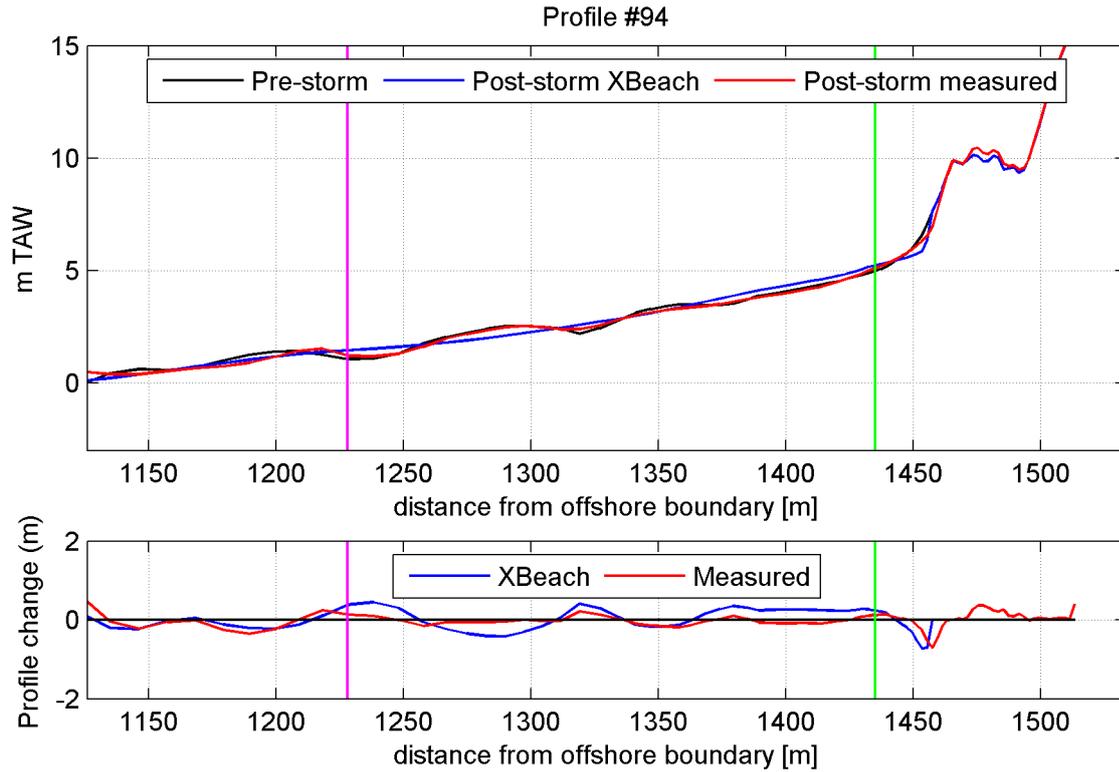
Measured: Above 5 m TAW:  $-2.98 \text{ m}^3/\text{m}$ . Below 5m TAW:  $19.52 \text{ m}^3/\text{m}$ .



BSS = -1.58

Xbeach: Above 5 m TAW:  $-4.14 \text{ m}^3/\text{m}$ . Below 5m TAW:  $15.48 \text{ m}^3/\text{m}$ .

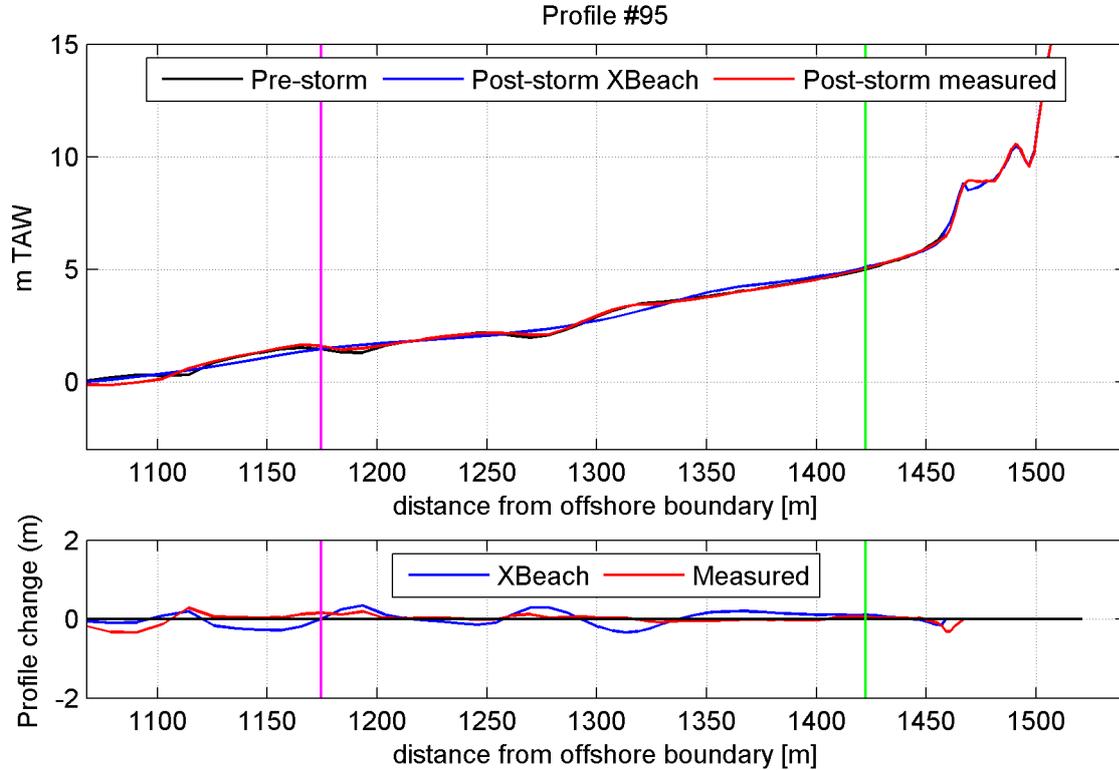
Measured: Above 5 m TAW:  $-5.94 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-5.82 \text{ m}^3/\text{m}$ .



BSS = -1.85

Xbeach: Above 5 m TAW:  $-3.92 \text{ m}^3/\text{m}$ . Below 5m TAW:  $15.43 \text{ m}^3/\text{m}$ .

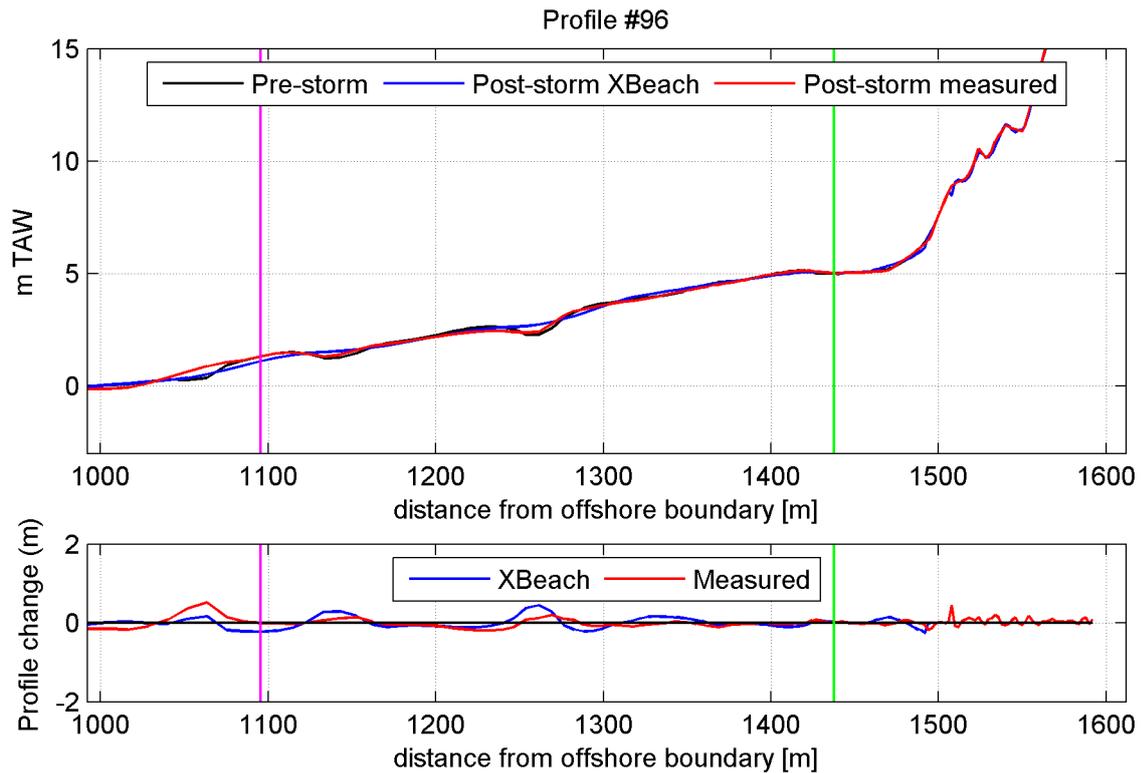
Measured: Above 5 m TAW:  $2.59 \text{ m}^3/\text{m}$ . Below 5m TAW:  $-4.08 \text{ m}^3/\text{m}$ .



BSS = -3.37

Xbeach: Above 5 m TAW:  $0.12 \text{ m}^3/\text{m}$ . Below 5m TAW:  $13.41 \text{ m}^3/\text{m}$ .

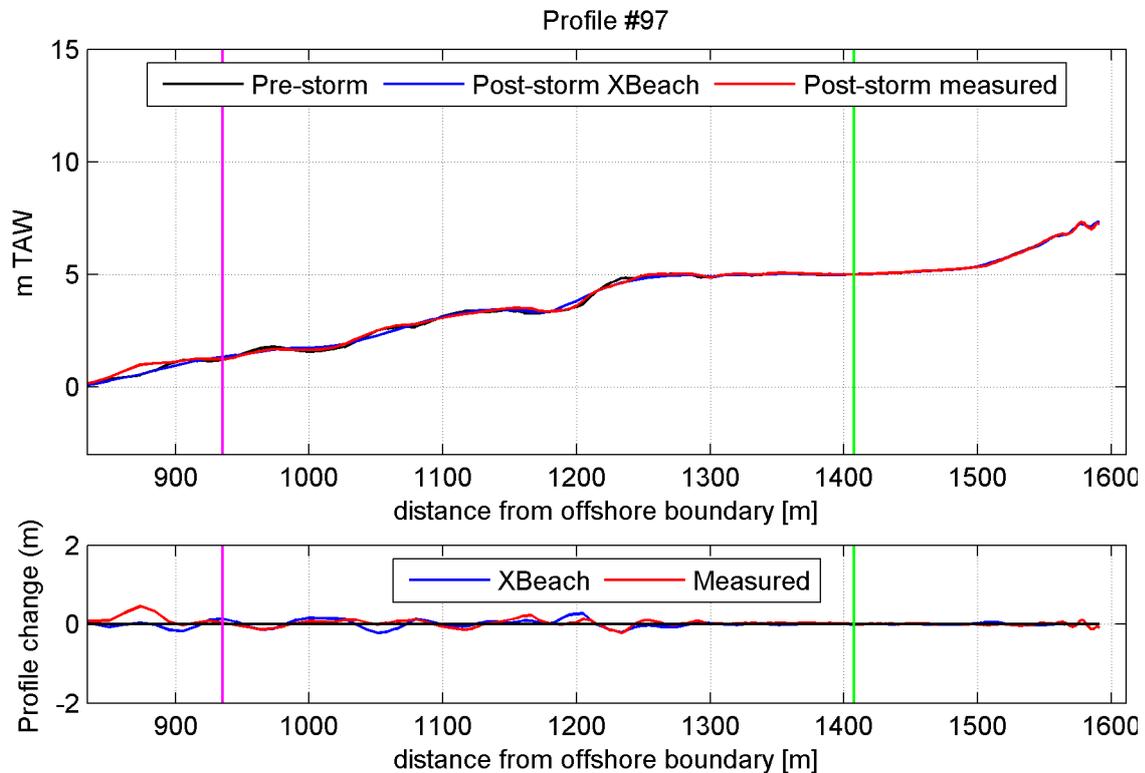
Measured: Above 5 m TAW:  $-1.70 \text{ m}^3/\text{m}$ . Below 5m TAW:  $6.49 \text{ m}^3/\text{m}$ .



BSS = -0.95

Xbeach: Above 5 m TAW: 0.23 m<sup>3</sup>/m. Below 5m TAW: 4.22 m<sup>3</sup>/m.

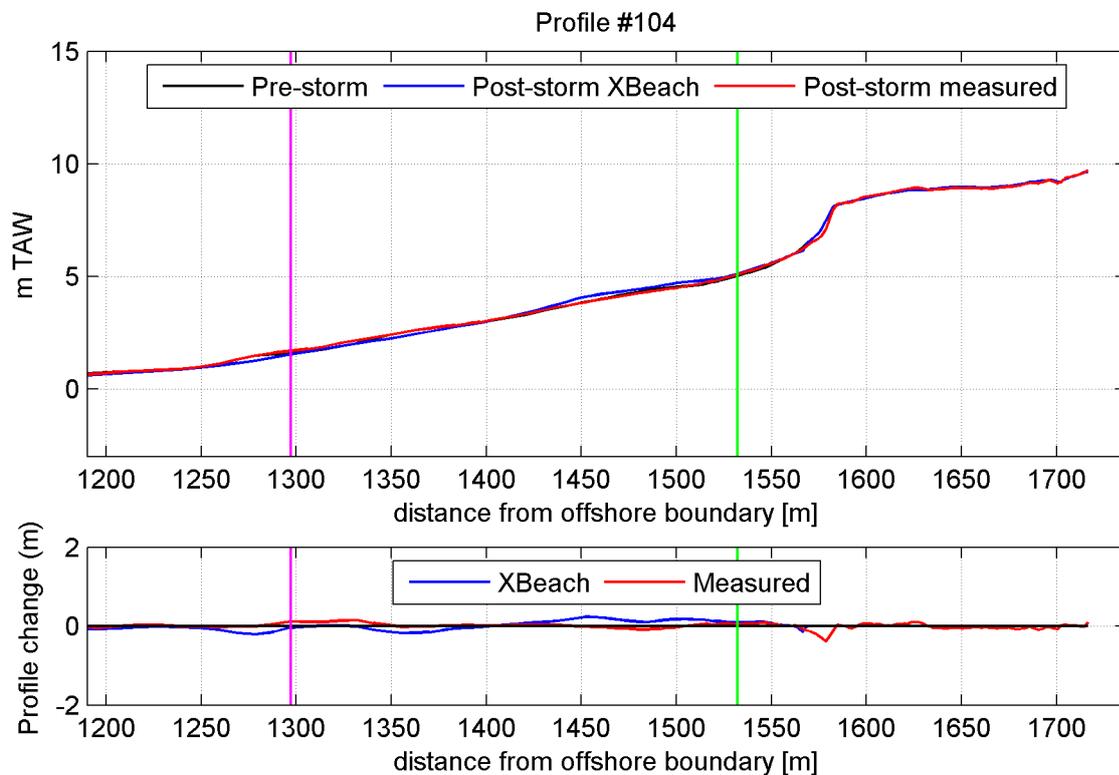
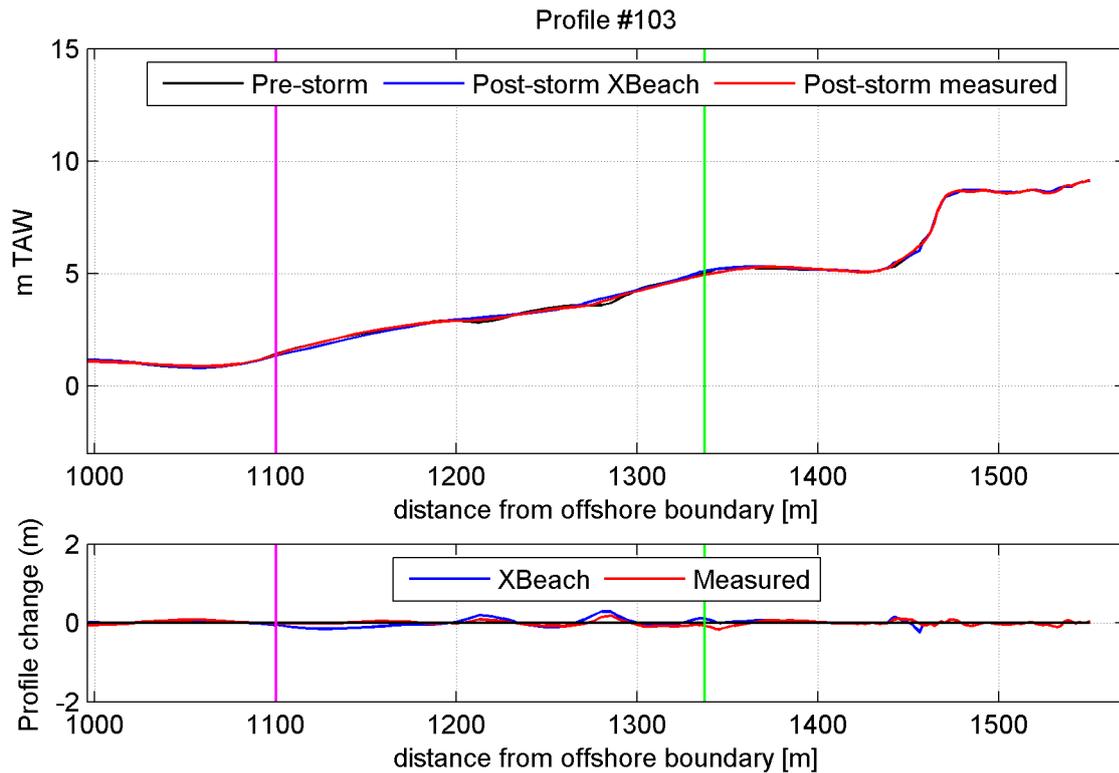
Measured: Above 5 m TAW: 3.68 m<sup>3</sup>/m. Below 5m TAW: -6.04 m<sup>3</sup>/m.

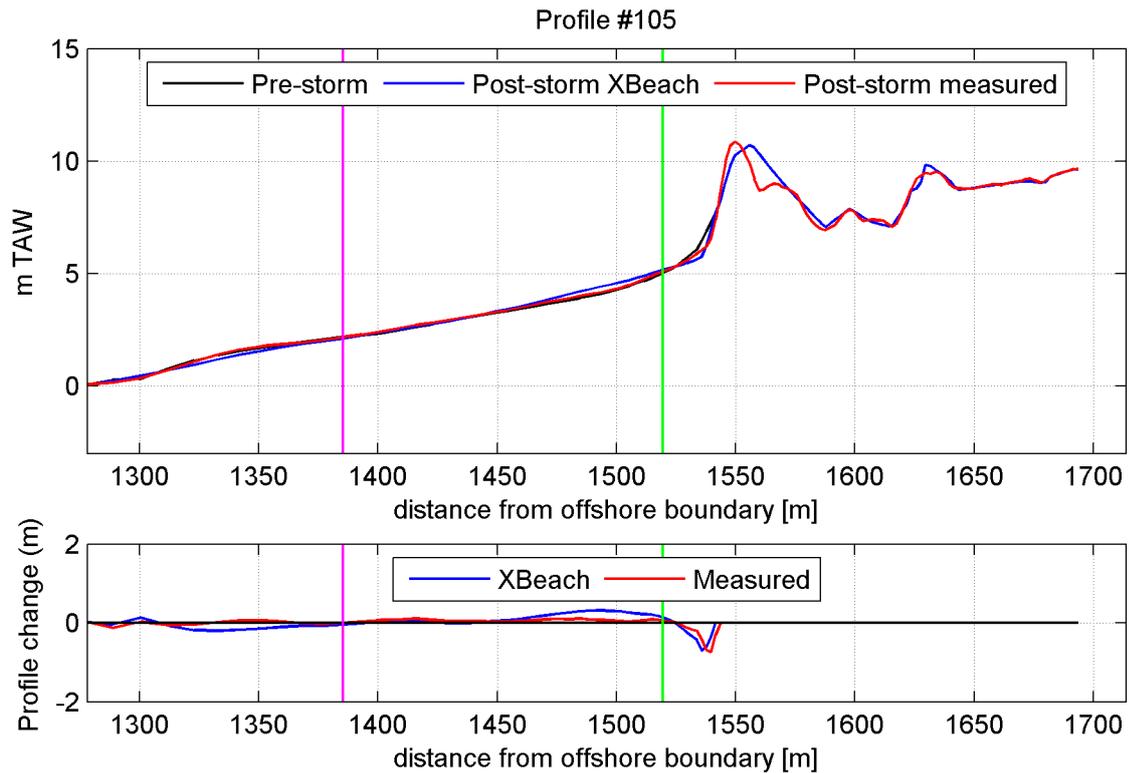


BSS = -0.17

Xbeach: Above 5 m TAW: 0.08 m<sup>3</sup>/m. Below 5m TAW: 3.52 m<sup>3</sup>/m.

Measured: Above 5 m TAW: -0.34 m<sup>3</sup>/m. Below 5m TAW: 8.22 m<sup>3</sup>/m.

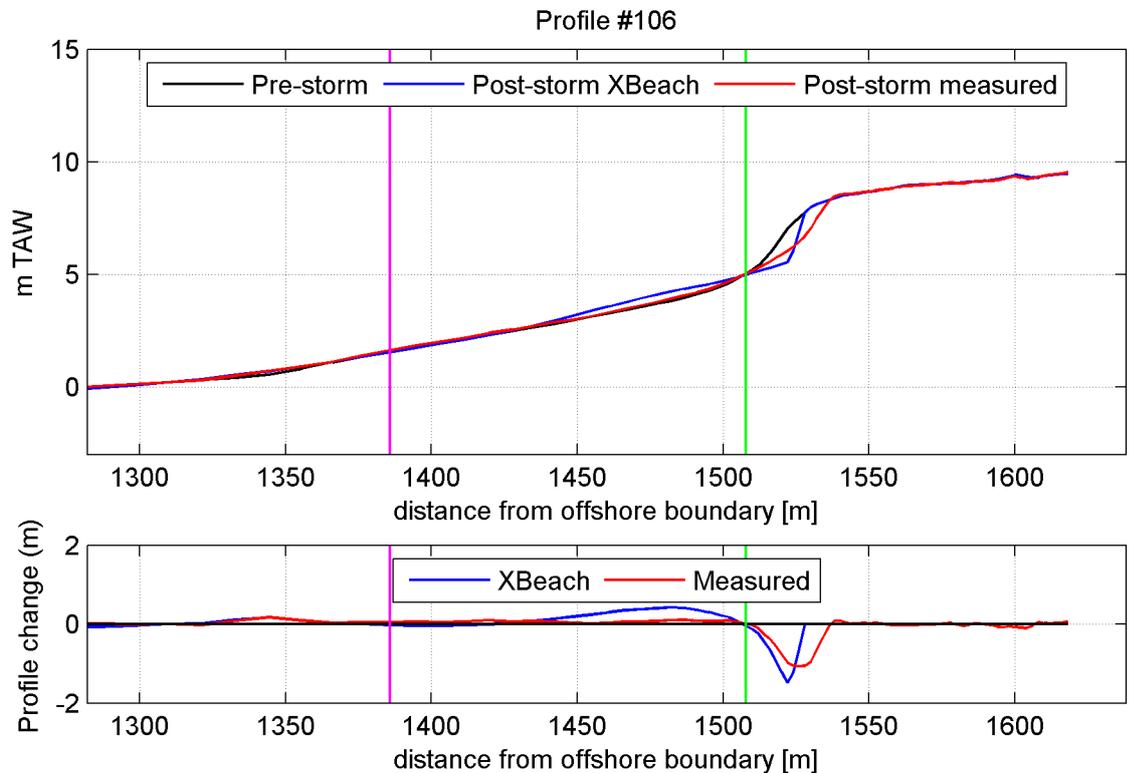




BSS = 0.14

Xbeach: Above 5 m TAW:  $-5.42 \text{ m}^3/\text{m}$ . Below 5m TAW:  $15.99 \text{ m}^3/\text{m}$ .

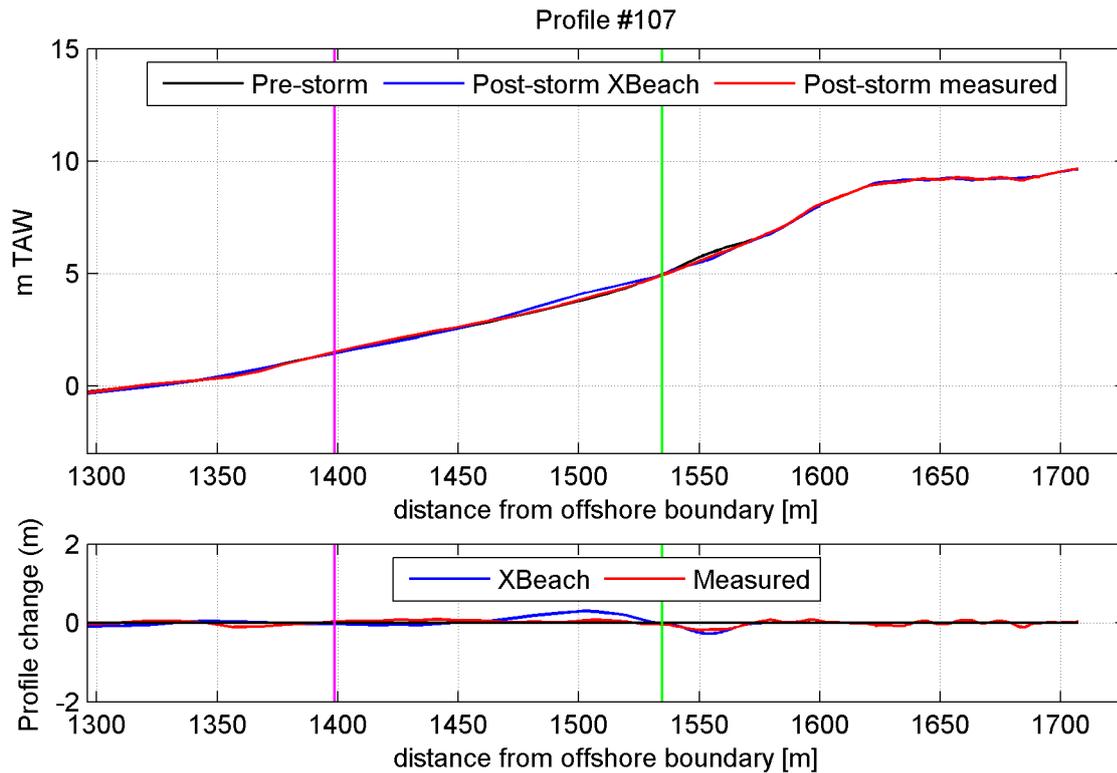
Measured: Above 5 m TAW:  $-5.28 \text{ m}^3/\text{m}$ . Below 5m TAW:  $8.59 \text{ m}^3/\text{m}$ .



BSS = 0.22

Xbeach: Above 5 m TAW:  $-14.07 \text{ m}^3/\text{m}$ . Below 5m TAW:  $18.86 \text{ m}^3/\text{m}$ .

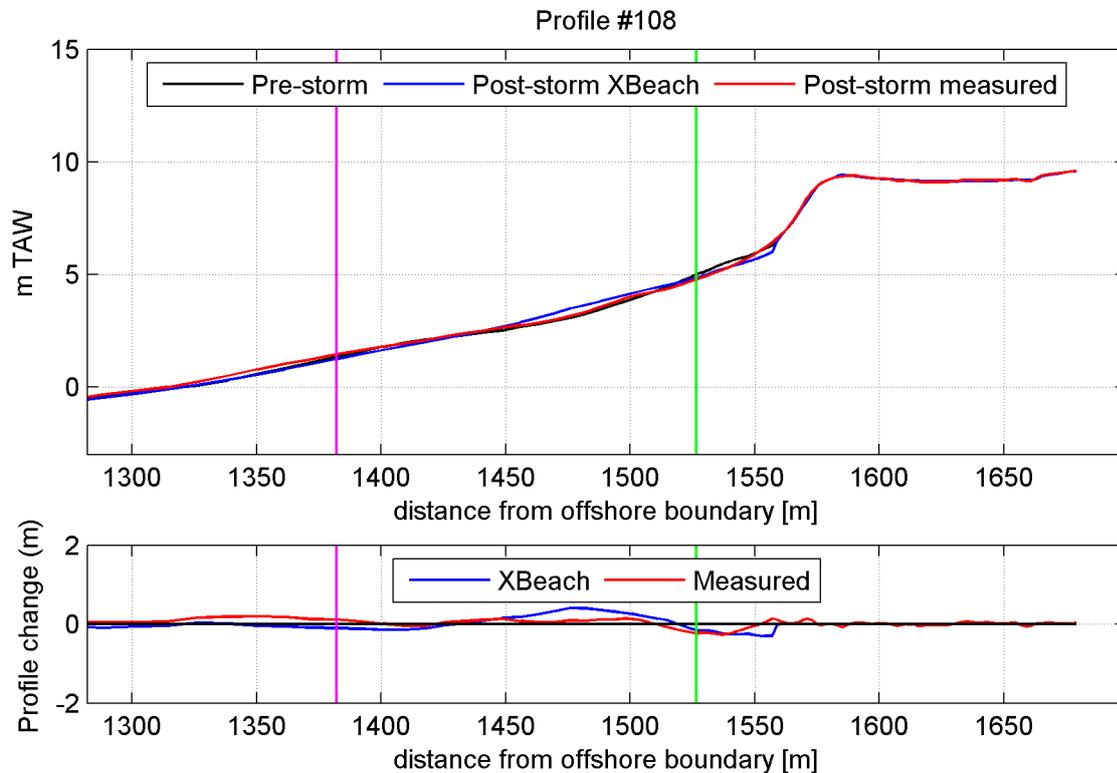
Measured: Above 5 m TAW:  $-16.77 \text{ m}^3/\text{m}$ . Below 5m TAW:  $7.99 \text{ m}^3/\text{m}$ .



BSS = -1.33

Xbeach: Above 5 m TAW:  $-5.58 \text{ m}^3/\text{m}$ . Below 5m TAW:  $11.28 \text{ m}^3/\text{m}$ .

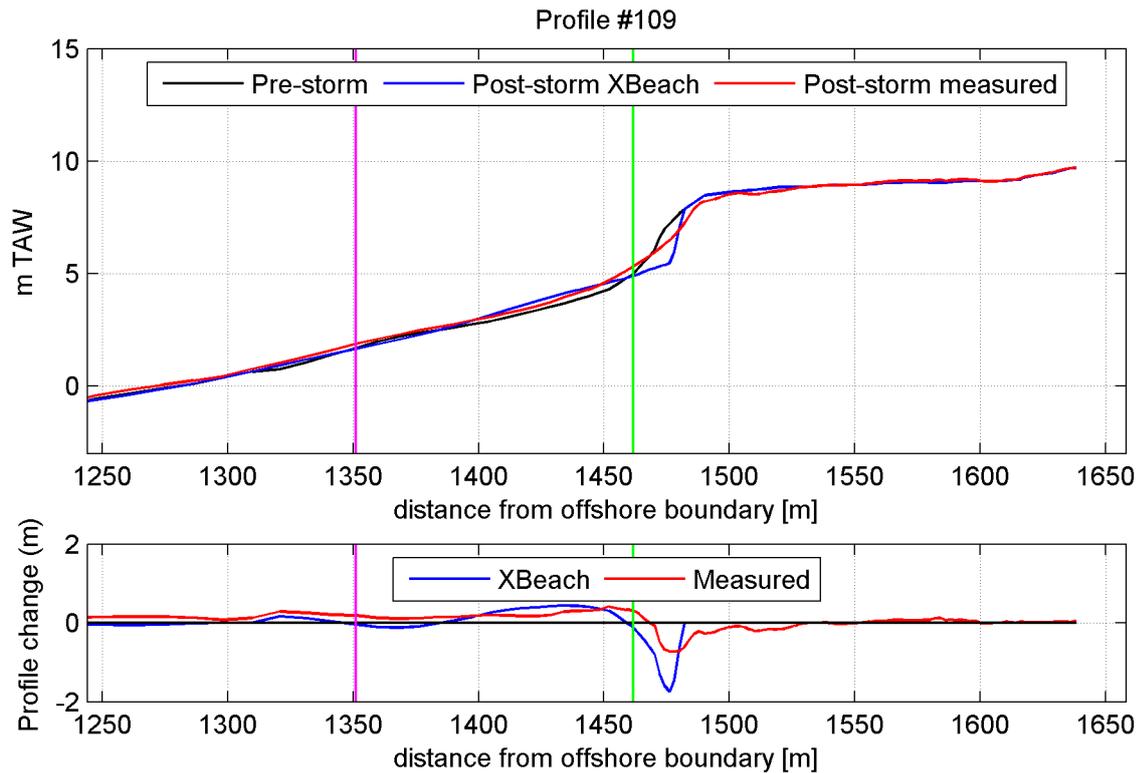
Measured: Above 5 m TAW:  $-3.70 \text{ m}^3/\text{m}$ . Below 5m TAW:  $6.14 \text{ m}^3/\text{m}$ .



BSS = -1.25

Xbeach: Above 5 m TAW:  $-7.54 \text{ m}^3/\text{m}$ . Below 5m TAW:  $14.07 \text{ m}^3/\text{m}$ .

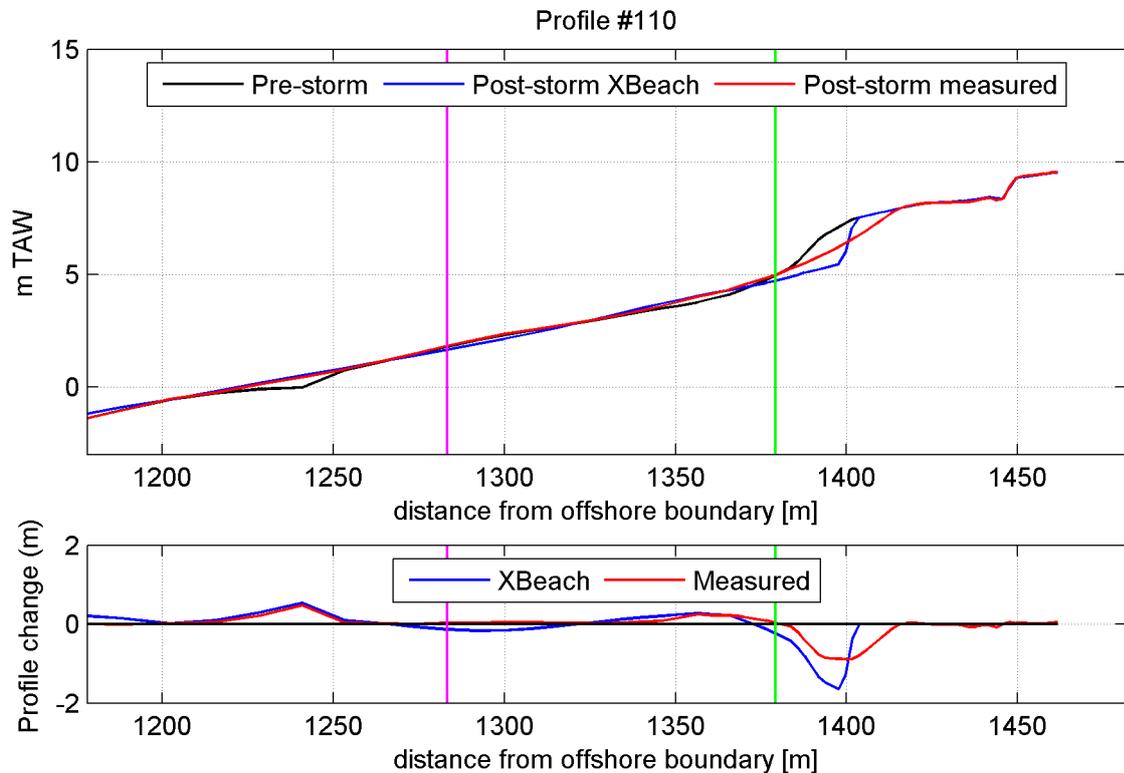
Measured: Above 5 m TAW:  $-2.73 \text{ m}^3/\text{m}$ . Below 5m TAW:  $6.25 \text{ m}^3/\text{m}$ .



BSS = -0.21

Xbeach: Above 5 m TAW:  $-17.92 \text{ m}^3/\text{m}$ . Below 5m TAW:  $18.52 \text{ m}^3/\text{m}$ .

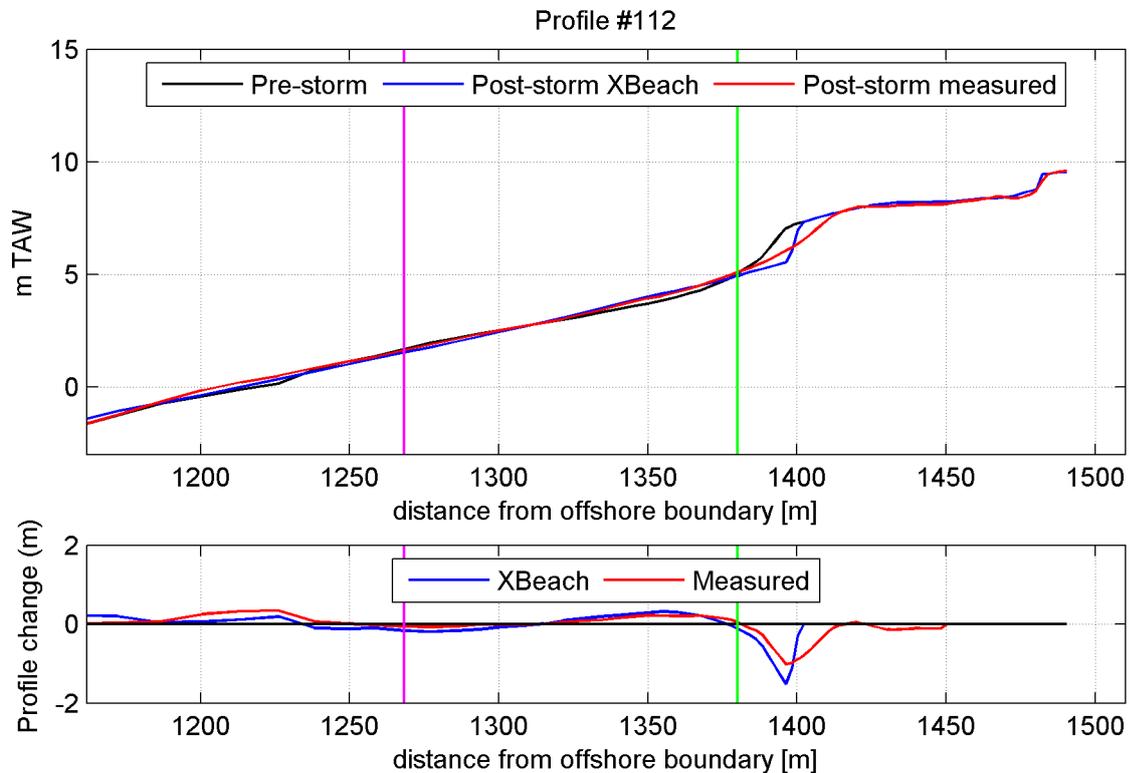
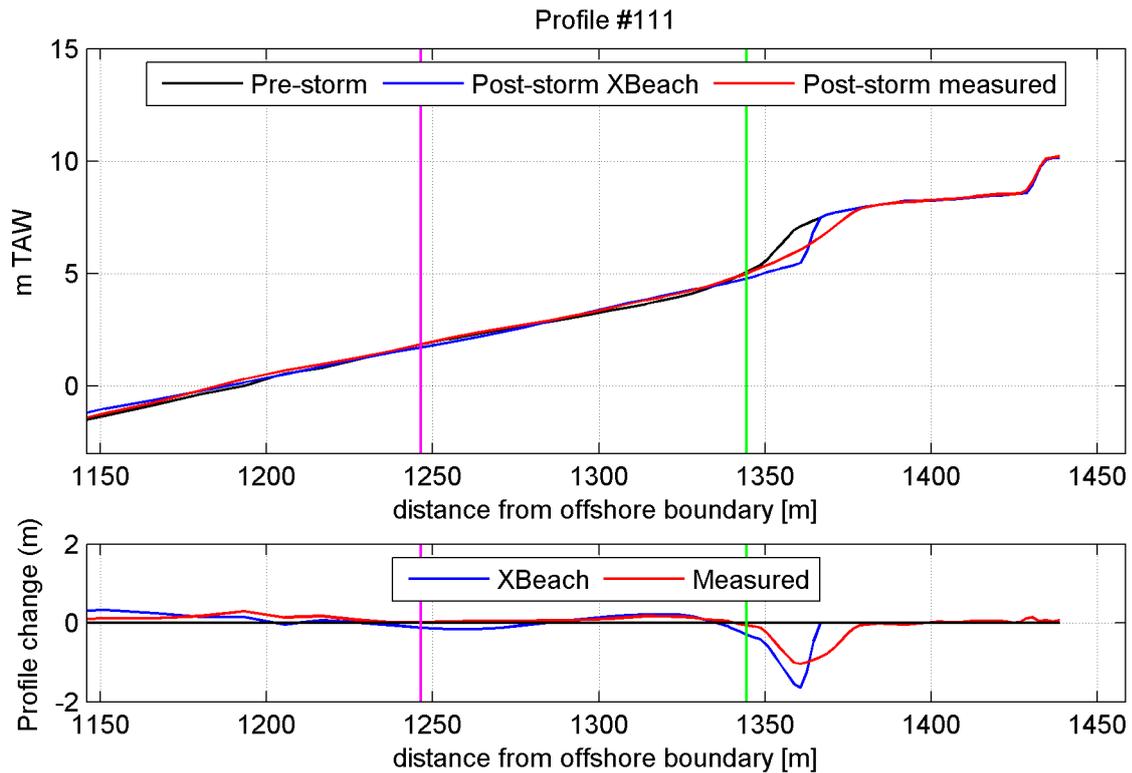
Measured: Above 5 m TAW:  $-11.22 \text{ m}^3/\text{m}$ . Below 5m TAW:  $22.69 \text{ m}^3/\text{m}$ .

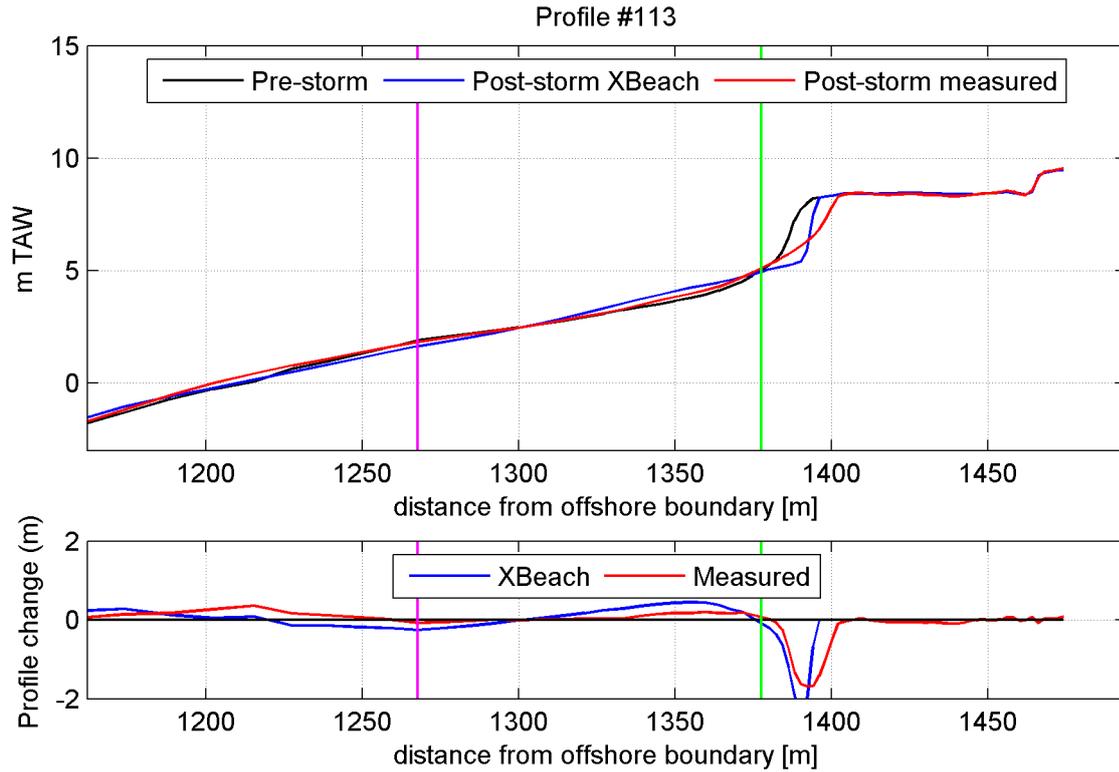


BSS = 0.24

Xbeach: Above 5 m TAW:  $-22.24 \text{ m}^3/\text{m}$ . Below 5m TAW:  $3.15 \text{ m}^3/\text{m}$ .

Measured: Above 5 m TAW:  $-18.27 \text{ m}^3/\text{m}$ . Below 5m TAW:  $8.50 \text{ m}^3/\text{m}$ .

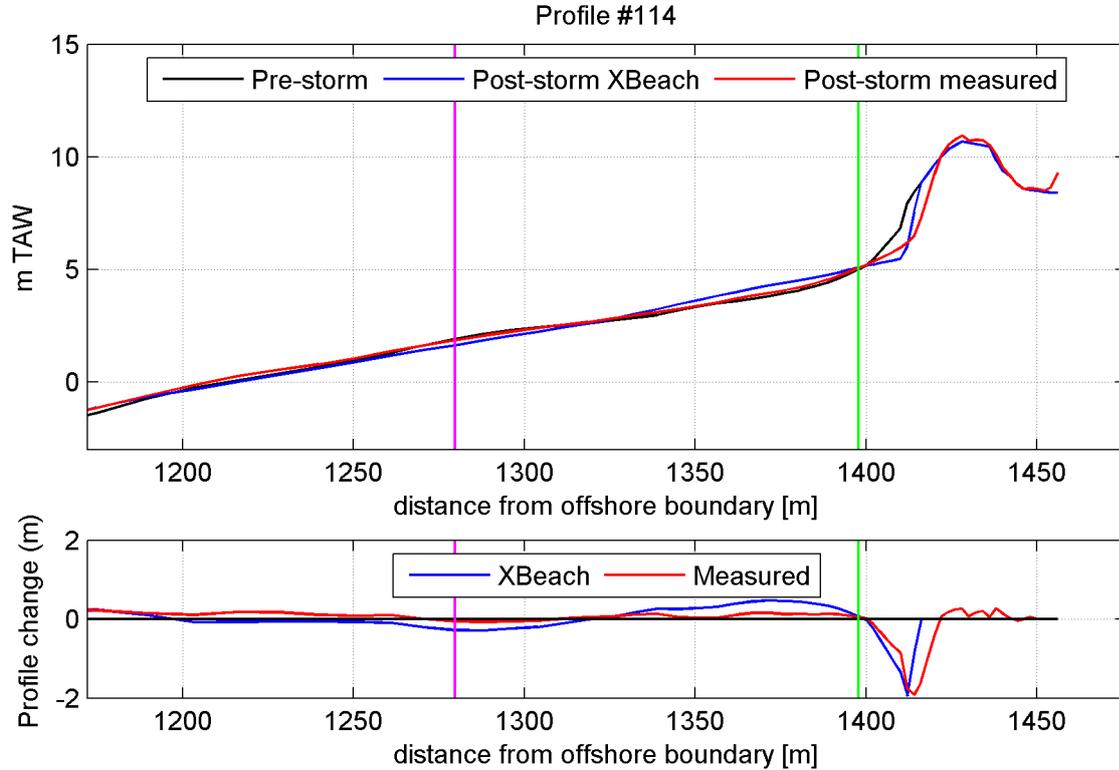




BSS = 0.48

Xbeach: Above 5 m TAW:  $-19.02 \text{ m}^3/\text{m}$ . Below 5m TAW:  $14.51 \text{ m}^3/\text{m}$ .

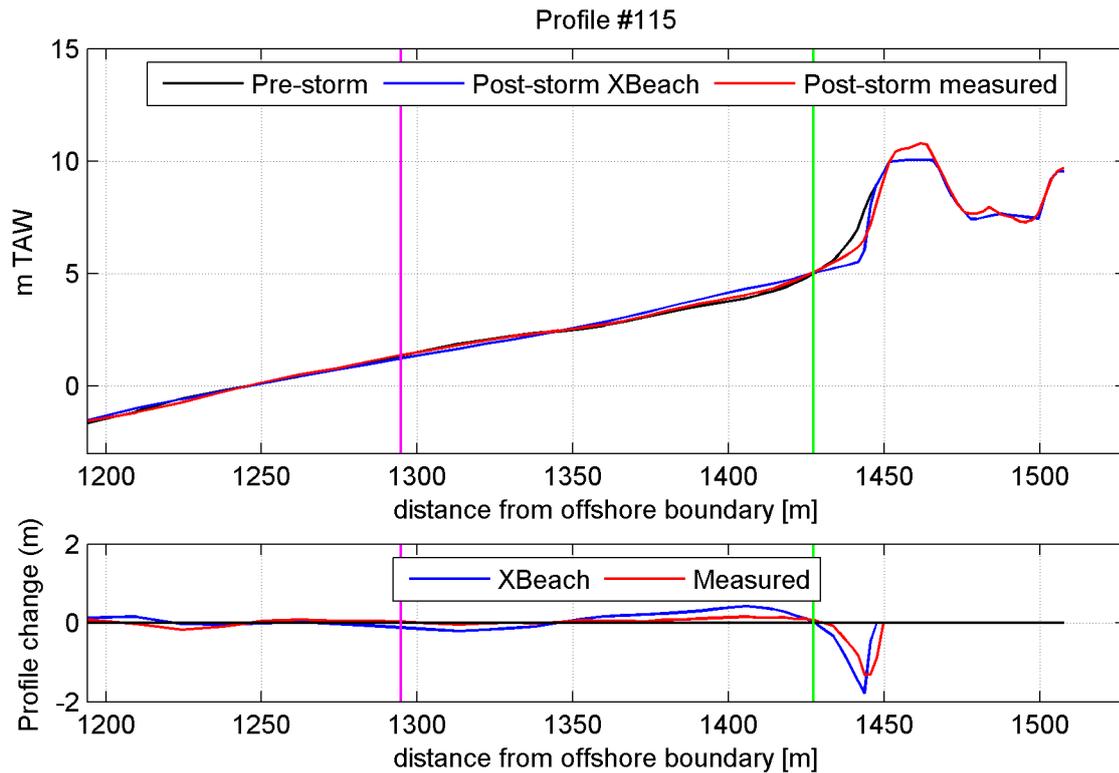
Measured: Above 5 m TAW:  $-22.10 \text{ m}^3/\text{m}$ . Below 5m TAW:  $6.36 \text{ m}^3/\text{m}$ .



BSS = 0.36

Xbeach: Above 5 m TAW:  $-13.58 \text{ m}^3/\text{m}$ . Below 5m TAW:  $15.08 \text{ m}^3/\text{m}$ .

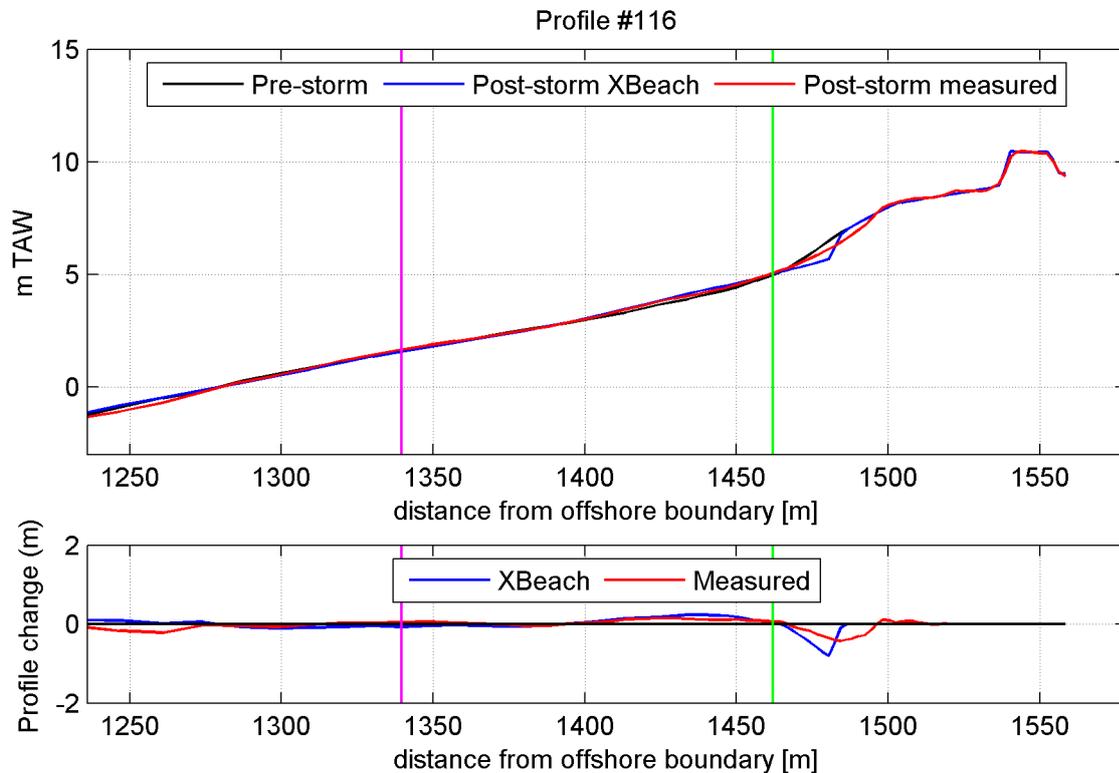
Measured: Above 5 m TAW:  $-14.86 \text{ m}^3/\text{m}$ . Below 5m TAW:  $6.60 \text{ m}^3/\text{m}$ .



BSS = 0.23

Xbeach: Above 5 m TAW:  $-14.06 \text{ m}^3/\text{m}$ . Below 5m TAW:  $12.75 \text{ m}^3/\text{m}$ .

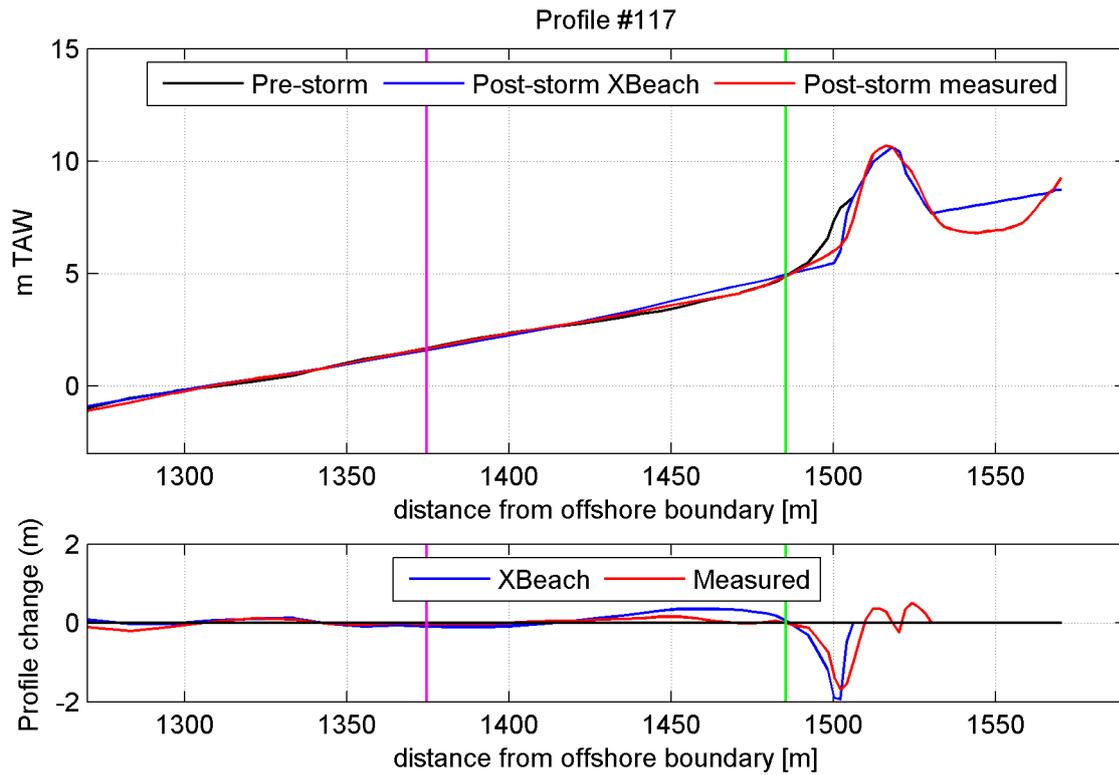
Measured: Above 5 m TAW:  $-11.39 \text{ m}^3/\text{m}$ . Below 5m TAW:  $6.97 \text{ m}^3/\text{m}$ .



BSS = 0.05

Xbeach: Above 5 m TAW:  $-7.92 \text{ m}^3/\text{m}$ . Below 5m TAW:  $7.99 \text{ m}^3/\text{m}$ .

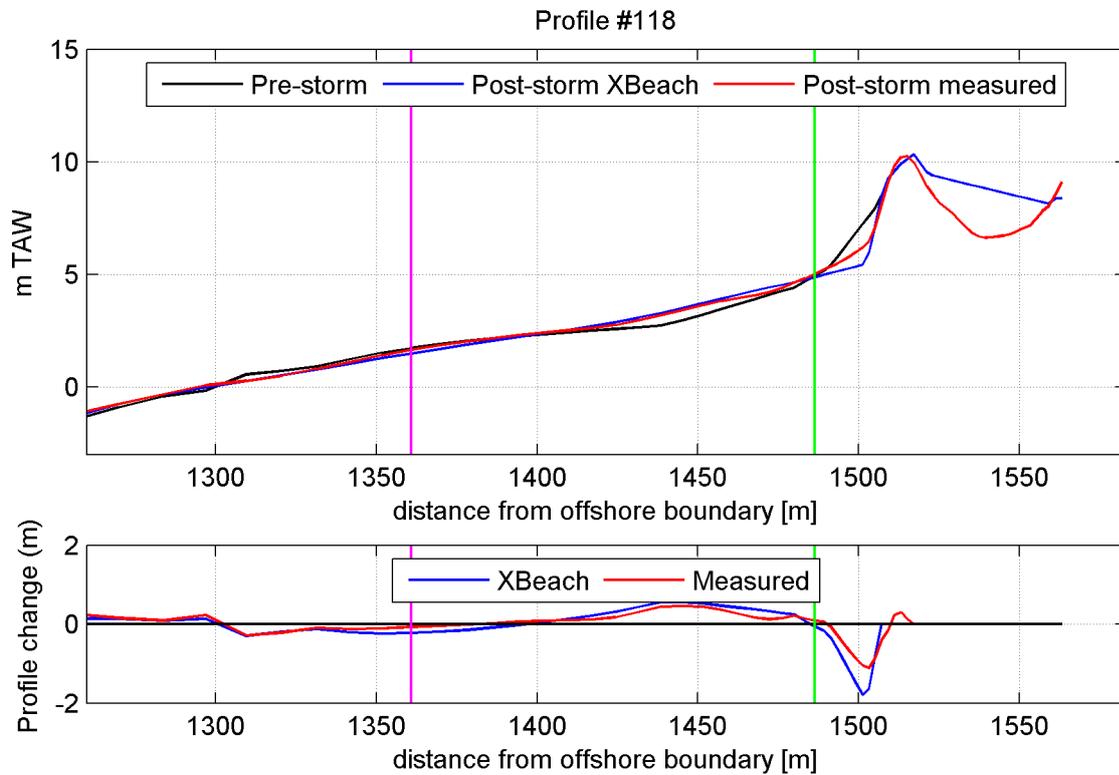
Measured: Above 5 m TAW:  $-6.06 \text{ m}^3/\text{m}$ . Below 5m TAW:  $7.28 \text{ m}^3/\text{m}$ .



BSS = 0.46

Xbeach: Above 5 m TAW:  $-15.07 \text{ m}^3/\text{m}$ . Below 5m TAW:  $13.47 \text{ m}^3/\text{m}$ .

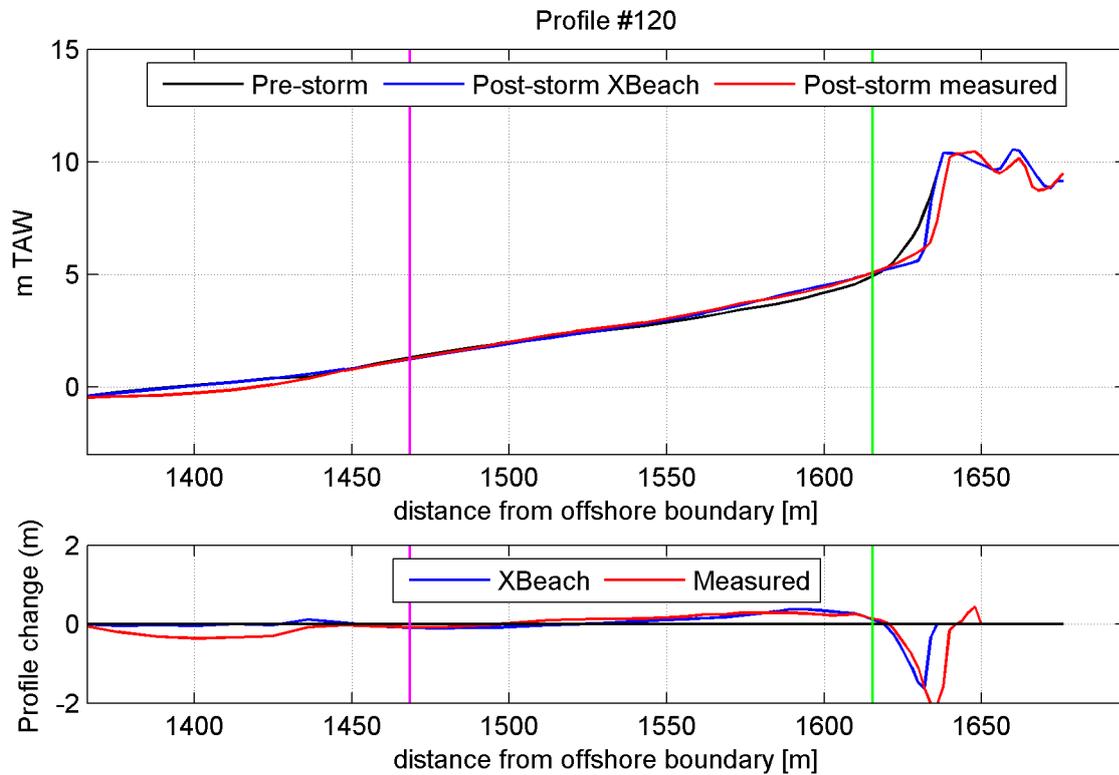
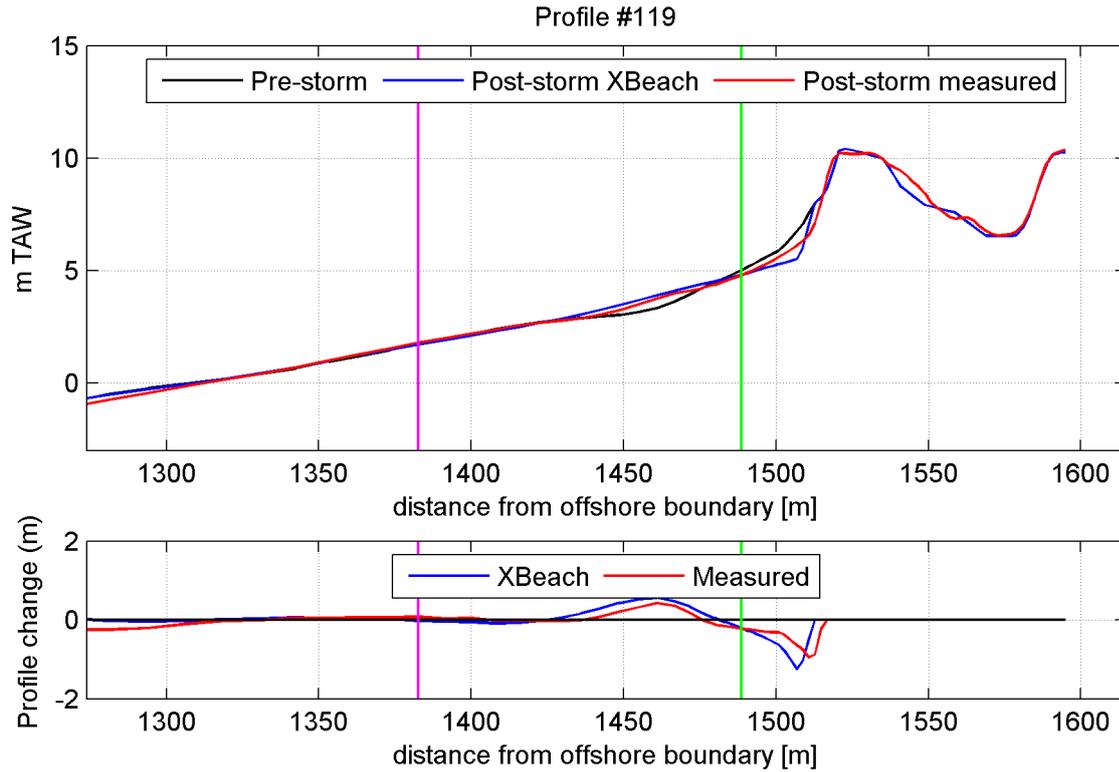
Measured: Above 5 m TAW:  $-11.02 \text{ m}^3/\text{m}$ . Below 5m TAW:  $5.01 \text{ m}^3/\text{m}$ .

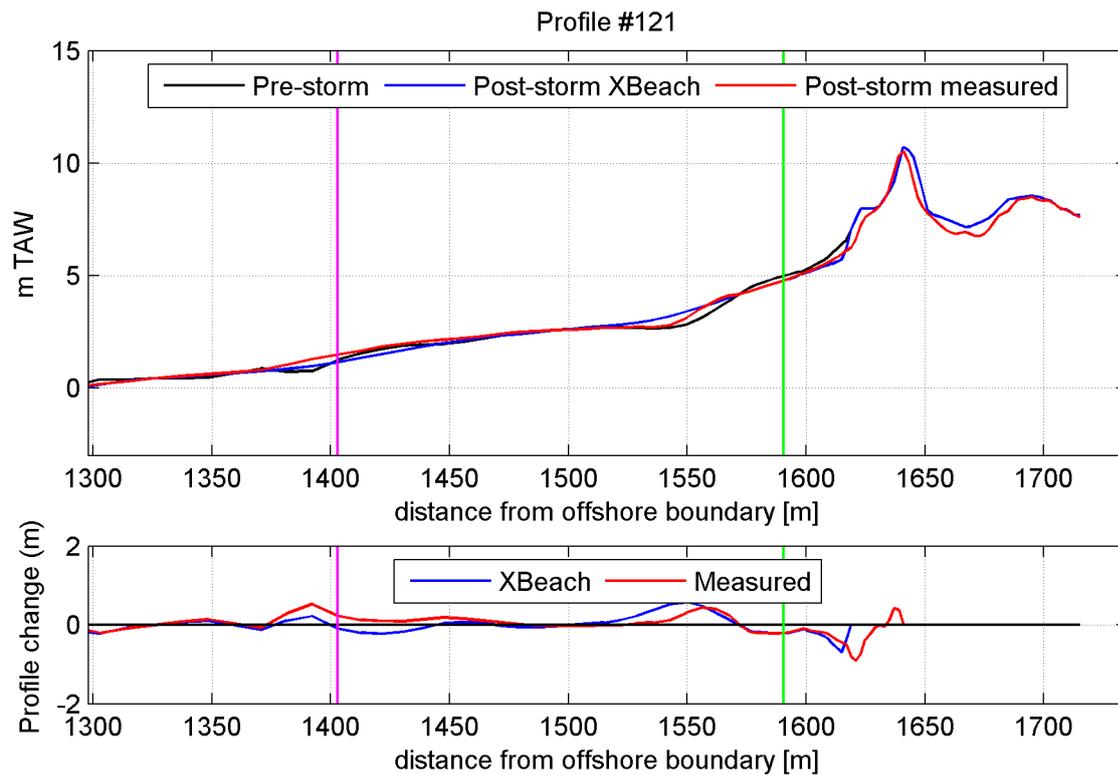


BSS = 0.61

Xbeach: Above 5 m TAW:  $-18.14 \text{ m}^3/\text{m}$ . Below 5m TAW:  $24.14 \text{ m}^3/\text{m}$ .

Measured: Above 5 m TAW:  $-10.39 \text{ m}^3/\text{m}$ . Below 5m TAW:  $20.93 \text{ m}^3/\text{m}$ .





BSS = 0.01

Xbeach: Above 5 m TAW:  $-8.22 \text{ m}^3/\text{m}$ . Below 5m TAW:  $9.10 \text{ m}^3/\text{m}$ .

Measured: Above 5 m TAW:  $-10.96 \text{ m}^3/\text{m}$ . Below 5m TAW:  $15.56 \text{ m}^3/\text{m}$ .



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