Wave climate and sediment dynamics in the tidal flats and marshes of Galgeschoor

Synthesis report

Alexander Van Braeckel, Jean-Philippe Belliard, Dieter Meire, Frank Van de Meuter, Alexandra Silinski, Stijn Temmerman, Sieglie De Roo, Gerasimos Kolokythas, Ya'ir Levi, Tjeerd Bouma en Erika Van den Bergh

Authors:

Alexander Van Braeckel, Jean-Philippe Belliard, Dieter Meire, Frank Van de Meuter, Alexandra Silinski, Stijn Temmerman, Sieglie De Roo, Gerasimos Kolokythas, Ya'ir Levi, Tjeerd Bouma en Erika Van den Bergh
Research Institute for Nature and Forest (INBO)

Reviewers:

Stefaan Ides

The Research Institute for Nature and Forest (INBO) is an independent research institute of the Flemish government. Through applied scientific research, open data and knowledge, integration and disclosure, it underpins and evaluates biodiversity policy and management.

Location:

INBO Brussel
Havenlaan 88 bus 73, 1000 Brussel
www.inbo.be

e-mail:

alexander.vanbraeckel@inbo.be

Way of quoting:

Van Braeckel A., Belliard J., Meire D., Van de Meuter F., Silinski A., De Roo S., Kolokythas G., Levi Y., Temmerman S., Bouma T. en Van den Bergh E. (2019). Wave climate and sediment dynamics in the tidal flats and marshes of Galgeschoor. Reports of the Research Institute for Nature and Forest 2019 (48). Research Institute for Nature and Forest, Brussels.
DOI: doi.org/10.21436/inbor.17169167

D/2009/3241/300

Reports of the Research Institute for Nature and Forest 2019 (48)

ISSN: 1782-9054

Responsible publisher:

Maurice Hoffmann

Cover photograph:

Alexander Van Braeckel

This research was carried out in collaboration with:

Flanders Hydraulics, University of Antwerp - group ECOBE, NIOZ -Yerseke (NL)
on behalf of Port of Antwerp

**Ecosystem Management
Research Group (Ecobe)**
University of Antwerp

**Port of
Antwerp**

**Flanders
Hydraulics Research**

WAVE CLIMATE AND SEDIMENT DYNAMICS IN THE TIDAL FLATS AND MARSHES OF GALGESCHOOR

Synthesis report

Alexander Van Braeckel, Jean-Philippe Belliard, Dieter Meire, Frank Van de Meuter, Alexandra Silinski, Stijn Temmerman, Sieglie De Roo, Gerasimos Kolokythas, Yaïr Levi, Tjeerd Bouma en Erika Van den Bergh

doi.org/10.21436/inbor.17169167

Flanders
State of the Art

RESEARCH INSTITUTE
NATURE AND FOREST

Flanders
Hydraulics Research

Universiteit
Antwerpen

ECOSYSTEM MANAGEMENT
RESEARCH GROUP

Preface

In 2006 the Deurganck dock, a tidal dock just opposite the Galgeschoor, became operational. The Natuurpunt 'Schorrenwerkgroep' started to monitor the marsh edge dynamics just opposite the dock opening, where container vessels have to take a wide bent before they enter the dock. The purpose was to assess possible effects of increased wave climate on the nature reserve, an aspect not fully considered in the EIA for the dock.

In view of the EIA for a potential second tidal dock near Doel, the Saeftinghe dock, the working group MONA LISA defined three research topics to fill in the knowledge gaps needed for this EIA. One of the topics was the influence of wave impact on tidal mudflat and marsh morphology of the Galgeschoor and the relative influence of wind and ship induced waves. This was studied by INBO (Research Institute for Nature and Forest), and FHR (Flanders Hydraulics Research) commissioned by the Port of Antwerp.

The conclusion of this study was that increased hydrodynamics in front of the tidal marsh edge facing Deurganck dock since 1990 coincided with subtidal and intertidal morphological changes, yet no direct link or causality with waves or ship movements could be found.

On the mudflats correlations were found between wave height and sedimentation/ erosion, between maximum wind speed and wave height, ship passage and wave height, fetch and sedimentation/ erosion. However the limited dataset and the applied measuring method did not allow identifying the relative importance of wind and ship waves on morphologic changes. Moreover the study did not compare tidal currents and waves as morphodynamic drivers.

In the present study, also commissioned by the Port of Antwerp, the goal is to assess the (relative) importance of hydrodynamic stressors tidal current, wind and ship waves and the related morphological response of the Galgeschoor lower and higher tidal mudflats and marsh edge.

Summary

In spring 2016 the MSC shipping line activities were moved to Deurganck dock and in June 2016 the Kieldrecht Lock, connecting the latter dock to the Waaslandhaven, became operational. In the near future container handling capacity in the Port of Antwerp may be increased by the construction of a new tidal dock on the left bank of the river Scheldt.

The possible impact of increased shipping traffic on the tidal mudflats and marshes of the Galgeschoor, a protected area facing Deurganck dock is investigated. The relative importance of hydrodynamic stressors (tidal currents, wind and ship waves) is studied and the wave climate before and after the MSC relocation and opening of the Kieldrecht Lock is compared. The results can provide input for an environmental impact assessment of a new tidal dock.

MORPHODYNAMICS

The morphodynamic long term and short term evolution on the Galgeschoor is reconstructed with the integration of data from MONEOS ecotope mapping, NGO Natuurpunt and INBO marsh edge monitoring, MONA LISA cross shore profile data and specific monitoring on the same transects for this project.

Due to high morphodynamics at the Galgeschoor, soft bottom low **tidal mudflat ecotopes** evolved into middle tidal mudflats and into low tidal hard substrate zones in respectively 2012-2013 and 2015-2016. Tidal marsh ecotope areas, including glaux-vegetation, near the marsh edge seemed relatively stable.

Tidal marsh edge retreat clearly differed between the northern and southern transect with respectively long term retreat rates of 2.5 and 14.6 cm/year since 2010, respectively. Consequently the proportion of high solid old marsh area decreased. However, pioneer marsh vegetation seems to be establishing itself. Whether this will consolidate and develop into a tidal marsh or may only be an ephemeral event is not clear at this point.

Tidal flat-bed level changes were in general much more pronounced at the southern plots (order of magnitude 5 – 10 cm) than at the northern plots (<5 cm). This is likely due to differences in sediment type and sediment cohesion. Net bed level changes are difficult to infer from the data because of strong daily and seasonal variation. The southern transect was generally more dynamic showing larger seasonal and day-to-day variations. Also low tidal plots were much more dynamic than high tidal plots. The daily bed level fluctuations on the low tidal flat plots displayed a spring-neap tidal cycle signature (i.e. 14.77 days).

HYDRODYNAMICS

Maximum tidal current velocity on the low tidal flat varied between 0.3 m/s and 1.25 m/s. Maximum tidal current velocity at ebb was relatively constant over a neap-spring tide cycle. Maximum flood current however, was significantly related to tidal amplitude. Highest current velocities were invariably recorded during the flood phase near spring tide, hence the flood phase may be predominant in tidally-induced (eroding) morphodynamics. Less is known of current velocities at the high tidal flats, but the available data suggest current velocities are generally lower.

An averaged significant **wind wave** height of 0.06 to 0.07m was found. Above 10 m/s, wind speed positively affected wind wave height. At higher wind speed, significant wave height per tidal cycle increased to 0.2m (approx. 0.38m maximum wave height at the highest wind speeds

////////////////////////////////////

Nederlandse samenvatting

In 2016 verhuisden de activiteiten van MSC in de Antwerpse haven naar het Deurganckdok, én de Kieldrechtsluis die dit dok met de Waaslandhaven verbindt werd operationeel.

De bouw van een potentieel tweede getijdedok in de buurt van Doel is één van de bouwstenen van het Complex Project Extra Containercapaciteit Antwerpse haven (CP-ECA).

In deze studie wordt de mogelijke impact van toegenomen scheepvaart op de slikken en schorren van het natuurgebied Galgeschoor, tegenover het Deurganckdok, bestudeerd.

De relatieve impact van hydrodynamische stressoren (getij, wind en golven) wordt onderzocht. Tevens wordt het golfklimaat voor en na de verhuus van MSC en de opening van de Kieldrechtsluis vergeleken. De resultaten kunnen mogelijks input leveren voor een project MER van CP-ECA.

MORFODYNAMIEK

De morfologische evolutie van het Galgeschoor op korte en lange termijn wordt gereconstrueerd door integratie van MONEOS ecotopenkaarten, schorrandmetingen van INBO en Natuurpunt, MONA LISA en MONEOS-dwarse hoogteprofielen en specifieke metingen voor dit project langs diezelfde raaien.

De intense morfodynamiek op het Galgeschoor wordt duidelijk uit de omzetting van laag slik tot middelhoog slik in de periode 2012-2013 en tot lage harde substraat zones in 2015-2016. De totale schoroppervlakte nabij de schorrand (inclusief pionierende melkkruidvegetatie) veranderde nagenoeg niet.

De schorranderosie verschilt tussen de noordelijke en zuidelijke raai met respectievelijk gemiddelde erosiesnelheden van 2.5 en 14.6 cm/jaar sinds 2010. Het aandeel oud schorplateauvermindert dus maar anderzijds ontwikkelt zich ook pionierschor in de potentiële pionierzone. De vraag is hoe duurzaam deze ontwikkeling is.

Bodemhoogte-ontwikkelingen op het slik waren over het algemeen meer uitgesproken aan de zuidelijke raai (grootteorde 5-10 cm) vergeleken met de noordelijke raai (<5 cm). Dit houdt mogelijk verband met verschillen in sedimentcohesie (want verschillen in de samenstelling van het sediment) tussen beide locaties. Netto bodemhoogte wijzigingen zijn moeilijk te duiden uit de gegevens omdat er sterk interfererende dagelijkse en seizoensgebonden schommelingen zijn. Algemeen is het zuidelijk transect meer dynamisch en vertoont het meer uitgesproken korte termijn schommelingen. Ook zijn de lage slikken algemeen meer dynamisch in vergelijking met de hoge slikken. De kortetermijschommelingen op het laag slik vertonen een duidelijke springtij-doodtij variatie (i.e. 14.77 dagen).

HYDRODYNAMIEK

Maximale stroomsnelheid op het laag slik varieert tussen 0.3 m/s en 1.25 m/s. De maximale ebsnelheid is redelijk constant over springtij-doodtij maar de maximale vloednelheid is significant gecorreleerd met de getijamplitude en dus de springtij-doodtij cyclus: de grootste stroomsnelheden worden telkens tijdens springvloed gemeten. Vloed is dus logischerwijze de belangrijkste getijfase voor wat betreft getij-geïnduceerde morfodynamiek. Er zijn minder data over stroomsnelheden op hoog slik, maar de weinige die er zijn suggereren alvast dat die over het algemeen lager zijn.

////////////////////////////////////

Het aantal scheepsgolven ter hoogte van het Galgeschoor nam recent toe door de ingebruikname van de Kieldrechtsluis en de verhuis van MsC, maar het is voorlopig niet mogelijk om een uitspraak te doen het relatieve belang hiervan aan schorerosie, in vergelijking met windgolven of getijstromingen.

////////////////////////////////////

Table of contents

Preface	2
Summary	3
Nederlandse samenvatting	6
List of figures	11
List of tables	16
1 Introduction	1
2 Description and history of the study site and the research stations.....	3
2.1 Description and history of the study site	3
Historical changes on planimetry including riprap (1940 – 2010).....	4
Morphological changes around the study area (2010 – 2016)	6
Intertidal cross-shore profiles (2008 – 2017)	8
Tidal marsh edge measurements (2006 – 2017)	10
2.2 Research stations for this study (2015 – 2017): transects GSb (N) and GSc (s).....	12
Measurements performed at the transects.....	13
3 Morphodynamics.....	15
3.1 Long-term morphodynamics	15
3.1.1 Ecotope evolution	15
3.1.2 Horizontal morphological changes.....	17
3.1.3 Vertical morphological changes	19
3.2 Short-term detailed morphodynamics.....	21
3.2.1 Horizontal changes: tidal marsh edge retreat	21
3.2.2 Vertical morphological changes	22
Vertical morphological tidal flat changes along the cross shore profiles	22
Vertical morphological changes at the low and high tidal flat stations	24
Location dependent cohesion characteristics of the upper sediment layer	26
Periodicity in detrended morphological data at the tidal flat stations	27
3.3 Conclusions on morphodynamics	29
4 Hydrodynamics	31
4.1 Tidal currents on the low tidal mudflat.....	31
4.2 Wind wave regime	34
4.2.1 Long-term wind regime.....	34
4.2.2 Fetch length	36
4.2.3 Short-term wind and wind wave regime (October 2015 and 2016).....	36
1.1.1.1.1 4.2.3.1 (Wind) wave regime per tidal cycle.....	37
1.1.1.1.2 4.2.3.2. Wind wave regime per 10 min. periods of no ship passages	39
1.1.1.1.3 Wave amplification and attenuation of wind waves.....	40
4.3 Ship wave regime	42
4.3.1 Ship traffic.....	42
4.3.2 Ship waves.....	43
Primary waves 44	
Secondary waves.....	46
Wave attenuation of secondary ship waves	51
4.4 Comparing wind and ship wave height between low and high tidal flat	52
4.5 Conclusions on hydrodynamics	54
5 Relationship between hydro- and morphodynamics	55
5.1 General observations	55
5.2 Where and under which circumstances is the wave climate dominant to tidal currents?	57
5.3 Relation between hydrodynamics and potential morphological changes	58
5.4 Where is tidal regime dominant in the morphological changes?.....	62

////////////////////////////////////

List of figures

Figure 1.1 Aerial photograph of the Galgeschoor in the inner bend of the Scheldt (© Vildaphoto-Yves Adams)	2
Figure 2.1 Overview of the location of the Scheldt Estuary (a) within Europe, (b) over the stretch from Antwerp to the North Sea and (c) of the study area. Locations of the Galgeschoor (hatched area), the two monitoring transects (white lines) of the Deurganck dock (S-GSc) and a plan scenario location for a new tidal dock (Saeftinghe dok –N-GSb), the gauge stations used for additional field data collection are displayed, the shipping channel are indicated and corresponding wind fetch for the main wind directions per measurement transect are also displayed	3
Figure 2.2 Boundary between the marsh and tidal flats at Galgeschoor with the presence of the riprap ridge.....	4
Figure 2.3(A) Map showing declining tidal marsh area of Galgeschoor over time (B) Long-term cumulative marsh edge erosion (m) with indication of direct impact measures.	4
Figure 2.4 Absolute height range of the rip rap zone (mTAW) at Galgeschoor from south (left) to north (right)	5
Figure 2.5 (a) Digital Elevation Model (DEM) of Galgeschoor area in 2016 based on a multibeam and lidar data (elevation unit meter T.A.W.), dashed polygon is dredging area of Frederick, white line is fairway, 0m TAW is the low water mark (b) Consistent erosion/sedimentation map based on the yearly DEM difference classification map between 2011 and 2016 (% of 5 maps see Figure 2-6)	6
Figure 2.6 Yearly Digital Elevation Model (DEM) difference classification map of Galgeschoor area between 2011 and 2016 (except of 2012) supplemented with the DEM difference classification map of the total period 2016-2011 (all DEM data provided by Maritime Access Division), high erosion/deepening in 2009-2010 is an effect of the 3th deepening of the navigation channel, high sedimentation is a response (f.e. on the left river bank and inner bend at GSc).	7
Figure 2.7 Topographical changes at the intertidal cross shore profiles of the Galgeschoor (A-E, GSa-d & LH). Since 6/2010 for GSa, GSb, GSc and since 5/2008 (before the channel deepening) for GSd and LH)	10
Figure 2.8 Tidal marsh edge retreat at erosion tongues near the Southern cross shore profile location (GSc) in the period 5/2006 -9/2017 (data Natuurpunt Schorrenwerkgroep, www.scheldeschorren.be/wp/studie-en-monitoring).....	10
Figure 2.9 Tidal marsh edge retreat measurement locations of the vertical pins of Natuurpunt and the horizontal erosion pins of this campaign at the Southern cross shore profile location (GSc) in the period 2004, 2013 and 2016.....	11
Figure 2.10 Detailed measurements of the tidal marsh edge near the Galgeschoor central cross shore profile location (GSd, data Hug Van Beek-Natuurpunt); local reference points is measured with a RTK-GPS	11
Figure 2.11 Topographic profiles of (top) the northern (GSb) transect and (bottom) the southern (GSc) transect. These profiles were processed using elevation data recorded with the help of a RTK GPS on November 3 rd 2015 (at the start of the 2015 intensive measurement campaign). The displayed experimental set-up corresponds to that during the 2016 intensive campaign (see Kolokythas et al. (2016), Belliard & Temmerman (2017) and Levy (2017))......	13
Figure 3.1 Ecotope evolution in the marsh edge zone of Galgeschoor and Tidal marsh edge erosion at erosion tongues at the Southern cross shore profile location (GSc) in the period 5/2010 -9/2017)	15
Figure 3.2 Evolution of the tidal marsh in summer at the northern cross shore profile location (GSb) in the period 9/2003 -7/2016).....	16

////////////////////////////////////

Figure 3.3 False-colour images at summer conditions showing evolution of the tidal marsh at the Southern cross shore profile location (GSc) in the period 9/2003 -7/2016 17

Figure 3.4 True colour areal image at winter conditions of high tidal flat and pioneer zone with increasing cover of *Vaucheria* and *Glaux maritima* (darker zones between the rip rap and marsh cliff)..... 17

Figure 3.5 Tidal marsh edge retreat (horizontal erosion, cm + SE) at the Northern and Southern cross shore profile location in the period 5/2010 -9/2017, rectangle focuses on the study period 18

Figure 3.6 Mean elevation changes at the SEB in absolute values (m T.A.W.) in the **tidal marsh** of the northern transect (GSb1, red) and the southern transect (GSc1) in the period 5/2010 -3/2017. The SEB locations are presented in Figure 2-11. 19

Figure 3.7. Elevation changes along the northern and southern cross shore profile (GSb &c) on the **tidal mud flat** in the period 5/2010 -3/2017 20

Figure 3.8. Total volume changes along the northern and southern cross shore profile (GSb &GSc) on the **tidal mud flat** in the period 5/2010 -3/2017 20

Figure 3.9. Tidal marsh edge retreat at A) the Northern and B) Southern cross shore profile location in the period 10/2015 -9/2017) 21

Figure 3.10. A) Picture of the marsh edge at the Southern transect B) the horizontal pin in the marsh edge which has retreated 20cm in the period 10/2015 -9/2017) 22

Figure 3.11. Temporal evolution of bed level changes relative to t_0 at the Northern (GSb) and Southern cross shore profile (GSc) in the study period 11/2015 -7/ 2017 23

Figure 3.12. Temporal evolution of sediment volume changes relative to t_0 at the Northern (GSb) and Southern cross shore profile (GSc) in the study period 11/2015 -7/ 2017 24

Figure 3.13. Temporal evolution of SED-derived (grey lines) and monthly SEB-derived (blue dotted lines) bed level changes relative to t_0 (Δz_{t0}) recorded at the (a) northern high (NH-GSb2), (b) southern high (SH GSc2), (c) northern low (NL- GSb4) and (d) southern low (SL-GSb4) tidal flat measurement stations during the long-term campaign (i.e. from October 29 2015 to May 11 2017). The absence of bed level data at NH at the beginning of the field campaign was due to a technical failure of the corresponding SED sensor. Every SED-derived bed level change time series was smoothed out using a weighted moving average with a Gaussian window of 1 month (black lines). Time evolution of monthly SEB-derived bed level changes monitored at NH – GSb2 and SH – GSc2 as part of a previous field campaign from June 2010 to June 2011 (red dotted lines) are displayed for comparison. For all data series, negative values represent net erosion and positive values represent net deposition. Note that the corresponding SEB plot and SED sensor were deployed at the same exact location at site SL, while at the other sites, the respective SEB plot and SED sensor were placed a few meters apart. 25

Figure 3.14. Photo sequence of SEB plot on the high tidal flat of (a) the northern transect and (b) the southern transect between December 2016 and January 2017 on moments of a changing bed level trend..... 25

Figure 3.15. Temporal evolution of the median grain size diameter d_{50} of the upper 2cm in sediment samples collected monthly *at the tidal marsh* (GSb1 and GSc1) and *high* (NH-GSb2 and SH-GSc2) *tidal flat* plots of the two measurement transects. Samples collect sediment from the upper 2cm. 26

Figure 3.16. Temporal evolution of the median sediment diameter d_{50} of sediment samples collected monthly at the northern high (NH-GSb2), northern low (NL-GSb4), southern high (SH-GSc2) and southern low (SL-GSc4) tidal flat measurement stations. Sediment samples were collected up to a depth of 2 cm from the surface. Sediment grain size was determined using LDPSA. The dash line $d_{50} = 63 \mu\text{m}$ defines the limit between cohesive and non-cohesive sediments based on the grain size distribution. 26

Figure 3.17 Lomb-Scargle power spectral density (PSD) of the detrended bed level changes recorded at the (a) northern high (NH, GSb2), (b) southern high (SH, GSc2), (c) northern low

/

(NL, GSb4) and (d) southern low (SL, GSc4) tidal flat measurement stations during the long-term campaign (i.e. from October 29 2015 to May 11 2017). Main frequency peaks occurred precisely at (a) $f = 0.068 \text{ days}^{-1}$ ($T = 14.74 \text{ days}$) for NH, (b) $f = 0.068 \text{ days}^{-1}$ ($T = 14.73 \text{ days}$) for SH, (c) $f = 0.067 \text{ days}^{-1}$ ($T = 14.76 \text{ days}$) for NL and (d) $f = 0.068 \text{ days}^{-1}$ ($T = 14.73 \text{ days}$) for SL.....	27
Figure 3.18 Wavelet power spectrum of the detrended bed level changes recorded at the (a) northern low (NL) and (b) southern low (SL) tidal flat measurement stations during the long-term campaign (i.e. from October 29 2015 to May 11 2017), and supplemented with corresponding time series of detrended bed level changes at the low tidal flat plots (c) NL-GSb4 and (d) SL-GSc4.	28
Figure 4.1: Relation between tidal range [m] and maximum flow velocities [m/s] at the low plot of the northern transect (left) and southern transect (right) in the flood phase. Values from 2015 are indicated in red, values from 2016 are indicated in blue	31
Figure 4.2: Relation between tidal range [m] and maximum flow velocities [m/s] at the low plot of the northern transect (left) and southern transect (right) in the ebb phase. Values from 2015 are indicated in red, values from 2016 are indicated in blue.	31
Figure 4.3 Velocity measurements with ADCP (solid line) and ADV (dashed line) on the lower tidal flat and measurements at Meetpaal Lillo (dotted line). The vertical line indicates the moment of high water at Liefkenshoek. The shown ADV measurements are averaged values over 1 minute.	32
Figure 4.4: Water level above the ADCP measurements (top). Depth-averaged flow velocities on the low tidal flat (GSc4) for both the northern and southern transect at the intensive campaign of 2015, together with flow measurement near the navigation channel at Meetpaal Lillo	33
Figure 4.5 Wind rose with directional bins of 5° , along with several wind speed ranges for period of October 2015 to February 2017.	34
Figure 4.6 Seasonal wind roses with directional bins of 5° , along with several wind speed ranges for every season between October 2015 to February 2017.	35
Figure 4.7 a) Map with fetch length to the two research stations, b) total fetch length at bank full conditions at the northern (GSb) and southern transect (GSc)	36
Figure 4.8 Overview of the wind conditions during the intensive measurement campaign of 2015 (left) and 2016 (right)	37
Figure 4.9 Calculated significant wave height [m] per tidal cycle in relation to averaged wind velocity [m/s] at the northern transect (a) the low plot GSb4 and (b) the high plot GSb2.	39
Figure 4.10 Averaged wind direction [$^\circ$] for wind velocities [m/s] higher than 10 m/s.....	39
Figure 4.11 Calculated significant wave height [m] in relation to averaged wind velocity [m/s] at GSb4 in periods of no ship passages	40
Figure 4.12: Calculated significant wave height [m] in relation to averaged wind velocity [m/s] at (a) low tidal flat GSc4 and (b) high tidal flat GSc2 in periods of no ship passages	40
Figure 4.13: Comparison of wind waves (maximum, $H_{\max}$, and significant, $H_{1/3}$, wave heights), recorded at the high (GSb2 and GSc2) and low (GSb4 and GSc4) tidal flat plots for the respective Northern (GSb) and Southern (GSc) transects for the measurement campaigns of November 2015 and November 2016. The boxes represent the interquartile range of the data	41
Figure 4.14 Time series of daily ship passages at the Deurganck dock (GSc) entry line from November 2015 to January 2017. The red dots depicts all local minima.	42
Figure 4.15 Temporal evolution of monthly ship traffic differentiated by ship type that crossed the Deurganck dock (GSc) entry line from the period of November 2015 to January 2017. Each bar is supplemented with the corresponding number of ship passages. Only passing ships with speed > 2.5 knots have been considered similar to Kolokythas et al. (2016) and Levy et al. (2017).	42

////////////////////////////////////

Figure 4.16 (a) Typical ship wave pattern for a heavy trimmed displacement ship consisting of a primary wave and a secondary wave pattern (De Roo, 2013, p. 51); (b) An example of a registered ship wave in the first intensive campaign November 2015.	43
Figure 4.17 Maximum wave height (primary) versus ship speed & length, distance from the measuring gauge, and water level for the selected ship events at NL-GSb4 (north) location in 2016	44
Figure 4.18 Maximum wave height (primary) versus ship speed & length, distance from the measuring gauge, and water level for the selected ship events at NL-GSb4 (north) location in 2015.....	45
Figure 4.19 Maximum wave height (primary) versus ship speed & length, distance from the measuring gauge, and water level for the selected ship events at SL- GSc4 (south) location in 2016.....	45
Figure 4.20 Maximum wave height (primary) versus ship speed & length, distance from the measuring gauge, and water level for the selected ship events at SL- GSc4 (south) location in 2015.....	46
Figure 4.21 Secondary wave height versus sailing speed, ship length, distance from the measuring gauge, and water depths for the selected inland ship events at the northern low tidal flat NL- GSb4 in 2016	47
Figure 4.22 Secondary wave height versus sailing speed, ship length, distance from the measuring gauge, and water depths for the selected inland ship events at the northern low tidal flat NL-GSb4 in 2015	47
Figure 4.23 Secondary wave height versus sailing speed, ship length, distance from the measuring gauge, and water depths for the selected inland ship events at the southern low tidal flat SL-GSc4 in 2015.....	48
Figure 4.24 Secondary wave height versus ship speed & length, distance from the measuring gauge, and water level for the selected seagoing ship events at NL- GSb4 (north) location in 2016	49
Figure 4.25 Secondary wave height versus ship speed & length, distance from the measuring gauge, and water level for the selected seagoing ship events at NL-GSb4 (north) location in 2015	49
Figure 4.26 Secondary wave height versus ship speed & length, distance from the measuring gauge, and water level for the selected seagoing ship events at SL-GSc4 (south) location in 2016	50
Figure 4.27 Comparison of (top) maximum secondary ship wave heights and (bottom) significant ship wave heights recorded at the high (GSb2 and GSc2) and low (GSb4 and GSc4) tidal flat plots for the Northern (GSb) and Southern (GSc) transects for the measurement campaigns of November 2015 and November 2016. The boxes represent the interquartile range of the data and the whiskers delimit 1.5 times the interquartile range. The horizontal line indicates the median and crosses indicate outliers.	51
Figure 4.28 (a) Maximum (H_{max}) and (b) significant (H_s) wave heights for single ship and wind waves recorded commonly at the low (GSc4) and high (GSc2) tidal flat plots of the Southern transect . Wind waves are differentiated by the corresponding wind speed recorded during the detection of the “no-ship” event. The dashed lines indicate where $x=y$	52
Figure 4.29 (a) Maximum (H_{max}) and b) significant (H_s) wave heights for single ship and wind waves recorded commonly at the low (GSb4) and high (GSb2) tidal flat plots of the Northern transect. Wind waves are differentiated by the corresponding wind speed recorded during the detection of the “no-ship” event. The dashed lines indicate where $x=y$	53
Figure 5.1 Temporal evolution of (a) daily-averaged wind speed W_s and direction W_{dir} , (b) tidally-maximum wave heights H_{max} , (c) tidally-significant wave height H_s , (d) water depth at high tide h_{max} , (e) tidally-averaged SSC and (f) bed level changes $[\Delta z]_{t0}$ from October 29, 2015 to January 17, 2017 (for clarity purpose all time series were displayed until January	

List of tables

Table 2.1 Overview of the coordinates and elevations of the different plots for the two measurement transects recorded by a Real Time Kinematic Global Positioning System (RTK-GPS). Coordinates are given in WGS 1984. Note that elevations of the plots located in the tidal flats were recorded at the start of each of the two intensive campaigns, i.e. in November 2015 and November 2016.....	12
Table 2.2 Summary table of the measured variables/parameters during the measurement campaign. NIOZ: Netherlands Institute of Sea Research; INBO: Research Institute for Nature and Forest; UA: University of Antwerp; FHR: Flanders Hydraulics Research; HA: Antwerp Port Authority; SRK = Schelde Radar Keten.	14
Table 3.1 Net area change of tidal flat and marsh ecotopes near the marsh edge of Galgeschoor since 2010	16
Table 4.1 Overview of the slopes and the coefficient of determination of the linear relationships ($y = ax+b$) between the tidal range and maximum depth-averaged velocities in 2015 and 2016 for both transects.....	32
Table 4.2 Overview of the minimum, mean and maximum ebb and flood peak velocities of the ADV near the ground and ADCP with depth-average flow velocities (m/s) at the Northern and Southern transect at the intensive campaign of 2015 (<i>italic</i>) and 2016.	33
Table 4.4 Overview of mean and SD of the significant wave heights for periods without ship traffic, calculated per tide and averaged over all tides, for the different measurement locations.	38
Table 4.5 Relative velocities [%] of ships passing at southern location (GS _c) versus the northern location (GS _b) for three types of ships.....	43
Table 5.1 Correlation analyses between deseasonalized bed level changes $[\Delta z]_{t0}$ and corresponding forcing factors recorded at the Southern high (GS _{c2}) and low (GS _{c4}) tidal flat plots during the long-term campaign. H _s = significant wave height; H _{max} = maximum wave height; H _{rel} = relative wave height; D = water depth at high tide; C: suspended sediment concentration recorded at the Lillo measurement pole located in the estuarine channel in the proximity of the tidal flat of Galgeschoor. ρ = Spearman's rank correlation; r = Pearson product moment correlation. Significant correlations ($p < 0.05$) are underlined.	62

////////////////////////////////////

Shipping traffic movements in the port of Antwerp changed in 2016 due to the transfer of the MSC shipping company activities to the Deurganck dock (April- May 2016) and the commissioning of the Kieldrechtlock which connects the latter dock to the Waaslandhaven (June 2016). Overall, the number of seagoing vessels decreased in the port of Antwerp in recent times, yet at the same time more freight is shipped due to increasing vessel size. A possible future scenario for the realisation of extra container handling capacity is the construction of a new tidal dock at the left bank of the river Scheldt. This economic development may induce environmental impacts. In particular, the protected nature reserve of Galgeschoor which lies within the port of Antwerp area may experience changes in hydrodynamic exposure as a result of the expected increase in ship-induced wave climate intensity. For this reason, a study was initiated by the Antwerp Port Authority with the aim to assess the morphological response of the tidal flats and marsh edge of Galgeschoor, with respect to effects of tidal currents, ship and wind waves on sedimentation-erosion dynamics.

The project, carried out by INBO (Research Institute for Nature and Forest), UA (University of Antwerp), FHR (Flanders Hydraulics Research) and NIOZ (Royal Netherlands Institute for Sea Research) comprises a long-term measurement campaign that took place from November 2015 to May 2017 intersected with two intensive one-month measurement campaigns in November 2015 and November 2016 respectively (i.e. before and after the opening of the Kieldrecht Lock). The long-term measurement campaign investigated the morphological evolution of the tidal flats of the Galgeschoor and attempted to elucidate potential internal and/or external controls. Results and findings based on the analysis of the long-term measurement campaign are reported in Silinski et al. (2016) and Beillard et al. (2017). The intensive campaigns focused on a range of measurements including current velocities, water levels and wave climate. It also aimed at differentiating ship and wind wave characteristics and their relative importance. The findings and conclusions for these intensive campaigns are reported in Kolokythas et al. (2016) and Levy et al. (2017) respectively. A synthesis of all results and findings as well as reflection in time and space are documented in this report.

Chapter 1 is the introduction, chapter 2 describes the Galgeschoor, including its history and the measuring set up, chapter 3 focuses on the morphodynamic measurements for this study as well as earlier data from the previous Galgeschoor projects, chapter 4 contains the analysis of wind and ship wave measurements and tidal current measurements. In chapter 5 the relation is made between the morpho- and hydrodynamic measurements in the study. Chapter 6 and 7 contain the discussion and conclusions.

2 DESCRIPTION AND HISTORY OF THE STUDY SITE AND THE RESEARCH STATIONS

2.1 DESCRIPTION AND HISTORY OF THE STUDY SITE

The Galgeschoor nature reserve is located on the right bank of the lower Sea Scheldt, within the brackish zone of the Scheldt Estuary, between the village of Lillo and the Europaterminal (Figure 2-1). On the left bank of the Scheldt, directly opposite from the Galgeschoor, lies the Deurganck dock (S-GSc) as well as a plan scenario location for a potential new tidal dock (Saeftinghe dock – N -GSb).

The Galgeschoor is a wetland area (46 ha) of tidal flats and marshes protected by national and international legislative and policy frameworks (Nature reserve, Natura 2000, Habitats and Birds directives, Ramsar convention). The boundary between the marshes and flats is at most places formed by a cliff with a height of up to 50cm. *Phragmites australis* is the dominant plant species present on the marsh. The tidal flat extends seaward from the marsh edge where a riprap ridge first covers an elevation gradient of up to 4 m locally (Figure 2-4) to stabilize a steep slope, followed by a gentle slope toward the low water line.

Figure 2.1 Overview of the location of the Scheldt Estuary (a) within Europe, (b) over the stretch from Antwerp to the North Sea and (c) of the study area. Locations of the Galgeschoor (hatched area), the two monitoring transects (white lines) of the Deurganck dock (S-GSc) and a plan scenario location for a new tidal dock (Saeftinghe dok –N-GSb), the gauge stations

////////////////////////////////////

on the higher tidal mudflat and marsh edge. The vertical dashed lines indicate the southern and northern transects of current study. The lower riprap range at the Southern transect may lead to a higher erosion vulnerability. In 2005 the tidal Deurganck dock was opened on the opposite site of the river.

Figure 2.4 Absolute height range of the rip rap zone (mTAW) at Galgeschoor from south (left) to north (right)

Morphological changes around the study area (2010 – 2016)

The subtidal area adjacent to the Galgeschoor is morphologically heavily managed due to the nearby presence of the sandbar of Frederick at the merging of a restricted flood channel and the main ebb channel (Figure 2-5 A). Guaranteed safe port access for larger ships requires continuous dredging in the maritime access routes in the lower Sea Scheldt. The yearly maintenance dredging volumes for the nearby sandbar fluctuate around 300.000 m³. Between July 2009 and July 2010 an additional 2.5 mm³ of sand was dredged to deepen and widen the navigation channel locally (Figure 2-5 A).

After this deepening and widening the river reacts in search of a new morphological equilibrium. A consistency map of erosion/sedimentation between 2011-2016 (Figure 2-5 B) shows a continuous sedimentation on the tidal mudflats (>0m T.A.W.) and shallow water zones on the left bank of the river and in front of the southern end of the Galgeschoor on the right bank. In front of the remainder of the Galgeschoor to the north, the river bed has mainly eroded.

Figure 2.5 (a) Digital Elevation Model (DEM) of Galgeschoor area in 2016 based on a multibeam and lidar data (elevation unit meter T.A.W.), dashed polygon is dredging area of Frederick, white line is fairway, 0m TAW is the low water mark (b) Consistent erosion/sedimentation map based on the yearly DEM difference classification map between 2011 and 2016 (% of 5 maps see Figure 2-6)

The Galgeschoor shows a downstream-upstream gradient towards a wider tidal marsh and decreasing riprap range and tidal flat slopes that decreases in upstream direction towards the inner river bend. A typical tidal flat at present extends riverward from the marsh edge where a riprap ridge first covers an elevation gradient of up to 2 m locally to stabilize a steep slope, followed by a gentle slope towards the lower mudflat zones (Figure 2-7 A-E).

////////////////////////////////////

Since 2006 NGO working group ‘Natuurpunt Schorrenwerkgroep’ measures the marsh edge retreat near the southern transect (GSc) of Galgeschoor using vertical pins. These pins are located within 4 so-called erosion tongues, and showed that these erosion tongues further eroded nearly 45 cm inwards within 10 years (Figure 2.8); a retreat rate of 3.9 cm per year.

2.2 RESEARCH STATIONS FOR THIS STUDY (2015 – 2017): TRANSECTS GSB (N) AND GSC (S)

Of the above shown cross shore profiles, two were selected for this study: a northern transect GSb (Figure 2-3 top), in the fetch of the potential location for a new tidal dock (Saeftinghe dock –SDK or GSb) (see also Figure 2-1) and a southern transect called DGK or GSc (Figure 2-3 bottom), in the fetch of the Deurganck dock (see also Figure 2-1). These two transects are similar to those already mentioned in Verelst et al. (2011 & 2012), Michels et al. (2012), Silinski & Temmerman (2016), Kolokythas et al. (2016), Belliard & Temmerman (2017) and Levy (2017). The location of these transects was chosen in order to (i) analyse the effect of the evolution of ship traffic near the Deurganck dock after the opening of the Kieldrecht lock on wave climate intensity and (ii) collect information as a reference situation near the location of the planned Saeftinghe dock. Additionally, these two locations allow gaining insights into differences between ship wave and wind wave characteristics. These transects cover an elevation gradient of about 5 m, extending from approximately 0.5 m TAW on the low tidal flat to about 5.5 m TAW on top of the cliffed marsh edge, although slight elevation changes may occur between years (see Table 2-1).

Table 2.1 Overview of the coordinates and elevations of the different plots for the two measurement transects recorded by a Real Time Kinematic Global Positioning System (RTK-GPS). Coordinates are given in WGS 1984. Note that elevations of the plots located in the tidal flats were recorded at the start of each of the two intensive campaigns, i.e. in November 2015 and November 2016.

Transect	Location	Plot ID	Latitude (°N)	Longitude (°E)	Elevation (m TAW)	
					Nov. 2015	Nov. 2016
North (GSb)	Marsh	GSb1	51.318087944	4.282887075	5.50	-
	High flat	GSb2	51.318101220	4.282651453	5.00	5.00
	Middle flat	GSb3	51.318149699	4.281687978	1.20	-
	Low flat	GSb4	51.318193706	4.280844119	0.57	0.56
South (GSc)	Marsh	GSc1	51.309393794	4.283916865	5.69	-
	High flat	GSc2	51.309330421	4.283657855	4.69	4.66
	Middle flat	GSc3	51.309058105	4.282691246	2.69	2.57
	Low flat	GSc4	-	-	1.11	1.11

////////////////////////////////////

Table 2.2 Summary table of the measured variables/parameters during the measurement campaign. NIOZ: Netherlands Institute of Sea Research; INBO: Research Institute for Nature and Forest; UA: University of Antwerp; FHR: Flanders Hydraulics Research; HA: Antwerp Port Authority; SRK = Schelde Radar Keten.

Measurement	Responsible	Location	Duration	Frequency	Measurement principle	Comments
Horizontal changes of the marsh edge	INBO	GSb transect GSc transect	5/2010 – 9/2017	1 month (1 year)	Erosion pins	Deployed at low, middle, high tidal flat and marsh plots
Elevation changes	INBO	GSb transect GSc transect	5/2010 – 9/2017	1 month (1 year)	SEB	Deployed at low, middle, high tidal flat and marsh plots
Elevation changes	INBO	GSb transect GSc transect	5/2010 – 9/2017	1 month (1 year)	RTK GPS measurements	Cross-shore profiles
Elevation changes	NIOZ	GSb transect GSc transect	11/2015 – 05/2017	1 day	SED sensors (Phototransistors)	Deployed at low and high tidal flat plots
Sediment characteristics	INBO	GSb transect GSc transect	11/2015 – 01/2017	1 month	Sediment samples	Performed at all tidal flat and marsh plots
Waves	UA	GSc transect	11/2015 – 05/2017	16 Hz	Pressure transducers (PDCR 1830)	Deployed at GSc4 and GSc2
Waves	FHR	GSb transect GSc transect	11/2015 ; 11/2016	20 Hz	Pressure transducers (OSSI-010-003B/C)	Deployed at GSb4, GSc4 and GSc3
Water velocities	UA INBO	GSb transect GSc transect	11/2016	1 month	Point velocity measurements (ADV)	Performed at both high tidal flat plots
Water velocities	FHR	GSb transect GSc transect	11/2016	1 month	Profile velocity measurements (ADCP)	Performed at both low tidal flat plots
Turbidity	UA INBO	GSc transect	11/2016	1 month	LISST OBS	Deployed at GSc4 and GSc2
Wind	HA	Zandvliet	11/2015 – 01/2017	1 min		10 m above ground level
Water level	FHR	Zandvliet Liefkenshoek	11/2015 – 05/2017	1 min	Radar (OTT-RLS)	MONEOS
Ship traffic	SRK	Region of Galgeschoor	11/2015 – 01/2017	Ship dependent		GSb and GSc transects define entry lines for ship passages
Turbidity	FHR	Lillo	11/2015 – 01/2017	10 min	Aanderaa Seaguard	MONEOS

////////////////////////////////////

Table 3.1 Net area change of tidal flat and marsh ecotopes near the marsh edge of Galgeschoor since 2010

Ecotope		To reference 2010 (ha)				
		2012	2013	2014	2015	2016
tidal flat	natural hard substrate tidal flat	-0.2	+0.7	+1.0	+0.6	+5.0
	low tidal mudflat	+1.0	-2.7	-3.1	-2.4	-6.7
	middle tidal mudflat	-0.6	+3.5	+4.6	+3.1	+2.7
	high tidal mudflat	+0.5	+0.5	+0.5	+0.6	+0.7
	potential pioneer zone	-0.6	-0.8	-0.7	-0.9	-0.9
Marsh	tidal marsh edge	+0.1	+0.6	+0.6	+0.7	+0.6

Figure 3.2 Evolution of the tidal marsh in summer at the northern cross shore profile location (GSb) in the period 9/2003 -7/2016)

Figure 3.3 False-colour images at summer conditions showing evolution of the tidal marsh at the Southern cross shore profile location (GSc) in the period 9/2003 -7/2016

Especially at the northern plot, since 2011 an increasing abundance (Figure 3.4) of *Vaucheria* and the higher plant pioneer vegetation *Glaux maritima* in front of the marsh cliff can be found.

Figure 3.4 True colour areal image at winter conditions of high tidal flat and pioneer zone with increasing cover of *Vaucheria* and *Glaux maritima* (darker zones between the rip rap and marsh cliff)

3.1.2 Horizontal morphological changes

In 2010 INBO started to monitor the tidal marsh edge retreat with horizontal pins at 5 random locations for both the southern and northern transect (Michels et al. 2012). A difference in retreat rate between the transects (Figure 3.5) was found. A low retreat rate of 2.5cm/ year occurred at the northern transect while at the southern transect the marsh edge retreats with 14.6cm/year. Marsh edge retreat is a discontinuous process: the period of strongest erosion occurred in the first 2 years (2010 – 2012) with a retreat rate of 31.7cm/year. In the last 2 years with the commissioning of Kieldrechtlock the retreat rate has slow down to less than a cm per year.

////////////////////////////////////

Figure 3.5 Tidal marsh edge retreat (horizontal erosion, cm + SE) at the Northern and Southern cross shore profile location in the period 5/2010 -9/2017, rectangle focuses on the study period

Also vertical changes differ between the southern and northern transect. In general tidal marshes raise similar to the rise of the mean high water level. In a period of mean high water raise of nearly 3cm, the mean elevation of the marsh at the northern GSb1 increased parallel with 2.25cm. This in contrast with the tidal marsh plot at the southern GSc1 which increased with 4.7cm between June 2010 and July 2017. Based on these SEB (sedimentation erosion bars) measurement locations in the old *tidal marsh plateau*, mean raising rate at the southern transect (GSc1, 2.26cm/year) is since 2010 two times higher than the northern transect (GSb1, 1.2cm/year). A higher sedimentation rate can result in a higher marsh plateau and marsh cliff which is more vulnerable for erosion in the southern versus the northern location. .

The mudflat zones beneath the riprap zone shows at the northern transect (GSb, Figure 3.7) mainly an eroding trend, while the southern transect shows a trend of sedimentation which amplifies downwards along the profile from middle to the low water zone. Conversely the high tidal flats above the riprap zone increases of the northern transect increases while the high tidal flat of the southern transect fluctuates around zero. In 2016 the only change in trend is the middle tidal flat that starts to increase again after a period of slight decrease.

Location dependent cohesion characteristics of the upper sediment layer

In the tidal marsh plot the median grain size throughout the long-term campaign is lower than $63\mu\text{m}$ (Figure 3.15) which classifies it as fine silt, a rather cohesive sediment-type². The median grain size of the upper 2cm sediment layer is higher, thus including more sand, at the southern marsh plot (GSc1) than at the northern marsh plot (GSb1). Sediment composition at the high tidal flat (GSb2 and GSc2) is very similar to that of the marsh at the northern plot while at the southern plot it is more variable, sometimes finer and at other times coarser.

Figure 3.15. Temporal evolution of the median grain size diameter d_{50} of the upper 2cm in sediment samples collected monthly at the tidal marsh (GSb1 and GSc1) and high (NH-GSb2 and SH-GSc2) tidal flat plots of the two measurement transects. Samples collect sediment from the upper 2cm.

In the tidal flat plots (Figure 3.16), the mud fraction (i.e. $d < 63\mu\text{m}$) at the GSb2, GSb4 and GSc2 accounts for more than 50 % of the total sediment composition throughout the long-term campaign, implicating that cohesion between sediment grains in these locations is rather important. Sediment composition at GSc4 on the other hand is characterized by a dominant sand (non-cohesive) fraction throughout the whole campaign. This is also reflected in the grain size distribution with the median sediment diameter at GSc4 being always above the threshold diameter $d_{50} = 63\mu\text{m}$ (Figure 3.16).

Figure 3.16. Temporal evolution of the median sediment diameter d_{50} of sediment samples collected monthly at the northern high (NH-GSb2), northern low (NL-GSb4), southern high (SH-GSc2) and southern low (SL-GSc4) tidal flat measurement

² The cohesiveness is above all determined by the percentage of clay in mud (with 5-10% of clay being the threshold above which the sediment starts to behave cohesively).

3.3 CONCLUSIONS ON MORPHODYNAMICS

The morphodynamics chapter starts with the general ecotone evolution, includes horizontal changes at the tidal marsh edge and focuses on vertical changes at the tidal flats on different time scales.

Due to high morphodynamics at the Galgeschoor the area of soft bottom low tidal mudflat **ecotopes** evolved to middle tidal mudflats in the period 2012-2013 and in low tidal hard substrate zones in the period 2015-2016. Tidal marsh ecotope areas near the marsh edge neighbourhood seem relatively stable.

Tidal marsh edge retreat clearly differs between the northern and southern transect with respectively long term retreat rates of 2.5 and 14.6 cm/ year since 2010 with the biggest losses before 2013. Consequently the proportion of high solid old marsh plateau area decreases. However in the same period pioneer marsh vegetation seems to establish along the marsh whether or not temporarily. In the last 2 years the retreat slowed down except for the most north erosion pin at the Southern transect near the Natuurpunt marsh retreat measurement points.

At the long term the northern transect the bed level of the high tidal flat tended to increase and traps small volumes of sediment while the tidal mudflat zones beneath the riprap decreased and lost sediment volume. The southern transect has shown an opposite trend with bed levels of lower mudflats increasing, trap large sediment volumes while the high tidal flat fluctuates around zero. The sediment trapping at the southern transect in the tend to slow down since 2014 and the net increase stopped since 2016 at the middle and high mudflat. At the northern transect only the middle tidal mudflat level trend changed since 2016 and started to increase.

In general, **bed level changes** at the southern plots were much more pronounced (order of magnitude 5 – 10cm) than those at the northern plots (<5cm), difference in sediment properties can be a reason. Both seasonal and day-to-day variation were clearly larger at the southern plots of Galgeschoor. This means that the southern transect was more dynamic. Further, low tidal plots were much more dynamic than high tidal plots. The seasonal variation at southern transect knows a period of sedimentation between spring and autumn while between autumn and spring mostly erosion takes place. The daily fluctuations in bed level in the low and less pronounced in the high tidal flat plots reveals a spring-neap tidal cycle signature (i.e. 14.77 days).

Page 30 of 93

(low) tidal flats of the Galgeschoor. In general, no clear (statistical) distinction can be made between the measured values for 2015 and 2016.

Figure 4.3 Velocity measurements with ADCP (solid line) and ADV (dashed line) on the lower tidal flat and measurements at Meetpaal Lillo (dotted line). The vertical line indicates the moment of high water at Liefkenshoek. The shown ADV measurements are averaged values over 1 minute.

Table 4.1 Overview of the slopes and the coefficient of determination of the linear relationships ($y = ax+b$) between the tidal range and maximum depth-averaged velocities in 2015 and 2016 for both transects.

	Northern transect		Southern transect	
	<i>Flood</i>	<i>Ebb</i>	<i>Flood</i>	<i>Ebb</i>
2015	0.329 (R ² = 0.81)	0.034 (R ² = 0.11)	0.276 (R ² = 0.86)	0.072 (R ² = 0.06)
2016	0.303 (R ² = 0.93)	0.025 (R ² = 0.06)	0.342 (R ² = 0.81)	0.058 (R ² = 0.24)

In addition to the ADCP measurements conducted at the low tidal flat, velocity measurements are also performed at the high tidal flat for this intensive campaign using Acoustic Doppler Velocimeters (ADV). Table 4.2 displays the mean, minimum and maximum ebb and flood peak velocities recorded throughout the current measurement campaign.

The maximum fetch lengths at the two transect at bank full conditions (Figure 4.7) strongly varies with wind direction. This is particularly the case when the wind comes from the direction of the very elongated dock. The northern transect experiences the longest fetch length with a maximum of 4.5 km between 200 and 210°. The longest fetch lengths at the southern transect occurs between S to SW and NW to WNW with a maximum at 220°. It should be noted also that the maximum fetch lengths have a very small directional angle, because of the (relative) small width of the dock. Furthermore, these fetch lengths in the dock have to be considered as an absolute maximum, as due to the high quay walls, the effective stretch length will be smaller.

For the different measurement campaigns, a clearly different wind field was observed (Figure 4.8). In October 2015, the wind was mainly coming from the south south-west and wind velocities higher than 9 m/s were frequently observed. In 2016, two dominant wind directions can be observed, namely from the east and from the southern direction, yet wind was blowing harder and more frequent from the south than from the west. Wind velocities were much smaller during the second measurement campaign (generally below 9 m/s).

m. Above wind speeds of 10 m/s, a clear increase can be observed in the $H_{1/3}$ values. The data of 2016 confirm this statement, albeit that the number of data points (tides with a high averaged wind speed) is limited. The maximum significant wave heights reach approx. 0.2 m at wind speeds in excess of 15m/s.

Table 4.3 Overview of mean and SD of the significant wave heights for periods without ship traffic, calculated per tide and averaged over all tides, for the different measurement locations.

Transect	Tidal flat zone	Location	H _{1/3} 2015	H _{1/3} 2016
Northern transect	high	GSb2	0.065 ± 0.03	0.062 ± 0.02
	low	GSb4	0.070 ± 0.03	
Southern transect	high	GSc2	0.079 ± 0.03	
	middle	GSc3	0.077 ± 0.03	0.069 ± 0.01
	low	GSc4	0.075 ± 0.03	0.067 ± 0.02

Figure 4.9 Calculated significant wave height [m] per tidal cycle in relation to averaged wind velocity [m/s] at the northern transect (a) the low plot GSb4 and (b) the high plot GSb2.

To investigate the effect of wind direction on wave height parameters, we plotted wind direction against wind speed for the events where wind speed was higher than 10m/s in Figure 4.11, Figure 4.12 and Figure 4.13. It appears that wind was coming from a south west direction for all events in 2015 (Figure 4.11). In 2016 the number of events is smaller, but also the wind direction for the different events is more diverse.

Figure 4.10 Averaged wind direction [°] for wind velocities [m/s] higher than 10 m/s

1.1.1.1.2 4.2.3.2. Wind wave regime per 10 min. periods of no ship passages

The same plots, with significant wave height in relation to wind velocity, are shown in Figure 4.12 and Figure 4.13. In this case the significant wave heights are calculated on 10 minutes time periods, for periods where no ship passages were observed. For the measurement period of 2015 a similar pattern as for the tidally calculated values is observed, with an increase of the values above a wind speed of ca. 10 m/s. For the measurement period of 2016 this pattern cannot be observed. No clear reason for this difference could be found, except maybe that in 2016, because of a more southerly wind direction, the Galgeschoor shore was often more sheltered from wind. The maximum significant wave heights reaches approx. 0.40 m at the low tidal plots and 0.3 m at the high tidal plots at wind speeds in excess of 15m/s.

////////////////////////////////////

Figure 4.11 Calculated significant wave height [m] in relation to averaged wind velocity [m/s] at GSb4 in periods of no ship passages

(a)

(b)

Figure 4.12: Calculated significant wave height [m] in relation to averaged wind velocity [m/s] at (a) low tidal flat GSc4 and (b) high tidal flat GSc2 in periods of no ship passages

1.1.1.1.3 Wave amplification and attenuation of wind waves

Wind-generated waves recorded at the low tidal flat (GSb4 and GSc4) were compared directly to the waves measured at the high tidal flat (GSb2 and GSc2). Figure 4.13 gives an overview of the wave heights recorded for all detected wind events at all plots in November 2015 and 2016 (with limited data for the high plots in 2016). Wind wave heights were lower in 2016 than in 2015 although the higher outliers for the different November 2016 plots denote higher extreme wind events. Overall slightly higher wind waves occur on the high plots and lower waves on the low tidal flat, except for GSb in 2016, but only 3 values were recorded for the high plot GSb2. A clear explanation for this observation cannot be found.

4.3 SHIP WAVE REGIME

4.3.1 Ship traffic

Both in 2015 and 2016 the number of ship passages – both seagoing vessels and inland vessels – and the related characteristics of the ships were recorded by the AIS (“Automatic Identification System”). The intensity of ship traffic increased with 15% in the studied period: the average ship passage per day is 215 in November 2015 and 252 in November 2016. For November 2015 and November 2016 the proportion of passages from inland and seagoing vessels is identical, accounting for respectively 78% and 22% of the total.

The number of ship passages during the intensive campaigns, passing the Galgeschoor, in 2015 was 7097 at the southern location (GSc) and 7159 at northern location (GSb). In November 2016 the total number of ship passages was 11926 (GSc) and 11881 (GSb). In November 2015 a total number of respectively 677 seagoing and 934 inland ships were observed.

Figure 4.14 displays the daily time series of ship passages (max. of 347 at 9 Dec. 2016), notice the clear 7-day periodicity with minima at Sundays and holidays.

Figure 4.14 Time series of daily ship passages at the Deurganck dock (GSc) entry line from November 2015 to January 2017. The red dots depicts all local minima.

In Figure 4.15 the number of ships is depicted, sailing with a minimum speed of 2,50 knots. In this figure, no distinction is made between seagoing and inland vessels, and the ship type is based on the AIS code (as depicted in Kolokythas, 2019). Cargo ships account for nearly half of the total number of ship passages in the area, followed by tankers and special category ships. The highest ship traffic per month occurred in October 2016 with 236 passages per day.

Figure 4.15 Temporal evolution of monthly ship traffic differentiated by ship type that crossed the Deurganck dock (GSc) entry line from the period of November 2015 to January 2017. Each bar is supplemented with the corresponding number of ship passages. Only passing ships with speed > 2.5 knots have been considered similar to Kolokythas et al. (2016) and Levy et al. (2017).

In Table 4.4 the relative passing velocities, i.e. the speed of the same vessel at GSc relative to GSb, of tugs, cargo ships and tankers at the GSb and GSc measurement locations are shown. Tug boats moving upstream are generally slower at the southern measurement location (GSc) compared to the northern location (GSb), respective values of 0.93 and 0.86 are found for 2015 and 2016. This means that tug boats moving upstream have a higher velocity at GSb compared to Gsc. Cargo ships are travelling approximately 5 % faster at the GSb transect compared to the GSc transect if they are travelling upstream. In the downstream direction, no difference could be observed. For tankers, no distinction can be made between the relative velocities at GSb or GSc.

Table 4.4 Relative velocities [%] of ships passing at southern location (GSc) versus the northern location (GSb) for three types of ships.

Type of ship	2015		2016	
	UP	DOWN	UP	DOWN
Tug	0.93	1.05	0.86	1.05
Cargo	0.96	0.99	0.95	0.99
Tankers	1.00	1.00	0.99	1.01

If we compare the distance from the passing ships to the lowest point of the transects at the low tidal flat (GSb4 for northern GSb transect and GSc4 for the southern GSc transect), we observe no differences. We can observe ships passing from 400 to 750 m from GSc4 and ca. 500 – 800 m from GSb4. No clear difference in the average distance to the measurement points can be observed for seagoing and inland vessels.

4.3.2 Ship waves

In the signal of a single ship wave, two different phases can be observed, a primary wave and a secondary wave, which are superimposed. The primary wave pattern is a water level depression (drawdown) observed along the hull of the ship that propagates in the direction of the movement. Its wave length is about equal to the ship's length (Schierneck, 2001). The secondary wave pattern includes transverse and diverging waves induced by discontinuities in the ship's hull profile, which are found at the bow and the stern. These wave patterns form interference cusps, of which the envelope propagates obliquely towards the river bank with an angle of attack equal to 55° considering that the bank is parallel to the sailing line (De Roo, 2013). A typical ship wave pattern for a heavy trimmed displacement ship is shown in Figure 4.16.

Figure 4.16 (a) Typical ship wave pattern for a heavy trimmed displacement ship consisting of a primary wave and a secondary wave pattern (De Roo, 2013, p. 51); (b) An example of a registered ship wave in the first intensive campaign November 2015.

////////////////////////////////////

Primary waves

To find the signals of primary waves in the total wave signal, a specific methodology was used to detect (and isolate) this type of waves (Figure 4.16). For the primary waves, special focus was put on the largest ships, as the water level depression is related to the volume of the displaced water (and as such the volume of the ship). Time windows of 9 minutes before and after the passage of ships, longer than 200 m and faster than 2.5 knots, were selected. Within these time windows no other large ships should be present, to consider the event as a clear wave event originating from one large vessel. The wave height is calculated on the resulting fluctuations, after using a low pass filter (0.05 Hz).

In 2015 maximal primary wave heights of ca. 0.65 m were recorded in the northern transect and 0.35 m in the southern transect (Figure 4.18 and Figure 4.20). These highest waves are created by cargo ships in the northern transect, in the southern transect it are mainly ro-ro ships which are responsible for the higher primary waves. It is very prominent that in the results of 2016, the primary waves recorded are much smaller (ca. 0.30 m and 0.20 m respectively for the northern and southern transect). A positive relation between sailing speed and wave height can be found for the results of 2015, albeit that for the highest velocities the wave height seems to drop again. A clear inverse relation can be observed between the water level and the recorded wave height. This is probably due to the larger relative water displacement of the ship at low water compared to high water.

Depending on the location primary waves at the northern transect NL- GSb4 (GSb) are clearly higher than at the southern transect SL- GSc4 (GSc). The maximum primary wave values at SL- GSc4 of approx. 0.25 m are found in 2016 (Figure 4.19). In 2015 a few primary waves had higher values (approx. 0.5 m, Figure 4.20), which were caused by roro ships instead of general cargo ships. The large cargo ships do not seem to induce high primary waves at the low tidal flat SL- GSc4.

Figure 4.17 Maximum wave height (primary) versus ship speed & length, distance from the measuring gauge, and water level for the selected ship events at **NL-GSb4** (north) location in **2016**.

////////////////////////////////////

Wave attenuation of secondary ship waves

In the following, ship-induced wave heights using a filter of short period waves (2-10s), recorded at the low tidal flat plots (GSb4 and GSc4; elevation ~1m TAW) are compared to those recorded at the high tidal flat plots (GSb2 and GSc2; elevation ~5m TAW) for the Northern (GSb) and Southern (GSc) transects. Figure 4.27 shows the distribution of wave heights for all recorded waves at the four plots ($n(\text{GSb2})=33$, $n(\text{GSb4})=524$, $n(\text{GSc2})=43$, $n(\text{GSc4})=431$) during the 2015 and 2016 intensive measurement campaign.

Ship waves are attenuated because both maximum and significant ship wave heights are lower in the high tidal flat plots than in the low tidal flat plots (both variables significant at $p < 0.001$ using Mann-Whitney U-test).

Additionally comparing the intensive campaign in 2015 and 2016, a decrease in maximum and significant ship wave height can be observed on the high tidal flat plots (GSb2 & GSc2), despite the higher outliers of the maximum wave height at the low tidal flat (GSb4 & GSc4).

The behaviour of ship waves along the low to high tidal flat gradient is shown in Figure 4.27. For some instances, differences are marginal and insignificant, but the trend is consistent: ship waves are higher at the low tidal flat and decrease towards the high tidal flat.

Figure 4.27 Comparison of (top) maximum secondary ship wave heights and (bottom) significant ship wave heights recorded at the high (GSb2 and GSc2) and low (GSb4 and GSc4) tidal flat plots for the Northern (GSb) and Southern (GSc) transects for the measurement campaigns of November 2015 and November 2016. The boxes represent the interquartile range of the data and the whiskers delimit 1.5 times the interquartile range. The horizontal line indicates the median and crosses indicate outliers.

////////////////////////////////////

4.4 COMPARING WIND AND SHIP WAVE HEIGHT BETWEEN LOW AND HIGH TIDAL FLAT

Globally, during the 2016 intensive campaign, (secondary) ship-induced waves by single ship events were higher than wind waves, recorded during “no-ship” events, both at the Southern (Figure 4.28) and Northern (Figure 4.29) transects. Such results are not surprising considering the geographical situation of the study site. Indeed, the Galgeschoor is located within the area of the port of Antwerp, characterized by heavy shipping traffic where the shipping channel passes very close to the lower limit of the tidal flat while the wind fetch of the dominant south-westerly winds is rather short to moderate. The heavy shipping traffic in the area also explains the lower recorded number of wind waves compared to ship waves in both transects during the 2016 intensive campaign.

Interestingly, both maximum and significant ship wave heights for common ship events were generally higher at the low tidal flat plots (GSb4 and GSc4) than at the high tidal flat plots (GSb2 and GSb2) when measured simultaneously. This means that for a same single ship event, secondary ship waves typically decrease in height when moving to the high tidal flat. This observed *attenuation*, is attributed to the energy loss by frictional dissipation, particularly experienced by the ship waves, having typically the highest wave heights, while travelling across the tidal flat. On the other hand, despite the lower number of records, both maximum and significant wind waves for common “no-ship” events were generally higher at the high tidal flat plot (GSc2) than at the low tidal flat plot (GSc4) at the Southern transect, meaning that during a same “no-ship” event, wind waves typically increase in height when moving to the high tidal flat, also called *wave amplification*. In particular, the increase in wind wave heights becomes more pronounced at high wind speed (see Figure 4.28) and when the wind blows from the south-west, although we have too few data to clearly establish the latter relationship (see **Fout! Verwijzingsbron niet gevonden.**). The increase in wind wave height towards the higher tidal flat, especially at strong wind force, may reflect the role of the wave shoaling as well as wind fetch which gets longer as the water inundates the tidal flat.

Figure 4.28 (a) Maximum ($H_{\max}$) and (b) significant (H_s) wave heights for single ship and wind waves recorded commonly at the low (GSc4) and high (GSc2) tidal flat plots of the **Southern transect**. Wind waves are differentiated by the corresponding wind speed recorded during the detection of the “no-ship” event. The dashed lines indicate where $x=y$.

Figure 4.29 (a) Maximum ($H_{\max}$) and (b) significant (H_s) wave heights for single ship and wind waves recorded commonly at the low (GSb4) and high (GSb2) tidal flat plots of the Northern transect. Wind waves are differentiated by the corresponding wind speed recorded during the detection of the “no-ship” event. The dashed lines indicate where $x=y$.

////////////////////////////////////

4.5 CONCLUSIONS ON HYDRODYNAMICS

The observed changes in morphology described in chapter 3 are the result of physical forces acting on the mudflat and the marsh edge. In current chapter we report the behaviour of three principal physical forces acting at the Galgeschoor: tidal currents, wind waves and ship waves.

Tidal current velocity varies between 0.3 m/s and 1.25 m/s, yet high current velocity is invariably recorded near spring tide and during the flood phase. Tidal current velocity is relatively constant at ebb over the whole neap-spring tide cycle. During the flood phase however, tidal current velocity may both be lower (near neap tide) or much higher (near spring tide). These results emphasize that the flood phase may be predominant in tidally-induced morphodynamics. The above description of tidal current at the Galgeschoor is based on recordings at the low tidal flat domain. Less is known of current velocities at the high tidal domain but the available data suggest current velocities are lower.

Wind speed positively affected **wind wave** height, yet this effect did not act below wind speeds of 10 m/s. At higher wind speed, significant wave height per tidal cycle increased to 0.2m (approx. 0.38m maximum wave height) at the highest wind speeds recorded during the study (between 15-20 m/s). Wind wave height appeared marginally higher at the southern transect compared to the northern transect, but in general no clear differences can be observed.

In general the **ship wave climate** intensified during the study period with an increase of ship passing intensity of 15% between October 2015 and 2016. Tug boats and cargo ships, sailing upstream, are slower in southern then northern transect, for tankers there was no difference. The percentage in seagoing and inland ship passages remains similar for both intensive measurement campaigns.

Looking to the Galgeschoor wave data is very challenging. Similar studies have been performed to a study area close to the Saeftinghe area (the east side), which is only a few kilometres downstream of the Galgeschoor area. Ship waves here are very clearly recognizable, with (for larger ships) a clear primary wave followed by a secondary wave. This clear patterns are not often monitored in the Galgeschoor section. Moreover, a wave pattern with long wave period (few minutes) is clearly present on peculiar times of the tidal period (see Kolokythas et al., in prep), which additionally adds noise to the different selected wave events.

Some trends about the observed ship waves are revealed in this report. For primary waves, a clear difference in maximum wave heights is observed between 2015 and 2016 without a clear reason. It is clear on the data of 2015 that there is an inverse relation between the tide and the primary wave height, maximum waves are observed during the moments of lower water levels. This can be important with relation to the morphodynamics of tidal marshes, as the important wave loadings due to (high) primary waves are not felt on this level. For some vessel types, and for some years, sailing speed correlated positively with wave height. Maximum ship wave height was largely below 0.2m but some peaks were recorded up to 0.7m. As such, overall, ship maximum wave height was higher than wind maximum wave height.

For the secondary waves, it is clear that in the southern transect the waves due to inland navigation seems to be higher compared to seagoing vessels. Ship waves are attenuating from low to the high tidal flat. This means that they tend to decrease in height when they advance towards the shoreline, a pattern opposite from that observed for wind waves (at least at high wind speed).

5.1 GENERAL OBSERVATIONS

Although long-term seasonal bed level changes recorded at SH- GSc2 and SL- GSc4 (Figure 5.1 subplot f) seem to coincide with the seasonality in wind climate and associated hydrodynamics (waves and tides), effects of these various forcing factors on the observed short-term (daily) bed level changes are not so discernible at first glance (see 3.2.2). Daily erosional events during stormy conditions (light blue-shaded areas) can be indeed identified both at SH- GSc2 and SL- GSc4, yet other erosional events sometimes of even higher magnitudes occurred during calmer conditions.

Figure 5.1 Temporal evolution of (a) daily-averaged wind speed W_s and direction W_{dir} , (b) tidally-maximum wave heights H_{max} , (c) tidally-significant wave height H_s , (d) water depth at high tide h_{max} , (e) tidally-averaged SSC and (f) bed level changes $[\Delta z]_{t0}$ from October 29, 2015 to January 17, 2017 (for clarity purpose all time series were displayed until January 17, 2017 corresponding to the end of the wind measurement records). Figure 5.1b, c, d and f are further differentiated by measurements performed at the southern high (SH-GSc2, red lines) and low (SL-GSc4, blue lines) tidal flat stations. Only validated SSC data of the upper Andraaa Seaguard sensor at the Lillo measurement pole is displayed in subplot e. SSC was derived using a SSC – turbidity linear relationship drawn up following calibration campaigns that took place at Lillo. Light blue-shaded areas indicate stormy conditions, as defined by the 90th percentile of wind speed, here taken as 11.2 m s⁻¹. The light beige-shaded area delineates the period where the intensive campaign took place.

5.2 WHERE AND UNDER WHICH CIRCUMSTANCES IS THE WAVE CLIMATE DOMINANT TO TIDAL CURRENTS?

To compare the hydrodynamic forcing between the two transects, we have to rely on the measurements performed during the last intensive campaign, i.e. during November 2016, where the experimental set-up allowed us to measure both wave (wind and ship waves) and tidal characteristics in the high (GSb2, GSc2) and low (GSb4, GSc4) tidal flat plots of the two transects simultaneously.

In particular, the addition of ADVs measuring 10cm above ground level on the high tidal flat plots (GSb2, GSc2) during the 2016 intensive campaign allowed to perform velocity measurements and to calculate proxies of hydrodynamic forcing.

The proxies for current-induced bed shear stress are computed based on the classical quadratic friction law commonly used (Van Rijn, 1993). The proxies for wave shear stress are computed using a quadratic friction law based on the linear wave theory following Fagherazzi and Wiberg (2009). These estimates for current-induced bed shear stress which, together with the wave-induced bed shear stress, constitute relevant parameters to compare the relative potential contribution of tides and waves to sediment mobilization and transport.

Figure 5.2 displays this estimate of a tidally averaged dimensionless wave-induced bed shear stress $\langle\theta_w\rangle$ and the equivalent current-induced bed shear stresses $\langle\theta_c\rangle$ differentiated by transect location, i.e. between the Northern transect high plot (NH-GSb2) and its Southern analogue (SH- GSc2 Figure 5.2 a), and between the Northern transect low plot (NL- GSb4) and its Southern analogue (SL- GSc4; Figure 5.2 b).

A first pattern that emerges is that, regardless of the transect considered, the wave-induced bed shear stress $\langle\theta_w\rangle$ was dominant over the current-induced bed shear stresses $\langle\theta_c\rangle$ at the high tidal flat plots, while at the low tidal flat plots, the current-induced bed shear stress was more dominant than the wave-induced bed-shear stress. That the current-induced bed shear stress $\langle\theta_c\rangle$, which is further modulated by the tidal regime (neap-spring tide cycle), is the dominant force at the low tidal mudflat, was revealed before by the spectral analysis of the SED-derived elevation change data (3.2.2).

Figure 5.2 (a) Dimensionless tidally-averaged wave-induced bed shear stress $\langle\theta_w\rangle$ vs. dimensionless tidally-averaged current-induced bed shear stress $\langle\theta_c\rangle$ differentiated by the high tidal flat plots of the Northern and Southern transects (GSb2 and GSc2 respectively) during the 2016 intensive campaign; (b) Dimensionless tidally-averaged wave-induced bed shear stress $\langle\theta_w\rangle$ vs. dimensionless tidally-averaged current-induced bed shear stress $\langle\theta_c\rangle$ differentiated

////////////////////////////////////

Figure 5.3 Scatter plot of tidally-averaged dimensionless wave-induced bed shear stress $\langle \tau_w \rangle$ vs. tidally-averaged dimensionless current-induced bed shear stress $\langle \tau_c \rangle$ recorded at the (a) northern high (NH-GSb3), (b) southern high (SH-GSc2), (c) northern low (NL-GSc4) and (d) southern low (SL-GSc4) tidal flat measurement stations during the intensive campaign (i.e. from October 27, 2016 to December 12, 2016, except for SH where the pressure sensor was repaired and reinstalled on November 09, 2016). Dashed lines with corresponding critical Shields bed shear stress τ_{cr} for sediment motion are displayed for every station considered. $\langle \tau_w \rangle$ and $\langle \tau_c \rangle$ at NL and SL are further differentiated by periods of neap and spring tides.

////////////////////////////////////

Figure 5.4 Temporal evolution of water level η , wave height H , wave orbital velocity U_w current velocity U and turbidity respectively recorded at the (a, c, e) southern high (SH –GSc2) and (b, d, f) southern low (SL-GSc4) tidal flat measurement stations during a spring tidal cycle starting on November 16, 2016 23:18:00. Tidally-averaged W_s was 7.0 m s⁻¹ and tidally-averaged W_{dir} corresponded to southwesterly winds. For a matter of visualization, recorded η , H , U_w and turbidity were averaged over 2 min at both locations. U measured at SH –GSc2 corresponds to (ADV-derived) point current velocities measured at 10cm above the bottom, also averaged over 2 min, whereas U at SL-GSc4 represents (ADCP-derived) depth-averaged current velocities, kept at the original measurement frequency (i.e. 5 min; see Table 1). Every green dot represents the time of passage of a ship in the S entry line, retrieved using the AIS data. The light beige shaded areas delineate the actual inundation phases at SH and SL during the recorded tidal cycle

At the low tidal domain of the southern plot (SL-GSc4), dominance of wave shear stress shifts to the benefit of current shear stress (Figure 5.3d). Current shear stress also becomes morphologically more relevant, as it exceeds the critical threshold in the majority of cases. Yet, contrary to the high tidal flat, the low tidal flat is more subject to incoming ship waves due to corresponding longer inundation time and frequency as well as proximity to the estuarine channel. These ship waves that are characterized by high wave heights, which can result in

Southern transect

In the *high tidal flat zone*, both waves and tidal currents are less strong, and the observed bed-level changes are much less pronounced. Current velocities are less than half those of their low counterparts. Waves are relatively more important within tides in controlling morphological changes, especially when focusing on the comparisons of shear stress. This accords to the observation that, within a single tidal cycle, turbidity primarily covaried with bottom wave orbital velocities at the high tidal flat plot of the Southern transect (SH-GSc2), especially at the shallow leading and trailing edges of advancing and retreating waters, causing wave-induced bed shear stress $\langle \theta_w \rangle$ sometimes exceeding the local critical shear stress (Shields stress) for sediment motion θ_{cr} . However, contrary to the low tidal flat, wave height parameters did not relate to the net (between tidal cycles) bed level changes over the long-term campaign, thus suggesting that waves have a poor impact on the net morphological changes (Table 5-1). Long-term deseasonalized bed-level changes exhibited a weak yet significant recurrent pattern related to the tidal cycle. Indeed, bed-level changes correlated negatively with local water depth (D), a proxy for current velocity, but the correlation was less strong compared to the low tidal flat.

As mentioned earlier, similar patterns of hydrodynamic forcing took place at the Northern transect: tidal currents dominate morphodynamics in the low tidal flat zone while waves and currents both contribute to morphodynamics at the higher tidal flat zone. Yet, contrary to their Southern counterparts, neither tides nor waves trigger significant morphological changes at the respective low (NL-GSb4) and high (NH-GSb2) tidal flat plots over the long-term. The nearly absence of tidal cycles in bed-level changes (spectral analysis) is congruent with the near-absence of tidally-averaged wave-induced bed shear stress $\langle \theta_w \rangle$ at NH- GSb2 or the dominant tidally-averaged current-induced bed shear stress $\langle \theta_c \rangle$ at NL- GSb4 exceeding the critical shear stresses for sediment motion θ_{cr} .

Besides the large scale hydrodynamic and morphological setting of the study area, one reason for the observed differences in the impact of hydrodynamic forcing on the morphological changes between the two transects can be attributed to the difference in surficial sediment characteristics. The mud fraction (grain size $< 63\mu\text{m}$) at the NH-GSb2, NL-GSb4 and SH-GSc2 accounts for more than 50 % of the total sediment composition throughout the long-term campaign. Cohesion between muddy sediment grains is relatively strong. Sediment composition at SL-GSc4 on the other hand is characterized by a dominant sand (non-cohesive) fraction throughout most of the long-term campaign (Figure 3.1). The combination of fine cohesive sediments with a comparatively reduced tidal regime and wave climate at the respective low and high tidal flat plots of the Northern transect as opposed to their Southern counterparts may explain the observed low morphological changes.

At the southern transect a long term seasonal trend is found in the bed level changes with a sedimentation trend between spring and autumn and an erosion trend between autumn and spring. Although these long-term seasonal bed level changes at the southern transect seem to coincide with the seasonality in wind climate and associated hydrodynamics (waves and tides), effects of the various forcing factors on the observed short-term (daily) bed level changes play a role. Under maximal tidal conditions (i.e. spring tide) the current shear stress exceeds the local critical shear stress at *the low tidal flat* of both transects, thus suggesting a tidal current impact on morphology. In average conditions only the southern low tidal flat plot exceeds the critical value. The effectiveness of the impact of this hydrodynamic forcing is also dependent on sediment type. In contrast to the other sites the southern low tidal flat has non-cohesive (sandy) sediment and endure the highest impact. Also this site shows a positive correlation of water depth or the strong related maximum flow velocities with the net daily bed level changes on the longer term.

6 DISCUSSION

The tidal mudflat of the Galgeschoor shows an ecotope evolution after the third deepening (2009-2010) similar to other estuarine areas more upstream. The middle tidal flat area has increased mainly at the expense of low tidal flats (Van Braeckel et al. 2012). Also the potential pioneer zone, the mudflat area above mean high water at neap tide, has declined. More recently (2014-2016), morphological monitoring of the Sea Scheldt (Van Braeckel & Elsen in Van Ryckegem et al. 2017) revealed that large tidal mudflats at inner bends in the upper Sea Scheldt display shrinking sedimentation areas and increasing erosion areas. This phenomenon is expanding yearly in upstream direction, and is observed in the Galgeschoor as well. On the Galgeschoor this process changes soft bottom low tidal areas into hard substrate. There is some debate on as to why this is happening, yet one current hypothesis is that hydrodynamic pressure on the intertidal areas has increased during flood, the tide phase with the highest current velocities on the intertidal areas.

The marsh cliff of Galgeschoor is retreating continuously since 1940. Originally, cliff erosion occurred by meters per year. After the installation of a rip rap zone retreat rates became in the order of cm's per year. The nature of the marsh has changed due to the rip rap from an exposed-bare marsh to a sheltered-bare and pioneer marsh, due to the shrinking of adjacent mud flats and decreasing width of the marsh after dike reinforcements (Wang et al. 2017). Recently (2010-2012) erosion rates have been rather high again (31.7 cm/year). This coincided with the third deepening and widening of the navigation channel, yet there is no other evidence to link both phenomena. After 2013, retreat rates have decreased again to the normal background level (Figure 3.5). Overall, the marsh edge at the southern transect showed higher retreat rates (15–32 cm/year) than the marsh edge at the northern transect (2.5 cm/year).

Research in the Westerscheldt (Wang et al. 2017) by NIOZ revealed a scale-dependence of factors driving tidal marsh edge retreat. (i) At a large scale, wind exposure (fetch length, orientation,...) and presence of vegetation in front of the cliff govern the cliff retreat rates; (ii) at the intermediate scale, foreshore morphology was related to cliff retreat; (iii) at the local scale, the erodibility of the sediment itself at the marsh edge played a large role in determining the cliff retreat rate; and (iv) at the mesocosm scale, cliff erodibility was determined by soil properties and belowground root biomass. Thus, both extrinsic (wind exposure and foreshore morphology) and intrinsic factors (soil and vegetation properties) determine the fate of the salt marsh edge, but at different scales.

Galgeschoor, which is located at an inner bend (from east to north direction; Figure 4.7) at the right bank of the Scheldt, is one of the areas of the inner estuary that (i) experiences a high wind exposure. On the other hand the increasing abundance of the pioneer vegetation *Glaux maritima* in front of the marsh cliff may temper impact on the marsh cliff however this is a minute type of vegetation (GSb2, Figure 3.4, Figure 3.14). Along the southern transect the (rather scarce) increase of *Vaucheria* and some pioneer vegetation *Glaux maritima* (southern part in Figure 3.4) may have helped slowing down the cliff rate erosion in GSbc (Figure 3.4). As such, the northern transect can be seen as a sheltered-pioneer and the southern transect as a sheltered-bare marsh type (Wang et al. 2017) (ii) At the intermediate scale the foreshore morphology at Galgeschoor is highly influenced by the width, height and shape of the soft bottom mudflat and the (maximal) height of the rip rap zone (Figure 2.4) and width of the natural hard peat layer at the low tidal mudflat in the north. (iii) At the local scale near the tidal marsh cliff on the high tidal flat, the composition and grain size of the mud substrate (Figure 3.15) is important as well as the depth of the clay subsurface (old marsh soil). The highest median grain size values for GSc2 are found in erosion periods. (iv) at the very local

(a)

(b)

Figure 6.1 a) Composition of the different fraction (% volume) per transect and depth zone (Michels et al. 2012); b) relation between D50 of the upper soil layer in this study on high tidal flat plot and the nearest tidal marsh plot

The southern transect, which is located at an inner bend and endures more differentiation in current velocity patterns, shows a higher variability in soil layers than the northern plot. The marsh soil at the northern transect (raai3) consists for 70-80% of muddy/clay fraction ($<63\mu\text{m}$), whereas this was less than 60% at the southern transect. The marsh soil profile at the southern transect also showed a clearer stratification than the northern GSb. This may explain partly the higher vulnerability of the southern marsh edge to erosion. Furthermore the median grain size of the tidal marsh surface layer is similar to that of the high tidal flat for the northern transect (Figure 6-1a) but not for the southern transect where it seems coarser on the tidal marsh indicating differences in hydrodynamic forces in the marsh edge.

In the Westerscheldt, four tidal flat–salt marsh ecosystems with contrasting wave exposure (sheltered vs. exposed) and lateral development (shrinking vs. expanding) were studied by Callaghan et al. (2010). They found that hydrodynamic forces and related sediment bed motion are consistently higher at sites with shrinking marshes than sites with expanding marshes, regardless of wind exposure of the sites. The main cause was the bathymetry of the tidal flat in front: tidal flat bathymetry determines hydrodynamic forces and whether waves will reach the cliff or not. Therefore our research focused on sediment bed motion and proxies of hydrodynamic forcing which are relevant to bed sediment motion.

In the Galgeschoor the bed level changes showed a clear seasonality with a tendency (2 years data) for mudflat erosion in (late) winter and spring and deposition during the rest of the year. These seasonal bed level changes are similar to what Kirby et al. (1993) noticed over a 22 month period on a mudflat of the mesotidal Ardmillan Bay (UK). In particular, storm-generated waves were found to cause erosion in winter and spring, and deposition under calmer summer conditions was enhanced by algal binding of the bed sediment. They concluded that episodic wind waves were the main cause of tidal flat instability and noted that this seasonal pattern in accretion and erosion is consistent with previous studies. Uncles and Stephens (2010) concluded similarly for the Tavy estuary that a summer solstice period of weaker spring tides has slower wind speeds, smaller waves, lower freshwater runoff and, potentially, the growth of stabilizing benthic algae over the mudflats to facilitate deposition and consolidation of mud. For Galgeschoor we also ascribe this seasonality in bed level changes at GSc2, GSc4 and to a lesser extent at GSb2 to both seasonality of hydrodynamics (generally more windy

In the Westerscheldt, four tidal flat–salt marsh ecosystems with contrasting wave exposure (sheltered vs. exposed) and lateral development (shrinking vs. expanding) were studied by Callaghan et al. (2010). They found that hydrodynamic forces and related sediment bed motion are consistently higher at sites with shrinking marshes than sites with expanding marshes, regardless of wind exposure of the sites. The main cause was the bathymetry of the tidal flat in front: tidal flat bathymetry determines hydrodynamic forces and whether waves will reach the cliff or not. Therefore our research focused on sediment bed motion and proxies of hydrodynamic forcing which are relevant to bed sediment motion.

In the Galgeschoor the bed level changes showed a clear seasonality with a tendency (2 years data) for mudflat erosion in (late) winter and spring and deposition during the rest of the year. These seasonal bed level changes are similar to what Kirby et al. (1993) noticed over a 22 month period on a mudflat of the mesotidal Ardmillan Bay (UK). In particular, storm-generated waves were found to cause erosion in winter and spring, and deposition under calmer summer conditions was enhanced by algal binding of the bed sediment. They concluded that episodic wind waves were the main cause of tidal flat instability and noted that this seasonal pattern in accretion and erosion is consistent with previous studies. Uncles and Stephens (2010) concluded similarly for the Tavy estuary that a summer solstice period of weaker spring tides has slower wind speeds, smaller waves, lower freshwater runoff and, potentially, the growth of stabilizing benthic algae over the mudflats to facilitate deposition and consolidation of mud. For Galgeschoor we also ascribe this seasonality in bed level changes at GSc2, GSc4 and to a lesser extent at GSb2 to both seasonality of hydrodynamics (generally more windy

were found with wave forcing. Galgeschoor, characterized by mainly short fetch lengths (< 2.5 km, Figure 4.7) except 10 degrees of winds coming from the Deurganck dok (GSb 210°, GSc 220°), can also be considered as a sheltered site compared to Westerscheldt sites. The absence of relations between tidal forcing and bed level dynamics in the high sites and the low site of GSb is in line with the findings at Baarland.

Ship traffic is high at Galgeschoor and manoeuvres related to the docks may amplify wave exposure locally. At the Galgeschoor maximum ship wave height measured at the low water line was largely below 0.2 m but some peaks were recorded up to 0.7 m. As such, overall, ship maximum wave height was higher than wind maximum wave height. However, ship waves were observed to attenuate from the low to the high tidal flat. Similar to the Galgeschoor study, wave measurements were also performed in Dendermonde (Upper Sea Scheldt) and Saeftinghe (Western Scheldt) recently. In Dendermonde, clearly smaller wave characteristics were observed. Maximum wave heights of approx. 0.45 m were observed. The higher waves can be linked to ship traffic, even with the much smaller ships (max. length 100 m) passing here. In the signature of the ship waves, only secondary waves could be discerned. In Saeftinghe, maximum wave heights of 1.1 m were recorded. The significant wave heights, calculated over a full tide, ranged between 0.06 m and 0.10 m, which is similar for the Galgeschoor case. The relation between the secondary wave heights and the ships characteristics showed large variation, similar to the Galgeschoor measurements. Maximum secondary wave heights of approximately 1.1 m were recorded. In contrast with the Galgeschoor measurements, the primary wave signal of ships was in most cases much more pronounced. Maximum primary wave heights of ca. 0.8 m were recorded. These high values are mostly accounted for by the largest ships (>350 m length).

Looking at estimates of both current and wave forcing, wave-induced bed shear stress $\theta_{w,max}$ at GSc2 and GSc4, occurring during the early and late stages of the tidal inundation, were higher than the current-induced bed shear stress $\theta_{c,max}$. This is also found by Zhu et al. (2014) in an intensive study on the intra-tidal sedimentary processes (Yangtze River Delta, China). At the high plot at the southern transect (GSc2) the calculated wave-induced bed shear stress $\langle \theta_w \rangle$ also more often exceeded the local critical shear stress for sediment motion than current-induced bed shear stress (θ_{cr} , Figure 5.3a) in comparison to the northern transect (Figure 5.3b). Measurements on turbidity at high and low tidal flat plot at the southern transect (GSc2, GSc4; Figure 5.4) also showed high values at the early and late stages of the tidal inundation. At the high tidal plot GSc2 it is even higher than the overall turbidity induced by the currents. Similar results were found by Verelst et al. (2011a; Figure 6-2) for 20 - 22 April 2011 measurements at the low tidal flat at the southern transect (ADV: 1.15m T.A.W.)

Figure 6.2 Turbidity (black, NTU), current velocities (red, m/s) and water level (blue, m T.A.W.) measured with an ADV at 20 to 22 April 2011 (adapted from Verelst et al. 2011a)

Uncles and Stephens (2010) describe these intratidal variations in turbidity over the mudflats. Generally it exhibits a 'U'-shaped temporal behaviour within each tidal inundation, except in

////////////////////////////////////

6.1 MORPHOLOGICAL CHANGES

The Galgeschoor tidal marsh **historically** endured high morphodynamic changes with high historical marsh cliff retreat rates since the 1940s. The driving forces were the shrinking width of the adjacent mud flat from the riverside as well as dike enforcements from the landside. The construction of the rip rap wall on the riverside around 1990 apparently slowed down the long-term erosion of the marsh cliff, likely by exposure reduction on the marsh edge.

Nowadays the total area of tidal marsh ecotope in Galgeschoor near the marsh edge seems relatively stable. On the initial marsh **cliff retreat** areas pioneer marsh vegetation seems to establish, currently compensating the loss of tidal marsh by retreat, albeit a different successional phase. Consequently the proportion of high solid old marsh area decreases. The marsh cliff retreat rate also differs between the northern and southern transects with retreat rates of 2.5 and 15–32cm/year since 2010, respectively. Michels et al (2012) concluded that in view of its long term evolution an average marsh edge retreat of 25 cm/year can be considered as a background value for a normal tidal marsh cycle at the Galgeschoor, allowing for establishment of pioneer marsh. Apparently this coincides with the current observations in most of the area. However these changes are very recent and it is yet impossible to judge whether this is resilient in nature and part of the natural tidal marsh cycle.

At the Galgeschoor (low) tidal mudflat, high morphodynamics were observed during the past decade. This **ecotope** lost quantity as well as quality. It evolved into middle tidal mudflats due to accretion in 2012-2013 or into hard substrate zones by erosion in 2015-2016. These transitions are not only locally observed but also more widely in the estuary. The accretion period of the mudflats is believed to be an initial morphological reaction of the system to the last widening of the navigation channel (2009-2010) along the Scheldt estuary (Van Braeckel et al. 2014). In the more recent years, lower mudflat zones tend to erode more in the Flemish part of the Scheldt (Van Ryckegem et al. 2017).

On the **long term, bed level** of the high tidal flat at the northern transect tended to increase and traps small volumes of sediment while the tidal mudflat zones beneath the riprap decreased and lost sediment volume. The southern transect has shown an opposite trend with bed levels of lower mudflats increasing, trapping large sediment volumes while the high tidal flat fluctuates around zero accretion. The sediment trapping at the southern transect tended to slow down since 2014 and the net increase stopped since 2016 at the middle and high mudflat. At the northern transect only the middle tidal mudflat level eroding trend changed since 2016 and started to accrete.

During the 2-year intensive monitoring campaign (2015-2016), **bed level changes** were generally much more pronounced at the southern plots (order of magnitude 5 – 10 cm) as compared to the northern plots (<5 cm). This may be attributed to differences in sediment properties (more sandy at the low southern plot). Both seasonal and day-to-day variations were clearly larger at the southern plots of Galgeschoor. This means that the southern transect was more dynamic. Further, low tidal plots were much more dynamic than high tidal plots. The seasonal variation at southern transect exhibits a period of sedimentation between spring and autumn while between autumn and spring mostly erosion takes place. The daily fluctuations in bed level in the low and to a lesser extent in the high tidal flat plots, reveals a spring-neap tidal cycle (i.e. 14.77 days).

6.2 PHYSICAL FORCING FACTORS

The observed morphological changes result from the combined and simultaneous action of several **physical forcing factors** on the mudflats and marsh edge.

Tidal current velocity as measured during two one month autumn campaigns varied between 0.3 m/s and 1.25 m/s. High current velocity is invariably recorded near spring tide during the flood phase. Tidal current velocity at ebb (0.5-0.75 m/s) is relatively constant over the neap-spring tide cycle. During the flood phase however it is lower near neap tide and much higher near spring tide. These high velocities in the flood phase during spring tide emphasize that flood may be predominant in tidally-induced morphodynamic changes. The above description of tidal currents at the Galgeschoor is based on recordings at the low tidal flat. Less is known about current velocities at the high tidal flat but the available data suggest that current velocities are generally lower.

Wind speed positively affected **wind wave** height, yet this effect did not act below 10 m/s. At higher wind speed, significant wave height per tidal cycle increased to 0.2 m (approx. 0.38m maximum wave height) at the highest wind speeds recorded during the study period (between 15-20 m/s, 7-8 Beaufort). Further analysis also suggested that wind waves tend to increase from the low towards the high tidal flats indicating an amplifying behaviour of the incoming wind waves, yet only at high wind speeds. At high wind speed, fetch may become increasingly important and is longest at the high plots, at least for the common wind directions that were observed (dominant SW-wind). Lastly, wind wave height appeared marginally higher at the southern transect compared to the northern transect.

In general the **ship wave climate** intensified during the study period with an increase of ship passing intensity of 15% between October 2015 and 2016. Tug boats and cargo ships, sailing upstream, are slower at the southern than at the northern transect, for tankers and downstream sailing vessels there was no difference.

The **ship wave** study revealed several important trends yet more sophisticated statistical analyses may be needed to deal with collinearities and demonstrate unique relationships. A possibly important trend was that ship wave height may fairly strongly increase when the tide is low. This pattern may be attributed to the proportionally large displacement of water at low tide. For some boat types, and for some years, sailing speed correlated positively with wave height. Maximum ship wave height was mostly below 0.2 m but regularly higher peaks were recorded up to 0.7 m. As such, during periods when wind speed was low to moderate (most of the time), ships frequently generate waves that exceeded the background wind maximum wave height, yet for short durations. A peculiar aspect of ship waves is the attenuation behaviour from low to the high tidal flat. This means that they tend to decrease in height when they advance towards the shoreline, a pattern opposite to that observed from wind waves at high wind speed.

In order to translate driving forces to potential morphodynamic effects, calculated **shear stress parameters** were used during the intensive campaign in 2016. At the high tidal flat, wave-induced bed shear stress was higher than the current shear stress, especially in the southern plot, while on the low tidal flat current bed shear stress was more important. Expected morphological effects were obtained by comparing calculated wave- and current-induced bed shear stresses to the local critical Shields stress for sediment motion, based on sediment characteristics obtained during the study. During the flood phase of tides near spring tide, the current shear stress exceeded the local critical Shields stress causing sediment

References

- Andersen, T. J., Pejrup, M., & Nielsen, A. A. (2006). Long-term and high-resolution measurements of bed level changes in a temperate, microtidal coastal lagoon. *Marine Geology*, 226(1–2), 115–125. <https://doi.org/10.1016/j.margeo.2005.09.016>
- Belliard, J.-P.; Temmerman, S. (2017). Part II: Analysis of elevation changes and potential controls during the long-term measurement campaign from November 2015 to May 2017. University of Antwerp, Belgium
- Callaghan, D. P., Bouma, T. J., Klaassen, P., van der Wal, D., Stive, M. J. F., & Herman, P. M. J. (2010). Hydrodynamic forcing on salt-marsh development: Distinguishing the relative importance of waves and tidal flows. *Estuarine, Coastal and Shelf Science*, 89(1), 73–88. <https://doi.org/10.1016/j.ecss.2010.05.013>
- Christiansen, C., Vølund, G., Lund-Hansen, L. C., & Bartholdy, J. (2006). Wind influence on tidal flat sediment dynamics: Field investigations in the Ho Bugt, Danish Wadden Sea. *Marine Geology*, 235(1–4 SPEC. ISS.), 75–86. <https://doi.org/10.1016/j.margeo.2006.10.006>
- Christie, M. C., Dyer, K. R., & Turner, P. (1999). Sediment Flux and Bed Level Measurements from a Macro Tidal Mudflat. *Estuarine, Coastal and Shelf Science*, 49(5), 667–688. <https://doi.org/10.1006/ecss.1999.0525>
- De Roo, S. (2013). Experimental Study of the Hydrodynamic Performance of a Nature-Friendly Bank Protection Subject to Ship Waves in a Confined, Non-Tidal Waterway. PhD Thesis, University of Ghent, Belgium.
- Delloffre, J. et al., (2005). Sedimentary processes on an intertidal mudflat in the upper macrotidal Seine estuary, France. *Estuarine, Coastal and Shelf Science*, 64(4), pp.710–720.
- Fagherazzi, S., and P. L. Wiberg (2009), Importance of wind conditions, fetch, and water levels on wave-generated shear stresses in shallow intertidal basins, *J. Geophys. Res.*, 114, F03022, doi:10.1029/2008JF001139.
- Hu, Z. & Lenting, W. & van der Wal, D. & Bouma, T. (2015). Continuous monitoring bed-level dynamics on an intertidal flat: Introducing novel, stand-alone high-resolution SED-sensors. *Geomorphology*. 245. 10.1016/j.geomorph.2015.05.027
- Hu, Z., Yao, P., van der Wal, D., & Bouma, T. J. (2017). Patterns and drivers of daily bed-level dynamics on two tidal flats with contrasting wave exposure. *Scientific Reports*, 7(1), 7088. <https://doi.org/10.1038/s41598-017-07515-y>
- Hunt, S., Bryan, K. R., Mullarney, J. C., & Pritchard, M. (2016). Observations of asymmetry in contrasting wave- and tidally-dominated environments within a mesotidal basin: implications for estuarine morphological evolution. *Earth Surface Processes and Landforms*, 41(15), 2207–2222. <https://doi.org/10.1002/esp.3985>
- Kirby, R., Bleakley, R.J., Weatherup, S.T.C., Raven, P.J., Donaldson, N.D., 1993. Effect of episodic events on tidal mud flat stability, Ardmillan Bay, Strangford Loch, Northern Ireland. In: Mehta, A.J. (Ed.), *Coastal and Estuarine Studies* 42. Nearshore and Estuarine Marine Cohesive Sediment Transport. American Geophysical
- Kolokythas, G.; Meire, D.; De Roo, S.; Plancke, Y.; Verwaest, T.; Mostaert, F. (2017). Wave measurements at Galgeschoor: Sub report 1 – Analysis of velocities and waves during an intensive measuring campaign. Version 2.0. FHR Reports, 15_054_1. Flanders Hydraulics Research: Antwerp.
- Levy, Y. and Meire, D. (2018). Wave measurements at Galgeschoor: Part 1: Analysis of velocities and waves during an intensive measuring campaign. Version 0.18. FHR Reports, 15_054_1. Flanders Hydraulics Research: Antwerp.
- Meire, D.; Kolokythas, G.; Smolders, S.; Plancke, Y.; Verwaest, T.; Mostaert, F. (2016). Agenda voor de Toekomst – Waves in the estuary: Analysis of wave measurements at

- Maeflinghe, Version 4.0. FHR Reports, 16_000_1. Flanders Hydraulics Research: Antwerp.
- Meire, D.; Levy, Y.; Plancke, Y.; Mostaert, F. (2016). Agenda voor de Toekomst – Waves in the Scheldt estuary: Analysis of wave measurements at Dendermonde. Version 4.0. FHR Reports, 14_082_2. Flanders Hydraulics Research: Antwerp.
- Michels, H.; Van Braeckel, A.; Speybroeck, J.; Milotic, T.; Van den Bergh, E.; Verelst, K.; De Mulder, T.; Taverniers, E.; Mostaert, F. (2012). Onderzoek naar de invloedsfactoren van golfbelasting en de morfologische effecten op slikken en schorren in de Beneden Zeeschelde, meer specifiek op het Galgeschoor: Deelrapport 9 - Analyserapport met betrekking tot de morfologische ontwikkelingen op het Galgeschoor. Versie 1_4. WL Rapporten, 837_03. Waterbouwkundig Laboratorium: Antwerpen, België
- Silinski, A., and Temmerman, S. (2016). Wave measurements at Galgeschoor Part II : Analysis of velocities and waves during an intensive measuring campaign. Draft report. University of Antwerp, Belgium.
- Uncles, R. J., & Stephens, J. A. (2010). Turbidity and sediment transport in a muddy sub-estuary. *Estuarine, Coastal and Shelf Science*, 87(2), 213–224. <https://doi.org/10.1016/j.ecss.2009.03.041>
- Van Braeckel, A., Elsen, R. & Van den Bergh, E. 2014. MONEOS – Geomorfologie: Hoogteraaen van slik en schor in de Zeeschelde - evolutie van toestand tot 2012. Rapporten van het Instituut voor Natuur- en Bosonderzoek; no. INBO.R.2014.1860252.
- Van Ryckegem, G., Van Braeckel, A., Elsen, R., Speybroeck, J., Vandevorde, B., Mertens, W., Breine, J., Spanoghe, G., Buerms, D., De Beukelaer, J., De Regge, N., Hessel, K., Soors, J., Terrie, T., Van Lierop, F. & Van den Bergh, E. 2017, MONEOS – Geïntegreerd datarapport INBO: Toestand Zeeschelde 2016: Monitoringsoverzicht en 1ste lijnsrapportage Geomorfologie, diversiteit Habitats en diversiteit Soorten. Rapporten van het Instituut voor Natuur en Bosonderzoek, nr. 37, Instituut voor Natuur- en Bosonderzoek. <https://doi.org/10.21436/inbor.13479033>
- Van Ryckegem, G., Van Braeckel, A., Elsen, R., Speybroeck, J., Vandevorde, B., Mertens, W., Breine, J., Spanoghe, G., Bezdenjesnj, O., Buerms, D., De Beukelaer, J., De Regge, N., Hessel, K., Lefranc, C., Soors, J., Terrie, T., Van Lierop, F. & Van den Bergh, E. 2018, MONEOS – Geïntegreerd datarapport INBO: Toestand Zeeschelde 2017: Monitoringsoverzicht en 1ste lijnsrapportage Geomorfologie, diversiteit Habitats en diversiteit Soorten. Rapporten van het Instituut voor Natuur en Bosonderzoek, nr. 74, Instituut voor Natuur- en Bosonderzoek. <https://doi.org/10.21436/inbor.15000892>
- Van Rijn, L. C. (1993). Principles of sediment transport in rivers, estuaries and coastal seas (Vol 1006). Amsterdam: Aqua publications.
- Verelst, K.; De Mulder, T.; Vereecken, H.; Taverniers, E.; Mostaert, F. (2012). Onderzoek naar de invloedsfactoren van golfbelasting en de morfologische effecten op slikken en schorren in de Beneden Zeeschelde, meer specifiek op het Galgeschoor: Deelrapport 8 - Analyserapport golfbelasting op het Galgeschoor. Versie 2_0. WL Rapporten, 837_03. Waterbouwkundig Laboratorium: Antwerpen, België
- Verelst, K.; De Mulder, T.; Vereecken, H.; Michels, H.; Speybroeck J.; Van Braeckel, A.; Van Den Bergh, E.; Taverniers, E.; Mostaert, F. (2011a). Onderzoek naar de invloedsfactoren van golfbelasting en de morfologische effecten op slikken en schorren in de Beneden Zeeschelde, meer specifiek op het Galgeschoor: Deelrapport 5: Verslag ad hoc-meetcampagne van 20 tot 22 april 2011. Versie 2_0. WL Rapporten, 837_03. Waterbouwkundig Laboratorium & INBO: Antwerpen, België
- Verelst, K.; De Mulder, T.; Vereecken, H.; Michels, H.; Speybroeck J.; Van Braeckel, A.; Van Den Bergh, E.; Taverniers, E.; Mostaert, F. (2011b). Onderzoek naar de invloedsfactoren van golfbelasting en de morfologische effecten op slikken en schorren in de Beneden Zeeschelde, meer specifiek op het Galgeschoor: Deelrapport 6: Verslag ad hoc-

Meire, D.; Levy, Y.; Plancke, Y. ;Mostaert, F. (2016). Agenda voor de Toekomst – Waves in the Scheldt estuary: Analysis of wave measurements at Dendermonde. Version 4.0. FHR Reports, 14_082_2. Flanders Hydraulics Research: Antwerp.

Michels, H.; Van Braeckel, A.; Speybroeck, J.; Milotic, T.; Van den Bergh, E.; Verelst, K.; De Mulder, T.; Taverniers, E.; Mostaert, F. (2012). Onderzoek naar de invloedsfactoren van golfbelasting en de morfologische effecten op slikken en schorren in de Beneden Zeeschelde, meer specifiek op het Galgeschoor: Deelrapport 9 - Analyserapport met betrekking tot de morfologische ontwikkelingen op het Galgeschoor. Versie 1_4. WL Rapporten, 837_03. Waterbouwkundig Laboratorium: Antwerpen, België

Silinski, A., and Temmerman, S. (2016). Wave measurements at Galgeschoor Part II : Analysis of velocities and waves during an intensive measuring campaign. Draft report. University of Antwerp, Belgium.

Uncles, R. J., & Stephens, J. A. (2010). Turbidity and sediment transport in a muddy sub-estuary. *Estuarine, Coastal and Shelf Science*, 87(2), 213–224. <https://doi.org/10.1016/j.ecss.2009.03.041>

Van Braeckel, A., Elsen, R. & Van den Bergh, E. 2014. MONEOS – Geomorfologie: Hoogteraaian van slik en schor in de Zeeschelde - evolutie van toestand tot 2012. Rapporten van het Instituut voor Natuur- en Bosonderzoek; no. INBO.R.2014.1860252.

Van Ryckegem, G, Van Braeckel, A, Elsen, R, Speybroeck, J, Vandevoorde, B, Mertens, W, Breine, J, Spanoghe, G, Buerms, D, De Beukelaer, J, De Regge, N, Hessel, K, Soors, J, Terrie, T, Van Lierop, F & Van den Bergh, E 2017, MONEOS – Geïntegreerd datarapport INBO: Toestand Zeeschelde 2016: Monitoringsoverzicht en 1ste lijnsrapportage Geomorfologie, diversiteit Habitats en diversiteit Soorten. Rapporten van het Instituut voor Natuur en Bosonderzoek, nr. 37, Instituut voor Natuur- en Bosonderzoek. <https://doi.org/10.21436/inbor.13479033>

Van Ryckegem, G, Van Braeckel, A, Elsen, R, Speybroeck, J, Vandevoorde, B, Mertens, W, Breine, J, Spanoghe, G, Bezdenjesnji, O, Buerms, D, De Beukelaer, J, De Regge, N, Hessel, K, Lefranc, C, Soors, J, Terrie, T, Van Lierop, F & Van den Bergh, E 2018, MONEOS – Geïntegreerd datarapport INBO: Toestand Zeeschelde 2017: Monitoringsoverzicht en 1ste lijnsrapportage Geomorfologie, diversiteit Habitats en diversiteit Soorten. Rapporten van het Instituut voor Natuur en Bosonderzoek, nr. 74, Instituut voor Natuur- en Bosonderzoek. <https://doi.org/10.21436/inbor.15000892>

Van Rijn, L. C. (1993). Principles of sediment transport in rivers, estuaries and coastal seas (Vol. 1006). Amsterdam: Aqua publications.

Verelst, K.; De Mulder, T.; Vereecken, H.; Taverniers; E.; Mostaert, F. (2012). Onderzoek naar de invloedsfactoren van golfbelasting en de morfologische effecten op slikken en schorren in de Beneden Zeeschelde, meer specifiek op het Galgeschoor: Deelrapport 8 - Analyserapport golfbelasting op het Galgeschoor. Versie 2_0. WL Rapporten, 837_03. Waterbouwkundig Laboratorium: Antwerpen, België

Verelst, K.; De Mulder, T; Vereecken, H.; Michels, H.; Speybroeck J.; Van Braeckel, A.; Van Den Bergh, E.; Taverniers; E.; Mostaert, F. (2011a). Onderzoek naar de invloedsfactoren van golfbelasting en de morfologische effecten op slikken en schorren in de Beneden Zeeschelde, meer specifiek op het Galgeschoor: Deelrapport 5: Verslag ad hoc-meetcampagne van 20 tot 22 april 2011. Versie 2_0. WL Rapporten, 837_03. Waterbouwkundig Laboratorium & INBO: Antwerpen, België

Verelst, K.; De Mulder, T; Vereecken, H.; Michels, H.; Speybroeck J.; Van Braeckel, A.; Van Den Bergh, E.; Taverniers; E.; Mostaert, F. (2011b). Onderzoek naar de invloedsfactoren van golfbelasting en de morfologische effecten op slikken en schorren in de Beneden Zeeschelde, meer specifiek op het Galgeschoor: Deelrapport 6: Verslag ad hoc-

Wang, H., D. van der Wal, X. Li, J. van Belzen, P. M. J. Herman, Z. Hu, Z. Ge, L. Zhang, and T. J. Bouma (2017), Zooming in and out: Scale dependence of extrinsic and intrinsic factors affecting salt marsh erosion, *J. Geophys. Res. Earth Surf.*, 122, 1455–1470, doi:10.1002/2016JF004193.

Zhu, Q., Yang, S., & Ma, Y. (2014). Intra-tidal sedimentary processes associated with combined wave-current action on an exposed, erosional mudflat, southeastern Yangtze River Delta, China. *Marine Geology*, 347, 95–106. <https://doi.org/10.1016/j.margeo.2013.11.005>