Projecting Hydro-Morphodynamic Impacts of Planned Layout Changes for a Coastal Harbor

Oliver Lojek[1]; Nils Goseberg, M.ASCE[2]; and Torsten Schlurmann[3]

Abstract: The macrotidally influenced harbor of Dagebüll on the North Sea coast of Germany features a piled south jetty, for which provided constructive designs are investigated regarding their potential hydro-morphological impacts on the harbor area and adjacent navigational channel. The harbor experiences a steady accumulation of sediment. This results in a reduction of navigational depth and necessitates regular maintenance dredging constituting a cost aspect. A comprehensive field study was conducted, deploying a ridged inflatable boat (RIB) equipped with differential Global Positioning System, a winch for conductivity, temperature, and depth casting as well as sediment and water sampling and an acoustic Doppler current profiler for current profiling. Measurements reveal a tidally governed alternating flow pattern inducing a vortex current inside the harbor basin. Hydrodynamic sea floor grain sorting is detected through sediment sampling. A numerical model cascade is developed and calibrated against available tide gauge and sediment inventory data as well as multibeam survey data and acquired field measurements. The calibrated model cascade is used to simulate layout variants and compare resulting impacts to identify preferable jetty designs. **DOI: 10.1061/(ASCE)WW.1943-5460.0000666**. *This work is made available under the terms of the Creative Commons Attribution 4.0 International license, https://creativecommons.org/licenses/by/4.0/.*

Introduction

Hydro-morphodynamics drive deposition and erosion of sediments across scales and are a topic of continuous interest as they affect the operational cost of harbors and coastal infrastructure (Christiansen 1987; Verlaan and Spanhoff 2000). Furthermore, harbors constitute a focal point of interest in humans striving towards becoming a sustainable and beneficial civilization, as ship actions in harbors contribute approximately 70% of all marine emissions (Endresen 2003; Corbett et al. 2007). Developing green harbor infrastructure depends on multiple critical factors according to Chen et al. (2019), calling for an integrative concept. Such an integrative concept has been developed for the harbor of Dagebüll within a framework of offshore harbors and hinterland connections across supply chains initiated 2013 by the federal state of Shleswig-Holstein (Harborcooperation Offshore-Harbors North Sea SH 2013). A major contribution to the environmental impact of harbors apart from the commuting ferries and service vessels stems from their sedimentation, calling for extensive recursive maintenance dredging operations. Harbor siltation caused an estimated €500 million dredging cost for marinas and ports situated at the Dutch coast from 1990 to 1995 with an anticipated backlog of twice as much (Ommen and Schaap 1995), whereas a total of $3.025 billion were allocated to maintenance and operation in US harbors (USACE 2019). Dredging, treatment, or disposal costs are often high and continue to grow, as regulations are becoming more strict (Frittelli 2019). This leads to sediments being classified as contaminated and this complicates maintenance works, a serious problem for small harbors, e.g., those located along the German North Sea coast (BfG 2000) with associated dredging costs of up to €36/m^3 (City of Hamburg 2016). High maintenance cost poses an economical threat to ports and small harbors in particular, as their turnover and productivity may fall short of balancing the accumulating costs. Initial trial-and-error-based investigations (Bonnet and Lamoen 1948) of mitigation methods have since been replaced by increasingly more sophisticated research approaches (Christiansen 1987; Nasner 1996; van Schijndel and Kranenburg 1998; Hofland et al. 2001; Winterwerp 2005; Kuijper et al. 2005; van Maren 2009; van Maren et al. 2011). Krone (1987) introduced the concept of *keep the sediments in the system* (KSIS), rather than removing them, in order to prevent unnatural concentration gradients which, in turn, could accelerate siltation processes. This concept has been developed further by PIANC (2008) and is summarized by Headland et al. (2007) proposing three main strategies to minimize harbor siltation (MHS): (1) *keep sediment out*, (2) *keep the sediment moving*, and (3) *keep sediment navigable*. Those categories are further subdivided into passive (e.g., constructional) and active measures (e.g., sluices, locks). In particular, approach (1) will encompass constructional measures which require extensive planning and investigations prior to any practical implementation. Similarly, Kirby (2011) presented sediment management strategies serving as best-practice examples on how harbors cope with the ongoing challenge of erosional and depositional processes in and at close proximity to harbors. However, many

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Note. This manuscript was submitted on November 15, 2020; approved on May 28, 2021; published online on August 31, 2021. Discussion period open until January 31, 2022; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Waterway, Port, Coastal, and Ocean Engineering***, © ASCE, ISSN 0733-950X.

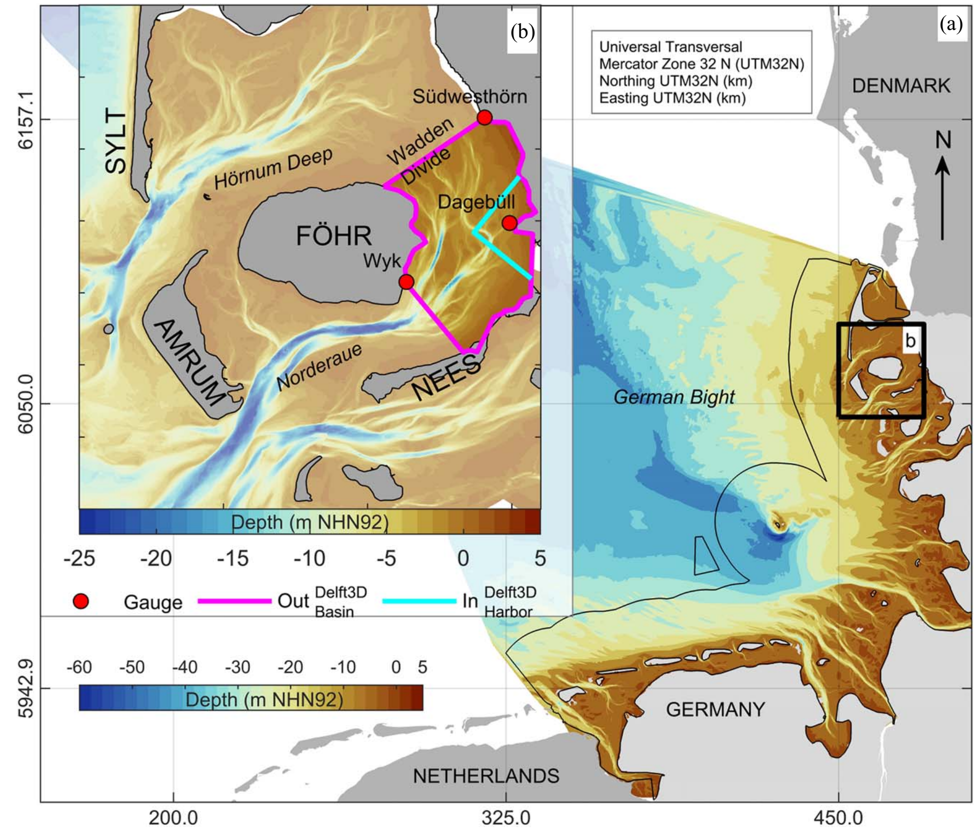


Fig. 1. (a) Location of the focus area with the Port of Dagebüll in relation to the German North Sea coast; and (b) focus area tidal basin, with indicated extents of the larger model and the detailed near-field harbor model.

situations require more detailed planning of constructional changes; this is particularly important in regions where environmental restrictions apply as is the case for the harbor of Dagebüll, the harbor for which this study presents a work flow of tasks to arrive at reliable decisions when required to assess the impact of refurbishments on local hydro-morphodynamics.

Study Area

The port of Dagebüll is situated within a tidal basin in the North-Frisian Wadden Sea [see Fig. 1(b)]. The tidal basin around the island of Föhr is delineated by Sylt in the North, Amrum to the West, Nees to the South, and the North-Frisian coast with the harbor of Dagebüll to the East, latter being the focal point of interest.

Such a combination of barrier islands, deeper tidal channels, tidal flats, and coastline is typical for the North-Frisian coast (Hayes et al. 2005) where morphological interactions within the tidal basin are strongly coupled. The tidal system around the island of Föhr comprises two subbasins, namely the northern *Hörnum Tief* and the southern *Norderaue* comprising a total area of 539 km^2. The tidal basins are characterized by intertidal flats and tidal inlets, which branch out into tributaries towards the coast. Both basins are separated by Wadden divides running along the Föhrer Schoulder and the Föhrer Ley on the North East side of Föhr and one between Amrum and Föhr on the South West side of Föhr. For tidal characteristics and spatial distribution, the interested reader is referred to Schmidtke and Lammers (2004) and LKNSH (2013). The port, located at the coast as depicted in Fig. 1, hosts a tide gauge at the tip of the south jetty. The mean tidal range is 2.99 m (Waterways and Shipping Administration of the Federal Government 2020). The current layout of the port features two jetties, a 145 m long heavy-duty north jetty and a 40 m long south pier (see Fig. 2). A particularity of the south jetty is its split construction (permeable–rigid) allowing the front section to be flown through (Hafengesellschaft-Dagebüll 2016). The maintenance depth of

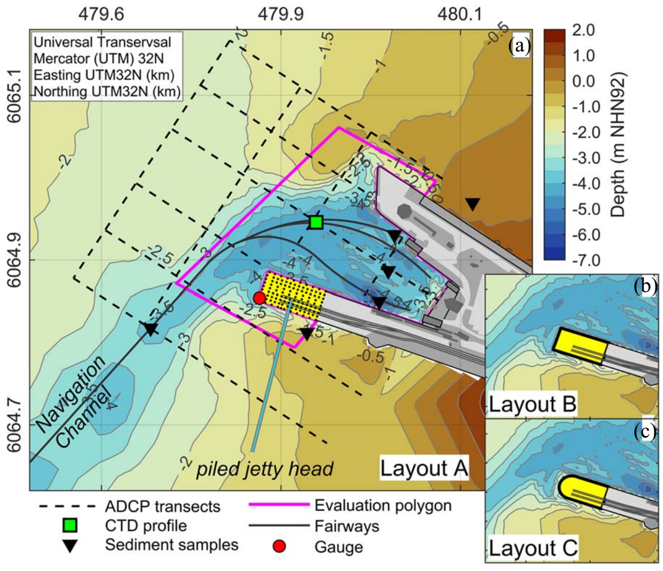


Fig. 2. (a) Layout A flow-through pile foundation tip with indicated tide gauge location, ADCP-transects, navigational channel, fairways, sediment sampling sites and evaluation polygon on (dredged) bathymetry; (b) layout B with impermeable sheet pile wall; and (c) layout C featuring a rounded jetty tip as sheet pile wall.

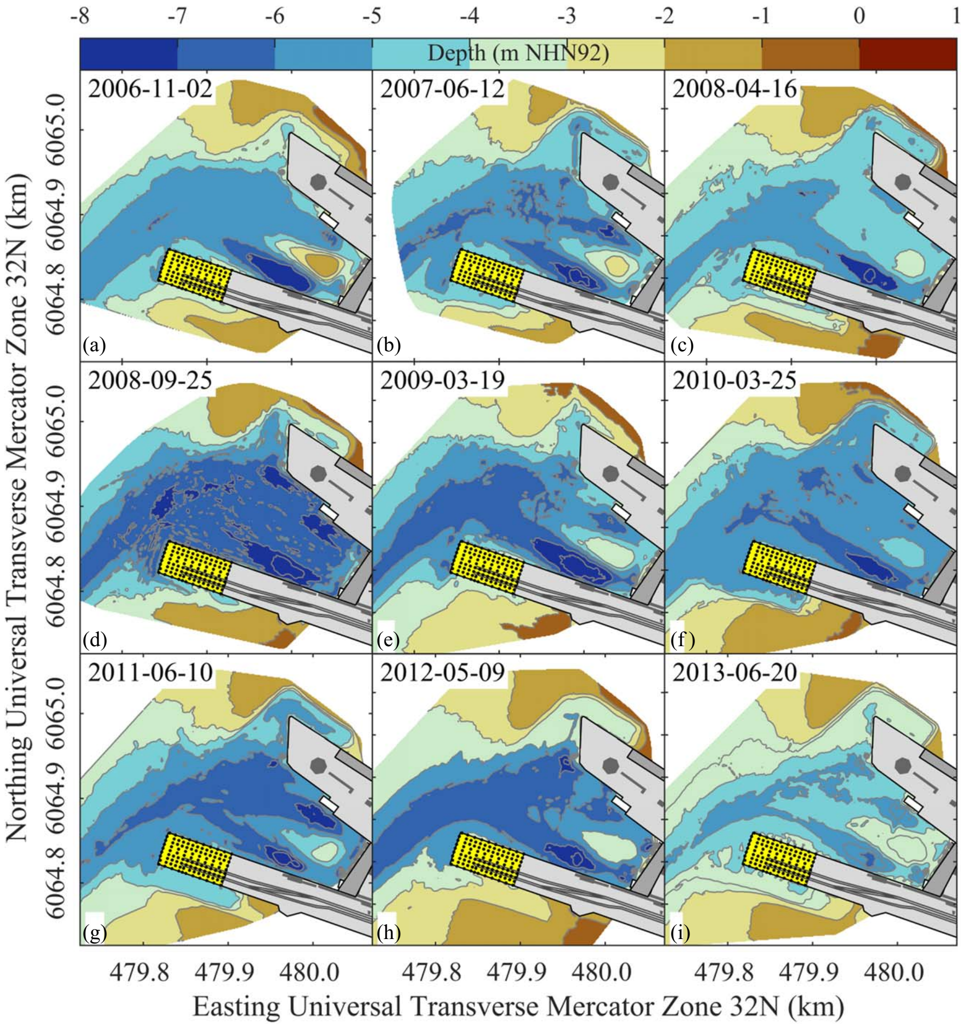


Fig. 3. Survey data compilation for the port of Dagebüll 2006 to 2013 with the jetty head in need of refurbishment indicated. Depth is referenced to NHN92: (a) Survey date 2006-11-02; (b) Survey date 2007-06-12; (c) Survey date 2008-04-16; (d) Survey date 2008-09-25; (e) Survey date 2009-05-19; (f) Survey date 2010-03-25; (g) Survey date 2011-06-10; (h) Survey date 2012-05-09; and (i) Survey date 2013-06-20.

4.5 m standard elevation zero (*Normalhöhennull*) (NHN92) is ensured by irregular dredging operations. The port is subjected to the continuous influence of tides and wind waves. Sediment transport causes siltation of the harbor basin. Therefore, the harbor basin requires seasonal dredging operations to maintain navigability (Wyker-Dampfschiffs-Reederei 2016). Available survey data is given in Fig. 3. This data stems from dredging campaigns and was used to compute differences, which are visualized in Fig. 4, showing increasing siltation of the berthing areas and navigational channel. The survey data raised questions regarding the hydromorphodynamic situation developing at the harbor of Dagebüll during flood and ebb emphasizing the need for comprehensive field measurements, because no other data than presented existed when the study was commissioned. Maintenance dredging was achieved using water-jet injection (WI) dredgers, mobilizing sediments during ebb stream. Dredged volumes were computed and together with corresponding dates, compiled in Table 1. The port, initially planned for fishery and island supply, is also referred to as the Gate to the islands (Hafengesellschaft-Dagebüll 2016) and faces growing volumes and loads handling off-shore energy structures. Off-shore energy parks partially serviced and installed from Dagebüll amount to a total of 2,130 MW and constitute the windparks HelWin and SylWin (BMWE 2019) rendering Dagebüll a fifth-generation harbor according to Chen et al. (2019) especially considering the integrative concept (Harborcooperation Offshore-Harbors North Sea SH 2013).

The tip of the south jetty currently rests on steel piles, which require refurbishment owing to corrosion. In light of the increasing and diversifying loads, the south jetty is not only in need for repair but requires reinforcement. Thus, constructional options for the south jetty refurbishment were considered in a predesign phase of the project. In the sequel, their potential effects on the local hydro-morphodynamic situation were questioned; however, engineering expertise alone in combination with an analytic model, for example that developed by van de Kreeke (1996, 2006), would not have been sufficient to assess the complex interdependencies that exist between the harbor area and its sediment budget's response.

Objectives

The specific aim of this study is to establish a hydro-morphodynamic model of the Port of Dagebüll, which can first reproduce the overall magnitude of the sedimentation and erosion pattern. Second, it ought to be used as a prognostic tool to facilitate further constructional planing. Based on the above-presented motivation, the objectives of the current study more generally are as follows.

1. To provide a comprehensive overview over required data sets, their processing, merging in the context of small harbor siltation

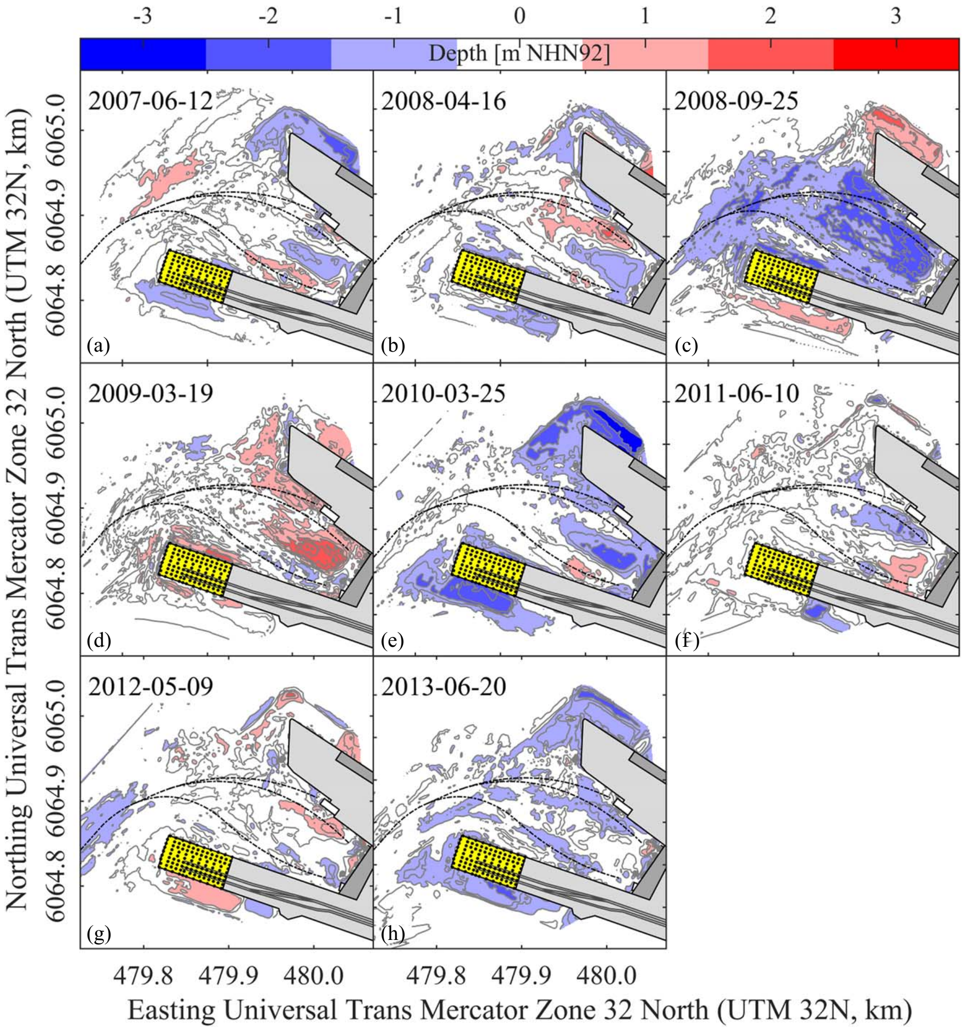


Fig. 4. Computed difference maps based on survey data given in Fig. 3: (a) differences post WI dredging after 222 days; (b) control survey after 309 days; (c) differences post WI dredging after 162 days; (d) control survey after 175 days; (e) differences post WI dredging after 371 days; (f) control survey after 442 days; (g) control survey after 334 days; and (h) differences post WI dredging after 407 days.

Table 1. Dredging volumes computed from survey data, based on survey date (first column), time span (second column) between adjacent surveys, observed volume change (third column) and additional information (fourth column)

Date (yyyy-mm-dd)	Span (days)	Volume (m^3)	Additional information
2007-06-12	222 (b-a)	−6,300	WI, unpolluted
2008-04-16	309 (c-b)	+1,250	Control survey
2008-09-25	162 (d-c)	−23,950	WI, unpolluted
2009-03-19	175 (e-d)	+18,350	Control survey
2010-03-25	371 (f-e)	−21,600	WI, unpolluted
2011-06-10	442 (g-f)	+2,000	Control survey
2012-05-09	334 (h-g)	+28,600	Control survey
2013-06-20	407 (i-h)	−17,500	WI, unpolluted

studies while specifically providing insight into problems in cases where appropriate data sets are missing.

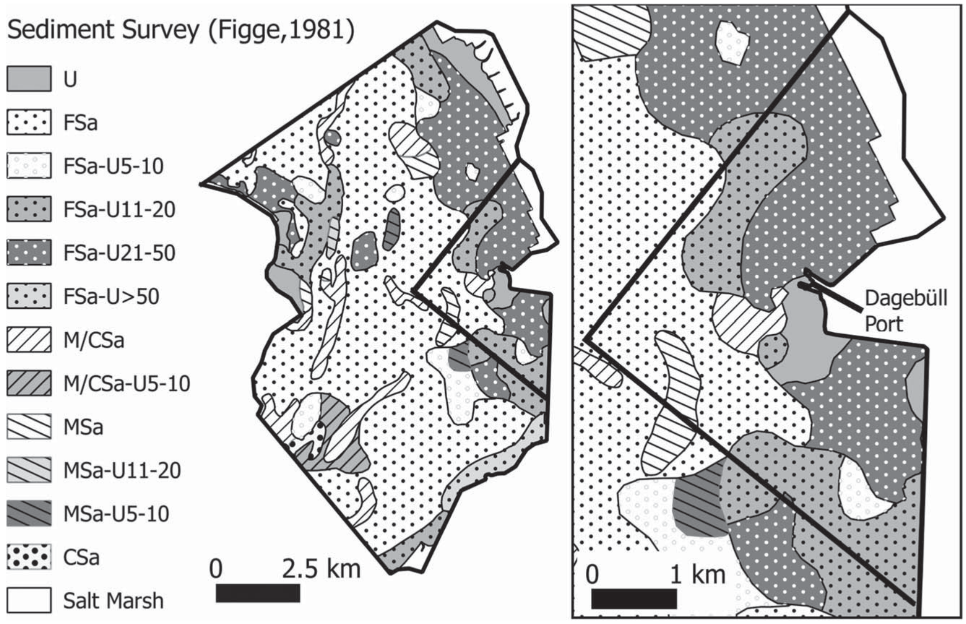
2. To showcase the work flow, its limitations, and challenges, required to set up and reach a calibrated and validated small harbor model based on the example of the harbor of Dagebüll.
3. To discuss and outline the usefulness of seconding in-situ measurements which turned out to be invaluable for the overall assessment of model accuracy and correctness.

Methods

Available data comprised nine survey charts of the harbor basin (Fig. 3), as well as grain size analyses of surface sediments sampled with a grab sampler at the harbor. Methodologically, the available database was extended by a hydrographic survey conducted in August 2013. Measurements of current velocities by acoustic Doppler current profiler (ADCP), and water quality by conductivity, temperature, and depth (CTD) probe over a spring–neap tide cycle were acquired. Additional surface sediment samples were collected. Finally, initially provided and acquired data were combined to develop a hydro-numerical (HN) model of the tidal basin with a detailed model nested inside of the port of Dagebüll.

Numerical Model

For the numerical modeling, the Delft3D model suite (Deltares 2014; Lesser et al. 2004) was employed to govern the problem at hand by employing a nesting approach. The numerical model setup is erosion limited and conceptualized to reproduce hydromorphodynamics on short- to medium-scale time spans, given the survey data at hand (see Fig. 4). The outer HN model discretizes the tidal basin system delineated by the coastline, tidal inlets, and



(a) (b)

Fig. 5. Sediment survey information from Figge (1981) for the model domains: (a) large domain, nested domain outlined by black lines; and (b) nested domain with indicated harbor position. Sediment classification according to DIN (2003).

Wadden shed divides (Lindhorst et al. 2008) with a regular grid cell resolution of 75 m × 75 m covering 311 km^2 of tidal flats (see Fig. 1). The nested, inner HN model spans the port of Dagebüll at a much higher resolution of up to 1 m × 1 m covering 30 km^2 and is forced with boundary conditions generated by the outer model. The HN models are subsequently calibrated against gauge and vessel-based field measurements of a spring–neap tide cycle as no reasonable data sets are available for the region. Subsequently, the calibrated model cascade is employed to simulate sediment transport and morphodynamic bed-level changes as a response to refurbishment-related layout changes. The basin of the harbor Dagebüll is susceptible to muddy siltation and to date requires regular, costly maintenance. Therefore, potential changes as a result of refurbishment measures on hydrodynamics and coupled sediment transport processes needed to be investigated.

Boundary Conditions

The tidal basin system is tide-dominated (Lindhorst et al. 2008). At the Dagebüll harbor site, morphodynamic processes are mainly governed by tidal currents, as wind waves induced by westerly winds are blocked by the barrier islands Amrum, Sylt, and Föhr (Franzius-Institute 2004; BSH 2016; HZG 2016). Recent studies showed that modeling approaches applying tidal boundary forcing alone are generally able to reproduce characteristic morphodynamic patterns within tidal basins in the Wadden Sea (van der Wegen and Roelvink 2008; Dissanayake et al. 2009, 2012). In a similar manner, only tidal boundary forcing is applied to the outer tidal basin model, for inducing sediment transport, which in turn is exported along the boundaries of the nested harbor model. This information is subsequently used to drive morphodynamic simulations within the smaller model. The southern boundary is therefore forced by water surface elevation data (time history) derived from a tide gauge which is located on the island of Wyk as indicated in Fig. 1(b). It was hypothesized that lateral inflow along the southern boundary may be disturbed by Coriolis forcing or complex bathymetric interactions and feedback during tidal filling. However, this hypothesis was tested and rejected employing a precalibrated continental shelf model. Furthermore, the northern boundary was placed on a Wadden divide with negligible overflow (LKNSH 2013; Schmidtke and Lammers 2004). Simulations with Dirichlet as well as Neumann boundaries did not have any effect upon the focus region and were thus replaced by a closed boundary for the sake of simplification. Similar approaches for delineating tidal basins are reported in literature (Rahbani 2011; Dissanayake et al. 2012). The nested model domain is forced with a water level boundary at the South Boundary and a current velocity boundary to the West. Values for water levels, current velocities as well as sediment concentrations, temperature, and salinity are extracted from the larger domain and used to force the smaller domain in a subsequent step.

Table 2. Sediment fractions implemented in the bed stratigraphy of the numerical models

Fraction	Type	d_{50} (mm)
Cohesive	U	≤0.063
Fine sand	FSa	≤0.15
Medium sand	MSa	0.2
Medium/coarse sand	MCSa	0.38
Coarse sand	CSa	0.63

Bed Composition and Stratigraphy

In order to investigate potential morphological changes due to refurbishment options planned by the harbor, a bed stratigraphy approach with five sediment fractions is utilized. Consequently, bed composition information is obtained for the upper 0.2 m of top soil from soil survey maps as a first indication of bed stratigraphy (Figge 1981; DIN 2003; Valerius et al. 2015), which were then verified by soil samples in sample areas. The distribution of sediments at the surface of the domains is presented in Fig. 5 with fractions summarized in Table 2. Total number of sublittoral bed layers was set to 10 with a homogenous thickness of 1 m and a composition of 50% FSa and 50% MSa. The available sublittoral information was aggregated into a layered 3D seabed model. This was subjected to bed composition generation runs by deactivating morphodynamic update of the

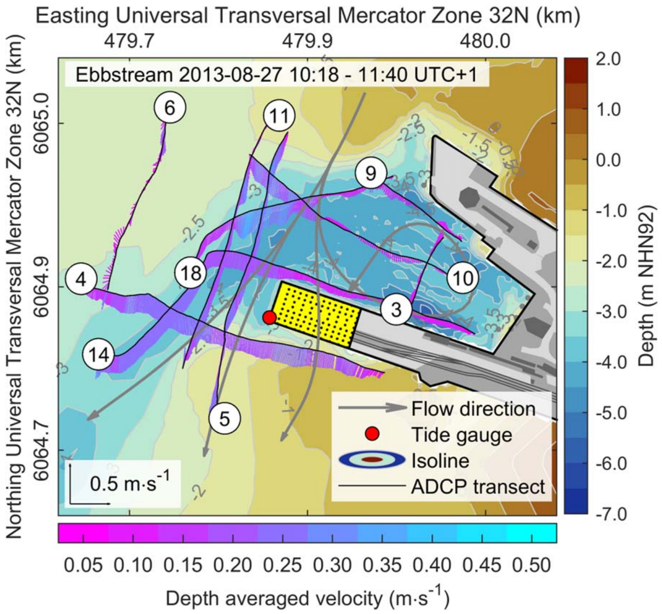


Fig. 6. ADCP transects measured at the port of Dagebüll. Vectors indicate depth-averaged flow velocities and direction. Scale vector is given in the bottom left.

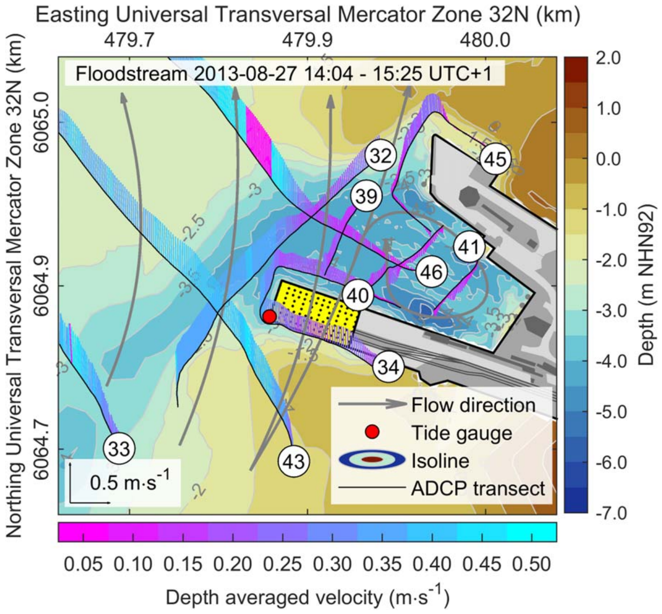


Fig. 7. ADCP transects measured at the port of Dagebüll. Vectors indicate depth-averaged flow velocities and direction. Scale vector is given in the bottom left.

bed elevation but allowing a redistribution of the sediment volume fractions according to tidal hydrodynamics until quasi-equilibrium states were obtained for the fractional volume changes as presented in Figs. S1 and S2, resulting in a generated bed distribution shown in Fig. S3, which was used as initial conditions for the calibration and validation runs and the variant study.

Field Observations

Measurement results for ADCP transects of depth-averaged velocities are depicted in Figs. 6 and 7. During ebb flow, the tidal flats around the harbor fall dry and only the navigational channel connecting the harbor with the *Norderaue* carries enough water for vessels to access Dagebüll independent of tide. During ebb flow, patterns are directed South-South-West in front of the port basin, as well as within the navigational channel (cf. Fig. 6).

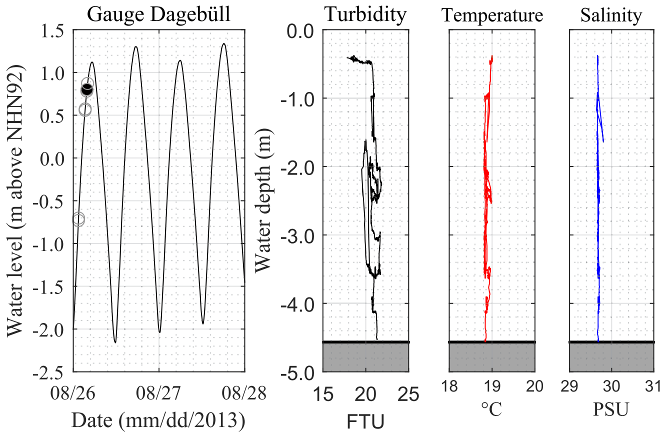


Fig. 8. Tide gauge data with indicated CTD profiles measured. Solid dot indicates CTD profile displayed.

Current velocities average 0.6 m s^{-1} in front of the port and a maximum of 0.2 m s^{-1} within the basin. The tip of the south jetty is clearly flown through as current velocities are slightly larger here than in the rest of the port basin. During flood (cf. Fig. 7) the overall flow pattern is inverted, flowing North-North-East past the port basin and over the sanders onto the intertidal flats. Current velocities exhibit a similar magnitude between 0.1 to 0.2 m s^{-1} within the basin and reaching maximum values of 0.6 m s^{-1} passing in front of the harbor.

Observed depth-averaged g l^{-1} suspended sediment concentration (SSC) values exhibited 0 g l^{-1} for almost all measurements and maximum of 0.47 g l^{-1} for the beginning of the flood stream throughout the whole water column (see Fig. 8). Hence, no vertical density stratification was identified in the measurements. Laboratory analysis of three water samples of 2 l each and a linear regression of a dilution series yielded the following equation with a correlation coefficient $R^2 = 0.93$:

$$\mathrm{SSC}(\mathrm{g\,l^{-1}}) = 6.82 \times 10^{-3} \cdot (\mathrm{FTU}) - 4.5583 \times 10^{-1} \qquad (1)$$

Sediment Parameters

Sediment transport for the sand fractions was calculated based on the Rijn TR2004 equation (van Rijn 2007), whereas a fines section ($\leq 63\,\mu$m) was used to represent the Wadden Sea tidal flats. This fraction's transport was calculated using the Partheniades-Krone formulations (Krone 1962; Partheniades 1965). The model was set up with a stratified sea bed model (Wegen et al. 2011), composed of an active transport layer on top and a user-defined number of sublayers for sediment book keeping. According to van der Wegen (2010), the most dominant calibration parameters are the critical shear stresses for erosion and sedimentation, dry bed density, settling velocity, and erosion. However, sensitivity analysis revealed the critical shear stress to be most predominant, controlling erosion and deposition of the sediments and reflected findings by Dissanayake et al. (2012). Parameters determined by a sensitivity study prior to modeling the Dagebüll harbor domain are the critical shear stress for erosion with a mean value of $\tau_{\mathrm{crit},e} = 0.15$ N/m^2 (cohesive fraction). The critical shear stress for deposition $\tau_{\mathrm{crit},d}$ was varied from 0.1 and 100 N/m^2, where 100 N/m^2 was implemented in the final simulations, implying a constant settling of sediments, unless the hydrodynamics remobilize these. The dry bed density ρ_{dry}, for which a range from 189.3 to 485.1 kg was inferred from lab analyses of soil samples, was varied between 2×10^2 to 5×10^2 kg/m^3, with 3.8×10^2 kg/m^3 giving the results. The erosion rate constant M (kg m^2/s) was varied between 1×10^{-1} and 1×10^{-3}, following approaches from Ledden et al. (2006) and Dissanayake et al. (2012), with 5×10^{-3} yielding best values. The particle sinking velocity in saltwater $w_{\text{sink,salt}} = 4.7 \times 10^{-2}$ mm/s was initially obtained from samples collected. Final simulations where conducted with $w_{\text{sink,salt}} =$ 0.3 mm/s. The deviation from the observed value here is necessary, as the chosen 2D approach lacks depth-resolving information of the water column and entrained sediments, which does not accumulate sufficient sediments otherwise. The transport layer thickness was set to 0.4 m in accordance with previous findings by Ledden et al. (2006) and van der Wegen (2010), scaling the transport layer thickness to 50% of the local bed form heights.

Calibration and Validation

A calibration phase from June 12, 2007 to April 16, 2008 (309 days) has been defined. An ensuing validation period lasted from September 25, 2008 until March 19, 2009 (175 days). Both periods are oriented at the dredging intervals documented in Figs. 3 and 4 for modeling the siltation of a dredged bathymetry. Model hydrodynamics have been calibrated and validated against tide gauge data from Südwesthörn as well as Dagebüll, whilst Wyk auf Föhr records have been used to force the outer model domain. Main calibration parameter is the variable bed Manning roughness coefficients ranging between 0.018 to 0.025 s/m$^{1/3}$ (cf. Fig. S4), which are aligned with a sediment distribution mapped by Figge (1981) and Valerius et al. (2015) given in Fig. 5 and refined to minimize errors in water levels and current velocities. Near-field hydrodynamics around the port of Dagebüll have been compared with ADCP measurements acquired during the field campaign and showcase a good representation of the general flow field around the port by the numerical model (cf. Figs. 6 and 7). A qualitative hydrodynamic comparison is compiled in Table 3. General flow patterns and magnitudes simulated for flood and ebb in a silted state with the validated model are compared with field measurements of a similar system state. It is noted that the simulation uses bathymetric data from 2009 and tide gauge data from 2013, whereas measurements were acquired in 2013. Hydrodynamic model performance exhibits a correlation coefficient for water levels of 0.97. Current velocities can only be compared on a qualitative level and reach a correlation coefficient of 0.85 for the validation period.

Morphodynamics have been calibrated using dredging-related survey data from June 12, 2007 [cf. Fig. 3(b)] and April 16, 2008 [cf. Fig. 3(c)], in conjunction with field data on sea bed sediment characteristics and laboratory analysis of soil samples. For evaluating the morphodynamic model performance, the Brier skill score (BSS), as well as the Brier skill score including measurement error (BSSp) proposed by Sutherland et al. (2004) are used (see the following section for details). The BSS score for the validated model reached 0.42 and the BSSp scored 0.57, both these values attest the numerical model a *good* morphodynamic performance according to a classification proposed by Sutherland et al. (2004) and van Rijn et al. (2003).

Model Skill (BSS)

The model skill is evaluated applying the Brier Skill Score (BSS; Sutherland et al. 2004) using the Murphy and Epstein decomposition (Murphy and Epstein 1989):

$$\text{BSS} = \frac{\alpha - \beta - \gamma + \epsilon}{1 + \epsilon} \tag{2}$$

where α is a measure of bed form phase error, a perfect model yields $\alpha = 1$; β is a measure of bed form amplitude error with $\alpha = 0$ indicating a perfect model; γ is the average bed level error, $\gamma = 0$ equals a perfect model; and ϵ is a normalization term, indicating the measurement error. Simulation endpoints are advised to coincide with an end of a hydrodynamic cycle (spring–neap) in order to be comparable (Roelvink 2006). A BSS of 0.5 is considered sufficient for complex applications (van Rijn et al. 2003). It is cautioned that the BSS is not developed for this application purpose and does not necessarily capture characteristics such as lateral displacement of navigational channels and tidal flats and especially filling of a harbor basin. Regardless of its potential shortcomings it constitutes the most widely accepted method for assessing model skill (Dissanayake et al. 2012; Roelvink et al. 2009). Furthermore, the effect of measurement errors on the BSS have been assessed, using an adjusted formula proposed by Sutherland et al. (2004) denominated as BSSp, giving a higher magnitude of skill score compared with the standard BSS.

Table 3. Comparison of velocity measurements acquired in 2013 at the harbor of Dagebüll and along a 10 km long ADCP transect between Wyk and Nees and simulation values of the numerical model. Measurements and simulation values both represent a silted system state

		Ebb		Flood	
Location	Method	Dir (°)	Mag (m s^{-1})	Dir (°)	Mag (m s^{-1})
Wyk–Nees	ADCP	190	0.50–1.60	300	0.20–1.10
	Delft3D	190	0.40–1.50	300	0.20–1.00
Dagebüll harbor	ADCP	190	0.10–0.40	300	0.10–0.60
	Delft3D	190	0.10–0.45	300	0.10–0.61

Variant Study

Variant layouts were implemented into the validated model geometry in order to simulate potential impacts upon hydrodynamics and coupled sedimentation patterns. Similar studies looking into layout impacts have been carried out previously, however these feature higher current magnitudes (van Schijndel and Kranenburg 1998; Hofland et al. 2001; Winterwerp 2005; Leys 2007; Oberrecht and Wurpts 2014; Jade-Weser-Port 2008; van Rijn and Grasmeijer 2018) whereas the novelty of the current study consists of showcasing the model performance and the work flow to a siltation problem in a harbor in the midst of a sensitive protection zone in the Wadden Sea. For the port of Dagebüll, three layouts regarding the south jetty have been drafted and developed by the port authority for further scrutiny. The initial layout resembles the current status of the harbor; it comprises a transparent south jetty, tagged "layout A" [see Fig. 2(a)]. An evaluation polygon was used to quantify the morphological changes occurring on site. The first layout proposed termed "layout B" comprised a sheet pile wall around the southern jetty, obstructing the tidal flow. A "layout C" was suggested that differed by comprising a rounded pier head; both layouts for the refurbishment alternatives are shown in Figs. 2(b and c). The piled jetty layout A was represented within the model, using a parametric hydraulic structure with an energy loss coefficient $c_{\text{loss}} = 0.7127$ determined based on the pile diameter and quantity per numerical grid cell (Farraday and Charlton 1983 in Deltares 2014, p. 313, Eq. (10.75)). However, the opaque layouts are represented by closing off the grid cells using Delft3D's "thin-dam" function (Deltares 2014).

Results

Based on the input data and parametrization presented in section "Methods," the tidal basin model as well as the detailed nested harbor model are used to project potential impacts on hydrodynamics

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and morphodynamics, arising from layout changes. Accuracy of validation and calibration are presented in section "Calibration and Validation," showing promising levels or reproduction of the situation investigated. As was noted by Roelvink and Reniers (2011), a calibrated model likely deviates from reality the longer the simulated period exceeds the calibration and validation period (see section "Discussion"). For this reason, the simulations conducted here are oriented at dredging intervals covering roughly six months real time between consecutive surveys [cf. Figs. 3(d and e)].

Effect on Hydrodynamics

Simulating refurbishment Layout A (cf. section "Variant Study"), hydrodynamic patterns and magnitudes are readily assessed. In good agreement with field campaign data (cf. section "Field Observations"), the numerical model shows distinct flow patterns developing around the Port of Dagebüll. Furthermore, the semitransparent area beneath the south jetty, shows tidal flow patterns with reduced magnitudes owing to pile drag. Simulated depth-averaged flow velocities closely resemble field observations [cf. Figs. 7 and 6 with 9(a and b), respectively]. Fig. 9 shows simulated maximum flood currents during flood for Layouts A, B, and C [cf. Figs. 9(a, c, and e)]. Similar to the field measurements presented in section "Field Observations" the flood passes along the harbor entrance, develops a vortex already found by in-situ surveying of the site. Vortex flow structures accumulate sediments within their quiescent centers (PIANC 2008). Compared with Layout A, Layout B indicates that the

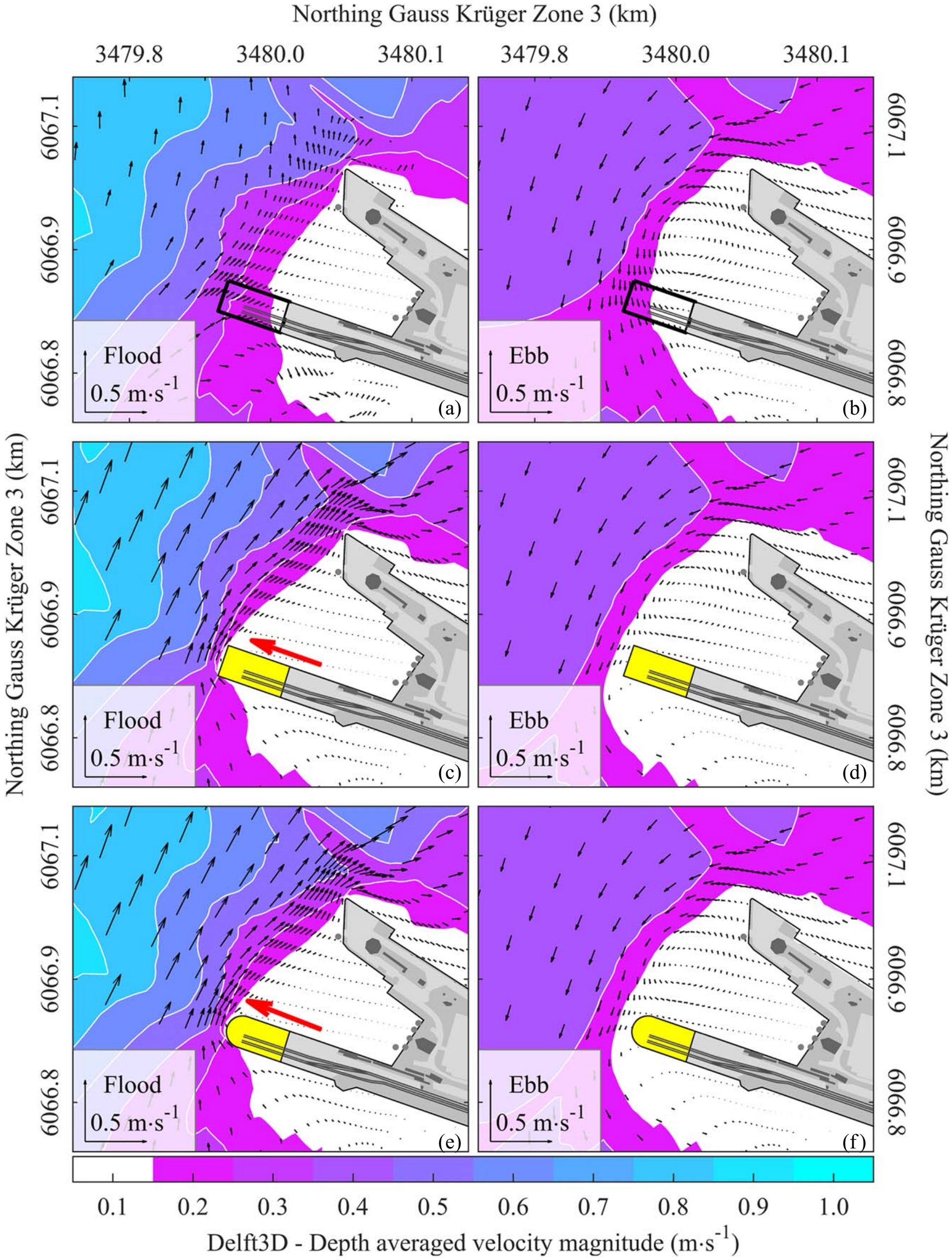

Fig. 9. Depth-averaged current velocity magnitude and flow patterns for Layouts A, B, and C during flood (left panels) and ebb (right panels). Simulation time July 29, 2013 23:50 UTC+1 (flood) July 30, 2013 03:50 UTC+1 (ebb) during spring tide. Isotachs delineate areas of similar depth-averaged flow velocities. Vectors indicate depth averaged flow directions. Note that model results have been resampled for visualization purposes and do not show the subdecimeter resolution.

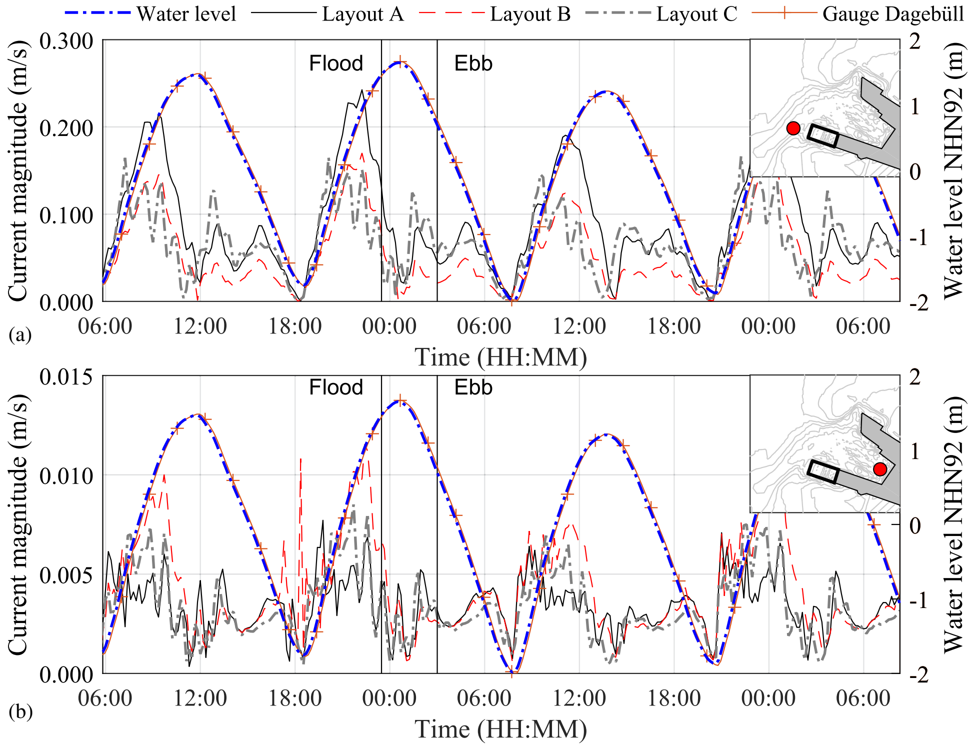

Fig. 10. Comparison of simulated depth-averaged velocity magnitudes during spring tide for Layouts A, B, and C: (a) at the tip of the south jetty; and (b) behind the south jetty inside the harbor basin. Simulation time shown span July 29, 2013 to September 30, 2013.

protruding south jetty diverts the flood current further away from the harbor basin, slightly elevating the overall flow velocity of the vortex and thereby lowering overall siltation rates. Layout C with the rounded jetty head prevents the flood from fully diverting into the harbor basin as effectively as the squared tip of Layout B did [cf. Figs. 9(c and e)].

The ebb stream in Layout A [Fig. 9(b)], induces a vortex flow, rotating counterclockwise within the entrance of the harbor. A possible reason for this difference compared with Layouts B and C lies within the fact that only the square tip would cause a distinct shear zone to develop at the harbor entrance whereas the rounded top would smooth the streamlines without producing considerable shear at the entrance. Layouts B and C both develop a similar vortex; yet compared with Layout A the center of the vortex is relocated approximately 50 m westward. Current magnitudes are similar for ebb stream for all three layouts.

In general, the impact of a jetty layout on hydromechanics in the main tidal channel appears to be limited owing to the comparatively low-energy environment. However, depth-averaged flow velocities within the harbor basin located behind the tip of the south jetty are affected significantly by the layout changes investigated, which becomes apparent in Fig. 10 where depth-averaged velocities over two tidal cycles for two different locations in the vicinity of the harbor are compared.

Sediment transport magnitudes and directions are influenced directly by hydromechanics, described previously. Subsequently, morphodynamics are investigated for the different Layouts.

Effect on Erosion and Sedimentation

Sediment transport patterns and resulting sea-bed level changes are evaluated based off the re-established maintenance depth from 2008 [Fig. 3(d)], which is used as a reference state for modeling the siltation of the port basin until the consecutive survey in 2009. A rapidly occurring in-fill of sediments was identified, which accumulated 18,350 m^3 of sediment within 6 months. Fig. 11 depicts the harbor basin at the two consecutive states, dredged [Fig. 11(a)] and silted up [Fig. 11(b)] based on observations and simulation results [Fig. 11(c)]. The bottom panels show differences between the initial bed morphology and final bed levels, either observed [Fig. 11(d)] or numerically deduced [Fig. 11(e)]. Observation data stem from a single-beam echo sounder campaign. Observed and modeled sedimentation patterns show distinct differences. Most remarkably, the observed sedimentation pattern depicts a distinct subaqueous mound in the harbor basin center and remaining deeper parts at the berthing areas. In contrast, the numerical model results in a smoother, more uniform sedimentation pattern within the harbor basin. Nevertheless, cumulative sedimentation/erosion volumes compare well reaching 83.3% of the observed volume within the evaluation polygon, facilitating ensuing morphodynamic simulations.

On the basis of a calibrated hydro-morphodynamic model that is capable of reproducing hydrodynamic (section "Field Observations") and morphodynamic features, the different harbor layouts proposed were investigated in greater detail with regard to their potential impact on morphological pattern.

Layout B with the opaque south jetty is modeled with the same set of parameters used for Layout A. Over the simulation time of 6 months, a total of 14,700 m^3 (96% of calibration) accumulated within the evaluation polygon, exhibiting slightly favorable siltation rates [see Fig. 12(b)]. Sedimentation patterns are similar to those of Layout A, however the deposition center shifted from the harbor to the channel following the relocation of the vortex ("Field Observations"). As Layout B alters the port entrance width slightly, sheltering it from the tidal flood stream, these findings are in accordance with KSO strategies (PIANC 2008; Smith et al. 2000). Morphodynamic results for Layout C given in Fig. 12(c). This design yielded a net sediment import of

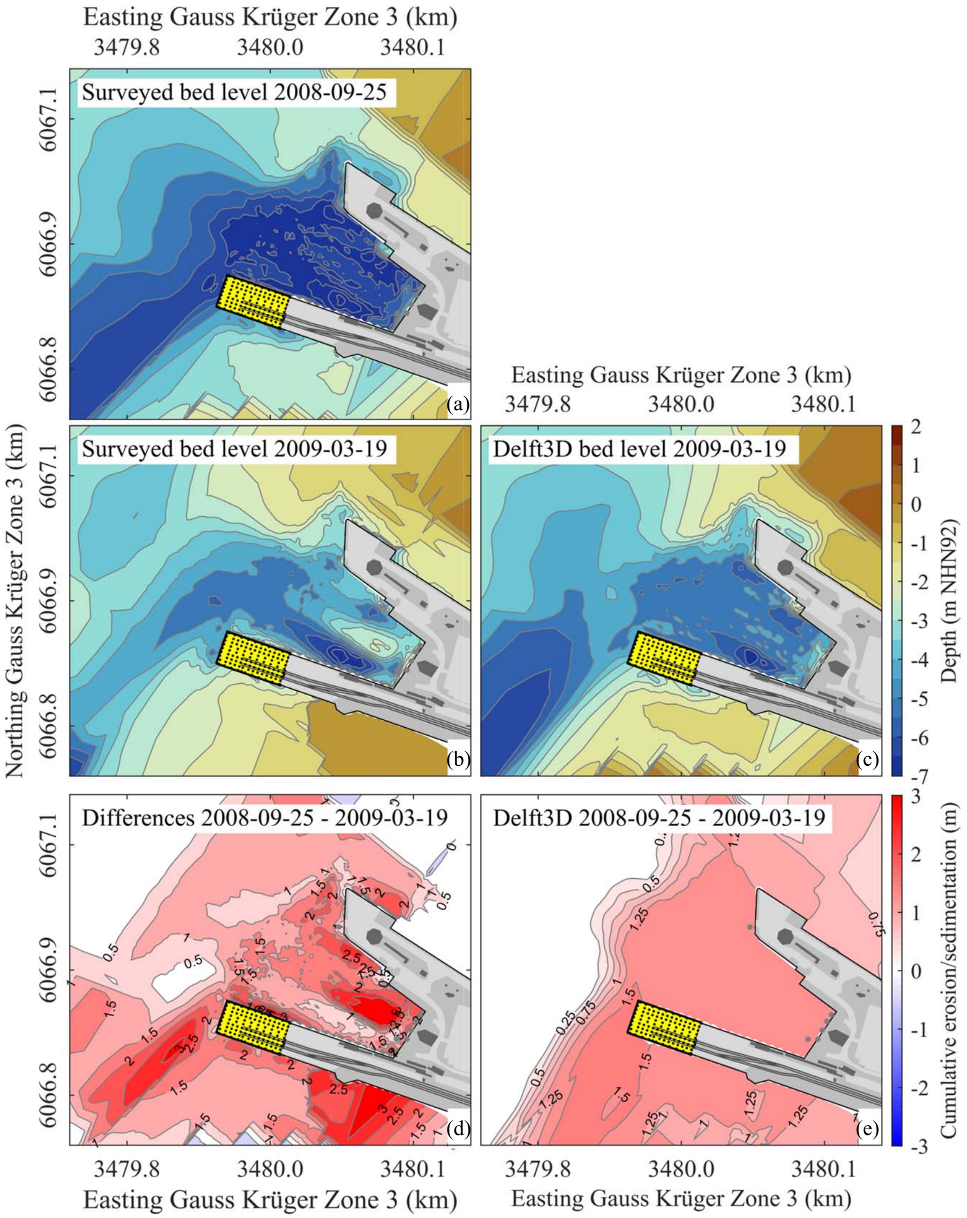

Fig. 11. Port survey data for (a) dredged; and (b) silted situation with (c) simulation result of silted state and respective differences; (d) survey based; and (e) model based. Survey data originates from a single-beam echo sounder.

15,150 m^3 (99% of calibration). It can be conjectured that the rounded pier head shape contributes only little to the overall morphodynamics close to the harbor basin.

Skill Score

Apart from volumes and patterns derived from morphodynamic simulations, results for the status quo (Layout A) are also analyzed using the BSS metrics introduced in section "Model Skill (BSS)" for the evaluation polygon. Simulations yield $\alpha = 0.67$, $\beta = 0.10$, $\gamma = 0.38$, and $\epsilon = 0.11$, resulting in BSS = 0.42 for modeled versus observed Layout A. Based on performance classification proposed by van Rijn et al. (2003) these values are appropriate for this type of study and indicate the model performs well. It is, however, noted that according to Dissanayake et al. (2012) and van der Wegen (2010), the BSS metrics scales as a function of the evaluation polygonal area. The BSSp scores 0.57, slightly higher than the standard BSS, which was expected (Sutherland et al. 2004, p. 935, lines 1–4). Measurement errors for the BSSp include (1) survey instrument-related accuracy of ±0.1 m and (2) transfer-related errors from measurements onto the numerical grid, assessed through reverse interpolation, resulting in ±0.075 m.

Discussion

Recapitulating the motivating and leading questions given in section "Objectives," numerical investigations are based on data covering different scales and periods. Digital bathymetries were generated using dredging-related survey data from 2007–2009, in conjunction with tide gauge date from these years. However, field data acquisition yielded flow field information and vertical stratification, as well as point-based sea floor sediment composition information from 2013. The data was combined within this study

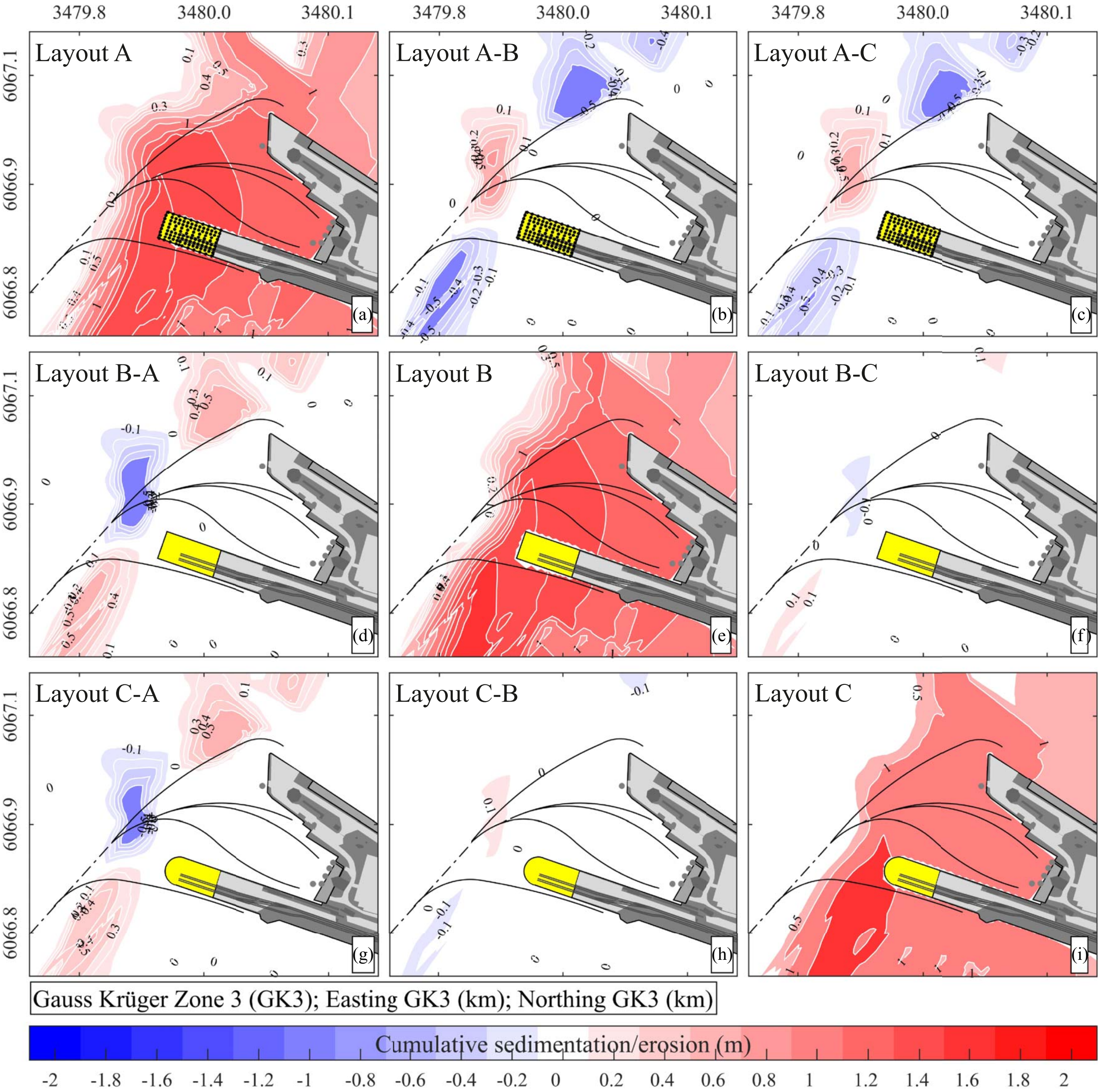

Fig. 12. Cumulative erosion/sedimentation for Layouts A, B, and C and their relative differences after 6 months simulation time.

given the following line of thought. (1) Dredging concepts at the port of Dagebüll have not been altered in regards to their extend or maintenance depth and (2) the port itself was not subjected to constructive alterations pertaining to its berthing areas or jetties since the acquisition of the survey data used within this study. (3) Initial bed composition generation runs have been conducted with the numerical model to induce hydrodynamic grain sorting and thereby reduce unrealistic and undesirable bathymetry and sediment composition adjustments in the initial simulation phase, potentially obscuring actual results. The survey data shows two system states, (i) dredged and (ii) silted, between which the morphodynamic system oscillates. Consequently, the qualitative flow field developing around the port of Dagebüll during different tidal phases is oscillating between the documented flood and ebb patterns. Confined by stable sea dikes and revetment, the tides bathing the harbor of Dagebüll move sediments within a morphodynamic system with a very low degree of freedom. Therefore, the ADCP measurements are valued as generic observations, they are representative for a similar (silted) system state on the investigated time scale (1–5 years), which does not include sea level changes and associated impacts on tidal dynamics or constructive alterations. This facilitates comparing numerical hydrodynamics from 2007–2009 with field data from 2013 for the identical tidal phase (spring tide) for a similar system state representing a silted harbor area. Furthermore, morphological macrofeatures such as tidal channels, tidal flats, but also sediment distribution patterns, develop on a much longer time scale compared with tidal hydrodynamics. As a result, the bathymetry of the tidal basin around Föhr is relatively constant and void of large lateral displacements of tidal channels and sea gats, which would otherwise conflict with the approach chosen for this study. Last but not least, sampled sediment characteristics compare well with initial sediment mapping (Figge 1981; Valerius et al. 2015) and thereby corroborate the chosen approach. Simulation periods are kept reasonably short, only spanning months. Numerical models are calibrated and validated for specific periods, which should be representative system states. However, every natural system may slowly change under variable environmental forcing. Consequently, even the best validated models encounter diminished validity, with increased simulations spans. In addition, the model at hand does not incorporate wind waves, which also rework the tidal area. Finally, maintenance activities are not implemented in the model, but are used as benchmarks for simulation periods. Potential sources and drivers responsible for the observed differences between simulated and measured sedimentation pattern around the harbor area not included in this model could stem from: (1) wind wave action, even though the fetch is very limited for this area, the winter storm period will likely have an influence on the redistribution; (2) fluid mud, known to form estuaries could potentially form under certain circumstances and consolidate in the harbor basin; (3) continuous nautical traffic causes wake-related resuspension of sediments and draws sediment plumes into the berthing areas where they settle, this was especially well observed during the field campaign; (4) tidal pumping could play a role during certain tidal phases, as the harbor basin is connected to the North Sea by an artificial navigational channel, traversing tidal flats that fall dry during ebb; (5) a potential alteration of the sediment composition could change the deposition characteristics, this could be caused by invasive species such as mussels; (6) far-field construction measures such as beach nourishment could introduce new sediment sources; (7) numerical grids influence energy fluxes and coupled transport characteristics. BSS and BSSp are used as statistic performance indicators apart from absolute volumes for sediment transport and classify the results as good. Numeric hydrodynamics compared well with observed tidal water levels as well as depth-resolving ADCP transects and reproduce the flow field and magnitudes and support the chosen approach. CTD measurements indicate no vertical layering and thus justify the simplification of a depth-averaged numerical approach for this design study, increasing computational efficiency.

The deviation of the modeled sedimentation and the observed volumes is attributed to the comparably high nautical traffic at the port, with berthing operations every 30 min importing suspended sediments into the harbor basin, as was observed during the field campaign.

Nevertheless, the observed marginal reduction of harbor sedimentation between the investigated alternative layouts reveals, that if the slightly favorable layout B would be realized without any other system changes, a 5% reduction could be achieved. Despite the small number, given the average dredging costs of €5/m^3 (City of Hamburg 2016) and the high environmental restrictions and additional operations costs owing to the Wadden Sea nature park (BfG 2000) this could render economically attractive to the harbor authorities. Additional options could be current-deflection walls at the jetties to diverge the sediment-laden tidal streams away from the harbor (Hofland et al. 2001; van Maren et al. 2011; Stoschek and Zimmermann 2006). Given the integrative concept (Chen et al. 2019; Harborcooperation Offshore-Harbors North Sea SH 2013) for harbors, however, another substantial aspect to consider are the nautical activities.

Conclusion

The study aimed at exemplifying a typical work flow and steps required to facilitate harbor design on a smaller scale. In regard to the objectives of the morphological study, the following conclusions can be drawn.

- In order to provide reliable and accurate output of a hydromorphodynamic model, a meaningful database of bathymetric data of the study site and additional information about sedimentological as well as stratigraphical information is required that also exhibits a temporal component with dredging events and, ideally, the inclusion of potential storm events. Moreover, conducting in-situ measurements of water depth, closely surveyed flow velocities and sampling of sediment over at least two tidal cycles is highly recommended as it provides invaluable data to calibrate and validate the model setup.
- The work flow outlined in the current study may be seen as a minimum example to setup an informative numerical model; close communication between the planners and modelers is recommended as local specialties and planed layout modifications need to be included in the model as accurate as possible.
- It is indispensable to inform and discuss with planners and designers about factors that at current are beyond standard modeling practice. For one, it cannot be modeled easily how scour as a result of ferries stopping at the berthing areas evolves and how the scouring interacts with the tide-driven morphodynamic evolution.
- Although the presented results do little in terms of reducing overall sedimentation volumes, the conclusions with respect to the original questions by the harbor operator are all the more valuable as the study was able to confirm that the intended layout modifications would not turn the status quo sedimentation rates into something worse. This is especially valuable given the jurisdictional constraints of the Wadden Sea national park, because detrimental effects upon adjacent park areas due to intensified sedimentation and associated dredging activities would inevitably be connected to higher costs and legislative hurdles. Insofar, small-scale morphodynamic modeling appears to be invaluable to answer questions of harbor operators and designers. These inevitably represent an invaluable tool set for engineers to facilitate harbor industry in their quest to reinvent their operational basis.

Data Availability Statement

Field observation data and model input files can be acquired from the corresponding author upon reasonable request.

Acknowledgments

We would like to thank all students who participated in the in-situ measurements. Special thanks go to the technical staff of the Ludwig-Franzius-Institute for Hydraulic, Estuarine, and Coastal Engineering for developing and adopting field equipment for the project accordingly. Funding was provided by the Harbor of Dagebüll through the Engineering Office Mohn, tasked with developing constructive layout options for the jetties.

Notation

The following symbols are used in this paper:

M = erosion rate constant (kg m^2);
c_{loss} = pile energy loss coefficient (−);
d_{50} = average grain size diameter (mm);
w_{sink} = settling velocity (mm/s);
α = bed form phase error (−);
β = bed form amplitude error (−);
γ = average bed level error (−);
ϵ = normalization term (−);

ρ_{dry} = dry bed density (kg/m^3);
$\tau_{\mathrm{crit},c}$ = critical bed shear stress for erosion (N/m)^2; and
$\tau_{\mathrm{crit},d}$ = critical bed shear stress for deposition (N/m)^2.

Supplemental Materials

Figs. S1–S5 are available online in the ASCE Library (www.ascelibrary.org).

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