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Future sediment exchange between the Dutch Wadden Sea and North Sea Coast - Insights based on ASMITA modelling

Quirijn Lodder[a,c,*], Ymkje Huismans[b], Edwin Elias[b], Harry de Looff[c], Zheng Bing Wang[a,b]

[a] Faculty of Civil Engineering and Geosciences, Delft University of Technology, 2600, GA, Delft, the Netherlands
[b] Deltares, 2600, MH, Delft, the Netherlands
[c] Rijkswaterstaat, 3500, GE, Utrecht, the Netherlands

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ABSTRACT

The sediment exchange between the Dutch Wadden Sea and the North Sea coastal zone is of key importance to Dutch coastal management. Net sediment import from the coastal zone to the Wadden Sea results in coastal erosion which needs to be compensated through nourishments. At the same time net sediment import is the source of sediment for the intertidal flats in the Wadden Sea to adapt to sea level rise (SLR). Understanding the current and future sediment exchange is therefore essential for sustainable coastal management. Insights in the sediment exchange directly influence the coastal nourishment strategies applied to the Dutch coasts.

Projections of the future sediment exchange between the Dutch Wadden Sea and the North Sea are established using the aggregated morphodynamic model ASMITA for five sea level rise scenarios, viz. the present rate of 2 mm/yr and accelerated rates of 4, 6, 8 and 17 mm/yr in 2100. The differences in the projected import rates between the five sea level rise scenarios until 2100 are not as large as the differences in sea level rise rates may suggest. For the Eastern part of the Dutch Wadden Sea, where the morphology is near its dynamic equilibrium, the projected import rate in 2100 varies with a factor 3 (300%), for sea level rise rates from 2 to 17 mm/yr (factor 8.5, 850%). In the western part of the Dutch Wadden Sea, where the morphology is still far from equilibrium due to the closure of the Zuiderzee, the projected import rate in 2100 varies a factor 1.45 (145%) for these sea level rise rates. For the total Dutch Wadden Sea this is a factor 1.7 (170%). The projected increase of the import rate until 2100 with respect to the present situation (2020) is up to a factor 1.45 (145%) for the highest sea level rise scenario, which is significant but not substantial.

1. Introduction

The Wadden Sea spans nearly 500 km of the northern coast of the Netherlands and the North Sea coasts of Germany and Denmark. The Wadden Sea is connected to the North Sea by a series of tidal inlets and estuaries between barrier islands, and characterized by a wide variety of channels, sandy shoals and mud flats, gullies and salt marshes. The Dutch Wadden Sea, bounded by the tip of the Holland coast in the southwest and the Ems Estuary in the east, consists of six major tidal inlet systems (Fig. 1), and several smaller inlets that form the Groninger Wad area just west of the Ems Estuary. The eastern Dutch Wadden Sea, consisting of Ameland Inlet, Pinkegat Inlet and Zoutkamperlaag Inlet, is close to its morphodynamic equilibrium (Wang et al., 2018). The Western part of the Dutch Wadden Sea, consisting of Texel Inlet, Eierland Inlet and the Vlie Inlet, is still far from equilibrium as the morphological changes are still influenced by the closure of the Zuiderzee in 1932 (Elias et al., 2012; Wang et al., 2018). Specifically, by morphodynamic equilibrium in this paper we mean that the average vertical sedimentation rate in the basin is equal to the sea level rise (SLR) rate. This means that a basin in morphodynamic equilibrium, experiencing sea level rise, is importing sediments and therefore has a net positive absolute sediment budget and a net zero sediment budget relative to mean sea level. For an in-depth review of the concept of morphodynamic equilibrium we refer to Zhou et al. (2017).

Knowledge of sediment exchange between the (North Sea) coastal zone and the Wadden Sea informs policy and decision making in the Netherlands. In particular, long-term flood protection and the associated coastline maintenance require an understanding of the sediment budget

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* Corresponding author. Faculty of Civil Engineering and Geosciences, Delft University of Technology, 2600, GA, Delft, the Netherlands.,
E-mail addresses: q.j.lodder@tudelft.nl, quirijn.lodder@rws.nl (Q. Lodder), ymkje.huismans@deltares.nl (Y. Huismans), edwin.elias@deltares.nl (E. Elias), harry.de.looff@rws.nl (H. de Looff), zheng.wang@deltares.nl, z.b.wang@tudelft.nl (Z.B. Wang).

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of the coast (Mulder et al., 2011; Lodder et al., 2019b). In Dutch coastal management policy, the total average annual sand nourishment volume for the coast is among others determined by the sediment exchange through the tidal inlets of the Wadden Sea (Rijkswaterstaat, 2020). The degree of adaptation of Wadden Sea intertidal flats, which have high ecological values, to sea level rise also depends on this sediment exchange. Therefore, insight into the sediment exchanges between the coastal zone and the Wadden Sea through the various tidal inlets is essential for the management of the Dutch coastal system. The objective of the present study is to project the long-term development in sediment exchanges through the tidal inlets between the Dutch Wadden Sea and the (North Sea) coastal zone. Future system behavior and relative import rates are key parameters informing Dutch coastal policy, since one of the objectives of the coastal nourishments is to compensate sediment losses from the coastal zone (Rijkswaterstaat, 2020; Lodder et al., 2019b).

Field measurements and data analysis form core components in gaining insight into the sediment exchange between the coastal zone and the Wadden Sea. Sediment budget analyses based on bathymetric data not only provide information on historical sediment exchanges through the inlets, but also provide insight into the morphological status of the Wadden Sea (Elias et al., 2012; Wang et al., 2018). For example, sediment exchanges are not only determined by SLR but are also influenced by past human interventions, such as the closure of the Zuiderzee in 1932 and closure of the Lauwerszee in 1969. Extrapolating present-day trends provides a direct projection of trends in sediment exchange for the near future. For this short timescale (years to decades), we can safely assume that large-scale processes remain the same. On longer timescales (decades to centuries) accelerating SLR will start to become increasingly important for sediment exchange processes, and this assumption may no longer be valid.

Sea level rise creates a sediment demand in the basin as the tidal flats tend to grow in height, following the development of high-water levels (Wang et al., 2018). As a result, more sediment needs to be imported into the basins. Especially in the basins that are presently close to equilibrium (e.g. the eastern Dutch Wadden Sea), this sediment demand will be a dominant factor in the sediment loss of the nearshore zone.

How the sediment exchange between the coast and the basins develops quantitatively can only be projected by numerical modelling, as the response of the system to the development of SLR will be delayed and the time scale of the delay is dependent on morphological characteristics of the inlet systems and the SLR rate (Lodder et al., 2019a).

In the Western Dutch Wadden Sea, the effect of SLR is even more difficult to project. At present the system is still far from equilibrium due to past human interference (Elias et al., 2012; Wang et al., 2018) and it is not known when or how the effects of SLR will start to dominate the sediment exchanges.

This study focusses on the following research questions:

- How will the sediment exchange rates through the tidal inlets develop in the future (up to 2100)?
- How are the sediment exchange rates influenced by sea level rise?

The modelling approach in combination with recent insights from field observations and data analysis is described first. Then the existing models of the tidal inlets of the Dutch Wadden Sea are characterized and a selection is made regarding the future sea level rise scenarios for the projections. Next, the adjustments to the parameter settings of the existing models to adequately reflect current understanding of the responses of the tidal basins to a continuation of the present sea level rise rate are reported. The projections for the selected sea level rise scenarios are then described. A discussion on the interpretation of the model results and the implications for coastal management and policy follows. The paper ends with recommendations for future model developments.

2. Method

2.1. Modelling approach

Three methods for predicting sediment exchange through the Wadden Sea inlets can be applied:

1. Data analysis (e.g. sediment budgets).
2. Process-based modelling (e.g. Delft3D).
3. Aggregated modelling (e.g. ASMITA).

The first approach cannot be used to investigate Wadden Sea sediment exchange processes on long timescales. Extensive sediment-budget analyses based on bathymetric datasets (the so-called Vaklodingen) have been carried out (Elias et al., 2012; Elias, 2019). However, extrapolation of sediment budgets is only valid on short timescales. Numerical modelling approaches are needed to project sediment exchange on long timescales.

Various Delft3D process-based models for the Dutch Wadden Sea are available. However, applications of process-based models for simulating impact of SLR to the Dutch Wadden Sea (Dissanayake et al., 2012; Wang et al., 2018) have not been very successful yet. The major problem is that these models do not reproduce a realistic morphologic equilibrium. As a consequence, the models spin up due to the discrepancy between

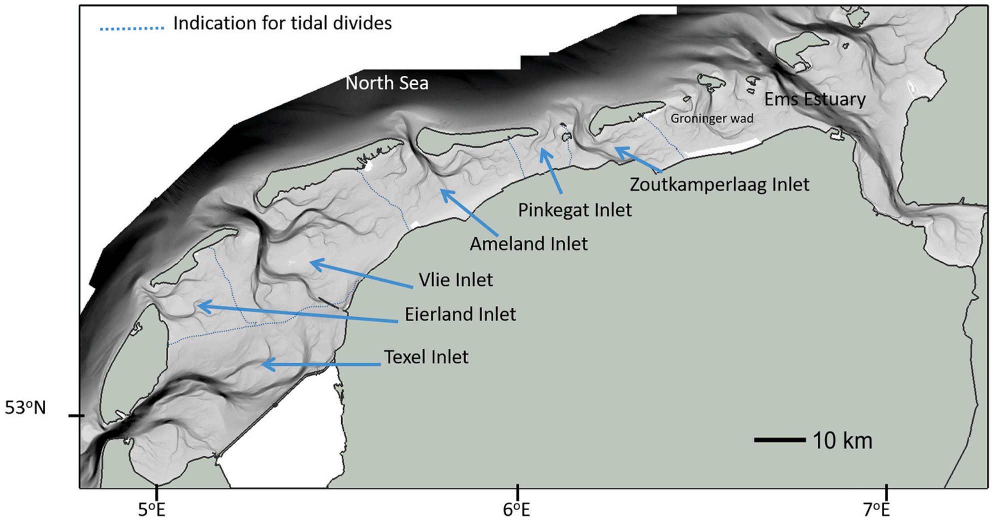

Fig. 1. Tidal basins in the Dutch Wadden Sea (after Lodder et al., 2019a).

morphodynamic equilibriums according to model and reality, and the changes due to spin up cannot be distinguished from the development to be simulated. Furthermore, long-term morphodynamic simulations at the scale of the entire Dutch Wadden Sea would result in infeasible long run times and computational expense. Potentially, process-based models can be useful in the future for long-term morphodynamic simulations including those for studying the effects of (accelerating) SLR by evaluating the results of the different projections in a relative manner, as demonstrated by applications in the German Wadden Sea (Becherer et al., 2018; Hofstede et al., 2018).

The ASMITA model was developed to simulate the long-term large-scale morphological developments of tidal inlet systems (Stive et al., 1998; Stive and Wang, 2003). In addition to the higher level of aggregation, the most important difference from the process-based models is the implementation of the empirical relationships for morphodynamic equilibrium. This allows the model to reproduce morphodynamic equilibrium if the forcing conditions remain constant over time. Reproduction of the morphodynamic equilibrium is an essential requirement for projecting the effect of SLR on morphological development (Lodder et al., 2019a). The sediment exchange through the inlet is a direct output of the model. When appropriately set up and calibrated, this type of model is suitable for achieving the objective of this study.

As a basis for this study, previously developed ASMITA models are used (van Goor et al., 2001; Kragtwijk, 2002; Van Goor et al., 2003; Kragtwijk et al., 2004). The model settings are updated to include the latest morphodynamic insights from data analysis studies (Wang et al., 2018; Elias, 2019). In addition, the insights from Lodder et al.'s (2019a) theoretical analysis on the impact of SLR on a tidal basin using a simplified (single-element) ASMITA model are used in interpreting the ASMITA model results of this study. The projections extend from the present till 2100, using five scenarios with different SLR rates.

2.2. Existing parameter settings for ASMITA models

For ASMITA each tidal inlet system is schematized into three morphological elements, comprising tidal flats (sediment volume) and channels (water volume) in the basin and the ebb-tidal delta (sediment volume) (Fig. 2). The effect of SLR on the Eierland Inlet and the Ameland Inlet were studied by Van Goor et al. (2003) after which his schematization was used for setting up the ASMITA models for the other inlet systems in the Dutch Wadden Sea (Kragtwijk et al., 2004; Bijsterbosch, 2003; Hinkel et al., 2013). The parameter settings reported by Wang et al. (2006), presented in Table 1, are considered the most representative, despite several attempts to improve the models further (Van Geer, 2007; Wang et al., 2008; Wang and Van der Spek, 2015).

Wang et al. (2018) used these parameter settings to calculate critical rates of SLR (R_c) for drowning of the tidal flats in the inlet systems following the formulation of Van Goor et al. (2003) (see also Bijsterbosch, 2003; Hinkel et al., 2013). Therefore, the starting point for the parameter setting in this study is Wang et al. (2006), see Table 1. These are adjusted with new insights from data-analysis (Elias, 2019) and theoretical analysis (Lodder et al., 2019a), as elaborated in the section "Improvement of parameter settings".

2.3. Sea level rise (SLR) scenarios for projections

The objective of the present study is to project changes in sediment import to the Wadden Sea under different probable SLR rates in order to assess system behavior and the sensitivity to SLR rates. The selected scenarios are respectively a continuation of the observed present relative SLR rate and 2, 3, 4 and 8.5 times the current rate (Table 2 and Fig. 3). The scenarios span the likely range (17th-83rd percentile) of sea level rise rates for Representative Concentration Pathway (RCP) 2.6 to RCP 4.5 in 2100 by Vermeersen et al. (2018) and Shared Socio-economic Pathway (SSP) 2–4.5 of the IPCC sixth assessment report (IPCC, 2021; Fox-Kemper et al., 2021; NASA, 2021). For the accelerating scenarios a SLR rate is used that increases linearly in time until a maximum is reached at the end of the acceleration period (except for the highest scenario where the maximum is reached in 2100), in line with the methodology of Vermeersen et al. (2018). The rate of increase is higher, and the period of acceleration is longer, for a higher scenario. The acceleration ends in 2050, 2060, 2070 respectively for the three intermediate scenarios. In the scenarios of Vermeersen et al. (2018), the acceleration of SLR commenced earlier than 2020. However, this feature was not incorporated in the scenarios used in this study to preserve coherence with the observed present relative SLR rate of 2 mm/yr in 2020 based on tide gauges at the Dutch coast as reported by Baart et al. (2019).

3. Improvement of parameter settings

As part of this study, the parameter settings of the models were optimized. The models were run using the present SLR rate (scenario SLR-2). The results were compared with insights derived from field observations and data analyses of sediment exchange between the Wadden Sea and the coastal zone. Adjustments are made in the parameter settings (Table 1) to achieve enhanced agreement with the most recent insights.

The most recent sediment budget model based on field data analysis (Elias, 2019) distinguishes between the long-term trend and the present trend (see Table 3). The long-term trend is determined using all the available bathymetry data since the closure of the Zuiderzee in 1932, estimates of the local subsidence (Hijma en Kooi, 2018a,b) and data on dredging and dumping of sediments. The present trend is determined using data from a recent period in which the development exhibited a linear trend in the considered system (since around 2000, variable per system). The trends in basin volume change and the sediment transport rate through the inlets are not in full agreement with each other due to sediment exchange across the tidal divides between the basins (Table 3). The net sediment exchange between the basins is estimated to be 0% (Eierland), 18% (Vlie), 25% (Ameland), 28% (Pinkegat +

Fig. 2. Schematization of a tidal inlet system into a 3-element ASMITA model.

Table 1
Input parameters of the existing ASMITA models for the tidal inlets of the Dutch Wadden Sea (Wang et al., 2006).

Inlet	Texel	Eierland	Vlie	Ameland	Pinkegat	Zoutkamperlaag
Basic configuration: tidal range H and horizontal area A of the three elements. The subscripts indicate the elements, i.e. f = flat, c = channel, d = ebb tidal delta.						
H (m)	1.65	1.65	1.90	2.15	2.15	2.25
A_f (km^2)	133	105	328	178	38.1	65
A_c (km^2)	522	52.7	387	98.3	11.5	40
A_d (km^2)	92.53	37.8	106	74.7	34	78
Parameters influencing the morphological timescale: n = power in the relationship for the local equilibrium sediment concentration, C_E = global equilibrium concentration, w_s = vertical exchange coefficient in the element indicated by the second subscript (f = flat, c = channel, d = ebb tidal delta), δ = horizontal exchange coefficient between the two elements indicated by the two subscripts (o = outside world).						
n (−)	2	2	2	2	2	2
C_E (−)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
w_{sf} (m/s)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
w_{sc} (m/s)	0.0001	0.00005	0.0001	0.00005	0.0001	0.0001
w_{sd} (m/s)	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
δ_{od} (m^3/s)	1550	1500	1770	1500	1060	1060
δ_{dc} (m^3/s)	2450	1500	2560	1500	1290	1290
δ_{cf} (m^3/s)	980	1000	1300	1000	840	840
Initial conditions: volumes of the three morphological elements in 1970						
V_{f0} (million m^3)	51.5	55	162	120	29.6	69
V_{c0} (million m^3)	2160	106	1230	302	18.5	177
V_{d0} (million m^3)	509.1	132	369.7	131	35	151
Parameters for defining the morphodynamic equilibrium: V_{fe} = equilibrium volume of the flat element, α = coefficient in the relationship between the equilibrium volume (V) of the element indicated by the subscript and the tidal prism (P): $V_{ce} = \alpha_c P^{1.55}$, $V_{de} = \alpha_d P^{1.23}$ Volumes f and d are sediment, c is water						
V_{fe} (million m^3)	151	57.83	190	131.2	30.3	70
α_c (10^{-6})	10	13.13	9.6	10.241	10.14	27.266
α_d (10^{-3})	4.025	8	2.662	2.92157	6.9278	9.137

Table 2
Definitions of the considered SLR scenarios.

Scenario	Definition
SLR-2	Continuation of the present SLR rate: R is constant and equal to 2 mm/yr.
SLR-4	R = 2 mm/yr until 2020, from 2020 to 2050 R increases linearly to 4 mm/yr, and then remain constant, R = 4 mm/yr.
SLR-6	R = 2 mm/yr until 2020, from 2020 to 2060 R increases linearly to 6 mm/yr, and then remain constant, R = 6 mm/yr.
SLR-8	R = 2 mm/yr until 2020, from 2020 to 2070 R increases linearly to 8 mm/yr, and then remain constant, R = 8 mm/yr.
SLR-17	R = 2 mm/yr until 2020, from 2020 to 2100 R increases linearly to 17 mm/yr.

Zoutkamperlaag) and 38% (Texel) of the sediment import through the inlet (Elias, 2019, Fig7.3). Due to the model setup of ASMITA it is not (yet) possible to include sediment exchanges between the basins as basins have closed borders in ASMITA. Ignoring the inter-basin interaction results in differences in the projected net sediment import per basin. However, the overall relative trends, the total net sediment import rate to the basins combined and large-scale system behavior are not significantly influenced. These parameters are most important for informing the coastal nourishment policy and strategy.

The present trend in the basin volume change of the Frisian Inlet (Pinkegat + Zoutkamperlaag) approximates the dynamic equilibrium value, i.e. the increase rate of the accommodation space (=basin area * SLR rate = 0.31 million m^3 per year). Therefore, for the Pinkegat and Zoutkamperlaag the results of Elias (2019) confirm the conclusion of Wang et al. (2018) that this system is close to morphodynamic equilibrium at present. The much larger long-term trend is caused by the closure of the Lauwerszee. Wang et al. (2018) characterize the Ameland Inlet as in morphodynamic equilibrium. However, the present and the long-term trends in the basin volume change determined by Elias (2019) are much larger than the increase rate of the accommodation space (about 0.55 million m^3 per year). As we do not yet have a sound explanation for the extra sedimentation and are not certain if the observed trend will continue, we adhere to the conclusion of Wang et al. (2018) here. Accordingly, for the three inlets in the eastern Dutch Wadden Sea (Ameland, Pinkegat, Zoutkamperlaag), the model results (Fig. 5) for the present SLR rate (2 mm/y) largely agree with the insight that they are in or close to morphodynamic equilibrium. The sediment

Table 3
Results of the sediment budget analysis, in sediment volume change trends (Elias, 2019).

Inlet	Texel	Eierl.	Vlie	Amel.	Pinkeg. + Zoutk.
Long-term trend basin volume change (10^6 m^3/yr)	3.53	−0.15	2.30	1.25	2.02
Present trend basin volume change (10^6 m^3/yr)	1.23	−0.32	1.43	1.63	0.35
Long-term transport rate through inlet (10^6 m^3/yr)	4.40	−0.15	1.77	1.01	2.12
Present transport rate through inlet (10^6 m^3/yr)	1.98	−0.32	1.18	1.23	0.45

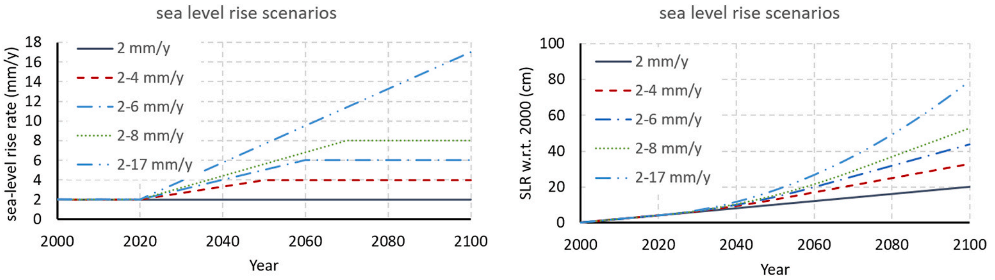

Fig. 3. The sea level rise scenarios considered in the present study. Left: change of SLR rate; right: SLR since 2000.

imported through the inlets balances the effect of SLR in the basins and the existing ASMITA models for these three inlets were therefore not modified.

For the three inlets in the western Dutch Wadden Sea (Texel, Eierland, Vlie), the existing ASMITA models were adjusted by changing the parameters determining the morphodynamic equilibrium in the basins, i.e. the equilibrium volume of the tidal flat V_{fe} and the coefficient in the relationship for the equilibrium channel volume α_c (see Wang et al. (2020) for details of the empirical relationships for morphodynamic equilibrium). In the parameter setting of Wang et al. (2006) for Texel Inlet, V_{fe} was increased following the empirical relationships that determine V_{fe} from the basin area A_b and the tidal range. However, the tidal flat area A_f in the basin of Texel Inlet is relatively small (Table 1), and is constant during the model simulation. This has the consequence that the (effective) equilibrium height of the tidal flat is almost 70% of the tidal range, instead of the more typical 40% found in the other basins of the Wadden Sea (Eysink, 1990; Wang et al., 2020). Therefore, V_{fe} is decreased so that the effective equilibrium height of the tidal flat is 40% of the tidal range ($V_{fe} = 88$ million m^3 instead of 151 million m^3). This change has also consequences for the equilibrium of the channel and the ebb-tidal delta, because a smaller tidal flat volume means a larger tidal prism. This causes the sediment import to the basin to decrease, but the effect is limited (decrease less than 5%). Therefore, α_c is also increased (from $10{*}10^{-6}$ to $15{*}10^{-6}$). This choice is motivated by the consideration that the anticipated change of subtidal areas (belonging to the channel element) to intertidal areas (flat) will likely not happen because the strong flow prevents the deposition of fine sediment. There seems to be limited effective sedimentation space (i.e. area's with energy levels are low enough to allow for net sedimentation), which limits the amount of accretion. In other words, the potential sediment demand according to the empirical relationships is not yet an effective sediment demand (Elias et al., 2019). This argument also supports the choice to decrease the V_{fe} value. The simulation outputs for an increased α_c value and for an increase in α_c combined with a decrease in V_{fe} are shown in Fig. 4. The effect of decreasing V_{fe} is dependent on the value of α_c because of its effect on the tidal prism. The combined changes yielded the lowest sediment import, although this was still higher than the results from the data analysis (Table 3) of Elias (2019). As further changes in the parameter settings are difficult to justify, the parameter setting with increased α_c combined with a decreased V_{fe} were used for the projections of sediment exchange under SLR for Texel inlet.

Similar reasoning was applied in determining the V_{fe} value for the Vlie Inlet. According to the existing parameter setting (Table 1) the effective equilibrium height of the tidal flat is about 30% of the tidal range. This was altered to about 40% so that V_{fe} increased from 190 to 250 million m^3. The effect of this change is illustrated in Fig. 4. The import rate is decreasing in time and has a magnitude between 1 and 2 million m^3 per year (see also Table 3). As the updated model results are more or less in line with recent insights derived from data analysis (Elias, 2019), this parameter setting was used in the projections of sediment exchange under SLR scenarios for Vlie inlet.

The Eierland Inlet is the only inlet through which net sediment export has taken place according to field observations and data analysis (Elias et al., 2012; Wang et al., 2018). Such export is not reproduced using the existing ASMITA model. In the model an incorrect value for the tidal range was used. Using a correct tidal range of 1.78 m initially resulted in sediment export (about 0.8 million m^3/yr.), which however quickly (within less than 20 years) turned to a simulated import and approached a similar level as that of the simulation with the lower original tidal range (1.65 m). In both simulations, the import approaches the morphodynamic equilibrium (import rate equal to basin area multiplied by SLR rate), about 0.3 million m^3 per year. Given the relationships used for the morphodynamic equilibrium in ASMITA, a constant export through the inlet with rising sea level is only possible if the tidal prism increases consistently with time. An increase in the tidal prism can be caused by an increasing tidal range, a decreasing tidal flat volume, or an increasing basin area. Field observations indicate that the tidal flat volume in the basin has not been decreasing. Therefore, the only options are an increasing tidal range or an increasing basin area. Observations of the changes in the tidal divides suggest that the basin area of this inlet is increasing (Wang et al., 2013). However, in the present version of ASMITA the horizontal areas of the morphological elements remain constant in time, so it is not possible to simulate the situation of an increasing basin area. Therefore, various scenarios of linearly increasing tidal range were simulated. The simulations show that the sediment transport through the inlet at the dynamic equilibrium is dependent upon and sensitive to the rate of increase of the tidal range. Export can occur consistently under conditions of rising sea level and increasing tidal range. The increasing tidal range increases the tidal prism which in turn causes the equilibrium volumes (water) of the channels in the basin and the ebb-tidal delta (sediment) to increase. The resulting sediment demand on the ebb-tidal delta and the sediment

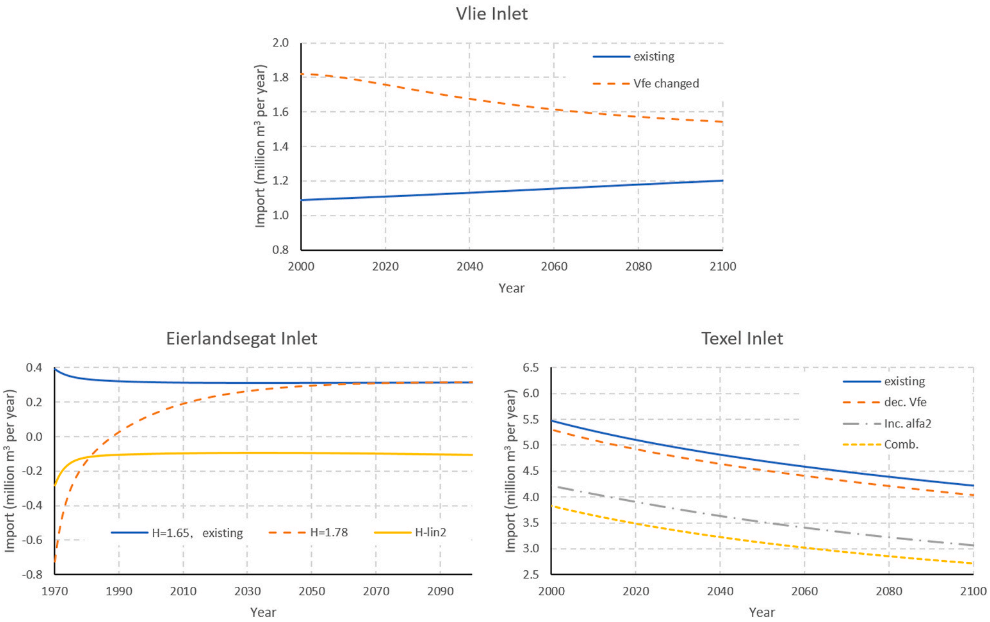

Fig. 4. Improving the parameter settings concerning morphodynamic equilibrium in the ASMITA models for the three tidal inlets in the western Dutch Wadden Sea. The final settings used in the projections are: Vfe changed (V_{fe} increased from 190 to 250 million m^3) for the Vlie Inlet, H-lin2 (Linear increase of tidal range, starting from 1.73 m in 1970 with 3 mm/yr) for the Eierland Inlet, and Comb. (V_{fe} decreased from 151 to 88 million m^3 combined with increase of α_c from $10{*}10^{-6}$ to $15{*}10^{-6}$) for the Texel Inlet. Note that the vertical and horizontal scales vary among the basins.

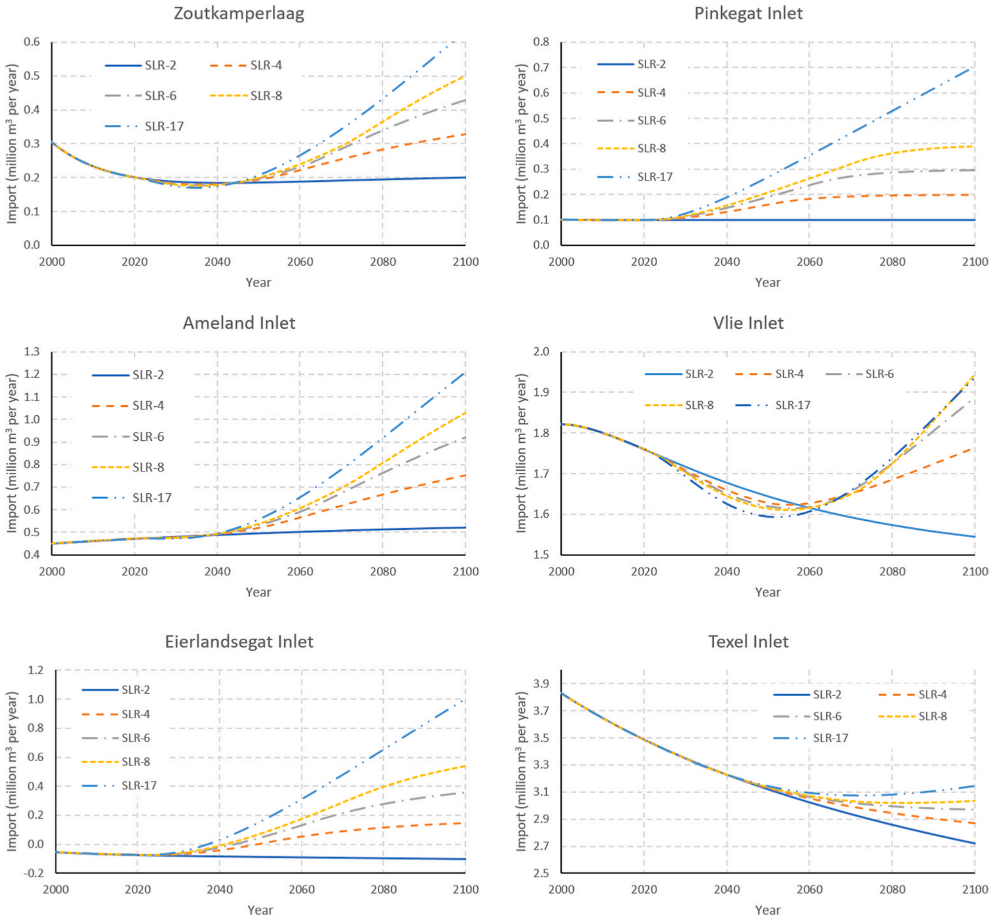

Fig. 5. Sediment transport exchange between the Wadden Sea basins and the North Sea coasts through the various tidal inlets (positive = directed to Wadden Sea, i.e. import). Note that the vertical scales vary among the basins.

surplus in the channels drive sediment transport from the channels to the ebb-tidal delta – the export of sediment.

The parameter setting scenario H-lin2 (tidal range starts at 1.73 m in 1970 and increases with 3 mm per year) shown in Fig. 4 was used to project the sediment exchange using the five SLR scenarios for Eierland inlet. This parameter setting maintains an export rate of about 0.1 million m^3 per year, which is lower than observed (Table 3). However, with this increase rate, the tidal range will increase by 39 cm over the simulation period (130 years). This is already very high even though it is meant to represent increasing basin area. The increase in tidal range has the same effect on the total sediment demand in the basin as an increase of basin area of about 20 km^2 (i.e. a relative increase with a factor 1.125 (112.5%), which is in the same order of magnitude as reported by Wang et al. (2013)). Given the objective to assess future system behavior and relative transport rates to inform long-term coastal policy development, the applied approach is deemed sufficient. The reproduced trends and magnitudes of sediment transport are adequate to inform coastal policy (Rijkswaterstaat, 2020). Important in this aspect is the comparatively limited contribution of 6% of Eierland inlet to the observed net sediment transports from the coastal zone.

4. Model results and interpretation

The projected sediment imports into the tidal basins are depicted in Fig. 5. The differences between the five SLR scenarios start in 2020 (Fig. 3), however the differences between the simulated imports to the Wadden Sea basins become noticeable later in time (Fig. 5). For the inlets Pinkegat and Eierland Inlet significant increase (+10% difference between lowest and highest scenario's) in the projected sediment import starts around 2025, i.e. 5 years later than those in the development of SLR. For Zoutkamperlaag and Ameland inlets this difference in increase is projected around 2050. For the Vlie and Texel inlets the projection is respectively 2080 and 2090. The difference in delay in response depends on two factors, the size of the basin and the present morphological state of the basin. Larger tidal basins have a longer delay compared to smaller basins. In addition, the existing sediment demand in the basin due to past human interference can make the delay longer. This explains the long delay exhibited by the Texel Inlet. The development of this tidal inlet system in ASMITA is almost fully controlled by the sediment demand due to the closure of the Zuiderzee, also for the accelerating SLR scenarios.

In Fig. 6, the total import to the western part (Texel, Vlie and Eierland inlets), eastern part (Ameland, Pinkegat, and Zoutkamperlaag inlets) and the total Dutch Wadden Sea are presented. There is a clear distinction between the eastern and western parts in terms of changes in their projected sediment imports under the five SLR scenarios. For the eastern part, where the present morphology is close to dynamic equilibrium (Wang et al., 2018), the import rate in 2100 varies from about 0.8 million m^3 per year for the lowest SLR scenario (2 mm/yr) to about 2.5 million m^3 per year for the highest SLR scenario (17 mm/yr), a factor of 3.1 (310%). For the western part, where the large sediment demand due to the closure of Zuiderzee is still not damped out, it varies between about 4.2 and 6.0 million m^3 per year, a difference of about 145% between the highest and lowest SLR scenarios. The current sediment import is at nearly the same rate as projected for the highest scenarios (8 and 17 mm/yr) in 2100., indicating that human impact on the sediment import is likely to remain dominant over SLR in the coming century.

Considering the total projected sediment import to the whole Dutch

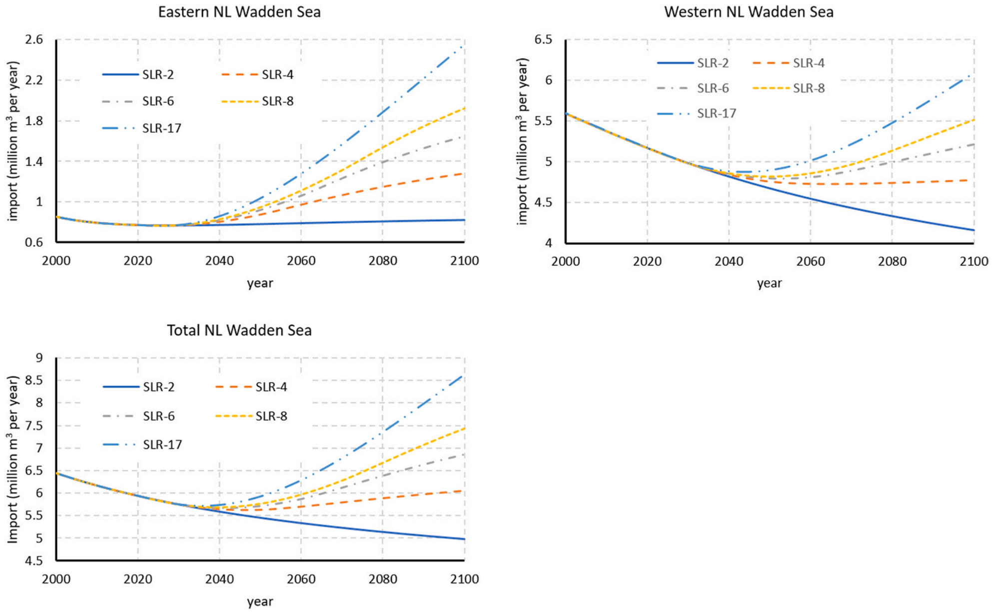

Fig. 6. Total sediment import to the eastern part, the western part and the total Dutch Wadden Sea. Note that the vertical scales vary among the basins.

Wadden Sea, the differences between the five projections do not become significant (+5 – 10%) until about 2060 (Fig. 6). The differences increase in time, but even in the last 40 years of this century the differences are relatively restricted: in 2100 the total import varies between 5 million m^3/yr. (SLR-2) and 8.5 million m^3/yr. (SLR-17), i.e. a difference of about 70% between the highest and lowest SLR scenarios. Note that the SLR rate varies by a factor 8.5 (850%) between the scenarios. The restricted differences are due to the delayed response of the system to variation of SLR and due to the existing sediment demand caused by past human interferences.

The differences between the four scenarios with SLR acceleration are relatively small compared with the difference between the lowest acceleration scenario SLR-4 and the scenario without acceleration of SLR (SLR-2). This can be explained by the time variations of the rate of sea level rise (shift from accelerating to linear) according to the scenarios (Fig. 3) and the delay in response of the system to SLR. The sensitivity of the model is directly related to the variations of SLR over time and is thus expected to be limited.

Due to the delay in response of the system to SLR, the sediment import at present provides a good indication of the sediment import for the coming years to decades, despite the uncertainty in future SLR development. Projections based on extrapolating the present trend are thus potentially valid for longer than we initially thought. This means that the projections of tidal flat losses in the Dutch Wadden Sea made by Wang et al. (2018) by extrapolating with a constant sedimentation rate are reasonable. This also emphasizes the importance of studying the present system state using measurement observations and process-based modelling.

No substantial increase of sediment import to the total Dutch Wadden Sea is projected until 2100. The import rate is projected to decrease in time if the present SLR rate continues, because the adaptation of the system due to past human interference is dominant over SLR. An acceleration of SLR is projected to change this decreasing trend, however not until 2050. For the highest SLR scenario (17 mm/yr), the import rate is projected to increase by about 2.5 million m^3 per year in 2100 compared to the present (2020, about 6.0 million m^3 per year) import rate, i.e. an increase with a factor 1.45 (145%).

5. Concluding discussion

5.1. Characteristics of the updated ASMITA models

The new parameter settings in the ASMITA models represent a second update since the original model setup. Both this and the 2006 update of the parameters defining the morphodynamic equilibrium in these basins, were based on new insights from data analyses (Elias, 2006, 2019). The update reflects improved insights in the morphological development of the Wadden Sea. However, the necessity of changing the parameters in the relationships defining the morphodynamic equilibrium to obtain agreement between the model results and observations reveals that our understanding of the future morphodynamic equilibrium in the Texel and Vlie inlet systems is still not satisfactory. Investigations of future morphological developments of the basins are needed to improve our understanding of the morphodynamic equilibrium and to assess if further updates to the parameters are necessary.

5.2. Interpreting the model results

According to the model results, the tidal inlet systems in the Wadden Sea will respond differently (i.e. delay and magnitude of sediment import) when SLR accelerates. These differences can be explained by three factors: (i) the morphological time scales of a tidal inlet system (Kragtwijk et al., 2004), (ii) the morphological state with respect to equilibrium, and (iii) the dimensionless SLR rate (r) which is defined as the ratio between SLR rate and the critical SLR for drowning (Lodder et al., 2019a). In Table 4 the critical SLR rates for the six studied tidal basins in the Dutch Wadden Sea, as calculated by Wang et al. (2018), are presented together with the dimensionless SLR rate r for the five SLR rates used in this study (2, 4, 6, 8 and 17 mm/yr). The dimensionless SLR rate r determines the morphodynamic equilibrium and the morphological timescale for achieving the dynamic equilibrium (Lodder et al., 2019a). We see that for the same SLR rate, r is different for the basins as the critical SLR rate for drowning is different. This explains the key differences in the simulated behavioral responses of the different basins to SLR. A basin with $r > 1$ has a sediment import rate which is lower than is needed to compensate for SLR. Although it is still importing sediment, the average vertical sedimentation rate in the basin is lower than the SLR rate. Such a basin will therefore eventually transit into a drowned system like a lagoon (Lodder et al., 2019a; Huismans et al., 2022). No

Table 4
Critical SLR rate (R_c) for drowning of the various tidal inlet systems in the Dutch Wadden Sea from Wang et al. (2018) and the dimensionless SLR rate *r* for five different SLR rates (2, 4, 6, 8 and 17 mm/yr). The area (A_b) is provided for reference.

Inlet	A_b (km^2)	R_c (mm/ yr.)	*r for SLR rate* =				
			2 mm/ yr.	4 mm/ yr.	6 mm/ yr.	8 mm/ yr.	17 mm/ yr.
Texel	655	7.0	0.29	0.57	0.86	1.14	2.43
Eierland	157.7	18.0	0.11	0.22	0.33	0.44	0.94
Vlie	715	6.3	0.32	0.63	0.95	1.27	2.70
Ameland	276.3	10.4	0.19	0.38	0.58	0.77	1.63
Pinkegat	49.6	32.7	0.06	0.12	0.18	0.24	0.52
Zoutkamperlaag	105	17.1	0.12	0.23	0.35	0.47	0.99

morphodynamic equilibrium is possible for such a basin. A basin with $r > 0.8$ is experiencing such a rapid SLR rate that the average vertical sedimentation rate can only just follow the SLR in the long term. Due to the delay in response and morphological timescale of adaptation, it will take centuries for such a basin to reach morphodynamic equilibrium (Lodder et al., 2019a). Morphodynamic equilibrium can only be reached when SLR acceleration stops and becomes linear like in scenarios 2, 3 and 4. The differences in critical SLR rate for drowning depend on the size of the basin (Van Goor et al., 2003), as also shown in the German GETM study (Hofstede et al., 2018). The critical rate of SLR for drowning also depends on the tidal range, which varies in the whole Wadden Sea from 1.6 to 3.5 m. Larger basins and basins with a present depth exceeding the equilibrium depth are more vulnerable to drowning.

5.3. Uncertainties in the model results

Various sources of uncertainty affect the presented results. First, as already mentioned, the models have previously not been extensively calibrated for reproducing the morphological developments since 1970. This uncertainty was overcome by using the results from data analysis studies (e.g. Elias, 2019). An exact match with the results of Elias (2019) was not possible. However, the new parameters provide a good estimation of the observed quantitative import rate. These parameter settings where then used to project future developments, especially focusing on relative differences in sediment transport. Relative trends and magnitudes of sediment exchange are the most important parameters for informing policy, the main objective of this study.

A major uncertainty concerns SLR development itself, as indicated by the five different scenarios. However, the model results indicate that the effects of these differences on the sediment import to the Wadden Sea are relatively limited in the coming decades (less then relative change in SLR). This reduces the uncertainty in the conclusions relevant for the management of the coastal system (e.g. nourishment strategy) significantly. This means also that the uncertainty introduced in the exact definition of the scenarios, i.e. how the acceleration of SLR takes place in time, is of less importance. Many more high-end projections of global and local sea level rise surpass the used scenarios (i.e. IPCC, 2019; IPCC, 2021), however the morphological response of the Wadden Sea under these projections is likely to be comparable. The delayed response of the Wadden Sea will manifest itself as well, just as in the projections for the used scenarios. A significant increase in sediment import is projected to happen but with a delay (decades), first in the Eastern part later also in the Western part of the Dutch Wadden Sea.

The remaining source of uncertainty relates to shortcomings in the models. By considering the tidal divides as fixed and closed boundaries between the basins, and by keeping the internal distribution between the subtidal and intertidal areas unchanged during the simulation, the sediment demand of a basin is affected. The effect on the model results can be determined by varying the parameters in the relationships for the morphodynamic equilibrium as was done in updating the models for Texel Inlet and the Vlie Inlet. The conclusion that the update did not significantly affect the model results concerning the relative differences and trends (Fig. 4) implies that the uncertainty associated with these particular model shortcomings remains limited. For the Eierland Inlet the effect of increasing basin area due to moving tidal divides is simulated by introducing an increasing tidal range in time. This also causes uncertainty however its effect on the total sediment import to the Dutch Wadden Sea is limited because of the relatively small share of this inlet. More important is the shortcoming that the change in tidal range due to morphological development of the system is not taken into account. The model results are sensitive to an increase in tidal range, as demonstrated by the update of the model for Eierland Inlet (Fig. 4). Acceleration of SLR is expected to increase the tidal range in the Wadden Sea slightly (Pickering et al., 2017; Becherer et al., 2018; Hofstede et al., 2018). According to the results for the Eierland Inlet, an increase tidal range results in a lower import (c.q. higher export) rate. This effect might increase the delay in the response of the basin to an increase in SLR, and represents a significant source of uncertainty.

Another aspect is that the ASMITA models do not consider waves explicitly as driving force for the morphological development. However, the effects of waves are implicitly considered via the used relationships for morphodynamic equilibrium and via the parameters determining the morphological time scales. This is a source of uncertainty if wave climate in the Wadden Sea area will significantly change in the future.

A further shortcoming relates to the single fraction sediment transport module. On the one hand, as explained by Wang and Van der Spek (2015), the parameter settings of the models take the effects of sand-mud mixture in the system into account, limiting the effect of this uncertainty on model results. On the other hand, the theoretical analysis by Lodder et al. (2019a) shows that the value of the power *n* in the equilibrium concentration formulation influences the critical SLR rate for drowning at the same morphological timescale (related to decay of disturbances with respect to the morphodynamic equilibrium without SLR). Wang et al. (2008) showed that the value used ($n = 2$) is quite low. According to the theoretical analysis, this results in a critical rate of SLR that is too high, implying that errors are introduced into the model results at very long timescales (related to the drowning process, centuries). However, in this study the projected period (until 2100) is relatively short in comparison with the timescale of drowning. Therefore, the uncertainty corresponding to this model shortcoming is considered limited.

5.4. Relevance of system understanding for management and policy

The enhanced system understanding derived from the interpretation of the ASMITA model results and the consideration of the uncertainties in these results, is used to support long-term management of the Dutch coast. In particular, the system understanding is used to determine the sediment nourishment strategy aimed at maintaining the position of the Dutch coastline. The magnitude and trends in sediment import from the coastal zone to the Wadden Sea is directly used in the assessment of current and future nourishment volumes. Especially the limited relative differences in sediment import to the Wadden Sea for different rates of SLR are very relevant (Rijkswaterstaat, 2020).

In particular, this study reveals that the effect of SLR acceleration on the projected sediment import for the whole Wadden Sea is not noticeable before 2040, even if the acceleration starts in 2020. Further, the differences between the projections of sediment import to the Wadden Sea under SLR are much less than the differences in SLR rate might suggest until 2100. The difference in import rates between the highest (17 mm/yr) and the lowest (2 mm/yr) scenarios is only about 3.5 million m^3 per year in 2100, and varies from about 5 million m^3 per year (for the lowest scenario) to about 8.6 million m^3 per year. Most significantly, no substantial increase of sediment import to the Wadden Sea is projected until 2100. If the present SLR rate continues, the import rate is projected to initially decrease with time as the system persists in its dampening response to past human interferences. The acceleration of SLR is projected to cause this initial decreasing trend to change, but not until 2040, according to all projections. For the highest SLR scenario (17 mm/yr), the import is projected to increase by about 2.5 million m^3 per year in 2100 compared to the present rate of about 6 million m^3 per year (Fig. 6).

This means that the effect of accelerating SLR on the loss of sand from the coastal zone due to import to the Wadden Sea is projected to be limited until 2100. In terms of sediment nourishment for coastline maintenance, this limited effect of changing SLR on the sediment import to the Wadden Sea can be considered positive. However, it is likely to have negative consequences for the conservation of the ecological value of the Wadden Sea as the acceleration of SLR is expected to result in an increased loss of intertidal flat area (Huismans et al., 2022). Given the uncertainty in the development of SLR and the potentially conflictual effects of sediment import on the nourishment requirements compared with the conservation of the ecological value in the Wadden Sea, strategies for influencing the sediment import rates through the inlets become of management interest. Strategies such as nourishments on the ebb-tidal deltas, at or directly landwards of the tidal inlets are among the possibilities that will need to be considered. These strategies might benefit both mitigation of sediment loss from the coastal zone and provide sediment for the shoals of the Wadden Sea to adapt to SLR. How the import of sediments can be influenced by ebb-tidal delta nourishments remains uncertain. The studies of Wang et al. (2018) and Lodder et al. (2019b) indicate that the net sediment transport is mainly dependent on either the accommodation space of the basin or the sediment transport capacity of the inlet, indicating that the availability of sediments at the North Sea coast is of less importance. Following the ASMITA model formulation it can be reasoned that ebb-tidal delta nourishments will only have very limited influence on the import unless if the nourishment amount is so large that the ebb-tidal delta volume (in the order of 10^8 m^3) is significantly influenced. In any case, a delay in increased sediment import should be expected, just as the projected delay due to accelerating SLR in this study.

In terms of monitoring, field measurements can be used to determine the morphological development under SLR, however this study has indicated that combined modelling and field observations will be needed to ascertain whether relevant limits such as those pertaining to the drowning of a tidal basin will be exceeded or not. Recent research indicates that inter-basin interaction might be of more importance than previously assumed in ASMITA (Herrling and Winter 2015; Duran-Matute et al., 2016). Field investigations of the development of and sediment transport over the tidal divides in the Wadden See, like Van Weerdenburg et al. (2021), in response to SLR are therefore required to determine whether the assumption that the tidal divides form a closed boundary between the tidal basins as applied in the ASMITA model simulations is justified. Further, model results indicate that sediment exchange between the North Sea coasts and the Wadden Sea is sensitive to the development of the tidal range in the Wadden Sea, e.g., for the Eierland inlet. Accordingly, the changes in tidal range in the tidal basins caused by SLR and morphological development will also need to be investigated, special focus on the Eierland inlet is recommended.

In conclusion, this study has affirmed the relevance of ASMITA modelling for informing long-term coastal management and policy making. However, it has also highlighted necessary future model developments. These include extending the present focus on the sediment exchange through the inlets to an analysis of the development of morphological elements such as the ebb-tidal deltas, channels and intertidal flats within the tidal inlet systems, including interaction between basins. It is recommended that a graded sediment transport module is implemented within ASMITA. The parameter settings indirectly take the effects of sand-mud mixture in the system into account. However, directly including a sand and a mud fraction is important for improved projection of the critical SLR rate for drowning, and is also important for understanding the behavior of the tidal inlet systems in response to accelerating SLR as determined by the dimensionless SLR rate. A further step is to implement morphodynamic equilibrium relationships like in ASMITA in process-based models like Delft3D.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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