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RESEARCH ARTICLE

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Future sediment transport to the Dutch Wadden Sea under severe sea level rise and tidal range change

Z. B. Wang[1,5*], Q. J. Lodder[1,2], I. H. Townend[3] and Yonghui Zhu[4]

Abstract

Future sediment transport from the North Sea coasts to the Dutch Wadden Sea for various future sea level scenarios has been studied because it influences the future sand nourishment demand for the maintenance of the coastline and because it determines bio-geomorphological development of the Wadden Sea. The present study focuses on two questions which have not yet been considered in the previous modelling studies using ASMITA: How will the transport develop around drowning of the intertidal flats in the Wadden Sea? How will tidal range change influence the future sediment exchange? By using SLR scenarios with faster acceleration and running the simulations for longer periods of time some inlets exhibited drowning, i.e., where the tidal flat volume vanishes. When drowning occurs, the sediment import rate approaches a maximum or a minimum, depending on the initial morphological state of the tidal inlet system. This maximum or minimum rate for a certain tidal inlet system depends on the SLR scenario. Theoretical analysis as well as modelling results show that tidal range change will influence the sediment import to the Wadden Sea. A tidal range increase will cause a decrease of the sediment demand in the Wadden Sea resulting into less sediment import to the Wadden Sea. It is thus important to study the tidal range development in the Wadden Sea by considering the interaction between SLR, tidal range change and morphological development in the system. It is further concluded that the empirical relation used in the previous studies is not representative of conditions in a tidal basin with fixed basin area, even though this relation has been derived from field observations in many tidal inlet systems worldwide. The equilibrium channel volume should be proportional to the tidal prism instead of to its 1.5th power.

Keywords Sea level rise, Wadden Sea, Morphological equilibrium, Tidal inlet

1 Introduction

The Wadden Sea, spanning nearly 500 km of the coast of the Netherlands, Germany and Denmark, is connected to the North Sea by a series of tidal inlets and estuaries between barrier islands. It consists of a wide variety of channels, sandy shoals and mud flats, gullies and salt marshes, which are important internationally and a key component in the designation of the Wadden Sea as a UNESCO World Natural Heritage site. The Dutch Wadden Sea, including six major tidal inlet systems (Fig. 1), is an important part of the Dutch coastal system.

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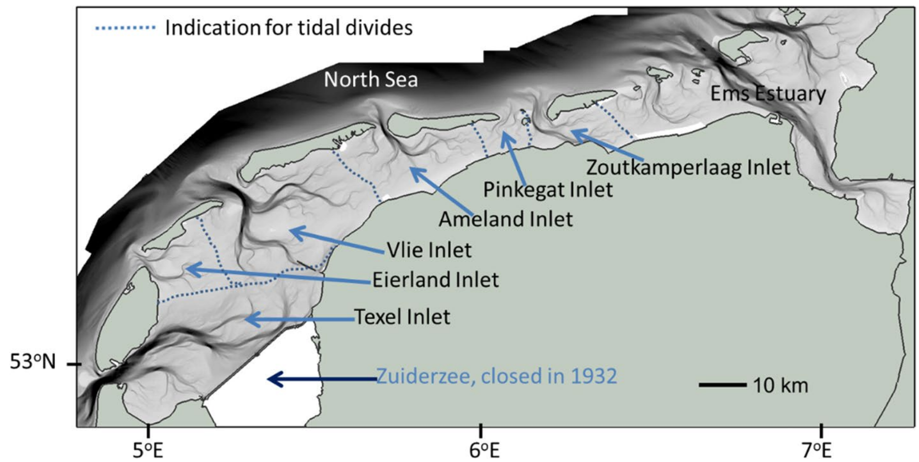

Fig. 1 Tidal basins in the Dutch Wadden Sea (after Lodder et al. 2019)

The morphological development of the Dutch Wadden Sea has been influenced by sea level rise (SLR) as well as human interferences within the Wadden Sea area (Elias et al. 2012; Wang et al. 2018). In the last century the influence of human activities has been more important than that of sea level rise (Elias et al. 2012). For example, the Western part of the Dutch Wadden Sea, consisting of Texel Inlet, Eierland Inlet and the Vlie Inlet, is still responding to the closure of the Zuiderzee in 1932. However, SLR and in particular any acceleration in SLR will become relatively more important for the morphological development of the Wadden Sea in the future (Wang et al. 2018; Lodder et al. 2019).

Understanding the future development of the Wadden Sea under the influence of SLR is important for the management of the Dutch coastal system for two reasons. First, SLR causes an increase in sediment transport from the North Sea to the Wadden Sea and induces coastal erosion outside the tidal inlets. The morphological development of the Wadden Sea under the influence of SLR thus influences the amount of sand nourishment required to maintain the coastline and the coastal foundation. Second, the ecologically valuable tidal flats in the Wadden Sea will be influenced by SLR. If SLR is too fast the system may drown, i.e., disappearance of the intertidal flats over the longer term (Van Goor et al. 2003; Lodder et al. 2019). The development of the sediment transport to the Wadden Sea through the six main tidal inlets has been studied for several future SLR scenarios by Lodder et al. (2022) and the development of the tidal flats in the Wadden Sea, for the same SLR scenarios, by Huismans et al. (2021). Both studies are based on ASMITA model simulations. 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; Townend et al. 2016a, b). A similar approach, based on sediment concentration gradients, has also been developed to study Venice Lagoon (Di Silvio et al 2010; Bonaldo and Silvio 2013). Whereas much of the literature has tended to focus on conditions for inlet stability (e.g., Escoffier 1940; Van de Kreeke 2004).

The studies by Lodder et al. (2022) and Huismans et al. (2021) are based on model simulations from the present to 2100. Only in the highest scenario considered in those studies did SLR exceed 1 m by 2100. Drowning did not occur in any of the simulations, even though in some of the scenarios the SLR rate exceeded the critical level for drowning in some of the tidal basins. These studies do thus not provide insight concerning the development of the tidal inlet systems around drowning, which is likely to occur at some time in the future. To close this knowledge gap, longer simulations and/or simulations for more extreme scenarios are needed.

Longer period and/or more extreme SLR scenarios will result in higher total SLR. The higher sea level in the future will affect the tidal wave propagation in the North Sea and the Wadden Sea. Hydrodynamic modelling studies show that tidal range in the North Sea and in the Wadden Sea will increase due to higher sea level in the future (Idier et al. 2017; Jänicke et al. 2021; Jordan et al. 2021). This makes it necessary to reconsider the assumption that tidal range is not changing in time as made in the studies of Lodder et al. (2022) and Huismans et al. (2021), especially when higher SLR values because of more extreme scenarios and/or longer periods are considered.

The objectives of the present study are (1) to obtain insights into the sediment transport from the North Sea coasts to the Wadden Sea, especially in the far future around occurrence of drowning (total disappearance of intertidal flats due to SLR), and (2) to obtain insights into the influence of changing tidal range accompanying SLR. The research questions are:

- How will the sediment exchange between the North Sea and the Wadden Sea develop around drowning of the intertidal flats in the Wadden Sea?
- How will SLR scenarios influence the development of the sediment exchange?
- How will a changing tidal range influence the future sediment exchange?

Tidal inlets are an omnipresent feature along the world's coastline, all facing similar management issues under pressure of accelerating SLR. Our study focuses on the tidal inlet systems in the Dutch part of the Wadden Sea, but the findings are also relevant for tidal inlet systems worldwide, especially the other tidal inlet systems of the Wadden Sea spanning from Germany to Denmark.

2 Approach

The study is based on the ASMITA model, which was developed to simulate the long-term large-scale morphological developments of tidal inlet systems (Stive et al. 1998; Stive and Wang 2003; Townend et al. 2016a, b). The ASMITA model has proven valuable for investigating effects of (changing) SLR on the morphological development of tidal inlet systems in earlier studies (Van Goor et al. 2003; Lodder et al. 2019).

The research questions concerning the development around drowning are answered by carrying out new simulations using the same models as used by Lodder et al. (2022), for new SLR scenarios and an extended period until 2200. The model parameter settings are the same as given in Table 1 *op.cit.* but the new SLR scenarios are more extreme than those considered previously. In combination with the longer simulated period, drowning occurs during some simulations.

Four new SLR scenario's haven been designed for the new ASMITA simulations (see Fig. 2):

- S-Low: SLR rate constant at 2 mm/y until 2020. Then it accelerates linearly to 5 mm/y in 2055 before it remains constant at this rate. This scenario is in between the scenarios 4 mm/y and 6 mm/year in Lodder et al. (2022).
- S-Mid: SLR rate constant at 2 mm/y until 2020. Then it accelerates linearly to 13.8 mm/y in 2150 before it remains constant at this rate. The acceleration rate is practically the same as in the scenario S-Low, but it continues much longer in time.
- S-High: SLR rate constant at 2 mm/y until 2020. Then it accelerates linearly to 25 mm/y in 2200, the end of the simulations.

Table 1 Year in which drowning (intertidal flat volume becomes zero) occurs in various tidal basins in the different simulations

		Ameland inlet	Vlie	Eierlandsegat	Texel inlet
Tidal range constant	S-High	2189	2167	-	2173
	S-Extr.	2142	2128	2166	2128
Tidal range increasing	S-High	-	2180	-	2197
	S-Extr.	2149	2135	2180	2141

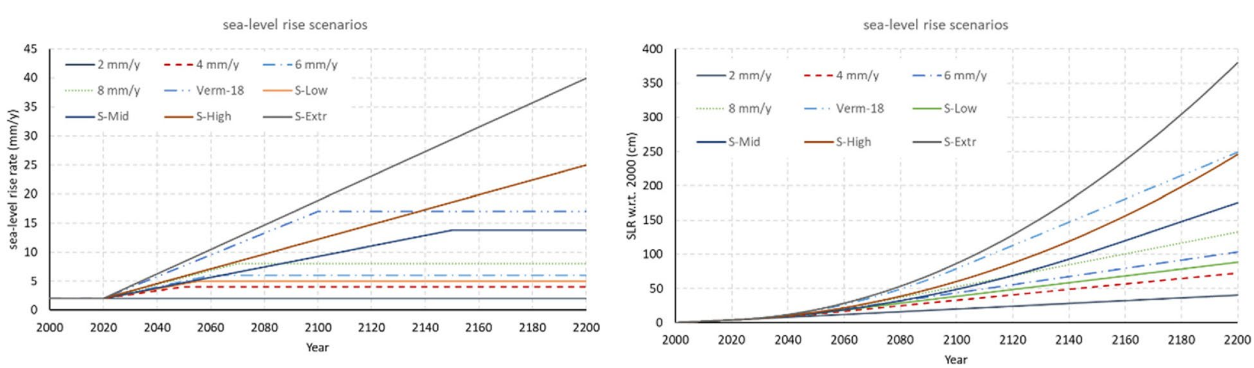

Fig. 2 The new SLR scenarios together with those used by Lodder et al. (2022), for which the SLR rate remains constant after 2100. The left plot shows the rates of SLR used and the right plot shows sea level relative to 0 datum in 2000

- S-Extr: SLR rate constant at 2 mm/y until 2020. Then it accelerates linearly to 40 mm/y in 2200, the end of the simulations.

The design of these four scenarios is inspired by those considered in the Dutch national research programme Sea Level Rise (Taal et al. 2022; Min. IenW 2023). In that research programme the question was asked how the Dutch coastal system will have developed when SLR reaches the values 0.5, 1, 2, 3 and 5 m. The scenarios used in the two studies are similar but the acceleration processes in the ones in the current study are made consistent with those used by Lodder et al. (2022).

The research question concerning the influence of changing tidal range accompanying SLR is also answered by carrying out additional model simulations. The same four SLR scenarios are simulated but with an increase in tidal amplitude Δa, dependent on SLR $\Delta\zeta$:

$$\Delta a = f(\Delta\varsigma) \tag{1}$$

Increase of the tidal amplitude Δa starts from 2020. For a given SLR scenario, the tidal range is then a prescribed function of time.

In addition, theoretical analysis on the sediment demand under the influence of changing tidal range is carried out, by considering how the equilibrium state in a tidal basin will change due to tidal range change. The results of the analysis indicate that the response of the Wadden Sea to SLR can be very sensitive to tidal range change. This leads to a reappraisal of the empirical relations that are used to define morphological equilibrium. A new empirical relation for the equilibrium volume of the channel element is implemented in the model for the simulations considering tidal range change.

3 Theoretical analysis on effects of increasing tidal range

Following the ASMITA model concept, tidal range has two types of effect on the morphological development, via a change of the morphological state and via a change in the morphological equilibrium of the system. According to the ASMITA model concept, residual sediment transports between the morphological elements are driven by gradients of sediment demand, and the sediment demand in a morphological element is determined by comparing the morphological state and its equilibrium. Therefore, changes in the morphological state as well as changes in the morphological equilibrium influence the residual sediment transport and thus the morphological development.

A change in tidal range means changes in high water (HW) and low water (LW). Such changes have an effect

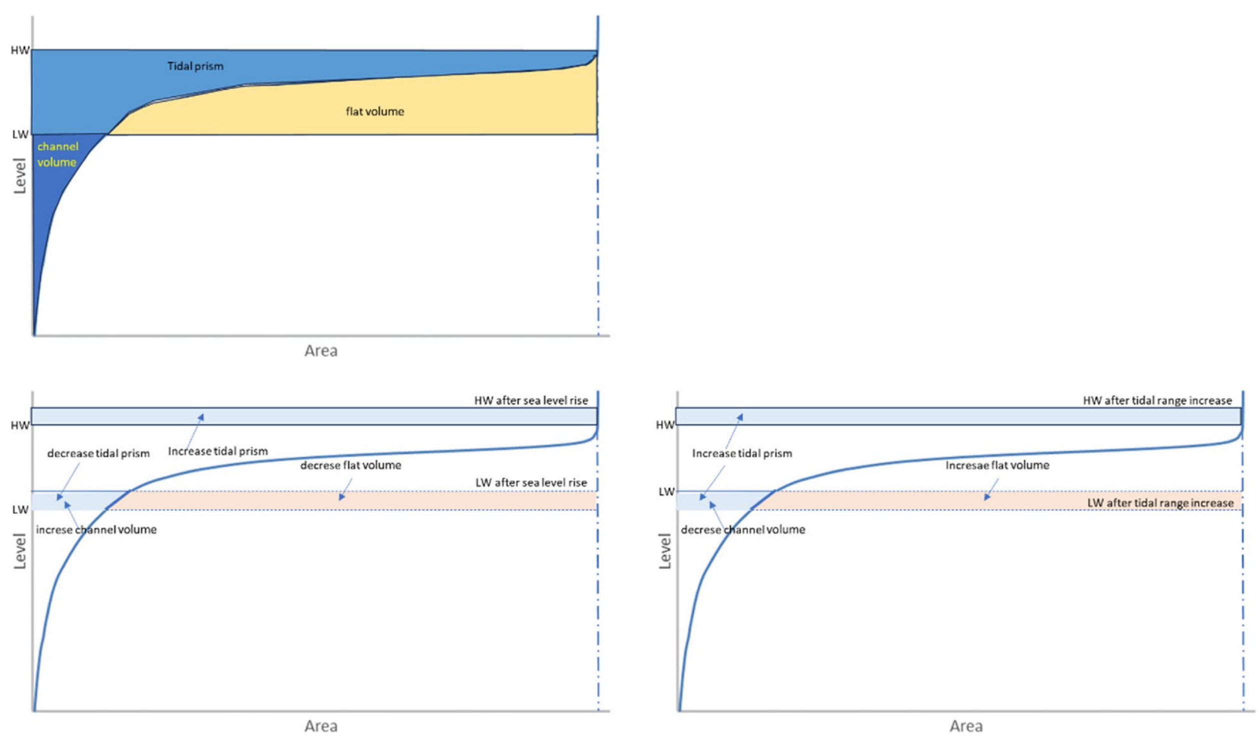

Fig. 3 Sketch based on hypsometric curve to illustrate the direct effects of SLR (bottom left) and an increase of tidal range (bottom right) on intertidal flat volume, channel volume and tidal prism, as defined in the top panel

on the morphological state of both morphological elements in the back barrier basin (see Fig. 3). The volume of channels in the basin is defined as the water volume below LW. Assuming the increase in tidal range corresponds to an equal amount of HW increase and LW decrease, i.e., the change of tidal amplitude Δa, or half of the tidal range change, the change of channel volume ΔV_c can be calculated as follows:

$$\Delta V_c = -S_c \Delta a + O\left(\Delta a^2\right) \tag{2}$$

Where S_c is the surface area of the channel at low water. Note that the assumption applies to cases without change of mean sea level (MSL) but is a simplification of reality if SLR takes place at the same time. Model results (see e.g., Jeuken et al. 2008) as well as field observations (see e.g., Supplementary material) show that LW rises less than MSL and HW when tidal range increases accompany SLR.

The volume of the intertidal flat is defined as the sediment volume between LW and HW. Its change due to a change of the tidal range is thus:

$$\Delta V_f = S_f \Delta a + O\left(\Delta a^2\right) \tag{3}$$

Where S_f is the surface area of the tidal flat between high and low water. An increase of tidal range leads thus to a decrease of channel volume and an increase of intertidal flat volume. Both changes of the morphological state induce a decrease of the sediment demand in the back-barrier basin. Note that in the two equations above it is assumed that the horizontal areas of both the channels and the tidal flats in the basin remain constant. In reality, the horizontal areas do change (see Fig. 3), and the assumption causes an error of order Δa^2, as indicated by Eqs. (2) and (3). If a water volume is used for the tidal flat the same argument applies, except that the change is determined by the change at high water. This only makes a difference if the changes at high and low water are asymmetric (or the bed slopes are different when considering the second order term and changes in surface area).

A change in tidal range leads to changes of the morphological equilibrium of all three morphological elements in a simple 3-element tidal inlet system. The equilibrium height of the tidal flat is proportional to the tidal range (Eysink and Biegel 1992). Therefore, an increase of tidal range leads to an increase of the equilibrium intertidal flat volume, which can be calculated as follows:

$$\Delta V_{fe} = 2\alpha_f S_f \Delta a \tag{4}$$

α_f is an empirical constant expressing the ratio between the equilibrium tidal flat height and the tidal range ($=2a$).

The equilibrium volumes of the channels in the basin and the ebb-tidal delta are proportional to a power (respectively 1.55 and 1.22) of the tidal prism, of which the change is related to the change of tidal amplitude as follows:

$$\Delta P = 2S_b \Delta a - \Delta V_f = 2S_b \Delta a - S_f \Delta a = \Delta a\left(2S_c + S_f\right) \tag{5}$$

Herein $S_b = S_c + S_f$ is the total basin area. An increase of tidal ranges leads thus to increases of the equilibrium volumes of both the channel and the ebb-tidal delta volume.

By comparing the changes of the volume and its equilibrium the change in sediment demand of a morphological element can be evaluated. For the tidal flat element both the volume and the equilibrium volume increase if tidal range increases, but in most cases the increase of the equilibrium volume is the smallest of the two as α_f is usually smaller than 0.5 (Eysink and Biegel 1992). An increase of tidal range thus leads to less sediment demand for the tidal flats. With increasing tidal range, the volume of the channels in the basin decreases and the equilibrium volume increases, leading to a decrease of sediment demand (or the potential to erode). For the ebb-tidal delta the equilibrium volume increases if tidal range increases, leading to an extra sediment demand. Thus, if a tidal range increase is the only driving force, sediment will be transported from the basin to the ebb-tidal delta to restore morphological equilibrium. However, whether the sediment demand of the whole system (i.e., all three morphological elements together) decreases or increases due to a tidal range change depends on the configuration of the system.

The sediment demand of the whole back-barrier basin, i.e., tidal flats and channels together, can also be considered by using the water volume V below HW as a state variable. A change of tidal range leads to a change of HW equal to the change of tidal amplitude, thus

$$\Delta V = S_b \Delta a = \left(S_f + S_c\right)\Delta a \tag{6}$$

The equilibrium value of V is a function of the basin area and the tidal range (Lodder et al. 2019, see also Supplementary material):

$$V_e = f(S_b, a) = (2S_b a)\left(1 - \alpha_f\left(1 - 2.5 \cdot 10^{-5}\sqrt{S_b}\right)\right)\left(1 + \alpha_c\left((2S_b a)\left(1 - 2.5 \cdot 10^{-5}\sqrt{S_b}\right)\right)^{0.55}\right) \tag{7}$$

It increases with increasing tidal range, and the increase ΔV_e is more than ΔV as can be reasoned as follows. Per definition

$$V = P + V_c \text{ and thus } \Delta V_e = \Delta P + \Delta V_{ce} \text{ where } \Delta V_{ce} = f(\Delta P) \tag{8}$$

As the change in the tidal prism ΔP $(=S_b\Delta a+S_c\Delta a)$ is already larger than ΔV and ΔV_{ce} is positive, ΔV_e is larger than ΔV, or in other words, an increase of tidal range leads to a decrease of sediment demand in the whole basin (or an increase in the potential to export sediment). Thus, if only driven by an increase of tidal range, sediment will be exported from the Wadden Sea through the tidal inlets.

To consider the combined effect of SLR and tidal range change, it is more convenient to use the averaged water depth H under HW in the basin as a state variable, as already introduced by Lodder et al. (2019). It changes due to SLR $\Delta\zeta$ as well as tidal range change:

$$\Delta H = \Delta\varsigma + \Delta a \tag{9}$$

The change of its equilibrium value is only influenced by the tidal range change:

$$\Delta H_e = \frac{\Delta V_e}{S_b} \tag{10}$$

It is even more convenient to use the HW before any tidal range change occurs as a reference for the water depth. Then the change in the water depth ΔH-Δa is only related to SLR (see Eq. 9) and the change of its equilibrium value ΔH_e-Δa is only related to the tidal range change (See Eqs. 7 and 10).

Figure 4 shows how increasing tidal range influences the equilibrium water depth (with respect to unchanged HW) for the six tidal basins in the Dutch Wadden Sea, as derived from the theoretical analysis above. For all the basins the relation is practically linear (R^2 linear trend line > 0.99). The slope of the trend line indicates how sensitive the equilibrium depth is to tidal range change. If the increase of the equilibrium depth is equal to SLR then the sediment demand in a basin remains unchanged due to the combined effects of SLR and changing tidal range. Using the information in the figure it is thus possible to determine how much tidal range increase would be required to balance a certain SLR. For all the basins the effects of tidal range increase will not be sufficient to balance SLR, if 1 m SLR causes 10% increase of tidal range. Nevertheless, the effect of tidal range change is significant. For the Ameland Inlet the sediment demand increase reduces by about 23% (tidal range increase = 0.1*2.2 = 0.22 m, equilibrium depth increase = 0.22*1.03 ≈ 0.23 m, i.e. 23% of 1 m SLR), and for the Texel Inlet the reduction is 40% (0.1*1.65 = 0.165 m, 0.165*2.4≈0.4 m).

Apparently, the development of sediment demand and the sediment transport through the tidal inlets are very sensitive to tidal range development. Field observations in the Texel Inlet suggest that, over the long-term,

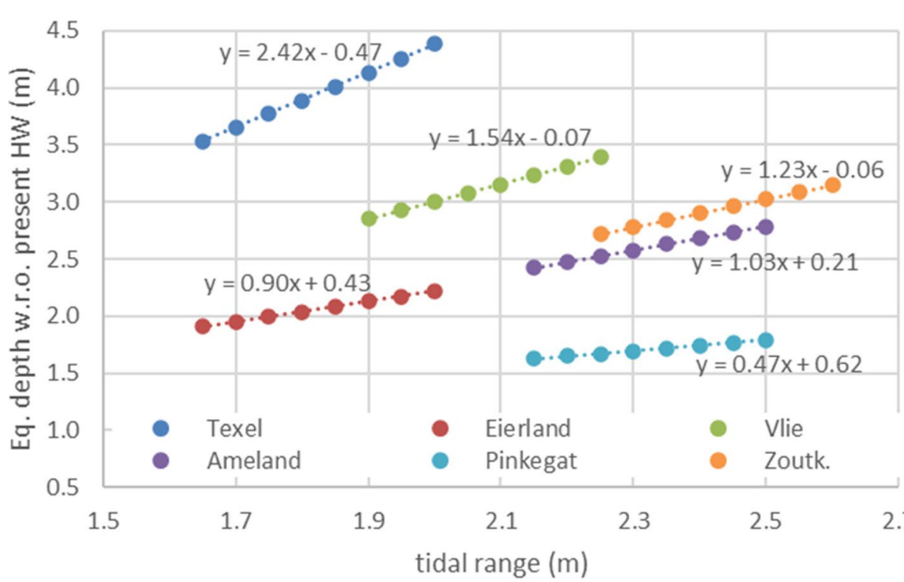

Fig. 4 Relation between tidal range and averaged equilibrium water depth for the various tidal basins in the Dutch Wadden Sea. The parameters in the present ASMITA models (as used by Lodder et al. 2022) for morphological equilibrium are used. For each basin the most left point represents the initial state for the tidal range used in previous applications of ASMITA to the Wadden Sea inlets. The equilibrium water depth is calculated with respect to the HW at this initial state

changes in tidal range could even have a greater effect than SLR (From 1877 to 2020 the tidal range at Harlingen increased by 0.63 m and SLR in the same period was less than 0.3 m). This means that the combined effect of SLR and the accompanying tidal range change could be a negative sediment demand. This reveals the importance of studying tidal range change corresponding to SLR, although a large part of the tidal range increase was caused by the closure of the Zuiderzee). That this is indeed the case becomes evident from the ability of large systems to exhibit a morphological response to the nodal tidal cycle as well as the accompanying SLR (Townend et al. 2007; Wang and Townend 2012).

The sensitivity of the tidal range change also led to the reconsideration of the empirical relations used for defining the morphological equilibrium. In the model, the equilibrium channel volume is proportional to the power 1.55 of the tidal prism. This empirical relation is derived from the field data measured in various tidal inlet systems. That the power is near 1.5 also has a possible theoretical explanation (Renger and Partenscky 1974; Renger 1978): the cross-sectional area of a channel is proportional to the tidal prism and the length of all channels together in a basin is proportional to the square root (power 0.5) of the basin area and thus to the power 0.5 of the tidal prism, which is proportional to the basin area, i.e.:

$V_c = AL, \quad A \propto P, \quad L \propto \sqrt{S_b}, \quad S \propto P \quad \text{hence } V_c \propto\sim P^{1.5}$, where A is the averaged cross-sectional area of the channels, L is the total length of the channels.

However, this theoretical explanation also tells us that it is not correct to use this relation in the ASMITA simulations, when the simulations are carried out for a single tidal inlet system with *fixed* basin area. Figure 5 illustrates why it is incorrect to use the relation with a power near 1.5 for the simulations. The variation of channel volume with tidal prism is linear for a given size of tidal basin (For a fixed basin length, L is constant. The channel volume, $V_c = AL$, then only depends on cross-section area, A, and hence is linearly proportional to the tidal prism). A corrected relation with a power of 1 is therefore implemented in the model in cases where the basin surface area does not change over time.

In previous studies, data from different tidal inlets and estuaries have been merged (e.g., Townend 2005) and exponents between 1 and 1.25 have been suggested (Townend et al. 2016a, b), further illustrating the perils of

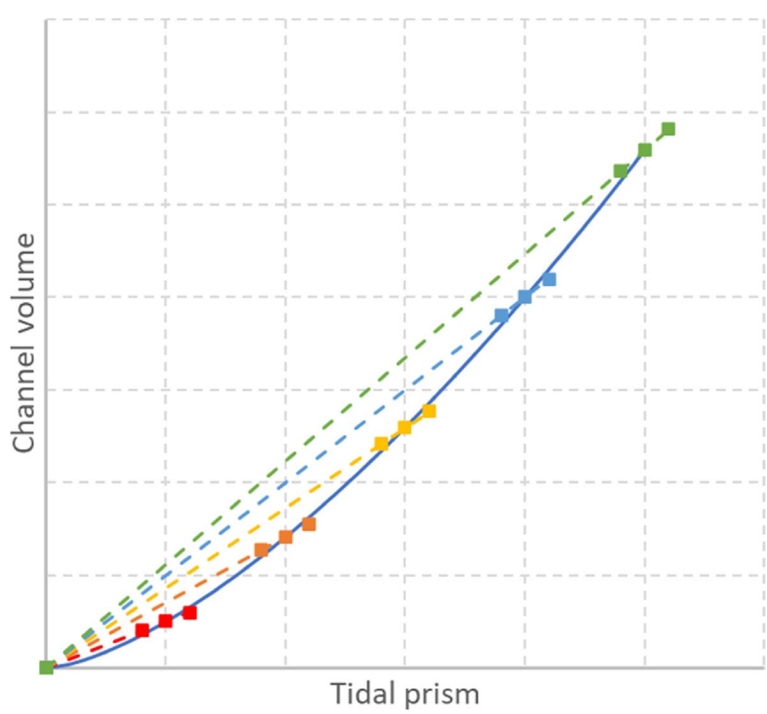

Fig. 5 Sketch for relation between tidal prism and equilibrium channel volume. The solid line is a power law relationship with power 1.5 and is consistent with field data measured in various tidal inlet systems. The dashed lines and points represent how individual inlet volumes vary with tidal prism. For each individual tidal basin, with fixed basin area, the relation between the equilibrium channel volume and the tidal prism is linear. However, the coefficient in this linear relation is not a constant but increases within increasing basin area (with power 0.5 based on geometric considerations). Therefore, if field data from various tidal basins with different basin areas are used to derive the empirical relation between (equilibrium) channel volume and tidal prism, the power will be found to be around 1.5

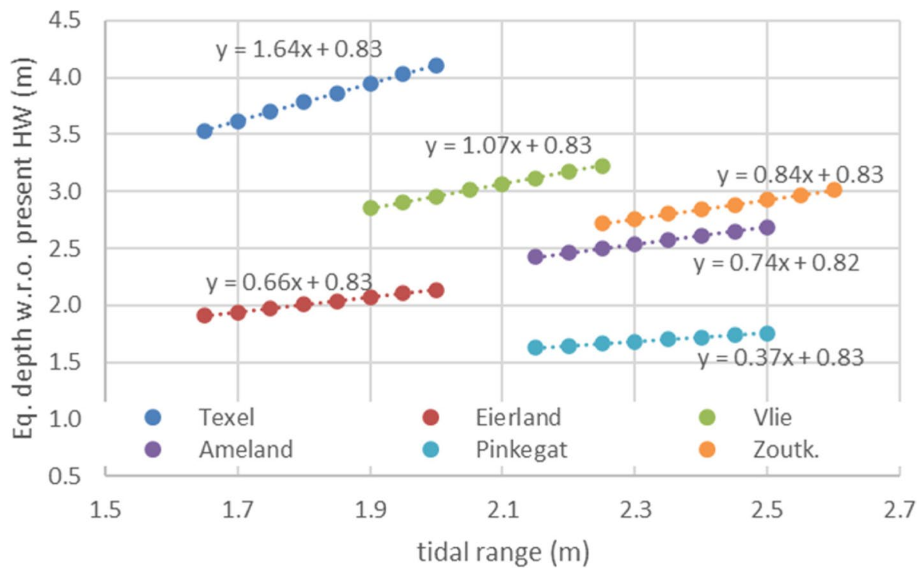

Fig. 6 Relation between tidal range and equilibrium water depth for the various tidal basins in the Dutch Wadden Sea, derived from the analysis based on a linear relation between equilibrium volume and tidal prism. For each basin the most left point represents the initial state with the tidal range used in previous applications of ASMITA to the Wadden Sea inlets, and the coefficient in the linear relation is such that the equilibrium depth at this initial state remains the same as in Fig. 4

using compound data sets. Isolating the tidal inlets does suggest a higher exponent as compared to the predominantly single channel estuary systems but the sample is too small to draw any firm conclusion. However, it should also be noted that setting the exponent to 1 provides an equally good fit to the data for channel volumes (Table 1 in Townend et al. 2016a, b).

Figure 6 depicts the same relations as shown in Fig. 4 but now from the analysis using a linear relation between the equilibrium channel volume and the tidal prism. The equilibrium depth is now less sensitive to the tidal range change as indicated by the smaller slope of the linear trend lines.

4 Model results and interpretation

4.1 Behavior near drowning

We first consider the potential for drowning, where drowning entails the total disappearance of intertidal flats. The simulated sediment import rates to the various Wadden Sea basins for the new SLR scenarios are shown in Fig. 7. The import rates to the eastern part, western part and the whole Dutch Wadden Sea are shown in Fig. 8. The following observations are made from the results of the simulations with the new SLR scenarios:

- Drowning does not occur before 2100, even for the new and more sever SLR scenarios. Drowning occurred during the simulation in Ameland, Vlie and Texel Inlet for SLR scenarios S-High and S-Extr., and in Eierlandsegat Inlet for the SLR scenario S-Extr. The year in which drowning occurs in each of these cases is given in Table 1.
- When drowning occurred in the simulations the import rate develops to a maximum, but the maximum values are not equal for the different SLR scenarios. Apparently, the maximum value just before drowning does not represent the maximum transport capacity of the system. This is also confirmed by the fact that in a scenario without drowning the import rate can increase above the values at drowning.
- The conclusion that the import rate is less sensitive to the SLR rate than expected (Lodder et al. 2022) remains valid. The highest SLR rate (scenario S-Extr.) in 2100 considered is up to 18 mm/yr, i.e. factor 9 higher than the lowest scenario (2 mm/y). For 2200 this is a factor 20 (40 vs 2 mm/yr). The projected import rate for the highest scenario (S-Extr.) for the eastern part of the NL Wadden Sea is about 330% (575% in 2200) of that for the lowest scenario (2 mm/yr), of the western part of the NL Wadden Sea about 150% (205% in 2200) and of the Whole NL Wadden Sea about 180% (275% in 2200).
- The projected increase of the import rate until 2100 with respect to the present situation (2020) is up to a factor 2.05 (205%) for the highest sea level rise scenario (S-Extr.), which is significant but much less than the increase in SLR rate (by factor 9, or 900%) might suggest.

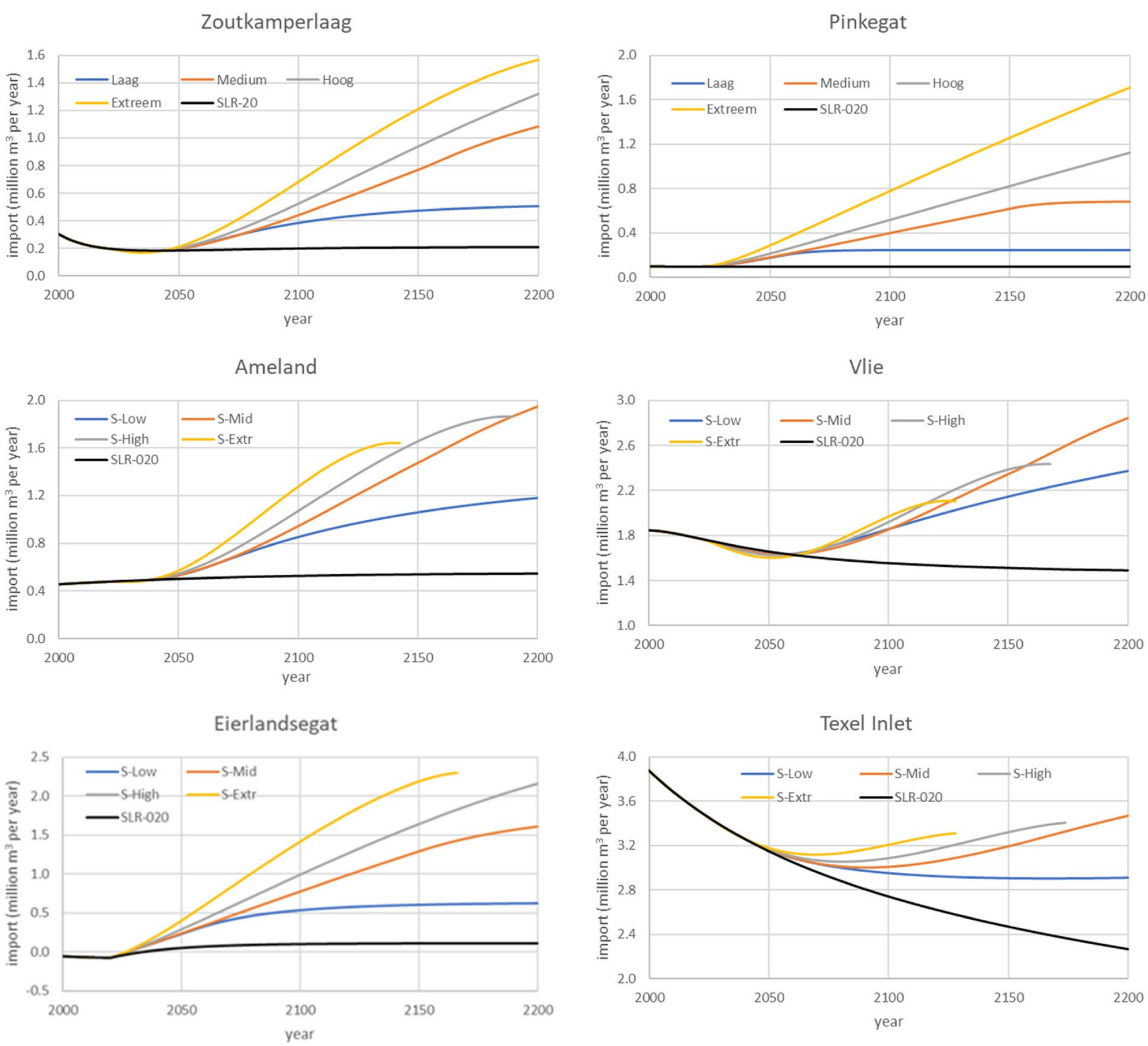

Fig. 7 Simulated sediment transport to the Wadden Sea through the various tidal inlets for the SLR scenarios considered. Note that SLR-020 represents the case without change in the ongoing SLR rate in the last century (i.e., a constant rate of 2 mm/y). Note that series which stop before the end of the simulation period indicate drowning of the tidal flat under that scenario

4.2 Influence of tidal range change

Tidal range change is implemented in the model with two parameters: a percentage per century and a fraction of SLR, both becoming effective starting from 2020. According to the model formulation, a change in tidal range influences the morphological development of the tidal flats and the channels in the basin via two mechanisms: First, it influences the equilibrium volume of the two elements via the changed tidal range and via the changed tidal prism, as already analyzed above. Second, it also influences the volume of both elements via the changes in LW, as LW is involved in the definition of the volumes for flat and channel elements (and HW in the case where water volumes are used for the tidal flat).

The simulated sediment exchange for the same SLR scenarios but with tidal range increasing in time, starting from 2020 is shown in Figs. 9 and 10. The increase consists of two parts: 4% per century and 0.1 of SLR above that of 0.2 m per century. This choice is made after analyzing the observed changes given in Supplementary material. The model results make clear that:

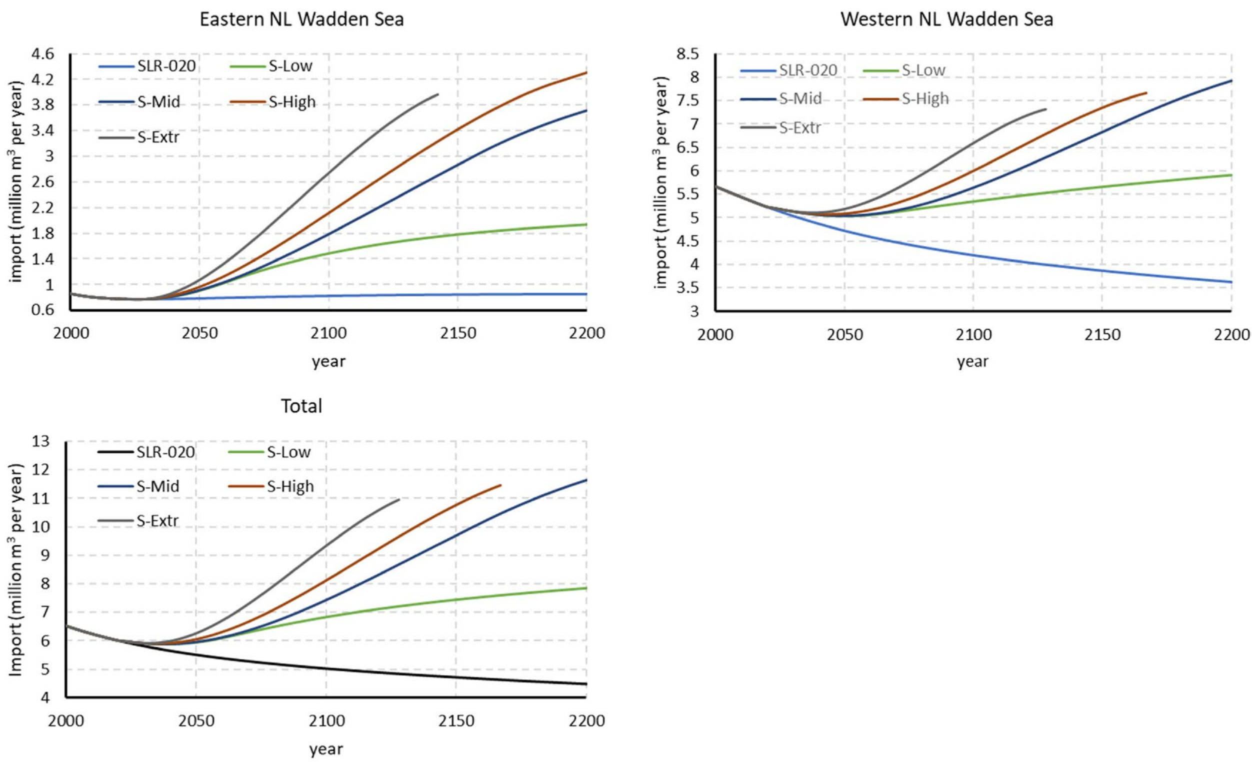

Fig. 8 Simulated sediment transport rate to the Eastern part (Zoutkamperlaag, Pinkegat Z and Amelanderzeegat), the western part (Vlie, Eierlandsegat and Texel Inlet) and the whole Dutch Wadden Sea for the various SLR scenarios. Note that after drowning in a basin the sediment transport rate through the inlet is kept constant to make this figure

- The effect of tidal range change is significant. This emphasizes the importance of studying the future tidal range development in tidal inlets such as the Wadden Sea.
- The effect including tidal range in the SLR scenarios is to decrease the import of sediment to the Wadden Sea basin in most cases. This is consistent with the conclusion from the theoretical analysis on the influence of tidal range increase on the sediment demand in the basin.
- Due to the increase in tidal range, drowning occurs later, despite the decreased sediment import. Table 1 summarizes the year of drowning for the various cases. Note that the basins of Pinkegat and Zoutkamperlaag do not drown in any of the simulations, and none of the basins drown for the low and medium SLR scenarios.

5 Discussions

5.1 Sediment import near drowning

Most of the conclusions from the model results concerning the differences between the various SLR scenarios are consistent with those from the previous study by Lodder et al. (2022). However, it seems that this does not apply for the behavior around drowning. The model results show that the sediment import approaches a maximum when drowning occurs. This agrees with the theoretical analysis using a single element model (Lodder et al. 2019) that there is a sediment transport capacity for each inlet (Wang et al. 2018). However, the model results also show that the maximum import rate achieved at drowning depends on the SLR scenario. Apparently, the calculated import rate at drowning is not equal to the import capacity as described by Lodder et al. (2022) based on the single element model. This is for two reasons. Firstly, the definition of drowning in the 3-element model is not the same as the single-element model used for the theoretical analysis. In the single element model drowning is taken as the point at which the water depth of the element becomes infinite. Whereas in the 3-element model, drowning occurs when the intertidal flat volume becomes zero. In reality, the import rate can still increase after the disappearance of the intertidal flat. Secondly, there is a difference between the development of the source area of imported sediment. In the

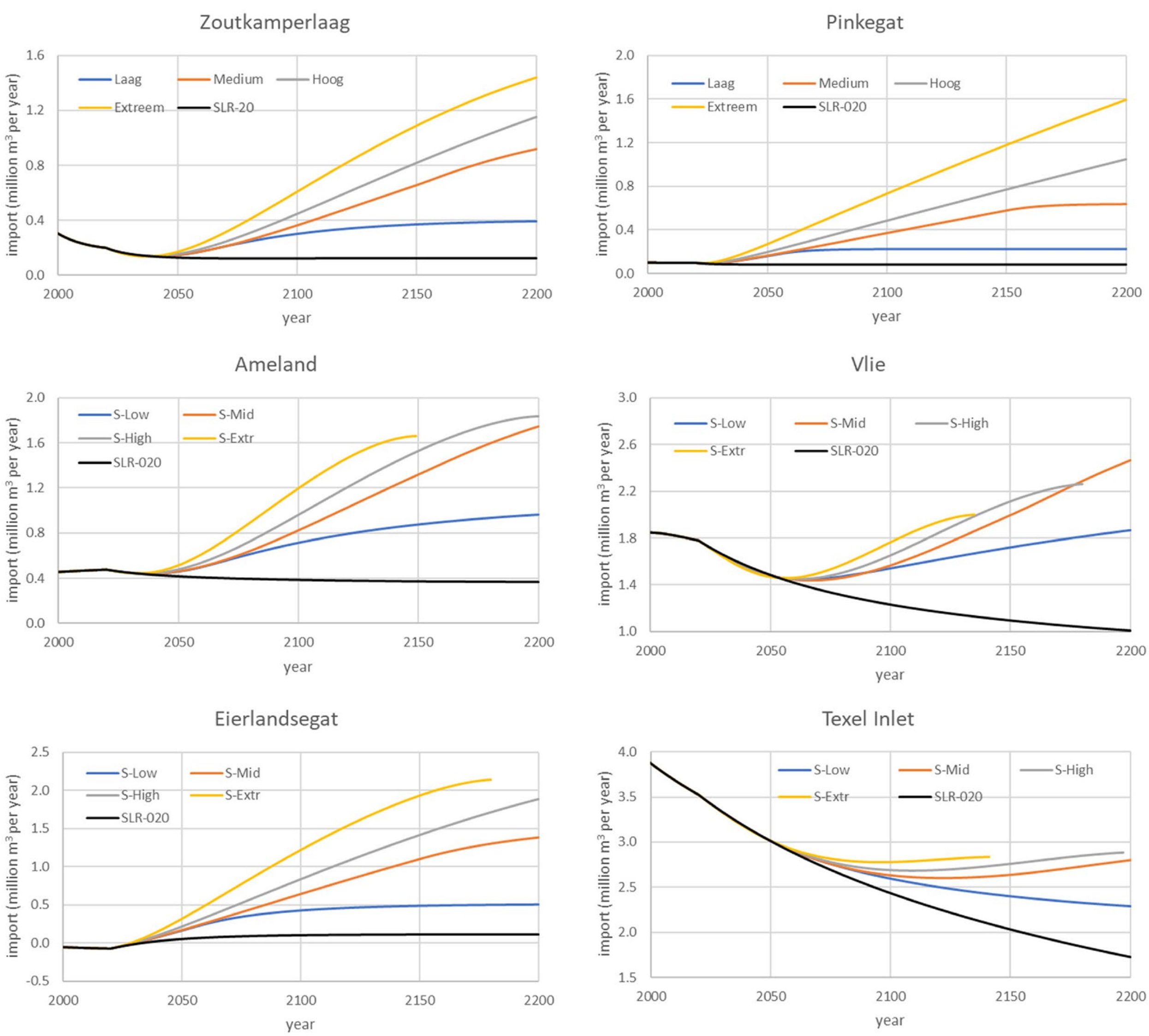

Fig. 9 Simulated sediment import through the tidal inlets for various SLR scenarios, with tidal range change (4% per century + 0.1 of SLR, starting from 2020)

3-element model the element representing outside the Wadden Sea is the ebb-tidal delta which, as one of the three elements in the model, changes in time. In contrast, in the single element model there is only the basin and the outside world, which is assumed to bein permanent equilibrium. The simulated sediment import into the Wadden Sea depends on SLR scenarios because the sediment transport between the ebb-tidal delta and the channels depends on the morphological states of the morphological elements. For most of the inlets a higher SLR scenario leads to a lower import rate near drowning, because the over-depth on the ebb-tidal delta is larger at time of drowning as it occurs in a shorter period than in a lower SLR scenario. The only exception is the Texel Inlet which is still adjusting to a new dynamic equilibrium after the disturbance due to the closure of the Zuiderzee (Elias et al. 2012; Wang et al. 2012, 2018). The sediment import has been and is decreasing in time. A higher SLR scenario leads to earlier drowning resulting in higher sediment import rate at the end of the simulation.

5.2 Interaction between morphological change and tidal range change

In the aggregated model ASMITA, the hydrodynamic module is simplified and the tidal range needs to be

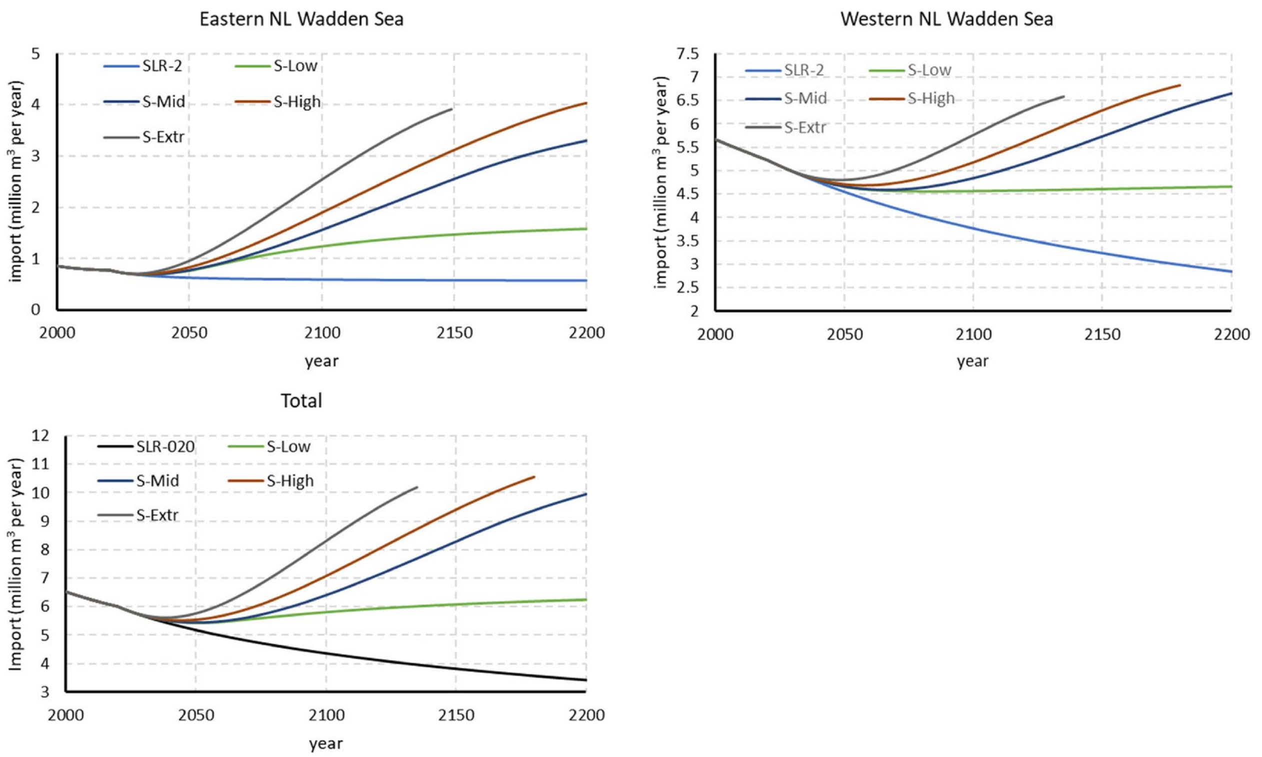

Fig. 10 Simulated sediment import to the eastern part (Zoutkamperlaag, Pinkegat and Ameland Inlet), western part (Vlie, Eierlandsegat and Texel Inlet) and the whole Dutch Wadden Sea

prescribed as a function of time (via a relation with SLR). In reality, the tidal range in the Wadden Sea depends on sea level development as well as on morphological development. The tidal range development outside the Wadden Sea along the North Sea coast mainly depends on SLR (Idier et al. 2017; Jordan et al. 2021), whereas within the Wadden Sea the tidal range also depends on the morphological development of the tidal inlet systems. This dependency is not considered in the model simulations. Therefore, the model results concerning increasing tidal range are only indicative rather than predictive. More research is required to understand the effects of morphological change on the tidal range development in the Wadden Sea, before the change of tidal range depending on morphological changes rather than a prescribed function of time can be implemented in the ASMITA model.

To obtain some insight into the interaction between tidal range change and the morphological development in the Dutch Wadden Sea, the historical records of the tidal range development are analyzed in Supplementary Material. There is an apparent long-term increasing trend in tidal range at all stations, but the recent short-term development (since the 1980's) of different parts of the system show different trends, which agrees with the finding of Janicke et al. (2021) who analyzed the data from 1958 to 2014. At the stations along the North Sea coasts, outside the Wadden Sea, no clear increasing nor decreasing trend is found. In the Ems estuary the tidal range shows a clear increasing trend, which has been ascribed to the interaction between tidal amplification and sediment dynamics triggered by human interference (Winterwerp et al. 2013a, b). At all stations within the Dutch Wadden Sea, except Harlingen, the tidal range shows a decreasing trend. This can be caused by the ongoing shallowing of the Wadden Sea as the averaged sedimentation rate in the Dutch Wadden Sea has been higher than the SLR rate in the last century (Elias et al. 2012; Wang et al. 2018). However, further analysis of the observations is required to understand the interaction between the morphological changes and the tidal range changes. The observed records also show a marked variation in tidal amplitude in response to the lunar nodal cycle. This has been shown to be an identifiable response in larger estuary systems (Townend et al. 2007; Wang et al. 2012) and is likely to play a role in the dynamics of the Wadden Sea inlets. For predictions for the coming decades, it is reasonable to assume that the tidal range remains constant, but over the longer term the interaction of SLR and tidal range may become important.

Revision of the empirical relation for the equilibrium channel volume raises two questions: (1) what is the implication for previous studies which have used a power law relationship? (2) should a similar modification be made for the empirical relation for the ebb-tidal delta volume? In previous studies of the Wadden Sea, the tidal range was kept constant. This means that the tidal prism can only change in time due to the change of the intertidal flat volume. The magnitude of change is thus limited implying that the change of the empirical relation for the equilibrium channel volume would hardly influence the results (e.g., Lodder et al. 2022; Huismans et al. 2021). According to the empirical relation for the ebb-tidal delta the equilibrium volume is proportional to the power 1.23 of the tidal prism. The power 1.23 is purely empirical, derived from field data at various tidal inlet systems. It is quite possible that this value has a similar reason as the power 1.5 for the channel volume, as power 1 would be logical based on dimension analysis. Future study is recommended on this question.

6 Conclusions

By using SLR scenarios with faster acceleration and running the simulations for longer periods of time some Wadden Sea inlets exhibited drowning. The model results show that the sediment import rate approaches a constant value when drowning occurs. The import rate increases to a maximum or decreases to a minimum, depending on the initial morphological state of the tidal inlet system. This maximum or minimum rate for a given tidal inlet system depends on the SLR scenario, the higher the scenario (faster acceleration to a higher SLR rate) the lower the maximum level or higher the minimum level. This implies that the import rate approached at drowning is not the sediment transport capacity derived from the single element model (Lodder et al. 2019). In reality, the import rate will keep on changing after drowning and approach the transport capacity mentioned by Lodder et al. (2019) after a longer time.

As concluded by Lodder et al. (2022), acceleration of SLR will lead to higher sediment import rates for the Wadden Sea inlets: the faster the acceleration, the higher the import rate. However, the increase of the import rate is less than the increase in SLR rate may suggest. These conclusions are confirmed again by the results of the model simulations in the present study. The simulated increase of the import rate until 2100 with respect to the present situation (2020) is up to a factor 2.05 (205%) for the highest sea level rise scenario (S-Extr.), which is much less than the increase in SLR rate (by factor 9, or 900%) might suggest.

One of the limitations in the previous study (Lodder et al. 2022) is that the tidal range is assumed to be constant through the simulation period. Theoretical analysis as well as modelling results show that tidal range change will influence the sediment import to the Wadden Sea. A tidal range increase will cause a decrease of the sediment demand in the Wadden Sea resulting in less sediment import to the Wadden Sea.

The analysis on the influence of tidal range on the sediment demand in the Wadden Sea led to a consideration of the empirical relation used for the equilibrium channel volume in a tidal basin. It is concluded that the empirical relation used in previous studies, which has been derived from field observations in a wide range of tidal inlets, is not representative of a single tidal basin with a fixed area.. The equilibrium channel volume should be proportional to the tidal prism instead of to its 1.5th power.

The significant influence of tidal range change on the sediment import to the Wadden Sea implies that it is important to study the tidal range development in the Wadden Sea. It is essential to understand the interaction between tidal range change and morphological development in the system in order to make predictions, especially for the far future scenarios. It is further recommended to reconsider the power 1.23 in the empirical relation relating the ebb-tidal delta volume to the tidal prism, similar to the consideration in this study for the channel volume.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44218-024-00044-y.

Supplementary file 1.

Authors' contributions

ZBW and QJL carried out the theoretical analysis and numerical simulations. IHT helped the analysis concerning the empirical relation for defining morphological equilibrium. YZ contributed to the initial set up of the study and to the discussions of the results. All authors contributed to the writing of the paper.

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Availability of data and materials

Not applicable.

Declarations

Competing interests

The authors declare that they have no competing interests.

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