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NUMERICAL MODELLING OF THE IMPACT OF SEA LEVEL RISE ON LARGE TIDAL INLET/BASIN SYSTEMS

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ABSTRACT

The response of a large tidal inlet/basin system to Climate change driven sea level rise, in combination with local subsidence is simulated with two very different numerical modelling approaches: process-based and scale-aggregated. Delft3D (process-based) and ASMITA (scale-aggregated) models are used to simulate the morphological evolution of a schematised inlet/basin system representing the Ameland inlet in the Dutch Wadden Sea for a Relative Sea Level Rise scenario (RSLR) of 10 mm/year over a 25 year period. While the quantitative forecasts of the two models are different to each other, both models qualitatively indicate, over the 25 year simulation period, (a) a flood-dominant transport system which agrees with the contemporary measurements of the Ameland inlet, and (b) RSLR driven enhancement in the sediment transport. The ASMITA suggests stable tidal flats with an RSLR of 10 mm/year while the tidal flats diminished in the Delft3D.

Keywords: Delft3D, ASMITA, sea level rise, tidal inlet, Wadden Sea

1. INTRODUCTION

Climate change driven sea level rise is very likely to have a significant impact on large tidal inlet/basin systems, including transgression (landward retreat) or regression (seaward advance) of inlet adjacent coastlines, erosion of ebb-tidal deltas and sedimentation of tidal basins, and drowning of tidal flats (Dissanayake et al., 2012a). These large inlet/basin systems usually contain extensive tidal flats that are rich in bio-diversity (Sha, 1989; Fenster and Dolan, 1996; Duc, 2008). Due to the associated increase in economic activities, local communities in these areas have grown rapidly in recent decades. The continued existence and/or growth of these environmental systems and communities are directly linked to the extensive tidal flats in the basins that are host to a plethora of diverse flora and fauna. However, these tidal flats are particularly vulnerable to any rise in the mean sea level. Therefore, in view of projected climate change impacts, a clear understanding of the potential impacts of relative sea level rise (i.e. the combination of Eustatic sea level rise and local effects such as subsidence/rebound) on these inlet/basin systems is a pre-requisite for the sustainable management of both the inlet/basin system and the communities that depend on them.

Different modelling approaches such as process-based models and scale-aggregated models can be adopted to forecast the possible evolution of tidal inlet systems under the effect of relative sea level rise (RSLR). Process-based models are based on detailed ‘process-knowledge’ which describes hydrodynamic and sediment transport characteristics (and their feedbacks) using basic physical principles. These models have been successfully used to simulate coastal evolutions up to decadal time scales with tidal forcing only (Dissanayake et al., 2012a,b; Dissanayake et al., 2009; Dastgheib et al., 2008; Van der Wegen and Roelvink, 2008) and up to inter-annual time scales with tide and wave forcing (Dissanayake and Wurpts, 2013; Lesser, 2009). An alternative modelling approach is provided by scale-aggregated models that are based on empirical-equilibrium assumptions which have been formulated using ‘data-knowledge’. These are behaviour oriented and describe coastal evolution over time scales of centuries (Van Goor et al., 2003; Ranasinghe et al., 2013).

The present study attempts to assess the performance of these two different types of models in predicting the evolution of large tidal inlet/basin systems to RSLR over a 25 year period. The process-based model Delft3D and the scale-aggregated model ASMITA (Aggregated Scale Morphological Interaction between a Tidal basin and the Adjacent coast) (Stive et al., 1998) are used in this study to compare and contrast the predictions obtained via the two different modelling approaches.

2. STUDY AREA

The case study employed herein is the Ameland inlet, one of the five Dutch Wadden Sea tidal inlets, and is located between the barrier islands of Terschelling (on the west) and Ameland (on the east). This inlet was specifically selected as a case study because it is a relatively closed basin with minimal connectivity to other adjacent basins and hence lends itself to being numerically modelled as a closed system (Ridderinkhof, 1988). (Figure 1).

Figure 1. Location of Dutch Wadden Sea tidal inlets, the Ameland inlet and basin (source: Google Earth)

The bathymetry of the Ameland inlet has an average foreshore slope of about 1:100 and the ebb-tidal delta is westward skewed and has an area and volume of about 25 km^2 and 130 Mm^3 respectively, while its maximum seaward protrusion is about 5 km (Cheung et al., 2007). The tidal signal in the area is semidiurnal with a mean tidal range of about 2.0 m. The tide propagates from West to East at a speed of about 15 m/s. The average annual significant wave height is about 1.0 m (Cheung et al., 2007). The tidal inlet consists of a two-channel system. The main inlet channel is oriented to the east at the basin end and to the west at the seaward end. The inlet width is about 4 km and the maximum inlet channel depth is about 27 m. The basin area is about 300 km^2 and the associated tidal prism is approximately 480 Mm^3 (Sha, 1989) resulting in a high tidal prism to alongshore sediment transport rate ratio (Ω/M_{tot} = 480) indicative of a highly stable inlet (Bruun and Gerritsen, 1960). A large part of the basin (~ 60%) consists of tidal flats which are submerged during high tide and exposed during low tide. The tidal flats restrict the water exchange with adjacent basins of the Frisian inlet to the east and of the Vlie to the west during low tide (Figure 1). During high tide, the flats form a tidal divide between the Ameland inlet basin and the adjacent basins making the basin a virtually closed system.

In the study area, RSLR causes by two mechanisms; 1) Climate change (i.e. thermal expansion of oceans and melting ice caps) and 2) vertical land movement (i.e. tectonic activities and subsidence). At present, sea level rise of the former mechanism appears to be increasing at a moderate rate of 1.4 to 1.7 mm/year (Rakhorst, 2000; Holgate, 2007). Vertical land movement mainly occurs by land subsidence due to gas extraction on the Ameland island (Marquenie and Vlas, 2005). Local land subsidence rate is expected to be 0 – 0.1 m in the next 50 years (Van der Meij and Minemma, 1999). Van Dongeren and De Vriend (1994) have estimated that the average RSLR is about 0.4 m to 0.6 m for the next 100 years. Van Goor et al (2003) investigated the morphological evolution of the Ameland inlet/basin system using the ASMITA model under different rate of sea level rise. Resulting evolution showed, the critical RSLR of the system (i.e. the maximum RSLR rate which results in morphological equilibrium of a system) is about 10 mm/year. We employed this higher rate of RSLR (i.e. 10 mm/year) which could result in strong evolution of the system in order to compare and contrast both modelling approaches over a 25 years period.

3. MODEL APPROACH

A highly schematised Ameland bathymetry, based on measurements obtained in 2004, was used as the initial condition in the present study. The model domain consists of three rectangular areas: back barrier basin, inlet gorge and open sea area (Figure 2). The back barrier basin has dimensions of 24 km × 13 km while the inlet gorge dimensions are 4 km × 3 km. The open sea area is 60 km in width and 24 km in length. The back barrier basin and the inlet gorge have a flat bed of 3 m depth. The cross-hatched area in Figure 2 indicates dry banks (erodible area) which are specified at the beginning of simulations to enable the gradual development of conditions that are representative of the present morphology. Initial inlet width is set to 1 km following the historical observations (Rijzewijk, 1981). The open sea area consists of a concave profile from the shoreline up to 9 km offshore where the depth varies from 3 m to 20 m. Beyond that, a constant depth of 20 m is specified.

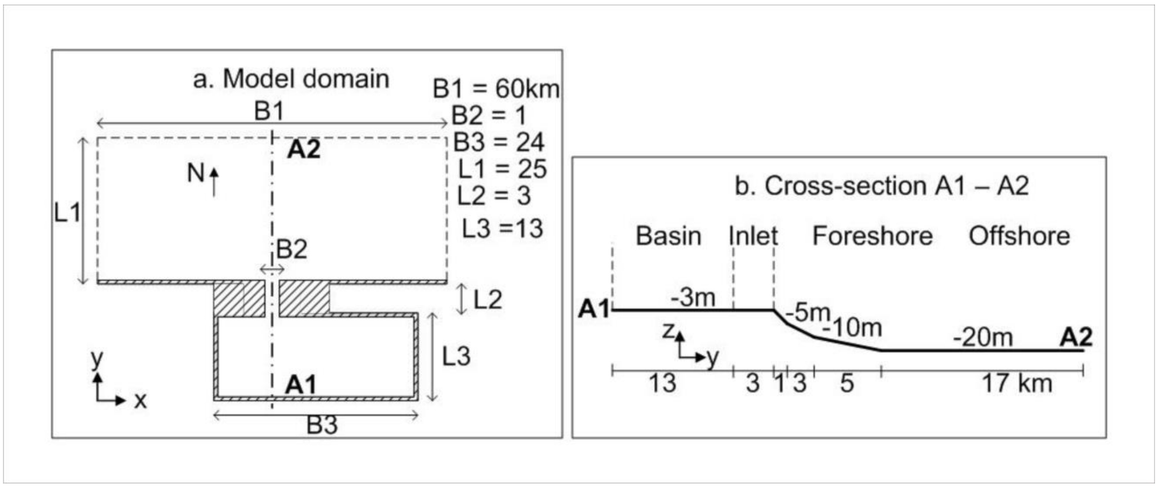

Figure 2. Schematised Ameland inlet; Model domain (a), Cross-section A1-A2 (b). All depths are relative to mean sea level (MSL) (cf from Dissanayake et al., 2009; 2012)

This highly schematised Ameland bathymetry was used to simulate a 50-year morphological period imposing both tide and wave boundary forcings. Tidal forcings for the schematised model were extracted from a well-calibrated North Sea model (Roelvink et al., 2001), which is forced with the astronomical tidal constituents and then the amplitudes and phases of the main tidal constituents of the study area (i.e. M2, M4 and M6, see Wang et al., 1995) were extracted at the offshore corner points of the computational model domain. The wave effect on bed evolution was simulated by employing the stationary (i.e. no infragravity waves) version of the XBeach model (Roelvink et al., 2009). A yearly wave climate was schematised into three dominant wave conditions using the OPTI routine discussed in Dissanayake and Wurpts (2013). Three schematised wave conditions resulting from the OPTI routine had different weight factors indicating their relative contributions on the bed evolution. Therefore, the MORFAC values (used to update morphological changes, Roelvink, 2006) of these waves were selected in proportion to the corresponding weight factor. Wave conditions were then simulated for durations of a fixed hydrodynamic period reaching to one-year morphological period altogether (Table 1). The effect of RSLR was included as a time-varying water level at the northern boundary via a gradually increasing water surface (i.e. mean sea level).

Table 1. Schematised wave climate and MORFAC values representing one-year morphological period.

WAVE	HS(M)	TP(S)	DIR. (DEG.)	WEIGHT FACTOR	MORFAC	MORPHO. PERIOD (MONTHS)
W1	1.5	6.3	330	0.33	46.8	4
W2	0.6	4.5	50	0.58	81.4	7
W3	3.4	7.7	290	0.09	13.3	1

Initially an established morphology following the Realistic Analogue (RA) approach of Roelvink and Reniers (2011), which is analogous to the measured Ameland inlet bathymetry, was developed applying the highly schematized inlet/basin system in the Delft3D model from 0 to 50 years (section 4.1). Then, the ASMITA element coefficients suitable for the established bed (i.e. at 50 year bed) were explored calibrating the ASMITA model against the Delft3D results from 50 to 75 years under No RSLR (section 4.2). Finally, the inlet/basin response to RSLR (i.e. 10 mm/year) in both models was investigated from 75 to 100 years (section 4.3).

4. RESULTS

4.1 Established morphology

Following the RA approach, the first step is to analyse the existing bathymetric data to determine whether the study area is in (or close to) morphological equilibrium state. Two equilibrium relations (tidal prism vs inlet cross-sectional area, P-A (Jarret, 1976; Eysink, 1990); and tidal amplitude to mean channel depth ratio (a/h) vs shoal volume to channel volume ratio (Vs/Vc) (Wang et al., 1999)) were used for this purpose.

Bathymetric data from 1930 to 2004 were available for the present analysis. These bathymetric data were plotted in comparison to the equilibrium relations (Figure 3). Arrows indicate the general trend of the data points. According to both empirical equilibrium relations, the 2004 bathymetry appears to be very close to equilibrium. Therefore, the RA approach then dictates that the initial 'establishment simulation' starting from a schematised flat bed bathymetry should reproduce a bathymetry that is qualitatively similar to the 2004 measured bathymetry.

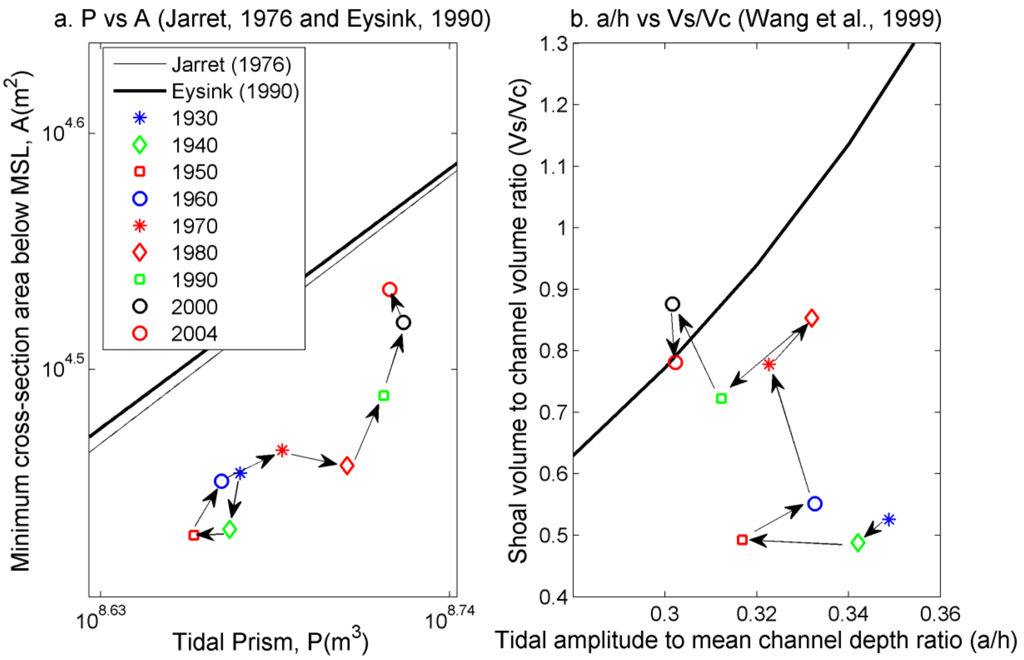

Figure 3. Comparison of bathymetric data from 1930 to 2004 with empirical equilibrium relations, (a) Tidal prism vs inlet cross-sectional area (Jarret, 1976 and Eysink, 1990), (b) Tidal amplitude to mean channel depth ratio vs shoal volume to channel volume ratio (Wang et al., 1999)

Following the next step of the RA approach, the establishment simulation was initialised with the schematised bathymetry (Figure 2), and forced with the tidal (i.e. M2, M4 and M6) and wave boundary conditions described above. At the start of the 'Establishment simulation' an inlet width of 1 km was specified in line with the historical observations (Rijzewijk, 1981). As the 2004 measured bathymetry appears to be in near-equilibrium, the expectation of this establishment simulation is that it produces a near-stable bathymetry that is similar to the 2004 measured bathymetry. The modelled bathymetry can then be used as an analogue to the measured bathymetry to effectively investigate system behaviour under slightly varied forcing conditions (e.g. RSLR).

The evolution of the ebb-tidal delta and tidal basin volumes during the Establishment simulation is shown in Figure 4. A very rapid morphological evolution is shown at the beginning of the simulation while the initial flat bed bathymetry attempts to reach a state that is in equilibrium with the forcing (see, for example, the growth rate of the ebb-tidal delta during the first 30 years shown in Figure 4a). However, after this initial rapid adjustment, the evolution of both the ebb-tidal delta and the basin appears to reach quasi-steady conditions after 50 years of simulation implying near-equilibrium conditions. Therefore, the length of the establishment simulation, the purpose of which is to establish a morphology that is in (or close to) equilibrium, was limited to 50 years.

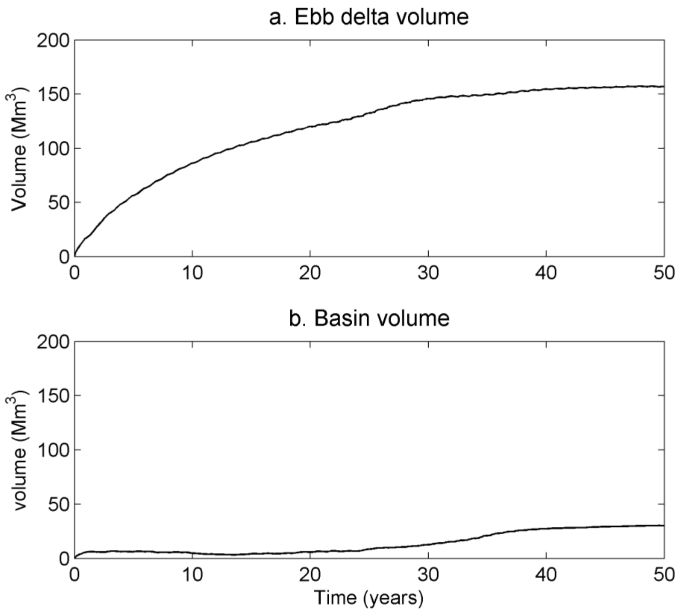

Figure 4. Evolution of ebb-tidal delta volume (a) and basin volume (b) in the 50 year establishment simulation

To quantitatively determine the agreement between model prediction and measured bathymetries, a statistical analysis was undertaken using the Brier Skill Score (BSS) (Van Rijn et al., 2003), which provides a classification of BSS values to assess the model performance. The BSS is defined by Van Rijn et al (2003) as in Eq. [1]:

$$BSS = 1 - \frac{\left\langle (z_{measured} - z_{MORFAC})^2 \right\rangle}{\left\langle (z_{Flat} - z_{MORFAC})^2 \right\rangle} \qquad [1]$$

where, brackets <> indicate the mean value. $z_{measured}$, z_{MORFAC} and z_{Flat} are bed levels corresponding to measured bathymetry, predicted bathymetry with MORFAC and initial flat bathymetry.

In the above definition of the BSS, a value of 1 indicates an excellent comparison between the measurements and the model results (i.e. numerator is in the limit zero). Negative BSS values (i.e. numerator is large and/or denominator is small) imply large differences between the modelled and measured bathymetries.

In this simulation, the entire model domain has not developed evenly (i.e. there are areas of high and low morphological change) (Figure 5b). To minimize the effect of small bed level differences having an undue effect on the overall BSS, a control area which consists only of area of interest enclosing the ebb-tidal delta, inlet and basin was isolated for BSS calculations (area enclosed by the rectangle in Figure 5a).

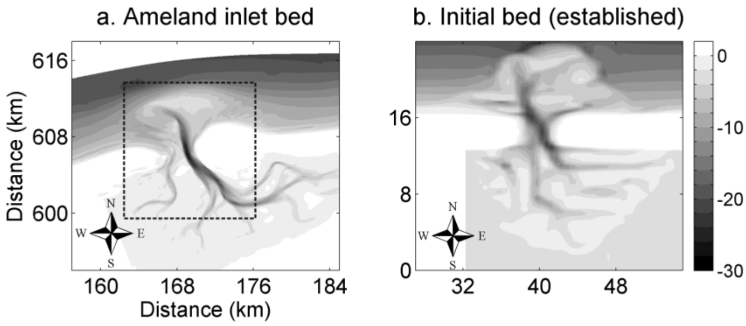

Figure 5. Measured 2004 Ameland bathymetry (a) (Control area for BSS analysis is indicated within the rectangle) and Predicted established morphology (after 50 years of evolution of the initial flat bed) (b)

The BSS value of the final predicted bed is greater than 0.3 which qualifies as a Reasonable/Fair model skill according to the classification of Van Rijn (2003).

The above comparisons indicate that, the predicted morphology after a 50-year simulation period appears to be sufficiently close to the equilibrium morphology of the study area. Following the RA approach, this 'established morphology' is therefore adopted as the initial bathymetry to qualitatively investigate system response to RSLR in subsequent model simulations.

4.2 Calibration of the ASMITA model against the Delft3D results

ASMITA predictions are known to be highly sensitive to the element coefficients: Tidal Flat (α_f), Channel (α_c), and Ebb-tidal delta (α_d), and their sensitivities to the element evolution are referred to Dissanayake (2011) and Van Goor (2003) and the references thereon. For applications of ASMITA to real-world systems, empirically determined values are adopted. However, in the present study, ASMITA is applied to a morphology that has been developed by Delft3D (i.e. the established morphology). If the element coefficients based on the real-world system are applied, we impose different initial conditions in the modelling approaches which will necessarily lead to contrasting morphological evolution. Therefore, the established morphology of Delft3D which is analogous to the Ameland measured bathymetry, was used to define an additional set of coefficients for the present model set-up. The ASMITA element coefficients were calibrated via a baseline 25 year simulation (starting from the established morphology) of both models where RSLR was specified as zero, i.e. the equilibrium element coefficients α_f, α_c, and α_d were tuned (by trial and error) until the comparison between the No RSLR simulations of ASMITA and Delft3D was optimal in comparison to the tidal flat height evolution.

In a tidal inlet/basin system, tidal flat height is used as an indicative parameter to investigate the system response to sea level rise (see Van Goor et al., 2003; Dissanayake et al., 2012a). Therefore, the evolution of tidal flat height (flat volume/flat area) was used as a diagnostic to compare the two model simulations. The ASMITA model assumes constant element areas throughout the simulation and thus element areas of ebb-tidal delta, channel and tidal flat are adopted from the measured data of the Ameland inlet.

The results obtained for the optimal ASMITA settings (see Table 2) are shown in Figure 6. For these settings, average tidal flat height was determined as the ratio of flat volume to flat area. For the first 20 years, ASMITA predicted flat height is lower than that of Delft3D. This discrepancy is most likely due to the different flat areas in the two models. ASMITA assumes a constant flat area (i.e. measured area in the Ameland inlet), while the flat area in the Delft3D simulation varies as the evolution occurs. Despite this initial discrepancy, after the first 20 years, the flat heights predicted by both models are almost identical.

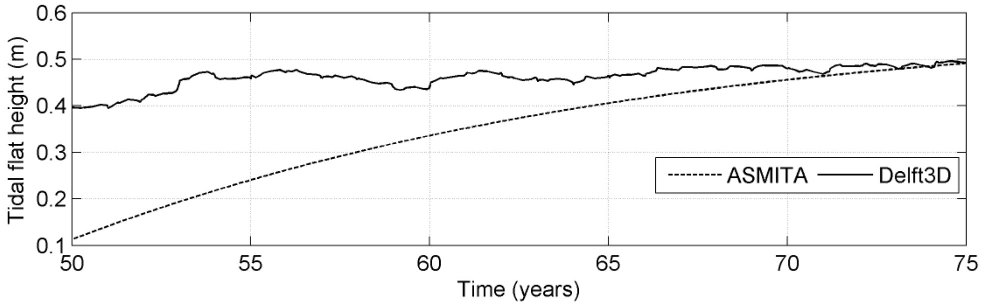

Figure 6. Evolution of tidal flat height for 25 years starting from the established morphology (from 50 to 75) under No RSLR (ASMITA: dash-line, Delft3D: solid-line)

The above described agreement in the diagnostic adopted (i.e. tidal flat height) by the end of the 25 year baseline simulation (starting from the established morphology) with No RSLR indicate that the equilibrium element coefficients used in this ASMITA simulation are optimal. These optimal coefficient values are rather similar to their empirically obtained default values (Table 2). The largest difference between optimised and default coefficient values is for the channel coefficient (~47%), followed by the tidal flat coefficient (~17%) and the ebb delta coefficient (6%). It is noted that the equilibrium element coefficients are affected by the initial conditions of the inlet elements rather than the boundary forcings. Therefore, the optimal element coefficient values thus determined are then used in the RSLR=10 mm/year ASMITA simulation described below.

Table 2. Default and Optimised equilibrium element coefficients of the ASMITA model.

INLET ELEMENT	EQUILIBRIUM ELEMENT COEFFICIENT	
	DEFAULT	OPTIMISED
TIDAL FLAT	0.18	0.21
CHANNEL	11.0	16.2
EBB-TIDAL DELTA	2921	3100

4.3 Model predicted system evolution with RSLR of 10 mm/year

The Delft3D simulation commenced with the 75 year schematised morphology (i.e. final predicted bed of the calibration simulation spanned from 50 to 75 years compared to the flat bed in Figure 2) and was forced with tides, waves and an RSLR of 10 mm/year. The ASMITA simulation adopted the element characteristics based on the 75 year schematised morphology and the optimal element coefficients shown in Table 2. Both simulations were 25 years long (i.e. from 75 to 100 years referring to the schematised initial flat bed). The same diagnostic used above in Section 4.2 (i.e. tidal flat height) was used to compare the predictions given by the two different modelling approaches.

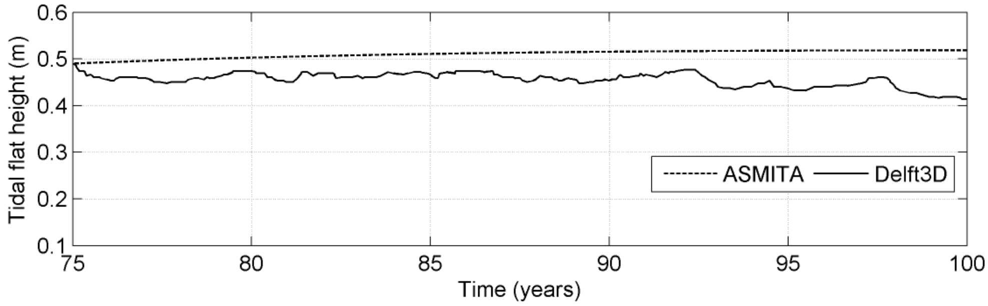

Figure 7. Evolution of the tidal flat height for 25 years (from 75 to 100 years compared to the initial flat bed) under RSLR of 10 mm/year in both modelling approaches (ASMITA: dash-line, Delft3D: solid-line)

The evolution of the tidal flat height is shown in Figure 7. Predicted evolution of the ASMITA model indicates increase of the flat height in the first 15 years (up to 90 years) and then remains constant from 90 to 100 years. Therefore, the tidal flat height during the 25 years period shows marginal increasing trend (~ 1 mm/year). However, resulting flat height of the Delft3D has a decreasing trend from 0.49 m to 0.41 during the 25 years period. The discrepancy between the model predicted flat heights at the end of the 25 year simulation is about 0.1 m, which appears to be increasing if the models are simulated for a longer period, i.e. the models comprise of contrasting trends of evolution.

Despite the quantitative discrepancies between the two model predictions, both models qualitatively indicate different trends of evolution over a 25 year period with an RSLR of 10 mm/year. At the end of the simulation period, the ASMITA model shows constant tidal flat height evolution (i.e. tidal flats keep up with the rate of RSLR 10 mm/year as found in Van Goor et al., 2003) while a decreasing trend (~ 8 cm) of tidal flats suggests in the Delft3D model.

5. DISCUSSION

The sediment transport rates predicted by the two modelling approaches are compared in Figure 8. Delft3D results indicate flood dominant systems (i.e. sediment importing into the basin shown by positive values) in both No RSLR and RSLR (10 mm/year) cases. They have similar transport patterns in the first year. Under No RSLR, a slight increase of transport occurs during the 25 years period (from 0 to about 0.1 Mm^3). The RSLR = 10 mm/year simulation indicates strong sediment import throughout the simulation due to the increased sediment demand of the basin with the increased mean sea level (Dissanayake et al., 2012a). Therefore, the RSLR driven enhancement of sediment transport in the Delft3D simulation is about 0.9 Mm3 (from 0.1 Mm3 to 1 Mm^3) during the 25 year simulation period.

The comparable ASMITA indicator of sediment transport is the sediment exchange between ebb-tidal delta and channels (E-C). Positive values show sediment supply from ebb-tidal delta to channels. As observed in the Delft3D results, both scenarios show similar transport pattern in the first years. Thereafter, the No RSLR case shows increase of sediment supply up to 27 Mm^3 at the end of the simulation period (t = 100 years) while the RSLR indicates higher rate of transport and results in about 33 Mm^3 at t = 100 years. Therefore, RSLR driven sediment transport enhancement of the ASMITA model is about 6 Mm^3 which is about 6 times larger than that of the Delft3D model.

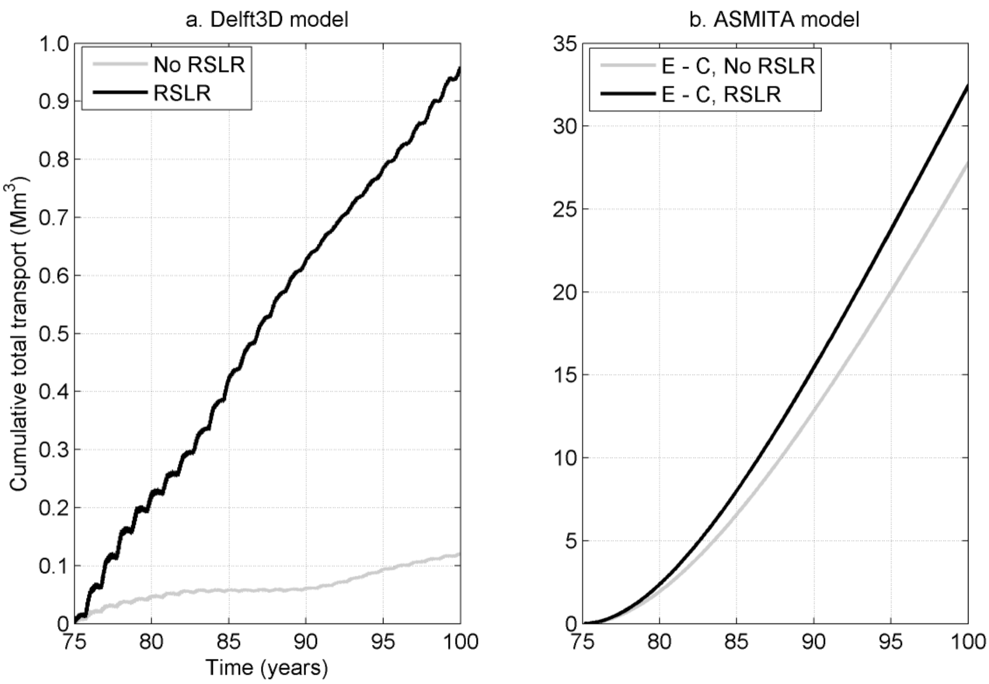

Figure 8. Cumulative total sediment transport; landward transport through the inlet gorge of the Delft3D (a) and Sediment exchange from ebb-tidal delta to channels (E - C) of the ASMITA (b) starting from the 75 year (referring to schematised flat bed) developed morphology of the Delft3D; No RSLR (gray-line), RSLR (black-line)

Despite the differences between the magnitudes of sediment transport volumes (i.e. the ASMITA volumes are 1 order of magnitude larger) predicted by the two different approaches, both qualitatively indicate a sediment importing system which agree with contemporary observations at the Ameland inlet (Dronkers, 1998). The quantitative difference of element evolution and transport rates is not surprising due to the very different model formulations of the 2 models. The Delft3D model uses basic physical principles of water motion to estimate the sediment transport which is dominated by advection. Therefore, the evolution of element occurs due to the gradual movement of sediment from one element to another until equilibrium state is reached. In contrast, ASMITA formulations which consists of empirical-equilibrium relations, always force any system to evolve to an ultimate equilibrium state via diffusive sediment transport among inlet elements. The rate of element evolution is proportional to the difference in sediment concentration (i.e. between element concentration and its equilibrium sediment concentration) of adjacent elements. Element evolution is manifested via volume changes while element areas remain constant throughout the simulation.

It is noted that each model has its own merits. The Delft3D simulations require systematically arranged grid setup and bathymetry of the model area together with different boundary forcings (i.e. tide, waves, wind and sea level rise). This demands extensive pre-processing and also a high level of user experience to setup the model. Furthermore, the simulation itself needs a few days even in a super-computer to estimate decadal evolution of the system. However, the resulting evolution shows detailed information of morphological changes in the model domain (e.g. where erosion or deposition occurs) which is of utmost importance for management decisions. In contrast, ASMITA requires only characteristic numbers (i.e. equilibrium coefficients, area, volume) of inlet elements (i.e. ebb-delta, channels and tidal flats) as input parameters, and the simulation takes only a few minutes to calculate element evolution (i.e. volume change) even for centuries. Therefore, the ASMITA model is more suitable to investigate morphodynamic trends of the system in response to sea level rise whereas the Delft3D can potentially be used to get more physical and detailed insight of the system response to RSLR.

6. CONCLUDING REMARKS

The response of a large tidal inlet/basin system to Climate change driven sea level rise, in combination with local subsidence effect has been simulated with two different numerical modelling approaches: process-based and scale-aggregated. Long term evolution of a schematised inlet/basin system representing the Ameland inlet in the Dutch Wadden sea was investigated for a Relative Sea Level Rise scenario (RSLR) of 10 mm/year using Delft3D (process-based model) and ASMITA (scale-aggregated model). The Delft3D model was implemented following the Realistic analogue approach in which the initial highly schematised bathymetry is allowed to evolve under tidal and wave forcing until quasi-equilibrium conditions are reached (i.e. established morphology). This established morphology was then adopted to compare and contrast the evolution of Delft3D and ASMITA models. As ASMITA is here applied to the Delft3D established morphology (rather than a real-world morphology), it was first calibrated against Delft3D results (from 50 to 75 years) for a baseline 25 year simulation with No RSLR. Applying the calibrated coefficients and the 75 year predicted Delft3D morphology, the ASMITA was then simulated for another 25 year period (from 75 to 100 years) under RSLR = 10 mm/year and results were compared with that of the Delft3D simulation undertaken with similar initial conditions.

Although there are some discrepancies between the quantitative predictions of sediment transport obtained from these two very different modelling approaches, qualitatively, both approaches predicted a sediment importing system during the 25 year forecast period. Both models with an RSLR of 10 mm/year indicate contrasting evolution of the tidal flat height which is the representative parameter of an inlet/basin system to explore the morphological response to RSLR. The Delft3D suggests decreasing trend of the tidal flats throughout the simulation period while the ASMITA shows a slight increase in the beginning and then remains constant at the end of the simulation. Thus, the tidal flats diminish in the Delft3D and they will keep up stable in the ASMITA with an RSLR of 10 mm/year as suggested by Van Goor et al (2003). While the forecasted ability of tidal flats to keep up with an RSLR of 10 mm/year means that the highly environmentally sensitive ecological systems that are abundant on tidal flats may be preserved, the consistent prediction of a significant increase of sediment transport into the basin is a cause for concern. Significant increase in landward transport may have a range of negative physical impacts on the inlet/basin/coast system such as, for example, erosion of the downdrift coast, reduced tidal attenuation at the inlet resulting in stronger inlet velocities (deeper/wider inlet gorges) and enhanced vertical mixing of basin waters.

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