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Transitional polders along estuaries: Driving land-level rise and reducing flood propagation

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ABSTRACT

Dikes are the conventional means of flood defence along rivers and estuaries. However, dikes gradually lead to the superelevation of waterbodies compared to the subsiding embanked areas, resulting in a rapidly increasing unstable situation under sea-level rise. Therefore, future flood management requires new, sustainable strategies that not only minimise flood risk, but also steer land-level rise. An example is a transitional polder, where a dike-protected area is temporarily reopened to the tide to capture sediment until it has risen well above mean sea-level, after which it could be returned to its original function. This study explores how the sequence of opening transitional polders affects sediment capture and large-scale estuary dynamics through 2D modelling in Delft3D. To this end, different opening sequences were tested along a large estuary, using the Western Scheldt (NL) as an example. Findings show land-level rise in all permutations. However, polders opened later in an opening sequence temporarily experience a lag in muddy sediment capture, most likely due to a deficit in fines. Opening more upstream located polders alone or at the start of an opening sequence generally causes a stronger reduction in mean tidal range than opening more downstream located polders. This is explained by increased friction due to (1) locally added intertidal width and (2) shallowing of the main channels because of increased flood dominance. An upstream-to-downstream opening sequence caused the greatest reduction in mean tidal range, but this is negligible compared to the increase in tidal range due to historic dredging within the estuary for navigational purposes. Further work is needed to determine how dredging, closure of transitional polders and storm surges may negate this benefit to flood safety.

1. Introduction

A rising sea-level, large peak discharges and land-subsidence pose an increasing flood risk for millions of people living along estuaries and coastlines [52,77]. Rivers and estuaries are commonly fixed and squeezed between dikes to protect the hinterland against flooding and to provide more arable and habitable land. However, dikes impede natural floodplain aggradation that would otherwise balance background subsidence [5,8,43], which may result in land subsidence that is worsened further by groundwater extraction practices [52,77]. As a result, water bodies become superelevated above the land (e.g., [16]), which strongly increases flood risk especially in light of future sea-level rise [60]. So, the conventional management of mainly heightening and widening hard structures such as dikes is no longer a sustainable solution [40,59,68]. Hence, new strategies under the collective of "managed realignment" are being investigated that combine green and grey infrastructure to minimise flood risk and drive land-level rise through natural processes and natural ecosystems (e.g., [28,80,105]).

Managed realignment involves the landward relocation of a primary flood defence to an existing or new landward flood defence to restore tidal exchange on former embanked areas [31]. This landward relocation of primary flood defences has been realised and studied for a variety of reasons [see for review 28], including: flood protection (e.g., [39, 76]), increased intertidal habitat (e.g., [94,100]), controlled tidal restoration (e.g., [18,63]) and managed retreat (e.g., [1]). Tidal exchange may be restored by lowering, removing or breaching part of the former primary dike and can be regulated via culverts and sluices. Subsequently, tidal flows deliver sediment to the low-lying

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de-embanked land where it contributes to land-level rise. Corresponding rates of land-level rise range from a few millimetres to tens of centimetres per year and level off over time as the inundation period decreases [56,79]. Yet, it has proven challenging to predict actual accretion rates and determine how these depend on e.g., sediment supply and salt marsh vegetation (e.g., [29,34]). Over time, sediment accretion contributes to the development of ecologically rich intertidal flats and salt marshes [65,103]. For example, managed realignment at the Sieperda polder [26] and the Wallasea Island [25,39] promoted the formation of high vegetated foreshores that stabilised the shoreline and reduced flood risk by attenuating waves and storm surges (e.g., [54, 105]). Nevertheless, many managed realignment sites have a lower biodiversity [58,102] and less diverse topography [45] compared to natural tidal marshes, which may be linked to rapid sediment accretion [27] and limited tidal exchange [49]. Alternatively, tidal exchange may be regulated such that sediment delivery is kept at a minimum, so the site of managed realignment acts as a floodbasin to reduce high water levels during storm surges, for example for the Kruibeke–Bazel–Rupelmonde polders along the Scheldt Estuary [18].

A novel strategy that resembles current managed realignment projects is the concept of a transitional polder between double dikes [82, 105] and will be the focus of this study. Managed realignment sites are intended to remain open to the tide indefinitely to maintain their functions of e.g., flood protection and habitat (e.g., [28,65,102]). So, the land is permanently lost for anthropogenic use, which can be problematic in low-lying deltas with limited space availability, where people do not want to give up valuable space. Hence, in contrast to managed realignment, a transitional polder is intended to be only temporarily opened to the tide to elevate the land. After sufficient land-level rise into a supratidal regime, the transitional polder will be closed off from the tide to restore its original anthropogenic function of e.g., agriculture on the newly elevated land [82,105]. Following a controlled dike breach (Fig. 1a), a low-energy floodbasin is formed that promotes sediment deposition and salt marsh establishment [103]. Continued filling elevates a transitional polder well into a supratidal regime especially if vegetation is present (Fig. 1b) [4,29,42,55]. So far, this process is essentially similar to managed realignment projects that also had their seaward dikes breached, either by storms (e.g., [26,31]) or by planned efforts (e.g., [25,34]). Recent numerical modelling [34] suggests a supratidal salt marsh may cover an initially low-intertidal polder within 50 years, but longer time spans may be needed for systems without abundant suspended sediment supply and pre-carved channels to better distribute the sediment. The third and final step is the closure of the inlet (Fig. 1c), after which the original function of the embanked area is restored whilst the inland dike remains the primary dike for flood defence, resembling the practice of Tidal River Management in Bangladesh (e.g., [2]). The result is a high and wide body of sediment in front of the primary inland dike that is protected by a secondary seaward dike and greatly reduces inundation of the low-lying hinterland in case of a dike failure [41,105]. Also, ecologically important habitats that have formed during the phase of land-level rise (Fig. 1b) will be lost upon inlet closure (Fig. 1c), so multiple transitional polders in different phases or a combination of different managed realignment strategies may be needed to maintain biodiversity and ecosystem integrity, but this analysis is beyond the scope of this study.

Building and raising new land in a transitional polder differs fundamentally from land reclamation. Land reclamation is mainly conducted to increase the extent of arable and habitable land by the embankment of high foreshores, either developed naturally [42,94] or stimulated by artificial obstacles to promote accretion [23,65,92], as has happened in many estuaries around the world (e.g., [3,9,71,74]). This confines an estuary, which amplifies the tidal range [74] and narrows shore-connected tidal flats and foreshores, leading to less wave attenuation and a higher risk of dike breaching (e.g., [41,53,54,104,105]). Moreover, estuary confinement reduces the landward-directed sediment import by tidal asymmetry, which leads to natural channel deepening in large friction-dominated estuaries [61,62] as observed in e.g., the Weser Estuary [3], the Columbia River Estuary [71] and the Western Scheldt Estuary [74] prior to large-scale dredging. In absence of sediment input, the newly gained land becomes subjected to sediment compaction and background subsidence [63,83,89]. As a result, younger reclaimed lands tend to be highest and oldest tend to be lowest (Fig. 2), making the latter most prone to inundation. In contrast, the strategy of transitional polders aims at lowering flood risk by raising already existing land to a supratidal elevation before returning it to its original function. To maintain flood safety, transitional polders may need cycles of inlet opening and closing to capture new sediment to compensate for land subsidence and eustatic sea-level rise.

So far, most deliberate de-embankments in estuaries were smaller than 400 ha and were single efforts in individual tidal systems [84,102]. Therefore, little is known about how the location of a transitional polder along an estuary influences the import of sand and mud and the tides with an estuary. 1D numerical modelling of estuaries suggests a local widening of intertidal storage area, which can be interpreted as a transitional polder, dampens the tidal range and increases tidal prism (e.g., [32,48]). Yet, it remains unclear how such altered tidal characteristics influence the channel and bar pattern within an estuary, which requires two-dimensional modelling. Recent numerical modelling [61,62] showed that added floodbasins (about 10 m deep) along the Western Scheldt Estuary locally change the tidal flow and sediment transport patterns within the estuary, causing the development of a shoal in front of a floodbasin inlet. Such a shoal is analogous to a local ebb-tidal delta and its size becomes larger with a wider floodbasin inlet and relocates the main estuary channel further away from the outer banks [62]. This raises questions (1) whether a similar shoal will develop in case of much shallower transitional polders and (2) whether such a development will limit the desired sediment import into the corresponding transitional polder.

Finally, as increasingly more de-embankment projects are being considered, it is necessary to study how multiple transitional polders will function. In particular, it remains an open question how a planned sequence of opening transitional polders affects their ability to bring about land-level rise, needed to reduce flood risk. This exploratory study aims to investigate this question using the Western Scheldt Estuary (NL)

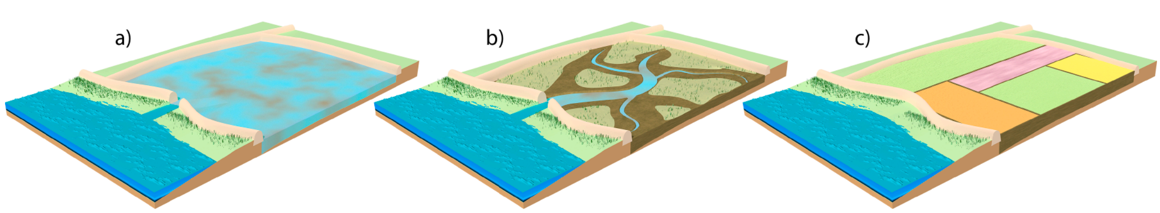

Fig. 1. Conceptual box models of a transitional polder between double dikes. (a) Dikes inhibit sediment deposition and land-level rise on embanked land which may lead to subsidence and land elevations below sea-level. To cause land-level rise, transitional polders can be formed by artificially breaching a dike to reintroduce the tide. (b) As time progresses, sediment is net imported by tidal flow which elevates a transitional polder into an intertidal-to-supratidal reach. (c) After sufficient sediment import and land-level rise, the transitional polder may be closed off and returned to its original function, for example, as arable land. The inland dike remains the primary dike for flood defence, and the cycle of opening and closing may be started anew to keep up with relative sea-level rise.

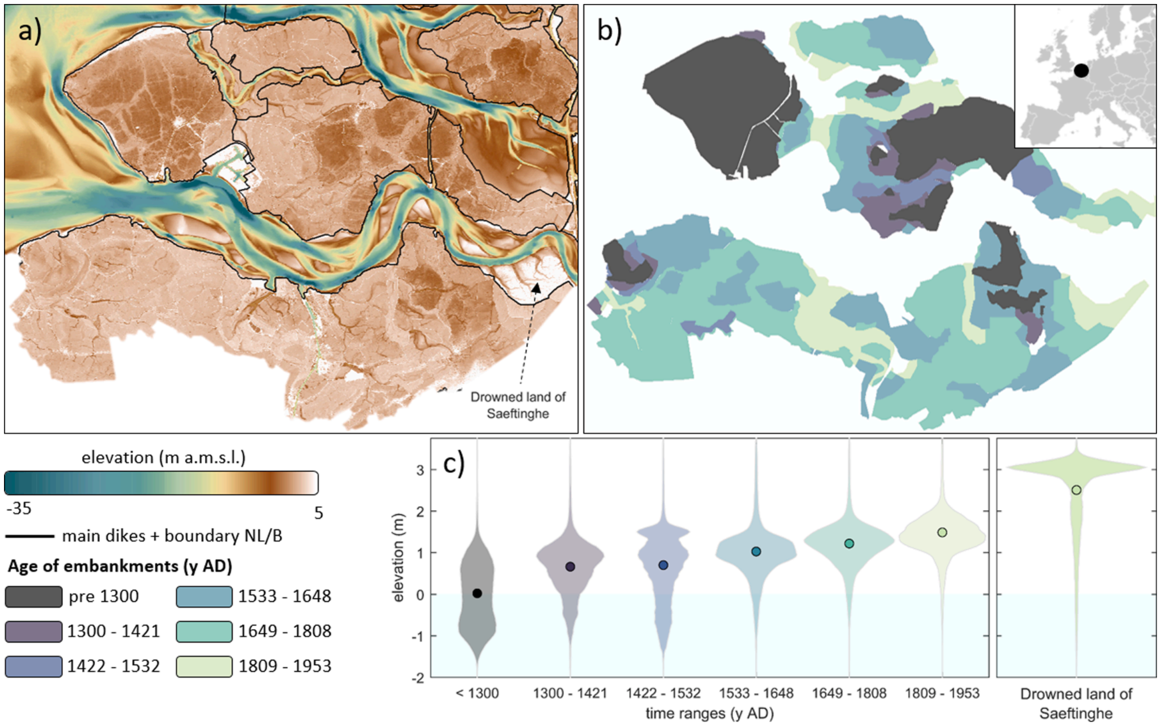

Fig. 2. Overview of land reclamations along the Western Scheldt Estuary. (a) Map of bed elevation of the area near the Western Scheldt Estuary. Note that the highest bed elevations along the estuary are found outside the main dikes (exluding the barrier coast and the harbour near the estuary mouth). (b) Age of embanked areas along the Western Scheldt Estuary. Uncoloured regions represent unreclaimed land. The geographical location is given in an inset. (c) Violin distribution plots of bed elevations split per age of embankment, showing older polders have a lower bed elevation than younger ones. For reference, an unembanked salt marsh named "Drowned Land of Saeftinghe" is shown for comparison, which has a much higher bed elevation.

as an example of a typically large estuary and simulates the effect of different opening sequences of four transitional polders along the estuary by means of two-dimensional modelling in Delft3D. Opened polders were not closed again, so the insights of opening multiple polders are also relevant for current and future managed realignment projects that focus on e.g., attaining a rich biodiversity and carbon sequestration [81]. Here, only sand and mud is considered, disregarding bioturbation by benthos, salt marsh vegetation dynamics and dredging for navigational purposes.

2. Case study: Western Scheldt Estuary

This study uses the Western Scheldt Estuary as an example for reasons of data availability and recent aspirations of applying transitional polders [82]. The multi-channel estuary is located in the southwestern part of the Netherlands (Fig. 2) and is on average convergent. This convergent shape is largely the result of large-scale land reclamations since the 14th century, which transformed the highly branched estuary with large intertidal flats and salt marshes into the convergent shape of today (Fig. 2). This drastically decreased the intertidal and supratidal areas [74] which are vital for habitat, breeding grounds and biodiversity [e.g., 7]. Additionally, the increased channel convergence amplified the tidal range [17]. Currently, the mean tidal range increases from 3.5 to 4 m at the estuary mouth to nearly 5.5 m at the city of Antwerp. The tidal prism at the mouth of the estuary is about 1×10^9 m^3 and the yearly averaged river discharge is 120 m^3/s [85]. Sediment input via the river is negligible and mainly depends on littoral drift and flood-dominant tidal flows, a condition that has been prevalent for a few thousand years (e.g., [74]).

The large-scale land reclamation in the past points at ample sediment supply in the Western Scheldt Estuary that was needed to elevate intertidal bars and flats into a supratidal regime before embankment was possible. This potential for land-level rise is especially evident from the "Drowned Land of Saeftinghe". This former embanked area was breached by storms and intentionally breached during the Eighty Years' War in the late 16th century and became part of the estuary again (hence "drowned"). Over time, new intertidal flats and salt marshes started developing as sediment was net imported [38,91]. This naturally elevated most of the formerly drowned land into a supratidal regime with a median elevation of 3 m above mean sea-level (Fig. 2a,c). Irony is in the name, as this 3580 ha "drowned land" is currently the highest parcel of land in the region, being 4 m higher than the lowest embanked areas (Fig. 2a,c). This development of land-level rise equals observations of recently breached embanked areas in the same estuary (e.g., [26]). Similar developments elsewhere are seen to follow an unintended dike breach, where, given sufficient sediment supply, land-level rise may allow re-embankment [44].

The estuary is dredged to maintain access for ships to the port of Antwerp. Small-scale dredging has been done since the 20th century and was intensified with three major deepening events (in the 1970s, 1990s and 2010s) to accommodate increasingly larger ships and maintenance dredging to maintain the newly desired channel depth (e.g., [37,74,85]). The resultant deeper continuous channel further amplified the tide, increasing tidal range at the port of Antwerp by roughly 0.5 m between the 1970s and the 2000s [17,36]. Current disposal activities near intertidal flats aim at "maintaining the steady state of the multi-channel system and preserve ecologically valuable intertidal habitats" (e.g., [21, 66]).

3. Methods

The morphodynamic modelling was done using Delft3D FLOW2D3D version 6.02.13.7658 from tag 7545 [20]. Delft3D is an open source numerical model that solves the non-linear shallow water equations (see [46]), for equations and numerical implementation]. Here, the depth-averaged flow version was used, which has been widely tested and used in studies on the morphodynamics of rivers (e.g., [88]) and estuaries (e.g., [19]). Delft3D includes a stratigraphical module that enables the modelling of sediment mixtures of sand and mud [12,87].

3.1. Model setup and scenarios

The model domain of this study is part of the curvilinear NeVla-Delft3D schematisation of the Western Scheldt Estuary, which was calibrated for hydrodynamics (e.g., [50,93]) and morphology [35,67]. The original NeVla-Delft3D schematisation covers part of the North Sea and the Western Scheldt Estuary up to the city of Ghent in Belgium, which is the upstream limit of tidal influence. Here, a nested model was used to reduce computational time. The computational domain stretched from the city of Antwerp to the estuary mouth at the city of Vlissingen (Fig. 3a) and comprised grid cell sizes ranging from 30 to 300 m. To assess the implementation of transitional polders, four small grids were added to the computational domain (Fig. 3) (Table 1). The polders had an assumed initial bed elevation of -1 m NAP (i.e., the Amsterdam ordnance datum, close to mean sea-level at the Dutch coast), which is equal to the lowest polders along the Western Scheldt (Fig. 2c) and within the intertidal range. The four transitional polders were inspired by Van Belzen et al. [82] and selected based on the following criteria. Firstly, the transitional polders reached at maximum 2 km inland to limit the fetch for locally generated waves in real-life, although wave modelling was not accounted for in the model. Secondly, the minimal area was set to 4 km^2, i.e. equally large or larger than most current de-embanked areas (see for review [84,102]), to have an observable effect on tidal wave propagation in the estuary. Thirdly, the locations for the transitional polders-to-be lacked urban buildings, industry and solar panels to have a minimal impact on society. Dikes between the transitional polders and the estuary were implemented as thin dams in the model domain that prevented flow and sediment exchange between two adjacent cells, limiting flow interaction to ±200 m wide inlets between the transitional polder and the main estuary (Fig. 3).

Flow conditions at the upstream and downstream boundaries of the model were determined by time series in the Western Scheldt Estuary of water levels at the estuary mouth and water discharges at the river inflow over the first 10 months of the year 2013 [22]. These boundary conditions are considered representative for typical hydrodynamic forcing of this system and captured seasonal and diurnal variability, spring-neap cycles and storm surges. River discharge was partitioned over the upstream boundary to mitigate strong channel incision. Also, this partitioning allowed the discharge to be varied sinusoidally over time from one bank to the other to cause natural inflow perturbations [69,99].

Sediment was modelled as a mixture of one sand fraction and one

Table 1
Spatial characteristics of the selected sites to implement controlled floodbasins.

Site	Area (km^2)	Distance to mouth (km)
Hoofdplaatpolder	4.61	14
Ellewoutsdijk	4.38	22
Ossenisse	5.10	34
Kruispolder	7.43	49

Table 2
Sediment characteristics, after Braat et al. [12].

Sediment property	Value	Unit
Sand		
Median grain size	2×10^{-4}	m
Specific density	2650	kg m^{-3}
Dry bed density	1600	kg m^{-3}
Transverse bed slope parameter α_{bn}	30	-
mud		
Settling velocity	2.5×10^{-4}	m s^{-1}
Critical bed shear stress for erosion	0.2	N m^{-2}
Erosion parameter	1×10^{-4}	kg m^{-3} s^{-1}
Specific bed density	2650	kg m^{-3}
Dry bed density	1600	kg m^{-3}

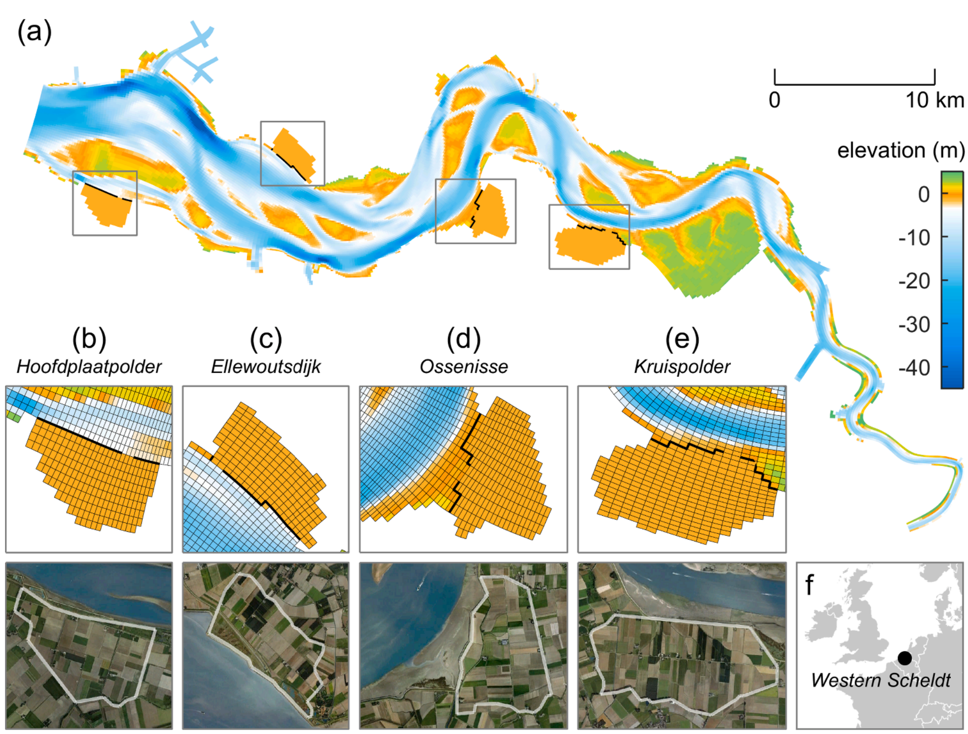

Fig. 3. (a) The NeVla model schematisation of the Western Scheldt Estuary (NL/B) in the numerical model Delft3D (after e.g., [35,50,93]) including four added transitional polders outlined in the squares. (b-e) A zoom of the numerical grid and a satellite image (Google Earth; accessed: April 2021) of the four transitional polders. The average grid cell size in the transitional polders is 160 m^2. (f) The location of the estuary.

mud fraction using the stratigraphic module by Van Kessel et al. [87] (sediment characteristics are listed in Table 2). This module tracks the spatial and temporal bed composition in layers of a user-defined thickness, here 0.05 m. The initial bed consisted of a uniform mixture of 95% sand and 5% mud. Sand was supplied at both the upstream and downstream boundaries as an equilibrium concentration boundary condition; this means sand supply was equal to the transport capacity of the flow to prevent erosion or deposition at the boundaries. Mud was supplied at both boundaries at a constant concentration of 0.04 kgm^{-3} to acquire mud concentrations throughout the estuary matching field observations [86]. Mud was treated as a cohesive sediment, for which the amount of erosion and deposition was determined by the Partheniades-Krone formulation [64] and depended on user-defined critical bed shear stresses. Here, the erosion shear stress was set to 0.2 Nm^{-2} and the deposition by settling of mud was set to occur in all flow conditions (following [12]). For simplicity, a constant 2.5×10^{-4}m s^{-1} settling velocity was assumed for mud, disregarding that the settling velocity is influenced by flocculation, a process that depends on concentration, biochemistry, residence time, turbulence, salinity, season and pH (e.g., [51]). The settling velocity is similar to previous numerical modelling in estuaries (e.g., [12,14]) and is typical for fluvial mud [79] and on the low side for marine mud.

Sediment transport was calculated using the Van Rijn [90] predictor (TRANSPOR2004), which is well-suited for sediment mixtures of bedload and suspended load and applicable to tidal environments. The downslope sediment transport on transverse bed slopes was parameterised using an α_{bn} of 30, following Baar et al. [6]. The Manning bed roughness was spatially variable along the estuary (cf. [15,62,85]) and varied between 0.02 and 0.028 $sm^{1/3}$. To speed up the numerical computation, the bed level change calculated after every hydrodynamic time step was multiplied with a factor of 20. Such a morphological acceleration factor is common practice in long-term morphological modelling (e.g., [24,46,97]) and enables a faster computation of longer timescales. In the case of this study, this means that the 10

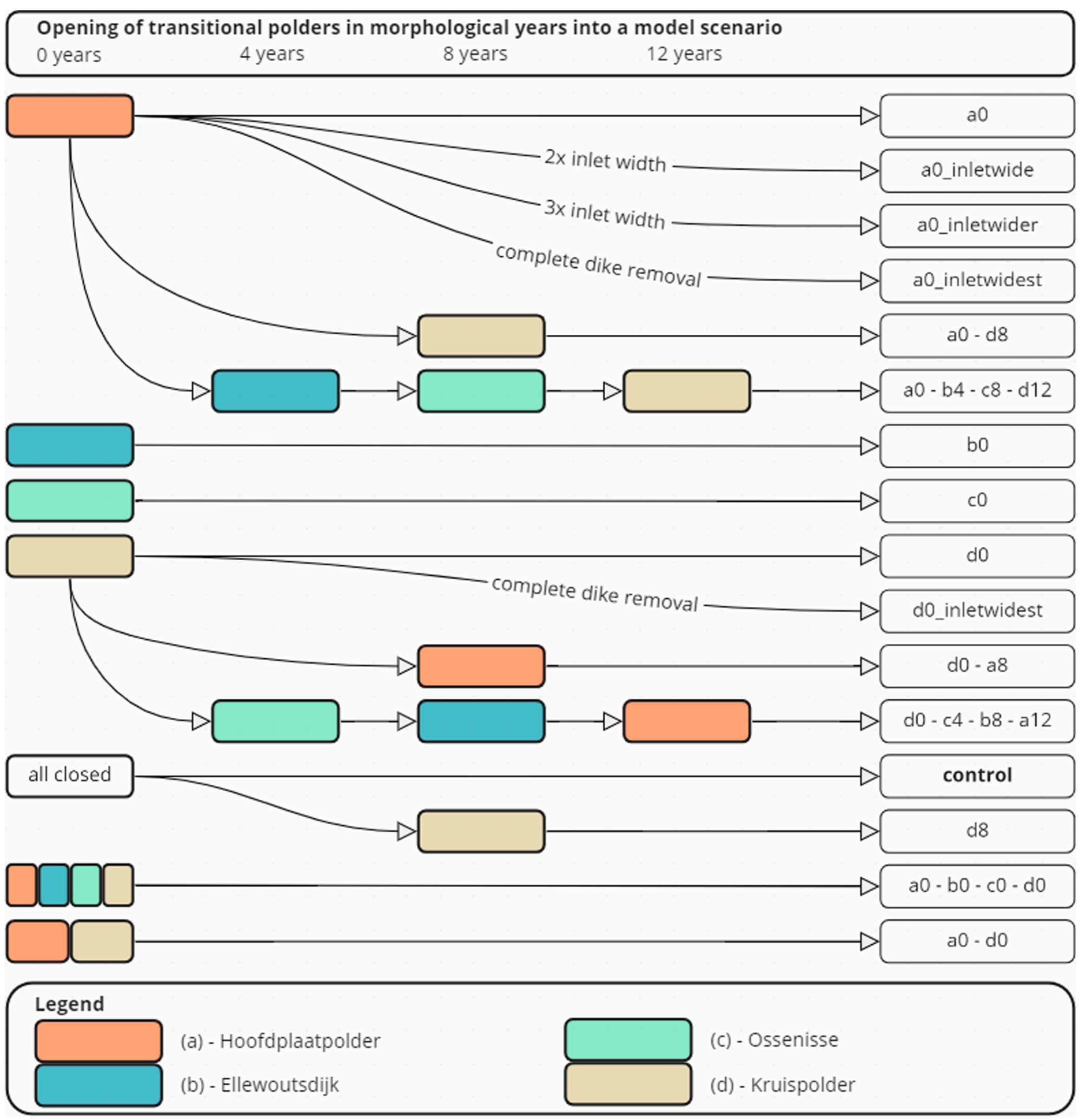

Fig. 4. Overview of the 16 model scenarios with the scenario name in the right-most column. Transitional polders were opened at the start or after 4, 8 or 12 morphological years. In the scenario name, transitional polders are denoted from downstream to upstream as “a”, “b”, “c” and “d”, and the suffix (0, 4, 8 and 12) denote after how many years they were opened. Annotations indicate when a wider inlet to a transitional polder was applied, where “complete dike removal” is essentially the widest inlet possible.

hydrodynamic months of 2013 [22] resulted in 16.6 morphological years.

In total, 16 scenarios were run in which the opening of transitional polders was systematically varied (Fig. 4). These include scenarios of different configurations of transitional polders (1) opened throughout a scenario, (2) opened after 4, 8 or 12 morphological years, and (3) with a larger inlet width. The analysis focused on the morphological development within the transitional polders and their effect on tidal range, tidal prism and morphology along the estuary. For clarity, the terms "upstream" and "downstream" are used for along-estuary directions and "seaward" and "landward" are used for cross-sectional directions.

4. Results

This section will first describe the general development of the scenarios in which only one of four transitional polders was open. Next, the effect is presented of different opening sequences of transitional polders on their sediment capture and the estuary hydrodynamics.

4.1. Effect of individual polders

All transitional polders showed a net gain in bed elevation once they were opened to the tide (Figs. 5–7 a-d). Typically, highest gains in elevation were found in the centre of the transitional polders in the form

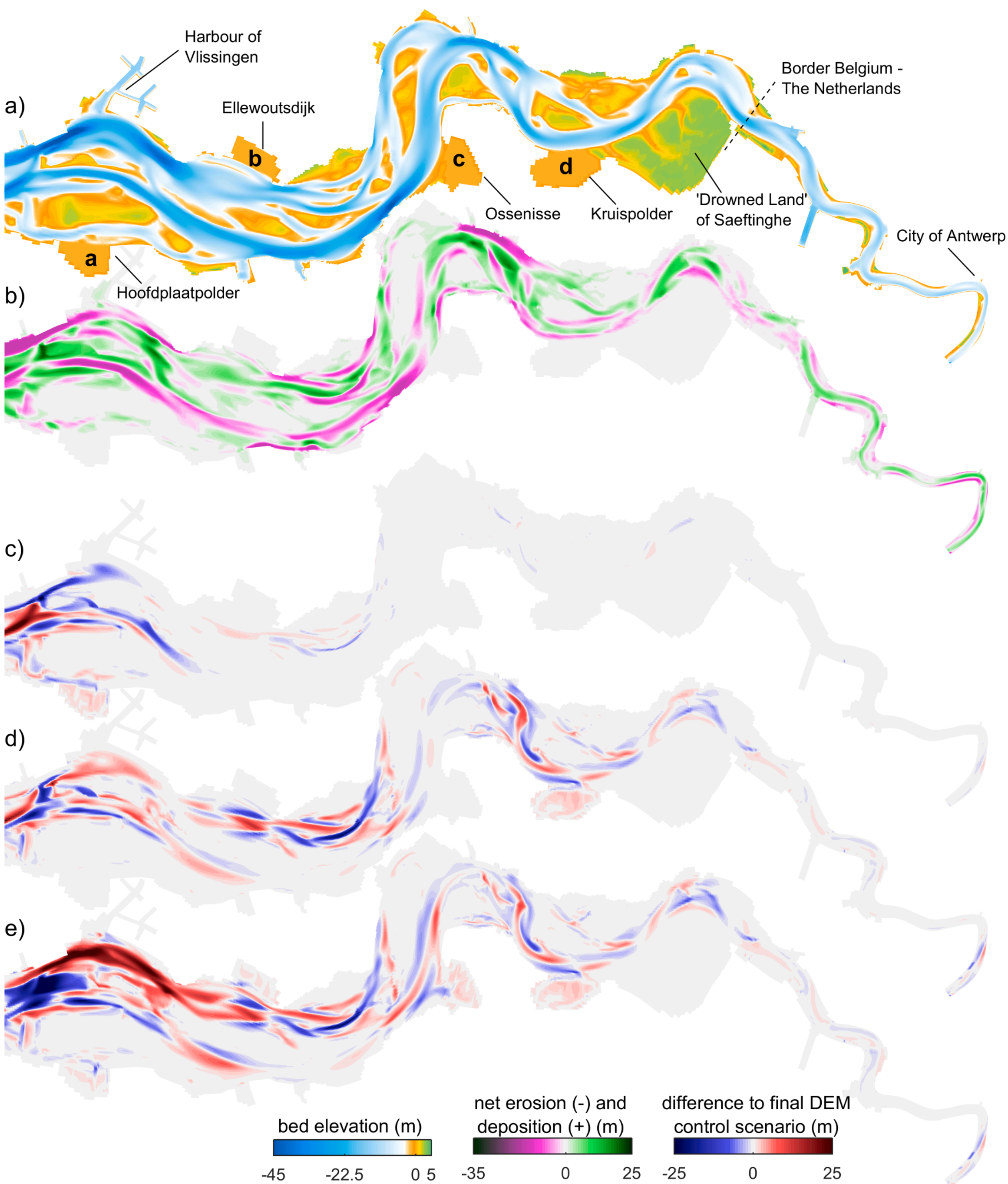

Fig. 5. (a) Bathymetry and (b) morphological change in the estuary after 16.6 years for the control scenario where all transitional polders remained closed. The difference is shown between the final bathymetry of the control scenario and (c) scenario a0 in which the downstream-most polder was open (d) scenario d0 in which the upstream-most polder was open and (e) scenario d0–c4–b8–a12 in which all polders were opened in a sequence from upstream to downstream.

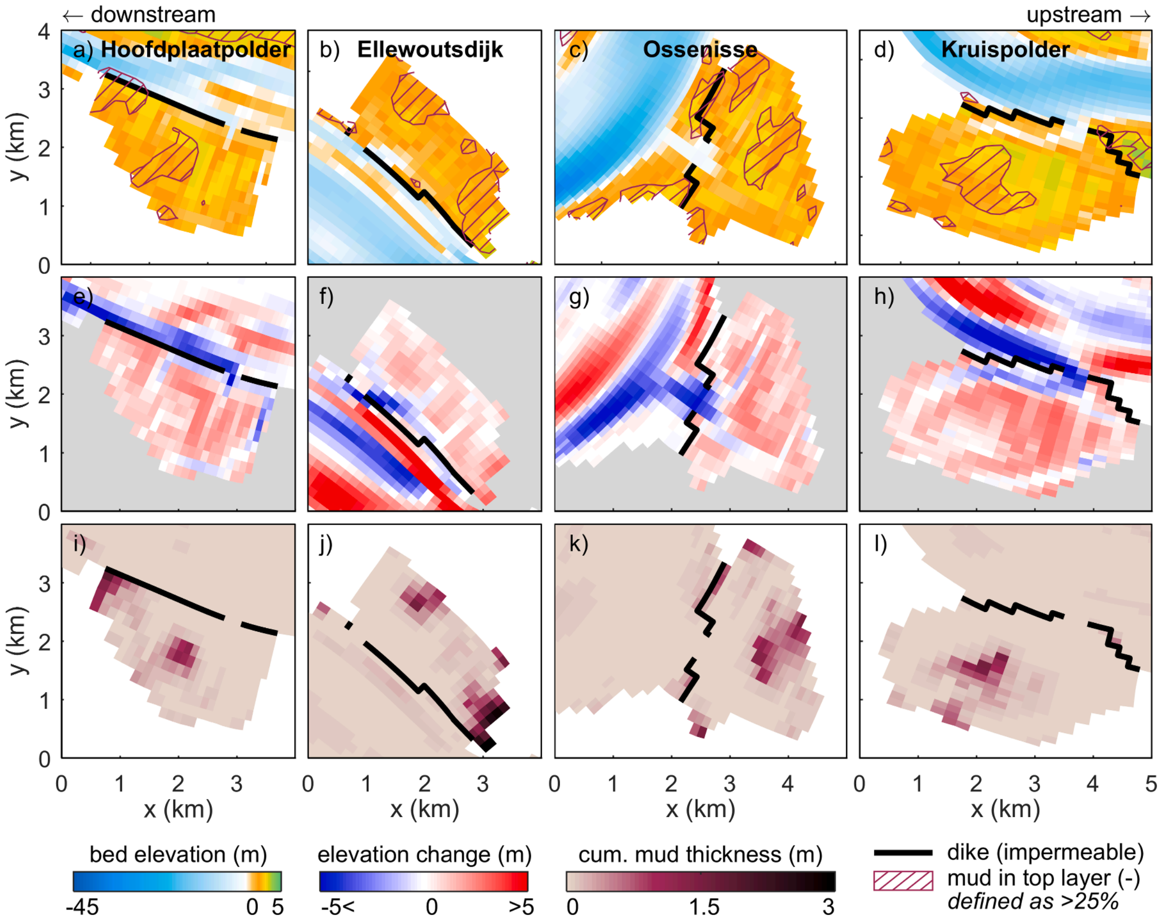

Fig. 6. Morphological development in the transitional polders for the four scenarios in which only one transitional polder was open with a default inlet width. (a-d) The final bed elevation after 16.6 morphological years plus the presence of mud in the top 0.05 m layer. (e-h) Bed elevation change, expressed as the final bathymetry of subplots (a–d) compared to the final bathymetry of the control scenario in which no transitional polder was opened. (i-l) Cumulative mud layer thickness after 16.6 morphological years of new mud deposits, disregarding mud in the unreworked sediment (i.e. 5 % mud in the initial sediment bed). Mud-related compaction was not included in the modelling.

of a sandy flood-tidal delta. Mud generally settled at the lee side of the flood-tidal delta and at the low-energetic edges of the polders (Fig. 6i-l). The most upstream and downstream polders, i.e. *Kruispolder* and *Hoofdplaatpolder*, were most efficient at importing sediment, with 25 % of their area having been elevated by more than 2 m after 16.6 morphological years. Interestingly, whilst sand primarily accounted for the elevation gain in most transitional polders, mud accounted for more than half in case of *Ellewoutsdijk* (Fig. 7a-d). As mud concentrations at the inlet of *Ellewoutsdijk* were within range of the other inlets (Fig. S1), the enhanced trapping efficiency of mud could be largely ascribed to the elongated shape of *Ellewoutsdijk*.

The location of a transitional polder influenced the tidal range and tidal prism. In the control run without transitional polders, the mean tidal range amplified in the upstream direction from 4 m at the mouth to 6 m near the city of Antwerp (Fig. 8b). Opening of a transitional polder changed this amplification, with the direction of change depending on the location of a polder. That is, a more upstream located polder led to a strong reduction in tidal range (Fig. 9c), while in contrast, the most downstream transitional polder slightly increased the tidal range. The temporal development of tidal range along the estuary in Fig. 8c indicates that the reduction in mean tidal range (*i*) increases over time and (*ii*) increases during larger amplified spring-neap cycles becomes more pronounced during temporarily higher mean tidal ranges related to yearly variations in tidal forcing (see temporal change in the amplitude of spring-neap cycles in Fig. 8a). Tidal prism was increased downstream of an opened transitional polder due to the added intertidal storage volume (Fig. 9d). The smallest gain in tidal prism correlated to the smallest polder *Ellewoutsdijk* (Table 1). Interestingly, the upstream-most polder *Kruispolder* resulted in a locally increased tidal prism, while the other more downstream polders resulted in a roughly constant increase up to the estuary mouth (Fig. 9d).

In the control scenario when no transitional polders were opened, small intertidal bars formed in the downstream half of the estuary (Fig. 5). The channel bed in the upstream reach of the estuary aggraded by a few metres mainly because of fluvial sediment input and erosion of flanking sand bars. This resulted in a shallower but slightly wider channel. Along the entire estuary, sills formed in the main channel (in absence of dredging) especially near large bends (Fig. 6). Consequently, the main channel was split into discontinuous, mutually evasive channel sections, for example seen at the channel bend northeast of the “Drowned Land of Saeftinghe”. Despite some channel migration and sill formation, the bed elevation distribution remained largely constant in the middle reach between the Dutch-Belgian border and the (in the control scenario unopened) transitional polder at *Ossenisse*. Downstream of this polder, morphological change was largest, including strong channel incision of the main channel and a major shift of the main channel south of the harbour of Vlissingen (Fig. 6).

4.2. *Effect of opening sequences*

Transitional polders that were opened later in a sequence had a smaller import of mud compared to when they were opened at the start

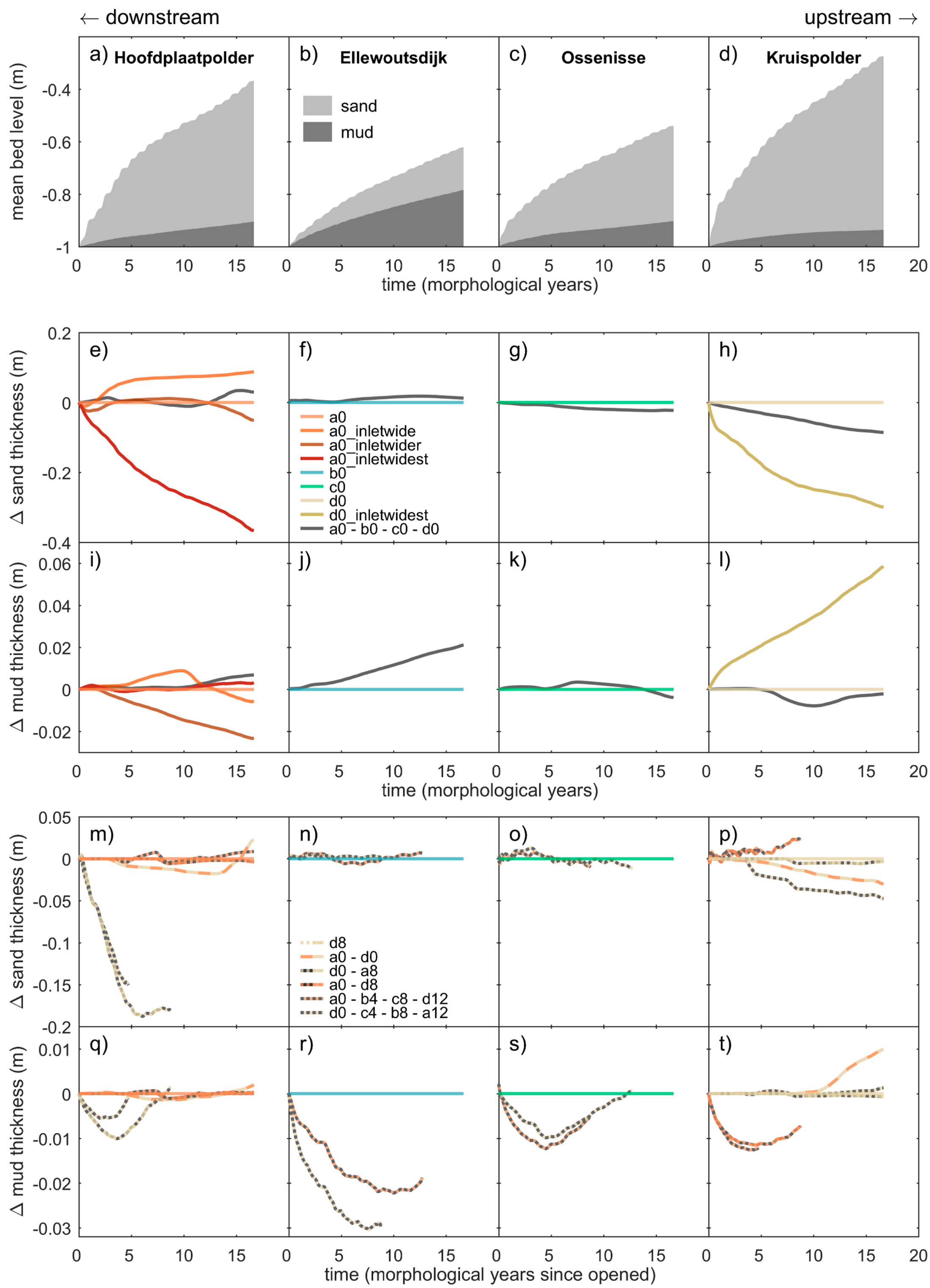

Fig. 7. Development of (a-d) mean bed level, attributed to sand and mud deposits, for the four scenarios in which only one transitional polder was open with a default inlet width (i.e. a0, b0, c0, d0). Panels (e-t) show the difference in mean sand and mud thickness compared to panels (a-d), where panels (e-l) show scenarios with one or all polders opened at the start of a model run, and panels (m-t) show scenarios with opening sequences of multiple transitional polders. Note the smaller y axis for panels (m-t).

of a scenario (Fig. 7q-t). Nonetheless, this lag in mud import was only temporal and decreased over time, as is evident from the temporal development of the mean mud thickness in the transitional polders (Fig. 7q-t). In contrast, most sequences had a negligible effect on import of sand, with deviations in Fig. 7m–p of about two orders of magnitude smaller than the sand deposits of scenarios with only one transitional polder in Fig. 7a–d. The two exceptions to this trend at *Hoofdplaatpolder* (Fig. 7m) were linked to a shore-connected bar migrating in front of the inlet before the inlet was opened. This bar migration happened in all scenarios, but while early openings allowed for sufficient reworking to ensure a shallow channel connection to the main channels, an entirely new channel had to be carved through the foreshore after opening at 12

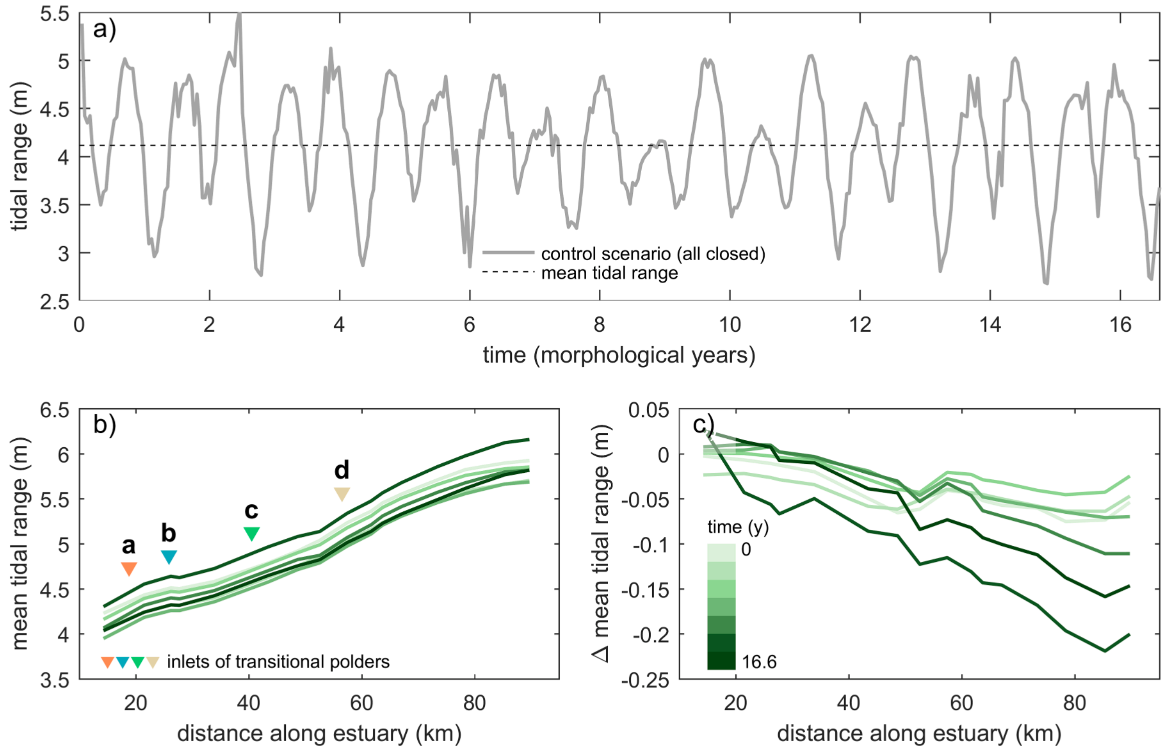

Fig. 8. Development of tidal range. (a) Time series of tidal range at the estuary mouth for the control scenario in which no transitional polder was open. (b) Mean tidal range per spring-neap cycle along the estuary for the control scenario. (c) As an example, the difference in mean tidal range between scenario d0 and the control scenario, showing an increasingly smaller tidal range when the upstream-most transitional polder is open. Final along-estuary trends for all scenarios are given in Fig. 9c,e.

morphological years. This led to deeper inlet incision (Fig. 6e) and therefore lower mean bed elevations (Fig. 7m). Furthermore, this development partly explained the lower mean bed elevation at *Ossenisse* (Figs. 6e, 7c), where a wide foreshore is in front of the inlet in all scenarios at all times.

Tidal range and, to a lesser extent, tidal prism were influenced by an opening sequence. Typically, tidal prism increased downstream of an open transitional polder due to added volume storage (Fig. 9d). The opening of all polders simultaneously or from downstream to upstream resulted in the largest increase in tidal prism. Fig. 9e shows that an opening sequence from upstream to downstream reduced tidal range considerably, while the other way around tidal range hardly reduced or even increased in the upstream half of the model domain. This trend was more pronounced in the sequences with four open polders but also present in the sequences with only the two outermost polders (Fig. 9e). However, Fig. 10 shows it was probably not the added storage volume of the transitional polders but instead their impact on estuary morphology that influenced the tidal range. For example, most opening sequences starting with *Kruispolder* exhibited channel shallowing just downstream of the *Kruispolder* inlet and in the downstream 20 km of the domain. In contrast, opening sequences starting with *Hoofdplaatpolder* resulted in channel deepening in the downstream 15 km (Fig. 10). Therefore, the incoming tide experienced less friction that enabled larger tidal ranges in scenarios with channel deepening, whilst channel shallowing produced more friction that led to smaller tidal ranges (Fig. 9c,e).

4.3. Effect of inlet width

Inlet width had a considerable effect on the net import of mud and sand. Scenarios including the most downstream transitional polder *Hoofdplaatpolder* (Fig. 7e) hinted at an optimum inlet width for sand import around twice the default inlet width and a reduction of sand import by about half upon complete dike removal. This trend of reduced sand import is similar for the most upstream transitional polder *Kruispolder* (Fig. 7h). However, complete dike removal caused nearly a doubling of mud deposition in the most upstream polder, whilst the most downstream polder experienced less mud deposition (Fig. 7i,l). This is probably related to the shape of the transitional polders, which extended further landward for the upstream-most polder with lower flow velocities near the landward boundary.

Also tidal range was affected by inlet width. Whilst the opening of most transitional polders contributed to a similar or smaller tidal range, the transitional polder closest to the seaward boundary instead increased tidal range once opened (Fig. 9c). This increase was more pronounced if larger inlet widths were used. However, this increasing trend stood in contrast to the most upstream transitional polder, where complete dike removal resulted in a much smaller tidal range throughout most of the estuary (Fig. 9c). As for tidal prism, it was largely unaffected by different inlet widths.

5. Discussion

This study reports on the numerical modelling of four transitional polders between double dikes along the Western Scheldt Estuary. The incentive to applying transitional polders was to import sandy and muddy sediments to cause land-level rise that could strongly reduce flood risk [82,105]. Here, this potential for sediment import, as well as the effect on estuary morphology and tidal wave propagation, was tested for four polders opened (1) alone, (2) in a sequence and (3) with increasingly larger inlet widths. These effects are placed in the context of current estuary management that includes managed realignment and dredging, after which implications are inferred for flood risk management.

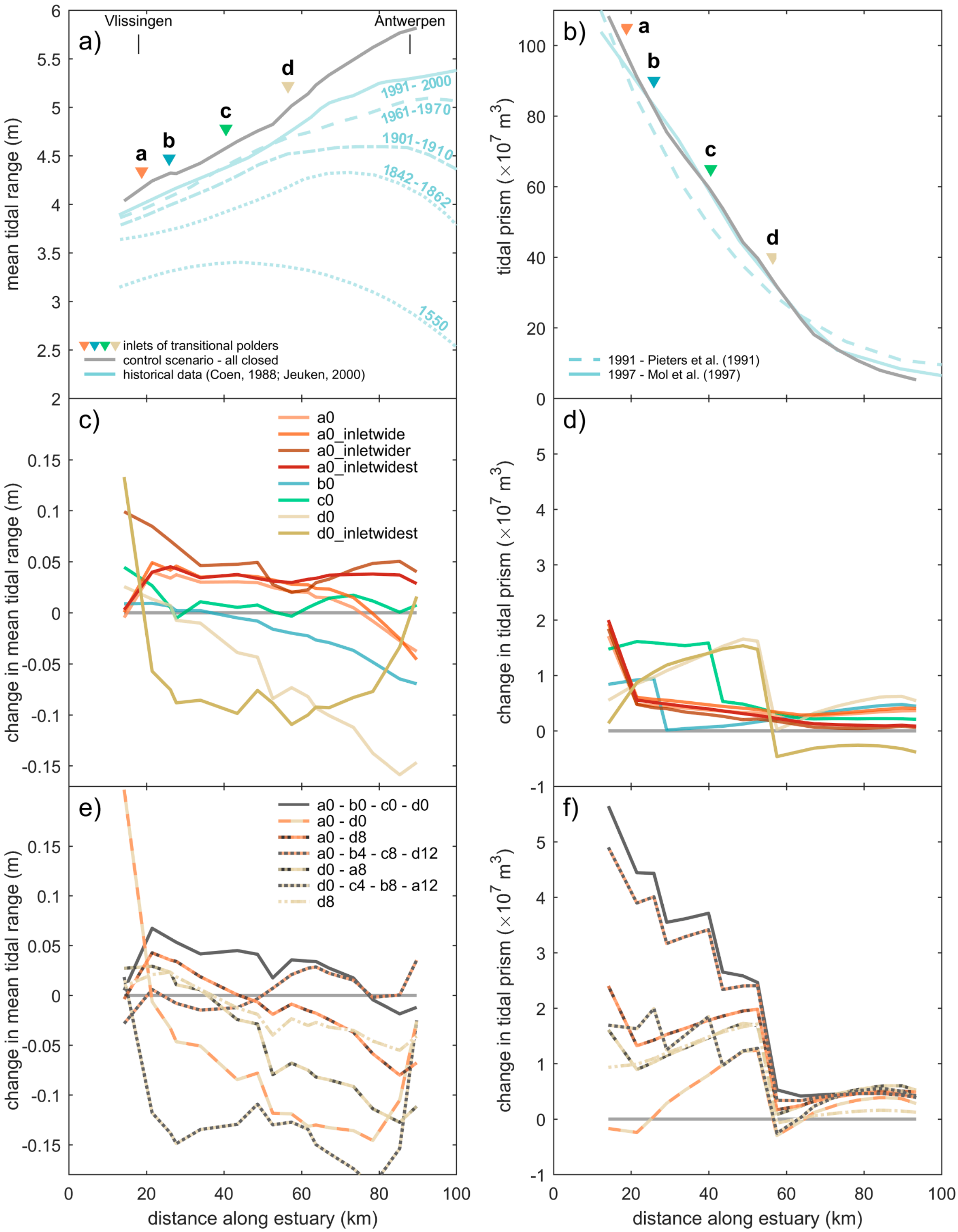

Fig. 9. Tidal range and tidal prism along the Western Scheldt Estuary. (a) Tidal range and (b) tidal prism, averaged over the last two spring-neap tidal cycles, for the control scenario without transitional polders together with historical data [17,36]. (c) Change in tidal amplitude and (d) tidal prism if any one transitional polder was open throughout the model run. (e) Change in tidal amplitude and (f) tidal prism for scenarios with an opening sequence of transitional polders.

5.1. *Effects of transitional polders*

The general morphology in a transitional polder developed towards a landward extending sandy flood-tidal delta with thin mud deposits at the lee side of the delta and at the rims of the polder (Fig. 6). This seaward-to-landward filling resembles the initial stages of filling in tidal basins with sand, mud and live vegetation [10]. However, such filling differs from field observations (e.g., [25,26,45]) and models [34,73] of managed realignment projects, where mud-dominated filling typically starts at the landward rims of managed realignment site and progresses in the seaward direction. A possible explanation lies in the initial bed elevation of the transitional polders, which was at a much lower elevation (i.e. -1 m below mean sea-level) with respect to the tidal range than many managed realignment sites. This low initial elevation was selected based on the lowest embanked areas along the Western Scheldt Estuary (Fig. 2) and therefore first required sand import before tidal

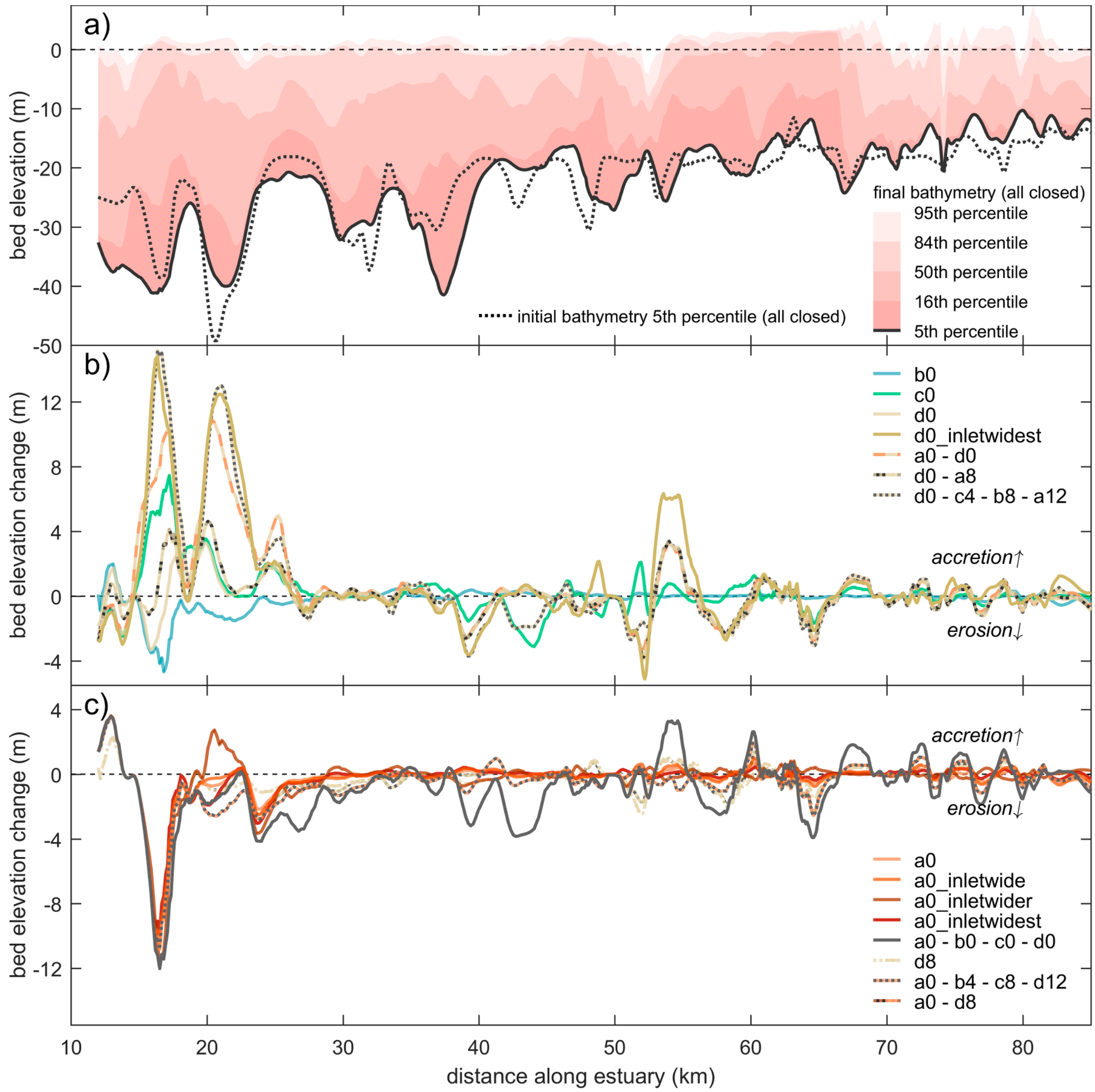

Fig. 10. Channel depth along the estuary over time. (a) Bathymetry expressed as bed elevation percentiles. The initial bathymetry curve shows the 5th percentile, which represents the main channels. (b/c) Differences in bed elevation shown as the 5th percentile compared to the control run presented in (a). (b) shows scenarios that experienced net channel shallowing (accretion) and (c) shows scenarios that experienced net channel deepening (erosion).

conditions were weak enough to achieve mud-dominant filling from the rims. Additionally, a landward-to-seaward filling is often ascribed to laterally expanding salt marshes that capture mud and stabilise the bed [34], but such vegetation dynamics were beyond the scope of this study. As opposed to this study, some managed realignment sites had an initial channel network excavated to improve drainage and jump-start the formation of creeks and channels (e.g., [34,95,101]). These channels may allow focused transport and import of sediments and stimulate land-level rise, but when located too high or low with respect to the tidal range, such pre-carved channels have little effect on the trend of landward-to-seaward filling in managed realignment, for example in the Tijuana Estuary, USA [95].

The effects of a single transitional polder can be described in relation to its location relative to the local estuary morphology and its location along the estuary. Firstly, the location relative to the estuary morphology, in particular the presence of a wide foreshore or shore-connected bar, influenced the import of sand. The presence of a wide foreshore or shore-connected bar coincided with strong inlet channel erosion that net reduced the sand import in the first years after opening. Inlet erosion upon a deliberate or storm-induced dike breach was also observed for managed realignment sites landward of well-established vegetated foreshores, e.g., “the Freiston shore” in The Wash Estuary (UK) [75,76]. Regarding the Freiston shore, inlet erosion was ascribed to an elevation drop into a lower-lying basin, causing fast inflow and slow outflow during high spring tide, and most reworked sediment was net imported into the basin, situated high in the tidal range [75,76]. In contrast, the transitional polders in this study were below mean sea-level and therefore experienced stronger ebb currents and ebb-directed sediment transport, which explains the smaller net import of sediment compared to the Freiston shore. Nonetheless, in practice, such a wide (vegetated) foreshore or shore-connected bar is probably preferred as this attenuates waves and reduces the risk of the outer dike breaching [41,54,105]. Mud import appeared generally unaffected by the local estuary morphology and was instead predominantly governed by the local suspended sediment concentration. In this study, the suspended sediment concentrations were largely similar for the domain of the four selected polders (Fig. S1). Yet, higher concentrations and correspondingly higher accretion rates are expected for sites closer to the turbidity maximum further upstream. Moreover, adding flocculation [51] and mud-fixating lifeforms [14], which depend on e.g., salinity and biochemistry that vary along-estuary, may also alter mud accretion rates and cause a stronger along-estuary trend in mud deposition if included.

Secondly, the along-estuary location had a strong impact on estuary morphology, where a more upstream polder resulted in more cumulative erosion and deposition in the main estuary (Fig. 6c,d). This is explained by the added intertidal storage volume, which increases tidal prism from the estuary mouth up to the inlet of a transitional polder (Fig. 9d), conform to previous one-dimensional modelling of estuaries [48]. Yet, it remains an open question if the increase in morphological change downstream of a polder inlet is mainly caused by a larger tidal prism or whether perturbations also travel from the polder inlet in the downstream direction. This would be in contrast to the current theory of macro cells in tidal systems (e.g., [22,72]), which suggest that perturbations do not propagate to other downstream or upstream macro cells. This question requires further work. Another consequence of added intertidal storage volume is a reduction in tidal range that becomes more pronounced for transitional polders located further upstream (Figs. 8c, 9c). This is associated with the net converging estuary width, which means a similarly sized transitional polder further upstream leads to a relative larger gain in intertidal area that can dampen the tide [32]. And although a reduction in tidal range 0.1 to 0.2 m may appear small, this is significant for flood defences that are constructed to a centimetre accuracy. Yet, when compared to a 0.5 m tidal range increase at Antwerp, Belgium, between the 1970s and 2000s [17,36] due to dredging [37,74, 85], transitional polders are of a lesser influence. Regarding the amount of sediment import into the transitional polders, the along-estuary location appeared to be of negligible influence as the modelled suspended sediment concentrations were largely similar for the estuary reach that contained the four polders (Fig. S1), in line with previous modelling of the same estuary [e.g., 13,14].

The opening sequence of multiple transitional polders generally had little effect on the import of sand (Fig. 7m-p). This excludes effects of migrating shore-connected bars which induced channel inlet erosion and less sand import for the downstream-most polder *Hoofdplaatpolder* when opened after 12 years (Fig. 7m). On the other hand, mud import was temporarily lagging behind in transitional polders opened later in a sequence compared to when they were opened at the start of a scenario (Fig. 7q-t). As this lag was only temporal, the four transitional polders appeared not to compete for mud import in the current setup of a sand-dominated estuary. However, it remains unclear if this also applies to later stages of filling beyond the modelled time, as more mud is taken out of the estuary and preserved in the transitional polders.

Scenarios including the most upstream transitional polder *Kruispolder* typically developed shallower main channels in the middle-to-downstream reach of the estuary (Fig. 10b). In contrast, deepest channels were formed in scenarios without transitional polders or with only the downstream-most polder *Hoofdplaatpolder* (Fig. 10c). This appears similar to historical records [e.g., 3,71] in which land reclamation and progressive embankment (i.e. fewer transitional polders) were linked to a natural channel deepening and consequently a larger tidal range. Long-term numerical modelling [61] corroborates this modelled trend for estuaries with moderate to high friction and ascribed this to a decrease in sediment import driven by tidal asymmetry. Consequently, the altered estuary morphology affects the amplification of the incoming tide. Shallower channels increase friction that reduces the tidal range, while deeper channels lead to a larger tidal range [33]. Generally, the trend of channel shallowing or deepening was dominated by the first polder in a sequence (i.e. deepening for the downstream-most polder and increasingly more shallowing for polders further upstream). However, this does not explain the outlier of scenario “d8”, where opening of the upstream-most *Kruispolder* after 8 years instead resulted in channel deepening and the reason for this remains an open question.

The inlet width and geometry of the transitional polder mainly affected the net import of sand and mud (Fig. 7e,h,i,l). This is understandable, as a smaller inlet width focuses and increases flow velocities at the inlet up to a point where the friction of the inlet width becomes a limiting factor; an example is the managed realignment at Alkborough, where a 20 m narrow inlet greatly limits tidal exchange and the input of sediments [100]. Consequently, transitional polders with complete dike removal experienced weaker tidal exchange flows and significantly less sand import (Fig. 7e,h). As for mud, the distance to the inlet strongly correlated with mud deposits, simply because more distal parts have weaker tidal flows that favour net mud deposition. This is conform to tidal restoration sites, where low-energy intertidal areas furthest away from the inlet generally retain most of the deposited mud (e.g., [26,38]), a process that is promoted by salt marsh vegetation (e.g., [70,78]). Nnafie et al. [62] showed a wider inlet width to subtidal secondary basins resulted in a larger shoal development just seaward of the inlet, which “pushes” the channel away from the outer banks. However, such a shoal development was not clearly observed in the modelling of the shallow, intertidal transitional polders with complete dike removal. This absence may be caused by the smaller and shallower geometry of the transitional polders or a relatively short modelling time of 16.6 morphological years. Yet, the modelling time-span was sufficient to develop a flood-tidal delta in the transitional polder (Fig. 6).

The flow conditions in this study excluded large storm surges and the modelling of waves, but their effects on land-level rise can be inferred from observations at managed realignments. Examples at Tollesbury (UK) [96] and Chowderness (UK) [57] show that locally generated waves and waves entering via a narrow inlet are generally not energetic enough to erode newly deposited sediments due to a limited fetch. In contrast, unsheltered sites of realignment experience slower salt marsh establishment [e.g., 57]. Accordingly, only model scenarios with complete outer dike removal will probably have less land-level rise when wave modelling was included, where the balance between sediment delivery and lateral erosion by waves affects the extent of the salt marsh (e.g., [30]). As for storm surges, these events are a main cause for dike failure and the creation of new unplanned sites for managed realignment (e.g., [31,38,91]). Yet, on a longer, centennial timescale of estuary filling, storm surges are not regarded as a limiting factor for sediment accretion in sheltered foreshores and floodbasins, evident from e.g., the extensive historical formation of supratidal salt marshes of the Western Scheldt [74,91]. How storm surges will affect the shallowing of the main tidal channels in the estuary due to added floodbasins remains under-investigated and benefits from future studies.

5.2. Implications for estuary management

The modelling excluded dredging, which has a strong influence on the estuary morphology and is linked to strongly increasing the tidal range in the Western Scheldt (e.g., [17,36,74]) (Fig. 9a). In comparison, the transitional polders have a decreasing, albeit much smaller effect on the tidal range by causing the estuary channels to shallow (Figs. 8c,e, and 10). This would reduce flood risk. However, the natural shallowing of channels will most likely be negated by maintenance dredging to maintain a deep fairway connection to harbours further upstream. Additionally, this suggests that continued dredging will probably prevent the development of mutually evasive tidal channels in the main fairway [85] as modelled in this study, for instance, at the estuary bend northwest of the “Drowned Land of Saeftinghe” (Fig. 6a). Consequently, it remains to be investigated to what extent dredging, adapted to local issues, may negate the tidal range reduction by transitional polders, which is especially relevant for determining future flood risk.

In light of future sea-level rise, large estuaries in terms of convergence length and channel depth will likely experience drowning of ecologically invaluable intertidal and supratidal areas [47,98]. Transitional polders may be part of the solution to limit estuary drowning, enhance flood safety on its margins, and restore ecological habitat area. The opening of multiple transitional polders, especially ones further upstream, increases the flood-dominant import of marine sediment. Not only will this sediment be used to build and raise land in the transitional polders, but it may also allow already existing intertidal area to keep up with sea-level rise. Storm surges are dangerous events in terms of flood risk that were unaccounted for in this study. Nevertheless, this study indicated that transitional polders dampen larger mean tidal ranges more strongly (Fig. 8c). This suggests that transitional polders may also contribute to lower flood risks during storm surges as well, which is in line with findings for managed realignment sites (e.g., [11,80,84]), and requires further work.

6. Conclusion

Numerical modelling was conducted of transitional polders between double dikes along the Western Scheldt Estuary in the Netherlands using different opening sequences and inlet widths, which led to the following findings that is also relevant for other managed realignment practices. Land-level rise occurred in all transitional polders in all scenarios by net import of sand and mud, but transitional polders opened later in a sequence experienced a temporal lag in net mud import, probably due to a deficit in fines. More upstream located polders typically led to smaller tidal range that was attributed to two mechanisms. First, the added intertidal width caused more friction that reduced tidal amplification. Secondly, the opening of more upstream polders led to natural channel shallowing particularly in the downstream reach of the estuary, which further reduced tidal amplification and improved flood safety. The modelling suggests an upstream-to-downstream opening sequence reduces tidal range strongest. However, further work is needed to determine to what extent redirected dredging activities, closure of transitional polders and the inclusion of storm surges may negate this benefit to flood safety.

Data availability

Additional materials are available in an online supplement and in an online data package. The online supplement contains a supplementary figure. The data package includes the Delft3D files needed to run the scenarios presented in this paper and is available at: https://public.yoda.uu.nl/geo/UU01/ISQ31Y.html. Delft3D is an open source code available at this site (https://oss.deltares.nl).

Author contributions

The authors contributed in the following proportions to concept and design, numerical modelling, analysis and conclusions, and manuscript preparation: SAHW (60%, 80%, 60%, 60%), AWB (10%, 15%, 10%, 10%), JvB (20%, 0%, 10%, 10%), TJB (0%, 0%, 10%, 10%) and MGK (10%, 5%, 10%, 10%).

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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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2022.100022.

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