4 Discussion

The results show an increase of *TR* in the Elbe estuary due to *SLR* and reveal, that tidal flat growth with *SLR* can have no effect, decrease or increase the *TR* relative to sole *SLR*, depending on the location and amount of tidal flat elevation. Further analysis shows that geometric parameters of the Elbe estuary are changing due to *SLR* and tidal flat elevation. In the following we will discuss the changes in estuarine geometry and their possible causes. Subsequently, explanatory approaches for the changes in *TR* based on changes in geometry will be proposed.

4.1 Convergence Length

Our estimated values for the convergence length (L_a) of the estuary in reference condition is 46.5 km. This value lies in the same order of magnitude of the values estimated by Dronkers (2017) (42 km) and Savenije et al. (2008) (30 km) for the Elbe estuary. Scenario *slr110t0* results in a significant decrease of L_a and therefore a stronger convergence of the Elbe estuary relative to reference condition. In scenario *slr110t110* a weakening of upstream convergence relative to *slr110t0* is detected, which results in a L_a close to reference condition.

A change in L_a is a result of differing changes of cross-sectional area (*A)* along the estuary in upstream direction due to regional differences in cross-sectional geometry. As discussed in Friedrichs et al. (1990), change of intertidal storage capacity, cross-sectional-flow-area and channel width due to *SLR* is strongly dependent on the gradient of the estuary banks. Correspondingly, the model results show a stronger increase in cross-sectional-flow-area in the mouth section of the Elbe estuary which contains larger tidal flat areas (meaning low topographic gradient) compared to other sections. It can therefore be assumed, that increased convergence of *A* in upstream direction due to *SLR* is based on the fact that the amount of relative intertidal area in the Elbe estuary is declining in upstream direction (Fehler! Verweisquelle konnte nicht gefunden werden.). This effect is sketched in Figure 1. Tidal flat elevation decreases *A* regionally and seems to significantly counteract *SLR* induced changes of the convergence in scenario *slr110t110*, but not in the other scenarios.

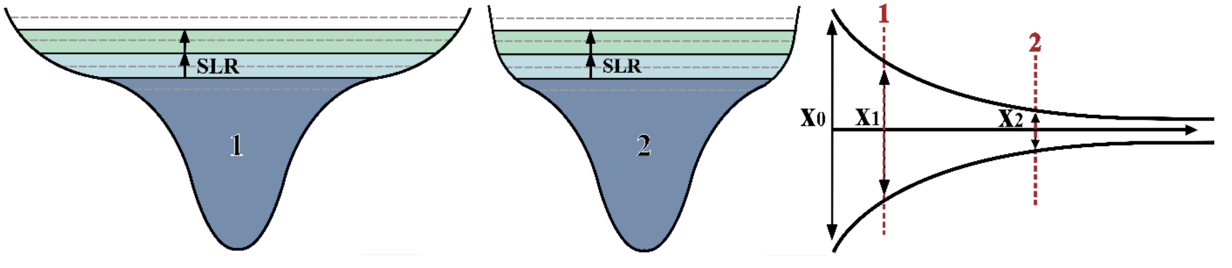

Figure 1: Schematic display of SLR in estuary cross-sections (left) and schematic plan view of an estuary (right). For two cross-sections with large (1) and small (2) S_{INT}. The cross-sections show the MW as black lines for a reference scenario (dark blue), and two SLR scenarios (light blue and light green).

4.2 Mean hydraulic Depth

In the reference scenario we derive a mean hydraulic depth averaged over the entire estuary (until the weir in Geesthacht) of 7.0 m for h_t (including intertidal area) and 9.2 m for h_c (excluding intertidal area). In comparison, Savenije et al. (2008) listed a mean depth at *MW* of 7.0 m decreasing upstream to 9.0 m for the Elbe estuary and Dronkers (2005) listed a time-averaged channel depth of 10.0 m for the Elbe estuary. However, it is not clear how these numbers were derived.

Our simulation results for the *SLR* scenarios might be unexpected and counterintuitive, as they show that *SLR* of 110 cm does not in general cause an increase in mean hydraulic depth along the estuary. In contrary, mean hydraulic depth shows varying changes and even a decrease in some parts of the estuary for *slr110t0* relative to the reference scenario. These differing changes of mean hydraulic depth along the estuary are caused by the differing topographic gradients of the control volumes. A decrease of h_c due to *SLR* can be explained by shallow areas next to the previous channels becoming part of the now wider channel (Friedrichs et al., 1990). Due to *SLR* some previously intertidal areas next to the channel can become subtidal areas and therefore part of the channel (Figure 12). The relatively small water depth over this new part of the channel will cause a decrease in hydraulic depth averaged over the channel cross-section. A decrease of h_t can be in addition explained by shallow previous supratidal areas becoming intertidal areas (Figure 2). If tidal flats are elevated with *SLR* in the model, they cause a regional increase in mean hydraulic depth relative to *slr110t0* and relative to reference condition in the Elbe estuary. This can be explained by tidal flat elevation counteracting the previously mentioned effect of shallow areas becoming part of the subtidal and intertidal cross-section, which overall results in an increase of mean hydraulic depth due to *SLR* in these scenarios.

4.3 Relative intertidal Area

For the reference condition we analyse a mean ϙS_{INT} of 0.4 for the entire estuary, which is slightly lower than the value of 0.5 derived by Dronkers (2005) for the Elbe estuary and in the range of 0.412 decreasing upstream to 0 given by Savenije et al. (2008). Note that Dronkers (2005) and Savenije et al. (2008) used a different form (ratio of width at *HW* to width at *LW*) and these numbers are converted for comparability. According to our simulation results, SLR of 110 cm causes regionally strongly scattering changes of ϙS_{INT} along the estuary with a decrease in some control volumes and an increase in others. Tidal flat elevation counteracts these changes regionally. The varying changes along the estuary can be explained by the differing topographic gradient. Sea level rise can in general cause an increase, decrease, or no change in S_{INT}, depending on the local topographic gradient above *LW* and a potential change in *TR* (see Figure 2). An increase in S_{INT} can be the result of previously supratidal areas (above old *HW*) becoming part of the S_{INT} due to sea level rise (Dronkers, 2005) and/or can be caused by the increase of *TR*. A decrease of S_{INT} can occur in tidal systems which are e.g. restricted by dikes or high gradient topography which can result in larger previously S_{INT} becoming subtidal area (S_{LW}) than previously supratidal area becoming S_{INT} due to *SLR* (Dronkers, 2005) (see Figure 2) and/or can be caused by a decrease of *TR*.

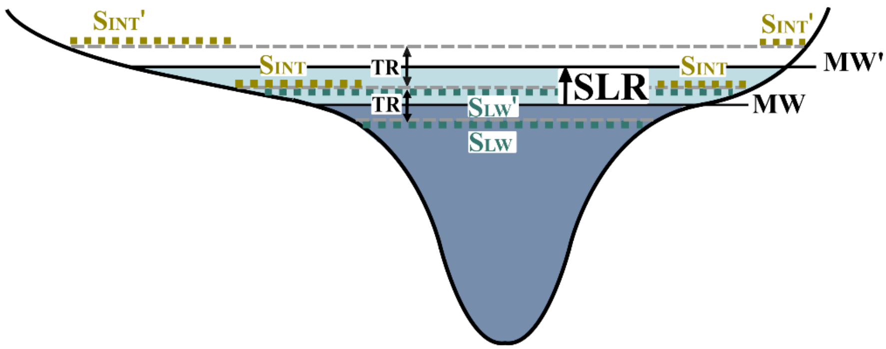

Figure 2: Schematic display of SLR in estuary cross-sections and its resulting change in intertidal area (SINT) for different topographic gradients between high water (HW) and low water (LW). The left side of the figure shows a low gradient, while the right side shows a higher gradient. The black lines correspond to the MW for the reference condition (dark blue) and SLR (light blue). All parameters with an apostrophe belong to the scenario with SLR. The dashed grey lines are showing HW and LW for both scenarios, while the coloured dotted lines show SHW and SLW.

4.4 Changes in Tidal Range and explanatory approaches

The effects of the previously discussed changes in geometric parameters on tidal dynamics act simultaneously and can therefore counteract, outweigh or enhance each other in the resulting effect on *TR*. However, we want to point out correlations between the detected changes of geometry and *TR* to find explanatory approaches for the latter.

SLR of 110 cm without topographic changes

The simulation results show an increase of *TR* in the estuary in scenario *slr110t0* relative to reference condition. In accordance, analysis of the upstream convergence of cross-sectional-flow-area (*A*) shows a significant increase of convergence in scenario *slr110t0* relative to reference condition. We suspect this is the main reason for the increase in *TR* in *slr110t0*, as gradually converging width and depth causes amplification of a tidal wave according to Green's law (1837) (Sect. 2.3.3). Averaged over sections, a decrease of ϙS_{INT} is detected in the mouth section and an increase further upstream, which could contribute and counteract the increase in *TR* respectively (Sect. 2.3.5). According to our analysis, *SLR* of 110 cm does not cause a general increase in mean hydraulic depth, but strongly varying changes along the estuary. Averaged over sections, mean hydraulic depth stays approximately unchanged relative to reference condition in the largest part of the estuary. In the Hamburg section and the upper section an increase of mean hydraulic depth is detected. The hydrodynamics in this upper part of the estuary are not fully dominated by the tide, but also highly influenced by the discharge. Therefore, we assume the strong increase in *TR* in these sections to be caused by an increase of tidal influence relative to discharge-influence.

SLR of 110 cm with tidal flat elevation in scenario A

In scenario *slr110t55 TR* does not change compared to *slr110t0*. In accordance, analysis of convergence does not show significant changes compared to *slr110t0*. In contrast, if tidal flats in scenario A are elevated by 100% with *SLR* (*slr110t110*), *TR* decreases relative to *slr110t0* along the entire estuary. In accordance, our analysis shows a significant decrease of convergence in *slr110t110* compared to *slr110t0*, which might be the main reason for *TR* to decrease. An increase in both the relative intertidal area and the mean hydraulic depth is detected on average in the mouth section, the impacts of which might counteract each other.

<u>*SLR* of 110 cm with tidal flat elevation in scenario B</u>

In scenario slr110t55e *TR* shows a strong increase relative to sole *SLR* (scenario *slr110t0)* in the entire estuary, while in scenario slr110t110e a decrease can be seen in the mouth section and an increase further upstream. In both scenarios a significant change in convergence relative to *slr110t0* cannot be detected with a significance level of α=0.1. The average of ϱS_{INT} in the lower section shows a decrease for slr110t110e compared to slr110t0 which might be part of the reason for the increase of *TR*. However, a notable decrease in slr110t55e cannot be seen. Therefore, we suspect that the main reason for the increase in *TR* in the scenarios slr110t55e and slr110t110e is due to the change in mean hydraulic depth, which increases as tidal flat are elevated. In contrast to the scenarios were tidal flats are only elevated in the mouth of the estuary, mean hydraulic depth increases in a much larger part of the estuary and therefore most likely has a stronger effect on *TR*. As mentioned in Sect. 2.3.4, changes in water depth influence frictional damping of a tidal wave due to energy dissipation and can also push a system closer to, or further away from resonance. Whether the increase in *TR* due to increased mean hydraulic depth is mainly caused by a decrease of frictional damping or by a shift towards resonance needs further investigation.

4.5 Comparison to other studies

Seiffert and Hesser (2014) simulated the effects of 80 cm SLR without topographic changes in the Elbe estuary and found an increase in *TR*, which is in accordance with our results. Jordan et al. (2021) did not focus on the estuaries when investigating the effects of *SLR* and tidal flat elevation on tidal dynamics in the Wadden Sea. Nevertheless, their results show a slight increase in M2-amplitude in the Elbe estuary due to *SLR* of 80 cm without tidal flat elevation and a much stronger increase when tidal flats are elevated in the entire estuary, which qualitatively corresponds to our results. Du et al. (2018) analysed tidal response to SLR in different types of idealized estuaries and for different realistic U.S. estuaries and point out the relevance of length, convergence and lateral bathymetry of estuaries on the resulting changes due to *SLR*. In contrast to our study they try to find explanatory approaches for the changes in the realistic estuaries by matching their geometric characteristic to the different types of geometry of the idealized estuaries (e.g. different length, convergence and cross-sectional bathymetric gradient), but do not analyse the changes in geometry due to *SLR*. Without further evaluating, they mention the possible change in convergence characteristic under *SLR* conditions and spatial variable tidal response due to spatially variable lateral geometry (e.g. amount of intertidal area).

4.6 Limitations

In our study, *SLR* induced changes in tidal dynamics seaward of the German Bight model are neglected. Previous research by Jordan et al. (2021) shows large-scale changes of the M2 amplitude in the North Sea due to *SLR*. Referring the results of Jordan et al. (2021) to our model boundary, we neglect changes of the M2-amplitude in the range of less than ±2 cm. We assume the neglection of the changes at the German Bight model boundary not to be of importance for the key results of our study, which aims to improve the system understanding of *SLR* and tidal flat growth induced changes in the Elbe estuary.

To reduce computational effort the generation of wind waves as well as sediment and heat transport is not included in our model setup. Thus, potential changes in sediment dynamics, e.g. changes in the *ETM* (estuarine turbidity maximum) and their potential effect on tidal dynamics are neglected. Furthermore, our investigation does not include potential future changes in river discharge into the Elbe estuary, as the discharge in the model is kept constant (600 m^3/s).

We selected the *SLR* scenario of 110 cm with corresponding hypothetical tidal flat elevation scenarios which we analysed in detail. For scenarios with 55 cm *SLR* we found qualitatively similar changes in max. *TR* and therefore assume similar alterations in estuarine geometry. However, to ensure that our results are in principle applicable to other *SLR* scenarios than 110 cm, it would be necessary to simulate a range of several *SLR* scenarios and their corresponding tidal flat growth scenarios and analyse the changes of tidal dynamics and estuarine geometry for each of them.

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