Modelling the impact of anthropogenic measures on saltwater intrusion in the Weser estuary

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Reply to the comments

Dear Prof. Huthnance, dear referees,

Thank you very much for taking the time to review our manuscript and providing valuable feedback for further minor revisions.

Your comments have helped us to identify weak points in our analysis and encouraged us to revisit our method and interpretation. We can now explain why the total salt flux through the cross-section is so large, which will hopefully improve the confidence in our results. We have also reviewed other parts of the text and hope that we could improve our manuscript.

A note on the discussion on salt flux decomposition: The salt flux decomposition had been an important addition to the manuscript (previous revision). We hope that it improves the applicability of the study´s results to other estuaries. In addition, evaluating the impact of anthropogenic measures on individual salt flux components proves highly interesting and promising. Our new revision corroborates the analysis and clarifies details, which were pointed out by the reviewers. However, to implement all suggestions of the reviewers would constitute a new study and the focus of our manuscript would shift completely. We thus decided to analyze salt flux through one cross-section only, which already provides a novel characterization of the Weser estuary and first indications on the impact of deepening measures on salt flux mechanisms. The specific salt transport decomposition for one critical transect under conditions of channel deepening provides novel results that are transferable to coastal plain estuaries in general. A more in-depth analysis would certainly require more time and a separate publication. To this end, we have an ongoing research project in collaboration with the University of Kiel, Germany, working group of Christian Winter and Marius Becker. In this project, salt transport processes are analyzed on different cross-sections and timescales, based on both our simulations and measurements. With this paper, we wish not to anticipate too much of their ongoing work, which will hopefully also be ready for publication soon.

Please find below our reply to individual comments in italics.

Kind regards,

Pia Kolb on behalf of all authors

Comments to the author:

Dear Authors

I now have referee comments on your revised manuscript. Both recommend “accept subject to minor revisions” but their comments are quite substantial as follows. Please respond to these comments and revise the manuscript accordingly. I will then have to decide whether to send it to the referees again.

Yours sincerely

John Huthnance (editor)

Referee 1.

[This referee wants to see more rigorous analysis of the processes as described in the review below, rather than simply a case study. I agree; Ocean Science is an international journal and most potential readers will be interested in what they can learn for other estuaries.]

The authors have done a nice job in their response to the reviews of the original manuscript. Both reviewers pointed out that a salt flux analysis could help in the interpretation of the results, and that has been done in the revision. While the revision is responsive to the previous comments, I feel that the new analysis is rather cursory and at times confusing. This detracts from the utility of the salt flux analysis for understanding the physical processes and how they’ve been modified in this estuary.

For example, in the abstract [lines 20-23], it states that the salt flux is driven primarily by tidal pumping, but this sentence is followed by a statement that the changes in salinity intrusion between 1972 and 1981 are due to an increase in the estuarine circulation. This seems contradictory, or at least counter-intuitive, that changes in the secondary salt flux mechanism (and no changes in the primary?) dominate the response of the system. These statements need some transition to acknowledge the incongruity, or further explanation to resolve it.

Action: We changed the sentence to improve the clarity: “An analysis of the salt flux through a characteristic cross-section has shown that saltwater intrusion in the Weser estuary is primarily driven by tidal pumping and only to a lesser degree due to estuarine circulation. However, results indicate that the contribution of individual processes has changed in response to anthropogenic measures” (line 20ff).

Looking at Figure 8, the increase in the estuarine circulation between 1972 and 1981 appears to be similar in magnitude as the change in the tidal pumping flux between 1981 and 2012. That raises the questions as to why there was not a similar or greater response in the salinity intrusion length in the latter period, as well as why there are such differences in the response of the salt flux mechanisms to deepening of the estuary among the different periods.

Reply: Differences in the response of salt flux mechanisms to deepening among different periods are related to the scale and the location of the measure, as described in the discussion: "A possible interpretation could be that deepening measures in the Weser estuary locally induce an increase in estuarine exchange flow and globally induce an increase in tidal pumping. In addition, the shape of the estuary and the depth distribution are complex and the impact of a deepening measure depends on its location, meaning a deepening of the outer estuary as between 1981 and 2012 has a different impact than a deepening of the inner estuary as between 1972 and 1981. This aspect could be further explored in future studies […]" (line 494). It has to be noted that, while our results provide first indications for changes of salt flux mechanisms between scenarios, a full explanation of the examined effects will require an in-depth analysis of salt flux mechanisms on cross-sections throughout the estuary.

The text also notes that the salt flux balance is expected to sum to zero, but it does not. This does seem troubling, particularly since the residual term (error?) is similar in magnitude to the estuarine exchange and tidal pumping terms that are being diagnosed. Is the inflow boundary condition salinity at the landward end equal to zero? It appears not be in some of the simulations (e.g., Equation 3), and if it were not this would lead to a net seaward salt flux in a steady system. Or is there some unsteadiness that could explain the residual (i.e., the estuary is getting fresher/shorter)? The fact that the volumetric flux balances the river discharge is heartening, but it makes the large residual in the salt flux all the more disconcerting, and it makes it hard to have confidence in the interpretation of the results.

Reply: Thank you very much for pointing out this problem and giving valuable suggestions for the interpretation of the residual term. Our explanation of the total salt flux was not sufficient. The total salt flux includes the effect of non-zero salinity in river discharge, which is in case of the Weser not negligible due to salt mining upstream. The salinity influx from the river discharge in our calculations amounts to a seaward salinity flux of 360 psu m^3s^{-1}, resulting from a mean salinity of 1.2 psu at a discharge rate of 300 m^3s^{-1}. This is approximately in the same magnitude as the total flux. Moreover, there are slight changes in the storage of salt in the estuary caused by the varying water level at the seaward model boundary (see Table 1, scenario study). The boundary data do not only contain the tidal signal, but also other variations, for example of the mean water level. Due to these variations, there is an overall decrease in salinity at the examined cross-section and thus, some additional seaward salt flux contributes to the residual.

Action: We included the information in the text in 4.6. Furthermore, we have indicated in Fig 8 the contribution of the river discharge to the total salt flux.

The Knudsen analysis (section 4.6.2) seems largely redundant to the salt flux decomposition, and it also suffers from the large, unexplained residual that undermines the results. It would be helpful to clarify what we learn from this approach, or else remove it. The salt flux decomposition was suggested to assess the extent to which the Weser is similar or different to other systems where response to deepening has been studied. What new do we learn through the Knudsen approach?

Action: We removed this section in the interest of brevity.

This section (4.6.3) on stratification and mixing is also disappointingly cursory. First, the section should be titled "stratification" or "potential energy anomaly", rather than "Tidal mixing" since mixing is not quantified. The changes in PEA are shown in Fig 10, but there's little explanation of the physical processes that lead to those changes. For example, the tides are similar in the 1981 and 2012 cases, but the PEA is quite different. The tides in 1981 and 2021 are bigger than in the earlier years and one might expect bigger tides result in greater tidal mixing and less stratification, but that's not the case and the PEA is greatest in 2012. Understandably the PEA depends on the tides, the local salinity (or salinity gradient), and the water depth, but none of this is addressed in the analysis or discussion. The results would be far more informative if there were analysis to explain (or even speculate on) the spatial and temporal variability in PEA, particularly for readers interested in implications for other estuaries. Alternatively, this section could also be removed in the interest of brevity.

Action: We removed this section in the interest of brevity.

Overall, the manuscript is improved, however deficiencies remain that if addressed could greatly increase the value of this contribution.

Referee 2

Thank you for addressing my comments and including more in-depth analysis on the salt transport processes including tidal pumping. The clarity of the paper has also been much improved. However, I still have some concerns mainly about their decomposition method, which can affect the reliability and impact of their findings.

Main comment:

Equation (7): Why did the authors decompose only vertical and temporal variations with their three-dimensional model outputs? As Becherer et al (2016) pointed out, lateral circulation can also directly influence longitudinal transport. Wei et al. (2022) confirmed that lateral variations of gravitational circulation and residual salinity can largely contribute to landward salt transport in wide sections with large lateral bathymetrical changes. Becherer et al (2016) couldn't analyze this contribution because their observations were based at one location. However, with the authors' three-dimensional model, they can certainly quantify the contribution of lateral processes in comparison to the other processes. To that end, I suggest the authors to consider another decomposition method that includes all these processes, such as equation (6) in Hughes & Rattray (1980), for a more complete and reliable analysis.

Reply: Thank you for your suggestion which addresses two main points: the way we have carried out the chosen analysis method and the choice of method itself. Concerning the first point, please note that we have carried out the analysis over the full cross-section instead of one location. We have further clarified that in Section 3.5.2. Given that, of course it would theoretically be possible to look into the lateral variations of fluxes within one cross section or even into residual circulation patterns of secondary currents. This would be a very interesting point for future studies, but it would not contribute to the focus of this study and shift the focus of the paper. Concerning the method itself, the decomposition according to Becherer et al. (2016) divides the salt flux into three components, which are associated with certain mechanisms. A different decomposition method would generate other terms, which are interpreted differently. We selected the decomposition according to Becherer et al. (2016) because it provides a comprehensive analysis of the main mechanisms for salt transport in the estuary. The method is complete in the sense that the sum of all salt flux components is equal to the total salt flux. We have explicitly verified this *during our calculations. Our results improve the applicability of the study´s results to other estuaries and help to explain differences in saltwater intrusion between scenarios. A further analysis of individual processes is not the focus of our manuscript.*

Action: In Section 3.5.2, we have clarified our approach: "We conducted the salt flux decomposition for equidistant points along the cross-section (distance of 25m) and integrated the results over the whole width of the cross-section" (line 254f). In our discussion, we have emphasized that an evaluation of lateral processes would be an interesting next step and could help understand the dynamics of salt transport in the estuary (line 498ff). Moreover, we have included the suggested decomposition method in the outlook (line 452).

other comments:

Line 253: The importance of various salt transport processes can strongly depend on the location of the cross-section. It is surprising that the authors only analyze the salt transport processes for one transect (60 km) with their three-dimensional model outputs.

Reply: As we mention in our discussion (line 598f), we completely agree that an analysis for other cross-sections would be a valuable addition. However, in this paper, we decided to limit our analysis to one characteristic cross-section. The focus of our paper is the analysis of the impact of anthropogenic measures on the saltwater intrusion length. An in-depth analysis of the salt flux for different cross-sections seems out of scope. However, to that end, we have an ongoing research project in collaboration with the University of Kiel (see above).

Line 270: How did you define W? Is it time dependent in your calculation? Since wetting and drying is activated in your model, the cross-sectional width also changes with time and should also contribute to the total flux. Right?

Reply: The cross-section width W is defined as the distance between the first and the last point on the analysed cross-section. When integrating salt flux values over W (see equation 7), permanently dry stretches are taken into account with the value of zero salt flux. As the salt flux components are time-independent (average for evaluation period), W is time-independent (see Equation 7). However, changing water depth or temporarily dry elements will influence the salt flux components at the locations along the cross-section which are integrated over W.

Action: We have explained more in detail our approach for the salt flux decomposition (Section 3.5.2).

Line 428: What do you mean by advective flux? Is it the same as "barotropic flux"?

Reply: Thank you for pointing out this mistake. We mean the "barotropic flux".

Action: We changed "advective flux" to "barotropic flux".

Line 440: Isn't it concerning that the total residual salt flux is much larger than the exchange flow contribution and comparable to tidal pumping. Can you explain why the total flux is so large?

Reply: Yes, thank you for pointing out this problem. We have examined the total flux and can now explain why it is so large, see also the response to referee 1: The total salt flux includes the effect of non-zero salinity in river discharge, which is in case of the Weser not negligible due to salt mining upstream. The salinity influx from the river discharge in our calculations amounts to a seaward salinity flux of 360 psu m^3s^{-1}, resulting from a mean salinity of 1.2 psu at a discharge rate of 300 m^3s^{-1}. This is approximately in the same magnitude as the total flux. Moreover, there are slight changes in the storage of salt in the estuary caused by the varying water level at the seaward model boundary (see Table 1, scenario study). The boundary data do not only contain the tidal signal, but also other variations, for example of the mean water level. Due to these variations, there is an overall decrease in salinity at the examined cross-section and thus, some additional seaward salt flux contributes to the residual.

Action: We included an explanation in Section 4.6. Furthermore, we edited Fig. 8, so that it now shows the contribution of the river discharge to the total salt flux.

References:

Becherer, J., Flöser, G., Umlauf, L., & Burchard, H. (2016). Estuarine circulation versus tidal pumping: Sediment transport in a well-mixed tidal inlet. Journal of Geophysical Research: Oceans, 121(8), 6251-6270.

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Wei, X., Williams, M. E., Brown, J. M., Thorne, P. D., & Amoudry, L. O. (2022). Salt intrusion as a function of estuary length in periodically weakly stratified estuaries. Geophysical Research Letters, 49(15), e2022GL099082.