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Salt Intrusion around the World under Influence of Climate Change

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Abstract

We investigate the changes in surface water salinity intrusion lengths for estuaries around the world under influence of climate change. To do this, we make use of information from global data sets on present river geometry and present and predicted future river discharges, mean sea levels and tidal ranges, which we combine with various models for salt intrusion lengths. The used predictions are based on the RCP8.5 climate scenario and we use 2050 as time horizon, with the 10-percentile lowest discharge as representative value used as input in the intrusion length calculations. The salt intrusion models are two parametric descriptions and a semi-analytical model. With this, we calculate absolute and relative changes in salt intrusion length for a selection of estuaries around the world, to eventually scale up the analysis and develop a global map of changes in salt intrusion around the world under influence of climate change. The results so far indicate that many estuaries may be expected to experience a relative increase of salt intrusion length of over 10%. We also investigate which of the changing forcings most strongly affects the intrusion lengths and what type of estuary is most sensitive to changes. For most systems, the changes in river discharge characteristics are the most influential change, exceeding the influence of sea level rise. This study highlights the importance of studying the effect of climate change on estuarine salt intrusion in more detail, both in global analyses as in system specific detailed studies.

Keywords: Salinity intrusion; Estuaries; Climate change; Projections; Droughts;

1. INTRODUCTION

Fresh water is a vital resource. In deltaic areas, the availability of this resource is affected by salinity intrusion, both via groundwater and surface water. Surface water salt intrusion into estuaries is caused by net inward transporting mechanisms like gravitational circulation (Hansen and Rattray, 1965; Chatwin, 1976) and tidal trapping (Fischer et al., 1979). These mechanisms are in competition with the outward transport due to the river discharge which flushes salt out of the system. The balance of these mechanisms determines the length of the salt intrusion and mainly depends on the estuarine geometry and bathymetry and the forcing by sea level elevations (mean sea level, tides and surges), river discharges and density differences. As both sea levels, river discharges and also tides are changing under influence of climate change, it may be expected that also salinity intrusion into estuaries will change. This may threaten the availability of freshwater.

Here, we investigate the changes in surface water salinity intrusion for estuaries around the world under influence of climate change. We do this to explore the relevance of this potential effect of climate change globally and to develop a way to make quick-scans of potential salt intrusion changes in specific systems as first phase of any possible more detailed analyses with more complex numerical modelling instruments in research projects on those specific system. In this study, we develop a method and estimate for a selection of estuaries from around the world what change in salt intrusion may be expected between 2015 and 2050. Next, we study which of the changing driving forces has the greatest effect on the salt intrusion lengths, and explore what type of estuaries generally experiences the largest (relative) increase in salt intrusion length and is thus most vulnerable for climate change.

2. METHODS

2.1 General approach

To investigate changes in salt intrusion around the world under influence of climate change, we set up a work flow that essentially combines three sources of information; 1) information from global data sets on estuarine geometry and bathymetry; 2) information from global data sets of present and predicted future river discharges, mean sea levels and tidal ranges that have recently become available; and 3) parametric descriptions and a semi-analytical model that can provide estimates of estuarine salt intrusion lengths given the information on system geometry and system forcing.

2.2 Global datasets

Present system geometry

In the present study, information on Global River Widths is obtained from Landsat (GRWL, Allen and Pavelsky, 2018). We retrieved information on the depth at the mouth of the estuaries from GEBCO (2020), with additional bathymetry information from data sets of Savenije (1993) and Navionics.

Present and predicted system forcing

For information on river discharges, we use discharge data from the global hydrology and water resources model PCR-GLOBWB 2.0 (Sutanudjaja et al., 2018), based on bias-corrected HadGEM2 climate data. Projections for monthly discharges were available for RCP4.5 and RCP8.5 up to 2066. We use data for the period 2005-2015 to represent the current situation and for between 2050-2060 to represent the future situation. From the total of 132 months (12 x 11 years), we determined the 10-percentile lowest discharge and used this as representative 'low discharge' for the current and the future situation.

For information on forcing by the tide, we use data from the Global Tide and Surge Model (GTSM), based on CMIP6 HighRes climate forcing and mean sea level initial conditions, following Muis et al. (2020). Information was available for the present climate (ERA5 re-analysis data), and for the two climate scenarios RCP 4.5 and RCP 8.5. We use the re-analysis data for 2015, and data of the RCP 8.5 simulations for the year 2050. We extract data of the tidal range for the closest tidal station near the mouth of the selected estuaries. Note that we use an averaged tidal range, neglecting for the moment separate effects of changes in spring and neap tides.

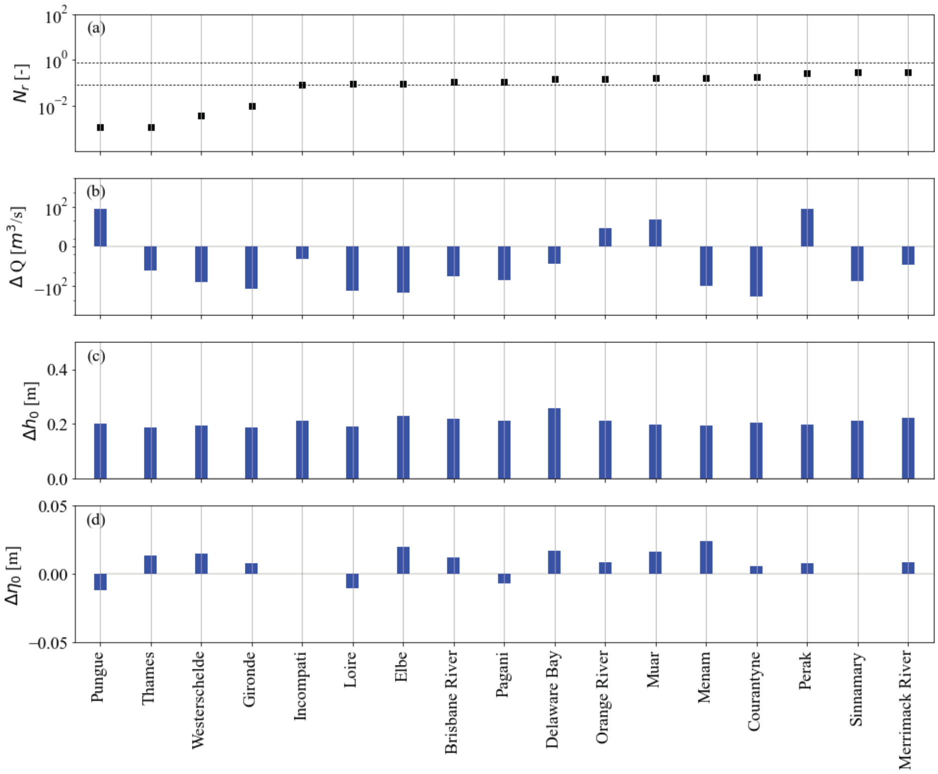

Figure 1. Climate change induced changes in forcing for the considered systems, with in (b) change in river discharge, (c) sea level rise (accounted for via change in depth) (d) change in tidal amplitude; The systems are listed in order of increasing estimated Estuarine Richardson number N_r (a), with N_r≈0.08 indicating the transition from well-mixed to partially stratified estuaries and N_r≈0.8 the transition towards salt wedge estuaries.

Mean sea levels are obtained from the same dataset as the tidal range. Similar to the tidal range, we extract data of the mean sea level for the closest tidal station near the estuary mouth and use RCP 8.5 based results as projections.

Figure 1 shows the projected climate change induced changes in river discharge, sea level and tide for the systems considered in this study.

2.3 Salt intrusion models

Parametric expressions for salt intrusion

The first parametric description used in this study is the model by Gisen et al. (2015), an extension of the earlier model by Savenije (1993), which expresses the intrusion length L_s as:

$$L_s = L_a \ln\left(\frac{A_0 D_0}{K L_a Q} + 1\right) \quad [1]$$

with L_a the convergence length of the estuary, A_0 the cross-sectional area at the estuary mouth, Q the river discharge, D_0 a dispersion coefficient at the mouth and K the Van der Burgh coefficient, which can be seen as a 'shape factor' in the salinity curve (Savenije, 1993). Gisen et al. (2015) provide equations for D_0 and K based on a combination of analytical derivation and empirical expressions based on analysis of a database of 30 estuaries, mostly with low to mid-range estuarine Richardson number.

The second parametric description is the scaling expression by Ralston et al. (2008) (following Monismith et al. 2002) which provides a salinity intrusion length scale L_x which reads:

$$L_x \sim \frac{(\beta g S_0)^{2/3} A^{1/3} H^{5/3}}{\gamma Q_r^{1/3} U_t} \quad [2]$$

with β the haline contraction coefficient, g the gravitational constant, S_0 the salinity at the estuary mouth, A a cross sectional area, H the depth (both taken here at the mouth), Q_r the river discharge and U_t the tidal velocity amplitude. The parameter γ is a constant related to the parameterization of vertical mixing, see Ralston et al. (2008) for details. The expression has basically been derived for partially stratified systems, so mid-range estuarine Richardson numbers.

Semi-analytical model for salt intrusion

Next to the parametric descriptions, we also estimate salt intrusion lengths using a semi-analytical model. This was later added to the analysis to be able to solve more of the physical processes and account for more details of the geometry. The semi-analytical model used here is the MC-2022 model by Biemond et al. (2022), which builds upon the model by MacCready (2007) and solves the tidally averaged, width-averaged flow and salinity structure, via splitting of the velocity and salinity in their respective depth-averaged and depth-dependent parts and using a parameterization for vertical mixing. For more details, see Biemond et al. (2022).

2.4 Processing

Not all relevant information from the databases can directly be used as input for the parametric descriptions or the semi-analytical model. For instance, to account for sea level rise, we add the (present and predicted) mean sea level from GTSM to the depth from the geometry data, so sea level rise is accounted for through a change of the depth at the estuary mouth. (Note that we assume the estuarine geometry and bathymetry to be constant in time, which is of course disputable but a restriction we deemed justified and inevitable considering the scope of this study).

To estimate salt intrusion length using the parametric descriptions, the geometry needs to be characterized using the width at the mouth and a convergence length, and we determine this from the geometry information by fitting an exponential function through datapoints of the width of the main branch against the distance from the estuary mouth.

Tidal elevation amplitudes are translated into tidal velocity amplitudes using a relation between these two depending on the geometry of the system.

Next, the model of Ralston et al. (2008) only provides a length scale and is focused on how that scales with various parameters. To enable comparison also for absolute changes, the outcome of the Ralston model has been scaled such that it equals the outcome of the Gisen et al. (2015) model for the reference situation.

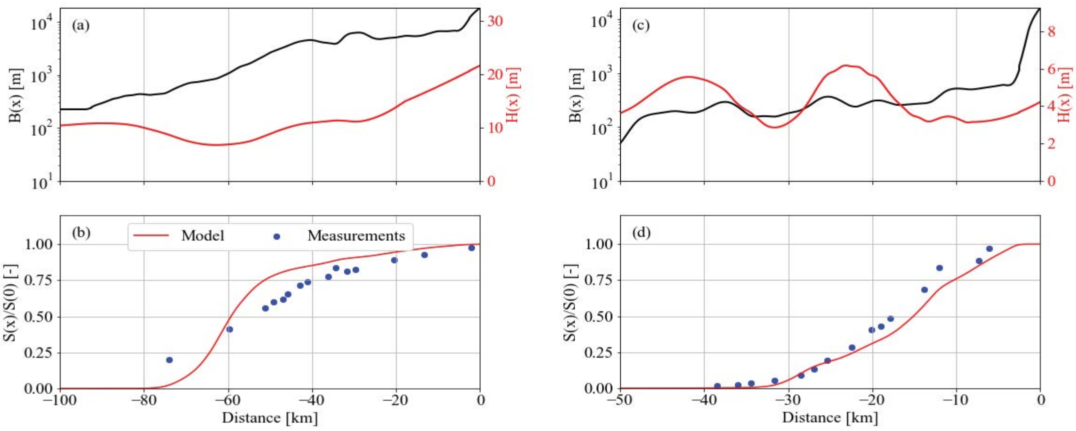

Figure 2. Data-model comparison for tide-averaged salinity intrusion into the Western Scheldt (left) and Incomati (right) for the MC-2022 model; (a&c) width *B* and depth *H* along the estuary; (b&d) salinity *S* along the estuary normalized with the salinity at the mouth *S*(0).

2.5 Verification

To get a sense of the value and validity of the results for present and future salt intrusion lengths we will generate by connecting the information on geometry, bathymetry, system forcing and system reaction, a very brief validation has been carried out. Figure 2 shows a data-model comparison for tide-averaged salinity intrusion into the Western Scheldt (left) and Incomati (right) for the MC-2022 model.
This validation gives some confidence in this approach and illustrates the potential of semi-analytical models for studies like this. However, we recommend considering the results of this study so far as estimates and note treat them as detailed predictions, as both input data and descriptions/model do capture the details and complexity of the physical situation only to a limited extent, and the results do need further verification. Nevertheless, the method provides some useful results for the purpose of this study.

3. RESULTS

3.1 Changes in salt intrusion length

Figure 3 panel (a) shows salt intrusion lengths for the considered estuarine systems as estimated with the parametric description of Gisen et al. (2015) and the semi-analytical model MC-2022. Panel (b) and (c) show absolute and relative changes in salt intrusion length, now also including the parametric description of Ralston et al. (2008), scaled in such a way that the intrusion length in the reference situation equals the estimate for the reference situation using Gisen et al. (2015) (which was shown in panel a). From the figure for the absolute change (panel b) it can be observed that the estimated salt intrusion length increases for almost all systems considered. This observation is the same for all three of the estimation methods, though in general the estimated changes are much larger using Ralston et al. (2008) in comparison with the other methods. For the systems considered here, the averaged increase in salt intrusion length is about 4 km using MC-2022, and 6 and 12 km using Gisen, respectively Ralston. The relative increase in salt intrusion length shows quite a range but is more than 10% for most of the systems. Changes of this order of magnitude may very well impact the fresh water availability, as with such changes salt may more frequently intrude beyond fresh water intake locations causing down-time for their operation.

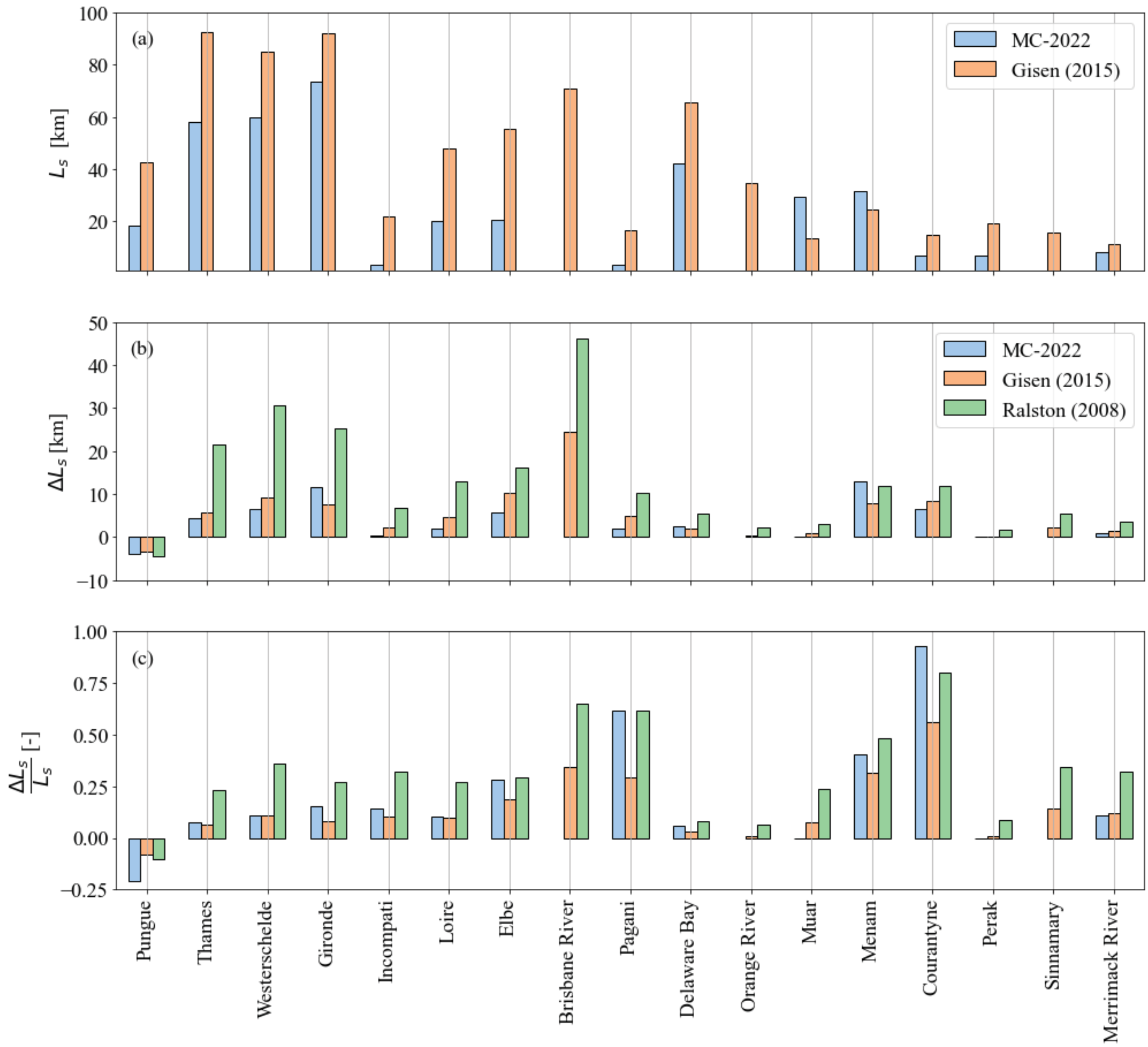

Figure 3. (a) Estimated salinity intrusion length L_s; (b) absolute changes in salt intrusion length for the changes in river discharge, sea level and tide from figure 1; and (c) relative changes in salt intrusion length; Calculated with the Gisen and Ralston parametric descriptions and the semi-analytical model MC-2022.

3.2 Contribution to change by separate forcings

Next, we study which of the changing driving forces has the greatest effect on the salt intrusion lengths. We do this by estimating the change in salt intrusion considering the change in one of the forcings only, keeping the other conditions the same. Note that due to interactions, the thus obtained three separate results do not necessarily add up to the earlier results obtained by jointly considering all changes in forcing. The separate results for changes in river discharge, sea level and tide only are shown in figure 4. It can be observed that in general the change in river discharge is the most influential forcing change, generally exceeding the influence of sea level rise. So, climate change seems to affect salt intrusion particularly through its hydrological effects. This is an important observation, and might also hold an indication on what type of measures against salinity intrusion could be effective (for instance retaining water in the wet season to partially compensate decreased discharges in the dry season). However, note that this dominant influence of the change in river discharges might become different when considering another time horizon.

The effect of sea level rise is especially large using the Ralston model. This may be related to the fact that this model is essentially derived for systems in which gravitational circulation is dominant, which makes changes in depth more influential compared to situations where other dispersion processes are dominant. However, in particular these results are larger than expected and require further checks and consideration.

The effect of changes in the tides are small, which is as expected as also the changes in the tidal amplitudes themselves are only small (figure 1). It is interesting to note the direction of the effect: for Ralston, an increasing tidal amplitude causes a decrease of the salt intrusion length, while for Gisen it is the opposite. This seems in line with the type of system(s) at the base of their derivation: a gravitational circulation dominated situation for Ralston and a list of mostly quite well-mixed systems for Gisen.

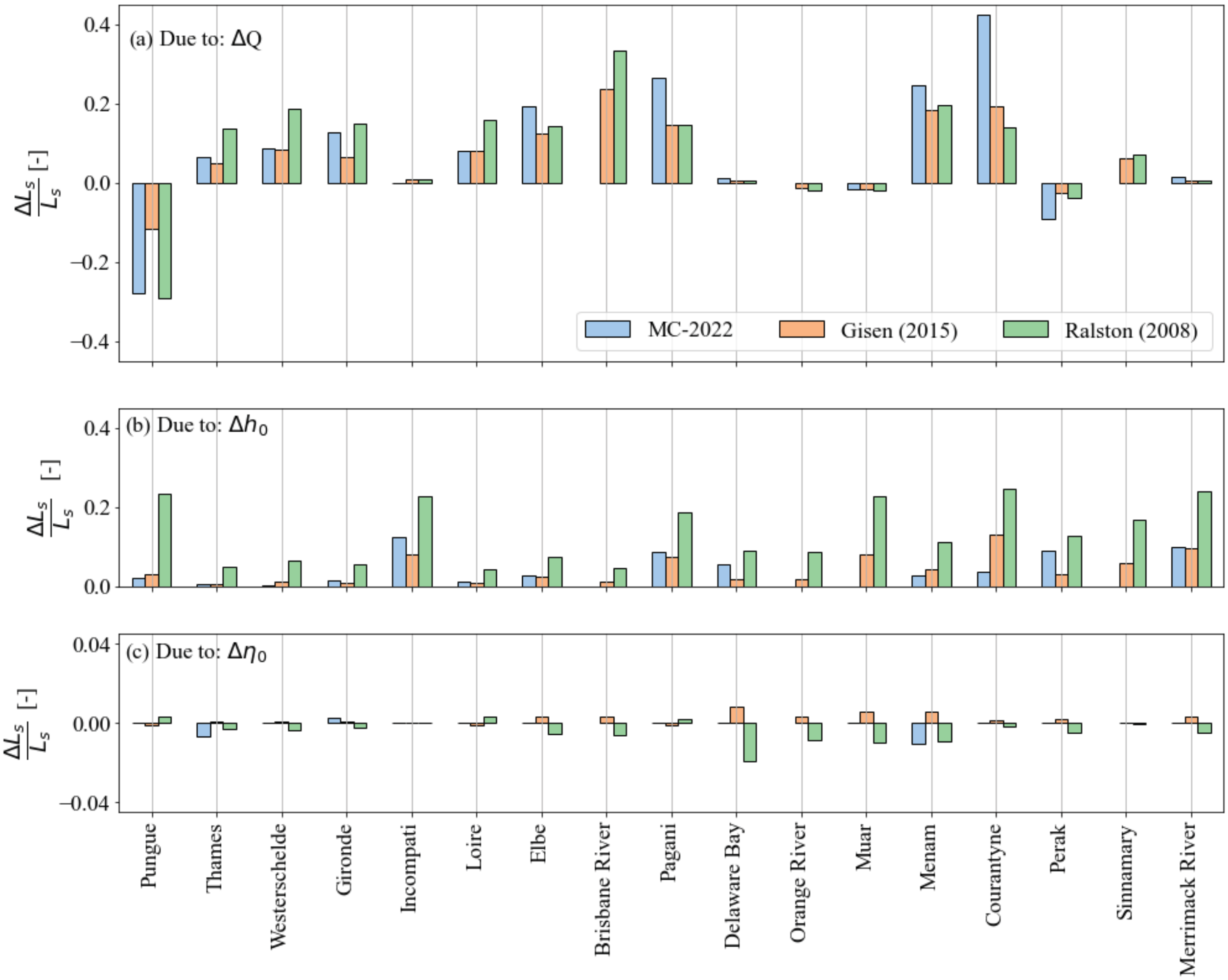

Figure 4. Contribution of the various changes in forcing to the relative change of salt intrusion length L_s; (a) due to changes in river discharge; (b) due to changes in mean sea level (accounted for through changes in depth); (c) due to changes in tidal amplitudes.

The parameter dependencies for the various systems and using the various descriptions/models have been investigated further by looking at the relative change in salt intrusion length for a relative change in forcing, e.g. $r = (\Delta L_s/L_s) / (\Delta Q/Q)$. This ratio r actually describes the scaling of the salt intrusion length with the parameter involved, so: $L_s \sim Q^r$. In the parametric descriptions, these relations are basically fixed. However, calculating this for results of the semi-analytical model provides unique scaling parameters for each system. This provides insights in the sensitivity of the various systems for changes in forcing, which is a step on the way to determine what systems are most vulnerable for climate change.

4. CONCLUSIONS AND OUTLOOK

We investigated the changes in surface water salinity intrusion lengths for estuaries around the world under influence of climate change between 2015 and 2050 by combining information from global data sets on present river geometry and present and RCP8.5 based predicted river discharges, mean sea levels and tidal ranges, with various models for salt intrusion lengths. The results so far indicate that many estuaries may be expected to experience a relative increase of salt intrusion length of over 10%. Next, we find that (in this study with a time horizon at 2050) for most systems the changes in river discharge characteristics are the most influential change, exceeding the influence of sea level rise. As changes in salt intrusion lengths of the ranges found here may threaten fresh water intakes and the availability of fresh water, this study underlines the importance of investigating the effect of climate change on estuarine salt intrusion in more detail, both in global analyses as in system specific detailed studies.

For this study on global impacts, we see opportunities for improvement for various elements of the method. Firstly, it is important to retrieve and include more detailed bathymetric information, as salt intrusion estimates are very sensitive for depth. Next, we aim to scale up and further expand the number of systems considered, by further improving and automatising our workflow and by expanding the range of estuarine systems for which we can apply the method. The step to include the semi-analytical model made it possible to include more of the physical processes and characteristics of the geometry – compared to the parametric descriptions we started with. This needs to be further expanded and the further automatization of the workflow is also aimed at making it possible to include other (semi-analytical or numerical) models and/or recently developed emulators (Hendrikxs et al., under review) as well. The present approach of using the 10-percentile lowest discharge should be replaced by more elaborate statistics on river discharges and consequently salinity intrusion length probabilities. With these improvements we can be more conclusive on the changes in salt intrusion, the contribution of the various forcing changes and the most vulnerable (type of) systems, and develop a global map of changes in salt intrusion for estuaries around the world. Ultimately, the results need to be translated into societal impacts, e.g. through calculation of effects on irrigation operations, crop yields or human health effects. However, that is beyond the scope of this study.

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6. REFERENCES

Allen, G. H. and Pavelsky, T. (2018) ‘Global extent of rivers and streams’, *Science,* 361(6402), pp. 585–588. doi: 10.1126/science.aat063.

Becker, J. J. et al. (2009) ‘Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS’, *Marine Geodesy*, 32(4), pp. 355–371. doi: 10.1080/01490410903297766.

Biemond, B., de Swart, H. E., Dijkstra, H. A., & Diez-Minguito, M. (2022). Estuarine salinity response to freshwater pulses. *Journal of Geophysical Research: Oceans*, 127.

Chatwin, P.C. (1976). Some remarks on the maintenance of the salinity distribution in estuaries. *Estuar. Coast. Mar. Sci.,* 4, 555–66.

Fischer, H.B., List, E.J., Koh, R.C.Y., Imberger, J. and Brooks, N.H. (1979). *Mixing in Inland and Coastal Waters.* Academic Press, 483 pp.

Gerritsma, A. (2021). *Salt intrusion in estuaries around the world under influence of climate change*. MSc internship report. Deltares and Wageningen University and Research.

Gisen, J. I.A., Savenije, H. H. G. and Nijzink, R. C. (2015) ‘Revised predictive equations for salt intrusion modelling in estuaries’, *Hydrology and Earth System Sciences*, 19(6), pp. 2791–2803. doi: 10.5194/hess-19-2791-2015.

Hansen, D.V. and Rattray, M. (1965). Gravitational circulation in straits and estuaries. *J. Mar. Res.,* 23, 104–22.

Hendrickx, G.G., Kranenburg, W.M., Antolinez, J.A.A., Huismans, Y., Aarninkhof S.G.J. and Herman, P.M.J. (under review). Sensitivity of salt intrusion to estuary-scale changes: A systematic modelling study towards nature-based mitigation measures.

MacCready, P. (2007). Estuarine adjustment. *Journal of Physical Oceanography*, 37(8), 2133– 2145. https://doi-org.tudelft.idm.oclc.org/10.1175/JPO3082.1

Monismith, S. G., W. Kimmerer, J. R. Burau, and M. T. Stacey, 2002: Structure and flow-induced variability of the subtidal salinity field in northern San Francisco Bay. *J. Phys. Oceanogr.*, 32, 3003–3019.

Muis, S. et al. (2020) ‘A High-Resolution Global Dataset of Extreme Sea Levels, Tides, and Storm Surges, Including Future Projections’, *Frontiers in Marine Science*, 7(April), pp. 1–15. doi: 10.3389/fmars.2020.00263.

Ralston, D. K., Geyer, W. R. and Lerczak, J. A. (2008) 'Subtidal salinity and velocity in the Hudson River estuary: Observations and modeling', *Journal of Physical Oceanography*, 38(4), pp. 753–770. doi: 10.1175/2007JPO3808.1.

Savenije, H. H. G. (1993) 'Predictive model for salt intrusion in estuaries', *Journal of Hydrology*, 148(1–4), pp. 203–218. doi: 10.1016/0022-1694(93)90260-G.

Sutanudjaja, E. H. et al. (2018) 'PCR-GLOBWB 2: A 5 arcmin global hydrological and water resources model', *Geoscientific Model Development,* 11(6), pp. 2429–2453. doi: 10.5194/gmd-11-2429-2018.