ENGINEERING GUIDELINES FOR NATURE-BASED SOLUTIONS TO MITIGATE SALT INTRUSION

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INTRODUCTION

Worldwide, deltas are attractors of life. Due to their provision of freshwater and fertile land while having an open connection to the sea, deltas have become some of the most densely populated and heavily utilised systems in the world. Thereby, deltas—and the estuaries within—are of interest to a wide variety of stakeholders. The crucial functions of deltas are strongly related to the natural dynamics of these systems, e.g., the availability of freshwater and flood safety. At the same time, these natural dynamics are dominated by complex, nonlinear relations in which the interests of all the stakeholders is a delicate balance.

Generally, the socio-economic and flood safety functions in a delta are well-accounted for in the political arena and in engineering practice. However, in recent years, the threat of droughts and the resulting lack of freshwater availability has gained traction. Where research on and practice of nature-based solutions have mainly addressed their use for flood safety, freshwater availability has largely remained out of the picture. As freshwater availability is linked to salt intrusion, here we present engineering guidelines to mitigate salt intrusion in estuaries using nature-based solutions.

METHOD

The engineering guidelines for nature-based solutions to mitigate salt intrusion follow from a collection of studies: from a general, extensive sensitivity analysis to in-depth investigations of specific solutions. The extensive sensitivity analysis addresses the question how the salt intrusion responds to estuary-scale modifications, providing insights into the most promising solution-directions (Hendrickx et al., 2023). Examples are (1) large-scale reduction of the water depth (Hendrickx et al., 2023); (2) a temporary sill (Hendrickx et al., 2024); and (3) intertidal area (Hendrickx and Pearson, 2024).

These studies simulated idealised geomorphologies of estuaries with a process-based hydrodynamic modelling software, namely Delft3D Flexible Mesh. This way, the modelling assumptions are limited, allowing us to fully focus on estuarine dynamics being modelled; and the idealised geomorphologies enable us to compare the wide range of estuaries explored.

RESULTS & DISCUSSION

In general, the estuary-scale parameters must all coincide unfavourably in order for extreme extensive salt intrusion events to occur (Hendrickx et al., 2023). This means that favourably modifying one of the estuary-scale parameters can greatly reduce the salt intrusion length, while all the rest remains the same. For example, there is such a relation for the channel depth: A larger water depth enables the possibility of a larger salt intrusion length, but does not necessarily mean that there is a large salt intrusion length; a smaller depth does, however, mean that the salt intrusion length is suppressed. In other words, the channel depth puts a clear upper limit to where the salt intrusion can reach, and other key factors further determine the extent of the salt intrusion. This principle holds for other key estuary-scale parameters as well, e.g., river discharge and width convergence.

This capping behaviour is an indication of the dominance of nonlinearities in estuarine dynamics. The sensitivity of the salt intrusion to estuarine modifications also depends on what type of estuary is at hand; e.g., the salt intrusion length is more strongly influenced by river discharge for larger discharges (Hendrickx et al., 2023), i.e., for salt wedge estuaries. In anticipation of these complicating factors, a neural network has been coupled to a web-API for first-order assessments of potential nature-based solutions to mitigate salt intrusion (Hendrickx, 2022).

This case-dependent efficiency of mitigation measures is clearly visible when considering the implementation of a sill to mitigate salt intrusion: A sill is more effective in keeping salt water out in a micro-tidal

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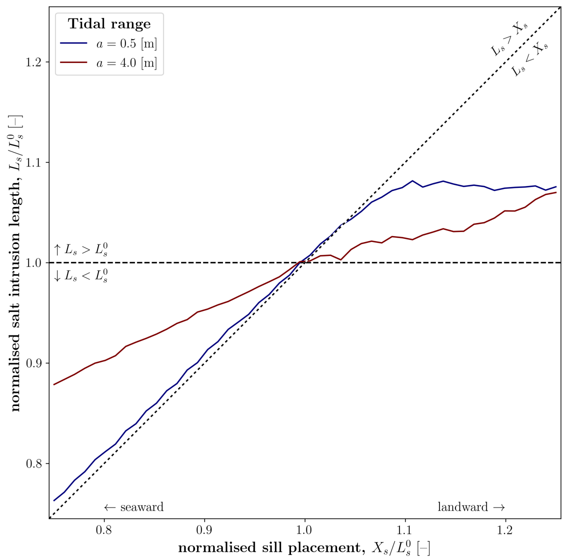

Figure 1: Salt intrusion length as function of the location of a sill for two tidal ranges: micro-tidal (a = 0.5 m), and macro-tidal (a = 4.0 m). L_s^0: salt intrusion length without a sill (reference); L_s: salt intrusion length with a sill; X_s: sill placement (from mouth). (Figure modified from Hendrickx et al., 2024.)

system compared to a macro-tidal system, as depicted in Figure 1 (Hendrickx et al., 2024). In case of little tidal energy—and thereby a relatively strong gravity-driven salt wedge—the sill functions as a wall; conversely, for larger tidal energy inputs, the sill acts like a speed bump.

However, a sill can also have the unintended effect of enhancing the salt intrusion when it is placed too far landward: When the sill is placed beyond the salt intrusion length without a sill (L_s^0), the salt water intrudes further than it otherwise would have. This makes the sill's along-channel position (i.e., sill placement, X_s) one of the key design considerations when applying a sill as salt intrusion mitigation measure.

The influence of intertidal areas on the salt intrusion length is even more dependent on the level of estuarine stratification: If there is stratification in the estuary, the addition of intertidal area reduces the salt intrusion; while in well-mixed estuaries, the intertidal area enhances the salt intrusion (Fig. 2; Hendrickx and Pearson, 2024).

The salt intrusion-reducing capacities of intertidal areas—or tidal flats—can be up to 25% for partially mixed estuaries. However, in well-mixed estuaries, adding a similar intertidal area may double the salt intrusion length. Here, the dominant salt transport mechanism is important: When the estuarine circulation is the dominant landward salt transport mechanism, increasing the intertidal area reduces the salt intrusion; and vice versa when tidal dispersion is the driving force.

CONCLUSION

Nature-based solutions to mitigate salt intrusion are found in system-wide modifications. Depending on the estuary at hand, different estuary-scale parameters are more (or less) effective in mitigating salt intrusion. This system-dependency is crucial when implementing (nature-based) solutions in estuaries. The studies highlighted in this abstract demonstrate the necessity to thoroughly understand the physics controlling an estuary's dynamics before implementing any (nature-based) solution there, since a badly-implemented solution can have the opposite effect and worsen salt intrusion.

Therefore, before a solution is implemented, the estuary class and the dominant salt transport mechanisms at play should be determined. These findings largely determine the potential of a nature-based solution, which becomes increasingly important in times of climate change-induced sea level rise and prolonged droughts.

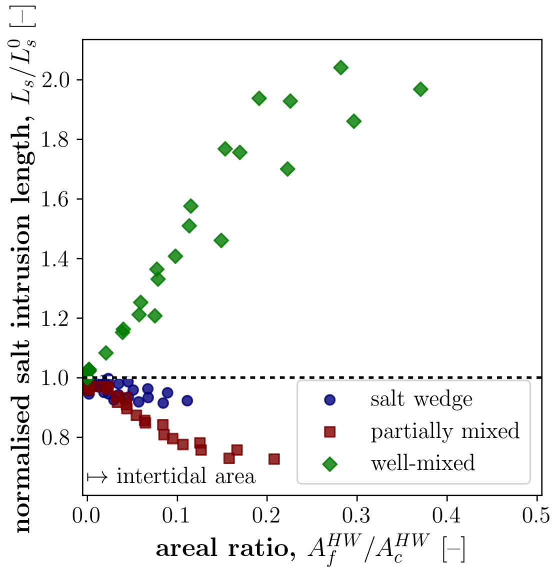

Figure 2: Salt intrusion length as function of intertidal area for three different estuary classes. L_s^0: salt intrusion length without intertidal area (reference); L_s: salt intrusion length with intertidal area; A_f^{HW}: wetted cross-section during high water, flats; A_c^{HW}: wetted cross-section during high water, channel. (Figure modified from Hendrickx and Pearson, 2024.)

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References

G. G. Hendrickx. ANNESI: An open-source artificial neural network for estuarine salt intrusion, 2022. URL `https://doi.org/10.4121/19307693`.

G. G. Hendrickx and S. G. Pearson. On the effects of intertidal area on estuarine salt intrusion. *Journal of Geophysical Research: Oceans*, 129(9):e2023JC020750, sep 2024. doi: 10.1029/2023JC020750.

G. G. Hendrickx, W. M. Kranenburg, J. A. A. Antolínez, Y. Huismans, S. G. J. Aarninkhof, and P. M. J. Herman. Sensitivity of salt intrusion to estuary-scale changes: A systematic modelling study towards nature-based mitigation measures. *Estuarine, Coastal and Shelf Science*, 295:108564, dec 2023. ISSN 02727714. doi: 10.1016/j.ecss.2023.108564.

G. G. Hendrickx, L. A. Manuel, S. G. Pearson, S. G. J. Aarninkhof, and E. A. Meselhe. An earthen sill as a measure to mitigate salt intrusion in estuaries. *Estuaries and Coasts*, 47(5):1199–1208, jul 2024. doi: 10.1007/s12237-024-01359-2.