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Water Resources Research

REVIEW ARTICLE
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The Effectiveness of Nature-Based Solutions in Mitigating Salt Intrusion in Estuaries: A Review

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Key Points:

- Effects of forcing and geomorphological factors on salt intrusion in estuaries are reviewed
- Advection-based mitigation measures can reduce salt intrusion length by up to 40%
- Mixing-based measures are effective in estuaries with some degree of stratification

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Abstract Climate change and anthropogenic activities are enhancing salt intrusion in many estuaries, which reduces the supply of drinking water as well as freshwater for agricultural and industrial uses and can further cause severe economic losses. Nature-based solutions emerge as sustainable and ecologically sound strategies to mitigate salt intrusion in estuaries. This review paper explores the effectiveness of nature-based solutions in salt intrusion mitigation. Advances in the understanding of estuarine salt dynamics are summarized, thus identifying the dominant parameters that determine the salt intrusion in different types of estuaries. Six potential nature-based solutions (NBSs) for salt intrusion mitigation are conceptualized, including improvement of river discharge management, reduction of channel cross-section, modification of bottom topography, utilization of friction-convergence balance, enlargement of intertidal area and introduction of meanders. These NBSs are grouped into two types: (a) advection-based and (b) mixing-based. Numerical model assessments indicate that all these NBSs have potential to reduce salt intrusion lengths, depending on the salinity structure of the estuary. Nevertheless, applications of NBSs to real estuaries are rare. Directions toward improving the implementation of nature-based solutions for mitigating salt intrusion in estuaries are provided.

1. Introduction

Estuaries are coastal areas connecting rivers and the sea, influenced by freshwater flow of rivers and saline water from sea (Pritchard, 1967). Drinking water supply, as well as agricultural and industrial activities in estuarine regions heavily rely on the supply of freshwater from the river system. When saline water moves into the fresh water area, salt intrusion occurs. Anthropogenic activities (such as deepening waterways for shipping and removal of intertidal area), and climate change (including sea level rise, increased frequency and duration of both storms and droughts) are continuously aggravating salt intrusion (Chant et al., 2018; Hong et al., 2020; Loc et al., 2021; Ralston and Geyer, 2019). The extent of salt intrusion in an estuary is commonly quantified by the salt intrusion length, which is conventionally defined in the literature as the longitudinal distance from the estuarine mouth to the upstream location where the estuary water is fresh, typically taken as a salinity of 1–2 psu (see for instance Cai et al., 2015; Hendrickx et al., 2023; Lee et al., 2024). Salt intrusion lengths in nine European estuaries are projected to increase by 10%–30% at the end of the 21st century due to a warming climate (Lee et al., 2024). Enhanced salt intrusion can disturb ecosystems by altering the salinity levels of soils and water bodies, harming plant life and aquatic species adapted to lower salinity environments (Saccon et al., 2025, 2026; Tully et al., 2019). It can also degrade agricultural lands, reduce freshwater availability for drinking and irrigation, and lead to the abandonment of affected lands, further intensifying water scarcity issues (Bakker et al., 2025; Loc et al., 2021; Mondal et al., 2023; Shammi et al., 2019; Smajgl et al., 2015).

Salt dynamics in estuaries are complex due to intricate coupling and feedback among various physical processes (Fischer, 1979; Geyer & MacCready, 2014). Variable river discharge and tidal forcing are the two dominant external forces that determine salt intrusion (Guha & Lawrence, 2013). Other forcing factors include winds, storm surges and sea level rise (Geyer, 1997; Jongbloed et al., 2022; Khojasteh et al., 2021; Li et al., 2012; Wegman et al., 2025). The estuary's shape and geomorphology influence how salt intrusion responds to changes in forcing (Hendrickx et al., 2023). All of these factors vary in time and space, resulting in different physical processes being dominant in different estuaries. A good understanding of the physical processes that influence the salt intrusion in different estuaries in the context of climate change is important for identifying what measures are effective in

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mitigating salt intrusion. These measures can generally be classified into two categories: (a) hard measures; and (b) nature-based solutions (NBSs).

The use of hard measures, such as dams and locks, can have many negative side-effects on the environment (Little et al., 2022). For instance, they can raise evaporation rate, cause soil erosion, and damage habitats (Dixon et al., 1989; Larinier, 2001). Additionally, hard interventions are static and can thus hardly adapt to climate change (Borsje et al., 2011). Alternatively, nature-based solutions, as more adaptive and sustainable measures, are receiving increased attention in the framework of natural hazards (Kumar et al., 2021; Ourloglou et al., 2020; van Wesenbeeck et al., 2014; Vuik et al., 2016). NBSs are commonly more resilient to changes in climate conditions and often have lower costs than hard solutions on a life-cycle basis, as they attempt to utilise natural processes (Borsje et al., 2011). However, the implementation of NBSs can be challenging due to the complexities and uncertainties of natural processes, requiring a comprehensive system understanding that is sometimes still lacking.

While the discussion on defining NBS is still open in the scientific literature, most conceptualizations are based on or refer to the definitions provided by IUCN (International Union for Conservation of Nature) and the EC (European Commission) (Calliari et al., 2019). Both definitions emphasize that NBS should use nature to address societal challenges, deliver co-benefits, and ideally support biodiversity enhancement. In this study, we adopt the definition by IUCN that NBSs are actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (Cohen-Shacham et al., 2016).

NBSs have been utilised to mitigate coastal flood risk (e.g., Barbier et al., 2013; Gourevitch et al., 2020; Vuik et al., 2016), impacts of droughts (e.g., Kalantari et al., 2018; Yimer et al., 2024), landslides (e.g., Barik et al., 2017; Fornaciai & Park, 2019), coastal erosion (e.g., Feagin et al., 2023; Unguendoli et al., 2023) and other hazards. There are quite some review papers on the effectiveness of NBSs in reducing coastal flood risks (Gijsman et al., 2021; Jordan and Fröhle, 2022; Saleh and Weinstein, 2016), coastal erosion (Kindeberg et al., 2023; Temmerman et al., 2023) and other hydro-meteorological risks (Kalantari et al., 2018; Kumar et al., 2021).

The intensifying hazards caused by saltwater intrusion in estuarine regions underscore the urgent need for a systematic understanding of the potential of NBSs in addressing this issue (D. Li et al., 2024). For instance, the 2016 and 2020 droughts resulted in significant disruptions (~450–650 k ha of crop loss) in the Mekong Delta due to salt intrusion (Eslami et al., 2021). There have been increasing trends of salt intrusion in the Mekong Delta that are being driven by bed level changes induced by anthropogenic sediment starvation (Räsänen et al., 2017). This sediment starvation is itself caused by sediment trapping by upstream dams (Thi Ha et al., 2018). A comprehensive evaluation is essential to identify the most suitable and effective approaches tailored to the specific characteristics of local environments. However, a review on the effectiveness of NBSs to mitigate salt intrusion in estuaries does not exist yet. As a consequence, it is necessary to systematically understand the complex salt dynamics in the estuaries and explore potential NBSs to effectively mitigate salt intrusion.

The objectives of this review paper are threefold (a) to identify key factors that influence salt intrusion in different types of estuaries; (b) to discuss the effectiveness of NBSs in mitigating salt intrusion; and (c) to recommend future directions toward enhancing the understanding of interactions of salt dynamics, and NBSs, and improving the implementation of NBSs for mitigating salt intrusion in estuaries.

This paper is organized as follows: Section 2 first introduces the widely used methods to classify estuaries. Then, key factors that affect salt intrusion in different types of estuaries are identified. In Section 3, NBSs that are (potentially) utilised to mitigate salt intrusion are deduced, followed by a discussion on their effectiveness in reducing salt intrusion length. Section 4 summarizes the main findings and knowledge gaps with respect to the addressed NBSs. Finally, recommendations for future research aimed at improving the implementation of NBSs and their effectiveness in limiting estuarine salt intrusion are provided.

2. Estuarine Salt Dynamics

Understanding estuarine salt dynamics is a prerequisite for mitigating negative impacts of salt intrusion. Classifying estuaries enables comparison of different estuarine systems and identification of predominant physical processes that control salt intrusion in a certain system. It contributes to the advancement in understanding

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estuarine salt dynamics as well. In this section, classification schemes of estuaries are first introduced (Section 2.1). Subsequently, key factors that control the salt intrusion in different types of estuaries are identified (Section 2.2). Understanding the influence of these factors on salt intrusion can help develop more effective measures to mitigate the negative impact.

2.1. Classification of Estuaries

Due to the diversity of processes that control estuarine dynamics, estuaries can be classified in several ways based on geomorphology (e.g., Pritchard, 1952), tidal characteristics (e.g., Lanzoni and Seminara, 1998; Toffolon et al., 2006), and stratification-mixing balance (e.g., Fischer, 1972; Geyer & MacCready, 2014; Table 1). The last type of classification is a widely accepted estuary classification due to its physical appeal (Valle-Levinson, 2010), considering that salt intrusion in estuaries directly results from the balance between water column stratification and mixing. The classical four-type scheme distinguishes salt-wedge, strongly-stratified, weakly-stratified and well-mixed estuaries based on their longitudinal salinity structure and mixing characteristics (e.g., Schultz and Simmons, 1957; Table 1). Conceptually, the eight estuarine regimes identified by Geyer and MacCready (2014; Table 1) can be broadly related to the classical four-type classification. Salt wedge and time-dependent salt wedge regimes correspond to salt-wedge estuaries, strongly-stratified and Fjord schemes correspond to strongly-stratified estuaries, partially mixed and Bay schemes align with weakly-stratified estuaries, and strain-induced periodic stratification (SIPS) and well mixed schemes correspond to well-mixed estuaries. In the following sections, we adopt the classical four-type classification scheme in order to better organize and compare reported salt intrusion mitigation effects of nature-based solutions.

2.2. Key Factors That Influence Salt Intrusion

Decomposition methods of along-estuary salt transport are widely used to gain insight into the physical processes governing estuarine salt transport and, consequently, salt intrusion. By separating the net salt flux into mean and covariance-based contributions involving velocity and salinity, these approaches provide a useful framework for linking mathematically derived transport terms to physically interpretable mechanisms (e.g., Becherer et al., 2016; Dijkstra et al., 2022; Lerczak et al., 2006). Within this framework, the primary physical processes (Figure 1) influencing estuarine salt intrusion can be summarized as follows (Rummel et al., 2025): (a) river-driven and residual advection, represented by the subtidal depth-averaged transport, which mainly exports salt seaward by river discharge, tidal residual currents and lateral circulation; (b) tidal pumping, represented by tidally correlated depth-averaged transport arising from phase shifts between velocity and salinity, as well as tidal trapping; (c) tide-induced shear transport, associated with tidally correlated vertical shear and commonly referred to as s-ESCO (shear-induced Estuarine Salt Circulation Oscillation), resulting from tidal straining (Hans Burchard et al., 2023); and (d) estuarine circulation, represented by subtidal shear transport and characterized by landward near-bed transport of saline water and seaward near-surface transport of fresher water, which is mainly driven by gravitational circulation and tidal straining circulation (Burchard & Hetland, 2010; Geyer & MacCready, 2014). All of these processes may additionally be influenced by lateral circulation and lateral salinity gradients, which can further modify the magnitude and spatial distribution of salt transport. Figuring out how different physical processes influence saline water movement provides a basis for developing effective and targeted measures for mitigating salt intrusion.

In this section, factors which influence salt intrusion are explored more explicitly. As mentioned above, salt intrusion is commonly quantified by the salt intrusion length, defined as the landward distance from the estuarine mouth to the upstream location where salinity drops below a threshold value, typically 1–2 psu. In most studies (e.g., Hendrickx et al., 2023; Lee et al., 2024), this limit is evaluated along the main estuarine channel using near-bed or depth-averaged, tidally averaged salinity, depending on data availability and study objectives. The way in which various processes contribute to the salt intrusion length depends on hydrodynamic forcing variables and estuarine geomorphology. Therefore, factors that influence salt intrusion are introduced and discussed from the perspectives of forcing conditions and geomorphological characteristics.

Equations for parameters that are used in estuarine classification indicate that river discharge and tidal current velocity amplitude are important factors that predominantly control the stratification-mixing balance (Geyer & MacCready, 2014; Kuijper and van Rijn, 2011; Lerczak et al., 2009). In general, salt intrusion length decreases with increasing river discharge due to enhanced seaward advection of salt (Hansen & Rattray, 1965; Rigter, 1973;

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Table 1
Summary of Estuarine Classification Methods Based on Hydrodynamics

Reference	Parameters	Equations	Criteria	Estuary classes	Nomenclature
Schultz and Simmons (1957)	φ	$\varphi = \frac{f_{T_{HW}} Q \mathrm{d}t}{P}$	$\varphi \leq 0.005$	Well-mixed	T_{HW} is the period of tidal high water [s];
			$0.005 < \varphi \leq 0.1$	Weakly stratified	Q is the river discharge [$m^3 s^{-1}$];
			$0.1 < \varphi \leq 1.0$	Highly stratified	P is the tidal prism [m^3];
			$\varphi > 1.0$	Salt wedge	u_s is the tide-averaged surface flow velocity [m/s];
Hansen and Rattray (1966)	Ω, Σ_0	$\Omega = \frac{u_s}{Q/A_c}$	See Figure 2 in Hansen and Rattray (1966)	Well-mixed	A_c is the flow conveyance area [m^2];
				Partially mixed	∂S is the top-to-bottom time-averaged salinity difference;
		$\Sigma_0 = \frac{\partial S}{S}$		Stratified	S is the sectional mean salinity;
				Salt wedge	g is the gravitational acceleration [$g = 9.81$ m/s^2];
Fischer (1972)	Ri_E	$Ri_E = \frac{g\beta s_0 Q}{W_c u_t^3}$	$Ri_E \leq 0.08$	Well-mixed	β is the haline contraction coefficient [$\beta = 7.6 \times 10^{-4}$ psu^{-1}];
			$0.08 < Ri_E \leq 0.8$	Partially mixed	s_0 is the oceanic salinity (i.e., at the mouth) [$s_0 = 30$ psu];
			$Ri_E > 0.8$	Salt wedge	W_c is the channel width [m];
Geyer (2010)	Fr_f, Fr_t	$Fr_f = \frac{Q}{A_c c_i}$	see Figure 2.7 in Geyer (2010)	Well-mixed	u_t is the tidal flow velocity [m/s];
		$Fr_t = \frac{u_t}{c_i}$		Partially mixed	c_i is the internal wave celerity [m/s];
		$c_i = \sqrt{g\beta s_0 h}$		Highly stratified	h is the water depth [m];
Guha and Lawrence (2013)	Φ_0	–	$\Phi_0 \leq 0.1$	Well-mixed	C_D is the bottom drag coefficient [–];
			$0.1 < \Phi_0 \leq 1.0$	Partially mixed	ω is the tidal frequency [s^{-1}];
			$\Phi_0 > 1.0$	Highly stratified	$N_0 = \sqrt{\beta g s_0 / h}$, the buoyancy frequency for maximum top-to-bottom salinity variation [s^{-1}];
Geyer and MacCready (2014)	Fr_f, M	$Fr_f = \frac{Q}{A_c c_i}$	See Figure 6 in Geyer and MacCready (2014)	Well-mixed	K_v is the vertical diffusivity coefficient [m^2/s];
				SIPS[a]	K_h is the horizontal diffusivity coefficient [m^2/s];
				bay	
				Fjord	
		$M = \sqrt{\frac{C_D U_T^2}{\omega N_0 h^2}}$		Partially stratified	
				TDSW[b]	
				salt wedge	
Dijkstra et al. (2022)	Fr_f, Fr_t, Ra, St	$Fr_f = \frac{Q}{A_c c_i}$	see Figure 1 in Dijkstra et al. (2022)	Dispersive	
		$Fr_t = \frac{u_t}{c_i}$		CHATWIN	
		$Ra = \frac{g\beta s_0 h^3}{K_v K_h}$		Chatwin with front subtidal salt wedge	
		$St = \frac{K_v}{\omega h^2}$		Tidally correlated depth	
				Tidally correlated shear	
				Tidal salt wedge	

[a]strain-induced periodic stratification. [b]time-dependent salt wedge.

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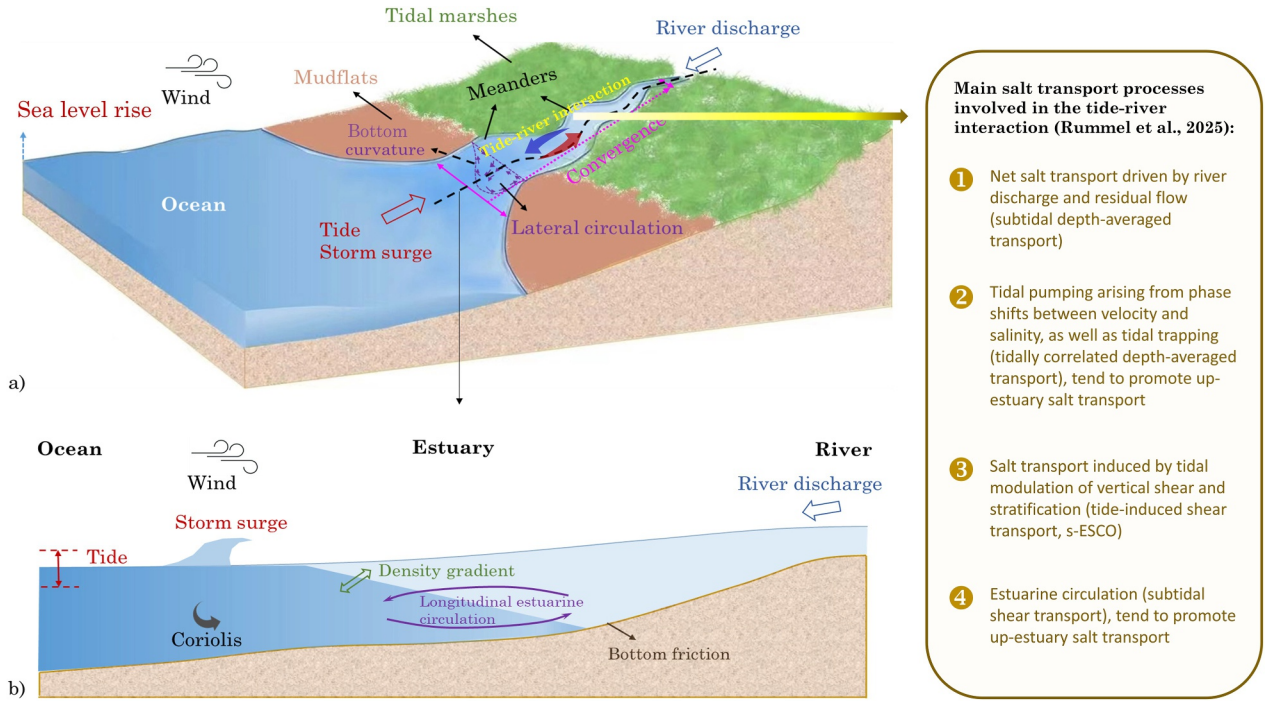


Figure 1. Conceptual diagram of key factors and physical processes that control salt intrusion in an estuary with (a) overview of an estuary and (b) longitudinal section of a channel.

Savenije, 1993; Tian, 2019). Studies show that salt intrusion responds faster to increasing discharge than decreasing discharge (e.g., Biemond et al., 2022; Chen et al., 2015; MacCready, 1999). The asymmetric response suggests opportunities for improved freshwater regulation through flow management (Huismans et al., 2024; Monismith, 2017). Nevertheless, further research on the response of salt intrusion to variations in river discharge with a wider range of estuarine settings and forcing time-scales is still needed. A higher tidal range leads to stronger tidal flow and enhanced turbulence, further altering salt intrusion length depending on the dominant salt transport mechanism (Fischer, 1979; Haddout et al., 2023). In well-mixed estuaries, where tidally driven dispersive processes dominate landward salt transport, analytical and vertically integrated models predict that salt intrusion length scales linearly with the effective longitudinal dispersion coefficient (Dijkstra & Schuttelaars, 2021; MacCready, 1999), while in partially mixed and salt wedge estuaries, intrusion length is more strongly controlled by vertical mixing and stratification, often parameterized through vertical eddy viscosity or diffusivity (e.g., Dijkstra & Schuttelaars, 2021; Monismith et al., 2002). The dependence of these parameters on tidal velocity is regime-dependent. In well-mixed systems, enhanced tidal velocities generally increase shear and effective dispersion. In strongly stratified systems, however, vertical mixing may be suppressed by stratification, and increases in tidal velocity do not necessarily lead to proportional increases in vertical mixing (e.g., Banas et al., 2004; Guha & Lawrence, 2013; Ralston et al., 2008). Consequently, the response of salt intrusion length to tidal forcing depends on the balance between stratification and mixing (Hendrickx, 2024), and may vary across the spring-neap cycle.

In addition to these two factors, sea-level variations and winds have also been found to influence the salt intrusion length (e.g., Chen et al., 2015; Cook et al., 2023; Lerczak and Geyer, 2004). These external forcing factors can hardly be changed artificially, except in intensely controlled systems in which the river discharge may be partially modified. To what extent the hydrodynamic forces can influence salt intrusion is largely constrained by the estuarine geomorphology. It is feasible to modify estuarine geomorphology, making the influence of geomorphological factors more relevant to the design of NBSs to mitigate salt intrusion. According to expressions for estuarine classification parameters, channel water depth, width and convergence play a role in determining the salinity distribution. Additionally, the channel bottom friction/bed forms, intertidal area, channel meandering and bottom curvature can also affect the salt transport processes (as illustrated in Figure 1). Impacts of these geomorphological factors on the salt intrusion length are further introduced in the remainder of this subsection.

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2.2.1. Channel Depth

The channel depth in many estuaries worldwide is becoming deeper to accommodate access of large vessels to port areas. Channel depth is one of the primary controls on estuarine salt intrusion because it directly influences the balance between stratification and tidal mixing. This balance can be interpreted through the Simpson number which is defined as follows

$$Si = \frac{g\beta h^2}{c_f u_t^2} \frac{\partial s}{\partial x} \tag{1}$$

where β is the haline contraction coefficient [$\beta = 7.6 \times 10^{-4}$ psu^{-1}]; h the channel depth; c_f the dimensionless bottom friction coefficient [−]; u_t the tidal flow velocity [m/s]; and s the salinity of which the longitudinal gradient is taken. Because the channel water depth enters quadratically, deeper channels promote stronger stratification and potentially enhanced exchange flow. Consequently, channel deepening often increases salt intrusion length by promoting exchange-dominated dynamics (Liu et al., 2019; Ralston and Geyer, 2019; Rummel et al., 2025; Siemes et al., 2026). However, the response to deepening is not uniform across estuaries. Channel deepening can modify both stratification and mixing processes. For instance, Grasso and Le Hir (2019) reported enhanced estuarine circulation associated with increased stratification, whereas Ralston and Geyer (2019) observed increased stratification in the Hudson River without a corresponding increase in exchange flow. These findings indicate that channel deepening can shift the relative importance of salt transport mechanisms (such as exchange flow and tidal pumping) depending on local bathymetry and dredging configuration (Rummel et al., 2025).

2.2.2. Channel Width and Convergence

In addition to depth, channel width also influences salt intrusion by modifying cross-sectional area and flow structure. Reducing channel width decreases the cross-sectional area, thereby increasing freshwater velocity for a given discharge. Additionally, smaller channel width results in reduced estuarine circulation and tidal straining (Burchard et al., 2011), where especially the depth-to-width ratio is relevant (Schulz et al., 2015). As a consequence, these mechanisms including the enhanced river advection, reduced estuarine circulation and tidal straining acting together tend to limit the salt intrusion length, although this reductive influence on the salt intrusion length is less obvious than that of the channel water depth (Hendrickx et al., 2023; Veerapaga et al., 2020). However, channel convergence, progressive narrowing toward the estuary head, modifies both tidal propagation and exchange flow (Familkhalili & Talke, 2016; Jay et al., 2011; Winterwerp, 2013). Geometric constriction can amplify tidal waves and intensify longitudinal salinity gradients, thereby strengthening density-driven exchange flow under classical assumptions of constant eddy viscosity (Ianniello, 1979). However, when tidal straining and temporally varying eddy viscosity are considered, Burchard et al. (2014) showed that convergence can reduce or even reverse tidal straining circulation because convergence modifies the temporal asymmetry of eddy viscosity between flood and ebb. In energetic tidal systems, this effect can weaken the total estuarine circulation. Moreover, Gay and Donnell (2009) found that the channel convergence can have a significant effect on buffering the salt intrusion. The spatial variation in cross-sectional area modifies the effective dispersion and exchange processes experienced by the intrusion and reduces its sensitivity to runoff fluctuations. Consequently, the response of salt intrusion length to convergence depends on the interplay between buoyancy forcing, river advection and tidal mixing. Additionally, bottom friction can also influence how the convergence impacts the salt intrusion (Hendrickx et al., 2023).

2.2.3. Bottom Friction/Bed Forms

In contrast to the channel convergence which causes the tidal amplification, the bottom friction enhances the tidal damping (Prandle and Rahman, 1980). The salt intrusion length is not monotonically influenced by the convergence or bottom friction. Instead, it depends on the competition between these two factors. The joint influence of channel convergence and friction on the tide is represented by a tidal damping coefficient δ (Van Rijn, 2011) defined as:

$$\delta = \frac{1}{2}\left(\frac{f}{c_t} - \gamma\right) \quad (2)$$

where f is a friction parameter [s^{-1}]; c_t the frictionless tidal wave celerity [m/s]; γ the convergence [m^{-1}]. The salt intrusion reaches the maximum when amplification and damping are balanced (so-called "ideal estuary") corresponding to $\delta = 0$ (Dronkers, 2017; Savenije, 2005). In addition to bed friction, numerous studies (Farmer & Smith, 1980; Geerts et al., 2025; Hendrickx, Manuel, et al., 2024; Hendrickx, Pearson, & Aarninkhof, 2024; Klymak and Gregg, 2003) have emphasized the influence of bed forms on mixing in salt-wedge estuaries. Flow over these topographic variations, such as sills and sand waves, perturbs the pycnocline and Eulerian residual circulation. These features can enhance salt intrusion when they strengthen stratification or promote landward near-bed transport, for example, by trapping dense water downstream of sills or intensifying local exchange flow (Hendrickx, Manuel, et al., 2024; Hendrickx, Pearson, & Aarninkhof, 2024). Conversely, strong topographic-induced mixing and internal hydraulic processes can weaken stratification, increase vertical mixing, and thereby reduce landward salt transport (Geerts et al., 2025). The net impact therefore depends on the geometry, location, and hydraulic regime of the bedforms (Farmer & Smith, 1980; Geerts et al., 2025; Hendrickx, Manuel, et al., 2024; Hendrickx, Pearson, & Aarninkhof, 2024).

2.2.4. Intertidal Flats

Intertidal flats along estuaries are located between the low and high water levels, periodically inundated and exposed due to tidal fluctuations (Reineck et al., 1980). They consist of tidal flats (or mudflats) and tidal marshes. The presence of extensive intertidal areas increases the tidal prism, enhancing oscillatory exchange between the main channel and adjacent shallow zones, which can strengthen tidal pumping by modifying phase relationships between velocity and salinity and further promote landward salt transport (e.g., Bootsma et al., 2026; Hendrickx and Pearson, 2024; Siemes et al., 2025; Yang and Wang, 2015). At the same time, shallow intertidal flats enhance bottom friction and vertical mixing during inundation, which can weaken stratification and reduce density-driven exchange flow (Hendrickx and Pearson, 2024; Siemes et al., 2025). The net outcome depends on the estuary class. For salt-wedge estuaries dominated by the estuarine circulation, the addition of intertidal area slightly reduces the salt intrusion by weakening stratification and exchange flow while for well-mixed estuaries dominated by the tidal mixing, larger intertidal area increases the salt intrusion length through strengthened tidal pumping (Hendrickx and Pearson, 2024).

2.2.5. Channel Meandering and Bottom Curvature

Channel meandering can induce the secondary circulation which reduces stratification by enhancing vertical mixing (Bo & Ralston, 2022). Numerical simulations show that meanders can transform up to 30% of the along-channel momentum into lateral circulation and induce a specific asymmetry of the secondary flows, reducing intrusion length (Pein et al., 2018). In contrast, model results in Hendrickx et al. (2023) show no distinct relation between meandering and salt intrusion length. The difference might be due to different locations and configurations of meanders introduced to the estuary, as well as how the salt intrusion length is defined in their studies. These findings are not conclusive, and thus require further research on the effect of meanders on estuarine salt intrusion.

Bottom curvature, which refers to lateral depth variation can change both lateral and along channel circulation through centrifugal acceleration and helical lateral flow (Burchard et al., 2011; Lerczak and Geyer, 2004). Bottom curvature leads to stronger flow velocities in the deep part of the channel resulting in stronger advection of high-salinity water than that on the flanks. This process induces a lateral density gradient and drives a lateral baroclinic circulation (Smith, 1976). Nunes and Simpson (1985) found that channel curvature reduces the stratification and limits the development of the longitudinal circulation. However, Hendrickx et al. (2023) indicated that the bottom curvature has a negligible effect on the salt intrusion length within their idealized parametric configurations. However, the authors noted that these results may depend on the chosen parameter ranges and geometric simplifications. In more complex or fully three-dimensional estuarine systems, lateral depth variations could influence exchange flow and lateral circulation, and thereby affect salt transport. Further research is needed to comprehensively assess the influence of bottom curvature on the estuarine salt intrusion length.

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Recent research (Hendrickx et al., 2023) shows that large salt intrusion events do not result from a single favorable factor, such as deep channels or low river discharge, but from the combined alignment of multiple unfavorable estuarine characteristics. Since these factors interact nonlinearly, the system exhibits a "capping" behavior which means that unless several conditions simultaneously promote intrusion, the intrusion length remains moderate. This insight implies that mitigation does not require altering all governing factors. Modifying one of the relevant factors can be sufficient to prevent maximum intrusion, which opens up avenues for more adaptive and sustainable management of salt intrusion mitigation in estuaries.

3. Nature-Based Solutions

Before a detailed discussion on the effectiveness of NBSs on salt intrusion mitigation, it is necessary to clarify what constitutes as NBS to mitigate salt intrusion. In line with of the definition of NBS given by IUCN, NBSs to mitigate salt intrusion can be defined as approaches that leverage natural dynamics to suppress estuarine salt intrusion while creating opportunities for the restoration and development of ecosystems. These interventions rely on natural materials without the use of concrete or other hard engineering materials. They can potentially not only mitigate salt intrusion but also restore natural functions, enhance ecological resilience, and reduce dependency on conventional gray infrastructure. In this section, the methods that are used to evaluate the effectiveness of interventions on salt intrusion mitigate is first introduced. Then, the NBSs are grouped based on their underlying mechanisms. Combined with the effects of different hydrodynamic and geomorphological factors on the salt intrusion summarized in Section 2, a list of NBSs to mitigate estuarine salt intrusion are deduced. Following that, examples of NBSs for salt intrusion mitigation are presented and the potential effectiveness of different NBSs is summarized.

3.1. Methods to Assess the Effectiveness of NBSs

The effectiveness of NBSs in mitigating salt intrusion is commonly evaluated by comparing the salt intrusion length with a certain type of NBSs implemented to that of a baseline condition without NBSs implemented (e.g., Geerts et al., 2025; Yang and Wang, 2015). Many approaches, such as analytical models, empirical formulas, field observations, artificial intelligence, physical models and numerical models, have been used to quantitatively predict the salt intrusion length. There are at least three general approaches, to predict the response of salt intrusion length to implemented NBSs: (semi-)empirical formulas, analytical approaches and advanced numerical models.

Several empirical formulas are available to predict the salt intrusion length. These empirical formulas are derived based on combinations of physical model tests, field observations, analytical solutions and/or numerical models (Haddout, 2020; Haddout et al., 2023; Prandle, 2004; Rigter, 1973; Savenije, 1993; Van Os and Abraham, 1990). They have simple forms and are easy to apply. However, these empirical formulas have been developed for specific estuaries or estuaries with simple shapes (prismatic and converging shapes). It might be possible to assess the response of salt intrusion length to NBSs related to river discharge and channel convergence in a simple way using some of the empirical relationships (e.g., Savenije, 1993; Savenije, 2005). It is hardly possible to consider other types of NBSs, such as maintaining or creating tidal flats, changing channel bottom topography, as they are commonly not parameterized in the empirical formulas. Their limited physical generality restricts applicability to evaluating the effectiveness of NBSs in limiting salt intrusion in estuaries.

To make predictions of the effect of interventions, process-based models are employed. Ideally, before implementation of a nature-based solution a case-specific modeling study is carried out. Models can be subdivided into analytical and numerical models, each having their advantages and perks.

Analytical approaches are based on simplified tidally averaged and cross-sectionally averaged equations for conservation of mass for water and salt by introducing some assumptions and empirical parameterizations (e.g., Hansen & Rattray, 1965; Jay and Smith, 1990a, 1990b; McCarthy, 1993; Savenije, 1993, 2005; Van den Burgh, 1972). These approaches allow swift predictions on how salt intrusion reacts to variations in driving forces and geometries (Jay and Smith, 1990a; Savenije, 1993). However, similar to empirical approaches, analytical results are derived for simple prismatic or converging estuaries. They do not consider complex estuarine shapes and bathymetries. Appropriate parameterizations of NBSs would be necessary to enable analytical approaches to take into account effects of a wider range of NBSs on salt intrusion in estuaries, and needs further research.

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Advanced numerical models can consider various driving forces, channel geometries, bottom topography and their interactions. This comes, however, at the expense of requiring large computational power. Estuarine-wide numerical models normally solve Reynolds-averaged Navier-Stokes equations plus a transport equation for salt with suitable boundary conditions. Laterally or width-averaged two-dimensional models (2DV), such as LAEM (Laterally Averaged Estuarine Model; McAnally and Pritchard, 1997) and 2DV Delft3D model schematization set up by Geerts et al. (2025), have been used to investigate the influence of channel bottom topography on salt intrusion. In order to evaluate the effects of tidal flat and channel geometry (e.g., convergence and meanders), three-dimensional numerical models are commonly applied. These include both unstructured-grid models such as Finite Volume Community Ocean Model (FVCOM; Chen et al., 2003), Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM; Zhang et al., 2015) and Delft3D Flexible Mesh (e.g., Martyr-Koller et al., 2017), and structured-grid models which have also been widely used to investigate salt intrusion dynamics (Garcia et al., 2025; Rummel et al., 2025). When tidal flats are present, it is important to include wetting-and-drying processes in the hydrodynamic simulations (Yang & Wang, 2015). Most of the numerical models are based on the hydrostatic assumption in the vertical direction which makes these numerical models more computationally efficient compared to taking non-hydrostatic effects into account.

The above mono-disciplinary assessment approaches only consider the physical aspect, that is, the effectiveness of interventions on reducing the salt intrusion length. However, estuaries provide various natural and ecosystem services (Barbier et al., 2011; Pinto et al., 2010), and NBSs are intended to be multidisciplinary, involving not only physical aspect but also non-physical components (e.g., socio-economics and ecology).

There is recent work on how salt intrusion mitigation measures can be included in a multidisciplinary assessment. For instance, Bakker et al. (2025) proposed a multidisciplinary method to assess trade-offs of opposing socio-economic stakeholder objectives: improvement of port navigability by channel deepening and freshwater availability. Performance indicators reflecting port functioning and freshwater availability are defined, based on which the trade-off is assessed using multi-objective optimization. Similarly, Hendrickx (2024) provided a method to compare socio-ecological objectives in an estuarine system in which ecology is accounted for.

Considering these non-physical aspects are highly location-dependent and the objective of this review is to explore the effectiveness of NBSs in salt intrusion mitigation, we focus here mainly on the physical aspect, which is the least location dependent. However, decisions and policies should be made based on a multi-disciplinary assessment which takes salt intrusion mitigation, socio-economics and ecology into account.

3.2. Classification of NBSs Based on Mechanism

Based on the impacts of forcing and geomorphological factors on estuarine salt intrusion, NBSs can be designed to mitigate salt intrusion by improving management of river discharge, reducing channel cross-section, modifying bottom topography, using the friction-convergence balance (i.e., modifying the tidal propagation), enlarging of intertidal area and introducing meanders (Figure 2). According to how these interventions influence the salt intrusion, these potential NBSs can be grouped into two types: (a) advection-based, and (b) mixing-based (Hendrickx, Manuel, et al., 2024; Hendrickx, Pearson, & Aarninkhof, 2024). The advection-based mitigation focuses on limiting salt intrusion by means of advective processes that drive the whole saline structure seaward. The mixing-based mitigation reduces the salt intrusion by enhancing mixing and breaking down the stratification, which leads to a reduction of the estuarine circulation flow. These two groups are not necessarily exclusive and some NBSs can contain components of both.

Figure 3 shows the qualitative distribution of potential NBSs within a conceptual two-dimensional process space defined by advection-based and mixing-based mitigation mechanisms. The horizontal axis represents the relative degree to which an NBS enhances seaward salt export or suppresses landward salt transport through advective processes, while the vertical axis represents the relative degree to which an NBS modifies the stratification–mixing balance and density-driven exchange flow. The figure is intended as a qualitative conceptual framework rather than a quantitative parameterization, and several NBSs influence both mechanisms simultaneously. Advection-based mitigation measures are generally considered effective across a wide range of estuarine conditions, whereas mixing-based measures are expected to be effective primarily when some level of stratification is present. In well-mixed systems, enhanced mixing may instead increase horizontal dispersion and thereby increase salt intrusion (Hendrickx & Pearson, 2024). Examples of NBSs for salt intrusion mitigation are elaborated in the following section.

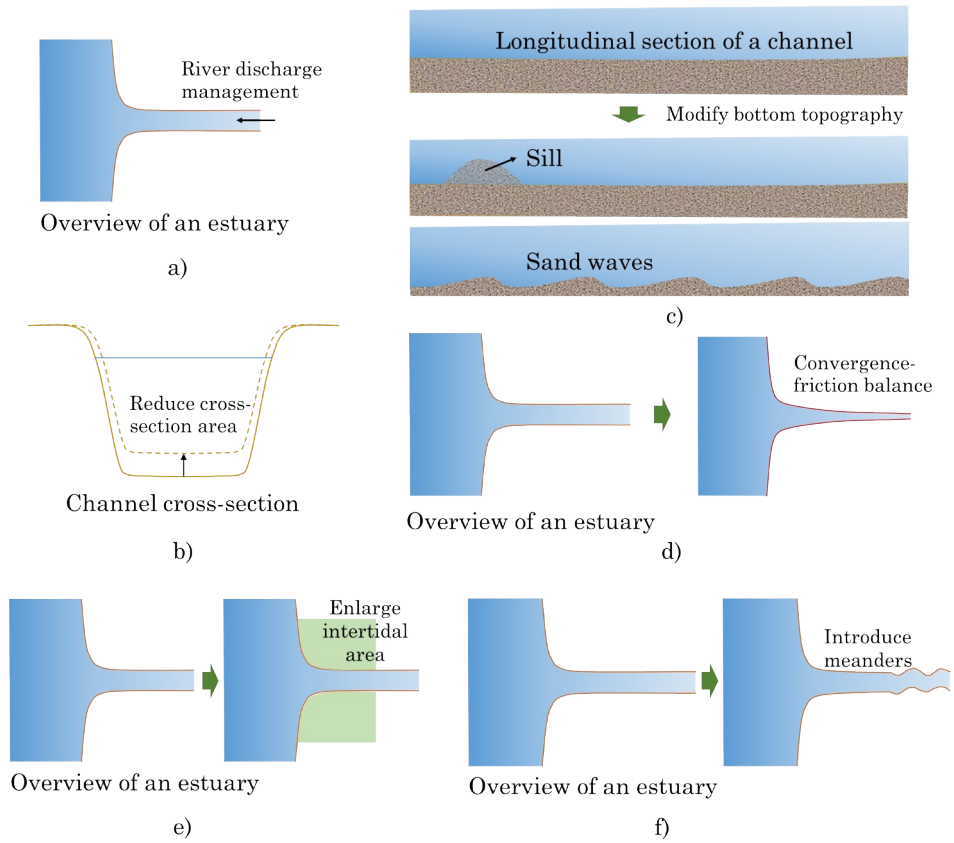


Figure 2. Schematic diagram of NBSs for salt intrusion mitigation by (a) river discharge management, (b) reduction of channel cross-section, (c) modification of bed topography, (d) convergence-friction balance, (e) enlargement of intertidal areas, (f) introduction of meanders.

3.3. Examples of NBSs to Mitigate Salt Intrusion

In this section, examples of NBSs to mitigate salt intrusion are introduced in the order of their potential effectiveness in limiting the estuarine salt intrusion length.

3.3.1. Efficient Management of River Discharge

River discharge is a crucial parameter controlling salt intrusion length. Conventional mitigation through increasing freshwater discharge often relies on engineered flow regulation and reservoir operations and is therefore outside the primary scope of this review on nature-based solutions. Within the context of process-based and nature-based approaches, strategies related to river discharge include rerouting freshwater through delta networks and exploiting the asymmetric response of salt intrusion to temporal discharge variations.

Network approaches are widely applied in water management and regional control of drought and flood (Cui et al., 2009; Poulter et al., 2008; Tilley and Brown, 1998). For example, sluices were built near the confluence between tributaries and the main channel in the multi-channel Pearl River in China, in order to mitigate salt intrusion by managing the release of freshwater discharge (Chen, 2006). Although this measure is effective in controlling salt intrusion, it is costly due to large consumption of freshwater. In response, Zhang et al. (2012) designed a wetland network to mitigate salt intrusion in the Pearl River by integrating the wetlands for freshwater storage with existing sluices responsible for freshwater control. The freshwater could be stored in wetlands during wet seasons, and be allocated to river channels when salt intrusion occurs according to a predictive model. The new wetland network results in a reduction in freshwater requirements by approximately half (46.1%–61.8%), while being cost-effective and providing social and ecological benefits.

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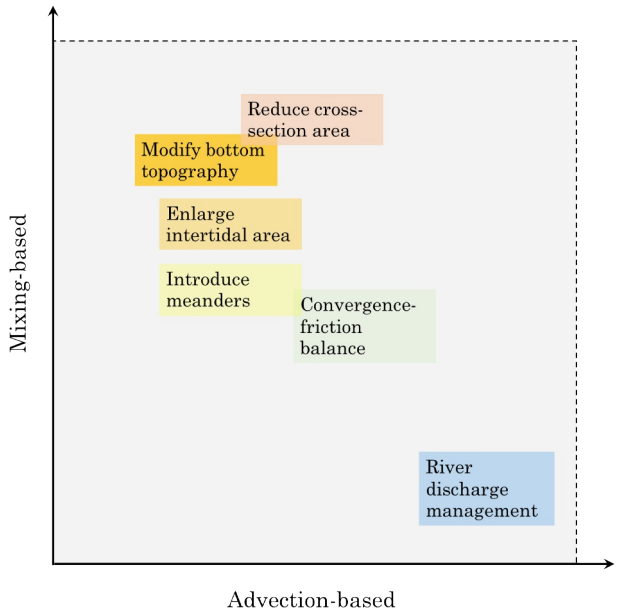


Figure 3. NBSs for salt intrusion mitigation in the 2D solution space.

The salt intrusion length responds quicker to an increase in river discharge than a decrease (Biemond et al., 2022; Hendrickx, 2024; Huismans et al., 2024; Monismith, 2017). This asymmetric response also provides a useful mechanism to exploit during a drought when river discharge is scarce to reduce estuarine salt intrusion length. One way to make use of the asymmetric response could be to implement controlled amounts of release of freshwater from upstream reservoirs at strategic times, managing river flow efficiently to reduce salt intrusion during a drought. Biemond et al. (2022) found that the change in salt intrusion length caused by a freshwater pulse is proportional to the ratio between peak and background river discharge, and is linearly related to the duration of the pulse when the duration is too small to reach equilibrium. However, the effectiveness of discharge management in salt intrusion mitigation using the asymmetric response still requires more detailed research to quantify.

3.3.2. Reduction of Channel Cross-Section

Reducing the cross-sectional area through which the river discharge flows, enhances the relative river flow velocity. As a result, the freshwater Froude number is increased, which has a limiting effect on the estuarine salt intrusion length. The reduction of the channel water depth can effectively reduce the salt intrusion length (Chant et al., 2018; Hendrickx et al., 2023; Yuan and Zhu, 2015).

Ralston and Geyer (2019) found that channel deepening in the lower Hudson River estuary increased the salt intrusion by 30%. Reducing the water depth from 15 to 12 m can lead to a decrease in salt intrusion length by over 50% in a highly engineered estuary: the Rotterdam Waterway, The Netherlands (Siemes et al., 2025). However, reducing the channel depth in many estuaries might be difficult as the water depth requires to be maintained at a deep level to ensure the port navigability. In this case, a method to assess the trade-off between freshwater availability and channel navigability as exemplified by Bakker et al. (2025) provides a possibility to optimize the water depth by balancing the competing needs of salt intrusion mitigation and efficient port operations. Alternatively, reducing the width instead of the depth could be a more feasible solution to mitigate salt intrusion, although manipulating the width is less effective than changing the depth (Hendrickx et al., 2023). A narrower channel can increase overbank flooding frequency and duration during high tides, which supports floodplain and wetland inundation, beneficial for maintaining marsh health and biodiversity (Tockner et al., 2008).

3.3.3. Modification of Bottom Topography

Modification of bottom topography fits in the group of mixing-based mitigation measures, and it is expected to be effective in highly-stratified or salt-wedge estuaries. There are two main ways to modify the bottom topography: (a) placing a sill; and (b) creating sand dunes.

The US Army Corps of Engineers built an underwater sill in the Lower Mississippi River, USA to limit the significant salt intrusion during an extreme period of drought. The construction of the salinity control sill has been proved to be very effective in mitigating salt intrusion (McAnally and Pritchard, 1997). The salt wedge toe retreated from 167 km in July 1988 seaward to 110 km in September 1988 with the sill constructed in August 1988. A mouth bar at the entrance of an estuary may function as a sill, thereby affecting the exchange flow between the estuary and ocean. Gong et al. (2022) utilized the widely used community modeling system (COAWST) to investigate the effects of a natural mouth bar in the Modaomen estuary (partially-mixed), China, on salt intrusion. Model results indicate that the mouth bar suppresses the salt intrusion length by 15%–23% under typical conditions of river discharge (1,500–5,500 m^3/s). The reduction percentage can reach 40% when the river discharge is high. Hendrickx, Manuel, et al. (2024) and Hendrickx, Pearson, and Aarninkhof (2024) explored the applicability of a sill in idealized systems and identified key features for an effective implementation using a Delft3D model. They found that building a sill within the salt wedge reduces the salt intrusion length while a sill beyond the original salt intrusion length aggravates the salt intrusion. The mitigating efficiency reduces with increasing tidal range. A sill has great potential to limit salt intrusion in salt wedge estuaries if there is sufficient

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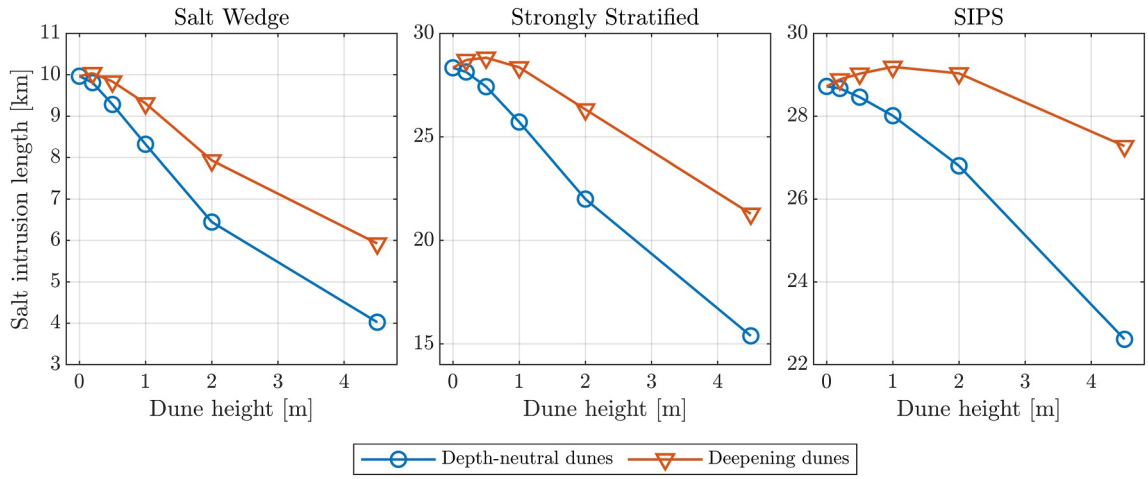


Figure 4. Influence of dune height of both depth-neutral dunes and deepening dunes on the subtidal salt intrusion length for three different estuaries with decreasing stratification (from left to right): salt wedge, strongly stratified and strain-induced periodic stratification (adapted from Geerts et al., 2025).

water depth available. The design should focus on the longitudinal placement and the height of the sill. In addition to mitigating salt intrusion, the troughs of sand waves can provide grounds more suitable for benthic organisms (Damveld et al., 2020).

Sand dunes can mitigate estuarine salt intrusion by increasing bed roughness, generating internal waves that enhance vertical mixing, and inducing recirculation cells over bedforms. Using an idealized 2DV hydrostatic model based on the Rotterdam Waterway, Geerts et al. (2025) showed that dunes can reduce salt intrusion length by several kilometres (Figure 4). The reduction is most sensitive to dune height, with steeper dunes producing stronger mixing and less intrusion. This effect is stronger when the initial stratification of the flat-bed system is larger. Notably, "deepening" dunes can offset the effects of channel deepening, suggesting that estuarine sand dunes may serve as effective nature-based solutions for mitigating salt intrusion.

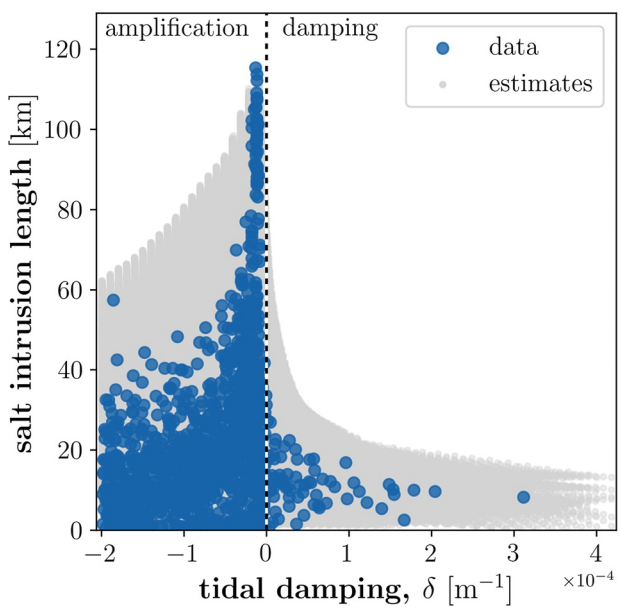


Figure 5. Variation of salt intrusion length with the tidal damping coefficient (adapted from Hendrickx et al., 2023).

3.3.4. Convergence-Friction Balance

Applying the channel convergence as a nature-based solution requires careful consideration of its interaction with bottom friction. Hendrickx et al. (2023) has shown that the salt intrusion length depends on the competition between the convergence and bottom friction which can be represented by a tidal damping coefficient δ (Equation 2) as mentioned in Section 2.2.2 (see Figure 5). For $\delta < 0$ corresponding to tidal amplification, increasing the channel convergence tends to suppress the salt intrusion length while increasing bottom friction can even lead to enhanced salt intrusion length. Semi-analytical three-dimensional model results in Wei et al. (2017) showed that applying exponential convergence to a channel reduces the salt intrusion length by 12.5%. Delft3D results presented in Zhong et al. (2024) also confirmed that salt transport is weakened by greater convergence. For $\delta > 0$ corresponding to tidal damping, increased value of δ by increasing bottom friction or reducing channel convergence leads to less salt intrusion. The effective bottom friction can be further enhanced by (a) artificially increasing the bottom friction using large boulders or rocks on the bed, or vegetated banks, and (b) creating bed forms, such as sand waves described in Section 3.3.3. Changing channel convergence or bottom friction to mitigate salt intrusion should carefully take their interactions into account. The ecological value that the convergence-friction balance can add depends on how it is implemented. When achieved through channel convergence or controlled channel morphology that mimics natural estuarine forms, convergence-

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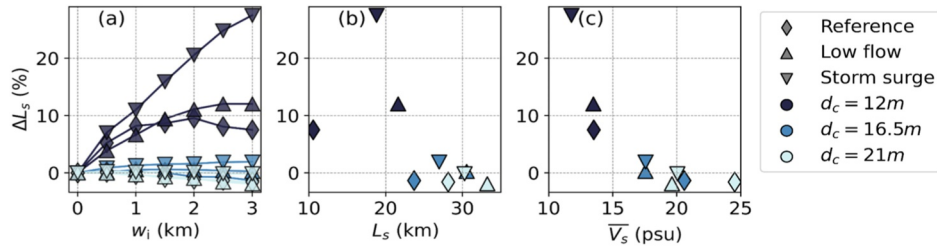


Figure 6. Influence of intertidal wetland width on tide-averaged slat intrusion length L_s with relative change in salt intrusion length ΔL_s due to (a) an increase in wetland width w_i (positive ΔL_s represents that salt intrusion length increases), and (b) ΔL_s caused by the maximum increase of w_i ($w_{i-max} = 3$ km) compared to the salt intrusion length, and (c) compared to the mean stratification (adapted from Siemes et al., 2025). d_c denotes the channel depth.

friction balance can play an important role in stabilizing salinity gradients essential for estuarine habitat zonation. If the balance is achieved through enhanced friction, the friction elements can contribute to flow resistance, promoting settling of suspended particles and improving water clarity and quality (Vandenbruwaene et al., 2012).

3.3.5. Enlargement of Intertidal Area

The enlargement of intertidal area changes the salt intrusion length by influencing the balance between stratification and mixing. The effectiveness in mitigating salt intrusion largely depends on the type of estuaries.

Yang and Wang (2015) present a modeling study to investigate the responses of estuarine hydrodynamics to the loss of intertidal flats in Whidbey Basin of Puget Sound on the northwest coast of North America. Model results showed that loss of intertidal flats results in an increase in salt intrusion and a phase shift in salinity and velocity fields in the bay front areas. Salt intrusion extended upstream - 5 km during the low-flow condition and 4 km on an annual average basis. This study demonstrated the importance of preservation of intertidal flats and its effectiveness in suppressing the salt intrusion in a strongly-stratified estuary.

Siemes et al. (2025) investigated the response of salt intrusion length to the increasing intertidal wetland width in the Rotterdam Waterway, the Netherlands, using a process-based Delft3D model (see Figure 6). Increasing intertidal wetland area was found to always reduce stratification. This is because the wetland restoration increases the tidal prism, further resulting in an increase in tidal flow and therefore a decrease in stratification. In cases with shallow channel depths, when stratification is relatively low, the salt intrusion length increases with increasing wetland area. In cases with large channel depths, when stratification is relatively high, the salt intrusion is slightly reduced (up to 3%) by addition of wetland area. Results highlight that increasing wetland width reduces salt intrusion length in strongly stratified estuaries where estuarine circulation is the dominant process for salt import, while it increases salt intrusion in more mixed estuaries, consistent with the findings of Hendrickx and Pearson (2024). As the Simpson number (Equation 1) describes the stratification-mixing balance, this number can be used to preliminarily estimate whether intertidal areas enhance or suppress the estuarine salt intrusion (Hendrickx and Pearson, 2024).

3.3.6. Introduction of Channel Meanders

Research about the effectiveness of introduction of channel meanders in salt intrusion mitigation is relatively limited. Pein et al. (2018) compared two idealized estuaries, one straight and one meandering near the estuary head, based on the Ems Estuary in Germany. Their model results show that meanders enhance vertical mixing during flood tidal phases and lateral circulation during ebb phases, shifting the salinity front seaward by about 3 km, roughly 20% of the tidal excursion. Pein et al. (2021) further examined meanders located in the freshwater reach, contrasting with the brackish-zone configuration of the earlier study. In this case, meanders locally weakened stratification and generated vertical density gradients downstream via ebb-current asymmetry but had negligible influence on the overall salt intrusion length. These findings suggest that meanders primarily affect salt transport locally, with their mitigating effect on salt intrusion being significant when located within the saline reach (Bo & Ralston, 2022; Pein et al., 2018). Moreover, the presence of meanders was found to decrease turbidity and increase oxygen concentration, indicating potential ecological benefits. Bo and Ralston (2022) did find a small effect of meanders on the salt intrusion, but only for sharp bends. The bend sharpness B is defined as the

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radius of curvature R over the width W: $B = R/W$ with $B \sim 1$ for sharp bends and $B \sim 2 - 4$ for smooth bends. However, Hendrickx et al. (2023) did not find any clear influence of meanders on the salt intrusion. This might be because most meanders in Hendrickx et al. (2023) are smooth bends—according to the same metric of smoothness by Bo and Ralston (2022). The inconsistency in these studies indicate the need of further investigation into the effect of meanders on estuarine salt intrusion.

3.4. Reflection on NBSs to Mitigate Salt Intrusion

In this section, NBSs for salt intrusion mitigation, which are grouped into stratification-based and mixing-based measures, are introduced. These NBSs show various (potential) levels of effectiveness in reducing the salt intrusion length, of which an overview is presented in Table 2.

It is worth mentioning that in addition to salt intrusion mitigation, these NBSs also provide other benefits. For instance, restoring or expanding intertidal areas can provide ecological and economic benefits. A previous study (Attrill, 2002) indicated that a reduction in salinity variation can increase species diversity. Model results in Siemes et al. (2025) showed that adding wetlands reduces the tidally averaged stratification which is beneficial for some ecological functions in the channel. Moreover, the natural vegetation and complex root systems in intertidal areas enhance shoreline stability by stabilizing sediments and attenuate wave energy, reducing coastal flooding risk (e.g., Gedan et al., 2011; Stark et al., 2016; Temmerman et al., 2012). Changing bed forms strategically offers a sustainable and resilient approach to mitigate salt intrusion. This method makes use of natural dynamics, creating room for natural development, while minimizing the detrimental impact that implementation of hard structures can have on ecosystems. By using natural dynamics, NBSs can be more cost-effective than traditional hard structures (Borsje et al., 2011). For example, cost-benefit analysis of constructed coastal wetland case studies demonstrated that ecosystem service benefits outweighed capital and maintenance costs, with added value in flood control, water quality, and land appreciation (García-Herrero et al., 2022; Lin et al., 2023). Additionally, it was mentioned in McAnally and Pritchard (1997) that the cost of the salinity control sill in the Mississippi River estuary built by the US Army Corps of Engineers was $790,000. The cost of barging dilution water from upriver for those downstream communities was over $50,000,000 without the sill in place. Building the sill could save at least half of the water supply for those communities (McAnally and Pritchard, 1997).

Even though NBSs have strong potential to deliver multiple benefits, they also have some limitations. NBSs alone may not limit salt intrusion sufficiently and therefore in many cases it will be necessary to combine NBSs with traditional hard structures (McAnally and Pritchard, 1997). Combining NBSs with gray solutions, so-called hybrid solutions, requires a good understanding of interactions among these different types of measures to adapt and improve their effectiveness in mitigating salt intrusion in estuaries. The effectiveness of NBSs varies based on the specific characteristics of each estuary. Different from traditional gray solutions, NBSs working well in one location may not be as effective in another. For example, building an underwater sill in the Mississippi River estuary was effective in suppressing salt intrusion while having limited influence on salt intrusion in the Rotterdam Waterway (Hunter, 2023; McAnally and Pritchard, 1997). This emphasizes a necessity to develop a complete model that includes the feedback among sand wave evolution, hydrodynamics and salt intrusion. Ensuring the shape characteristics of dredged sand waves match with local hydrodynamics helps with the sustainability of the NBS. In tropical deltas such as the Mekong and Ganges, monsoonal discharge regimes, sediment scarcity, and population pressures create challenges distinct from those in temperate estuaries (Bricheno et al., 2021; Eslami et al., 2019, 2021; Thi Ha et al., 2018). Social acceptance, land use intensity, and institutional capacity also shape the feasibility of NBS implementation. Therefore, we emphasize that NBSs need to be tailored to the local hydrological, ecological, geomorphic and social conditions. Additionally, uncertainties of climate change, geomorphic and hydro-ecologic interactions over various temporal and spatial scales lead to many uncertainties in the effectiveness of NBSs. The potential of these NBSs for salt intrusion mitigation needs to be rigorously assessed, and their implementation should be based on approaches that can adapt to the development of the effectiveness over time, for example, dynamic adaptive policy pathways approach by Haasnoot et al. (2013).

The NBSs identified in this review each have distinct implications for governance, stakeholder interests, and ecosystem service delivery. These interventions often require coordination among water authorities, environmental agencies, agricultural stakeholders, and local communities. For instance, managing river discharge to mitigate salt intrusion may involve trade-offs between upstream hydropower operations and downstream agricultural water needs (Paiva et al., 2024), while changing channel morphology or introducing meanders may affect

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Table 2
Overview of Model Studies on Potential NBSs and Related Processes

Nature-based solutions	Study area	Type of estuary	Research method	Effectiveness	Reference
Build wetland network (River discharge management)	Modaomen estuary in the Pearl River Delta	Partially-mixedpartially-mixed	Network method	Effective in mitigating salt intrusion and save over 50% freshwater	Zhang et al. (2012)
Reduce channel water depth (Reduction of channel cross-section)	Rotterdam Waterway	Partially-stratified	Delft3D model	Reducing the water depth from 15 to 12 m can lead to a decrease in salt intrusion length by over 50%.	Siemes et al. (2025)
Create underwater sill (Modification of bottom topography)	Mississippi River estuary	Salt wedge	Lateral Averaged Estuarine Model (LAEM)	Very effective in mitigating the salt intrusion with cost savings of over $50,000,000	McAnally and Pritchard (1997)
Maintain mouth bar (Modification of bottom topography)	Modaomen estuary in the Pearl River Delta	Partially-mixed	Numerical model (COAWST-Coupled Ocean-Atmospheric Wave Sediment Transport)	The salt intrusion length is decreased by 15~23%	Gong et al. (2022)
Create/maintain estuarine sand dunes (Modification of bottom topography)	Rotterdam Waterway	Partially-stratified	Idealized 2DV numerical model	Salt intrusion length can be reduced by several kilometers	Geerts et al. (2025)
Apply channel convergence (Convergence-friction balance)	Delaware estuary	Well-mixed	Semi-analytical three-dimensional model	Applying exponential convergence to a channel reduces the salt intrusion length by 12.5%.	Wei et al. (2017)
Restore intertidal flats (Enlargement of intertidal area)	Puget Sound	Strongly-stratified	High-resolution unstructured-grid coastal ocean model (FVCOM)	Loss of intertidal flats results in an increase in salinity intrusion up to 5 km during the low-flow condition	Yang and Wang (2015)
Addition of intertidal wetland area (Enlargement of intertidal area)	Rotterdam Waterway	Partially-stratified	Delft3D model	Reducing intrusion lengths slightly by 3% for strongly stratified or salt wedge estuaries increasing intrusion lengths for well-mixed estuaries	Siemes et al. (2025)
Create channel meanders	Ems estuary	Partially-stratified	3D Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM)	Overall reduction of salt intrusion length by 20%	Pein et al. (2018)
	Elbe Estuary	Slightly-stratified	A coupled hydrodynamic and water quality model (SCHISM + ECOSMO)	Little influence on salt intrusion, which might be due to the location of meanders	Pein et al. (2021)
	North River estuary	Periodically stratified	Regional Ocean Modeling System (ROMS)	Little influence on salt intrusion for smooth bends and very small reductive influence for sharp bends	Bo and Ralston (2022)

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land tenure or navigation interests. Similarly, restoring intertidal areas or modifying bed topography can enhance carbon sequestration, habitat provision, and flood mitigation (Stark et al., 2016; Temmerman et al., 2012), but may temporarily disrupt aquaculture or farmland use. Integrating these NBSs into planning processes therefore demands a systems-based approach that considers the trade-offs and synergies between hydrodynamic benefits and ecosystem services through actively incorporating stakeholder engagement. As emphasized by Calliari et al. (2019) and Raymond et al. (2017), successful NBS implementation relies not only on scientific soundness, but also on institutional alignment, long-term co-benefits, and the ability to navigate socio-ecological trade-offs through participatory and adaptive governance.

4. Synthesis

4.1. Novelty of Mitigating Salt Intrusion Using NBSs

Research on NBSs for mitigating salt intrusion is still in its early stages. Further research is essential to explore the integration of NBSs with salt intrusion mitigation strategies. NBSs for salt intrusion mitigation do not depend on vegetation or animal species, which traditionally form the basis for defining NBSs in other areas, such as flood risk reduction through coastal vegetation or reef systems. As such, the connection between salt intrusion mitigation and NBSs may not be very straightforward and apparent, and it is necessary to establish a clear understanding of how these solutions can be effectively employed to address this critical environmental issue.

This study first summarizes the estuarine classification schemes based on stratification and mixing balance, and their corresponding classification parameters. This helps identification of predominant physical processes that control salt intrusion in a certain system. The effects of forcing factors (river discharge, tides, sea level rise and winds) and geomorphological factors (channel depth, channel width, channel convergence, bottom friction/bed forms, intertidal areas, channel meandering and bottom curvature) on the estuarine salt intrusion are reviewed and clarified. Based on that, several potential NBSs for salt intrusion mitigation can be conceptualized, including improvement of river discharge management, reduction of channel cross-section, modification of bottom topography, friction-convergence balance, enlargement of intertidal area and introduction of meanders. These NBSs are grouped into two types: (a) advection-based, and (b) mixing-based (see Figure 3). Advection-based mitigation measures are considered generally effective in most estuarine environments, whereas mixing-based measures are expected to be effective in estuaries exhibiting some degree of stratification.

4.2. Knowledge Gaps With Respect to the Addressed NBSs

The conceptualized NBSs show their potential in reducing the estuarine salt intrusion. Nevertheless, there are knowledge gaps that are identified regarding the effectiveness of NBSs in salt intrusion mitigation. The four most important ones are:

1. The effectiveness of using the asymmetric response to temporal changes in river discharge in reducing salt intrusion still remains unclear with different studies and approaches showing different results (Hendrickx, 2024; Monismith, 2017). Studies have confirmed that the salt intrusion responds differently to an increase and a decrease in river discharge (e.g., Chen, 2015; Gong & Shen, 2011). However, further research is needed to figure out how to utilize this asymmetric response to reduce salt intrusion. This requires the exploration of different signals of river discharge with a wider range of estuarine settings and forcing timescales by performing physical experiments and/or numerical simulations.
2. The accurate estimate of the effectiveness of bedform modification as an NBS would require knowledge of its natural morphodynamic behavior. Research has demonstrated that sand waves can limit salt intrusion. However, on the other hand, the estuarine circulation can also influence the evolution of sand waves, as for instance investigated by Van der Sande et al. (2021). Incorporating feedback mechanisms between sand waves and salinity distribution within models helps toward a resilient design of estuarine sand waves as NBSs. Coupling the idealized model developed by Van der Sande et al. (2021) and the 2DV model set up by Geerts et al. (2025) could be a starting point. Accurately predicting the evolution of sand waves for a certain estuary is important for ensuring the shape characteristics align with nature's equilibrium, minimizing the need for periodic dredging activities to maintain the sand waves.
3. The effectiveness of channel meanders in reducing salt intrusion remains unconclusive. The inconsistent findings of these studies might be related to the bend sharpness, location of meanders and/or different

definitions of the salt intrusion length. In either case, the inconsistency opens the door for further research on the effect of meanders on estuarine salt intrusion.

4. Estuarine salt intrusion is a complex and uncertain phenomenon governed by dynamic interactions among tidal forces, river discharge, and estuarine geomorphology. Given the complexity and uncertainty of future conditions, mitigation strategies should not rely on a single optimal NBS. Instead, a resilient approach requires the integration of diverse, adaptive, and robust strategies (Hendrickx, 2024, Ch. 8). While no single intervention can fully eliminate salt intrusion, a combined and system-aware strategy can significantly enhance resilience, reduce risks, and maintain estuarine function under long-term uncertainty. Very limited studies that explicitly evaluate these combined effects of NBSs, particularly in the context of salt intrusion dynamics.

4.3. Recommendations for Future Research

In this study, we have explored the (potential) effectiveness of NBSs in reducing estuarine salt intrusion. While operational salt intrusion management through engineered flow regulation and reservoir releases is implemented in several estuaries (e.g., the Delaware River estuary), the literature on process-based and geomorphology-based NBSs remains relatively limited, with little practical knowledge available regarding their implementation. It is worth noting from Table 2 that only one real case which built an underwater sill in the Lower Mississippi River (McAnally & Pritchard, 1997) is available to demonstrate the effectiveness of NBSs in salt intrusion mitigation. Other studies are mostly based on numerical simulations. The NBSs that are identified in this review paper are conceptual measures with ecological potential. This underscores that the research on NBSs for salt intrusion mitigation is still in its infancy, and substantial further efforts are required to advance the understanding and practical implementation of these solutions. Recommendations for future research to facilitate implementation of NBSs for salt intrusion mitigation are provided as follows.

1. The capabilities of numerical models for salt intrusion simulations require development and improvement. Hydrostatic estuarine models generally rely on semi-empirical turbulence closure schemes to represent turbulent mixing. While these models capture the bulk effects of turbulence, they may not fully resolve small-scale processes associated with complex bathymetry and bed forms, such as internal wave breaking. High-resolution, depth-resolved models (such as OpenFOAM) can help improve the understanding and parameterization of these processes, particularly near sand waves. Improved parameterizations may enhance engineering-scale modeling of NBS effectiveness for salt intrusion mitigation. Besides that, many studies utilize 2DV models in which lateral processes are not considered but they can be highly relevant for salt intrusion.
2. Another understudied perspective is the long-term resilience and performance of the presented NBSs subject to various manifestations of climate change (sea-level rise, see e.g., Khojasteh et al., 2021; changes in discharge variability). Understanding the long-term resilience requires insights in the morphodynamic response of each NBS, as well as the morpohydnamic response of the environment affected by the NBS, also to locally changing forcing conditions as a consequence of a globally changing climate (see e.g. Siemes et al., 2024). As for long-term performance, the framework presented in this review can be extended with studies to solutions under changing conditions.
3. It is recommended to develop a multidisciplinary assessment framework that accounts for the physics, ecology and socio-economy of NBSs for salt intrusion mitigation. This framework should not only account for the hydrodynamic and geomorphological processes underlying salt intrusion but also consider the ecological responses of estuarine habitats and species to changes in salinity, as well as the socio-economic impacts, such as fresh water availability, navigability and flood safety. The assessment methods proposed by Bakker et al. (2025) and Hendrickx et al. (2026) provide insights that can help the development of such a framework. By incorporating diverse perspectives, the framework will enable a more holistic evaluation of NBSs, ensuring that both environmental and societal goals are met while maximizing the effectiveness of salt intrusion mitigation strategies.
4. It is essential to implement NBSs in real-world settings, while concurrently establishing monitoring systems to collect data on their performance. This will provide valuable insights into their effectiveness under real environmental conditions. By analyzing the monitoring data, we can derive critical lessons that inform the optimization and refinement of NBSs, ensuring they are suited to addressing salt intrusion and other coastal challenges in the future.

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5. Salt intrusion and its potential implications, such as freshwater shortages, deserve the same level of attention as flood risk in decision-making and policy formulation. Given the increasing frequency of extreme weather events and rising sea levels due to climate change, salt intrusion is projected to intensify, making it imperative that policymakers and stakeholders incorporate effective salt intrusion management strategies into broader environmental planning and risk management frameworks. This would ensure a more comprehensive approach to ensure both human and ecological resilience in the face of ongoing environmental changes.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Data were not used, nor created for this research.

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