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Review

Sea level rise impacts on estuarine dynamics: A review

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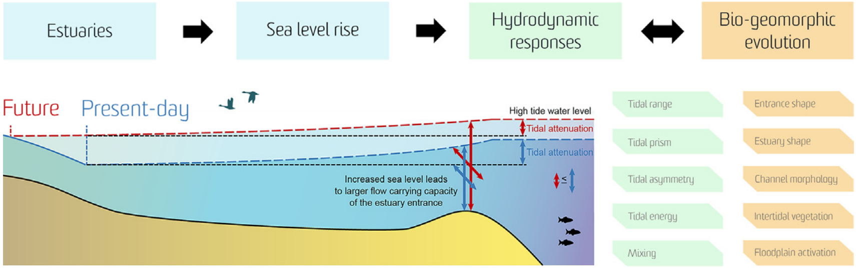
HIGHLIGHTS

- Hydrodynamic models are required to assess estuarine responses to sea level rise (SLR).
- Knowledge gaps exist in linking SLR-induced changes in physical and ecological processes.
- Most hydrodynamic models do not include geomorphic and hydro-ecologic feedback loops.
- Conceptual framework of the tiered nature of estuarine responses to SLR is introduced.
- Emphasis on human/ecological values pose challenge for estuarine management under SLR.

GRAPHICAL ABSTRACT



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ABSTRACT

Sea level rise (SLR) poses a hazard to ecosystems and economies in low-lying coastal and estuarine areas. To better understand the potential impacts of SLR in estuaries, a comprehensive review of existing theory, literature, and assessment tools is undertaken. In addition, several conceptual models are introduced to assist in understanding interlinked estuarine processes and their complex responses to SLR. This review indicates that SLR impacts in estuaries should not be assessed via static (bathtub) approaches as they fail to consider important hydrodynamic effects such as tidal wave amplification, dampening, and reflection. Where hydrodynamic models are used, the existing literature provides a relatively detailed understanding of how SLR will affect estuarine hydrodynamics (e.g., tides and inundation regimes). With regards to the current understanding of, and ability to model, the connections between altered hydrodynamics (under SLR) and dependent geomorphic, ecological, and bio-geochemical processes, significant knowledge gaps remain. This is of particular concern as there is currently a paradigm shift towards more integrated and holistic management of estuaries. Estuarine management under accelerating SLR is likely to become increasingly complex, as decision-making will be undertaken with uncertainty. As such, this review highlights that there is a fundamental requirement for more sophisticated and interdisciplinary studies that integrate physical, ecological, bio-geochemical, and geomorphic responses of estuaries to SLR.

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Contents

1. Introduction

By 2100, oceanic sea level rise (SLR) is predicted to reach between 0.61 and 1.10 m under higher emissions scenarios (Oppenheimer et al., 2019) and may even exceed 2 m due to instabilities of the Antarctic and Greenland ice sheets (Bamber et al., 2019; DeConto and Pollard, 2016; Horton et al., 2020; Wong et al., 2017). SLR will increase water levels in estuaries, potentially leading to the inundation of adjacent low-lying lands, erosion and the landward recession of shorelines, and impacts to or failure of coastal and stormwater infrastructures (Hanslow et al., 2018; Pachauri et al., 2014; Sweet and Park, 2014). In addition, altered estuarine hydrodynamics under SLR can adversely influence natural features, such as the size and distribution of intertidal wetlands, which are critical for maintaining estuarine biodiversity (Saintilan et al., 2018; Schuerch et al., 2018). As such, the sustainable management of estuaries, adjacent low-lying areas, and associated ecosystems requires a thorough understanding of the complex impacts of accelerating SLR on estuarine processes.

To date, static (bathtub, GIS-based) modelling approaches remain the most commonly used methods for estimating SLR impacts on estuarine inundation extent and tidal dynamics (Cai et al., 2012; Passeri et al., 2015c). Static approaches simulate the water surface as a 2D, flat plane that can be adjusted vertically to estimate the lateral inundation extents under SLR (typically using GIS techniques). These methods do not consider local or temporal flow distortion effects (e.g., due to presence of levees, floodgates, bridges), or hydrodynamic effects that influence the tidal wave propagation (e.g., tidal amplification or dampening) from the open ocean boundary into the estuary (Alizad et al., 2016; Khojasteh et al., 2020; Kidwell et al., 2017; Kirwan et al., 2016; Moftakhari et al., 2019; Rodríguez et al., 2017). To overcome these limitations, analytical methods can be applied in some circumstances with simple estuarine shapes (i.e., prismatic and converging) (van Rijn, 2011), but these approaches are inappropriate in estuaries with complex shapes (Hibma et al., 2004; Palmer et al., 2019).

In contrast, hydrodynamic modelling can consider various energy drivers to predict most aspects of estuarine dynamics under SLR. For instance, it is predicted that the rate of wetland loss induced by SLR could double when using an advanced hydrodynamic model in comparison to a rate given by a static model as the latter does not consider flow attenuation effects due to the presence of culverts, levees, and vegetation (Rodríguez et al., 2017). Detailed hydrodynamic studies that account for the complex interactions between hydrodynamics as well as ecological, bio-geochemical, and dependent processes over appropriate spatial and temporal scales, however, remain limited (Rodríguez et al., 2017). At the same time, decision-making in estuaries is currently shifting towards more holistic and integrated management paradigms (Boerema and Meire, 2017; Peirson et al., 2015) that require a quantification of these secondary impacts, such as changes in the ecology (e.g., impacts to function of wetlands as well as protected or threatened species) (Rayner et al., 2021; Rodríguez et al., 2017) changes in water quality (e.g., impacts to water quality from increased saltwater intrusion) (Kim et al., 2020), changes in sedimentation (e.g., impacts to dredging operations) (van Maren et al., 2015) or changes in drainage and flooding (e.g., impacts to land-use zoning) (Khojasteh et al., 2020; Moftakhari et al., 2017). As such, a gap remains between the methods and tools that are commonly used to estimate SLR impacts in estuaries (i.e., prediction of future tidal regimes, tidal energy, sediment transport, mixing and circulation, saltwater intrusion, drainage efficiency, water quality, geomorphology, and intertidal ecology), and the data and knowledge required by decision makers to establish evidence-based management plans for estuaries under accelerating SLR and ongoing rapid coastal development (Boerema and Meire, 2017; Passeri et al., 2015c; Rayner et al., 2021; Rodríguez et al., 2017).

To better understand the limitations in the literature, the primary aim of this review is to quantify the current knowledge of, and ability to model, direct and indirect impacts of SLR in estuaries. To this end, the review first provides an overview of relevant estuarine physical processes. This is followed by a detailed review of recent studies that applied process-based modelling to investigate SLR impacts on estuarine hydrodynamics at an estuary-wide scale (rather than a local scale) and, where appropriate, dependent bio-geomorphic processes. In the discussion, the implications of these knowledge gaps are discussed in relation to future estuarine management, highlighting the need for interdisciplinary studies that accurately link SLR-induced physical changes (e.g., altered hydrodynamics) with geomorphic, ecological, and bio-geochemical processes.

2. An overview of estuarine processes

Estuarine processes are highly-complex, with numerous knowledge gaps currently recognized (Hoitink and Jay, 2016; Khojasteh et al., 2020; Rodríguez et al., 2017). As shown in Figs. 1 and 2, estuarine hydrodynamics are mainly driven by forces external to the estuary, including river and groundwater inflows, tides, wind, and waves. These external driving forces are the primary sources of energy behind the motion of water within an estuary. Depending on the shape (e.g., length, width, depth, slope, entrance condition, water storage capacity) and boundary conditions of the estuary (e.g., bed/bank roughness and vegetation),

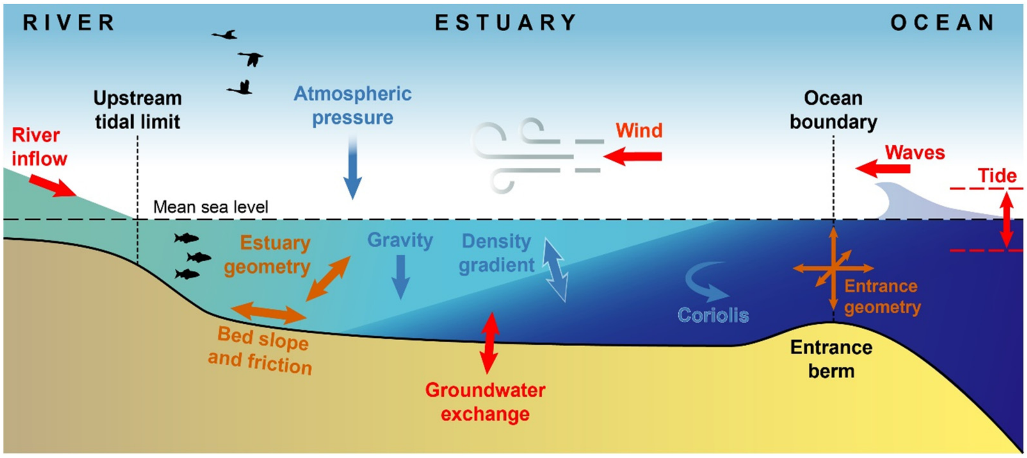

Fig. 1. Conceptual diagram illustrating the key factors that govern estuarine hydrodynamics. Red arrows depict the major external driving forces (1st order). Orange arrows correspond to the shape and boundaries of the estuary. Blue arrows illustrate internal forces within the estuary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

these external forces help to create the unique hydrodynamic regime of an estuary.

The hydrodynamic regime also depends on the intrinsic fluid properties that continuously vary over time and space (i.e., density and viscosity of water) and forces acting directly within the estuarine waterbody (Figs. 1 and 2). For instance, gravitational and hydrostatic pressure differential forces arise within an estuary, including the density differential between the upland freshwater inflows and the oceanic saltwater current flows. Resultant density gradients may generate residual circulations that can result in mixing and/or increased turbulence (Savenije, 2006).

The resulting hydrodynamic regime controls the distribution and movement of sediment, organic matter, and other constituents within an estuary, thereby shaping (or reshaping) a unique ecological and geomorphic environment over various time scales. To present a broad understanding of estuarine dynamics across disciplines, a simple conceptual model is proposed, where estuarine processes are grouped hierarchically into external boundary forcing (1st order) and estuarine internal direct (2nd order) and indirect (3rd order) responses (Fig. 2). Although the boundary between 2nd and 3rd order processes may not be simply identifiable in real-world estuaries, a key distinguishing factor between them is that the latter typically manifests at longer time scales (1 to 2 orders of magnitude larger (Passeri et al., 2015c)), due to the slower nature of ecological and geomorphic responses as well as associated adjustments. The following sub-sections summarise estuarine external driving forces as well as 2nd and 3rd order processes and their interactions.

2.1. Estuarine 1st order driving forces

Estuarine tidal dynamics are unique for every estuary (Du et al., 2018). For more than 100 years, estuarine hydrodynamic studies have investigated how tides perturbate from the estuary entrance to the upper tidal limit (Cartwright, 1968; Doodson, 1921; Dronkers, 1964; Ippen, 1966; LeBlond, 1978; Parker, 1984; Pugh, 1987; Savenije, 2006; Schureman, 1941). Tidal variations are influenced by daily (due to the Earth's rotation), fortnightly (due to the Moon's rotation around

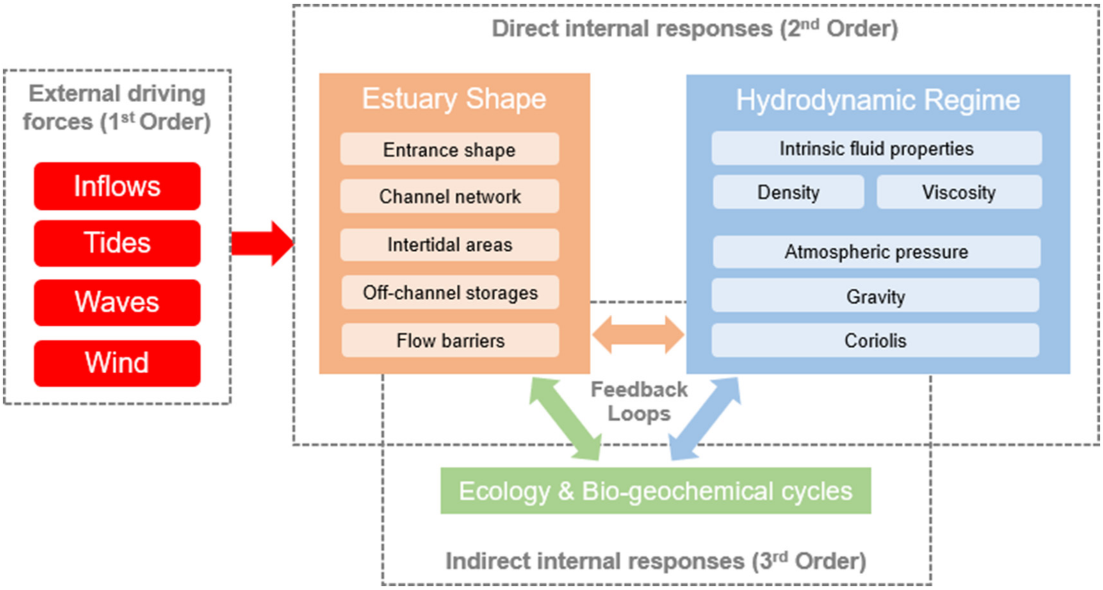

Fig. 2. Conceptual diagram illustrating the hierarchical structure of estuarine hydrodynamics in line with the processes detailed in Fig. 1. Due to its unique shape and system boundary conditions, an estuary will exhibit a unique hydrodynamic regime (2nd order) as a response to the external driving forces (1st order). Over time, the hydrodynamic regime shapes and interacts with the ecological and bio-geochemical processes (3rd order) which, in turn, can alter the system shape (e.g., geomorphic adjustment – shown as feedback loops) and the hydrodynamic regime.

the Earth), semi-annual (due to annual revolution of the Earth around the Sun), 4.4-, 8.8-, and 18.6-year cycles (induced from an inclination between orbital planes of the Moon and the Earth) (Rinehart, 1975). Numerous studies have reported considerable changes in the tidal evolution during the 20th and 21st centuries for several open ocean locations and estuaries worldwide. These observed tidal variations are greater than what would be expected as a direct result of gravitational forces (Müller, 2012; Müller et al., 2011). Thereby, tidal changes are likely influenced by other factors (Mawdsley et al., 2015), including changes in water depth (e.g., due to SLR) (Haigh et al., 2020; Müller et al., 2011; Talke and Jay, 2020), channel width (convergence) (Haigh et al., 2020; Talke and Jay, 2020), morphology (Araújo and Pugh, 2008), seasonal variations due to ice cover (St-Laurent et al., 2008), water column stratification (Müller, 2012), and anthropogenic activities (Talke and Jay, 2020) (for more details, see Haigh et al. (2020), Talke and Jay (2020), and references therein).

Freshwater inflows to an estuary are primarily influenced by runoff resulting from rainfall in the catchment as well as groundwater discharges. Runoff volumes can be amplified (e.g., urbanisation of catchments) or reduced (e.g., dams and upstream diversions) due to natural processes or anthropogenic pressures. Freshwater inflows influence estuarine hydrodynamics primarily through changes in circulation, mixing, and frictional effect, particularly in upstream locations far from the estuary entrance (Haigh et al., 2020; Uncles et al., 2013), where tidal range can be partially or fully attenuated in the presence of (major) river inflows (Godin, 1985; Horrevoets et al., 2004; Vongvisessomjai and Rojanakamthorn, 1989).

Other important external sources of energy related to water movement within estuaries include wind and waves. Waves in an estuary include those generated in the ocean that penetrate through the mouth of an estuary and those generated internally that affect shorelines, shoals, or beds of shallow estuaries. Waves can have a significant effect on sediment distributions by eroding shorelines, stripping substrates, and redistributing sediments (Bricker et al., 2005; French et al., 2000; Green et al., 1997; Osborne and Greenwood, 1993). In the absence of a major river discharge or a significant tidal range in an estuary, wave energy may control the onshore transport of sediments and/or closing of the estuary entrance (Kench, 1999). A wave-dominated estuary often features a barrier at the mouth that restricts the entrance and controls the water exchange between the estuarine system and the sea (Roy et al., 2001). Wind forcing affects mixing, water levels, flow velocities, and surface conditions within an estuary (Cho, 2007; Li and Li, 2011). Over the estuary surface, momentum in the atmosphere may be directly transferred onto the underlying water column by wind shear, inducing surface currents and waves that can elevate the water level in the downwind area of the estuary (Pareja-Roman et al., 2019). The Coriolis effect arises from the Earth's rotation and deflects currents towards right in the Northern Hemisphere and left in the Southern Hemisphere (Anderson and Lucas, 2008), resulting in secondary circulations in estuaries (Xie et al., 2017). Coriolis effect becomes important in wide estuaries that are located at high latitudes by help in determining the velocity structure of gravity currents (Martin and McCutcheon, 1998; Wells and Cossu, 2013).

2.2. Estuarine 2nd order responses

The unique hydrodynamic regime of an estuary is the manifestation of the driving forces acting on an estuarine waterbody with a unique shape and internal parameters. As such, the configuration of an estuary is a key factor controlling the propagation of the tidal waves from the mouth to the upstream tidal limit(s). Depending on the shape of an estuary and the boundary conditions, the propagating tidal wave may be amplified (Fig. 3(a)), dampened (Fig. 3(b)), reflected (Fig. 3(c)), and/or deformed (Fig. 3(d)). Fig. 3 conceptually details the role of estuarine shape on the propagation of the tidal wave within an estuary.

As discussed by van Rijn (2010), tidal amplification occurs due to the gradual decrease of the width of the estuary, called funnelling, or the gradual decrease of the depth of the estuary, called shoaling, as well as tidal reflection and/or resonance. van Rijn (2011) described the funelling and shoaling phenomena via the concept of tidal wave energy flux, which is the multiplication of the total energy for a sinusoidal tidal wave per unit of length $E = 0.125\rho gBH^2$, and the propagation celerity of a sinusoidal tidal wave $c = \sqrt{gh}$, where ρ is the water density, g is the gravitational acceleration, B is the estuary width, H is the tidal range, and h is the mean water depth. Assuming no energy loss and no reflection at the head, the energy flux is constant at the estuary mouth or any other location in the estuary, and therefore, tidal ranges in upstream reaches increase as the width and depth decrease (van Rijn, 2011). The wavelength L is proportional to the wave celerity, i.e. $L = cT$, where T is the tidal period. As the celerity decreases with decreasing depth, the wavelength decreases, resulting in shorter and higher tidal waves (Fig. 3(a)).

Tidal resonance occurs when the tidal frequency is synchronized with the natural frequency of an estuary (Garrett, 1972; Le Souëf and Allen, 2014; Sutherland et al., 2005). For a frictionless prismatic channel, the amplitude of the water surface elevation (called resonance amplitude L_R) can theoretically tend to infinity, as below:

$$L_R = \frac{(2m-1)L}{4} = \frac{(2m-1)T\sqrt{gh}}{4} \tag{1}$$

where m is an integer. A quarter wavelength resonance occurs when $m = 1$ (Du et al., 2018; Khojasteh et al., 2019), and is likely to be observed in some estuaries worldwide (Savenije, 2006; Talke and Jay, 2020). It is reported that estuaries close to resonance are most sensitive to length variations (Talke and Jay, 2020). Thereby, estuaries with a length less than the resonant length may result in an increased tidal amplification with increasing length, whereas estuaries with a length above resonance length may experience tidal amplification as estuary length decreases (Talke and Jay, 2020).

The tidal range may decrease due to dampening effects caused by friction at the estuary bed and banks, as shown in Fig. 3(b). This frictional effect plays a key role in controlling the tidal dynamics of shallow estuaries and this effect increases with increasing tidal amplitude and/or decreasing water depth (Parker, 1984).

As explained by van Rijn (2010), tidal wave reflections arise when the tidal wave encounters a sudden obstacle on the bed or banks of the estuary (Fig. 3(c)). The wave reflection is highest when the obstacle is vertical and non-porous (e.g., massive rocks). Further, when there is a sudden shallowing of the bed in an estuarine system, the wavelength will decrease as the wave celerity reduces with decreasing depth. The newly propagated tidal wave will have a shorter wavelength but a greater height than the incident wave (van Rijn, 2010), as illustrated in Fig. 3(c).

As a tidal wave perturbates from the deep ocean into a shallower estuary, the sinusoidal tidal wave will not remain harmonic (van Rijn, 2010). Since the wave celerity is proportional to the water depth ($\sqrt{h}$), the crest of the wave travels faster in the upstream direction, causing a change in the tidal wave pattern, called tidal wave deformation (van Rijn, 2010), as depicted in Fig. 3(d).

2.3. Estuarine 3rd order responses

The hydrodynamic regime of an estuary interacts with and controls the 3rd order responses/processes, such as changes in bio-geochemical cycles that underlie inter- and sub-tidal vegetation communities/processes (i.e., ecological response) as well as the dependent geomorphic adaptation (as the feedback mechanism) (Fig. 2). The processes of sediment erosion, suspension, and deposition, which drive the geomorphology of an estuarine system, are primarily influenced by tidal characteristics including tidal range, tidal prism, tidal current velocity distribution, wind waves, as well as fluvial flows and their corresponding sediment loads (Allen et al., 1980; De Swart and Zimmerman, 2009; Dronkers, 1986;

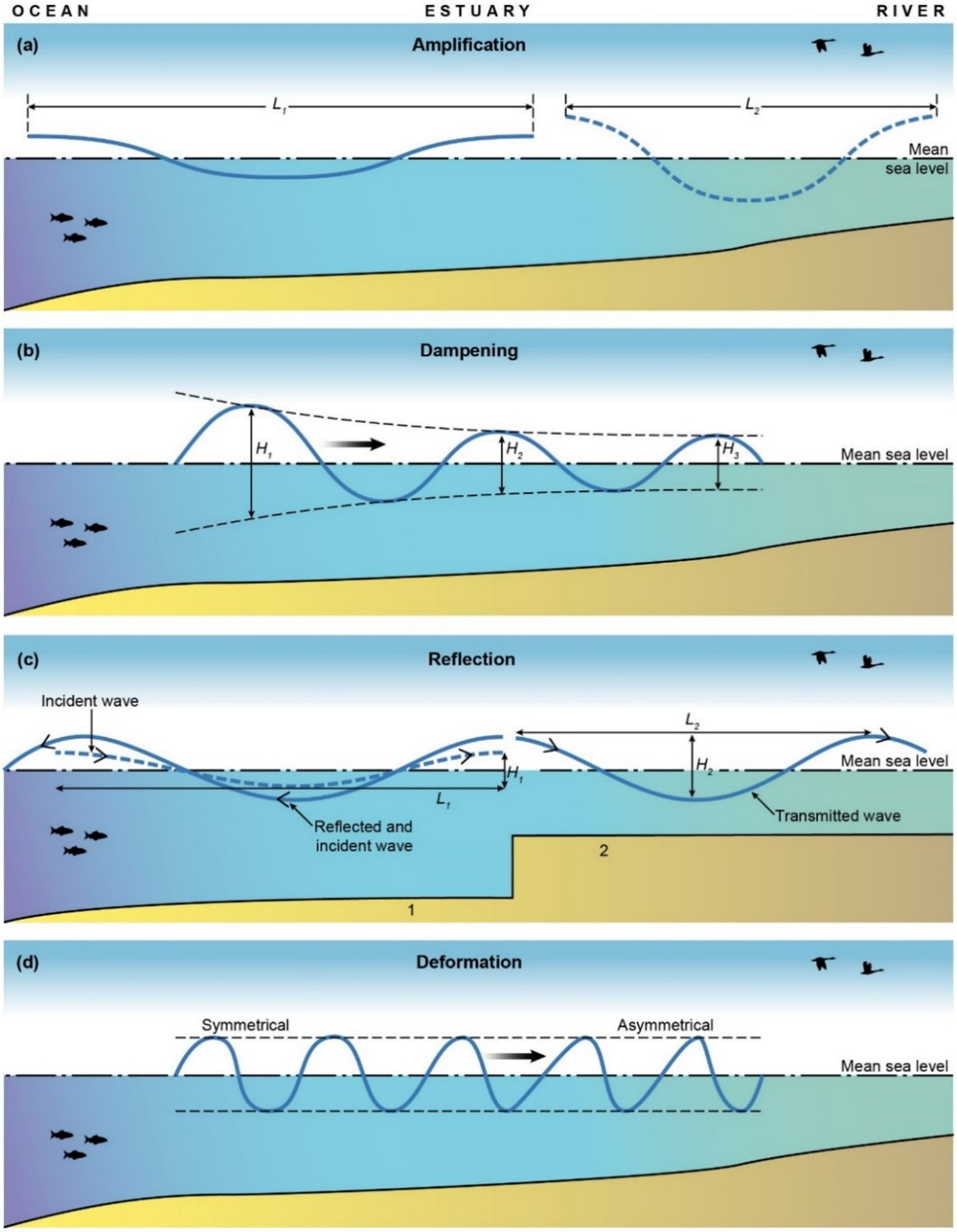

Fig. 3. Conceptual mechanisms influencing the propagation of tidal waves in estuaries, highlighting the concepts of (a) amplification, (b) dampening, (c) reflection, and (d) deformation (after van Rijn (2010)).

Wu et al., 2020). Sediments are deposited in zones of low flow velocities, such as where the tidal currents and river inflows counterbalance each other (e.g., knickpoint zones) (Kaiser et al., 2011; Kennish, 2019b) or in sections where the cross-sectional flow area increases abruptly. Sediments are suspended where tidal or fluvial currents are above a critical shear velocity, (Wells, 1995) as is often the case in narrow entrance channels. Importantly, sediment transport in river-dominated estuaries or sections is often largely driven by floods, which act as intermittent erosive events, while in the lower, tide-dominated sections, bi-directional tidal flows often control a longer-term and more continuous redistribution of sediments (Dyer, 1988). Estuarine hydrodynamics and the resulting patterns of sediment transport are key processes controlling water quality as they can influence nutrients, dissolved oxygen, pH, light attenuation, and algae growth (Ji, 2017; Uncles, 2018). Another important feature of sediment transport in estuaries is the turbidity maximum zone, which is defined as an area with the highest sediment concentrations within an estuarine system (Dyer, 1988; Wells, 1995). In estuaries, the turbidity maxima can be generated by either the residual circulation due to density gradients induced by the transition from freshwater to saltwater or the tidal wave asymmetry (van Maanen and Sottolichio, 2018).

Any changes in estuarine water salinity (as a water quality component) can adversely impact estuarine vegetation communities (Xiao et al., 2018). For instance, saltwater intrusion leads to increased ionic strength, alkalinisation, and sulfidation (Tully et al., 2019). For salinity intrusion, several numerical and empirical models have been developed to predict the saltwater intrusion length within an estuary as a function of measurable parameters, such as estuarine geometry, water characteristics, river inflow, and tidal parameters (Prandle, 2004;

Rigter, 1973; Savenije, 1993). Rigter (1973) empirically showed that the intrusion length λ is defined as:

$$\lambda \approx 4.7 \frac{h_0}{f} \frac{P_t}{Q_f T} \frac{\Delta \rho g h_0}{\rho U_0^2} \tag{2}$$

where f is the Darcy-Weisbach friction factor, P_t is tidal prism, Q_f is freshwater discharge, ρ is water density, $\Delta\rho$ is density difference over the intrusion length, and U_0 is the tidal current velocity amplitude at the estuary mouth. Any potential variations in these parameters can influence the salinity distribution in an estuary, inducing changes in existing vegetation communities (e.g., loss or retreat of coastal forests and freshwater plant communities). The changes in vegetation distribution induced by shifts in estuarine hydrodynamics could then influence the friction (as the new vegetation community may have a different roughness) (Cheng, 2011; Tang et al., 2014a), which in turn leads to further changes in the system's hydrodynamic regime. Therefore, an ongoing interlinked feedback loop exists between estuarine 2nd and 3rd order processes (Fig. 2). The impacts of SLR on these 2nd and 3rd order processes and their interactions in estuaries are further elaborated in Section 4.

3. Common tools for assessing sea level rise impacts in estuaries

To accurately assess the impacts of SLR in estuaries, 2nd and 3rd order responses, including the nonlinear changes and feedback processes outlined above, should be taken into consideration. Despite significant advances in estuarine and SLR studies over the past decade, static approaches, where SLR projections are added to existing bathymetry and tidal range, are still widely applied to assess SLR impacts in estuaries (for more details, see Passeri et al. (2015c), McInnes et al. (2016), Alizad et al. (2016), Kidwell et al. (2017), Moftakhari et al. (2019), Palmer et al. (2019), and Khojasteh et al. (2020)). As a static approach is based on topography and assumes a constant (or nil) energy loss for the tidal wave propagation, it does not consider estuarine physical processes outlined in Section 2, namely the alteration of the tidal wave dynamics via dampening, amplification, reflection and/or deformation (Anderson et al., 2018; Barnard et al., 2014; Hoeke et al., 2013; Khojasteh et al., 2020; Melet et al., 2018; Moftakhari et al., 2019; Rodríguez et al., 2017) (Fig. 3). This approach is inappropriate for most estuaries, especially where flood levees or flow control structures distort the flows and alter the hydrodynamics (Kirwan et al., 2016; Passeri et al., 2015a; Woodroffe and Murray-Wallace, 2012). Therefore, static methods typically do not provide accurate information regarding the potential changes in estuarine processes under SLR. This lack of accurate knowledge is of particular concern as it implies that the SLR risks will not be effectively identified or managed.

In some circumstances, analytical approaches can be used to predict estuarine hydrodynamics, mainly tidal dynamics, as they solve momentum and energy equations for the moving fluid. These approaches have been developed for certain simplified types of estuaries including prismatic and converging (Cai et al., 2012; Dronkers, 2005; Dronkers, 1964; Ensing et al., 2015; Friedrichs, 2010; Huijts et al., 2009; Hunt, 1964; Jay, 1991; Lanzoni and Seminara, 1998; LeBlond, 1978; Prandle, 2003; Prandle, 2009; Savenije, 2006; Savenije et al., 2008; van Rijn, 2011). Analytical solutions permit a rapid assessment on how estuarine tidal dynamics may alter under SLR by testing various driving forces, geometries, and boundary conditions (Cai et al., 2012; Ensing et al., 2015). However, the analytical solutions assume that tidal amplitudes are small and encompass a multitude of limitations as they do not consider complex estuarine shape, Coriolis force, and density gradients (Cai et al., 2012; Talke and Jay, 2020).

In contrast, advanced hydrodynamic (numerical) modelling of estuaries can consider various driving forces and their interactions, accurate concepts of energy exchange, tidal processes (e.g., via amplification, dampening, deformation, reflection), floodplain and linear structural connections (e.g., bridges, levies), as well as the ecological and bio-geochemical processes and related geomorphic interactions. For instance, there are many numerical models that predict changes in wetland/marsh processes under SLR which cannot be fully captured via physical models or lab/field experiments (FitzGerald and Hughes, 2019). These models range from zero-dimensional (e.g., predicting elevation change at a single point), to one-dimensional (e.g., sedimentation over a transect), to two-dimensional (e.g., channel development over a planform), to three-dimensional (e.g., vertical erosion and deposition) (Fagherazzi et al., 2012; FitzGerald and Hughes, 2019). However, detailed datasets, including topographic and bathymetric features as well as flow observations for initialisation, calibration, and validation purposes are required to accurately establish and verify such models. Further, differences in spatial and temporal scales of various processes can add further complexity into numerical modelling of estuarine processes under SLR. The processes can occur on the scale of microseconds (e.g., turbulence), minutes (e.g., tides), months (e.g., plant growth), years (e.g., variations in estuarine meanders), and centuries (e.g., inland migration of marshes), and each timescale is correlated with a different spatial scale ranging from sediment interaction to landscape formation (FitzGerald and Hughes, 2019). As such, most of these studies attempt to link ecological or biological responses to local processes (e.g., response of a freshwater species to salinity increase) (for details, see Fagherazzi et al. (2012), FitzGerald and Hughes (2019), Fagherazzi et al. (2019), Wiberg et al. (2020), and references therein). Due to their growing use in supporting estuarine management decisions under SLR, only numerical assessments based on detailed hydrodynamic modelling at an estuary-wide scale (rather than a local scale such as a wetland) are considered in the remainder of this review.

4. Estuarine processes and sea level rise

When investigating estuaries under SLR, a range of processes or parameters are commonly selected to characterise estuarine responses including tidal parameters (tidal range, prism, current velocity, energy, asymmetry), mixing and circulation, saltwater intrusion, stratification, sediment dynamics, and turbidity. Several researchers have explored how these processes/parameters may be influenced by SLR in non-estuarine marine settings, such as seas, oceans, and continental shelves (Arns et al., 2017; Arns et al., 2015; Carless et al., 2016; Chen et al., 2017; Chen and Liu, 2017; Clara et al., 2015; De Dominicis et al., 2018; Haigh et al., 2020; Harker et al., 2018; Idier et al., 2017; Müller, 2012; Müller et al., 2011; Pelling and Green, 2013; Pelling and Mattias Green, 2014; Pelling et al., 2013a; Pelling et al., 2013b; Pickering et al., 2017; Pickering et al., 2012; Schindelegger et al., 2018; Tang et al., 2014b; Tang et al., 2014c). The present review solely focuses on estuarine environments and the reader is referred to the above references for further guidance on the impacts of SLR in non-estuarine marine environments.

This section reviews the current evidence on how SLR may affect estuarine processes and provides insights into how these processes are inter-related (Table 1). The studies presented in Table 1 are organized based on the driving forces, evaluated parameters/processes, rates of SLR, study site, applied hydrodynamic model, and significant findings. Considering the available literature presented in Table 1, there are knowledge gaps regarding SLR impacts on estuarine processes, which will be further discussed in the following sub-sections.

4.1. Sea level rise and estuarine 2nd order responses

Fig. 4 indicates conceptual models to highlight important changes of tidal wave dynamics that are likely to be induced by SLR. Note that the concepts do not consider potential confounding interactions between estuarine processes. In real estuaries, responses to SLR may be counteracted or amplified by geomorphic adaptations to the altered hydrodynamics, variations in inflows or engineered mitigation measures (see Section 2). For illustrative purposes, however, these confounding

Table 1

Summary of hydrodynamic modelling studies on effects of SLR on estuarine parameters and processes.

Study	Driving force(s)	Evaluated parameters & processes	SLR	Investigated estuary	Hydrodynamic model	Significant finding(s)
Hong and Shen (2012)	Tide, wind, river inflow	Tidal range, saltwater intrusion, stratification	0.3 to 1.1 m	Chesapeake estuary, USA	A 3D finite difference model (HEM—3D) that solves mass balance equations.	• SLR intensifies the estuary stratification, resulting in a stronger gravitational circulation.
Hall et al. (2013)	Tide	Tidal range	1, 3.5 m	Delaware estuary, USA	A 2D finite element model.	• Tidal ranges in the lower part of the estuary remained constant over time but increased by 100% for the upper part.
Valentim et al. (2013)	Tide, river inflow	Tidal asymmetry, tidal energy dissipation, circulation velocity	0.42 m	Ria de Aveiro lagoon and Tagus estuary, Portugal	A 3D finite volume model (MOHID) that solves Reynolds-averaged Navier–Stokes equations.	• SLR decreases the residual circulation in both estuarine systems.
Tang et al. (2014b) & Tang et al. (2014c)	Tide, river inflow	Tidal energy, tidal power, tidal range, phase lag, tidal current velocity	0.5, 1 m	Estuaries along the New Jersey coastlines from Hudson River to the eastern side of the Delaware estuary, USA	2D and 3D finite volume Coastal Ocean Models (FVCOM).	• SLR reduces tidal power for the bays along the New Jersey coastlines facing the Atlantic Ocean but increases tidal power in the Delaware estuary.
Chua and Xu (2014)	Tide, river inflow	Circulation velocity, salinity profile	0 to 0.81 m	Ideal estuary and San Francisco Bay, USA	A 3D finite volume model (SUNTANS) that solves Reynolds-averaged Navier–Stokes equations.	• SLR decreases the vertical mixing, resulting in a stronger gravitational circulation.
Lopes and Dias (2015)	Tide, river inflow	Tidal range, residual velocity	0.42 m	Ria de Aveiro lagoon, Portugal	A 2D finite volume/finite difference model that solves the shallow water equations.	• Residual current increases with SLR, highlighting an intensification in exchange processes between ocean and lagoon as well as changes in the sediment distribution.
Passeri et al. (2015a)	Tide, wind	Tidal range, tidal prism	0.46 m	5 estuaries between Mobile Bay estuary and St. Andrew Bay estuary, Northern Gulf of Mexico	A 2D finite element model that solves the shallow water equations.	• A hydrodynamic (rather than static) approach should be adopted to capture SLR as a dynamic process in estuaries. • Tidal range and tidal prism increase under SLR.
Passeri et al. (2015b)	Tide	Tidal range, phase lag, tidal current velocity	0.13, 0.26, 0.47 m	Grand Bay estuary, USA	A 2D finite element model that solves the shallow water equations.	• By considering SLR, tidal amplitudes of this estuary remained constant in open shorelines and decreased in semi-enclosed embayments. • The tidal velocities were historically faster, and tides turned from flood dominant in 1848 to ebb dominant in 2005.
Yang et al. (2015)	Tide, wind, river inflow	Salinity, temperature, tidal current velocity, tidal range, tidal power	0.166, 0.325, 0.618, 0.911 m	Snohomish River estuary, USA	A 3D finite volume Coastal Ocean Model (FVCOM).	• With SLR, the salinity intrusion increases linearly for the main channel of the estuary. • Salinity intrusion points move upstream of the estuary with SLR.
Chen et al. (2016a)	Tide, wind, river inflow	Tidal current velocity, salinity distribution	0.5, 1, 2 m	Yangtze River estuary, China	A 3D finite volume method (MIKE3) that solves the incompressible Reynolds-averaged Navier–Stokes equations.	• The isohaline moves nonlinearly upstream of estuary under SLR. • With SLR, saltwater overflow is strengthened from the northern into the southern branch.
Chen et al. (2016b)	Tide, wind, river inflow	Tidal range, tidal current velocity, saltwater intrusion, residual velocity	0.3, 0.5, 0.8 m	Pearl River estuary, China	A 3D finite volume Coastal Ocean Model (FVCOM).	• The saltwater intrusion and stratification increase under SLR. This increase also depends on the amount of seasonal freshwater inflow.
Passeri et al. (2016)	Tide	Tidal range, phase lag, tidal current velocity, morphology	0.1 to 2 m	7 estuaries between Mississippi Sound estuary and Apalachicola Bay estuary, Northern Gulf of Mexico	A 2D finite element model (ADCIRC-2DDI) that solves the shallow water equations.	• SLR of 2 m increases the tidal amplitude by 0.1 m (67%). • Phase analysis of tidal constituent shows a faster tidal propagation under SLR. • For Weeks Bay and Apalachicola, tidal currents become more ebb dominant, while they become flood dominant in Grand Bay with SLR.
Lee et al. (2017)	Tide, river inflow	Tidal range, phase lag, tidal energy	1 m	Chesapeake and Delaware estuaries, USA	A 3D finite volume Coastal Ocean Model (FVCOM).	• With levees, tidal range increases; without levees, tidal range decreases due to increased energy dissipation in newly inundated areas.
Ross et al. (2017)	Tide, wind, river inflow	Tidal range, phase lag	1 m	Chesapeake and Delaware estuaries, USA	A 3D finite volume Coastal Ocean Model (FVCOM).	• For Chesapeake estuary, SLR shifts the locations of amphidromes, generating spatially variable changes in tidal constituents. • In Delaware estuary, SLR diminishes the effect of bed friction, increases bank convergence, and produces amplification of tides.

(continued on next page)

Table 1 (*continued*)

Study	Driving force(s)	Evaluated parameters & processes	SLR	Investigated estuary	Hydrodynamic model	Significant finding(s)
Van der Wegen et al. (2017)	Tide, wave	Sediment dynamics, morphology	0.83, 1.67 m	A sub-estuary in the San Francisco estuary, USA	A 1D finite volume model (Delft3D) that solves the shallow water equations.	• Estuarine mudflats may become unstable when SLR is large or suspended sediment concentration decreases fast.
Du et al. (2018)	Tide	Tidal range	1 m	Ideal estuaries (prismatic and converging) and Chesapeake estuary, USA	A 2D semi-implicit finite element/finite volume method named semi-implicit cross-scale hydroscience integrated system model (SCHISM).	• SLR leads to tidal attenuation in short, narrow, and shallow idealised estuaries. • Idealised approach provides initial understanding of estuarine tidal response to SLR.
Vu et al. (2018)	River inflow	Salinity intrusion	0.25, 0.3 m	Mekong Delta, Vietnam	A 1D finite difference method (MIKE11) that solves the shallow water equations.	• Under SLR, saline water intrudes up to 50–60 km into the river.
Carrasco et al. (2018)	Tide	Tidal range, tidal current velocity	0.63, 0.98 m	Ria Formosa lagoon, Portugal	A 2D finite volume model (Delft3D) that solves the shallow water equations.	• Peak flood velocity and entrance flood duration increase under SLR.
van Maanen and Sottolichio (2018)	Tide, river inflow	Salinity profile, turbidity profile, sediment dynamics, tidal range, tidal current velocity	1 m	Gironde estuary, France	A 3D finite difference model (SiAM) that solves the Navier-Stokes equations.	• Location of the salinity front remains unchanged under SLR, but the salinity increases by 1 psu in the middle part of the estuary.
Mulamba et al. (2019)	Tide, river inflow	Salinity distribution	0.05, 0.15, 0.3 m	St. Johns River estuary, USA	A 2D finite element model that solves the shallow water equations.	• Under SLR, salinity intrusion increases over the whole estuary nonuniformly.
Khojasteh et al. (2019)	Tide	Tidal range	1 m	Ideal estuary (prismatic)	A 2D finite element model (RMA) that solves the shallow water equations.	• SLR increases the tidal range in a prismatic estuary near the resonance. • SLR displaces the nodal points in prismatic estuaries due to increasing water depth, causing an uneven spatial distribution of tidal response.
Palmer et al. (2019)	Tide, wind, river inflow	Tidal range, tidal asymmetry	0.23, 0.85 m	Tamar estuary, Australia	A 2D finite volume model (TUFLOW) that solves the shallow water equations.	• SLR has negligible effect on tidal range but reduces the flood tide dominant asymmetry by up to 40%.
Leuven et al. (2019)	Tide, river inflow	Tidal range, sediment dynamics, morphology	1 m	36 estuaries worldwide	A 1D hydrodynamic model that solves the shallow water equations.	• Estuarine shape and size significantly influence their hydrodynamic responses to SLR. • Small and shallow estuaries are currently friction dominated and will experience tidal amplification under SLR. Large estuaries currently show tidal amplification, but this amplification is unlikely to continue under SLR.
Yin et al. (2019)	Tide, wave	Tidal current velocity, residual velocity, sediment dynamics, morphology	0.2, 0.5, 0.8 m	Deben estuary, UK	A Delft3D model coupled with flow model and SWAN wave model.	• The geomorphic response of estuary will be significantly affected by SLR through making the ebb shoal of the estuary more unstable.
Hong et al. (2020)	Tide, wind, river inflow	Tidal range, salinity profile, residence time, stratification	0.3, 0.6, 1, 1.5 m	Pearl River estuary, China	A 3D hydrodynamic model (EFDC).	• Under SLR, salinity, stratification, and tidal range will increase.
Song et al. (2020)	Tide, river inflow	Salinity profile	0.25 m	Changjiang estuary, China	A 3D MIKE3 Flow Model that solves the shallow water equations.	• Under SLR, salinity of north and south branches as well as north channel increases.
Khojasteh et al. (2020)	Tide	Tidal range, tidal prism, phase lag, tidal current velocity, tidal asymmetry	0, 1, 2 m	Ideal estuary (prismatic) with and without restricted entrance	A 2D finite element model (RMA) that solves the shallow water equations.	• Estuary length and tidal forcing mainly control tidal wave dynamics. • Entrance restriction can potentially mitigate SLR-induced tidal amplification.
Yuan et al. (2020)	Tide, river inflow	Sediment dynamics, morphology	1–5 mm/year	Ideal model of the Yangtze River estuary, China	A 1D finite volume model (Delft3D) that solves the shallow water equations.	• Decreasing sediment supply and SLR will increase sediment trapping ratio, changing the estuarine morphology.
Rayner et al. (2021)	Tide, river inflow	Sediment dynamics, hydroperiod, vegetation distribution	1.73, 6.16, 8.08 mm/year	Hunter River estuary, Australia	A 1D/2D finite difference method (MIKE Flood) that solves the shallow water equations.	• A significant shift in vegetation composition was observed when the rate of SLR exceeds the accretion ability of the estuary.

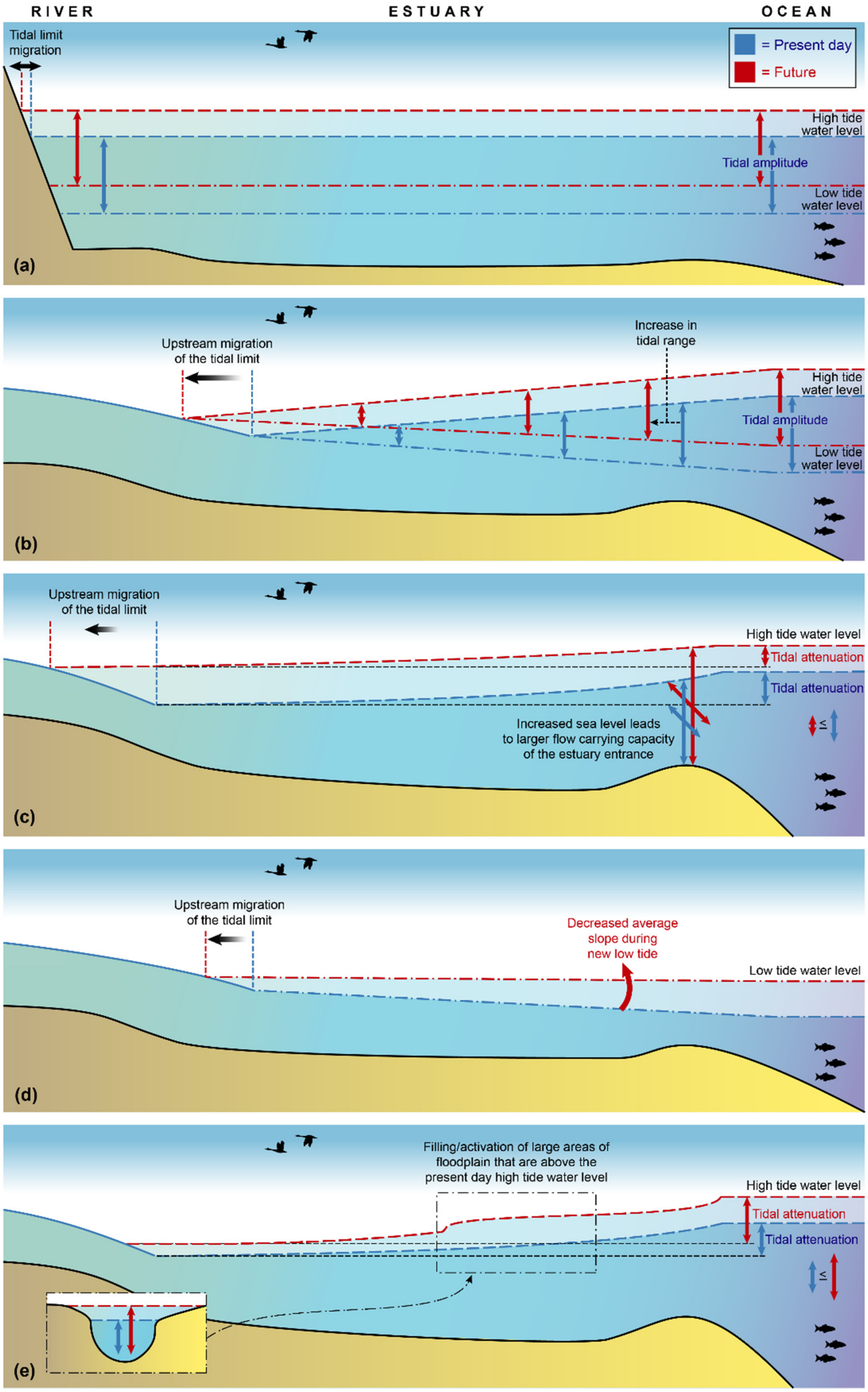

Fig. 4. Conceptual models of the effects of SLR on estuarine hydrodynamics: (a) insignificant changes in tidal hydrodynamics under SLR for an open embayment without entrance restrictions; (b) upstream migration of the tides into an estuary with a low gradient in the upstream river boundary; (c) reduced tidal dampening due to an increased cross-sectional flow area at the entrance; (d) decreased drainage during the ebb tide cycle due to the elevated low tide at the ocean boundary; (e) increased tidal attenuation due to the activation of floodplain areas within the estuary under increasing mean sea level.

factors are not considered (i.e., the shape of the estuary is assumed to remain unchanged) so that critical responses to SLR could be better highlighted in isolation.

Fig. 4 details simplified along-channel estuary cross-sections with and without SLR for a) estuaries with negligible frictional losses at the boundaries; b) tidal dynamics of estuaries with shifting high and low tidal levels; c) influence of SLR on high tide levels; d) influence of SLR on low tide levels; and e) influence of floodplain inundation induced by SLR. A further description of the conceptual models presented in Fig. 4 is provided below.

Assuming a bay setting with a large open entrance, a non-converging shape, and steep geological upstream barriers, it can be assumed that an increase in mean sea level results in an increase in the baseline water level, with minor changes in tidal dynamics. In this case, SLR would have very limited, or negligible, influence on tides as the tidal envelope is shifted upwards under SLR (Fig. 4(a)). However, it is demonstrated that the tidal response of such idealised estuaries to SLR is still nonlinear and affected by changes in the water depth as well as the length of the estuary, particularly for estuaries close to resonance length (Du et al., 2018; Khojasteh et al., 2020; Talke and Jay, 2020).

If the shape and bathymetry of an estuary remain unchanged (i.e., no infilling or erosion), an increase in the mean sea level at the open ocean boundary may cause upstream tidal migration, as illustrated in Fig. 4(b). The tidal reach into this type of estuary will then largely depend on the tidal range at the ocean boundary, estuarine shape and bathymetry, entrance conditions (e.g., constrictions), bed friction/slope throughout the estuary and upstream river inflows/location. Estuaries sometimes have constricted entrances that attenuate the incoming flood tides and thereby, the corresponding high and low tide levels. This attenuation is due to frictional losses as only a limited water volume can flow through the available cross-sectional area in the entrance (Hinwood and McLean, 2015; Khojasteh et al., 2020; MacMahan et al., 2014).

If the shape of the estuarine entrance remains largely unchanged, an increase in the mean sea level due to SLR will increase the available cross-sectional flow area of the entrance, as indicated in Fig. 4(c). The increasing flow area will influence estuarine tidal dynamics by resulting in a larger tidal prism. This larger tidal prism also changes the frictional effect, patterns of tidal wave propagation, and tidal current velocity (for more details, see Khojasteh et al. (2020)). The altered current velocity under SLR can also modify the spatial and temporal distribution of tidal power ($\propto U^3$) within an estuarine system. To illustrate, SLR reduces the current power density of the bays along the New Jersey coastlines, but increases it in the nearby Delaware estuary (Tang et al., 2014b; Tang et al., 2014c).

If the shape and bathymetry of the estuary remain unchanged, the increase in the low tide water level at the open ocean boundary may lead to a reduced energy slope during an ebb tide cycle (not necessarily in all estuaries), as depicted Fig. 4(d). The low tide level is critical as this is when the head difference between the drainage infrastructure or outfalls within the estuary is greatest.

Many estuaries worldwide are surrounded by large areas of low-lying floodplains in the lower reaches, which are either above current high tide levels or maintained dry via adequate drainage infrastructures. With SLR, many of these low-lying areas may become intertidal in the absence of protective measures, and in some settings, a relatively small increase in sea levels could lead to a large increase in intertidal areas, as illustrated in Fig. 4 (e). The effect of this increase in intertidal areas will depend on the location, size, and elevation of the new intertidal areas as well as the existing tidal regime of the estuary. For the Chesapeake and Delaware estuaries, it is indicated that the tidal range will decrease in both estuaries under SLR, if adjacent low-lying lands can be inundated, but will increase if protective walls are constructed (Lee et al., 2017). For the upper part of the Delaware estuary, it was found that the tidal range will decrease under future SLR due to additional intertidal areas (Hall et al., 2013). This floodplain/intertidal connection to the main estuarine system under SLR dissipates tidal energy over a larger area and, in some cases, can dampen the resonance effect, as observed in the Bay of Fundy (Pelling and Green, 2013).

In addition, SLR can also shift the tidal wave asymmetry (or flood/ebb domination), which is significant for sediment dynamics and net transport under SLR (Passeri et al., 2015c). Tidal wave asymmetry generally refers to the tidal wave deformation phenomenon where the duration of the falling and rising tide is unequal, resulting in net ebb or flood current velocities (Guo et al., 2019). Tidal asymmetry is important since flood dominated flows may transport sediments landward, while ebb dominated flows result in seaward sediment movements (Passeri et al., 2015c). The effect of tidal asymmetry on the sediment dynamics also depends on the local sediment grain size, shear force, settling velocity, and related factors (Dronkers, 1986; Van de Kreeke and Robaczewska, 1993). Changes in the residual net flow due to SLR may influence the formation of flood or ebb tide deltas (i.e., flood domination tends to move sediment in the flood tide direction) (Dronkers, 1986; Van de Kreeke and Robaczewska, 1993). For instance, in Point aux Chenes and Grand bays in the USA, a decrease in tidal velocities and a shift to an ebb dominant estuary under SLR were observed (Passeri et al., 2015b). Changing asymmetry under SLR can also affect the location of top sites for tidal power installations as it is recommended to exploit sites with tidal symmetry rather than with tidal asymmetry (Neill et al., 2014).

SLR can also impact other aspects of estuarine hydrodynamics (rather than tidal dynamics mentioned above), including mixing and circulation patterns. Estuarine mixing is generated by external forcing (e.g., inflows, wind, tides) and internal responses (viscosity, density) as well as boundary conditions (e.g., roughness), and, hence, is likely to be influenced by SLR. It is demonstrated that the exact location of the tidal mixing front ($=h/U^3$) will likely alter under SLR as rising mean sea levels will change the estuarine water depth and tidal current velocities (for details, see Haigh et al. (2020)). Further, geomorphology of an estuary is a key factor in characterising the circulation pattern. For instance, in the Ria Formosa in Portugal, considerable variations in tidal circulation were observed when considering different morphological scenarios including barrier island rollover and basin infilling. In these scenarios, the total basin volume diminished, the volume of exchanging water increased (relative to SLR), and an increase in flood duration was observed, leading to a variation in circulation patterns (Carrasco et al., 2018).

4.2. Sea level rise and estuarine selected 3rd order responses

As discussed above, SLR will significantly influence estuarine hydrodynamics (2nd order responses). Altered hydrodynamics, in return, affect a range of estuarine 3rd order processes such as the distribution of intertidal vegetation communities and bio-geochemical processes followed by dependent geomorphic adjustments. There are many studies in the literature that provide guidance regarding the impacts of SLR on ecological and ecological estuarine processes (i.e., 3rd order processes) but often not with a clear connection to changes in the physical processes (i.e., 2nd order processes) (Bianchi et al., 1998; Chambers et al., 2014; Day Jr et al., 2012; Gillanders et al., 2011; Kennish, 2019a; Statham, 2012; Tully et al., 2019; Woodroffe et al., 2016). Other studies tried to partially address this limitation, although they primarily linked biological and/or ecological responses to processes at a local scale (e.g., a wetland) (Dominguez et al., 2019; Rodríguez et al., 2017). This section provides selected examples of how altered estuarine hydrodynamics under SLR (as 2nd order processes) may influence 3rd order processes at the system-wide estuarine scale, including the distribution of vegetation communities, geomorphology, and saltwater intrusion through ongoing feedback loops. These examples provide an indication of the complex feedback loops likely to be experienced under SLR but are not a comprehensive list of potential impacts.

Fig. 5 conceptually illustrates how altered estuarine hydrodynamics under SLR can potentially influence the timing and depth of inundation, vegetation communities, geomorphic adaptation, as well as the sunlight penetration in estuaries and intertidal zones. For instance, SLR can induce changes in tidal range, which then influences intertidal ecosystems, depending on the size of the estuary and sediment supply (Leuven et al., 2019). As illustrated in Fig. 5, increased water depths

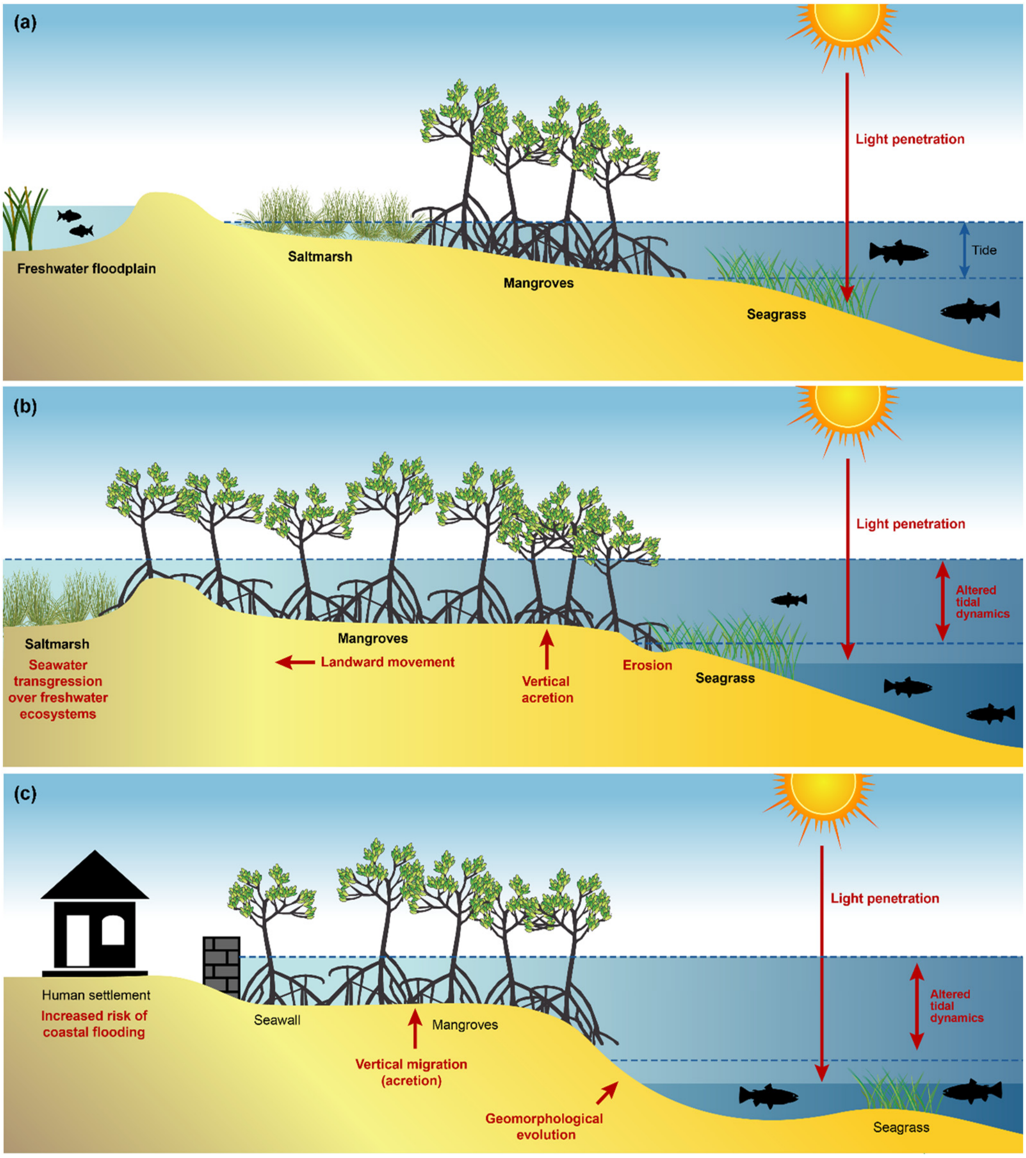

Fig. 5. Estuarine 2nd and 3rd order responses to SLR illustrating tidal dynamics, coastal squeeze, vegetation community, bed morphology and sunlight penetration in intertidal ecosystems (a) before SLR, (b) after SLR, and (c) feedback loops among the processes (after Dominguez et al. (2019)).

alter inundation patterns over a tidal cycle, increasing the tidal range in the landward direction, thereby expanding the area suitable for the establishment of intertidal ecosystems. If the sediment supply decreases over time, the increasing water depth can increase the sediment trapping ratio in the system (Yuan et al., 2020), bring about loss of intertidal areas (Van der Wegen et al., 2017), and thereby alter the geomorphology and dynamics of the system through feedback loops. If the rate of SLR exceeds the accretion ability of an estuary, an alteration in vegetation composition and open water coverage are predictable, leading to further changes in estuarine dynamics (Rayner et al., 2021; Sadat-Noori et al., 2021). Further, as many intertidal ecosystems border on hard or armoured shorelines, erosion and drowning progressing from the ocean side, towards the hardened shorelines, may result in coastal squeeze (Kirwan and Megonigal, 2013). In these circumstances, the intertidal ecosystems cannot migrate upland and undergo a reduction in area, leading to further changes in hydrodynamics (Kirwan and Megonigal, 2013; Kirwan et al., 2016) (Fig. 5).

SLR can also influence estuarine turbidity structure. In the Gironde estuary in France, the turbidity maximum, which is physically controlled by tidal asymmetry and density gradients, has changed as mean sea levels increase (van Maanen and Sottolichio, 2018). In this example, SLR induced tidal amplification, which strengthened the tidal currents in the estuary and shifted the tidal asymmetry and density gradients. The altered tidal range, current, and density gradients then influenced the location and strength of the turbidity maximum in the estuary (van Maanen and Sottolichio, 2018). In a process that is comparable to the effects of SLR, channel deepening and the subsequent reduction in frictional effect have altered the tidal amplitude and tidal asymmetry in the Ems estuary, resulting in an upstream migration of the turbidity maximum and an increase in suspended matter concentrations as well as the formation of a fluid mud (de Jonge et al., 2014; Dijkstra et al., 2019; van Maren et al., 2015). In this feedback loop, the changes in suspended sediment dynamics and the development of mud layers have led to reduced mixing and bed friction, thereby influencing estuarine hydrodynamics (de Jonge et al., 2014; Dijkstra et al., 2019).

As indicated in Fig. 4(b), SLR can force tides further upstream within estuaries into formerly non-tidal zones, leading to the loss of freshwater ecosystems due to saline water intrusion (Ensign and Noe, 2018). As per Eq. (2), and as tidal prism and water depth are likely to increase under SLR, the saltwater intrusion length may increase under SLR. Prandle (2004) theoretically indicated that $\lambda \propto h^2$, highlighting that deeper water depths (e.g., due to SLR) can increase the saltwater intrusion length. Detailed numerical studies in the Delaware estuary (Ross et al., 2015), Yangtze River estuary (Chen et al., 2016a; Chen et al., 2020), Changjiang estuary (Song et al., 2020), Pearl River estuary (Chen et al., 2016b), Sebou estuary (Haddout and Maslouhi, 2018), and St. Johns River estuary (Mulamba et al., 2019) have also confirmed that SLR will likely increase the saltwater intrusion length, affecting freshwater ecosystems and aquifers.

In summary, when assessing the impacts of SLR in estuaries, it is important to account for interactions and complex feedback loops between estuarine hydrodynamics, geomorphic conditions, water quality and vegetation communities in addition to human activities. While the examples in this section indicate that some knowledge has been gained on the effects of SLR on a few selected ecological estuarine processes, other aspects require further attention. Future research should address these knowledge gaps, including improving linkages between the effects of SLR-induced changes in the hydrodynamic regime of estuaries with variations in geomorphology, vegetation distribution, bio-geochemical processes, and interconnected feedback loops over various temporal and spatial scales.

5. Sea level rise implications for estuarine management

The impacts of SLR on estuarine 2nd and 3rd order processes, as well as on the feedback mechanisms presented above, have significant implications for estuarine management which are briefly discussed in the following sub-sections. Integrated management of estuaries under accelerating SLR requires in-depth knowledge of the various interlinked pathways between rising mean sea levels, other climatic changes (e.g., rising temperature, altered catchment inflows), and complex physical, ecological, and bio-geochemical processes. However, estuarine decision-making is rarely based on detailed whole-of-system hydrodynamic assessments. Instead, estuarine management is typically driven by the need to preserve or improve human values and assets (e.g., shipping and navigation, swimming, fishing, aesthetics, drainage, farming, flood protection, etc), or prominent species such as well-known fauna (e.g., mammals, birds, fish, amphibians), flora (locally endangered species), or significant and/or threatened ecosystems (e.g., high priority wetlands) (Boerema and Meire, 2017; Iwamura et al., 2014; Janousek et al., 2016; Meyers and Luther, 2020; Moomaw et al., 2018; Peirson et al., 2015; Sadat-Noori et al., 2021; Thorne et al., 2018). As shown in this review, however, the ability to accurately model these complex 2nd and 3rd order processes and feedback loops (i.e., sediment erosion and accretion, distribution of intertidal vegetation communities) over various time scales (e.g., daily to decadal) remains limited (see Table 1 and references therein). Bias towards decision-making based on particular human or ecological values, combined with the uncertainties involved with modelling these processes in the future, poses a significant conundrum for estuarine managers. This conundrum is elaborated in the following sub-sections by discussing selected management challenges.

5.1. Modelling capabilities vs. management requirements

The multitude of nonlinear 2nd and 3rd order responses of estuaries to SLR has significant implications for estuarine management over the coming decades. As elaborated in Sections 3 and 4, the still widespread use of static models is unlikely to provide accurate estimates of the effects of SLR on future water levels, tidal prism, and intertidal inundation patterns. Further, the review of published numerical studies of SLR in estuaries (provided in Section 4) illustrates that most of today's complex models only account for a limited subset of 1st order driving forces as well as 2nd and 3rd order processes and responses. This limitation highlights that existing estimates of estuarine changes under SLR, even if inferred from complex and data-rich numerical models, are subject to a range of uncertainties, with geomorphic and hydro-ecologic feedback loops over various temporal and spatial scales remaining key challenges (Mitchell and Uncles, 2013; Passeri et al., 2015c; Rodríguez et al., 2017). On top of that, any inaccuracies in the estimates of the future hydrodynamic regime may propagate into estimates of longer-term 3rd order responses (e.g., salinity intrusion, geomorphic adjustment, intertidal vegetation communities). Consequently, future decision-making in estuaries that requires robust estimates of 2nd and 3rd order processes should carefully consider the limitations of the available models (i.e., static, analytical, and hydrodynamic) to accurately simulate the various interlinked processes.

Importantly, many estuarine management decisions are based on 3rd order ecological processes and their associated ecosystem services (e.g., fishing, tourism). This includes the preservation (and/or restoration) of ecosystems or endangered species, such as avifauna, aquatic species (e.g., salmonid species), or selected flora, which often drive decision-making (Erwin, 2009). This is most apparent in internationally important systems such as Ramsar listed intertidal wetlands that have identified limits of acceptable change that are often indirectly reliant on the tidal regime (e.g., hydroperiod) (Sadat-Noori et al., 2021). As shown in Section 4 and Table 1, current modelling investigations of estuaries under SLR are largely limited to 2nd order processes (i.e., physical changes). Significant additional research in modelling of SLR and other climate change impacts in estuaries (e.g., future freshwater inflows, water temperature, salinity, acidity, morphology) is required to effectively identify future hazards and establish holistic, long-term, and evidence-based estuarine management strategies.

5.2. Managing shifting boundaries and intertidal zones

In estuaries, tidal currents, wind waves, and river discharges are key factors determining the magnitude and direction of sediment transport, and thereby, influencing the erosion/deposition dynamics (Burchard et al., 2018; De Swart and Zimmerman, 2009). The geomorphic alteration of estuaries is also driven by a variety of other factors, including the frequency, magnitude, and sequencing of fluvial floods and storm surges, as well as land use changes in the catchment that influence fluvial sediment loads (Cooper, 2002; Leuven et al., 2019; Rogers and Woodroffe, 2016). Due to the limited ability to predict these future events, and their potential influence on geomorphic changes, some researchers suggest to explore historic datasets for locally-relevant information on the potential impacts of future SLR (Talke and Jay, 2020). However, as the future rate of change is unprecedented, and likely exceeds the equilibrium rate of geomorphic adaptation, the use of historic analogues may not always be of value for use in future risk assessments.

The geomorphic adjustment of estuaries under SLR will also strongly depend on future decisions as to how the tidal prism is managed. For instance, as tidal levels increase, large floodplain areas may no longer be viable for agricultural use, and levees or other flow control structures may be removed to permit tidal ventilation/flushing. Depending on the areas opened to the tides, these potential changes in the tidal prism may influence the tidal dynamics in shallow estuarine channel networks and at the estuary mouth, which, over time, may lead to significant geomorphic changes. Consequently, every significant intervention affecting the intertidal zones (e.g., removal of armoured shorelines, tide gates, and drainage networks) should be carefully assessed with regards to its impacts on the wider system response.

Closely linked with the geomorphic adaptation of estuaries under SLR is the dynamic response of intertidal vegetation communities to rising sea levels. The bio-geomorphic response of intertidal vegetation communities to current projections for mid-to-end-of-century SLR rates under RCP 8.5 remains the subject of an ongoing and conflicting scientific debate. The rate of global mean SLR is already accelerating (Nerem et al., 2018), posing an increasing threat to intertidal wetlands with some studies predicting that up to 78% of worldwide coastal wetlands are likely to submerge by 2100 (Spencer et al., 2016). In a recent study, Saintilan et al. (2020) reported that historically, the maximum rate of SLR that mangrove forests can adapt to via vertical accretion is 6.1 mm/year, which is likely to be exceeded in some regions globally by 2100 under RCP 8.5 (15 mm/year in 2100 (Oppenheimer et al., 2019)). In contrast, other studies suggest that increases in global intertidal wetland areas are possible under SLR (Kirwan et al., 2016; Schuerch et al., 2018). However, these increases depend on the availability of accommodation space for new intertidal wetlands to form upslope in adjacent lands (although some newly submerged ecosystems may become open water) (Kirwan et al., 2016). The degree to which intertidal vegetation communities will be able to migrate horizontally depends on site-specific factors, such as the presence/absence of physical barriers, geomorphic conditions, management paradigms, and the underlying socio-economic complexities (e.g., private land ownership, cost-benefit of defend vs. restore) (Kirwan et al., 2016; Schuerch et al., 2018).

Existing limitations in modelling capability, and inherent uncertainties in future environmental conditions, suggest that estuarine management under SLR requires significant enhancements of the current modelling tools. Indeed, the decision-making process for (and within) estuaries requires extensive interdisciplinary studies that consider the implications of SLR on hydrodynamics as well as ecological, biogeochemical, and dependent processes. Management aims and values may need to consider these uncertainties and the ability/inability of models to provide management advice.

5.3. Managing altered tidal levels

Under increasing mean sea levels, the peak of high tides may approach present-day flood levels, leading to an increase in nuisance and devastating flood events (Moftakhari et al., 2017). As recently reported by the Intergovernmental Panel on Climate Change (IPCC), any minor increase in mean sea level can considerably enhance the frequency and intensity of flooding by acting as an elevated platform for tides, waves, and storm surges (Oppenheimer et al., 2019). For instance, even a SLR of only 5–10 cm can double the frequency of flooding in the tropics (Vitousek et al., 2017). In addition, a moderate SLR projection by 2050 may result in high tide levels above flood levels for several global regions, threatening ~150 million people who live in these areas (Kulp and Strauss, 2019). To develop accurate mitigation plans against estuarine flooding, it is vital to have precise predictions of changes in estuarine hydrodynamics and the associated feedback mechanisms that occur over various temporal scales. In addition to SLR, other mechanisms that may also enhance flood risks including river inflows, precipitation, storm surges, and anthropogenic activities (e.g., urbanisation) should be taken into account as they can add complexity into predicting compound flood events (Moftakhari et al., 2017; Paprotny et al., 2018; Wahl et al., 2015). Therefore, it is recommended that future studies of estuarine flood management should examine the influence of all flood contributory factors (rather than SLR alone).

To date, the majority of estuarine SLR hydrodynamic studies have focused on future high tide estimates (i.e., the level of high tide after SLR) and the associated inundation of adjacent lands. With SLR, however, the entire tidal dynamics (including low tide levels) will change (Khojasteh et al., 2020). The variations in low tide levels can potentially lead to reduced drainage (or prolonged inundation) of adjacent low-lying lands, thus impacting aquaculture/agriculture and urban systems (Fig. 6). The variations in water level (high and low tide levels), along with the changes in tidal current velocity and sediment dynamics (geomorphology) under SLR, may also influence navigation through estuarine channels. The increased mean sea level may permit deeper-drafted vessels to navigate an estuary, and the altered duration and frequency of slack water can influence maritime traffic management (Meyers and Luther, 2020). Changes in tidal energy dynamics under SLR may intensify sedimentation and silt up the estuary navigation channels, creating economic challenges in regions with large estuarine harbours (Oppenheimer et al., 2019). Therefore, future studies related to SLR and estuary management should consider follow-on effects not solely related to future high tide levels but to the full hydrodynamic tidal regime, and the associated implications to floodplain drainage, drainage efficiency, and navigation. Until these altered tidal levels have been accurately examined, planning decisions related to inundation, drainage and navigation should be undertaken with caution.

6. Conclusions

Estuarine ecosystems and adjacent coastal communities, with often dense human populations, may be vulnerable to accelerating SLR due to their proximity to the open sea and low-lying elevations. The present review highlights that despite the potentially far-reaching physical and environmental impacts associated with SLR and substantial improvement in numerical models, significant knowledge gaps remain regarding the current ability to accurately connect SLR-induced physical changes (e.g., altered hydrodynamics) to geomorphic and hydro-ecologic feedback loops at an estuary-wide scale. Further, most SLR studies in estuaries primarily focused on future high tide levels and the associated overland flooding, despite the broad implications of rising low tide levels on navigation, inundation patterns, drainage efficiency, and sediment dynamics

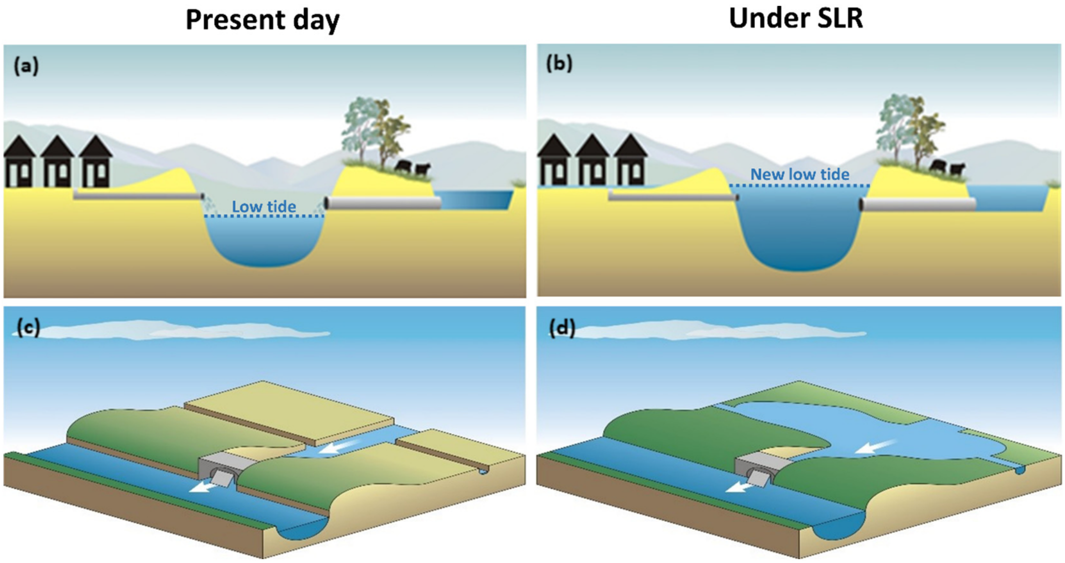

Fig. 6. Increased estuarine low tide level under SLR causes reduced drainage ((a) vs (b)) and prolonged inundation of low-lying areas ((c) vs (d)).

(e.g., geomorphology). The limited ability to accurately predict the impacts of SLR on interlinked physical, ecological, and bio-geochemical processes over various temporal and spatial scales in estuaries is likely to pose challenges in developing holistic, whole-of-system management strategies for estuarine environments. In the face of accelerating SLR, estuarine managers will be required to make increasingly difficult decisions based on relatively uncertain predictions. As such, further interdisciplinary research is recommended.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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