Quantifying the Effects of Sea Level Rise on Estuarine Drainage Systems

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Key Points:

- The *drainage window* is conceptualised and applied to two estuaries to quantify the effects of sea level rise on tidal drainage systems.
- Areas that are protected from intermittent flooding may be vulnerable to chronic waterlogging due to impeded drainage.
- Areas characterised by tidal dampening and ebb-dominant asymmetry are more vulnerable to reduced drainage.

Abstract

Constructed flood mitigation and drainage systems are integral to the development of many estuarine floodplains. These systems function throughout the tidal range, protecting from high water levels while draining excess catchment flows to the low water level. However, drainage can only be achieved under gravity when suitable water levels are available for discharge. Changes to the tidal range and symmetry that occur throughout estuarine waters mean that the window of opportunity for gravity discharge will vary dynamically within and between different catchments. It will also be affected by sea level rise (SLR). Concerns regarding the impacts of SLR have focussed on the acute effects of higher water levels, but SLR will affect the full tidal range and drainage systems will be particularly vulnerable to changes in the low tide. This study introduces the concept of the *drainage window* to assess how the tidal regime may influence the drainage of estuarine floodplains, and particularly the potential impact of changing tidal regimes under SLR. The results of applying the drainage window to two different estuaries indicate that SLR may substantially reduce the opportunity for discharging many estuarine floodplain drainage systems. Additionally, measures proposed to mitigate flood risks may exacerbate drainage risks. Reduced drainage creates a host of chronic problems that may necessitate changes to existing land uses. A holistic assessment of future changes to all water levels (including low tide water levels) is required to inform strategic land use planning and management.

Plain Language Summary

Estuaries are the tidal waters located where the rivers meet the sea. The floodplains adjacent to estuaries are some of the most heavily developed areas in the world. Much of

this development relies on integrated flood management and drainage schemes that use one-way valves (floodgates) to protect the floodplains from inundation by high tides and floods, while allowing the floodplain drains to discharge when the water level in the estuary is lower than the water level in the drains. Tidal levels can vary along an estuary, providing greater opportunity to drain some areas than others. This study introduces the concept of the *drainage window* to quantify how much drainage time is available to different catchments within an estuary and to identify the potential impact of sea level rise (SLR) on the drainage of estuarine floodplains. The drainage window was analysed for two estuaries, with the results indicating that SLR may substantially reduce the available drainage time in each. Areas with less time to drain are more susceptible to chronic problems associated with prolonged inundation and waterlogging that may necessitate changes to existing land uses. These results could therefore be used to inform strategic land use planning and management.

1 Introduction

As the nexus between land and sea, coasts and estuaries have been a focal point for human settlement, with their abundance of natural resources and ecosystem services attracting extensive and ongoing development (Martínez et al., 2007; Neumann B, 2015). Worldwide, over one billion people reside less than ten metres above current high tide levels (Domingues et al., 2018; Kulp & Strauss, 2019). Two-thirds of the world's megacities are situated on coasts and estuaries (Oliver-Smith, 2009) and approximately 14% of the world's gross domestic product is generated in the low elevation coastal zone (Magnan et al., 2019).

Globally, the impacts of sea level rise (SLR) are already being experienced in the low elevation coastal zone (Magnan et al., 2019) with the largest changes in tidal dynamics occurring in estuaries (Talke & Jay, 2020). According to the latest report from the Intergovernmental Panel on Climate Change (IPCC), the average global mean sea level is predicted to increase by between 0.28 m and 1.01 m by 2100, relative to 1995 (Masson-Delmotte et al., 2021). A growing body of literature indicates that, within estuaries, the impact of SLR will vary throughout the full tidal range, with diverse effects from high to low tide levels (Haigh et al., 2020; Khojasteh, Glamore, et al., 2021; Talke & Jay, 2020). Each estuary, including tributaries and different reaches within an estuary, may respond differently to SLR (Du et al., 2018; Khojasteh, Chen, et al., 2021).

Implications of changing tidal dynamics on floodplain drainage have received limited attention, with the majority of research focused on the potential impacts of SLR on the extent and frequency of extreme coastal storms and flooding (Bosello & De Cian, 2014; Vitousek et al., 2017), groundwater emergence (Hoover et al., 2017; Manda et al., 2017; Wake et al., 2019) and increased nuisance ("sunny day") flooding resulting from higher high tide levels (B. S. Hague et al., 2020; Hanslow et al., 2019; Karegar et al., 2017). Yet despite the importance of drainage infrastructure in managing these intermittent events, there is little information available regarding the impact that SLR may have on the daily operation of tidally affected drainage systems or on how that impact may be assessed and compared within or between various estuaries.

Much of the development of the low elevation coastal zone has been facilitated by the anthropogenic drainage of floodplains and wetlands, predominantly for agriculture, but also for urban, maritime, and industrial use (Church et al., 2010; James G Titus et al., 1987; Tulau, 2011). Channels, pipes and culverts have been installed throughout estuarine catchments to efficiently remove excess surface and groundwater from backswamps, wetlands, and floodplains (J. G. Titus et al., 2009). These constructed drainage systems play a critical role in maintaining public health and amenity (Barbosa et al., 2012; Gaffield et al., 2003). In agricultural catchments, floodplain drainage schemes are designed to minimise waterlogging and enable access and trafficability over farmlands (Vlotman et al., 2020). Drainage systems are also frequently implemented to optimise crop yields (Cavazza & Pisa, 1988; Hurst et al., 2004). In urban and industrial environments, drainage systems are primarily designed to mitigate flood risk (ASCE, 1992).

A typical floodplain drainage scheme consists of a series of interconnected open channels or piped culverts which allow surface and groundwater to drain under gravity and ultimately discharge into the adjacent waterway. Frequently, natural levees are augmented and dykes and seawalls constructed to protect estuarine floodplains from tidal inundation or high water levels (Kroon & Ansell, 2006; Lugo & Snedaker, 1974; Poulter et al., 2008). To further enhance this protection, one-way valves (floodgates) are often installed where the drainage scheme discharges to the estuary to prevent tidal backflows and inundation onto floodplains when estuarine water levels are high (Johnston et al., 2005; Rayner et al., 2015). These floodgates preclude the flow of tidal waters from the estuary to the floodplain, only permitting discharge from the floodplain catchments when water levels in the catchment drains are higher than those in the estuary, providing a positive hydraulic head. To maximise the opportunity for discharge, floodgates are typically located at the lowest tidal water levels (Ruprecht et al., 2018).

At any point within an estuary, the availability of a positive hydraulic head is influenced by the upstream catchment runoff characteristics (upstream water level, or hydraulic head) and the downstream tidal water elevation (downstream hydraulic head). The tidal water levels are characterised by the amplitude (tidal range) and shape (tidal asymmetry) of the tidal wave, which may be distorted by the effects of friction, convergence, reflection and inertia (L. C. van Rijn, 2011). Changes to the geometry and/or bathymetry of an estuary may alter the tidal water levels. Additionally, sea level rise (SLR) has the potential to modify the water depth, width convergence, floodplain connectivity or entrance conditions of an estuary, which, in turn, can affect the propagation of tidal waves along an estuary (Haigh et al., 2020; Khojasteh, Glamore, et al., 2021; Talke & Jay, 2020). Any changes to the tidal water levels and/or duration can influence the time available for drainage of the estuarine catchments, which may have significant impacts on current land use and management.

To assess how the tidal regime may influence the drainage of estuarine floodplains, and particularly the potential impact of changing tidal regimes under SLR, this study introduces the concept of the *drainage window.* The drainage window describes the relationship between hydraulic head and the time available for the gravity discharge of floodplain catchments based on local tide characteristics. The drainage window is calculated and applied at two different estuaries in south-east Australia to highlight how SLR may influence floodplain drainage. Model results illustrate how different hydrodynamic responses, under current conditions and future SLR, influence the drainage window. The impact of SLR is then discussed in relation to reduced catchment drainage and potential impacts on existing land management practices. It is anticipated that the drainage window concept may be incorporated in the management of coasts and estuaries to assess the drainage efficiency of various floodplain catchments and predict their relative vulnerability to SLR.

2 Methodology

2.1 Defining the drainage window

Within an estuary, the drainage window is the portion of the tidal cycle when a positive hydraulic head is available to facilitate gravity discharge to the receiving waters at a selected elevation (Figure 1). This describes the temporal period provided both by the tide (at a given water level) and to the drainage catchment (at the same topographic level). Under wet weather and flood conditions, the drainage window will vary dynamically, with differential water levels between the estuary and floodplain drainage system subject to local and regional variations in rainfall distribution and the diverse hydrologic and hydraulic responses of catchments throughout both the estuary and upstream river system. Conversely, during non-flood periods the drainage window at a given site is controlled by chronic tidal conditions. The drainage window would typically be restricted to the ebb tide with floodgates precluding discharge as a negative hydraulic gradient develops during the rising tide. Chronic tidal conditions provide a benchmark for assessing the relative opportunity for flows from different floodplain catchments to discharge to the low tide, with increased potential for waterlogging and prolonged inundation to develop when drainage is consistently limited.

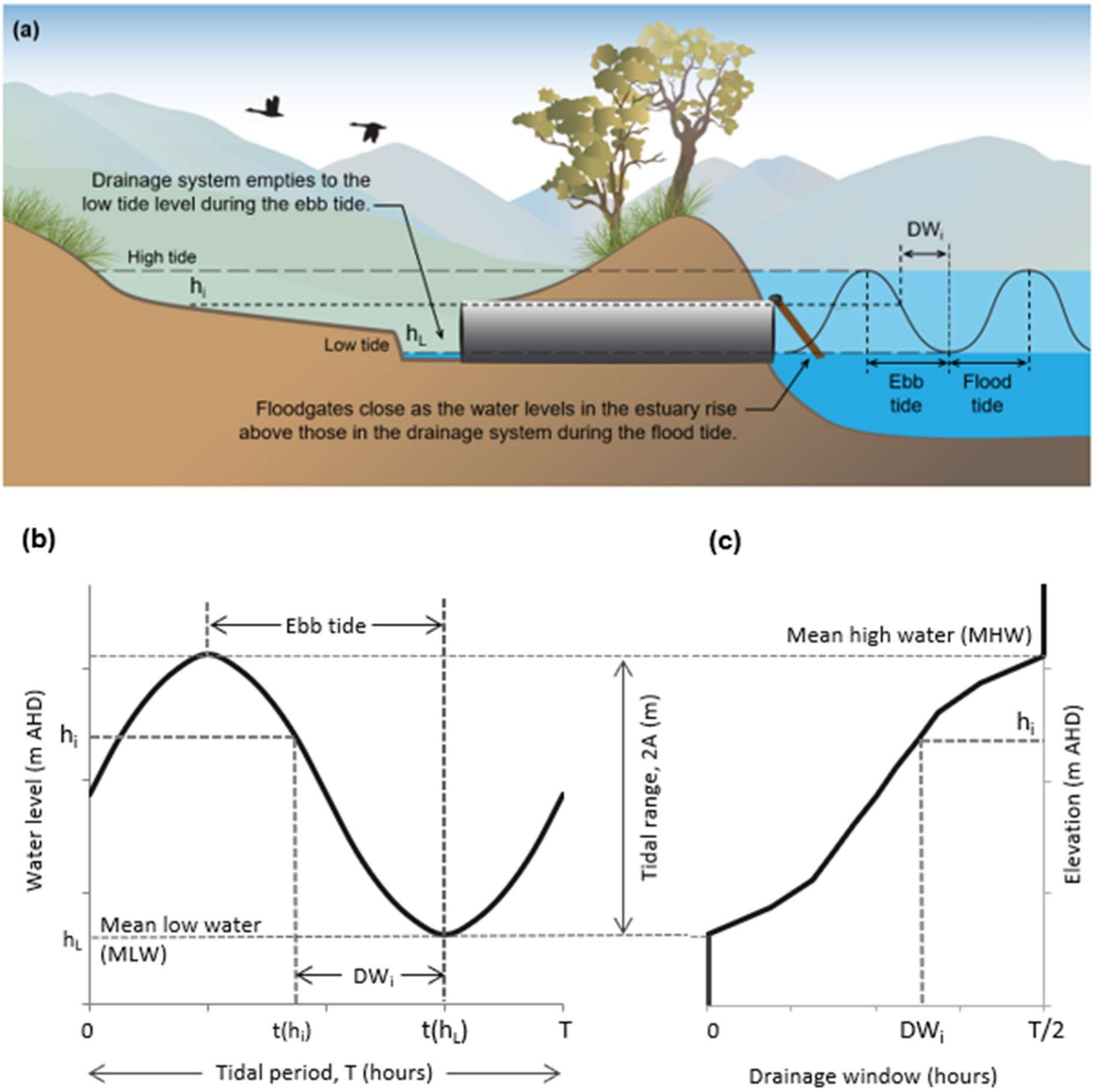

Figure 1 (a) Graphic representation and (b) mathematical definition of the drainage window (DW). Discharge is precluded during the flood tide as increasing water levels in the estuary close the tidal floodgates, limiting the drainage window to the time available to discharge from a given elevation, $h_{i,}$ to the low tide level, h_L. The duration-elevation curve for the drainage window (c) is developed by calculating the drainage window at regular intervals over the full tidal range.

For a given elevation (h_i), the drainage window for a single tidal period (DW_i) is a function of the time (t) it takes for the tide to fall from a given water level h_i to the low tide level (h_L):

$$DW_i = t(h_i) - t(h_L) \quad (1)$$

For an average tidal cycle, the drainage window can be calculated as a function of the tidal amplitude (A) and period (T):

$$DW_i = \frac{T}{A} \ (h_i - MLW) \quad (2)$$

where MLW *is* the mean low water level (Figure 1(b)). For levels at or below the low tide, there is no opportunity for gravity discharge to the receiving estuary:

$$DW_i = 0 \quad when\, h_i \ \leq \ h_L \quad (3)$$

However, the amplitude and period of the tidal cycle are highly variable, and a statistical analysis of a representative time series of tidal cycles is required to calculate the range of drainage windows at any given location:

$$DW_i(mean) = \frac{1}{n} \sum_{tidal\ cycle=0}^{n} \ t(h_i) - \ t(h_L) \quad (4)$$

When calculated incrementally over the full tidal range, the results can be graphed as a drainage window duration-elevation curve (Figure 1(c)), representing drainage conditions specific to the associated catchment. The elevation axis of the drainage window duration-elevation curve can then be equated to topographic levels (as described by a hypsometric curve) to identify areas vulnerable to reduced drainage, or to critical levels within drainage infrastructure to assess capacity.

The drainage window duration-elevation curve may vary throughout an estuary as a change in either the amplitude (tidal range) or the duration of the ebb tide (asymmetry) would alter the hydraulic head and/or the time available for discharge. Comparing the drainage window duration-elevation curve for various catchments can provide an indication of the relative drainage risk throughout an estuary. Additionally, estimating the drainage window under varying hydrodynamic or catchment conditions can provide insights into how natural and anthropogenic changes may impact the drainage of coastal and estuarine floodplains. This study uses SLR as an example, as it is expected that changing water levels would affect the drainage window throughout the full tidal range, with the extent of these changes reflecting varying characteristics of the estuary (Figure 2). For instance, where a rise in water level results in dampening of the tidal range (Figure 2(a)), as may be experienced when the inundation of low-lying land increases energy dissipation, the reduction in the drainage window would be greater at elevations below, and less at elevations above, the mid-tide level. Under either existing or future conditions, dampening of the tidal range would enhance the opportunity for discharge to levels above the mid-tide height compared to tidal amplification (Figure 2(b)), while reducing the drainage window available at lower levels. An increase in the duration of the flood tide under conditions of ebb-dominant asymmetry (Figure 2(c)) would reduce the drainage window over all water levels compared to areas experiencing flood-dominant asymmetry (Figure 2(d)).

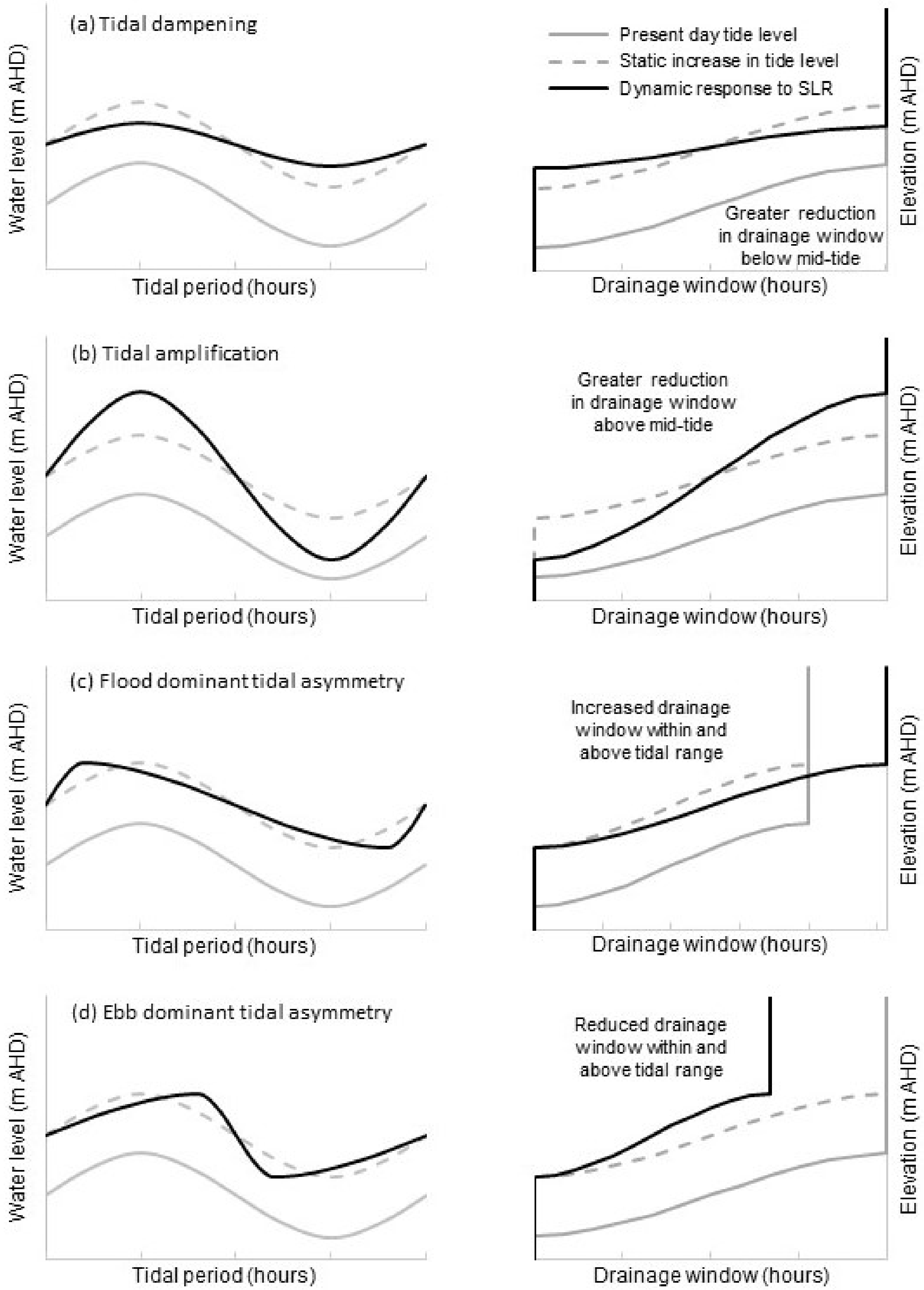

Figure 2 Impacts on a conceptual drainage window (DW) resulting from (a) dampening or (b) amplification of the tidal range and (c) flood dominant or (d) ebb dominant tidal asymmetry compared to that of a static increase in water levels under SLR. The impacts of changes to the

tidal range vary about the mid-tide (mean water level), with opposite effects at high and low water levels.

2.2 Study area

To test the drainage window concept across multiple catchments within different estuary types, the estuaries of the Hastings and Clarence Rivers were selected as they provide insights into how the drainage window will respond to varying tidal range, asymmetry condition, estuary geometry, and SLR scenarios. The Hastings (Figure 3) and Clarence (Figure 4) Rivers are located in north-east New South Wales (NSW), Australia. Each river has a shallow estuary with an open, trained entrance permitting regular exchange of the semi-diurnal tide, which has an average offshore mean tidal range of just under 2 m. The Clarence River is the largest coastal river in NSW, with the estuarine section reaching 108 km inland and incorporating extensive intertidal areas. These features provide an opportunity to examine the effect of varying tidal characteristics on the drainage window compared to the Hastings River estuary, where the main arm is only 36 km long and the variation in the tidal range is almost one third that experienced in the Clarence River estuary (Couriel et al., 2012.).

Table 1 Characteristics of study estuaries

Estuary	Catchment area[a] (km^2)	Estuary area[a] (km^2)	Estuary volume[a] (ML)	Estuary length[a] (km)	Average depth[a] (m)	Variation in tidal range[b] (m)
Hastings River (Wauchope to Port Macquarie)	3,659	30 (0.8%)	52,690	36	1.9	0.511
Clarence River (Grafton to Yamba)	22,055	132 (0.6%)	283,000	110	2.2	1.375

Notes: [a] Environment NSW (2020) [b] Couriel et al. (2012)

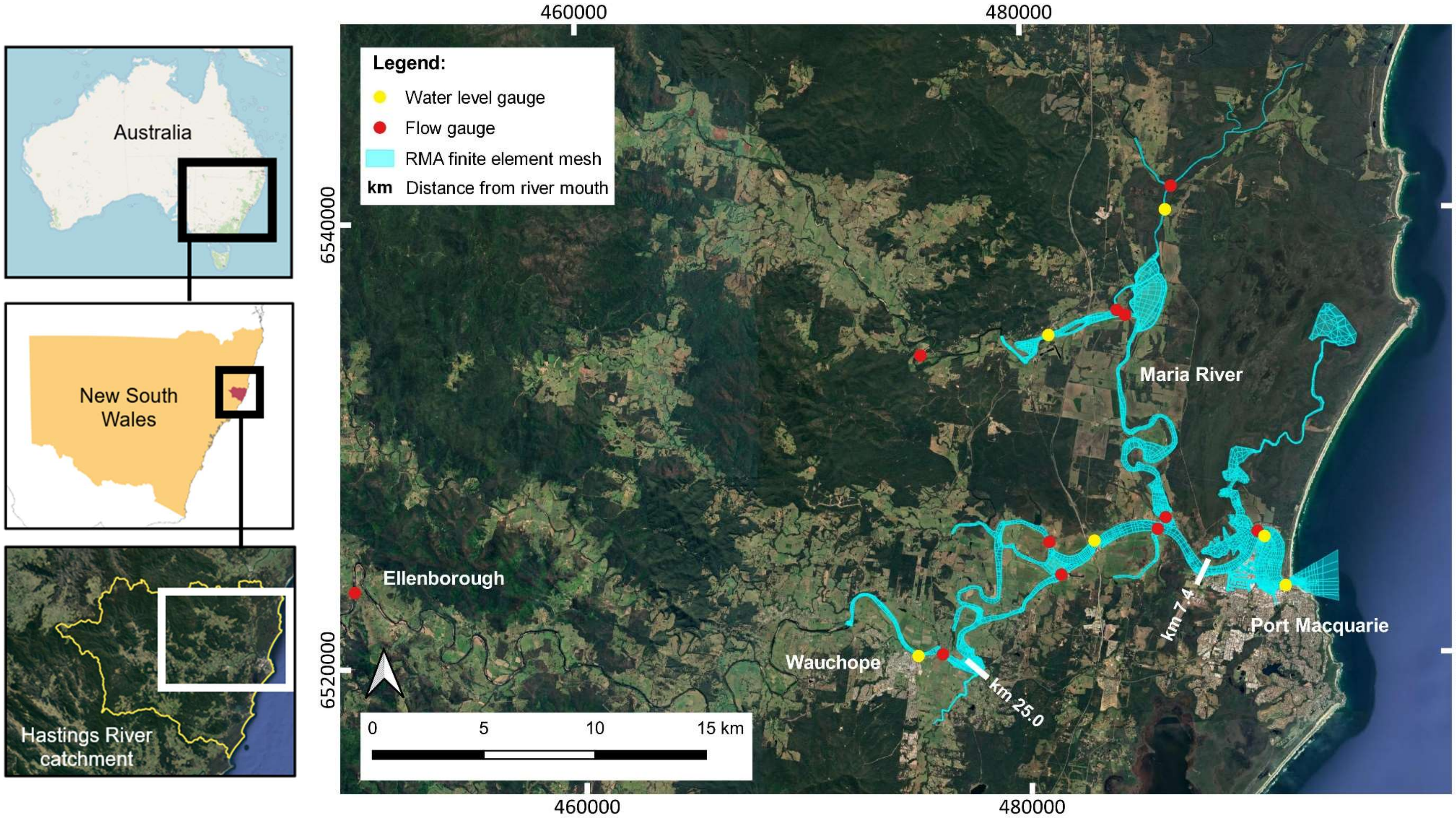

Figure 3 Location of study area and extent of RMA-2 hydrodynamic model for the Hastings River

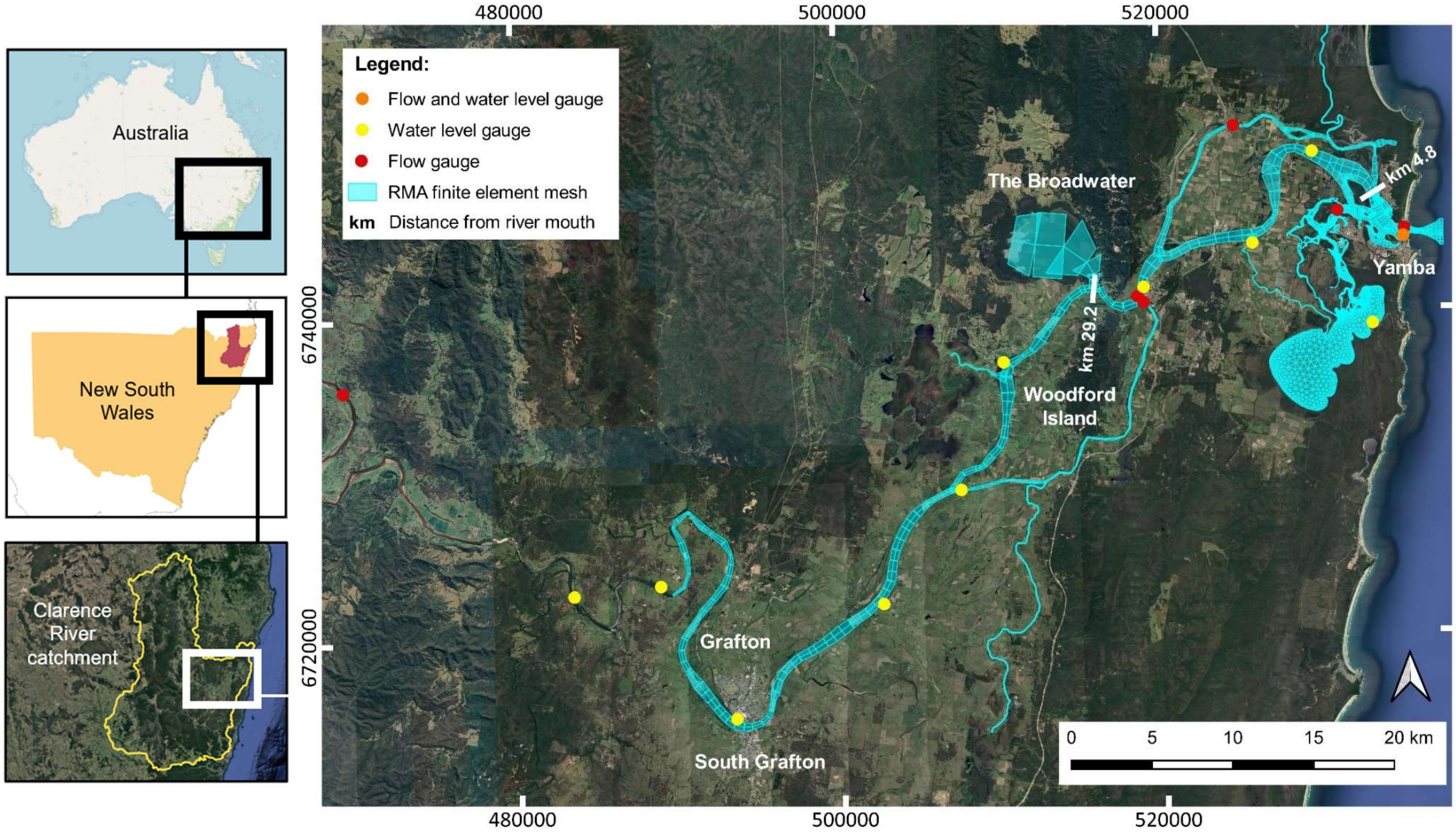

Figure 4 Location of study area and extent of RMA-2 hydrodynamic model for the Clarence River

2.3 Hydrodynamic modelling and water level data

Detailed hydrodynamic models of the estuarine sections of the Clarence and Hastings Rivers were developed using the RMA suite of models to generate long-term, continuous water level data that can be used to determine the statistical distribution of the drainage window. RMA-2 has been widely used to represent tidal estuaries (Elmoustafa, 2017; Hottinger, 2019; Proudfoot et al., 2018). The model solves depth-averaged, shallow water wave equations using the Reynolds' form of the Navier-Stokes equation for turbulent flows to calculate water levels and flow velocities at each node of a flexible, two-dimensional mesh (King, 2015).

The model development, calibration, and verification are detailed by Harrison (2021a) for the Clarence River and Harrison (2021b) for the Hastings River. In summary, the RMA-2 finite element mesh was varied to represent the irregular configuration of each estuary, providing higher resolution at locations with more complex energy transitions such as lagoon entrances, junctions, and bends, as indicated in Figures 3 and 4. Upper reaches of the estuaries, with well-defined channel cross-sections, were modelled using one-dimensional elements. Model bathymetry was obtained from detailed spatial surveys undertaken between 2014 and 2020, with the most recent data given preference. All levels are relative to the Australian Height Datum (AHD), with 0.0 m AHD approximately representative of oceanic mean sea level.

Upstream and downstream boundary conditions were defined by gauged catchment inflows and oceanic tide levels respectively. Long-term water level and flow gauges throughout each catchment were also used for model calibration, which was undertaken by adjusting the Manning's 'n' roughness coefficients, with adopted values varying from 0.020 to 0.023 in the main channels, up to 0.045 in tributaries. The models' ability to represent a range of tidal conditions throughout each estuary was then verified by simulating both 'wet' and 'dry' rainfall years, the selection of which was based on historic rainfall records. The water level and flow gauge locations used for boundary conditions, calibration, and verification of the model are indicated in Figures 3 and 4. The boundary conditions for the representative 'dry' year were adopted for the drainage window analysis to mitigate the impact of catchment hydrology and to isolate, as far as possible, the effect of SLR on the drainage window during typical dry weather (non-flood) periods.

To calculate the statistical distribution of the drainage window, the hydrodynamic models were run over an annual time series representative of dry weather conditions. Varying downstream boundary conditions were applied to reflect the present-day, near- and far-future SLR scenarios (refer to Section 2.4). Water levels were extracted at hourly timesteps at the main drainage discharge locations for each catchment throughout both estuaries (located between 5 km and 29 km along the Hastings River, and between 5 km and 70 km along the Clarence River) and used to calculate the drainage window at 0.1 m increments in elevation.

2.4 Sea level rise scenarios

The impact of SLR on the estuarine water levels was modelled by adjusting the downstream tidal boundary condition to reflect near-future (NF) and far-future (FF) sea levels. Locally adopted SLR benchmarks of +0.4 m by 2050 and +0.9 m by 2100, relative to the mean sea level (MSL) of 1996, were applied (Glamore, 2016). These values represent the median for the representative concentration pathway (RCP) 8.5 'business-as-usual' scenario (Pachauri et al., 2014) and are the most up to date values specific to the NSW coastline and consistent with the Shared Socioeconomic Pathway, SSP5 (Masson-Delmotte et al., 2021). To account for SLR that has occurred between 1996 and 2020, downstream tidal water levels were increased by +4.5 mm/year, as per White et al. (2014), so that all water levels applied in the hydrodynamic models are relative to 2020, nominally the present day (PD). Values for mean sea level applied to the downstream boundaries of each hydrodynamic model for the near- and far-future cases, relative to the present-day, are presented in Table 2.

Table 2 Oceanic boundary SLR predictions for NSW, representing near-future (NF) and far-future (FF) scenarios adjusted to present day (PD).

	NF (2050)	**FF (2100)**
RCP 8.5 - median SLR relative to MSL 1996	+ 0.27 m	+ 0.78 m
SLR from 1996 to 2020 @ 4.5 mm/year	+ 0.11 m	+ 0.11 m
Adopted SLR relative to PD (2020)	+ 0.16 m	+ 0.67 m

2.5 Topographic data

By adopting the same vertical datum for both topographic and water levels, the drainage window analysis can be used to provide an indication of the vulnerability of floodplain catchments to reduced drainage. To this end, one-metre resolution digital elevation models (DEMs) were sourced from the NSW Spatial Services (DFSI NSW Department of Finance) to represent the catchment topography for each estuary. The data is reported to have an accuracy of 0.3 m in the vertical direction and 0.8 m horizontal.

QGIS geographic information system was used to process the DEMs. Discrete catchment areas were defined based on the floodplain topography, including consideration of the connectivity of watercourses, drains and major floodplain infrastructure. The hypsometric curve function in QGIS was used to plot the cumulative area against 0.1 m increments in elevation for each catchment. This increment is representative of water level calibration in the hydrodynamic models and considered suitable for indicating the extent to which changes in the drainage window may impact the floodplain catchments.

3 Results

3.1 Drainage window analysis of exemplar catchment

An analysis of the drainage window under present-day, near- and far-future scenarios is illustrated in Figure 5 for the west Woodford Island catchment, located 38 km upstream from the mouth of the Clarence River (Figure 4). Floodgates and levees around the island perimeter (Figure 5(a)) would protect against the highest annual (dry year) water levels predicted under both present day (maximum predicted water level of 0.84 m AHD) and far-future (maximum 1.61 m AHD) scenarios. Natural watercourses have been adopted, modified, and supplemented by constructed channels to improve floodplain drainage (Figure 5(b)) and enable unimpeded discharge to the present-day low tide at -0.3 m AHD (mean zero drainage window for simulated dry year). Potential inundation by the far-future low tide (+0.3 m AHD) would be limited to 30 ha (Figure 5(h)), however, almost 10% of the existing channels would have no drainage capacity, while the capacity of approximately 40% of the channels (all drainage infrastructure below 0.7 m AHD) would be reduced by over 50% (Figure 5(e)). Thus, despite an apparently high degree of protection from inundation by low or high water levels, the area affected by a reduced drainage window has the potential to cause extensive waterlogging throughout the catchment in the far future.

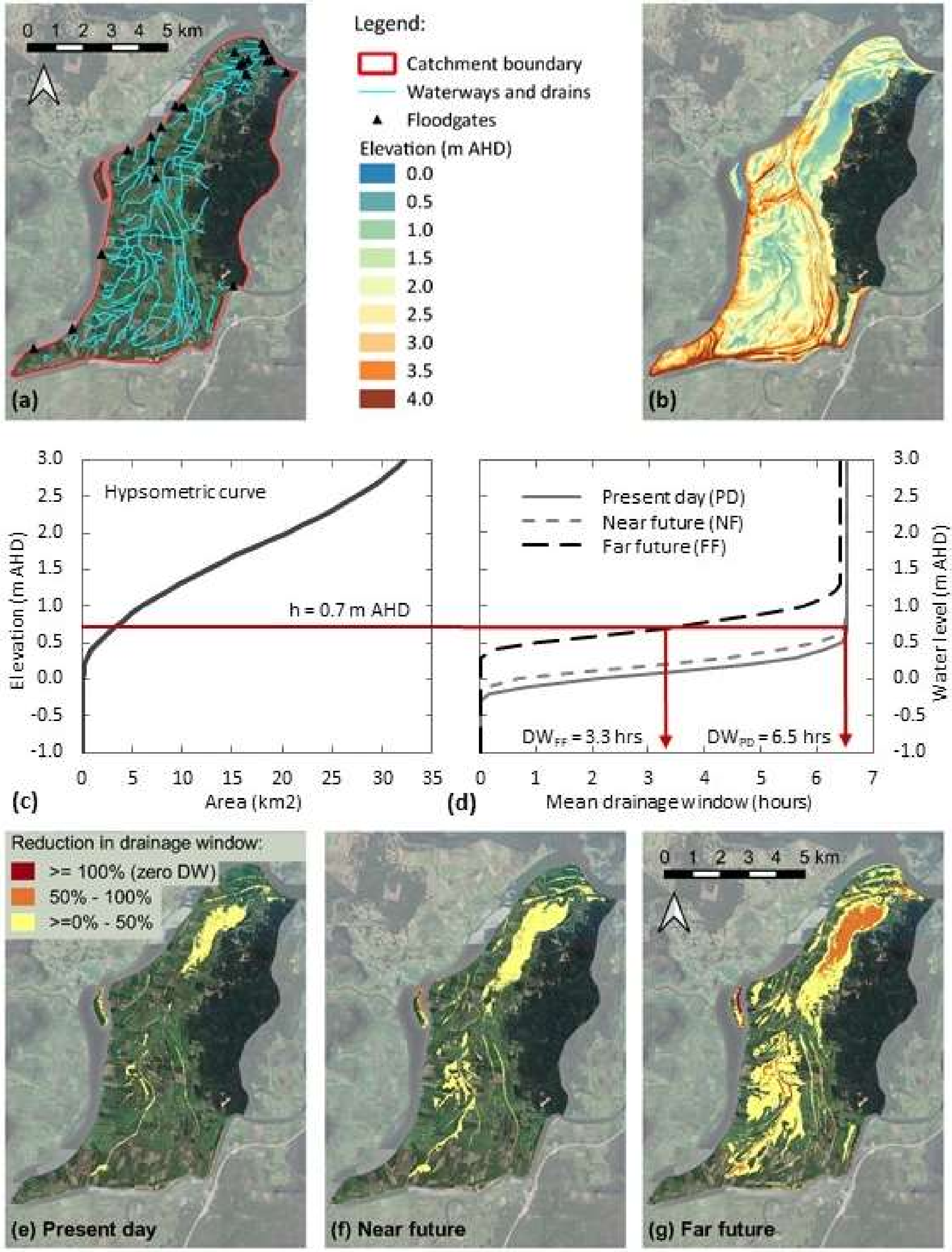

Figure 5 Drainage window (DW) analysis for West Woodford Island. The catchment has a network of natural and constructed drainage channels (a), with catchment topography (b) indicating the perimeter of the island is protected from high water levels by natural and constructed levees. SLR would have a variable impact on the drainage window up to 1.6 m AHD. As indicated on the hypsometric curve (c), over 1,400 ha would be affected by a

reduced drainage window, with a 50% reduction in the mean drainage window (d) at 0.7 m elevation. The extent of the catchment affected by a limited drainage window is presented for (e) present-day, (f) near- and (g) far-future scenarios.

The floodplain extent that would be directly affected by a reduced drainage window is presented in Table 3 and Figure 6 for the Hastings River estuary and Figure 7 for the Clarence River estuaries under present-day, near- and far-future scenarios. Comparing these results with Figure 5 indicates that there would be extensive low tide inundation and waterlogging due to reduced drainage. Currently, the Hastings River, and all but 2 ha of the Clarence River's estuarine floodplains, discharge freely to the low tide at some stage of the tidal range. However, under the far-future scenario, SLR would increase the area of impeded drainage by over 70% in both estuaries. Low-lying backswamp and lagoon foreshore areas would be particularly susceptible to reduced drainage and almost 2,500 ha of the Clarence River estuarine floodplain would be permanently inundated unless a pumped discharge scheme was implemented.

Table 2: Floodplain area directly impacted by limited drainage window

Estuary	Scenario	Area at or below low tide, unable to discharge freely (ha)	Area with immediate discharge limited by up to 50% (ha)	Area with discharge directly limited by tidal range (ha)
Clarence	Present-day	2	896	20,100
	Near-future	6	2,948	23,635
	Far-future	2,499	15,202	34,474
Hastings	Present-day	0	132	8,480
	Near-future	0	124	10,898
	Far-future	124	3,371	15,913

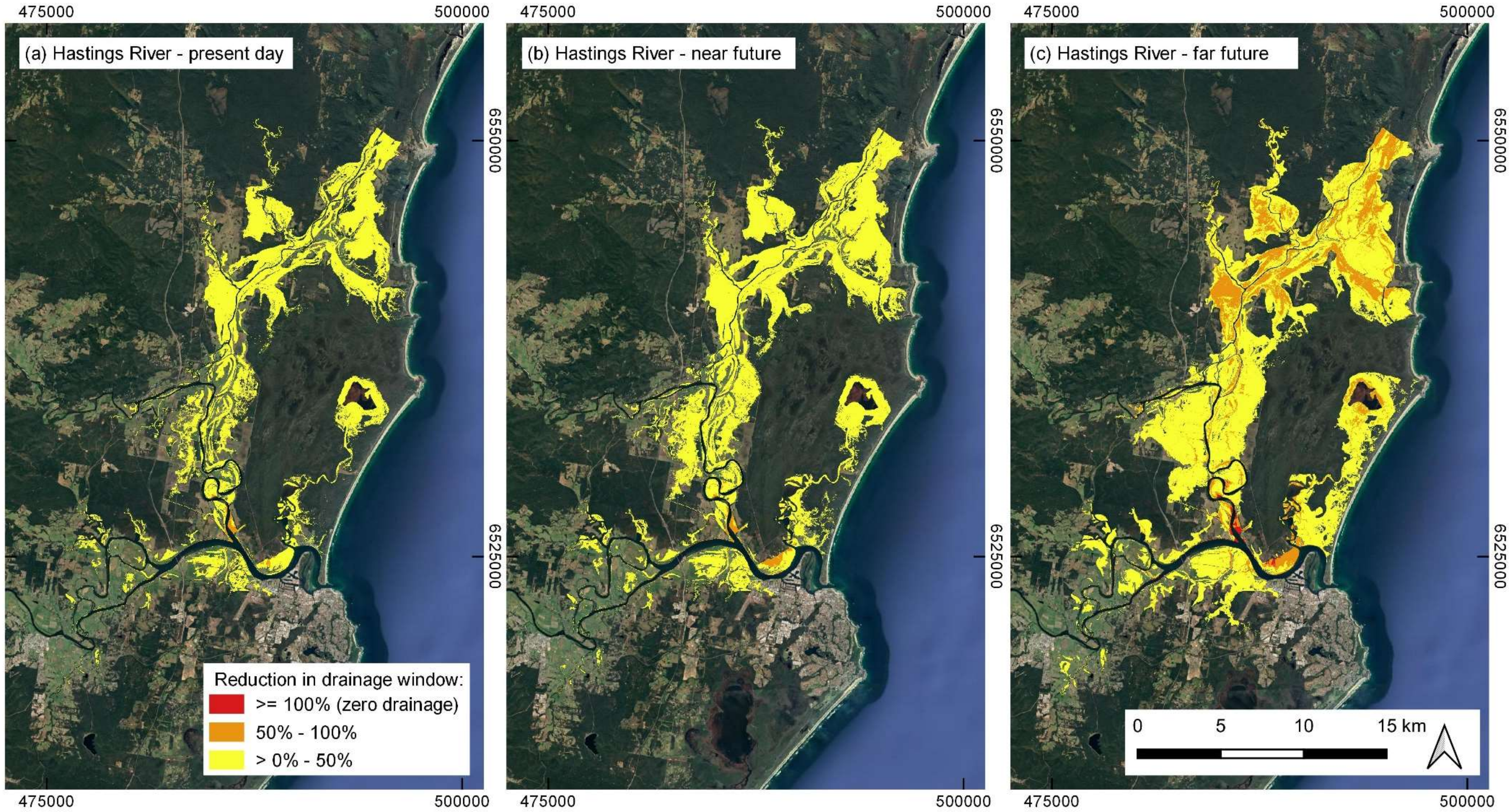

Figure 6 Extent of estuarine floodplain impacted by limited drainage in the Hastings River for (a) present-day, (b) near- and (c) far-future scenarios.

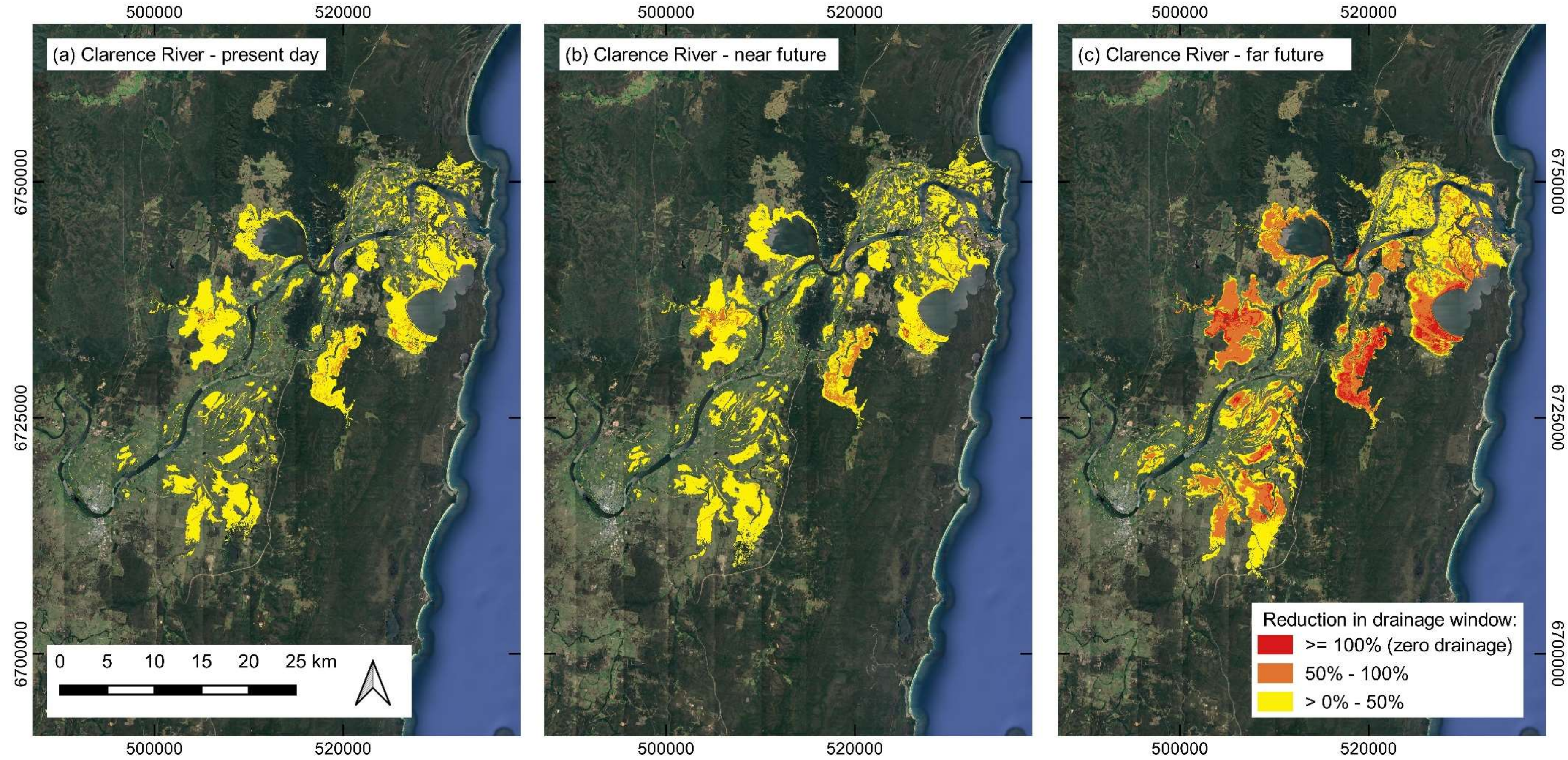

Figure 7 Extent of estuarine floodplain impacted by limited drainage in the Clarence River for (d) present-day, (e) near- and (f) far-future scenarios.

3.2 Variation in the drainage response along an estuary and under SLR

Under present-day conditions, the drainage window varies in response to the tidal range and tidal asymmetry as the tide propagates along the Clarence and Hastings Rivers (Figure 8(a, b)). In the lower reaches of both estuaries, energy dissipation across the deltaic network of anabranches and shoals contributes to tidal dampening and an increase in the ebb tide duration (Friedrichs & Aubrey, 1988). Conversely, in the upper reaches of each estuary, the tidal wave is confined within the main channel where convergence effects tend to amplify the tidal range (Savenije & Veling, 2005). As the tidal range increases, reduced friction at high water allows the wave peaks to travel faster than the troughs (Friedrichs & Aubrey, 1988). As shown in Figure 8(e, f), both estuaries exhibit a tendency for progressively longer duration ebb tides upstream, excluding the major flow bifurcations at the Maria River (km 9.3) in the Hastings River estuary, and The Broadwater (km 29.2) in the Clarence River estuary. At these junctions, increasing hydraulic losses at higher water levels reduce the extent of flood dominance in the tidal symmetry. This effect is particularly pronounced around The Broadwater, where extensive intertidal wetlands slow the propagation of the high tide (Friedrichs & Aubrey, 1988; L. Van Rijn, 2010).

In the main arm of the Hastings River estuary, the impacts of tidal amplification and asymmetry are presently limited, with the effects of channel convergence approximately balanced by frictional losses. For a given water level, the drainage window does not vary by more than 0.5 hours throughout the estuary. Similarly, there is minimal variation in the tidal range, tidal asymmetry and drainage window under the future SLR scenarios (Figure 8(c)). The results are similar to those that would be achieved by the static addition of +0.67 m SLR to present-day water levels, although minor tidal range amplification coupled with an increasingly flood dominant tidal asymmetry (favouring a longer ebb tide duration) in the far-future scenario would slightly reduce the influence of SLR on the drainage window. Throughout the estuary, gravity discharge would currently be available to a minimum level of -0.6 m AHD (Figure 8(a)), increasing to 0.0 m AHD in the far-future (Figure 8(c)).

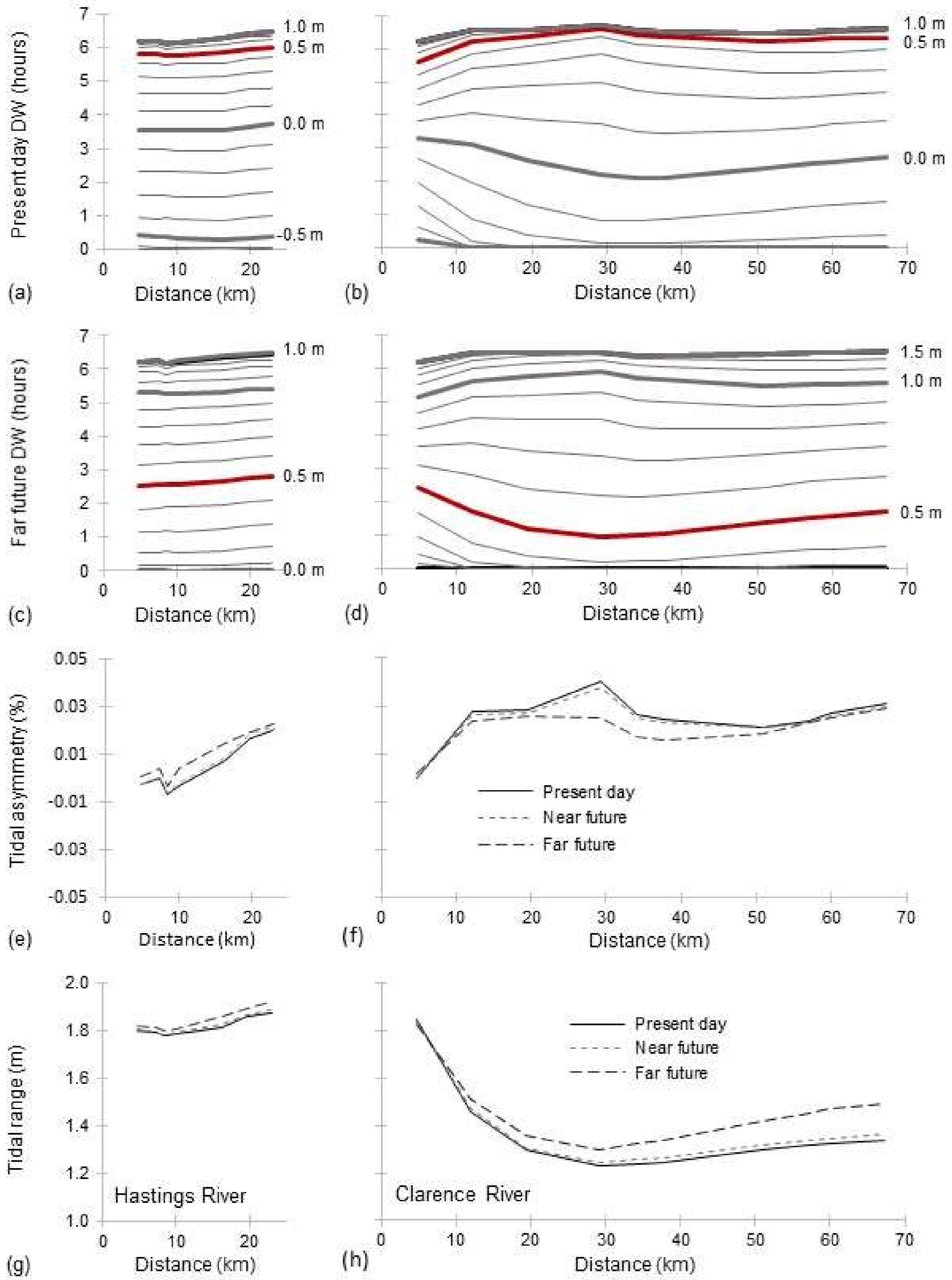

Figure 8 Longitudinal changes in the drainage window, tidal asymmetry and range with distance from the river mouth. Variations in the drainage window (DW) under present-day (a, b) and far-future (c, d) scenarios at 0.1 m increments for the Hastings (left) and Clarence (right) River estuaries. The red line highlights the future reduction in the drainage window at a level of 0.5 m AHD. The variations in the drainage window reflect changes in the tidal asymmetry (e, f) and tidal range (g, h) along the Hastings and Clarence Rivers from the estuary

mouth (km 0). Tidal asymmetry was calculated as the difference in the average annual (dry year) duration of the ebb tide compared to the flood tide. Positive asymmetry indicates flood dominance, whereby the longer duration of the ebb tide extends the drainage window. Tidal range was measured as the difference between the annual maximum and minimum water levels. Changes in the drainage window are particularly pronounced at changes in hydrodynamic conditions such as the Maria River junction (Hastings River km 9.3) and The Broadwater (Clarence River km 29.2).

The tidal range and tidal asymmetry are more varied along the length of the Clarence River estuary (Figure 8(b)). This can be largely attributed to energy losses associated with a complex network of anabranches, channels and shoals, and the diversion of flows into extensive shallow lagoon areas. Comparing the drainage window (Figure 9(b)) of a catchment near the mouth of the estuary (at km 4.8, this is most representative of undistorted tidal conditions) with one near the point of maximum tidal distortion (km 29.2) reveals the direct impact of tidal asymmetry, with greater flood dominance increasing the upstream drainage window by up to 0.5 hours in the present-day and 0.3 hours in the far-future scenario. Under current conditions, the increase in the drainage window attributed to asymmetry would be augmented by the effects of tidal dampening above the mid tide level of 0.2 m AHD. Below the mid tide level, the drainage window would be reduced by up to 1.9 hours at a level of -0.1 m AHD. Higher water levels under future SLR scenarios would reduce the degree of tidal dampening and the maximum reduction in the drainage window would be limited to 1.5 hours at a level of 0.5 m AHD. However, the most substantial change in both estuaries is the reduction in the drainage window resulting from an elevated tidal range under SLR.

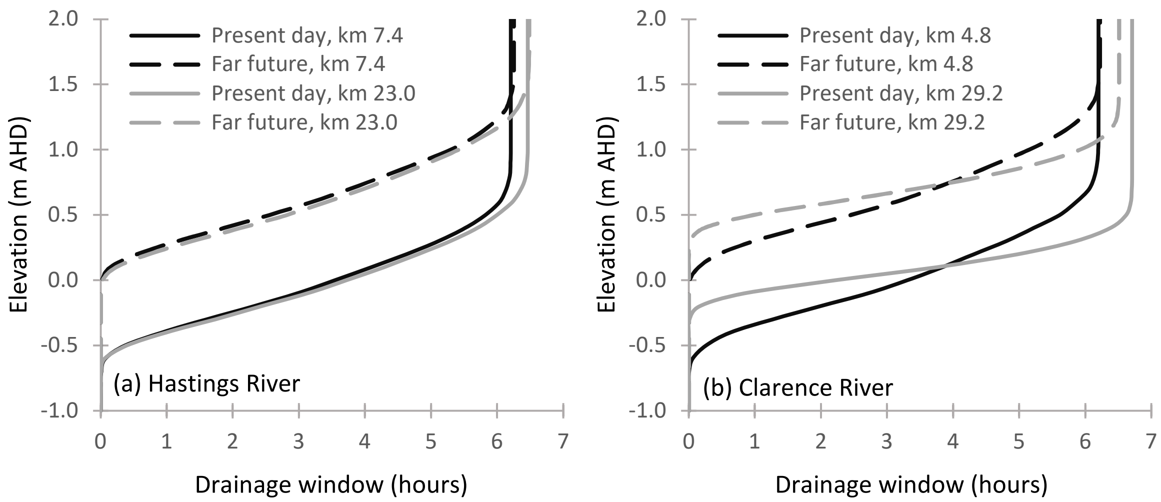

Figure 9 Changes in the drainage window (DW) from the mouth of the estuary upstream to the location displaying the greatest change in the drainage window for the Hastings (a) and Clarence (b) Rivers under present-day and far-future scenarios. The changes in the Hastings River estuary (a) show little variation between sites. In the Clarence River estuary, tidal dampening at km 29.2 reduces the drainage window below the mid tide level. The increase

in the drainage window above the tidal range reflects flood dominant tidal asymmetry. The impacts of tidal dampening and tidal asymmetry are mitigated by SLR, which dominates the change in the drainage window under the far-future scenario.

4 Discussion

To date, studies regarding the potential impacts of SLR on low-lying floodplains have primarily focused on the increased risk of intermittent flood and storm inundation associated with altered high tide levels. In contrast, the reduction in the drainage window predicted in this study highlights the chronic pressures likely to affect floodplain drainage systems. Prolonged periods of reduced drainage are likely to lead to higher groundwater levels, soil waterlogging, and inundation of low-lying areas.

The actual impact realised by a reduced drainage window will depend on the local drainage efficiency, the volume of storage available within the catchment and how much water needs to be discharged, whether this is from excess irrigation, wastewater, intercepted groundwater, or rainfall runoff. As drainage decreases, numerous floodplain catchments will be faced with economic pressures to protect or preserve existing land use. Historically, the response to these pressures has involved the construction of hard engineering structures such as levees, dykes, seawalls, pumps, and diversion channels to defend vulnerable areas from flooding and/or promote drainage (Day & Templet, 1989). However, the construction, operation, and maintenance of this infrastructure is only viable if it is offset by societal and/or economic returns, such as in the Netherlands (Xu & Blussé, 2019). Consequently, pumped systems are more typically implemented where periodic usage can augment gravity discharge, for example in parts of Australia (Yang, 2008), the USA (Lang et al., 2010) and Asia (Marfai & King, 2008). However, the future expansion of pumped discharge systems would only be economically justifiable where there are adequate commercial returns and may be complicated by environmental issues such as land subsidence (Nicholls, 2015; Talke & Jay, 2020) or acid sulphate soils (Dawson et al., 2010).

Where gravity systems remain the preferred option for drainage management, additional attenuating storage may be required to offset the reduction in drainage capacity. The relationship between the local topography and drainage window for a given catchment can be used to identify areas with sufficient capacity within the existing landscape to provide effective attenuation. Examining variations in the drainage window throughout an estuary and comparing it to catchment topography provides a means of identifying floodplain areas at risk from reduced drainage. As such, the drainage window analysis may complement topographic studies when considering future land use and management options and is particularly beneficial in examining future SLR scenarios. Comparing the hypsometric curve to the anticipated change in water levels resulting from SLR may indicate if (and when) a catchment is likely to experience a rapid increase in vulnerability to inundation (Kane et al., 2015). Extending this analysis to encompass the change in drainage window would also indicate the susceptibility of a local catchment to drainage risks. In high-risk drainage areas, there may be substantial merit in considering alternative nature-based solutions, including blue habitat (and blue carbon) restoration projects (Gulliver et al., 2020; Raw et al., 2021; Sheehan et al., 2019). In some circumstances, the removal of tidal barriers to low-lying estuarine floodplains may be used to increase flood protection while creating highly valued coastal and estuarine ecosystems using nature-based solutions to accommodate SLR. This prospect is particularly relevant with the emergence of a global blue carbon market that may incentivise tidal inundation of poorly drained land over other low return agricultural production measures.

High risk drainage areas (with low drainage windows) are associated with tidal dampening or flood dominant tidal asymmetry. Tidal dampening is commonly associated with longer estuaries, estuaries which are prismatic or weakly converging, or those with restricted entrances (Khojasteh et al., 2020). Areas with extensive intertidal flats are also susceptible to tidal dampening (Du et al., 2018; Lee et al., 2017). In these areas, typified by shallow coastal lagoons and backswamps, the reduction in the drainage window due to tidal dampening may be exacerbated by flood dominant asymmetry (Friedrichs & Aubrey, 1988). However, varying responses to changes in water levels may redefine which areas within the estuary are more adversely affected by limited drainage conditions. For example, in many highly developed areas, such as San Francisco Bay (Holleman & Stacey, 2014) and Chesapeake and Delaware Bays (Lee et al., 2017), shoreline protection works have channelised tidal flows, leading to an amplification of the tidal range. Holleman and Stacey (2014) note that concerns have been raised that further reinforcement of the shoreline for flood protection from rising sea levels may increase tidal amplification and the associated flood risks in adjacent areas. Dampening of the tidal range by facilitating the inundation of low-lying areas has been postulated as an alternative flood mitigation strategy (Lee et al., 2017). The results presented in this study indicate that such overbank inundation strategies may impede drainage and increase chronic inundation and waterlogging from rising sea levels. This highlights that consideration of the drainage window may help to provide a holistic assessment of the impacts of changes through the whole tidal range. These changes are not limited to SLR and include natural and anthropogenic activities such as changes to river flow (Jalón-Rojas et al., 2018), sedimentation (Talke & Jay, 2020), dredging (Chant et al., 2018), channel realignment or armouring (Guo et al., 2018) and land reclamation or wetland restoration (Holleman & Stacey, 2014).

5 Conclusion

This study has introduced a ‘drainage window’ concept to quantify and compare the time available for the effective drainage of estuarine catchments under present-day and future SLR conditions. As a proof of concept, hydrodynamic models of the Hastings and Clarence Rivers’ estuaries in Australia were used to simulate tidal responses to varying oceanic water levels under current and future SLR scenarios. Modelling results indicate that the drainage window responds dynamically to changes in tidal range and tidal asymmetry as the tide propagates within an estuary. Tidal dampening and flood dominant tidal asymmetry were highlighted as key contributors to a reduced drainage window. Understanding the interactions between tidal range and tidal asymmetry within an estuary may help quantify potential reductions in the drainage window. This may be particularly important in long prismatic or weakly converging estuaries as they may become increasingly vulnerable to reduced drainage following SLR (Khojasteh, Chen, et al., 2021).

While previous studies have examined the impact of SLR on acute flooding events associated with higher high tides (Ben S. Hague & Taylor, 2021; Hino et al., 2019; Moftakhari et al., 2018), this research highlights chronic impacts that occur across the full tidal range. In direct contrast to flooding risks, which will be exacerbated by increased tidal amplification, reduced drainage capacity is likely to be more pronounced in areas subject to increased tidal dampening. A thorough assessment of the risks posed by SLR at all water levels is therefore required as the reduction in the drainage window could result in changes to land-use and broader management policy. This may provide opportunities for adaptation using nature-based solutions given that shallow coastal lagoon and backswamp areas are particularly susceptible to reduced drainage.

Acknowledgements

The authors thank Priom Rahman for generating continuous water level data from the hydrodynamic models and Anna Blacka from UNSW Sydney for her assistance with the preparation of figures. Katrina Waddington is supported by an Australian Government Research Training Program Scholarshiop. Danial Khojasteh is supported by a UNSW Scientia PhD Scholarship.

Declaration

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

References

ASCE. (1992). *Design and construction of urban stormwater management systems*. Reston, Va. Alexandria, Va.: Reston, Va. : American Society of Civil Engineers.

Barbosa, A. E., Fernandes, J. N., & David, L. M. (2012). Key issues for sustainable urban stormwater management. *Water Research, 46*(20), 6787-6798. https://www.sciencedirect.com/science/article/pii/S0043135412003569

Bosello, F., & De Cian, E. (2014). Climate change, sea level rise, and coastal disasters. A review of modeling practices. *Energy Economics, 46*, 593-605. https://www.sciencedirect.com/science/article/pii/S0140988313001977

Cavazza, L., & Pisa, P. R. (1988). Effect of watertable depth and waterlogging on crop yield. *Agricultural Water Management, 14*(1), 29-34. https://www.sciencedirect.com/science/article/pii/0378377488900571

Chant, R. J., Sommerfield, C. K., & Talke, S. A. (2018). Impact of channel deepening on tidal and gravitational circulation in a highly engineered estuarine basin. *Estuaries and Coasts, 41*(6), 1587-1600.

Church, J. A., Woodworth, P. L., Aarup, T., & Wilson, W. S. (2010). *Understanding Sea-Level Rise and Variability*.

Couriel, E., Alley, K., & Modra, B. (2012). OEH NSW Tidal Planes Analysis 1990–2010 Harmonic Analysis (Report MHL2053). *Sydney, Australia*.

Dawson, Q., Kechavarzi, C., Leeds-Harrison, P. B., & Burton, R. G. O. (2010). Subsidence and degradation of agricultural peatlands in the Fenlands of Norfolk, UK. *Geoderma, 154*(3), 181-187. https://www.sciencedirect.com/science/article/pii/S0016706109003188

Day, J. W., & Templet, P. (1989). Consequences of sea level rise: implications from the Mississippi Delta. *Coastal Management, 17*(3), 241-257.

DFSI NSW Department of Finance, Services and I., Spatial Services. Retrieved from https://elevation.fsdf.org.au/

Domingues, R. B., Santos, M. C., de Jesus, S. N., & Ferreira, Ó. (2018). How a coastal community looks at coastal hazards and risks in a vulnerable barrier island system (Faro Beach, southern Portugal). *Ocean & coastal management, 157*, 248-256. https://www.sciencedirect.com/science/article/pii/S096456911730978X

Du, J., Shen, J., Zhang, Y. J., Ye, F., Liu, Z., Wang, Z., et al. (2018). Tidal Response to Sea-Level Rise in Different Types of Estuaries: The Importance of Length, Bathymetry, and Geometry. *Geophysical Research Letters, 45*(1), 227-235. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017GL075963

Elmoustafa, A. M. (2017). Evaluation of water intake location suitability using a hydrodynamic approach. *Journal of Applied Water Engineering and Research, 5*(1), 31-39. https://doi.org/10.1080/23249676.2015.1118364

Environment NSW. (2020, 29 July 2020). Estuaries of NSW. Retrieved from https://www.environment.nsw.gov.au/topics/water/estuaries/estuaries-of-nsw/

Friedrichs, C. T., & Aubrey, D. G. (1988). Non-linear tidal distortion in shallow well-mixed estuaries: a synthesis. *Estuarine, Coastal and Shelf Science, 27*(5), 521-545. https://www.sciencedirect.com/science/article/pii/0272771488900820

Gaffield, S. J., Goo, R. L., Richards, L. A., & Jackson, R. J. (2003). Public Health Effects of Inadequately Managed Stormwater Runoff. *American Journal of Public Health, 93*(9), 1527-1533. https://ajph.aphapublications.org/doi/abs/10.2105/AJPH.93.9.1527

Glamore, W. C., Rahman, P., Cox, R., Church, J. & Monselesan, D. (2016). *Sea Level Rise Science and Synthesis for NSW*. Retrieved from

Gulliver, A., Carnell, P. E., Trevathan-Tackett, S. M., Duarte de Paula Costa, M., Masqué, P., & Macreadie, P. I. (2020). Estimating the Potential Blue Carbon Gains From Tidal Marsh Rehabilitation: A Case Study From South Eastern Australia. *Frontiers in Marine Science, 7*(403). Original Research. https://www.frontiersin.org/article/10.3389/fmars.2020.00403

Guo, W., Wang, X. H., Ding, P., Ge, J., & Song, D. (2018). A system shift in tidal choking due to the construction of Yangshan Harbour, Shanghai, China. *Estuarine, Coastal and Shelf Science, 206*, 49-60. https://www.sciencedirect.com/science/article/pii/S0272771417302688

Hague, B. S., McGregor, S., Murphy, B. F., Reef, R., & Jones, D. A. (2020). Sea Level Rise Driving Increasingly Predictable Coastal Inundation in Sydney, Australia. *Earth's Future, 8*(9). Article. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85091427283&doi=10.1029%2f2020EF001607&partnerID=40&md5=8792fcb844e4a19c69dd286ca70f506e

Hague, B. S., & Taylor, A. J. (2021). Tide-only inundation: a metric to quantify the contribution of tides to coastal inundation under sea-level rise. *Natural Hazards, 107*(1), 675-695. https://doi.org/10.1007/s11069-021-04600-4

Haigh, I. D., Pickering, M. D., Green, J. A. M., Arbic, B. K., Arns, A., Dangendorf, S., et al. (2020). The Tides They Are A-Changin': A Comprehensive Review of Past and Future Nonastronomical Changes in Tides, Their Driving Mechanisms, and Future Implications. *Reviews of Geophysics, 58*(1), e2018RG000636. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018RG000636

Hanslow, D. J., Fitzhenry, M. G., Power, H. E., Kinsela, M. A., & Hughes, M. G. (2019). *Rising tides: Tidal inundation in south East Australian estuaries.* Paper presented at the Australasian Coasts and Ports 2019 Conference: Future directions from 40 [degrees] S and beyond, Hobart, 10-13 September 2019.

Harrison, A. J., Rayner, D. S., Tucker, T. A., Lumiatti, G., Rahman, P. F., Glamore, W. C. (2021a). *Clarence River Floodplain Prioritisation Study* (WRL TR 2020/06). Retrieved from Sydney:

Harrison, A. J., Rayner, D. S., Tucker, T. A., Lumiatti, G., Rahman, P. F., Glamore, W. C. (2021b). *Hastings River Floodplain Prioritisation Study* (WRL TR 2020/08). Retrieved from Sydney:

Hino, M., Belanger, S. T., Field, C. B., Davies, A. R., & Mach, K. J. (2019). High-tide flooding disrupts local economic activity. *Science Advances, 5*(2), eaau2736. https://advances.sciencemag.org/content/advances/5/2/eaau2736.full.pdf

Holleman, R. C., & Stacey, M. T. (2014). Coupling of Sea Level Rise, Tidal Amplification, and Inundation. *Journal of Physical Oceanography, 44*(5), 1439-1455. https://journals.ametsoc.org/view/journals/phoc/44/5/jpo-d-13-0214.1.xml

Hoover, D. J., Odigie, K. O., Swarzenski, P. W., & Barnard, P. (2017). Sea-level rise and coastal groundwater inundation and shoaling at select sites in California, USA. *Journal of Hydrology: Regional Studies, 11*, 234-249. http://www.sciencedirect.com/science/article/pii/S2214581815002050

Hottinger, S. (2019). *Effects of entrance conditions on tidal hydrodynamics in idealized prismatic estuaries under sea level rise*. Retrieved from

Hurst, C. A., Thorburn, P. J., Lockington, D., & Bristow, K. L. (2004). Sugarcane water use from shallow water tables: implications for improving irrigation water use efficiency. *Agricultural Water Management, 65*(1), 1-19. http://www.sciencedirect.com/science/article/pii/S0378377403002075

Jalón-Rojas, I., Sottolichio, A., Hanquiez, V., Fort, A., & Schmidt, S. (2018). To What Extent Multidecadal Changes in Morphology and Fluvial Discharge Impact Tide in a Convergent (Turbid) Tidal River. *Journal of Geophysical Research: Oceans, 123*(5), 3241-3258. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017JC013466

Johnston, S. G., Slavich, P. G., & Hirst, P. (2005). The impact of controlled tidal exchange on drainage water quality in acid sulphate soil backswamps. *Agricultural Water Management, 73*(2), 87-111. https://www.sciencedirect.com/science/article/pii/S037837740400294X

Kane, H. H., Fletcher, C. H., Frazer, L. N., & Barbee, M. M. (2015). Critical elevation levels for flooding due to sea-level rise in Hawaiʻi. *Regional Environmental Change, 15*(8), 1679-1687. Article. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84947025825&doi=10.1007%2fs10113-014-0725-6&partnerID=40&md5=44bc8c7cdc9027795e15530bbf1b54f8

Karegar, M. A., Dixon, T. H., Malservisi, R., Kusche, J., & Engelhart, S. E. (2017). Nuisance Flooding and Relative Sea-Level Rise: the Importance of Present-Day Land Motion. *Scientific reports, 7*(1), 11197. https://doi.org/10.1038/s41598-017-11544-y

Khojasteh, D., Chen, S., Felder, S., Heimhuber, V., & Glamore, W. (2021). Estuarine tidal range dynamics under rising sea levels. *PloS one, 16*(9), e0257538.

Khojasteh, D., Glamore, W., Heimhuber, V., & Felder, S. (2021). Sea level rise impacts on estuarine dynamics: A review. *Science of The Total Environment, 780*, 146470. https://www.sciencedirect.com/science/article/pii/S0048969721015382

Khojasteh, D., Hottinger, S., Felder, S., De Cesare, G., Heimhuber, V., Hanslow, D. J., & Glamore, W. (2020). Estuarine tidal response to sea level rise: The significance of entrance restriction. *Estuarine, Coastal and Shelf Science, 244*, 106941. http://www.sciencedirect.com/science/article/pii/S0272771420306727

King, I. P. (2015). *RMA2 – A Two Dimensional Finite Element Model For Flow in Estuaries and Streams*. Sydney Australia: Resource Modelling Associates.

Kroon, F. J., & Ansell, D. H. (2006). A comparison of species assemblages between drainage systems with and without floodgates: implications for coastal floodplain management. *Canadian Journal of Fisheries and Aquatic Sciences, 63*(11), 2400-2417.

Kulp, S. A., & Strauss, B. H. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications, 10*(1), 4844. https://doi.org/10.1038/s41467-019-12808-z

Lang, T. A., Oladeji, O., Josan, M., & Daroub, S. (2010). Environmental and management factors that influence drainage water P loads from Everglades Agricultural Area farms of South Florida. *Agriculture, Ecosystems & Environment, 138*(3), 170-180. https://www.sciencedirect.com/science/article/pii/S0167880910001234

Lee, S. B., Li, M., & Zhang, F. (2017). Impact of sea level rise on tidal range in Chesapeake and Delaware Bays. *Journal of Geophysical Research: Oceans, 122*(5), 3917-3938. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016JC012597

Lugo, A. E., & Snedaker, S. C. (1974). The Ecology of Mangroves. *5*(1), 39-64. https://www.annualreviews.org/doi/abs/10.1146/annurev.es.05.110174.000351

Magnan, A. K., Garschagen, M., Gattuso, J.-P., Hay, J. E., Hilmi, N., Holland, E., et al. (2019). Cross-chapter box 9: integrative cross-chapter box on low-lying islands and coasts. In *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (pp. 657-674).

Manda, A. K., Owers, J. E., Jr., & Allen, T. (2017). Simulating marine and groundwater inundation on a barrier island setting under changing sea-level rise scenarios. In (Vol. 49). Boulder, CO: Boulder, CO, United States: Geological Society of America (GSA).

Marfai, M. A., & King, L. (2008). Potential vulnerability implications of coastal inundation due to sea level rise for the coastal zone of Semarang city, Indonesia. *Environmental Geology, 54*(6), 1235-1245. https://doi.org/10.1007/s00254-007-0906-4

Martínez, M. L., Intralawan, A., Vázquez, G., Pérez-Maqueo, O., Sutton, P., & Landgrave, R. (2007). The coasts of our world: Ecological, economic and social importance. *Ecological Economics, 63*(2), 254-272. https://www.sciencedirect.com/science/article/pii/S0921800906005465

Masson-Delmotte, V., Zhai, P., Priani, A., Connors, S. L., Pean, C., Berger, S., et al. (2021). *IPCC: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Retrieved from

Moftakhari, H. R., AghaKouchak, A., Sanders, B. F., Allaire, M., & Matthew, R. A. (2018). What Is Nuisance Flooding? Defining and Monitoring an Emerging Challenge. *Water Resources Research, 54*(7), 4218-4227. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018WR022828

Neumann B, V. A., Zimmermann J, Nicholls RJ. (2015). Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding-A Global Assessment. *PloS one, 10*(3), e0118571. https://doi.org/10.1371/journal.pone.0118571

Nicholls, R. J. (2015). Chapter 9 - Adapting to Sea Level Rise. In J. F. Shroder, J. T. Ellis, & D. J. Sherman (Eds.), *Coastal and Marine Hazards, Risks, and Disasters* (pp. 243-270). Boston: Elsevier.

Oliver-Smith, A. (2009). *Sea level rise and the vulnerability of coastal peoples: responding to the local challenges of global climate change in the 21st century*: UNU-EHS.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., et al. (2014). *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*: Ipcc.

Poulter, B., Goodall, J. L., & Halpin, P. N. (2008). Applications of network analysis for adaptive management of artificial drainage systems in landscapes vulnerable to sea level rise. *Journal of Hydrology, 357*(3), 207-217. https://www.sciencedirect.com/science/article/pii/S0022169408002199

Proudfoot, M., Valentine, E. M., Evans, K. G., & King, I. (2018). Calibration of a Marsh-Porosity Finite Element Model: Case Study from a Macrotidal Creek and Floodplain in Northern Australia. *Journal of Hydraulic Engineering, 144*(2), 05017005.

Raw, J. L., Adams, J. B., Bornman, T. G., Riddin, T., & Vanderklift, M. A. (2021). Vulnerability to sea-level rise and the potential for restoration to enhance blue carbon storage in salt marshes of an urban estuary. *Estuarine, Coastal and Shelf Science, 260*, 107495. https://www.sciencedirect.com/science/article/pii/S0272771421003474

Rayner, D., Glamore, W., & Ruprecht, J. (2015). Predicting the buffering of acid plumes within estuaries. *Estuarine, Coastal and Shelf Science, 164*, 56-64.

Ruprecht, J., Glamore, W., & Rayner, D. (2018). Estuarine dynamics and acid sulfate soil discharge: Quantifying a conceptual model. *Ecological Engineering, 110*, 172-184.

Savenije, H. H. G., & Veling, E. J. M. (2005). Relation between tidal damping and wave celerity in estuaries. *Journal of Geophysical Research: Oceans, 110*(C4). https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2004JC002278

Sheehan, L., Sherwood, E. T., Moyer, R. P., Radabaugh, K. R., & Simpson, S. (2019). Blue Carbon: an Additional Driver for Restoring and Preserving Ecological Services of Coastal Wetlands in Tampa Bay (Florida, USA). *Wetlands, 39*(6), 1317-1328. https://doi.org/10.1007/s13157-019-01137-y

Talke, S. A., & Jay, D. A. (2020). Changing Tides: The Role of Natural and Anthropogenic Factors. *Annual Review of Marine Science, 12*(1), 121-151. https://www.annualreviews.org/doi/abs/10.1146/annurev-marine-010419-010727

Titus, J. G., Hudgens, D. E., Trescott, D. L., Craghan, M., Nuckols, W. H., Hershner, C. H., et al. (2009). State and local governments plan for development of most land vulnerable to rising sea level along the US Atlantic coast. *Environmental Research Letters, 4*(4), 044008. http://dx.doi.org/10.1088/1748-9326/4/4/044008

Titus, J. G., Kuo, C. Y., Gibbs, M. J., LaRoche, T. B., Webb, M. K., & Waddell, J. O. (1987). Greenhouse effect, sea level rise, and coastal drainage systems. *Journal of Water Resources Planning and Management, 113*(2), 216-227.

Tulau, M. J. (2011). Lands of the richest character: Agricultural drainage of backswamp wetlands on the north coast of New South Wales, Australia: Development, conservation and policy change: An environmental history.

Van Rijn, L. (2010). Tidal phenomena in the Scheldt Estuary. *Report, Deltares, 105*, 99.

van Rijn, L. C. (2011). Analytical and numerical analysis of tides and salinities in estuaries; part I: tidal wave propagation in convergent estuaries. *Ocean Dynamics, 61*(11), 1719-1741.

Vitousek, S., Barnard, P. L., Fletcher, C. H., Frazer, N., Erikson, L., & Storlazzi, C. D. (2017). Doubling of coastal flooding frequency within decades due to sea-level rise. *Scientific reports, 7*(1). Article. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85019850825&doi=10.1038%2fs41598-017-01362-7&partnerID=40&md5=22d5766142e43f58ea1c267ee7f69253

Vlotman, W. F., Smedema, L. K., & Rycroft, D. W. (2020). *Modern land drainage: Planning, design and management of agricultural drainage systems*: CRC Press.

Wake, C. P., Knott, J., Lippmann, T., Stampone, M. D., Ballestero, T. P., Bjerklle, D., et al. (2019). New Hampshire Coastal Flood Risk Summary Part 1: Science.

White, N. J., Haigh, I. D., Church, J. A., Koen, T., Watson, C. S., Pritchard, T. R., et al. (2014). Australian sea levels—Trends, regional variability and influencing factors. *Earth-Science Reviews, 136*, 155-174.

Xu, G., & Blussé, L. (2019). Land Reclamation in the Rhine and Yangzi Deltas: An Explorative Comparison, 1600–1800. *Fudan Journal of the Humanities and Social Sciences, 12*(3), 423-455. https://doi.org/10.1007/s40647-018-0223-1

Yang, X. (2008). Evaluation and application of DRAINMOD in an Australian sugarcane field. *Agricultural Water Management, 95*(4), 439-446. https://www.sciencedirect.com/science/article/pii/S0378377407002946