Ashburton Salt

Response to Sea Level Rise

Seashore Engineering
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Prepared for
K+S Salt

Executive Summary

This assessment considers potential impacts to existing intertidal habitats, including mangroves and algal mats, which may be caused by construction of the proposed Ashburton Salt Project located approximately 40 km southwest of Onslow Western Australia, landward of Tubridgi Point.

Analysis of existing intertidal habitats in the proposed project area along the Turbridgi coast, has identified a strong linkage between mangroves and the existing tidal creek network, which controls salinity across the tidal flats, and therefore sets a limit for active mangrove habitat.

In this study, linkages between intertidal habitats and morphology have been used to project mangrove and algal mat habitat response to sea level rise. A morphometric approach (assessment of the relationship between creek morphology and water flow) has been used to characterise the relationship between creek structure and tidal exchange, which is modified by both the proposed infrastructure and sea level rise to assess potential response of mangroves and algal mats to sea level rise.

As samphire habitats cover a small area and are topographically controlled, future behaviour has been inferred from analysis of spatial distributions, tidal dynamics and sea level rise, including anticipated changes to the landforms occupied by samphire.

Evaluation of sea level rise impacts has been undertaken using the summary of projected sea level rise developed for coastal planning in Western Australia (Department of Transport 2010). This recommends a single forecast curve for sea level allowances, based on Intergovernmental Panel on Climate Change (IPCC) model projections:

- Allowance for 0.4 m of sea level rise over the next 50 years (by ~2070).
- Allowance for 0.9 m of sea level rise over the next 100 years (by ~2110).
- Sea level rise is projected to accelerate, with a rate of 0.008 m/yr reached by 2040-2050 and 0.012 m/yr reached by 2070-2080.

Projecting coastal response to sea level rise is not straightforward, as much of the understanding of coastal systems is based on observations from the 20th Century, or inference from recent millennia, which has involved a period of relative sea level stability. This limits available local evidence of processes active under rising sea levels, instead using of a global continuum of situations to guide a trajectory for the system's response, specifically through literature describing tidal network dependence on tidal prism.

It is acknowledged that understanding how other systems behave is not necessarily a direct indication of how intertidal habitats of the Tubridgi coast will respond. Local features can be capable of having significant influence, but their importance not presently being apparent under nearly stable conditions (e.g. micro-habitat development of the soil profile by mangroves will not create a constraint until the habitat zone migrates).

Therefore, it is acknowledged that the predicted short-term habitat response to small increases in sea level within this report are a "best estimate" based on available knowledge and can be considered indicative. However, as sea levels increase more dramatically in the long-term, processes of tidal creek evolution described in this report are likely to become increasingly dominant, causing migration of mangrove and algal mat habitats. These changes are ultimately constrained by biophysical limitations, including the inability of mangroves to cope with accelerated sea level rise and limited area available for algal mat expansion with suitable hydroperiod.

Table E1 and Figure E1 below summarise predicted morphodynamic and habitat responses to sea level rise with or without the project in place, arrived at by assessing and inferring relationships between tidal creek structure, tidal exchange and habitat response along the Turbridgi coast.

The Ashburton Salt Project is not expected to substantially affect the health or distribution of existing intertidal habitats. However, it is expected to modify the development of new potential habitat areas that would otherwise be expected to occur in response to low rates of sea level rise (before ~2050).

With the project in place, it is estimated that 40 to 250 ha of new potential mangrove habitat and 450 to 560 ha of potential new algal mat habitat will not develop between 2021 and 2050. However, this potential new habitat is expected to be impermanent, as accelerating sea level rise will place increasing stress on these habitats from 2055, with progressive habitat loss expected after 2075. Habitat stress and loss is expected to occur with or without the Ashburton Salt Project in place.

Samphire along the supratidal/intertidal fringe at the base of supratidal slopes near the Project area will be unaffected by the Project and are anticipated to contract under sea level rise at the same rate as they would without the Project, with a reduction in samphire of 50% by 2050 and ongoing loss as sea level rates accelerate beyond this.

Samphire habitat in supratidal basins and channels at the salt flat hinterland fringe will be affected by increased tidal flooding in the eastern basin of Urala Creek North due to the proposed Project. The predicted change is approximately 0.1 m higher peak tidal level, which suggests that the incidence of salt water flows into this samphire area will approximately double due to the Project. This will accelerate the process of wetland salinisation anticipated to occur due to sea level rise, bringing forward the approximate period of substantial ecosystem change which may cause samphire decline from 2070 without the Project in place, to 2055 with the Project in place.

Table E-1: Mangrove, Algal Mat and Samphire Response to Sea Level Rise with or without Project

Mangroves				
Years	**Sea Level Rise**	**Without Project**	**With Project**	**Project Stage**
2021 - 2050	0.05 - 0.2 m	Tidal exchange will increase with SLR, which is expected to cause tidal creek landward extension, up to 300-400 m per 0.1 m of SLR for long creeks (expected by ~2040). Smaller tidal creeks, including the networks supporting mangrove 'woodlands' will also expand. Mangroves will progressively occupy extended lengths of tidal creeks. Indicative potential increase in mangroves landward of Tubridgi Point has been estimated as: • ~40 ha along extended creeks. • 0 to ~190 ha mangrove 'woodland' expansion. The capacity for expansion is affected by levee stability along channel banks and basin margins, which can obscure wetland response to small changes of sea level. Levee instability is episodic, affected by sediment supply and runoff incision, and therefore expansion may lag years behind sea level change.	Excision of part of the salt flats will offset increased tidal exchange associated with SLR, limiting the projected expansion of tidal creeks. Long tidal creeks will not expand, and associated mangrove colonisation will not occur. Expansion of smaller tidal creeks is likely to be impeded by limited growth of primary tidal channels. The Project will limit potential estimated expansion of mangroves landward of Tubridgi Point: Extension of ~40 ha mangrove habitat along long creeks is unlikely to occur. Potential expansion of mangrove 'woodland' of up to ~190 ha (which might occur without the project in place) is possibly limited by stability of the primary channels, including the influence of bank levees.	Construction in ~2023 Operation in ~2026
2050 - 2075	0.2 - 0.45 m	Capacity for mangrove establishment or recovery after storm events will be physically limited by rates of SLR above 8 mm yr year (projected beyond ~2055). Increased stress will be placed on existing mangrove communities as sea levels continue to accelerate upward (from ~2055 to 2070).	Capacity for mangrove establishment or recovery after storm events will be physically limited by rates of SLR above 8 mm/yr (projected beyond ~2055). Increased stress will be placed on existing mangrove communities as sea levels continue to accelerate upward (from ~2055 to 2070).	Operation until ~2075
2075 - 2100	0.45 - 0.75 m	Progressive loss of established mangroves due to sea level rise is expected to occur once SLR rate exceeds 12 mm per year (by ~2075) due to sediment destabilisation and increased depth of inundation.	Progressive loss of established mangroves due to sea level rise is expected to occur once SLR rate exceeds 12 mm per year (by ~2075) due to sediment destabilisation and increased depth of inundation.	Closure from ~2075
2100 - 2121	0.75 - 1.0 m	Continuing mangrove loss is expected with limited capacity to establish new communities or recover after disturbance events.	Continuing mangrove loss is expected with limited capacity to establish new communities or recover after disturbance events.	

Algal Mats				
Years	**Sea Level Rise**	**Without Project**	**With Project**	**Project Stage**
2021 - 2050	0.05 - 0.2 m	Algal mats will migrate landwards with sea level rise by ~500-750 m per 0.1 m of sea level rise. Migration will occur until ~2030 to 2040, when they reach the crest of a low-profile sediment ridge which directs water flows westwards towards the coast. It is uncertain whether algal mats can subsequently migrate past the sediment ridge, into the eastern basins of the salt flats (this uncertainty exists given potential for interactions between hydroperiod, salinity and morphology).	The Project is not expected to substantially impact behaviour of algal mats, which will remain responsive to hydroperiod. Algal mats will migrate landwards with sea level rise by ~500-750 m per 0.1 m sea level rise. Migration will occur until for ~10 to 20 years, until they reach either the salt pond embankments or the crest of a low-relief sediment ridge on the western side of the salt flats. Construction of the salt ponds truncates the area of potential habitat expansion west of the sediment ridge by an estimated ~ 450 to 560 ha.	Construction in ~2023 Operation in ~2026
2050 - 2075	0.2 - 0.45 m	Increased stress will be placed on existing algal mats as sea levels continue to accelerate upward (from 2055 to 2070).	Increased stress will be placed on existing algal mats as sea levels continue to accelerate upward (from 2055 to 2070).	Operation until ~2075
2075 - 2100	0.45 - 0.75 m	Once sea level rise exceeds 0.45 m (by ~2075) inundation of the entire area west of the sediment ridge will occur more frequently than the present-day lower limit for algal mats, indicating sustained algal mat loss with further sea level rise.	Once sea level rise exceeds 0.45 m (by ~2075) inundation of the entire area west of the sediment ridge will occur more frequently than the present-day lower limit for algal mats, indicating sustained algal mat loss with further sea level rise.	Closure from ~2075
2100 - 2121	0.75 - 1.0 m	Algal mat loss expected with limited capacity for establishment or recovery.	Algal mat loss expected with limited capacity for establishment or recovery.	

Samphire				
Years	**Sea Level Rise**	**Without Project**	**With Project**	**Project Stage**
2021 - 2050	0.05 - 0.2 m	Samphire along the supratidal/intertidal fringe at the base of supratidal slopes will have increasing inundation, approximately doubling in frequency for every 0.1 m sea level rise. This samphire occupies berms, which are expected to narrow by 50% with 0.2 m sea level rise (~2050). Samphire in supratidal basins and channels will receive an approximate doubling of marine inundation occurrence per 0.1 m sea level rise, leading to ongoing salinisation. Although samphire response is uncertain, it is expected to be small from 2021 to 2050.	Samphire along the supratidal/intertidal fringe at the base of supratidal slopes inside the salt ponds will be isolated from marine processes and respond to pond management. Samphire along the supratidal/intertidal fringe at the base of supratidal slopes outside the salt ponds will still receive an approximate doubling of tidal inundation occurrence for every 0.1 m sea level rise. These samphire fringes are expected to narrow and reduce by 50% with 0.2 m sea level rise by 2050. Samphire in supratidal basins and channels will receive approximately 0.1 m higher peak tide level due to the Project as well as an approximate doubling of marine inundation occurrence for every 0.1 m sea level rise. This will accelerate the process of salinisation compared to projected behaviour without the project.	Construction in ~2023 Operation in ~2026
2050 - 2075	0.2 - 0.45 m	Samphire along the supratidal/intertidal fringe at the base of supratidal slopes will decline or be lost from 2050 to 2070, depending on their elevation, due to landform mobility with increasing marine inundation. Samphire in supratidal basins and channels to the north-east of the Project site will receive an approximate doubling of tidal inundation occurrence for every 0.1 m sea level rise, leading to accelerating salinisation.	Samphire along the supratidal/intertidal fringe at the base of supratidal slopes outside the salt ponds will still decline or be lost from 2050 to 2070 depending on their elevation. Samphire in supratidal basins and channels to the north-east of the Project site will experience regular tidal flows, causing development of a tidal channel network and decline of samphire habitat due to bed mobility and increasing salinity.	Operation until ~2075
2075 - 2100	0.45 - 0.75 m	Samphire in supratidal basins and channels to the north-east of the Project site will experience regular tidal flows, causing development of a tidal channel network and decline of samphire habitat due to bed mobility and increasing salinity.	Samphire in supratidal basins and channels to the north-east of the Project site will continue to decline, with tidal network expansion.	Closure from ~2075
2100 - 2121	0.75 - 1.0 m	Samphire in supratidal basins and channels to the north-east of the Project site will continue to decline, with tidal network expansion.	Samphire in supratidal basins and channels to the north-east of the Project site will continue to decline, with tidal network expansion.	

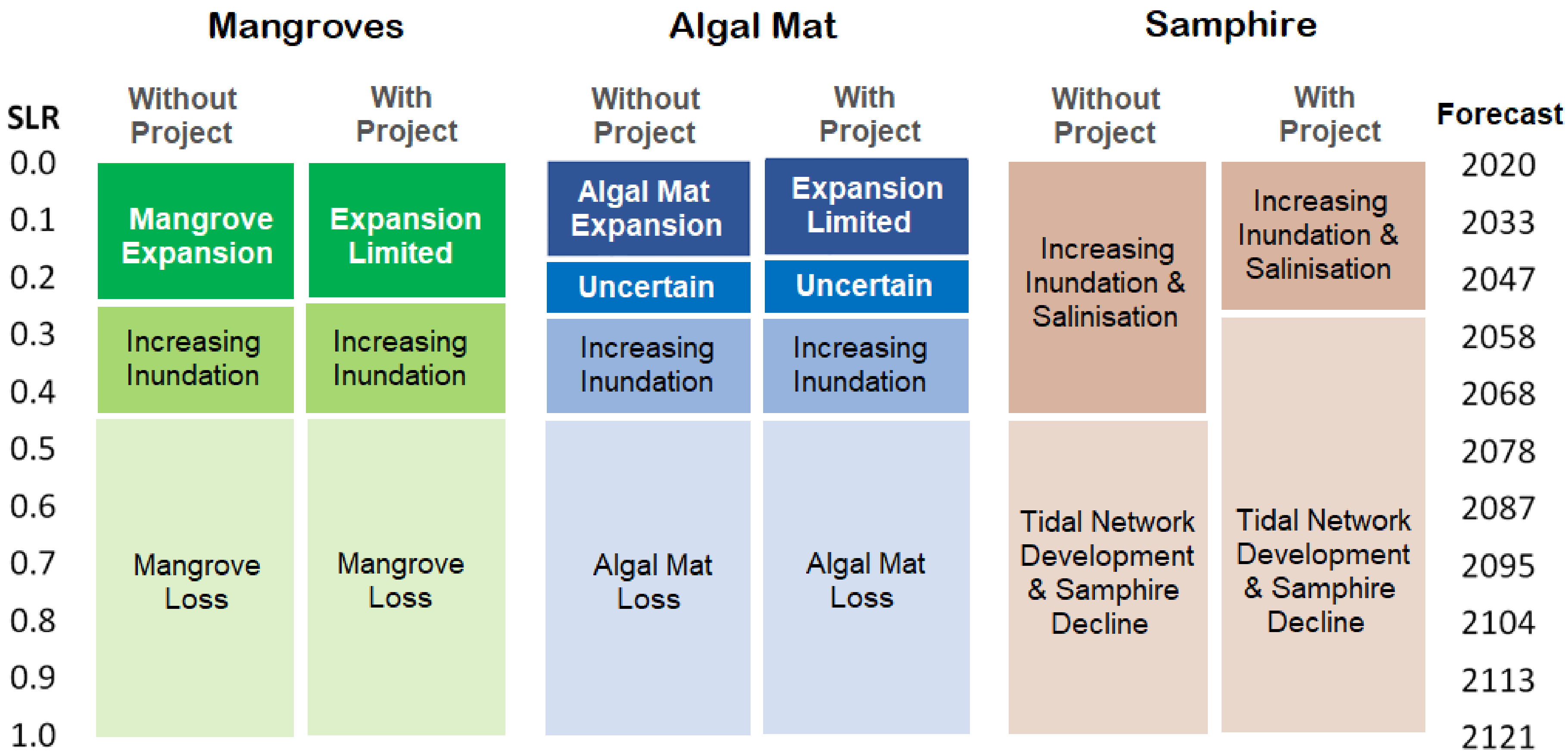

Figure E-1: Mangrove, Algal Mat and Samphire Response to Sea Level Rise with or without Project

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Limitations of this Report

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Document Control

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Rev A	M.Eliot	03.10.2020	I.Eliot	06.10.2020	Issued to Client
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Rev 2	M.Eliot	25.06.2021	L.Todd	07.07.2021	Minor Edits
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1. Introduction

Assessment of potential environmental impacts, with appropriate mitigation and management responses has been undertaken for the Ashburton Salt project at the northeast margin of Exmouth Gulf, landward of Tubridgi Point (Figure 1-1). The project includes approximately 100 km^2 of bunded evaporating ponds and 13 km^2 of crystalliser ponds, with water intake from Urala Creek South (Figure 1-2).

Planning for the facility has acknowledged potential sensitivity of existing intertidal habitats, including mangroves and algal mats, to construction of proposed works (Water Technology 2021a). Intertidal habitats, mangroves and algal mats play crucial roles in the biochemistry and bioproductivity of regional ecosystems, and consequently targeting a practical minimum impact on intertidal habitats is a desired objective for development (EPA 2001; Brocx & Semeniuk 2015; Creswell & Semeniuk 2018). Direct impact to high productivity intertidal habitats has consequently been minimised by locating most of the proposed works landward of existing algal mats. However, it is acknowledged that in the longer term, intertidal habitats have the capacity to migrate, in response to projected sea level rise.

This assessment evaluates factors influencing mangroves and algal mats at the Ashburton Salt project site. These factors are used to project potential changes to existing intertidal habitats in response to sea level rise. This is considered for scenarios with or without the proposed Ashburton Salt project infrastructure, to identify potential project impacts and support determination of suitable management and closure planning responses.

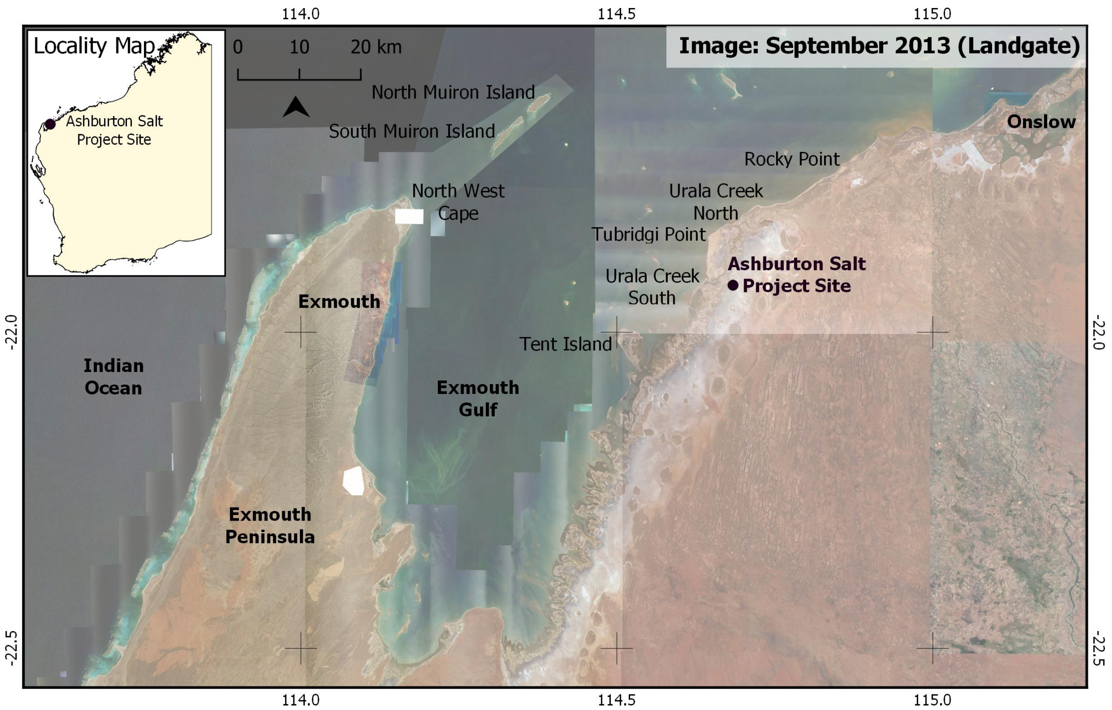

Figure 1-1: Location Diagram

The EPA recognises the important roles that benthic community habitats (BCH), including intertidal habitats, play in maintaining the integrity of coastal ecosystems and the supply of ecological services. Accordingly, the EPA provides technical guidance based on BCH as a key environmental factor and with the objectives to protect benthic communities and habitats so that biological diversity and ecological integrity are maintained (EPA 2016a).

The EPA Technical Guidance Protection of Benthic Communities and Habitats (EPA 2016b) was prepared to explain how impacts on benthic communities and habitats (BCH) are considered during Environmental Impact Assessment (EIA) and to set out the type and form of information that should be presented to facilitate the assessment of impact on BCH in Western Australia's marine environment. The assessment of potential impacts to BCH from the Ashburton Salt Project required consideration of both direct and indirect impacts. Advice received from the EPA indicates that the BCH assessment should include indirect impacts related to the proposed salt field potentially hindering the ability of BCH to adapt to climate change induced sea level rise.

An understanding of potential longer-term impacts of the proposed facility requires consideration of the dynamics of the coastal setting, including responses to both extreme storm conditions and the influence of projected sea level rise. This document provides an interpretation of anticipated changes to the adjacent coastal system, including evaluation of how these changes may be influenced by the proposed development.

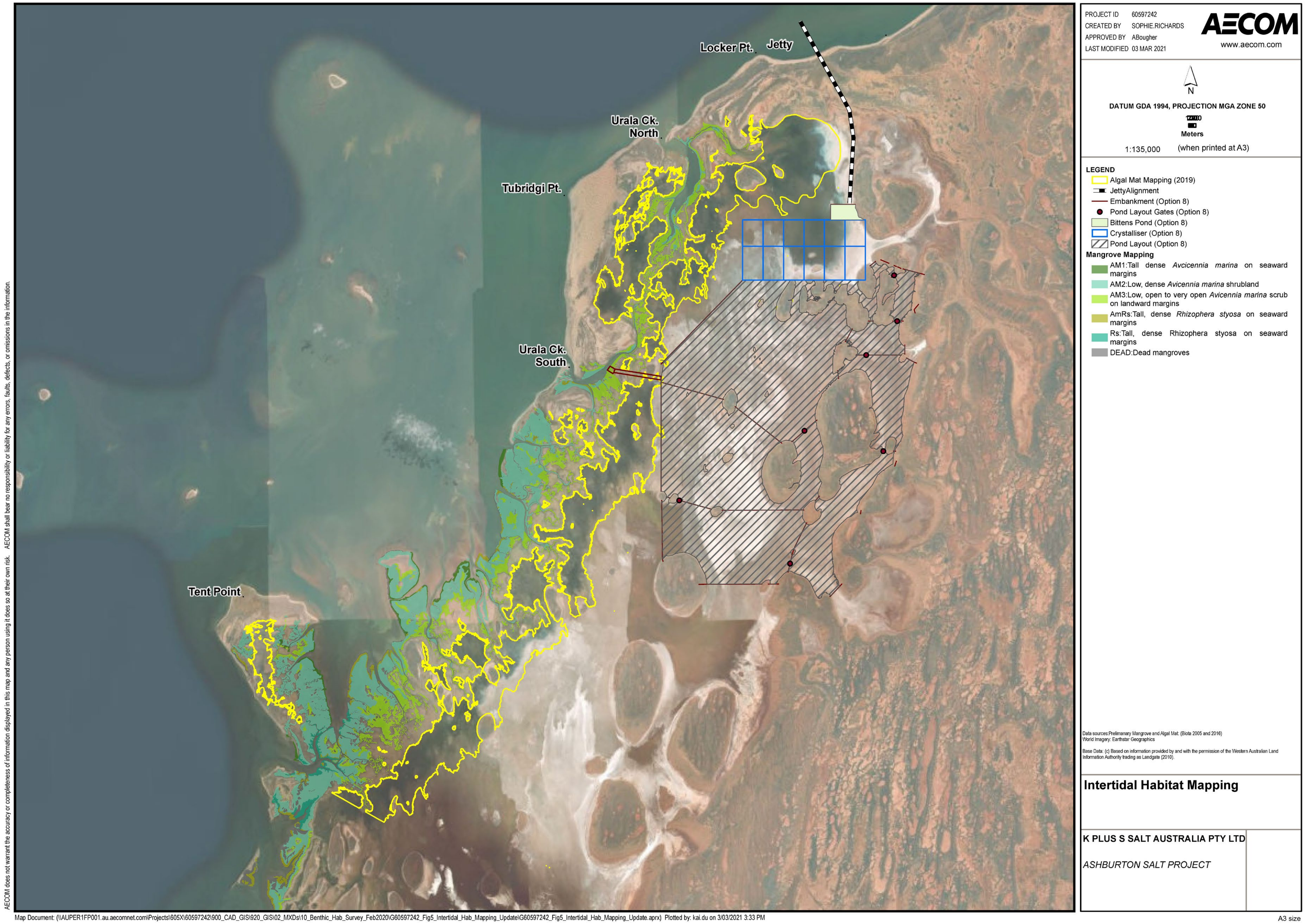

Figure 1-2: Development Area and Intertidal Habitats

2. Approach and Methods

The overall approach used for assessment has been to establish factors contributing to dynamics of intertidal habitats, using them to project response of mangroves and algal mats to sea level rise. Previous scientific studies of intertidal habitats, particularly for mangroves, have identified a range of influential factors (Figure 2-1). These may be:

- *Sensitivities* – where dynamics of a factor induces changes to the intertidal habitats, often involving feedbacks (Winterwerp *et al*. 2013; Anthony & Goichot 2020); or
- *Controls* – where the presence of absence of a factor provides a physical limit to the intertidal habitats (Semeniuk 1996).

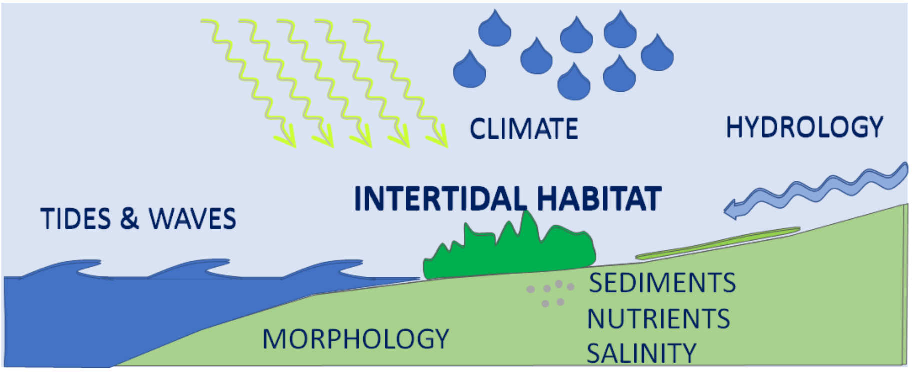

Figure 2-1: General Factors Influencing Intertidal Habitats

Mapping of existing intertidal habitats demonstrates a strong dependence on underlying morphology, particularly tidal creeks, which are themselves susceptible to change due to sea level rise. Consequently, this assessment integrates a conceptual model for intertidal habitat behaviour with an empirical model for tidal creek morphodynamics, to project response of intertidal habitats to sea level rise (Figure 2-2).

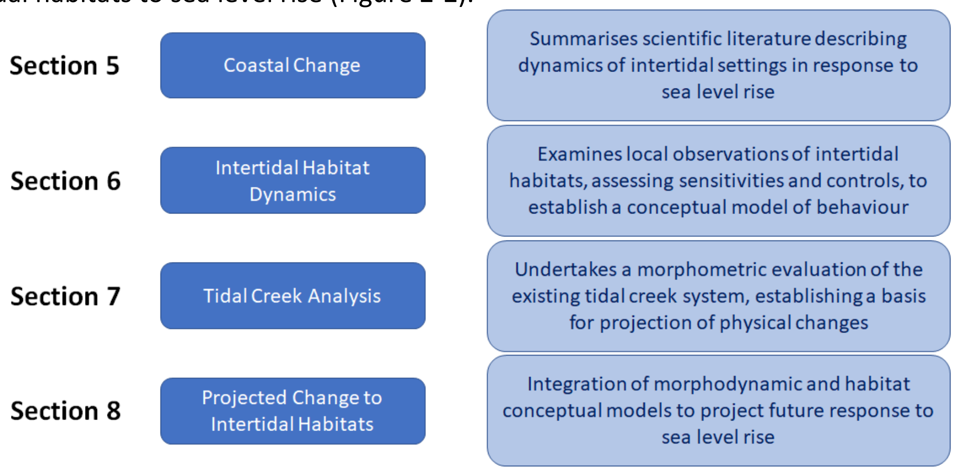

Figure 2-2: Assessment Framework and Document Sections

3. Setting

3.1. CLIMATE

The Exmouth-Onslow region is in the northwest Pilbara, experiencing an arid sub-tropical climate. Regionally, weather is affected by the latitudinal shift of the sub-tropical high-pressure belt, in combination with the summer continental heat trough (Gentilli 1971). Prevailing conditions are very dry, enhancing the influence of thermally driven winds, particularly southerly breezes, which are frequent year-round (Figure 3-1).

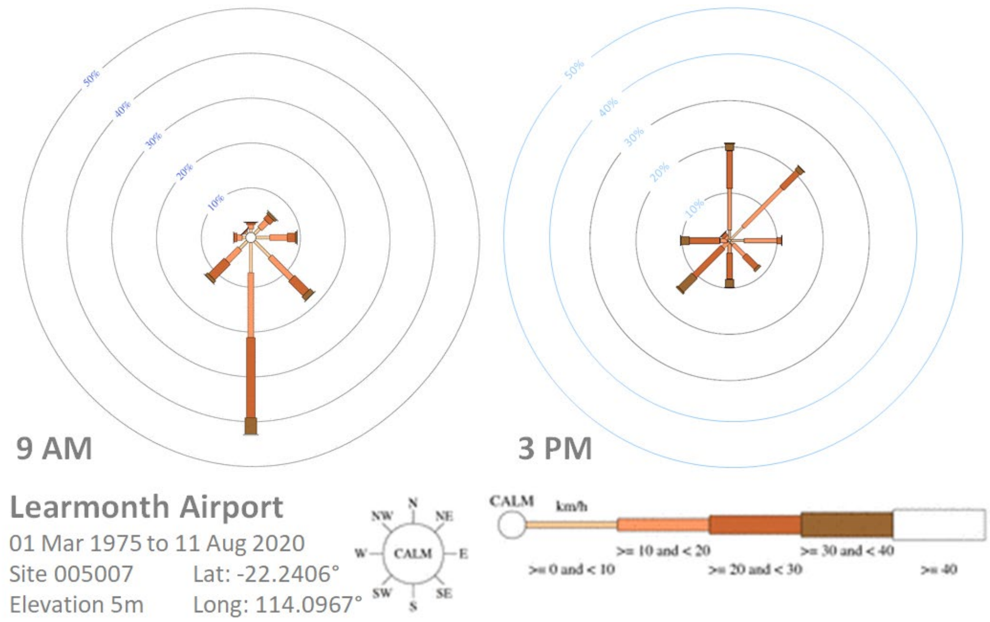

Figure 3-1: Learmonth Wind Roses (BOM)

Typically, the region experiences occasional (1-2 per year) tropical cyclones during summer months (Lourensz 1981; Dare & Davidson 2004) as well as the northern tail of mid-latitude storms in winter, including the tropical-temperate interaction of the northwest cloud band (Telcik & Pattiaratchi 2014; Reid *et al*. 2019). Regional annual rainfall is in the range of 200-300 mm, although much of this can fall within a single storm event, either from tropical cyclones from January through April, or from cold front winter storms with a high northerly excursion from May to July (Figure 3-2).

Episodic rainfall provides the capacity for highly variable streamflow conditions (i.e. flash flooding), as identified in the adjacent Ashburton River (Figure 3-3). Although this has some potential implications for interpretation of sediment dynamics across supratidal flats, it is noted that outwash fans are extremely small at all locations adjacent to the proposed salt farm, suggesting low sediment delivery.

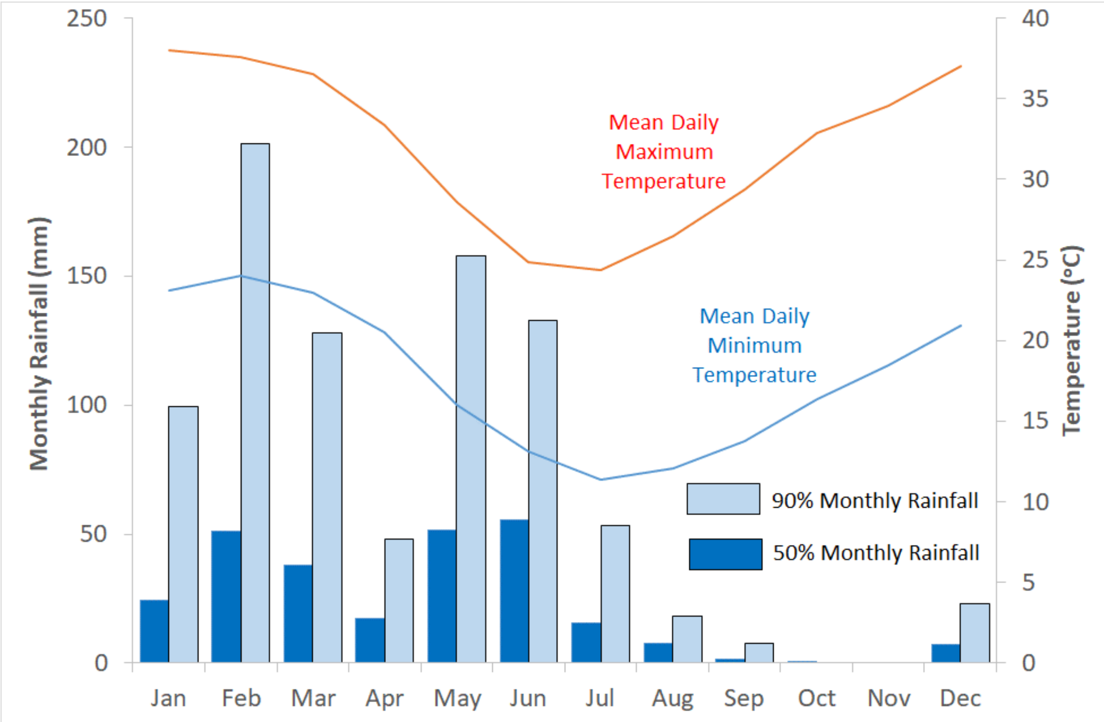

Figure 3-2: Seasonal Meteorological Records from Regional Sites
Monthly rainfall from Urala Station (17 km ENE) 1977-2019
Temperature from Learmonth Airport (75 km SW) 1945-2019

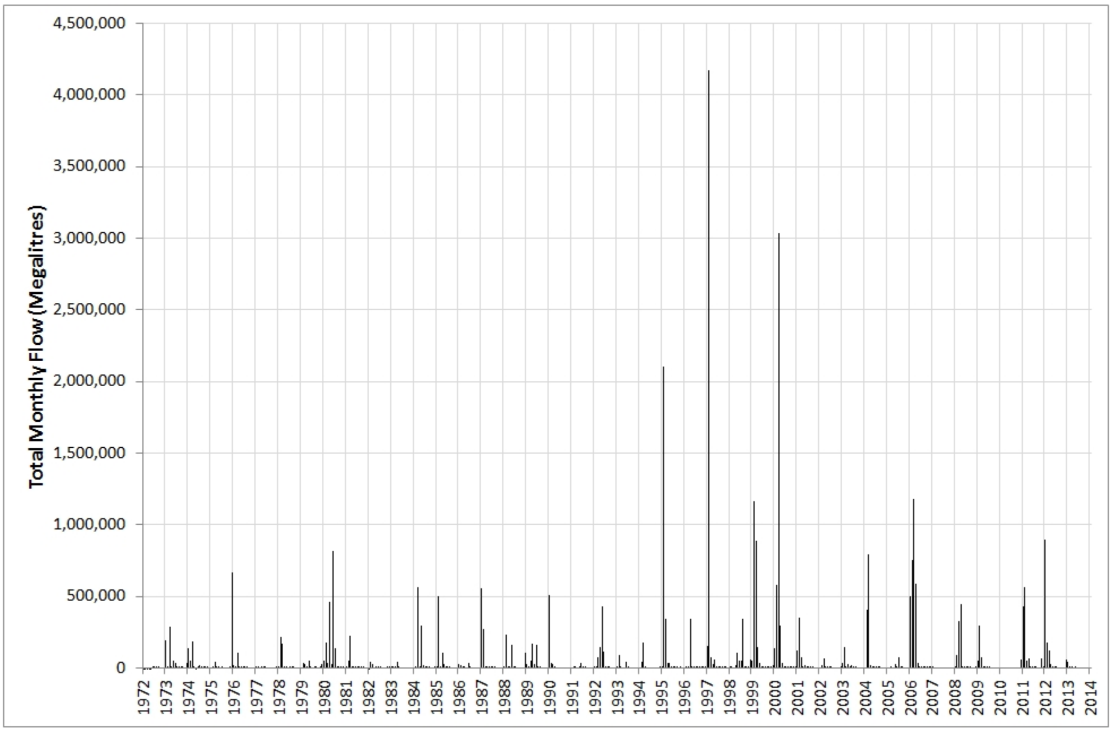

Figure 3-3: Ashburton River Flood History 1973-2013

3.2. GEOLOGY AND SEDIMENTS

The proposed site is located adjacent to Tubridgi Point, on the northeast side of Exmouth Gulf. This area lies within the Northern Carnarvon Basin, with surface geology resulting from marine sediment deposition between the Ordovician and Cretaceous eras, overlain by a modern veneer of Quaternary deposits (Hocking *et al*. 1987). Regional scale mapping of surface geology indicates dominance of Quaternary landforms in the coastal region, primarily distinguishing between landforms developed through tidal (Qt), wave (Qw), wind-blown (Qe) and swamp (Qp) formations. Surface landforms located landward are classified as older, but with similar origins, corresponding to floodplain and deltaic structures associated with former drainage paths from the Ashburton River catchment.

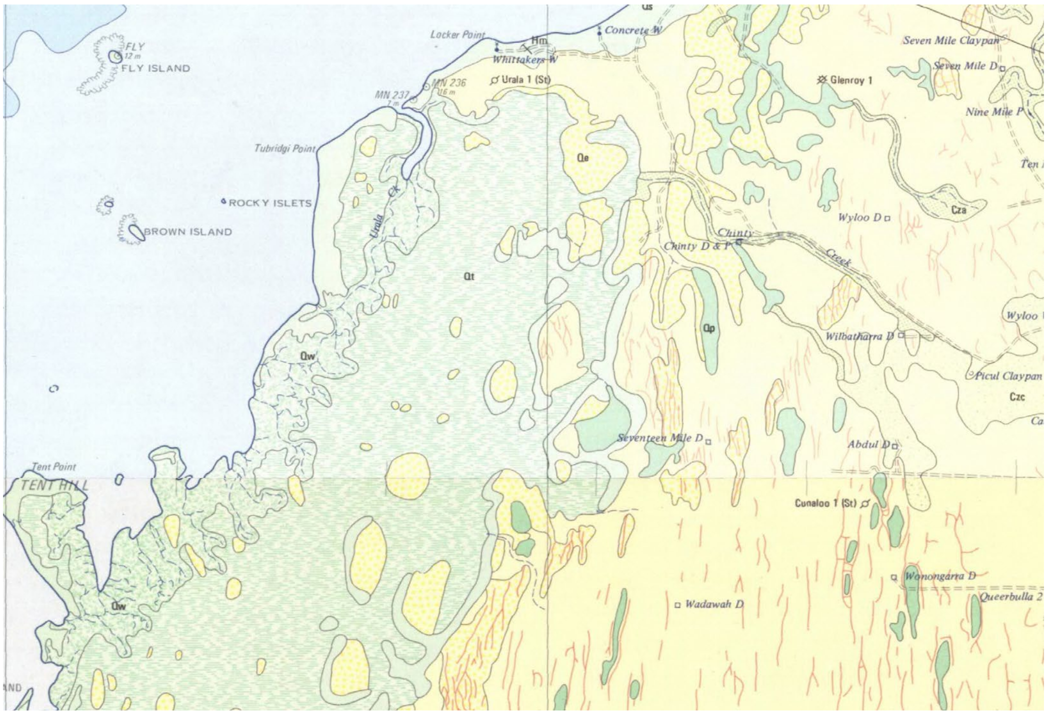

Figure 3-4: Regional Scale Surface Geology

At a regional scale, the eastern side of Exmouth Gulf is part of a large alluvial fan associated with the Ashburton River catchment. This 'super-delta' incorporates the modern Ashburton River towards its eastern limit with the smaller Yannarie River along the southern limit. The resulting 4,000 km^2 has low topography, dominated by longitudinal sandy dunes interleaved by elongated claypan basins.

Local geological mapping (Figure 3-5) has generally confirmed geological attributes mapped at 250k scale. This mapping gave less distinction between wave and tide determined landforms, with a class (Qw or Qt) that extended much further landward than the wave class (Qw) from larger scale mapping. The area of tidal landforms was also separated into active upper intertidal zone (Qt2) and supratidal zone (Qt1).

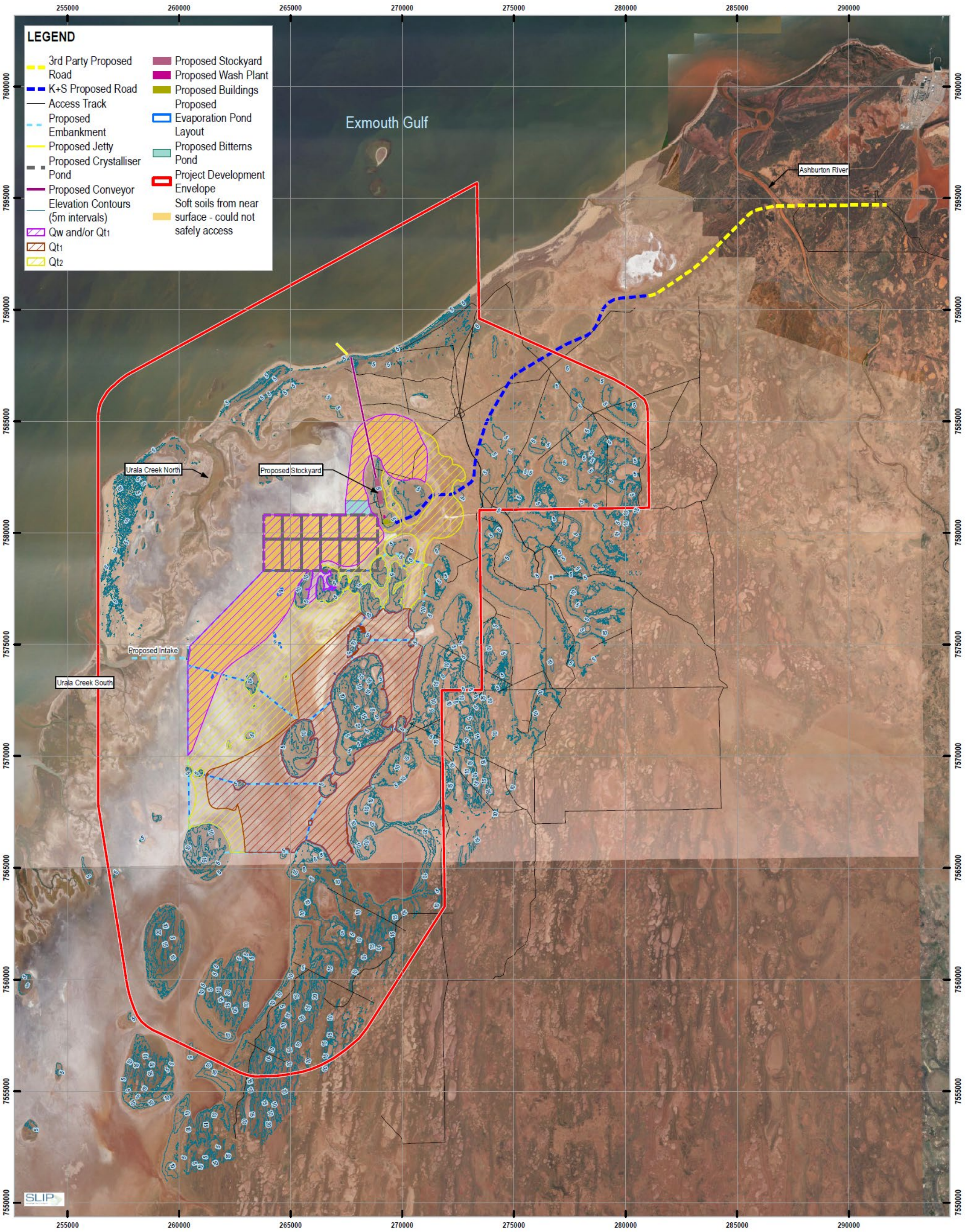

Figure 3-5: Local Geological Mapping Diagram from GHD (2020)

3.3. OCEANOGRAPHY

The proposed site is located 40 km south east of Onslow, on the eastern side of the mouth of Exmouth Gulf. The Gulf is a large, shallow embayment, sheltered from prevailing southwest ocean swell waves by Exmouth Peninsula. The shallow Gulf waters are biologically productive, provide economically and socially important commercial and recreational fishing, as well as a resting and nursing area for humpback whales on their southern migration (Commonwealth of Australia 2007; Fitzpatrick *et al*. 2019).

The position of Exmouth Gulf at the intersection of the north facing Pilbara coast and the west facing Gascoyne coast provides oceanographic complexity (Verspecht 2002; Commonwealth of Australia 2007). Within the Gulf waters, this is further complicated by shallow bathymetry and wide intertidal zones, which respectively increase the influence of wind-blown and tidal circulation.

Water levels within Exmouth Gulf are measured at a permanent tide gauge located in Exmouth Boat Harbour, with observations since 1997 allowing definition of tidal constituents and examination of mean sea level variability (Transport 2004). An approximation of tidal planes for sites between gauges, generated through interpolation of tidal constituents (Auscoast VDT 2017) suggests a smaller tidal range than at Exmouth (Table 3-1). However, this is an opposite outcome to estimation of tidal planes at Hope Point based on extrapolation of short-term measurements (Worley Parsons 2006). The discrepancy is typical for the variety of approaches used for estimating tidal variation and prompts caution in their interpretation or application at high resolution.

Table 3-1: Tidal Planes for Exmouth and Hope Point

		Exmouth	**Ashburton Salt**
	Source	Transport 2004	Auscoast VDT 2017
Highest Astronomical Tide	HAT	2.87mCD	2.45mCD
Mean High Water Spring	MHWS	2.35mCD	2.05mCD
Mean High Water Neap	MHWN	1.76mCD	1.46mCD
Mean Sea Level	MSL	1.44mCD	1.18mCD
Australian Height Datum	AHD	1.40mCD	1.18mCD
Mean Low Water Neap	MLWN	1.16mCD	0.92mCD
Mean Low Water Spring	MLWS	0.55mCD	0.33mCD
Lowest Astronomical Tide	LAT	0.03mCD	0.00mCD

Water levels in the Gulf are predominantly tidal, with mixed, mainly semi-diurnal tides, of meso-tidal amplitude. These conditions cause three main cycles, including a fortnightly spring-neap cycle, a bi-annual cycle related to latitudinal tilt and a 4.4-year cycle related to the lunar orbital plane. Non-tidal fluctuations include a small (~0.2 m) seasonal cycle, small (~0.3 m) inter-annual fluctuations associated with climate cycles (Feng *et al*. 2004) and typically moderate (<0.5 m) atmospheric surge (Appendix A). The relative timing of tides, atmospheric surges and mean sea level coincides to provide highest water levels around March and lowest water levels around September.

Higher storm surges are possible during tropical cyclones, with a water level of 4.89mCD recorded at Exmouth during Tropical Cyclone (TC) Vance in March 1999. There is also stratigraphic evidence of extreme storm surge and washover events above 7mCD occurring along the coast east of the project area (Dodson *et al*. 2014) and in the south of Exmouth Gulf (Steedman 1987; May *et al*. 2017). These have been inferred as a mixture of extreme storms and tsunami events.

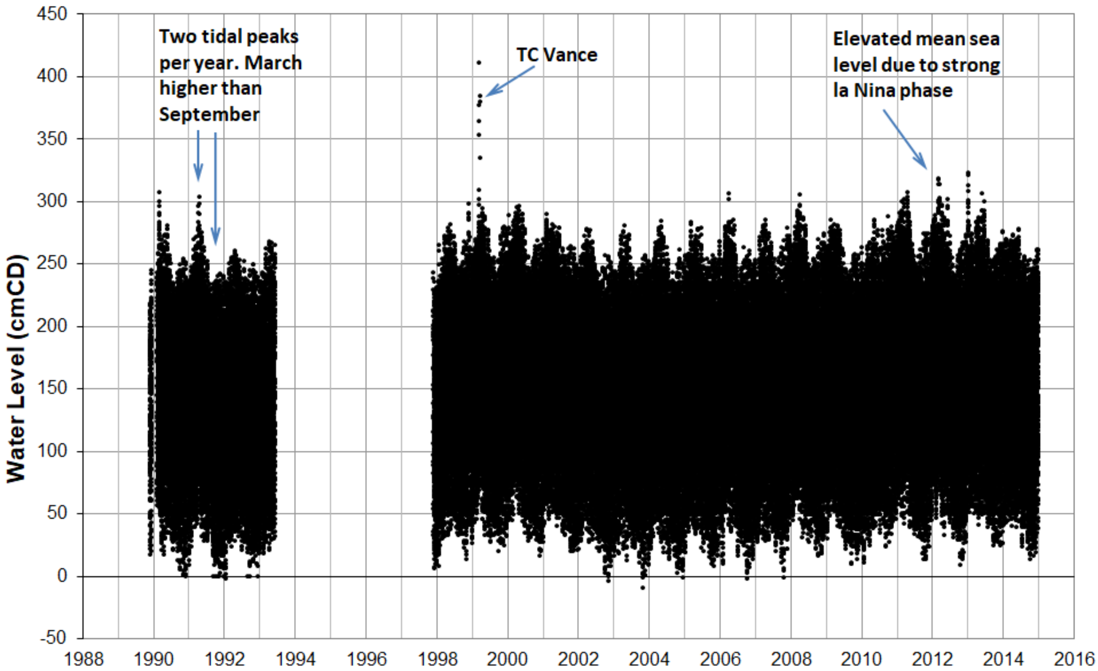

Figure 3-6: Exmouth Water Level Record

Wave observations outside Exmouth Gulf were made from a long-term offshore deployment of a waverider buoy from 2006-2012 (Transport 2020). The highest measured waves between 2006 and 2012 were associated with tropical storms, including tropical cyclones TC Pancho in March 2008 and TC Nicholas in February 2008 (Figure 3-7). The latter cyclone caused a 5.7 m significant wave height with 12 second wave period, indicating it was generated locally by extreme winds, which peaked at Exmouth from the north.

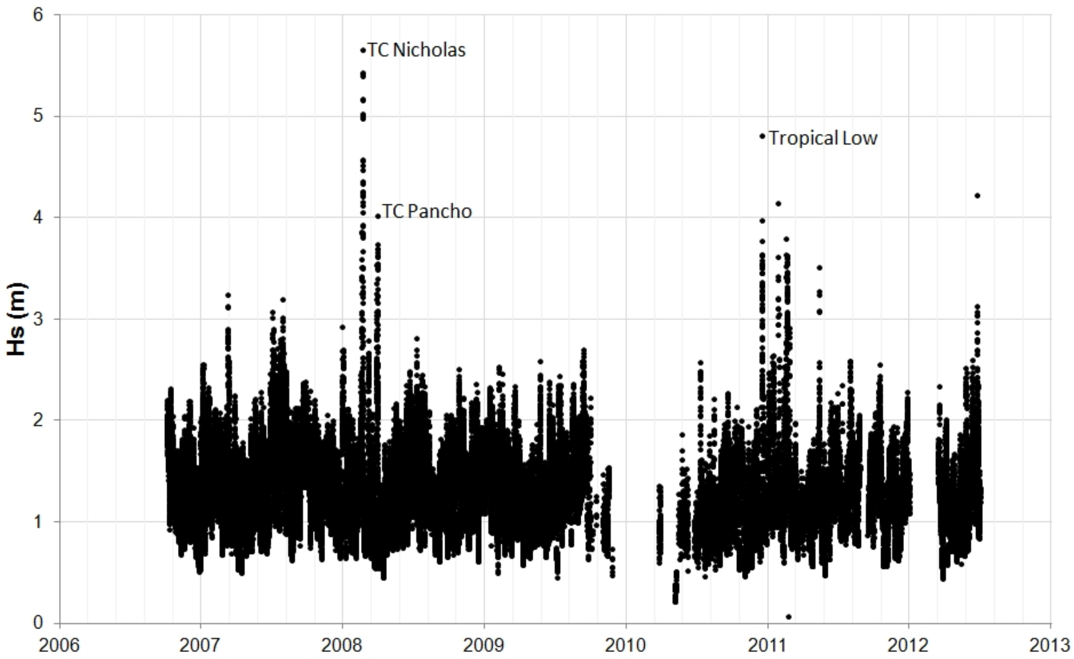

Figure 3-7: Wave Height Measured at Exmouth Waverider Buoy Located outside Exmouth Gulf

Unfortunately, the Exmouth waverider buoy was non-directional, which limits identification of conditions under which wave energy may be able to enter the Gulf and affect the Tubridgi coast.

Short-term wave measurements have been made to support development projects and proposals within the Gulf, including Exmouth Marina development (CIES 1996), the proposed Yanarrie solar salt farm (Straits Salt 2005) and Learmonth pipeline bundle launching facility (Subsea7 2019). These records confirmed that ambient waves are locally generated by winds across the available fetches of the Gulf. However, none of the deployments successfully recorded wave conditions during the passage of a tropical storm capable of driving wave energy into the Gulf from the north.

Modelling of wave conditions within Exmouth Gulf has been undertaken at several locations to estimate likelihood of coastal hazards and rates of alongshore sediment transport. Wind waves in the order of 1.5 m significant height are estimated to occur under ambient conditions (Massel *et al*. 1997), with estimates of 2-4 m significant waves caused by tropical cyclones (Steedman & Russell 1986). The capacity for extreme waves to affect the Ashburton Salt site is modulated by its position on the east side of the Gulf. This partly reduces the incidence of tropical cyclone waves, and the shallow nearshore depths, which provide frictional damping.

3.4. COASTAL MORPHOLOGY

3.4.1. Regional Coastal Compartments

A geomorphic framework for the Western Australian coast has been developed to support coastal planning and management by the State Government (Eliot *et al*. 2011). This includes definition of coastal compartments which are strongly related to geology, and sediment cells related to coastal sedimentary landforms. The two are linked, due to influence of the geological framework on the production of sediment and potential for the formation of structural controls on sediment transport, particularly through coastal headlands.

The east side of the Exmouth Gulf is indicated as two coastal compartments (Figure 3-9), with the division around Hope Point characterising the emergence (for the coast to the north) of coastal limestones. These are present as low scarps on Hope Point, and more generally occur as a coastal platform, with modern sedimentary coast perched on top. This is distinctive on Tubridgi Point (Figure 3-8) and provides structural control for the islands between Hope Point and Tent Island.

Figure 3-8: Tubridgi Point
Imagery from GSWA (2012)

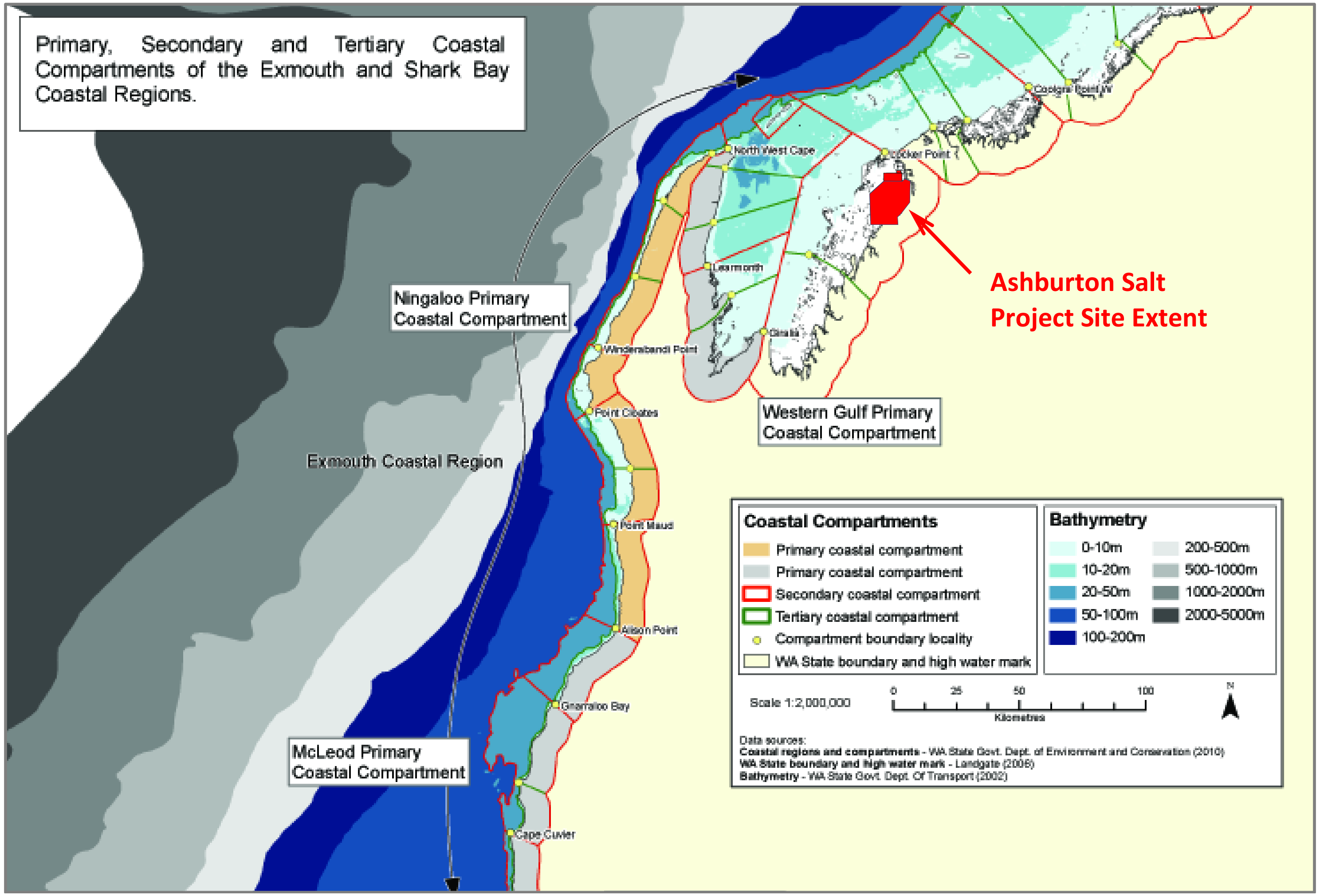

Figure 3-9: Regional Coastal Compartments
Diagram from Eliot *et al*. (2013)

3.4.2. Subregional Morphology

The subregional morphology has been broadly described for the region (Le Provost Environmental Consultants 1991; Biota 2005) as a land to seaward sequence of:

- Outwash Plain
- Dune Field
- Salt Flat
- Coastal fringe.

A similar pattern occurs at the Ashburton Salt site (Figure 3-10), although the outwash plain is a less distinct landform unit, with two ephemeral creek systems passing through the dune field and debouching into the northern part of the Salt Flat.

The *Dune Field Unit* is comprised of a complex arrangement of longitudinal dunes and swales, interspersed with claypans. This provides a convoluted drainage network, where rainfall from small-moderate events is likely to be locally retained and subject to evaporation. Larger rainfall events can drain through the ephemeral creeks, with a potential opportunity for breakout flow from the Ashburton River under extreme floods. Modern alluvial fans are very small, suggesting low sediment input to the salt flats.

Dune topography is relatively low lying, but is generally above 3 m AHD, forming a distinct boundary between the dunes and the salt flats. This fringe is typically comprised of a higher 'coastal barrier dune' typical of aeolian processes, fronted by a lower berm that can exhibit storm surge debris.

The *Salt Flat Unit* consists mainly of a very flat plain, with very low relief and slopes, from which higher 'relict mainland' areas emerge. The salt flat is rarely inundated by marine waters and is subject to either extreme tides or high tides combined with storm surge from tropical cyclones. Inundation events, particularly when associated with strong winds, can provide a landward push of fine sediments and debris, including algal mat fragments. These can be deposited as extended strandlines after a flood event. The seaward margins of the salt flat are occupied by algal mats which are a ~10mm thin, dense mass of cyanobacteria ('blue green algae') occurring on the ground surface.

The *Coastal Fringe Unit* provides a transition from the marine waters of Exmouth Gulf, which are wave affected and tidal, to the salt flats over which tidal influences decline. This is a complex landform unit, with different features determining how this transitional role manifests (described in Section 3.4.3).

Figure 3-10: Subregional Landform Units and Typical Local Landforms

Mangroves grow within an elevation range of approximately 0. 3m to 1.0 m AHD. They occupy the majority of sheltered waters including those landward of barrier dunes, spits and along the sheltered coastal margin leeward of Tent Island. Mangroves also occupy the fringes of tidal creeks and extend landward into the algal mats.

The coastal fringe is breached in a number of locations by tidal channels, forming a sinuous, dendritic network that dissipates tidal energy and drains floodwaters from the salt flats. These are most strongly defined in the north, where the tidal channels pass through the barrier dune; and are more complex in the south, where a portion of tides and drainage may also pass through the coast fringing mangroves.

3.4.3. Coastal Units

Variation of the subregional morphology within the *Coastal Fringe Unit* has been considered based on four Coastal Sub-units (Figure 3-11):

- Locker Point Barrier Dune;
- Tubridgi Point Perched Barrier;
- Barrier Spit Sequence; and
- Mangrove Shore.

Locker Point Barrier Dune (Figure 3-12a) is exposed to direct ocean wave action, which has enabled it to build a high (~8 m AHD) and wide dune ridge. The dune is underlain by a limestone platform, providing a high degree of coastal stability.

Tubridgi Point Perched Barrier (Figure 3-12b) has high coastal exposure, with strong alongshore wave action due to prevailing southerly wind waves. The underlying limestone platform (~0.5 m AHD) supports a perched beach and dune, with the west-facing alignment conducive to the development of migratory longitudinal dunes. The perched barrier provides a high overall level of landform stability, although the toe of perched dunes may be susceptible to high variability in response to sea level fluctuations (Gallop *et al*. 2020). Severe dune deflation was identified along the western margin of Tubridgi Point following impact of TC Vance in March 1999 (Blandford & Hegge 2005).

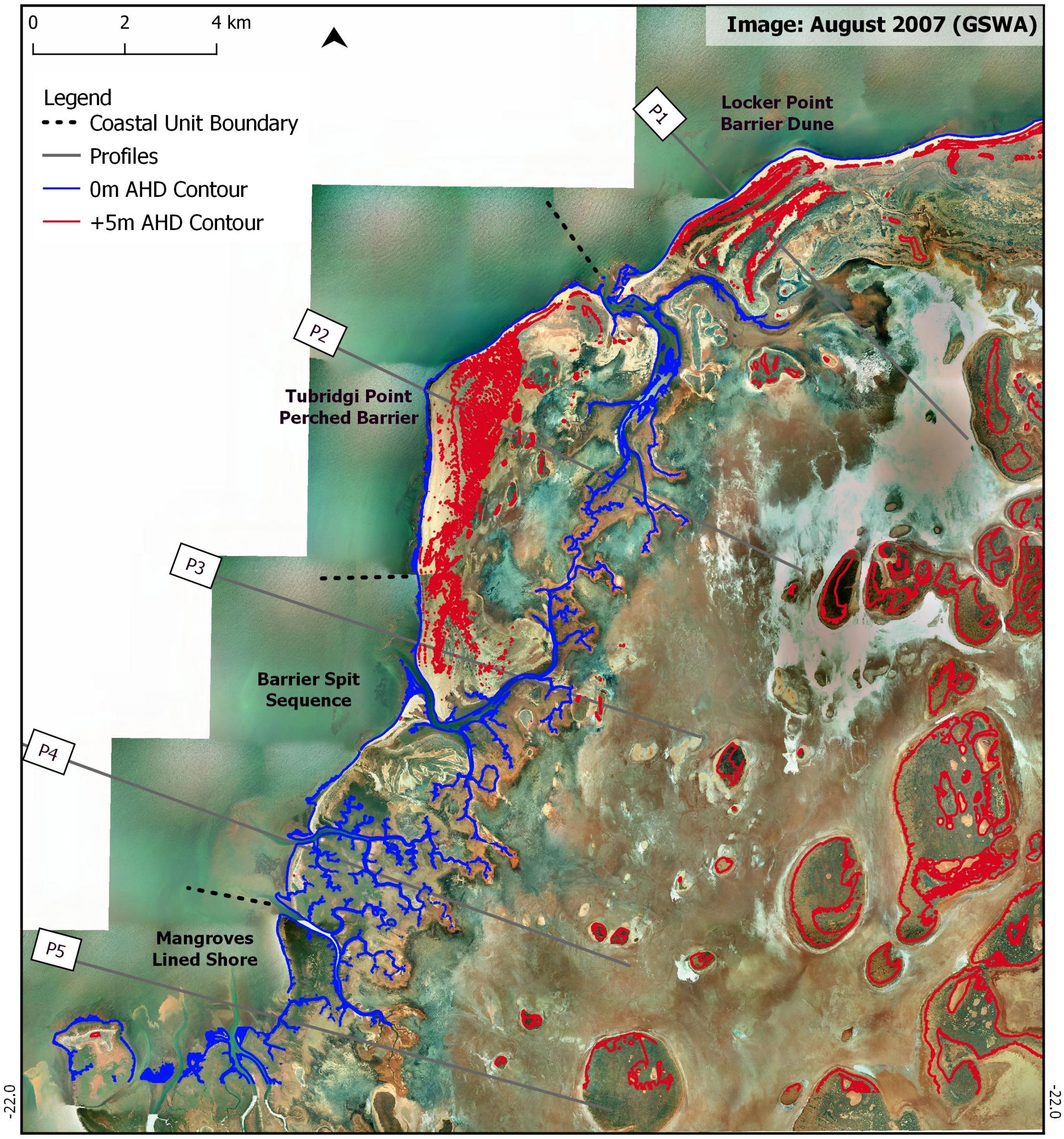

Figure 3-11: Coastal Units and Cross Sections

(Cross-section for profiles P1-P5 are shown in Figure 3-12)

The sequence of barrier spits south of Tubridgi Point (Figure 3-12c) has developed through sequential deposition under different alongshore (and onshore) events, which may be a combination of short-term (e.g. tropical cyclones) and longer-term events (e.g. raised sea level phases). Adjacent to Tubridgi Point, the spit sequence includes moderately high (6 m to 9 m AHD) dunes with multiple ridges to landward. The adjacent shore has 1 in 20 slope, characteristic of a sandy shore. There are small sections of intertidal rock platform apparent along this unit. Southward, the height and number of spits declines, with only a single ridge present for approximately half the length of this coastal sub-unit. The height and width of the spit declines where the spit has been breached by a tidal creek, although it retains approximately 50 m^2 cross-section above the salt flat elevation (Figure 3-12d). The shore has a 1 in 200 slope, characteristic of a muddy shore at the creek mouth.

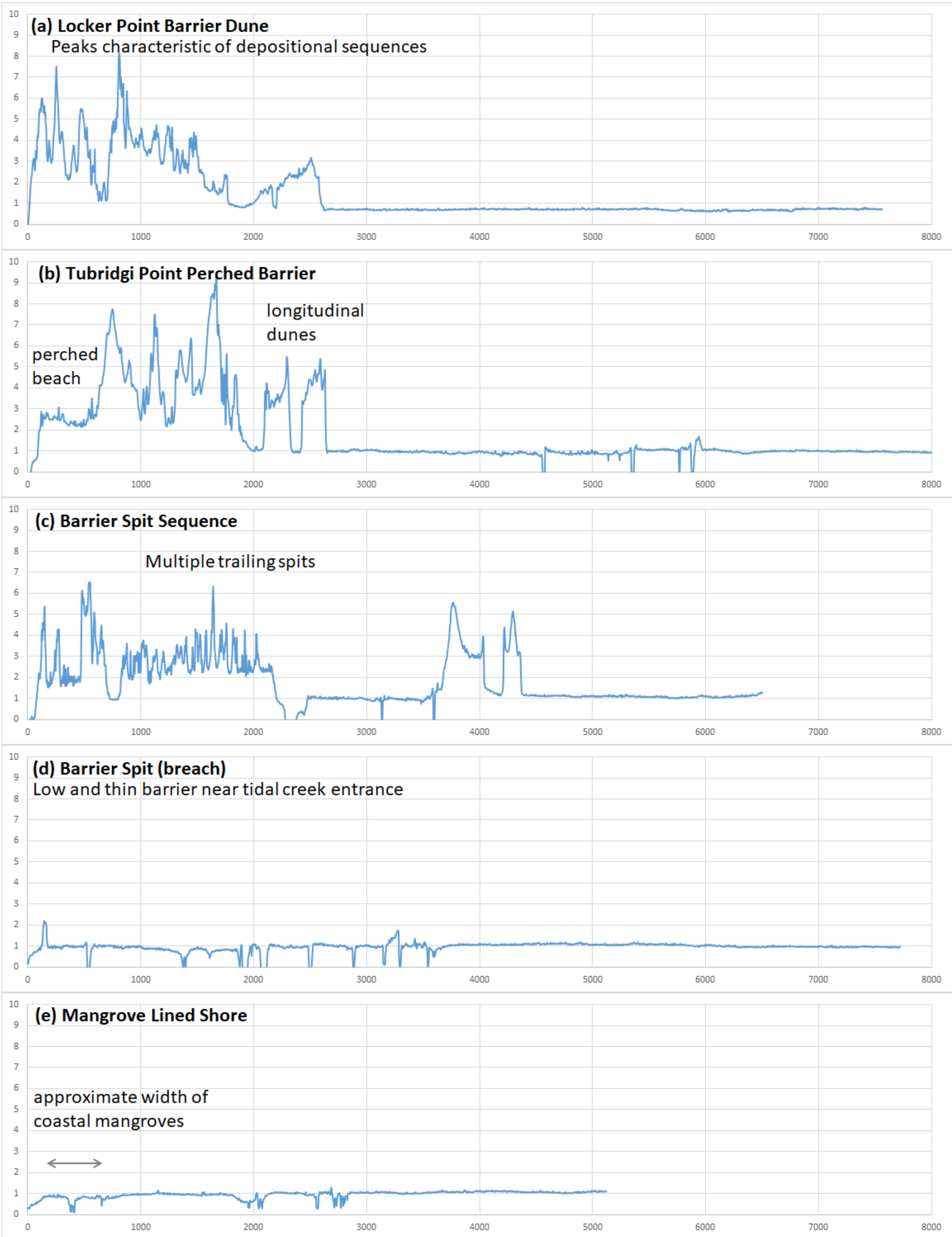

Figure 3-12: Illustrative Cross Sections from Profiles in Figure 3-11

There are morphologic connections between the intertidal rock platform, the coastal barrier and tidal creek systems. This is illustrated by the complex structure shown in Figure 3-13, where multiple relict spits occur landward of a section of rock platform. These spits are adjacent to a former tidal channel, which is presently blocked by the coastal barrier, although this feature appears subject to breaching under extreme conditions.

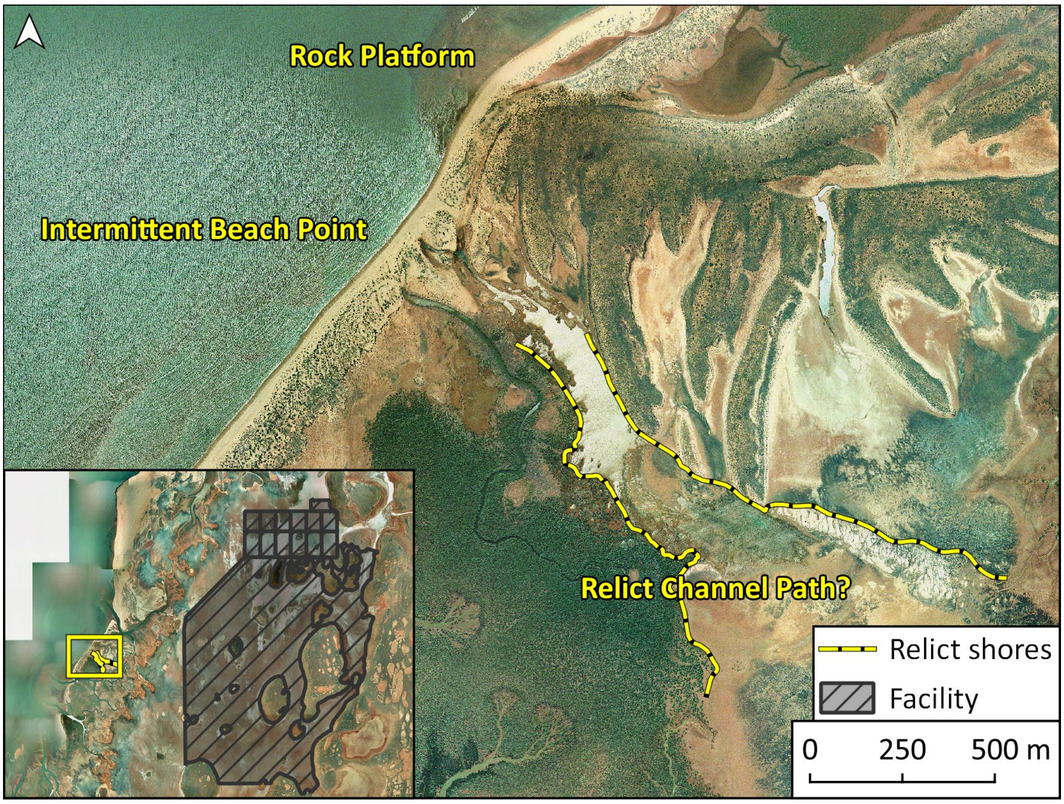

Figure 3-13: Relict Channel and Intermittent Breach Point

There is no barrier spit along the mangrove shore, which has a very gently graded slope (1 in 300) transitioning into an almost horizontal mangrove flat (Figure 3-12e). There is only small variation in level extending across the algal mat area and salt flat, except where incised by tidal channels.

3.4.4. Intertidal Habitats

The extremely flat topography of the coast fringing mangroves and salt flats described in Sections 3.4.2 and 3.4.3 belies the morphologic complexity of the intertidal zone. The main physical driver is tidal exchange through the channel network, which provides a mechanism for redistribution of fine sediments and affects the viability of vegetation through establishment of salinity gradients. Vegetation, including mangroves, locally modifies sediment mobility through root structures and flow baffling, and may also generate biogenic sediments (Chaudhuri *et al*. 2019).

Aeolian and hydraulic influences, as well as vegetation structures and heterogeneity of sediments, form depressions and basins over a range of scales (Perillo 2019). Tidal influx and drainage are approximately proportional to the area of these basins. When basins are connected to a tidal channel network, the size of the channel required to convey the flow tends to be related to the contributing areas, although not always directly (Davies & Woodroffe 2010; Perillo 2019). The range of basin scales can correspondingly provide a 'fractal' dimension to tidal channels, with smaller channels draining downstream into larger channels, with a dendritic structure (Figure 3-14). Extending from the main tidal channels the progressively smaller scale set of channel forms grade from creeks to gullies, to grooves, down to surface rills (refer to Section 6).

This complexity is further developed by the presence of mangroves, which require nutrients from water exchange and sediment input and are tolerant of a limited salinity range (Twilley *et al*. 1999; Winterwerp *et al*. 2013). These conditions can be developed along the fringes of tidal channels, but require greater water exchange in basins, resulting in mangrove flats closer to the ocean, with channel fringing mangroves extending landward toward the edge of the algal mat zone (Figure 3-14 & Figure 3-15).

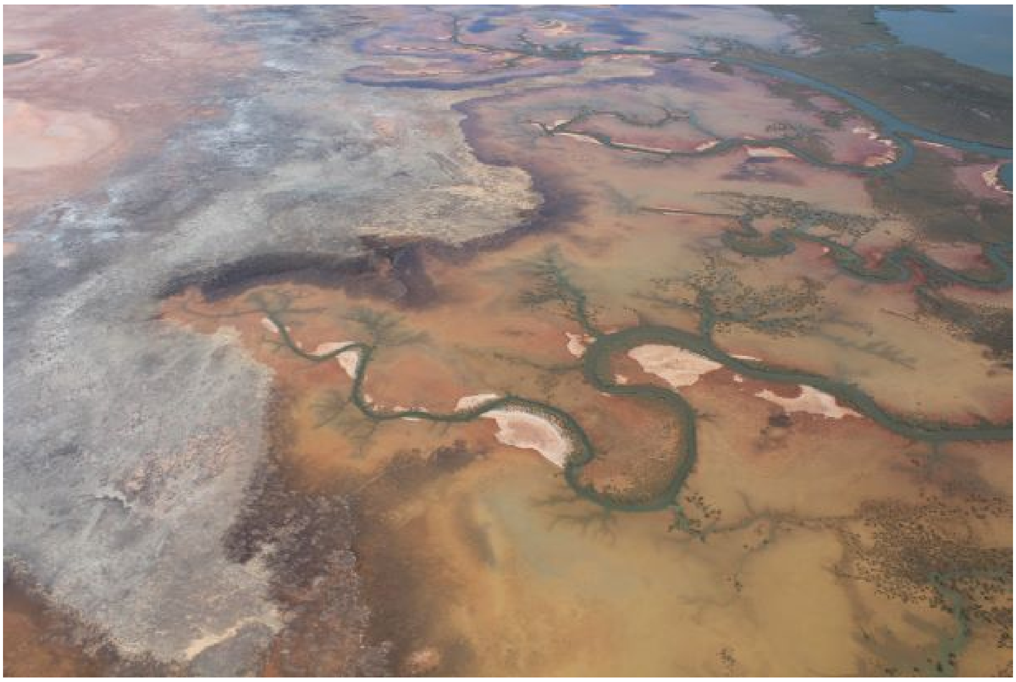

Figure 3-14: Tidal Channel Sinuosity and Dendritic Tertiary Structure

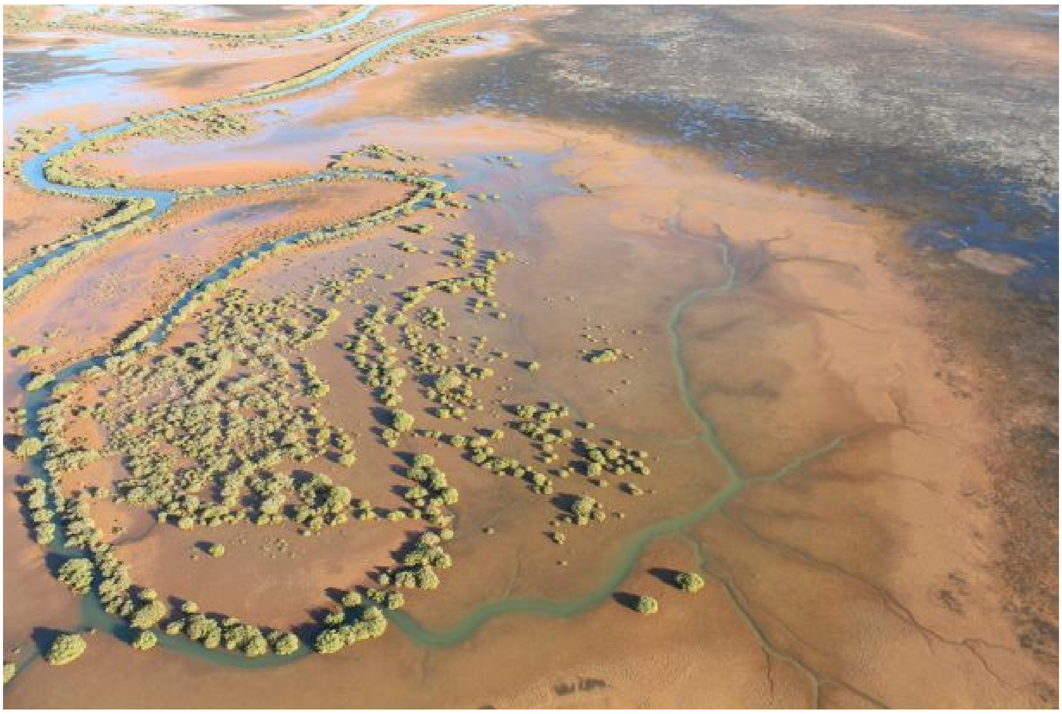

Figure 3-15: Upper Intertidal Mangroves Adjacent to Tidal Creek

This photograph illustrates the occurrence of fringing mangroves along the banks of the tidal creek and areas of less developed mangroves for parts of the adjacent 'flats'. Landward of the mangroves, the mudflats are morphologically dynamic (brown coloured) which grades into algal mat areas (dark coloured).

Tidal movement through the dendritic channel network provides focused flow, which can lead to deeply incised tidal creeks (Figure 3-16). Incision gives comparative stability under a range of flow conditions, with the shallower and steeper gradient channels of the network, including gullies and tidal grooves, being more susceptible to bed mobilisation or deposition through different tidal phases. Consequently, tidal channel networks are typically most dynamic at their 'headward' limit, with expansion (channel headcutting) or infilling occurring in response to changes in tide, mean sea level or channel structure (e.g. restriction due to wave-driven sediment supply at the mouth).

Landward expansion of the channel network, also referred to as channel headcutting, can provide a significant precursor to mangrove colonisation (Robertson & Alongi 2001). Channel expansion increases flows and drainage, which reduces porewater salinity of the adjacent mudflats, making them better suited to mangrove growth and sustainability.

Algal mats occur on mudflats landward of the mangroves, occupying a large spatial area, with ~6,000 ha in the Tubridgi Point to Tent Point area. Their presence and persistence is strongly influenced by tidal water inflow. For the project area, as with other sites around Western Australia (Paling *et al*. 1989), algal mats typically occur at elevations slightly above the mean high water springs tidal plane, within a very narrow (~0.1-0.3 m) elevation band. This means that algal mats are inundated intermittently under high tides, which occur less than 2.5% of the year (Biota 2005). Although the spring-neap tidal cycle is regular, with two peaks per month, variation in tidal phase and mean sea level determines that inundation patterns are highly seasonal. Inundation occurrence is also limited by the very flat terrain, with the volume of water overspilling from the tidal creeks insufficient to fill the flats to a corresponding tidal level. Overspilling, without a hydraulic gradient to provide drainage, combined with high evaporation rates, causes an imbalance of tidal exchange and results in enhanced salinity across the salt flats.

Figure 3-16: Incised Tidal Channels

Factors likely to influence the distribution of algal mats include:

- Very low frequencies of tidal inundation and flushing landward from the tidal channel networks impose extreme salinities and dehydration.
- Bed instability due to tidal network dynamics, plus grazing pressure by invertebrates contribute to the lower elevation limit of algal mat occurrence. High bioturbation, mainly from fiddler crabs, has been observed on predominantly bare mud flat areas between mangrove and algal mat areas for Onslow and Exmouth Gulf (URS 2010, Lovelock *et al*. 2010).

Investigations for other salt projects in northwest Australia have identified samphire (*Teticornia spp*.) as flora of interest occurring in the intertidal zone (EPA 2021). For the Ashburton Salt project site, samphires have not been mapped as a major floristic element (Biota 2020).

Samphire mapped by Biota (2020) occurs as:

(i) A dominant species in a narrow supratidal/intertidal fringe at the base of supratidal slopes, including upward slopes of mainland remnant islands, dunes abutting salt flats and the north-eastern bank at the mouth of Urala Creek North; or

(ii) Either a dominant species or mosaic presence in supratidal basins and channels upstream of where ephemeral drainage lines debouch onto the salt flats. This occurs along the north-eastern edge of the proposed Project site at the salt flat hinterland fringe, or on outwash banks of the Ashburton River.

As samphire habitats cover a small area and are topographically controlled, future behaviour has been inferred from analysis of spatial distributions, tidal dynamics and sea level rise, including anticipated changes to the landforms occupied by samphire (Section 4.6).

4. Coastal Change

The Ashburton Salt project has been required to consider the effect of relative sea level rise on the projection of future coastal change, with comparison of impacts with or without the proposed salt ponds and associated infrastructure.

This section summarises the scientific literature describing the dynamics of intertidal settings in response to sea level rise.

4.1. SEA LEVEL RISE PROCESSES

Sea levels relative to the coast are developed through a wide array of ocean, atmospheric and earth processes, occurring over different time and space scales, with astronomic tides providing the greatest source of variability (Gornitz 1993). Sea levels affect the coast by modifying the distribution of wave energy across the inner shelf and shore; altering sediment dynamics at marine-land interfaces (e.g. beach-dune, or estuary-floodplain); and being the main driver of physical and water quality change in estuaries and shallow coastal settings. As a generalisation, sea level rise causes a tendency for coastal retreat, however, this may occur through offshore sediment transfer, onshore sediment transfer, altered alongshore sediment transport patterns or simply inundation of higher areas (Bruun 1962; Dubois 1992; Davidson-Arnott 2005).

Sea level rise has been observed over most of recorded human history (Lamb 1982). Coastal sedimentology and climate indicators demonstrate sea level rise of more than 100m since the last glacial maximum, approximately 15-20,000 years ago (Figure 4-1), i.e. above 0.5m per century. However, this rate of rise slowed and in some parts of the world reversed. For Western Australia, sea level was 1-2m above present day levels, with the switch from rising to falling (albeit nearly steady) sea levels around 5,000 years ago appearing as a distinct horizon in sedimentological records (Semeniuk 1995; Wyrwoll *et al*. 1995; James *et al*. 2004). This also provided abrupt changes in geomorphology, with increased stability of coastal barrier dunes, commencement of deposition in modern estuarine basins and increasing proliferation of mangroves (Semeniuk 1995; Woodroffe *et al*. 1993).

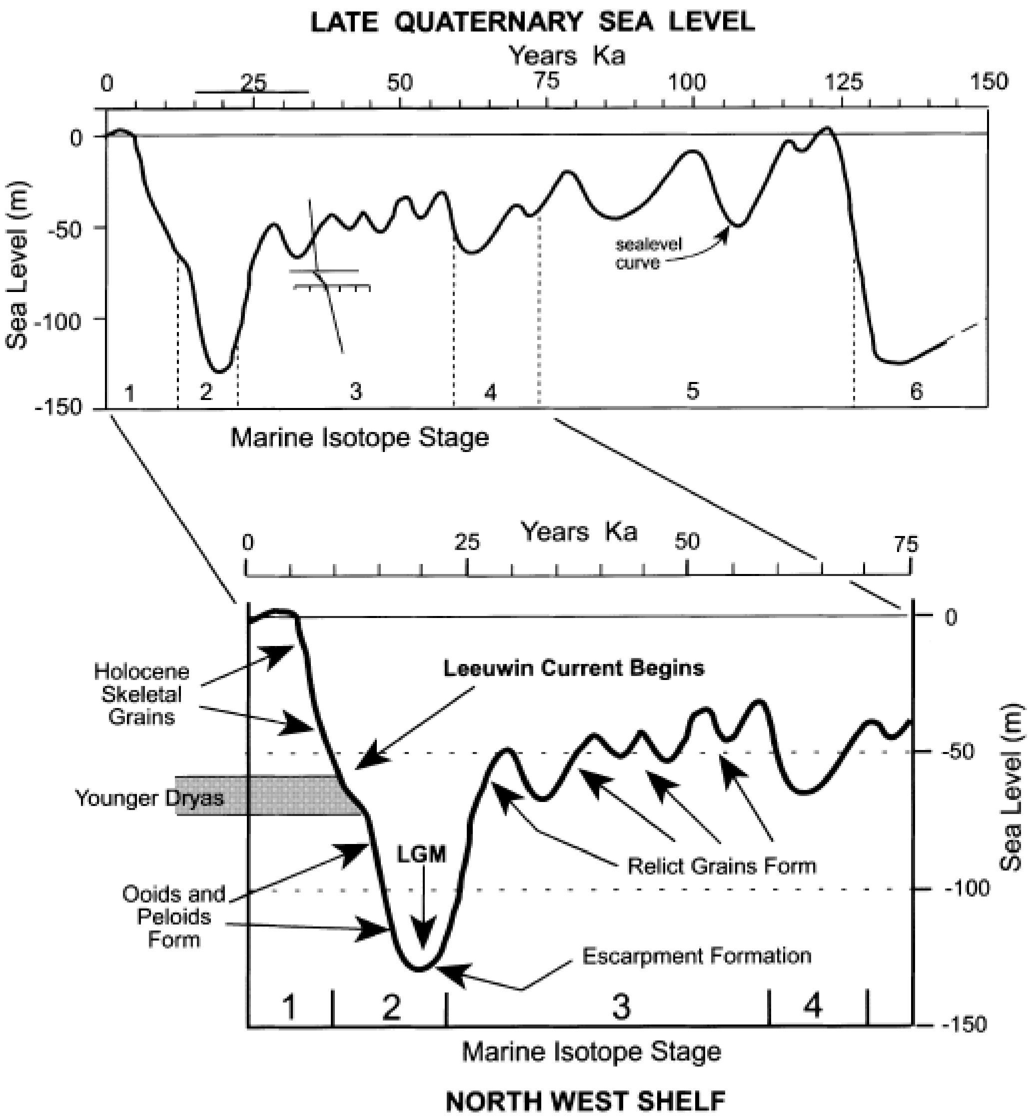

Figure 4-1: Last Glacial Cycle and Sedimentary Indicators for Northwest Australia Diagram from James *et al*. (2004)

Modern sea level measurements, via tide gauges since the 19th Century and using satellite altimetry since the late 20th century, demonstrate sea levels have been rising, on a global average (Douglas 2001; Church *et al*. 2004) with comparable change at a regional scale (Haigh *et al*. 2011a; White *et al*. 2014). This is also illustrated by the long-term Fremantle record (Figure 4-2). Global observations show spatial and temporal variation in trends of relative sea level, including effects of tectonics, vulcanism, subsidence or compression, deformation of the Earth's crust, and inter-annual variability of the ocean surface gradients. The last mechanism can affect sea levels at an ocean basin scale, with substantial responses to climate variability identified in the Pacific Ocean due to the El Niño phenomenon. This mechanism relates to the east-west balance of equatorial ocean heating and consequent prevailing winds (Willis *et al*. 2010). Similar mechanisms occur for each of the ocean basins, with interaction through connecting zones. A process crucial to Western Australian sea levels occurs at the Pacific-Indian Ocean connection, where the Indonesian Throughflow provides a source of water forming the Leeuwin Current travelling southward along the continental shelf boundary. This flow causes Ekman setup, with variation in current intensity and position affecting sea levels along the Western Australian coast (Pattiaratchi & Buchan 1991; Feng *et al*. 2004). Instability of this phenomena has been observed, with the 2012-2013 La Niña phase increasing the volume of tropical water travelling along the coast, causing a marine heatwave and substantially increasing mean sea level (Bureau of Meteorology 2012).

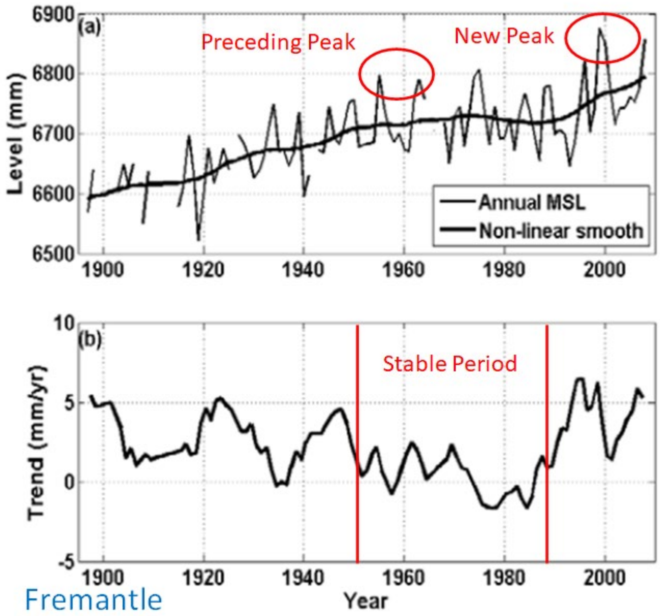

Figure 4-2: Fremantle Long-term Mean Sea Level and Trend Diagram from Haigh *et al*. (2011a)

Evidence of global heating over the 20th Century prompted investigation of both causes and potential response, with the Intergovernmental Panel on Climate Change (IPCC) established to provide a collaborative forum for collation and dissemination of relevant science (IPCC 2001, 2007). Industrial emissions of CO_2 and aerosols were identified as anthropogenic factors contributing to atmospheric heating, with consequences for weather systems, the hydrologic cycle and ocean-atmosphere dynamics. The IPCC established a common framework for the assessment of climate changes, defining a suite of emission scenarios based upon different patterns of human behaviour and technology. Integrated scientific research by different agencies and at different scales has been supported through IPCC coordination and use of common frameworks.

An outcome of IPCC assessments has been projection of sea level rise for emission scenarios, with accelerating rates of rise over time, and greater rise for higher emissions. These projections have been widely used as scenarios for forecasting coastal change and determining adaptive responses. Sea level response is not globally uniform and requires regional downscaling (Zhang *et al*. 2017). Choice of how to use multiple projections, each of which may be plausible, varies substantially between agencies and applications. For Western Australia, a widely used summary was developed for coastal planning, which provided a single forecast curve (Figure 4-3), corresponding to sea level projections for a moderately high emission scenario (Transport 2010). Opportunities for more severe rates of sea level rise and interaction with other processes, including inter-annual sea level variability, were identified. Global attempts to improve confidence in sea level projection have been challenged by the limited difference in projected trends within the available observation period (late 20th to early 21st Centuries) and effects of climate variability. However, emissions and global heating are tracking toward the upper limit of IPCC projections (White *et al*. 2014).

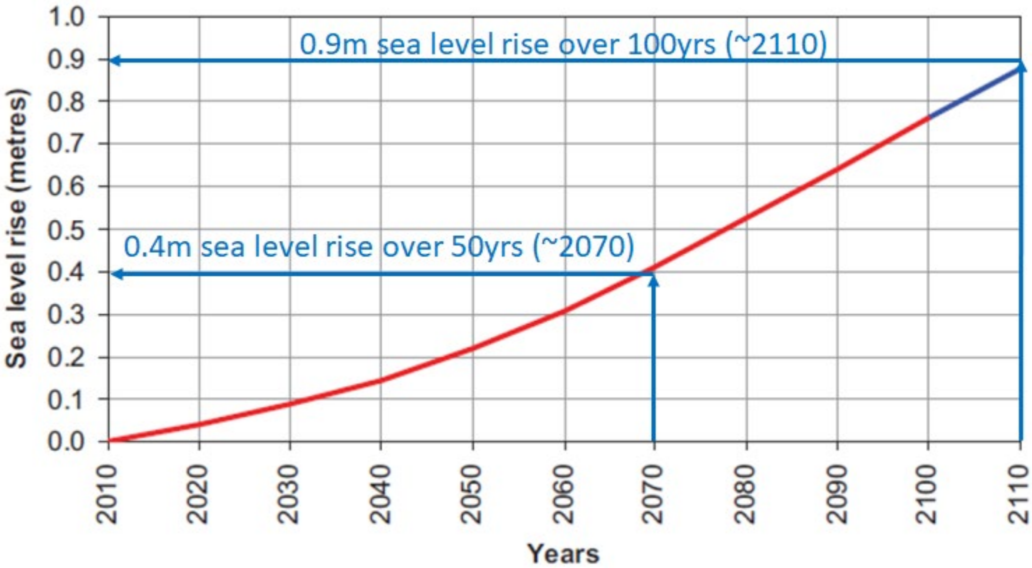

Figure 4-3: Sea Level Forecast Curve Used for WA Coastal Planning (Department of Transport WA 2010)

The State Government has previously advised to use the Department of Transport (2010) projection curve, using the current year as a base year (i.e. for planning purposes, use a 0.9m sea level rise allowance from 2021 to 2121).

Sea level rise is one of multiple processes causing year to year variation in sea levels, with climate variability, tidal cycles and storminess affecting both mean sea level and occurrence of extremes. These processes vary substantially around Western Australia's coast, with a major transition from north to south. The Pilbara region experiences semi-diurnal, meso-tidal conditions, with sub-monsoonal prevailing winds and the incidence of occasional, mobile tropical storms capable of causing severe winds, waves and surges. The tide range, which experience a small 4.4-year modulation (Eliot 2010; Haigh *et al*. 2011b), generally damps the influence of other sea level phenomena, although longer-term processes such as sea level rise may have effect through superposition with tides, and the severity of tropical cyclones can cause sea levels well above normal tides.

Characteristics determining the effects of sea level rise are likely to be gradually apparent. They are modulated by climate variability (related to El Niño-Southern Oscillation) with a moderate increase in the occurrence of high water levels. The significance of climate variability on mean sea levels has been demonstrated for Western Australia in trends observed from 1990-2014, which capture a transition from El Niño to La Niña dominated conditions, giving a rise of almost 0.3 m in less than 30 years (White *et al*. 2014). This rate of change has not been sustained subsequently.

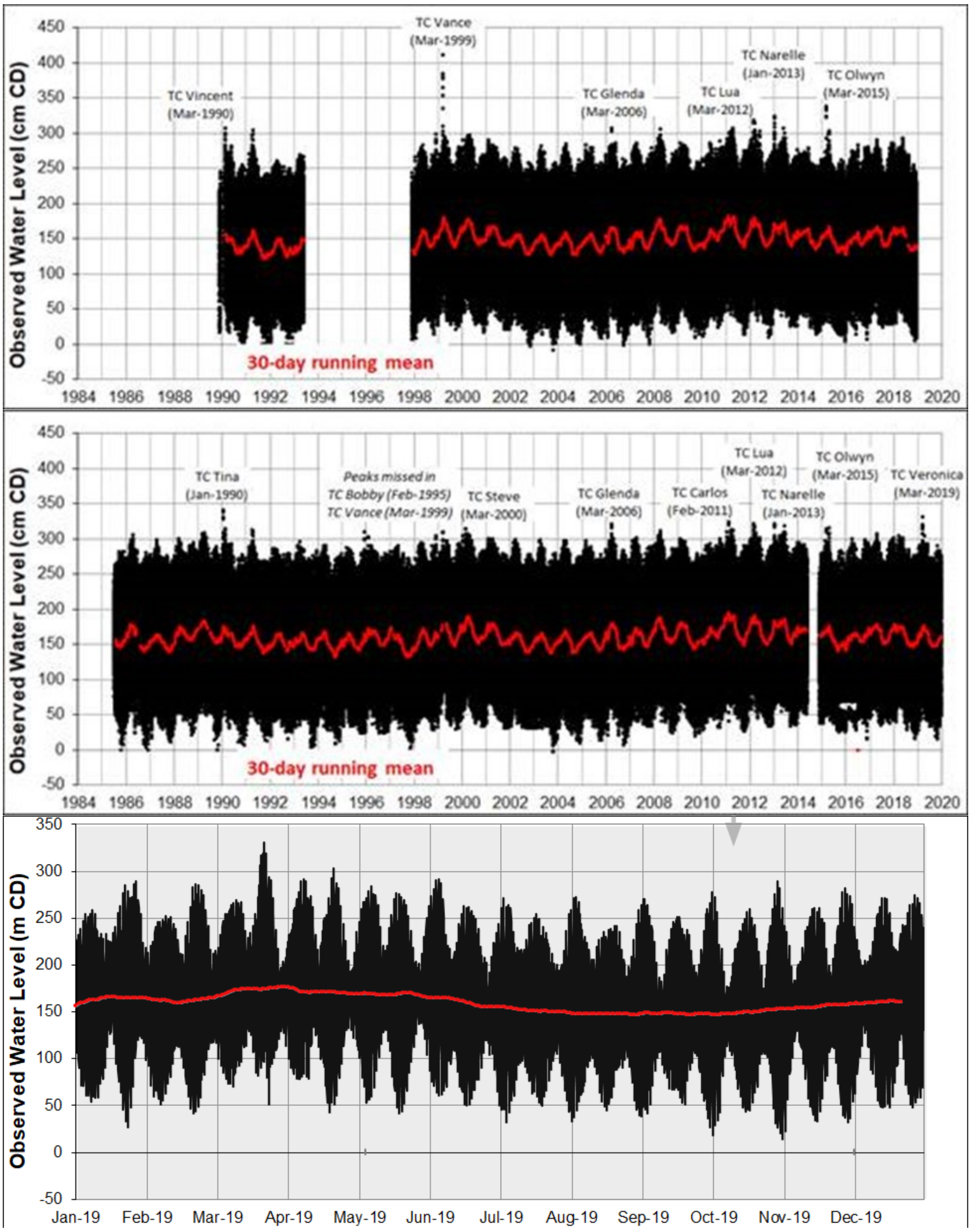

Figure 4-4: Observed Sea Level Records: Exmouth Tide Gauge Record; (b) Onslow Tide Gauge Record; (c) Onslow 2019 Water Level Record

Seasonal sea level processes also influence behaviour of the tidal channel network, including variation of monthly tidal range and monthly mean sea level. An indication of the difference is provided by comparison of calendar month submergence curves, derived from Exmouth tide gauge data (Figure 4-5). This indicates a substantial difference in inundation frequency, with the mean high water springs tidal plane (0.99 m AHD) being inundated 10 times more frequently in March than in August. The seasonal variability causes a correspondingly large variation in tidal exchange on and off from the tidal flats.

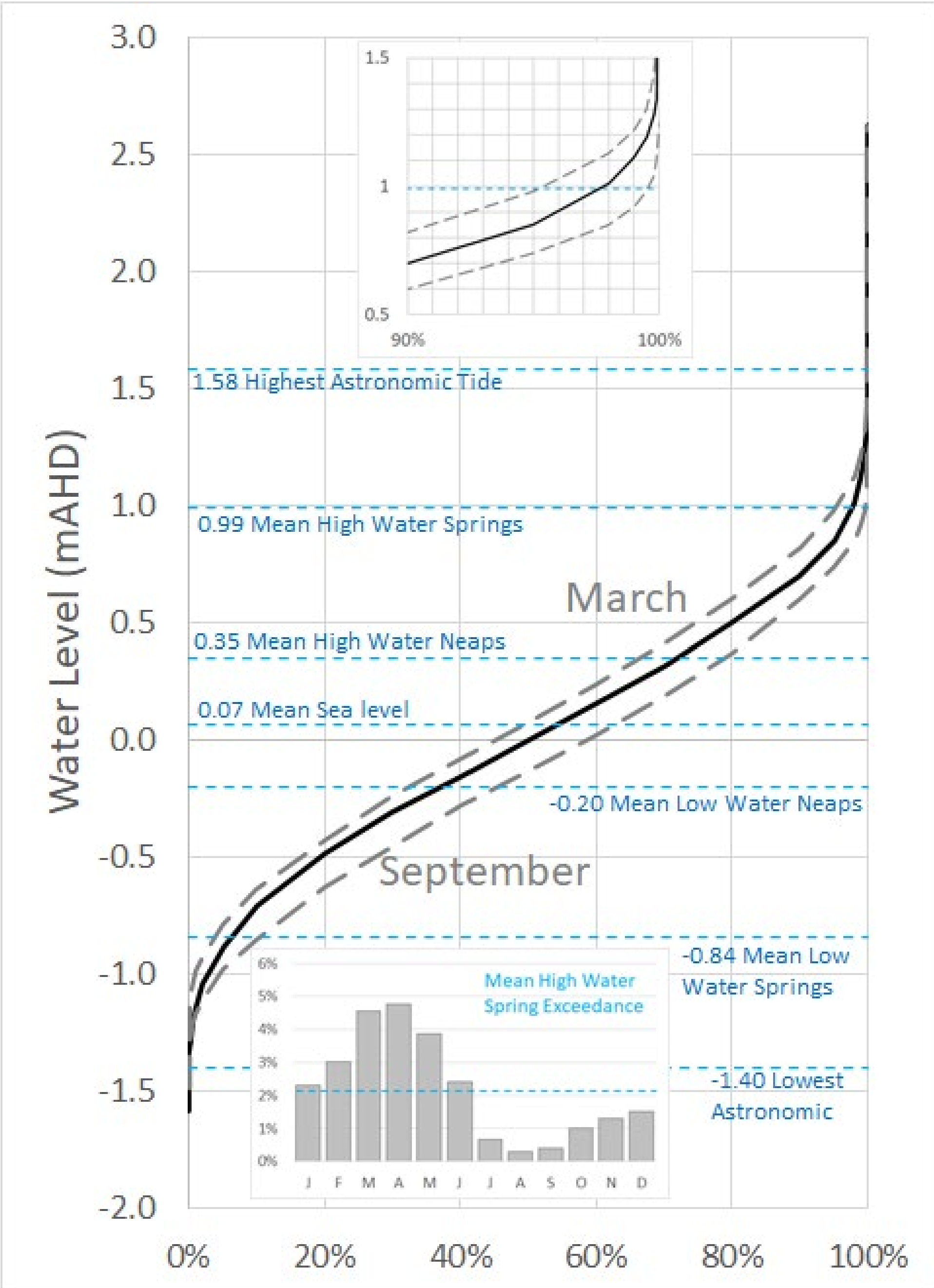

Figure 4-5: Exmouth Submergence Curve and Seasonal Range

4.2. COASTAL RESPONSE TO SEA LEVEL RISE

The role of sea level as a driver for coastal change has long been identified (Fairbridge 1950), with stratigraphic evidence confirming cycles of sea level over different time scales. This ranges from movements of hundreds of metres over hundreds of millions of years due mainly to vulcanology and atmospheric composition, down to cycles of ~0.1 m over hours due to meteorological fluctuations. At an intermediate time scale, sea level is related to global temperatures. Planetary orbital cycles over a time scale of approximately 100,000 years have been linked to large-scale climate fluctuations, particularly evident as glacial and inter-glacial phases (Milankovitch 1941). This link, and the associated process of water storage within glaciers, determines that global sea level can rise rapidly and decline comparatively slowly (Figure 4-6).

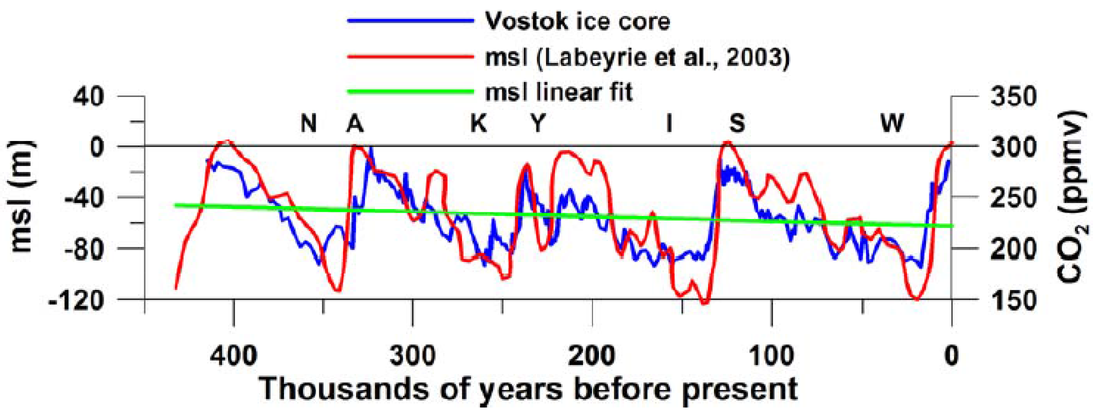

Figure 4-6: Global Sea Level Cycles at the Milankovitch Scale
Diagram from Perillo & Piccollo (2010)

Evaluation of how the coast responds to sea level change is often described relative to mean sea level change. However, constant fluctuations of tide and waves generally determine that the coast has small response to ranging within 'typical' conditions, with physical changes caused by the frequency or severity of conditions outside this range. Consequently, evaluation of sea level impacts can be related to either or both mean and extreme statistics.

The way the coast responds to changing sea levels has strong variation due to differences in coastal morphology, which varies due to geology, tide, waves and relative supply of sediment. Evidence of different modes of coastal response to sea level rise is available from stratigraphic sequences, combined with modern observations of coastal dynamics, with the recent 1990-2013 El Niño to La Niña transition providing a small-scale analogue for projected sea level rise (White *et al*. 2014). Conceptual models for coastal response to sea level rise remain under scientific development, with most projections based on far simpler sediment dynamics than revealed in either stratigraphy or modern coastal measurements.

The two most widely used conceptual models are developed through assumption that the coast will respond through cross-shore adjustment (Figure 4-7). The Bruun model (Bruun 1962), which is more applicable for high energy coasts, infers that sea level rise will change oscillatory shelf-shore sediment exchanges, resulting in a net transfer from the coast to the inner shelf. The Davidson-Arnott model (Davidson-Arnott & Fisher 1992; Davidson-Arnott 2005), which is more applicable for low energy coast such as within Exmouth Gulf, infers that sea level rise will cause the coast to rise and roll landward over low-lying areas. Response to both models is influenced by coastal geometry and composition, but in both cases, it is typically in the range of 25-100 m of coastal retreat per metre of sea level rise.

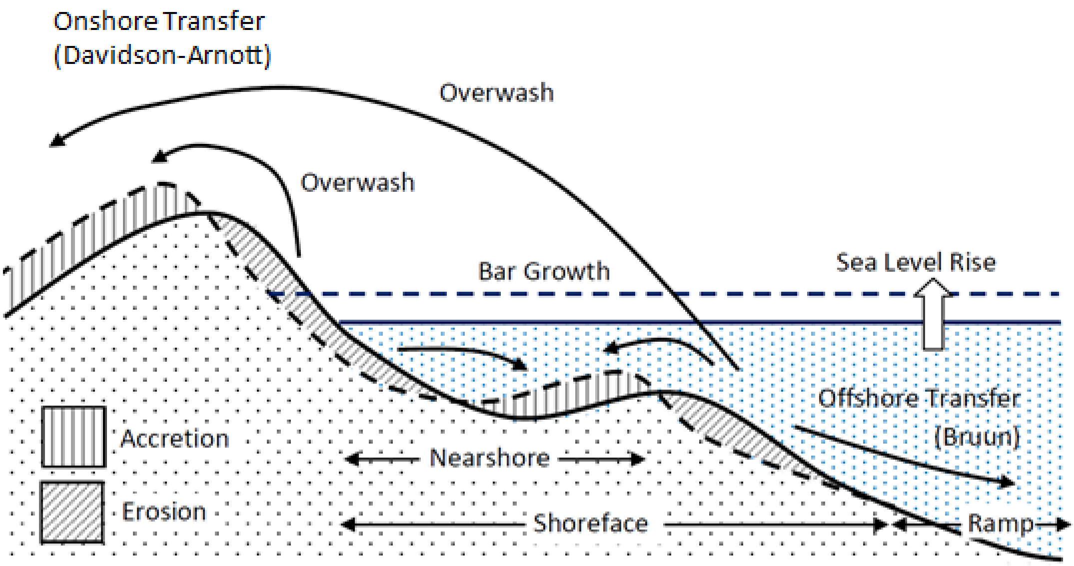

Figure 4-7: Typical Models of Cross-Shore Response to Sea Level Rise
Diagram adapted from Dubois (1992)

Cross-shore adjustment to sea level rise is potentially enhanced where nearshore features substantially affect the distribution of wave energy over the shoreface, including reef-protected shores, wide sub-tidal terraces or perched beaches. These features are extensive along the Western Australian coast, with limestone reefs present along almost the entirety of the west-facing coast and a very wide shallow margin along the Pilbara coast (Semeniuk 1996). Sea level rise will cause increased wave energy at the shore, with associated change to beach structure, as well as modified rates of alongshore transport.

The assumption in the Bruun and Davidson-Arnott conceptual models that coasts only respond to sea level rise in a cross-shore manner is not supported by either stratigraphic sequences or modern observations of coastal change. This is particularly so where there are geological structures, such as headlands or substantial reefs, capable of limiting alongshore transport. Coastal partitioning affects the distribution of sediments, with higher dunes, indicating greater stability of coastal position, occurring on the updrift side of most coastal headlands.

Localised response to sea level rise is also expected where coastal landforms facilitate sediment supply or storage. Estuaries will generally experience increased marine sediment influx, however if this is insufficient to keep up with sea level rise the estuary will 'drown' (Leuven *et al*. 2019). Tidal creek networks will typically extend landward through channel expansion and headcutting (see Section 4.3).

Response of coastal dunes to sea level rise will vary, influenced by the elevation and continuity of the dune crest (Donnelly 2007; Larson *et al*. 2009). For low or discontinuous dune systems, sea level rise may increase the risk of dune breaching. On larger dune systems, potential erosion of the dune toe can undercut dune vegetation, instigating wind-blown dune mobility. This is particularly significant for dune systems along the Western Australian coast which were highly active during the late Holocene sea level highstand but have subsequently been more stabilised. Dune mobilisation causes sediment to move landward, which can lead to loss from the beach and inshore system, contributing to coastal erosion.

4.3. TIDAL WETLAND RESPONSE TO SEA LEVEL RISE

The morphology of muddy coasts varies considerably from that of sandy coasts, due to the relatively higher mobility of fine sediment, combined with the influence of cohesion once a sediment matrix has been formed (van Rijn 1998, Coco *et al*. 2013). Accretion develops through the settlement of suspended sediment and therefore accretionary features characteristically develop in response to hydraulic advection and dispersion away from material sources, including resuspension. This typically creates very flat, low profile features, deposited in layers through successive flooding. In contrast erosion can be resisted by cohesion, providing capacity for relatively steep slopes, including incised banks. The contrast between eroding and accretionary phases is therefore often apparent (Winterwerp 2012), indicated at coastal margins by a switch from a convex to a concave profile (Figure 4-8).

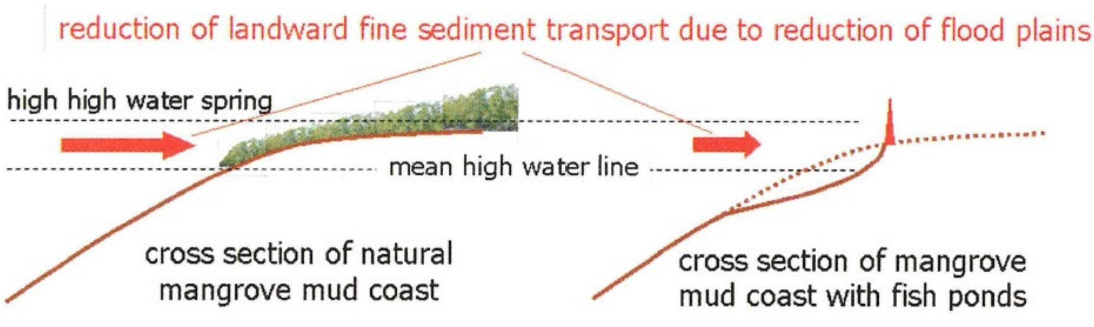

Figure 4-8: Profile Change Associated with Accretion-Erosion Switch Diagram from Winterwerp (2012)

Steep banks and flat depositionary features are important characteristics for the development of tidal networks, where hydraulic conveyance between the coast and floodplain is provided through relatively narrow tidal channels (Perillo 2019). These channels act as focal flow pathways, supporting relatively high rates of suspended sediment transport and providing a pathway for floodplain deposition, with incoming floodwaters spilling onto the adjacent flats. This is counterbalanced by the erosive power of downstream flow from ebb flows or rainfall drainage, which is focused at the high slope transition from the flat to the tidal channel, creating incision at a range of scales.

The difference between erosion and accretion phases on tidal channel networks can be apparent, with overwash fans, apparent as a 'cloud' around tidal creeks on aerial photographs, indicating an accretive phase and sharply incised channels indicating an erosive phase (Figure 4-9). With a dendritic structure, tidal flows are at their slowest near the head of the tidal creek, supporting local deposition. Under sustained deposition, this can result in the creek infilling, with a downstream progression. However, the relatively weaker cohesion of deposited material also provides a preferred pathway for channel incision, with long-term cycles of extension and contraction often recurring along paleochannels (former streamlines).

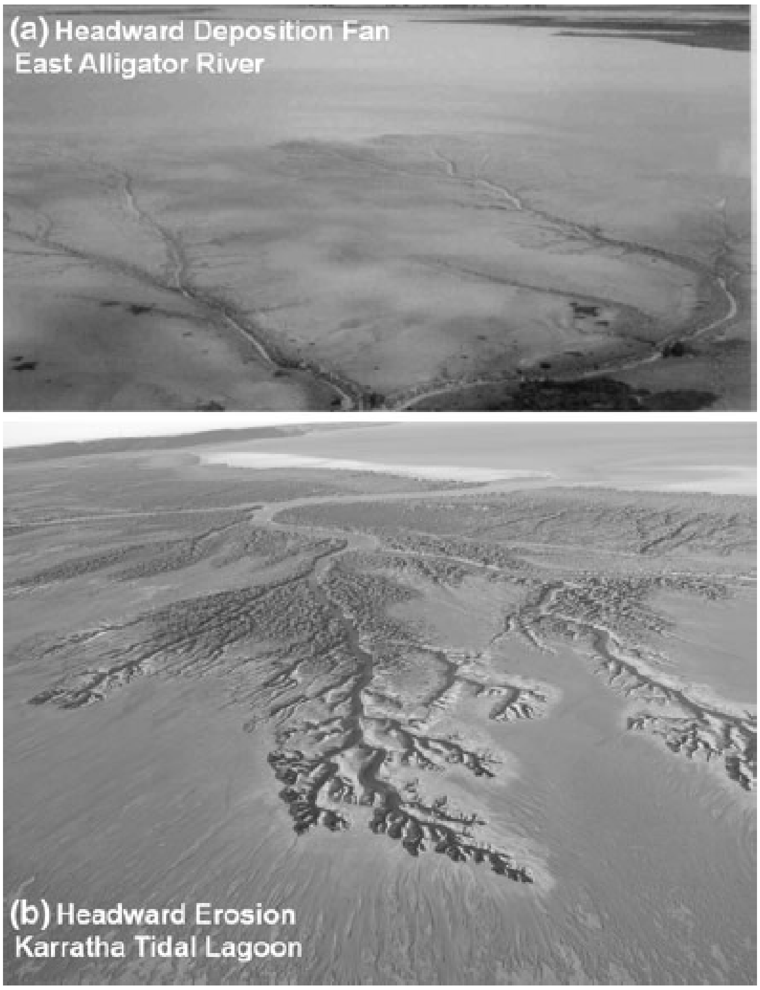

Figure 4-9: Deposition Fan and Incised Channel Indicators of Dynamics Diagram from Eliot & Eliot (2012)

Variation of flows and associated small transfers of sediment occur within the shift between each tidal ebb and flood, producing oscillatory transport. Consequently, tidal channel networks are dynamic, with the balance of sediment movements changing in response to tidal cycles (fortnightly, seasonal or longer) and more irregular fluctuations in mean sea level. Tidal network adjustment provides a mechanism for relatively rapid adjustment of the tidal flat level and therefore is an important potential response to mean sea level change.

Tidal network adjustment is one of the substantial differences in anticipated response to sea level rise expected between high energy sandy coasts and muddy wetland coasts (Rossington *et al*. 2009; Alizad *et al*. 2018; Leuven *et al*. 2019). Other mechanisms can include:

- Floodplain trapping of sediment influx from either marine or fluvial sources (Ryan *et al*. 2003).
- Generation of vegetation litter and biogenic sediments, locally raising the effective land level (Morris *et al*. 2002; Saintilan *et al*. 2020).
- Influence of vegetation, particularly due to their roots, in controlling the spacing and depths of tidal depressions and channels (Perillo 2019). There is often feedback between the two, such as a gutter developing along the fringe of a mangrove community that confines its expansion, or a line of riparian vegetation defining a basin (Figure 3-15).
- Formation of channel banks, rising above the adjacent flats, due to overbank deposition of suspended sediment spilling out from the tidal channel. Banks are often reinforced by riparian vegetation, with overflow and breaching capable of creating new tidal flow pathways (d'Alpaos *et al*. 2005; Gong *et al*. 2018).
- Development of cheniers through accumulation of low mobility material, including rubble, shells, gravel and vegetation debris, due to severe wave or flood flow events, effectively partitioning the floodplain surface.

4.4. MANGROVES AND SEA LEVEL CHANGE

Mangroves are a collection of different species of vegetation occupying a common ecological niche, on the comparatively narrow and dynamic marine fringe (Alongi 2008). Each species has different adaptive characteristics, making them better able to tolerate different stressors, such as bed instability, poor substrate, nutrient deprivation, inadequate water exchange, pollution or relative frequency of freshwater conditions (Winterwerp *et al*. 2013). Within the coastal margin, steep and often dynamic ecological gradients limit the viable habitat for any single mangrove species. In response, mangroves typically develop species zonation, with a transition from those species most adapted to marine conditions, (e.g. tolerant to bed movement) at the outer edge towards species more suited to fluvial systems (e.g. reliant on seasonal freshwater) located further landward (Duke 1985, AIMS 2008).

Species diversity may be complementary, providing different roles including sheltering or nutrient production. However, zonation can be convoluted by interactions between mangroves and sedimentary and hydrodynamic processes, as well as the relative influence of mangrove opportunism, maturity and competitive advantages (Ewel *et al*. 1998). This can produce complex arrangements of species, often reflecting very local scale hydrological and geomorphic influences (Thom 1982; Woodroffe *et al*. 1992), including groundwater seepage (Figure 4-10).

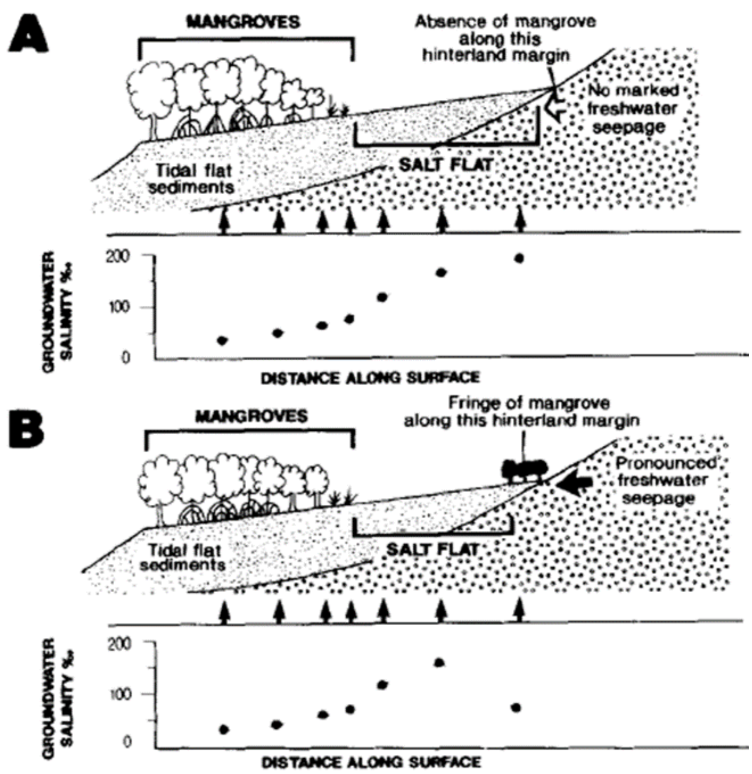

Figure 4-10: Mangrove Distribution due to Groundwater Seepage at Hinterland Diagram from Semeniuk (1996)

The capacity for complex mangrove communities to develop is affected by geographic variation in species diversity (Ellison 2002). The arid Pilbara coast has low mangrove diversity and consequently simple mangrove community structures compared to those in the wet-dry tropics (Semeniuk 1996; Cresswell & Semeniuk 2018). This determines that mangrove communities are influenced by a narrower capacity to tolerate changing conditions and have a strong association with geomorphic setting. A*vicennia marina* and *Rhizophora stylosa* are the prevalent species along the arid west Pilbara coast. They occur as a wide coastal fringe in the mid to upper intertidal area along the shore, or in a narrower fringe along the banks of tidal channels.

Dynamics of the coastal interface, including effects of storms; climate fluctuations; tidal network development; nutrient availability; particularly through mangrove litter; and sea level variability may affect the viability of different settings to provide mangrove habitat. This gives potential susceptibility to disturbance-recovery cycles. In a wide area of mangroves this may produce a complex arrangement of different species and maturity. For a narrow area of mangroves, these pressures may cause cycles of destruction and regeneration. In both settings, mangrove distributions are time dependent, requiring niche preservation and propagation pathways for regrowth after disturbance.

Morphodynamic change is particularly important in the context of accelerated sea level rise; especially if coastal change truncates the features suitable for mangroves or is too rapid for mangroves to colonise migrating features (Gilman 2007; Anthony & Goichot 2020). In many cases, it is decadal-scale morphodynamics that determine the capacity for geomorphic features to support mangrove communities, with a period of 5-8 years for mangroves to reach maturity in the wet-dry tropics (Twilley *et al*. 1999) and longer in the arid conditions of the Pilbara.

Evaluation of mangrove response to physical disturbances can be separated into the effects of ground salinity, hydroperiod (frequency of inundation), erosion, smothering, waves and sea level change:

- Effects of varying ground salinity have been examined by correlating the presence and abundance of mangrove species to salinity gradients. These indicate that *Avicennia marina* is most abundant when salinity is close to marine conditions, and it is unable to grow where porewater salinity is above 90 ppt (Semeniuk 1996).
- Hydroperiod affects the capacity of mangroves to absorb oxygen. This has been correlated with species distribution for Darwin Harbour (Crase *et al*. 2013).
- Mangroves occupy the mid to upper intertidal area, with the depth of root structure within the lower intertidal area strongly influenced by species and plant maturity. Consequently, seedlings can be susceptible to seasonal erosion, whereas a mature community may be able to tolerate short-term erosion to a depth of 0.5-1.0 m, depending upon species.
- Mangroves commonly act to trap sediment mobilised from adjacent coastal landforms. Sediment influx can be a source of key nutrients for mangroves (Anthony & Goichot 2020). However, a thick sediment deposition can smother juvenile mangroves.

- The capacity for mangroves to dissipate wave energy has been widely recognised (World Bank 2016) following a range of previous studies (Brinkman *et al*. 1997; Mazda *et al*. 2006; Quartel *et al*. 2007; Vo-Luong & Massel 2008; Bao *et al*. 2011; Horstman *et al*. 2014). However, under strong wave conditions, mangroves can be broken or uprooted, with damage typically reported where nearshore significant wave heights exceed 0.75-1.0 m.
- Evaluation of Australian mangrove community response to sea level has been largely inferred from late Holocene dynamics, which included substantial proliferation of mangroves across northern Australia following the sea level transgression (Woodroffe *et al*. 1993). Mangrove loss during phases of rising sea level has been analysed, suggesting that the mangrove capacity to capture sediment becomes limited when relative sea level rise (RSLR) is above 8 mm/yr. Mangrove loss occurs for RSLR above 12 mm/year (Woodroffe *et al*. 2016; Saintilan *et al*. 2020).

These attributes suggest an indicative framework for mangrove community responses to sea level rise, with several conceptual models of response (Figure 4-11).

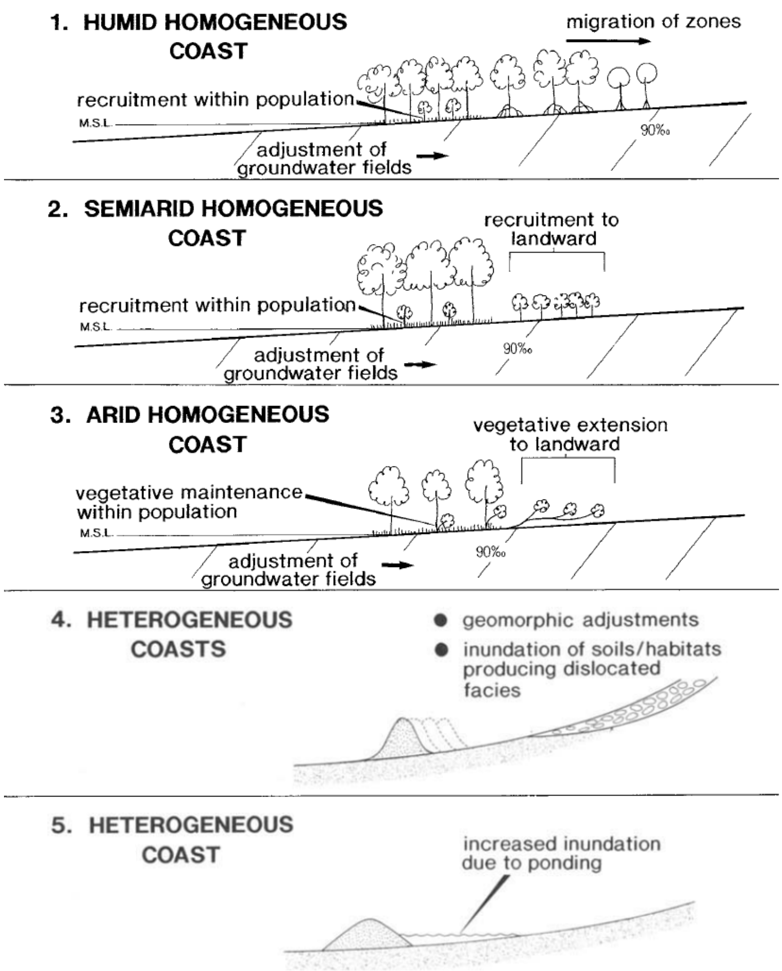

Figure 4-11: Conceptual Models for Response to Sea Level Rise
Diagram from Semeniuk (1994)

Characteristic zonation of mangrove species within different tidal planes has led to a common practice of describing habitat according to hydroperiod (Crase *et al*. 2013), and implicitly suggesting mangroves will migrate with sea level. However, the association of plant and location is more complex. Despite individual mangroves being capable of occupying marginal locations, change to inundation patterns due to sea level rise is not expected to cause a directly correspondent change to mangrove distribution. Instead, suitable habitat is expected to change due to geomorphic response to sea level rise such as tidal channel expansion, within which mangrove-morphology interactions are a secondary, although not unimportant process (van Maanen *et al*. 2015). One controlling factor is available sediment volume, with local sediment exchange and external supply determining the capacity for landform changes. The role of porewater salinity has also been identified as a controlling factor on the arid Pilbara coast (Semeniuk 1993).

Potential thresholds of relative sea level rise on the behaviour of mangrove communities suggests that projected sea level change will modify existing patterns of mangrove development. For the forecast sea level curve (Figure 4-3), the threshold submergence rate of 8 mm/yr is reached by 2040-2050, with a 'destructive' threshold of 12 mm/yr reached by 2070-2080. Under less severe projected scenarios for sea level rise, these thresholds will be reached later. It is noted that these thresholds require relative sea level rise to be sustained for long periods, with the decadal scale accelerated sea level rise of ~15 mm/yr reported for the Pilbara from 1990-2010 (Church *et al*. 2005) not apparently causing widespread mangrove loss.

For the project location, mangroves occupy two separate landform units, being (i) coastal mangroves and (ii) tidal creek fringing mangroves. The two areas have different landform origins and are occupied by mangrove species with different characteristics for adaptation to morphodynamics:

i. Coastal mangroves develop during episodes of coastal stability (3+ years), with damping of tidal hydrodynamics supporting sedimentation and development of mangrove muds, enabling growth of mangrove flats. The seaward face of the mangroves is exposed to wave action, with disturbance potentially a limiting factor on seaward extension.

   Full development of coastal mangroves involves a heterogeneous community, including bulwark species seaward, and increasingly 'estuarine' species landward. Consequently, coastal mangrove forests are comparatively slow to establish. Development and propagation of coastal mangroves over millennial time scales is strongly linked to late Holocene sea level standstill over the last 6,000 years (Woodroffe *et al*. 1993).

In Western Australian conditions, observed stability of coastal mangroves is often linked to intertidal sand terraces, which act to provide inshore wave damping. These may be subject to substantial change with long-term, inter-decadal variation in sea level.

Mangroves in this setting occur along much of the shoreline from Urala Creek South to Tent Point (Figure 4-12).

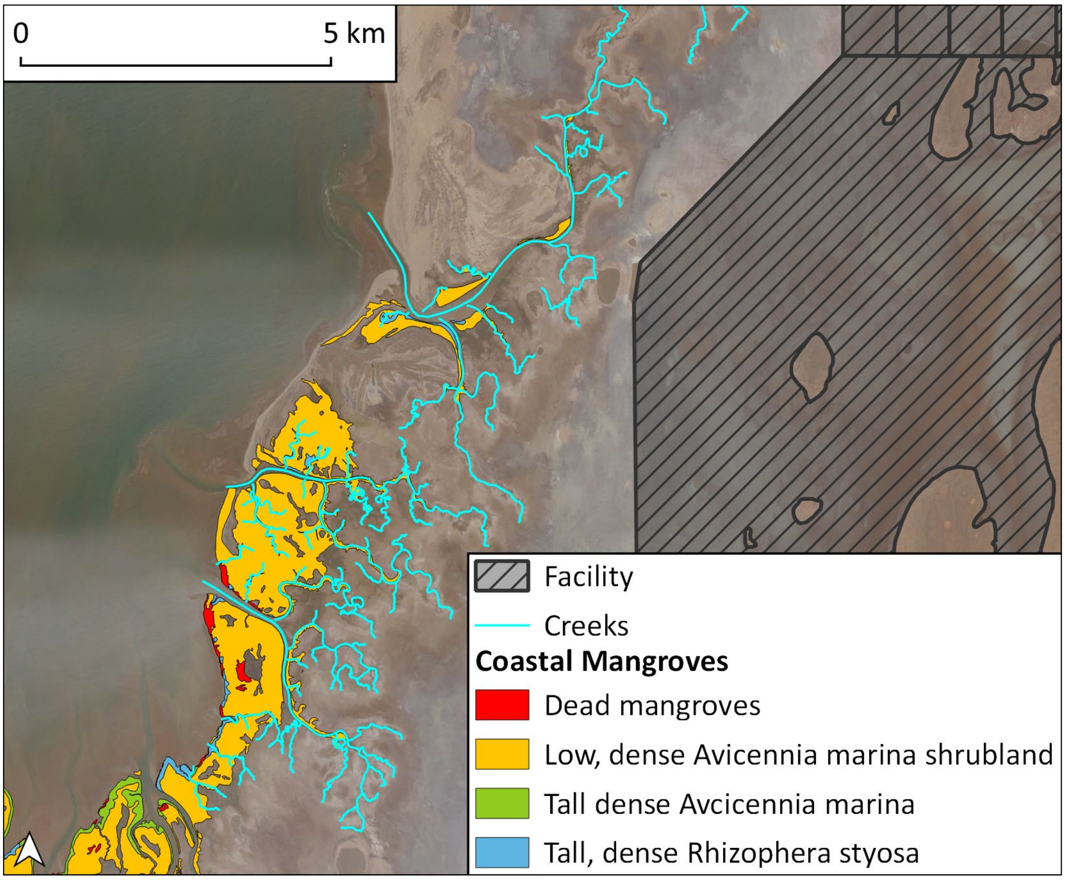

Figure 4-12: Coastal Mangroves

ii. *Mangroves fringing tidal creeks* occur where tidal flows support dispersion of mangrove propagules. These margins are highly dynamic, and creek networks may be subject to change in response to runoff flood events, marine inundation during storm events, tidal variability or mean sea level fluctuations (Perillo 2019).

Tidal creek fringing mangroves are most commonly homogeneous, comprised of opportunistic species, often with adjacent coastal mangrove communities providing the persistence niche. Development and propagation of tidal creek mangroves is strongly linked to disturbance and recovery cycles, particularly associated with bank formation and collapse.

Mangroves in this setting occur extensively in Urala Creek North and South adjacent to the project area (Figure 4-13). They also occur landward of the coastal mangroves between Urala Creek South and Tent Point.

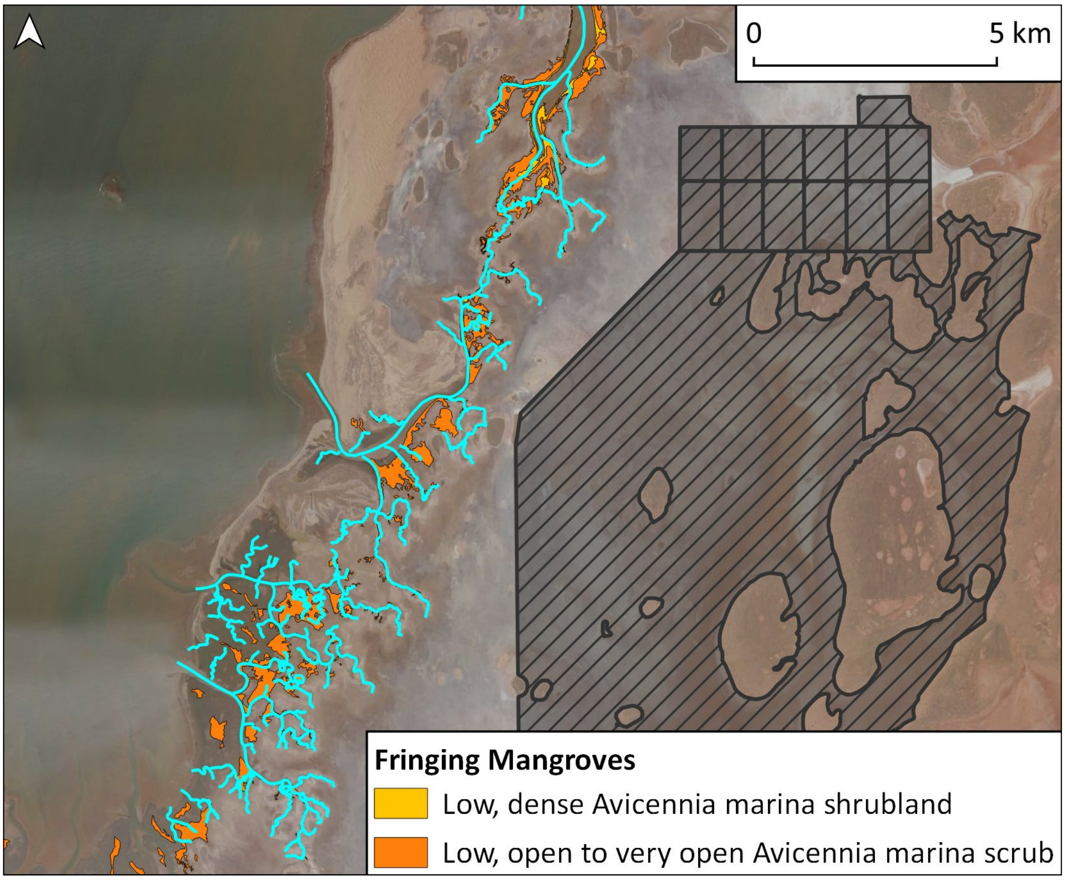

Figure 4-13: Channel Fringing Mangroves

4.5. INTERTIDAL ALGAL MAT DYNAMICS

Algal mats develop on land surfaces subject to inundation and ponding, particularly salt flats, mudflats and overbank basins adjoining tidal creeks. The accumulative nature of tidal flows from the landward tidal limit towards deeper water provides a cross-shore transition of bed stress, which in turn acts to providing natural sorting of bed sediments, with coarsest sediments near the zone of highest energy and declining sediment size landward. This zonation supports a classic convex structure for muddy coasts, with decreasing gradient toward land (Rossington *et al*. 2009). In the semi-arid tropics, as well as some more temperate settings, the upper intertidal area can become extremely flat and only occasionally inundated (Figure 4-14). Microtopography, including swash lines and vegetation, causes local ponding, with evaporation causing development of hypersaline conditions.

Algal mats are comprised of opportunistic, highly persistent cyanobacteria, which can take advantage of short-term benign conditions, such as seasonal rainfall or tidal inundation (Paling *et al*. 1989; Taukulis 2018). These may occur as a thin coating on surface sediments, or as a thick mat, comprised of multiple growth layers. Once developed, the algal mat helps to bind surface sediments and reduces permeability, potentially modifying local drainage and percolation pathways.

Figure 4-14: Tidal Inundation of Algal Mat Area

This illustrates how channels transport tidal flows to the algal mats.

Predictions regarding response of upper intertidal flats to sea level rise do not specifically account for algal mat interactions but relate to predicted change to the distribution of tidal flows and disturbance events (Townend *et al*. 2011; Goodwin & Mudd 2019).

The opportunistic nature of algal mats and their capacity for nitrogen fixing suggests that their distribution is strongly related to hydroperiod. Consequently, inferred response to sea level rise is typically upward migration of the landward contour for existing algal mats, which approximately describes the level at which the mats become desiccated too frequently to survive (Figure 4-15). The lower limit of algal mats is commonly attributed to bioturbation, including disturbance by crustaceans and waterbirds, but is also influenced by excessive inundation events, particularly under storm conditions, where floating algal mat can be pushed by wave action.

Under general conditions in the Pilbara, algal mats occupy very gently graded salt flats, with both the upper and lower limits of mats likely to move with sea level rise (Figure 4-15a). However, for the project area, presence of a low-relief sediment ridge causes local modification to hydroperiod, where the crest defines the minimum hydroperiod (Figure 4-15b).

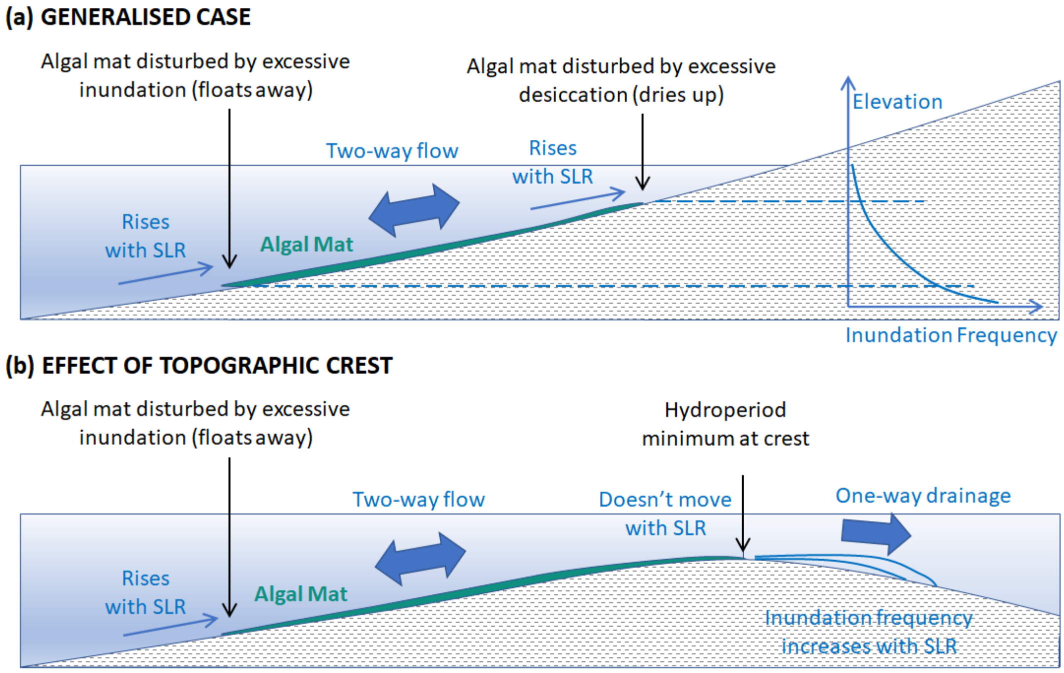

Figure 4-15: Factors Influencing Algal Mat Response to Hydroperiod

4.6. SAMPHIRE DYNAMICS

Samphire (*Teticornia spp*.) are perennial shrubs, with either a spreading or a more erect structure, up to 1 metre high. They are highly tolerant of saline and waterlogged conditions, commonly occurring as the first fringing community adjacent to the bare margins of salt lakes across Western Australia. Their shallow root structure determines that samphire are not bulwark species, preferentially occupying nearly flat land with infrequent bed disturbance – including effects of waves or bioturbation.

Samphire mapped by Biota (2020) occurs as:

(iii) A dominant species in a narrow supratidal/intertidal fringe at the base of supratidal slopes, including upward slopes of mainland remnant islands, dunes abutting salt flats and the north-eastern bank at the mouth of Urala Creek North; or

(iv) Either a dominant species or mosaic presence in supratidal basins and channels upstream of where ephemeral drainage lines debouch onto the salt flats. This occurs along the north-eastern edge of the proposed Project site at the salt flat hinterland fringe, or on outwash banks of the Ashburton River.

Location in upper intertidal to lower supratidal zones supports seasonal waterlogging. The topographic features of these samphire habitats allow local accumulation of freshwater, either downslope or downstream. Although rainfall is typically low, this combination provides occasional freshwater (brackish) phases, beneficial to halophytic vegetation. Due to the topographic control, these habitats are not anticipated to migrate with sea level rise. Change to samphire coverage may occur if sea level rise causes bed mobility too frequent for samphire occupation, or if tidal inundation substantially reduces the occurrence of brackish phases.

5. Intertidal Habitat Dynamics on the Tubridgi Coast

Predicting the response of an intertidal habitat to change, be it short term or long term, requires identification of influential factors. These factors may be distinguished as:

- *Sensitivities* – where dynamics of a factor induces changes to intertidal habitats, often involving feedbacks (Winterwerp *et al*. 2013; Anthony & Goichot 2020); or
- *Controls* – where the presence of absence of a factor provides a physical limit to intertidal habitats (Semeniuk 1996).

This section describes and interprets physical changes observed in the intertidal habitats of the Tubridgi coast through:

- Inference from other parts of the Pilbara coast with similar morphology (Semeniuk 1996; Eliot *et al*. 2013).
- Interpretation of site morphology, particularly for features indicating dynamic behaviour (see Section 3.4).
- Comparison of historic aerial imagery (see Section 5.1).

Then, combined with current understanding of the characteristic behaviour of mangroves and tidal channel morphology reported in literature (Perillo 2019), a conceptual model for the response of intertidal habitats to sea level rise has been developed (Section 5.2).

5.1. OBSERVED PHYSICAL CHANGES

Evaluation of historical imagery has been limited by image availability and quality. Although imagery covering the site is available as early as 1949 (Figure 5-1), image quality is limited until around 2000. Little change was detectable in the comparison of older and modern imagery, with most observable differences being comparable to changes detected solely from the high-resolution record.

High resolution imagery has been accessed from:

- 2004 LandGate / GSWA
- 2006 (June) Google Earth
- 2006 (Sep) Google Earth
- 2008 GSWA
- 2013 LandGate
- 2018 National Map

It is acknowledged that this period excludes the effect of TC Vance in March 1999, which is reported to have caused extensive coastal impacts, including mangrove destruction along part of the coast (Blandford & Hegge 2005). However, comparison of recent imagery with 1985 topographic mapping by Department of Defence, which is not available digitally, indicated differences within the range of mapping error (±20m). This corresponds to a general finding of rapid recovery after TC Vance (Paling *et al*. 2008), and no large-scale long-term coastal evolution.

Figure 5-1: Comparison of 1949 and 2006 Imagery

Interrogation of this imagery has been used to examine changes in coastal position, mangrove presence and tidal channel structures. Overall, there are no substantial changes apparent over the 14 years, although seasonal and local-scale dynamics were identified.

The most apparent area of change occurred along the sandy coastal barrier south of Tubridgi Point (see Section 3.4.3). Observed features include:

- Migration of a new spit head into the Urala Creek South tidal channel mouth occurred over 14 years (Figure 5-2). This matches the pattern suggested by the adjacent morphology, with multiple previous recurve spits already present.
- Infilling of a previous breach in the barrier (Figure 5-3) south of Urala Creek South mouth. This feature was apparently the mouth of a previous tidal channel, which has been closed for a long time. It is considered likely that the extreme conditions during TC Vance would have caused an inflow of water, but was not sufficient to re-establish a tidal network.
- A slight adjustment at the southern end of the barrier spit to the south of the barrier breach infilling noted above, with loss of beach sediment causing a slight inwards rotation of the spit head (Figure 5-4).

Changes across intertidal habitats, including mangroves and algal mats, are less clearly apparent, considering effects of shadowing and colour change. The boundaries of mangrove communities have changed little, but a general increase in canopy coverage is apparent, suggesting greater plant maturity. There are few locations of extensive colonisation, except for individual basins (Figure 5-5). Substantial changes in the colour of algal mat areas, related to seasonal changes in water availability, potentially obscure identification of any change in area.

Tidal channels across the area are remarkably stable, particularly as the period of observation included transition from low to high mean sea level and from few extreme events to a series of severe storms (Figure 4-4). Aerial images are characteristically variable at the upstream end of tidal channels (Figure 5-6), indicating patterns of channel incision and depositional fan formation. However, the channels themselves remain in the same place, with no clear evidence of channel head-cutting or sustained infilling, that would indicate floodplain evolution. The discrete nature of the imagery prevents evaluation of the time scale of incision-deposition cycles.

Figure 5-2: Spit Growth and Migration

Figure 5-3: Breach Infilling

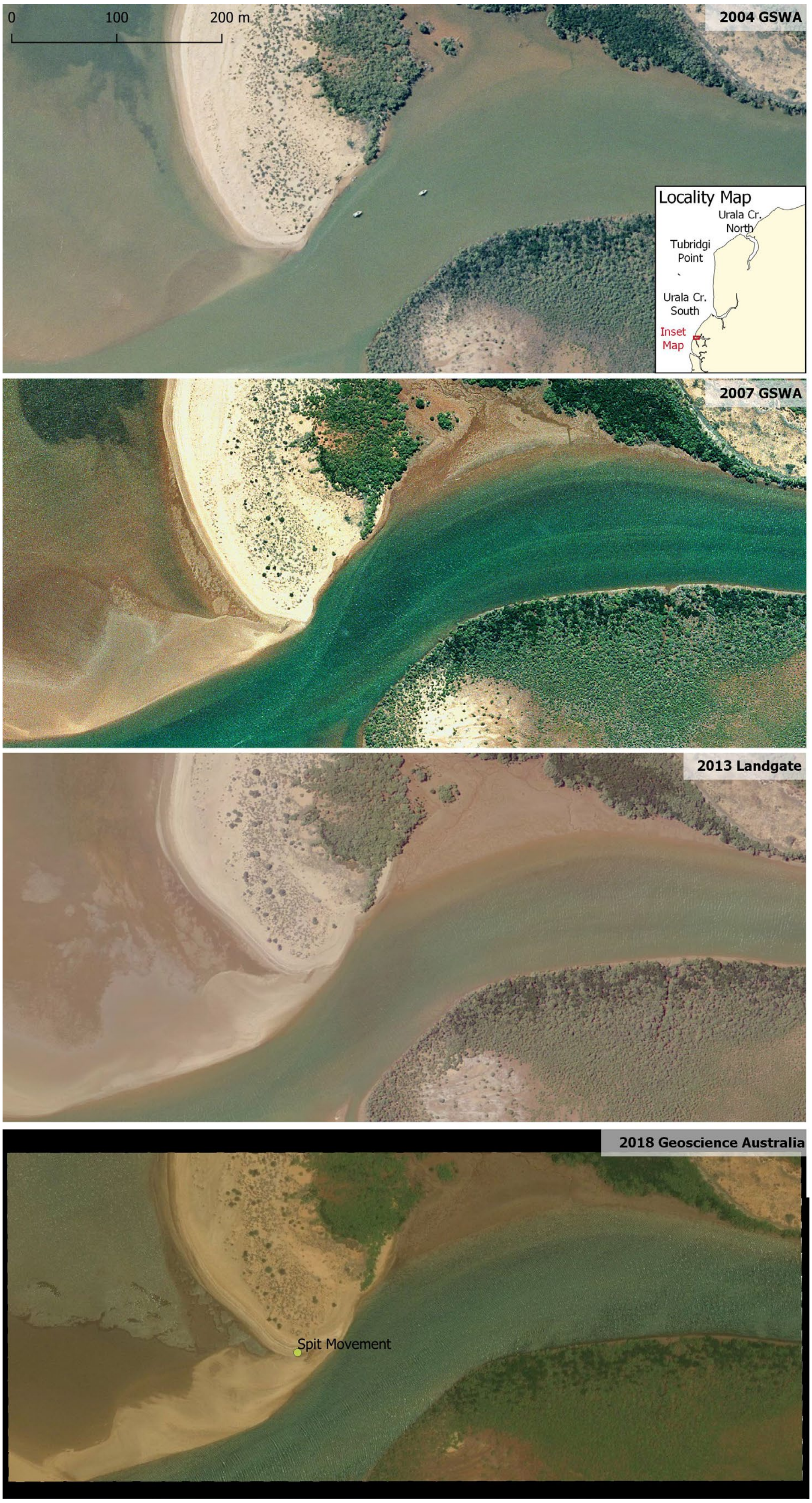

Figure 5-4: Spit Tail Movement

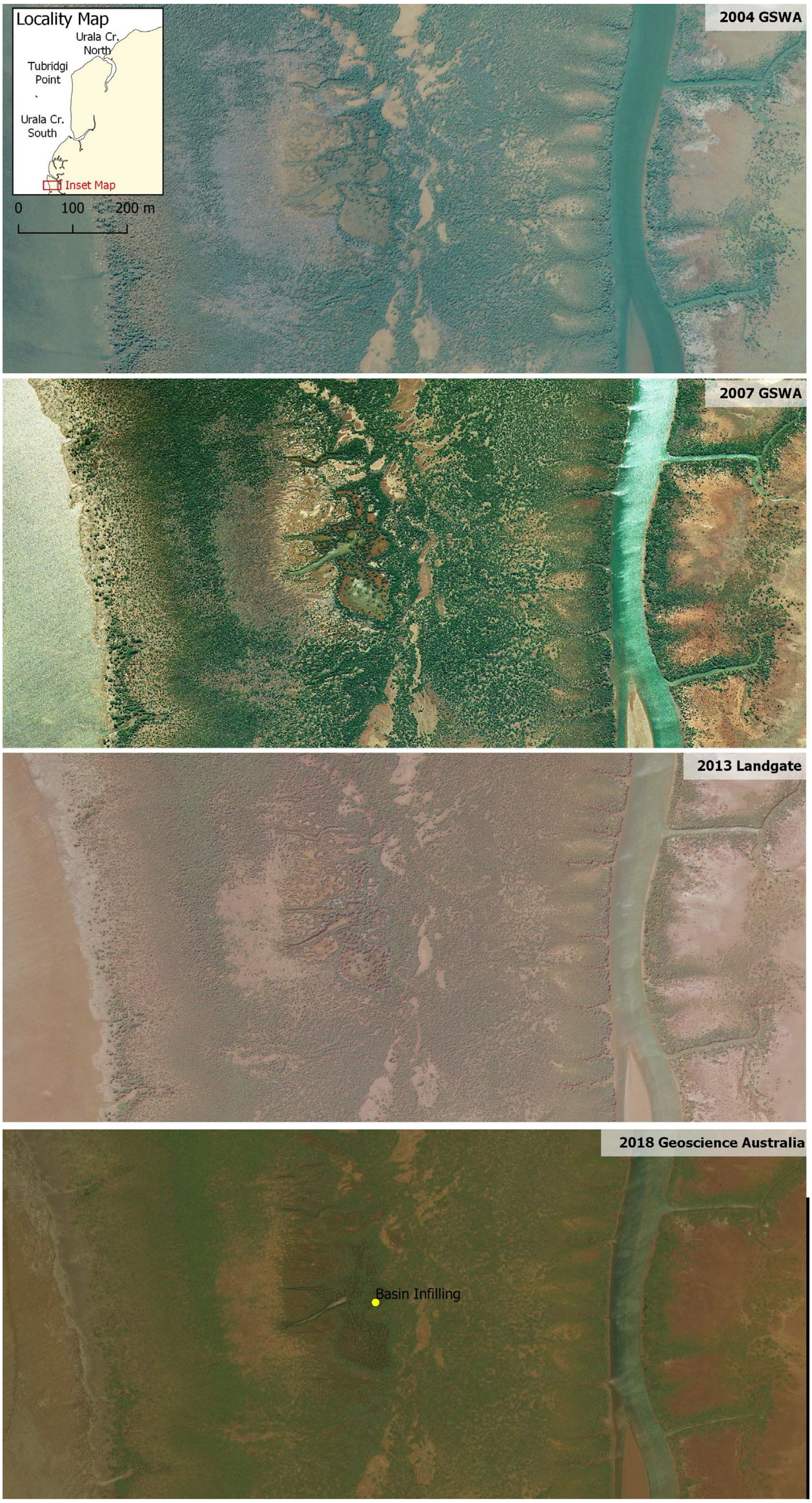

Figure 5-5: Mangroves Infilling Basin

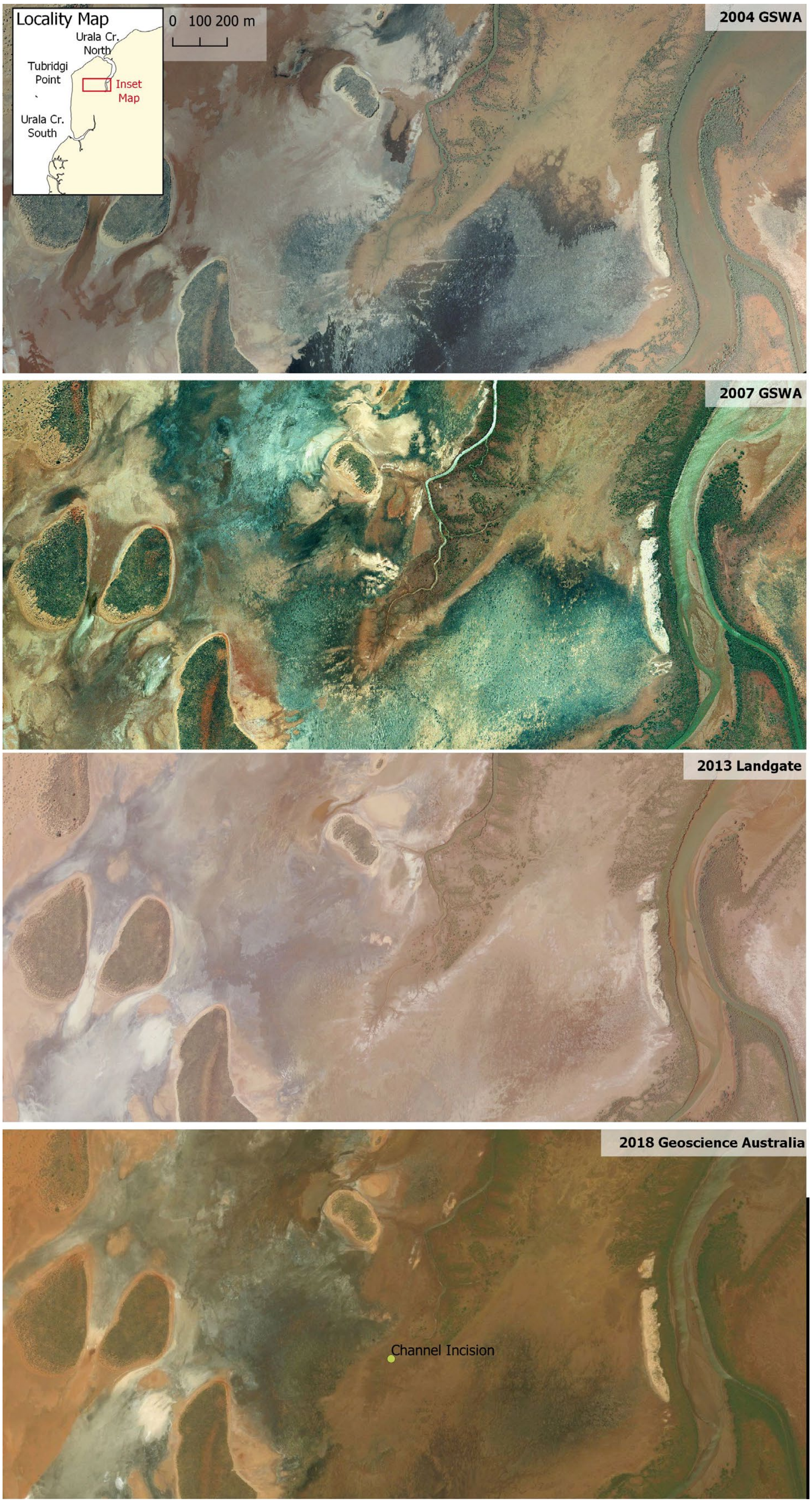

Figure 5-6: Channel Incision and Deposition Fan Patterns

Figure 5-7: Incised Channel on Salt Flats

5.2. INFERRED CONCEPTUAL MODEL

5.2.1. General

Studies of intertidal habitats including mangroves and hypersaline tidal flats have variously concluded the importance of hydroperiod (frequency of inundation), salinity, nutrient supply and morphodynamics (Twilley *et al*. 1999; Alongi 2008; Day *et al*. 2008; Crase *et al*. 2013). These controlling factors have been used to develop models for forecasting future evolution of intertidal habitats, with varying levels of success (Berger *et al*. 2008), suggesting that multiple factors and their interactions should be considered simultaneously (Figure 5-8).

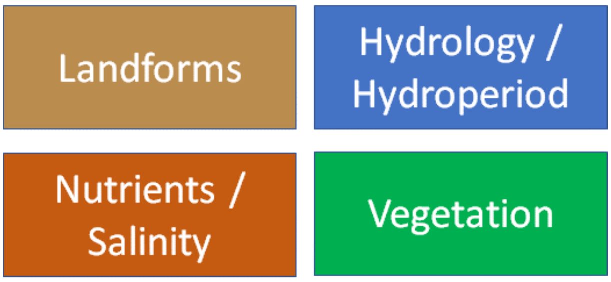

Figure 5-8: Key Conceptual Model Factors

Characteristics of the Tubridgi coast suggesting controlling attributes of a conceptual model include:

- Dominance of *Avicennia marina* indicates that mangrove evolution is likely to be constrained to areas that are similar to the existing mangrove habitat.
- Porewater salinity apparently provides a substantial control upon mangrove extent.
- Freshwater sources are highly episodic and show no evidence of substantially influencing mangrove or algal mat distributions.
- Most of the intertidal area is isolated from coastal evolution by high relief coastal barriers from east of Locker Point to south of Tubridgi Point (Figure 2-11).

- The mangrove-lined coast south of Tubridgi Point may be directly subject to coastal dynamics, including phases of storm damage, storm overwash processes and coastal recession (Figure 2-11).
- Tidal creek dynamics, as illustrated by incision and depositional fans, suggest at least a partial mechanism for adjustment of the floodplain level.

5.2.2. Sensitivities

5.2.2.1. Hydroperiod

It is noted that the separation between mangroves and algal mats, generally marked by a band of bare sediment, occurs at an approximate level of +1.0mAHD, which may indicate the influence of hydroperiod. However, the apparent stability of this boundary over recent decades, with 0.3 m variability of mean sea level, provides a stronger indication that the boundary is due to porewater salinity, which is typical of interpreted behaviour along the arid Pilbara coast (Semeniuk 1996).

Anticipated response to sea level rise is a landward migration of mangroves and algal mats (i.e. in response to changing hydroperiod), constrained by the porewater salinity, following Semeniuk (1996).

5.2.2.2. Morphodynamics

Morphodynamic adjustment is expected to include expansion of the tidal creeks, with material transfer to the salt flat area. Substrate within existing mangrove areas can rise due to litter production and sediment trapping (Yang *et al*. 2014). For those areas with no coastal barrier, sediment trapping may occur through onshore coastal sediment trapping. The resultant conceptual model for morphodynamics is indicated by Figure 5-9.

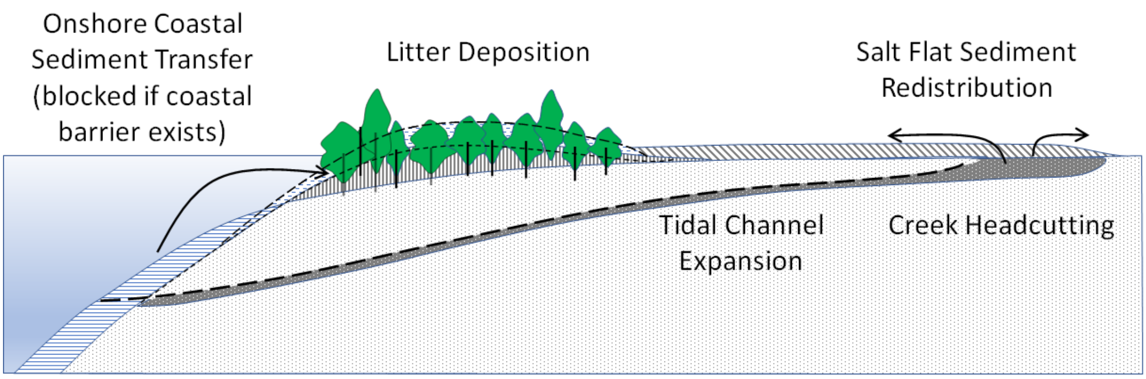

Figure 5-9: Conceptual Model of Sediment Transfers

5.2.2.3. Salinity – Pore Water

The response of porewater salinity to sea level rise, which controls the mangrove-algal mat boundary, is not commonly simulated in predictive models, possibly due to greater reporting of mangrove dynamics for the wet-dry tropics rather than arid settings. Processes contributing to porewater salinity include inundation, evaporation, infiltration, and drainage (Figure 5-10). In the arid west Pilbara setting, the extreme evaporation rates provide opportunity for an infiltration and desiccation sequence where there is substantially less water leaving the salt flats than arrives on an ebb tide. In some cases, shallow flooding moves on to the flats and does not return at all. Repeated flood events consequently result in an accumulation of porewater salinity.

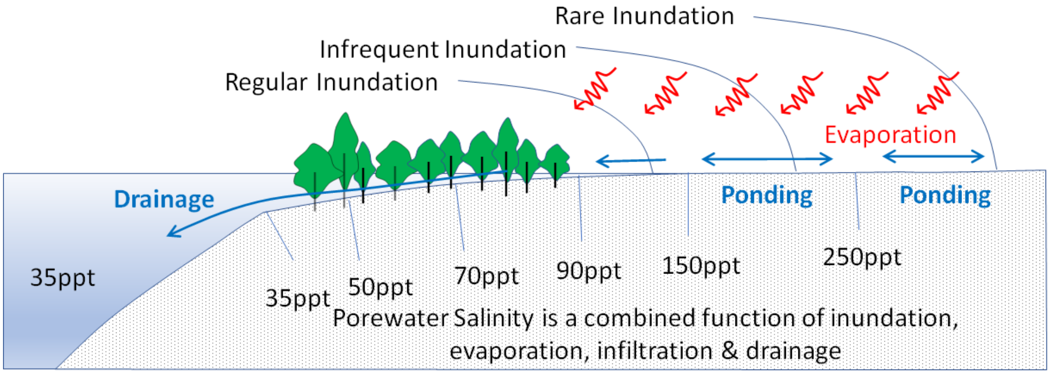

Figure 5-10: Factors Contributing to Porewater Salinity

Mangrove communities can affect porewater salinity processes in several ways, including:

- Substantially reduced evaporation rates underneath the mangrove canopy.
- Supporting inverterbrate fauna, notably crabs, that burrow through the mangrove soils, causing bioturbation, with associated changes to porewater salinity.
- Reduced infiltration rates due to development of a low permeability mangrove mud layer, which incorporates litter, debris and epiphytes.
- Development of drainage networks (Wolanski 1992), which typically interact with tidal channel networks.

Drainage (tidal flushing) is a crucial factor influencing porewater salinity, as concentration through evaporation is increased the longer a body of water is still. Drainage efficiency is strongly related to surface gradient, although this can be influenced by meso-scale to micro-scale topographic features (i.e. tidal channels down to ~10 mm deep basins on the salt flats). High drainage (tidal flushing) rates on channel banks can support locally low porewater salinity, enabling channel-fringing mangroves to persist a long way across the salt flats.

The role of drainage is also apparently significant for development of the algal mat area. The mapped landward limit of algal mat habitat approximately corresponds to the +1.0 to 1.1 m AHD contour on the western side of a low relief sediment ridge at approximately +1.2 to +1.3 m AHD that divides the salt flats (Figure 5-11). This ridge represents a slight elevation in the topography which limits the inundation area under most tidal conditions and prevents flows which overtop the sediment ridge during extreme tides or surges from draining back towards the coast.

Absence of algal mat habitat on the eastern side of the sediment ridge, within the lower elevated eastern basins of the salt flats sitting at 0.7 to 0.8 mAHD (Figure 5-11), suggests the ridge provides a physical restriction, such as excessive porewater salinity or excessive desiccation, both of which are linked to hydroperiod. Consequently, expansion of the algal mat habitat with sea level rise may occur up to the physical limit of the sediment ridge, but it will stall there until inundation becomes sufficiently frequent to reduce porewater salinity or prevent excessive desiccation.

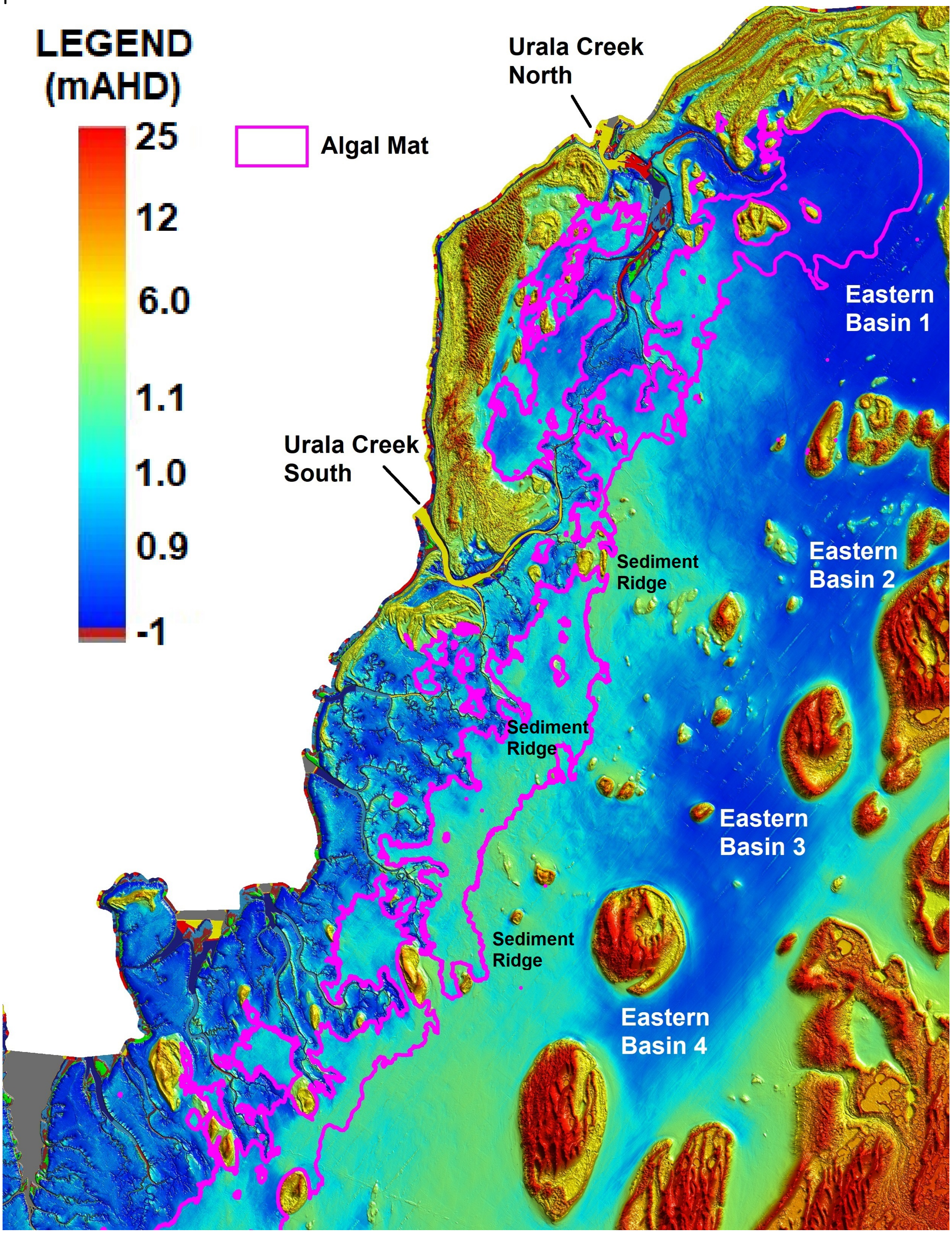

Figure 5-11: Algal Mat Distribution Overlaid on Lidar DEM

6. Tidal Creek Analysis

The apparent lack of progressive physical changes over 2004-2018 across the Tubridgi intertidal zone constrains the ability to correlate observed trends of forcing and response and directly extrapolate a response to projected sea level rise. Instead, variation of physical attributes across the tidal channel network has been assessed, specifically to explore how creek morphology changes with different volumes of tidal exchange. Consequently, changes in tidal exchange caused by sea level rise are analysed in this section and have been used as a basis for predicting future morphodynamic and intertidal habitat response (Section 7).

6.1. APPROACH

Mapping of intertidal habitats (Figure 1-2) indicates that mangroves and algal mats are inherently connected to the tidal creek morphology which occurs along the margins of Exmouth Gulf (AECOM 2021). These features are naturally dynamic, with focused tidal flows causing creek bed mobility and instigating sediment exchange (Perillo 2009). Creek systems display a strong dependence on tidal exchange and are expected to adjust to projected sea level rise. The framework for assessing creek changes, with corresponding implications for intertidal habitats, is indicated by Figure 6-1.

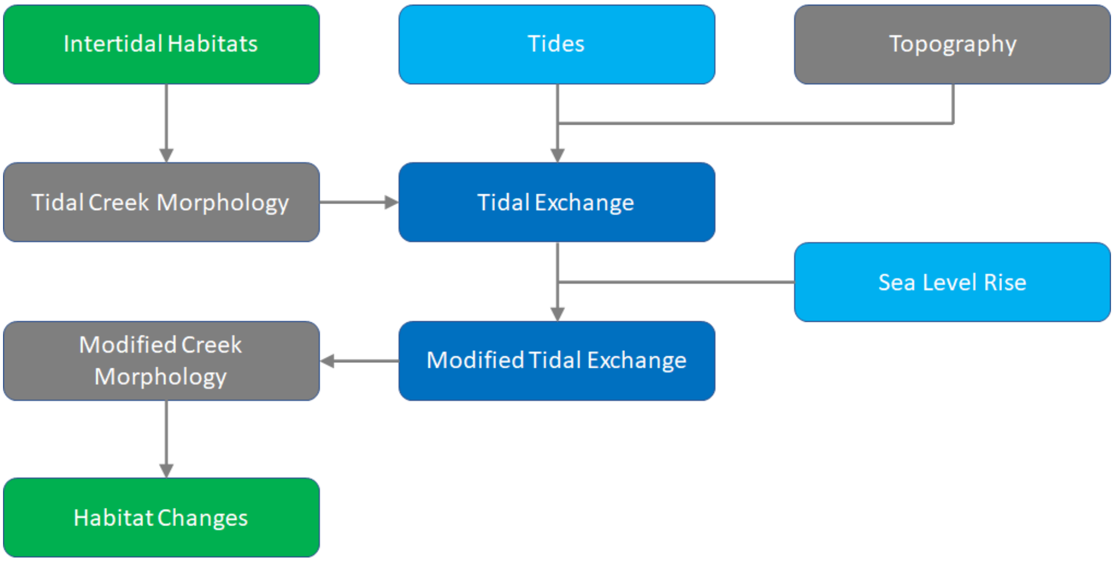

Figure 6-1: Framework for Tidal Creek Analysis

A high-resolution representation of topography across the Tubridgi coast has been developed following capture of surface LIDAR. Analysis of the tidal channel network has followed, to develop an understanding of how the channels vary in dimension due to differences in tidal exchange. The LIDAR indicates a large proportion of intertidal habitat occurs across a broad area but within a narrow topographic range from 0.5 to 1.5m AHD.

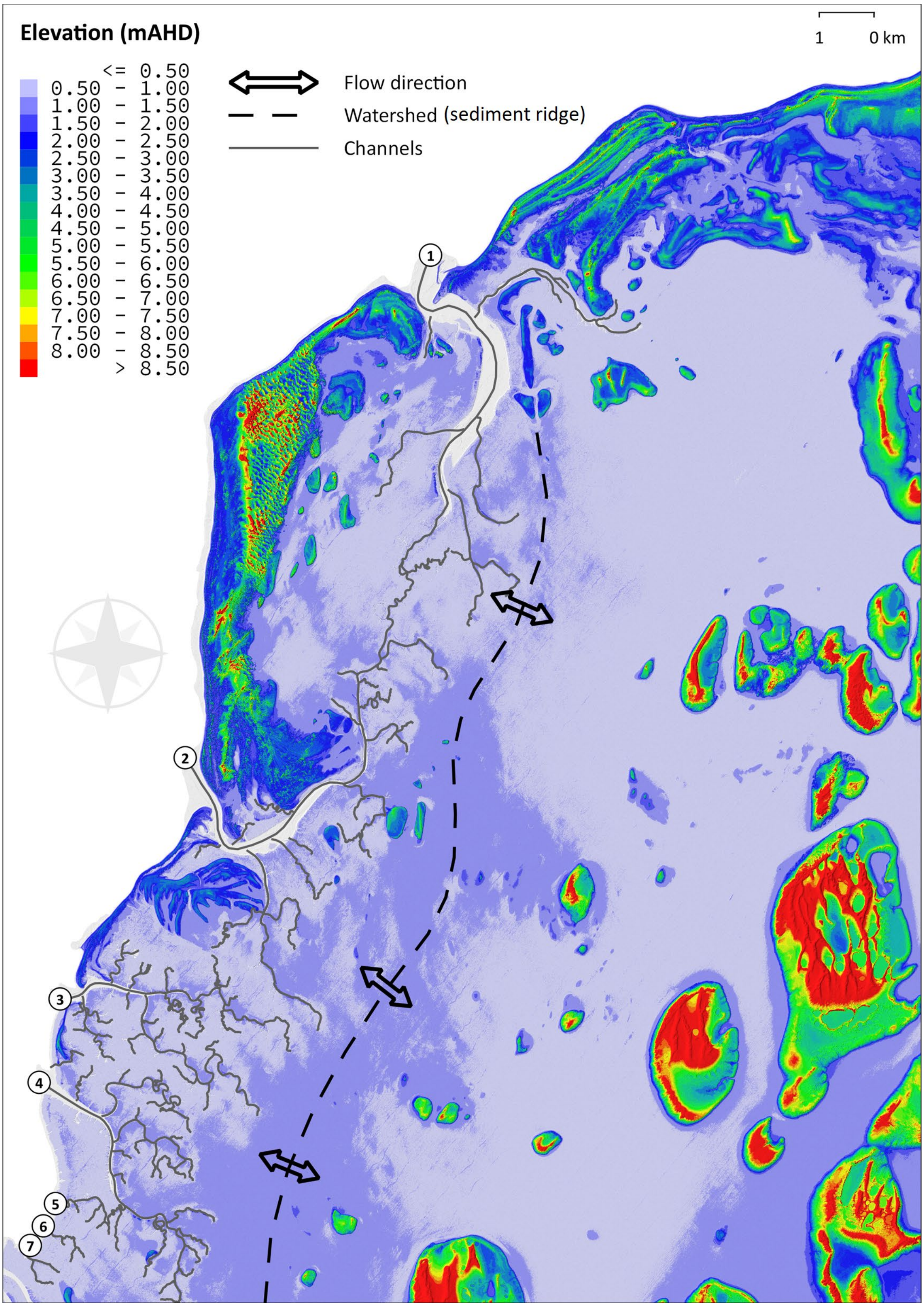

Figure 6-2: Salt Flat Topography (Lidar Digital Elevation Model)

Numbers identify Primary Creek Channels

General classification of 'tidal courses' is outlined in Perillo (2009), which includes a scale-based classification scheme (Table 6-1). Features identified via the Tubridgi LIDAR data set had attributes varying between tidal gullies (i.e. dry at low tide) and tidal channels. However, channel widths on the Tubridgi salt flats are generally greater, with channels less than 1m depth being 2 to 5m wide. This is possibly due to the fine sediments and relative absence of vegetation across the salt flats. As the LIDAR data set was unable to penetrate water, the full depth of larger channels could not be identified.

Table 6-1: General Classification and Size Range for Tidal Courses (From Perillo 2009)

Name	Wet at Low Tide	Depth (mm) Thalweg to Bank	Width (mm) Bankful Level	Cross-section (cm^2)
Tidal rills	No	<10	<20	<2
Tidal grooves	No	10-50	20-100	<50
Tidal gullies	No	50-1000	100-1000	50-1000
Tidal creeks	Yes	100-2000	100-2000	100-4000
Tidal channels	Yes	>1000	>2000	>2000

A hierarchical approach was used to classify the tidal network of the project area, mainly using creek width:

- Primary Channels were identified as those which connected to the ocean, with a width of >10 m. The 'full path' of primary channels was traced upstream, through selection of the larger channel where two channels merge.
- Secondary Channels were those connected to a primary channel, with an approximate width of >5 m at the junction. The 'full path' of secondary channels was traced upstream, through selection of the larger channel where two channels merge.
- Tertiary Channels were those connected to either a primary or secondary channel, with a width of roughly >2.5 m at the junction.

Smaller channels were not logged separately, and their areas were considered contributory to the connecting channel. This classification scheme yielded 7 primary channels (Figure 6-3), 31 secondary channels and 55 tertiary channels. The Urala Creek North and Urala Creek South primary channels are larger than the other primary channels that were mapped (Figure 6-3).

For each channel, several morphometric characteristics were determined, to characterise how the creek systems varied (spatially or with tidal exchange), including:

- Channel lengths and distance to the mouth.
- Contributing area, based upon approximate watershed (catchment) lines between creeks (Appendix B).
- Hypsometric distribution, which describes the area occurring at different topographic levels.
- Relative areas of mangrove and algal mat.
- Sinuosity of the tidal creek structure.

These are a sub-set of the parameters considered by Chirol *et al*. (2018), with selection partly constrained by limitations of surface LIDAR.

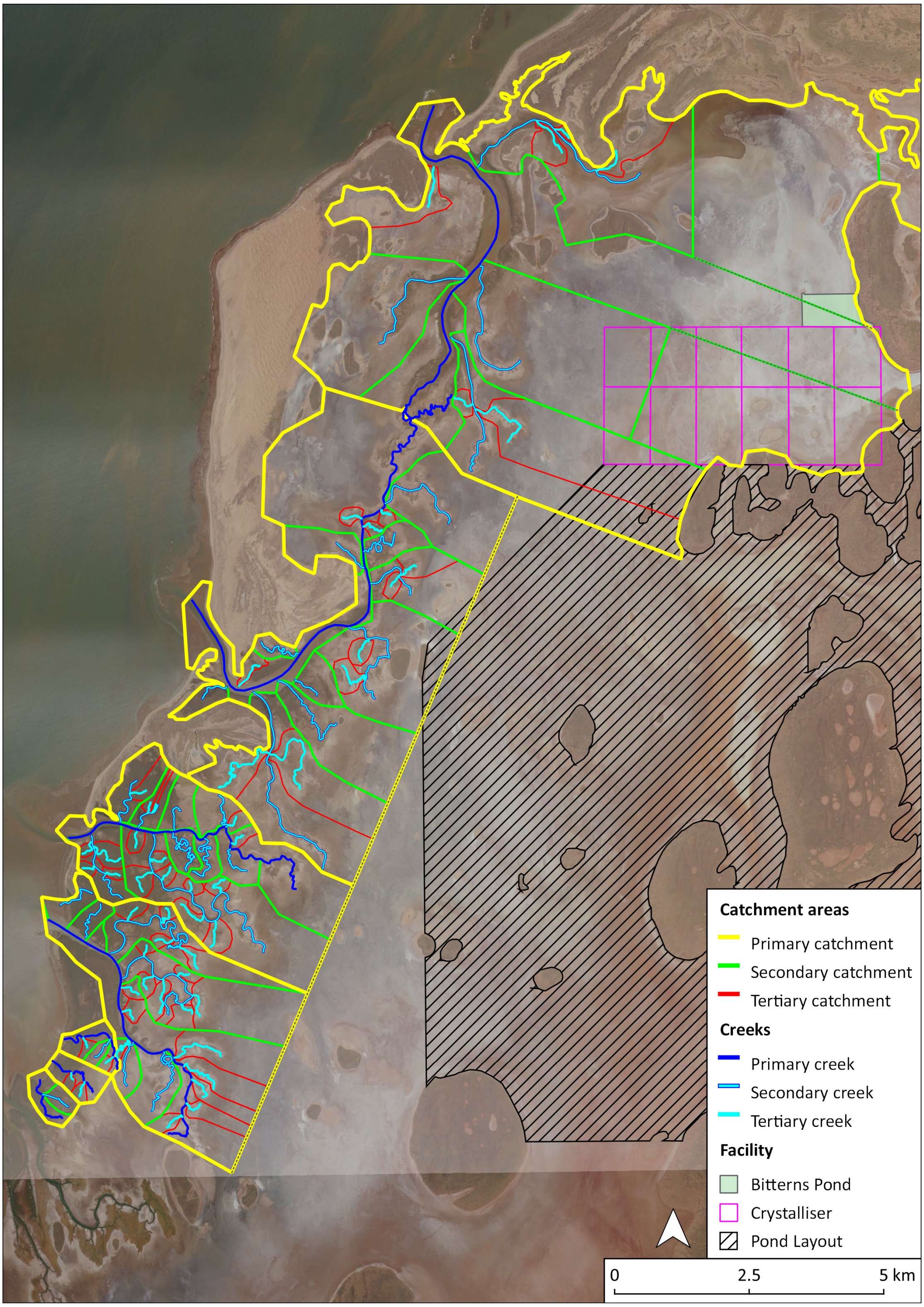

Figure 6-3: Mapped Channels in the Tubridgi Tidal Network

6.2. TIDAL CHANNEL MORPHOMETRY

Globally, tidal creek systems display similar general connectivity between creek structure and tidal exchange. However, diverse influences across different settings, including sediments, vegetation and oceanography determine that a unified model cannot be established (Chirol *et al*. 2018; Perillo 2019). Consequently, it is necessary to establish an empirical (site-specific) model of tidal creek behaviour, based on conceptual models of tidal exchange, to project dynamics of a creek system, including response to sea level rise.

This section outlines a morphometric analysis of the tidal creek systems adjacent to the project site, with an objective to confirm behavioural trends across different scales. Variation with tidal exchange provides a basis for extrapolating changes to the creeks in response to sea level rise, which is generally expected to enhance exchange.

Channels in the tidal network were distinguished as primary, secondary or tertiary and numbered sequentially in a clockwise order from the mouth of the primary creek, following a ternary numbering system:

- 1_0_0 refers to the first primary channel
- 1_1_0 refers to the first secondary channel off the first primary channel
- 1_0_1 refers to the first tertiary channel, directly off the first primary channel
- 1_2_3 refers to the third tertiary channel, off the second secondary channel, off the first primary channel

Plotting of the tidal channel lengths (Figure 6-4a) indicates that the largest (primary) channels are also the longest, and that there is a general reduction in the length for channels further south. Plotting the distance between the channel mouth (at the ocean end) and channel head (furthest upstream) indicates that this is relatively consistent for different creeks off the same primary channel (Figure 6-4b). These findings support the concept that channel length may be related to the tidal excursion distance, and therefore indicate a natural deposition limit for sediments suspended near the creek mouth (see Section 6.3). The distance to the channel mouth declines from the north to the south along the Tubridgi coast.

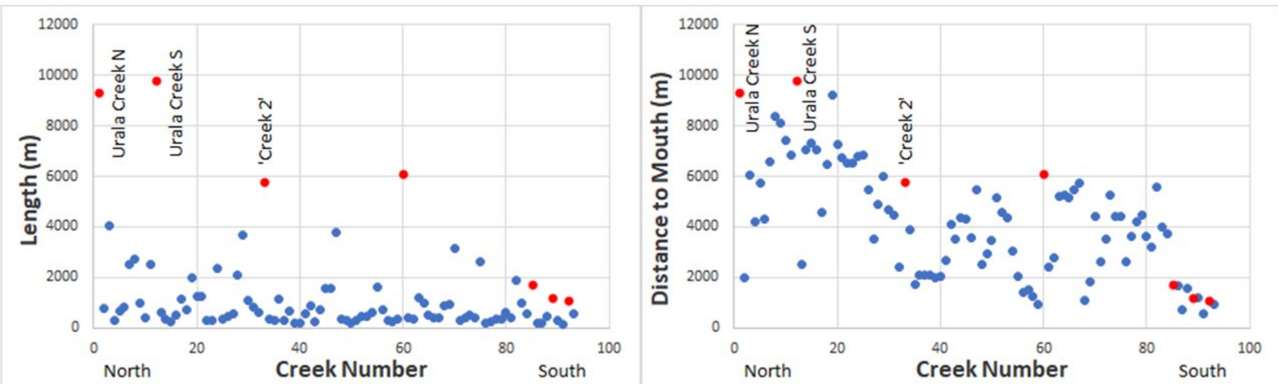

Figure 6-4: Tidal Channel Lengths and Distance to Mouth

Red dots indicate primary channels.

The contributing area below mean sea level describes the 'wet' area of the creek. The cross-plot of the creek length against the contributing area below mean sea level (Figure 6-5) yields a curve, which indicates geometric similarity. This is expected given the relative homogeneity of sediments across the flats.

The curvature plotted points becomes less apparent for contributing areas at higher levels, from mean high water springs and highest astronomic tide (Figure 6-6). Most of the channels which differ substantially from the 'curve cluster' are associated with Urala Creek North (primary channel 1).

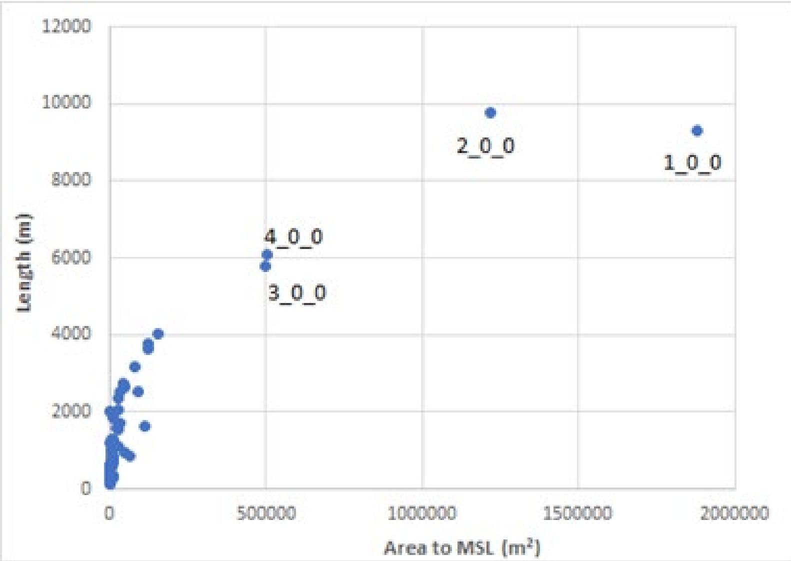

Figure 6-5: Cross-Plot of Creek Length and Contributing Area below MSL

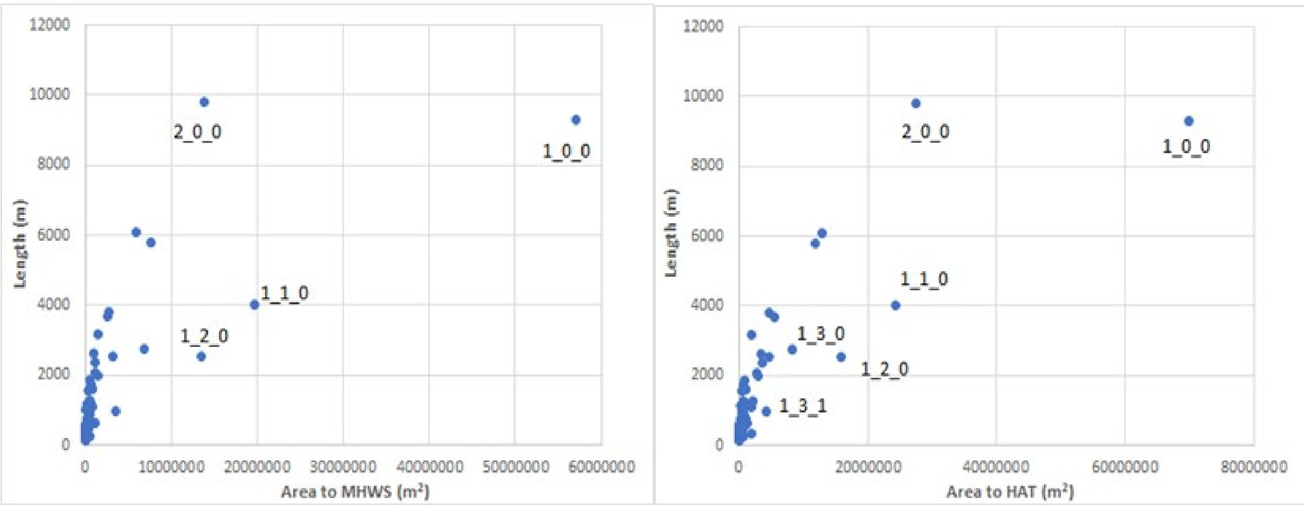

Figure 6-6: Cross-plots of Creek Length & Contributing Areas below MHWS & HAT

Intertidal coverage of mangroves and algal mats is generally related to the channel's contributing area, with algal mat habitat coverage greater for the northern creeks and more mangrove coverage for the southern creeks (Figure 6-7). Considered as proportional coverage (i.e. habitat area divided by the total contributing area for each creek), the distribution is variable, reflecting variation of tributary creeks and depending on whether they are located in conditions preferably suitable for one habitat or another (Figure 6-8). The increased range of proportional coverage is likely a consequence of the smaller contributing areas, enabling them to fall more completely in one habitat or another.

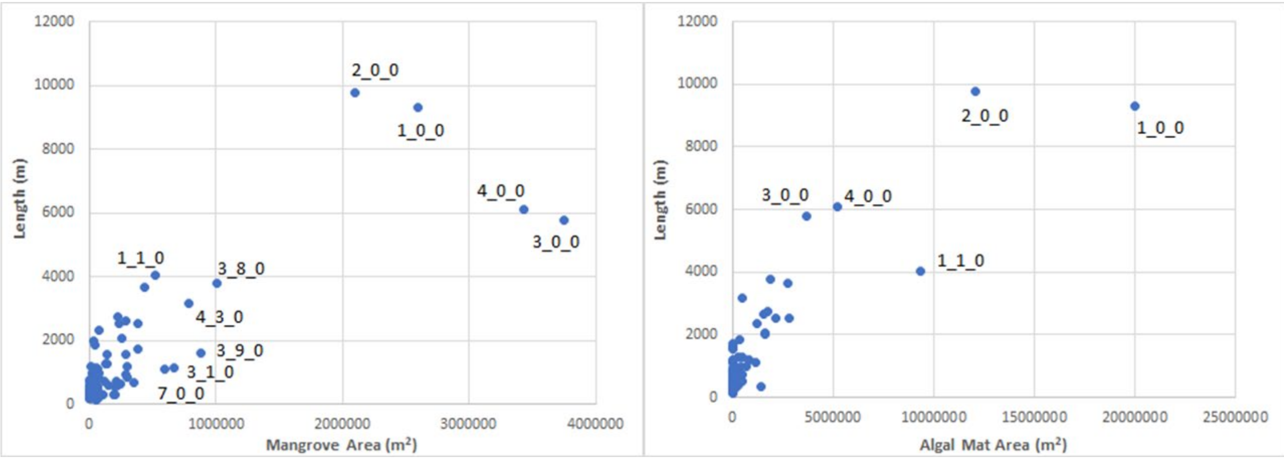

Figure 6-7: Cross-plot of Creek Length & Intertidal Habitat

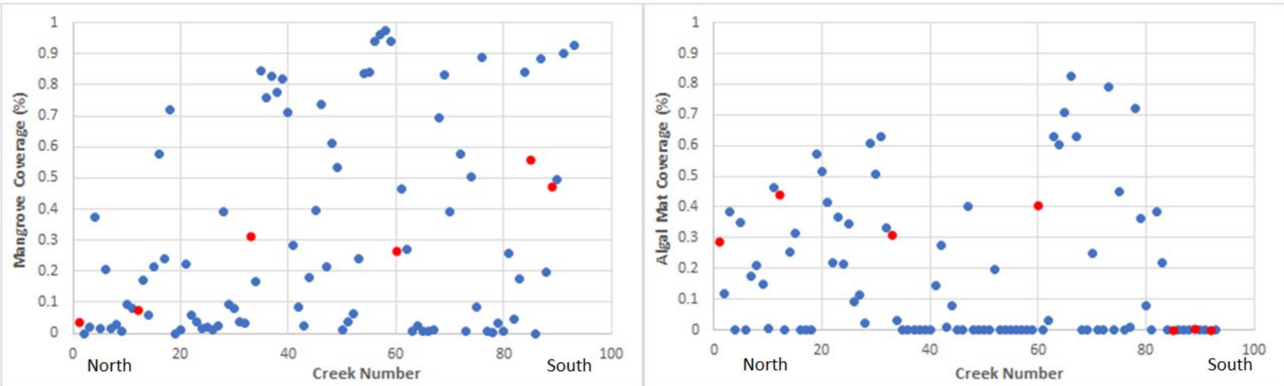

Figure 6-8: Proportional Coverage of Intertidal Habitats per Creek Area

The general transition from north to south between algal mat and mangrove habitat is illustrated for the six northernmost primary channels (Figure 6-9). These are presented as the relative proportion of mangrove or algal mat coverage (per unit area) on a ranked distribution generated from the entire set of primary, secondary and tertiary creek areas (i.e. 0% represents a creek area with the lowest coverage, whereas 100% represents the greatest coverage of all the creeks considered).

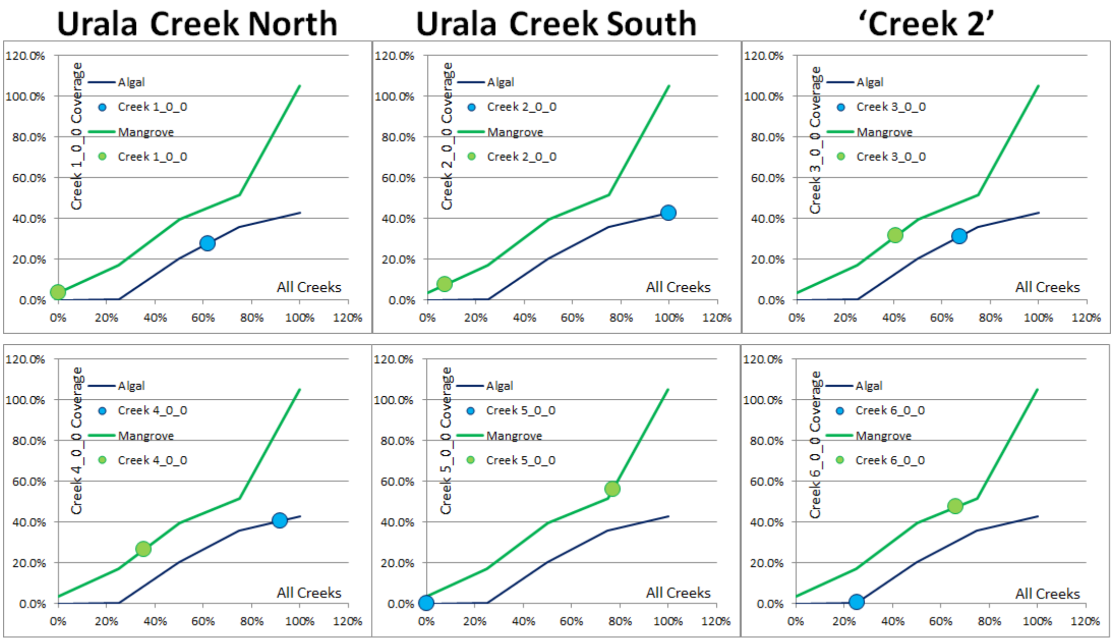

Figure 6-9: Variation of Intertidal Habitat Between Primary Channels

Hypsometry, which is the relationship between land area and elevation, plays an important role in tidal channel networks (de Ruiter *et al*. 2019). Variation of the intertidal elevation distribution modifies the tidal prism, altering tidal flows and changing the capacity for sediment resuspension and transport. For much of the salt flat areas, intertidal land is within a relatively tight band of elevations of +0.6 to +1.2 m AHD, as illustrated for Urala Creek North catchment (Figure 6-10). These elevations are in the upper part of the tidal range, experiencing inundation less than 15% of the time.

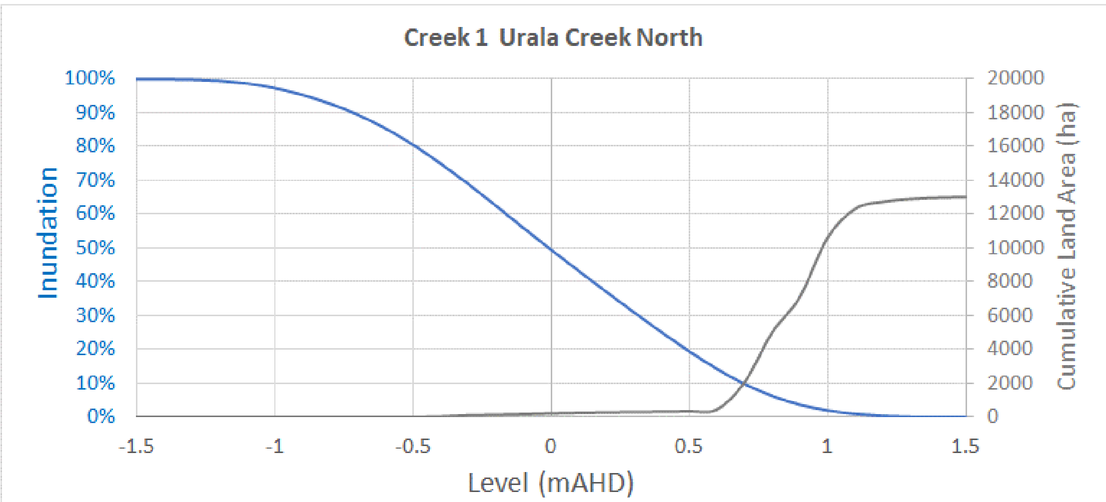

Figure 6-10: Hypsometric Structure and Inundation for Urala Creek North (Creek 1)

Comparison of hypsometric distributions for primary, secondary and tertiary channels (Figure 6-11) indicates a tight hypsometric range for the primary channels, with an increasingly wide range for the smaller tertiary channels.

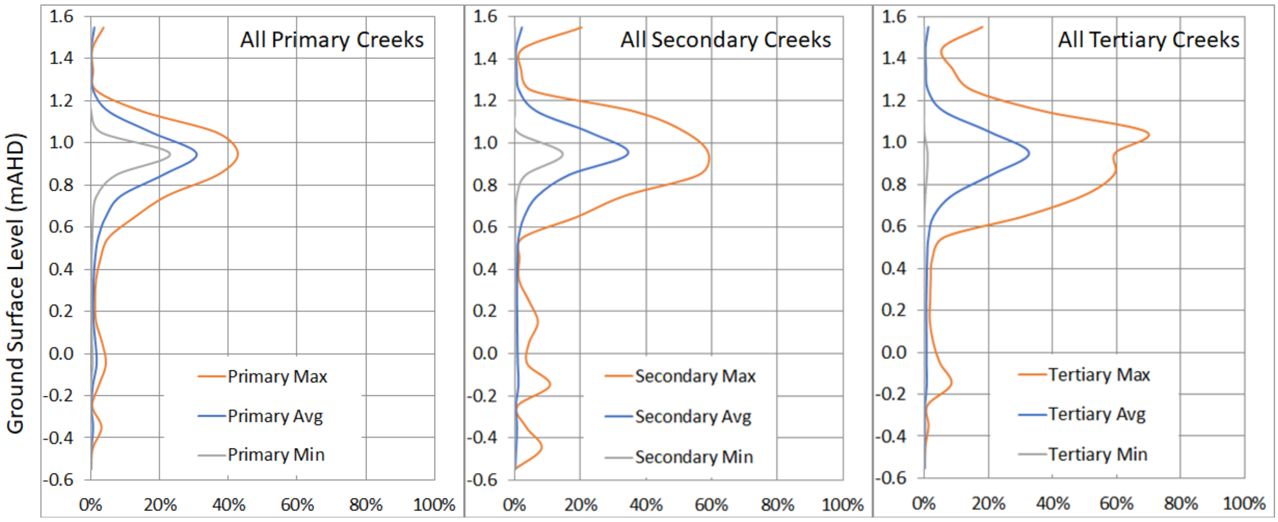

Figure 6-11: Variation of Hypsometry with Channel Scale

Urala Creek North has a bimodal hypsometric distribution (Figure 6-12), capturing the influence of the 'eastern' basin, that holds water for most of the time (Figure 6-2). The largest hypsometric mode of the four northern primary channels falls around 1.0 m AHD. Lower hypsometric modes around 0.9 m AHD occur for the next two primary channels, which have smaller contributing area and a greater proportional coverage of mangroves.

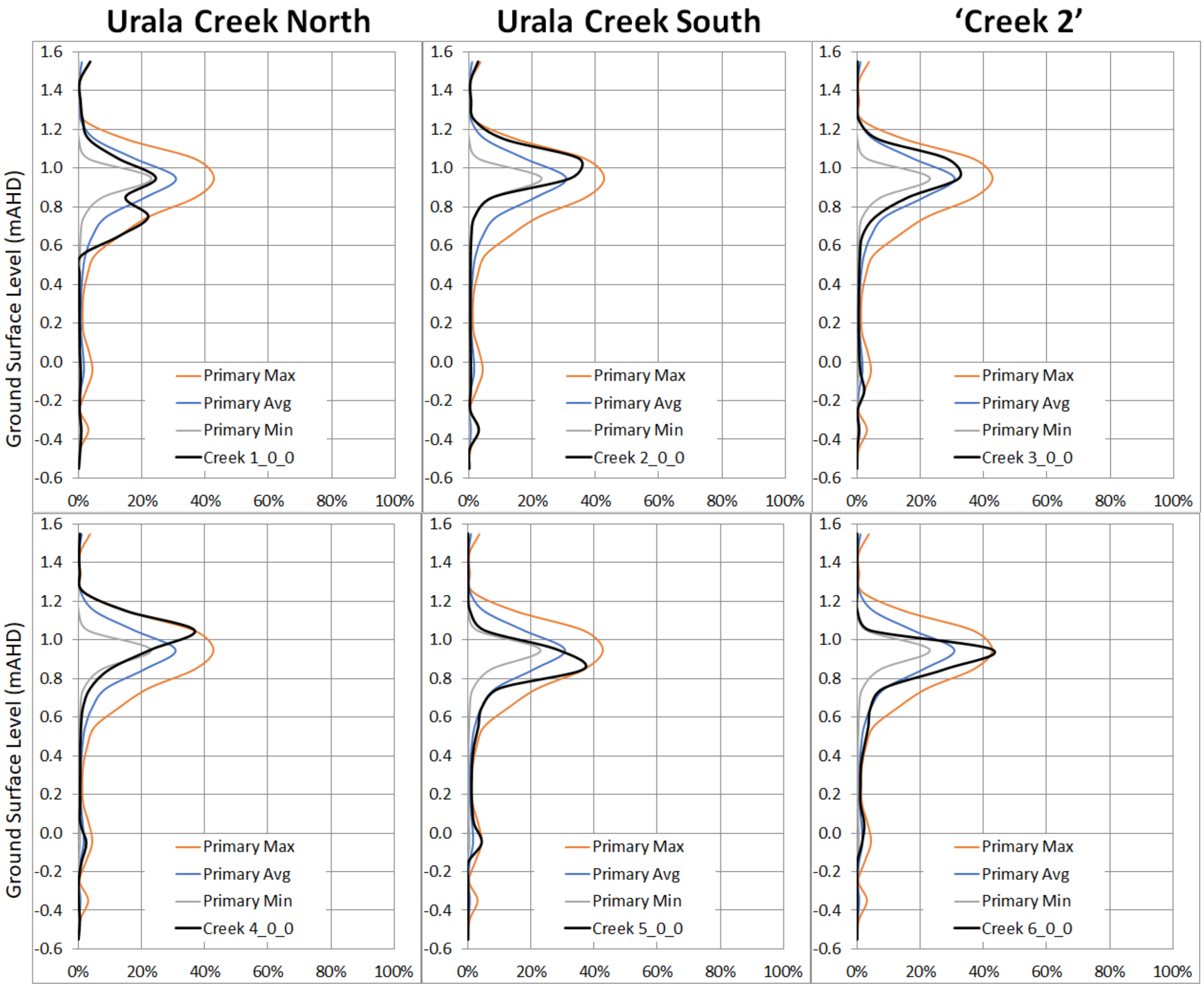

Figure 6-12: Hypsometry of Primary Channel Basins

Tidal channel sinuosity has been described as the full channel length compared to the largest distance between any two points on the channel, i.e. generally near the mouth and head of the channel. There is no strong pattern to sinuosity demonstrated for either position from north to south (Figure 6-13a) or creek length (Figure 6-13b), although the primary channels show a slight tendency for a spatial trend, with the longer, northerly channels tending to be more sinuous.

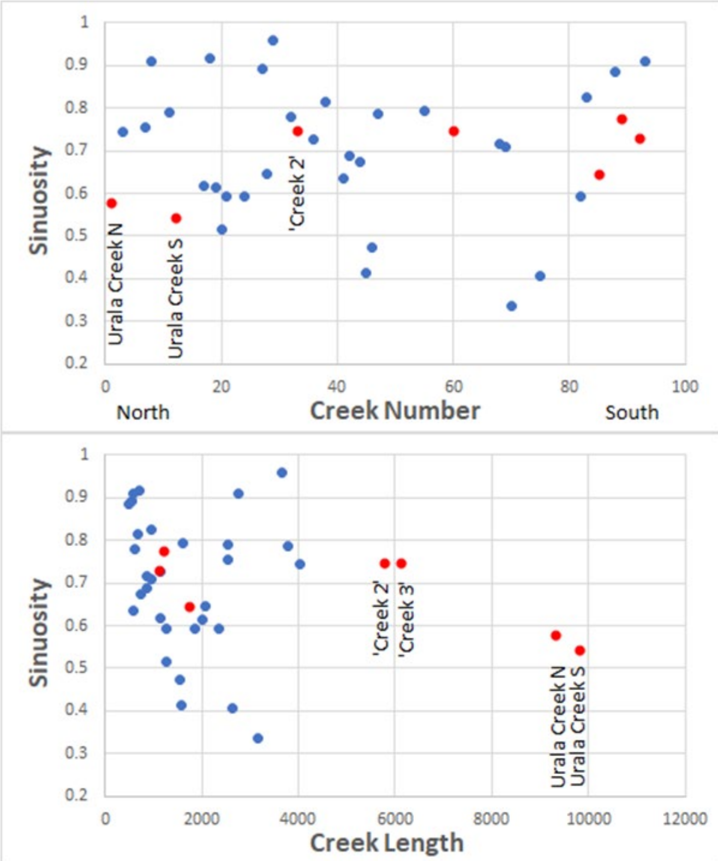

Figure 6-13: Creek Sinuosity

In summary:

- Total channel length, from the mouth to the head of the creeks reduces from north to south but is relatively consistent for different creeks off the same primary channel. The total length approximately corresponds to tidal excursion distance, indicating a natural deposition limit for sediments mobilised by strong tidal currents near the creek mouth.
- Analysis of creek length against the contributing area below mean sea level indicates geometric similarity. This is expected given the relative homogeneity of sediments across the flats. Those channels that do differ are associated with the main Urala Creek North channel.
- Intertidal coverage of mangroves and algal mats is generally related to the channel's contributing area, with algal mat habitat coverage greater for the northern creeks and more mangrove coverage for the southern creeks.
- Variation of the intertidal elevation distribution modifies the tidal prism (tidal volume exchange), altering tidal flows and changing the capacity for sediment resuspension and transport. For much of the salt flat areas, intertidal land is within a relatively tight band of elevations of +0.6 to +1.2m AHD. These elevations are in the upper part of the tidal range, experiencing inundation less than 15% of the time.
- There is no strong pattern to sinuosity demonstrated for either position from north to south.

6.3. TIDAL CREEK HYDRODYNAMICS

Modelling of Urala Creek Intertidal area has been undertaken as part of assessments for the Ashburton Salt project (Water Technology 2021b). The model domain was selected to capture both Urala Creek North and Urala Creek South (Figure 6-14).

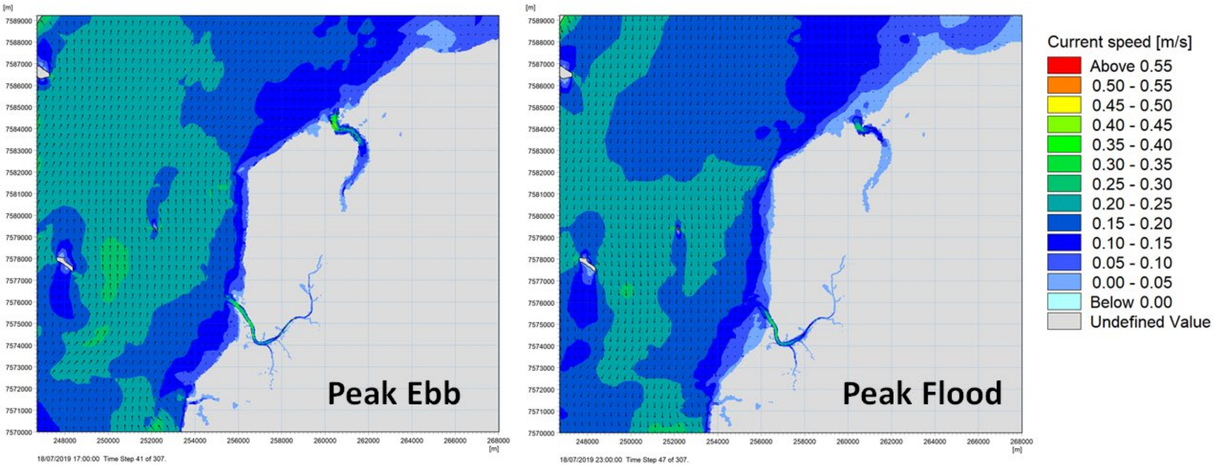

Figure 6-14: Intertidal area Scale Modelling Outputs

Modelled periods included:

- A 14-day period in July 2019, which included a spring tide phase of -0.85m to +0.85mAHD, causing a peak ebb flow of 0.42m/s at the mouth of Urala Creek South (Figure 6-15).
- April 2020, which included a spring tide range of approximately 2.6m, causing a peak flood flow approximately 0.6m and a peak ebb flow of nearly 0.8m/s near the mouth of Urala Creek South.

The July 2019 period is a moderate scale spring tide, exceeded approximately 90 days per year, whereas the April 2020 period is near to the annual peak.

Model outcomes match a general approximation that the peak tidal flow is proportional to the water level range within the tidal cycle. For a fine sediment bed, a flow speed in the order of 0.25-0.30m/s can cause sediment suspension.

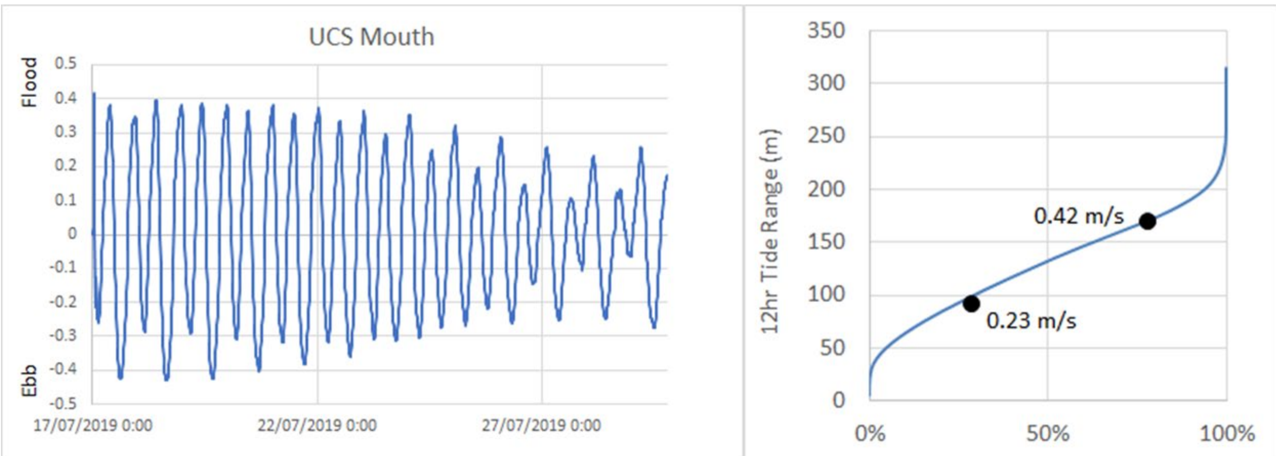

Figure 6-15: Modelled Flows at Urala Creek South from July 2019 and Long-term Range

Modelled flows are strongest near the creek mouth, declining upstream (Figure 6-16), suggesting the creek bed is likely to be highly mobile near the mouth, with reducing frequency of bed mobility upstream. Consequently, any coarse sediment suspended at the mouth will tend to settle within the channel, with finer material able to move further upstream and be deposited on the salt flats. For a peak flood flow speed of ~0.6 m/s at the entry, the maximum tidal excursion from the point of suspension in a single tidal cycle is approximately 6 km.

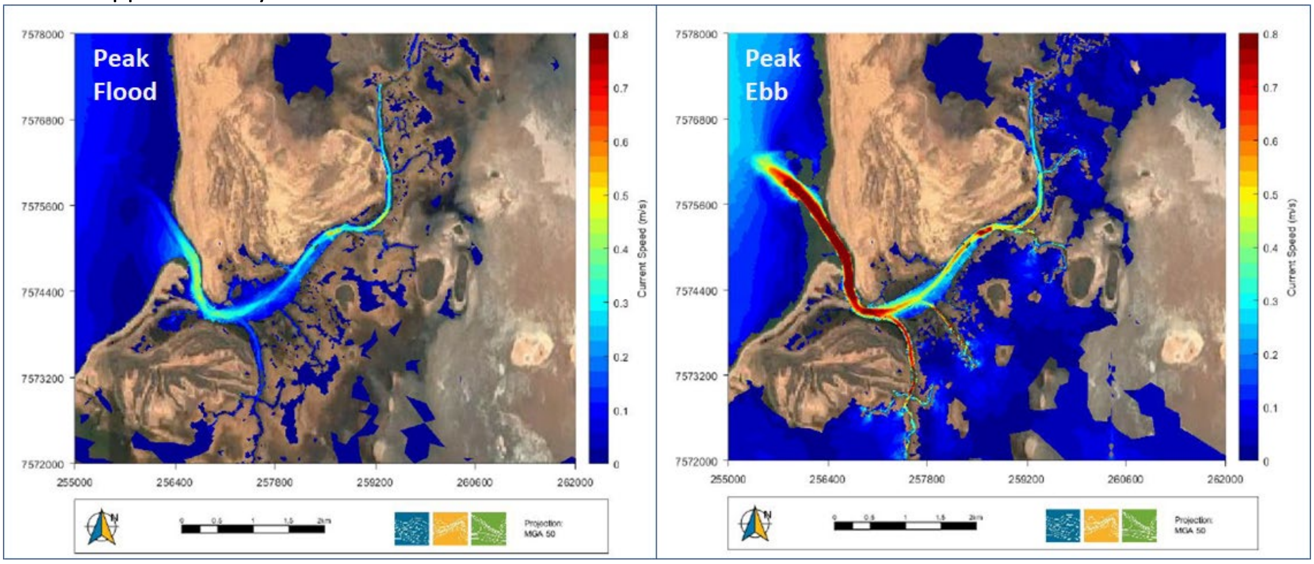

Figure 6-16: Creek Scale Modelling Outputs

Comparison of the intertidal area ground levels and observed frequency of inundation from satellite imagery (Mueller *et al*. 2016), as well as modelling by Water Technology (2021b) suggests tidal flows are constrained from reaching the eastern basins of the salt flats, despite the basin surface being below high tide level. Consequently, inundation frequency (and associated hydroperiod) does not directly correspond to topographic or bathymetric levels.

As discussed in Section 5.2.2, the mapped landward limit of algal mat habitat approximately corresponds to the +1.0 to +1.1 m AHD contour on the western side of a low relief sediment ridge at approximately +1.2 to +1.3 m AHD that divides the salt flats. This sediment ridge represents a slight elevation in the topography which limits the extent of inundation under most tides and prevents return flow of water which overtops the ridge during extreme tides or surges. Absence of algal mat habitat on the eastern side of the salt flats (within the lower elevated eastern basins sitting at +0.7 to +0.8 mAHD) suggests the ridge provides a physical restriction to algal mat growth, which may be due to extreme porewater salinity or infrequent wetting, leading to desiccation. Contouring and interrogation of the Lidar DEM of the project area shows the sediment ridge (Figure 5-11).

6.4. SEDIMENT DYNAMICS

Sediment dynamics within the Tubridgi tidal network are inferred based upon general descriptions for tidal networks (Coco *et al*. 2013; Perillo 2019) as depicted in Figure 6-18. The narrow hypsometric distribution of the salt flats provides a conundrum with respect to sedimentation dynamics. Relative uniformity of level typically suggests either formation during a common era with limited sediment dynamics, or an active modern landform with homogeneous processes. The active nature of the tidal channels is indicated by cycles of channel incision and development of depositional fans (Figure 6-17). However, the presence of a substantial coastal barrier along approximately three quarters of the intertidal area determines that sediment transfers are not homogeneous, with the southern quarter expected to have higher sediment availability. Instead, the only substantial difference in hypsometry occurs for the basin east of Urala Creek, suggesting low sediment supply. The remainder of the intertidal area has remarkably consistent hypsometric structure. This conundrum has not been resolved. However, plausible lower to upper limits of sediment transfer through the tidal channels can be from negligible supply up to sufficient input to match sea level rise. The latter effectively assumes that the tidal channels develop a form of equilibrium. This is arguably supported by the structure of the salt flats, which is as much as 0.7 m above the bed of the basin to the east (south of the project area).

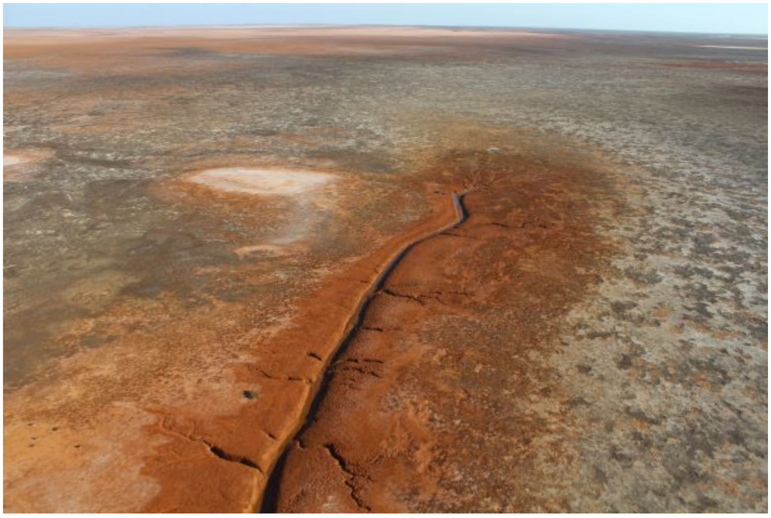

Figure 6-17: Characteristic Overbank Depositional Fan

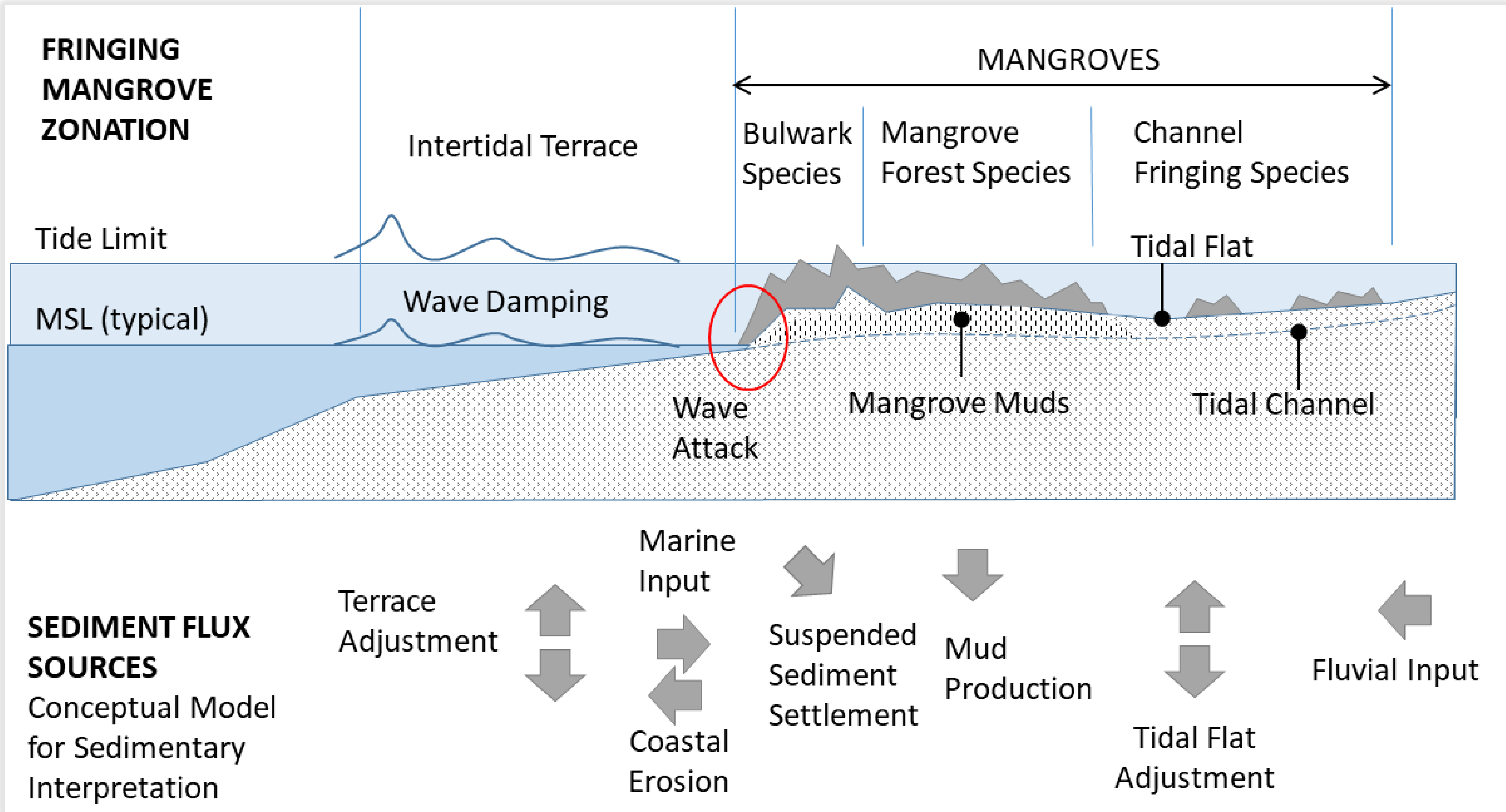

Figure 6-18: Conceptual Model of Sediment Dynamics

7. Projected Change to Intertidal Habitats

7.1. RESPONSE TO SEA LEVEL RISE WITHOUT PROJECT

Coastal response to sea level rise (without the proposed Project) has been predicted by interpreting the likely interactive response of the different landform units and associated habitats that comprise the Tubridgi coast (see Figure 7-1):

- Sedimentary Shore
- Coastal Barrier
- Tidal Creeks
- Intertidal Flats
- Mangroves
- Algal Mats
- Salt Flats Including: Sediment Ridge & Eastern Basins

7.1.1. Sediment Transfer

The sedimentary shore includes sandy beach in front of the coastal barrier and mudflats seaward of the mangrove shore to the south. These sedimentary landforms have morphology which actively responses to tides and waves, so they are expected to respond directly to sea level rise, primarily through an upward and landward migration of sediment onto the intertidal flats adjacent to tidal creeks.

Sediment from the mudflat shore seaward of the mangroves, is expected transfer onto the intertidal flats through the tidal channel network. Based upon the width of the existing fringing coastal mangroves which ranges from 0.5 to 2 km, the expected response is 20-40 m erosion per 0.1 m sea level rise. This has been estimated by the ratio of the average mangrove fringe width to the vertical tide range (i.e. a geometric response).

Litter production by mangroves can potentially reduce sediment infill needed for the mangroves to keep pace with sea level rise (Gilman *et al*. 2007). Typical rates of litter production are 1-2mm/yr, which can offset half the effects of sea level rise within 10-20 years, supporting natural migration of the mangrove habitat. However, the influence of litter production has less influence as the rate of sea level rise accelerates. This is critical for mangrove recruitment and disturbance-recovery cycles, which rely upon suitable soil conditions for establishment. For sea level rise above 8 mm/yr, sediment production is predicted to be insufficient to support mangrove recruitment, and above 12 mm/yr, it is insufficient to balance disturbance with recovery, leading to mangrove loss (Woodroffe *et al*. 2016; Saintilan *et al*. 2020).

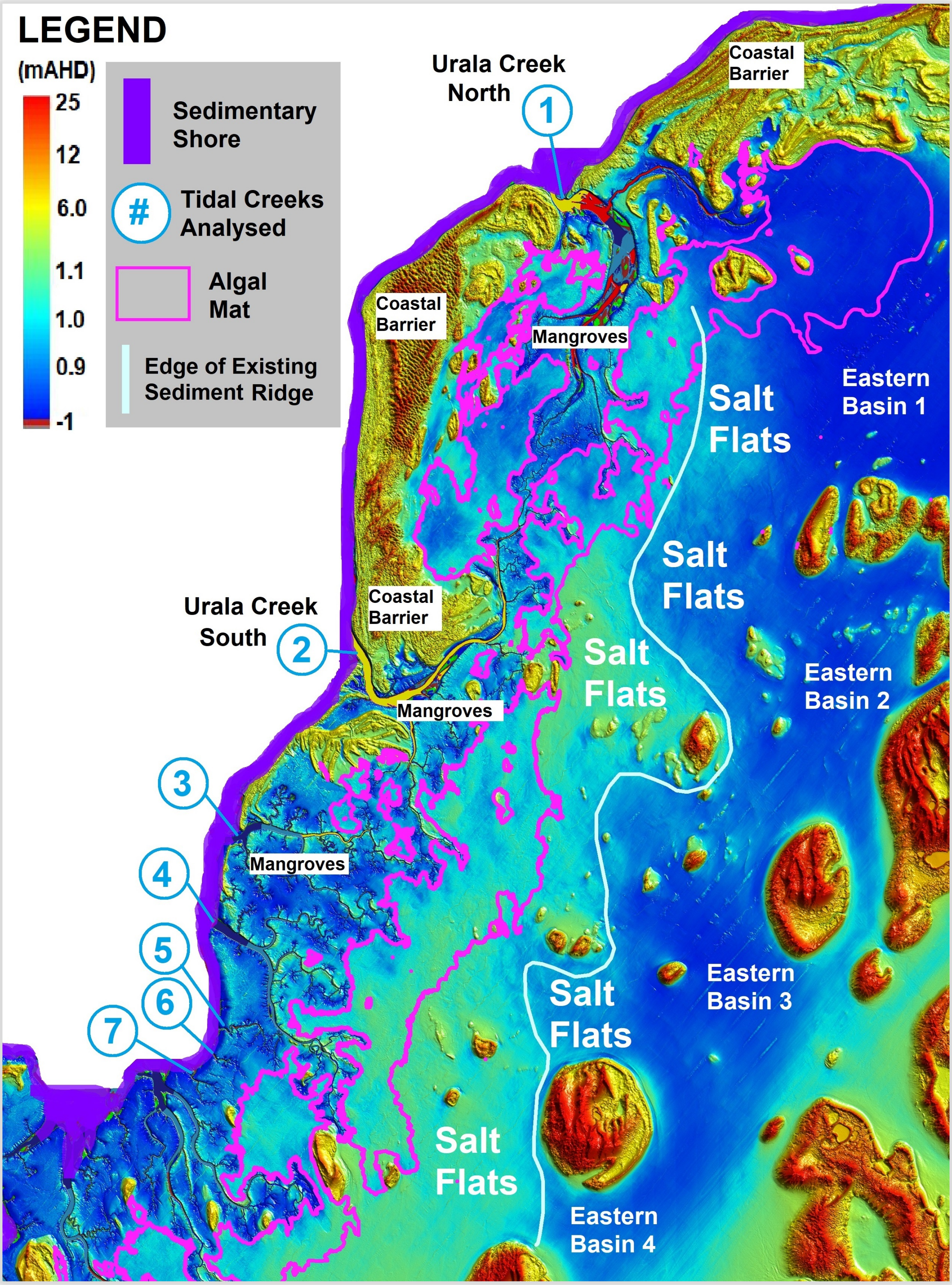

Figure 7-1: Tubridgi Coast Landform Units and Habitats

7.1.2. Erosion and Breaching of Coastal Barrier

The existing coastal barrier (sand dunes) is almost entirely above 3.0 m AHD, which provides a moderate freeboard above highest astronomic tide, maintaining a cross-section of more than 50 m^2/m above extreme storm water levels, which is a typical indicator of dune stability (Larson *et al*. 2009). Consequently, although the barrier may be subject to episodic breaching at low points or under extreme storm impacts, it is likely to remain substantially intact for sea level rise less than 0.75 m. With continued rise, the barrier is likely to become increasingly breached and collapse progressively.

7.1.3. Tidal Creek Expansion

Tidal creek channel dimensions (length and width) are determined by the volume of tidal water that flows through them (tidal prism), which is a function of tidal range and hypsometry, being the land area relative to sea level (Zhou *et al*. 2018). Sea level rise will increase tidal water exchange volume and cause expansion of tidal creek networks.

Along the Tubridgi coast, intertidal basins connected to tidal creek channels have an extremely narrow hypsometric range (i.e. the basins are almost flat). This narrow hypsometry causes a near linear relationship between sea level and tidal water exchange volume (Figure 7-2).

Projected response of the tidal creek channels is expansion landward, proportional to the increase in volume of tidal water exchanged (tidal prism). Due to the narrow hypsometric distribution (almost flat elevation) over the intertidal flats, the predicted expansion of tidal creeks is approximately linear, at about 10% per 0.1 m sea level rise (Figure 7-2). This corresponds to approximately 300-400 m landward extension of the tidal creeks per 0.1 m of sea level rise, estimated by the change in tidal exchange volume and projected proportional change in creek area.

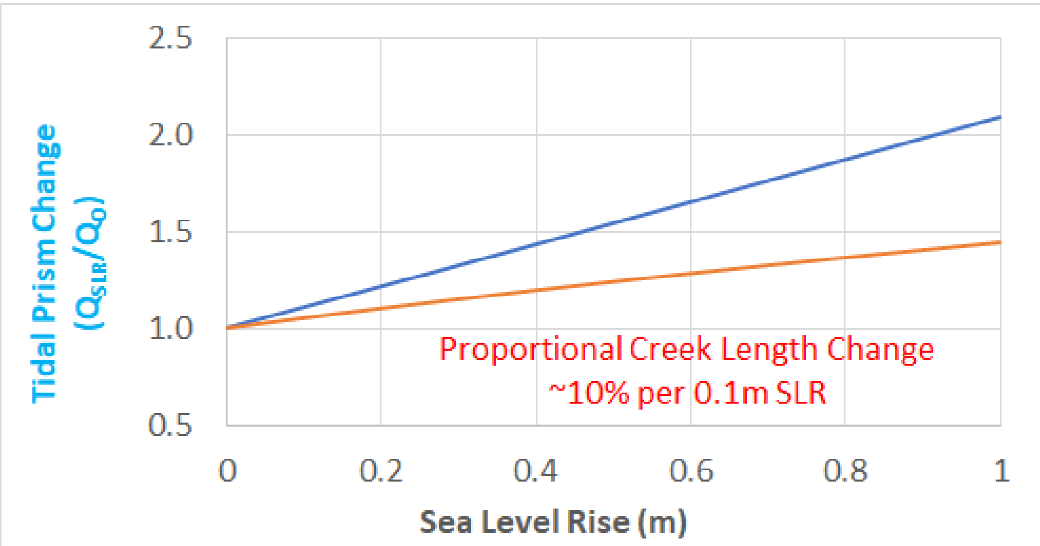

Figure 7-2: Tidal Prism (Volume of Tidal Water) Change with Sea Level Rise (SLR)

These lines were derived from Urala Creek North contributing area. However, due to the very narrow range of levels across the salt flats, there is less than 10% variation between different channels.

Assumption of a direct relationship between sea level rise and tidal creek length (via the mechanisms of tidal exchange volume) includes two key simplifications:

- The relationship between sea level rise and tidal exchange volume has assumed monotonic hypsometry (i.e. exchange is determined from the entire area below the tide level). This is substantially modified by natural levees and creek banks, which can hydraulically isolate lower areas (Figure 7-3). Breaching of the levees or creek banks can cause a sudden large increase of tidal exchange volume (Gong *et al*. 2018). Consequently, if natural levees have developed, particularly where reinforced by mangroves, the channel system is partly buffered against small changes to sea level. This is a major reason why observed historic changes have been mainly observed at the head of tidal creeks, with small changes apparent in the body of the channel network (Section 5.1).

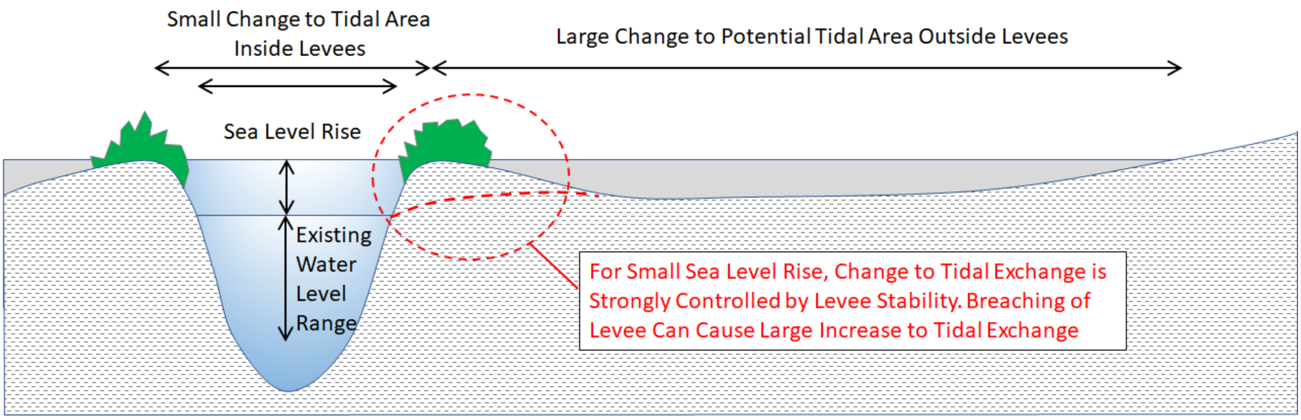

Figure 7-3: Effect of Levee Stability on Sea Level to Tidal Exchange Relationship

- Although a connection between tidal exchange volume and creek length is apparent when considering overall behaviour, response of individual creeks can be significantly different. This includes the effect of local features (e.g. levees or connectivity to adjacent basins), but is also related to how changes to tidal exchange are distributed throughout the tidal network: the largest changes will occur for channels which are hydraulically connected to areas which are not previously flooded (i.e. the ‘long’ channels located to landward). Notably, change will also occur for tidal channels within the coastal fringe (Section 4.4), as sea level rise increases tidal exchange, even with marginal change to contributing tidal area. The approach used for projecting mangrove habitat areas has been to assume proportional change for both coastal mangrove ‘woodland’ and channel fringing mangroves, which produces a larger horizontal change for the latter habitat due to the longer creek length.

Assumption of a direct relationship between sea level rise and tidal exchange gives a different outcome to hydrodynamic modelling undertaken for the creek system, which indicates a small change in inundation extent with sea level rise (Water Technology 2021b). This discrepancy is created because the hydrodynamic model includes the effect of levees and treats them as wholly stable, whereas this evaluation effectively assumes that natural levees are unstable. Assuming levee instability overestimates creek expansion for low levels of sea level rise expected over the next 25-50 years, but for accelerating rates of sea level rise, opportunities for natural levee building reduce and existing levees are certain to collapse eventually. Consequently, estimation of tidal creek expansion due to sea level rise is likely conservative for the next 25 to 50 years, but more closely simulates the dominant process for creek change with higher rates of sea level rise.

7.1.4. Mangrove Redistribution

Tidal creek expansion will cause increased flushing of the mangrove-salt flat fringe, gradually reducing the porewater salinity at this boundary and allowing mangrove colonisation to extend landward along expanded tidal creek channels. Litter production and sediment trapping by mangroves may potentially allow the mangrove substrate to rise under low rates of sea level rise.

Expansion of the creek systems creates potential new mangrove habitat. Proportional changes to existing tidal creeks and mangrove coverage has been approximated as corresponding to the increase tidal exchange volume developed by sea level rise. Overall an increase in mangroves of 16-35% (400-800 ha, adjacent to the project area) over ~30 years is estimated by the projected expansion of tidal creeks, based on tidal exchange volumes

Using the creek hypsometry, a +0.25m sea level rise by 2050 will increase tidal exchange by +30% for Urala Creek North and +27% for Urala Creek South. For the ~ 800 ha of existing mangroves adjacent to Urala Creek North and Urala Creek South and approximately 9 km total creek length, increased tidal exchange is estimated to extend the creek length by approximately 1 km and create approximately 40 to 250 ha of new mangrove habitat. Figure 7-4 gives an indication of relative change to mangrove habitat that may developed with 0.25m sea level rise – note that this illustration has been generated graphically using expansion and infilling of existing mangrove mapping and has not been developed using modelling. Approximately 40 ha of new mangrove habitat is developed along the margin of extended creek channels, with 0 to 190 ha developed through expansion of the mangrove 'woodlands'. The capacity for mangrove 'woodland' expansion is affected by natural levee stability along channel banks and basin margins, which can obscure wetland response to small changes of sea level. Levee instability is episodic, affected by sediment supply and runoff incision, and therefore expansion may lag years behind sea level change. Consequently, a potential range of 0 to 190 ha of mangrove 'woodland' expansion is possible by 2050.

Beyond 2050, with faster rates of sea level rise there will be reduced capacity for mangroves to capture or produce sediment sufficient to keep pace with sea level rise, resulting in destabilisation of mangrove communities. Capacity for mangrove recruitment will be physically limited by sea level rise above 8 mm/yr (projected by ~2055), with increased stress on existing mangrove communities as sea levels continue to accelerate upward. Mangrove loss due to sea level rise is expected to increase significantly once sea level rise exceeds 12 mm/year (projected by ~2075) with limited ability for mangroves to recover after disturbance events (e.g. storms).

7.1.5. Algal Mat Redistribution

The algal mat habitat will initially expand rapidly with sea level rise for approximately 10 – 20 years (to ~2040) from its present landward limit around +1.1 m AHD, up to the crest of the sediment ridge, which is 0.1-0.3 m higher. Expected expansion is 500-750 m per 0.1 m sea level rise based on existing LiDAR DEM contours. Increase of algal mat area is likely to be about 7% (~600 - 800 ha) over ~10 - 20 years based on existing surface contours and assuming preservation of existing hydroperiod.

After 10 – 20 years it is uncertain whether algal mats will continue to migrate past the slightly elevated sediment ridge, landwards into the lower elevation eastern basins. Present-day absence of algal mat on the east side of the sediment ridge suggests a physical limit, likely associated with salinity or excessive desiccation (both related to hydroperiod), and it is uncertain whether the algal mat habitat can expand beyond this physical limit. Uncertainty exists due to the potential for interactions between hydroperiod, salinity and morphology on the eastern basins of the salt flats.

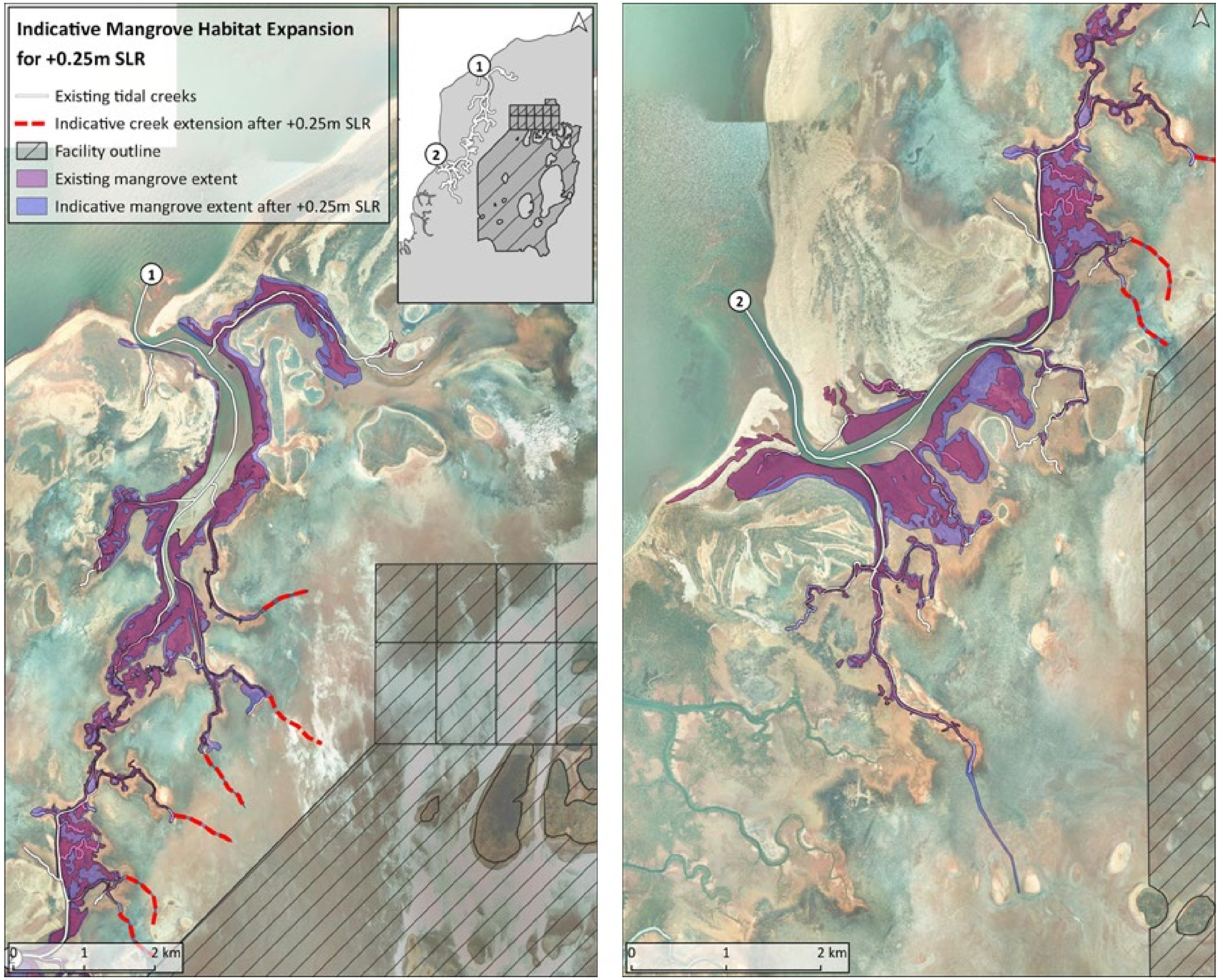

Figure 7-4: Indicative Area of Mangrove Expansion by 2050

Factors contributing to uncertain response across the sediment ridge include:

- Tidal drainage across the crest is largely one way (eastward) which results in abbreviated tidal inundation and high evaporation, presently creating hypersaline surface porewater. As sea levels rise, low to moderate increases to tidal inundation may increase salinity (Figure 7-5), although this will eventually approach marine salinity once inundation is sufficiently frequent.

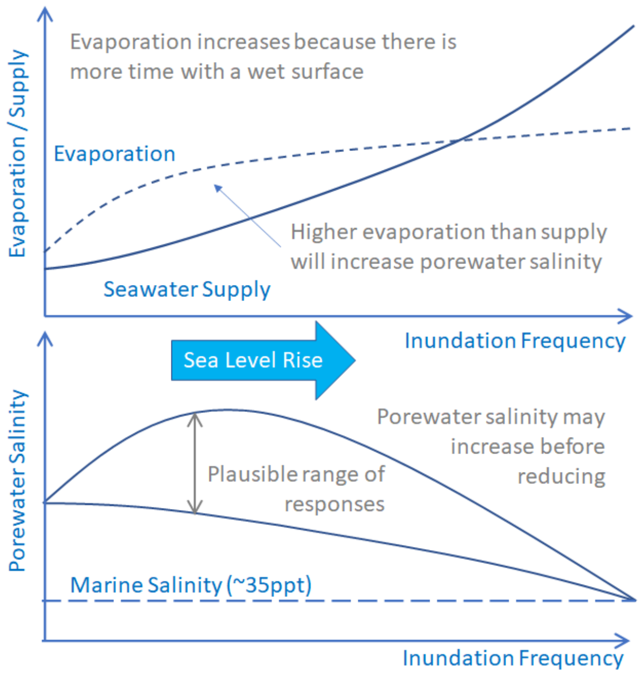

Figure 7-5: Basis for Uncertainty Projecting Porewater Salinity East of Sediment Ridge

- Higher tide levels will increase hydraulic connection from the eastern basins to the ocean. This may be through the existing, partly restricted pathway via Urala Creek North and/or new creek channels which breach the sediment ridge.
- Sediment deposition "filling" the eastern basins.

These uncertainties and complexities are further discussed in Section 7.1.6.

Potential new algal mat habitat has been estimated where expansion of the existing algal mat habitat (by 500-750 m per 0.1m SLR) overlaps the sediment ridge. The maximum area of potential habitat expansion is expected to occur with 0.25m SLR (~2050), with an expansion from 2200 ha (present day) up to 2800-3000 ha (~2050), providing an increase of 600 to 800 ha. Above 0.25m SLR, the sediment ridge crest level is below the estimated upper viable limit of algal mats (based on hydroperiod), so higher sea level creates negligible additional potential habitat area.

However, after a period of uncertain behaviour, increased sea level rise will cause the excessive inundation of algal mat areas, leading to stress and retreat. Once sea level rise exceeds 0.45 m (by ~2075) the entire area west of the sediment ridge will be inundated more frequently than the present-day lower limit for algal mats, indicating sustained habitat loss with further sea level rise.

7.1.6. Samphire Redistribution

Response to sea level rise is likely to differ for the two samphire habitats mapped by Biota (2020) and described in Section 4.6:

(i) Samphire along the intertidal to supratidal fringes of relict mainland islands, dunes and Urala Creek North mouth, occupy tidal berms (1.3-1.6 mAHD), which have been gradually built through accumulation of sediments over many successive inundations (supplied mainly from downslope sediment movement). Sea level rise will cause approximately doubling of tidal inundation occurrence for every 0.1 m sea level rise (Figure 4-5). The anticipated response is rollover and upward growth of the tidal berm, as well as progressive narrowing due to very small rates of sediment supply. Existing berm widths of 8-12 m are estimated to reduce by 50% with 0.2 m sea level rise (around 2050), with corresponding reduction in samphire presence. Continuing sea level rise will cause increased samphire loss, aggravated by its relative intolerance to changing ground conditions.

(ii) Extensive samphire habitat occurs in supratidal basins and channels upstream of where ephemeral drainage lines debouch onto the salt flats, along the north-east edge of the proposed Project area at the salt flat-hinterland margin. This samphire is presently supratidal, and due to seasonal tidal phases, is only exposed to high tide inundation for a few months per year (Figure 4-5), potentially supporting seasonal brackish conditions. Increased incidence of tidal flooding due to sea level rise will significantly change this environment.

LIDAR derived topography indicates there is a transitional ramp from 1.3 m AHD from the supratidal wetlands down to 0.9 mAHD on the mudflat. This suggests a progression of:

- From now to 0.4 m sea level rise (projected after 2070), tidal inundation will double for every 0.1 m sea level rise, with increased salinity potentially modifying samphire coverage. This impact is uncertain, as the influence of brackish phase frequency on samphire abundance and health is not clear. However, impacts will initially be gradual and progressively accelerate.
- Above 0.4 m sea level rise, significant areas of the wetland will become tidal, substantially affecting the existing samphire habitat, including development of tidal channels. Bed instability developed by tidal networks will cause partial loss of samphire coverage, however, as the area will remain subject to waterlogging and occasional brackish phases, samphire is likely to remain present.

7.1.7. Salt Flat Change

Change to the salt flat surface will be provided by increasing landward transfer of very fine sediments via the tidal channels. This has a physical limit determined by tidal excursion through the channel network, which will expand with sea level rise.

The sediment ridge (Figure 7-1) dividing the algal mats and the salt flats is a flimsy barrier to tidal exchange. This ridge could be breached with sea level rise through:

- Headcutting of the expanding tidal creek channels,
- Sufficiently frequent tidal overtopping to cause collapse of the gentle crest, and/or
- An extreme flooding event causing focused flow into the eastern basin.

Breaching of the sediment ridge barrier (through tidal channel extension) could potentially cause a substantial increase to available tidal exchange, with rapid expansion, forming an alternative hydraulic pathway from the eastern basins within the salt flats to the ocean (Figure 7-6).

An initial breach due to tidal overtopping is likely to occur when the future Mean High Water Spring (MHWS) tidal level is above the crest level, which requires 0.3-0.4 m sea level rise (~2060 – 2070). However, sediment deposition towards the limit of tidal excursion will potentially close any breach that forms, causing a phase of instability.

Channel headcutting, which can form a more sustained breach of the sediment ridge, would require expansion of existing tidal channel lengths by 1.5 to 2.0 times, which could occur with 0.5-1.0 m sea level rise (2075 – 2110).

The eastern basins within the salt flats are presently hydraulically connected through to Urala Creek North (mainly during heavy rainfall) but have a restricted flow path, with narrow channels passing through or around higher elevation areas of relict mainland. With regards to the eastern basins, two alternative scenarios could eventuate:

- Sea level rise may increase the tidal character of the eastern basins and could cut through the existing choke points to create a tidal channel (Figure 7-6). This may create an additional area of intertidal habitat suitable for mangrove and algal mat colonisation. However, by the projected time for potential channel development (~2060-2110), rates of sea level rise would be above 8 mm/yr, which would create challenging conditions for mangrove establishment. Subsequent sea level acceleration would limit the lifetime of any mangrove community that does develop.
- Sea level rise will result in increased sediment mobility within the tidal creeks, potentially including sediment deposition into the eastern basins, thereby raising their elevation and creating intertidal mudflat areas. Similar to the scenario above, this may create an additional area of intertidal habitat suitable for mangrove and algal mat colonisation which would be subsequently destabilised with accelerating sea level rise.

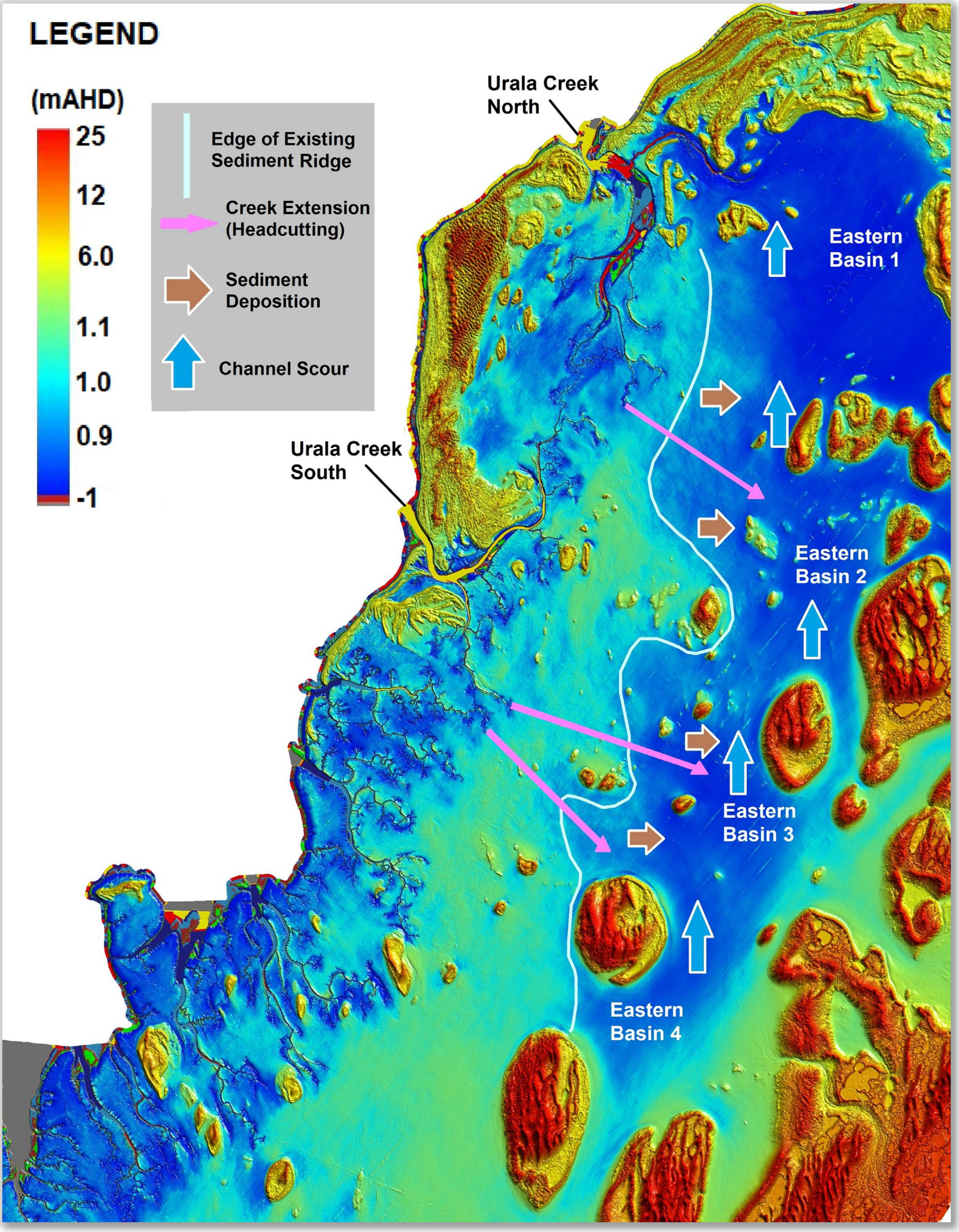

Figure 7-6: Potential Hydraulic Responses to Sea Level Rise

7.1.8. Summary

The above projected response of key morphological and habitat features to sea level rise suggests potential for transformative behaviour:

- Sea level rise will cause increased tidal exchange volumes, resulting in expansion of the tidal creek network. In the vicinity of the creeks, increased exchange will cause reduced surface porewater salinity, increasing potential mangrove habitat.
- For small increases of mean sea level, with low rates of rise, expansion of both mangroves and algal mats is expected to occur.
- Increase of algal mat area is likely to be about 7% (~600 - 800 ha) over ~10 - 20 years based on existing surface contours and assuming preservation of existing hydroperiod.
- After 10 – 20 years it is uncertain whether algal mats can migrate past the slightly elevated sediment ridge, eastwards into the lower elevation eastern basins. The maximum extent of algal mat habitat is expected to occur around 2050, with the west side of the sediment ridge wholly occupied.
- After ~30 years, the rate of sea level rise is expected to result in increased inundation and algal mat retreat, with algal mat loss projected to commence after about 50 years, due to excessive inundation.
- Corresponding growth of mangrove area will be 16-35% (400-800 ha) over ~30 years estimated by the projected expansion of tidal creeks (based on tidal exchange volumes), with 40 - 250 ha expansion of mangroves estimated adjacent to the project area (for Urala Creek North and Urala Creek South tidal catchments).
- After ~30 years, the rate of sea level rise is expected to affect the capacity for mangroves to trap sediment, resulting in increased inundation, with mangrove loss projected to commence after about 50 years, due to sediment instability, affecting the capacity for mangroves to recover after disturbances such as storm impacts.

Transformative change may occur from about 2060, when it will become possible for the sediment ridge to breach, with potentially substantial changes to the intertidal area hydraulics. This creates potential for expansion of the intertidal habitats into the eastern basins of the intertidal area, but behaviour is highly uncertain.

Figure 7-7 summarises the predicted sea level rise response described above for the different intertidal habitats and morphologies.

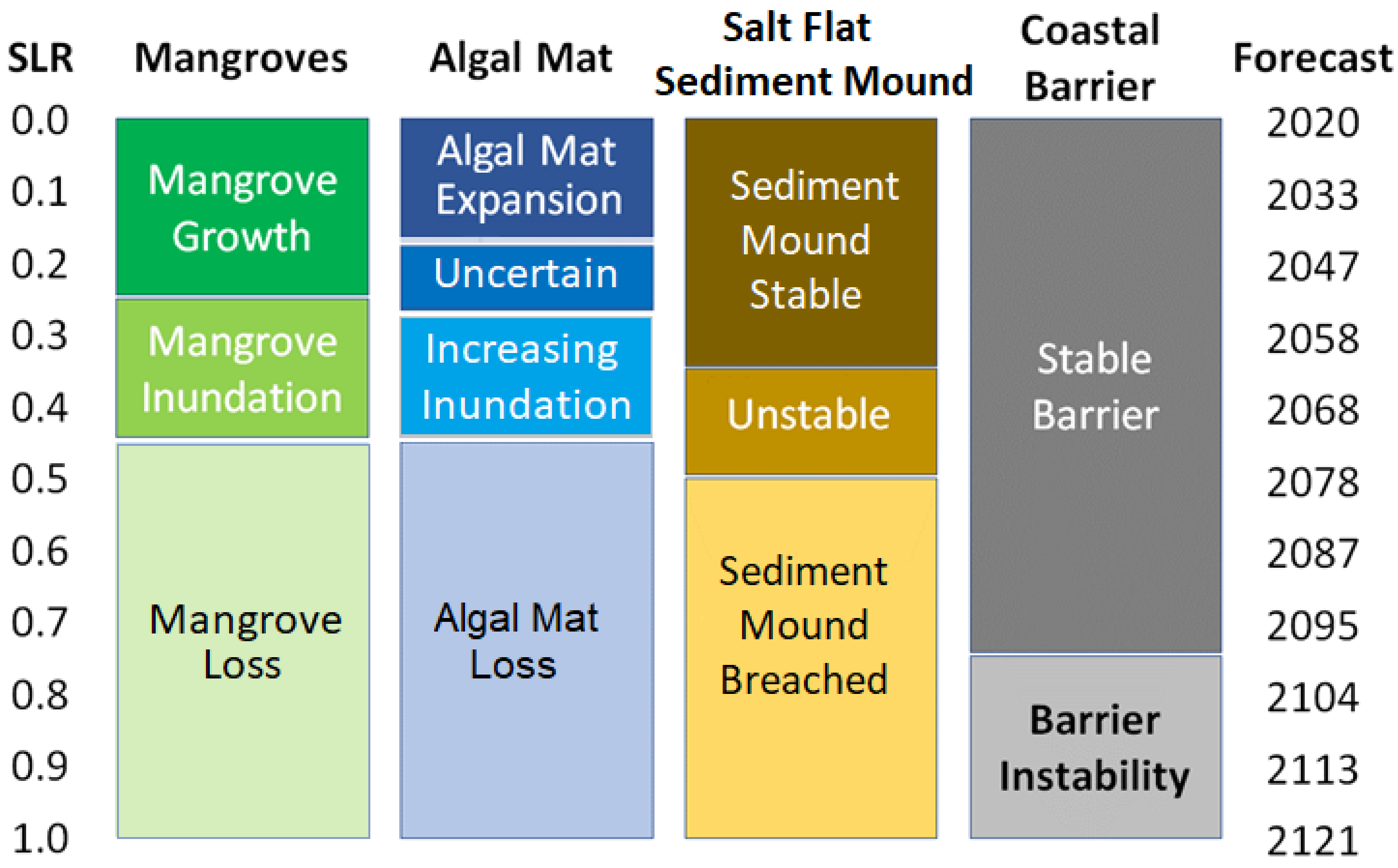

Figure 7-7: Response to Sea Level Rise of Key Coastal Features

7.2. RESPONSE TO SEA LEVEL RISE WITH PROJECT

A morphometric approach, assessing physical dimensions of existing creeks, has been used to characterise the relationship between creek structure and tidal exchange, which is modified by both the proposed infrastructure and sea level rise. The response to sea level rise with the project in place has been assessed by characterising changes to present and future tidal exchanges due to excising areas from Urala Creek North, Urala Creek South and the eastern basins of the salt flats. Potential impacts to tidal exchanges have been related, through the morphometric relationships, to interpret intertidal habitat responses to sea level rise.

7.2.1. Tidal Catchment Excisions

The proposed salt ponds are to be constructed in the upper intertidal area, mainly across areas of salt flat. Construction of the proposed salt ponds will cause:

- Excision of approximately 1700 ha from the catchment area contributing to high tide tidal exchange through Urala Creek North (Figure 7-8). This is above Mean High Water Spring (MHWS), but approximately 20% of the creek's contributing area below Highest Astronomical Tide (HAT). In effect, this means that tidal exchange and flows through Urala Creek North will be unaffected for more than 98% of the time (implied by Figure 4-5). The highest tidal flows, occurring <2% of the time, will be slowed causing ponding of water against embankments (Water Technology 2021b).
- Excision of approximately 2000 ha from the catchment area contributing to high tide tidal exchange through Urala Creek South (Figure 7-8). This is above MHWS, but almost 50% of the creek's contributing area below HAT. As with Urala Creek North, this change will only affect the highest tidal flows, occurring <2% of the time (Water Technology 2021b). The actual change to tidal exchange is partly obscured by the low-level 'sediment ridge' toward the eastern side of the catchment area (Figure 7-8), which is likely to modify the direction of tidal drainage – in general, a smaller impact on tidal exchange volume is anticipated, and a range of 25-50% reduction has been considered.
- Excision of approximately 6600 ha from the 'eastern basin' area east of the 'sediment ridge' toward the centre of the salt flats (Figure 7-8). Although this includes area below MHWS, the hydraulic pathway through to Urala Creek North is constricted, and this area is not considered part of the active tidal network. However, this area does presently act as a storage area during extreme coastal flooding events, with drainage passing through Urala Creek North.

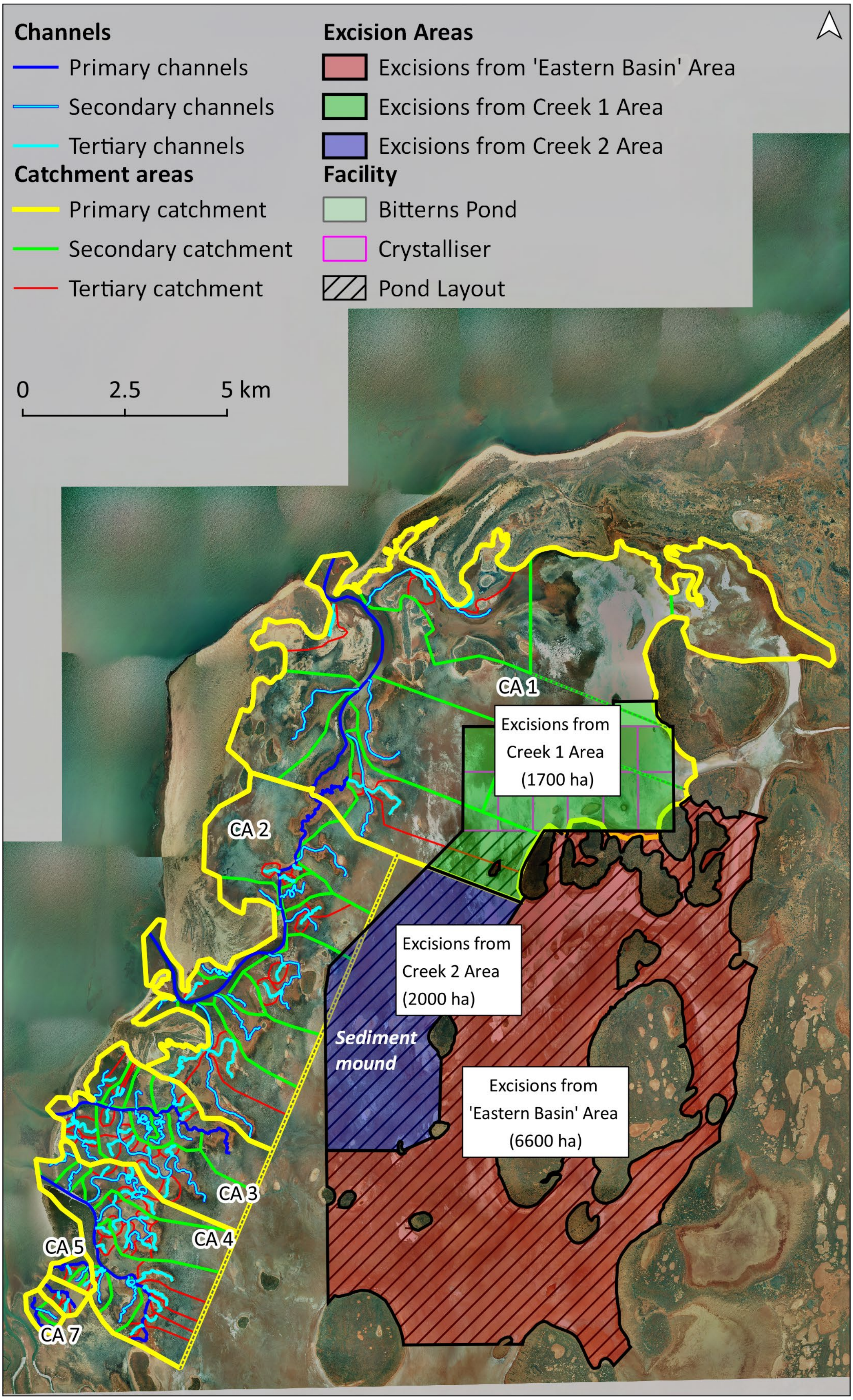

Figure 7-8: Attributed Areas Excised from Tidal Creek Networks

7.2.2. Predicted Change to Tidal Exchange

Changes to tidal exchange and modification of hydraulic pathways will alter the long-term response of the Tubridgi coast to sea level rise. Expected behaviour has been considered using hypsometric relationships for Urala Creek North and Urala Creek South (described in Section 6.2), which provide an estimate of tidal exchange volumes.

Proposed structures are located above the mean high water spring tide plane, and therefore present-day tidal exchange volumes will not change substantially. However, the structures occupy areas which would have contributed to tidal exchange with higher sea levels. Consequently, the project will reduce how much tidal exchange increases with sea level rise.

The combined effect on tidal exchange of increase due to sea level rise and decrease due to excision of contributing upper intertidal areas has been considered using hypsometric relationships (described in Section 6.2). For example, the hypsometric curve for Urala Creek North (Figure 7-9) suggests that a 31% reduction in total contributing tidal area due to the project structures would counteract the increase in tidal exchange caused by a 0.3 m sea level rise.

Given future hypsometric relationships are subject to local hydrodynamic variation, including creek evolution, our analysis has considered +/-50% of the decrease in tidal area caused by the proposed facilities. On this basis:

- The 20% reduction of tidal area at present-day HAT for Urala Creek North (Figure 7-9) is expected to offset response to sea level rise until it is in the range of 0.2-0.4 m (until ~2050-2070).
- The 25-50% reduction of tidal area at present-day HAT for Urala Creek South (Figure 7-10) is expected to offset response to sea level rise until it is in the range of 0.3-0.65m (~until 2070 - 2090).

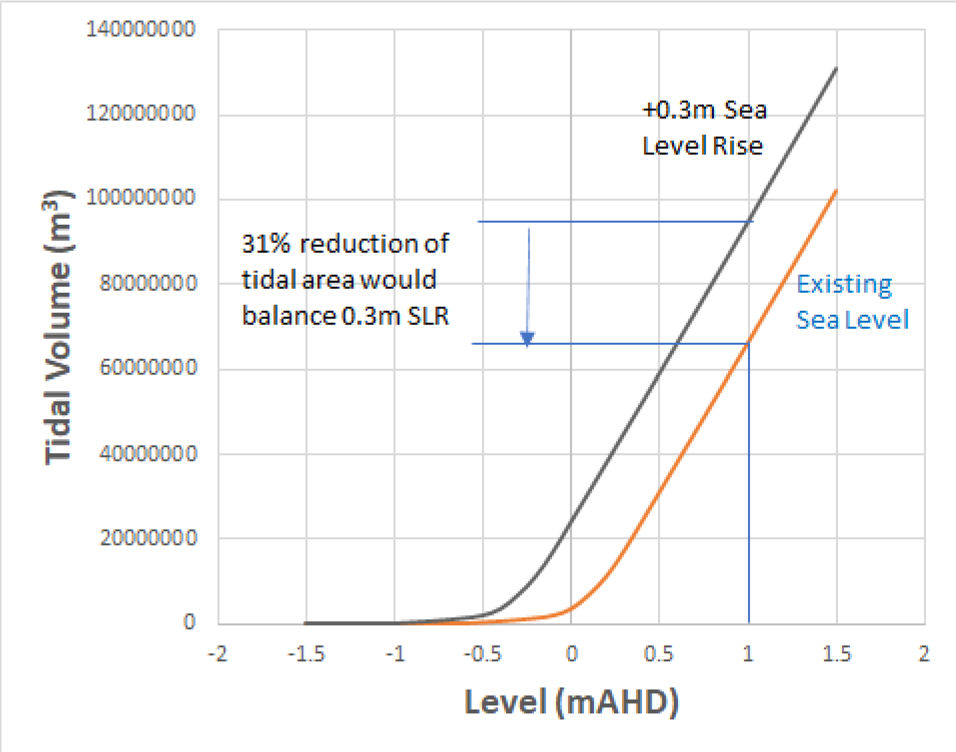

Figure 7-9: Tidal Exchange Volume Offset for Urala Creek North

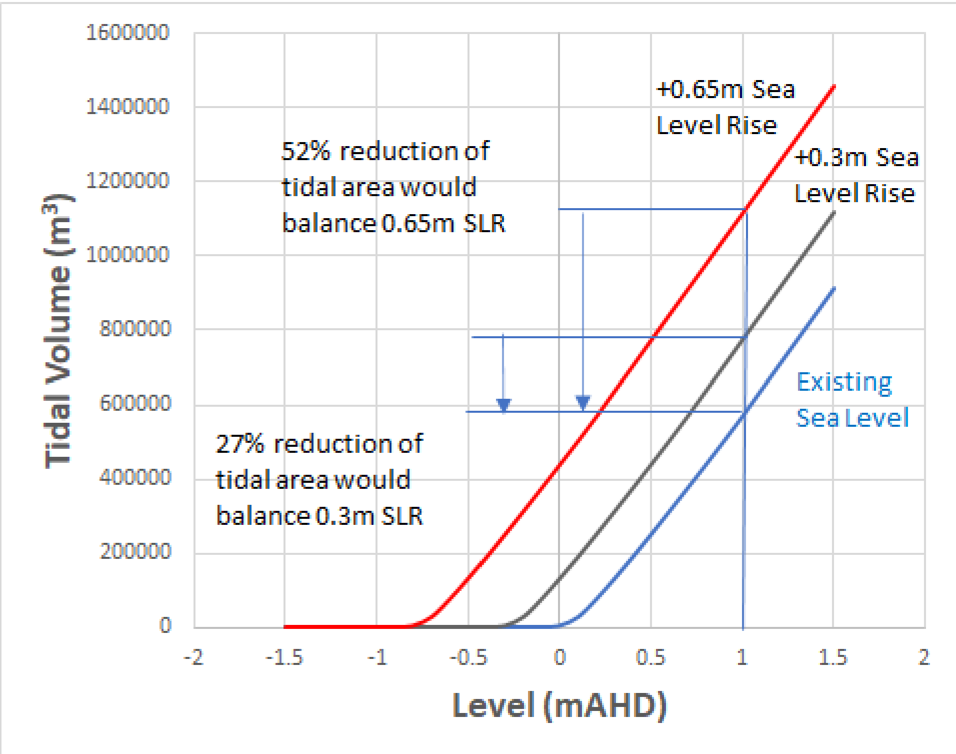

Figure 7-10: Tidal Exchange Volume Offset for Urala Creek South

7.2.3. Predicted Change to Tidal Creeks

Proposed salt project structures will not modify present day typical tidal exchanges (below MHWS), and therefore the tidal creek network adjacent to the project is likely to remain largely steady. However, reduction of the high tide tidal exchange (above MHWS) in Urala Creek North and Urala Creek South will retard expansion of tidal creek channels that would otherwise be developed by rising sea levels (see Section 7.1.3).

Isolation of eastern basin 4 south of the salt ponds may result in creation of a tidal creek channel connecting eastern basin 4 to the ocean via the existing tidal creek systems 4 and 5.

Local responses are likely to the pond embankments due to interfacing between the harder embankment material and softer salt flat sediments, including formation of a gutter channel along the embankment's base. Local guttering along the edge of embankments can connect to tidal channel networks. This process is usually initiated during severe flood events and can accelerate rapidly if the channel cuts below MHWS. This is a relatively unpredictable process. It has been considered in the embankment design including rock armouring and can also be actively managed by infilling gutters if they connect to creeks.

7.2.4. Predicted Mangrove Redistribution

Reduction of high tide tidal exchange (above MHWS) in Urala Creek North and Urala Creek South will retard expansion of tidal creek channels adjacent to the project and associated mangrove colonisation that would otherwise be developed by rising sea levels (i.e 40-250 ha new mangrove habitat adjacent to the project site, which was estimated to develop by around 2050, as described in Section 7.1.4).

It is noted that excision of areas from the upper part of the intertidal area is more likely to impede expansion of the longer tidal creeks, as these are hydraulically connected to the excised area. This will prevent expansion of the channel fringing mangrove habitat (by ~40 ha) but is likely to have less effect on expansion of the coastal fringing mangrove 'woodlands' (0 - 190 ha change depending on levee stability as described in Section 7.1.3). Assumption that there is negligible mangrove expansion until changes to tidal exchange (from sea level rise or reduced tidal area) are balanced is consequently considered conservative. In counterpoint, assumption that mangrove 'woodland' expansion will be unaffected by salt flat excision is non-conservative, as greater stability of the longer primary and secondary creeks enhances levee stability, limiting growth of tertiary and smaller creeks.

Expansion of tidal creek systems 4 and 5 would provide potential future habitat area for mangroves along the margins of the 'new' creek connected to eastern basin 4. Longer-term tidal exchange may ultimately reduce surface groundwater salinity in eastern basin 4, providing potential habitat areas for mangroves over a time scale of decades.

Mangrove communities will ultimately be challenged by to accelerating rates of sea level rise and subsequent sediment destabilisation, with rates above 8 mm/yr reducing the capacity for mangrove establishment, limiting their capacity to adapt to changing conditions.

7.2.5. Predicted Algal Mat Redistribution

The project is not predicted to substantially impact the overall behaviour of algal mats, which is controlled by hydroperiod (i.e. water levels, which increase with sea level rise), rather than creek structure. Algal mats are expected to increase in area for approximately 10 - 20 years, until they reach the edge of the sediment ridge on the western side of the salt flats or the salt pond embankments. The proposed ponds are located west of the sediment ridge crest for a length of roughly 3 km adjacent to Urala Creek South. Construction of salt ponds truncates the potential habitat expansion, with ~450 – 560 ha unable to be occupied by algal mats (Figure 7-11).

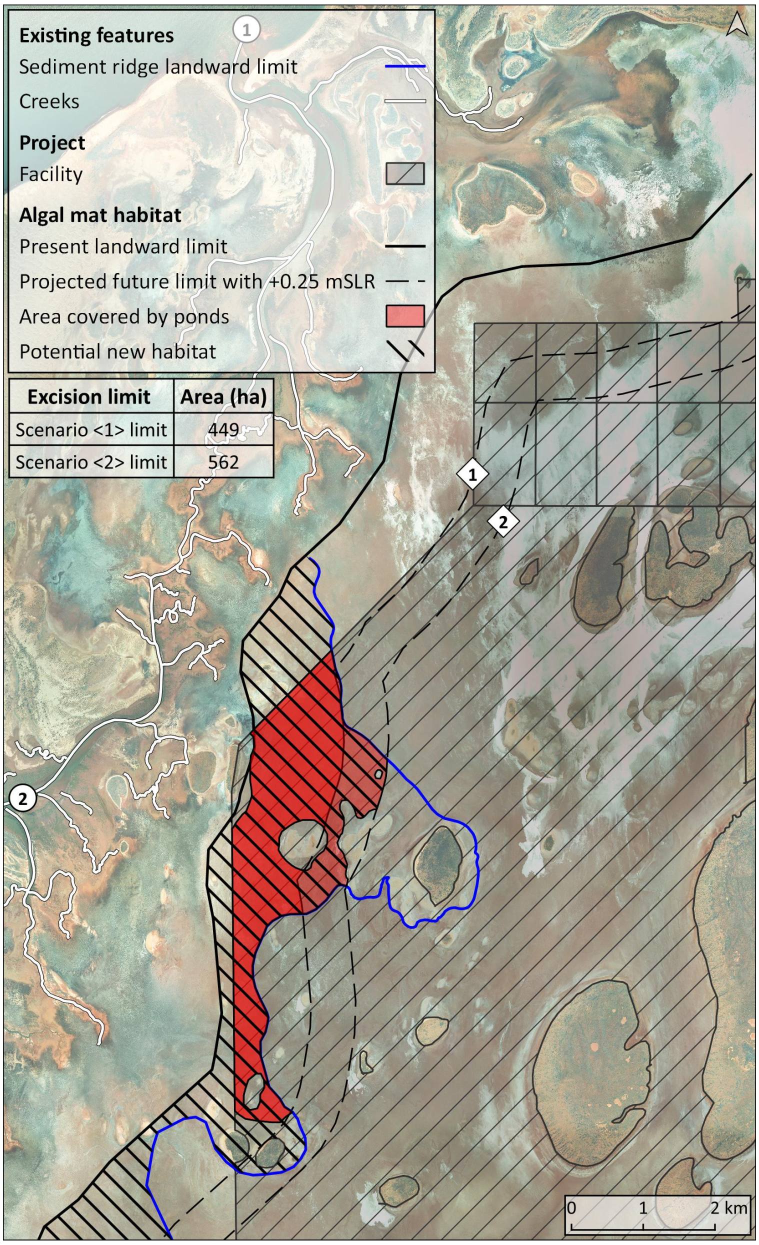

Figure 7-11: Area of Potential Algal Mat Habitat Excluded by Salt Ponds

Algal mats will eventually be lost because of insufficient land elevation west of the sediment ridge, making the mats susceptible to excessively depths of inundation, causing mat and sediment mobility.

7.2.6. Predicted Change to Samphire Habitats

Anticipated changes to samphire habitat due to sea level rise (see Section 7.1.6) will be modified by the project. Predicted responses for the two habitat types mapped by Biota (2020) and described in Section 4.6 include:

(i) Samphire along the supratidal/intertidal fringe at the base of supratidal slopes are located near the mouth of Urala Creek North, or around the margin of relict mainland islands and some dunes abutting the salt flats.
   a. Some samphire fringing the relict mainland islands will be contained within salt ponds, with their hydraulic regime controlled by management of seawater in the ponds. Impact to these samphire has been assessed in AECOM (2021).
   b. Remaining samphire habitat along the supratidal/intertidal fringe at the base of supratidal slopes will have response to sea level rise unaffected by the project. These habitats are anticipated to contract under sea level rise at the same rate as they would without the project. Sea level rise will cause approximately doubling of tidal inundation occurrence for every 0.1 m sea level rise (Figure 4 5). The anticipated response of the tidal berm occupied by samphire is rollover and upward growth, with progressive narrowing due to very small rates of sediment supply. Existing berm widths of 8-12 m are estimated to reduce by 50% with 0.2 m sea level rise (around 2050), with corresponding reduction in samphire presence. Continuing sea level rise will cause increased samphire loss, aggravated by its relative intolerance to changing ground conditions.

(ii) Samphire habitat in supratidal basins and channels upstream of the salt flat-hinterland margin will be affected by increased local flooding in the eastern basin of Urala Creek North (Water Technology 2021b). The projected change is approximately 0.1 m higher peak tidal level, which suggests that the incidence of salt water flows into the samphire area will approximately double. This will accelerate the process of wetland salinisation anticipated to occur due to sea level rise, bringing forward the approximate period of substantial ecosystem change which may cause samphire decline to 2055 – without the project, this change is expected to occur around 2070 (see Section 7.1.6).

7.2.7. Predicted Salt Flat Change

Construction of the salt ponds on the eastern basins of the salt flats and isolation of eastern basin 4 to the south of the salt ponds will prevent expansion/scouring of the existing hydraulic pathway through the eastern basins to Urala Creek North.

7.2.8. Predicted Sediment Transfer

Sediment transfer along the coast due to sea level rise is expected to remain largely unaltered due to the project, given this process will be occurring along the coastline some distance from the project.

Sediment transfer from the tidal creeks onto adjacent intertidal mudflats (which will increase with sea level rise) will occur along the existing tidal creek network and may result in increasing elevation adjacent to the project, within eastern basin 1 and 4 and along any potential new tidal creek connecting to eastern basin 4.

7.2.9. Predicted Coastal Barrier Behaviour

Increased breaching risk of the coastal barrier due to sea level rise is expected to remain largely unaltered due to the project. This process will be occurring along the coastline some distance from the project site.

8. Summary and Conclusions

Analysis of intertidal habitats in the proposed Ashburton Salt Project area has identified:

- Existing mangroves are strongly linked to the tidal creek network, with the eastern margin apparently controlled by surface groundwater salinity, consistent with previous findings in the Pilbara (Semeniuk 1996).
- Algal mats are present adjacent to the western side of the salt flats, apparently controlled by surface groundwater salinity and hydroperiod, with water exchange through the tidal creek network.
- The eastern part of the salt flats (south of the proposed salt ponds) is partly separated from the coast by a low-level sediment ridge, with a restricted hydraulic connection through Urala Creek North (activated by heavy rainfall). Although this area includes ground levels matching those of the mangroves and algal mats along the coast, it is not apparently suitable habitat.

Table 8-1 and Figure 8-1 below summarise the predicted morphodynamic and habitat responses to sea level rise with or without the project in place, arrived at by assessing relationships between tidal creek structure, tidal exchange and habitat response along the Turbridgi coast.The Ashburton Salt Project is not expected to substantially affect the health or distribution of existing intertidal habitats. However, it is expected to modify development of new potential habitat areas that would otherwise be expected to occur in response to low rates of sea level rise (before ~2050).

With the project in place, it is estimated that 40 to 250 ha of new potential mangrove habitat and 450 to 560 ha of potential new algal mat habitat will not develop between 2021 and 2050. However, this potential new habitat is expected to be impermanent, as accelerating sea level rise will place increasing stress on these habitats from 2055, with progressive habitat loss expected after 2075. Habitat stress and loss is expected to occur with or without the Ashburton Salt Project in place.

Samphire along the supratidal/intertidal fringe at the base of supratidal slopes near the Project area will be unaffected by the Project and are anticipated to contract under sea level rise at the same rate as they would without the Project, with a reduction in samphire of 50% by 2050 and ongoing loss as sea level rates accelerate beyond this.

Samphire habitat in supratidal basins and channels at the salt flat hinterland fringe will be affected by increased tidal flooding in the eastern basin of Urala Creek North due to the proposed Project. The predicted change is approximately 0.1 m higher peak tidal level, which suggests that the incidence of salt water flows into this samphire area will approximately double due to the Project. This will accelerate the process of wetland salinisation anticipated to occur due to sea level rise, bringing forward the approximate period of substantial ecosystem change which may cause samphire decline from 2070 without the Project in place, to 2055 with the Project in place.

Table 8-1: Mangrove, Algal Mat and Samphire Response to Sea Level Rise with or without Project

Mangroves				
Years	**Sea Level Rise**	**Without Project**	**With Project**	**Project Stage**
2021 - 2050	0.05 - 0.2 m	Tidal exchange will increase with SLR, which is expected to cause tidal creek landward extension, up to 300-400 m per 0.1 m of SLR for long creeks (expected by ~2040). Smaller tidal creeks, including the networks supporting mangrove 'woodlands' will also expand. Mangroves will progressively occupy extended lengths of tidal creeks. Indicative potential increase in mangroves landward of Tubridgi Point has been estimated as: • ~40 ha along extended creeks. • 0 to ~190 ha mangrove 'woodland' expansion. The capacity for expansion is affected by levee stability along channel banks and basin margins, which can obscure wetland response to small changes of sea level. Levee instability is episodic, affected by sediment supply and runoff incision, and therefore expansion may lag years behind sea level change.	Excision of part of the salt flats will offset increased tidal exchange associated with SLR, limiting the projected expansion of tidal creeks. Long tidal creeks will not expand, and associated mangrove colonisation will not occur. Expansion of smaller tidal creeks is likely to be impeded by limited growth of primary tidal channels. The Project will limit potential estimated expansion of mangroves landward of Tubridgi Point: Extension of ~40 ha mangrove habitat along long creeks is unlikely to occur. Potential expansion of mangrove 'woodland' of up to ~190 ha (which might occur without the project in place) is possibly limited by stability of the primary channels, including the influence of bank levees.	Construction in ~2023 Operation in ~2026
2050 - 2075	0.2 - 0.45 m	Capacity for mangrove establishment or recovery after storm events will be physically limited by rates of SLR above 8 mm per year (projected beyond ~2055). Increased stress will be placed on existing mangrove communities as sea levels continue to accelerate upward (from ~2055 to 2070).	Capacity for mangrove establishment or recovery after storm events will be physically limited by rates of SLR above 8 mm/yr (projected beyond ~2055). Increased stress will be placed on existing mangrove communities as sea levels continue to accelerate upward (from ~2055 to 2070).	Operation until ~2075
2075 - 2100	0.45 - 0.75 m	Loss of established mangroves due to sea level rise is expected to occur once SLR rate exceeds 12 mm per year (by ~2075) due to sediment destabilisation and increased depth of inundation.	Loss of established mangroves due to sea level rise is expected to increase significantly once SRL exceeds 12 mm per year (by ~2075) due to sediment destabilisation and increased inundation.	Closure from ~2075
2100 - 2121	0.75 - 1.0 m	Mangrove loss expected with limited capacity for establishment or recovery after disturbance events.	Mangrove loss expected with limited capacity for establishment or recovery after disturbance events.	

Algal Mats				
Years	**SRL (m)**	**Without Project**	**With Project**	**Project Stage**
2021 - 2050	0.05 - 0.2 m	Algal mats will migrate landwards with sea level rise by ~500-750 m per 0.1 m of sea level rise. Migration will occur until ~2030 to 2040, when they reach the crest of a low-profile sediment ridge which directs water flows westwards towards the coast. It is uncertain whether algal mats can subsequently migrate past the sediment ridge, into the eastern basins of the salt flats (this uncertainty exists given potential for interactions between hydroperiod, salinity and morphology).	The Project is not expected to substantially impact behaviour of algal mats, which will remain responsive to hydroperiod. Algal mats will migrate landwards with sea level rise by ~500-750 m per 0.1 m sea level rise. Migration will occur until for ~10 to 20 years, until they reach either the salt pond embankments or the crest of a low-relief sediment ridge on the western side of the salt flats. Construction of the salt ponds truncates the area of potential habitat expansion west of the sediment ridge by an estimated ~ 450 to 560 ha.	Construction in ~2023 Operation in ~2026
2050 - 2075	0.2 - 0.45 m	Increased stress will be placed on existing algal mats as sea levels continue to accelerate upward (from 2055 to 2070).	Increased stress will be placed on existing algal mats as sea levels continue to accelerate upward (from 2055 to 2070).	Operation until ~2075
2075 - 2100	0.45 - 0.75 m	Once sea level rise exceeds 0.45 m (by ~2075) inundation of the entire area west of the sediment ridge will occur more frequently than the present-day lower limit for algal mats, indicating sustained algal mat loss with further sea level rise.	Once sea level rise exceeds 0.45 m (by ~2075) inundation of the entire area west of the sediment ridge will occur more frequently than the present-day lower limit for algal mats, indicating sustained algal mat loss with further sea level rise.	Closure from ~2075
2100 - 2121	0.75 - 1.0 m	Algal mat loss expected with limited capacity for establishment or recovery.	Algal mat loss expected with limited capacity for establishment or recovery.	

Samphire				
Years	Sea Level Rise	Without Project	With Project	Project Stage
2021 - 2050	0.05 - 0.2 m	Samphire along the supratidal/intertidal fringe at the base of supratidal slopes will have increasing inundation, approximately doubling in frequency for every 0.1 m sea level rise. This samphire occupies berms, which are expected to narrow by 50% with 0.2 m sea level rise (~2050). Samphire in supratidal basins and channels will receive an approximate doubling of marine inundation occurrence per 0.1 m sea level rise, leading to ongoing salinisation. Although samphire response is uncertain, it is expected to be small from 2021 to 2050.	Samphire along the supratidal/intertidal fringe at the base of supratidal slopes inside the salt ponds will be isolated from marine processes and respond to pond management. Samphire along the upper intertidal base of slopes outside the salt ponds will still receive an approximate doubling of tidal inundation occurrence for every 0.1 m sea level rise. These samphire fringes are expected to narrow and reduce by 50% with 0.2 m sea level rise by 2050. Samphire in supratidal basins and channels will receive approximately 0.1 m higher peak tide level due to the Project as well as an approximate doubling of marine inundation occurrence for every 0.1 m sea level rise. This will accelerate the process of salinisation compared to projected behaviour without the project.	Construction in ~2023 Operation in ~2026
2050 - 2075	0.2 - 0.45 m	Samphire along the supratidal/intertidal fringe at the base of supratidal slopes will decline or be lost from 2050 to 2070, depending on their elevation, due to landform mobility with increasing marine inundation. Samphire in supratidal basins and channels to the north-east of the Project site will receive an approximate doubling of tidal inundation occurrence for every 0.1 m sea level rise, leading to accelerating salinisation.	Samphire along the supratidal/intertidal fringe at the base of supratidal slopes outside the salt ponds will still decline or be lost from 2050 to 2070 depending on their elevation. Samphire in supratidal basins and channels to the north-east of the Project site will experience regular tidal flows, causing development of a tidal channel network and decline of samphire habitat due to bed mobility and increasing salinity.	Operation until ~2075
2075 - 2100	0.45 - 0.75 m	Samphire in supratidal basins and channels to the north-east of the Project site will experience regular tidal flows, causing development of a tidal channel network and decline of samphire habitat due to bed mobility and increasing salinity.	Samphire in supratidal basins and channels to the north-east of the Project site will continue to decline, with tidal network expansion.	Closure from ~2075
2100 - 2121	0.75 - 1.0 m	Samphire in supratidal basins and channels to the north-east of the Project site will continue to decline, with tidal network expansion.	Samphire in supratidal basins and channels to the north-east of the Project site will continue to decline, with tidal network expansion.	

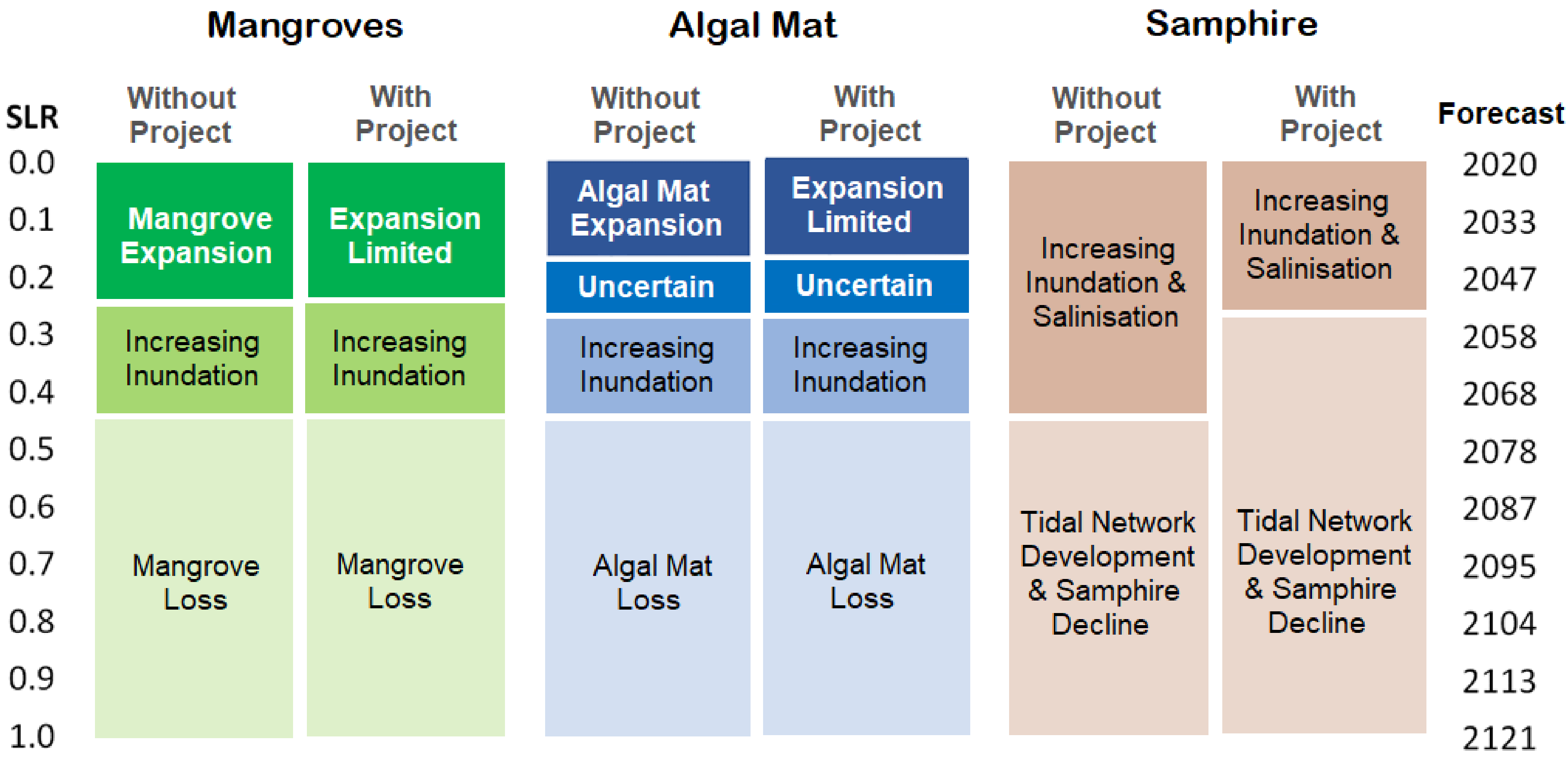

Figure 8-1: Mangrove, Algal Mat and Samphire Response to Sea Level Rise with or without Project

9. Assessment Key Assumptions, Limitations and Uncertainties

Projecting coastal response to sea level rise is not straightforward, as much of the understanding of coastal systems is based on observations from the 20th Century, or inference from recent millennia, which has involved a period of relative sea level stability. This limits available local evidence of processes active under rising sea levels, instead using of a global continuum of situations to guide a trajectory for the system's response, specifically through literature describing tidal network dependence on tidal prism.

It is acknowledged that understanding how other systems behave is not necessarily a direct indication of how intertidal habitats of the Tubridgi coast will respond. Local features can be capable of having significant influence, but their importance not presently being apparent under nearly stable conditions (e.g. micro-habitat development of the soil profile by mangroves will not create a constraint until the habitat zone migrates).

A key assumption of the approach used for this assessment has been interpretation of the existing mangrove habitat configuration as indicating control by porewater salinity, following Semeniuk (1996). This indicated significant influence of the tidal creek network, and consequently drove a further key study assumption that morphodynamic response is a key factor in intertidal habitat response to sea level rise. Projection of morphodynamic response has assumed that response is local (i.e. within the network itself) as there is limited evidence of substantial sediment influx from either marine or terrestrial sources.

Evaluation of tidal networks change is based on global literature, demonstrating scaling of tidal channels with tidal exchange volumes. However, it is acknowledged that this pattern is based on comparison between systems of different size, with substantially less information available showing response of a single system to changing tidal exchange. Projection of behaviour for the present assessment has used an assumption of direct response (i.e. any increased tidal exchange causes network expansion). However, observations of real systems demonstrate that change is more typically stepwise, with levee development and breaching providing important variation to direct response (Winn *et al*. 2006; Gong *et al*. 2018). Evidence of limited response to sea level variability over the late 20th Century suggests that the network response is at least partly buffered.

The assessment approach was developed within the framework of available data and information, using surface LIDAR, aerial imagery and intertidal habitat mapping. This information has limitations affecting method selection, which then convey limitations to the assessment (Table 9-1):

Table 9-1: Limitations of Information and their Implications

Limitation of Information	Constraint to Analysis Method	Implications for Evaluation
One topographic surface (DTM)	Limited ability to correct for survey biases. No ability to distinguish areas of change.	Used bulk hypsometry (i.e. did not incorporate possible influence of levees).
No channel bathymetry	Unable to derive channel cross-sections (i.e. network 3D structure).	Analysis based on areas only, reduces comparison with literature.
High resolution imagery covers 2004-2018	Limited ability to identify change, which is usually only after extreme weather events.	Extrapolated behaviour based on tidal exchange conceptual model.
Aerial imagery is discrete (years apart)	Unable to distinguish short or long-term responses, including disturbance-recovery cycles or seasonal patterns.	Applied 'continuous response' model for changing tidal exchange, rather than threshold-based model.
Mangrove mapping based on broad areas	Does not capture mangrove density variation, or connection to sub-scale features (e.g. basins).	Evaluation of future trends is biased with density – growth in low density areas likely to be exaggerated.

The approach to examine tidal creek morphometry, as a tool to examine how creeks in the Tubridgi region may scale with changing tidal exchange has some limitations, because:

- The key networks of interest are Urala Creek North and Urala Creek South, which are the largest systems, with the most significant barrier to the ocean. Consequently, morphometric analysis is effectively extrapolation, rather than interpolation, and consequently has less confidence.
- Structure of individual channel systems can be the consequence of multiple factors, rather than just tidal exchange. This is potentially important for Urala Creek North, which has potential for fluvial input – although there is limited evidence of high sediment input, it is possible that channel structure is partly due to incision during extreme flood events.

The conceptual model relating tidal exchange to tidal network scale was applied using a monotonic representation of hypsometry, which effectively assumes that the creek systems are completely responsive to change. As discussed in Section 7.1.3, a real system will tend to respond as a series of steps, generally associated with the connection or isolation of local basins relative to the tidal network. This behaviour, as well as disturbance-recovery of mangroves, is also strongly linked to critical threshold exceeding events (e.g. storms or floods), which are episodic in character.

Inference that tidal creek expansion can produce corresponding mangrove habitat expansion is predicated on the importance of porewater salinity as a control, with the tidal creek providing the necessary circulation. This process has several elements of time dependence, including propagation and establishment of mangroves, which has been identified as 5-8 years in more tropical conditions (Alongi 2008). Other ecological requirements for mangroves, such as establishment of suitable pH and nutrient balances may take longer to establish.

Thresholds of mangrove instability relating to accelerating sea level rise are important for the interpretation of longer-term dynamics. These figures are developed from analysis across the wider area of Australia and include interpretation of prehistoric patterns of change. Local responses may be different, particularly if there is moderate level of sediment supply to help mangrove beds keep pace with sea level rise. Absence of significant sediment supply to this area was considered when using these thresholds for interpretation.

Overall, while this assessment interpreted possible responses of habitats to sea level rise with or without the Project based on best available understanding of coastal dynamics, predictions for lower levels of sea level rise (next 25 – 50 years) exclude the effects of natural levees and the establishment time for mangroves. Consequently, projected behaviour should be considered indicative, and likely to overstate the potential for change.

As sea levels increase more rapidly over the longer term (50 to 100 years), simulated processes of tidal network change described within this report are likely to become increasingly dominant, causing migration of mangrove and algal mat habitats. These changes are ultimately constrained by biophysical limitations, including the inability of mangroves to cope with accelerated sea level rise and limited area available for algal mat expansion with suitable hydroperiod.

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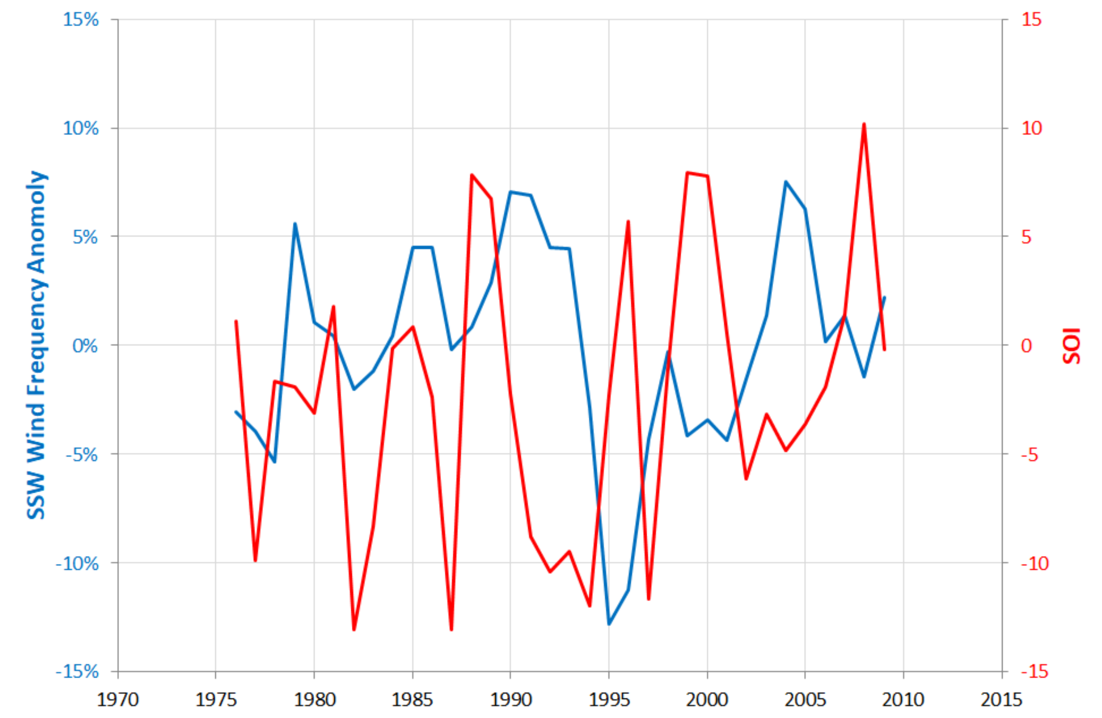
Appendix A Meteorological and Oceanographic Conditions

Regional Meteorological Observation Sites

	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Jan	2.8%	4.9%	2.8%	2.1%	2.7%	1.0%	1.7%	2.9%	8.4%	30.5%	22.0%	9.2%	5.8%	1.2%	0.9%	0.9%
Feb	3.7%	5.9%	3.8%	3.2%	4.2%	2.2%	2.3%	2.7%	8.5%	24.9%	18.9%	9.8%	6.6%	1.5%	0.9%	1.1%
Mar	4.3%	5.3%	3.7%	3.7%	5.1%	2.4%	3.4%	3.8%	10.1%	27.8%	16.3%	6.6%	4.5%	1.3%	0.8%	1.0%
Apr	4.8%	5.0%	4.2%	4.0%	5.9%	3.0%	4.0%	6.2%	10.6%	25.7%	15.0%	4.8%	4.0%	1.0%	0.7%	1.2%
May	6.2%	5.9%	5.3%	4.6%	6.7%	3.3%	5.6%	6.3%	11.5%	18.3%	15.5%	5.1%	2.1%	1.1%	1.0%	1.5%
Jun	5.7%	6.7%	6.8%	4.7%	6.4%	3.8%	4.8%	6.7%	11.1%	15.2%	15.9%	6.3%	2.5%	0.8%	1.1%	1.7%
Jul	6.1%	6.0%	5.2%	4.5%	4.9%	3.6%	5.8%	7.4%	12.5%	15.9%	15.7%	6.1%	2.3%	0.9%	1.0%	2.0%
Aug	5.6%	5.1%	3.5%	3.0%	4.6%	2.4%	5.2%	7.8%	13.1%	20.9%	17.8%	5.5%	2.7%	0.9%	0.9%	1.0%
Sep	3.2%	3.1%	2.4%	2.7%	3.4%	1.5%	3.9%	7.1%	11.7%	31.7%	17.9%	6.1%	3.1%	1.0%	0.7%	0.6%
Oct	2.0%	2.6%	1.7%	1.8%	2.2%	1.2%	2.7%	5.7%	11.3%	37.2%	18.5%	7.0%	4.3%	0.9%	0.5%	0.3%
Nov	1.8%	2.5%	1.7%	1.6%	2.2%	0.9%	1.7%	4.0%	10.5%	36.3%	21.6%	8.1%	5.1%	1.0%	0.6%	0.4%
Dec	1.8%	2.9%	1.7%	1.9%	2.2%	0.8%	2.0%	3.0%	9.1%	35.7%	22.8%	9.1%	5.3%	0.9%	0.3%	0.3%

Learmonth Monthly Wind Distribution

South-southwest winds prevalent all year, northeast winds occur February to July.

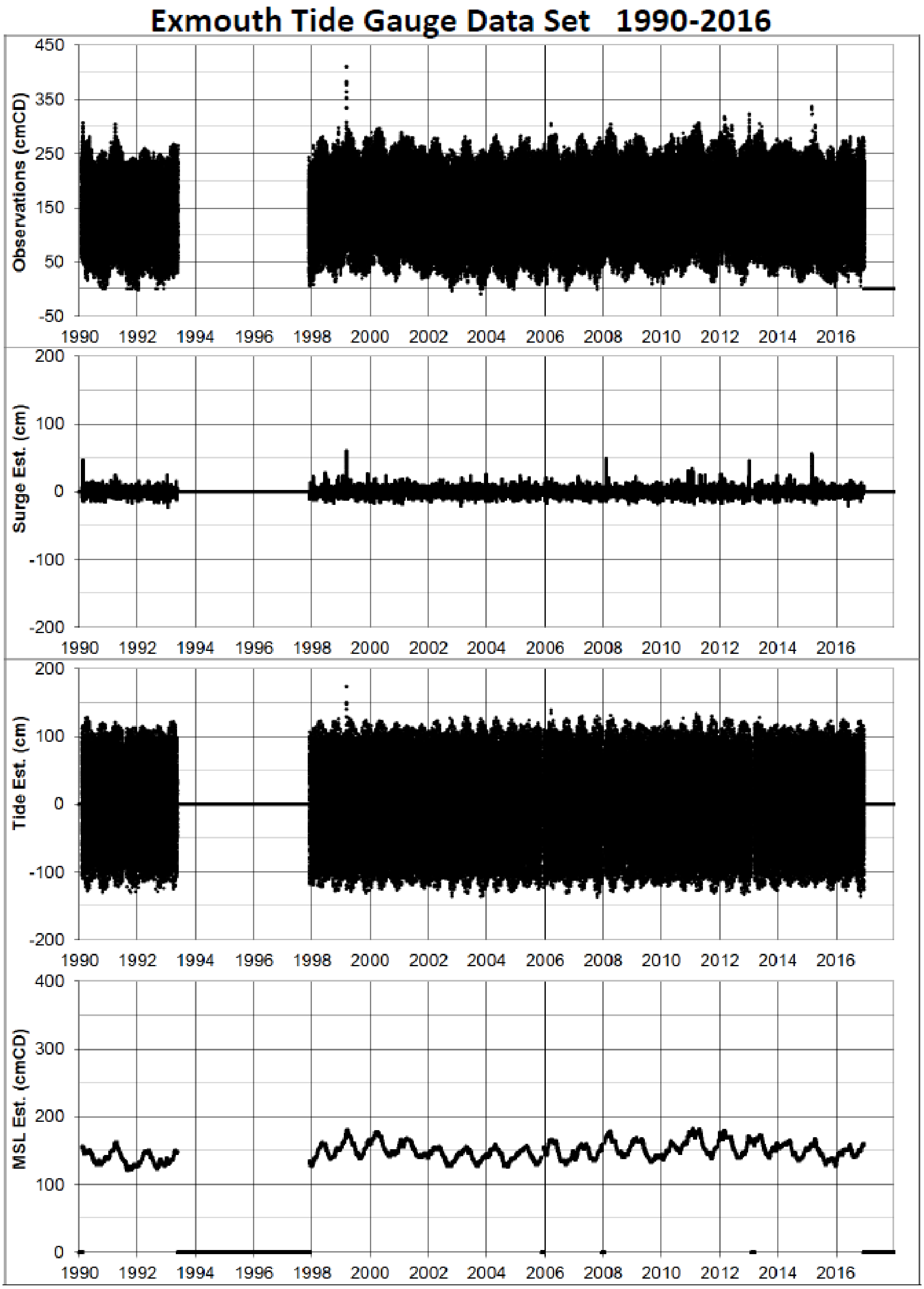


Learmonth SSW Wind Anomaly and SOI

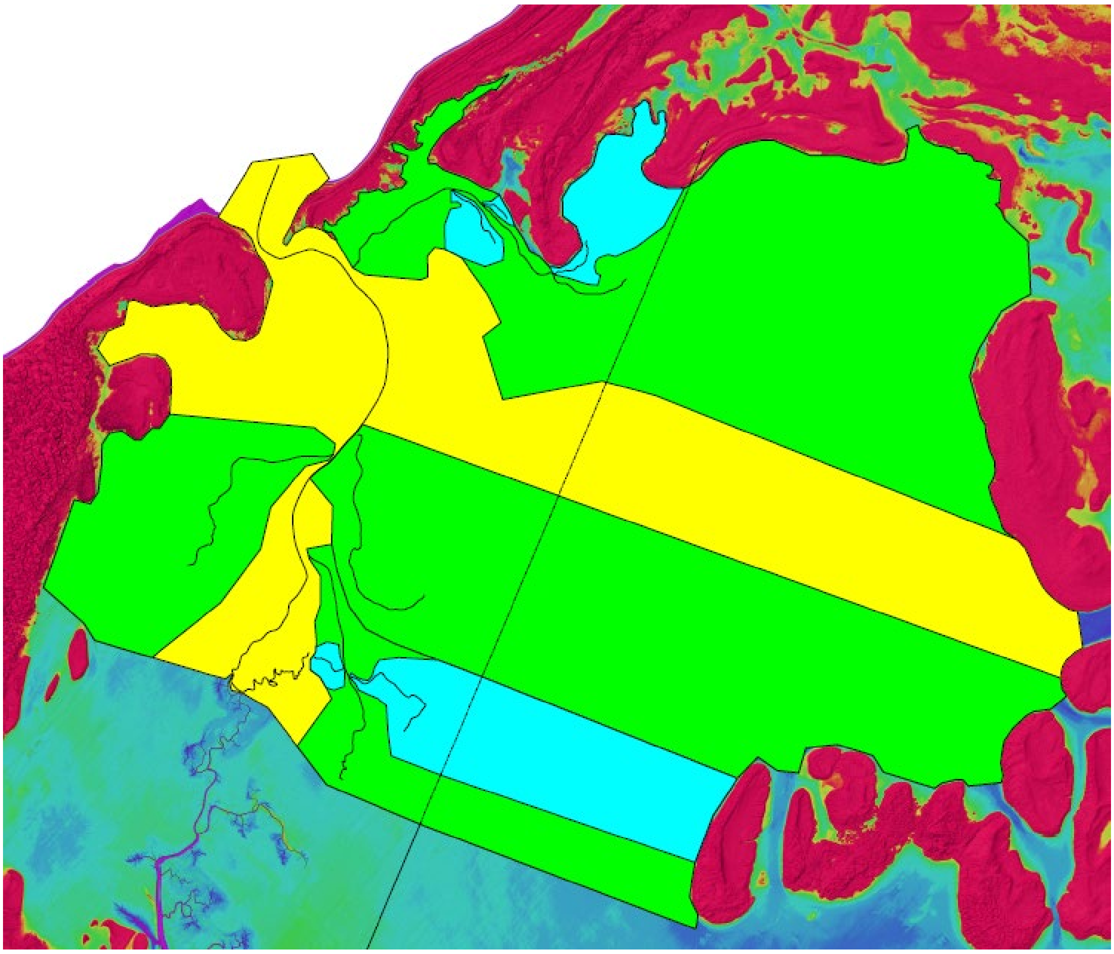
		Exmouth	Beadon Creek
	Source	Transport 2004	Transport 2010
Highest Astronomical Tide	HAT	2.87mCD	3.07mCD
Mean High Water Spring	MHWS	2.35mCD	2.48mCD
Mean High Water Neap	MHWN	1.76mCD	1.84mCD
Mean Sea Level	MSL	1.44mCD	1.56mCD
Australian Height Datum	AHD	1.40mCD	1.49mCD
Mean Low Water Neap	MLWN	1.16mCD	1.29mCD
Mean Low Water Spring	MLWS	0.55mCD	0.65mCD
Lowest Astronomical Tide	LAT	0.03mCD	0.09mCD

		Hope Point	Ashburton Salt
	Source	Worley Parsons 2006	Auscoast VDT 2017
Highest Astronomical Tide	HAT	3.2mLAT	2.45mCD
Mean High Water Spring	MHWS	2.7mLAT	2.05mCD
Mean High Water Neap	MHWN	2.0mLAT	1.46mCD
Mean Sea Level	MSL	1.6mLAT	1.18mCD
Australian Height Datum	AHD	1.5mLAT	1.18mCD
Mean Low Water Neap	MLWN	1.2mLAT	0.92mCD
Mean Low Water Spring	MLWS	0.4mLAT	0.33mCD
Lowest Astronomical Tide	LAT	0.0mLAT	0.00mCD

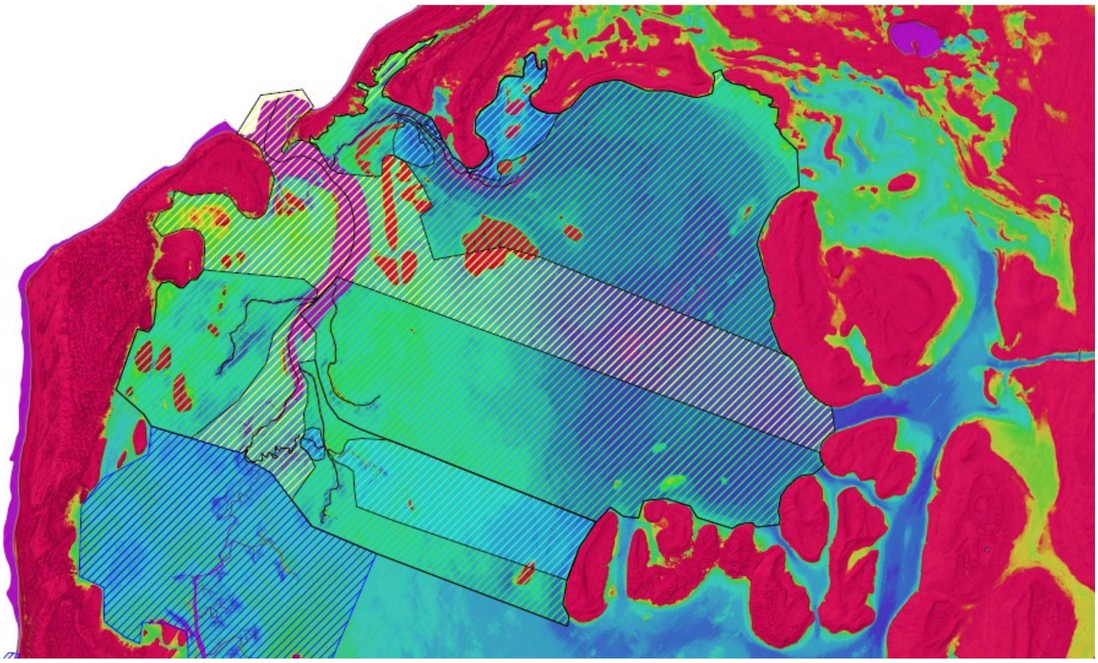
Estimated Tidal Planes


Exmouth Tide Gauge Data Set 1990-2016
Observations (cmCD)
Surge Est. (cm)
Tide Est. (cm)
MSL Est. (cmCD)
450
350
250
150
50
-50
200
100
0
-100
-200
400
300
1990 1992 1994 1996 1998 2000 2002 2004 2006 2008 2010 2012 2014 2016

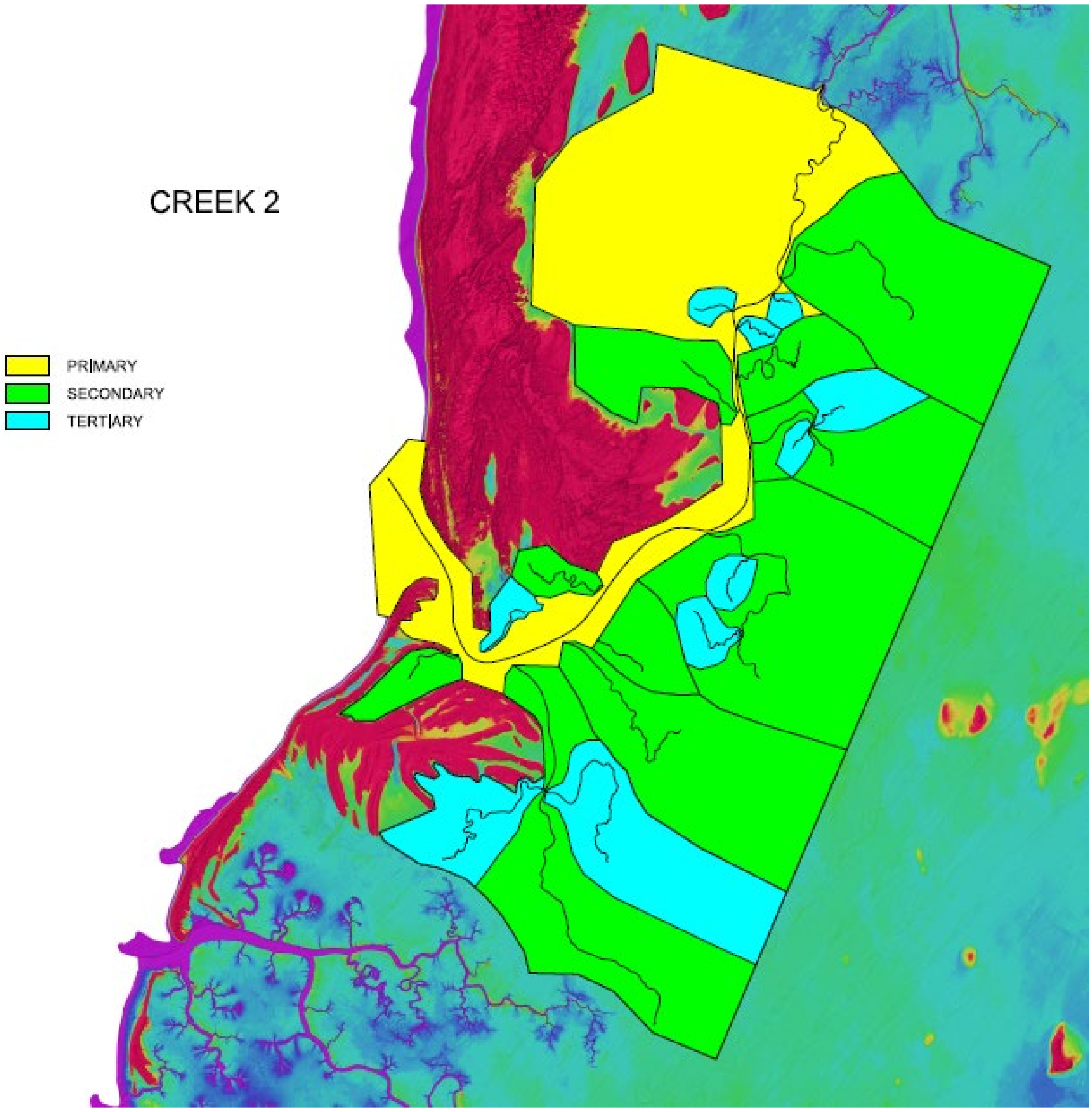
Appendix B Tidal Creek Contributing Areas



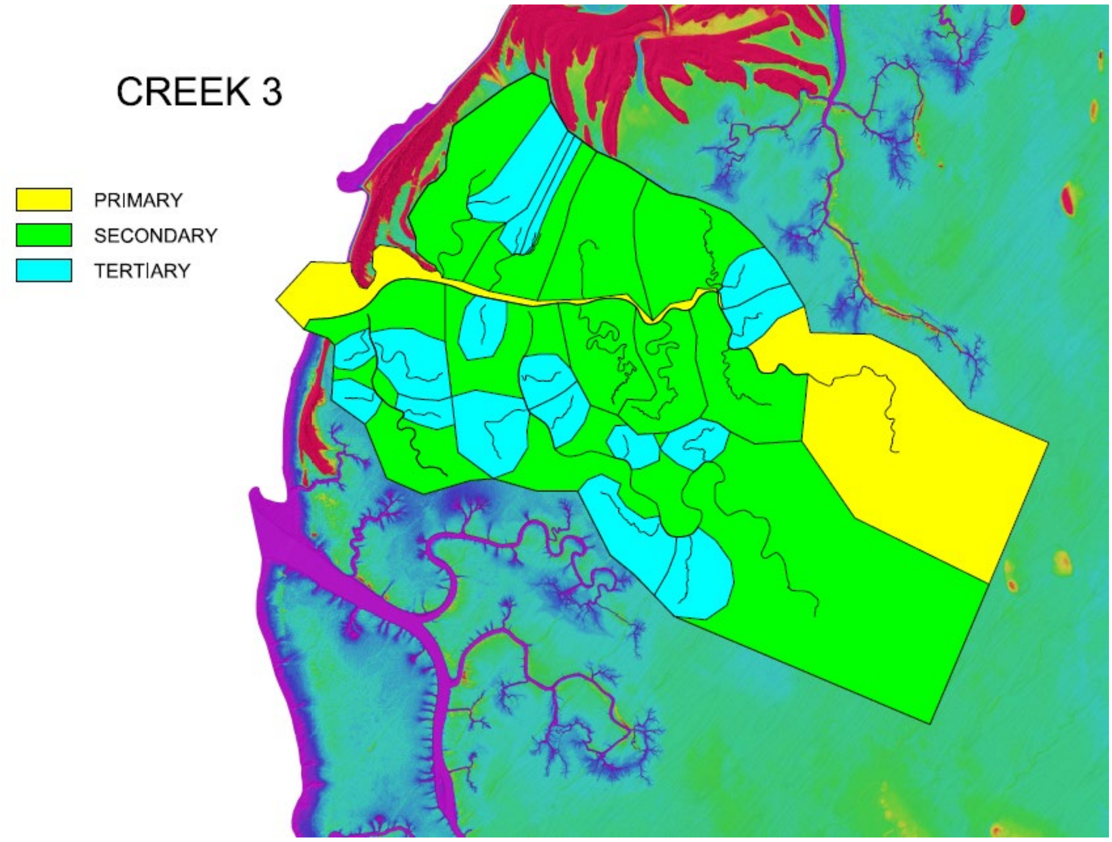
Sub-areas for Creek 1_0_0 (Urala Creek North)



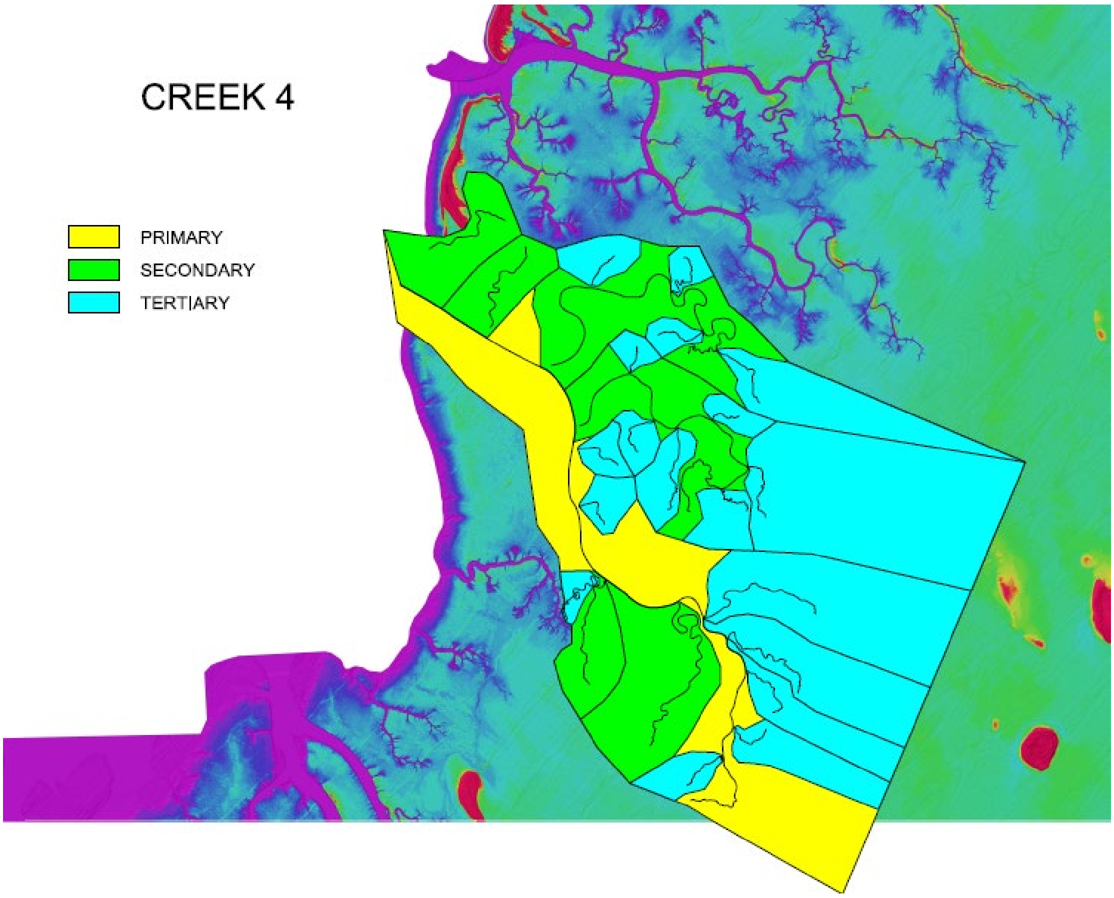
Hatched sub-areas, showing secondary eastern basin



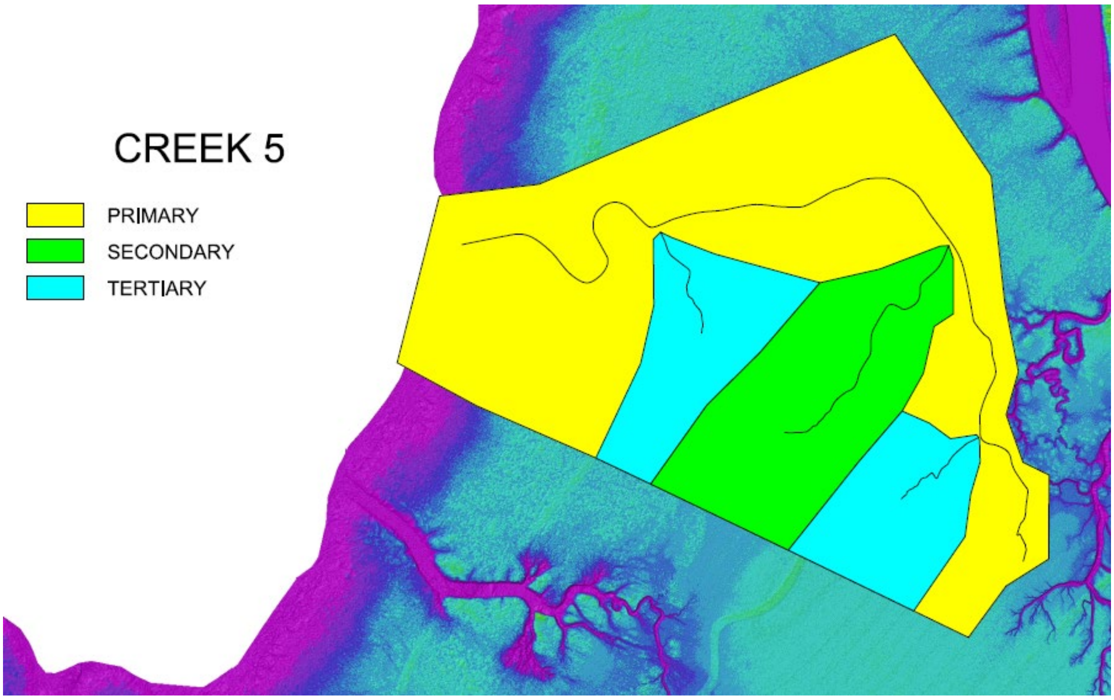
Sub-areas for Creek 2_0_0 (Urala Creek South)



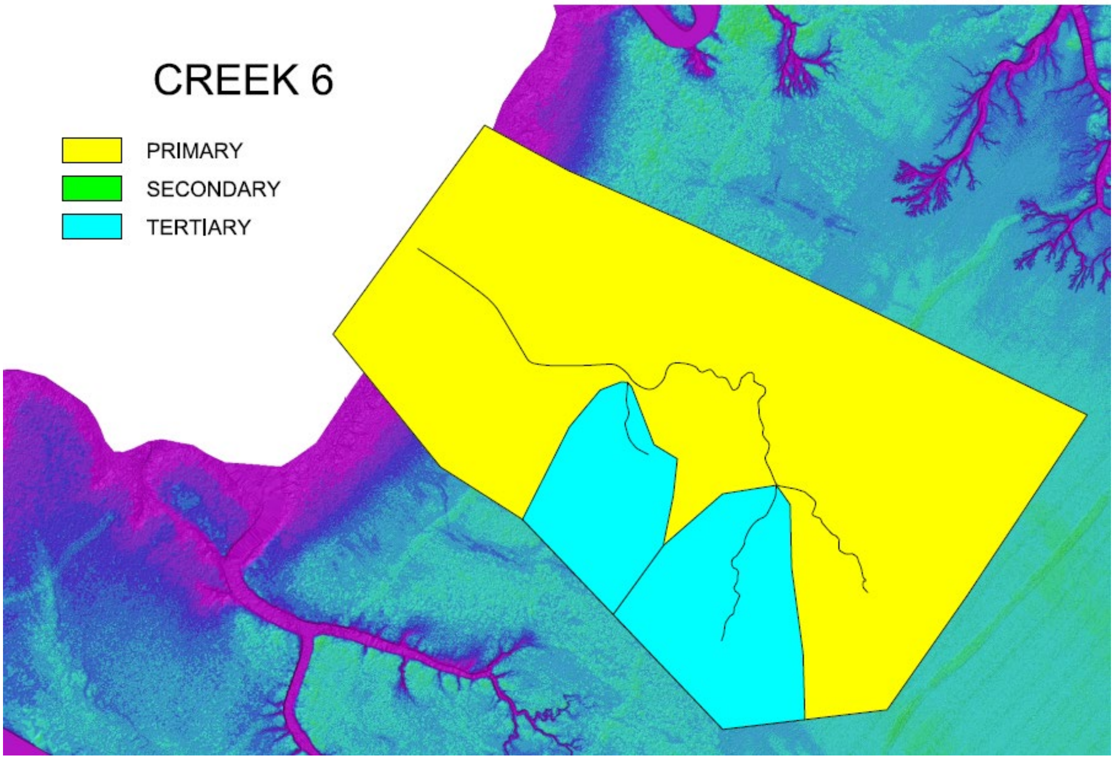
Sub-areas for Creek 3_0_0 ('Creek 2')



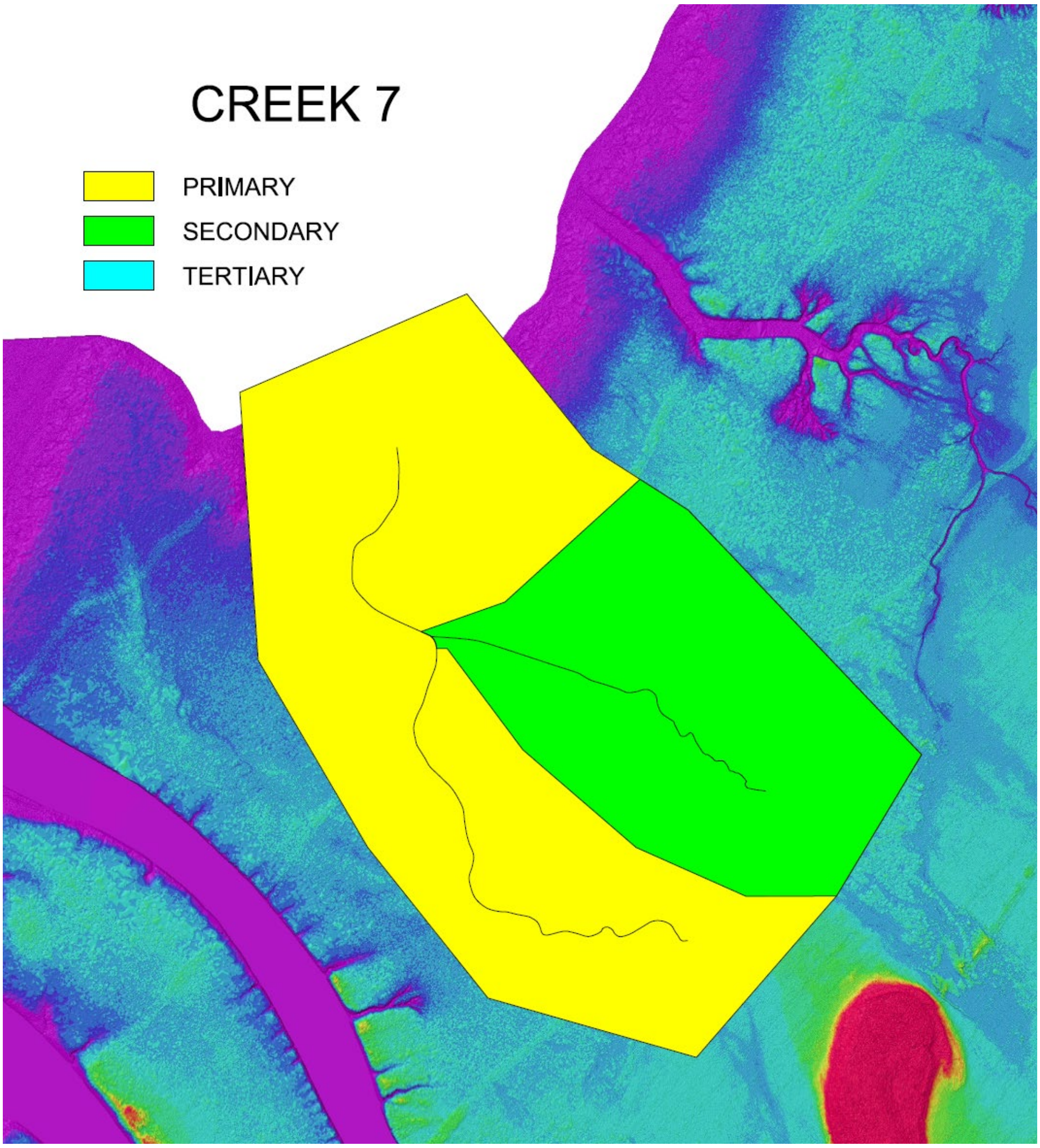
Sub-areas for Creek 4_0_0



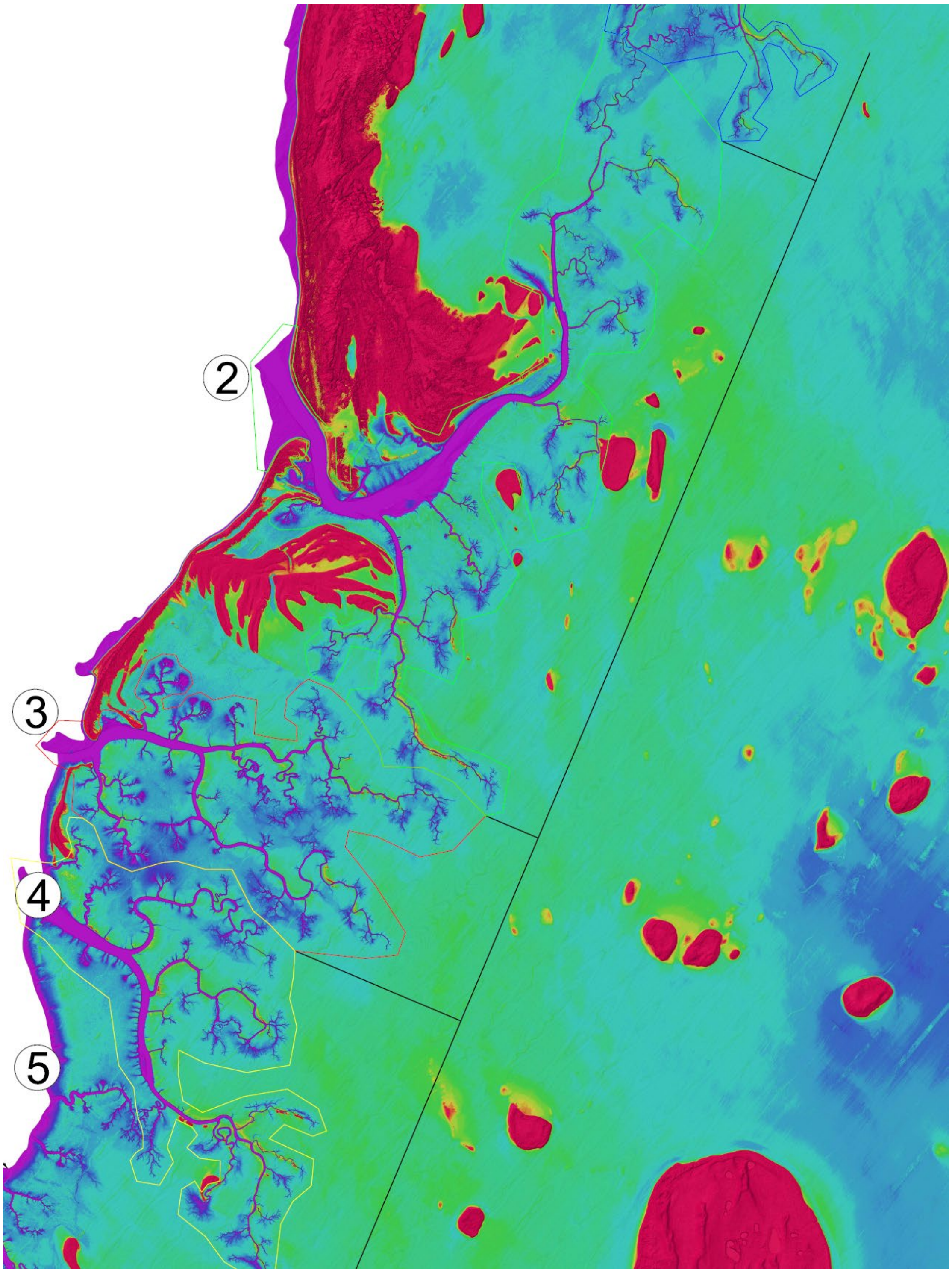
Sub-areas for Creek 5_0_0

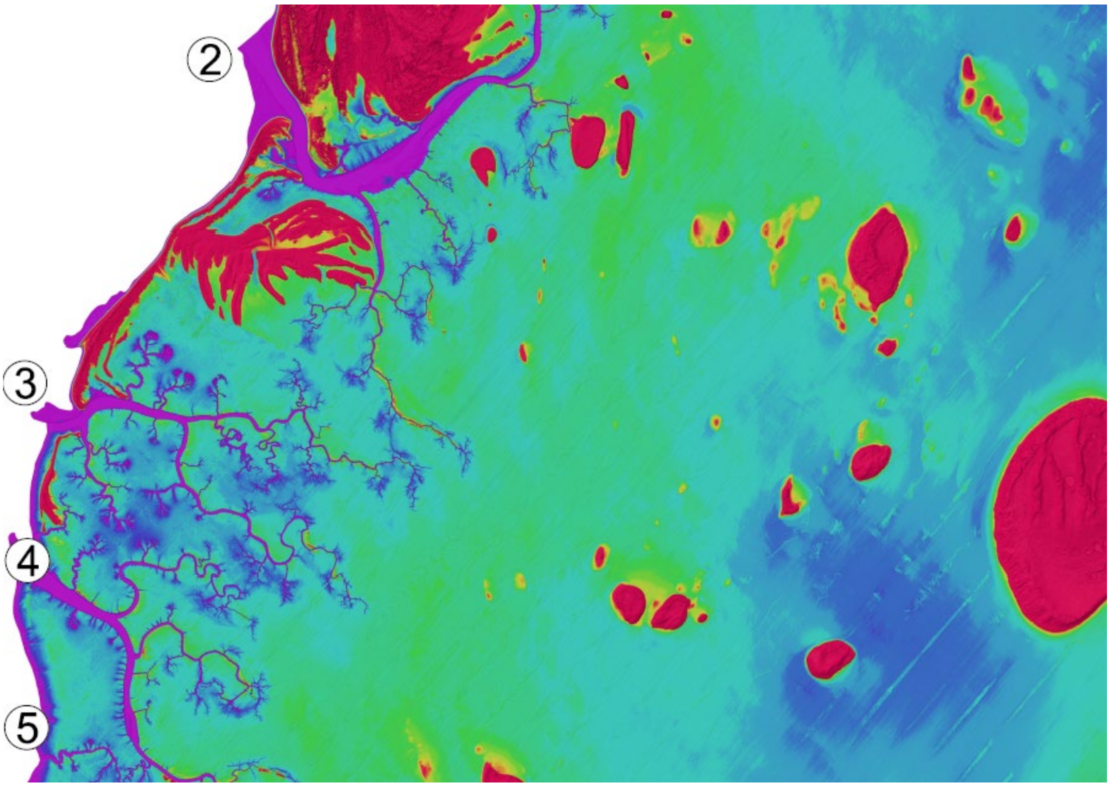


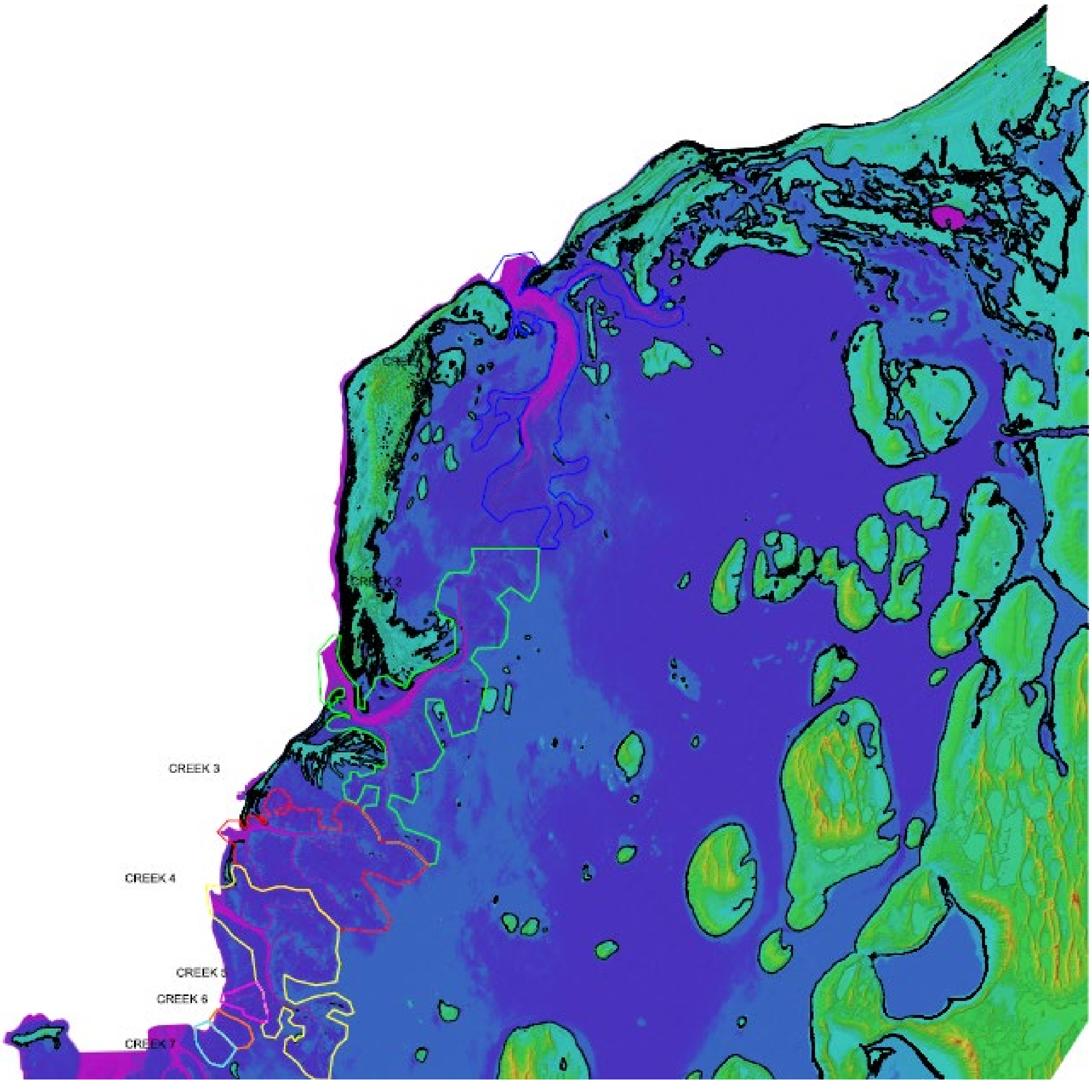
Sub-areas for Creek 6_0_0



Sub-areas for Creek 7_0_0


2
3
4
5


2
3
4
5


CREEK 3
CREEK 4
CREEK 6