Piers Larcombe Consulting
Coastal and Marine Geoscience

Seashore Engineering

Effects of future sea-level rise and solar salt ponds on the coastline, Eramurra Solar Salt Project, with implications for benthic habitats.

Eramurra Solar Salt Project

for

Leichhardt Salt Pty Ltd

Report No. PL2024-002, Version 3.1

Piers Larcombe Consulting
ABN 67049845765
piers.larcombe@gmail.com

Version and Quality Control

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Leichhardt Salt Document No. ESSP-EN-14-TRPT-0033

Table of Contents

Figures

Tables

Table 1. Abbreviations and terms

Abbreviation or term	Full meaning
AEP	Annual Exceedance Probability
AHD	Australian Height Datum
BCH	Benthic Communities and Habitats
Chl-a	Chlorophyll a
CPT	Cone Penetrometer Testing
DWER	Department of Water and Environmental Regulation
Deflated dunes	Sand dunes eroded by wind, down to the level where they are wet due to groundwater
EPA	Environmental Protection Agency
ERD	Environmental Review Document
ESSP	Eramurra Solar Salt Project
GBR	Great Barrier Reef
HAT	Highest Astronomical Tide
Hydroperiod	The frequency of inundation by tides
MSL	Mean sea level
NWS	North West Shelf
PSD	Particle size distribution
Qtz	Quartz
RFFE	Regional Flood Frequency Estimation
RSL	Relative sea level (relative to the land)
SLR	Sea-level rise
TC	Tropical Cyclone
Vs:Vc ratio	Ratio of volumes of water in a tidal creek system at different tidal elevations. Vs is the Storage Volume is, which for the ESSP area the volume at 2.5 m AHD, Vc is the Creek Volume, here the volume at 1.7 m AHD.

1. Introduction and Scope of Work

1.1. Introduction

This report responds in part to the "Scope of Works – Request for Proposal" sent by Regina Flugge, Leichhardt Document ESSP-EN-14-SOW-0030, with issue date 06/10/2023. Subsequent discussions led to a proposal from MetOcean Consulting to Leichhardt Salt (hereafter LS).

Below is the present understanding of the timeline:

- LS submitted draft documents to the EPA late last year.
- LS expect feedback from EPA early 2024, which feedback will be incorporated into …
- … the new work that LS know they will require on sea-level rise (SLR) and benthic community habitats (BCHs), with work to be completed by early April
- … so that Preston Consulting can put the Environmental Review Document (ERD) together. The EPA will then judge whether the ERD is fit to go out for public comment.
- ~Q4 of 2024 – ERD out for public comment.
- Later, required amendments are made and the information is resubmitted to the EPA for formal assessment in Q4 2025.

Below we refer to O2 Metocean 2022a (in the references)

> *"Coastal processes study to support BCH assessment" STATUS: Rev 2, REPORT NUMBER: 20MET-0016-13 / R210391, ISSUE DATE: 18 November 2022, Leichhardt Report No.: ESSP-EN-14-TRPT-0003*

as the "*CP-BCH Report*".

This report also draws on work undertaken by Piers Larcombe (Larcombe, 2024) to check the interpretations and conclusions made by the CP-BCH Report. This check was required because the CP-BCH Report used hypsometric data (catchment shapes and their volumes at different tidal elevations) that turned out to be incorrect, and the pond shapes have since changed.

This report was co-written by Piers Larcombe (of Piers Larcombe Consulting) and Matt Eliot (of Seashore Engineering), and Steve Buchan (MetOcean Consulting) contributed to some aspects of meteorology and oceanography. The contract was held by MetOcean Consulting.

This document should be referred to as:

Larcombe, P., Eliot, M. & Buchan, S (2024) Effects of future sea-level rise and solar salt ponds on the coastline, Eramurra Solar Salt Project, with implications for benthic habitats. Report to Leichhardt Salt Pty Ltd. Piers Larcombe Consulting, Report No. PL2024-002, Version 3.1, 19th July 2024.

1.2. Purpose

This report is designed to assess the impacts of sea-level rise on intertidal habitats and the potential response of mangroves, algal mats (hereafter referred to as benthic mats[1]) and samphire in the context of the Eramurra Solar Salt Project (ESSP). The general approach is to review existing reports on:

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[1] 'Benthic' mats replaces 'algal' because many are dominantly bacterial and secondarily algal. Although it could be more correct here to call them intertidal mats.

- the effects of sea-level rise on tidal inundation, surface water, groundwater, and coastal processes.
- intertidal benthic communities and habitats (BCH), and BCH cumulative loss assessment.

The work then integrates information to develop projections of the future mangrove, samphire and benthic mat habitats in response to future sea-level rise, with and without the ESSP in place.

1.3. Data supplied

LS supplied a range of reports, noted where appropriate in the references. LS also supplied GIS files of:

- Elevation contours between -19 m and +7 m AHD (in 0.5 m intervals between -1 m and + 5 m AHD, and in 1 m intervals otherwise; Figure 1, Figure 2) derived from a LIDAR survey.
- Distribution maps of mangroves, samphire and algal mats (hereafter referred to as benthic mats)
- The pond scenarios 6.2.0 and 7.2.1. (Figure 3, Figure 4)
- Creek catchment boundaries (watersheds) for a series of defined tidal creeks (Figure 5)
- Volumetric data (hypsometry) between -1 m and +5 m AHD (in 0.5 m intervals) for the individual tidal creek catchments for pond scenarios 6.2.0. and 7.2.1.
- and a variety of associated GIS information.

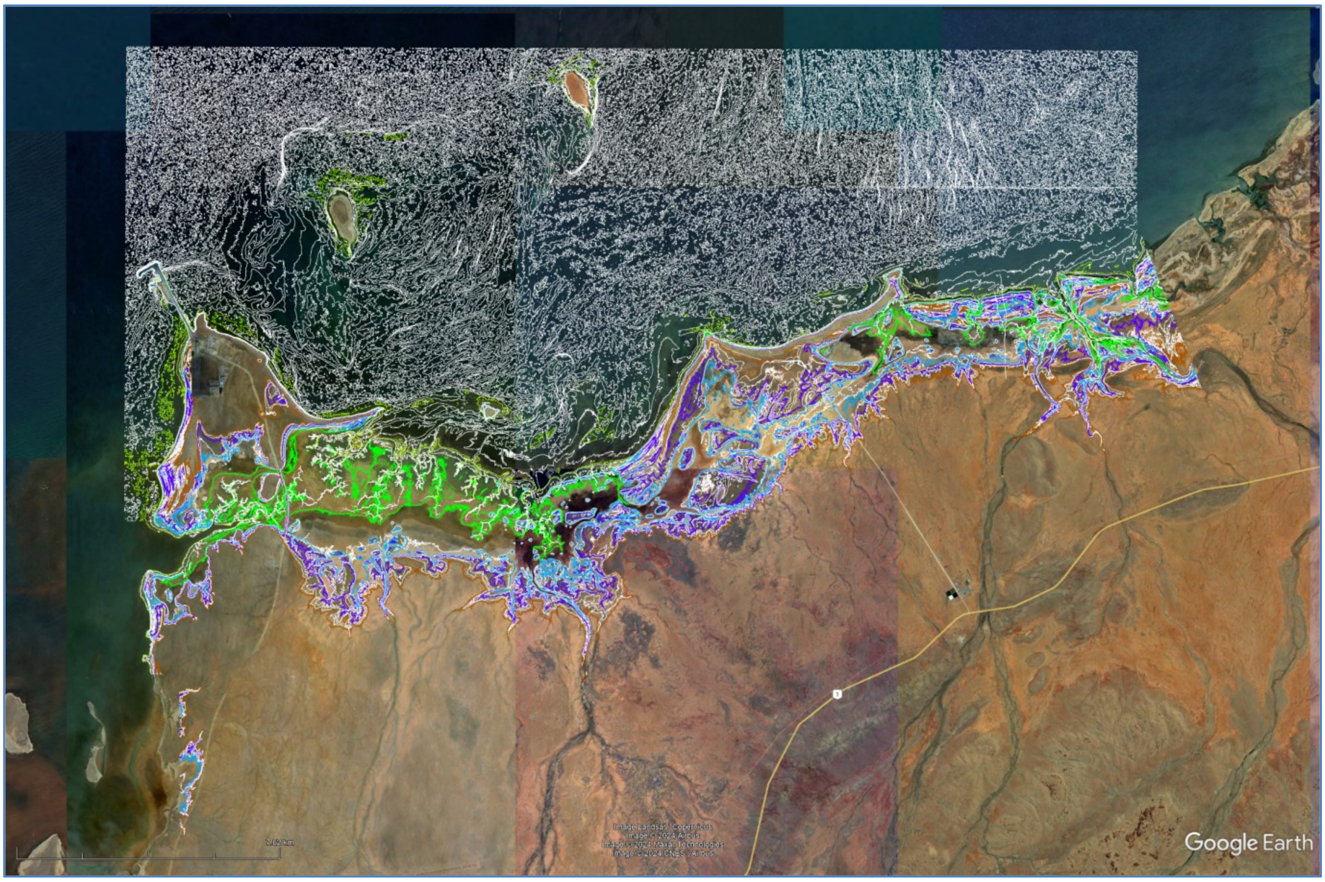

Figure 1. Aerial image of the ESSP pond area and associated areas, with elevation contours (AHD) between -19 m AHD and + 7 m AHD.

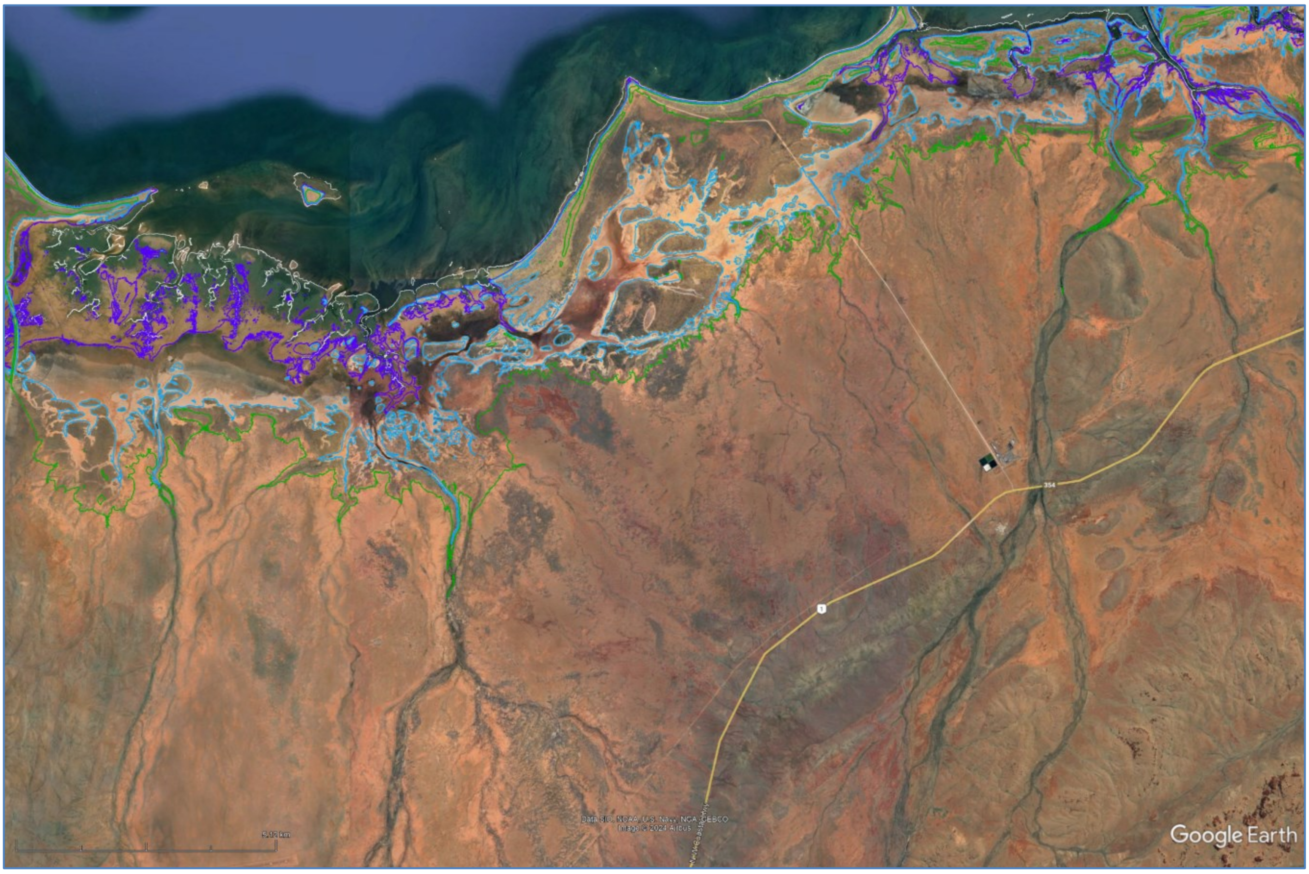

Figure 2. Aerial image of the ESSP pond area with selected elevation contours (AHD) at 0 m (white), +1.5 m (purple, approximating the top of the creek banks), +2.5 m (blue, mean high tide), and +5 m (green).

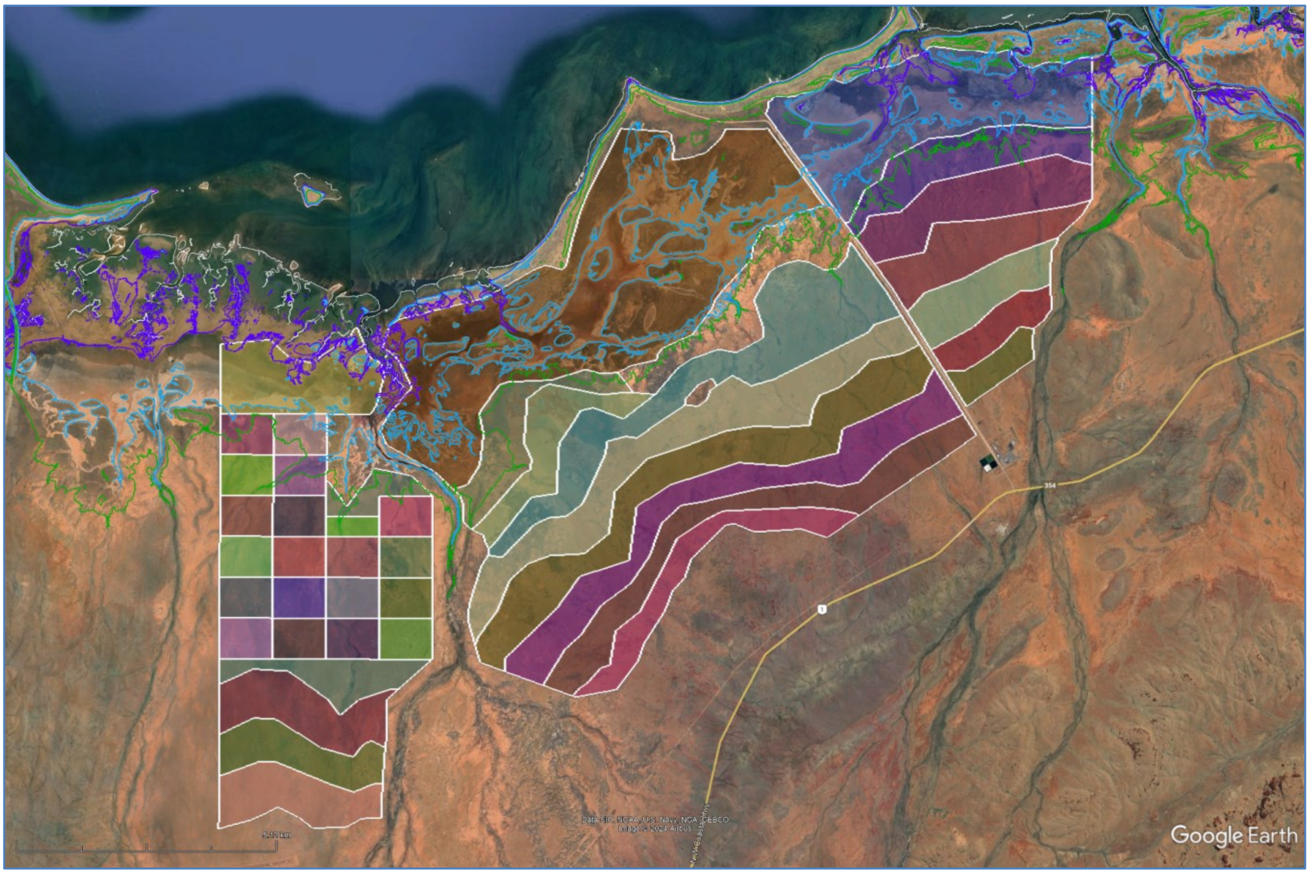

Figure 3. As Figure 2 plus the salt ponds of scenario 6.2.0. (Colours of ponds not significant). Superseded - not used in this report.

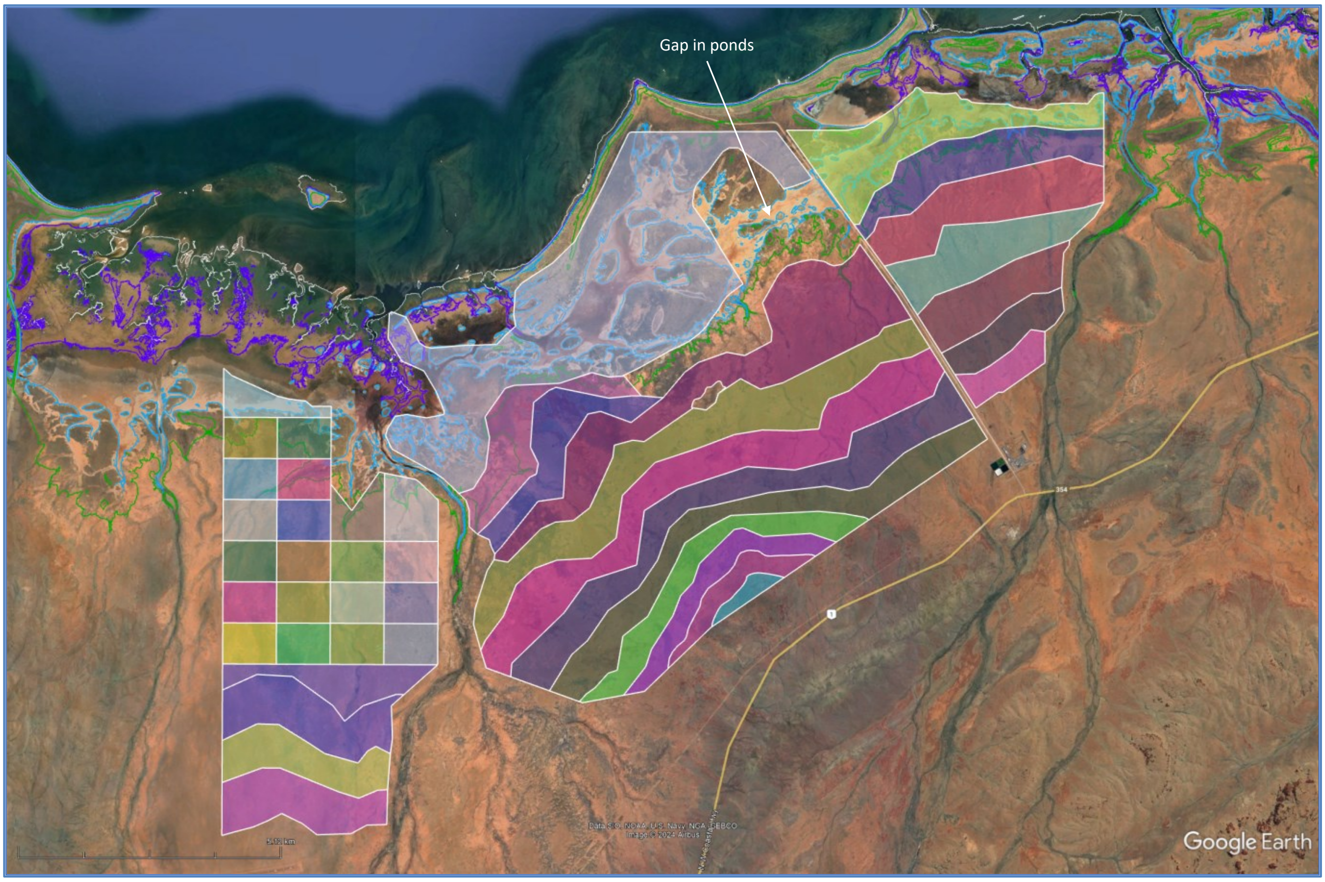

Figure 4. As Figure 2 plus the salt ponds of scenario 7.2.1. (Colours of ponds not significant).

Figure 5. Relevant creek catchments (watersheds) landward to just beyond the 5 m AHD contour.

2. Rationale and report structure

2.1. Rationale

This report is required to assess sea-level change and its effects on natural coastal physical change, then consider the specific aspects the ESSP area and possible complicating factors from the proposed development. As background, it is helpful to consider the relative knowledge of various key aspects of the coastline's geomorphology and processes.

Below we outline the aspects using a description specifically of estuarine change (Figure 6), very closely related to the ESSP setting:

- Trajectory – We know about the general direction of overall change. This includes various considerations, that are expanded below using the headings in Figure 6:
    - Basin structure is largely 'created' by Sea Level rise (SLR), i.e. it has flooded a pre-existing suitable surface.
    - The basin tends to migrate along a streamline, i.e. most estuaries will tend to move towards or away from the fluvial input and the marine entrance.
    - The basin becomes infilled to some extent, between zero and full.
- Pathway – We have some idea that the direction of overall changes is not straight.
    - Three main controls on estuarine change, waves, tides and fluvial input (often drawn as a ternary diagram) influence sediment input and accumulation. NB - this does not deal with episodic behaviour and no rates are derivable.
    - Directions of change vary between estuarine types, and thus locations.
- Rate – We have no knowledge about the variable rate(s) of change (without age dating).
    - The overall rates of development of the key sediment bodies are usually partly known (e.g., over several centuries).
    - Some process and/or controls are always present, and they modulate and/or filter the general longer-term morphological response. An example is a tidal creek. These creeks are always present and operate on timescales of say, several decades or so, within the overall trend.
    - A process or controlling feature more intermittent in nature and in its morphological effect is time variable, also within the overall trend. An example here is the sand spit anchored at Gnoorea Point, that will tend to cause changes over timescales of several decades or more.
- Response – We can make educated guesses about what the estuary's journey looks like, but only within a 'window' of rates, and noting the occurrence of unpredictable episodic changes. The morphological response incudes such aspects as:
    - What feature or set of features does the sediment form in the estuary?
    - What engineering intervention is appropriate?

The key message is that it is not possible to jump straight into the 'response', but we can build a lot of understanding towards it.

It is also important to understand that whilst mean sea level (MSL) is relevant, it's not the key or sole controlling factor upon the coastline. Other aspects of water level are more directly relevant to the actual processes that maintain the coastline and its associated BCHs. These include tidal range, various tidal periodicities, the influence of 'overbank tides' on tidal creek flows, and surges and tsunami. So, the work is about far more than just a future rise in MSL.

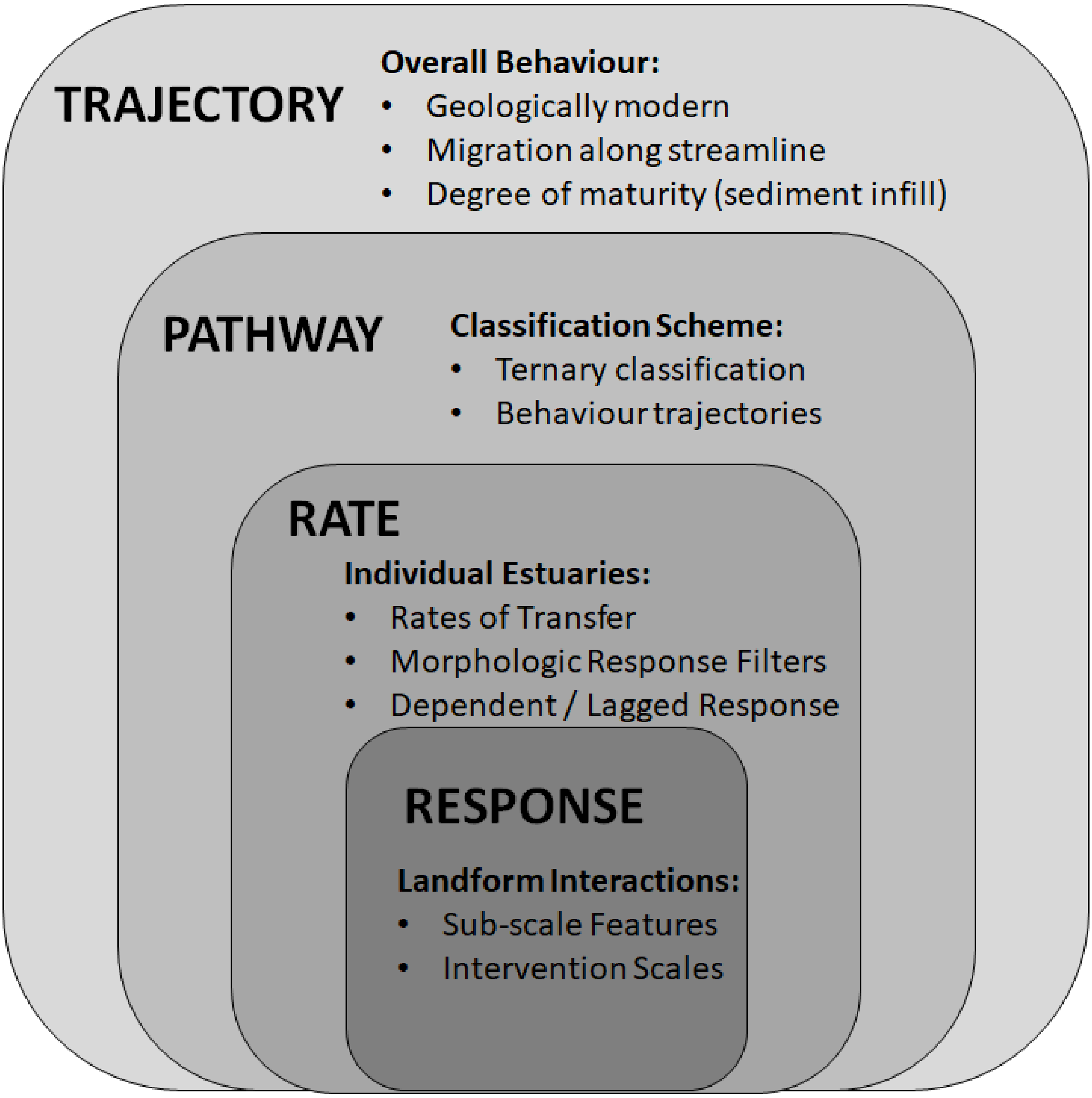

Figure 6. Conceptual differences in levels of understanding about different aspects of estuarine change. The smaller the squares, the less knowledge.

2.2. Report structure

This report reports on work conducted in a series of broadly sequential steps, which form the report's headings.

The report flow notes sea-level change, existing models of coastal physical response and controls on natural change, then considers the specific setting of the ESSP to develop key questions to be answered. The report then integrates available information to consider how several key parts of the ESSP might respond to SLR and arrives at conclusions on how the habitats of the ESSP area might vary with SLR, and how this might be altered by the emplacement of the ESSP ponds.

As a result, there are three main parts to the work, noted below:

- Review
    - Section 3 reviews the relevant aspects of sea-level changes.
    - Section 4 describes some key concepts regarding habitat viability, the various conceptual models for geomorphological changes associated with SLR, and for key hydrodynamic changes resulting from relative SLR.
    - Section 5 notes the variety of factors and processes that cause natural changes to coastal environments and explains the relevance to habitats.
- The ESSP
    - Section 6 describes the physical setting of the ESSP area, including the main hydrodynamic drivers of change, the main geomorphic units, their past changes, the evidence for past and present sediment dynamics.
    - Section 7 develops some sedimentary hypotheses and considers the potential age of the sediments involved in the coastal response to SLR and the effects of the proposed development.
    - Section 8 describes the planned development and notes the key features likely to generate physical and habitat changes.
- Analysis
    - Section 9 analyses the information available to answer Section 7's questions, in the light of predicted SLR over the next century and coupled with possible pond emplacement. It presents analysis of several factors that might affect coastal stability in the area with SLR, including detail on selected key areas and locations.
    - Section 10 describes the main uncertainties in the work, and the resulting caveats upon conclusions formed.
    - Section 11 presents the main conclusions, including a scale of confidence in each.

3. Sea-level changes

A key reason for this work is to assess natural changes with projected future SLR. To underpin this assessment, it is necessary to note the relevant past changes in relative sea level (rise and fall), because these changes have influenced the locations and nature of key sedimentary processes, deposits, environments and habitats. The key habitat-forming coastal environments are mangroves, samphire and benthic mats. A key question is what the inferred future changes are in these habitats caused by natural processes. A variety of relevant natural processes occur.

Here, we start with a key influence, sea-level change. Sea-level change is often taken to simply mean changes in MSL, but this is too simple. Whilst MSL is relevant, especially because it forms a long record of changes over the last few decades or more, it's not the key or sole controlling factor upon the coastline. Other aspects of sea level are more directly relevant to the actual processes that maintain the coastline and its associated BCHs. These include:

- **Tidal range.** The astronomical tide varies by up to 4.7 m or so (section 6.1.1.1), so that processes associated with inundation, currents and waves all vary every day in their location, elevation and nature;
- **Tidal periods**. There are multiple tidal periodicities involved. Together, these generate natural changes in the annual measure of MSL of ~0.3 m over several decades (section 3.1);
- **'Overbank tides'.** Those tides that flood the tidal flats above the tidal creek margins are far more powerful in creating sediment transport than others (section 6.1.1.1). Hence, a minor increase in MSL has the potential to induce a relatively great increase in potential sediment transport and geomorphic change;
- **Surges.** Surges are changes in expected sea level, mostly associated with strong winds, either blowing offshore to produce a negative surge (i.e., a lowered sea level), or onshore producing a positive surge (i.e., a raised sea level). Positive surges are most relevant here, and measurements from Dampier indicate that these have exceeded +1 m in magnitude around twice each decade, and have reached nearly +3 m in magnitude (section 6.2.4). These surges are generally associated with strong waves and may last several hours;
- **Tsunami.** Tsunami, although rare, do occur, and they have the capacity to raise water levels at the coast for periods of several tens of minutes or more. In doing so, they may create one or more unusually strong landward flows across areas that normally might not experience such flows, and also generate unusually strong seawards flows. They are thus another agent of potential coastal change.

SO, IN BRIEF, EVEN JUST FOR THE PHYSICAL ASPECTS, IT'S ABOUT FAR MORE THAN JUST A FUTURE RISE IN MEAN SEA LEVEL.

Below, the science of sea-level change is addressed, to provide essential context and background understanding of the past changes. Second, the regulatory component of future projected change is noted, to ensure the work encompasses the relevant timescales. Past informal feedback from the Department of Water and Environmental Regulation (DWER) was to consider a 100-year planning horizon, consistent with state coastal planning policies.

3.1. The past record

The WA Environmental Protection Agency (EPA) considers impacts to coastal processes in the context of the latest science. This science includes past and future sea-level changes. Understanding past changes in sea level is critical, because such changes form the basis of assessing present processes and future potential changes. Some recent published research in the region on this topic is provided by Ward *et al*. (2022a). Around 20,000 years ago, the polar ice caps were at their peak volumes (a time referred to as the last Glacial Maximum) and the volume of seawater was least, so that around the world sea level was thus at its lowest (termed sea-level lowstand) (Figure 7). At this time, the area of the ESSP was part of a broad, flat coastal plain stretching nearly 160 km northwards to the sea (James *et al*., 2004), dissected by riverine courses and containing scattered hills, some of which now make up the some 42 volcanic and limestone islands of Barrow Island, the Montebellos, the Dampier Archipelago, and similar islands. A period of major sea-level rise occurred between ~20,000 and 8,000 years ago (the Post-Glacial transgression). For much of the Southern Hemisphere, the rising sea passed through modern levels around 7,000 years ago (Figure 8) and continued rising to a mid-Holocene relative highstand of elevation +1.5 to +3 m (above present levels), lasting 3,000-4,000 years before returning to modern levels, probably falling in a gradual manner (see also Lewis *et al*., 2013). By the 20th Century, this longer-term trend had reversed, and relative sea level rise has been observed.

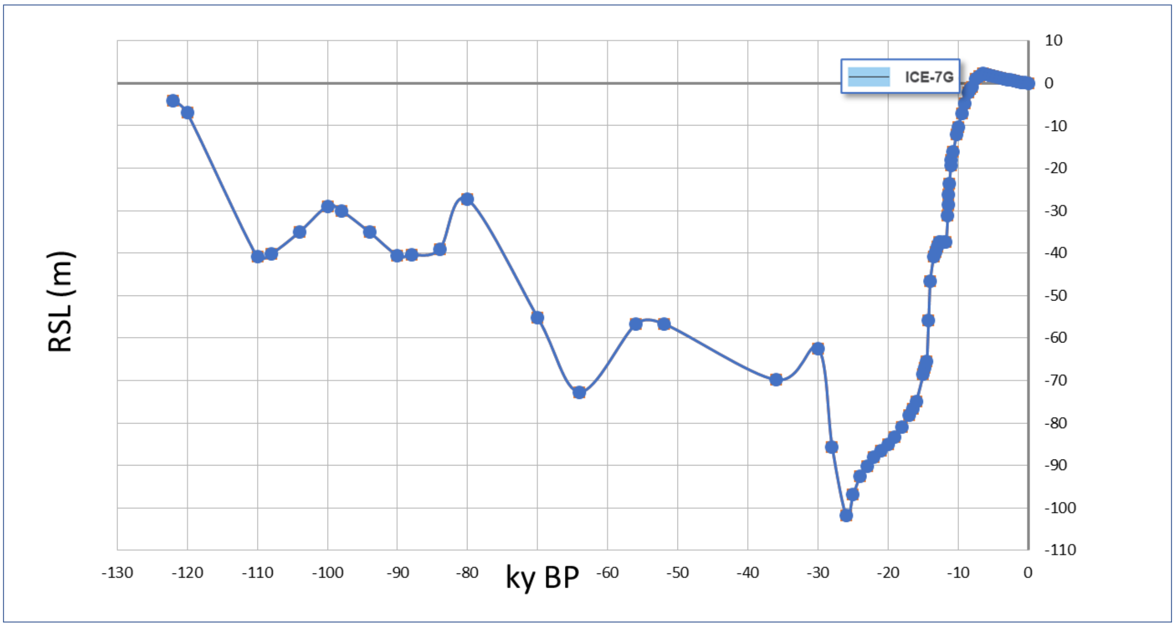

Figure 7. Simplified relative sea-level (RSL) curve for Barrow Island for the last 120,000 years derived from the Glacial Isostatic Adjustment model ICE-7G_NA (modified after Ward et al. 2022a). Error bars in elevations have not been shown.

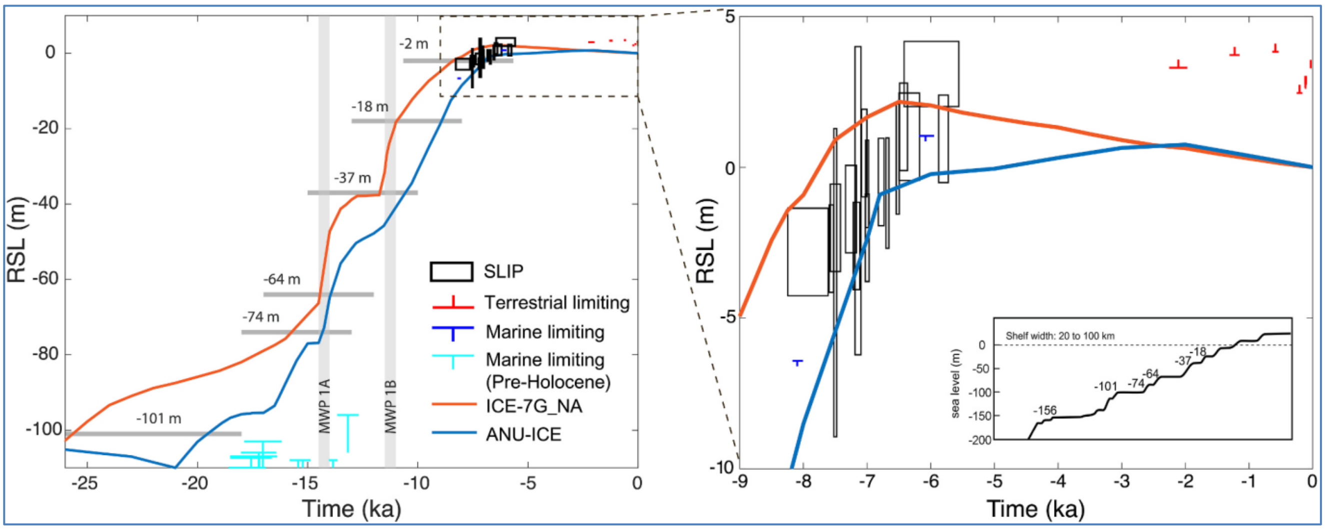

Figure 8. Deglacial relative sea-level (RSL) curves for Barrow Island derived from the Glacial Isostatic Adjustment models using the ICE-7G_NA and ANU-ICE ice models paired with the HetM-LHL140 3-D earth model (Ward et al. 2022a)[2]. SLIP = Sea level index point.

[2] The pre-Holocene data are from James *et al*. (2004) and Yokoyama *et al*. (2000, 2001), whilst the Holocene data (expanded right) are reinterpreted from Twiggs and Collins (2010) and May *et al*. (2015, 2016, 2018). Inferred timings of Melt-Water Pulses MWP1A and B are

Direct measurement of sea level has occurred since the 1800s, through installation of tide gauges and more latterly use of satellite altimetry (Douglas *et al*. 2001). This data has been used to assess mean sea-level change, acknowledging local variation through subsidence, isostatic, tectonic and oceanographic phenomena with a range of temporal and spatial scales (Gornitz 1993). Resulting estimates at any location are referred to as relative sea-level rise, i.e., the rise in sea level relative to the land. Synthesis of regional or global MSL trends, variously incorporating models for isostasy, have been developed. Relative SLR over the 20th Century was reported for most tidal stations, with rates of rise varying depending on coverage, time scales, statistical methods and observational frameworks. On the whole, accelerating relative SLR has been perceived, although evaluation over shorter time scales indicates the significant influence of cyclic processes.

In the Western Australian region, fluctuations in MSL of the order of 0.3 m have been observed, caused by fluctuations in basin-scale heating and consequent propagation of the shelf-edge Leeuwin Current (Feng *et al*. 2003). Consequent decadal-scale sea level variability introduces non-linearity of relative SLR and complicates comparison of trends from different length records (Haigh *et al*. 2011a). This has implications for interpretation of regional trends if different datasets are used (Church *et al*. 2005), or when analysis over several decades straddles a substantial climate phase shift (White *et al*. 2014). Since the 1990s, there has been a transition towards increasing occurrence and intensity of La Nina climate periods (BOM 2012). This complicates comparison of long-term trends between the Pilbara (2 to 5 mm/yr over recent decades) and southwest Australia (1 to 2 mm/yr over the 20th Century), although comparison of overlapping data periods indicates greater consistency.

Some important points arise:

- Relative Sea Level (RSL) approached modern levels around 120,000 years ago, at the time of the last Interglacial period, so that some geomorphological features at the modern coastline that could house BCHs might be remnants of that time.
- The Holocene highstand has seen sea levels close to modern levels for the last 7,000 to 8,000 years, so that some geomorphological features at the modern coastline might have been formed at any time in that period.
- The modern tidal range (e.g., 5 m at Dampier) is large compared to the Holocene RSL changes (Figure 9) and the geological evidence indicates far greater variations in coastal sea levels associated with episodic events such as cyclones). Hence, some geomorphological features at the modern coastline might represent the result of one or more past episodic events, so that the modern hydrodynamic regime might not be fully or partly responsible for their formation or dynamics.
- MSL rose by about 0.2 m over the 20th Century, subject to decadal-scale variability with a similar order of magnitude. Interaction of the two has produced two phases of 'accelerated' relative sea level rise, from 1950-1960 and 1992-2013 - aerial photographs of physical change are available for the latter phase.

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indicated, as are the elevations of the regional horizontal submarine terrace surfaces postulated by Fairbridge (1961; see inset). Pre-Holocene and Holocene marine limiting data are separated because for the pre-Holocene deglaciation, the hydro-isostatic effects are likely to be less variable across and along wider areas of the shelf and differences are less important than for the Holocene.

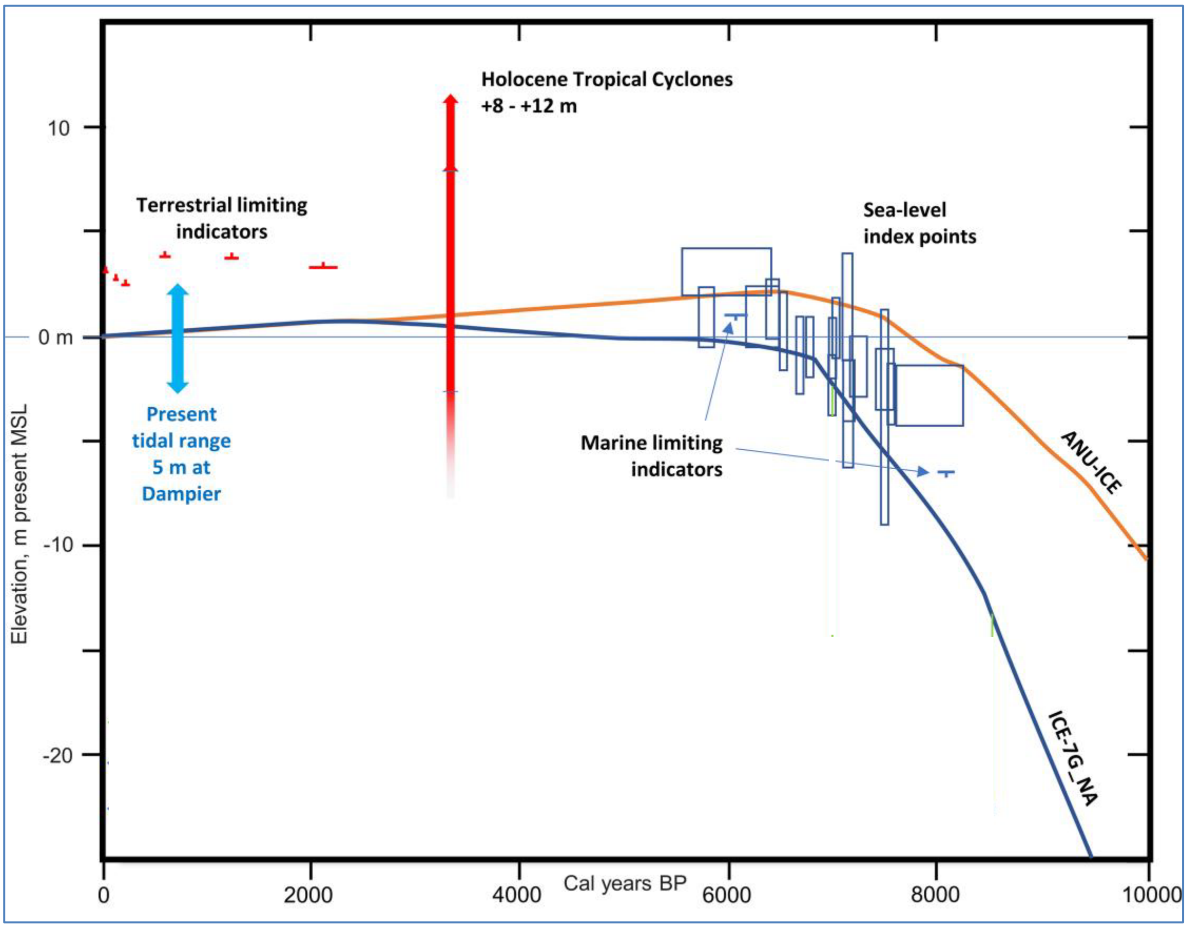

Figure 9. Regional relative sea-level change over the last 10,000 years (After Ward et al. 2022b). Note the modern tidal range at Dampier (blue arrow) and the elevation of Holocene indicators of extreme sea levels in the Dampier Archipelago area (red arrow), assumed to be caused by cyclones.

Tide gauges around the world provide measurement that provide information on the state of SLR around the world. Data are curated by the Permanent Service for Mean Sea Level, Liverpool, UK, from whom data are available (https://psmsl.org/). Data for the last 50 years around Australia indicate an average rate of SLR of 2.1 mm/yr. The ESSP is located between monitoring stations at Onslow to the SW and Dampier to the E, for which data (Figure 10, Figure 11) indicates high variability and a mean rate of SLR since 1985 of 2 to 4 mm/yr.

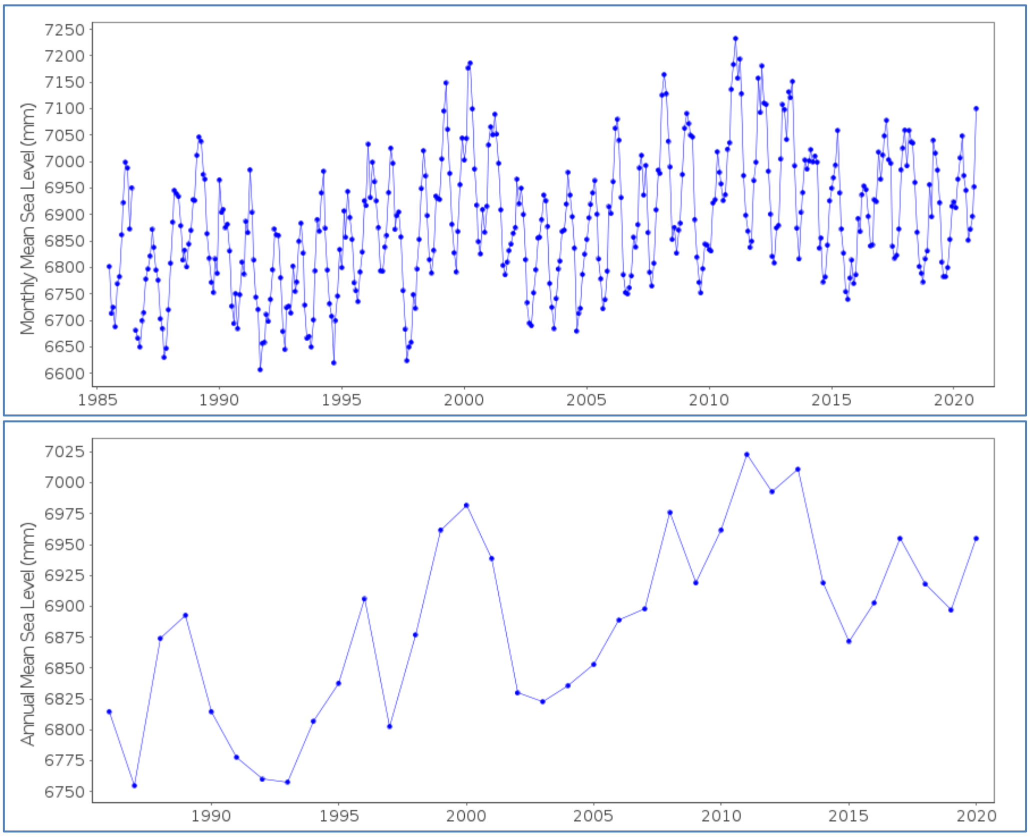

Figure 10. Onslow - monthly and annual sea level data since 1985 (PSMSL)

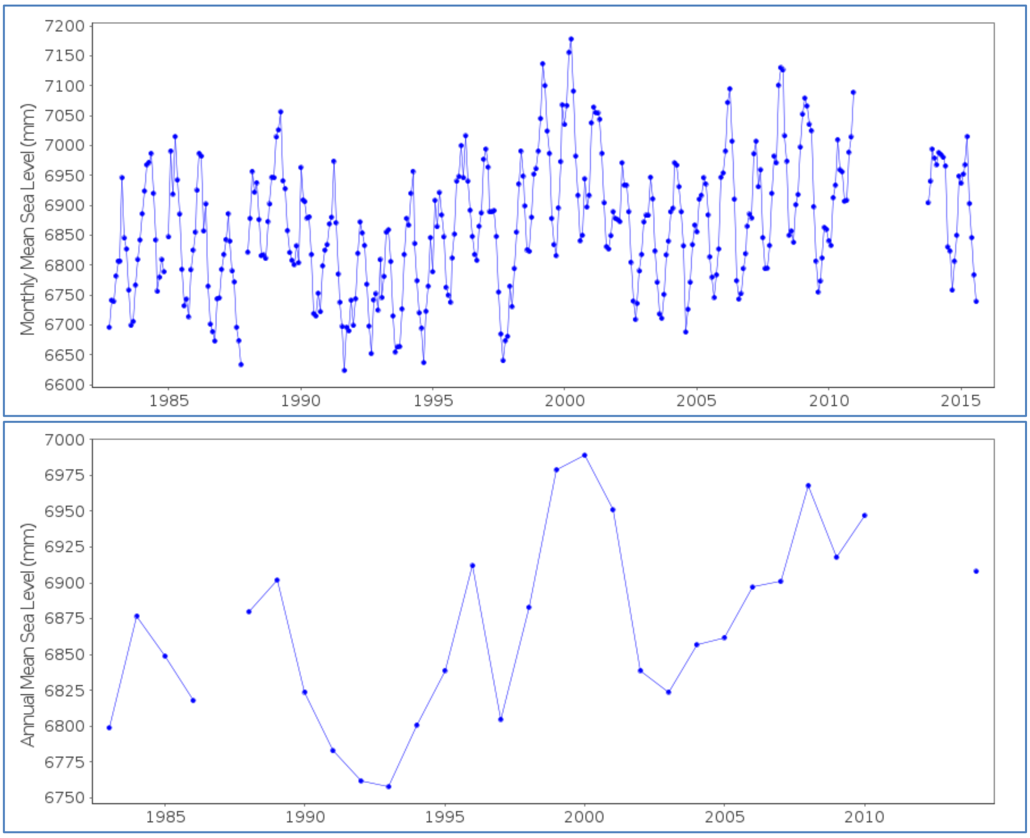

Figure 11. Dampier (King Bay) - monthly and annual sea level data since 1985 (PSMSL)

3.2. Projected future change

Future changes in MSL are unknown, but there are some relevant scientific predictions and some assumptions made for planning purposes. The EPA states that it will consider impacts to coastal processes in the context of the latest science, and while this is still a developing area and there are a range of predictions, the EPA recognises that a rise of 0.9 m in MSL (from 2020 levels) by 2110 is currently considered the best prediction for decision making (Figure 12). Further, previous informal feedback from DWER (in the CP-BCH report) was to consider a 100-year planning horizon, consistent with state coastal planning policies and the EPA guidelines for coastal processes (EPA 2016). Thus, a SLR of 0.9 m over the next century will underpin this work's considerations, i.e., roughly an average SLR of 10 mm/yr.

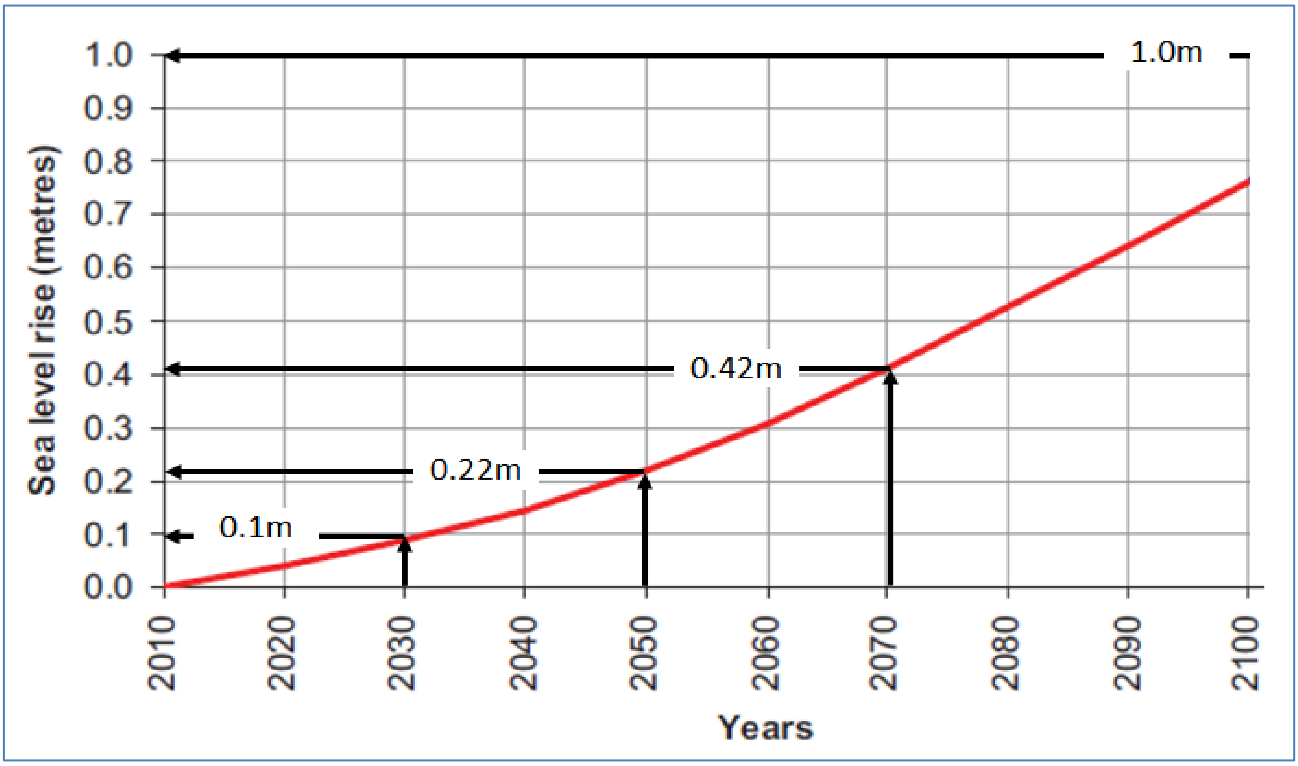

Figure 12. Future SLR trajectory used by the WA Department of Transport (DOT, 2010).

4. Review – the main factors and conceptual models of change

4.1. Intertidal habitat viability

Intertidal zones are spatially constricted areas, across which there is a steep transition from marine to wholly terrestrial conditions. Factors which may affect the viability of habitats to develop and thrive include salinity, sediments, nutrients/pollution, and wave energy, including change of these factors over time (Winterwerp *et al.* 2013). This report focusses on SLR and associated sedimentary change, but the key factor is perhaps the interaction of these with other aspects affecting habitat viability.

Benthic and coastal habitats present along the ESSP coast each have different relationships to the environment, which may determine connection to physical features (e.g. morphology or freshwater sources) or determine responsiveness to processes (e.g. erosion or hydrology) likely to change with human interventions or sea level rise. Sensitivity or tolerance of different intertidal species typically provides a general zonation, with habitats along the ESSP coast having a general sequence from the sea southward to the land (Table 2).

Table 2. Generalised zonation of main habitats across the coastline in the ESSP region

		Salinity	Sediments	Nutrients	Wave Energy (relative)
Ocean ↑	Bare seabed	Marine	Calcareous & mixed	N/A	High
	Mangroves (BCH)	Marine	Mixed	Low	Moderate
	Bioturbated zone	Hypersaline	Mixed	N/A	Low
	Benthic mats (BCH)	Hypersaline	Mixed	Low	Low
↓	Samphire (BCH)	Brackish	Mixed	Low-Mod.	Low
Land	Hinterland	Freshwater	Terrigenous	Moderate	N/A

The basic concept of zonation is modified by changing conditions over time, ability of species to modify their environment, and life-cycle effects on tolerance. A consequence is that intertidal habitats can create a complex habitat mosaic, reflecting a mixture of both active and relict physical conditions (Berger *et al.* 2008).

Conceptual models for intertidal habitat viability, which subsequently provide a basis for projection of response to change, correspond to four general classes, with some interaction.

- **Propagation.** Habitat presence is controlled by the propagation phase of a species life-cycle. In general, physical conditions viable for habitat occur across a wider area, but the habitat structure is developed through connection to a parent community.
- **Resources**. Habitat is controlled by occurrence of specific resources related to the species life-cycle, such as seasonal fresh water, or presence of suitable sediments. Species presence can be linked to the presence or absence of these resources, e.g. Porewater salinity provides a crucial influence on species zonation, with hypersaline conditions impeding both mangroves and samphire.
- **Competition**. If multiple species may occupy similar location, or where presence of a species can generate new areas of viability (e.g., wave sheltering behind mangroves), then adaptive or competitive advantages can determine the habitat distribution. This is usually indicated by the occurrence of intermixed species, often with substantially different life-cycles, or an environment illustrating relict or colonizing behaviour (Ewel *et al.* 1998).
- **Disturbance**. When species are affected by disturbance episodes (e.g. storm erosion or drought), their presence and structure can be determined by erosion-recovery cycles. This is particularly important on coast-fringing mangroves, with root-structure influenced by plant maturity, so that storm erosion pressure more frequent than once per 5 to 8 years tends to impede recovery.

It is noted that conceptual models relating the development of habitat distribution are likely to require interpretation when simulating future change (Twilley *et al.* 1999).

4.1.1. Mangroves

Mangroves are a collection of different species of vegetation occupying a common ecological niche, on the comparatively narrow and dynamic marine fringe of sub-tropical and tropical environments (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, Ellison 2002).

Mangrove species identified at the ESSP include *Avicenna marina, Rhizophora stylosa* and *Ceriops australis*, with *Avicennia* the dominant species (O2M 2023).

The viability of different settings to provide mangrove habitat depends on a series of dynamic factors at the shoreline, including the effects of storms, climate fluctuations, tidal network development, nutrient availability (particularly through mangrove litter), and sea level variability. These factors interact to vary the susceptibility of mangroves to cycles of disturbance and recovery, so that in a large area of mangroves there may be a complex arrangement of different species and maturity. For a narrow area of mangroves, these factors may cause repeated cycles of destruction and regeneration. Wherever mangroves occur, their distribution varies through time, and after disturbance they require the availability of niches and pathways for propagation for regrowth.

Morphodynamic change is particularly important in the context of rapid SLR, especially if coastal change truncates the geomorphic features and environments suitable for mangroves or is too rapid for mangroves to colonise them (Gilman *et al*. 2007; Anthony & Goichot 2020). In many cases, decadal-scale morphodynamics determine the capacity for geomorphic features to support mangrove communities, with a period of 5 to 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 soil salinity, hydroperiod (frequency of inundation), erosion, smothering, waves and sea-level change:

- Effects of varying soil salinity have been examined by correlating the presence and abundance of mangrove species to salinity gradients. Work indicates 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, and has been correlated with species distribution in 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 to 1.0 m, depending upon species.

- Mangroves commonly act to trap sediment mobilised from adjacent coastal landforms. Whilst sediment influx can be a source of key nutrients for mangroves (Anthony & Goichot 2020), rapid, thick accumulations of sediment 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 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 to 1.0 m (Eliot, personal observation).

Along many coastlines, in sedimentary terms, it is often convenient to distinguish fringing mangroves that occur along open coastlines exposed to waves, from estuarine mangroves that occur along the banks of estuarine channels and tidal creeks. In riverine mangroves, where wave action is negligible, there is an intimate relationship of the tide with the hydrodynamics, sediment transport and sedimentation (Wolanski *et al*. 1980; Larcombe and Ridd 1995). In large estuaries, where tidal elevations vary along the estuary, there will be a natural axial variation in mangrove elevations. In contrast, where mangroves are developed as fringe forests or overwash forests, waves and wet season floods might be expected to be a significant control on the zonation. Thus, a different spectrum of environmental conditions may induce a different relationship of mangrove zonation with elevation.

Larcombe *et al* (1995) reviewed the occurrence of mangroves and their elevations along the Great Barrier Reef (GBR) sub-tropical and tropical coastline, and the material below draws on that paper. Locally, mangroves may be strongly well related to tidal levels (Woodroffe 1998). For example, on the Townsville coastal plain, mangroves are found from 1.5 to 3.0 m (referred to Port Datum Townsville) on a local tidal spectrum of 0 to 3.8 m (Belperio 1979). Bunt *et al*. (1985) found that "the topographic height range of individual plants of a single species may be almost 4 m", and that erosion, accretion or other disturbances may cause variation of ~ 1 m in the elevation of a mangrove species or community. Spenceley (1982) showed that even in areas only 20 km apart, the heights of different zones within a mangrove system varied by up to 0.5 m.

In terms of the muds deposited within estuarine mangroves, for the central GBR's terrigenous-sediment dominated systems, mangrove muds represent an elevation range of -0.1 to +1.5 m AHD (Larcombe et al., 1995). Gagan *et al*. (1994) documented that the elevation of mangrove mud in mesotidal Mutcheroo Inlet becomes progressively lower in a landward direction, falling by 0.9 m in 4 km, possibly due to effects of freshwater runoff.

Details of the mangroves in the ESSP area are provided in section 6.5.1.

4.1.2. Benthic mats

Benthic mats are comprised of opportunistic, highly persistent cyanobacteria, which can take advantage of short periods of benign conditions, such as seasonal rainfall or tidal inundation, to grow rapidly (Paling *et al*. 1989; Lovelock *et al*. 2010, Taukulis 2018). These mats may occur as a thin coating on surface sediments, or as a thick mat, comprised of multiple growth layers. Once developed, the benthic mat helps to bind surface sediments and reduces permeability, potentially modifying local drainage and percolation pathways.

Benthic mats develop on land surfaces subject to inundation and ponding, particularly salt flats, mudflats and overbank basins adjoining tidal creeks. Tidal flows provide a cross-shore transition of bed stress, which in the long-term can generate spatial sorting of bed sediments, with coarser sediments near the coast and finer sediments further landward. This zonation supports a classic convex structure for muddy coasts, with a decreasing sediment surface 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 by tides. Microtopography, including swash lines and vegetation, causes local ponding, with evaporation causing development of hypersaline conditions.

The opportunistic nature of algal mats due to their capacity for nitrogen fixing, plus the capacity for disturbance of thin layers through bed stress, suggest 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 13). 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.

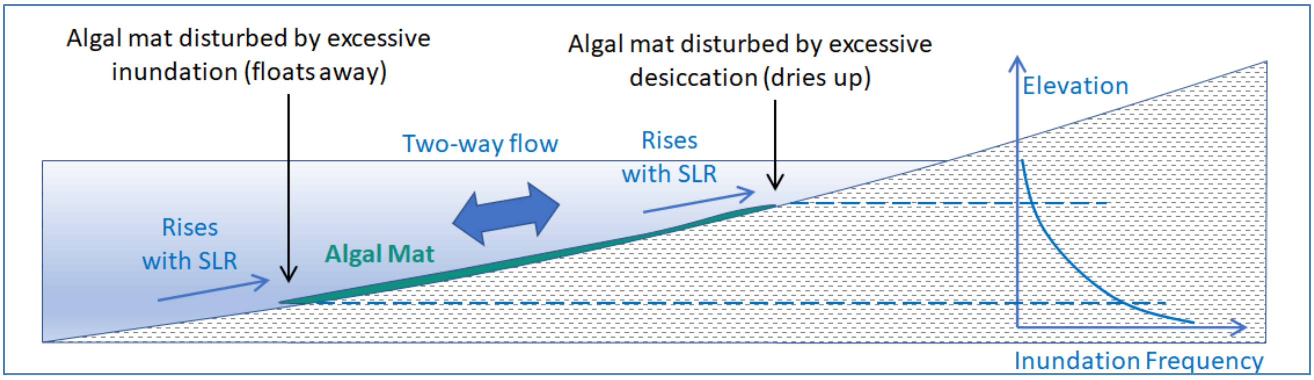

Figure 13. Conceptual uneven asymmetric distribution of algal mats under conditions of a rising sea level, whereby they are more prevalent towards the base of their distribution.

Details of the benthic mats in the ESSP area are provided in section 6.5.2.

4.1.3. Samphire

Samphire (*Tecticornia spp*.) are perennial shrubs, with either a spreading or an erect structure, up to 1 m high, and they are highly specialised to their environment, being arid-zone plants which tolerate heat, cold, drought and hypersaline conditions (Moir-Barnetson *et al.* 2014). 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.

Samphire generally occur as:

(i) a dominant species in a narrow upper-intertidal fringe at the base of supratidal slopes, including upward slopes of mainland remnant islands, dunes abutting salt flats or adjacent to banks; or

(ii) either a dominant species or mosaic presence in supratidal basins or in channels upstream of tidal conditions.

They are able to persist in highly saline environments because when direct rainfall occurs, they are able to quickly recover by growing fine roots and initiating shoot growth, ensuring foliage production, and have evolved high drought tolerance due to their succulent leaves and shallow woody roots. Their shallow root structure determines that samphire preferentially occupy nearly flat land with infrequent bed disturbance – including effects of waves or bioturbation.

The requirement for freshwater and damp ground at times each year means that they tend to occupy flat ground close to the base of a slope. The slope provides freshwater supply through runoff, and the adjacent low-gradient area means that the ground is well-watered, at least for at some stage, each year. 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.

The above characteristics mean that the samphire environment can be less amenable to physical migration than some other habitats, such as mangroves, but both are partly controlled by coastal slopes and the ability of the coastline to provide suitable sediment and other environmental conditions.

Details of the samphire in the ESSP area are provided in section 6.5.3.

4.2. Influence of SLR upon geomorphic dynamics and habitats

4.2.1. Geomorphic concepts

Models for coastal evolution, including response to SLR, are built around three main concepts, which are implemented and integrated in different ways depending on local morphology, including geological framework, sediment composition and role of vegetation. The three concepts are:

- Cross-shore adjustment, where sediment is redistributed up and down a coastal profile, in response to changing conditions, most typically tides and waves. Change mostly occurs within the intertidal zone but can be distributed from offshore as far landward as the extent of wave runup. Enhanced change can occur if a crest is overtopped (Sallenger 2000);
- Alongshore transport, where there is a net transfer of sediment from one section of coast to another. This is commonly related to wave-driven sediment transfer in the littoral zone, although this can also include tidal transfers, landform evolution or dispersion from a source, most typically a river mouth;
- Storage areas, where the volume of sediment contained within an area can change without modifying the profile or alongshore orientation. Dunes and estuaries are the main storage areas.

Adjustment to projected SLR is typically simplified to cross-shore adjustment (Bruun 1962, Davidson-Arnott 2005) integrated with the accumulated effect of alongshore transport over decadal timescales. Adjusted storage volumes in dunes and estuaries are commonly assumed as continuation of historic behaviour (e.g., sediment budgets) or based on projected relationships.

Although developing through diverse pathways, estuaries are basins that have not completely infilled with change in sea levels, with adjustment effectively controlled by the rate at which sediment can enter the basin, from marine or fluvial sources (Figure 14). This concept has been used as a general basis for estuarine classification, with a broad distinction between estuaries as sediment sinks and deltas as sediment sources, and further distinction based on key drivers and sediment availability (Galloway 1975, Ryan *et al.* 2003).

Although the morphology of estuaries can be related to different classes, the form of estuaries is often a result of different parts of the geological and sedimentary framework with the different drivers. For example, the overall structure of many Pilbara estuaries includes features defined by bedrock, lithology, sand and shell landforms, and silt landforms, listed in order of increasing dynamism. The response of estuaries to SLR is developed differently for each landform, generally with the less mobile features providing a framework within which the more active features experience redistribution.

The capacity for material storage within each landform framework varies. Changes in capacity become significant especially where the sediment supply is of a range of particle size. In particular, sand or gravel landforms (including coastal ridges) may form the landward side of a tidal basin that can only hold a certain amount of silt, with any excessive silt volume exported by the estuary. In these circumstances, silt landforms (e.g. floodplain areas) might adjust to SLR due to high silt supply, particularly if mangrove evolution can enhance capture of silt. However, if the effective storage volume is controlled by the sand and gravel landforms, then their adjustment to SLR may limit estuary response to sea level rise.

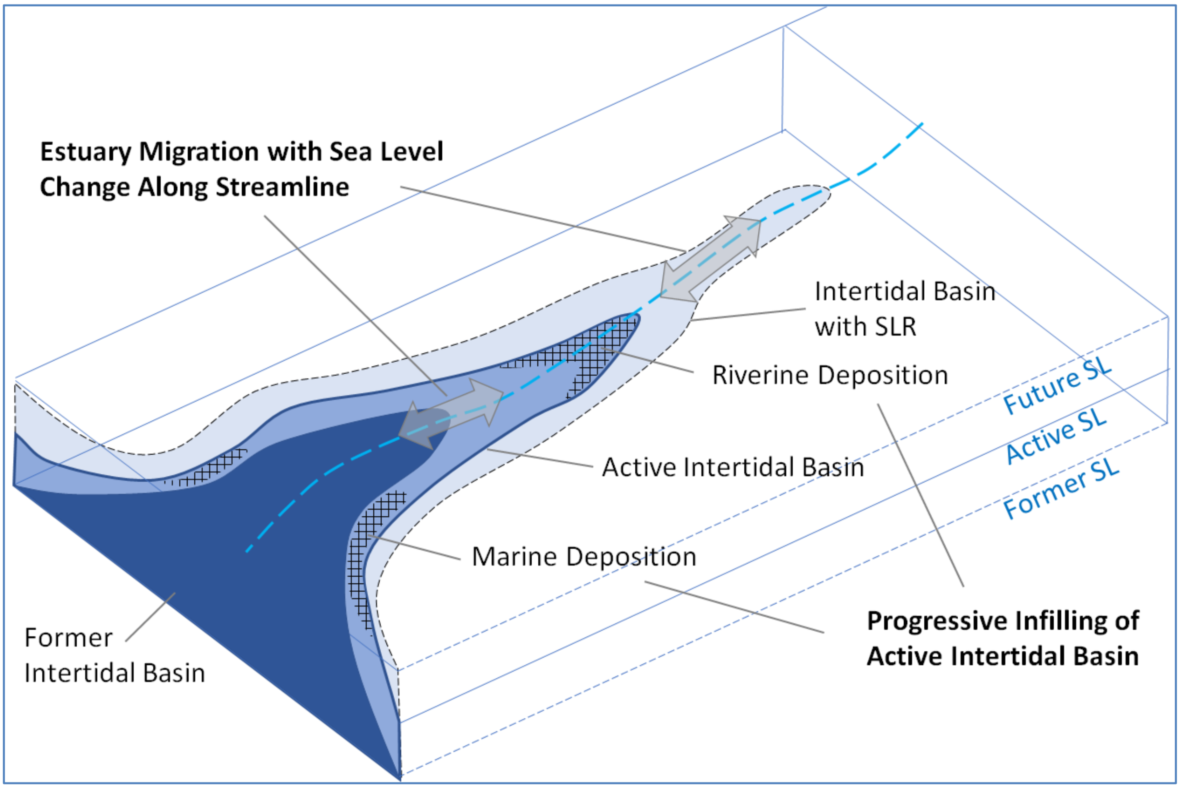

Figure 14. The coastal response in tidal systems subject to SLR can include accumulation of sediment input from the sea and from the land.

4.2.2. Dynamics of habitats

Dynamics in sedimentary environments and their habitats creates challenges for the associated biological assemblages, which therefore have created an array of adaptive characteristics supporting their survival, listed below.

- Saline tolerance, with some species able to withstand marine or even hypersaline conditions.
- Ability to withstand seasonal dry periods, or extended phases of drought.
- Resilience through phases of rapid growth, making opportunistic and effective use of ephemeral resources.
- Structural habitat modification, such as sediment trapping by mangrove root systems.
- Capacity to tolerate wave impacts and bed change (erosion or smothering), such as prop structures or buttress roots.
- Inter-species interactions supporting mutual benefit.

The tolerance and adaptive capacity of intertidal species have been noted as key attributes anticipated to support migration of these species under scenarios of projected sea level rise (Figure 15). Evidence of mangroves migrating with changing sea level is available from stratigraphy. However, the capacity to migrate can be constrained, particularly where resources contributing to adaptation are physically limited, including sediment.

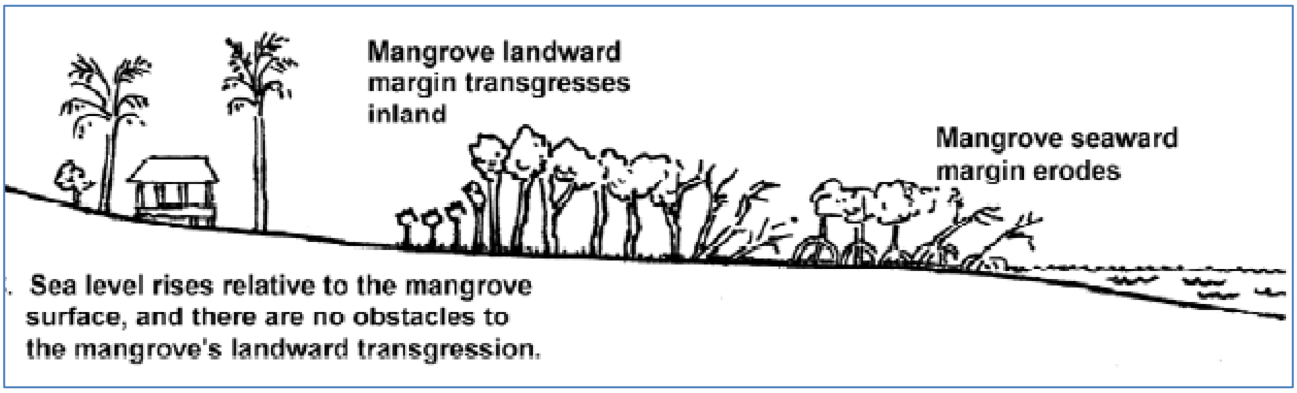

Figure 15. Concept of unrestricted mangrove evolution with SLR (from Gilman et al. 2007).

Semeniuk (1994) interpreted stratigraphic records to identify geomorphic response to Post-Glacial SLR. He also examined the existing structure of mangrove complexes and suggested their potential evolutionary response to SLR. Two main alternatives were identified, based on the availability of sediment and capacity for material to be distributed throughout the mangroves.

- For complexes with well-developed tidal networks and a suitable sustained supply of sediment, the network allows material to be distributed, enabling the floodplain to rise or fall with sea level (Ellison & Stoddart 1991; Gilman *et al*. 2007). Evidence of the headward expansion or retraction of tidal creeks in response to subtle sea-level fluctuations is available (Cobb *et al*. 2007), resulting in sediment supply to or from the adjacent coastal region. Interaction with resistant structures, such as walling or rock features, may limit movement of floodplain zones.
- For complexes with well-developed fringing ridges, notably where chenier ridges or coastal spits are present, there is limited capacity for sediment distribution through the mangrove complex, even in cases where there is a sustained sediment supply. In these situations, SLR might be likely to result in the progressive rise of the ridge, until it is breached, causing flooding of the mangrove flat, and potential rapid change to the mangrove system. This may subsequently enable formation of a tidal creek network, which then facilitates sediment distribution across the flat and associated estuarine mangroves.

Observations of modern coastal wetlands along the Pilbara coast indicate that different parts of estuarine systems can have progressive, incremental or adjustive responses to change (Figure 16). This is a useful concept and can help illustrate why coastal changes are rarely even and continuous, and why future changes might be less than readily predictable.

Different parts of a hypothetical sub-tropical arid coastal system might operate in different ways. Taking a century-scale perspective, examples are given here.

- Adjustive behaviour
  - This can occur at the mouth of tidal creek systems, along their narrow creeks and at their landward heads. Whilst there might be an overall trajectory of coastal response, such as landward migration or seaward progradation, there will be a variety of shorter-terms periodic and episodic responses that change creek morphology during a period of 100 years. The tidal flat can change from importing to exporting sediment and back again, producing repeated relatively small adjustments in volume, such as down-cutting of the heads of tidal creeks or the development of depositional fans or bank levees (Eliot & Eliot 2013).
- Incremental behaviour
  - This might typically occur for a coastal barrier system, whereby it might be stable between episodic storm events, but each significant storm event might drive erosion on its landward side, overwash and sediment accumulation on its landward side. This leads to long-term coastal rollover in one direction, but it actually occurs in small increments. Further, the barrier does not migrate seawards with periods between storms or falling sea level.

- A second example might be the accumulation of low sand bodies at the mouth of the major rivers where they discharge onto the highest tidal flats during episodic major river floods. Here, especially if the bed elevation is low and groundwater is near the surface, there may be no mechanism capable of removing any sediment once deposited. Hence, these sand bodies might accumulate material slowly and incrementally, only during rare major events.

- Progressive behaviour
    - Landward of active mangrove creeks and beyond the influence of the adjustive tidal creeks, there can be extensive areas of tidal flats that are only inundated by tides very infrequently, but periodically and predictably. If these areas are also away from sources of river input, then these large areas are effectively starved of sediment input. They might only very rarely receive any sediment, and even then at very low rates, for example by settling of silts and clays during surge-related inundation events. There may be no mechanism capable of removing any sediment once deposited, so that over a century, these areas might accumulate material very slowly and in one direction.

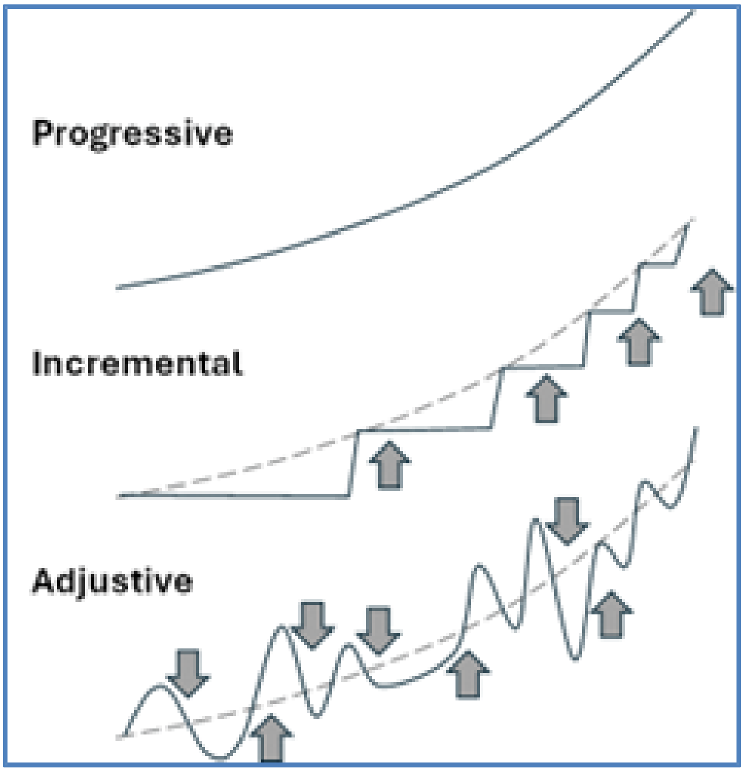

Figure 16. Conceptual diagram of the three main types of estuarine geomorphic response to change. These can apply to the whole system and each of its components. This can be applied to the ESSP area, with a century-scale perspective, and also shorter timescales.

Such variation in geomorphic response also occurs on smaller timescales, such as over only a few years. For example:

- For tidal creeks, adjustive behaviour can occur on seasonal timescales, through to sub-decadal timescales, due to variable hydrodynamic forcing from tides, episodic events and subtle associated changes in creek hypsometry. The tidal flat can switch rapidly from importing to exporting sediment, producing relatively small adjustments in volume, such as down-cutting of the heads of tidal creeks or the development of depositional fans or bank levees (Eliot & Eliot 2013).

Therefore, identifying the general behaviour of the various parts of the ESSP system is important to allow a first-order interpretation of the various datasets, and begin to form the basis of projections of possible future change. These concepts underpin the interpretations made through analysis of relevant datasets, such as such as geomorphological changes seen on aerial photographs, dated sediment cores, surface bedform types and their location, measured river flows and/or direct observations of changes in sediment-associated habitats.

4.3. Changes to hydrodynamics associated with SLR

Whilst a general consideration of hydrodynamics is provided later (Section 5.1), here are noted only those aspects likely to change with SLR. Here, 'hydrodynamics' includes aspects of tidal currents, waves and wind-driven currents. The changes are relatively simple in concept in the main different habitat-forming environments (Table 3). The relevant environments include the shallow marine seabed, a range of intertidal environments and low supratidal areas that may become more subject to surges than at present.

Table 3. Main generic change in selected hydrodynamic factors associated with a SLR of ~1 m on the main habitat-forming environments on a coastline similar to the ESSP area. Assumes no change in bed elevation levels nor coastal morphological change, i.e., it describes the general consequences of an 'instantaneous' SLR. The table also tends to note those conditions where changes in sediment transport would result and considers the net result of a year or more. Coloured cells indicate changes of greater significance.

		Hydrodynamic factor			
Present Environment		**Tidal currents**	**Waves**		**Wind-driven currents**
		With sea level 1 m higher than today ('instantaneous' change)			
Marine	**Shallow marine**	-	Incoming from the ocean	Locally generated by winds	-
Intertidal	**Low intertidal**	Weak increase in ebb speeds	Slight rise in wave size and potential for increased mobility	-	-
	Coastal fringing mangroves	Weak increase in current speeds	Greater bed mobility	Greater bed mobility	-
	Tidal creeks[3]	Tendency towards faster and longer-duration ebb flows	-	-	-
	Estuarine mangrove forest	Tendency towards faster tidal flows	Greater exposure, bed mobility	-	-
	High intertidal flats	Faster flows, greater period of inundation	Small increase where mangrove forest is narrow or absent	Greater exposure to bed disturbance, especially at downwind margins	Greater period of time and potential bed mobility
Terrestrial	**Low supratidal**	-	-	Greater chance of episodic exposure	-

Using the estuary as an example of different types of coastal and shallow marine morphology (Figure 17), the ~15 km long southern margin includes extensive areas of subtidal and intertidal flats, tidal creeks of various forms and sizes, fringing and estuarine mangroves, and other BCHs. East of Gnoorea Point are several tidal creeks, again of various forms and sizes (e.g., Figure 79 and section 9.3.5). The coastline bordering the ESSP area therefore contains a variety of coastal morphologies, sediment transport regimes and sediment transport pathways. Because of the broad geomorphological complexity and the variable influence of the hydrodynamic drivers on each environment, raised sea levels may change some coastal environments and habitats more

[3] Refer CP-BCH report.

than others. This also depends partly on the features in the area that are able to anchor the shoreline in certain places, whereas others are more able to change. For example, the presence of a rocky headland can limit nearby change to sedimentary coastlines.

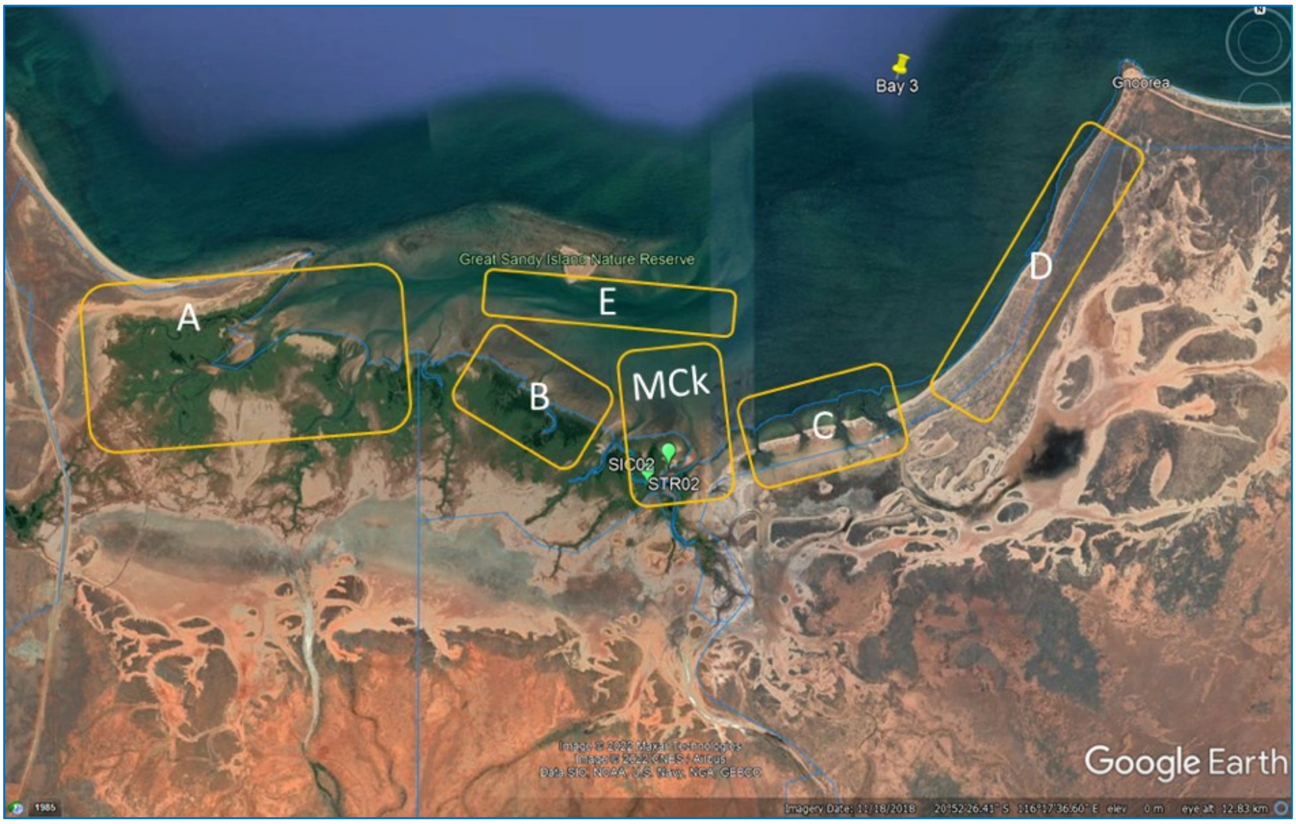

Figure 17. Distinct types of coastal and shallow marine geomorphology along the ESSP proposal frontage, i.e., the southern margin of the estuary (from CP-BCH report).

5. Review – the various controls on natural changes

5.1. Coastal changes and relevant processes

In the geological, geographical, and sedimentological literature, the complexity and dynamics of coastlines are well-described (Boyd *et al.* 1992; Davis & Dalrymple, 2012; Dyer, 1986). Coastlines may be characterized in many ways, including in terms of their:

- long-term mobility (e.g., hard or "soft"),
- shape seen in 2-D or 3-D form,
- perceived long-term change in location (e.g., progradation v erosion),
- planform (i.e., morphology seen from above),
- tendency for stability or for rapid change, and
- driving processes (e.g., high-energy, sheltered, macrotidal, microtidal, etc.).

Viewed simply, sedimentary environments can be considered as a combination of just three main factors:

- the volume of the sediments themselves,
- their physical nature and composition, and
- their dynamics (Pethick 1984).

In sub-tropical regions, interactions between these factors can generate environments as different as muddy mangrove swamps, silty salt flats, sandy beaches and shelly chenier ridges. Considering changes to "coastlines" necessarily involves assessing the interactions between a large suite of sedimentary environments, including those of the adjoining continental shelf, deltas, estuaries and rivers, and the coastal plain.

There are six main physical "drivers of change" in subtropical shelves and shorelines (Larcombe *et al*. 2018), these are:

i. fluvial sediment delivery,

ii. shelf sediment availability,

iii. shelf bathymetry, which includes the intertidal zone and all associated peritidal topography,

iv. waves,

v. tidal range and currents, and

vi. cyclones (including tropical lows).

Following Pethick (1984), these six drivers are either process-based (drivers iv–vi) or are physical particles (drivers ii–iii), to which is added pre-existing topography and bathymetry (driver i). Cyclones (driver vi) encompass several relevant processes and also involve fluvial sediment delivery, but they are a key driving feature of subtropical shelves (e.g., Carter *et al*. 2009; Larcombe & Carter 2004; Nott 2006) including contributing to the ephemeral nature of many sedimentary environments and habitats, so are listed separately here.

Coastal and marine environments are influenced by a mixture of these drivers. Other factors may also influence shelf and coastal sedimentation, such as (i) the effects of rare events such as tsunamis (Scheffers *et al*. 2008) and (ii) large-scale failures of submerged sedimentary bodies (Hengesh *et al.* 2012) or exposed reef edges. Further, there can be (iii) changes of coastal "state," whereby relatively small changes in coastal configuration, such as closure of the entrance of as narrow lagoon, estuary or river, can lead to major changes in sedimentary environments. Such changes can occur in regions where episodic events are a key feature, such as along the North West Shelf (NWS), and the environment of the Pilbara lends itself to such state changes.

Over long timescales, sea-level change by itself mainly influences the location of the primary process drivers, and, among other things, can affect shelf sediment availability through playing a part in modulating biogenic sediment production, and modulating the sedimentary results of cyclones through changing water depths. The full complexity of the interactions of sea-level change with shelf and coastal sedimentary processes has yet to be fully grasped in the biological and ecological literature, and similarly by regulators charged with managing human use of coastal environments (Larcombe & Morrison-Saunders 2017).

From the above, it is necessary to have a firm understanding of the interactions of past relative sea level, coastal configuration and sedimentation. This supports the ability to make defensible statements about the implications of human intervention in coastal environments and the impacts upon sedimentary environments and associated BCHs, or at least to be able to constrain the possible impacts. This report is based on an expert-driven integration of the above factors and processes, focused on the potential changes to coastal sedimentation, and where quantification is impossible, it is designed to constrain potential changes.

5.2. Relevance to BCH assessments

'Benthic Community Habitats' or BCHs, is a specific term for habitats on the seabed, but is often used in regulatory documents (e.g., EPA 2016) to include those habitats in intertidal and some supratidal environments. A key control upon such coastal and marine benthic habitats is the presence, nature, distribution and dynamics of bed sediments (Larcombe & Morrison-Saunders, 2017). In essence, the control is the nature of the sediment transport pathways, and especially of sandy sediments across the bed, which are a key component of so many habitats on Australia's dynamic NWS (Harris *et al*. 2005; Jones 1973; Passlow *et al*. 2005; Picard *et al*. 2014). Whilst there exist some regional maps of sea-bed type and of some sediment characteristics (e.g., Harris & Hughes 2012), appropriate sedimentary data and studies to define sediment transport pathways are largely absent. For some habitats, such as estuarine mangroves, the link is more towards those locations where the accumulation of silty sediments occurs.

Further, regarding 'natural variation', the requisite oceanographic, sedimentary and biological information is also largely absent for the NWS and shoreline. There are no published field studies on the 'age' (i.e., the time since their last major disturbance) of benthic habitats on the NWS, their natural changes of state through time, and the frequency and magnitude of mobility of their associated sediments. Although there are regional models on the issue of sediment mobility (Harris & Hughes 2012; Porter-Smith *et al*. 2004), these are not detailed enough to help gauge physical or temporal scales to apply in the EIA process, and they are unsupported by detailed measurements of sediment and their dynamics.

As a result, it remains unclear how assessments can realistically be made of the ecological resilience of benthic habitats on the NWS, and how to gauge the 'significance' of observed changes in relation to human activities. There is ample evidence that methods need to be developed to begin to resolve these fundamental issues and to underpin a new approach to assessment of habitat changes. The evidence includes:

- the highly active bed sediment dynamics on the NWS (Larcombe *et al*. 2014; Dufois *et al*., 2017)
- the existing understanding of similar tropical and sub-tropical cyclone-influenced carbonate continental shelves in Australia (Belperio 1983; Gagan *et al*. 1988, 1990; Larcombe & Carter 2004) and of those elsewhere (Hubbard 1992; Mearns *et al*. 1988; Morton 1988), and
- the increasingly well documented nature of decadal-scale coastal change (e.g., https://maps.dea.ga.gov.au).

This report integrates available information to indicate aspects of future potential sedimentary change in the ESSP area. It considers sediment transport processes and sedimentary changes close to the coast in the

ESSP area. Whilst the sedimentary aspect is critical to habitats, primarily in forming features and substrates available for colonization, there are a range of other factors involved (e.g., section 4.1).

As an example, the relative elevation of habitats compared to the tidal range is a good starting point, but is complicated by the physical responses that vary across places of similar elevation. All BCHs are associated with sediments, whether located on area where sediment is accumulating, is mobile and passing through, where it is actively eroding from the bed, or where it is absent. In this way, sedimentary processes are critical factors in understanding the processes that create and maintain BCHs. It is necessary to consider the dynamics of:

- the system within which habitats are located;
- the system's component parts, and;
- the links between those parts.

In the case of the ESSP, this means considering a very large area encompassing river catchments, channels and deltas, the coastline and intertidal area, and the subtidal seafloor of the inner shelf. Further, given the need to assess potential development-associated changes to BCH in terms of their past natural variation, there is also a need to include time periods between daily tidal variations out to a century in the future, to link with existing planning schemes for the Pilbara region.

The sedimentary environments in the area that house BCHs are many and varied, in their nature and their propensity for change. Indeed, most sub-tropical coastal and marine environments are ephemeral on various timescales, with implications for their associated habitats and organisms. For example, on the Great Barrier Reef coast and shelf, the frequency of habitat resetting for coastal mangroves is a few decades to perhaps a century (Larcombe 2007). Whilst there are no such data yet for the Pilbara, it is the timescales of resetting of the habitats and associated biological communities that are unknown – their fundamental ephemeral nature is not in question.

5.3. Modern sea-level variability

MSL around Western Australia has been measured by a network of tide gauges, and the data indicate a long-term rising trend, and substantial sea level fluctuations that correlate with ENSO climate phases (Pattiaratchi & Buchan 1991, Feng *et al.* 2004; Haigh *et al.* 2011a). Since the 1990s, there has been a transition towards increasing occurrence and intensity of La Nina climate periods (BOM 2012). These are associated with higher shelf temperatures, and an increased and repositioned Leeuwin Current, resulting in raised MSL. This substantial transition has dominated MSL trends in the Pilbara (Church *et al.* 2004, White *et al.* 2014) because observations commenced in the 1980s, although fluctuations are largely consistent with longer-term records available from other parts of Western Australia.

For the Dampier record, change in MSL from 1990-2020 is less apparent, due to a datum change (Figure 18). However, for stations with continuous records, a rise occurred over this period. At Fremantle, the MSL increased by 0.126 m from the 1990s to the 2010s, with MSL 0.20 m above the 1990s levels during the severe La Nina over 2011-2013 (BOM 2012). These increases in MSL are important for interpretation of coastal and habitat response to SLR.

It is noted that tidal modulation is of a similar magnitude, with the 4.4-year cycle (Eliot 2011, Haigh *et al.* 2011b) affecting monthly maximum tidal levels by around 0.2 m (Figure 13). Approximately half of the elevated tide phases have corresponded to La Nina phases, creating opportunity for more variable inundation patterns than represented solely by predicted tides or variability in MSL.

Tidal	1985	1989	1994	1999	2003	2008	2012	2017	2021
MSL	–	+ve	–	+ve	–	+ve	+ve	–	+ve

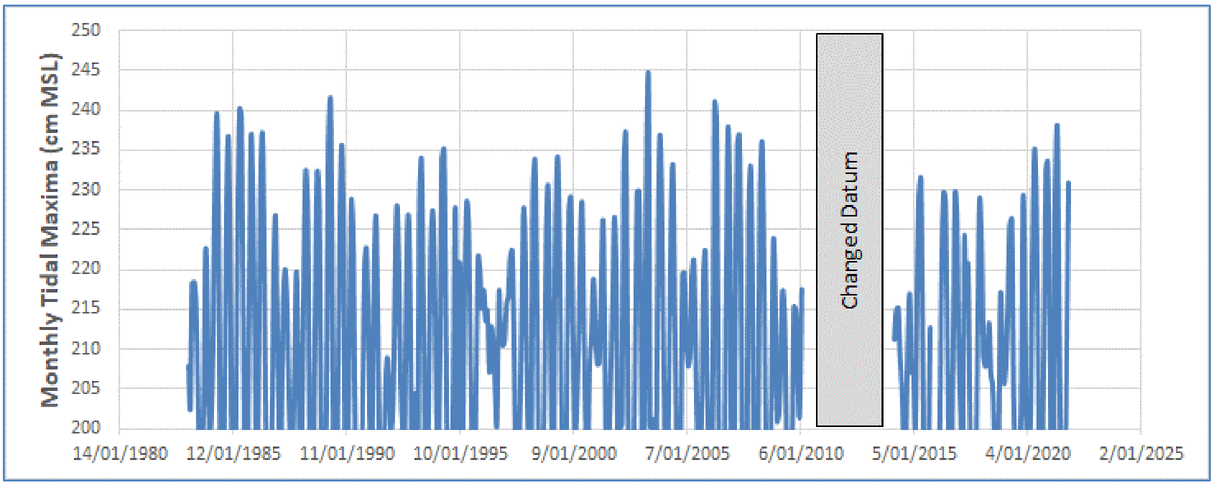

Figure 18. Monthly tidal maxima measured at Dampier.

6. ESSP physical setting – current knowledge

The key principles involved in assessing the key sedimentary processes and coastal changes on the NWS have been summarised in a suite of recent papers (Gallop *et al*. 2015; Dufois *et al*. 2017; Larcombe & Morrison-Saunders 2017; Larcombe *et al*. 2018, Ward *et al*. 2022a, 2022b). One of the most critical issues with these types of shorelines is their natural tendency for change. This relates in part to their exposure to a complex mix of periodic (repeating) and episodic driving forces. On generally decreasing timescales, these factors include SLR, inter-annual variability (ENSO), seasonality, storms, tides, waves and tsunami.

6.1. Periodic drivers

Here, periodic is taken as clearly and identifiably periodic – this essentially means the tides, but also includes some aspects of the wave regime (e.g., daily and seasonal) relevant to sediment transport at the coastline.

6.1.1. Tides

There are various stations that have produced oceanographic information specific to the ESSP region (Figure 19), with results summarised in O2 Metocean (2022b).

Regarding tidal currents, just outside the estuary (UNS05), spring tidal speeds approach 0.4 m/s. The M2 ellipse is orientated slightly west of N and east of S (Figure 20). The ellipse is relatively broad, so tidal currents rarely return to zero. Off the eastern end of the ESSP (ERA05), tidal currents are slightly weaker with spring tidal speeds rarely exceeding 0.3 m. The M2 ellipse is orientated WNW-ESE and is relatively narrow, so tidal current speeds often return to zero (O2 Metocean 2022b). Fine to medium sand is mobilised at around 0.3 m/s so these data indicate that flows are fast enough to mobilise fine sand, but would need to be supplemented by waves and/or wind-driven or other additional unidirectional current to transport medium sand and coarser material.

Figure 19. Locations of metocean data collection (O2 Metocean 2022b). Spectral wave observations were made at all sites except sites STR02 and SIC02. Locations UNS05 and ERA05 are most relevant to the ESSP area.

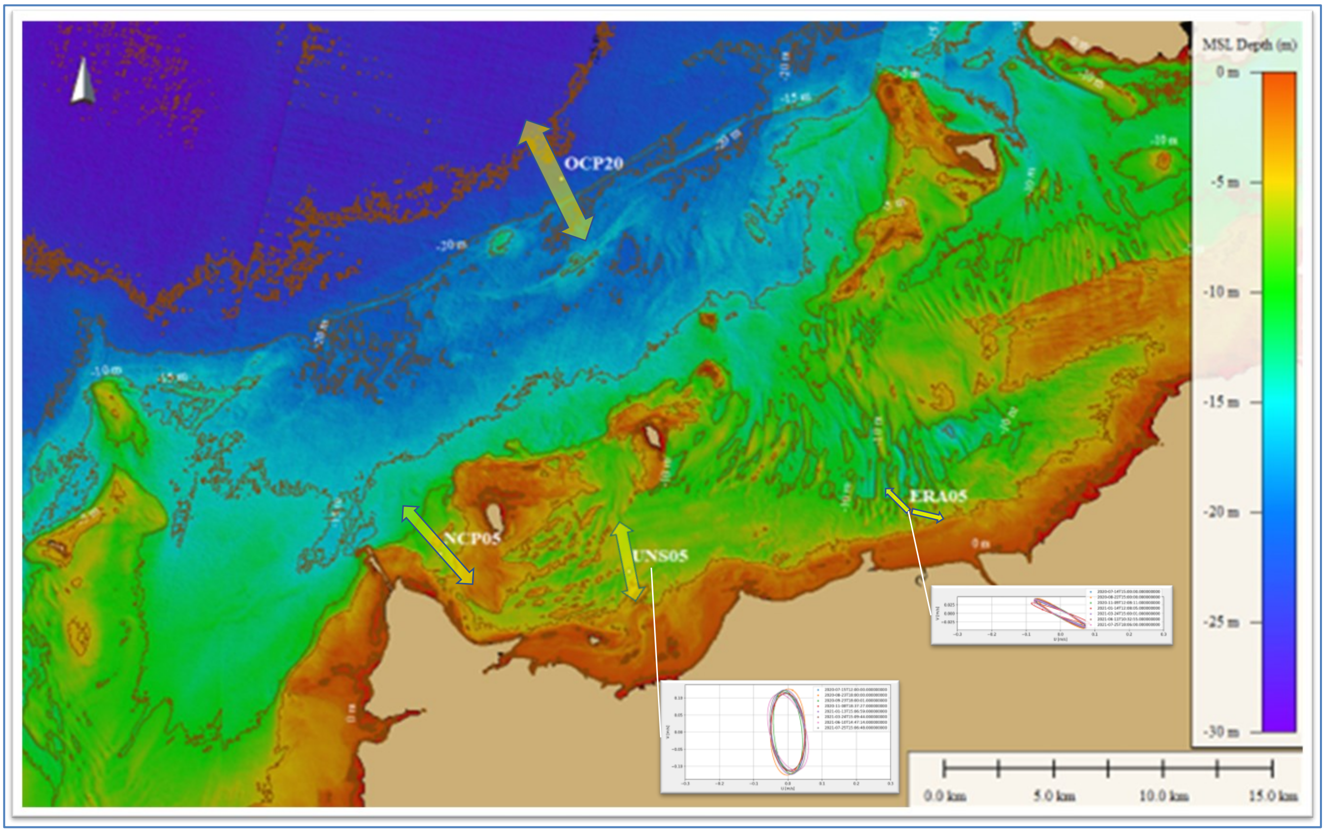

Figure 20. M2 tidal ellipses at the measured sites, with the ellipses illustrated for the two inshore sites.

6.1.1.1. Tidal creek flows are controlled by the elevations of high tide

The report uses the tidal planes adopted by LS (Table 4). The term 'hypsometry' means the measurement of the elevation of features of Earth's surface relative to a datum (generally MSL or similar). A hypsometric curve therefore represents the distribution function of elevations in a geographical area. Used in the context of the ESSP's tidal creek systems, the hypsometry of each creek is the vertical distribution of the bed elevations, which defines the volume of water within each creek system at different tidal elevations (Figure 21). This can be used to define the storage volume Vs (the volume at 2.5 m AHD) and the creek volume Vc (the volume at 1.7 m AHD). Emplacement of ponds in the intertidal zone will reduce the volume of water exchanged with each tide, especially above the level of the creek banks, therefore mostly affecting Vs (i.e. reducing storage), and reducing the ratio of Vs:Vc. This ratio is a strong indicator of key aspects of flow hydrodynamics and sediment transport capability (refer CP-BCH report).

The tides in the area generally exhibit a semi-diurnal inequality, i.e., there are two tides per day of dissimilar elevation, so that there is one large high tide and one smaller high tide within a 24-hour period. A section of the CP-BCH report noted three categories of tides (also described below), distinguished by the nature of flows in tidal creeks and the associated water elevations at high tide. In the ESSP project creeks, there are some uncertainties to note.

- Current measurements are only available for McKay Creek, and the characteristics of the tidal flows were used to derive the key tidal elevations noted in the CP-BCH report and used below.
- The elevations of high tides given in Table 4 are slightly lower (perhaps by 0.2 m) than derived in the CP-BCH report and used below. This is probably a result of some remaining uncertainty about the elevation of the instruments in McKay Creek used to derive water levels there, the differences in tidal elevations between McKay Creek and offshore locations and uncertainty about the data from the offshore locations (see O2 Metocean 2022b, Section 7 7. Water Level Measurements).

These uncertainties did not affect the main conclusions of the CP-BCH report, largely because other areas of uncertainty, including lack of flow data, lack of evidence of sand transport pathways and of sub-surface geology in the intertidal zone, are greater.

Table 4. Tidal planes in the area (supplied by LS), with the shaded column adopted by Leichhardt (from CP-BCH report)

Reference Level	Level (m CD)	Level (m AHD)	GEMS Tidal Planes* (m CD)	Tidal Planes Previously used by Advisian (m CD)	Tidal Planes Previously used by Advisian m AHD
HAT	4.71	2.34	4.71	4.73	2.485
MHWS	4.12	1.75	4.11	4.13	1.885
MHWN	2.87	0.5	2.86	2.90	0.655
MSL	2.37	0	2.36	2.33	0.085
MLWN	1.87	-0.5	2.31	1.90	-0.345
MLWS	0.62	-1.75	0.71	0.75	-1.495
LAT	0	-2.37	-0.04	0.00	-2.245
CD	0	-2.37		0	-2.245
	Adopted by Leichhardt		GEMS	Advisian	

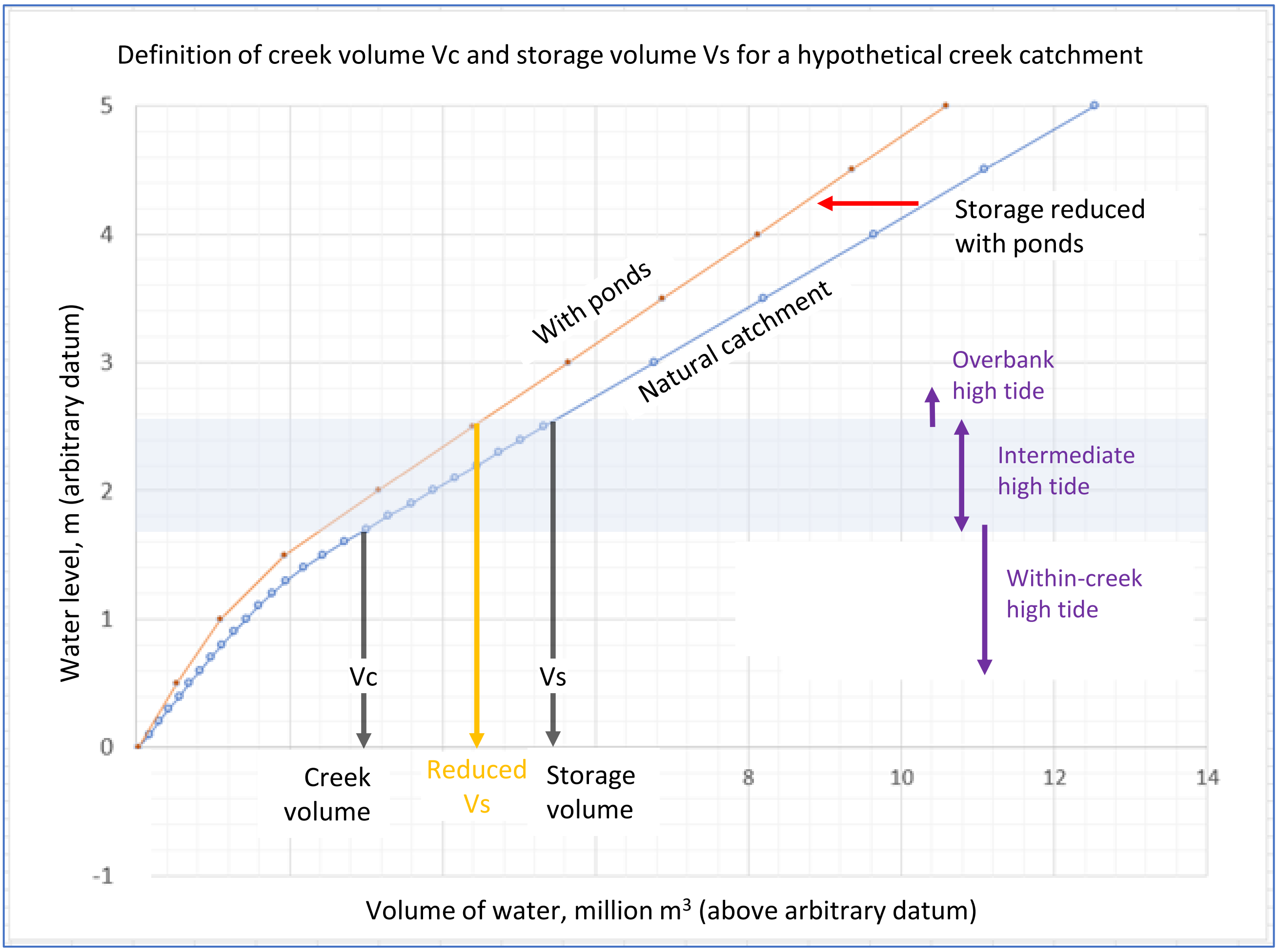

Figure 21. Example hypsometric curve of a tidal creek catchment (blue line) with reduced volumes due to emplaced ponds (orange line), and definitions of Vc and Vs.

Using the CP-BCH report, for McKay Creek, the key different types of tides are as follows.

- Overbank tides - where high tide ≥ ~2.5 m AHD
    - These large high tides cause water to flood the high intertidal areas beyond the estuarine mangroves and into the saltflats beyond, where samphire and benthic mats are located. Within the creek, these typically generate ebb tides stronger and of longer duration than the flood, and therefore tend to transport sandy sediment out of the creek mouth, helping maintain the creek channel. At the same time, the relatively long periods of inundation and slow currents within the estuarine mangroves and on the saltflats, can result in the deposition of fine sediment onto the bed in these environments.
- Intermediate tides – where high tide is 1.7 to ~2.5 m AHD
    - At high tides, these tides just begin to exceed the levels of the creek banks and show varying characteristics of overbank tides. Within the creeks, flows associated with these tides can vary in their character, probably associated in part with consequences of the preceding high water and strong ebb tide, and their impact on sediment transport is consequently variable.
- Within-creek tides - where high tide ≤ 1.7 m AHD
    - These small high tides move water into and out of the creeks, but the tide remains constrained at all times within the steep creek banks. These tides tend to drive little net transport of sandy sediment. In general, they can move fine sediment slowly towards the creek head, but this is neither a ubiquitous nor necessarily clear feature, and it is not significant in terms of the overall sediment budget.

Examples of these tides and the associated flows measured in the creeks are shown in Figure 22 for a tidal creek in Queensland, and in Figure 23, Figure 24 and Figure 25 for McKay Creek. Noting the fast, extended flow speed of overbank tides, and the fact that sand transport is a cubic function of flow speed, the most critical tides to understand are thus the largest overbank tides because they have the greatest potential consequences in terms of sediment transport and creek morphology. Using that logic, surges and heavy rainfall are also likely to be important, because:

- should a short-lived coastal surge drive water up onto the high tidal flats, above the predicted tidal levels, then it might generate some currents similar to those of overbank tide, and
- should there be a short-lived extreme rain event in the area (such as a squall) or a longer period of heavy rain that might result from a cyclonic low, the accumulation of water on the overbank areas might also drive a strong ebb-directed flow in the creeks, especially if the rainfall coincides with a falling tide.

In the ESSP project area, the elevation-flow relationship for natural conditions has only been derived for McKay Creek. However, the distribution of coastal slopes (section 6.3.1.1) allows moderate to high confidence that the relationship will be similar within the catchments in Areas A, B and McKay Creek of Figure 17. In the absence of more detailed information, that will be an assumption used in this report’s interpretations.

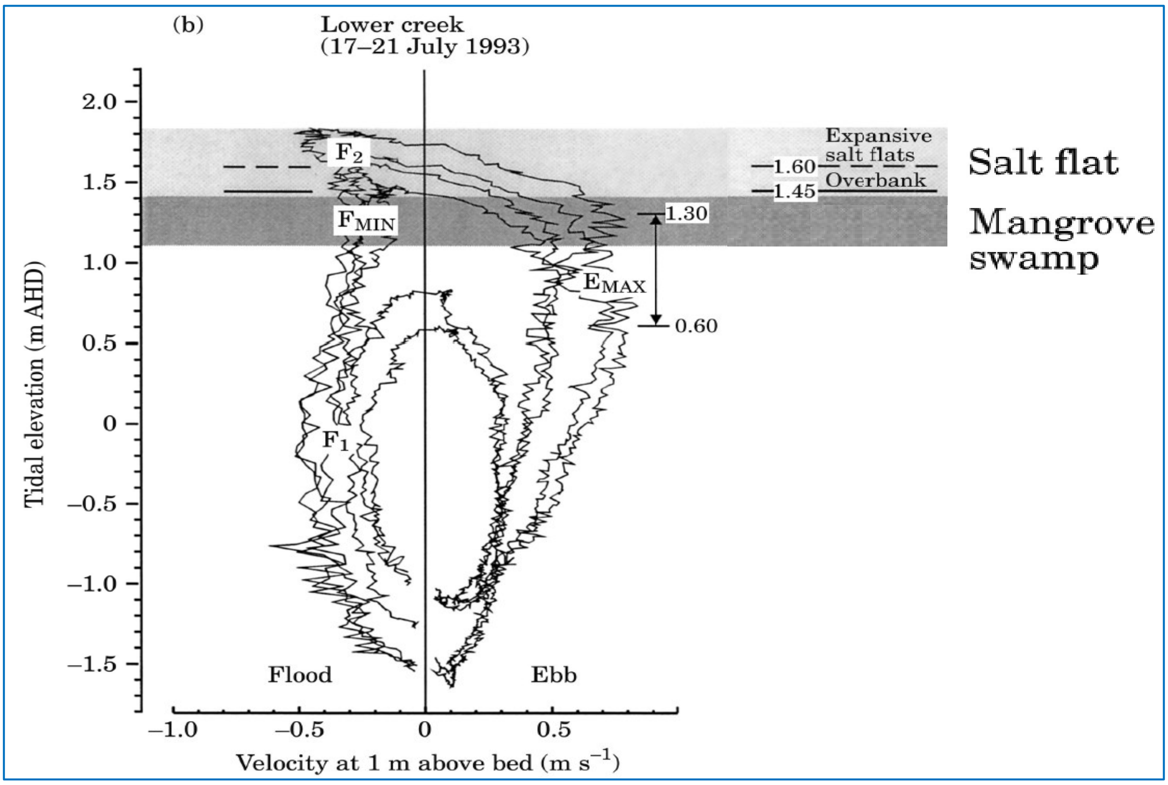

Figure 22. Velocity-stage diagrams for lower Cocoa Creek, Townsville, during a spring-tide period with strong semi-diurnal inequality. For the 3 overbank tides illustrated, the ebb speeds were far faster than the flood. For the 2 within-creek tides illustrated, the flood and ebb were largely similar in speed and duration. Velocity peaks have the following abbreviations: F1, initial flood peak; FMIN, bank-full minimum speed; F2, second flood peak of overbank tide; EMAX, maximum ebb speed, that occurs when the ebb flow has fallen to become constrained within the creek banks (Modified from Bryce et al., 2003).

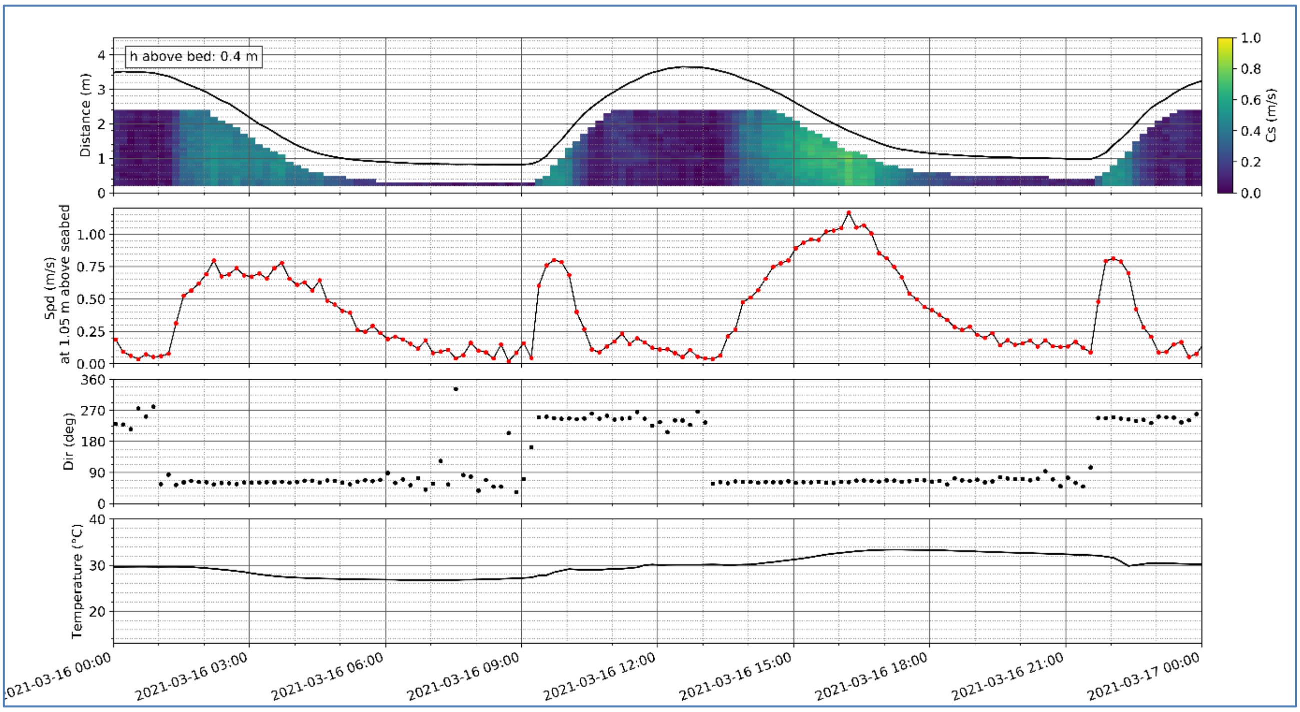

*Figure 23. Time-series data over a 24-hour period, showing ebb dominance in peak speed and duration of an **Overbank Tide**. The four time-series plots show: tidal height above the depth sensor with vertical distribution of speed, current speed 1.05 m above the bed, current direction 1.05 m above the bed, and water temperature at the bed (from CP-BCH report).*

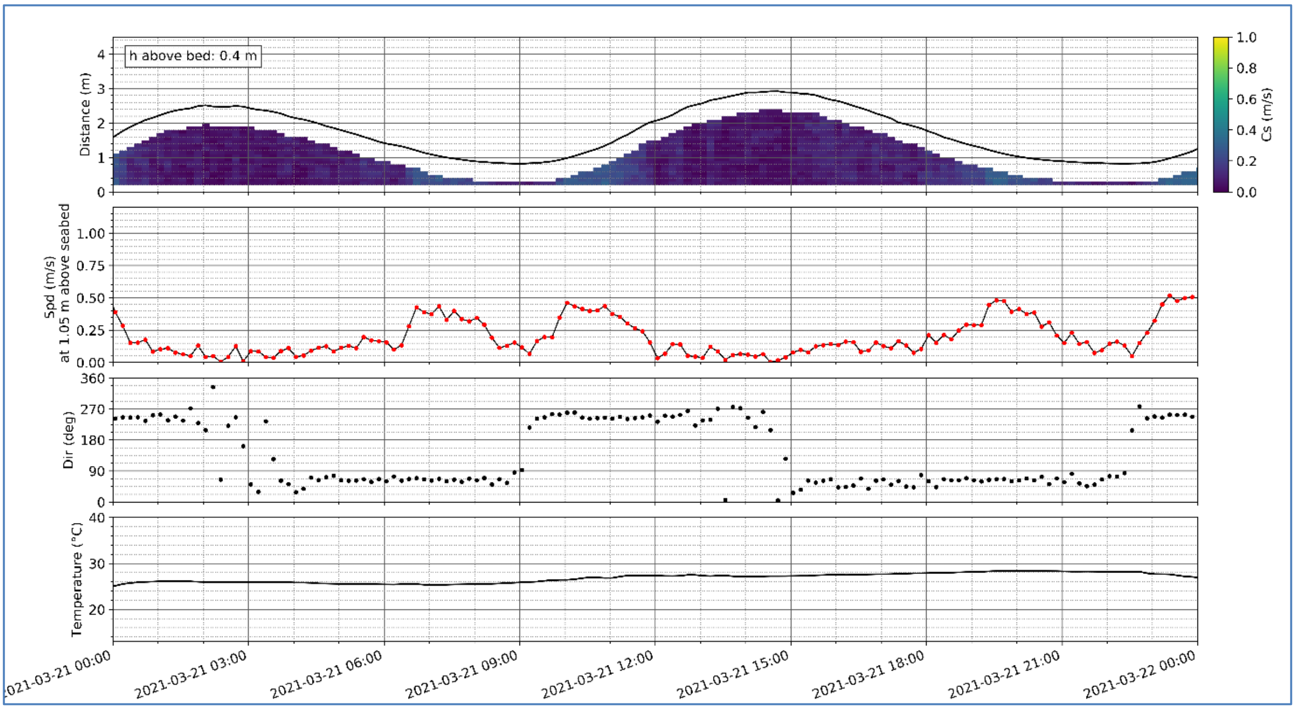

Figure 24. Time-series data over a 24-hour period, showing characteristics of an ***Intermediate Tide****. (Plots as described in Figure 23).*

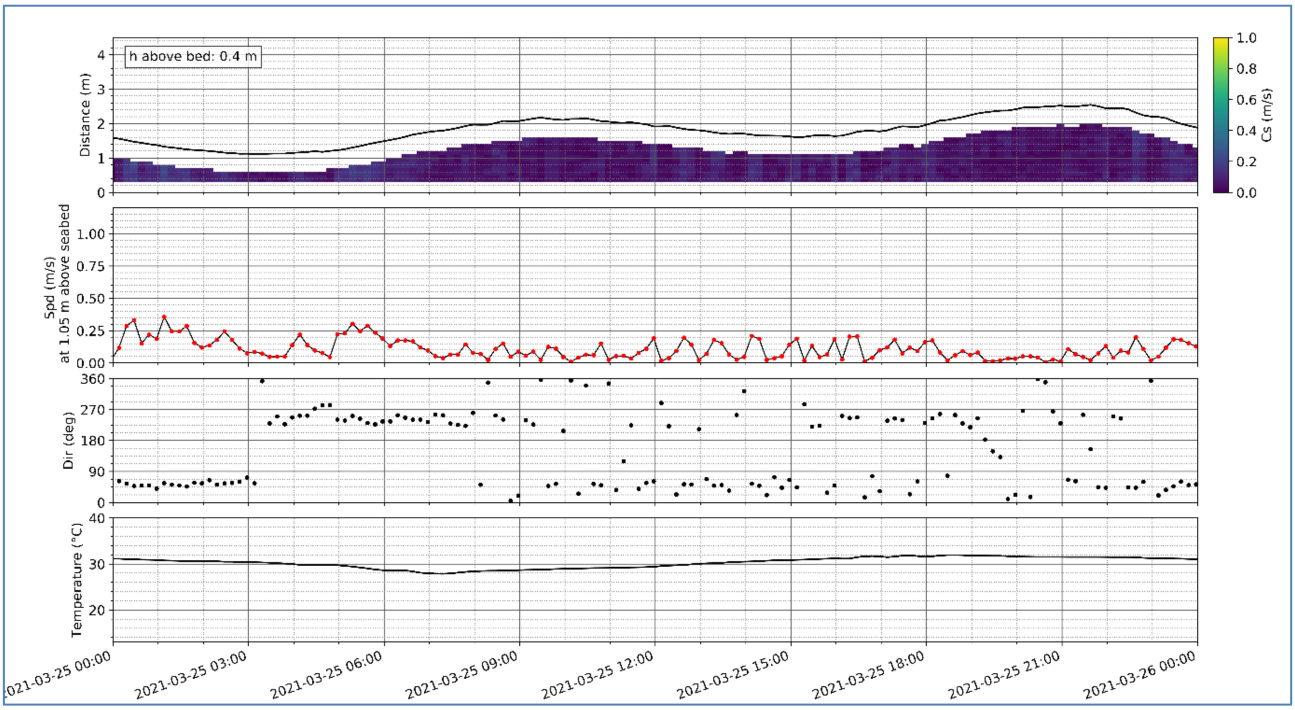

Figure 25. Time-series data over a 24-hour period, showing characteristics of a ***Within-Creek Tide****. (Plots as described in Figure 23).*

6.1.1.2. Tidal dynamics indicated by catchment hypsometry

As noted in Larcombe (2024), the hypsometric data and the ratio Vs:Vc for each catchment (Figure 26) can be used a first-order indicator of possible tidal flows through the creek mouths for those tidal creek systems where there have been no measurements (i.e., all creeks except McKay Creek), and the hypsometric curves (Figure 27) can help compare some catchment characteristics.

Dealing here with the natural flows, the western systems (Creek 2, Baldy/Straight and McKay) have very similar ratios, at 3.0 to 3.3, like those catchments fronting the easternmost ponds (Creeks 7 & 8).

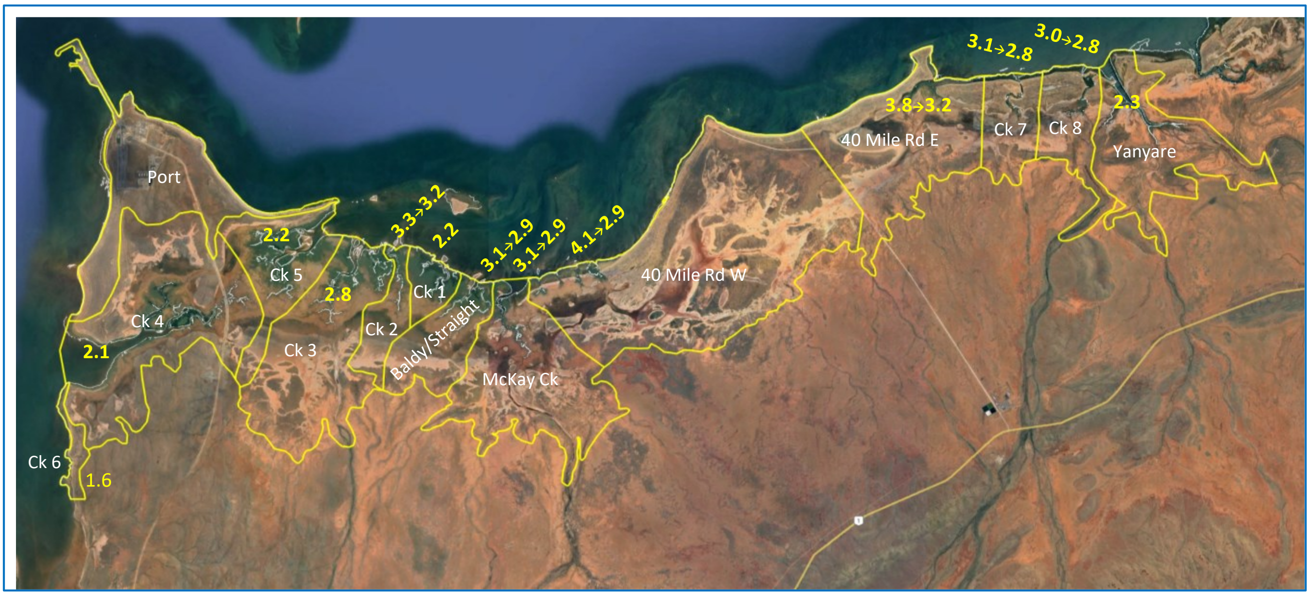

Figure 26. Calculated Vs:Vc ratios for the natural catchments. For those catchments where the ponds of scenario 7.2.1, the first number is the natural ratio, and the number after the arrows is the new ratio with the ponds (Larcombe, 2024).

It is notable that 40 Mile Road W and E are markedly different to other catchments. They have the largest Vs:Vc ratios for the entire ESSP region, at 4.1 and 3.8 respectively, are similar in overall hypsometry but both their curves are relatively shallow across the elevation range 1.7 to 2.5 m AHD (i.e., elevations between overbank tide and Highest Astronomical Tide (HAT) and therefore both indicate a relatively strong hypsometric effect on tidal flows for high tides. It is also notable that the shallow slope of the hypsometric curve for 40 Mile W (Figure 27) cuts across many other curves, indicating that it is not at a similar stage of physical equilibrium to those other catchments. This may be a result of the different range of sedimentary processes it has been subject to over several thousand years (or perhaps much more), including its relative lack of modern terrestrial sediment input and its partially sheltered nature behind the spit.

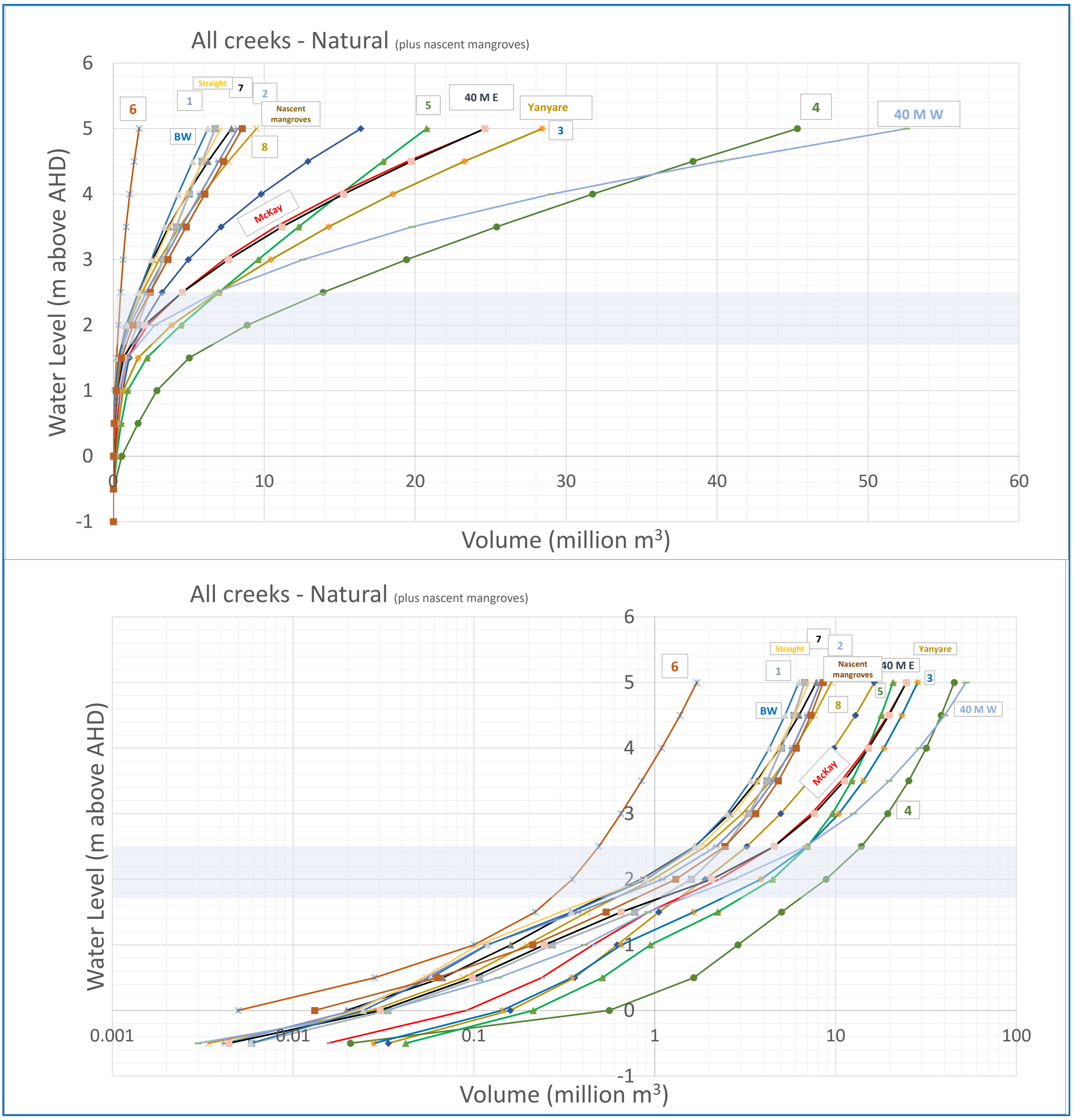

Figure 27. Hypsometric curves for all natural catchments (plus the artificial scenario 7.2.1 catchment of the nascent mangroves) (Larcombe, 2024). Note the shallow slope of the curve for 40 Mile Road W, that it cuts across many other curves, indicating that it is not at a similar stage of physical equilibrium to those other catchments. The blue bar highlights the elevation range 1.7 to 2.5 m AHD.

6.1.2. Seasonal waves

The sea state of the southern NWS comprises contributions from Southern Indian Ocean swell, Winter Easterly swell, 'West Coast' swell, tropical cyclone swell, local wind-generated sea and 'old sea' (O2 Metocean 2022b). Of these, several are notably seasonal in nature. (NB – cyclonic conditions are dealt with as an episodic driver, in section 6.2.3). In the winter months, three factors are of note:

- Southern Indian Ocean swell. This swell derives from the S and SW, is of typical period 12 to 16 seconds, and deep-water heights tend to be greater in winter, typically at 2 m, before refracting across the shelf;

- Winter Easterly Swell. Synoptic offshore winds can drive swell on the outer shelf. These winter offshore winds (see Figure 28, months of May, June & July) can reduce waves approaching the ESSP shoreline;
- Old Sea. Old Sea may be generated by surges in the winter SE Trade Winds in the deeper waters to the N of Cape Preston. In winter, old sea is refracted around the Dampier Archipelago and arrives at Cape Preston from the NNE.

In the summer months:

- Southern Indian Ocean swell is smaller in summer, typically 1 m;
- Old Sea is generated by surges in the summer NW Monsoon, and it is refracted around the north of the Montebello Islands to arrive at Cape Preston from the NNW.

Put simply, Regnard Bay is sufficiently protected from swell and sheltered from local winds that 'Old Sea' becomes an important part of the local sea state. Whilst at all times, the waves reaching the coast are modified by the presence of the offshore islands, the shallow shelf, the inner-shelf bathymetry and coastal orientation, there are seasonal differences in waves that will affect resuspension of sediments on the shelf and in the nearshore zone. The period, size and direction of waves approaching the ESSP region thus varies seasonally, potentially driving coastal sediment transport in different directions and at different rates.

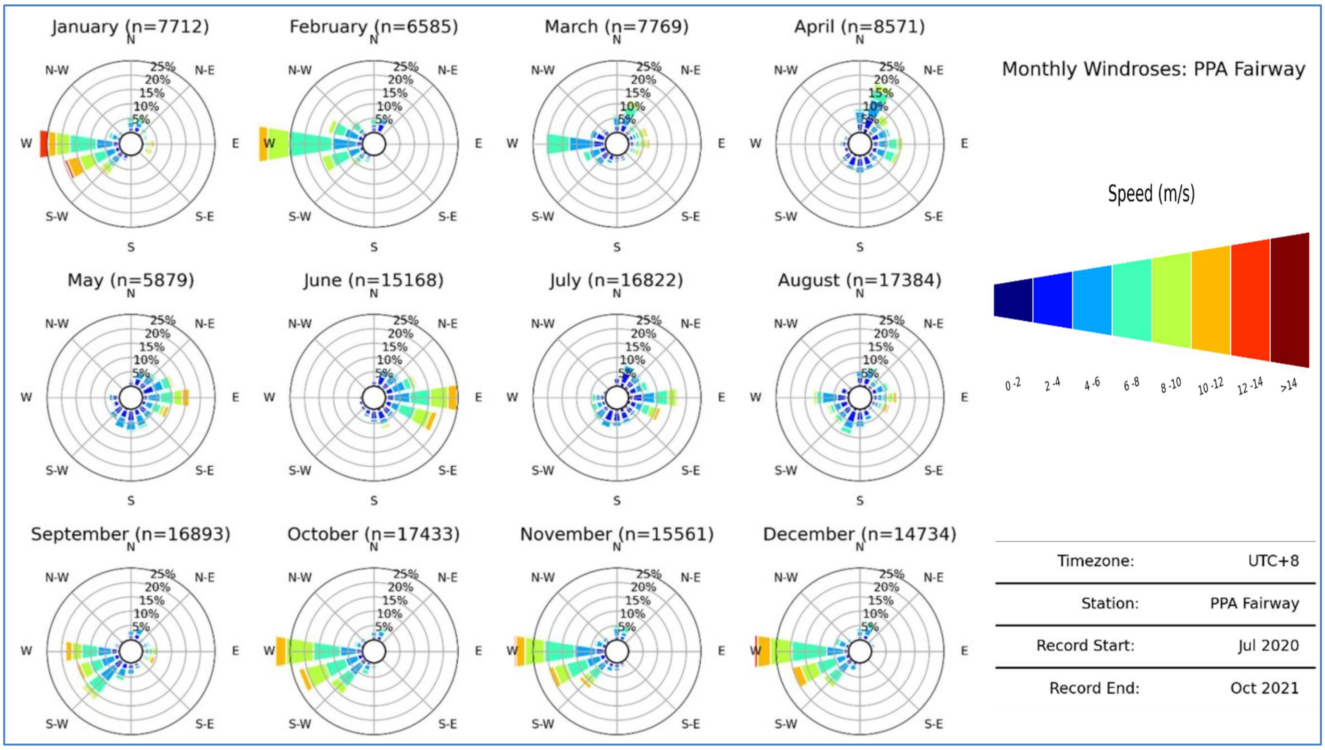

Figure 28. Monthly wind roses from the Dampier Fairway meteorological station (modified from O2 Metocean 2022b). This confirms the seasonal shift in winds, with the strongest winds associated with summer tropical storms. The most persistent winds are Westerlies - October to February, and Easterlies – May to July.

6.2. Episodic drivers

6.2.1. Meteorology

The climate of the Pilbara coast reflects its location at around 20°S latitude in the sub-tropical high-pressure belt, with its southern limit at the boundary between the Temperate and Tropical Coast Regions (desert and grassland Köppen zones in Stern *et al*. 2000). The region experiences an arid sub-tropical (sub-monsoonal) climate, which is hot throughout the year, with typically low but variable rainfall falling during both summer and winter seasons.

Most weather systems experienced are extra-tropical in origin, although occasional tropical cyclones are associated with almost all the severe wind observations on record. During summer months, rainfall mainly occurs from thunderstorms, with a highly variable contribution from tropical cyclones (Milton 1980). Tropical cyclones are the dominant weather system of the Pilbara (Dare & Davidson 2004), and the intensity of tropical cyclones is such that direct impact, even by a relatively weak cyclone, commonly causes “highest recorded” levels of wind, wave height and water level. Typically, 3 to 5 cyclones might approach the Pilbara coast during the cyclone season, with 1 or 2 causing destructive winds at any specific location (Eliot *et al*. 2013).

Synoptically, the region is dominated by relatively diffuse extra-tropical high-pressure systems, with latitudinal movement of the pressure belt inducing two distinct seasons, referred to here as ‘cool’ and ‘warm’ - there are short transition seasons between these two main seasons (Figure 29). The cool season typically extends from May to August, with the warm season normally from October through March (Pearce *et al*. 2003). Sea-breeze cells cause diurnal variation in the strength and direction of winds, for ~5 to 25 km both landward and seaward from the coast. Although these cells are strongest during the warm season, they may occur at any time of year.

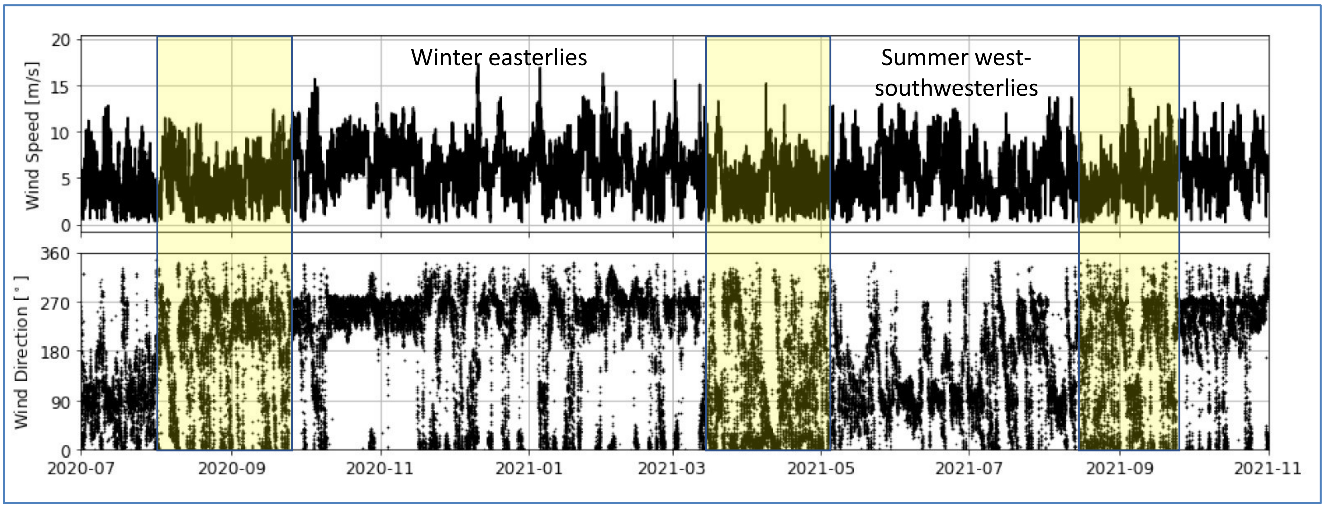

Figure 29. Dampier Fairway winds for July 2020 to Oct 2021. Note the seasonal shift from winter easterlies to summer west-southwesterlies. Yellow panels = Transitional seasons.

The relative intensity of seasonal winds is known to vary on an inter-annual basis. This behavior loosely corresponds to global climate variations, as described by El Nino-Southern Oscillation modes (Figure 30), with stronger easterly conditions typical during the La Nina phase and stronger westerly conditions during the El Nino phase. This pattern is in addition to local variations in the Indian Ocean climate, and modification of coastal winds by fluctuations of sea breeze cell intensity.

Rainfall within the Pilbara is generally low, but highly variable, with potential for heavy rainfall in either summer, often associated with tropical cyclones, or winter, commonly linked to northwest cloud-bands. Consequently, the region can experience both flooding and drought conditions, each of which can disturb intertidal habitats.

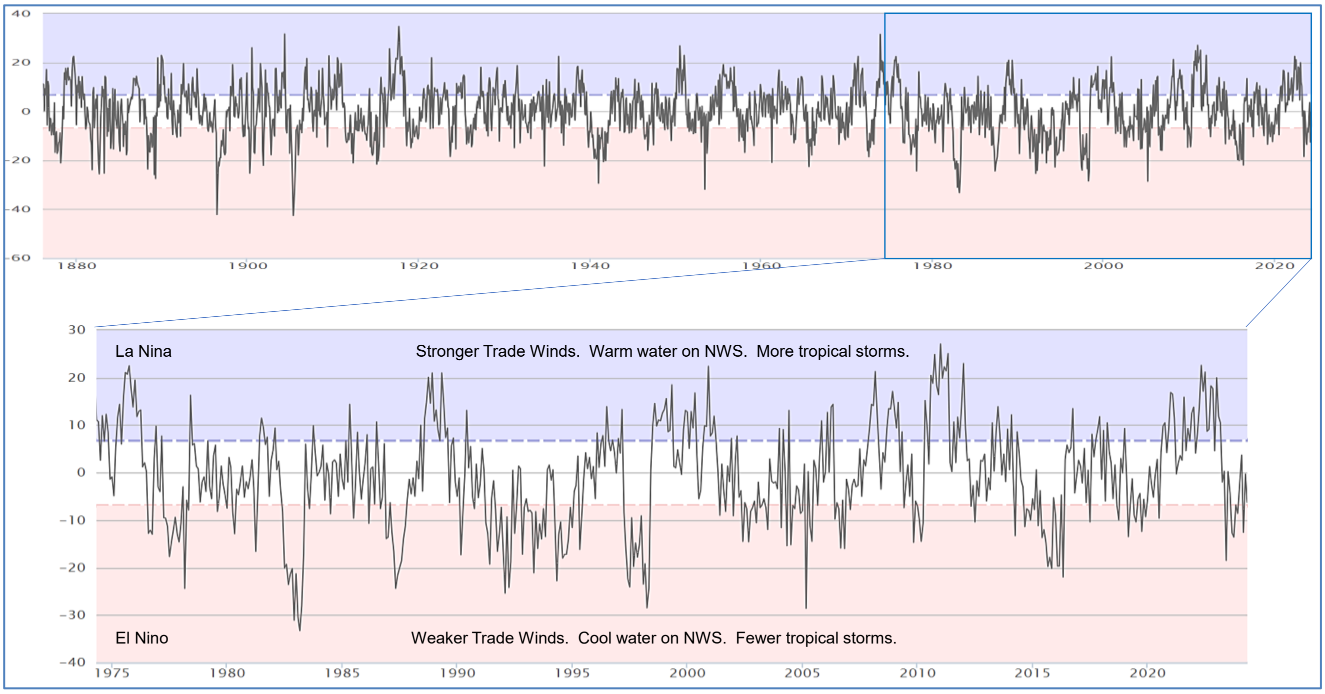

Figure 30. Monthly measures of the Southern Oscillation Index (SOI) since 1880, with detail for the period since 1975. The SOI is a monitor of the ENSO, so can inform on the El Nino and La Nina conditions. SOI above +ve 8 = La Nina = stronger Trade Winds, warmer water on the NWS and more tropical storm activity. SOI below -ve 8 = El Nino = the opposite.

6.2.2. Rivers & freshwater runoff

The ESSP area's rainfall regime is described by Land and Water Consulting (2023a, 2023b). Mean rainfall data for the area is around 290 mm/yr with most rainfall occurring between January and June. Annual pan evaporation rates average around 3,200 mm/yr (SILO station number 004083), far exceeding precipitation for every month of the year (Figure 31). There is significant variability between years, with episodic events generating high rainfall (e.g., Figure 32).

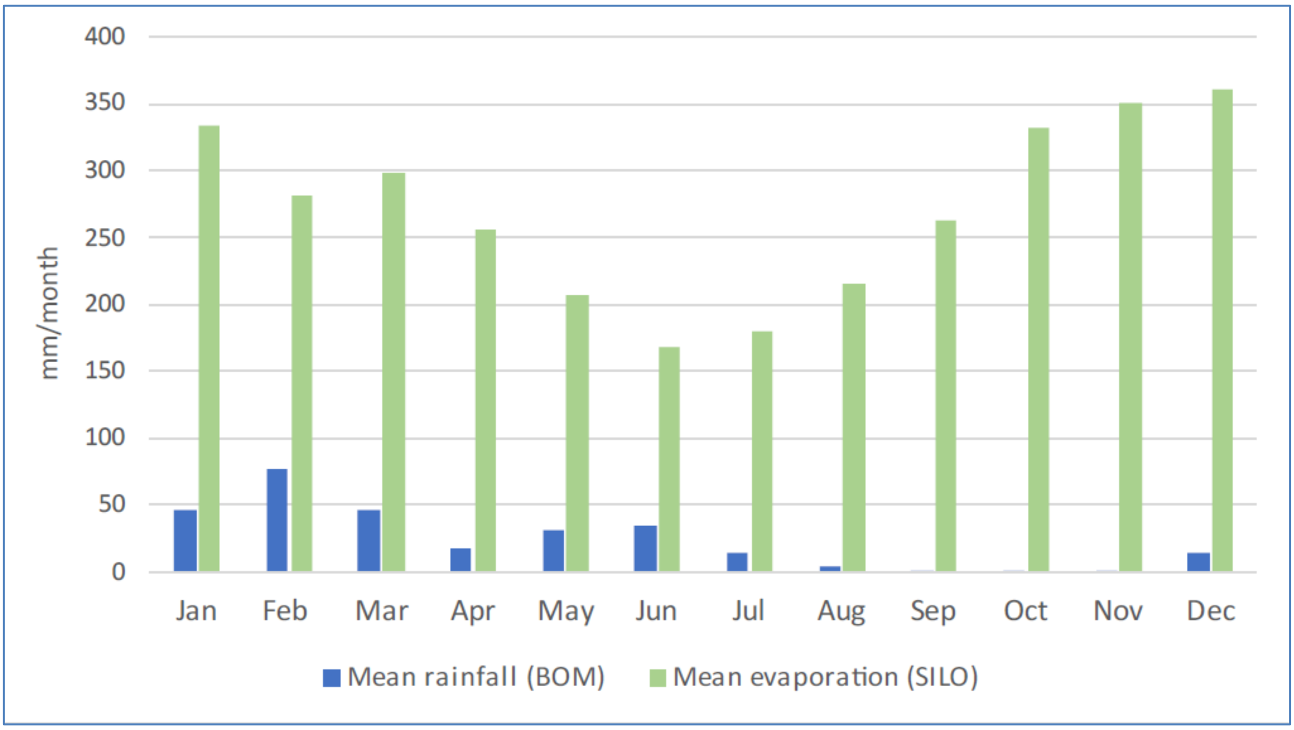

Figure 31. Mean monthly rainfall and evaporation data for the ESSP area (Land and Water Consulting 2023b).

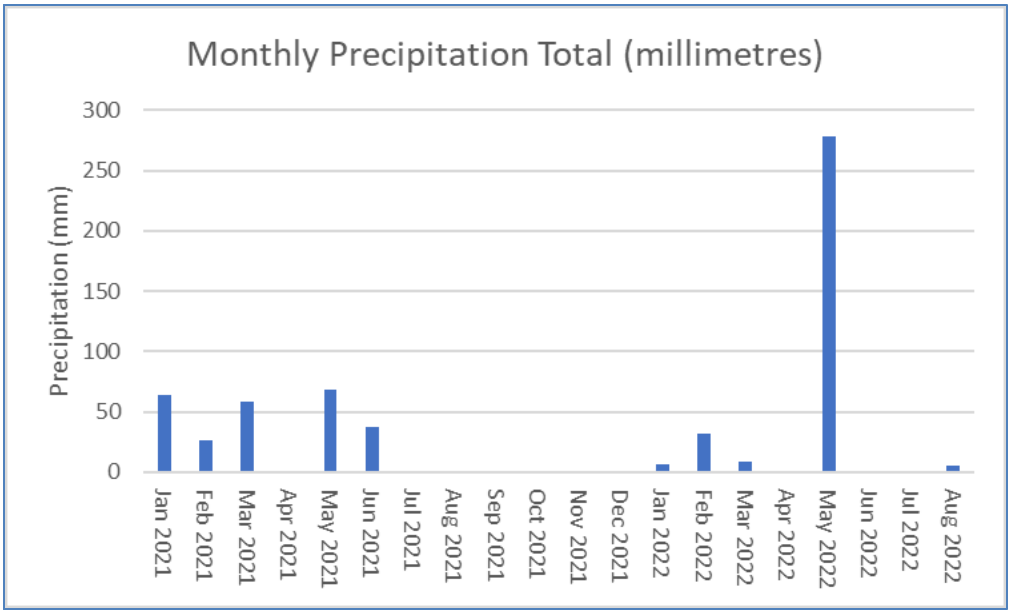

Figure 32. Monthly rainfall totals for Jan 2021 to Aug 2022.

As well as the major creeks (Eramurra, McKay and Devil; Figure 33), there are several minor creeks that can contribute freshwater and sediment to the coastal systems, notably between Eramurra and McKay creeks, and another that enters the 40 Mile Road W catchment (Figure 34, see also section 9.1.2).

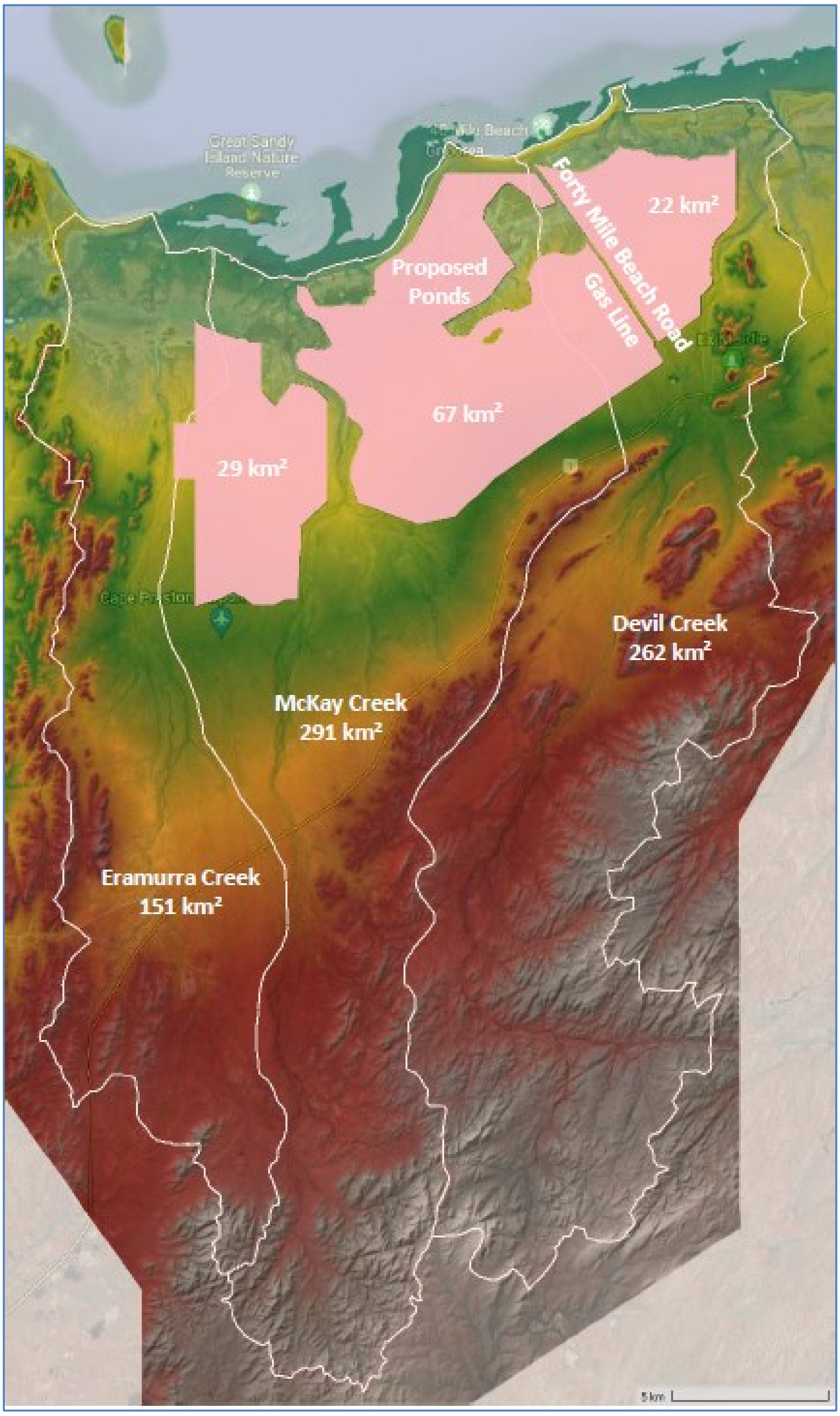

Figure 33. The ESSP and contributing river catchment areas (Land and Water Consulting, 2023a). The ponds mostly affect the McKay and Devil Creek catchments.

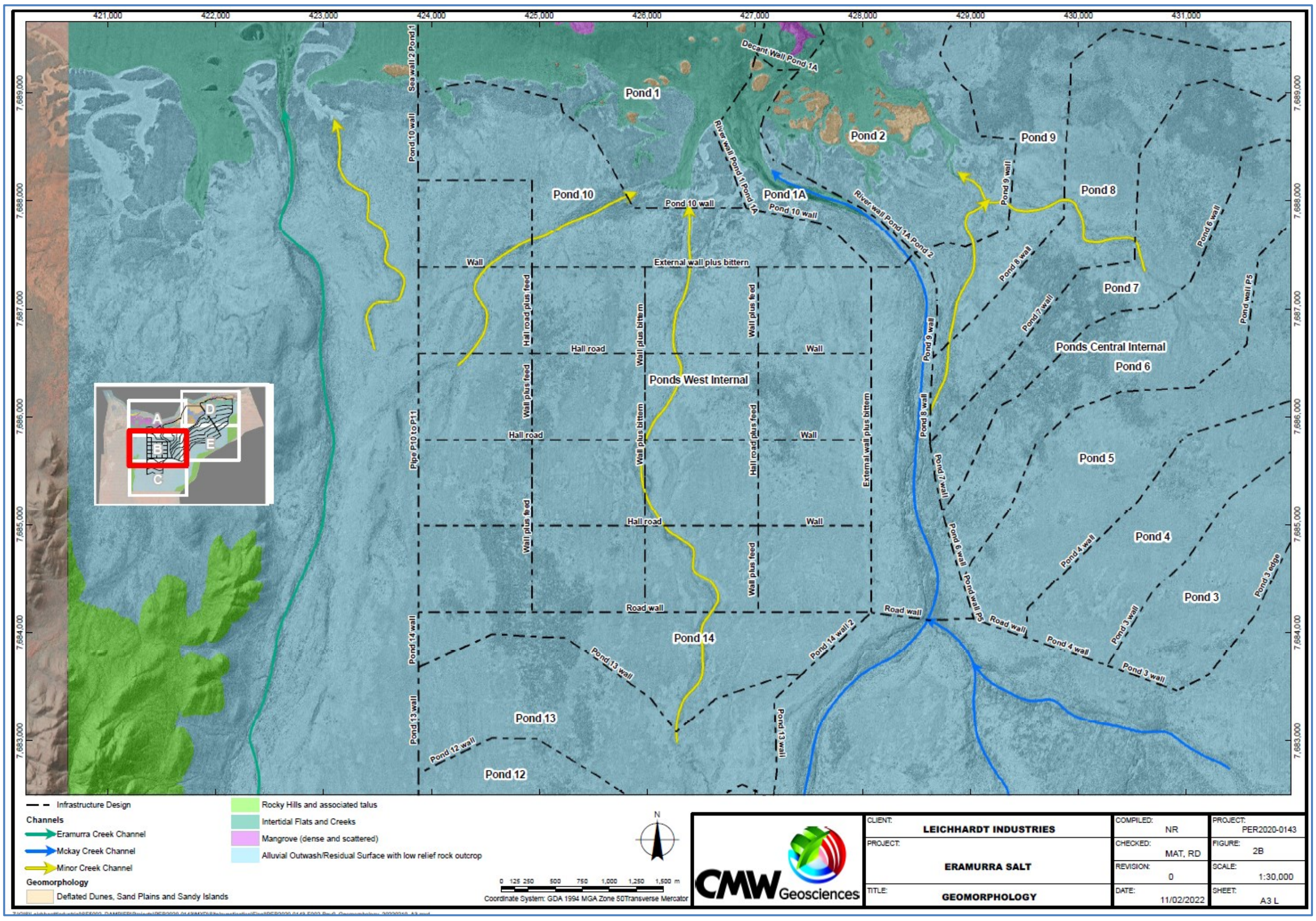

Figure 34. Minor drainage channels west of the uppermost tidal area of McKay Creek (CMW Geosciences 2022). Note that several minor channels are covered by the proposed ponds.

6.2.3. Tropical Cyclones

Tropical cyclones are intense, clockwise-rotating (in the Southern Hemisphere), mobile storm systems, developed through strong convective uplift from ocean heating when there is low tropospheric shear (McBride & Keenan 1981). These conditions typically occur during the Australian summer season (Nov-Apr), with 0 to 12 tropical cyclones occurring in a single season. Interactions with the continent, large-scale synoptic system and the Coriolis effect partly steer these storms, developing a focal area of cyclone activity off the Pilbara coast.

Tropical cyclones can develop storm surges through a combination of strong winds, low atmospheric pressure and bathymetric constraint. This can be further enhanced by storm mobility, with resonance developed if the cyclone travels in the same direction and speed as the propagating signal. However, extreme storm surges reported from the Pilbara (see section 6.2.4) are generally associated with very strong onshore winds, creating opportunity for wind setup against the coastline. The causes of positive surges are not simple. Extreme positive surges result from a combination of heavy wave breaking (usually but not always associated with onshore winds - swell can significantly contribute to this), and strong alongshore (southward or westward) current flow - which results in geostrophic setup due to the Coriolis effect. Surges might also occur as Kelvin Waves, setup further north, and propagating poleward along the coast (Fandry & Steedman 1994). Wind setup itself is usually too transient to be significant, but it does add to surge magnitude.

6.2.4. Surges

Positive surges are relevant because of their capacity to cause coastal change, through the action of associated waves as the surge rises and falls, of the flows across high tidal and supratidal areas, and of enhanced seaward-directed flows in creeks on the relaxation phase. RPS (2021) and Land and Water

Consulting (2023a) have presented the recurrence interval of a series of combined tide and surface water levels (Table 5, Figure 35).

Table 5. Combined tide and storm surge levels (m AHD) from the ESSP Metocean report (RPS 2021)

Location\AEP	1 in 10	1 in 20	1 in 25	1 in 50	1 in 100	1 in 500
Average Jetty+Bays	**2.69**	**2.85**	**2.89**	**3.04**	**3.19**	**3.50**
Jetty Head	2.63	2.76	2.80	2.92	3.03	3.30
Bay 1	2.69	2.85	2.90	3.05	3.19	3.50
Bay 2	2.71	2.87	2.92	3.07	3.22	3.54
Bay 3	2.71	2.89	2.94	3.11	3.27	3.63
Bay 4	2.70	2.86	2.91	3.07	3.22	3.54
Anchorage 2	2.53	2.64	2.67	2.77	2.87	3.07

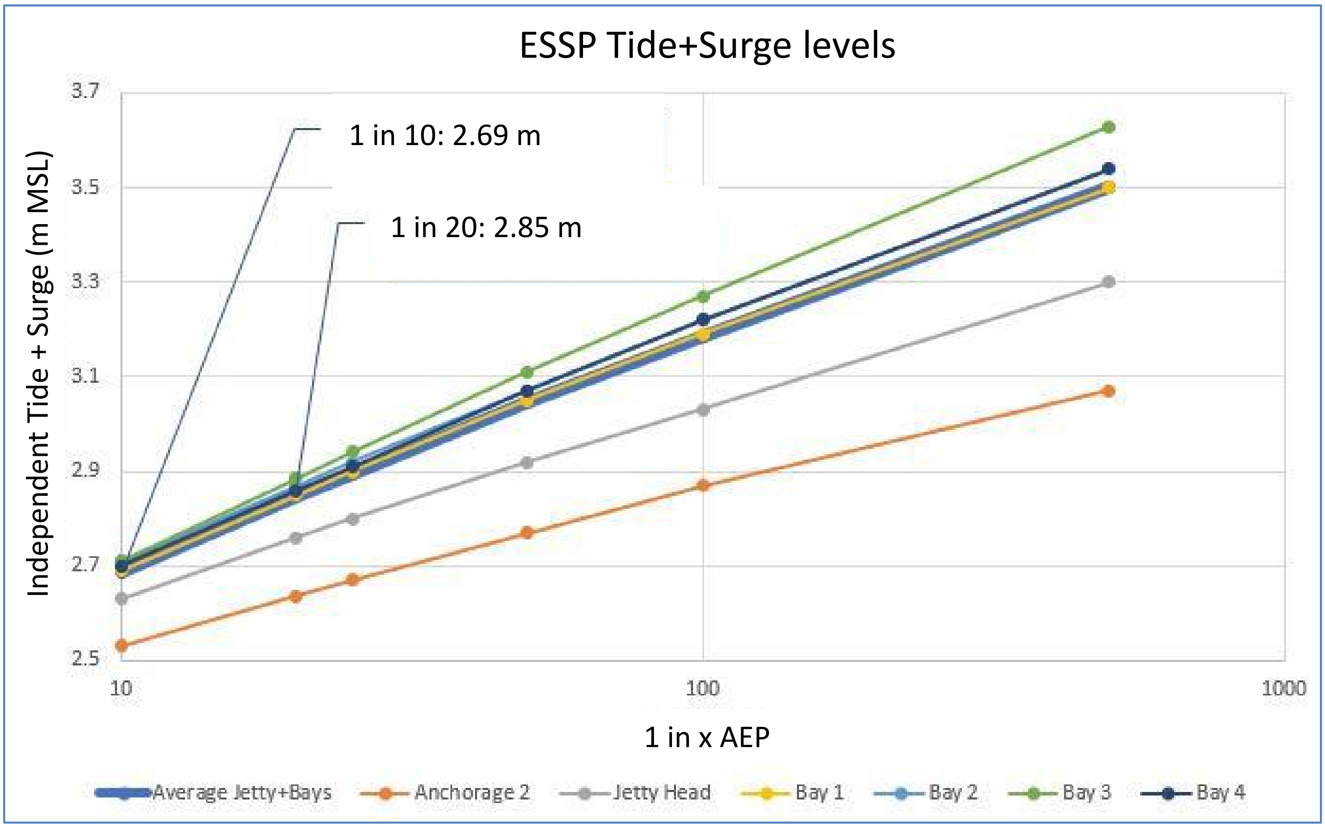

Figure 35. Tide and storm surge level interpolation (replotted from Table 5).

The Dampier tide gauge record has been analysed to describe a series of positive storm surges (Table 6). These measurements indicate that since 1980s, these have exceeded +1 m in magnitude around twice each decade, reaching nearly +3 m in magnitude. Of these, TC Orson and TC Clare had an almost direct impact on the ESSP coast, and all are likely to have generated a significant surge, as well as large waves. Note that tropical lows can be important, and TL02U in December 2020 would have generated a significant surge.

Despite this record of potential episodic events, the associated record of coastal advance or retreat is less than clearly related (CP-BCH report). For example, the western coast of Gnoorea spit (Area D of Figure 17) is a wave-exposed sandy shoreline, and it might be expected to respond to large wave events, especially where the waves have a component from the NW quadrant. In 1998-9, two major cyclones occurred only 4 months apart, TC Ilona in Dec. 1988 and TC Orson in Apr. 1989. There is no evidence that these generated major change at area D (Figure 36), nor indeed elsewhere along the ESSP shoreline (CP-BCH report section 7, ‘Quantitative changes in coastal erosion and progradation’), perhaps partly because TC Orson’s surge peaked near the time of low tide so that effects were minimised.

Table 6. Selected storm surges identified in the Dampier tide gauge record.

Residual	Date	Tropical Cyclone	Max Intensity, Approach, Position	Comments
2.89 m	23 Apr 1989	TC Orson[4]	Cat 5, N, 55 km SW of Dampier	Biggest influence would have been from inverse barometric pressure effect and wave setup. Winds would have been offshore at Cape Preston.
1.95 m	10 Apr 1996	TC Olivia[5]	Cat 4, NW, 100 km SW of Dampier	Crossed the coast as a Category 4, bringing strong wave setup and strong onshore winds (wind setup).
1.58 m	8 Feb 2020	TC Damien[6]	Cat 3, NNW, straight over Dampier	Only just reached Category 3. Passed directly over Dampier, so inverse barometric pressure would be significant. Strong wave setup. Probably offshore winds at Cape Preston. Maybe some wind setup at Dampier.
1.42 m	9 Jan 2006	TC Clare[7]	Cat 3, NE, 55 km SW of Dampier	Basically a 'shore parallel' storm, very effective in generating along-shelf currents. The associated geostrophic setup (from the Coriolis effect), was probably the biggest contributor to surge.
1.29 m	17 Dec 1988	TC Ilona[8]	Cat 3, NNW, 70 km SW of Dampier	Combination of wave setup and onshore winds would have contributed most to this surge.
1.15 m	30 Mar 2006	TC Glenda[9]	Cat 5, NNE, 180 km SW of Dampier	A shore-parallel storm, generating strong along-shelf currents and associated geostrophic setup (from Coriolis). Reached Category 5 briefly, when over 400 km from Dampier. Passed Dampier just below Category 4.
0.97 m	24 Feb 1995	TC Bobby[10]	Cat 3, NNE, 130 km SW of Dampier	Surge would have had contributions from wave setup and from current-induced geostrophic setup. Winds likely offshore at the time of peak surge.

[4] http://www.bom.gov.au/cyclone/history/pdf/orson.pdf
[5] http://www.bom.gov.au/cyclone/history/olivia.shtml
[6] http://www.bom.gov.au/cyclone/history/pdf/damien2020.pdf
[7] http://www.bom.gov.au/cyclone/history/pdf/clare.pdf
[8] http://www.bom.gov.au/cyclone/history/pdf/ilona.pdf
[9] http://www.bom.gov.au/cyclone/history/glenda.shtml
[10] http://www.bom.gov.au/cyclone/history/bobby.shtml

Figure 36. Area D - Time-series of erosion (-ve) and progradation (+ve) for selected points in Area D since 1988 (CP-BCH report). Note the ubiquitous erosion between 1995 and 1999, largest in the north, but there has been little overall change in coastal location over the entire period, with a total of ~4 m horizontal erosion over 32 years, i.e., 0.12 m/yr.

There was a 6-year long phase of erosion between 1993 and 1999, especially in the north of the spit, and generally in the ESSP area, within which period occurred TCs Bobby (Feb. 1995) and Olivia (April 1996). Later, TC Vance (1999) passed further offshore (Figure 37), and whilst local variations occur along the project area's coastline, there is a local and regional signal of coastal advance (1999-2003). As noted in the CP-BCH report, this 1993-1999 erosional phase of erosion and subsequent 1999-2003 recovery is consistent with the regional signal, which is present for many 10s of km in either direction along the coast. Further, since 2003 (i.e., post-recovery), five cyclones have passed nearby, during which time most of the ESSP coastline has experienced relatively little movement in the location of MSL, except for some fluctuations in Area C in 2011-2 (CP-BCH report).

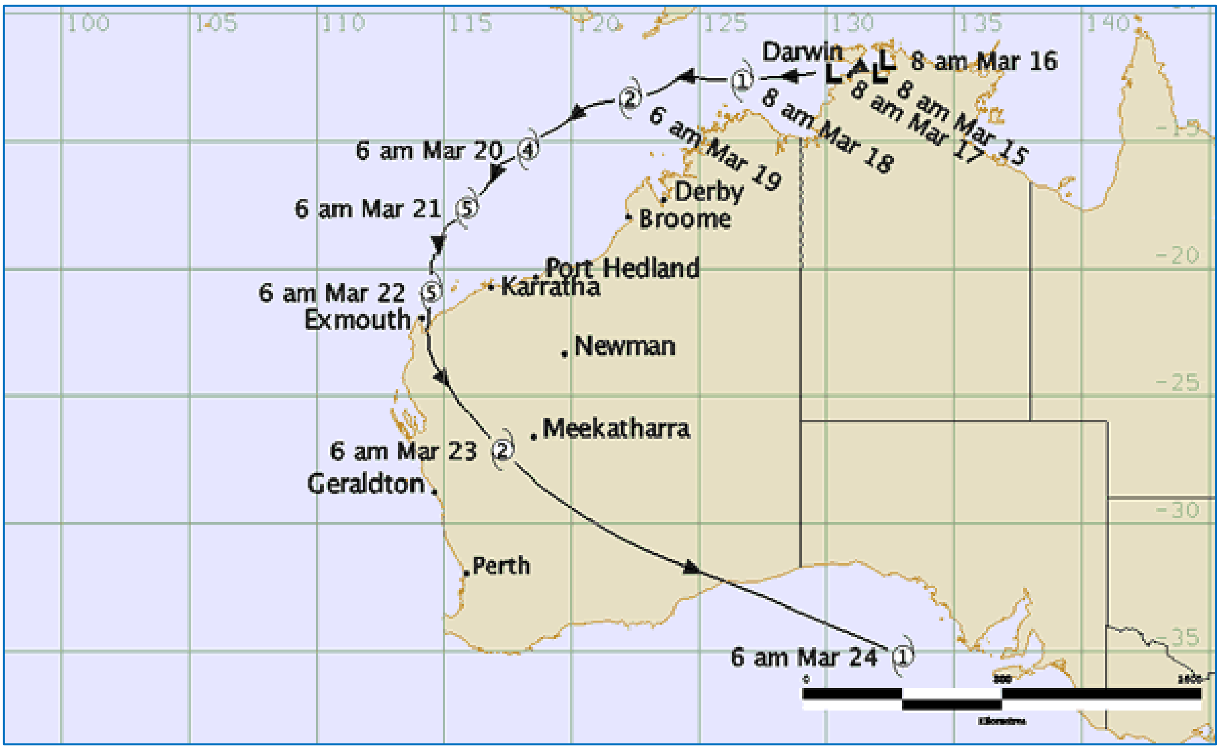

Figure 37. Track of Severe TC Vance in 1999 (BoM, 2000). The cyclone passed NW of the ESSP area, so exposing the coastline to the stronger eastern side of the wind field and associated waves.

We can conclude that the effect on the coastline of periods of several cyclones is not necessarily clear, and that the effect of individual cyclones is largely undetectable, at least in these annualized records. More broadly, the time-series data on coastal erosion cannot yet be closely linked with the geomorphic record.

There are however some possible relationships regarding the time-series data on coastal erosion with MSL (Figure 38). The plots indicate that the 1993-1999 phase of erosion matches a general rise in MSL from a minimum in 1993 to a peak in 1999/2000, then there is a fall in MSL coincident with recovery of the coastline. However, the subsequent slower rise in MSL to 2010 is not reflected by coastal erosion. These data are clearly not able to indicate cause and effect, but noting that this signal in coastal erosion is a regional one, it does indicate a potential relationship worthy of further investigation.

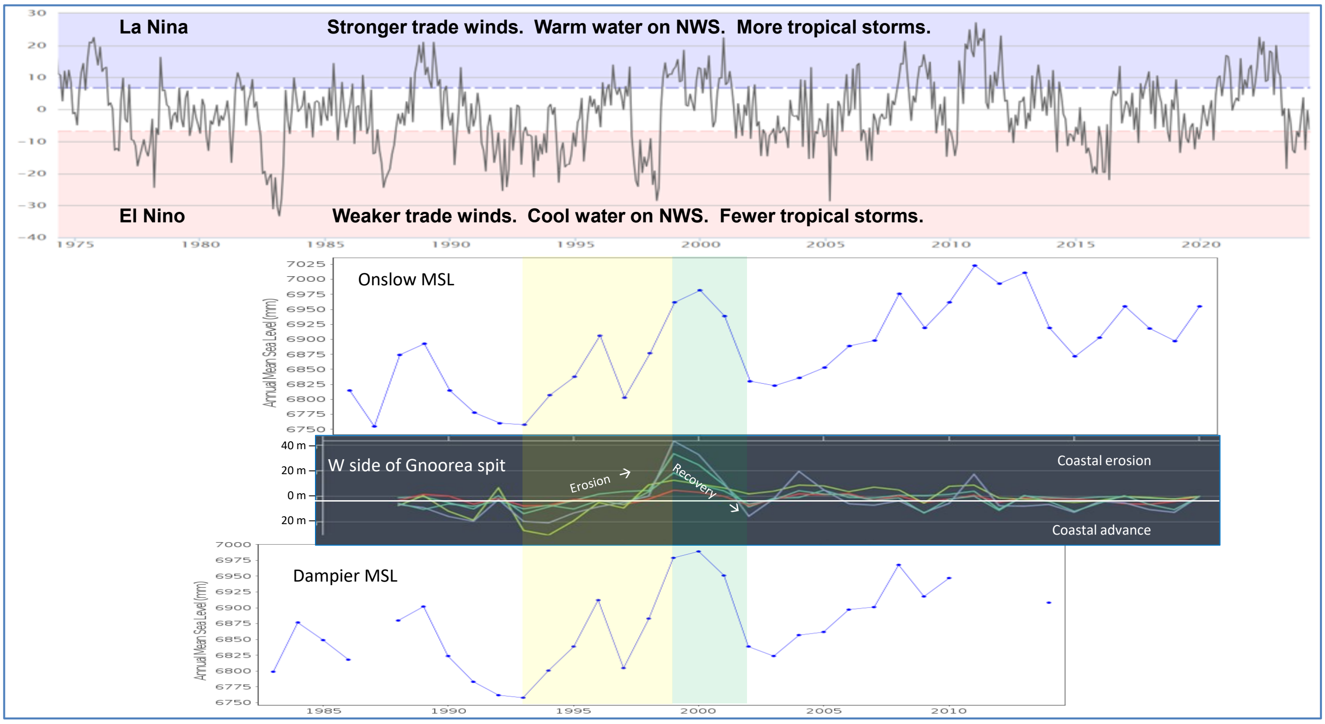

Figure 38. The SOI, plus data on mean annual sea level at Onslow and Dampier overlain with the mean annualised erosion or advance of the coastline along western Gnoorea spit (vertical scale inverted to aid comparison with SOI & MSL). Yellow bar = Erosional phase 1993-1999. Green bar = Recovery phase 1999-2002. (SOI from http://www.bom.gov.au/climate/enso/soi/).

6.2.5. Tsunami

Although rare, tsunamis are well documented in WA in historic times (Gregson & Van Reeken 1998) and in the late Holocene (Scheffers *et al*. 2008; May *et al*. 2015; 2016). The key regional generation mechanisms (e.g., seismic activity near Indonesia and on the NWS, and underwater landslides) would have also occurred throughout the Holocene as well as further back in time (see also Goff & Chagué-Goff 2014; Larcombe *et al*. 2022). After the typical drawdown of sea level at the coast, the arrival of a tsunami crest(s) is likely to raise water levels at the coast for periods of several tens of minutes or more. In doing so, they may create one or more unusually strong landward flows across areas normally supratidal, and also generate unusually strong seawards flows. They are thus another agent of potential coastal change and habitat disturbance.

6.3. Geomorphological units

6.3.1. Overall geomorphological setting

The Pilbara coast is an arid sub-tropical setting, with limited fluvial sediment supply to the coast, Holocene accumulation at it, and limited active sedimentary connectivity between major embayments, i.e. around rocky headlands such as Cape Preston (O2 Metocean 2022a). The habitats it contains are widespread in the greater NWS region (O2 Marine 2020).

Within this broader context, the Eramurra Solar Salt Project (ESSP) is located along the coast east of Cape Preston and west of Yanyare Creek, within the western part of Regnard Bay (Figure 39). Most of the ESSP area is underlain by rocks of the Dampier Granitoid Complex, i.e. various coarse-grained acidic igneous rocks, and in the west some metamorphosed conglomerates. These are overlain by a series of sedimentary units derived from weathering and erosion (section 6.3.3). The eroding and/or heavily weathered bedrock forms very flat land, with the McKay Creek catchment having a slope of only 0.7% (Figure 40, upper), and to the SE the slope averages only 2.5% (Figure 40, lower).

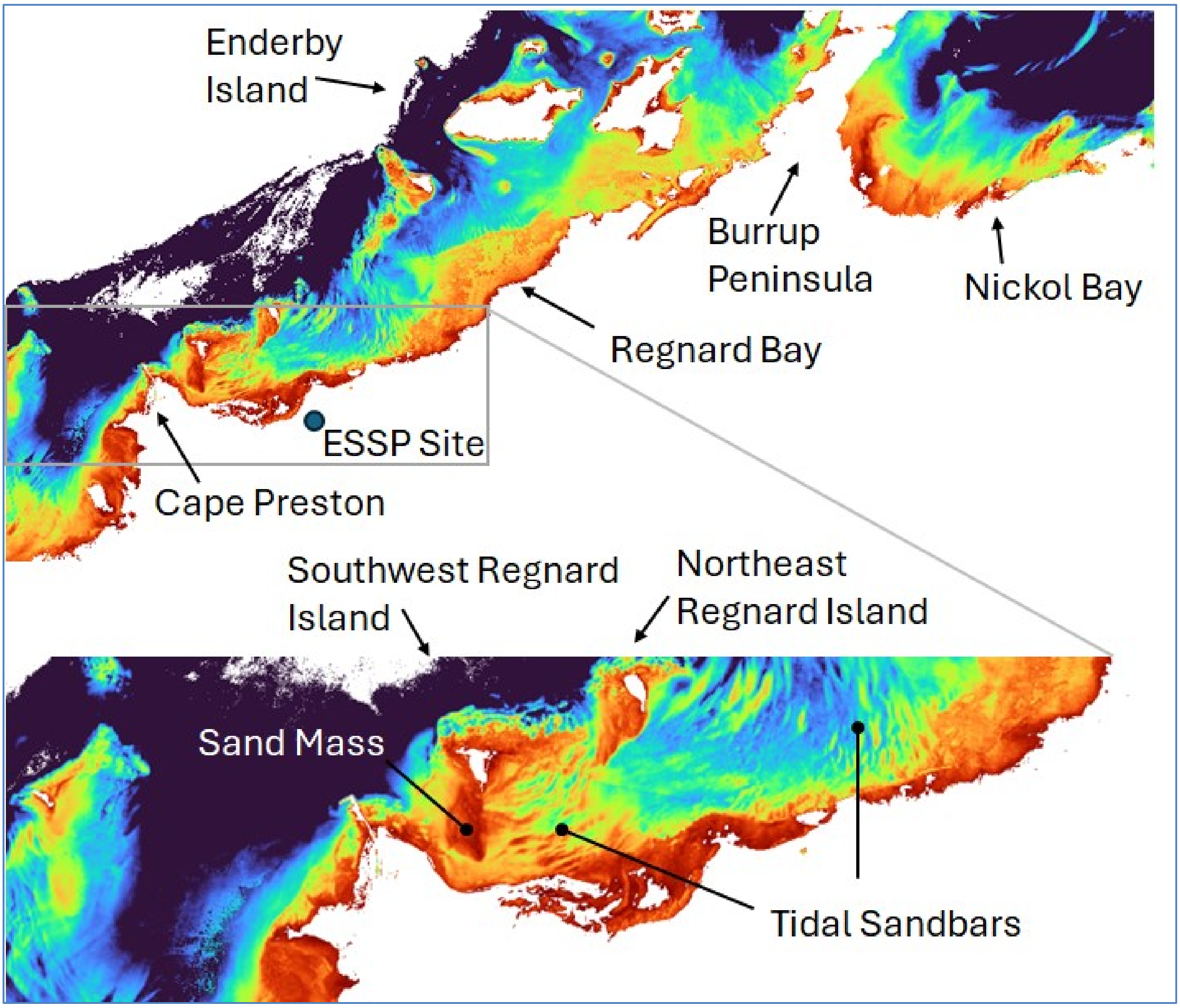

Figure 39. Western Regnard Bay Satellite Derived Bathymetry. Bathymetry derived by Dr Sam Blake (Neptune Remote Sensing).

Regnard Bay has a broadly crescentic shape, and has coastal structure suggesting geological inheritance, including:

- An island chain and shallow bathymetry (-2 to -4 m AHD) from Cape Preston to Northeast Regnard Island, with a 5 km gap before further extension to the Enderby Island group.
- A nearly straight coastal contour at around -2 m AHD running from the base of Cape Preston ENE for ~20 km, just past Yanyare Creek.

Within the bay, regular bathymetric features 1 to 2 m high and 2 to 3 km long occur southeast of Southwest Regnard Island (typical elevation -5 m AHD), and through the deeper channel entrance to Regnard Bay (typical elevation -9 m AHD). These features tend to indicate past and/or present mobility of sandy sediments developed under fast flows. However, the western end of Regnard Bay is partially blocked by a large sand body extending southwards from Southwest Regnard Island. The sand body has appeared to have changed little since 2001 (no older imagery is available at present).

Landward of the -2 m AHD coastal contour, the coast is occupied by a series of coastal lagoons from Cape Preston to Nickol Bay. Most of these are barrier lagoons, with a narrow coastal dune barrier, perforated by tidal creeks or river channels. The western lagoon (or the 'estuary') is larger, has deeper incised channels and wide tidal flats, with large areas of associated estuarine mangroves. Low-tide imagery (Figure 41) shows a distinct subtidal channel structure, with a sediment body at the channel mouth, probably fixed to west and east by outcropping bedrock. At the southern side of the estuary, low intertidal and shallow subtidal features occur, indicative of sediment accumulation associated with tidal creeks. The eastern lagoon contain low basins, has limited tidal exchange with the sea, and few sedimentary features indicative of mobile sediments and relatively few mangrove habitats.

The barriers that front these areas provide large areas sheltered from waves, with the capacity for accumulation of any finer sands and silts introduced by tidal currents or freshwater runoff.

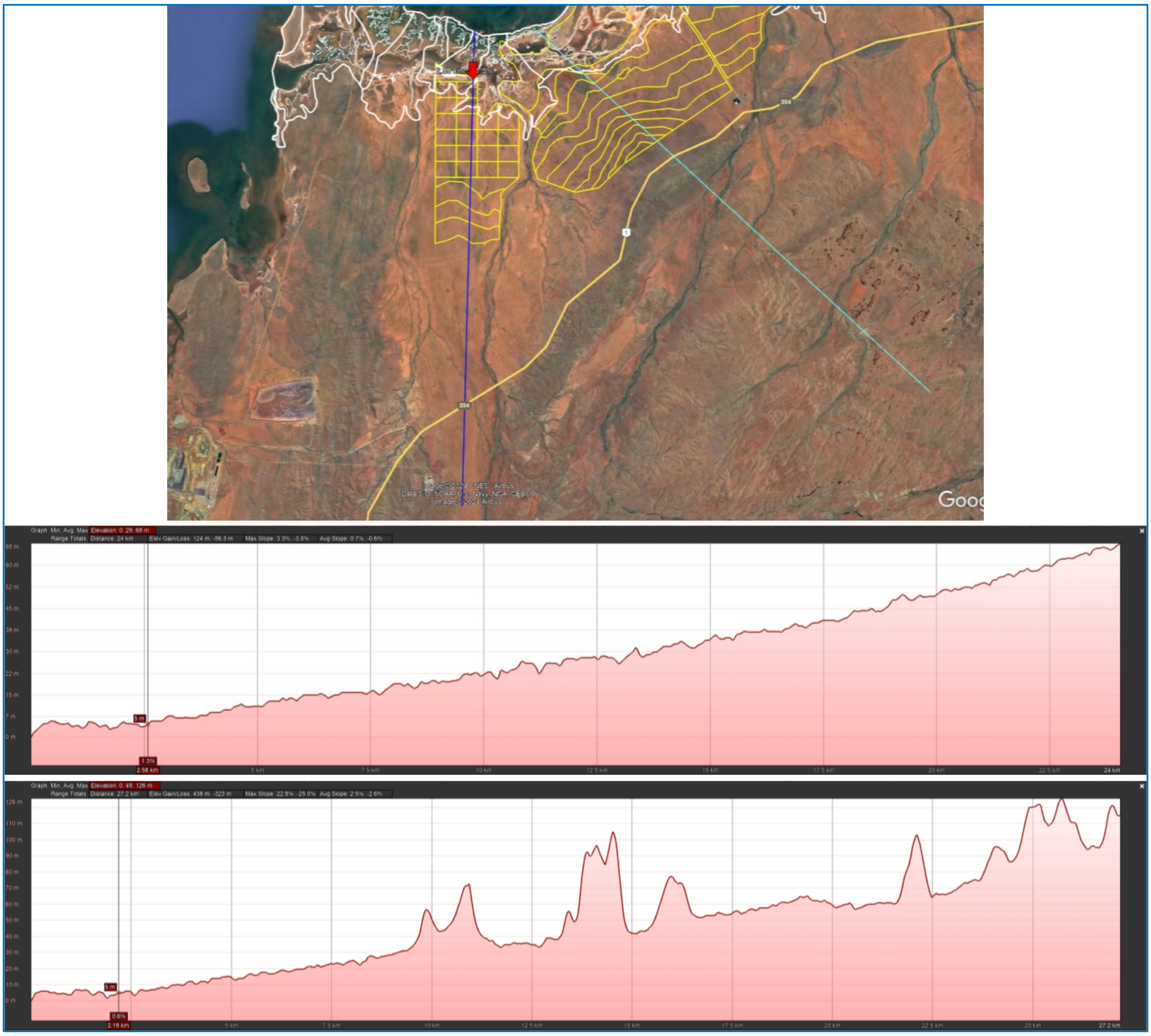

Figure 40. Vertical profiles across the coastal plain and hinterlands: Upper – 24 km long profile up the McKay Creek catchment (dark blue) from an elevation of 0 to 68 m. Lower – Profile 27 km long profile across a series of creeks (light blue) from an elevation of 0 to 126 m. Red arrow on map and vertical lines on profiles mark location of +5 m AHD.

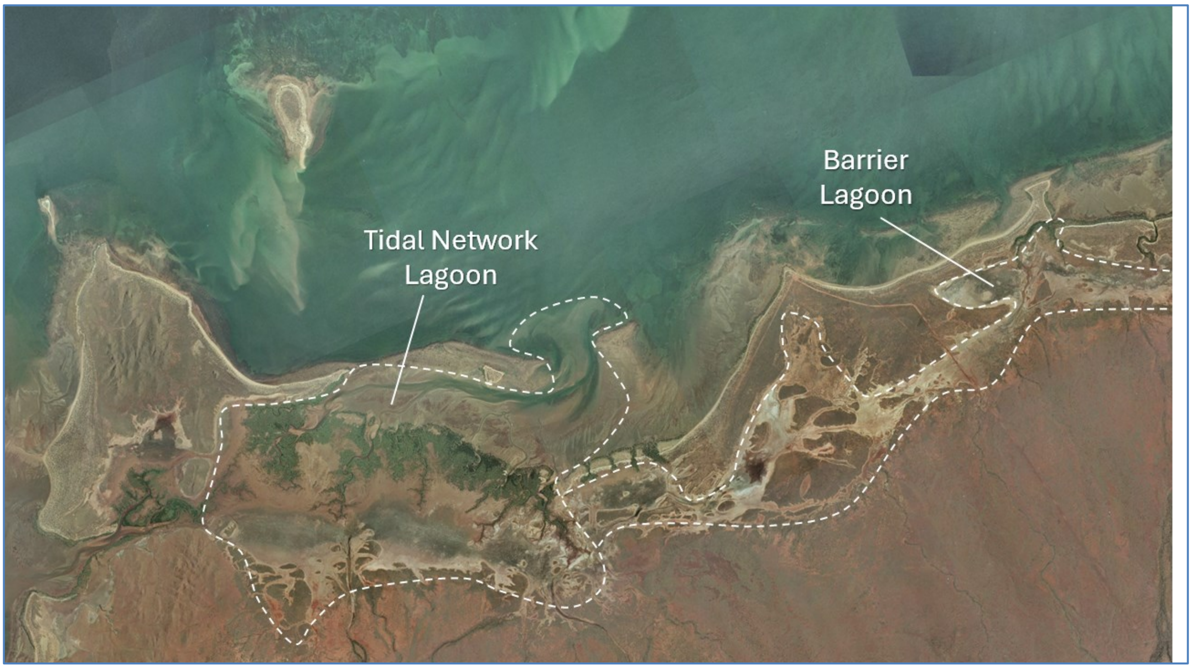

Figure 41. Coastal lagoon structures, illustrated by 2001 low-tide imagery.

6.3.1.1. Topographic slopes

The degree of past, present and potential future change in the coastline and its habitats is partly a function of the slope of the bed. There are some marked differences in slope at equivalent elevations (Table 7). Note the very low slopes (1:800 – 1:2400) in the elevation range 1 to 2 m AHD in areas A & B, which indicate that ponds placed in these areas would reduce large relative volumes of water exchanged by the tides. Pond scenario 7.2.1 contains only a small area of ponds between these elevations. It is helpful to define the storage volume Vs (the volume at 2.5 m AHD) and the creek volume Vc (the volume at 1.7 m AHD), and ponds in the intertidal zones thus reduce the Vs:Vc ratio. The capacity of scenario 7.2.1. to cause impacts is likely to be significantly reduced from pond scenario 6.2.0, especially because of the smaller area of ponds fronting catchments Creek 1 and Creek 2, and especially Baldy West and Straight Creek (Figure 42).

Table 7. Range of topographic slopes (expressed here as inverse slopes,1:n, i.e., 200 is shallow, 7 is steep) across the intertidal zone (-1 to 3 m) for the areas A, B, C & D of Figure 17. (The McKay Creek catchment is discussed separately in section 0).

Elevation range (m AHD)	Approximate topographic slopes (1:nnn)			
	Area in Figure 17			
	A & B	**C**	**D (south)**	**D (centre & north)**
2 - 3	20 - 250 Impinging on river delta deposits, restricted potential landward migration	6 - 7 Upper storm beach	6 - 7	6 - 7
1 - 2	800 - 2400 High tidal flats, incl. benthic mats	10 – 30 Lower beach	14 - 17 Active beach	10 - 20 Lower beach above sparse mangroves
0 - 1	200 Fringing mangroves, half sparse, half dense. (Estuarine all dense)	110 - 250 Sparse mangroves backed by bare sand flats	8 - 10 Active lower beach (toe)	70 - 140 Mangrove seaward limit at 0 m
-1 - 0	700 Unvegetated intertidal flats	250 - 600	330 - 650 Vegetated intertidal flats (seagrass)	500 - 700 (100 near tip)

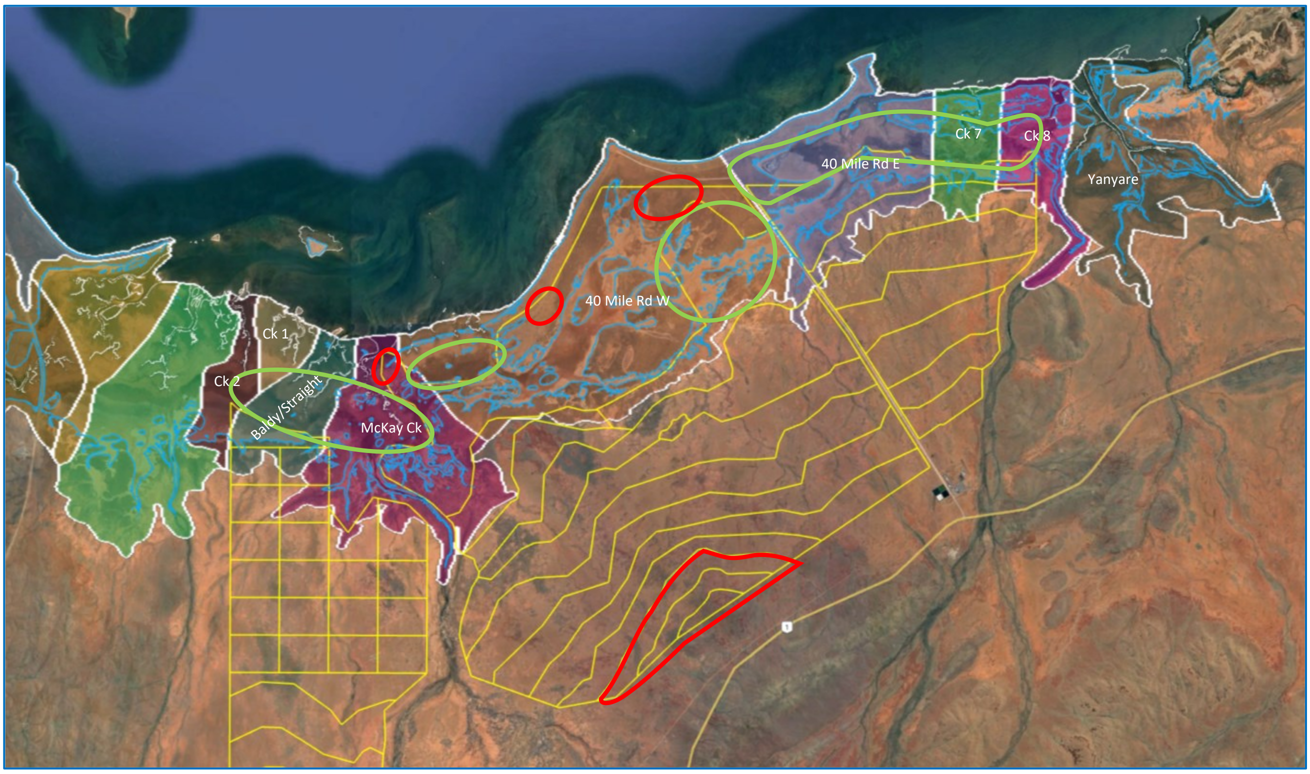

Figure 42. Pond scenario 7.2.1 overlain with main areas of change from previous scenario 6.2.0. Pond areas added by 7.2.1 = Red outline. Pond areas removed = Green outline.

6.3.2. Basins in the coastal plain

Shallow basins in the coastal plain (Figure 43, see also section 6.5.2) are important because at present they represent locations with possible capacity for ponding of water, accumulation of sediment and of benthic mats. In the future, with SLR, these basins may become more frequently inundated by seawater, and their hydrology and other characteristics might be altered. The sedimentary and habitat response are likely to be variable depending on the characteristics and dynamics of the catchment in which they occur.

Figure 43. Location of topographic basins in the coastal plain, with depths in m below their surroundings. Most basins deeper than 0.2 m are located in the catchments of 40 Mile Road W east of the spit complex (centre of figure) and 40 Mile Road E, south of the other presumably rocky promontory (upper right of figure).

6.3.3. Main units & key features

On land, geotechnical survey has characterised and described the main units in the ESSP area (e.g., CMW Geosciences, 2022, their section headed "Project Specific Engineering Geological Mapping and Observations"). Work included characterising the stratigraphy beneath the ponds and along some pond walls using field samples, Multichannel Analysis of Surface Waves seismic profiling (MASW) and Cone Penetrometer Testing (CPT) data, and interpretation of the results. Note that their work area did not extend east of 40 Mile Road, and no samples remain for viewing or analysis.

Most of the ESSP area is underlain by rocks of the Dampier Granitoid Complex, i.e. various coarse-grained acidic igneous rocks. In the west, test pits encountered metamorphosed conglomerates 1 to 1.5 m below surface.

The main relevant units for this work (Table 8) inform an understanding of past coastal evolution and processes. A map has been derived (Figure 44), using a range of sources, so that the overall disposition of the major sediment types is fairly clear. However, there is a degree of interpretation involved in all the boundaries, especially seawards of the present shoreline where there is little sedimentary information comparable to that on land, so that some habitats names occur rather than their sedimentary nature.

The surface sediments are outlined below.

- Sandy and gravelly sediments occur in the catchment above river channels, with sandy clay weathering products beneath them. The braided river channel beds contain gravels. The channel banks expose underlying granites, especially at the seaward edge of the river delta, where they sometimes form a wave-cut platform.

- The tidal flats include wide areas of silty sands that form broad, rolling, plains of low relief and almost flat in places. Within these plains occur multiple low ‘islands’, formed mostly of ‘deflated’ dunes, i.e., sand dunes where most of the sand has been blown away and the dune lowered to groundwater levels where the sand is wet and/or where the remaining sand is too coarse for movement by winds. Towards the coast, the deflated dunes merge with low fringing coastal dunes, that sharply rise in height to the coast itself. Beneath much of the sand plain are clasts of calcarenite, coralline limestone and beach rock, and the fringing coastal dunes contain gravels of similar lithology.
- The tidal flats also include wide areas of soft, muddy sediments (clayey sands and sandy clays) near and in tidal creeks and areas of mangroves. Similar sediments occur in supratidal areas, but they are stiffer. (The central band of remaining deflated dunes appear to have influenced the location of the tidal creeks on the flats, especially in the Baldy/Straight and McKay creek catchments, although it’s not the only possible interpretation. However, logically, the deflated dunes probably pre-date the active creeks).
- Finally, seawards of the present shoreline, where sampled, the low intertidal and shallow subtidal flats were relatively clean sands (see CP-BCH report and section 6.3.3.1.7).
- Overall, the ESSP area includes a wide range of sediment grain sizes, so that their distribution can provide information useful to determining past changes in sedimentary environments and on modern transport pathways.

Table 8. Sedimentary units in rough order from landward to seaward (modified from CMW Geosciences, 2022 and the CP-BCH report)

Unit name	Location and key characteristics	Nature	Significance to this study
Supratidal delta and river catchments			
Alluvial sheetwash	Thin veneer of gravel on the flanks above some river channels	Thin veneer of sheetwash sand with gravel (over residual soil derived from underlying rocks and also from weathering of thin alluvium)	Sediment source to the rivers and coastal plain
Residual soils	Largely in-situ weathering products beneath the sheetwash gravels – transport of clasts evident in places	Sandy Clay, medium to high plasticity, red brown, (5 to 12%) gravel of quartz, granite and dolerite and gravel-sized litho-relicts of extremely weathered granite or dolerite, stiff to very stiff	Ample supply of clays and sands in the catchments
Alluvial soils	Gravels in braided channel beds and in overbank deposits		Sediment source to the rivers and coastal plain
Granite – Moderately Weathered	Dampier Granitoid Complex is present under most of the site and outcrops: In the banks of incised creek bed channels and particularly near their discharge into the inter- and supra-tidal flats. At the southern margins of the playa (inter- and supra-tidal flats) sometimes as a coastal wave-cut platform.	Granite typically pale coloured, moderately to slightly weathered and medium to high strength. In places dolerite dykes infill the joint sets within the granite. A few low relief and small outcrops of gabbro.	Sediment source to the coastal plain. Will weather to sand-sized Quartz and to other hard grains, and clay minerals.

Unit name	Location and key characteristics	Nature	Significance to this study
Meta-conglomerate – Highly to Moderately Weathered	Present at 1 to 1.5 m depth within test pits along the western edge of the western ponds.	The metasediment was fine grained, dark pinkish brown, highly to moderately weathered, low to medium strength. It contains weakly to moderately cemented gravel- to cobble-sized clasts of (meta) conglomerate.	Possible past source to the coastal plain, especially in the west.
Supratidal flats, intertidal flats and coastal deposits			
Extremely weathered Granite, Dolerite and Calcarenite	Granite - Coastal area beneath Eolian[11] Sand at the southern edge of the sand plains adjoining the northern margin of the inter- and supra-tidal flats		
"Former Coastal rock ledges" **~ "Beach Rock"** **~ "Calcarenite"** **(calcareous sandstone)** **~ Coralline limestone**	Small areas on the southern edge of inter-tidal flats, e.g. the eastern edge of small sand plains, in 40 Mile Road W, in pond 2.	Beach Rock - carbonate cemented coarse-grained mixture of shells, coral fragments, cone and clam shells, pieces of calcarenite and calcirudite (former beach rock) and occasional igneous gravel and cobble-sized fragments.	Possible sediment source to the nascent mangroves, and also indicates km-scale progradation of coastline since their formation.
Sand plains Incl. **'Deflated dunes'** **& 'Sandy islands'**	Deflated Dunes and Sand Plains and sandy islands in the 40 Mile Road W catchment (pond 2). Broad, rolling areas of low relief, almost flat in places.	Silty Sand, up to ~2 m thick in the deflated dunes and sand plains (1 to 1.5 m more typical) and thinner on the sandy islands, rarely exceeding 1 m thick. Orange, brown to yellow brown, trace to with gravel; occasionally trace clay.	Possible past shoreline – sediment accretion and progradation since then.

[11] Eolian and aeolian mean the same – wind blown.

Unit name	Location and key characteristics	Nature	Significance to this study
		NB - Clasts of calcarenite, coralline limestone and beach rock were noted beneath much of the sand plain north from the margins of the Inter- and Supra-tidal Flats towards the fringing dunes.	
Eolian Sands & other coastal deposits	Fringing (Coastal) Dunes typically up to 10 m in height and sharply flattening out along the southern edge as they merge with the Deflated Dunes.	At the southwestern end of the fringing coastal dunes CPT data indicates potential multiple phases of dune deposition indicated by the clay bands between successive dune systems. Within the fringing dunes, are gravels formed of coralline limestone, shells and calcarenite. The dunes overlie older sediments, calcrete, ferricrete and igneous rocks.	Possible multiple phases of dune formation and/or coastal geomorphological changes This entire area likely to have been a shallow coastal/marine environment (presumably at highstand?). So considerable coastal progradation since then.
Lagoonal muds at and landward of the shoreline **~Soft intertidal muds** **~Soft mangrove muds**	Intertidal flats and creeks, areas of scattered mangroves. Supra-tidal flats - stiffer muds, possibly through drying.	Clayey Sand and Sandy Clay (observed at the surface) CPT data indicated: Inter-laminated Clay, Silt, Sand and Sandy Clay, very soft to soft, and also, firm to stiff & stiff to very stiff.	Soft modern muds, stiffer ones dried in supratidal areas. Also note images of fossil mangrove trunks.
The present shoreline	NB - the ESSP ‘shoreline’ is not a precisely defined line, it is a broad zone. Sandy, shelly and muddy beaches occur, and a gravel storm beach n places.	The sediments occur seawards of the established fringing mangroves, and/or the established coastal eolian dunes and/or the deflated dunes. They overlie older sediments or calcrete or igneous rock platforms.	Volumetrically small, and not of great significance to this work, but more significant in terms of it being there.

Unit name	Location and key characteristics	Nature	Significance to this study
Estuarine sediments **~Lagoonal muds**	Low intertidal and shallow subtidal flats, soft and mobile sediments	Clean sands occur a few hundred m seawards of the shoreline (Figure 59) but the areas are described by O2M (2023) as 'mudflat', so the areas is marked here as 'soft silty sands' on Figure 44.	Material available for potential exchange with marine environment to seawards and coastal environments to landward.
Estuarine tidal channels	Tidal channels incised into the intertidal flats	Mobile sands, as indicated by the bedforms observed in photos and aerial images	Site of mechanism (relatively strong ebb currents) of reworking of estuarine sediments and transfer of material, mostly to seaward.
Inner shelf sands	Seawards of the estuarine barrier and of the eastern ESSP coastline	Clean sands, probably gravelly in places, and silty sands and possibly sandy silts in the east, partially vegetated with macroalgae near the coast	Potential source of sediment to the ESSP coastline

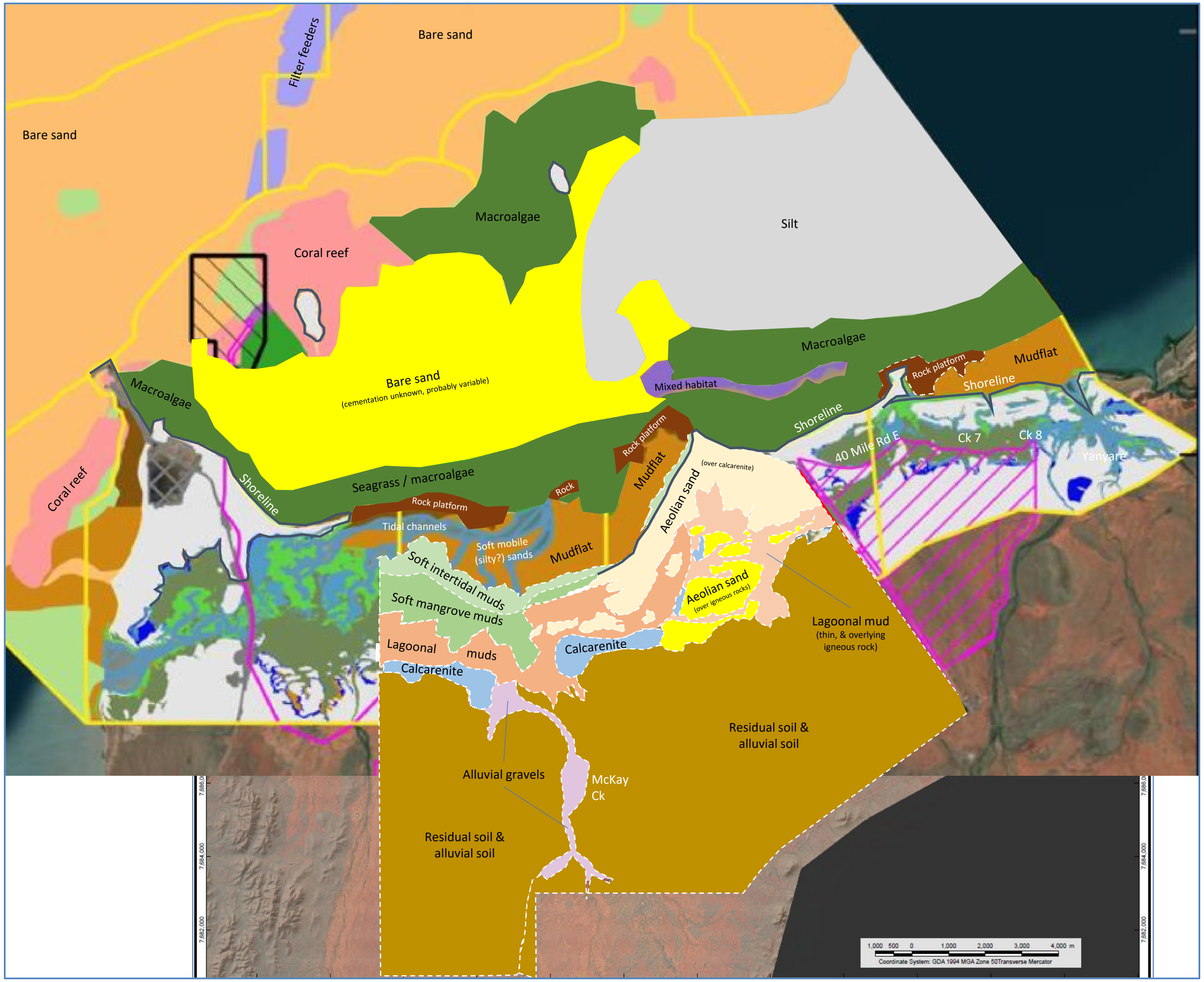

Figure 44. Map of surface sediments and main associated coastal units (after CMW Geosciences 2022 & Land and Water Consulting 2022) and incorporating the habitat map of O2M 2023). Seawards of the present shoreline, there is little sedimentary information, so that as well as variable spatial coverage, there is i) uncertainty in some designations and ii) inconsistency in naming of sediment types between terrestrial and marine surveys.

6.3.3.1. Sediment availability for (re-)mobilisation

Below the relevant features of the main sedimentary units are described, from landward to seaward, focusing on the potential contribution of each unit to provide sediments for mobilisation, with the perspective of a century ahead with SLR and with pond emplacement. Most of the available information occurs for the west and central parts of the ESSP area, where test pits, CPT profiles, soil sampling and geophysical testing has concentrated to date. Therefore, conclusions about areas east of 40 Mile Road can only be inferred and have not been described below, although are mentioned in the sections of worked examples (section 9.3).

6.3.3.1.1. River catchments

The catchment interfluves are a potential source of silt, sand and gravel sediment for the system, and they are heavily weathered to a depth of ~5 m. In the major river catchments themselves, sheetwash gravels (Figure 45) occur on the surface in places, overlying the widespread weathered residual soils. These soils are generally sandy clays, of medium to high plasticity, red brown, with 5 to 12% gravel of quartz, granite and dolerite and gravel-sized lithoclasts of extremely weathered granite or dolerite, stiff to very stiff. The residual soil contains primary minerals remaining from the parent rock, mostly the silicates quartz, feldspar (albite and microcline), amphibole, muscovite and chlorite, the carbonates dolomite and calcite, and iron oxides (hematite) with occasional sulfates (gypsum). The weathering has produced associated clay minerals, with most samples consisting of kaolinite, palygorskite, illite and montmorillonite. For clay-sand mixtures, laboratory studies of erosion by rain droplets indicate that zeolites are most resistant, followed by clay soils, phlogopite, kaolinite and finally bentonite (Ayoubi *et al*., 2022). Further, in the ESSP context, the time taken to cause erosion and movement is not a limiting factor, and clay content is not considered further here regarding potential mobility. Therefore, the significance of the residual soil unit is that it is generally 2 to 3 m thick (Figure 46) so there is ample supply in the catchment of clays, silts and sands (see PSD curves of Figure 84).

Figure 45. Sheetwash gravels occurring as a thin veneer. Particle size varies from sand (0.2 mm) to cobble (< 200 mm). (CMW Geosciences, 2022)

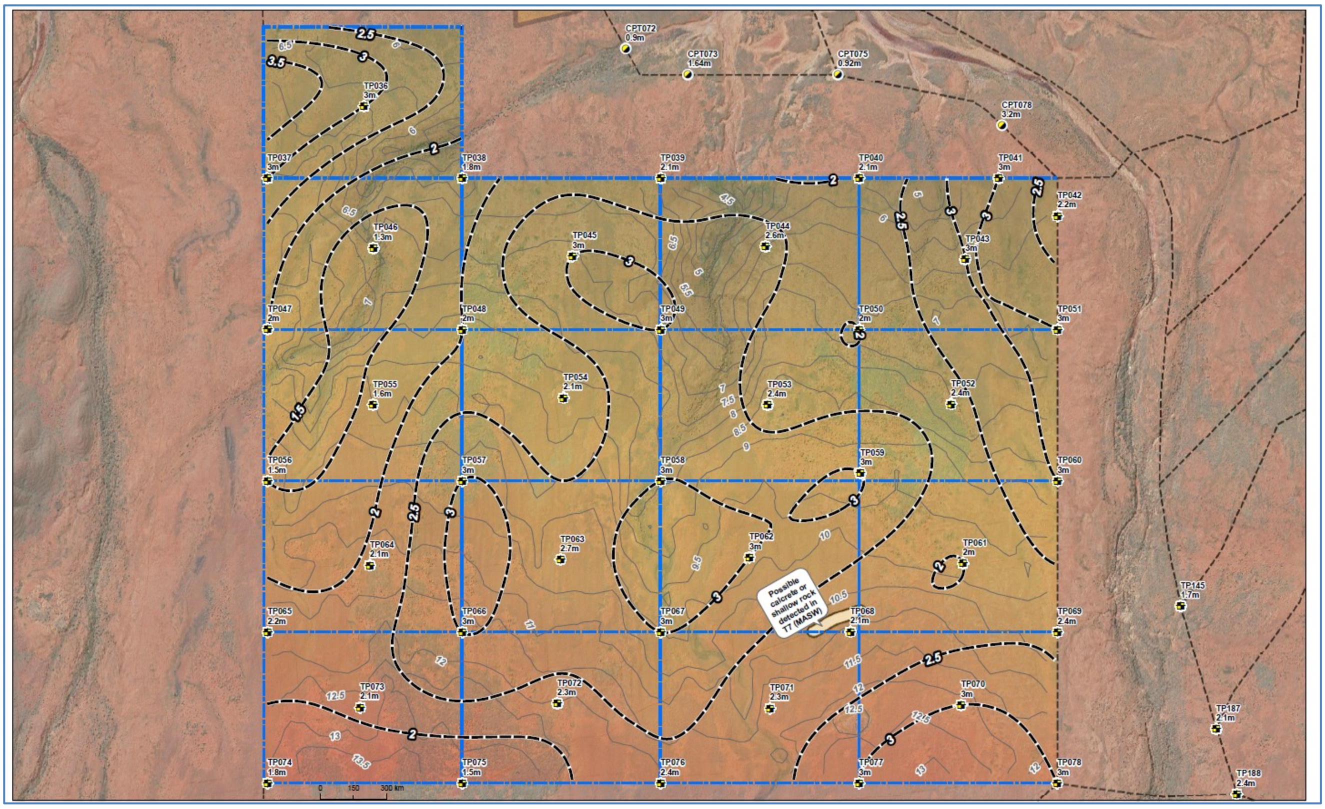

Figure 46. Thickness of residual soils above the bedrock in the higher ground between Eramurra and McKay creek (CMW Geosciences 2022). The bulk of the residual soil unit is 2 to 3 m thick. Note the these ponds occupy two drainage features that feed into the delta front area of McKay Creek.

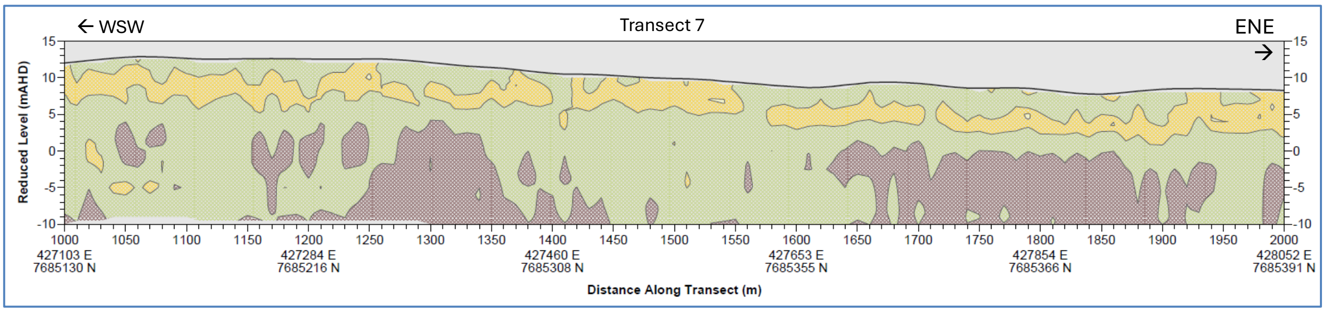

Figure 47. Interpreted material classification for Transect T7 of Figure 65, on the interfluve between Eramurra and McKay creeks. Key shown in Table 9.

Table 9. Key to shear wave velocity classification shown in Figure 47.

Seismic Shear Wave Velocity Material Classification

Class	S-wave Velocity (m/s)	Description
S.1	Equal to or greater than 1500	Moderately hard to hard rock
S.2	750 to less than 1500	Soft rock to moderately hard rock
S.3	350 to less than 750	Very stiff sediment or soft rock
S.4	175 to less than 350	Medium dense to stiff sediment
S.5	Less than 175	Loose to medium dense sediment

6.3.3.1.2. River channels

The main river channels and their high-tidal reaches contain gravels and some coarse sands of unknown thickness. Bedrock exposure has occurred due to scour in the larger river channels, especially along their lower fluvial reaches, e.g., there is extensive exposure of igneous rocks in McKay Creek bed and banks (Figure 48). Generally, the smaller creeks have not incised much into bedrock and their beds and banks comprise transported sands and gravel, or small cliffs (<<1 m) of exposed residual soil (red highly plastic clay). Overall, it is unlikely that potential future changes in or near the channels driven by SLR or pond emplacement would be limited by a lack of available gravel.

Figure 48. Left – the upper tidal reaches of McKay Creek at high tide, with rocks outcrops on banks and in the channel base. Right - Granite outcrops exposed in creek bed (CMW Geosciences 2022).

6.3.3.1.3. Calcarenite

Either side of the mouth of McKay Creek are exposures of calcarenite (which means cemented calcareous sand). In places in the east, in the 40 Mile Road W catchment, these exposures are denoted as beach rock, (a term meaning beach sediment cemented in-situ by groundwater, hence it can be highly variable in size and composition). The beach rock contains a mixture of shells, coral fragments, cone and clam shells, pieces of calcarenite and calcirudite (meaning carbonate-cemented cobble and pebbles), including fragments of the beach rock itself) and occasional gravel and cobble-sized fragments of igneous rocks. Overall, these will tend to weather to produce a wide variety of grain sizes. Their exposure in the creek banks and their heavily weathered nature in places (Figure 49) indicates that they might be a notable source of sediment in the uppermost parts of the tidal creeks and onto the tidal flats. Certainly, at present, some sands and gravels are discharged onto the tidal flats at the river mouths (Figure 50).

Figure 49. Sheet calcarenite (left and top right) and weathered nodular calcarenite (bottom right) along the edge of the river delta front (CMW Geosciences 2022).

Figure 50. Sands washed out onto the tidal flats the river mouth (CMW Geosciences 2022).

6.3.3.1.4. Lagoonal muds

Landward of the mangroves, the extensive tidal flats house large areas of lagoonal muds (Figure 44, Figure 51, Figure 52). (These are marked 'very soft clay' in the sections across the nascent mangrove flats, Figure 69, and through lower McKay Creek and Baldy/Straight creek, Figure 71). To the east, these sediments are thin and overlie igneous rocks, and the unit is not represented on cross-sections, presumably being too thin. The unit is a likely source of substantial volumes of silt and clay, especially in the McKay Creek area and further west.

Figure 51. Lagoonal muds (high tidal flats) above the normal tidal limit with some dried benthic mats (CMW Geosciences 2022).

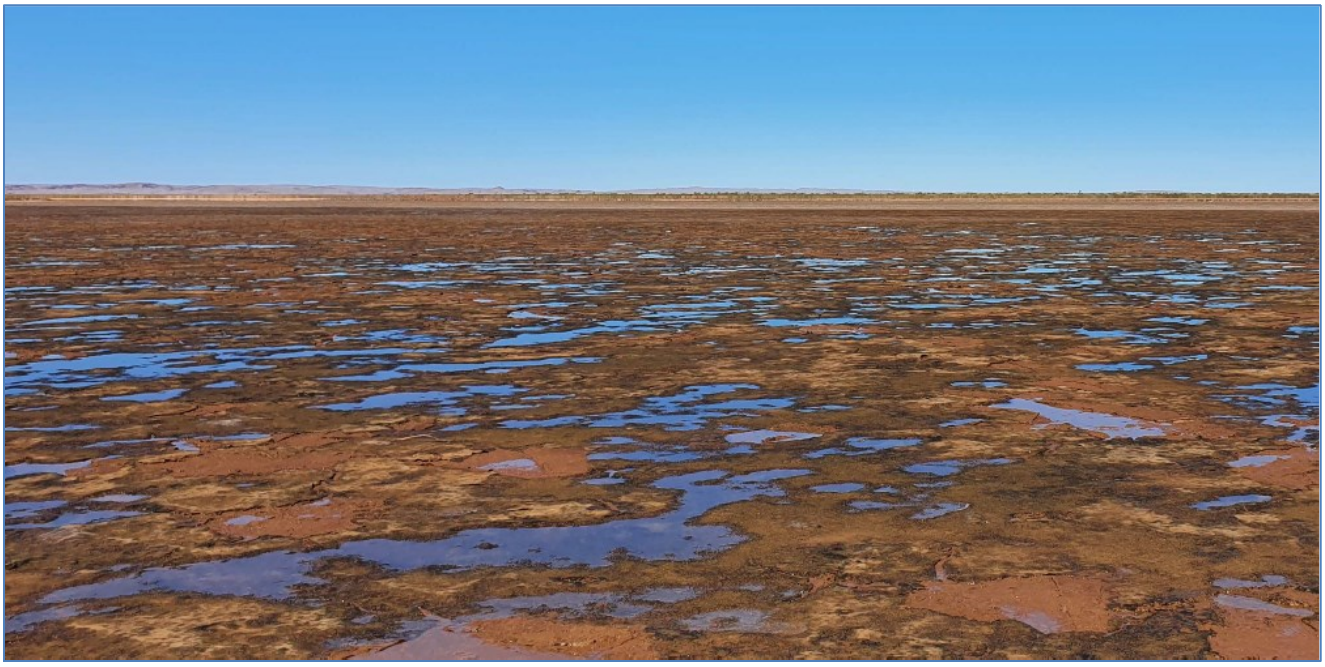

Figure 52. Lagoonal muds (high tidal flats) lower than Figure 51 and more frequently wet (CMW Geosciences 2022).

6.3.3.1.5. Soft intertidal muds

Further seawards are two units of soft muds, the ‘soft mangrove muds’ and ‘soft intertidal muds’ (Figure 44, Figure 53, Figure 54), that together incorporate the bed sediments within the main areas of estuarine and fringing mangroves, and intertidal soft sediments where mangroves are sparse or absent. Sedimentologically, these are likely to be broadly similar sediments, but with the difference that areas of established mangroves are less liable to rapid major erosive events because the bed is stabilized to some extent by the mangrove roots (Figure 54 bottom). Unit thickness is only available for the soft mangrove muds. This unit varies between 0.25 m and 2.75 m thick, and most of the unit is 1 to 1.5 m thick (Figure 55) indicating that i) there has been substantial accmulation of soft sediment, presumably relatively recently, and certainly since the mid-Holocene sea-level highstand, and ii) that there is ample muddy material able to be reworked by physical processes.

Figure 53. The upper part of the incised tidal creek and the transition to adjacent tidal flats (CMW Geosciencse 2022).

Figure 54. Top - Mangroves with accumulating mangrove mud at a creek edge. Bottom - Exposed mangrove root systems in an area of recent erosion (CMW Geosciences 2022).

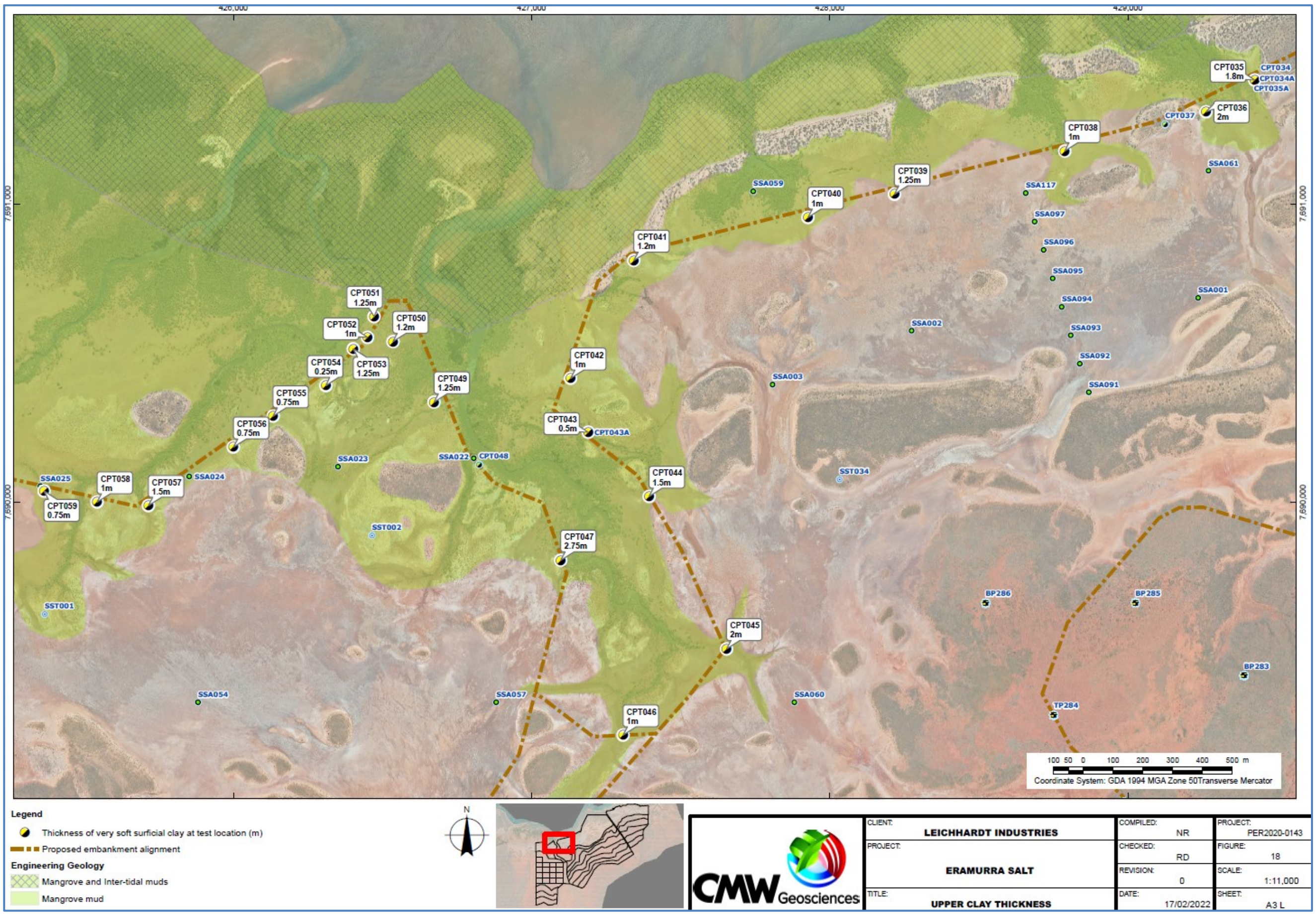

Figure 55. Thickness of very soft muds in lower McKay Creek and at the nascent mangroves (see also Figure 69 & Figure 71) (CMW Geoscience 2022).

6.3.3.1.6. Dunes and deflated dunes

In the east of the area surveyed by CMW Geoscience (2022, i.e., bounded by the 40 Mile Road) are various sandy units[12]. These include active eolian dune sands at the coast itself and the deflated dunes further inland – both overlying calcarenite. In the east along the road, the sands are described as "interbedded medium dense to very dense sands and silt sands and hard clays" (Figure 67) whereas in the northern road section and along the SW-orientated spit, they lack the interbedded clays (Figure 68, and Figure 69 upper). Along the road these eolian sands are 1 to 2 m thick and are slightly thicker along the spit.

Inland from these, equivalent deflated sand dunes overlie igneous rocks (Figure 44). Their thickness is generally a few decimetres (Figure 56, Figure 57, Figure 58) and they can be large, and sometimes termed sandplains (Table 8). The 'lagoonal mud' plains around the deflated dunes receive some sand especially from their edges. Where apparent, the bed features around the deflated dunes tends to indicate sediment transport to seawards, with sediment throughput and perhaps also some local erosion rather than any long-term accumulation. Thus, despite being low in elevation, with SLR, these deflated dunes have the potential to contribute sand to the coastal system mostly through erosion of their edges.

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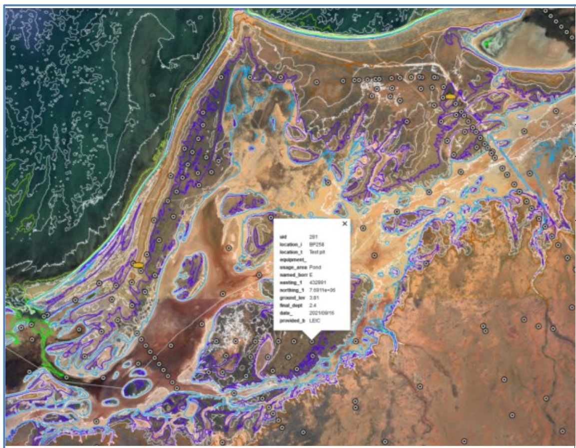
[12] Coastal sands also occur at Cape Preston (section 6.4) but are not of primary relevance to sediment availability along the ESSP shoreline.



TEST PIT LOG - BP258

Client: Leichhardt
Project: Eramurra Salt
Location: Eramurra, WA
Project ID: PER2020-0143
Date: 16/09/2021

CMW Geosciences

1:20 Sheet 1 of 1

Logged by: TR | Position: E.432991m N.7691097m | Plant: CAT 420 Backhoe
Checked By: AT | Elevation: 3.81 m | Contractor: Allround Plumbing | Dimensions : 0.60m x 3.00m

Groundwater	Samples & Insitu Tests: Depth	Samples & Insitu Tests: Type & Results	RL (m)	Depth (m)	Graphic Log	Material Description Soil Type, Plasticity or Particle Characteristics, Colour, Secondary and Minor Components	Moisture Condition	Consistency/ Relative Density	Structure & other observations
	0.2 - 0.5	B				SM: SILTY SAND: fine to medium grained, non-plastic, pale orange brown; trace gravel, fine to medium grained, subangular. (Eolian soil)	D		
	1.1 - 1.4	B	3.3	1, 2		CI: SANDY CLAY: medium plasticity, dark orange brown mottled pale yellowish brown; sand, medium to coarse grained; trace fine gravel sized lithorelicts of extremely weathered dolerite. (Residual Soil/ XW Dolerite)	≈PL	St to VSt	
			1.6			GC: GRAVELLY SANDY CLAY: medium plasticity, pale greenish grey mottled pale red and cream; sand, fine to coarse grained, subangular; gravels are extremely to highly weathered litherolicts of dolerite. (Residual Soil/ XW Dolerite)	≈PL		
			1.4			Test pit terminated at 2.40 m			

Figure 56. Sediment log for test pit at B258 on a deflated dune in the 40 Mile Road W catchment. The upper silty sand (yellow) is 0.5 m thick. (Core log from CMW Geosciences 2022).

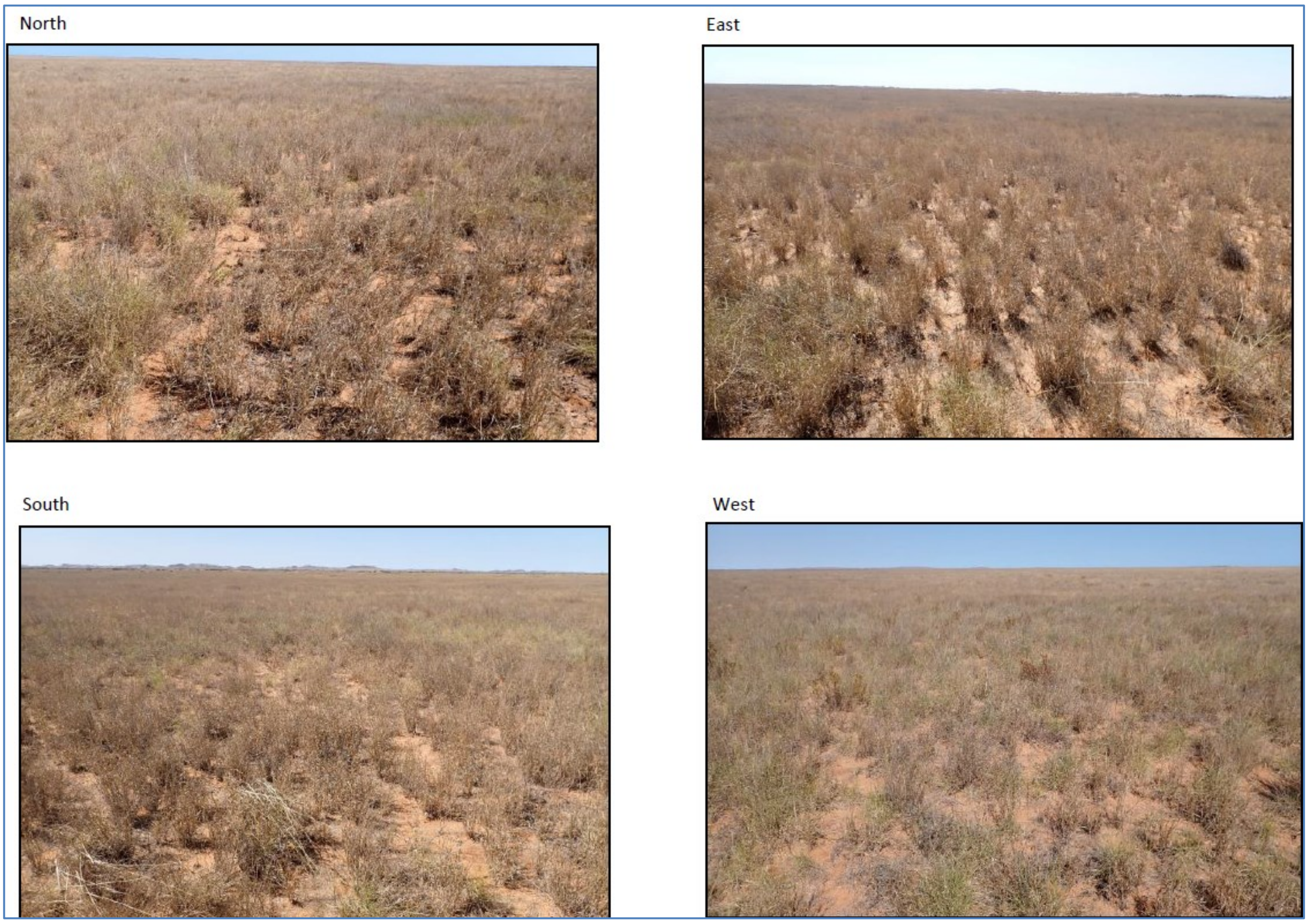
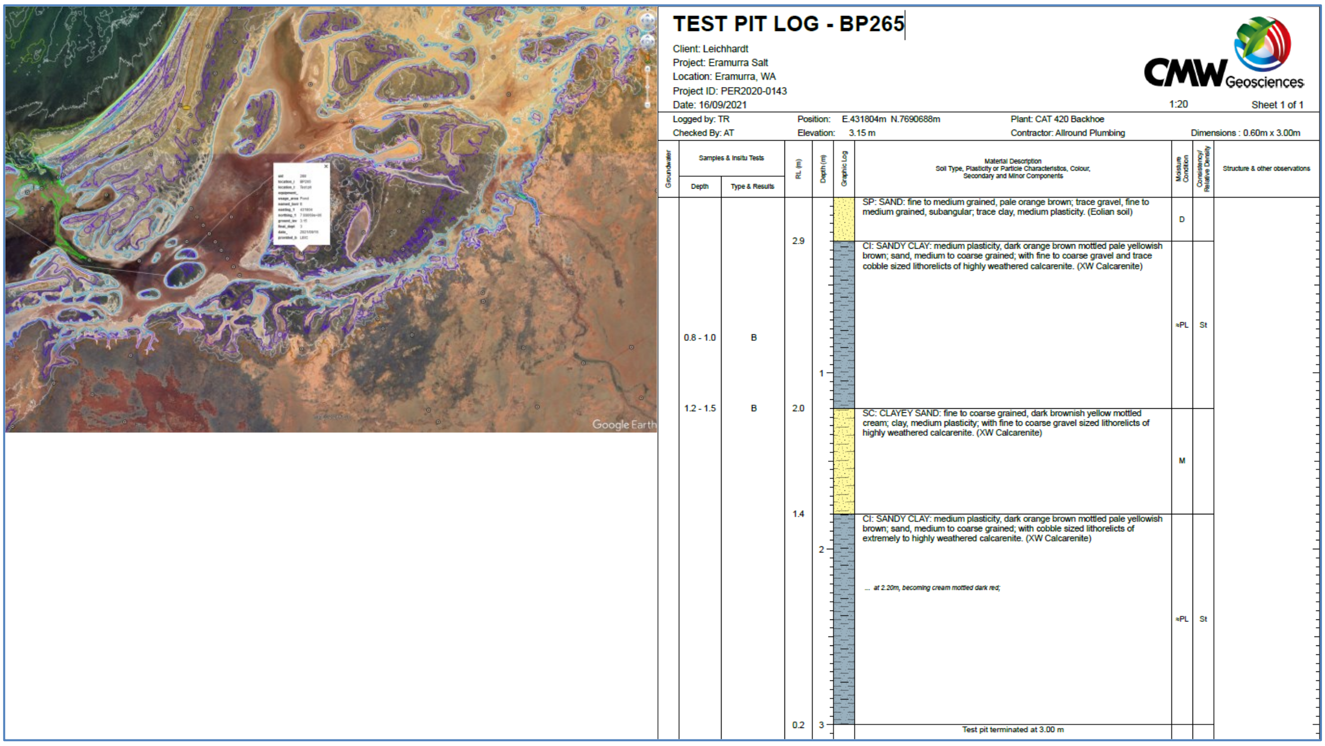


Figure 57. View in each direction from the test pit BP258 on a deflated dune (CMW Geosciences).



TEST PIT LOG - BP265

Client: Leichhardt
Project: Eramurra Salt
Location: Eramurra, WA
Project ID: PER2020-0143
Date: 16/09/2021

1:20 Sheet 1 of 1

Logged by: TR | Position: E.431804m N.7690688m | Plant: CAT 420 Backhoe
Checked By: AT | Elevation: 3.15 m | Contractor: Allround Plumbing | Dimensions : 0.60m x 3.00m

Groundwater	Samples & Insitu Tests: Depth	Samples & Insitu Tests: Type & Results	RL (m)	Depth (m)	Material Description Soil Type, Plasticity or Particle Characteristics, Colour, Secondary and Minor Components	Moisture Condition	Consistency/ Relative Density	Structure & other observations
			2.9		SP: SAND: fine to medium grained, pale orange brown; trace gravel, fine to medium grained, subangular; trace clay, medium plasticity. (Eolian soil)	D		
	0.8 - 1.0	B		1	CI: SANDY CLAY: medium plasticity, dark orange brown mottled pale yellowish brown; sand, medium to coarse grained; with fine to coarse gravel and trace cobble sized lithorelicts of highly weathered calcarenite. (XW Calcarenite)	≈PL	St	
	1.2 - 1.5	B	2.0		SC: CLAYEY SAND: fine to coarse grained, dark brownish yellow mottled cream; clay, medium plasticity; with fine to coarse gravel sized lithorelicts of highly weathered calcarenite. (XW Calcarenite)	M		
			1.4	2	CI: SANDY CLAY: medium plasticity, dark orange brown mottled pale yellowish brown; sand, medium to coarse grained; with cobble sized lithorelicts of extremely to highly weathered calcarenite. (XW Calcarenite) ... at 2.20m, becoming cream mottled dark red;	≈PL	St	
			0.2	3	Test pit terminated at 3.00 m			

Figure 58. Sediment log for test pit at B265 on a deflated dune in the 40 Mile Road W catchment. The upper silty sand (yellow) is 0.25 m thick, and the sequence below contains interbedded sandy clays (blue) and clayey sands (yellow) both containing cobbles of weathered calcarenite. (Core log from CMW Geosciences 2022).

6.3.3.1.7. The estuary / lagoon

The low intertidal and shallow subtidal flats and tidal channels of the estuary house soft mobile sediments, as evidence by the bedforms, aerial and field photographs and changes in successive satellite images. The area is described by O2M's habitat report (O2M, 2023) as 'mudflat' but clean sands occur a few hundred m seawards of the shoreline (Figure 46). This report labels the area as 'soft silty sands' on Figure 32. The significance is that there is ample material for potential exchange with the marine environment to seawards and coastal environments to landward, although there is no knowledge of the sediments' thickness.

Characterization of such material is required in order to assess their contribution to the coastal environments, especially at the more critical areas, i.e., Baldy/Straight Creek, McKay Creek, the nascent mangroves and the basins of 40 Mile Road E and Creeks 7 and 8. A sample from a few hundred metres seawards of McKay Creek (CP-BCH report section 4.4.1) was a dark-brown loose slightly calcareous medium quartz sand (size range 250 to 500 um) with no silt or clay component (Figure 59). The sand was of a mixed composition:

- ~70% Quartz, mostly stained red, generally moderately well rounded, sub-equant, moderately to well sorted
- 10% black minerals
- 10 to 20% Carbonate grains, comprising a wide variety of shell fragments (including some black) and some whole forams.

Data from a few samples further offshore are also available but these samples were taken too far from the modern shoreline to contribute to this report at present.

Figure 59. Image of clean medium sand sampled from a few hundred metres seawards of McKay Creek mouth. The sand grains are 250 to 500 um in diameter.

6.3.3.1.8. Inner shelf sands

Seawards of the estuary and of the eastern ESSP coastline are located sediments of the inner shelf. These are reported to be clean sands, probably gravelly in places, and silty sands and possibly sandy silts in the east, partially vegetated with macroalgae near the coast. They are a potential source of sands and silts to the ESSP coastline if there is a mechanism that is able to transport them into the estuary. Net bed-sediment transport at the western part of the mouth appears to be seawards by an ebb-dominated tidal channel, with its ebb-delta projecting just outside the estuary mouth onto the inner shelf. At present the most likely process to move sand into the estuary is likely to be net transport to the SE and SSE by waves in the eastern part of the estuary mouth, and especially towards and along the Gnoorea spit. There is no information on the thicknesses and volumes of mobile sediment on the inner shelf.

6.4. Stratigraphy

The stratigraphy means the vertical disposition of a sequence of sedimentary units. Across almost the entire ESSP site, a range of different sediments overlie granitic rock belonging to the Dampier Granitoid Complex (AgD of Figure 60), which is exposed in places in creek beds and encountered in boreholes.

6.4.1. Cape Preston

The regional bedrock geology and boreholes from Cape Preston (Figure 60, Figure 61, Figure 62, Figure 63, Table 10) can be taken to indicate that the Cape Preston promontory is also underlain by igneous and similar hard basement rocks, and the nearby islands are probably cemented limestones (Eliot *et al*., 2013). At Cape Preston, the surface coastal sand unit was present in all boreholes, varied from 0.5 to 6 m in thickness, and was formed of very loose to medium dense, poorly sorted, sub-rounded dark brown and grey, fine to coarse sands, with some silt and sub-angular gravel, shells, corals and rootlets. Beneath was a weathered off-white calcrete up to 4 m thick, and further down was a weathered, yellow-brown massively bedded ferricrete, 0.5 to 9 m thick. Interpretation in difficult without the core logs and photos, but it is concluded that there is little this can add to the body of this report other than indicate the presence of potentially mobile sediment near the tip of Cape Preston, itself evident from aerial photographs of the coastline (Figure 64) and previous reports (e.g. the CP-BCH report).

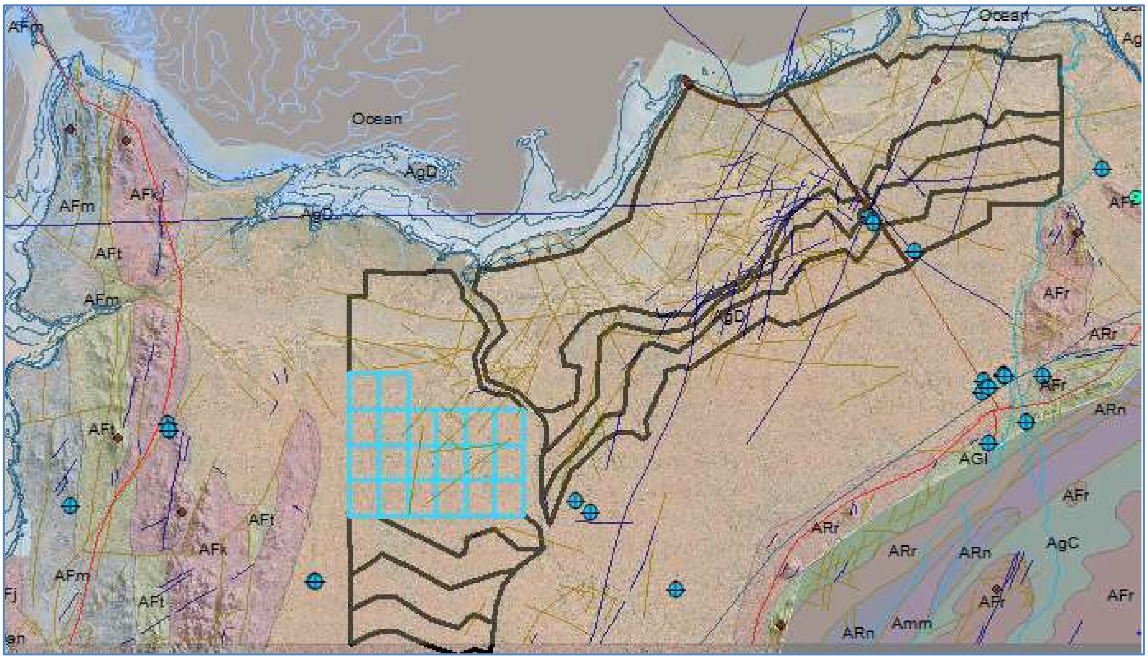


Figure 60. Bedrock geology (Geological Survey of Western Australia).

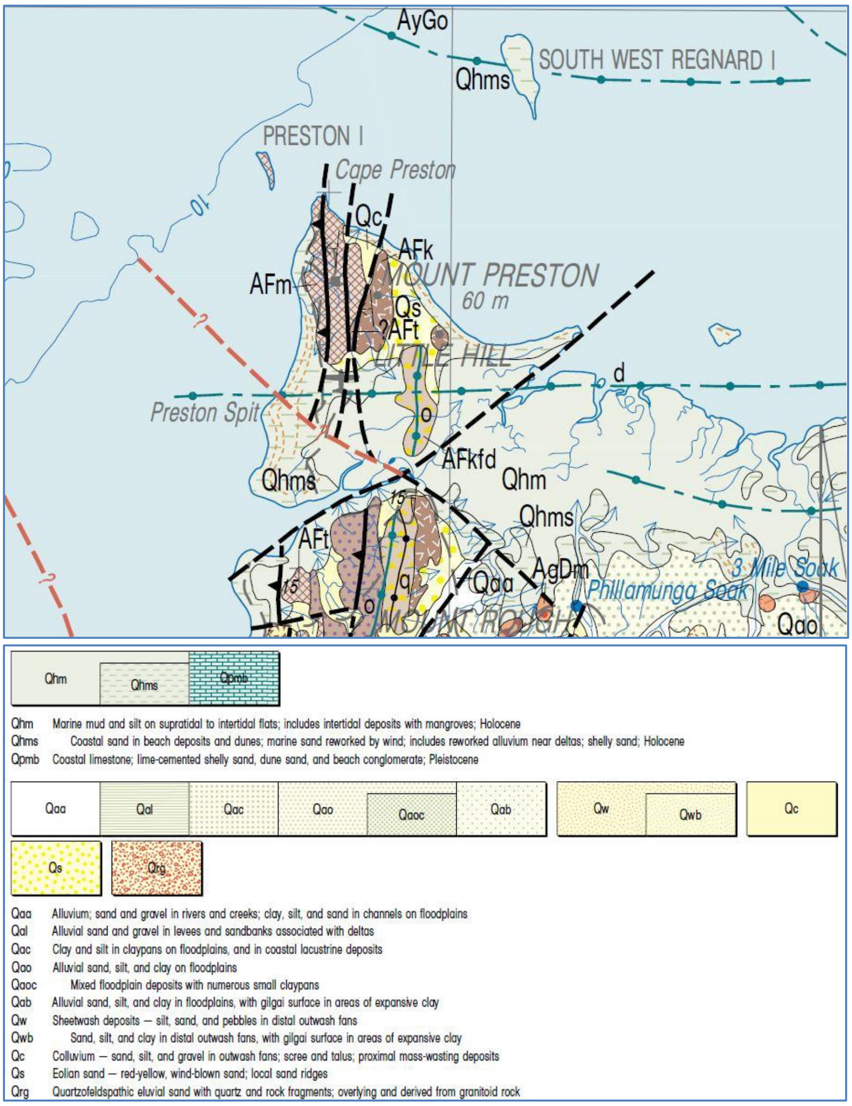


Figure 61. Regional geological map (from SKM, 2013a) covering the western end of the area of salt ponds. Much of the surface sediments are interpreted as Holocene and recent sands and muds (Qhm & Qhms).

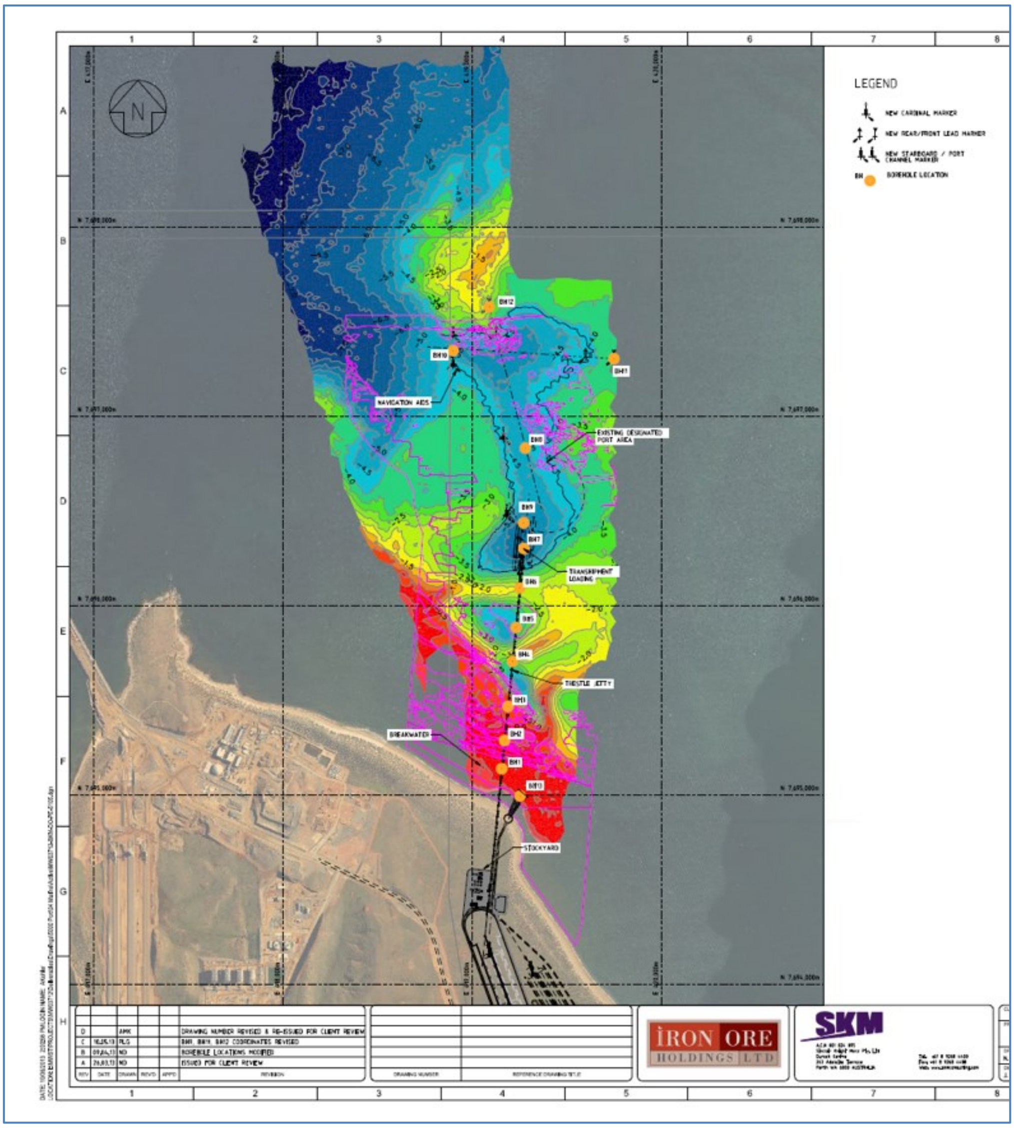


Figure 62. Location of boreholes at Cape Preston (SKM, 2013b).

South North

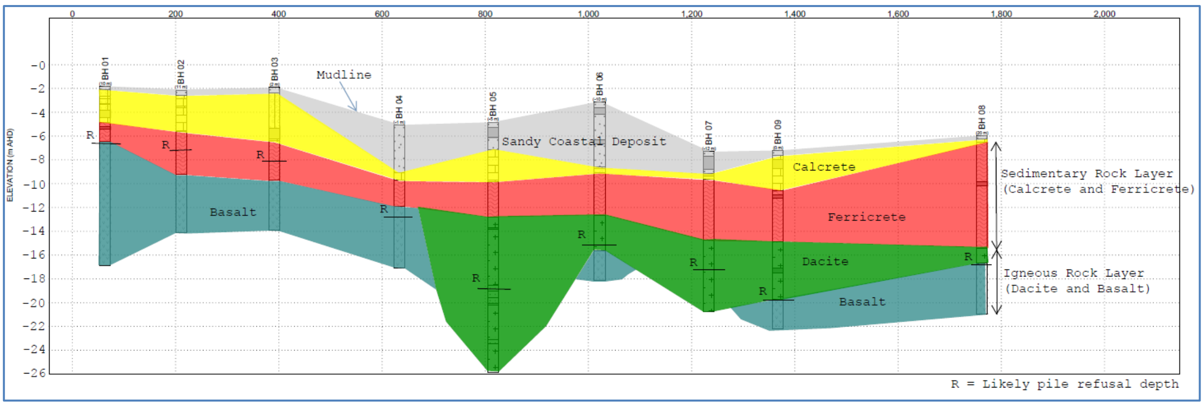


Figure 63. Geological cross-section at Cape Preston (S – N). (SKM, 2013b). The coastal sand unit was present in all boreholes, varied from 0.5 to 6 m in thickness, and is formed poorly sorted, sub-rounded dark brown and grey fine to coarse sands, with some silt and sub-angular gravel, shells, corals and rootlets.

Table 10. Main units described for boreholes at Cape Preston (SKM, 2013b).

Lithology	Depth Range to Top of Layer, m	Layer Thickness Range, m	Strength Range	Typical Description
COASTAL SAND DEPOSIT	-	0.5 to 6.0	Very loose to medium dense, SPT N ranges from 1 to 20.	Fine to coarse grained, well graded, sub-rounded, dark brown and grey, with silt and sub-angular gravels, shells, corals and rootlets. Encountered in all the boreholes.
CALCRETE	0.5 to 6.0	Absent to 4.0	Strength variable; highly fractured in some areas.	Fine, off-white, distinctly weathered. Encountered in all the boreholes.
FERRICRETE	0.5 to 5.0	0.5 to 9.0	Extremely low to high strength	Fine, yellow brown, massive, distinctly weathered. Encountered in all the boreholes.
DACITE	6.0 to 9.0	Absent to base of borehole	Highly variable, extremely low to high strength	Fine, much quartz, off-white, extremely weathered to fresh. Encountered in BH 05 to BH 10.
BASALT	4.0 to 12.0	Base of borehole	Medium to very high strength; highly fractured in some areas.	Fine, grey, massive, distinctly weathered to fresh. Encountered in all the boreholes except BH 05 and BH 07.

Figure 64. Cape Preston looking to SSW. Note the intertidal zone is sediment-starved in places exposing the underlying calcrete, and the dune sands are downlapping onto calcrete in places. The dune faces appear active, steep - perhaps erosive overall.

6.4.2. The main ESSP area

Key units have been described above in section 6.3.3., and below we note those aspects of the associated stratigraphy where it contributes towards the assessment of past changes.

The stratigraphy beneath the ponds and along some pond walls have been characterized and interpreted, using field samples, surface-wave seismic profiling and CPT data. A series of vertical sections across the ESSP area (locations shown in Figure 65) are described briefly below and summarised in (Figure 66).

The thickness and nature of surficial sediments above bedrock is highly variable. Starting in the catchment of the east, along the 40 Mile Road, section A indicates 1 to 2 m of dense sands at the surface along the road section (grey unit on Figure 66), probably residual and alluvial soil, which at the low point of the road (causeway) passes northwards into up to 12 m of mixed interbedded sands and silty clays and hard clay (blue), that possibly represent a channel or basin infill. This infill material is also evident in section B, where it passes northwards into clean sands containing no clays (yellow unit). The age of the infill is important in assessing the local supply of clay, silts and sand to the area, but its age is not known. The depth of the channel/basin indicates that the material might be Last Interglacial or older, and might represent a past possible river channel, and/or and over-deepened estuarine channel, orientated ~W-E behind the local rise of the Gnoorea (presumably igneous) rock.

From Gnoorea, the 1-2 m of dense surface sands (yellow) extend and thicken SW along the spit (section C) and overlies a bedrock surface at 1.5 to 2 m AHD. The SW end of section C indicates the presence of very dense sand, silty sand and clay (green – possibly pre-Holocene), apparently immediately landwards of the buried base of the sand spit. This unit continues the surface sand along the remainder of the spit to McKay Creek and also occurs under the Baldy-Straight Creek mangroves.

Towards the western end of the spit (section D) in the eastern part of the nascent mangroves, the rock is over-deepened, and the location (at CPT037 to 034) matches the overlying depression in the coastal plain of the modern tidal creeks. This tends to indicate that a similar control has acted through time, which might be the location of breach of the older sand barrier to landward in the 40 Mile Road W catchment. If so, and this is not tested, fluvial and/or tidal incision may be as old as the last Interglacial (125,000 years BP) with subsequent weathering to sand and clays immediately above. Given that the nascent mangrove areas is a key area of interest, because it is backed by proposed ponds, it is particularly important to clarify the ages of these units to help assess the area's capacity to adapt to SLR and pond emplacement.

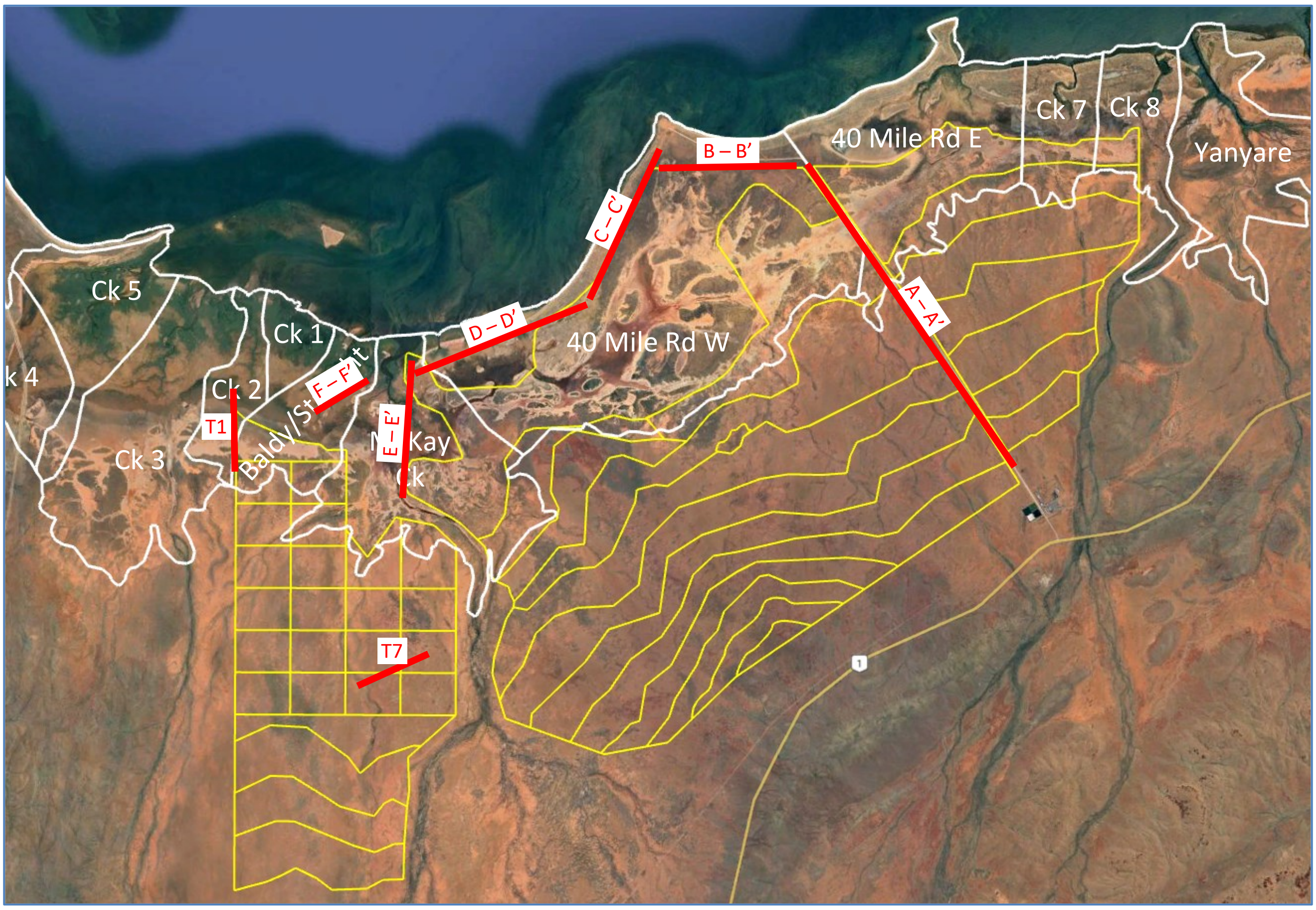


Figure 65. Location of interpreted stratigraphic sections in the area (after CMW Geosciences 2022).

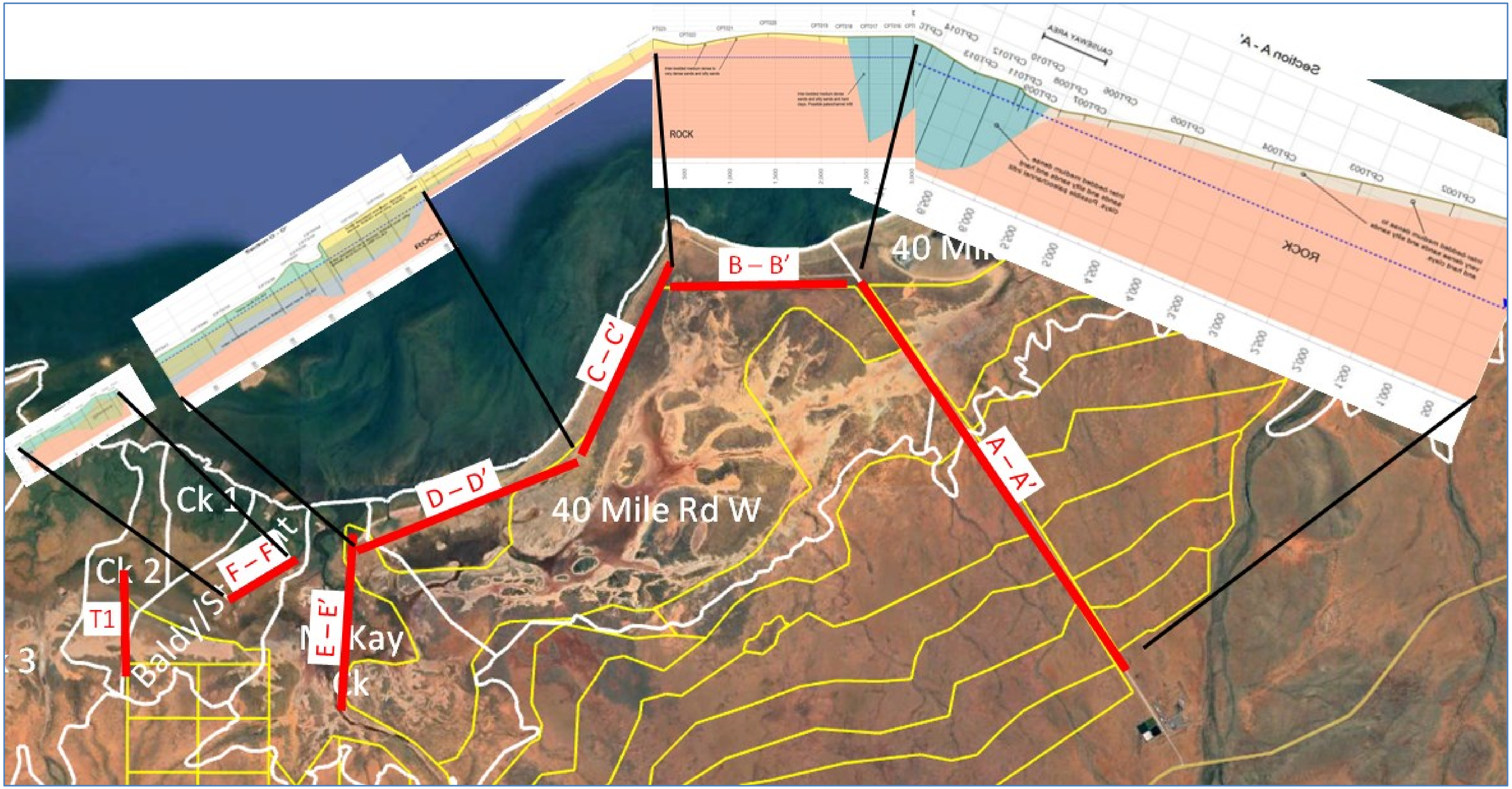


Figure 66. Ribbon diagram illustrating the overall stratigraphy of the area as defined by sections A, B, C, D & F. (Individual sections in Figure 67 to Figure 71 inclusive).

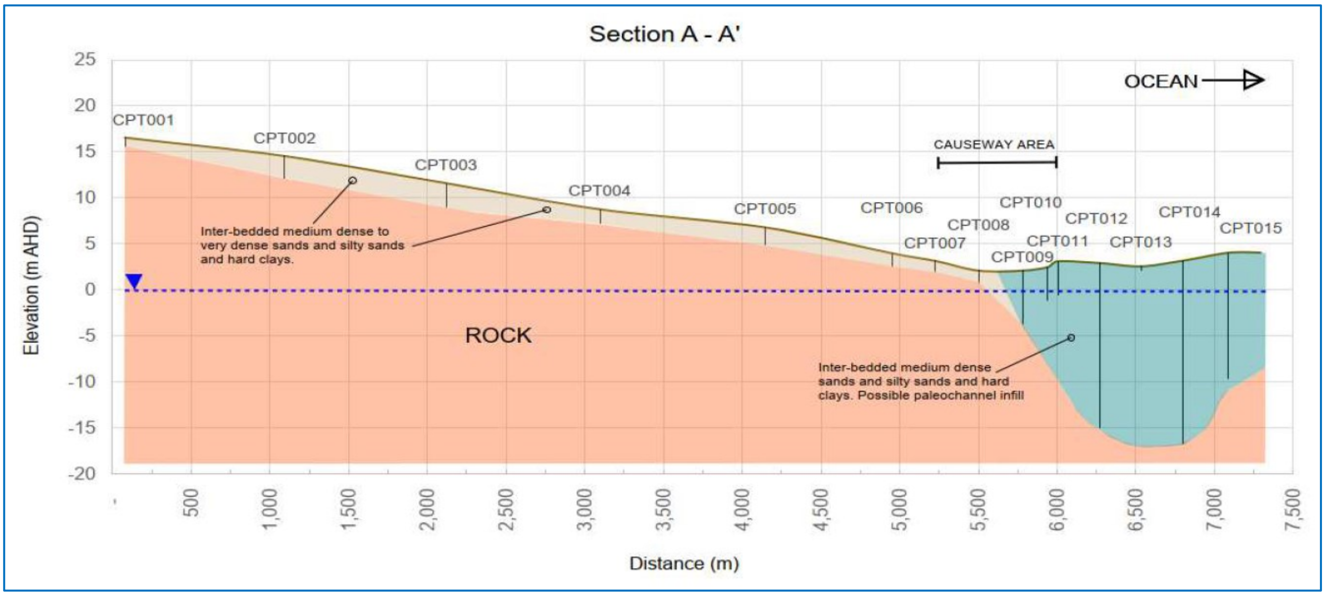


Figure 67. Interpreted stratigraphy along 40 Mile Road, A-A' (CMW Geosciences, 2022). Note the 1 to 2 m of dense sands along the road section, and the interpreted channel infill beyond the causeway towards the coast.

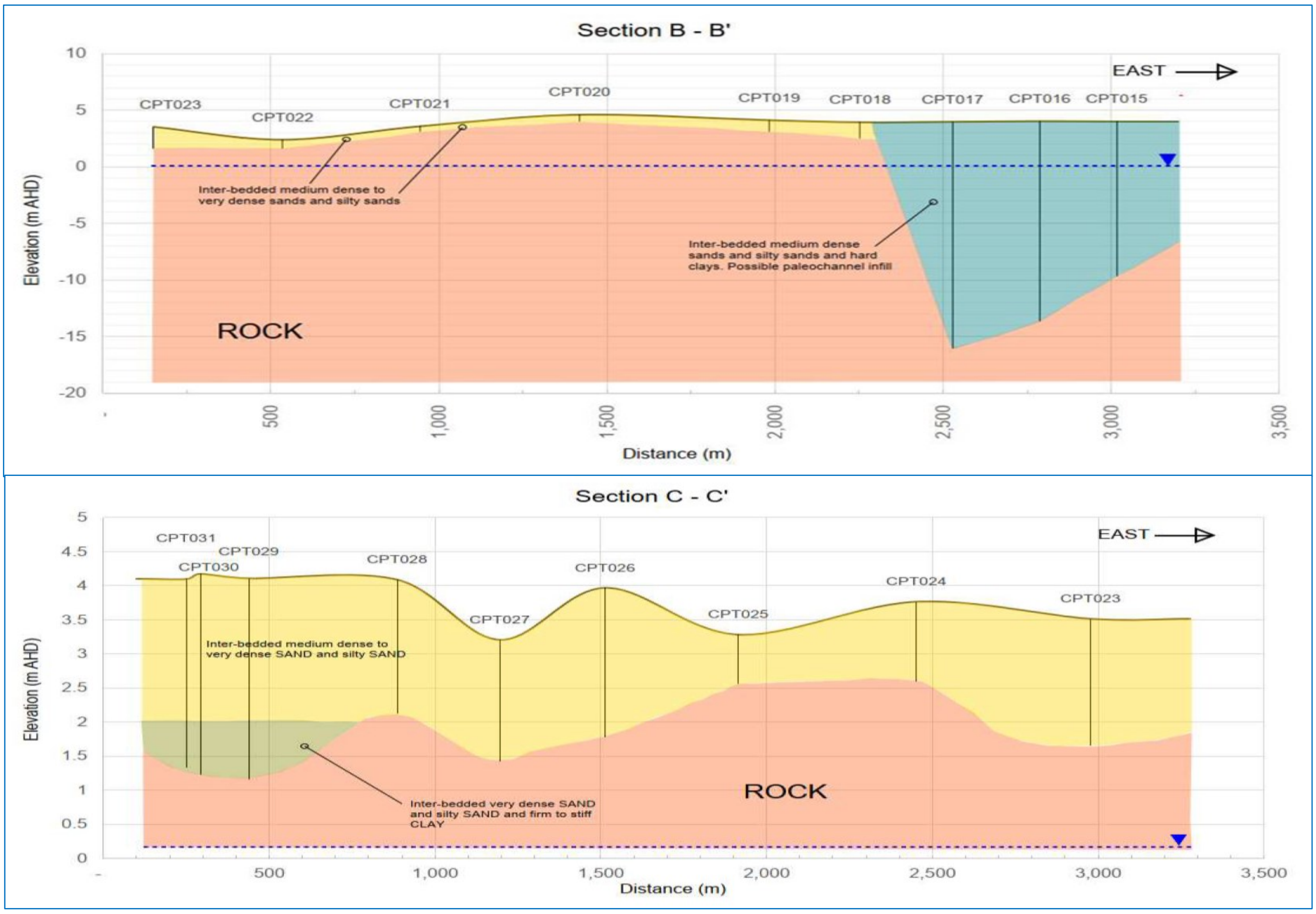


Figure 68. Interpreted stratigraphy (CMW Geosciences, 2022). UPPER – B-B', east of Gnoorea Point. Note the similar stratigraphy to the 40 Mile Road section (Figure 67), with 1 to 2 m of dense sands (no clays) along the road section, and the interpreted channel infill beyond the causeway towards the coast. LOWER – C-C', along the spit west of Gnoorea Point. In the west are buried deposits (green) of a possible palaeo-inlet.

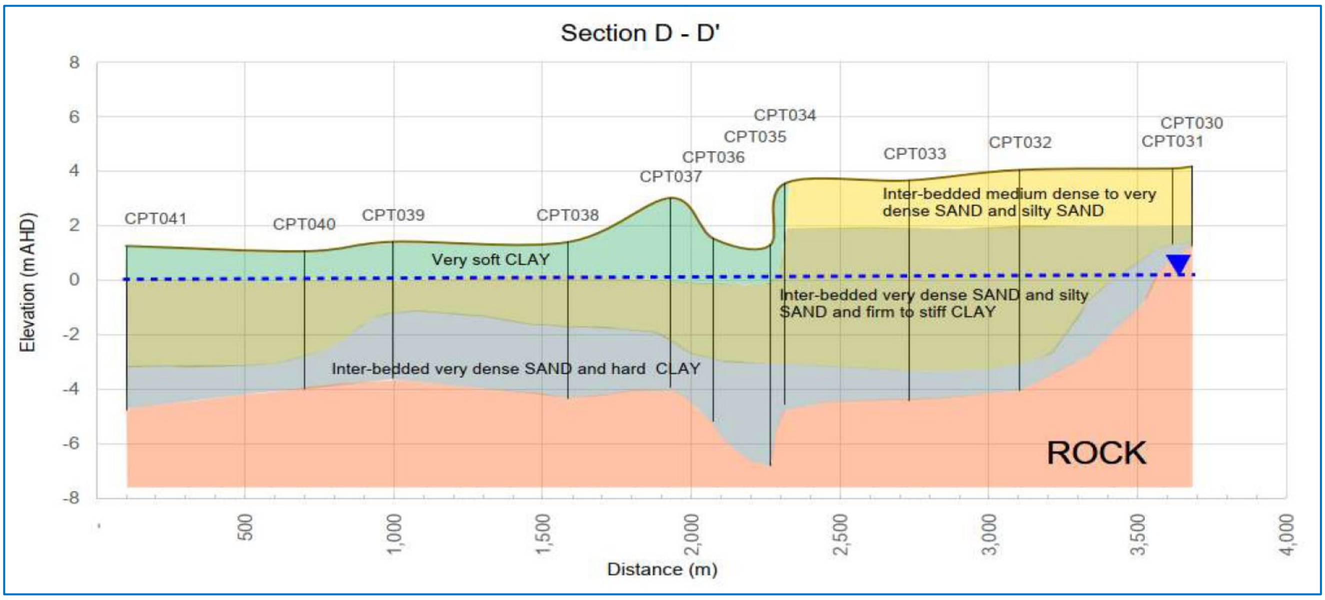


Figure 69. Interpreted stratigraphy in front of the nascent mangrove area (CMW Geosciences, 2022), along line D-D'. Note the barrier spit sand is replaced by soft mangrove muds at the location of the eastern, dominant tidal creek. Both sand and mangrove mud are probably Holocene (but not dated). They overlie very dense sand, silty sand and clay, interpreted as probably pre-Holocene.

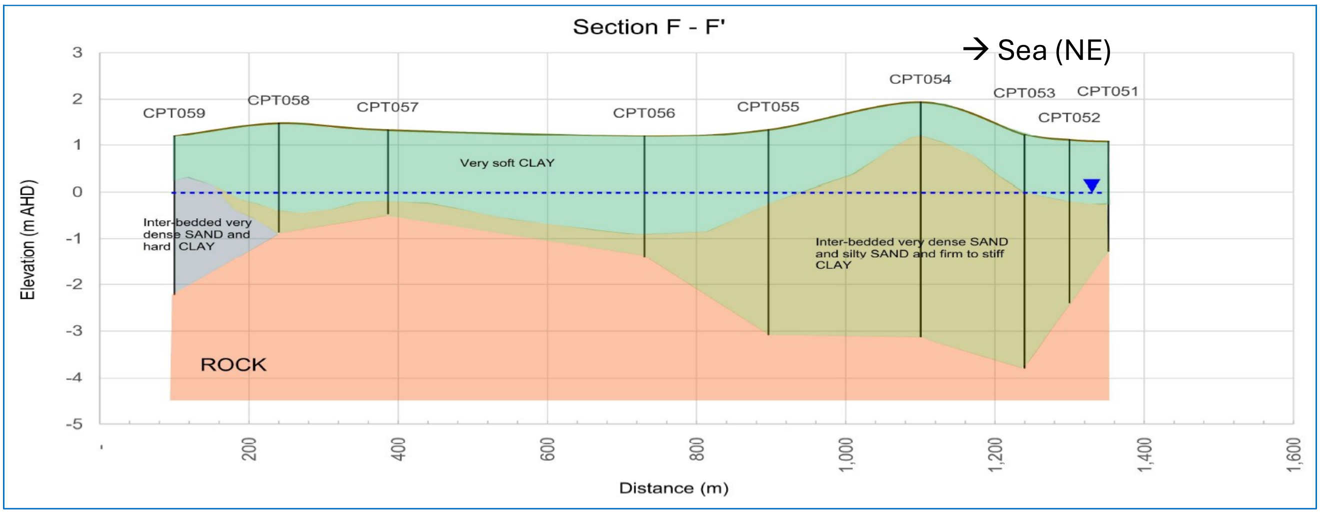


Figure 70. Interpreted stratigraphy: Section F-F', a shore-normal section though the mangroves of Baldy/Straight Creek catchment (CMW Geosciences, 2022).

Along the banks of McKay Creek, the section line E (Figure 71) is not a straight line – it actually remains just east of the present creek. The upper sediments are 1 to 2 m of mangrove mud (light green), that onlap and pinch out to landward at around 2.4 m AHD. It seems likely that this unit is Holocene in age. A similar gentle northward dip of the likely sedimentary units is indicated for Eramurra Creek (Figure 72), although lack of core control means there is some uncertainty.

The underlying dense sand (olive green) also onlaps at a shallow angle (~1:650 at the base CPT47 - 77) and forms low sandy outcrops at the base of the river delta mouth (now corresponding to a habitat for modern island-fringed samphire). To seawards, it forms a sand body underlying the low benthic flats of the nascent mangroves corresponding with outcrops of barrier fragments. Judging from their elevation, and assuming these are indeed coastal dune sands at the delta, the sands could represent coastal dune sands from the Holocene highstand or the Last Interglacial.

Both the Baldy Creek (Figure 70) and McKay Creek (Figure 71) sections indicate a thickened unit of "interbedded v dense sand, silt sand and firm to stiff clay" (olive green) located ~900 m inland of the modern coastline. These could represent a coastal accumulation (an infilled channel or lagoon and/or a shoreline bar).

Their "v. stiff clays" component could be compressed and or old mangrove muds, or weathered material from older sandflats.

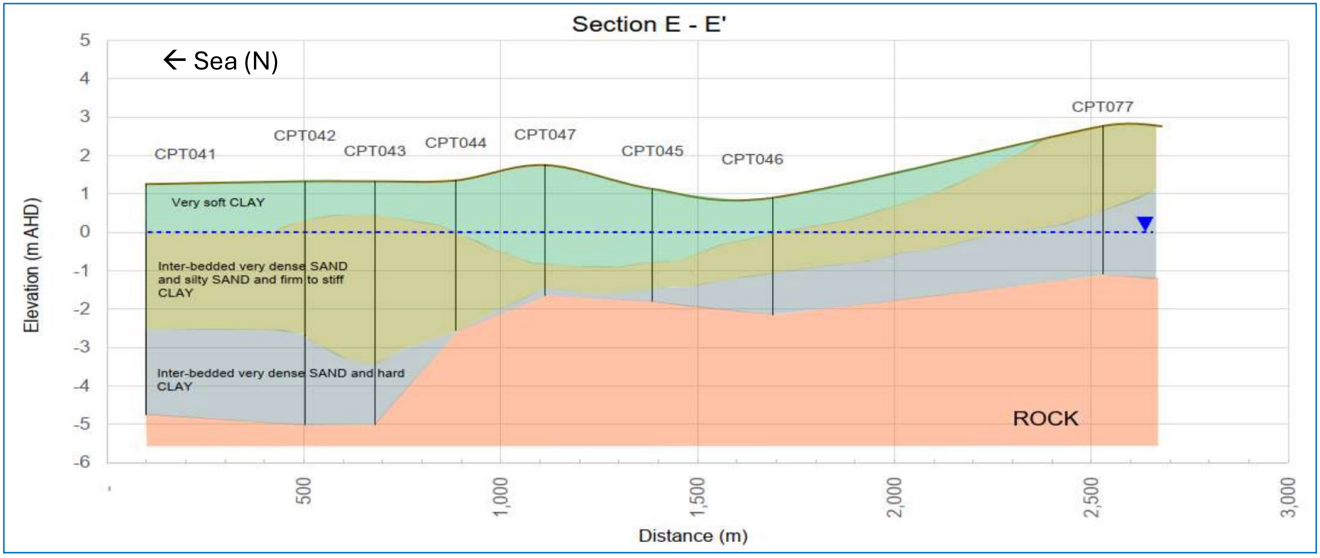


Figure 71. Interpreted stratigraphy: upper – E-E, along the eastern bank of McKay Creek from the sea landward to the delta mouth (CMW Geosciences, 2022). Note the seawards slope (i.e., northwards) to the three units above the bedrock – this tends to indicate that they might be diachronous, i.e., of different ages along their length. This gentle seawards dip of their base is also shown for Eramurra Creek (Figure 72).

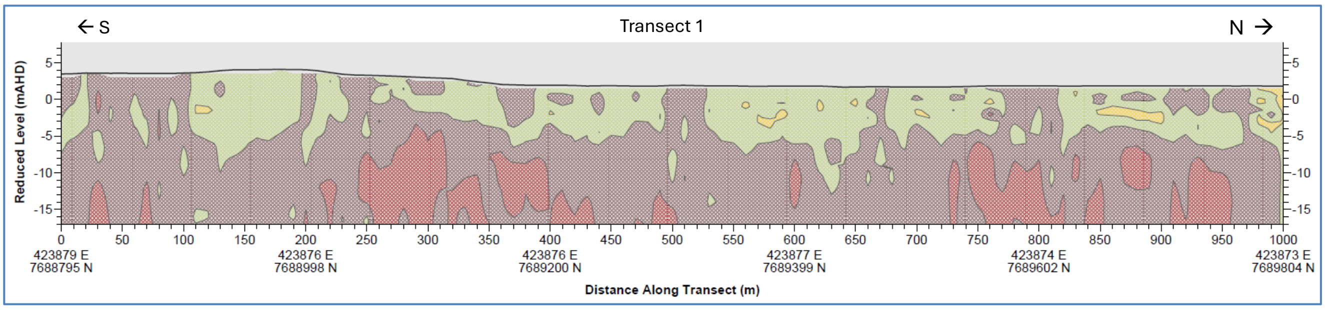


Figure 72. Interpreted material classification for Transect T1 of Figure 65, west of the other transects, perpendicular to the shoreline in the Creek 2 catchment, from the upper intertidal zone southwards across the eastern delta front of Eramurra Creek. Without core control, interpretation of this data is challenging, but it is possible that the section represents a patchy array of infilled basins (of unknown age but probably older than Holocene), above the igneous and/or meta-sedimentary bedrock in this western area. Like McKay Creek (Figure 71), there is a gentle northward dip of the likely sedimentary units (green). Key shown in Table 11. (CMW Geosciences 2022)

Table 11. Key to shear-wave velocity classification shown in Figure 72 & Figure 73 (CMW Geosciences 2022).

Seismic Shear Wave Velocity Material Classification

Class	S-wave Velocity (m/s)	Description
S.1	Equal to or greater than 1500	Moderately hard to hard rock
S.2	750 to less than 1500	Soft rock to moderately hard rock
S.3	350 to less than 750	Very stiff sediment or soft rock
S.4	175 to less than 350	Medium dense to stiff sediment
S.5	Less than 175	Loose to medium dense sediment

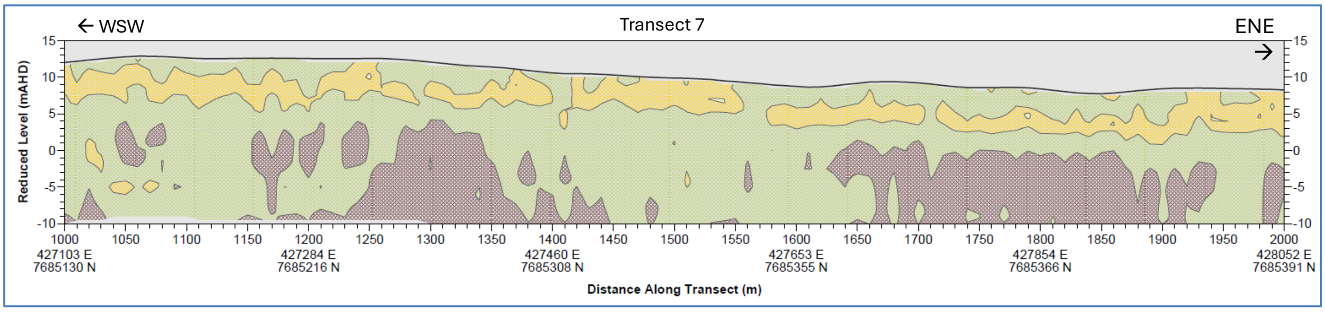


Figure 73. Interpreted material classification for Transect T7 of Figure 65, on the interfluve between Eramurra and McKay creeks. Key shown in Table 11. (CMW Geosciences 2022)

A conceptual cross-section through the coastal geology and sedimentary units (Figure 74) indicates well the complexity of the coastal system. Note that the intertidal areas (seawards of the river mouth, from 0 to 3200 m along the section) are geologically constrained at their landward end by the exposures of the underlying igneous rocks.

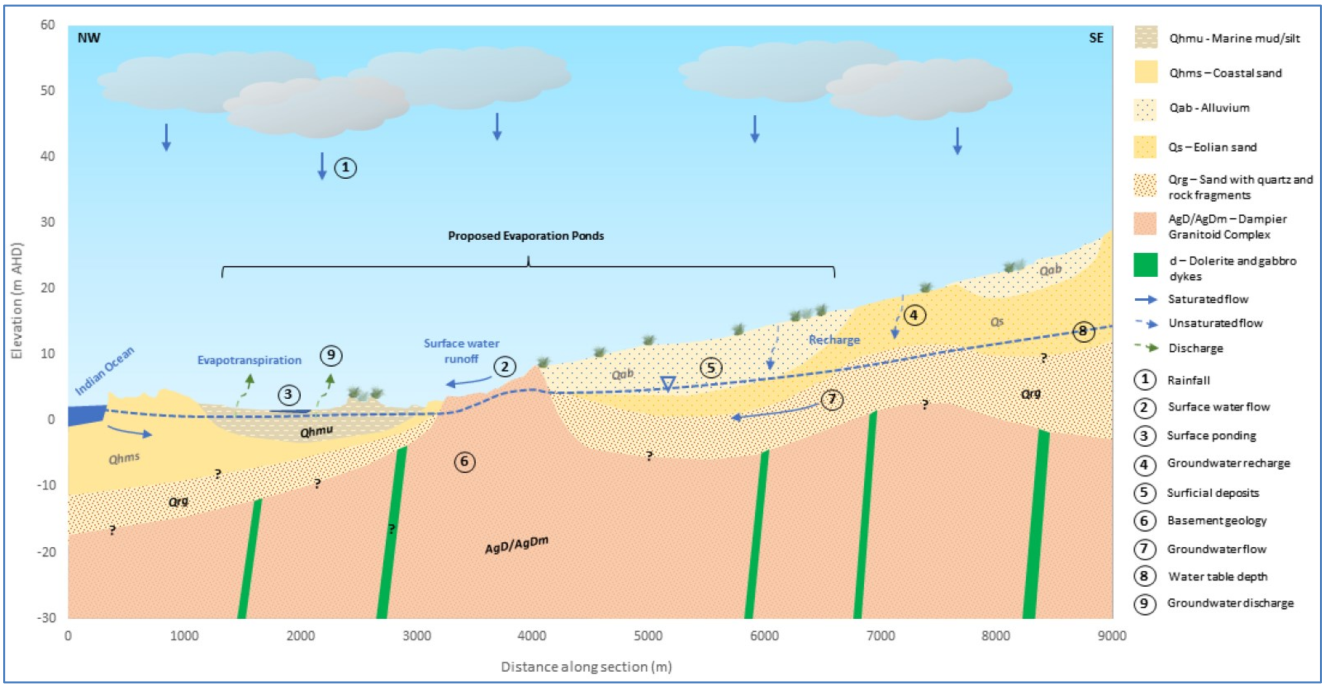


Figure 74. NW-SE vertical section of the geology and sedimentary units across the ESSP project area, showing a conceptual hydrogeological model (Land and Water Consulting, 2023b).

6.5. Physical aspects of key intertidal habitats

Intertidal habitats identified in the ESSP area include mangroves, benthic mats and samphire communities. Intertidal habitats generally occupy a narrow elevation range spanning the ecological transition from marine to wholly terrestrial conditions. This area can be extremely dynamic, with frequent hydrodynamic variability due to the many factors that control periodic sea-level changes and episodic events (Pattiaratchi & Eliot 2008)) and the presence of active geomorphic responses to changing conditions over multiple timescales (Wright & Thom 1977).

Mapping of intertidal habitats has been conducted using hyperspectral remote sensing, supported by limited field checking. Comparison of mapped habitats (Figure 75) with aerial imagery indicates strong linkages to tidal creek networks, although this differs within the project area.

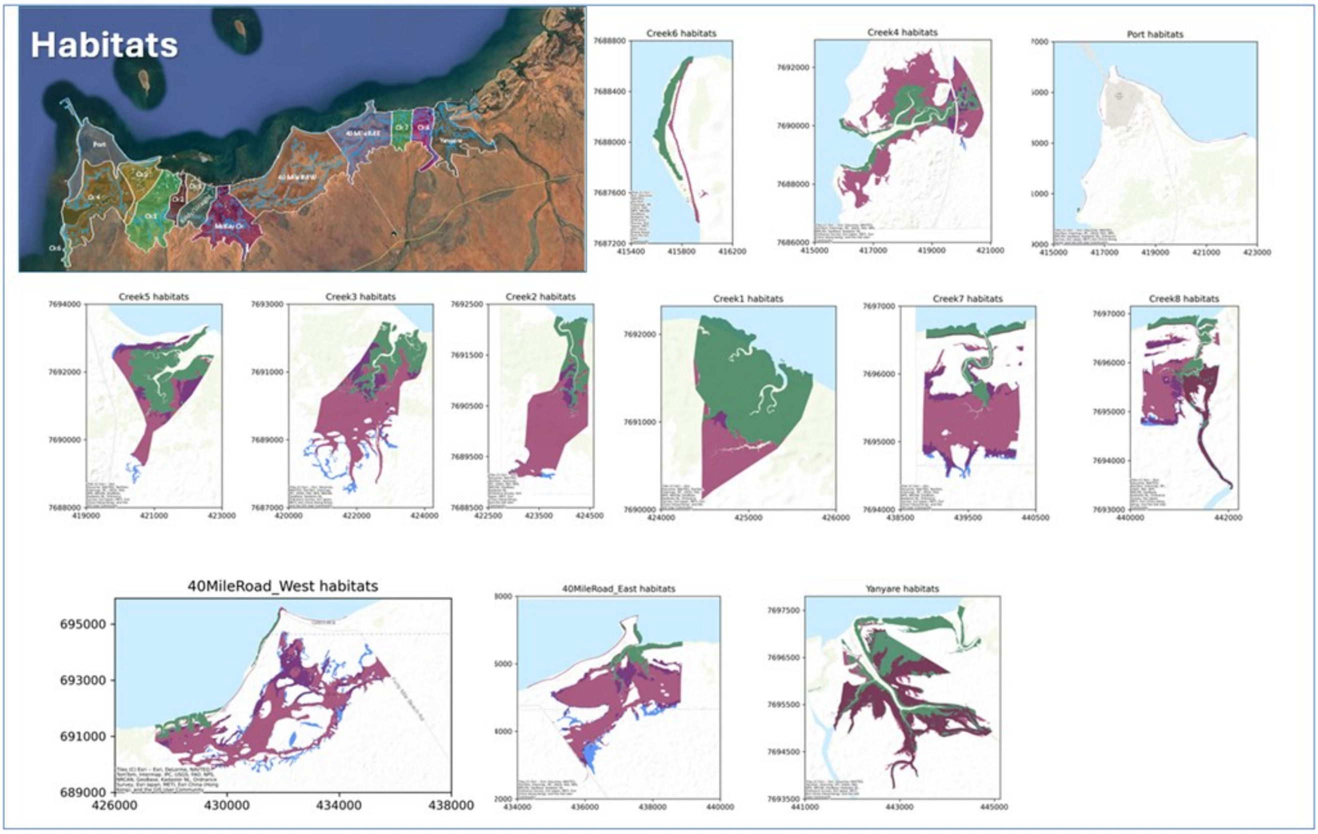


Figure 75. Mapped intertidal habitat areas in various ESSP tidal catchments.

There is a general progression from fringing mangroves adjacent to the coast, estuarine mangroves adjacent to channel margins, to benthic mats located near the upper limit of tidal inundation, and samphire communities occupying supratidal basins or slope margins. There is some complexity in this relevant to future habitats. Analysis of elevation distributions for each habitat (Appendix, section 13.1) has been undertaken using GIS, recognising that habitat classification defines an area encompassing the habitat, and therefore may contain locations and elevations within which the species may not thrive. General findings from this evaluation are as follows.

- Coastal fringing mangroves tend to occupy a relatively narrow elevation range around 0.7 m AHD and inundated almost daily (Table 12), whereas estuarine mangroves tend to occupy elevations around 1.4 m AHD, inundated every 4 to 10 days.
- The estuarine mangroves mapped for Yanyare Creek were at notably higher elevations than elsewhere, at 0.4 to 0.7 m higher (highlighted cell in Table 12). At present it is not immediately clear why this is the case.
- Benthic mats occur across a broad elevation range, from 1.2 m and intermittently inundated every 3 to 9 days, through to 2.5 m AHD, inundated only 1 to 5 times each year. Modal habitat levels are around 1.4 m AHD for Creeks 1, 3 & 5 (highlighted cells in Table 12), and at notably higher levels of ~1.7 m AHD in other catchments.
- Samphires were mapped to occur across a broad range of elevations, from 1.2 m AHD i.e., from intermittently inundated, every 3 to 9 days, through to 3.5 m AHD, being supratidal. Elevations within these habitat areas were typically bimodal, with one modal elevation almost matching that of benthic mats, and the other 0.5 to 1.3 m higher (compared in the same catchment), just below or higher than the upper limit of benthic mats.

Table 12. Modal elevations of key intertidal habitats (m AHD). (Full elevation details in Appendix, section 13.1).

Creek	Mangrove		Benthic Mat		Samphire	
	Fringing	**Estuarine**				
	low mode	**high mode**	**mode**	**(range)**	**low mode**	**high mode**
Creek 6	0.7		n/a		n/a	
Creek 4		1.2	1.8	1.2 - 2.5	1.4	
Port	0.6		2.1	1.0 - 2.5	n/a	
Creek 5		1.3	1.4	1.2 - 2.5	1.4	2.0
Creek 3		1.4	1.4	1.2 - 2.5	1.5	2.8
Creek 2		1.4	1.6	1.3 - 2.0	1.4	
Creek 1		1.4	1.4	1.3 - 1.7	1.4	
Baldy		1.3	1.7	1.3 - 2.0	1.6	2.5
Straight		1.3	1.7	1.3 - 2.5	1.6	2.1
McKay		1.3	1.8	1.2 - 2.5	1.7	2.5
40 Mile W	0.6	1.4	1.7	1.5 - 2.5	-	2.2 - 2.6
40 Mile E	0.7	1.4	1.6	1.2 - 2.5	1.6	2.5
Creek 7	0.7	1.4	1.7	1.2 - 2.5	1.7	2.1
Creek 8		1.5	1.8	1.2 - 2.5	1.7	
Yanyare		1.9	1.8	1.2 - 2.5	n/a	

6.5.1. Mangroves

For most practical purposes, as for the ESSP project, mangroves can be considered as tending to occur in two main coastal environments.

- **Fringing mangroves** – these occur along open coastlines exposed to waves. Typically, they establish in sediments that are accumulating along the coastline in periods of low wave activity, but where sediment availability is low, fringing mangroves can also establish in patches on rocky substrates. Their relative exposure to waves means that they can be ephemeral environments, subject to erosion by episodic events.
- **Estuarine mangroves** – these occur along the banks of estuarine channels and tidal creeks and extend onto the overbank flats for various distances. These environments are less exposed to waves and are more subject to tidal processes. These relatively sheltered environments are typically muddy but can vary and in places the plants can be based in sandy and locally even rocky environments. Established estuarine mangroves tend to be less liable to rapid major erosive events because they are relatively sheltered from episodic wave events, but migration and switching of tidal channels can lead to sediment erosion that may leads to their roots being exposed and the bed destabilised.

On a regional basis, where there are a variety of potential substrates on which to grow, the vertical range in which mangroves are found is largely controlled by the tidal range, but as noted above, is also influenced by other factors. Locally their range can vary by several decimetres, and this appears to be the case for the ESSP region (Table 12). There is a consistent difference along the ESSP coastline in the modal elevations of the fringing mangroves and their estuarine counterparts. The difference is 0.7 to 0.8 m, whether within or between tidal creek catchments. The elevation of the estuarine mangroves of ~1.4 m AHD is a typical elevation for a tidal floodplain (Figure 76), presumably related to low sediment supply at these elevations because of the infrequency of marine inundation there. The major difference in elevation might mean that fringing and estuarine mangroves might have some inherent differences in resilience. For example, fringing mangroves might receive and lose sediment relatively rapidly, through the action of waves, and have relatively frequent “habitat resetting” events. Estuarine mangroves are more likely to experience ongoing changes in tidal creek position and movement of mobile bank-attached bars, but also are subject to local major change of state such as a meander cut-off. These are both relatively small fluctuations in an estuarine environment of relatively longer-term stability.

Figure 76. Top – Tidal creek with water levels below overbank, and exposed horizontal mangrove root systems on the banks, indicting some recent lowering of the bed level. Bottom - Creek bed near the mouth at low tide, showing the creek bank (top) and a linear sandbank (upper centre) and starved small tidal dunes (centre and bottom) (CMW Geosciences 2022).

6.5.2. Benthic mats

Within the Pilbara, studies have identified mats dominated by cyanobacteria, generally formed of several genera. O2 Marine (2020) describe the microbial or cyanobacterial mats (here referred to as benthic mats) of the Mardie area, noting that these mats are a geographically widespread intertidal BCH type common to estuarine and intertidal mudflats and saltflats, and some subtidal marine environments (Paerl *et al*. 1993). They are typically exposed to extreme variations in salinity, temperature and moisture (Sørensen *et al*. 2005) and occupy areas without other organisms. Benthic mats vary widely in appearance, ranging from thin sticky coatings on sand, mud and organic debris to well-developed, layered carpets of leathery appearance in lagoonal, reef, mud and sandflat environments, as well as some saltmarsh systems (Paerl *et al.* 1993). Benthic mats are generally dominated by cyanobacteria, have many nitrogen-fixing taxa and possess a range of unique physiological traits enabling them to occupy these extreme environments (Sørensen *et al*. 2004, Sørensen *et al*. 2005).

In the ESSP area, benthic mats are mapped at 0 to 0.6 m higher than the estuarine mangroves (with the sole exception of the mapped mangroves of Yanyare Creek). This figure covers the full range of benthic mats, including those of low and high productivity. By comparison, Actis Environmental Services (2023) also found that the benthic mats are well-constrained by tidal elevation, with most samples in the range 1.5 to 1.9 m AHD and a few examples located 20 to 30 cm higher and of low chlorophyll-a concentrations. This led Actis Environmental Services (2023) to conclude that the key factor is the duration of local tidal inundation. This enables biological activity in an otherwise extreme environment for temperature, desiccation and salinity. This finding is consistent with that of Biota Environmental Sciences Pty Ltd (2005, their Table 4.2) who found a 0.1 m range for benthic mats at the Yannarie Salt Project and Lovelock *et al*'s (2010) range of ~0.4 m for Exmouth.

For benthic mats, seasonal variability appears significant. At the ESSP area, observations indicate that samples from the same approximate location (~± 10 m) but taken four months apart produced concentrations of Chlorophyll a (hereafter Chl-a), similar in some cases but far apart in others (Actis Environmental Services (2023).

Further, spatial variability is high. Field observations indicate that the benthic mats are patchy, particularly around their edges and in areas of physical disturbance where the mat may be disturbed and/or folded. There is also a tendency for high Chl-a concentrations to only occur closer to mangrove creeks (Figure 77), with most data above 150 mg/m^2 located within 2 km of a creek. At larger distances the Chl-a concentrations were generally below 100 mg/m^2.

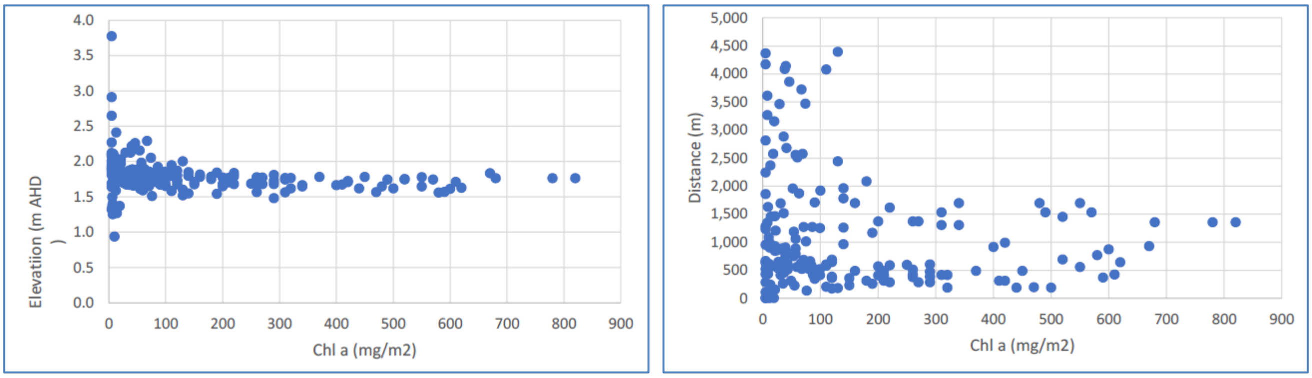


Figure 77. Chlorophyll-a content for all samples, measured as rewetted mats, plotted against bed elevation (upper) and distance from nearest landward mangrove fringe (lower) (Actis Environmental Services, 2023).

As a complicating factor, some shallow basins in the coastal plain recorded high concentrations of Chl-a, indicating production in areas of standing water. Some of these basins appear to be localised areas of modern bed scour (or at least sediment throughput) from tidal exchange and/or freshwater runoff, such as the narrow NW-SE aligned shallow basin SE of the nascent mangroves that links with the 40 Mile Road W catchment (bottom left of Figure 78). Other larger areas (i.e., most of the red areas of Figure 78 & to the centre left of Figure 79) are likely to be 'old' areas of low ground (i.e., basins that are able to be infilled but haven't received or retained sufficient sediment yet, because there is no clear mechanism to supply sediment from the rivers or the sea, and because little or no sediment is produced in-situ).

Therefore, when considering the use of these parameters to predict future habitats for benthic mats, care is needed, because in areas where there is a simple morphology, elevation and distance to creek may be strongly correlated, but this might not be the case where there is a levee beside the creek, or an eroding creek-head basin, and/or a pre-existing basin nearby.

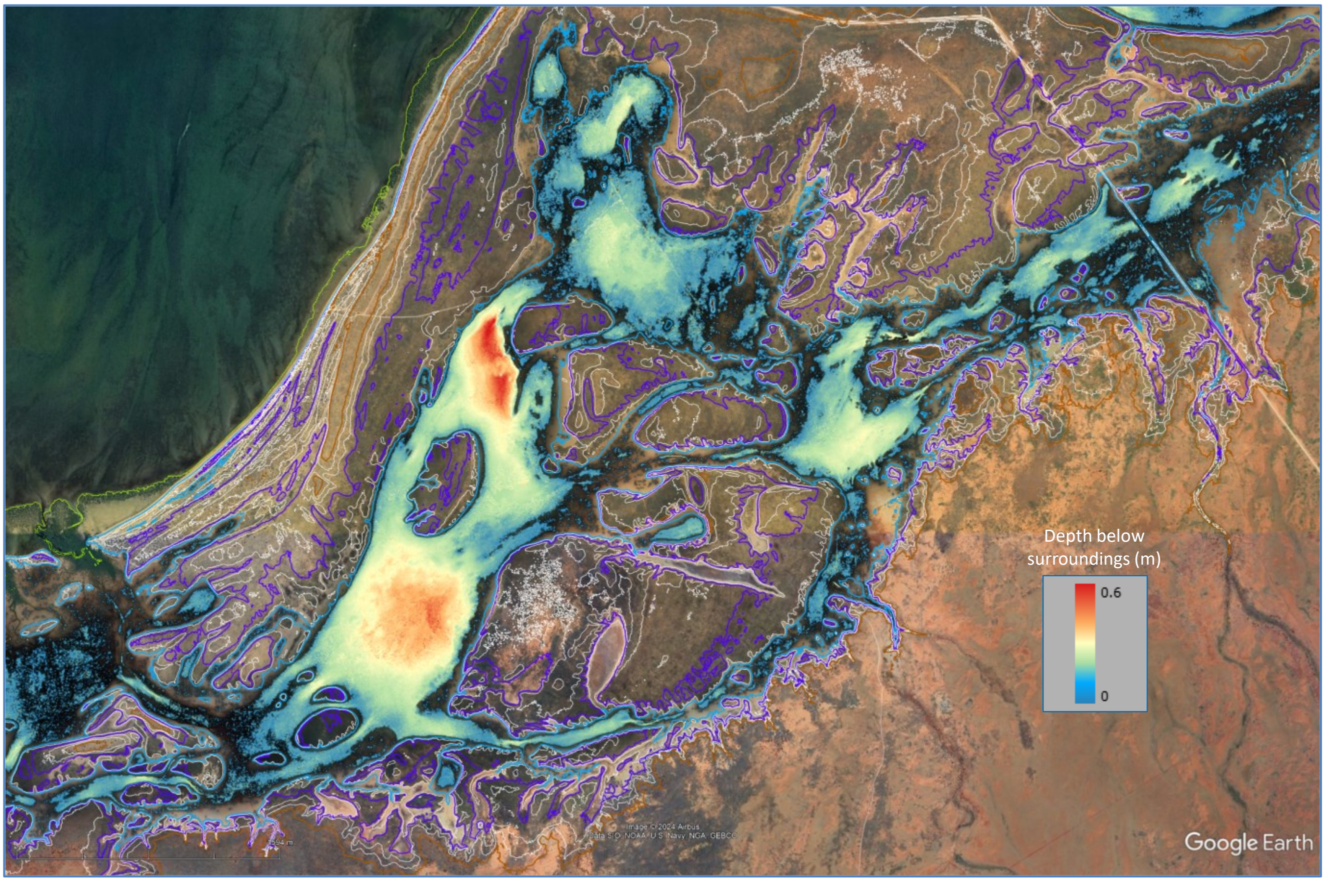


Figure 78. Basins in the 40 Mile Road W catchment are up to 0.6 m deep. The deepest area is behind (SE of) the spit, and together form an area 3 km by 0.8 km.

Other factors also are likely to affect the presence and productivity of benthic mats. Actis Environmental Services (2023) suggested several, which we have taken and modified here.

- Tidal range, because a large tidal range will cover a larger area of tidal flat and cover it faster.
- Local physical setting and coastal geomorphological features. This is a highly complex set of factors, but, for example, it might be considered feasible that an environment generally protected from winds and waves, liable to slow tidal flushing, and lacking internal topography (such as the NE part of the 40 Mile Road E catchment, at an elevation of 1.5 to 2 m AHD) may be associated with more extensive, productive and persistent benthic mats than areas of similar elevation more exposed to winds and waves and having topographically-induced fast currents. The latter factors might induce disruption of the surface mat.
- Freshwater runoff will affect the wetted area, fanning out from creeks and helping maintain saturation of the mat.
- Depressions or basins on the coastal plain may form temporary perched ponds where mats are likely to be more active. Such features would include basins formed near structures such as roads and banks where natural flows have been altered and have generated local scours.

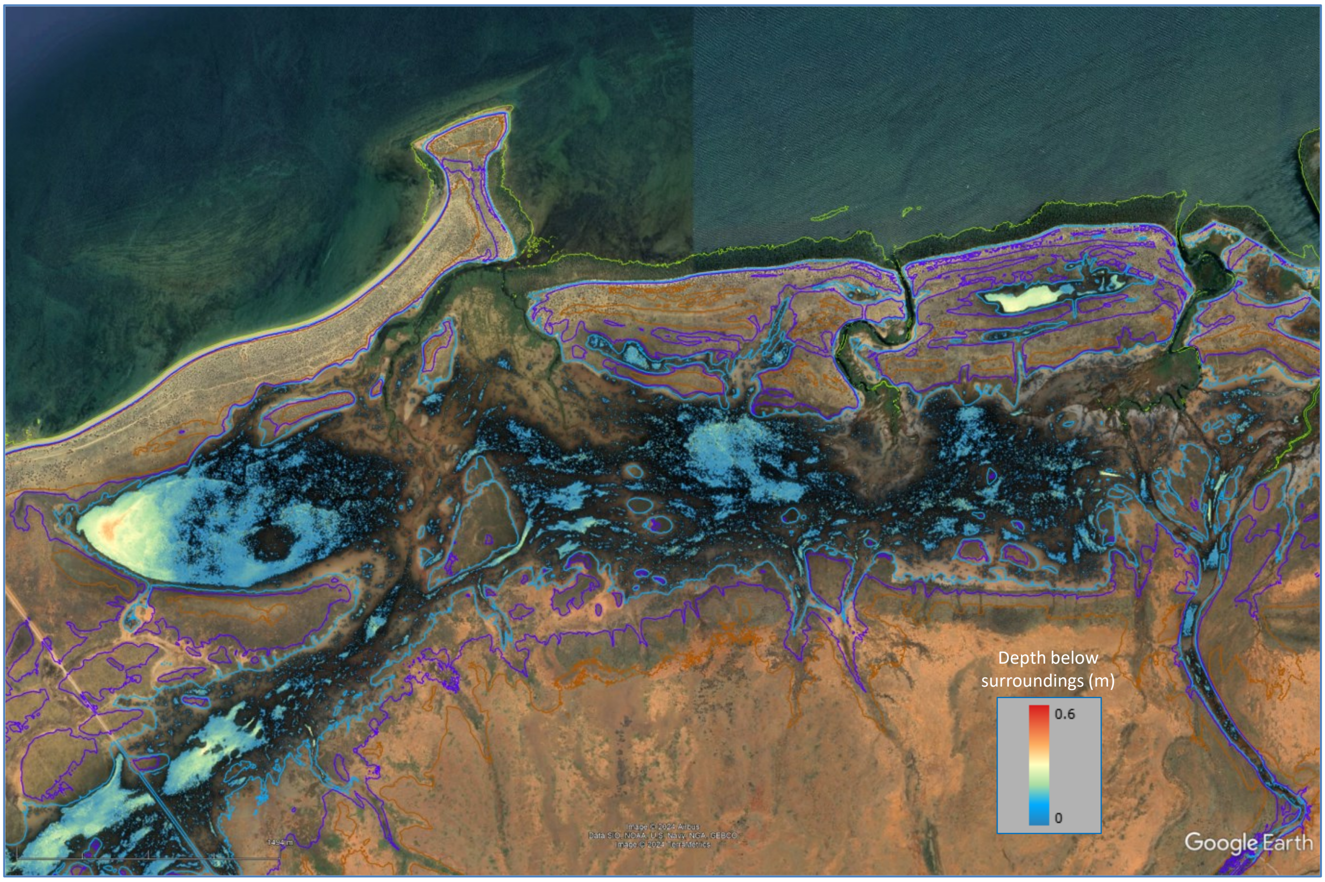


Figure 79. A smaller shallower basin ~1.5 km x 0.6 km occurs in the western part of the 40 Mile Road E catchment, as the extension of the low area landward of the barrier. A raised basin occurs in the coastal barrier to the east, 0.8 km long and 0.13 km across (light green area to upper right), with its lip at ~2.5 m AHD.

6.5.3. Samphire

As noted above, samphire occurs across a broad range of elevations, from intertidal at 1.2 m AHD to supratidal at 3.5 m AHD. Their distribution is typically bimodal, with one modal elevation similar to benthic mats (1.4 to 1.7 m AHD), and the other notably higher (2.0 to 2.8 m AHD), similar to or even above to the highest benthic mats. Noting that this report aims to assess the potential effects of SLR, initial visual analysis indicates that samphires occur in several general settings (Figure 80), that are also linked to their elevation:

- Channel-head samphire (high elevation mode) – i.e. infilling the relatively sheltered inner part of depressions between river-delta lobes, or other closed depressions, close to the base of relatively steep slopes, and with limited opportunity to migrate landward (southward) with SLR.
- Island-fringing samphire (low and high elevation modes) - surrounding sandy raised features on the coastal plain, also with limited opportunity to migrate upwards.
- Levee-fringing samphire (low elevation mode) – formed on the flanks of the raised levee beside a tidal creek. These have relatively good opportunity to migrate with SLR, assuming that the sediment accumulation that formed the low levee continues to be formed by sedimentary processes as the creek system migrates landwards. This depends on creek dynamics, the underlying inherited topography and sediment supply, perhaps especially from the sea.
- Open fringing samphire (mostly high elevation mode) – formed in relatively exposed locations at the base of raised ground to landward, with limited opportunities to migrate landward.

This designation is not claimed to cover all areas, nor be broadly applicable, but appears useful in considering the possibilities of change in the ESSP area. Firstly, it appears to reflect well the specialisation of samphires including their need for occasional freshwater and damp ground, and secondly it also indicates the likelihood of a variable and sometimes limited response to SLR depending on their type and elevation.

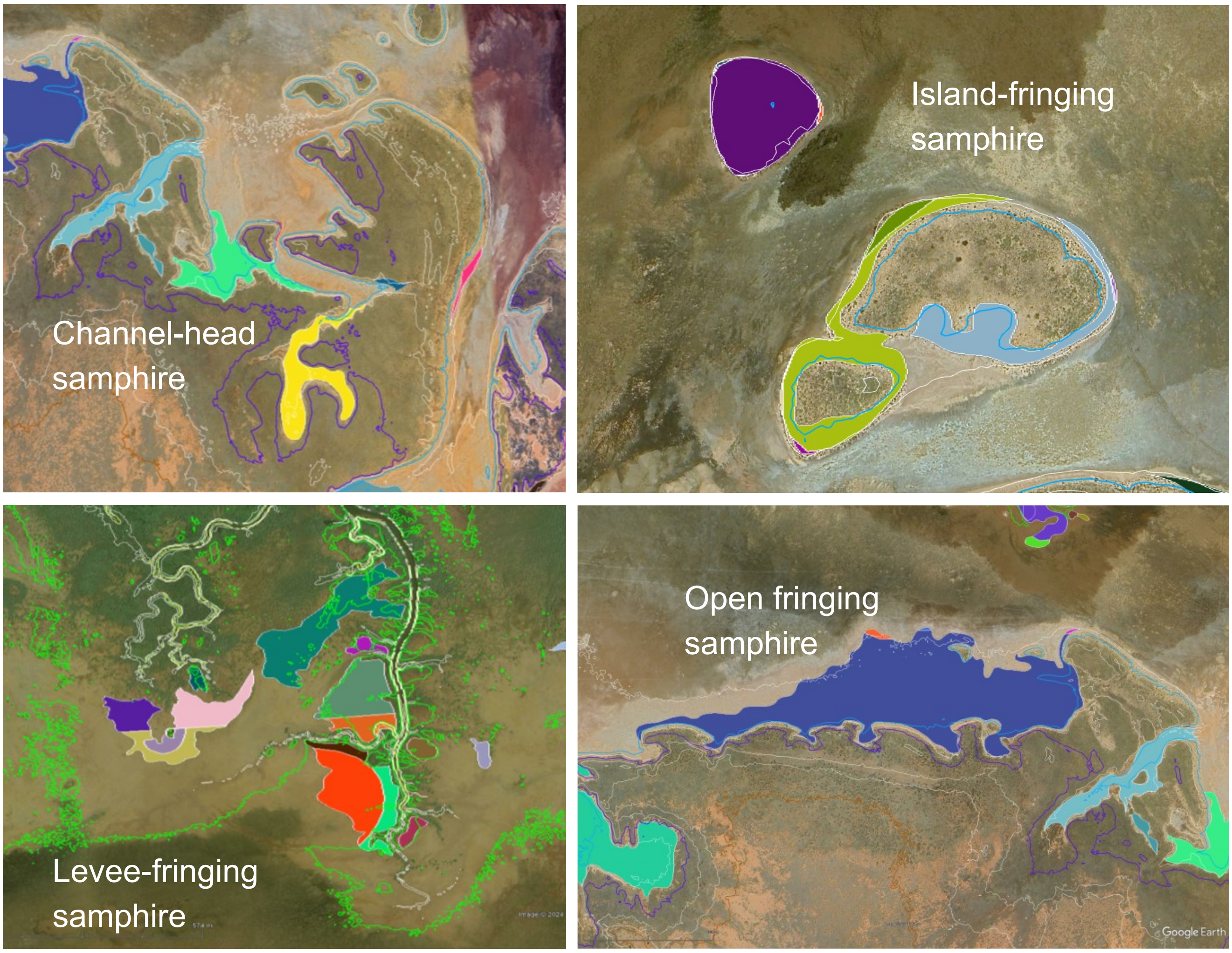


Figure 80. Four designated settings for samphire species, based on their geomorphological setting and different potential to migrate or persist with SLR. (Different colours are of no consequence – all indicate the presence of samphire).

6.6. Sediment transport

This section summarises indications of past and present sediment transport processes. This is necessary to help understand the potential mechanisms that maintain the coastal system and assess the system's resilience to change.

6.6.1. Sediment availability

The nature and disposition of the main stratigraphic units are described in sections 6.3.3 and 6.4, including descriptions of the grain size and thickness of the sediment available for transport. The relevant aspects in terms of sediment transport are summarised below (Table 13), and overall, there appears no obvious limitations on sediment availability across the coastal zone. However, there are some areas where there is limited sediment available because past processes acting over many centuries and longer have partitioned the sediments into their present locations and units. Therefore, even fast flows in some areas may generate limited rates of sediment erosion and transport.

Table 13. Key sedimentary units relevant to sediment erosion and transport and accumulation (see also Table 8).

Unit name	Location and key characteristics	Thickness	Significance wrt sediment availability
Supratidal delta and river catchments			
Alluvial sheetwash	Thin veneer of gravel on the flanks above some river channels	Thin, patchy	Ample supply in the catchment of clays, silts and sands
Residual soils	Largely in-situ weathering products beneath the sheetwash gravels	2 to 3 m	
Alluvial soils	Gravels in braided channel beds and in overbank deposits	Unknown, but absent exposed in places	Gravels available for transport
Granite – Moderately Weathered	Dampier Granitoid Complex - outcrops in creek banks and at the southern margins of the inter- and supra-tidal flats	n/a	Minor sand and clay source to the coastal plain.
Supratidal flats, intertidal flats and coastal deposits			
"Former Coastal rock ledges" **~ "Beach Rock"** **~ "Calcarenite" (calcareous sandstone)** **~ Coralline limestone**	Small areas on the southern edge of inter-tidal flats, e.g. the eastern edge of small sand plains, in 40 Mile Road W, in pond 2.	~1 to 2 m but generally far less	Minor source to the nascent mangroves
Sand plains Incl. **'Deflated dunes'**	Deflated Dunes and Sand Plains and sandy islands in the 40 Mile Road W catchment (pond 2).	1 to 1.5 m typical for the deflated dunes and sand plains, mostly <1 m on the sandy islands.	Source of silty sand, some calcareous gravels, some clay

Unit name	Location and key characteristics	Thickness	Significance wrt sediment availability
& ‘Sandy islands’			
Eolian Sands & other coastal deposits	Fringing (Coastal) Dunes typically up to 10 m in height and sharply flattening out along the southern edge as they merge with the Deflated Dunes.	Up to several m.	
Lagoonal muds at and landward of the shoreline **~Soft intertidal muds** **~Soft mangrove muds**	Intertidal flats and creeks, areas of scattered mangroves. Supra-tidal flats - stiffer muds, possibly through drying.	0.25 to 2.75 m but mostly 1 to 1.5 m.	Ample source of unconsolidated clays, silts and sands.
The present shoreline	NB - the ESSP ‘shoreline’ is not a precisely defined line, it is a broad zone. Sandy, shelly and muddy beaches occur, and a gravel storm beach in places.	Unknown but probably up to 1 m or so.	Negligible
Estuarine sediments **~Lagoonal muds**	Low intertidal and shallow subtidal flats, soft and mobile sediments	Unknown	Mobile sands and some silt
Estuarine tidal channels	Tidal channels incised into the intertidal flats	Unknown	Mobile sands
Inner shelf sands	Seawards of the estuarine barrier and of the eastern ESSP coastline	Unknown but appears patchy.	Sands, some gravel and silt

6.6.2. Controls on sediment transport

In general, all geomorphological indications are that the present hydrodynamics are sufficiently strong to transport sediment in most, if not all, areas of the coastal system, but this does not necessarily mean that sediment transport takes place. A variety of physical controls are relevant to future coastal change, particularly for the tidal creek systems (O2 Metocean 2022a):

- Underlying geology.
  - The location and morphology of the tidal creeks might be controlled in part by resistant rock that might underlie them. As noted above, the fluvial creek and tidal creek systems are be underlain by a variety of granitic, calcrete and/or ferricrete rocks, which have the capacity to influence the location of channel incisions. This is especially the case in the uppermost tidal area and fluvial regions, where the creeks (e.g. McKay Creek) are inset in a narrow rock-bounded channel and will remain constrained within these channels with SLR.
- Past creek migration.
  - The past and present tidal creeks have migrated laterally, and as they do so they rework older deposits. Long periods and/or high rates of lateral migration are more likely where coastal slope is relatively low, and this will tend to produce a more uniform and younger surface deposit. In general, it might be that the lateral migration of the creeks in the western part of the estuary (e.g., creeks, 3, 2 & 1) is greater than in the east, partly because, purely judging from their size and planform, the relatively sheltered areas of the west appear to house larger and more stable tidal systems, less influenced by fluvial runoff than for McKay Creek, and hence they might have more time to migrate. Thus, there might be W-E variation in types and thicknesses of the immediate sub-surface sediments along the estuarine portion of the ESSP coastline.
- Local sediment availability.
  - For systems to migrate seawards or landwards requires sediment being available to be moved and redeposited, and there is measurement evidence, from Regnard Bay and McKay Creek that sediment transport is limited by local availability, i.e., measured turbidity remains low even when current speeds rise greatly and/or waves increase (O2 Metocean 2022a). This means that the system might have limited ability to migrate landward in response to any driver or drivers, including those drivers changed by SLR.

Whilst other controls exist, it is clearly relevant how much sediment might be introduced into the coastal system directly associated with the emplacement of the salt ponds. For example, there are likely to be regions of the modified McKay Creek channel area that might quickly erode and provide new sediment into the system, and other areas with significant proportions of gravel and coarser material that might armour the underlying material so become resistant to further erosion. Other areas might also become areas of net accumulation for the newly released or other available sediment. Like most areas of the Australian shoreline and inner continental shelf, the available field data on sediments and sedimentary processes is insufficient to allow a quantitative assessment of sedimentary processes over such an area and range of time. The sediment budget of the existing coastal system is unknown, and the changed budget for the new system influenced by the pond walls is also unknown. This results in significant uncertainties that remain even after expert judgement is applied to a wide range of available evidence.

6.6.2.1. Bedforms - active and/or vegetated

A variety of (mostly) sandy bedforms are observed in fieldwork-associated photos and from aerial images. Bedforms include:

- Subaqueous bedforms such as:
  - Various bedforms in Regnard Bay, some of which may be cyclone-generated and/or related to modern or past tidal or even fluvial flows (section 6.3.1)

    - The major active incised tidal channel orientated W-E along the length of the estuary (lagoon), and its terminal fan to seaward (e.g., Figure 41).
    - Longitudinal bars and point bars in many of the active tidal channels, most with superposed tidal small dunes (e.g., Figure 76, Figure 130).
    - Areas of active erosion and comet marks in some river channels, especially where the major rivers meet the tidal flats, and similar areas and structures of lesser extent across some of the flat sand plains near minor freshwater inputs, e.g., 40 Mile Road E (section 9.3.5) and uppermost McKay Creek (Figure 132).
- Eolian bedforms such as:
    - Active dunes along the coast, e.g. along Gnoorea spit, and east of Gnoorea Point along the barrier that fronts the eastern part of the 40 Mile Road E catchments (section 9.3.5)
    - Deflated dunes of the intertidal sandplains (section 6.3.3.1.6)
- And some of possibly combined origin, including:
    - some large and/or long features on the Regnard Bay seabed that might relate in part to older sediment tails and spits anchored behind rock outcrops at times of lower RSL (section 6.3.1 and 6.3.3.1.8).

This suite of bedforms is largely consistent with the modern mix of hydrodynamic processes along the ESSP coastline, but as noted above, complications occur because where bedforms are not presently active, (i.e., they are vegetated or of very low relief) and so information on their age and sedimentary setting is needed to help them support an interpretation of shoreline response to SLR and other factors. Relevant aspects of these bedforms are generally covered in detail in the examples in Section 9.3.

6.6.2.2. Flow data

Tidal currents have been described and discussed in detail in O2 Metocean (2022a) and noted here in section 6.1.1. There is little applicable data on waves regarding their potential influence on sediment transport at the coast itself. Relevant information on fluvial runoff has been presented in section 6.2.2.

6.6.3. Evidence of past sediment transport pathways

6.6.3.1. Marine geomorphology

As noted in section 6.3.1, the ESSP area includes a series of offshore islands (probably drowned shoreline complexes), and their attached sediment bodies, that together now reduce exposure to waves and influence the flow of tidal currents and cyclone-associated flows. The array of topographic features on the bed in the estuary and to seawards are a mix of E-W features and bedforms of variable orientation. The complex seabed morphology in western Regnard Bay (Figure 81, Figure 82), indicates two intersecting sets of lineations, that might represent relict or modern, inactive or active sedimentary bedforms. The N-S lineations in the eastern estuary may represent features associated with the past channels and mouth(s) of what is now 40 Mile Road Creek W catchment, at a time of lower sea level and/or as the Gnoorea spit migrated landward.

Along the coast, immediately seaward of the shallow subtidal zone, there is a relatively sharp seaward boundary, shown on Figure 81 and Figure 82 as a sharp northern edge to the red colours. This might indicate a past barred and/or barrier shoreline, at a time of lower sea level. These features and other rock outcrops indicate likely control points on coastal evolution at Cape Preston, Gnoorea and similar smaller promontories to the east. Within Regnard Bay, there is little information on the state of the surface sediments especially regarding cementation, so it is difficult to assess their potential contribution to modern coastal processes in the ESSP area.

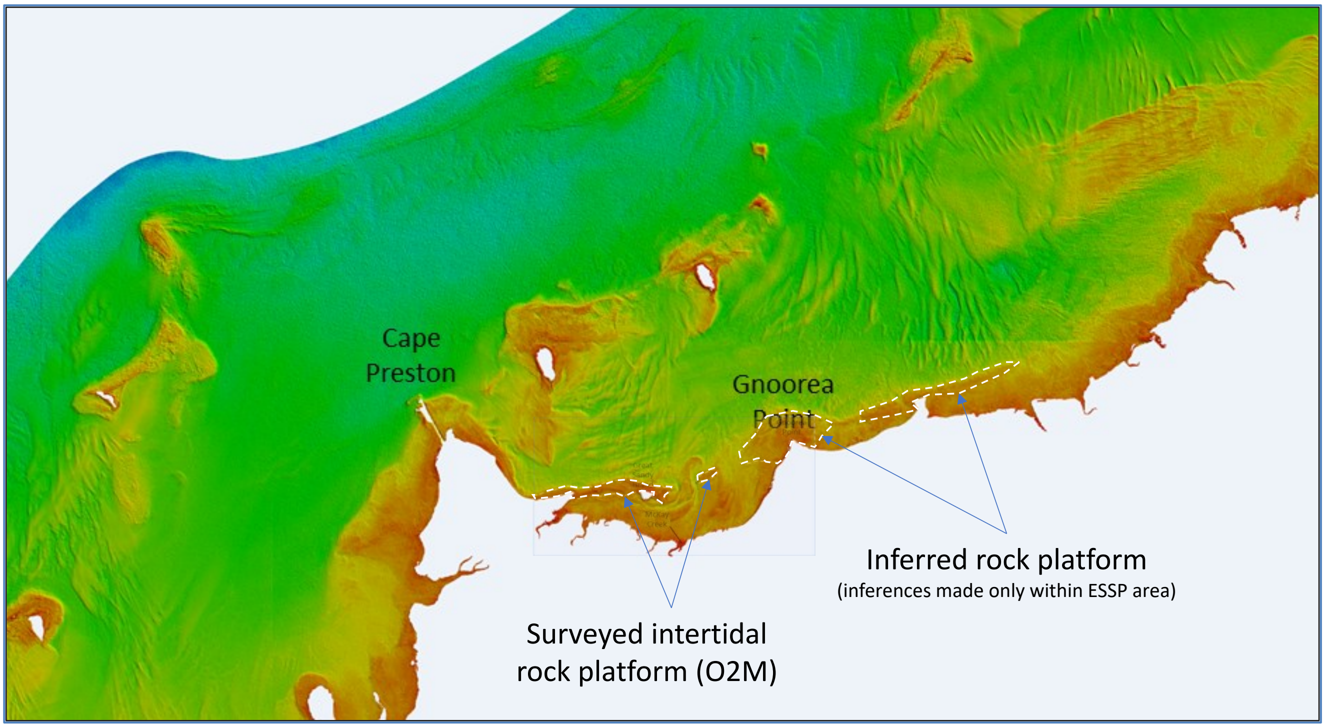


Figure 81. Regional bathymetry and seabed features (Lebrec et al., 2021). Islands occur in the west and centre of the figure, each with likely rocky and/or sedimentary aprons and associated relict and/or active sedimentary bedforms. Dashed lines indicate intertidal rock platform identified by survey (O2M 2023) from which can be inferred similar rock platforms off Gnoorea and further east.

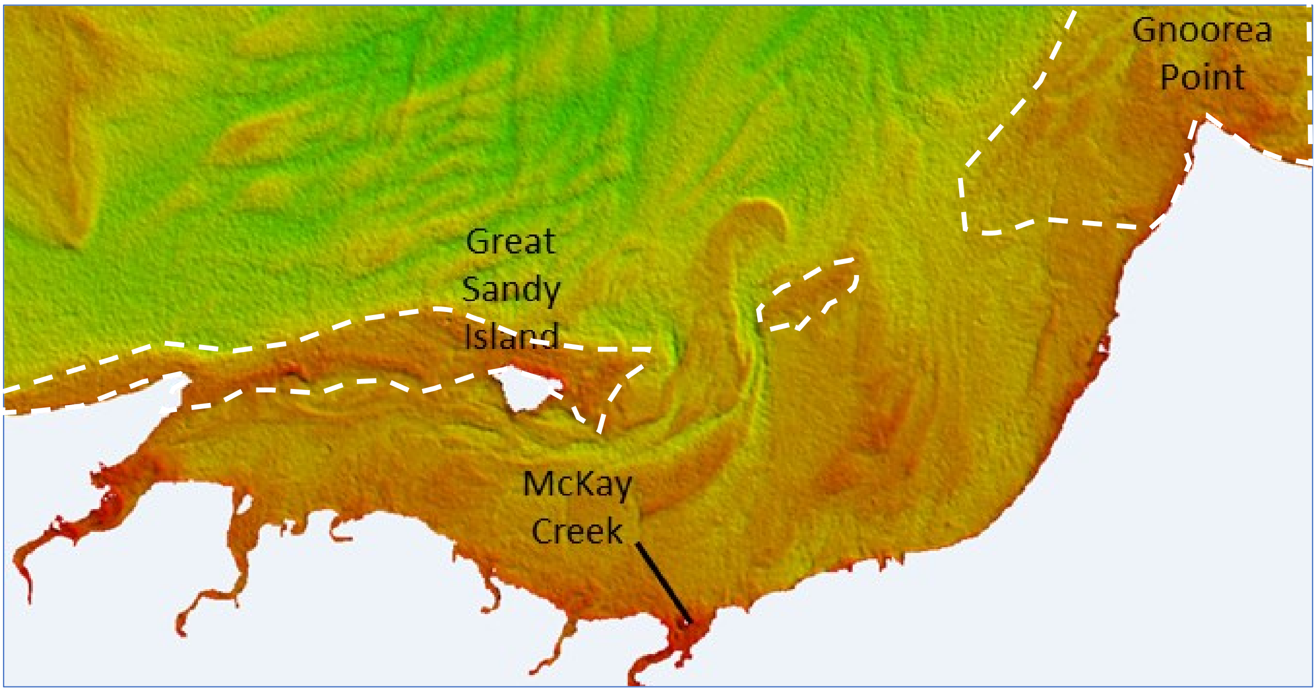


Figure 82. Local bathymetric and seabed features (Lebrec et al., 2021). Note the incised tidal channels within the greater estuary, and their termination east of Great Sandy Island between seabed outcrops of bedrock (see Figure 81).

6.6.3.2. Sedimentary particle size and compositional trends

Selected PSD data from the ESSP area have been tested for the possibility of using particle tracing through the system, using a combination of PSD and composition. The concept is that should modal sizes be present and readily identified, and their composition is consistent, then small decreases in their modal size across an area can indicate transport pathways of those modal sizes, whereby the direction(s) of size decrease indicates long-term sediment transport direction in that direction of that size mode. Different size modes might have different pathways and different directions. This concept has been widely tested and is effective in i) discriminating different sedimentary environments and ii) revealing sediment transport pathways (e.g., Bryce *et al*., 1998, 2003; Woolfe *et al*., 2000, Orpin *et al*., 2004).

To date, in the ESSP area, relatively few samples have been analysed for PSD using laser-sizing, which along with their distribution within the river catchments (Figure 83) does not facilitate such analysis, especially in addressing key questions about the sedimentary links between different parts of the tidal system and the environments near the coastline (e.g., the questions in Table 15, in section 7). Nonetheless, selected samples were briefly tested to see if such an analysis would assist the project, covering samples in the interfluve between Eramurra and McKay creeks, the McKay Creek catchment, and lower Devil Creek into Creek 8. The results are shown in Figure 84, Figure 85 and Figure 86.

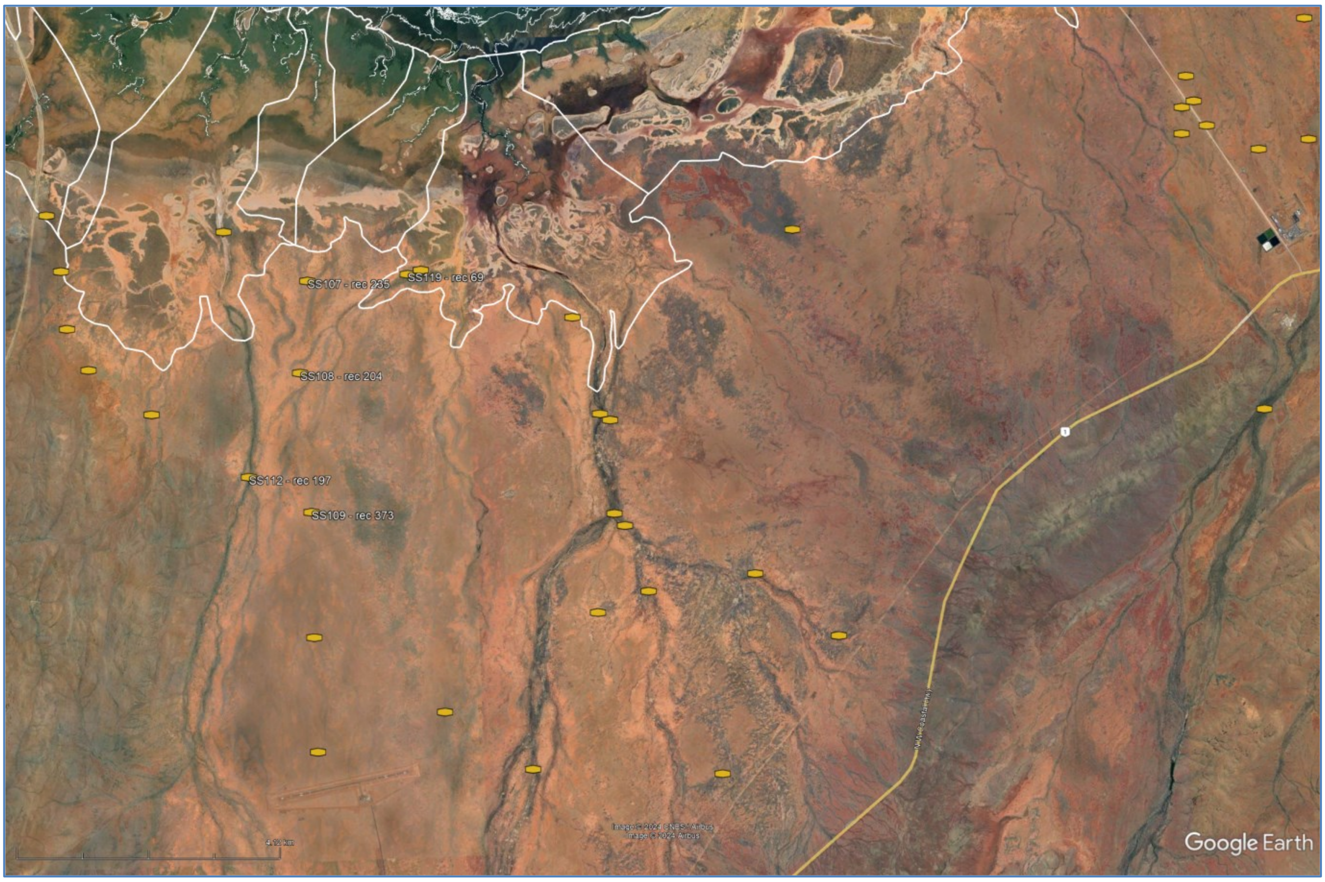
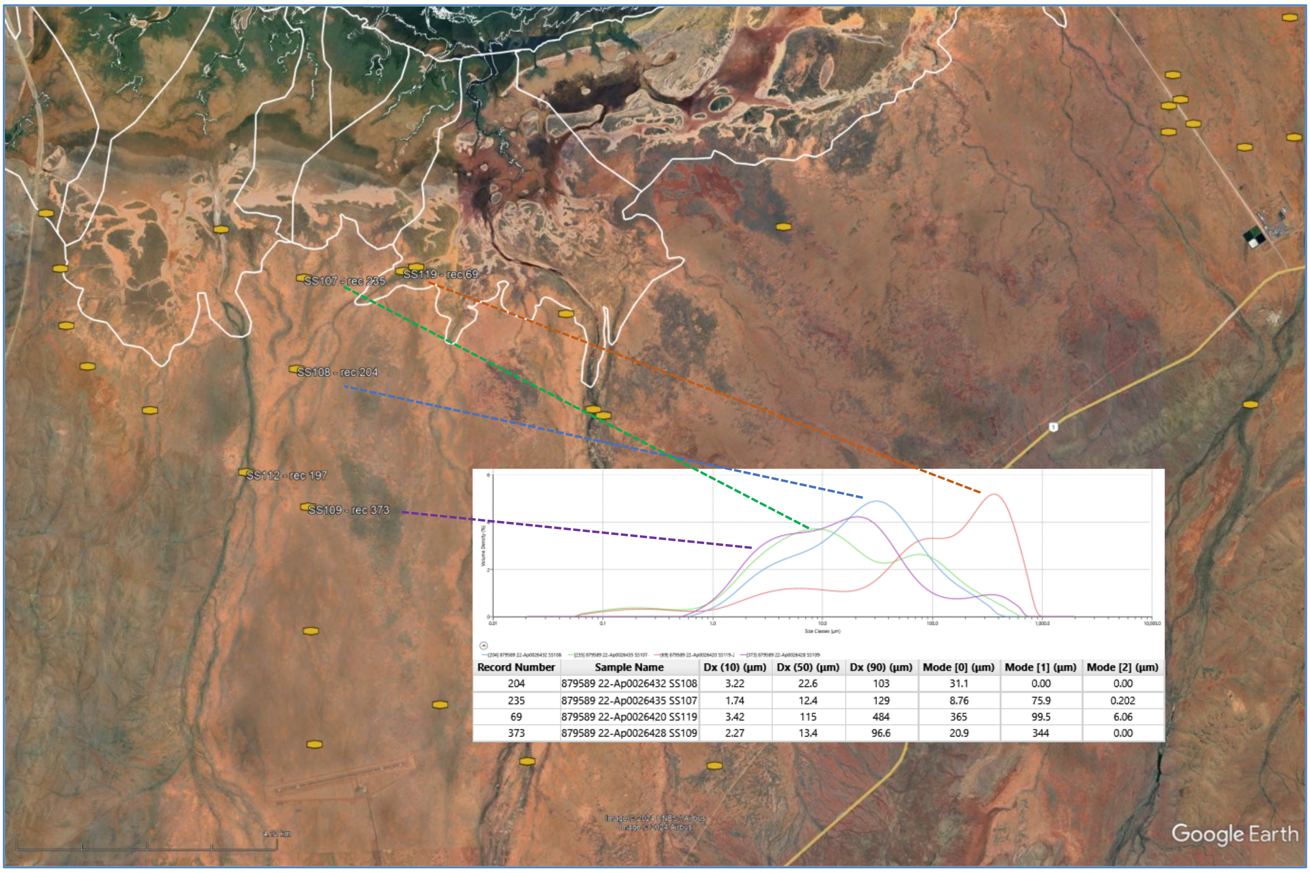


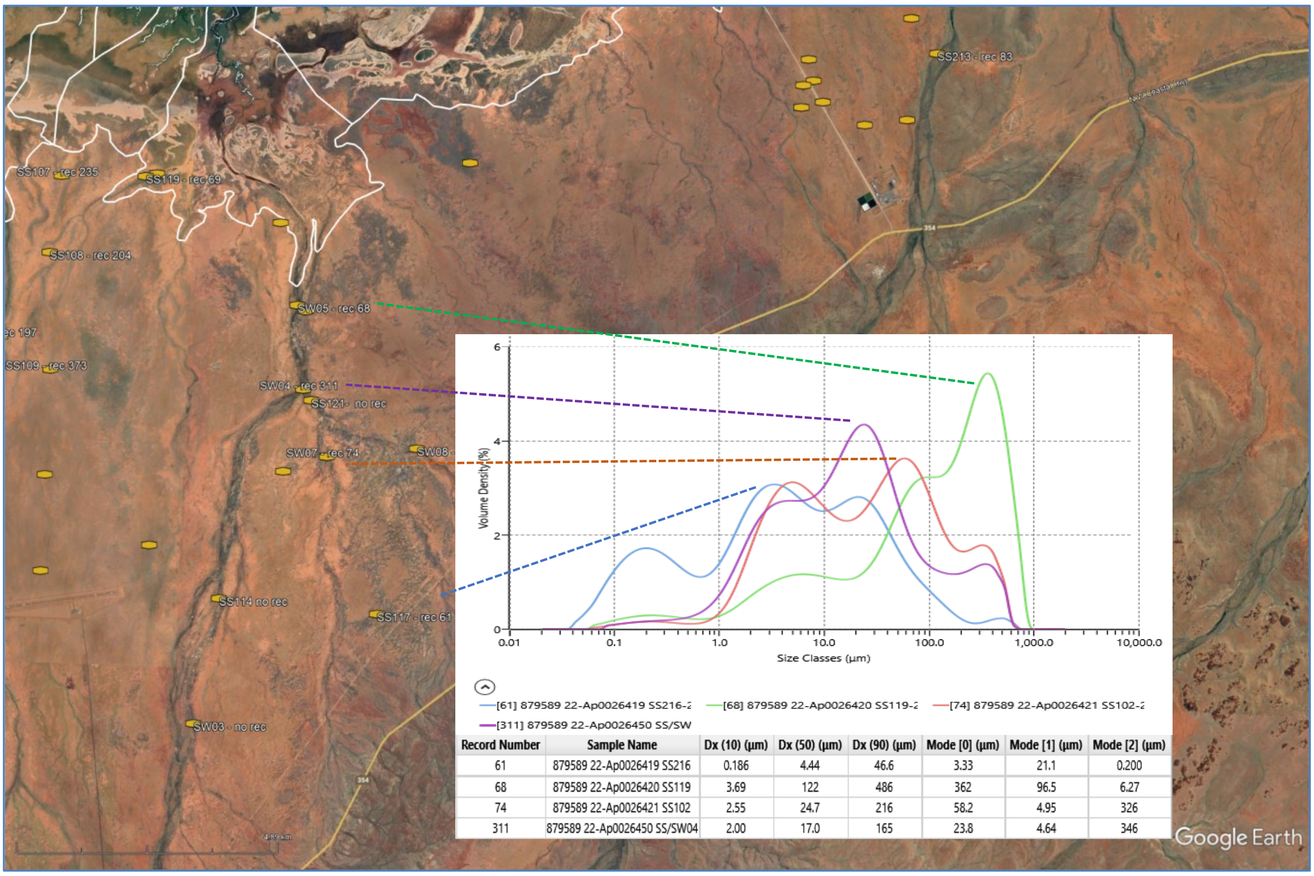
Figure 83. Distribution of surface sediment samples in the ESSP area that have had laser PSD analysis performed. No samples remain to check composition.

Even this small group of results contain a number of similar size modes (~50 to 110 and ~320 to 370 μm) which tends to indicate the strong possibility of modal sizes being traceable through the broader sedimentary system.



Record Number	Sample Name	Dx (10) (µm)	Dx (50) (µm)	Dx (90) (µm)	Mode [0] (µm)	Mode [1] (µm)	Mode [2] (µm)
204	879589 22-Ap0026432 SS108	3.22	22.6	103	31.1	0.00	0.00
235	879589 22-Ap0026435 SS107	1.74	12.4	129	8.76	75.9	0.202
69	879589 22-Ap0026420 SS119	3.42	115	484	365	99.5	6.06
373	879589 22-Ap0026428 SS109	2.27	13.4	96.6	20.9	344	0.00

Figure 84. PSD curves for samples between Eramurra and McKay creeks. The catchment (purple, green and blue) contains slightly sandy silts size 200 µm, the lower creek (brown) contains a bimodal medium sand (~370 µm) with a minor very-fine sand mode (~90 µm).



Record Number	Sample Name	Dx (10) (µm)	Dx (50) (µm)	Dx (90) (µm)	Mode [0] (µm)	Mode [1] (µm)	Mode [2] (µm)
61	879589 22-Ap0026419 SS216	0.186	4.44	46.6	3.33	21.1	0.200
68	879589 22-Ap0026420 SS119	3.69	122	486	362	96.5	6.27
74	879589 22-Ap0026421 SS102	2.55	24.7	216	58.2	4.95	326
311	879589 22-Ap0026450 SS/SW04	2.00	17.0	165	23.8	4.64	346

Figure 85. PSD curves for samples in McKay Ck catchment.

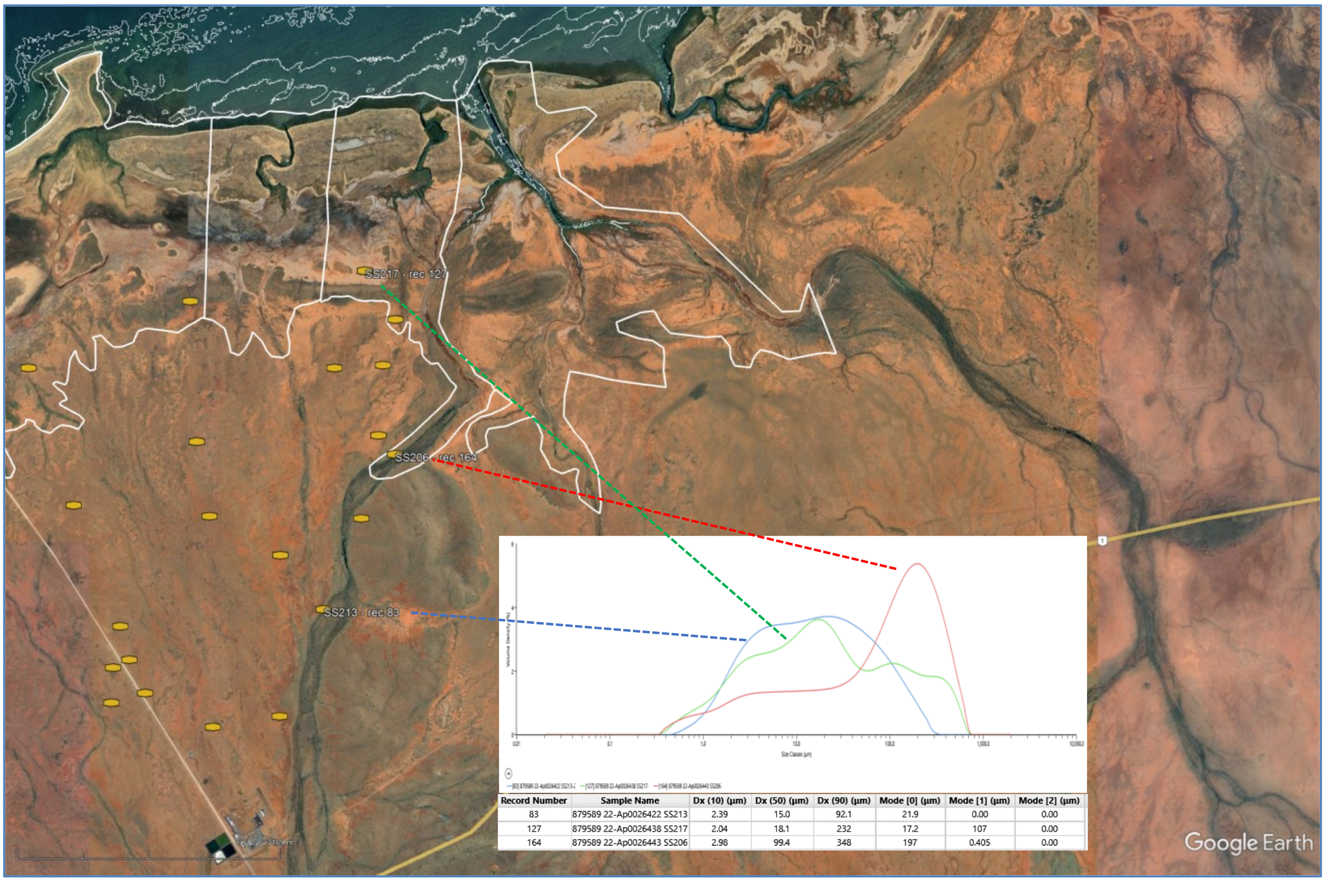


Figure 86. PSD curves for samples in Devil Creek and into Creek 8. The creek bed (red) contains a silty fine sand of modal size 200 µm, the creek flanks (blue) supply sandy silt and the back-barrier basin contains a sandy silt.

6.6.4. Evidence of present processes

6.6.4.1. Aerial photos

Geomorphic and habitat change throughout the ESSP area has been assessed through careful examination of historical imagery dated 1967, 1968, 2001, 2004, 2077, 2011 & 2022 (Figure 87, Figure 88) for each relevant tidal catchment. A series of locations (shown in Figure 89) have been identified as indicative of significant change, and the key features are illustrated in Figure 90 to Figure 103 inclusive. Results are summarized in Table 14.[13]

In the estuary overall, aerial images indicate a general increase in channel incision (Figure 90).

Overall, between 1968 and 2022, almost all observed geomorphic change has occurred in the tidal creek systems, and its nature is consistent with geomorphic responses to a raised sea level. The main geomorphic changes are as follows.

- Headward extension and widening of tidal creeks.
  - Headward extension occurred on the western creeks of the estuary, and these creeks also widened by 10 to 20%. The greatest extension was for Creek 5, although it should be noted that this catchment was subject to modification by the construction of the road to Cape Preston.
- Greater incision of tidal channels, across most of the ESSP area.
- Some geomorphic evolution in the lower tidal creeks, such as:

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[13] Table 14 contains links to the key Figures

    - some minor channel relocation (a jump) in Baldy Creek.
    - the breakdown of a meander in Creek 3.
- Variable changes in the nascent mangroves area.
    - A gradient from little change in the west towards greater changes in the east,
    - The easternmost creek mouth switched channel to the east, and the creek showed headward expansion.
- Variable accumulation at the mouth of the rivers.
    - McKay Creek has developed a new alluvial fan (~400 m^2 area) where the river discharges onto the tidal flats.
    - Eramurra Creek appears to have had little accumulation in the same location.
- Sediment fans at the heads of the active tidal creeks have migrated landwards across the flats and have increased in size.
    - Such increases typically indicate accumulation, but that can be quite short-term and not necessarily permanent.
- Yanyare Creek mouth has become increasingly constricted, apparently by marine sediment.

However, there is a smaller relative habitat response.

- Increasing density of mangroves, and in most areas the vegetation appears much more mature, and most trees are bigger.
- There was only a limited increase in the area of mangroves, with only a few small areas of new growth.
- Most intertidal habitats showed very limited apparent change, with most individual plants identifiable in imagery between 2001 and 2022.
- In the nascent mangroves, most new mangrove areas were in the easternmost creek.

The smaller scale of the habitat response might indicate a time lag with the sedimentary and geomorphological changes, but the timings are not clear. Further, some habitat responses are clearly consistent with their control by geomorphic features, such as the nascent mangroves being influenced by their narrow connection to the large catchment of 40 Mile Road W, and the greater changes occurring nearest to that connection (see section 9.3.1).

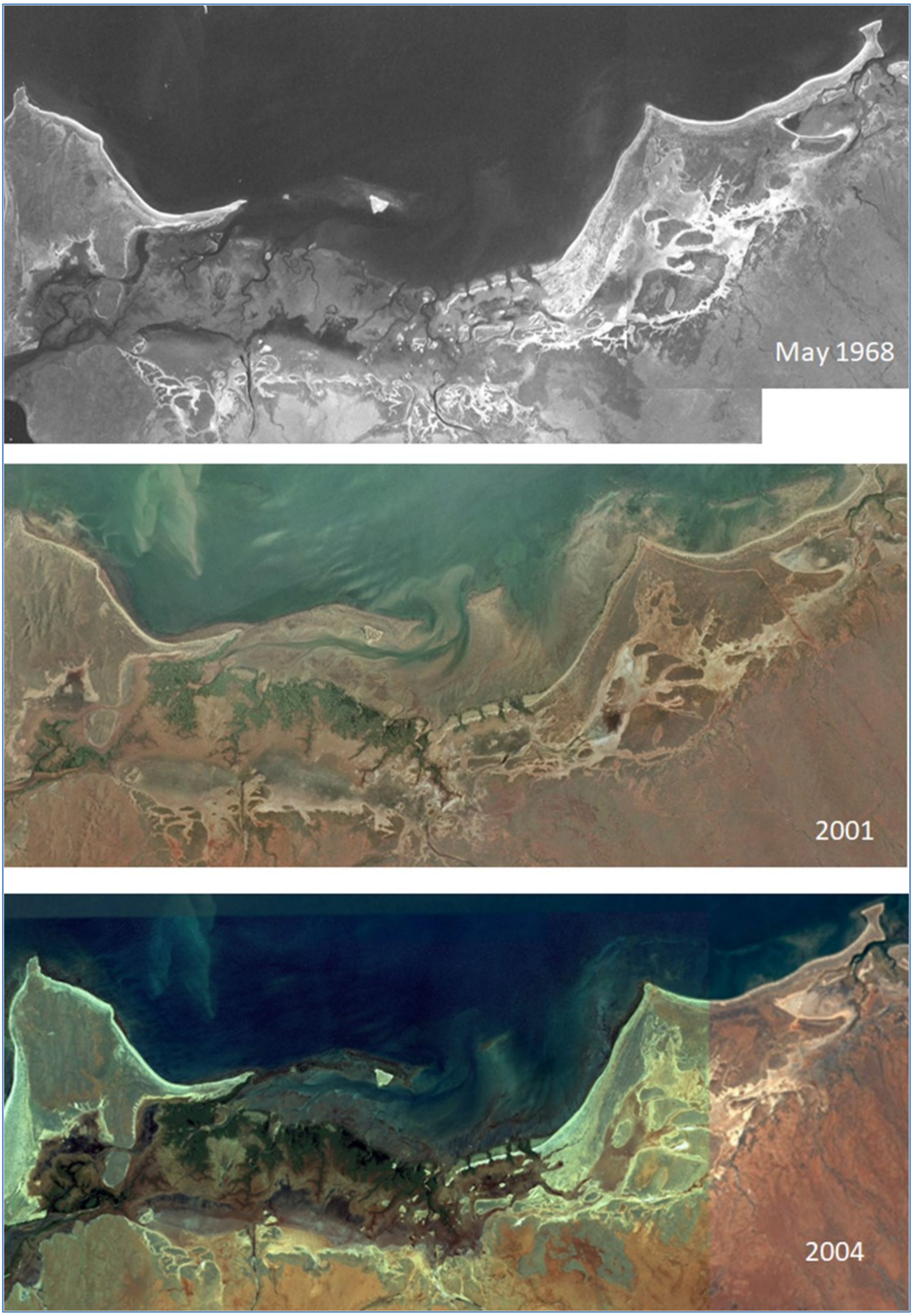

Figure 87. Historic Aerial Imagery 1968, 2001, 2004.

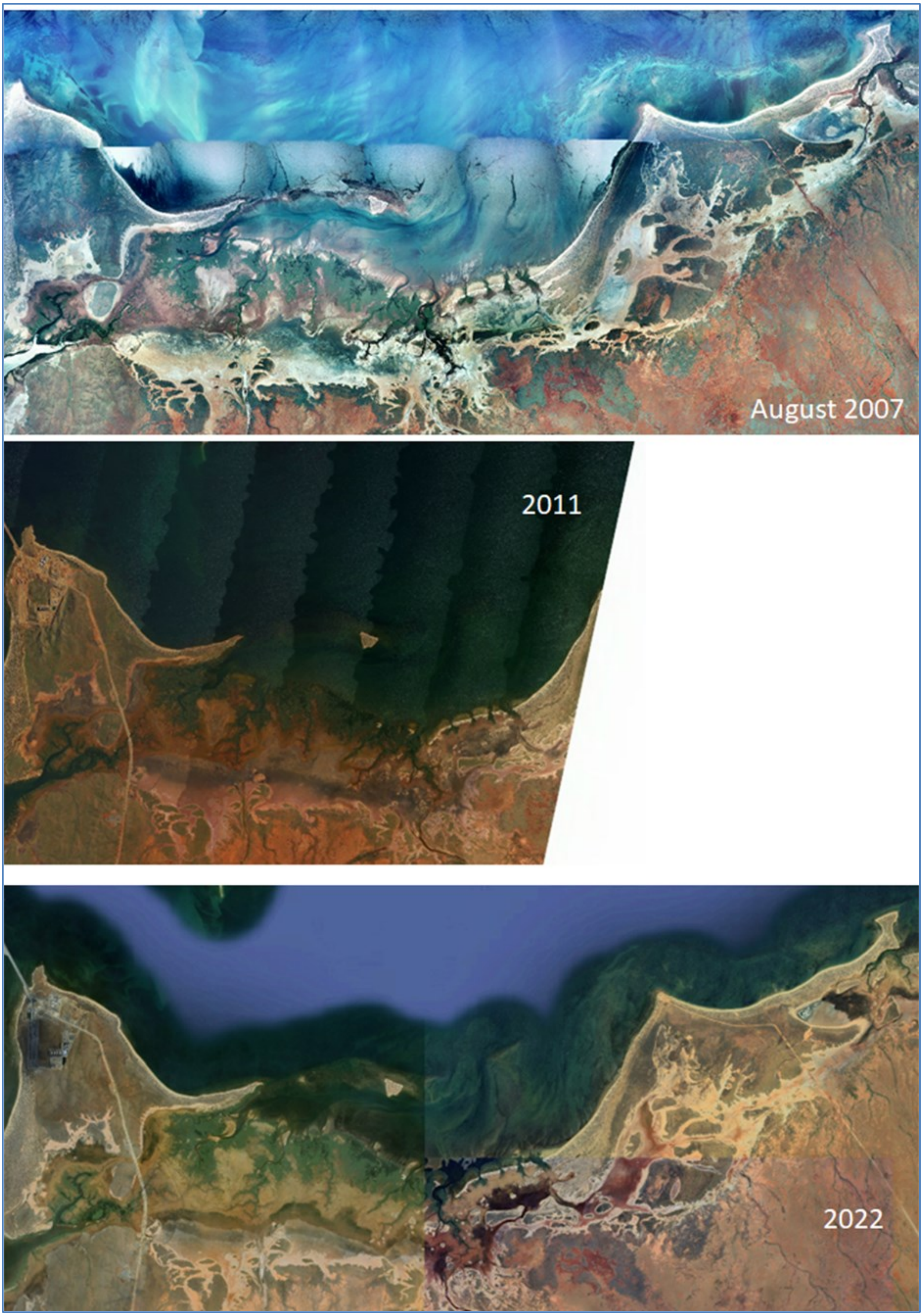

Figure 88. Historic aerial imagery 2007, 2011, 2022.

Figure 89. Locations of Figure 90 to Figure 103 inclusive.

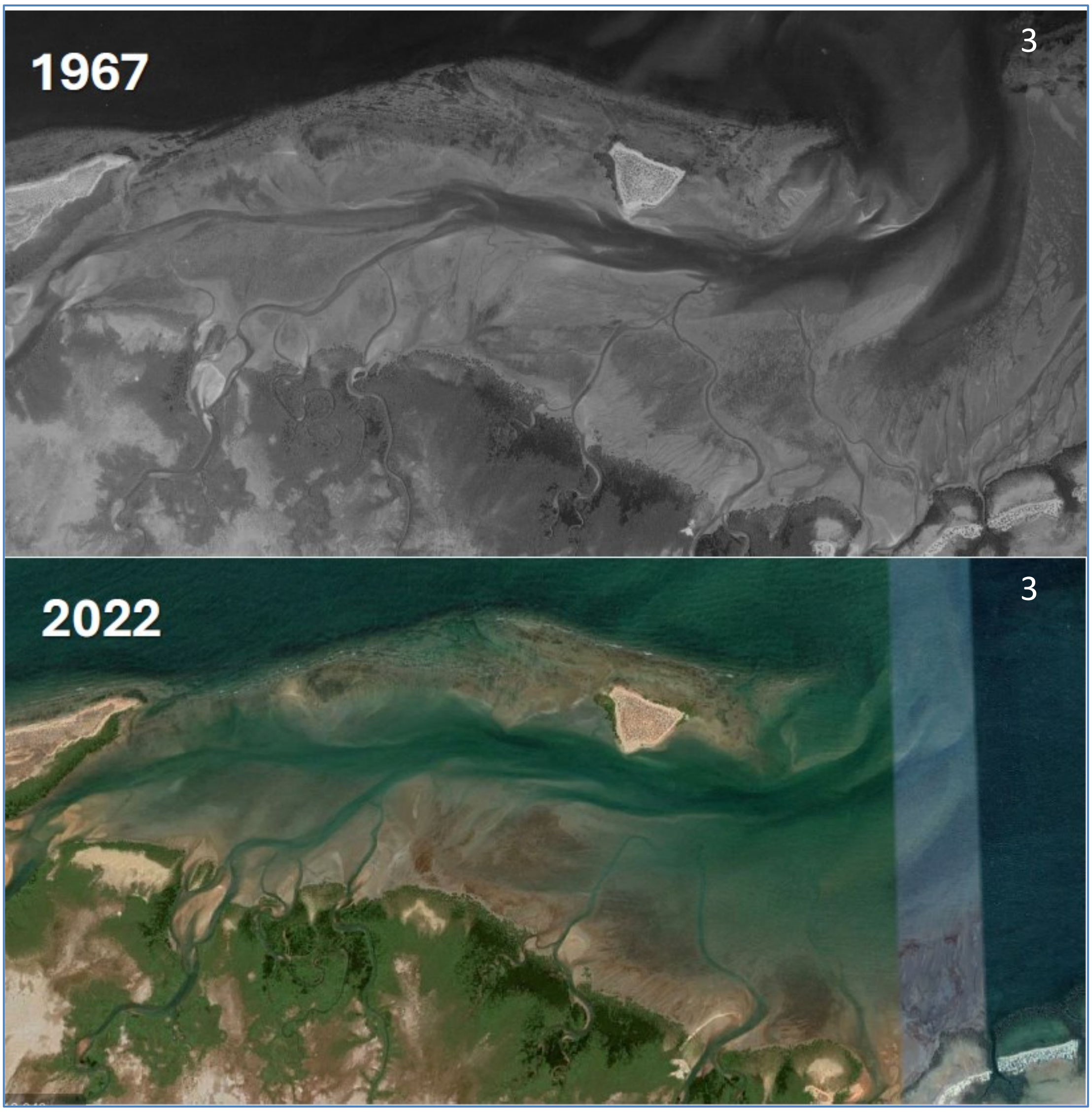

Figure 90. Changes in intertidal and shallow subtidal channel structure of the main estuary area, with most changes indicating a degree of channel incision.

Table 14. Observations of recent historic change in the relevant tidal catchments, 1968 - 2022. Note that mangrove density apparently increased everywhere over the period 2001 - 2022. Image quality restricts the ability to make some observations, especially for the older images.

Tidal catchment	Observations
Creek 6	Benthic mats dissected further
Creek 4	Local creek adjustment adjacent to road bridge
Creek 5	220 m headward extension towards construction road 2001-2022 (Figure 91)
Creek 3	• Direct link to fluvial channel • 170 m creek mouth retreat landward • 80 to 100 m headward extension 2001-2022 & greater channel incision • Secondary creek deeply incised (W) • Adjacent meander collapse (E) (Figure 92)
Creek 2	• Up to 300 m headward extension 2001-2022 • 30 m extension of mangroves
Creek 1	• Up to 350 m headward extension 2001-2022 (Figure 93) • 10% increase in typical channel width • 300 m extension of mangroves (scattered)
Baldy	• Channel incision • One channel switched location to outside the mangroves • 20% increase in typical channel width • Seawards edge of benthic mat has moved landward by 50 m (Figure 101) apparently replaced by muddy sediment
Straight	Negligible change identified
McKay	• Extensive sediment fan apparent (over previous benthic mat) (Figure 99) • Development of secondary creek (NE) • Large depositional fan developed in basin • Release of sediment from fluvial system (370 m^2 area) • 300 m landward advance of mangroves on secondary creek (Figure 98, Figure 100)
Nascent mangroves	1. Westernmost creek - negligible change identified 2. West central creek - negligible change identified 3. East central creek - 40 m of landward mangrove extension & channel incursion, mostly 1968-2001 (Figure 94), 4. Easternmost creek – landward edge of the estuarine mangroves fluctuates by 100 m landward (Figure 95) and channel incursion (Figure 96) Benthic mat coverage appears increased overall.
40 Mile E	• Extensive sediment fan apparent (over previous benthic mat) (Figure 97) • 100 m tertiary creek development
Creek 7	Negligible change identified
Creek 8	• Sediment input from creek apparent • Growth of breakout structure at mouth
Yanyare	Marine deposition providing increased restriction to entrance

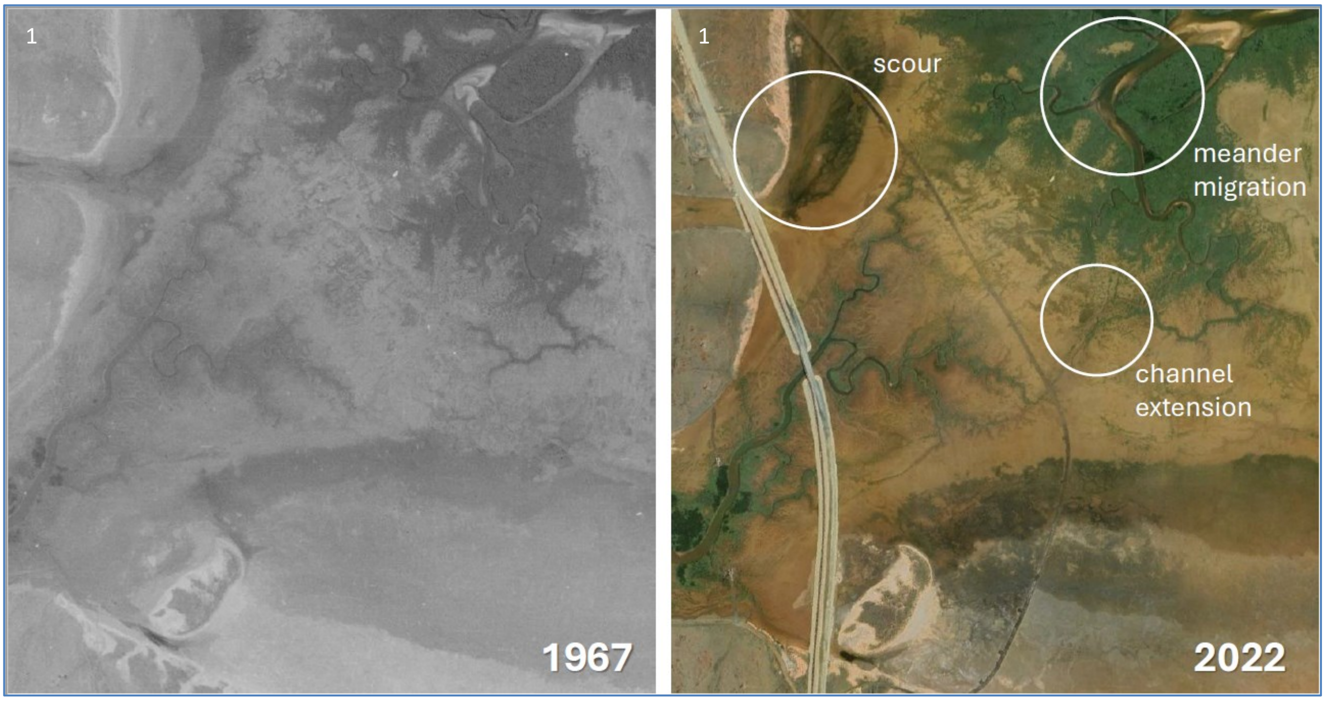

Figure 91. Differences in tidal creek characteristics for Creek 4 (scour at top left) and Creek 5 between 1967 and 2022 (after the construction of the Cape Preston road), including scour, meander migration and headward channel extension.

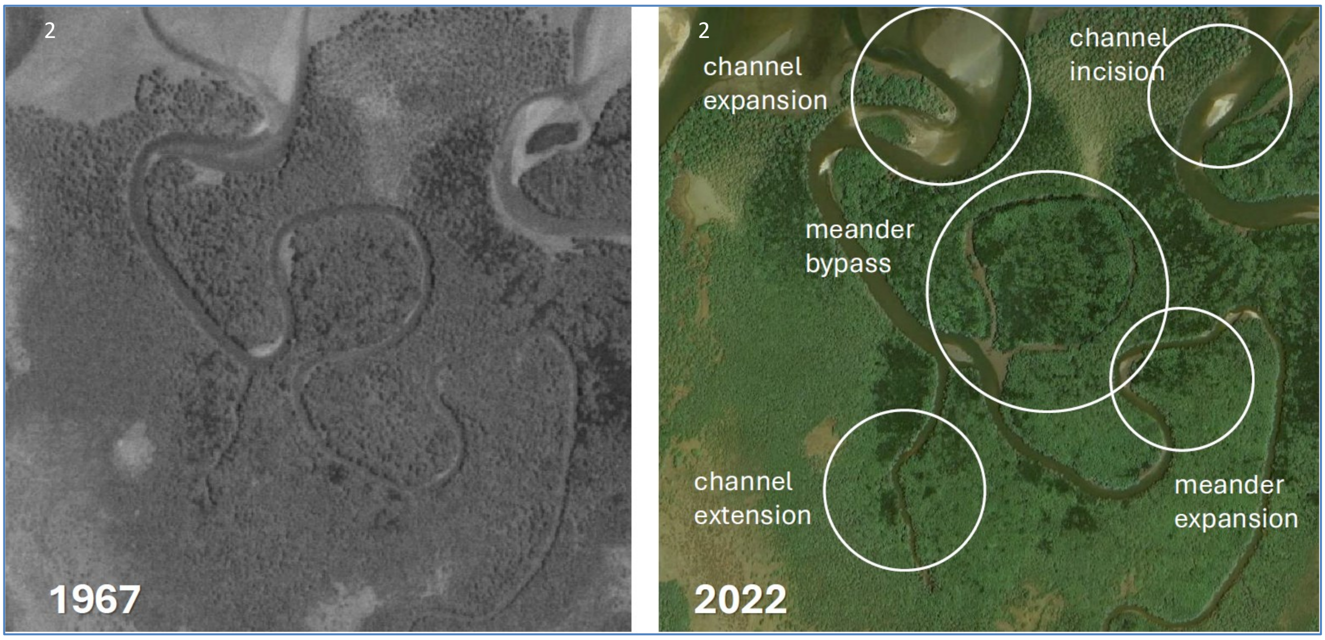

Figure 92. Various changes in the meandering eastern tidal creek of the Creek 3 catchment, including headward channel extension, the cut-off of a meander loop and channel expansion at the mouth (also for Creek 2, top right).

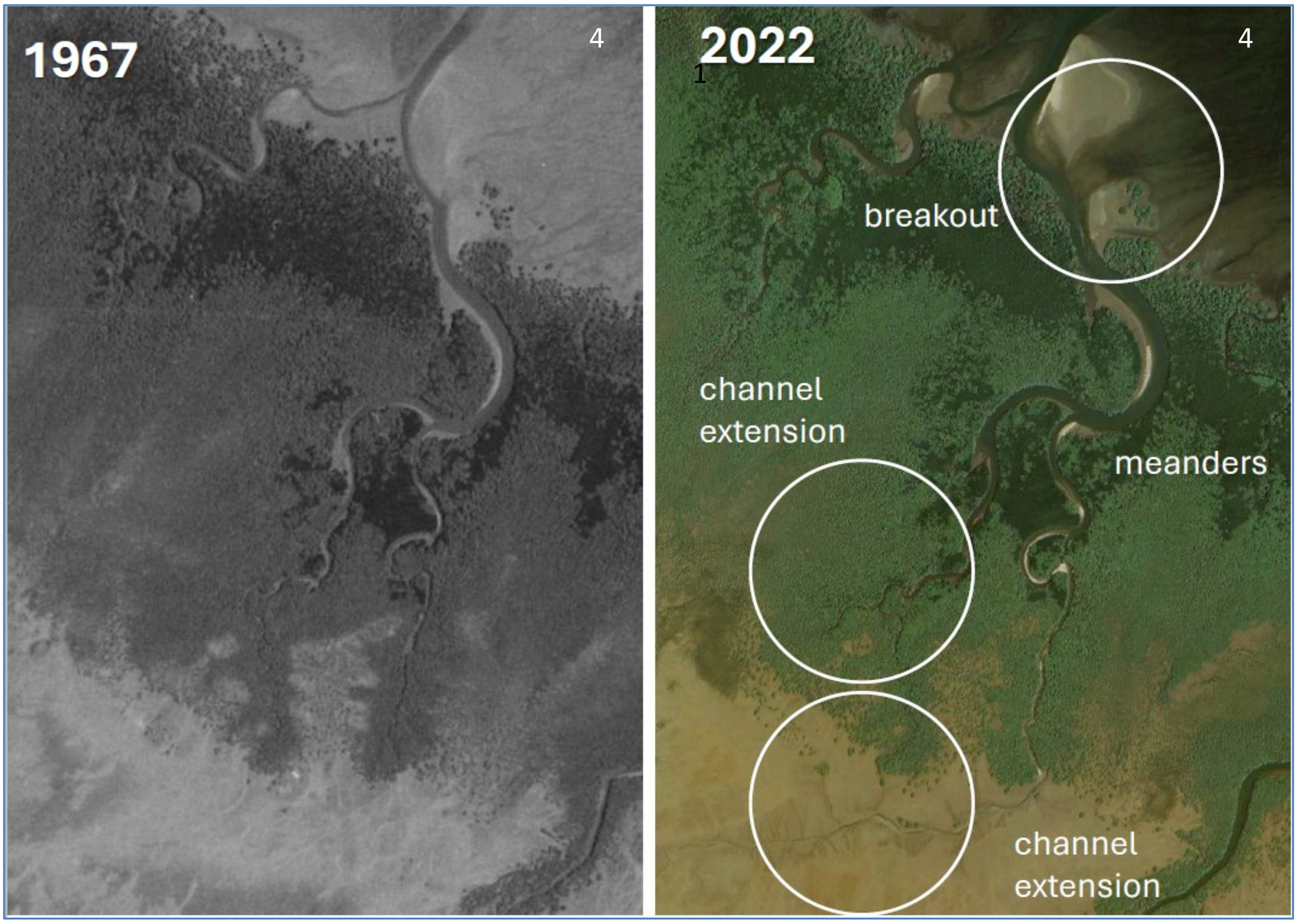

Figure 93. Headward channel extension in Creek 1, but note whilst the incised channels have extended landward, an increase in the extent of mangroves is far less apparent – they appear to have lagged the channel change.

Figure 94. Landward creek extension seawards of the central eastern barrier segment, nascent mangroves.

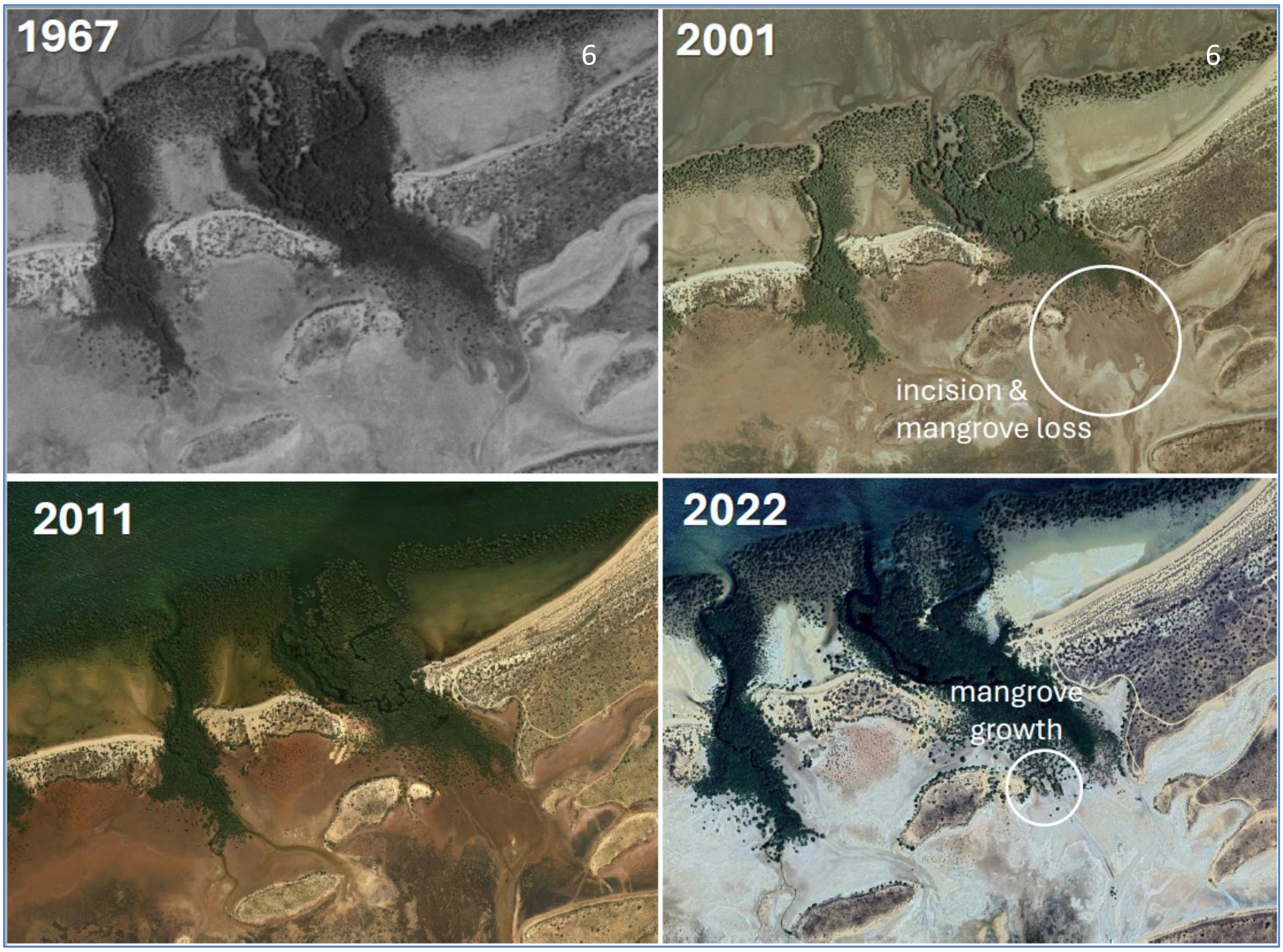

Figure 95. Fluctuations of channel incision with associated mangrove loss (2001) and subsequent regrowth (2022) at the head of the easternmost nascent mangrove creek.

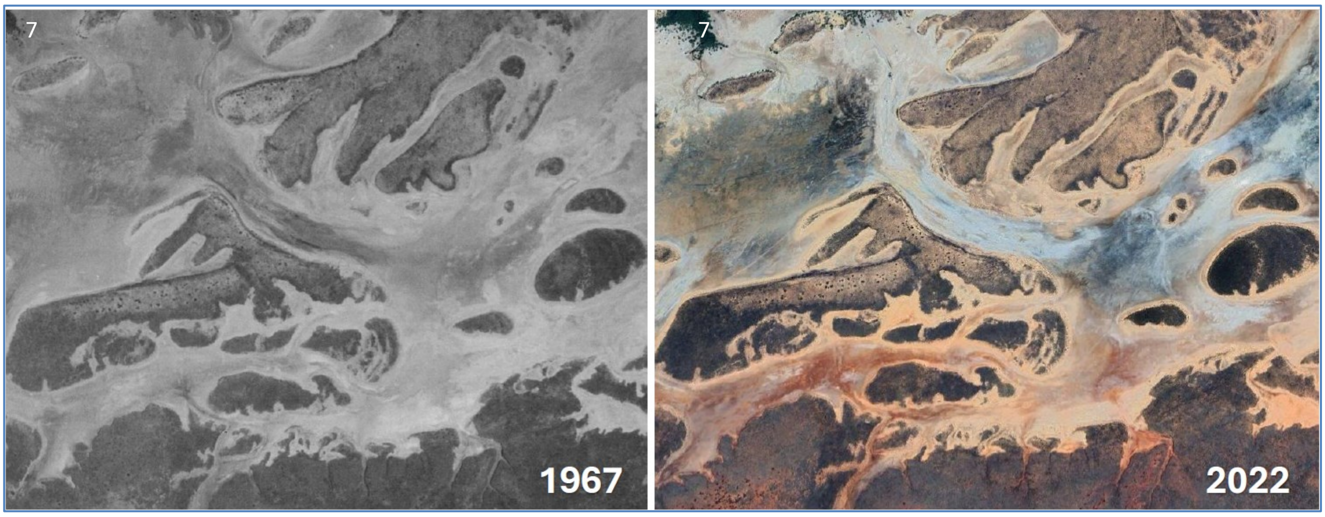

Figure 96. Numerous examples of channel incursion and expansion, SE part of 40 Mile Road W, behind the nascent mangroves.

Figure 97. Extension and incision of channels, and growth of sediment fans over benthic mats in the back-barrier basin of the 40 Mile Road E catchment.

Figure 98. Landward channel extension to the east, with some pioneering mangroves. 1 km inland from McKay mouth, adjoining the SW nascent mangrove area.

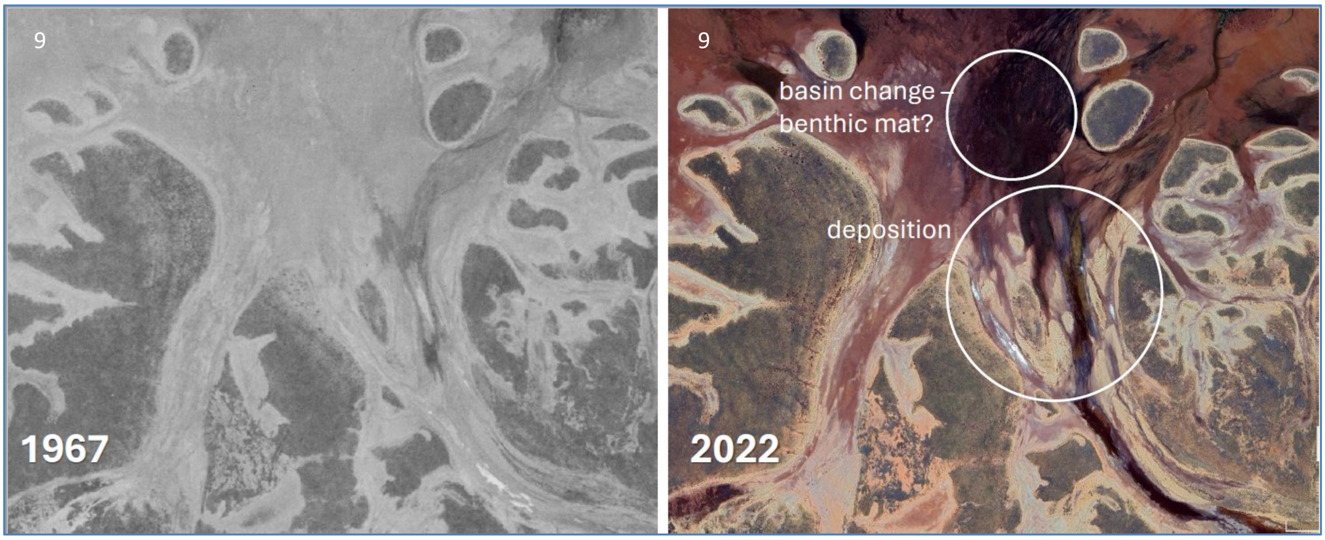

Figure 99. Sediment accumulation at the mouth of McKay Creek delta and associated apparent change in the benthic mat coverage to seaward on the tidal flats.

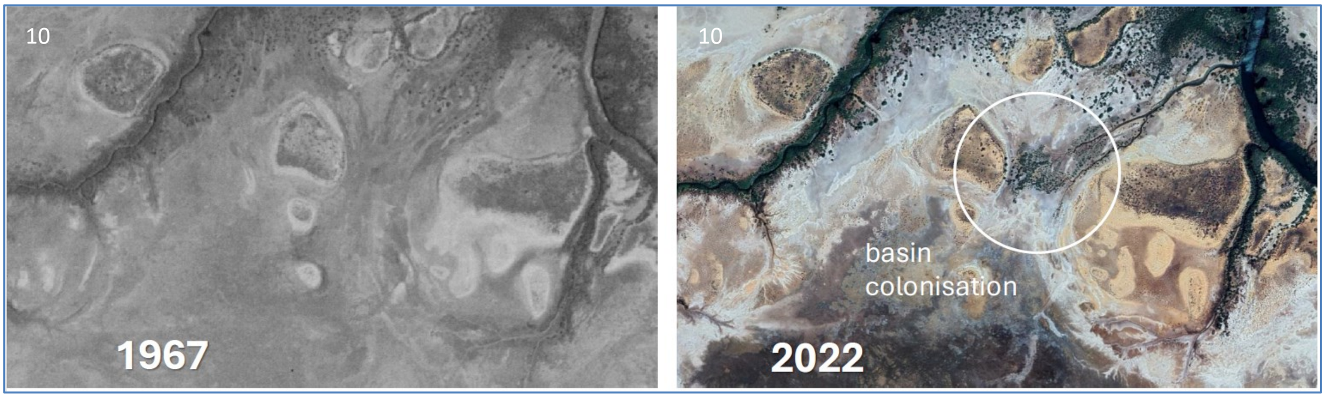

Figure 100. Creek extension to the SW and associated colonisation of a shallow basin on the western flank of the active tidal creek section of McKay Creek.

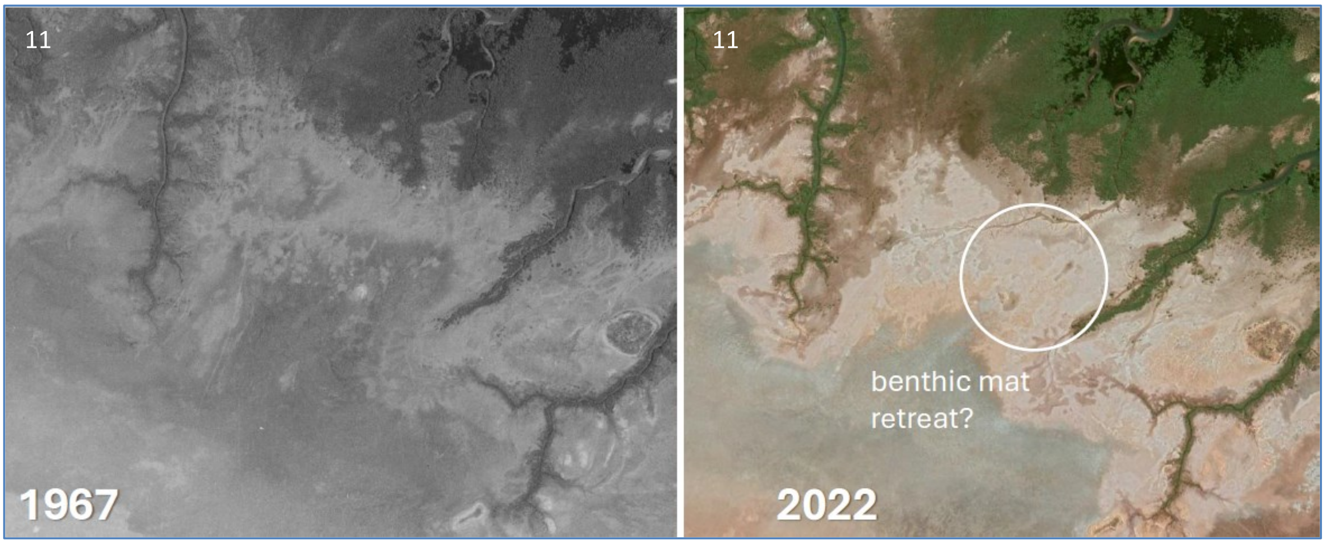

Figure 101. Landward (southward) advance of sediments associated with headward creek expansion and consequent benthic mat retreat (McKay Creek tidal flats).

Figure 102. Location of basin shown in Figure 103.

Figure 103. Fluctuations of channel incision in a back-barrier basin. To the left of the barrier segment is the mouth of Creek 8, and to the right is the mouth of the Yanyare catchment.

6.6.4.2. Summary of physical changes

Changes observed across ESSP coastal region from 1967 to 2022 from aerial imagery are substantively consistent with physical processes of change observed at other coastal wetlands along Northern Australia (Eliot & Eliot 2013). The presence of mangroves provides significant coastline resilience, with observed changes mostly related to the evolution of tidal creek networks, with subsequent change to mangrove communities occurring more gradually. In contrast, benthic mat coverage varies substantially, and is considered a likely consequence of large seasonal and inter-annual variability of inundation patterns, possibly interacting with subtle changes in the high tidal flats.

Within the period of aerial imagery, headward channel expansion and increasing mangrove canopy are prevalent, but there is limited change in plant numbers. This is similar to multiple sites evaluated across the Pilbara (Eliot *et al*. 2013). New mangrove communities have locally become established within shallow basins at several locations, occurring after tidal channel incision, indicating potential change from hypersaline to more marine conditions. Overall, these changes are consistent with the anticipated response to rising sea levels, which have accelerated since the 1960s.

The coastal geomorphic differences near Cape Preston access track and road construction is consistent with the capacity for the tidal creek network to adjust to modifications of the tidal catchment areas contributing to creek flows.

7. Sedimentary hypotheses to test

There is an overarching generic sedimentary question regarding this work -

> *'Can sufficient sediment be delivered for the ESSP's sedimentary environments to keep pace with future sea-level rise, through supply of sediments from rivers and the marine environment and/or reworking of existing coastal sediments.'*

Underlying this question is a suite of testable specific questions regarding the different types of change and their potential implications for the BCHs.

7.1. Sediment transport pathways

Regarding past and present sedimentary processes, information sources include the sedimentary stratigraphy, the disposition and age of geomorphological units, the nature of the various sedimentary bedforms, the overall distribution of surface sediments and spatial gradients in sediment size and composition. Integrating these data allows testing of postulated modern active sediment transport pathways. A series of specific sediment transport pathways (Table 15) are testable using the various physical features and spatial gradients of grain size and type, and by determining the ages of relevant key deposits. These pathways have specifically been identified and designed to address questions that pertain precisely to the implications for key habitats.

As an example, for McKay Creek, can the creek system deliver sufficient sediment for the high-tidal flats to keep pace with sea-level rise? This can be addressed by investigating the nature of the grain size and compositional gradients between the creek itself and the high tidal flats, to determine whether there are clear and sensible links.

- If the creek has a history of building levees (raised areas adjacent to the inset creek itself), then a possible outcome with SLR is a phase of accelerated levee growth, followed by potential breaching of the levees. This might produce initial minor changes in habitats followed by a major change associated with levee breaching.

- If there are no levees, then it is more likely that SLR will produce accumulation across the high tidal flats so that the associated habitats might be subject to more gradual change.

Cores through selected sites, such as channel margins, and dates on key units, would greatly help analysis of how the system has developed in the past.

Some specific examples of such associated physical changes in key areas and environments are given in section 9.3.

Table 15. Key sediment transport pathways to test and their significance.

Catchment / Location	Sediment Transport Pathway to test	Significance of result
Eramurra Ck	River to tidal creek to shoreline	River's contribution to (system and) shoreline stability
McKay Ck	River to tidal creek to shoreline	River's contribution to (system and) shoreline stability
	From south of the central ponds into the lower river	Erosion near pond walls might increase supply
	Dispersion of river sediment across the high tidal flats	Resilience of creek systems to changes in McKay River. Lateral dispersion might be enhanced with SLR
	From the eastern tidal flanks to the mouth	Supply (erosion?) of tidal flats to the shoreline
	Creek mouth to nascent mangroves area	Assess resilience of nascent mangroves
Nascent mangroves & 40 Mile Road W	Sand supply from the 40 Mile Road W catchment, passing through the breached barrier to the nascent mangrove area.	Pond walls would block such supply.
	Exchange between the coast and the low tidal area with its benthic mats, including through the tidal creeks.	This will be altered with hypsometry changes with SLR and then drastically by the ponds.
	Transport directions towards or away from nascent mangroves.	Is the spit a source for the nascent mangrove area?
	Past continuity of the barrier fragments with the spit and beaches to the NE.	During past episodic events, where was the sand transported to?
	Links with lowermost McKay Ck.	Assess resilience of nascent mangroves
Shallow Marine	Exchange between shallow marine area and coastline.	Contribution of shallow marine sediments to shoreline resilience, from episodic events and loss of supply from 40 Mile Road W.
	Alongshore marine transport	Resilience of creeks promoted by regional marine sediments
40 Mile Road E	Sources of sediment to the basin & its habitats	Resilience of the basin habitats to SLR and the pond walls.
	From the sea into the basin along the northern edge of the basin	Response of the basin to SLR
	Exchange along the central arm of the flood delta.	Response of the basin to SLR, runoff and pond walls
	From runoff and from the SW, including the link with 40 Mile Road W	Resilience of the basin to SLR & pond walls
Creek 7	Exchange between the sea and the back-barrier basin	Response of the basin to SLR & pond walls. Is the flood 'delta' shape i) downcutting and transporting material seawards, or ii) depositional and onlapping sediments into the basin?
	Supply by freshwater runoff from the south.	Pond walls will i) prevent future sediment supply and ii) landward migration of habitats with SLR.

Catchment / Location	Sediment Transport Pathway to test	Significance of result
Devil Ck / Yanyare Ck / Creek 8	Dispersal from Devil Ck river into and through the back-barrier region	Pond walls affect this source and/or landward migration of habitats with SLR.
Shallow Marine East	Exchange between shallow marine area and coastline.	Contribution of shallow marine sediments to shoreline resilience especially of the basin of 40 Mile Road E and creeks 7 & 8.
	Alongshore marine transport	Resilience of creeks promoted by regional marine sediments

7.2. Ages of sedimentary units

7.2.1. Significance

A single identified sedimentary unit is a sub-horizontal layer of sediment of the same broad texture, composition and internal structure, and it will always be youngest at its top. However, laterally, its age may vary between two end members.

- First, at the base of a unit, the ages might be similar everywhere, indicating that accumulation was widespread and commenced at the same time, i.e. the unit is broadly 'synchronous' – the same age everywhere. This would tend to indicate that for a time, the sedimentary environments were relatively stable, and that accumulation continued for that period, but accumulation commenced rapidly commencement and may also have ceased rapidly.
    - The significance of such variation in age is high. Depending on the controls on sediment accumulation, this condition might indicate a generally low past ability of the coastline to adapt to change, natural and/or anthropogenic.
- The second possibility is that a single unit is diachronous, i.e., of different ages in different locations. At the coastline, this can occur when an accumulating sediment body migrates with changing coastal morphology, and/or with changing sea level. Diachronous deposits tend to be favoured with an overall coastal configuration that has long-term stability, e.g., there is a relatively simple shoreline, migrating to landward and/or to seaward. The ESSP area has geomorphological complexity, with multiple shallow igneous and other hard outcrops and a complex array of associated sediment bodies. This means that the ESSP area is not obviously favourable to the formation and identification of diachroneity, but nonetheless it is sensible to find out.
    - The significance of such lateral variation in age is high, because it indicates the past ability of the coastline to adjust over a period of time and maintain a particular sedimentary environment, and by implication, probably the associated habitats.

In both cases, and all cases in between, the age or age range of the units is important to know, including the variable age of a critical unit across an area and the timescale involved in the unit's vertical accumulation.

7.2.2. ESSP units

The main units were outlined in the main text in section 6.3.3. and illustrated in simple form in Figure 44. No age dates exist. Based on their modern relationships to RSL, and the RSL curve in the last 120,000 years (Figure 7 to Figure 9), their state of weathering and other characteristics, some possible unit ages, and that of some associated features, are hypothesised below.

- Sandy and gravelly sediments occur in the catchments above river channels, with sandy clay weathering products beneath them.

- These are far older than the coastal units that support habitats and their ages is not of significance here.
- The braided river channel beds contain alluvial gravels.
  - These are of unknown age in terms of their vertical accumulation but are likely to be very highly variable from place to place. Their age is of minor significance here.
- Wave-cut platform in igneous rocks at the delta front.
  - The age of the platform is an indication of sea level at the time of formation. It is very difficult to date such erosive features and it will not be pursued here – other avenues are available.
- Calcarenite exposures.
  - These also indicate something about past sea levels. These will either be Last Interglacial or Holocene highstand in age.
- A lagoonal mud unit (silty sands) occur across wide areas of the tidal flats.
  - This unit might have a simple or complex history. It might represent accumulation during the i) Last Interglacial or ii) Holocene highstand, or iii) both, with an erosive gap within it. For all of the above three options, the unit might also be diachronous across the N-S width of the coastal plain, either during a rise in sea level and/or a fall.
- Eolian sands – deflated dunes.
  - The multiple low 'deflated dune' islands might be Last Interglacial or Holocene highstand in age, or a combination. The Last Interglacial age is perhaps more likely.
- Active eolian dunes.
  - The active surface coastal dunes are likely to be late Holocene, but in places may have a base that is mid-Holocene, and even Last Interglacial in age. They may also be strongly diachronous across the Gnoorea spit from its seaward face to its landward apron, and the same for the barrier at creeks 7 and 8.
- Intertidal muds (clayey sands and sandy clays) near tidal creeks and areas of mangroves.
  - This unit is likely to be Holocene in age and possibly diachronous, and if both, is most likely youngest at the landward edge.
- Sands within the incised mangrove creeks (and bars at the mouth).
  - These are likely to be late Holocene in age, i.e., less than 6,000 years, and perhaps only 1,000 to 2,000 years old, or much younger in places.
- Mangrove creek mouth bars
  - As above.
- Low intertidal and shallow subtidal mudflats / soft mobile (silty) sands.
  - The vertical extent of these sediment is unknown, as it their age. It is possible that they are as old as 8,000 years old at their base, representing the time when the rising Post-Glacial sea level first inundated the area, but it is also possible that they may be much younger.

Thus, several units in the ESSP area might be diachronous, notably the 'soft mangrove mud' unit and/or the underlying 'lagoonal muds', and some of the eolian sands.

8. The planned development

8.1. Generic environmental effects of solar salt developments

As noted in section 2.3 of the CP-BCH report, there are a range of proposed environmental impacts of solar salt projects. Brocx & Semeniuk (2015) noted that

> *"For solar salt production sites, the key impacts on the general coastal environment, particularly on those features that may relate to the maintenance of coastal systems, are:*
>
> *(1) the initial destruction of the coastal zone, and specifically the loss of the salt flat;*
>
> *(2) alteration of hydrogeology and geochemistry by plumes of supersaturated liquors and bitterns;*
>
> *(3) edge effects along retaining walls;*
>
> *(4) disruption of freshwater input; and*
>
> *(5) geomorphic alteration (direct and indirect)."*

Brocx & Semeniuk's (2015) work does not deal with those physical surface sedimentary processes that maintain tidal creek environments, nor the potential disturbances of the close natural interactions of flow and morphology. This report addresses such issues, because, as noted within section 5.2, they are fundamental to the assessment of the present operation of the coastal physical system operation and flows within it, of natural future changes in sedimentary environments, of the potential effects of the emplacement and operation of the ESSP, and to the assessment of the potential impacts through time of the ESSP upon BCHs.

Regarding SLR, and its relative importance in this instance, the investigation and conclusions of Guo *et al* (2022) are particularly pertinent.

> *"Removing a large portion of intertidal flats within the tidal basin induces significant changes in basin hypsometry and potentially, a reversal of flood/ebb dominance. The resulting hydro-morphodynamic impact of large-scale tidal flat embankment is more significant than SLR at a centennial time scale."*

In other words, over a century-long planning timescale, it's not SLR that matters most, it's the human intervention.

This is a largely unsurprising finding because the basis physics tends to dictate this result, at least in terms of tidal creek dynamics. This finding is consistent all the physical dynamic work done in the 1980s, 1990s and subsequently on the tidal controls on such creek systems (e.g., Friedrichs *et al*. 1990; Wolanski & Ridd 1990; Larcombe & Ridd,1996; and others, including Pethick 1984, on temperate saltmarshes), in the UK and the southern states of the USA, amongst others, and is a conclusion drawn on many occasions on a range of systems all around Northern Australia.

Assessment of the tides and the other geomorphological factors, listed in section 9.1.1, is noted in the sections below.

8.2. The disposition and nature of the pond walls

The ESSP proposal is an evaporative solar project that uses seawater to produce raw salt which is then processed into a high purity salt (Leichhardt Salt 2024). Proposed infrastructure includes:

- seawater intake, pump station and pipeline;
- concentration ponds totalling approximately 10,000 ha;
- crystallisers totalling approximately 1,900 ha;
- drainage channels and bunds;
- process plant and product dewatering facilities;
- water supply (desalination plant);
- bitterns disposal pipeline and outfall;
- pumps, pipelines, roads, and support buildings including offices and communications facilities;
- workshops and laydown areas;
- landfill; and
- other associated infrastructure.

The concentration and crystallisation ponds are formed into three main areas (Figure 104), with their layout determined by the design requirements, including the existing topography, geotechnical, hydraulic environmental and heritage conditions, and the position of existing infrastructure. The central area is separated from the western area by McKay Creek, and from the eastern area by the gas pipeline easement along 40 Mile Road. The central area of ponds has a gap within it located SE of Gnoorea Point (Figure 4, Figure 104).

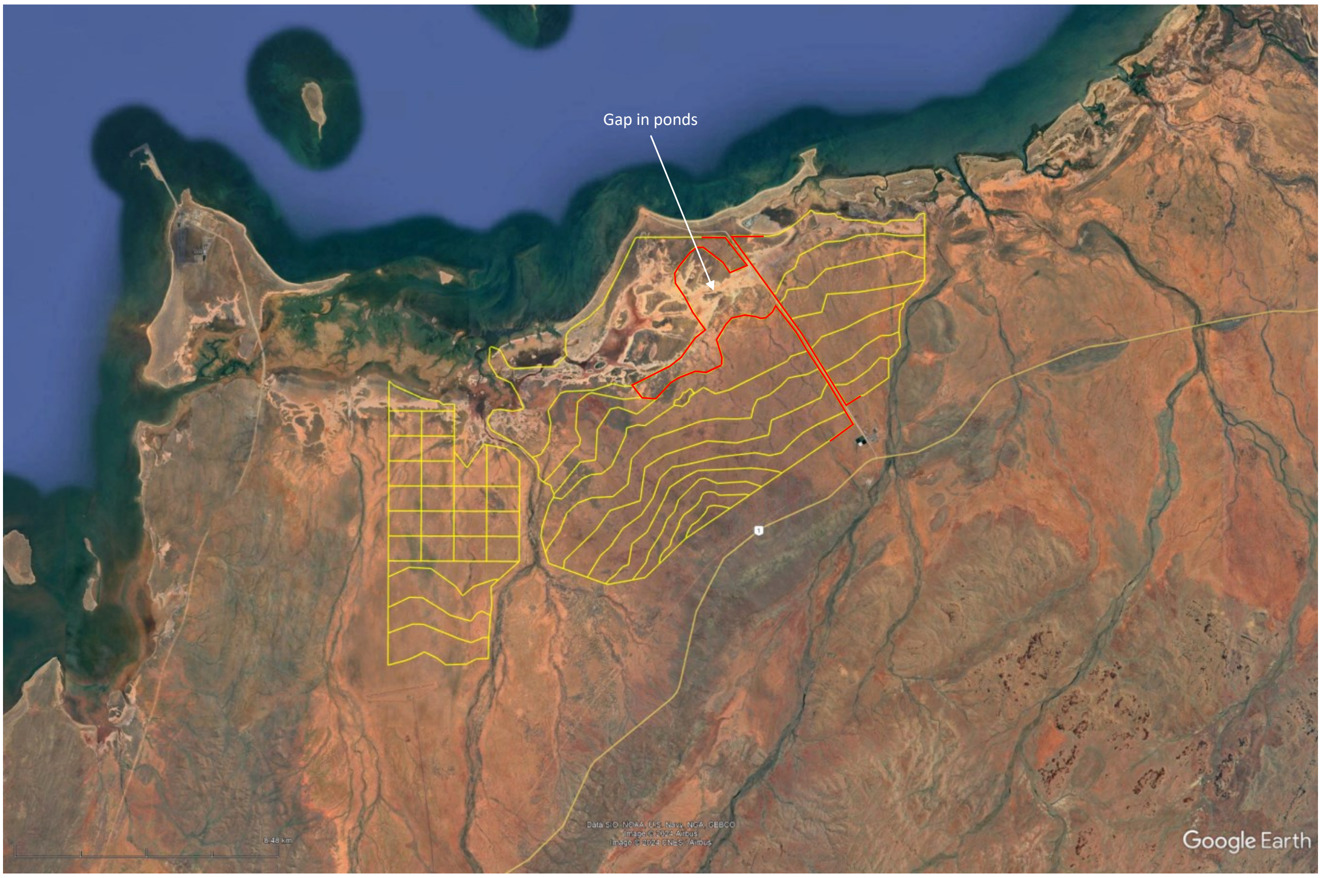

Figure 104. The ponds of scenario 7.2.1. Note the open-ended gap in the ponds SE of Gnoorea Point.

The pond walls (or embankments) will contain the brine within the concentration ponds and crystallisers. Pond walls with direct coastal exposure will be rock armoured to protect against erosion (Figure 105) and walls along creeks will also be armoured, but with smaller material. At the northern (seaward) boundary of the site, the external sea wall will be +5 m AHD or higher, to exceed the storm-surge level of a one in 100-year event. The southern (landward) boundary of the ponds will generally follow natural topography. Minor bunds will be provided to contain brine and external channels will divert external runoff from storm events, and some of the embankments on low-lying areas will be constructed on clay which compresses under load, so that provision will be made for settlement.

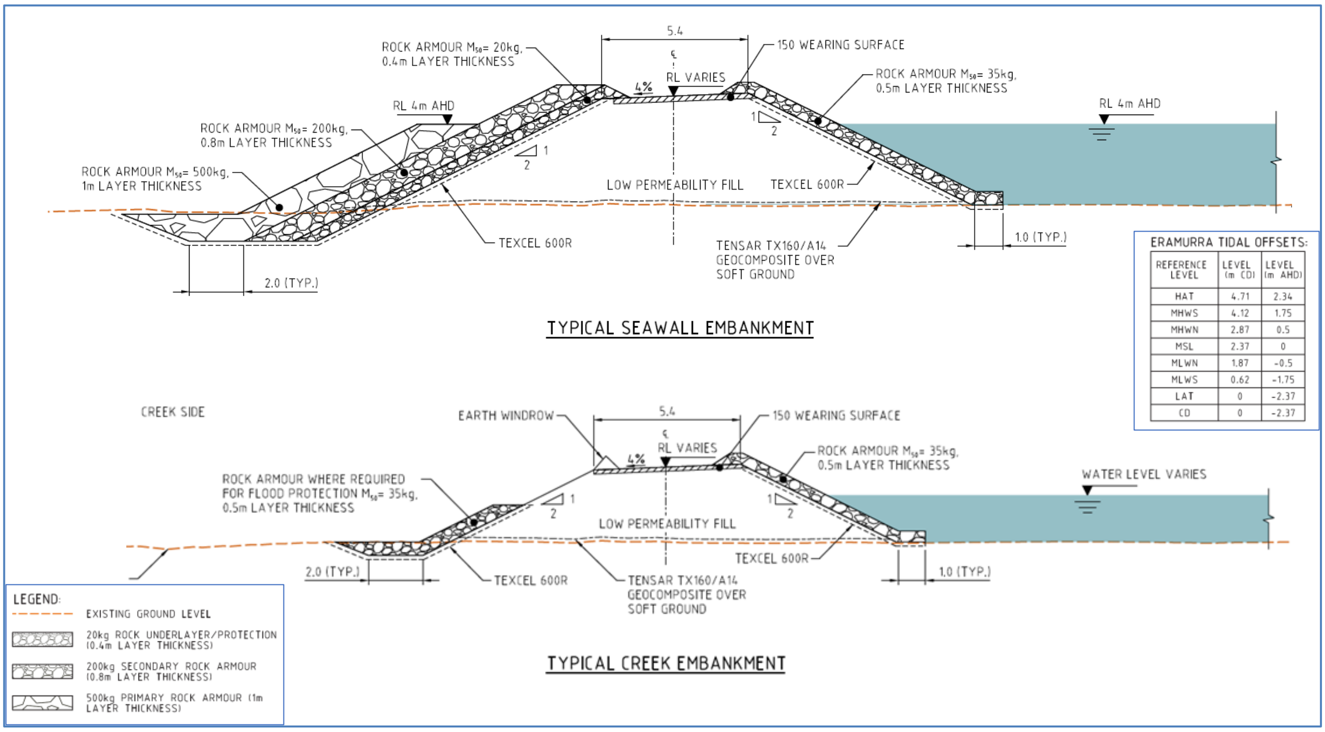

Figure 105. Typical embankment design for the seawall (upper) and the creeks (lower) (Leichhardt Salt, 2024). Note that the base of the walls that face the sea and the creeks are underlain by 1 and 0.5 m respectively of rock armour, which underlay extends underground horizontally away from the base for typically 2 m.

Hence, the pond walls themselves are designed to resist the effects of waves and currents, including freshwater runoff. However, the presence of the pond walls themselves alters hydrodynamic aspects nearby that might alter natural sedimentary processes (e.g., noted in sections 9.1.2 and 9.3).

9. Analysis

To revisit the purpose, this report is intended to:

- interpret the general nature and trends of changes to viable habitat, within the bounds of available information;
- analyse and describe how the presence of existing intertidal habitats relates to various controlling parameters;
- identify the most critical factors, based on spatial comparison using a GIS, and;
- describe the understanding of modern oceanographic and sediment transport processes, integrated with the various conceptual appropriate models of coastal evolution, for:
    - the existing situation
    - SLR over 100 years without the development
    - SLR over 100 years including the development.

Regarding the analysis, for ease of reading and understanding, the general approach is to distinguish theoretical trends from consequences of episodic disturbance events. Thus:

- first is described the potential effects of the overall trend over the next century (for example with SLR) assuming the absence of episodic disturbance events. Whilst this does not reflect reality, it is designed to help appreciation of some background trends (if any), especially in geomorphic evolution.
- comment is then made on the potential impacts of disturbance events (e.g., surges, extreme freshwater runoff, etc.) and how they might affect matters. These events may range from being minor and insignificant to the geomorphology, sedimentology and BCHs, to being large and highly significant. Further, the significance of a specific event might vary depending at what stage in the future geomorphic evolution it occurs, and on the precise nature of the event.

There are thus many possible aspects to consider, and over a century timescale, there are a very large number of possible combinations of geomorphology and events. Work will necessarily draw on the meteorology, oceanography and data interpretation, the CP-BCH report, reports on habitats, on hydrology, geotechnics, stratigraphy and other appropriate data and information. To make the analysis manageable and any conclusions explicable and defensible, it is necessary to concentrate on the main aspects. The analysis and conclusions are necessarily subjective and based on expert assessment.

We describe these factors in relation to several examples in the ESSP area and using the key questions of section 7. In places, we refer to a **Level of Confidence** in a statement, result or conclusion. This scale is described in section 11.1.

9.1. Factors that might influence sediment supply, transport and catchment morphology

9.1.1. Natural factors

In common with most areas of the Australian shoreline and inner continental shelf, the available field data on sediments and sedimentary processes is insufficient to allow a quantitative assessment of sedimentary processes over such an area and range of time. The sediment budget of the existing coastal system is unknown, especially limited by the lack of age-dated deposits.

Whilst the tides dominate day-to-day processes in these creek systems, several other factors require assessment regarding their influence on the processes in these tidal creek systems. These factors, some of which are episodic, become especially relevant when considering the possible future response of the coastline to sea-level rise and to the additional factors of the ponds of scenario 7.2.1. These factors include (in no particular order):

- sub-surface geology and inherited topography;
- groundwater;
- past coastal changes and timing of past changes;
- past climate changes, including centuries of high or low rainfall, and fluvial sediment supply;
- present sediment availability, including shallow stratigraphy and erodibility;
- shelf tidal forcing;
- shallow creek entrances – i.e., driven by other processes, especially waves, and;
- modern rainfall events and associated fluvial activity.

9.1.2. Factors changed by the planned development - general implications for hydrodynamics and sedimentary change

It is clearly relevant how much sediment might be introduced into the coastal system associated with the emplacement of the ESSP ponds. Any newly released sediment might be transported through the system into the marine environment or might be stored or accumulate in other coastal sedimentary environments. In all cases, the key question is whether the volume, nature and rates of such changes are significant.

As indicated by the bedforms in some of the creek beds (McKay Creek near tidal limit) and on the bed in some catchments (e.g., 40 Mile Road E and Creeks 7 and 8) runoff appears to have caused sediment transport, including causing bed erosion and forming sediment tails behind some bed features ('comet marks'). An assessment of runoff as a factor in changing sedimentary environments and habitats is therefore required for the ESSP area, and the possible effects of SLR and the ponds.

The proposed ponds occupy a total area of 118 km^2, which represents 17% of the total area of the three fluvial catchments involved (Figure 33). Modelling of rainfall events of various magnitudes and frequencies has been used to derive likely associated riverine flows (Land and Water Consulting, 2023a). This is referred to as a Regional Flood Frequency Estimation (RFFE). Events modelled included, from smallest flow to largest:

- the 63% Annual Exceedance Probability (AEP) or 1 Exceedance per Year (EY) rainfall event (the smallest modelled flow) for natural and scenario 7.2 conditions, and the same for 10% (1 in 10);
- the 5% (1 in 20), 2% (1 in 50) and 1% (1 in 100) AEP event for scenario 7.2 conditions;
- the 2% AEP event for scenario 7.2 conditions with 10% AEP storm surge;
- the 1% AEP event (the largest modelled flow) for scenario 7.2 conditions with 5% AEP storm surge;
- the 1% AEP event for scenario 7.2 conditions with 5% AEP storm surge and 0.9 m sea-level rise.

Severe Tropical Cyclone Damien (Feb. 2020) delivered substantial rainfall across the catchments feeding the ESSP area. The maximum recorded 24-hour rainfall of 150 mm was found to be equivalent to the 1 in 10 AEP event, which allowed some calibration of results. The RFFE results have substantial uncertainty, with peak flow estimates from 5% and 95% confidence limits varying by greater than an order of magnitude (Table 16, Table 17, Table 18). The level of uncertainty is related to the lack of available gauge data close to the site catchments, plus potential differences in loss rates (infiltration) and other parameters within the closest gauged catchments (Land and Water Consulting, 2023a). The results are therefore only indicative estimates of flood conditions.

Table 16. Results of the Regional Flood Frequency Estimation for Eramurra Creek

AEP (%)	Discharge (m^3/s)	Lower Confidence Limit (5%) (m^3/s)	Upper Confidence Limit (95%) (m^3/s)
50	27.0	5.31	138
20	77.5	15.3	397
10	126	24.9	647
5	184	36.2	942
2	267	52.6	1370
1	333	65.6	1710

Table 17. Results of the Regional Flood Frequency Estimation for McKay Creek.

AEP (%)	Discharge (m^3/s)	Lower Confidence Limit (5%) (m^3/s)	Upper Confidence Limit (95%) (m^3/s)
50	26.0	5.10	134
20	74.6	14.6	383
10	122	23.8	624
5	177	34.7	909
2	257	50.4	1320
1	321	62.9	1650

Table 18. Results of the Regional Flood Frequency Estimation for Devil Creek

AEP (%)	Discharge (m^3/s)	Lower Confidence Limit (5%) (m^3/s)	Upper Confidence Limit (95%) (m^3/s)
50	33.8	6.70	171
20	96.9	19.2	490
10	158	31.3	798
5	230	45.6	1160
2	334	66.3	1690
1	417	82.7	2110

A useful timescale to consider is the 10% AEP (equivalent to the 1:10 year event). Here, the model outputs for natural conditions indicate maximum stream speeds of ~1 m/s, sufficient to transport granules and small pebbles across the bed, along long sections of all three main creek systems (Figure 106) and the lower part of a minor creek that flows into the 40 Mile Road W tidal catchment.

9.1.2.1. The main fluvial systems

For the 10% AEP, Eramurra Creek, McKay Creek and Devil Creek all display long reaches where flows speeds attain up to 1 m/s (Figure 106). For Eramurra Creek, flows decrease markedly at the delta front and remain relatively slow across the high tidal flats, indicating likely deposition of any fluvially transport sand. For McKay Creek, speeds decrease markedly at the delta front, but speeds exceed 0.5 m/s across the upper intertidal flats and increase again in the lower parts of the tidal creek. This tends to indicate the potential for deposition of coarse sand at the delta front, consistent with field observations, and tends to infer that any medium sand and finer sediment might be transported directly into the tidal creek system, given flow of sufficient duration. A similar sharp decrease in speed occurs for Devil Creek where it meets the back-barrier basins and the tidal creek systems. Finally, it is worth noting that fast flows occur in the lower reaches of the minor creek that feeds the eastern section of 40 Mile Road W catchment.

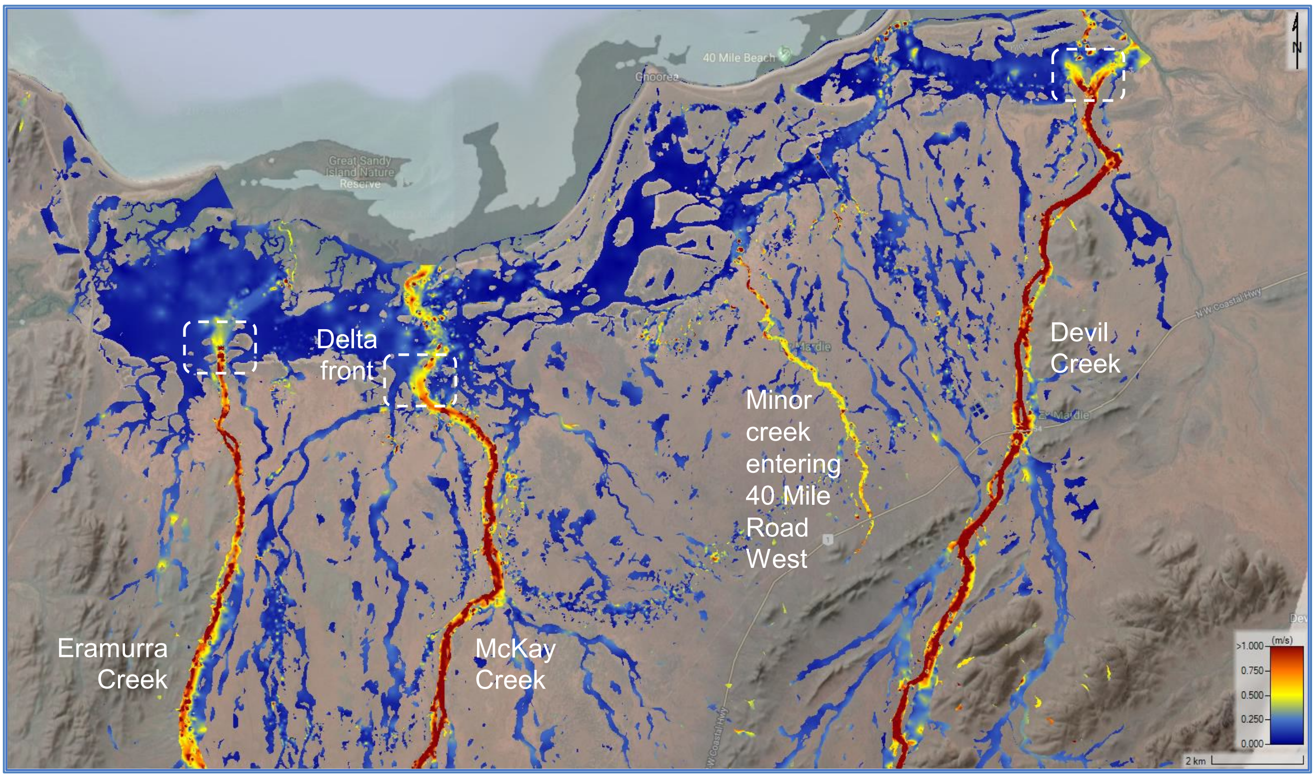

Figure 106. Natural conditions: 10% AEP existing conditions maximum velocity (m/s; Land and Water Consulting, 2023a).

With the ponds of scenario 7.2.1, expected changes would include possible increased influence of river-flood events and perhaps the relaxation phase of tidal surges that inundate above high tide level. The presence of the pond walls will divert water into some catchments, most notably McKay Creek, and potentially alter patterns of erosion, sediment throughput and accumulation, in places beyond the extent of the ponds themselves.

Viewed at this scale, the modelling outputs (Figure 107) indicate little major difference in flow speeds. Some areas of the output appear suspect regarding predicted flows - where the model indicates the presence of rapid flows similar to the base case, but the presence of the ponds means that there appears an inadequate catchment to produce such flows. These occurrences have some implications regarding potential sedimentation, runoff and thus habitats, although not major, but it raises caution on using these outputs to inform the possible sedimentary response to floods. Time-series of flow speeds for these events would be advantageous to consider the potential for bed armouring and other local sedimentary effects..

Noting these apparent issues, the information presented elsewhere is consistent with the qualitative expectation of possible enhanced sediment erosion in the narrowed channel between the western and central ponds, with associated enhanced accumulation in the delta front, near the seaward end of the narrowed section of McKay Creek (Figure 108, Figure 109, Figure 110). There may also be slightly enhanced accumulation in the lower 1500 m of the tidal creek itself, but given the tidal dynamics in this region, this appears a relatively minor issue.

The model outputs also indicate that the nascent mangroves are completely isolated from fluvial runoff, and that any minor supply of fluvially supplied sediment into the catchments of 40 Mile Road W and E, and supply to Creeks 7 and 8 will probably be diminished. For these cases, the model output appears appropriate.

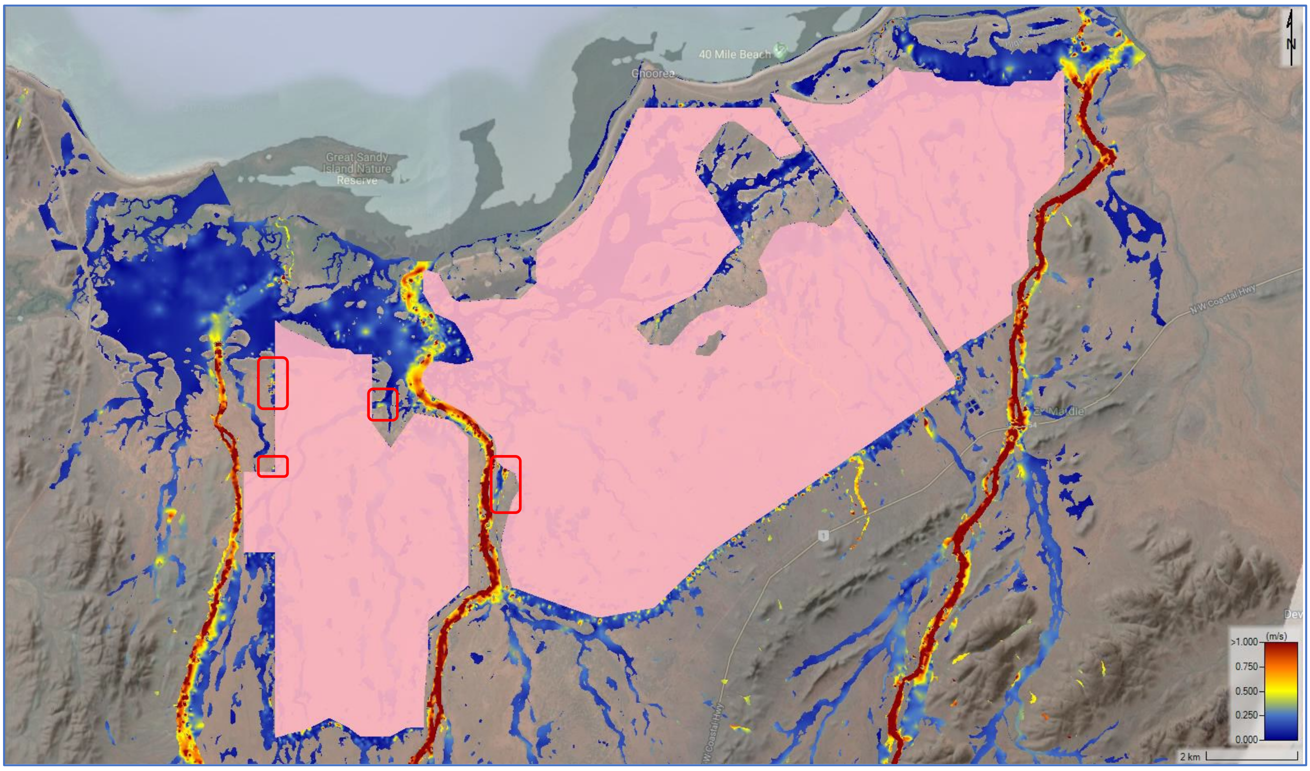

Figure 107. Pond scenario 7.2: 10% AEP existing conditions maximum velocity (m/s; Land and Water Consulting, 2023a). Red boxes indicate areas that appear suspect regarding flows. (No other events were presented in this form so that checking of these issues was not possible).

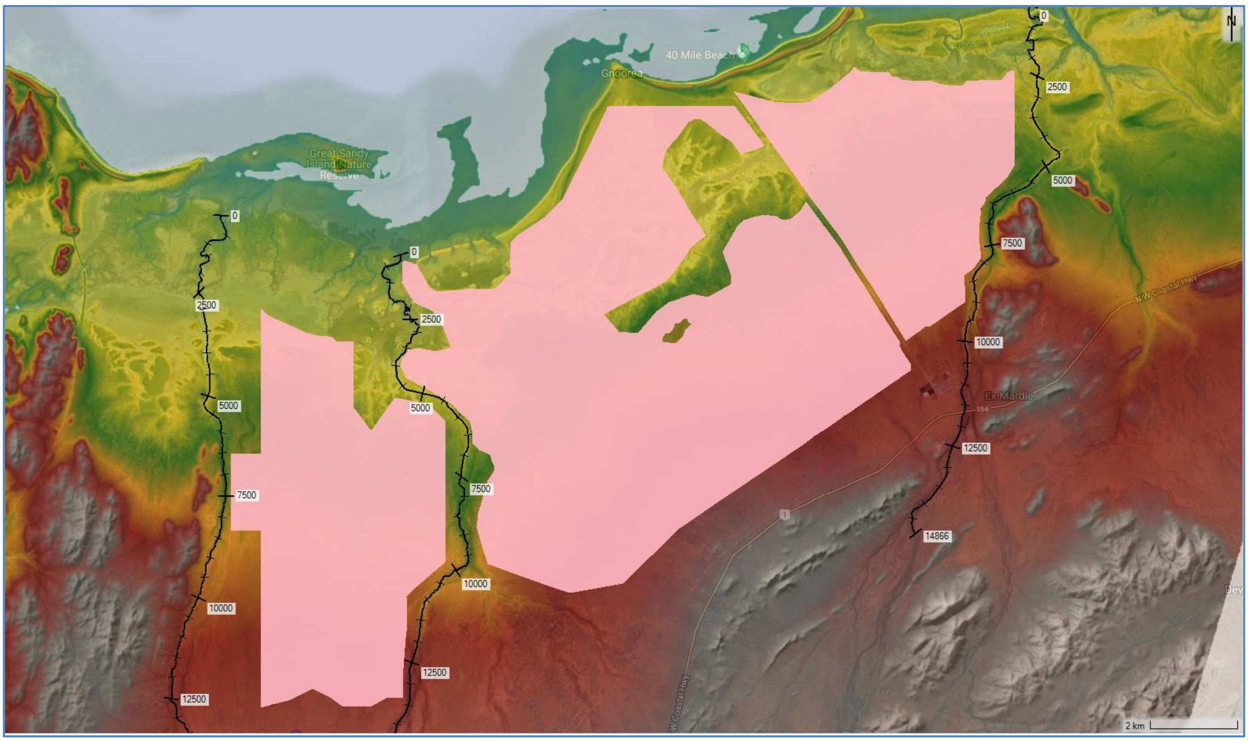

Figure 108. Chainage reference for Figure 109 and Figure 110.

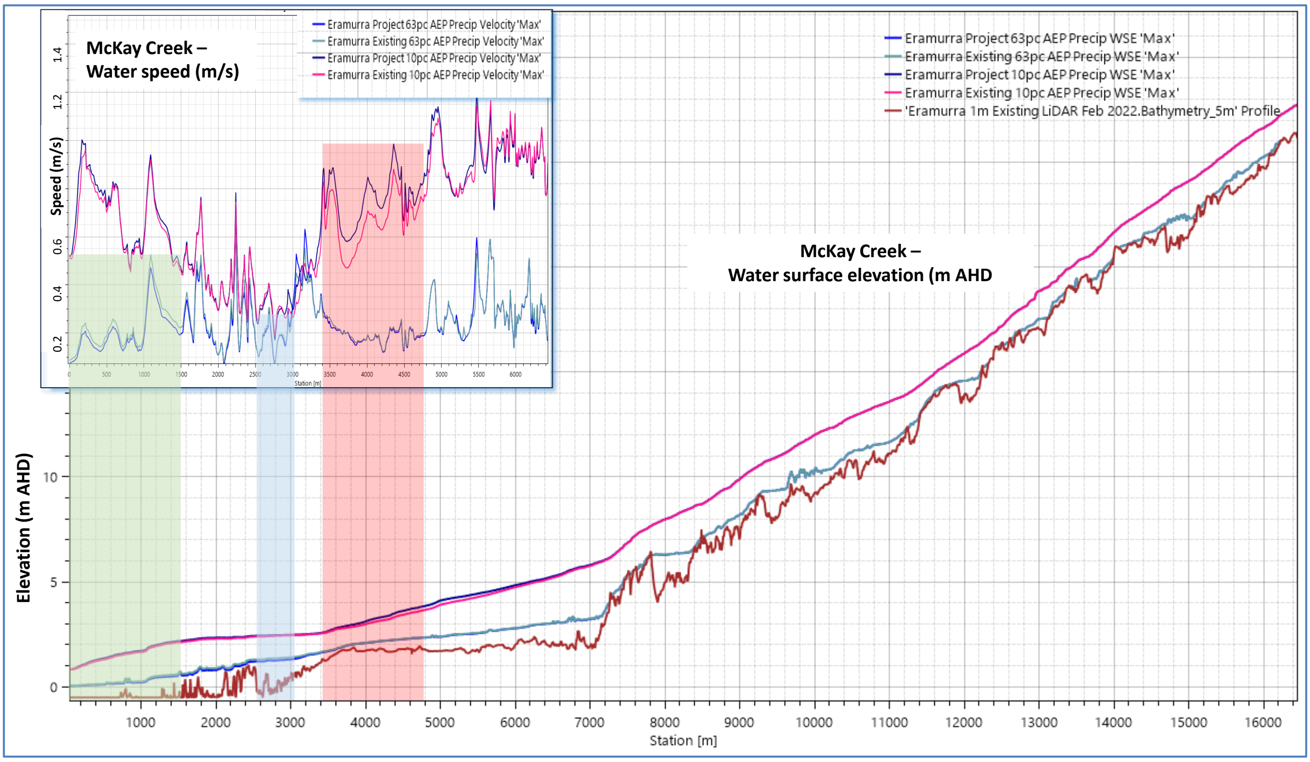

Figure 109. Overlay of 10% AEP flood water slope and speed for McKay Creek for natural conditions and scenario 7.2 (modified from Land and Water Consulting, 2023a). Red bar shows potential zone of enhanced erosion during the 10% AEP event. Blue bar shows zone of river flow speed below 0.3 m/s (i.e., potential sand deposition) in the area, even for the 10% AEP event. Green bar shows slower river flow with ponds in the lowermost 1500 m of the creek, presumably as a result of decreased fluvial input from the east (i.e., the effect of the presence of the central ponds). Details expanded in Figure 110.

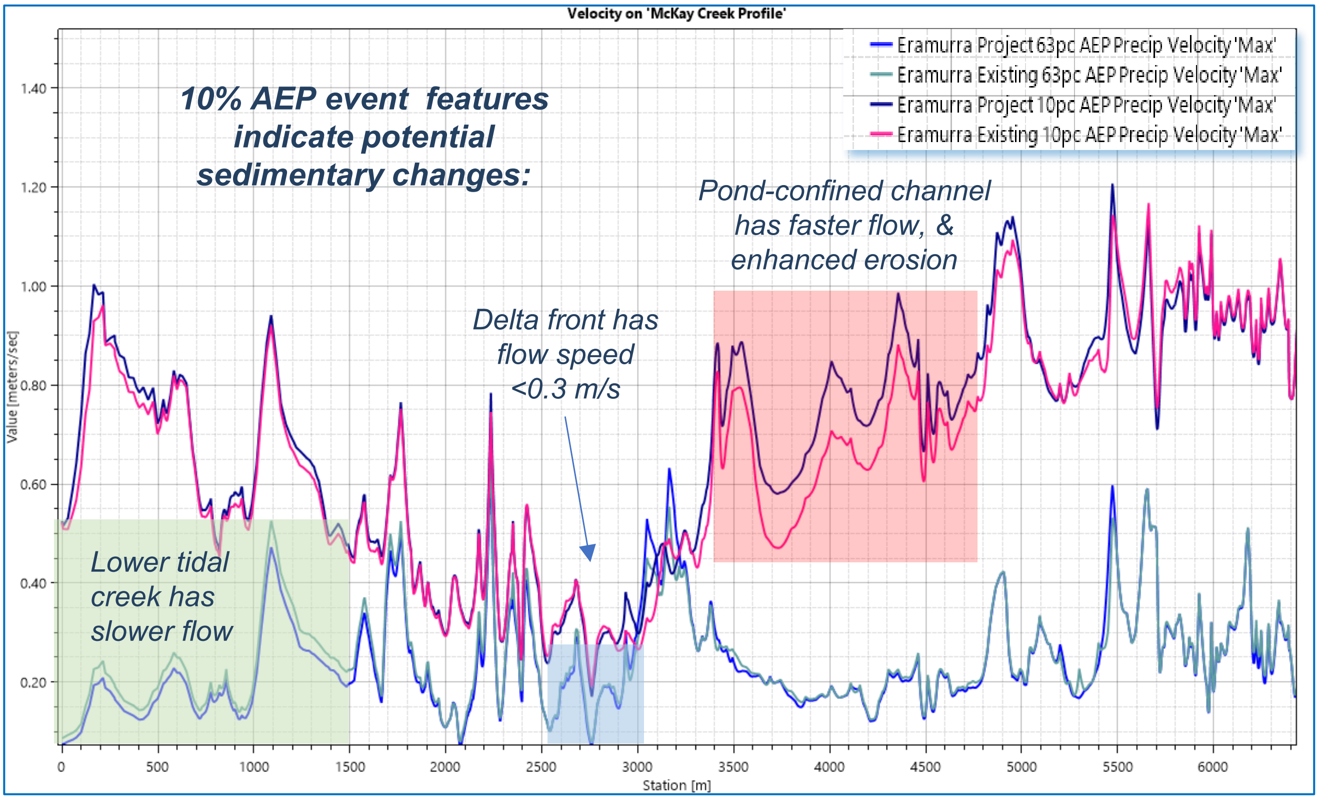

Figure 110. McKay Creek velocity profile (m/s; Land and Water Consulting, 2023a), expanded from Figure 109, indicating that changed flow speeds have the potential to generate changed sedimentary response.

9.1.3. Implications for changes in habitats

9.1.3.1. *Physical changes*

The implications of any physical changes to BCHs are many, varied and complex. These are dealt with on a case-by-case basis in the worked examples below (section 9.3).

9.1.3.2. *Groundwater changes*

Although outside the specific expertise of this report's authors, the potential changes in groundwater salinity over the next century, with 0.9 m of SLR and with the ponds in place have been assessed (Land and Water Consulting, 2023b). The changes are likely to influence some aspects of BCHs, including areas outside the ponds. Based on the existing disposition of sediments, modelling of potential groundwater changes (Figure 111), indicates several key points. Groundwater salinity will increase:

- at up to 1 km beyond the pond walls, and especially around the western crystallizer ponds;
- in many of the topographic basins in the coastal area, such as the basin in the catchments of 40 Mile Road E, and Creeks 7 & 8;
- in McKay Creek, especially in the channel formed between the western and central ponds and the tidal flats to their north;
- throughout the nascent mangrove area, particularly in the southern area close to the pond walls;
- in the gap within the central ponds (cf. Figure 104).

Given the net evaporation rates are far greater than rainfall (Figure 31), saline groundwater may become closer to the surface especially in areas where groundwater changes coincide with areas of likely future erosion, perhaps with consequences for surface BCHs. In areas where increased groundwater salinity coincides with future sediment accumulation, the significance of groundwater changes might be less.

As noted above (sections 4.1.3 and 6.5.3), samphire species tend to occupy flat ground close to the base of a slope. Therefore, where pond walls prevent the delivery of rainfall towards the lower ground there is the potential for negative effects on samphires. If there are areas where pond walls increase rainfall delivery towards lower ground, there may be a variety of changes in the nature and distribution of local BCHs. Of the four settings for samphires in the ESSP area, the levee-fringing samphires (Figure 80) are probably the most resilient to changed salinity, being buffered by their proximity to active tidal processes. The channel-head and open fringing samphire setting are probably most likely to be affected by groundwater salinity changes, mostly because they are closest to the northern walls of the ponds and might have their runoff reduced.

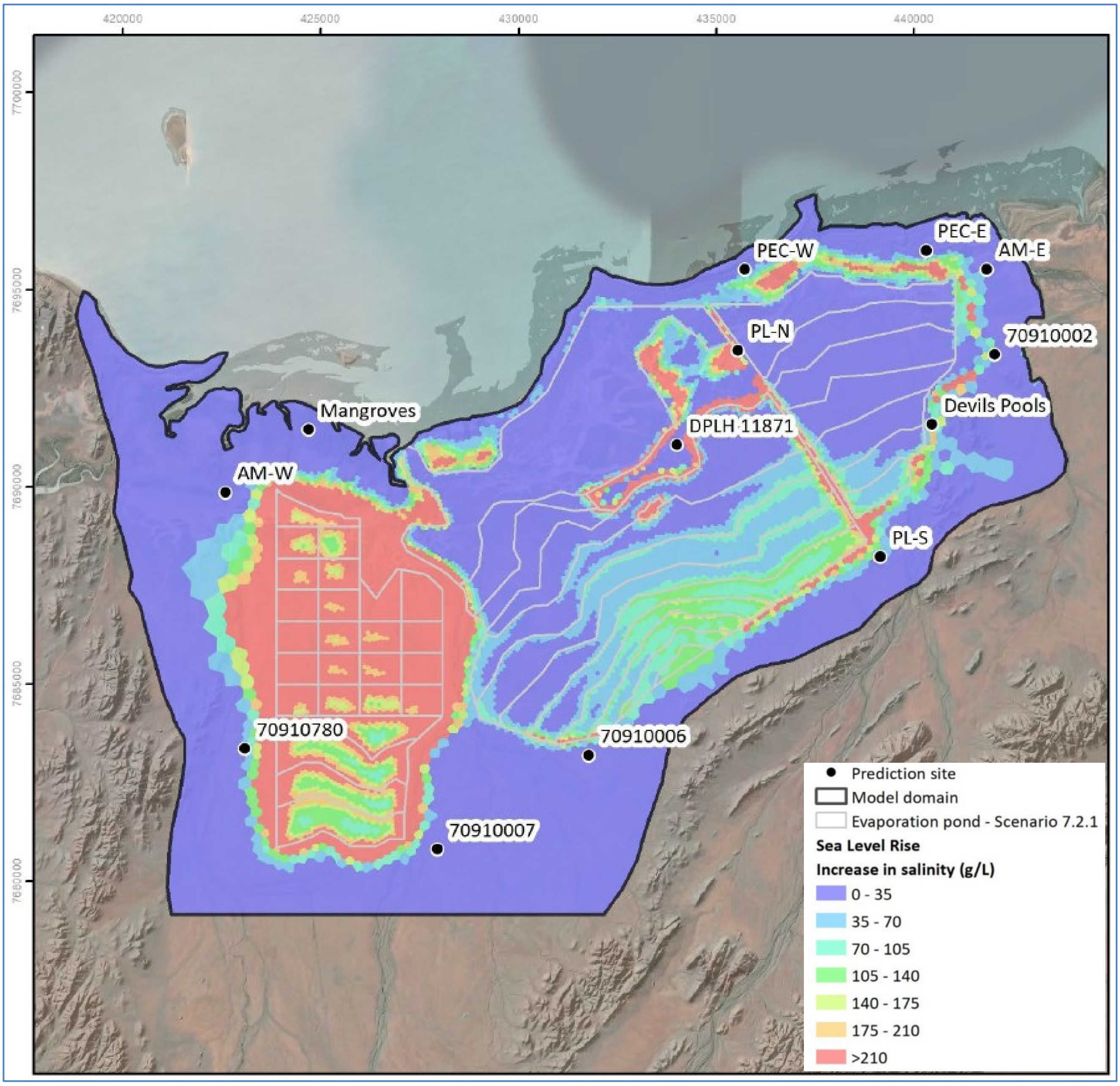

Figure 111. Predicted salinity change in the upper layer of groundwater after 100 years operation of the ponds with a sea level rise of 0.9 m (Land and Water Consulting, 2023b).

9.2. Aspects of coastal stability with SLR

The variety of coastal form and structure in front of the ESSP region, including the presence of some coastal barriers is likely to influence the way in which different areas might respond to projected SLR. At a simple level, there are three distinct areas:

- Unconstrained: From McKay Creek and westward, in the central and western part of the estuary, mangroves occupy the upper intertidal area, transitioning through to supratidal salt flats. This area includes Eramurra Creek and McKay Creek, which have historically released sediment on to the high tidal flats.
- Highly Constrained: From the mouth of the 40 Mile Road W catchment to the mouth of 40 Mile Road E, the coast is substantially protected by an extended, wide dune barrier. Although there are four breaches in the “nascent mangroves” area, the barrier is continuous for ~10 km, and which contains a large intertidal and supratidal area, with a small tidal outlet. The dune barrier has crest elevations of 5

to 8 m AHD and a cross-sectional area of 1,000 to 3,000 m^2 above 2 m AHD, making it resistant to short-term breaching by storms.

- Constrained: From 40 Mile Road E through to Yanyare Creek, the coastal dune barrier is relatively wide, and considered likely to overlay a rock base. The barrier has a series of narrow breaches, with a relatively small supratidal area, defined by local catchments. The dune barrier has crest elevations 5 to 13 m AHD and a cross-sectional area of 2,000 to 3,000 m^2 above 2 m AHD, making it resistant to short-term breaching by storms.

Dune barriers are comprised of comparatively immobile material compared with the silty-sand present across the supratidal flats. Consequently, under conditions where the barriers remain stable, their presence defines basins within which the flats may adjust to sea level, influenced by relative sediment supply and the capacity for sediment transfer through to the ocean. In essence, the barriers are effectively stable, their breaches define the capacity for exchange, and the back-barrier basins define the requirement for sediment to adjust to SLR. For large sea-level change, over millennial timescales, evolution of the dune barriers has probably been a significant control on the development of the ESSP coastline.

9.3. Worked examples

Below are presented a number of worked examples of possible changes with SLR and also with SLR plus ponds. These examples use the analysis of the hypsometry of the present catchments and their potential changes in Vs:Vc ratio with pond emplacement (Figure 26, and see Larcombe, 2024), indicating possible changes to tidal flows. These examples also draw on the generic likely changes in hydrodynamic processes with an instantaneous 1 m SLR (Table 3) and the information reviewed throughout this report. There are several general caveats to the sections below, including the past response of the coastline to change (section 10).

The examples focus on those areas most likely to show geomorphic and sedimentary changes and/or changes to BCHs. Analysis is most detailed for the nascent mangroves, for which it is clearest what the consequences might be, and less detailed for other areas where the information understanding is less clear.

Each section includes a descriptive assessment of the key factors and their possible changes, and then a quantitative assessment. The method of quantitative assessment is complex and requires explanation, detailed below.

9.3.1. Method of quantitative assessment

Some quantitative assessments have also been developed of the possible future distribution of BCHs for three cases.

- **Case 1 – 'SLR-only'** – This means SLR with no sedimentary response, i.e., assuming zero sediment erosion and/or accumulation over the next century. Although unrealistic, this was chosen because it is a manageable limiting case and provides a hard background with which to consider other cases. It represents drowning of the present coastline by a full metre and provides an estimate of might be predicted for future BCH's using 'hydroperiod' (i.e., bed elevation) in the absence of other factors.
- **Case 2 – 'SLR plus sedimentary response'**. This considers SLR and adds expert judgement of adjustments for likely sediment-associated effects, to provide a view of what 'natural' conditions might look like in 100-years' time. Ther term 'sedimentary response' includes some related aspects of slope and related features.
- **Case 3 –** '**SLR plus sedimentary response plus ponds'**. This considers both SLR and the presence of the ponds and adds expert judgement of their interactions regarding likely sediment-associated effects, to provide a view that can be compared to the above case, to assess the potential impact of the ponds. The process includes excising the ponds from the areas considered so that BCHs cannot migrate and colonize those areas.

Below the method is described, using the McKay Creek data.

9.3.1.1. Case 1 – SLR-only

In this first stage, the GIS data were used to determine the existing distribution of each BCH type (mangroves, benthic mat, samphire) within each catchment, as a function of their elevation (Figure 112).

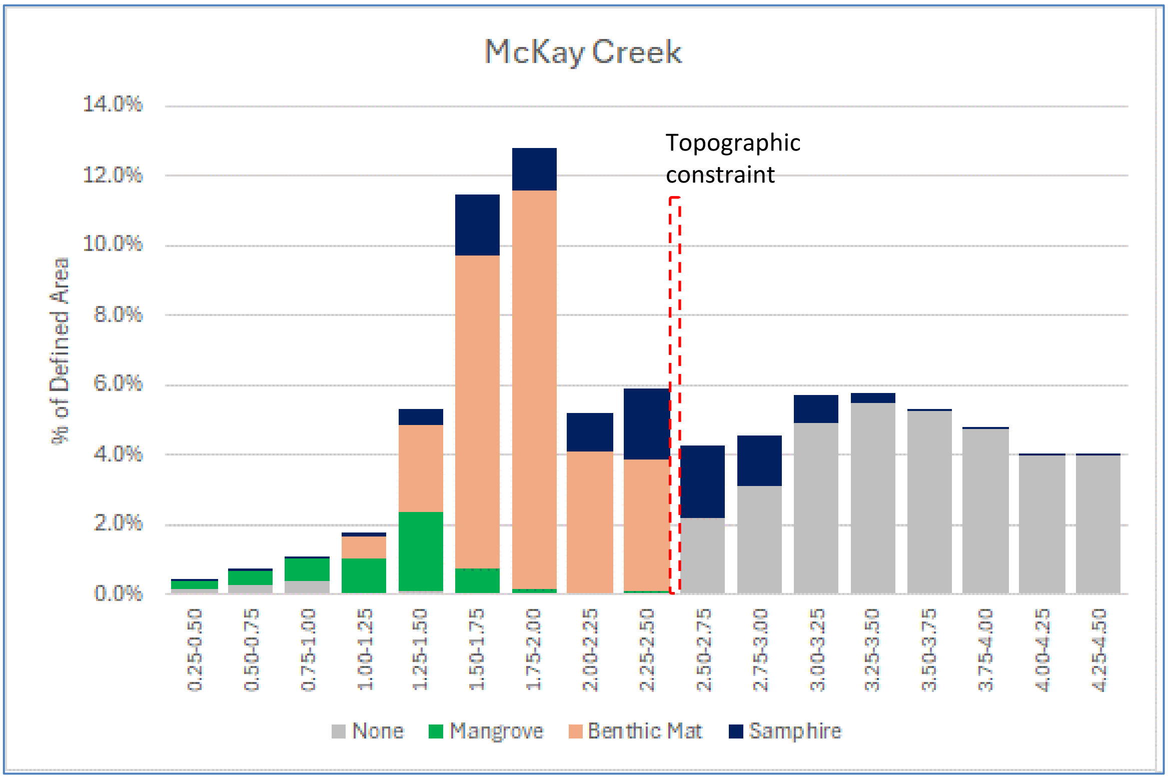

Figure 112. Vertical distribution (m AHD) of each BCH in McKay Creek, plus the vertical distribution of no BCH's, relative to the whole catchment area. Data are calculated for each 0.25 m elevation range. For example, the elevation range 1.75 to 2 m occupies 13% of the whole catchment. All this specific elevation range is occupied by one or other BCH. In this case, 0.2% of the whole catchment is mangrove in this elevation range, and similarly, ~1.5% samphire and around 11% benthic mat. Note the sharp upper limit of benthic mats in this catchment at around 2.5 m AHD.

These were then plotted vertically, to allow direct comparison with the catchment-averaged hypsometry, i.e., the distribution of bed elevation (Figure 113).

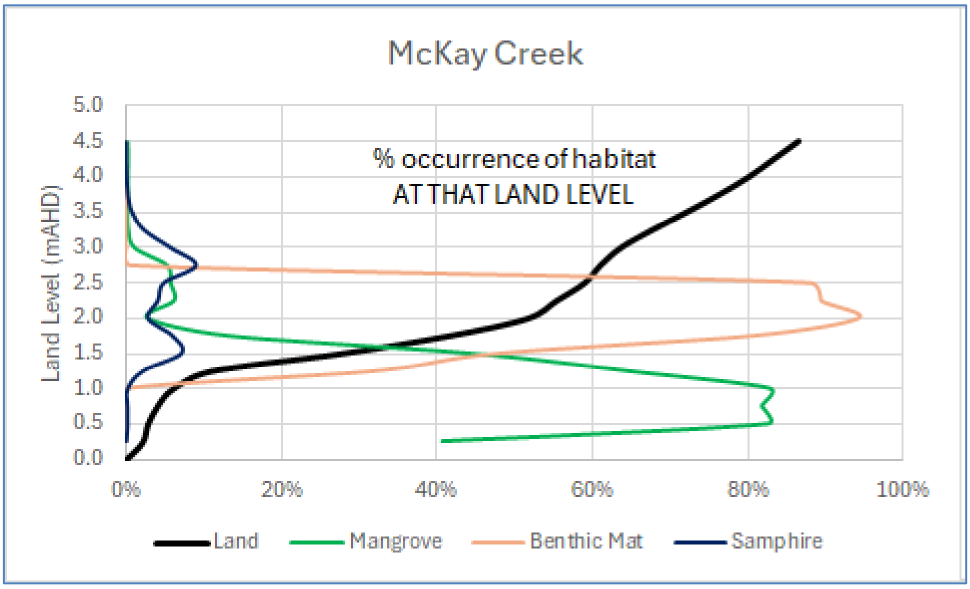

Figure 113. Vertical distribution of BCHs, expressed as a % of land occupied by each BCH at that specific elevation, to allow comparison with the catchment-averaged hypsometry (bed elevation). The bed elevation curve (black) indicates that there is a wide shallow-gradient area at 1.25 to 2 m AHD, above which are much smaller areas of the bed at 2 to 3 m AHD. Note that habitat classification indicates presence of the BCH as the primary species within the area but doesn't necessarily mean full coverage with that BCH. For the BCHs, as an example, at 2 m AHD, ~94% of the area is classified as benthic mat, with an additional ~3% of mangrove and ~3% of samphire – hence 100% of the available catchment at 2 m AHD is classified as one BCH or another.

The curves of Figure 113 for each BCH are then moved upwards in 0.25 m increments, so that the relative proportion of each BCH is maintained and overlain on the available area provided by the bed 0.25 m higher. This is repeated to provide data points for rises of 0.25, 0.5, 0.75 and 1.0 m for each BCH type and **the result represents Case 1 – the 'SLR-only' case** (Figure 114). These numbers are upper bounds and will over-estimate the proportions of BCH at each SLR increment. For example, mangroves are unlikely to colonise areas of tidal flats unless there is sufficient sediment available to support juveniles to become established, and for many such areas this would require accumulation of suitable sediment of sufficient thickness, which might not occur due to the location being too far away from an active sediment supply, such as a creek head.

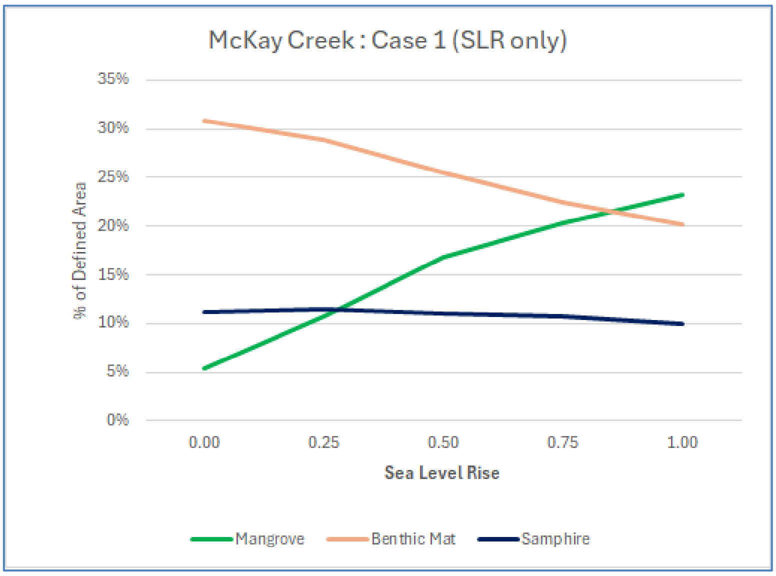

*Figure 114. The **'SLR-only'** case . Hypothetical proportion of each BCH in the tidal McKay Creek catchment at various stages of SLR (using 0.25 m increments) assuming no bed elevation change. So, taking all mangroves together, they occupy 5% of the catchment at present sea level, but will increase to 23% with a 1 m SLR. These numbers are upper bounds and over-estimate the proportions.*

9.3.1.2. Case 2 – SLR plus sedimentary response

The second stage is to estimate the BCH result with SLR plus a sedimentary response. This considers SLR and adds expert judgement of adjustments for likely sediment-associated effects, to provide a view of what 'natural' conditions might look like in 100-years' time. This process necessitated some simplification. For each BCH, the typical elevation range over which each BCH may be considered predominant was identified, using the condition where a BCH classification covered >25% of the area. Elevation ranges of 0.25 m were used. This resulted in three typical elevation zones:

- 2.5 to 3.0 m AHD. Samphire predominant;
- 1.5 to 2.5 m AHD. Benthic Mat predominant; and
- 0.5 to 1.5 m AHD. Mangrove predominant.

The physical changes that might be associated with translating each BCH upwards with SLR were considered visually by plotting the area covered by elevation zones + SLR, for successive increments of 0.25 m, as a series of maps. Then, expert judgement was used to modify the above maps by estimating the proportion of each incremental area against the estimated potential changes in bed elevation, taking into account the available information on sediment sources, volumes, and transport processes.

So, the process of applying expert judgement involved the series of maps, and for each Figure, answering this question –

> 'Of each new upward increment of SLR, what proportion (between 0 and 1) of the new area is likely to be colonized by the BCH in question?'.

These proportions (Table 19) were then applied to that vertical increment for that BCH. **<u>The result represents Case 2 – the 'SLR plus sedimentary response' case.</u>**

Table 19. Factors for viability of mangroves, benthic mats and samphire applied to each 0.25 m elevation band for Western (W), central (C) and Eastern (E) areas of the ESSP area.

Elevation (m AHD)	Mangroves			Elevation (m AHD)	Benthic Mats			Elevation (m AHD)	Samphire		
	W	C	E		W	C	E		W	C	E
>2.5	0.0	0.0	0.0	**>3.5**	0.0	0.0	0.0	**>4.5**	0.0	0.0	0.0
2.25 to 2.5	0.0	0.01	0.0	**3.25 to 3.5**	0.0	0.0	0.0	**4.25 to 4.5**	0.5	0.1	0.1
2.0 to 2.25	0.1	0.02	0.0	**3.0 to 3.25**	0.1	0.1	0.0	**4.0 to 4.25**	0.5	0.2	0.2
1.75 to 2.0	0.2	0.05	0.1	**2.75 to 3.0**	0.2	0.2	0.1	**3.75 to 4.0**	0.5	0.4	0.4
1.5 to 1.75[14]	0.5	0.25	0.2	**2.5 to 2.75**	0.5	0.5	0.2	**3.5 to 3.75**	0.5	0.5	0.5
<1.5	1.0	1.0	1.0	**<2.5**	1.0	1.0	1.0	**<3.5**	1.0	1.0	1.0

Appendix 13.4 shows the maps presented for each BCH covering the western, central and eastern sections of the ESSP area. As an example, for McKay Creek, the maps indicate landward advance and expansion of mangroves across the high tidal flats, with particularly major expansion occurring in the first and second 0.25 m increment of SLR (Figure 115, compare the top three images).

This landward expansion of habitat with 1 m of SLR required modification, because it is unrealistic for a variety of physical sedimentary reasons, including that is very unlikely that sufficient sediment can be delivered to and beyond the active creek heads fast enough to accumulate to a thickness able to support mangrove colonisation and establishment across such an area.

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[14] This table can be read thus – for the mangroves, for the first increment of SLR above present levels (from >1.5 to 1.75 m AHD), the newly inundated areas will support about half the potential mangroves in the western ESSP region (i.e., factor is 0.5), 25% in the central region (factor 0.25) and 20% in the eastern region (factor 0.2).

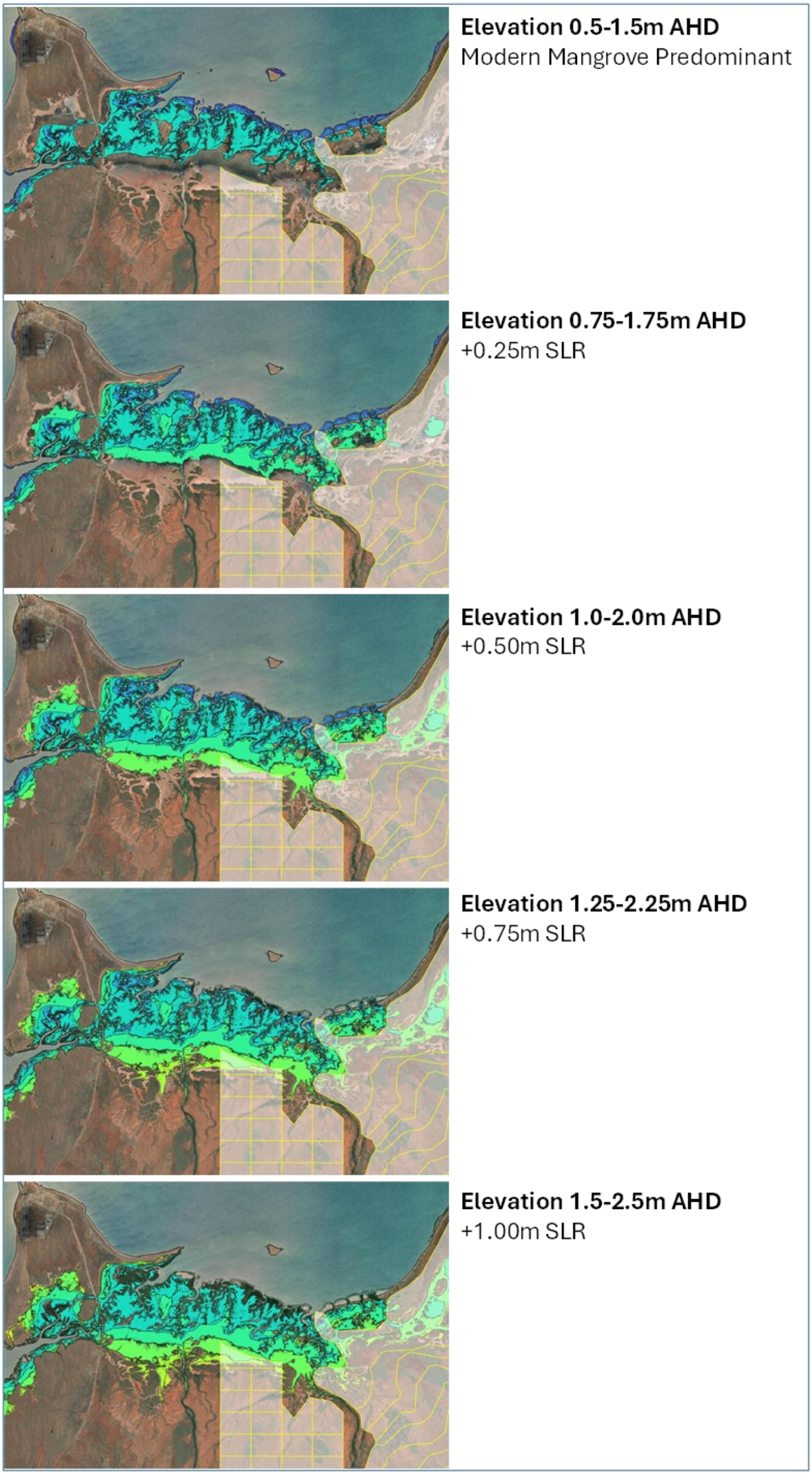

Figure 115. Elevation Zone of Present-Day Mangroves (Central), i.e. with no ponds. (The proposed ponds are shown only to help visual assessment with other figures).

Regarding benthic mats in the McKay Creek catchment, they currently form a large area in the elevation range 1.25 to 2.5 m (Figure 112, Figure 113) and are constrained at the upper limit by steeper topography and cemented rocks – they favour low undulating and basinal sedimentary settings. Therefore, SLR will inevitably decrease the available area for benthic mats (Figure 114). However, there is the possibility that erosion will occur at the lower intertidal zone, by increased exposure to waves releasing sediment that may be transported landwards and potentially accumulate on the shallow-gradient areas (Figure 116). Similar sediment release might also occur in locations further landward, but probably to a lesser extent because of the harder material.

9.3.1.3. Case 3 – SLR plus sedimentary response plus ponds

The third and final stage is to add the effect of the ponds. Therefore, the process considers SLR and the presence of the ponds and adds expert judgement of their interactions regarding likely sediment-associated effects. The process includes excising the ponds from the areas considered so that BCHs cannot migrate and colonize those areas. This provides a view that can be compared to the previous result, to assess the potential impact of the ponds. (The expert judgement notes but does not actively include the possible salinity effects around the pond walls, because it is not fully clear how the salinity predictions (Figure 111) can be linked with porewaters in existing surface sediments, the possible root structures of potential BCHs and to potential future sediments). The result is **Case 3 – the 'SLR plus sedimentary response plus ponds' case.**

Cases 2 and 3 are presented together on a single diagram (e.g., Figure 117), allowing a visual assessment of the estimated relative impacts of the ponds over a century of SLR. At all stages of SLR, the ponds reduce the area available to BCHs, so all Case 3 results for BCH coverage are lower than for Case 2.

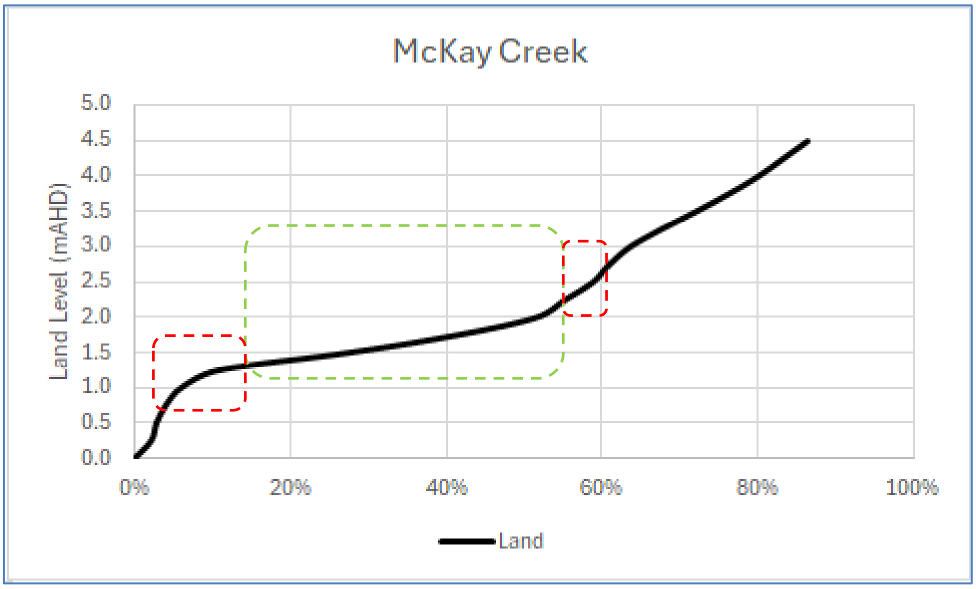

Figure 116. Hypsometric curve for McKay Creek, showing hypothetical areas of possible changed bed elevation (red = erosion, green = accumulation) for the 'SLR plus sedimentary response' case.

Some other features of the logic are notable. At any particular stage, the raw result might be less than expected for mangroves, but more than expected for the benthic mats, should only hydroperiod be used as a factor. This is because of the nature of the transition zone between the mangroves and the benthic mats. The lower (seaward) edge of the benthic mat is likely to be replaced only when the leading edge of the mangroves arrives, so that the delayed advance of the mangroves means that the benthic mats will tend to persist for longer. Further landward, as noted elsewhere (section 6.5.3), the topographic constraint at the landward edge of the tidal flats is generally formed of cemented sediments or in some cases igneous rocks, both unable to be readily eroded, so that the landward side of the benthic mats and some of the samphire's settings (Figure 80) are limited in their ability to migrate – they get spatially constrained by the rising sea level.

IT IS TO BE EMPHASISED THAT THESE RESULTS ARE NUMERICAL ESTIMATES BASED ON THE AVAILABLE INFORMATION AND EXPERT JUDGEMENT. THEY CANNOT BE CONSIDERED DEFINITIVE AND THE UNCERTAINTIES ON THESE NUMBERS MAY BE LARGE.

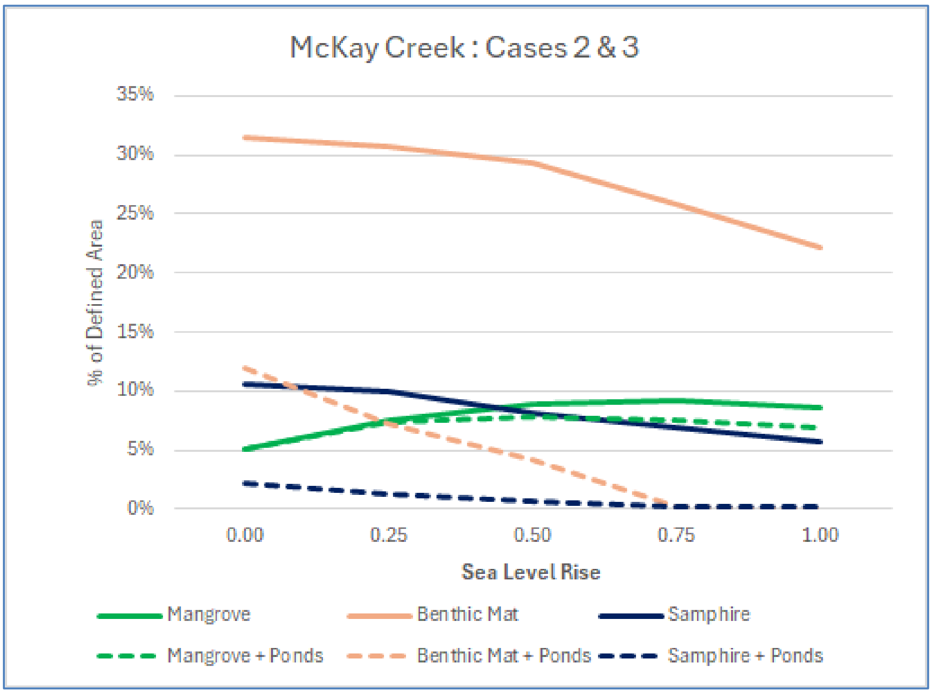

*Figure 117. Case 2 - **'SLR plus sedimentary response'** case (solid lines) and Case 3 - the '**SLR plus sedimentary response plus ponds'** case (dashed lines) for the McKay Creek catchment. The difference between solid and dashed lines is an indication of the changing effect of the ponds through time.*

A level of confidence is presented for each key result, with the terms used defined in section 11.1.

Descriptive effort and qualitative analysis have been focused on the cases of highest relevance, i.e. the nascent mangroves, the pond perimeters, the McKay Creek system and the combined catchments of 40 Mile Road E and Creeks 7 & 8. These are presented below, followed by the quantitative results.

9.3.2. Nascent mangroves

The term 'nascent mangrove' is used here to describe the range of features that occur along a complex section of coastline east of McKay Creek mouth, and west of the sandy shoreline connected to Gnoorea Point. The nascent mangroves occur at the mouth of the present large 40 Mile Road W catchment (Figure 118). This catchment's hypsometry has a high Vs:Vc ratio of 4.1 that with emplacement of pond scenario 7.2.1 would be reduced to 2.9 (Figure 26), indicating, regarding tidal flows alone, that the ponds would bring about a weakened ebb tide and reduced capacity to maintain tidal creeks being open.

This coastal area becomes isolated should the ponds be installed, but it is relevant more widely too. Here there is a discontinuous shoreline of mangroves, interpreted to be relatively young, that border a shallow intertidal flat that houses samphire and benthic mats (Figure 119, Figure 120). The intertidal flats appear to include surface exposures of fossil mangrove stumps (Figure 121), indicating a phase of coastal erosion since their formation. Given their sharp gradient with the base of the active beach (upper image of Figure 121), the flats represent a wave-cut platform, but may also be partly controlled by the presumed underlying mangrove muds. Overall, the deposits indicate a coastline varying in position, but no dates for these deposits are yet available.

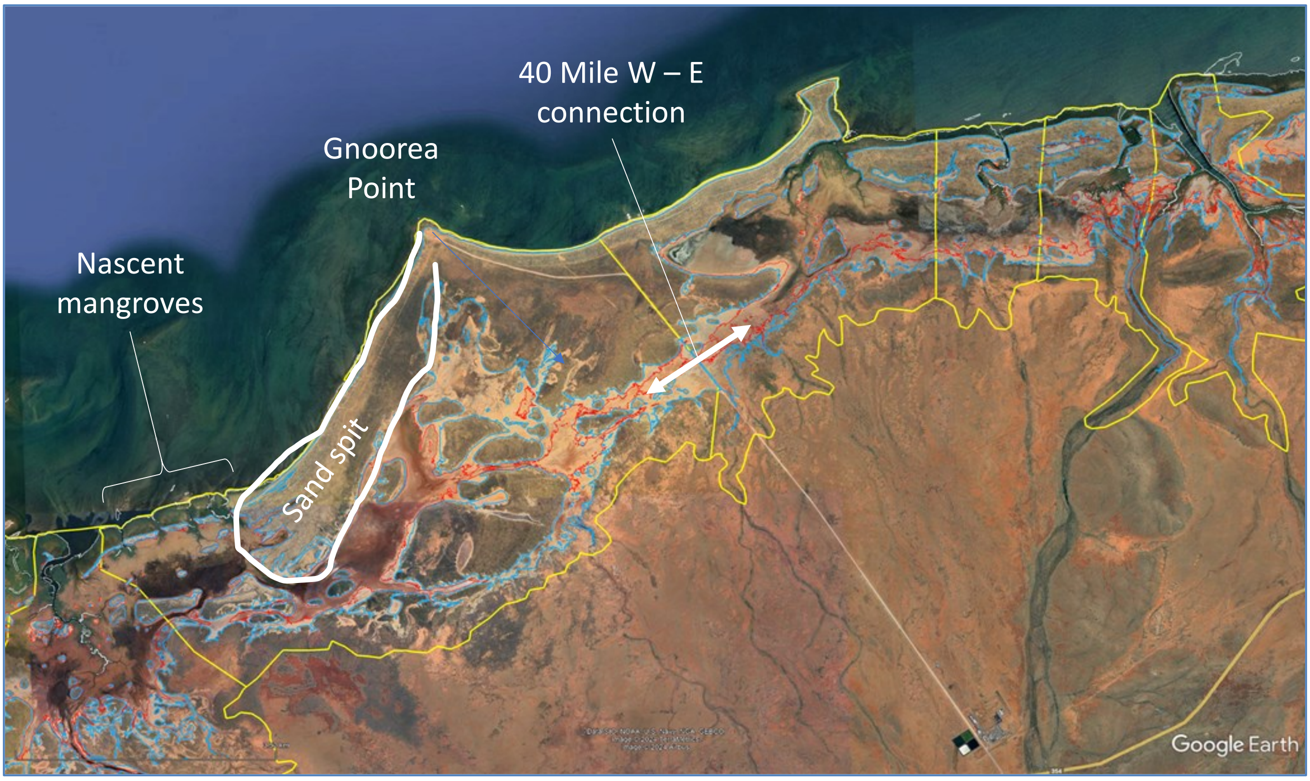

Figure 118. The sand spit complex SW of Gnoorea Point that fronts the western part of the 40 Mile Road W catchment, and the connection (before road construction) between the 40 Mile Road W and 40 Mile Road E catchments.

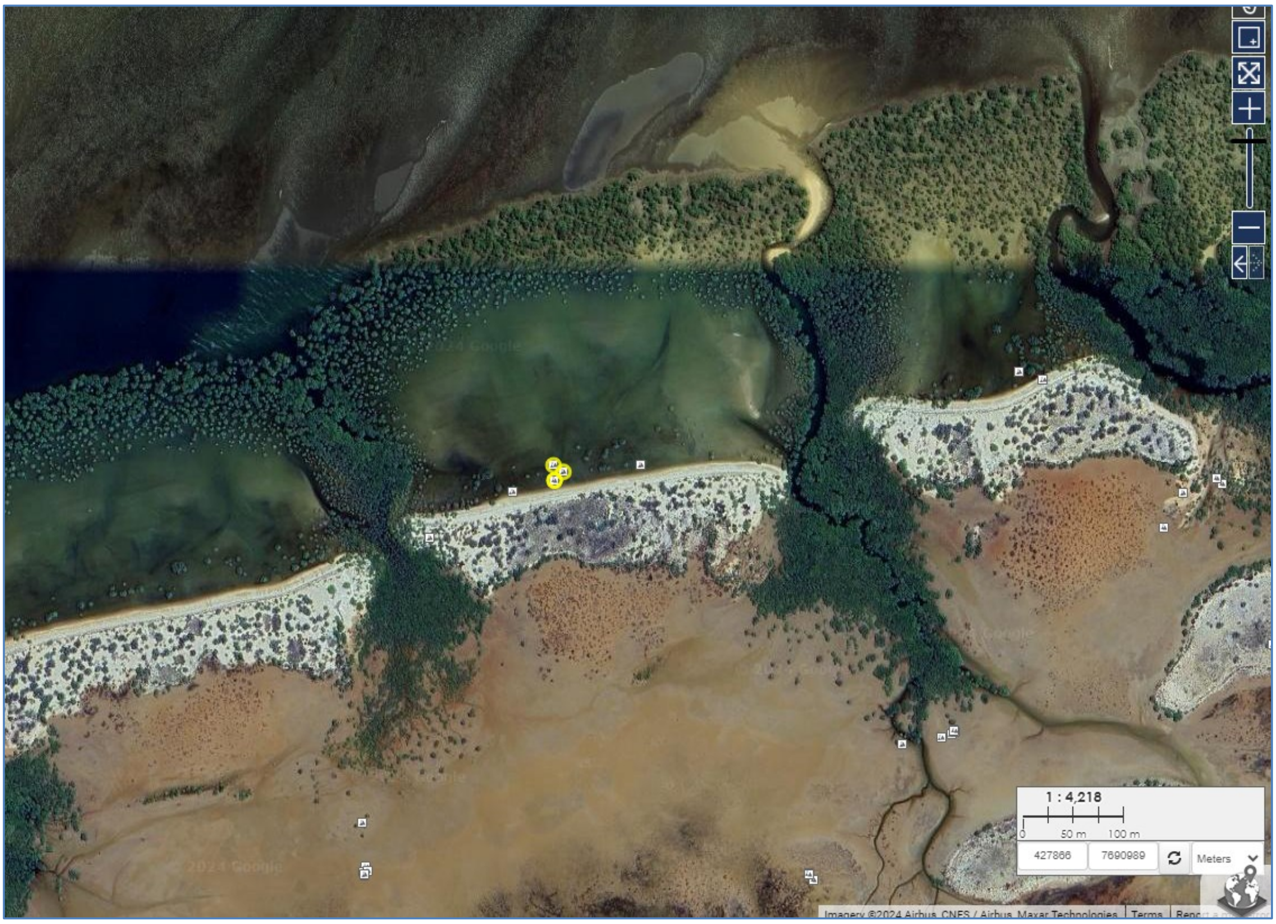

Figure 119. Aerial image of nascent mangrove coastline. Note the sparse fringing mangroves at the seaward fringe, and the more dense mangroves along creek margins and at their landward end. The creeks occur in gaps between remnants of the most recent sandy barrier. Yellow dots indicate location of photos in Figure 121.

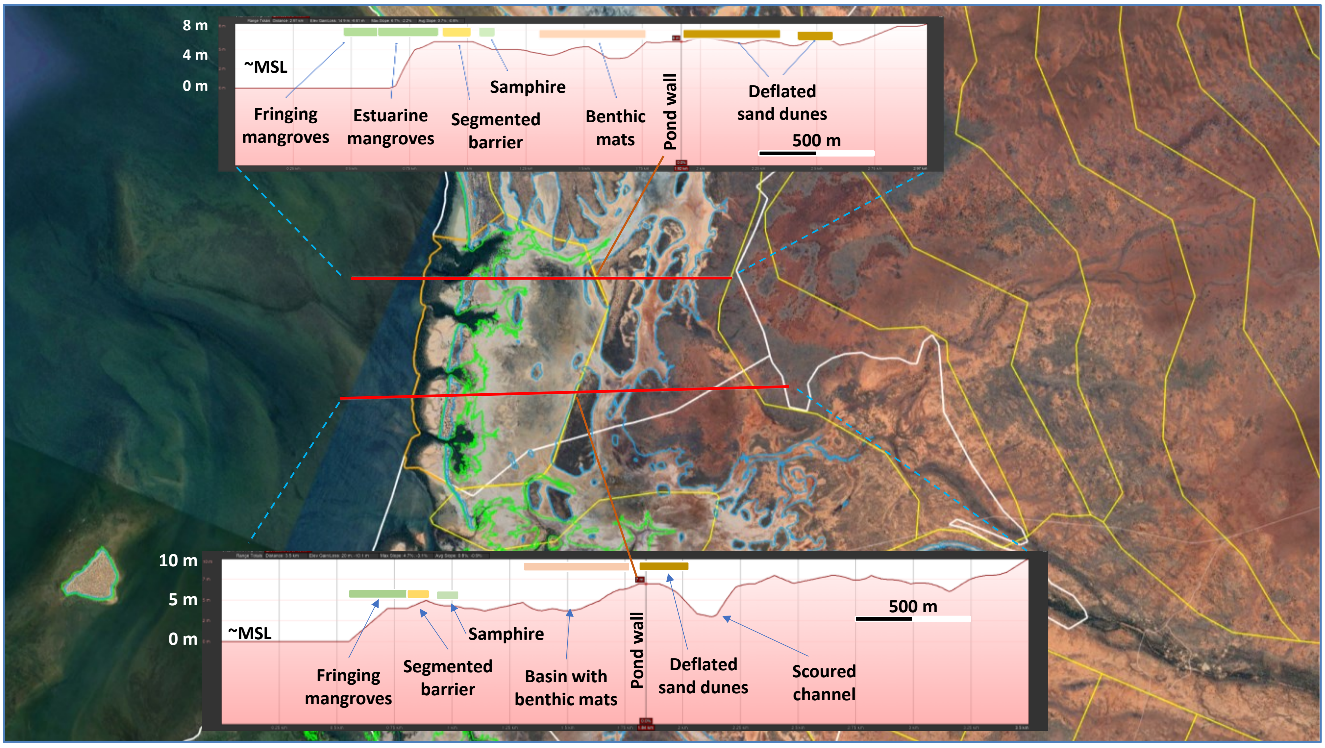

Figure 120. Contoured map of the nascent mangroves (using Google Earth profile tool – even with its inaccuracies it is a useful indication). Contours are in 1 m intervals from -0.5 to +5 m AHD derived from LIDAR survey. Elevation profile across the W (lower) and E (upper) of the area (red lines) marked with the location of key features and the proposed pond wall. (NB - Google Earth elevation data only occur for elevations above 0 m AHD).

Figure 121. Top image - Fish-eye view from beach onto relatively intertidal mixed sand and mudflats at 1 m AHD behind higher ground with nascent mangrove stands. The intertidal flats form a habitat for extensive rich benthic mats. Bottom images - The flats appear to include surface exposures of fossil mangrove stumps, indicating a phase of coastal erosion since their formation. Given the sharp gradient with the base of the active beach, the flats represent a wave-cut platform, but may also be partly controlled by the presumed underlying mangrove muds. Overall, the deposits indicate a coastline varying in position, but no dates for these deposits are yet available.

Behind the intertidal flats is a steep-fronted dissected barrier, and the large catchment of 40 Mile Road W. The barrier features (mottled white areas in Figure 119) form higher ground with a relatively flat top, at 2.5 to 3.5 m AHD (Figure 120), and were characterised as “Deflated Dunes, Sand Plains and Sandy Islands” by CMW Geosciences (2022) and “eolian sand (over calcarenite)” by Land and Water Consulting (2022).

This type of shoreline is markedly different to that further west in the estuary, and to the east along the Gnoorea Point sand spit (Figure 118). The nature of the shoreline here indicates that most of the associated habitats are likely to be ephemeral, probably on timescales of several decades to several centuries, although hard data is lacking. The catchments of 40 Mile Road W and E are large and complex and are located behind the rocky promontory of Gnoorea Point and its associated spit, and a similar promontory to its east. Their different hypsometry (compared to elsewhere on the coast, Larcombe 2024) and their location behind a rock-anchored spit, tend to indicate that these catchments are not yet adjusted to changes in sea level (Ward *et al*. 2022b) in the last few thousand years and possibly also to past periods of intense rainfall in the catchments (Rouillard *et al*. 2016). The ‘mouth’ of 40 Mile Road W is at the area of nascent mangroves. Here the fringing mangroves indicate a past episode of sediment accumulation in the lower intertidal zone as part of a process of coastal advance, following a preceding presumed erosive event (Figure 122, Figure 123).

Further, the sand spit based at Gnoorea Point affects the 40 Mile Road W catchment. The spit appears to have extended SW toward the nascent mangroves with splays extending into the tidal flat area, and there appear number of later breaches in the feature at its SW end, leading to segmentation. Through time, the southward and landward progression of the spit, driven by waves, might have concentrated tidal exchange and other flows at its SW end, potentially focusing the delivery of sand by tidal (and runoff) processes to the area now fronted by the nascent mangroves. This possibility of high rainfall is consistent with the hydrodynamic modelling outputs for the nascent mangrove creeks at the W and E ends (Figure 124) that indicated that the W creek is flood-dominated whereas the E creek is ebb-dominated. It is interpreted that the eastern creeks receive a relatively fast ebb current (and/or runoff) emanating from the breach of what is probably an older barrier coastline.

Figure 122. Aerial photo (view towards the E) of the nascent mangroves east of McKay Creek mouth.

Figure 123. View to SSE of the mouth of McKay Creek (right) and the first two barrier fragments each with fringing mangroves to seawards, and the tidal creek between. Two segments of older deflated dunes (old barrier fragments?) are to the upper left.

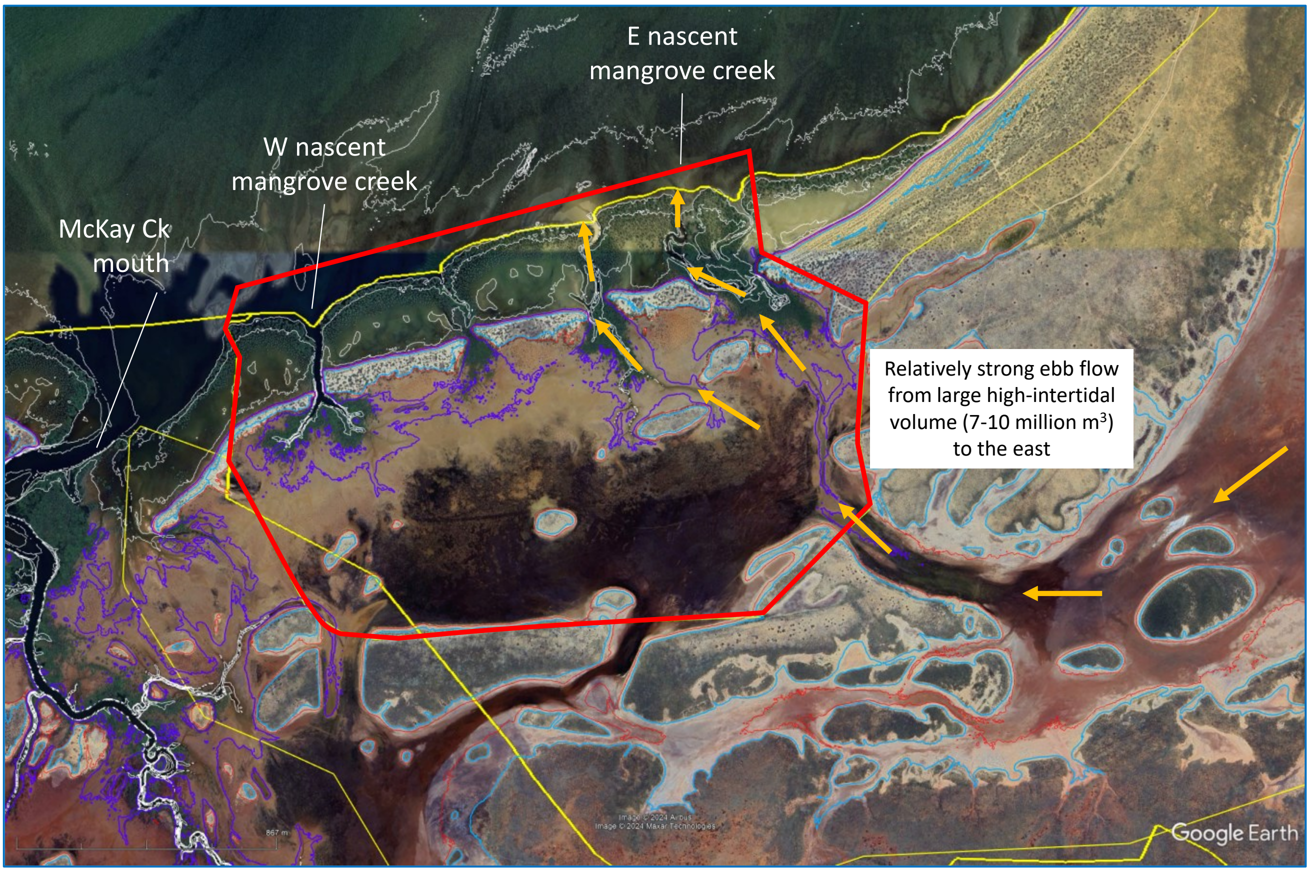

Figure 124. The possible flowlines (orange arrows) of strong ebb flows and/or runoff from the catchment to the east of the present nascent mangrove creeks east of McKay Creek. Elevation contours are at 0.5 m intervals from -1.0 m upwards, including +1.5 m (purple), +2 m (red) and to +2.5 m AHD (light blue, at approximately high spring tide). The bulk of the isolate area lies at +1.5 to +2 m AHD. Finally, note that with pond scenario 7.2.1, an area becomes isolated to seawards of the ponds (red outline).

The units in the core (Figure 125) indicate a mix of high-energy shelly deposits and low-energy uniform silty deposits. Whilst the shelly deposits might represent the deposits of a small tidal channel across mixed muddy flats, the stratigraphy is also consistent with the regional setting and local geomorphological evidence for the occurrence of episodic events. During such events, waves winnow the mixed sediment, removing the finer grains to leave a condensed concentration of shells. Such sediments occur at 80 to 100 cm depth, indicating an erosive event. Whether this is erosion along the length of the fringing mangrove shoreline, or localized to tidal channels, the relevance is the same - it indicates the occurrence of significant processes of erosion.

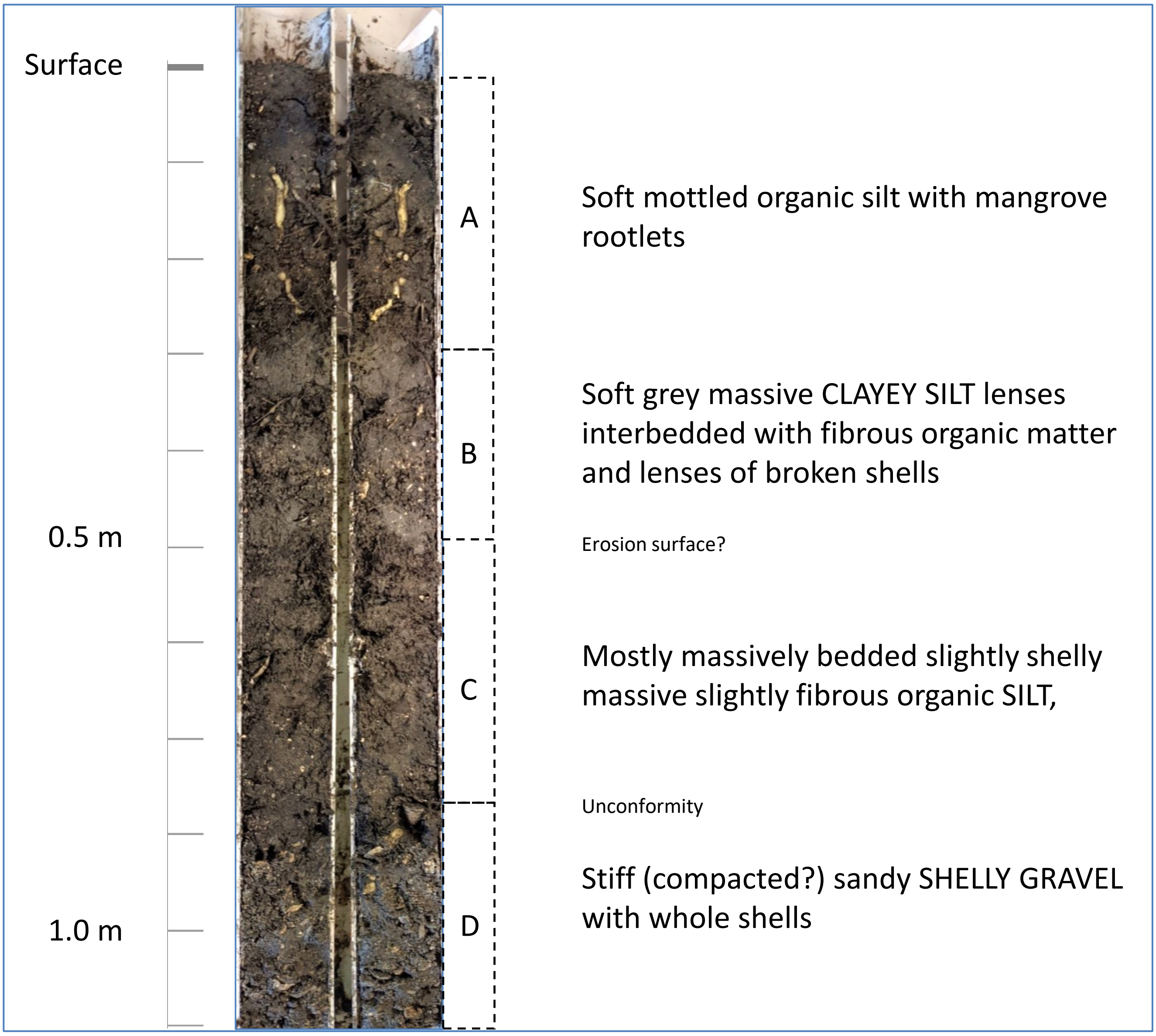

Figure 125. An unpublished 1 m-long core in the sediments in the easternmost nascent mangrove area showing 6 or 7 sedimentary units (ECU, pers comm.) with bioturbation (sediment mixing by biological organisms) throughout. Modern roots extend down to a depth of 0.25 m and organic matter occurs throughout the upper 0.45 m. Overall, there are layers rich in whole and broken shells interbedded with uniform grey, silty units.

9.3.2.1. Sedimentary concepts and key changes

The essential concepts about the nascent mangrove area are as follows.

- Processes – waves drive processes at the beach especially at high tide and during positive surges, sediment settling occurs on the flats at high tide enhanced by shelter from the mangrove fringe, seaward flows are associated with the relaxation phase of positive surges, there will be episodic erosive events (including cyclones), and effects will be minimal from freshwater runoff;

  - **With SLR**, most of these processes are likely to be changed. The seaward edge of the fringing mangroves will be subject to increased waves (assuming that bed elevation will not keep up with SLR) and might be less likely to recolonise. (Some core data would help understand the past record of coastal response to changing sea level). The coastline is more vulnerable to storms and coastal erosion, but all coastal components have some ability to move landward.
  - **With SLR plus ponds**, the tidal exchange will be reduced, leading to a smaller tidal system more vulnerable to closure, and further reduced during episodic events because of the smaller catchment for freshwater runoff and the smaller volume of water flowing back to sea during the relaxation phase of positive surges.
- Sediment sources – these are limited, and may include marine sediments, in-situ shell and organic production, settling of suspended material at high tide, some sand locally reworked or derived from erosion of the barrier's face and the low sandy islands, including internal reworking within the 40 Mile Road W catchment, and from the spit in the eastern part;
  - **With SLR**, there may be enhanced reworking of internal sources and increased chance of marine material entering the tidal creeks. It is unlikely that bed elevation will keep up with SLR, so that overall, the catchment will undergo drowning.
  - **With SLR plus ponds,** sediment supply from the 40 Mile Road W catchment will cease, so that marine sources and internal reworking of the barrier face become highly significant in terms of whether the bed elevation will keep up with SLR. It is unlikely that they will. Overall, the tidal creek systems might be more vulnerable to closure, and only a small volume of sediment would be required to close these small tidal entrances with a reduced catchment size.
- Sediment transport pathways – creek, waves and tides through the mangroves at high tide;
  - **With SLR**, waves become more important and tides very slightly less important.
  - **With SLR plus ponds,** waves become more important and tides much less important.
- Sediment stores & sinks – mangroves, back-barrier basins;
  - **With SLR**, the low areas in the 40 Mile Road W landward of the segmented barrier and especially landward of the older deflated dunes may become more likely to accumulate sediment.
  - **With SLR plus ponds**, the basin directly front of the pond walls (contains benthic mats on Figure 120) becomes likely to receive and accumulate some sediment, especially if the tidal creeks migrate landward towards the pond walls;
- Risks/Constraints/Limitations – short catchment, limited in elevation, vulnerable to storms and coastal erosion;
  - Habitat connections – limited with ponds in place.
  - Disturbance events – no perceived impediments to recolonisation apart from at the mangrove fringe.

9.3.2.2. Other factors

Over the next century, with the ponds emplaced and operating, the nascent mangroves area is predicted to experience an increase in groundwater salinity throughout, reaching an increase of over 210 g/L (Figure 111). This may be a factor in influencing BCHs in this area. In general, mangroves thrive in water salinities close to seawater, can have reduced canopy heights in higher salinities (Perri *et al.*, 2023) and can die in groundwater salinities above 60-70 g/L (Susilo, 2004). Where studied in the Pilbara, mangroves tend to occur only where groundwater salinity is below 90-100 g/L (Semeniuk, 1996).

9.3.2.3. Assessment - qualitative

The above assessment leads to a suite of possible qualitative outcomes for this area (Table 20). This table notes that there is the possibility of some drowning of the area over the next century, without or without the ponds.

Table 20. Range of possible outcomes for nascent mangrove BCHs. 'Change' refers to net change in area of habitats, e.g., loss by a cyclone, gain through coastal progradation.

General nature of change	Least 'change'	Favoured assessment at present	Most 'change'
Past natural (geological & historical)	Little change since 1968 or so	Past phases of erosion with subsequent progradation, i.e. habitat resetting. Some headward creek expansion related to SLR in last few decades	Event - Mangrove fringe removed by cyclone, disruption and some loss of samphire and benthic mats
Comments on timing			Can happen at any time, but no evidence for erosive event since 1968
SLR	Whole system raised in elevation matching SLR (very unlikely) Little net change	Mangrove fringe erodes, with some losses balanced by landward advance of estuarine mangroves. Samphire & benthic mats reduced but large areas remain E of the deflated dunes	Erosion back towards sandy barrier, by SLR plus erosive event(s). Mangrove fringe removed by cyclone, and reduced capacity for habitat migration. Major loss of fringing mangroves and some temporary disruption of benthic mats
Comments on timing	Gradual over several decades and more	Gradual with some events	Gradual over several decades and more, can be exacerbated by episodic event at any time
SLR PLUS PONDS	Progradation of mangrove fringe and increase in area of mangroves and associated habitats. Increase in mangrove density.	Whole system begins to drown because bed elevation does not keep up with SLR. Substantial reduction of areas of benthic mats and samphire because of their cover by ponds.	Erosion back towards sandy barrier with little capacity for headward creek expansion and habitat migration. Major loss of fringing mangroves. Wave-associated disruption of benthic mats near the pond walls, but no major impediments to recolonisation. Closure of tidal creek entrances.
Comments on timing	Likely to be initiated after first major surge and/or runoff event with sediment supplied by McKay Ck mouth	Drowning likely unless sediment is supplied from seaward by waves and/or from McKay Ck.	As above plus accelerated by pond-wall effects

As noted throughout this report, there is little information with which to infer rates of change such as coastal progradation, but for the area in front of the barrier, aerial photographs and coastal change data indicate that the fringing mangroves have been present to seawards of the segmented barrier for all of the 55 years of the coastal record (section 6.2.4). This allows an upper bound to be placed on the rate of coastal progradation following the formation of the barrier. This upper bound is 4.9 m per year (i.e., 270 m over 55 years). Volumetrically, this sediment body is roughly 2 m thick, 200 m wide and runs along 1500 m of the coastline, thus representing 6 x 10^5 m^3 of material. Over 55 years, this would mean a maximum annual supply rate of 11,000 m^3/year, a rate that is not completely out of the question, and which might imply some resilience in the coastal system. To emphasise, this evaluation only aims to estimate an upper bound, because aerial photographs indicate that the mangrove fringe has not apparently prograded over the period 1968 to 2023. A previous report (O2 Metocean 2022a) had used the Geoscience Australia (2023) dataset to derive some measures of possible coastal recovery rates following erosive events, noting the high level of complexity of the coastal system.

9.3.2.4. Assessment – quantitative

The result of the effect of the ponds on the BCH (as a % of the defined area, meaning the whole defined catchment) is illustrated in Figure 126.

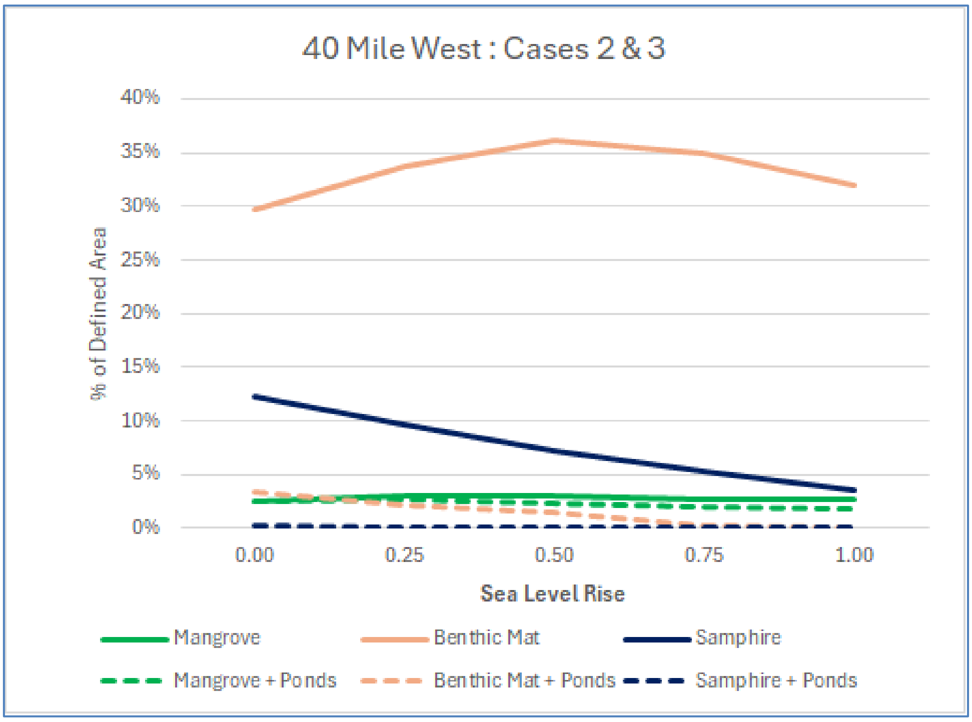

*Figure 126. Case 2 - **'SLR plus sedimentary response'** case (solid lines) and Case 3 - the '**SLR plus sedimentary response plus ponds'** case (dashed lines) for the 40 Mile Road W catchment. The difference between solid and dashed lines is an indication of the changing effect of the ponds through time.*

Key points of note are as follows.

- Considering a theoretical scenario (Case 1 above) where habitat migrates with elevation would indicate a large proportional increase in mangroves from around 2.5% to 20% (via occupying the flats), with overall small reduction of benthic mat and samphire habitats if they were to migrate towards steeper ground. **Very Low Confidence.**
- The modified response to SLR (Case 2), considering sediments and creek structure suggests limited capacity for mangroves to migrate, with mangrove coverage projected to increase, initially increasing from 2.5% to 3.0%, then reducing to 2.7% due to lower mangrove viability at the seaward edge. The effect of ponds is to limit the small landward migration of mangroves, giving a reduction from 2.5% to 1.7%. These numerical changes are well within the bounds of uncertainty, but the general theme is little significant change. **Low to Moderate confidence.**
- Also for Case 2, the mangroves are not migrating across the flats as much, which instead supports increased benthic mat coverage, with initial increase from 30% to 36%, before a decline to 32% due to reduced viability at both the lower (eroding) and upper (less horizontal) parts of the habitat. Samphire

is projected to progressively decline from 12% to 4%, due to benthic mat migration into the existing habitat, as well as reduced viability of the upper part of the habitat due to steepness and fewer basins. **Moderate confidence.**

- The ponds (Case 3) cover a large proportion of this catchment and greatly decrease the area available for BCHs. Existing fringing mangroves are seaward of the ponds, and are projected to have limited impact on habitat, reducing coverage from 2.5% to 1.7%. A substantial proportion of benthic mats and all existing samphire habitat will be included inside the pond areas, and therefore these BCH will experience decline. The remnant proportion of benthic mats is projected to reduce from 3% to 0% with sea level rise, replaced by mangroves. These numerical changes are well within the bounds of uncertainty, but the general theme is little significant change. **Moderate confidence**.

9.3.3. Pond perimeters

Whilst the pond walls are themselves designed to resist hydrodynamic forces, areas near the pond walls are potential locations of changed sediment erosion, throughput and accumulation, because the presence of the walls changes the natural pattern of some flows. This section precedes discussion of McKay Creek, because there are implications relevant to the interpretation of McKay Creek's sedimentary changes.

Hydrological modelling outputs produced water elevation, local water depths and current speeds at the pond's perimeters. With the ponds of scenario 7.2.1, the areas with the greatest depths at pond walls are near the coast, and highest speeds occur along the channel reaches where confined by the pond embankments (Figure 127, Figure 128). For the 1% AEP case (i.e., the 1:100-year event), the maximum inundation depth is 4.3 m, and the maximum 1% AEP speed is 1.2 m/s (Table 21). For the same event probability, greater flow depths occur with storm surge and climate-change scenarios, but greater flow speeds occur without storm surge – this is logical because without a surge there is a greater seaward slope to the water surface.

Table 21. Summary of maximum (and average) flow depths and speeds around pond perimeters (Land and Water Consulting, 2023a). The bottom section of maximum speeds is of most use regarding sediment transport.

Pond Area	1EY	10% AEP	5% AEP	2% AEP	2% AEP + Storm Surge	1% AEP	1% AEP + Storm Surge	1% AEP + Storm Surge and Climate Change
Average Depth around Pond Area Perimeter (metres)								
Western	0.02	0.18	0.29	0.50	0.52	0.64	0.67	0.84
Central	0.03	0.34	0.44	0.59	0.64	0.68	0.74	0.89
Eastern	0.01	0.12	0.19	0.34	0.42	0.46	0.55	0.77
Maximum Depth around Pond Area Perimeter (metres)								
Western	0.66	1.53	2.01	2.46	2.46	2.68	2.69	2.88
Central	0.78	2.79	3.28	3.80	**3.80**	4.07	4.07	**4.28**
Eastern	0.62	1.66	2.20	2.80	2.80	3.11	3.11	3.33
Average Velocity around Pond Area Perimeter (metres per second)								
Western	0.00	0.03	0.05	0.07	0.07	0.09	0.09	0.10
Central	0.01	0.08	0.08	0.09	0.09	0.10	0.09	0.09
Eastern	0.00	0.03	0.03	0.05	0.04	0.05	0.05	0.06
Maximum Velocity around Pond Area Perimeter (metres per second)								
Western	0.08	0.76	0.86	1.00	1.00	1.08	1.08	1.17
Central	0.29	0.89	0.93	**1.05**	0.97	1.10	1.00	1.04
Eastern	0.05	0.76	0.92	1.05	1.05	1.13	1.13	**1.23**

The model outputs indicate flows fast enough to transport gravel and coarser particles.

As for the speeds in the creeks and in constrictions between pond walls, especially through McKay Creek, it is also relevant to understand the possible time-series of flow from the rainfall events, not just the maximum speeds. This is because bed shear stress varies with speed and flow depth, so that it may not be the deepest or the fastest flows that are most significant in terms of erosion and sediment transport. Further, sediment transport will be partly dependent upon sediment availability before and during the flow event – it is possible that in places local mobile sediment is all removed relatively early in a flow event so that the latter parts of a flow might not actively transport much sedimentary material. Therefore, knowledge of the local sediment nature, size and thickness (e.g., Figure 129) is advantageous to assessing potential transport and thus potential morphological change at and near the pond walls.

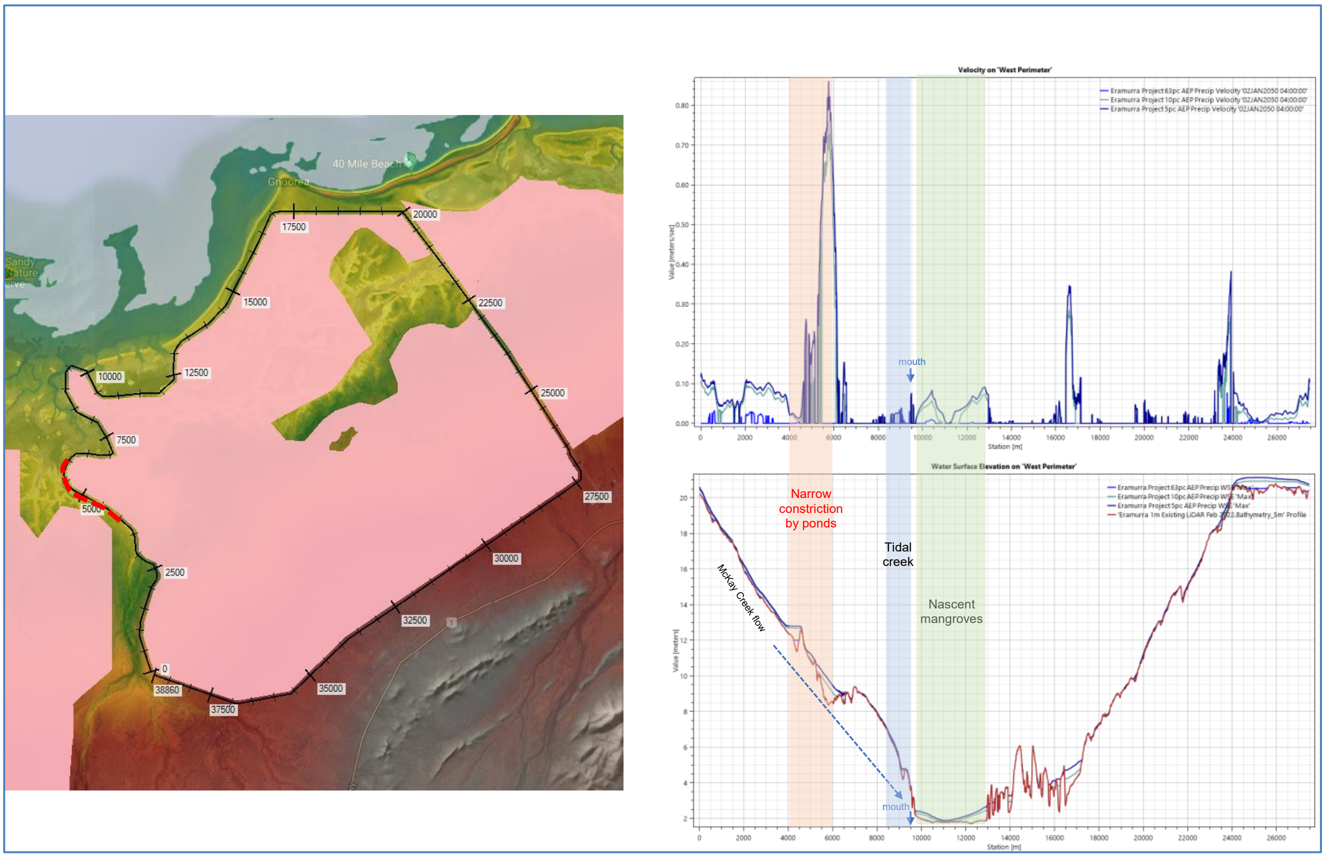

Figure 127. Modelled current speeds and elevation along the perimeter of the western ponds (modified from Land and Water Consulting 2023a) for 1EY, 10% AEP, and 5% AEP events.

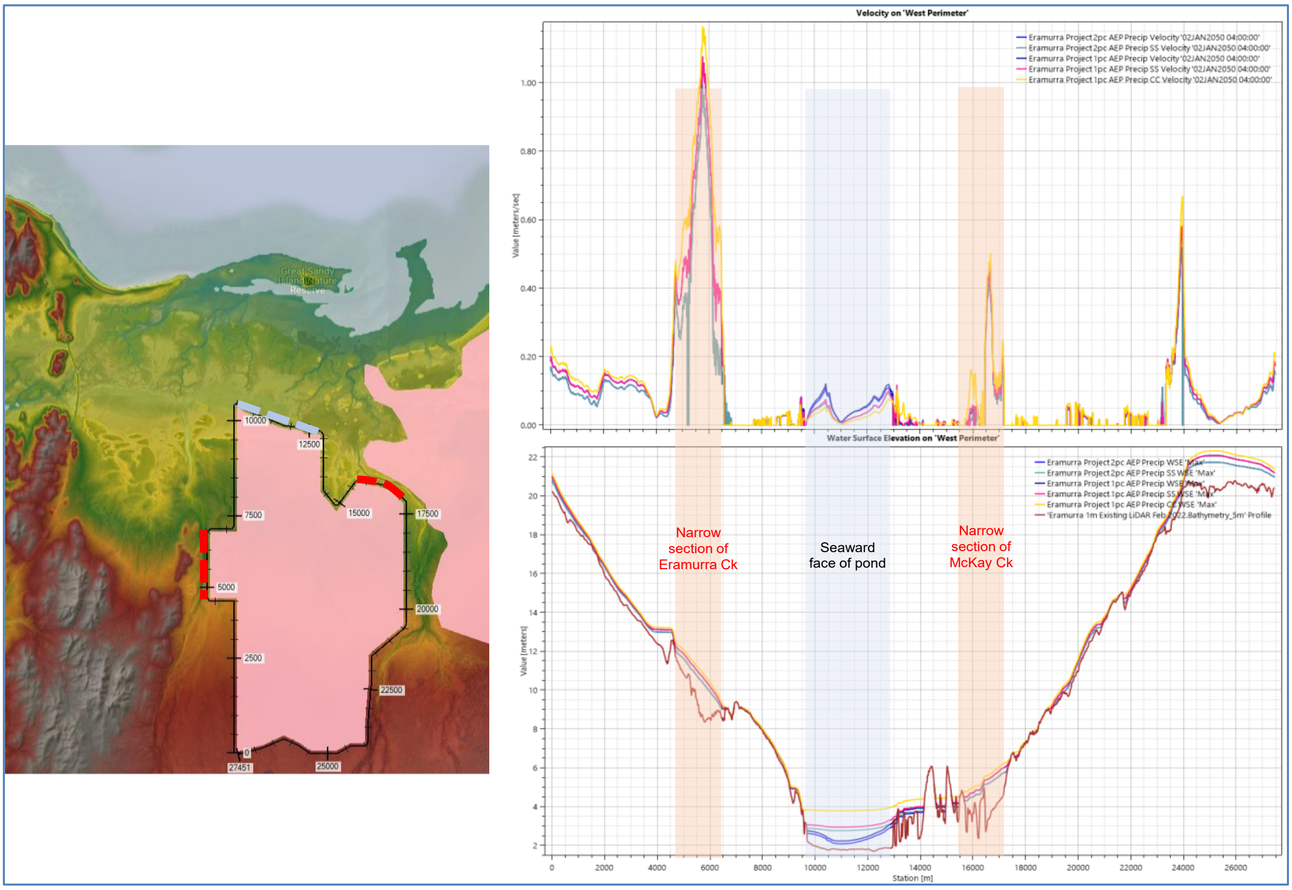

Figure 128. Modelled current speeds and elevation along the perimeter of the western ponds (modified from Land and Water Consulting 2023a).

A key issue is the lack of time-series data on individual events, as per section 10.4. Some examples of each scale for each of the three major creeks and/or the entire area would be very helpful in assessing the potential for sediment limitation to occur, either through exhaustion of the available sediment or by sediment armouring.

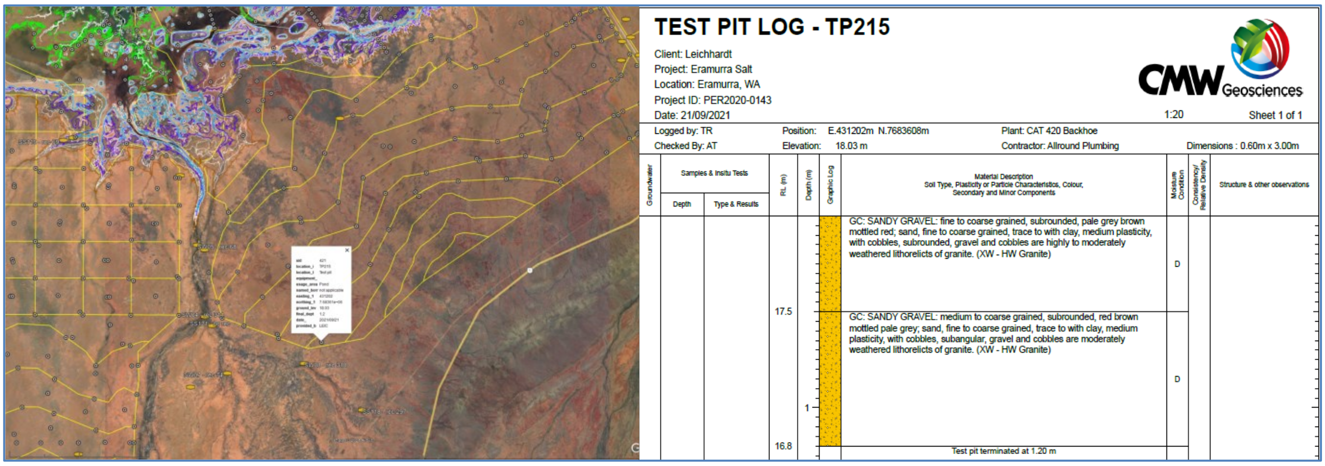

Figure 129. Sediment log for test pit TP215 at the landward edge of the proposed central ponds. The sandy gravel totals 1.2 m in thickness, with the upper unit containing a component of fine sand that is absent in the lower unit. The pit terminated in granite. (Core log from CMW Geosciences 2022).

9.3.4. McKay Creek system

The McKay Creek system encompasses a river catchment of 291 km^2 (Figure 33) that has a distinct delta, beyond which are wide tidal flats, mangrove systems, the complex dynamic tidal creek system itself, and the area to seawards and along the adjacent shoreline that influences and is influenced by the catchment's dynamics (Figure 130).

The tidal section of the McKay Creek catchment has a Vs:Vc ratio of 3.1 that with pond emplacement would be reduced to 2.9 (Figure 26). This reduction indicates a slightly reduced ebb tide and capacity to maintain tidal creeks being open.

Landward to seaward, there are a range of relevant elements of the sediment transport system, each has different sediment types, grain sizes, thicknesses and potential mobility, all of which are relevant to interpreting modern processes and possible future change (e.g., section 6.3.3. including Table 8, and section 6.6 including Table 13). This report focuses on what are assessed to be the key aspects. The river catchments have ample sediment available, of clays, silts and sands, with key processes being freshwater runoff, especially the infrequent events of intense rainfall. The river channels and overbanks deposits have an unknown thickness of gravelly sediments, and the channel beds have some areas where bedrock is exposed. Therefore, there is material available for transport towards the delta front and the tidal flats, given sufficient freshwater flow.

On the tidal flats themselves, there are sources of sand in the sand plains and deflated dunes, plus calcareous gravels sand and some clay, but these deposits are rarely more than a few decimetres thick. At the coastline, the coastal dunes attain several metres in height. Therefore, there is sand available for transport in various areas of the coastal plain, but with low local availability across large areas. Relative to sand, there are relatively large volumes of muddy sediments available, with 1 to 1.5 m of muds on the intertidal flats and mangroves areas, with more presumed sandy sediments in the intertidal areas seawards of the present coastline.

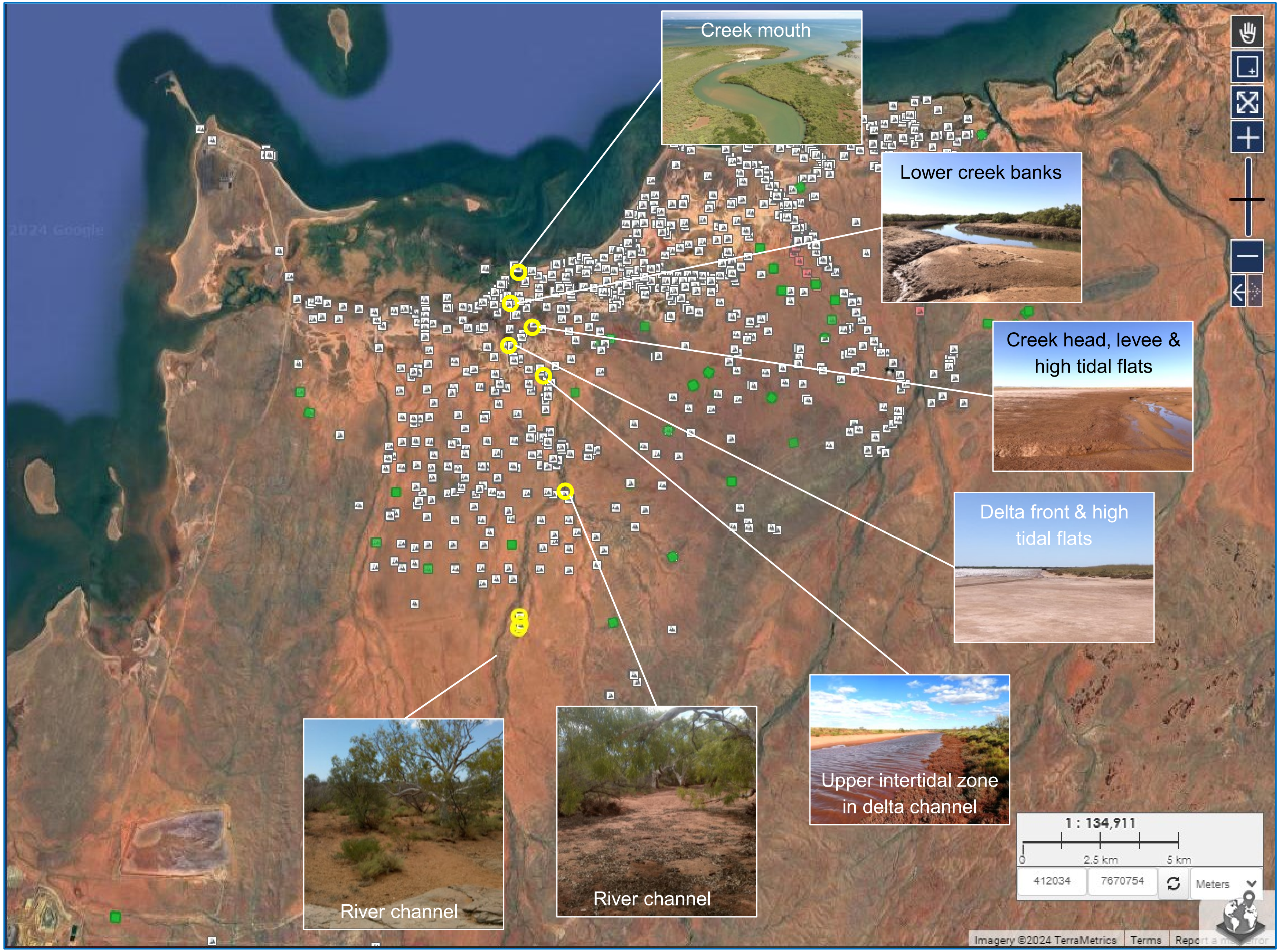

Figure 130. Selected sedimentary environments of the McKay Creek catchment and associated tidal creek system (photos from CMW Geosciences, 2022).

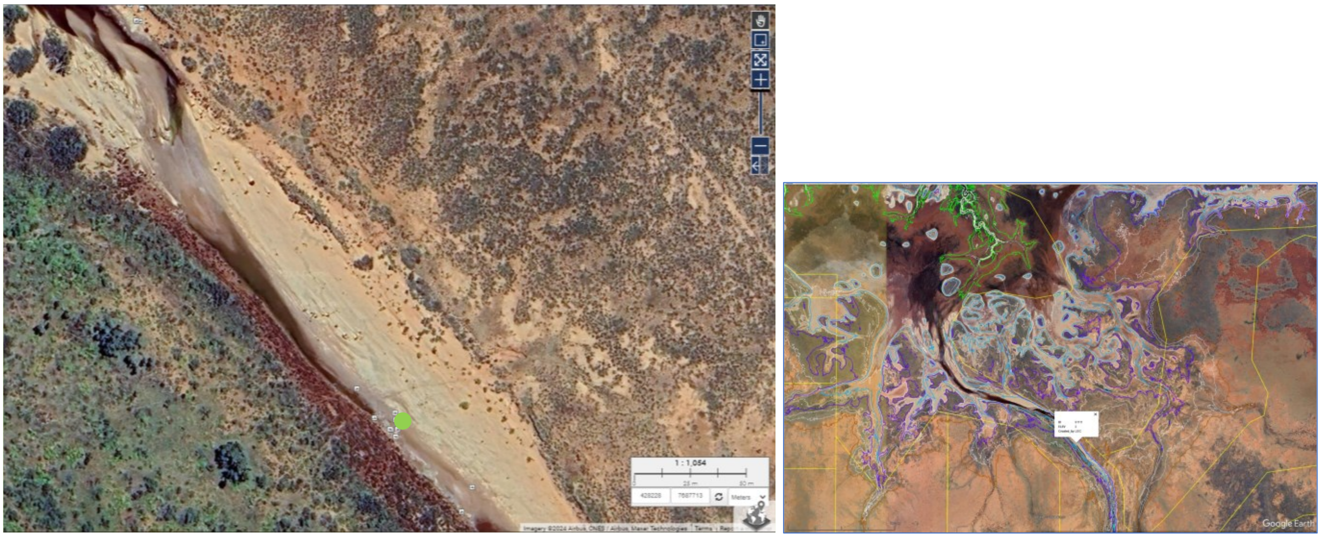

Figure 131. LEFT – Aerial photo of the channel of McKay Creek at 2 to 2.5 m AHD with multiple sediment tails developed seawards of vegetation. Green dot is location of image in Figure 132. RIGHT – Aerial photos of the lower McKay fluvial system and delta front. White label is location of detailed image to left. (Photos from CMW Geosciences, 2022).

Figure 132. Photo looking seawards within McKay Creek fluvial channel of a sediment tail (comet mark) downstream of vegetation. This is evidence of active seaward transport of sand across a lag surface. (Photos from CMW Geosciences, 2022).

9.3.4.1. Sedimentary concepts and key changes

The essential concepts about the McKay Creek system are as follows.

- Processes – Freshwater runoff drives processes in the catchment and down the rivers. At the delta front, there is a drop in flow competence and a rapid transition into lower energy conditions, that may be modulated by the height of the tide during the river flood event. If at low tide or a falling tide, the river flow may continue across the tidal flats and feed the creek system relatively directly. In the absence of river flow, some lower parts of the delta's channels are inundated by spring tides. The tidal flats are generally low-energy areas, but may undergo wave action at the margins at high tides and across large areas with winds from certain directions. Positive surges may lead to deep water and relatively fast currents on the flats. Generally, tidal currents on the flats will be weak, and will only be faster near creeks, especially on the ebbing tide in the creeks themselves. Similarly, currents in the creeks may be fast with the relaxation phase of a positive surge. In the delta-front creeks, tidal currents will be weak and only occur on the higher spring tides, and there will be episodic fast seawards flows of the river.
    - **With SLR**, many processes will be modified. The seaward edge of the fringing mangroves will be subject to increased waves, assuming that bed elevation will not keep up with SLR. Tidal flow through the tidal creeks and the overbanks estuarine mangrove areas will be less ebb-dominated. Mangrove creeks will slowly migrate landward, controlled by the availability of material to accumulate at their edges and on their levees on the shallow-gradient high tidal flats. The whole system, from the fringing mangroves through to the head of the active tidal creeks, will tend to migrate landward across the low-gradient tidal flats towards the cemented rocks at the delta front. Some degree of drowning of the system will occur, including the lower parts of the delta channels, where the present series of riffles and pools will sequentially evolve, cascading landward, to become more continuous pools infilling from the seaward side, at least during dry periods without river floods.
    - **With SLR plus ponds**, whilst the tidal exchange will generally be less because of changed hypsometry, the channel formed between the western and central ponds will tend to concentrate ebb flow and river flow towards creek heads, probably enhancing headward creek cutting.
- Sediment sources – Energy levels in most places are sufficiently high to transport mud where available, so that accumulation of mud is generally possible anywhere whenever there are sufficient periods of low energy, enhanced and/or stabilised in places by biological factors such as roots and benthic mats. Muddy material may enter the system from the marine side where resuspended from the seabed and reworked from fringing mangrove deposits, and moved through the mangroves by flood tide currents, enhanced if associated with surges and hence waves. Muds will also be supplied by the river catchment and will tend to deposit on the tidal flats. Fluvial sands are mostly deposited at the delta front, but large rainfall events may transport mud and sand directly across the tidal flats into the tidal system and potentially to the marine environment. The tidal creek system reworks some material internally, through lateral creek migration, that releases muds and sands. Fluvially derived sands deposit at the delta front, and sands in the tidal creeks will tend to be confined there, and at times transported seawards by overbank ebb tides, the relaxation phase of positive surges and with large rainfall events. McKay Creek is similar to other creek mouths along the shoreline (especially Baldy/Straight Creek mouth) in having bodies of mobile sand close to the creek mouth, so that the creek mouth may be restricted at times by migration of intertidal sand bars (section 7.1 of O2 Metocean 2022a).
    - **With SLR**, assuming no major accumulation across the system, the tidal hypsometry is slightly changed to generate more overbanks tides each year, so that creek head expansion and creek incision might also increase, as might accumulation of mud on the tidal flats. The effects of waves might increase so that there may be some periods of ingress of sandy sediments from the lower intertidal flats (seawards of the present coastline) into the lower parts of the tidal creeks, and formation of sand bars at the mouth. The fringing mangroves might be disrupted at their seaward edge, and other muddy areas on the creek banks and flats will tend to move

material landward. Most accumulation on the tidal flats near the creek heads will be muddy. Sands will remain mostly confined to the incised creeks. The fluvial source will largely be unchanged, but there may be a slightly greater tendency for accumulation of fluvial sands at the delta front due to the decrease in flow competence as the river more often meets the tide.

  - **With SLR plus ponds**, the tidal hypsometry is slightly changed so that the Vs:Vc ratio reduces from 3.1 to 2.9, to reduce the effect of sand flushing down the creek and thus channel maintenance, so that there may be some slight ingress of sandy sediments from the lower intertidal flats into the creek mouth. This change is not significant – the tidal system will remain ebb-dominated in the incised channel, driven by overbank tides. Transport of mud landward across overbank muddy areas is likely to increase, as will headward creek and levee extension. The western ponds may reduce freshwater and sediment input to the main McKay Creek delta front (Figure 34, Figure 46). There is likely to be some enhanced erosion and seawards sediment throughput between the western and central pond walls, and overall, there may be increased sand accumulation near the delta front. The broad tidal basin between the delta front and the head of tidal creeks might be largely drowned and also slowly constricted by sands from the south and muds from the north.

- Sediment transport pathways – the likely main pathways (noted above) are interpreted from the flow measurements, the hypsometry, the hydrodynamic modelling and geomorphology. Their sedimentary connectivity has not yet been tested by sedimentary gradients. Of particular importance are the pathways of clay, silt and sand down the McKay Creek fluvial system towards the McKay tidal creek (plus the adjacent Baldy/Straight Creek tidal catchment and the most seawards part of the 40 Mile Road Creek W catchment), as is the connectivity of the sandy sediments from the tidal creeks with the material at the creek mouths and along the shoreline.
  - **With SLR**, the potential sedimentary link from the river through the tidal creek to the sea might be reduced (assuming no significant change in long-term river discharge patterns) by some trapping on the high tidal flat basin. Assuming bed elevations in the lower intertidal zone do not keep up with SLR, longshore sand transport might be modified by a combination of increased waves and water depths, but with an uncertain response.
  - **With SLR plus ponds**, the main pathways will be maintained in their locations, with some enhanced (muds landward though the mangroves, muds, sands and gravels seawards between the ponds) and some slightly reduced (sands seawards down the tidal creeks).
- Sediment stores & sinks – the main temporary stores (order of centuries to several thousand years) are the patchy thin unconsolidated sediments on the tidal flats and sand plains, the thicker, muddy sediments in the mangroves and associated with the active tidal creek systems, and the sand and gravel in the river channels.
  - **With SLR**, the landward portions of the active tidal overbank areas will increase in storage potential, mostly of mud, and the high tidal basin near the delta front and reaches of the newly inundated riverbed both have increased potential of sediment storage, temporarily of mud but of sand closer to the delta front.
  - **With SLR plus ponds**, the above general pattern will occur, but some rates might be different. The narrowed area between the ponds might become a source, as might some areas elsewhere around the pond walls.
- Risks/Constraints/Limitations – the overall McKay Creek system is large, dynamic and has resilience including through internal sedimentary responses.
  - Habitat connections – with SLR, with or without the ponds, it is possible that mangroves will be slow to cross the tidal flats towards the delta front, limited perhaps by slow accumulation of mud near the creek heads, and thus slow to colonise any potential new habitats on the margins of the drowning delta channels. It is likely that benthic mats will persist in the slowly contracting basins.
  - Disturbance events – there are no major perceived physical impediments to recolonization.

9.3.4.2. Other factors

Over the next century, with SLR and the ponds emplaced and operating, some portions of the McKay Creek system are predicted to experience an increase in salinity. Most notably, the western side of the narrowed channel between the western and central ponds, and the area of tidal flats seawards of the western ponds reaching an increase of over 210 g/L (Figure 111). This may be a factor in influencing BCHs in this area, especially the viability of mangroves (section 9.3.2.2).

9.3.4.3. Assessment - qualitative

The above assessment leads to a suite of possible outcomes for this area (Table 22). Overall, regarding gradual changes, the concept is that SLR is most likely to drive landward migration through movement of muddy sediments, and most likely, through headward expansion of the active tidal creeks. This will be modified by the effects of episodic events, especially high intensity river floods and positive surges. There is likely to be a degree of drowning of the system, with or without the ponds.

At its tidal limit the McKay Creek system includes some creeks flooded by the highest tides, and landwards of the delta front, the main fluvial creek is tidal for ~3.5 km landward to creek. This creek contains a series of fluvial pool and riffle features, housing extensive benthic mats and several large areas of samphires. With 1 m of SLR, a further 900 m of the creek will become tidal and potentially house similar BCHs, but as at present, these will be ephemeral in nature.

9.3.4.4. Assessment – quantitative

The result of the effect of the ponds on the BCH (as a % of the defined area, meaning the whole defined catchment) is illustrated in Figure 133. Key points of note include that:

- Considering a theoretical scenario where habitat migrates with elevation (Case 1) would suggest a large proportional increase in mangroves (Table 23) from around 5% to 23% (via occupying the flats), with a corresponding reduction of benthic mat and small reduction of samphire habitat. **Low confidence.**
- The modified response to SLR, considering sediments and creek structure indicates that mangroves may increase in coverage over the next century (Table 23) from ~5% to 9% without ponds (Case 2) and up to 7% with ponds (Case 3). **Moderate confidence**.
- For Case 2, as the mangroves advance across the tidal flats, they replace large areas of benthic mats, so these mats decrease over time, from 32% to 22% of the creek area. **Low to Moderate confidence**.
- With ponds (Case 3), most of the existing benthic mats are covered by the ponds. The remnant 12% of benthic mats is projected to decrease further with SLR due to limited habitat viability (because of the influence of advancing sediments and mangroves, and the restriction on landward migration of steep bed slope) and they may disappear from this catchment. **Low to Moderate confidence**.

Also for Case 3, Changes in samphire are unrelated to sedimentary changes, being restricted by SLR and the low availability of suitable habitats at the rear of the tidal flats and up the main fluvial channel. They will be substantially covered by the ponds, which would reduce existing samphire area from 11% to 2.5%. **Moderate to High confidence**.

Table 22. Range of possible outcomes for changes to McKay Creek. 'Change' refers to net change in area of habitats, e.g., loss by a cyclone, gain through coastal progradation.

General nature of change	Least 'change'	Favoured assessment at present	Most 'change'
Past natural (geological & historical)	Most of the main channel structure hasn't responded substantially. Some sandy sediment expelled from the delta mouth as a fan.	Some observable local changes since 1968, including some headward creek expansion. Most change consistent with the past trajectory of SLR.	Mangrove colonisation and secondary creek development in the head section.
Comments on timing	No evidence for change by a major episodic event since 1968.		
SLR	Whole system raised in elevation matching SLR (Very unlikely). Little net change.	Partial drowning of the system as most bed elevations do not match SLR. Mangrove loss at the mouth partly offset by colonisation at creek heads. Samphires have variable response, including some constriction at delta front and some expansion along delta channels. Benthic mats decrease slightly in the basin and migrate up the delta channels.	Major loss of fringing mangroves, disruption of estuarine mangroves with little headward expansion. Partial drowning of high tidal flats reduces extent of benthic mats.
Comments on timing	Gradual over several decades and more	Gradual with some disruptive events, especially in the delta channels	Gradual over several decades and more, exacerbated by episodic event at any time
SLR PLUS PONDS	Whole system raised in elevation matching SLR (Very unlikely). Headward migration of habitats broadly matches loss by coastal erosion.	As above but plus some modification by greater sediment redistribution associated with pond-wall-associated changes in freshwater flows. Greater temporal variability in areas between the western and central ponds.	Major loss of fringing mangroves and disruption of estuarine mangroves. Increased activity of delta channel beds increases frequency of habitat resetting and reduces capacity for recolonisation after fluvial events. Wave-associated disruption of benthic mats near the pond walls. Increased salinity restricts mangrove recolonisation.
Comments on timing	Gradual over several decades and more, might be associated with surges and fluvial supply events	Gradual with some disruptive events, especially in the delta channels and between the pond walls.	As above

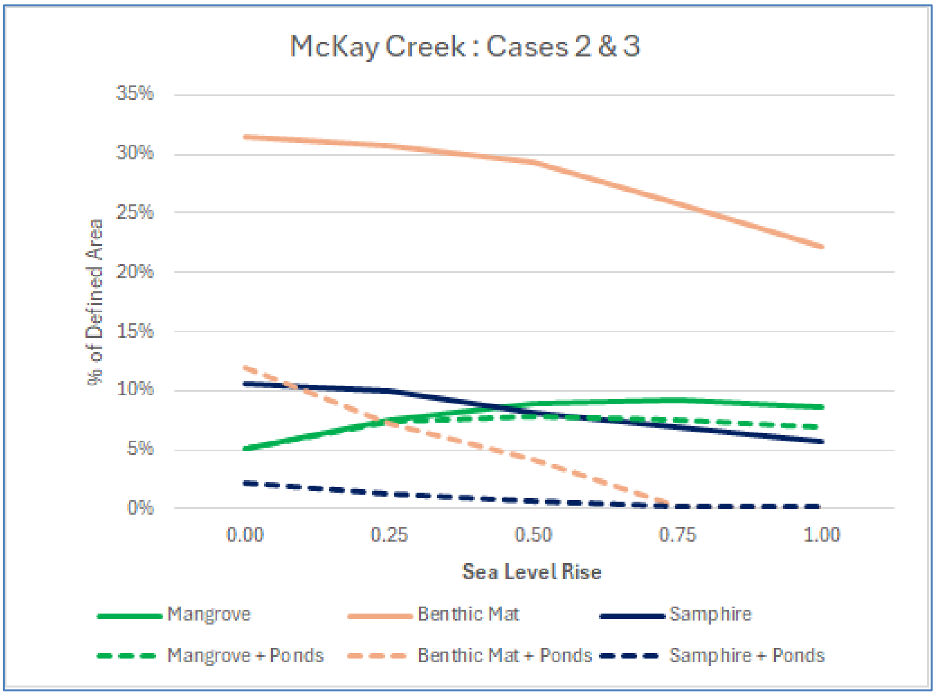

*Figure 133. Case 2 - **'SLR plus sedimentary response'** case (solid lines) and Case 3 - the '**SLR plus sedimentary response plus ponds'** case (dashed lines) for the McKay Creek catchment. The difference between solid and dashed lines is an indication of the changing effect of the ponds through time.*

Table 23. Data plotted for the mangroves in Figure 133.

Mangroves	**Magnitude of SLR (m)**				
	0	**0.25**	**0.5**	**0.75**	**1.0**
Case 1	2.6 %	5.4 %	10.5 %	15.3 %	20.5 %
Case 2	2.5 %	3.0 %	3.0 %	2.8 %	2.7 %
Case 3	2.5 %	2.6 %	2.3 %	2.1 %	1.7 %

9.3.5. 40 Mile Road E, Creeks 7 & 8

Note that the hypsometry of these creeks would all be changed with pond emplacement. At present, 40 Mile Road E catchment has a Vs:Vc ratio of 3.8 that be reduced significantly to 3.2 with ponds, the Creek 7 ratio would reduce from 3.1 to 2.8, and Creek 8 would reduce from 3.0 to 2.8 (Figure 26). In terms of tidal flow only, all these catchments would have a reduced ebb tide and weakened capacity to maintain tidal creeks being open.

The catchments of 40 Mile W and E are large and complex and are located behind the rocky promontory of Gnoorea Point and the associated sand spits to its west. Before the construction of the 40 Mile Beach access road, the catchments were connected at an elevation of 2 m AHD, but this is now constrained by the road and associated culverts (Land and Water Consulting 2023a, their Appendix C). Taken together, these geological and human factors tend to support an argument that their Vs:Vc ratios will not necessarily reflect the tidal processes of today. It is conceivable that both catchments might be in the geological process of adjusting to changes in sea level in the last few thousand years, either the rise in sea-level up to around 6,000 years ago or the fall of ~1.5 m since ~6,000 BP (Ward *et al*. 2022) and/or to past periods of intense rainfall in the catchments (Rouillard *et al*. 2016). Nonetheless, the high ratio for 40 Mile Road W is consistent with the presence of nascent mangroves at its mouth. Such young mangroves do not occur elsewhere along the ESSP coastline, and they indicate a past episode of sediment delivery and accumulation in the lower intertidal zone, which has been suitable for colonisation by mangroves, i.e., an episode of coastal advance, the timing of which is unknown at present, but occurred before 1968 (section 6.6.4.1).

These systems occur behind a wide (500 to 800 m) vegetated sand barrier up to 5 m high (Figure 134, Figure 135). On the seaward side of the barrier are stands of fringing mangroves 100 m wide, that occupy the elevation range 0 to 1 m AHD, behind which lies a storm beach. The existing tidal channels are incised deeply through these barriers (Figure 136) and are unlikely to greatly alter their location. Overall, this barrier has a high degree of stability, and the only indication of past change is a low feature in the barrier segment west of Creek 7 that appears to represent an infilled channel (Figure 137).

Figure 134. Oblique aerial photograph looking east, of the creek mouth that drains 40 Mile Road E catchment and the intertidal flats, fringing mangroves and sand barrier in front of the Creek 7 and 8 and Yanyare catchments. Note that the intertidal area in front of the Creek 7 is wider than elsewhere, indicating past and/or present greater supply.

With SLR and no significant change in sediment levels, the width of the fringing mangrove area will decrease greatly and perhaps be removed almost entirely, because its landward migration is heavily restricted by the barrier. Thus, reworking of the barrier sand by waves and natural adjustment of marine sediments at the coast will be a significant factor in the future development of the fringing mangroves.

Creeks 7 & 8 are very similar in their hypsometric shape (Figure 27), with the lines on the log plots strongly parallel – these systems are likely to operate in a similar way regarding tidal flows. Creek 7 has a larger ebb tidal delta (at least as inferred from its wider mangrove fringe) and its flood delta sits in a shallow basin, indicating formation that might have involved some head-cutting around the delta perimeter (Figure 137). On the western end of 40 Mile Road E, and along the southern margins of Creeks 7 & 8 are many comet marks, indicating erosive and/or translational areas, with the marks indicating downslope flow of freshwater runoff into the back-barrier basin.

To the west, the mouth of 40 Mile Road E shows a prominent flood-delta shape (Figure 137, Figure 138), indicating some sediment supplied from the marine environment into the basin. However, this feature might also be in part internal reworking of older barrier-related and deflated dune sands.

All these three catchments (40 Mile Road E, Creek 7 and Creek 8) have large areas of low gently undulating ground, forming several shallow basins (Figure 138), which are occupied by benthic mats and fringed in places by samphires. Mangroves are present at the coast as fringing mangroves and as estuarine mangroves along the small tidal creeks. These systems will be further constrained at their rear (south) by the proposed salt ponds that may limit landward migration of environments. Therefore, the effects of a SLR of 0.9 m in changing the location of HAT is very important, as are additional effects of the walls, altering hydrodynamics and sedimentation during spring tides, surges and rainfall events. Groundwater salinity is expected to increase markedly along the pond wall margins (Figure 111) that may affect BCH response to SLR.

Figure 135. A narrow band of active eolian dunes on the barrier fronting the basin of the 40 Mile Road E catchment.

Figure 136. Main channel of creek 7, inset within coastal plain and cut through past coastal deposits.

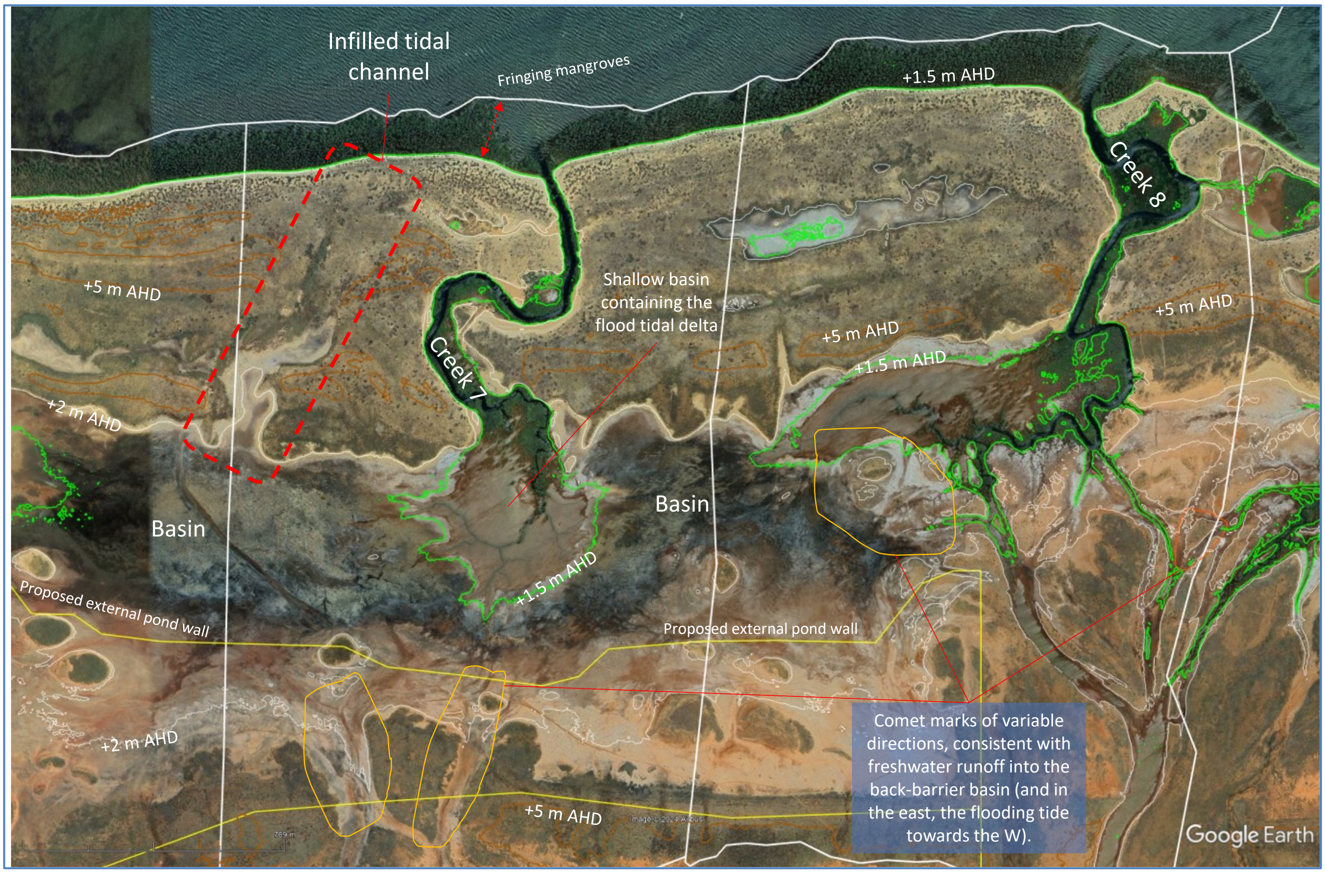

Figure 137. Details of the Creek 7 barrier, estuarine channel and back-barrier basin.

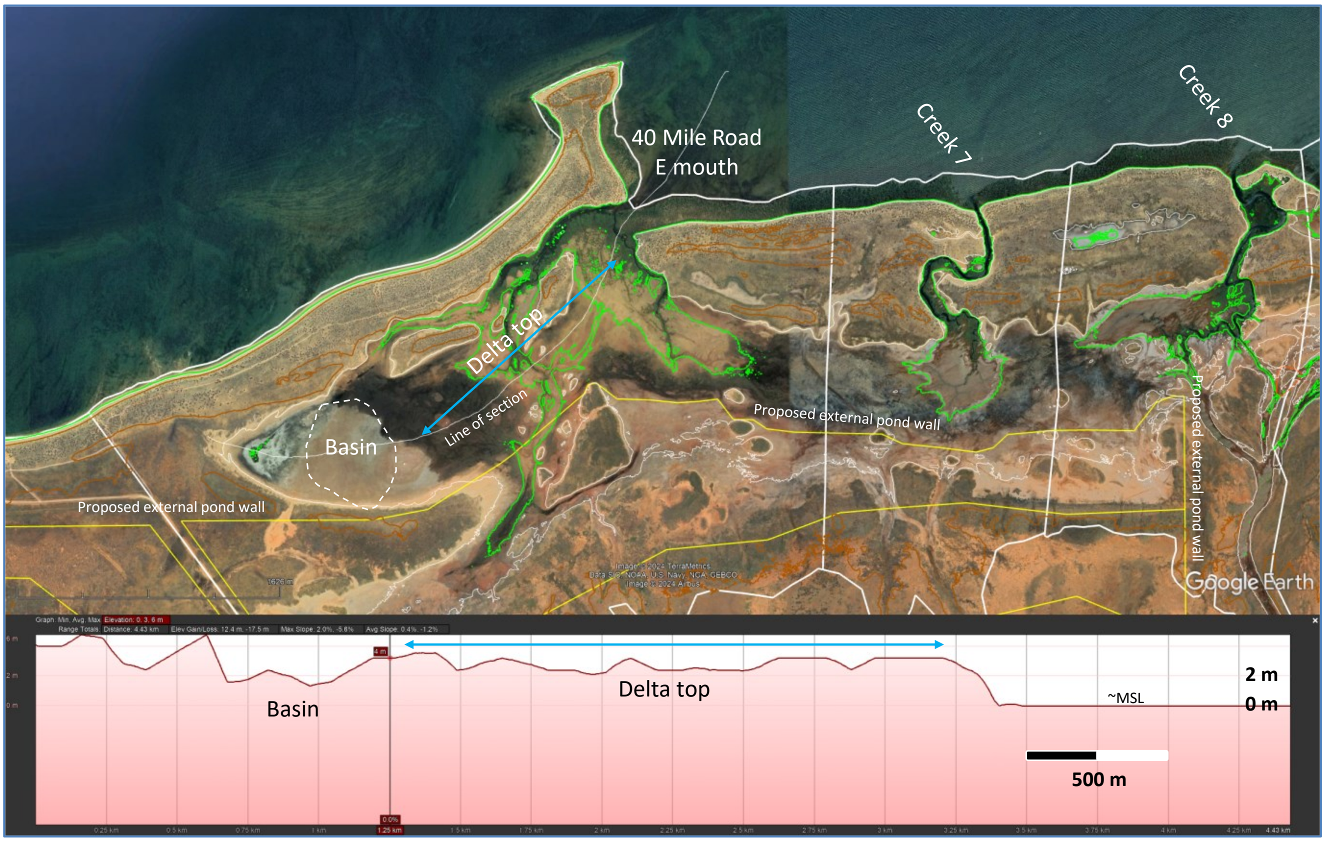

Figure 138. Detail of the barrier and back-barrier features of the combined area of 40 Mile Road E, Creek 7 & 8.

Just beyond the proposed ponds to the east, Yanyare is similar in hypsometric shape above high tide level (i.e., >2.5 m AHD) but more constricted at the mouth.

9.3.5.1. Sedimentary concepts and key changes

The essential concepts about these tidal creek systems and long back-barrier area are as follows.

- Processes – Fringing mangroves protect the barrier front from waves, with reduced effectiveness at the highest tides and during positive surges. Tidal currents maintain the channels through the barrier, and the back-barrier basin receives fast freshwater flows of runoff from its landward margins. Some muddy sediment settles on the flats at high tide enhanced by shelter from the barrier and the flood tidal delta of 40 Mile Road W. Extensive areas of benthic mats occur on the basins, with small areas of samphire liming some of the margins.
  - **With SLR**, the seaward edge of the fringing mangroves will be subject to increased waves (presuming that bed elevation will not keep up with SLR) and will become pinched against the barrier, and might be less likely to recolonise. Freshwater runoff might produce a little more deposition in the basin due to the higher likelihood of the runoff meeting tidal water in the back-barrier basin. Further, the tidal exchange might be modified by mangrove migration and expansion, that might act to decrease tidal flows on the landward side of the barrier.
  - **With SLR plus ponds**, in addition to the above, the tidal exchange will be reduced, potentially leading to a smaller tidal system a little more vulnerable to closure. The system will no longer receive part of its freshwater runoff potentially reducing the capacity for creek scouring during such events, and similarly during the relaxation phase of positive surges.
- Sediment sources – overall these are limited. Some supply may occur from the sea, indicated by the apparent flood tidal delta in 40 Mile Road E, but this feature might be a reworked remnant of older barrier-related and deflated dune sands. There will be negligible sand supply from the low deflated dunes and the barrier flanks, but potentially more from the rocky slope to the south. Settling of suspended material at high tide is likely in the sheltered western basin and elsewhere behind the barrier.
  - **With SLR**, there may be enhanced (but limited) reworking of internal sources and increased chance of marine material entering the tidal creeks. It is unlikely that bed elevation will keep up with SLR, so that overall, the area will undergo a degree of drowning. It is unclear whether the basinal flood tidal delta feature of Creek 7 will expand or contract in size, but there may be a feedback between mangrove change and tidal exchange.
  - **With SLR plus ponds,** sediment supply from the 40 Mile Road E catchment and the creeks to the south will cease, so that marine sources and internal reworking - which is likely to be very negligible - become more significant in terms of whether the bed elevation will keep up with SLR - it is highly unlikely that it will. Overall, the tidal creek systems might be more vulnerable to closure at the mouth(s).
- Sediment transport pathways – exchange between the sea and the basin along the tidal creeks, and some supply into the basin from the southern catchments, perhaps with clay dispersing along the basin during surges and major runoff events.
  - **With SLR**, waves become more important at the coast and tides very slightly less important, whilst runoff remains a factor into the basin.
  - **With SLR plus ponds,** waves become more important and tides less important and runoff almost negligible.
- Sediment stores & sinks – fringing mangroves, flood tidal delta, and back-barrier basins.
  - **With SLR**, the low areas in the back-barrier basin become more likely to accumulate sediment, especially perhaps (fluvially-derived) mud and some mud reworked from eroding fringing mangroves.
  - **With SLR plus ponds**, the back-barrier sinks remain the same but are likely to receive less sediment;

- Risks/Constraints/Limitations – The catchments become very small and limited in elevation, and have almost no capacity to respond to SLR and/or pond walls.
    - Habitat connections – very limited with ponds in place.
    - Disturbance events – few major physical impacts are likely from disturbance events, but there is probably a general impediment to recolonisation from pinching (steep slopes) near the pond walls, and increased salinity.

9.3.5.2. Other factors

As elsewhere along the seaward external pond walls, over the next century, there is predicted to be increased groundwater salinity along the external pond walls, reaching an increase of over 210 g/L (Figure 111). This may be a factor in influencing BCHs in this area.

9.3.5.3. Assessment - qualitative

The above assessment leads to a suite of possible outcomes for this area (Table 24). Overall, regarding gradual changes, SLR is most likely to drive drowning of the system, with minor responses landward of the barrier. Of the catchment areas studied here potentially affected by SLR and the ponds, this area is probably least vulnerable to the effects of episodic disturbance events, except along the fringing mangrove itself.

9.3.5.4. Assessment – quantitative

The result of the effect of the ponds on the BCH (as a % of the defined area, meaning the whole defined catchment) is illustrated in Figure 139, which compare results for cases 2 and 3 for these three systems. The nature and general pattern of potential future changes is very similar for each catchment. Key points of note include that:

- The limiting case of the theoretical scenario where habitat migrates purely with elevation (i.e., Case 1) would suggest a large proportional increase in mangroves from around 5% to ~30% (via occupying the flats), with a corresponding reduction of benthic mat and small reduction of samphire habitat. **Low confidence.**
- Over the next century with SLR and a sedimentary response (Case 2), mangroves are estimated to increase in coverage by 50% (40 Mile Road E) to 150% (Creek 8). Benthic mats lose 1/10 to 1/3 of their original coverage largely due to occupation by mangroves, and samphire are reduced to around 1/3 of their original coverage, due to reduced habitat viability towards the upper part of the habitat. **Low to Moderate confidence.**
- With the addition of ponds (Case 3), the mangroves increase to a sightly lesser degree, with coverage increased by ~20% (Creek 7) to 70% (Creek 8). **Low to Moderate confidence**.
- Ponds (also Case 3) cover some benthic mats, removing 50 – 75% of their present coverage. SLR reduces this further, partly because mangrove advance is likely to replace the mats. Very few areas of benthic mat are projected to remain a century from now. **Low to Moderate confidence**.

Ponds (also Case 3) cover most existing areas of samphire, and the low availability of suitable habitats means that these may be absent from this region within 25 or 50 years. **Moderate confidence**.

Table 24. Range of possible outcomes for changes to the combined area of 40 Mile Road E, Creek 7 & Creek 8. 'Change' refers to net change in area of habitats, e.g., loss by a cyclone, gain through coastal progradation.

General nature of change	Least 'change'	Favoured assessment at present	Most 'change'
Past natural (geological & historical)	Based on aerial images, there has been the development of a sediment fan over a previous benthic ma – this may well be a seasonal feature.	Little clear change, but what little there is appears consistent with the past trajectory of SLR.	About 100 m of tertiary creek has developed in the head section.
Comments on timing	No evidence for change by a major episodic event since 1968.		
SLR	Whole system raised in elevation broadly matching SLR (very unlikely). Little net change.	Partial drowning of the system as most bed elevations do not match SLR. Some fringing mangrove might be partly offset by some colonisation at creek heads. Benthic mats decrease slightly in the basin. Samphires become restricted.	Major loss of fringing mangroves, disruption of estuarine mangroves with little headward expansion. Partial drowning of high tidal flats reduces extent of benthic mats and samphire.
Comments on timing	Gradual over several decades and more	Gradual with some minor disruptive events, especially along the seaward side of the barrier	Gradual over several decades and more, slightly modified by episodic events at any time
SLR PLUS PONDS	Whole system raised in elevation matching SLR (very unlikely). Headward migration of habitats broadly matches loss by coastal erosion.	As above but plus some modification by decreased capacity for internal response, especially because of reduced fluvial input.	Major loss of fringing mangroves and disruption of estuarine mangroves. Benthic mats persist, and samphires reduce especially on the southern margin. Increased salinity restricts mangrove recolonisation.
Comments on timing	As above	As above	As above

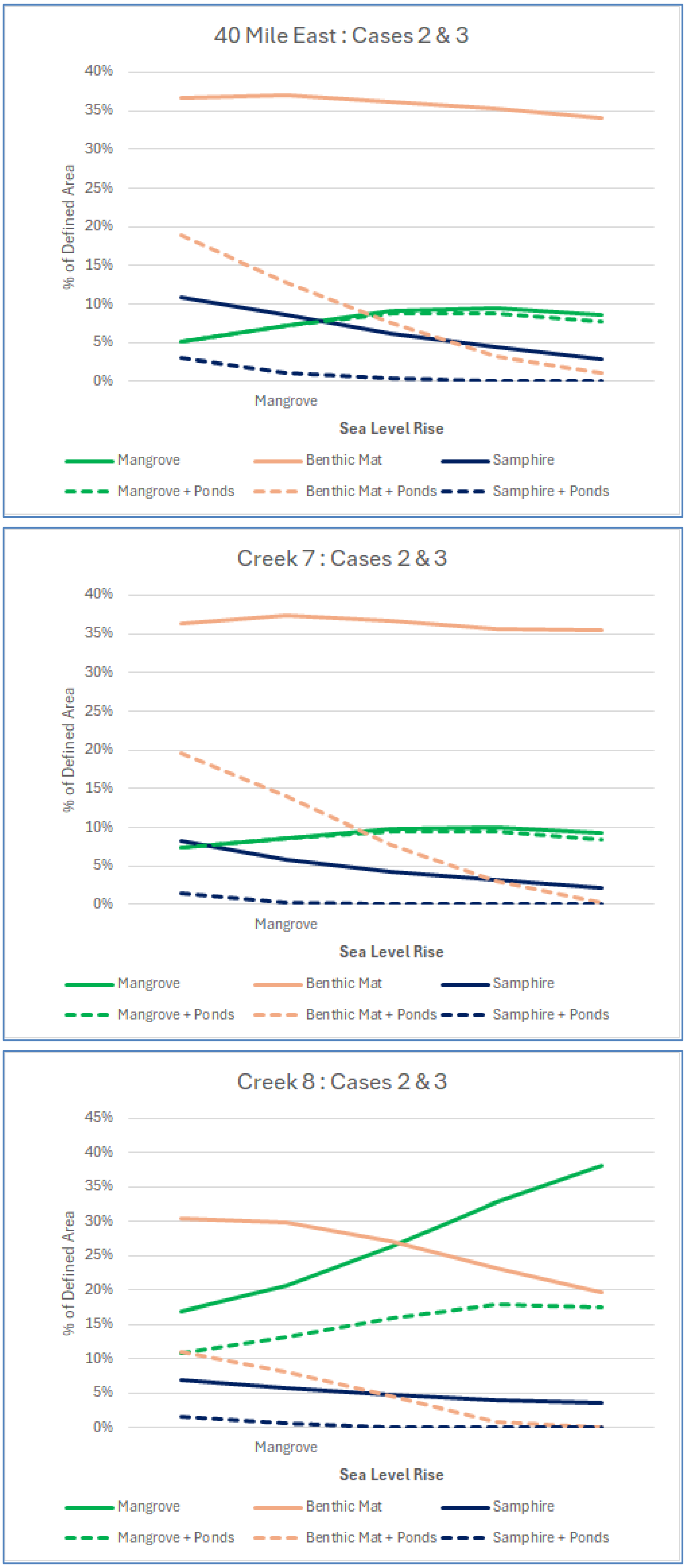

*Figure 139. Case 2 - **'SLR plus sedimentary response'** case (solid lines) and Case 3 - the '**SLR plus sedimentary response plus ponds'** case (dashed lines) for the systems of 40 Mile Road E, and Creeks 7 & 8. The difference between solid and dashed lines is an indication of the changing effect of the ponds through time.*

10. Caveats and uncertainties

Many of the caveats expressed in the CP-BCH report's section 14 remain present, but some have been mitigated to a greater or lesser extent. Although acknowledged to have significant uncertainties, the hydrological modelling work (Land and Water Consulting 2023a) improves knowledge of freshwater runoff events (CP-BCH caveat 4). The sediment descriptions and shallow stratigraphy of CMW Geosciences (2022) has greatly decreased uncertainties regarding sediment types and availability and thus potential mobility and habitat change (CP-BCH caveats 9 & 10). Together, and with associated information, these reports help reduce uncertainty about potential changes associated with future SLR, but the untested sediment transport pathways and the ages of key features remain critical gaps in this assessment (CP-BCH caveats 1, 9 to 13). The available information also improves understanding of the potential effects of pond emplacement and effects near the walls (CP-BCH caveats 14 & 18).

Below is highlighted the knowledge gaps in sediment transport pathways, the ages of key coastal units and features, and the sediment dynamics of major runoff events.

10.1. Sedimentary connections between different parts of the coastal system

The capacity for change of the various coastal features is a function of their location on an active sediment transport pathway, i.e., whether the feature is a sediment source to the pathway, a site of sediment transport past it, a temporary store or a more permanent site of sediment accumulation. Such pathways are tested in a number of ways. The pathways that are most relevant to assessing i) possible changes related with a century of SLR, and ii) the potential effects of the ESSP over similar timescales are those pathways that operate on timescales of several decades or more. Their presence and nature are best tested using deposits that can represent such timescales. In brief, this could be achieved using an array of surface sediment samples that can be used to test the spatial gradients in sediment grain size and composition, including the specific hypotheses in Table 15 (in section 7.1). Such samples do not exist at present, so that the hypotheses are untested and unable to contribute to the analysis of consequences for the habitats.

10.2. Ages of key features

A critical unknown is the age of the various positive-relief sandy features at the mouth of the river delta and elsewhere across the intertidal zone (section 6.3.3). Dated material does not exist at present for any the sedimentary units across the ESSP area, and dates are also lacking for equivalent features on areas of adjacent coastline. Until some dates are established, the feasible ages of these and other relevant features is such that calculated rates of past sediment accumulation in the ESSP area might be in error by a factor of at least 20, and possibly by a factor of 200. This means that predictions of future sedimentary and habitat change with SLR and with SLR plus ponds are also subject to such uncertainty. Whilst the predictions delivered in this report represent expert judgement, there remains great uncertainty and there is no substitute for data.

10.3. Ages of mangrove stands

The age of mangrove trees can add to the understanding of part coastal habitat changes and inform the significance of future changes. There are stands of fringing mangroves along the ESSP area, especially at the mouth of McKay Creek, at the nascent mangrove area, and along the shoreline in the east (40 Mile Road E, creeks 7, 8). At the coastline, the age of the mangroves can help in assessing past shoreline changes, especially episodic events, where a severe erosive event may lead to extensive areas of mangroves being killed. There may or may not be subsequent sediment accumulation and mangrove re-establishment.

There are also various areas of sparse estuarine mangroves, whose ages may assist in testing whether the habitats are migrating landwards or retreating seawards, and over what timescales, or are undergoing changes due to past natural processes such as channel switching. The latter might be the case for some areas near the eastern branches of Creek 5 and Creek 3 (Figure 140).

Figure 140. Sparse mangroves near the eastern branches of Creek 5 and Creek 3. The bedforms and morphology as seen on aerial images indicates that these may relate to past channels that received the outflow of Eramurra Creek.

10.4. The dynamics of runoff events and local sediment availability

Outputs of hydrogeological models are available for runoff events, showing maximum depths, water slope and speeds, albeit subject to a notable degree of uncertainty. Model outputs are available for the major and minor creeks, and for the pond perimeters. However, for the tidal and runoff flow speeds in the creeks and in constrictions between pond walls, especially for McKay Creek, it is also relevant to understand the possible time-series of flow from the rainfall events, not just the maximum speeds. These time-series data are not currently available.

The relevance is that it may not be the deepest or the fastest flows that are most significant in terms of erosion and sediment transport. Bed shear stress varies with speed and flow depth, and with unlimited sediment availability, sediment transport rate is a cubic or quartic function of flow speed. Further, actual sediment transport rate is dependent upon sediment availability before and during the flow event. It is possible that in places, the locally available mobile sediment is all removed relatively early in an event so that the latter parts of a flow might transport relatively little sediment, indeed the apparent eroded surfaces and clear comet marks indicate that this is possible in various locations in the catchments of 40 Mile Road W and E, Creeks 7 and 8, and Yanyare Creek. Therefore, knowledge of the local sediment nature, size and thickness is advantageous to assessing potential transport and thus potential morphological change.

Additional to this uncertainty about present fluvial dynamics is the unknown future nature of rainfall and river flow. River flood events are a significant factor in delivering sediment to the tidal flats and they potentially help maintain the tidal creek system including by flushing sand seawards at the mouth.

10.5. The past coastal evolution is uncertain

Taken together, the above uncertainties mean that it is not possible to construct a good understanding of the past evolution of the coastline. However, there are however some general possibilities that can help illustrate the geomorphological issues involved. The illustrated example below assumes that the past coastline features observed on the modern coastal plain are 6,000 years old.

10.5.1. Hypothetical coastal evolution of the ESSP area assuming that the documented palaeoshoreline deposits are 6,000 years old

First, in the latest stages of the Post-Glacial rise in MSL, at 7,000 to 8,000 years ago, MSL was at ~1.5 m below modern levels. Tidal range was similar to today. At this time the ESSP shoreline probably contained a wide expanse of estuarine mangroves in the deepening embayment seawards of the McKay Creek mouth, and fringing mangroves elsewhere. The shoreline was moving landwards, approaching the rocky areas near the now headlands (Figure 141).

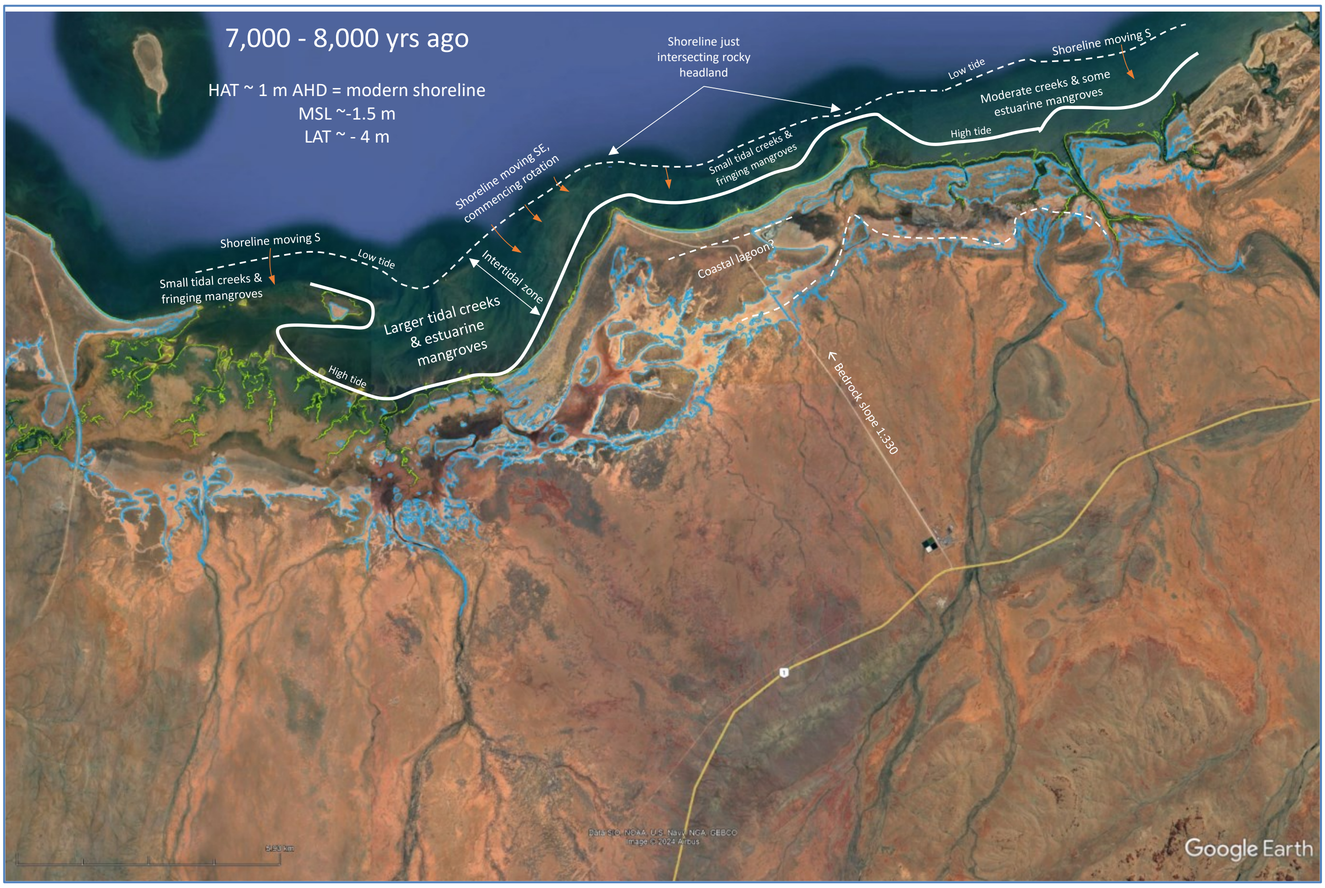

Figure 141. Generalised coastal position and possible features at 7,000 to 8,000 years ago for the ESSP area.

Second, and perhaps only 1,000 or 2,000 years later, with MSL only 3 m higher (at +1.5 m), the coastline was probably radically different in location and nature (Figure 142), with:

- barrier fragments with fringing mangroves on their seawards side, and behind which were developed various sand bodies (upper right),
- a series of spits to west and east of (presumed) rock outcrops (centre left),
- large areas of estuarine mangroves bordering tidal creeks on the southern margin of an infilling lagoonal complex, and finally
- a series of low sandy sediment bodies at the mouth of fluvial creeks.

This assessment of the ESSP coastline at 6,000 years ago is very similar to the modern Mardie shoreline. So Mardie appears to illustrate well a past stage in the development of the ESSP shoreline, that because of significant changes in sedimentary processes and coastal geomorphology now takes a very different form.

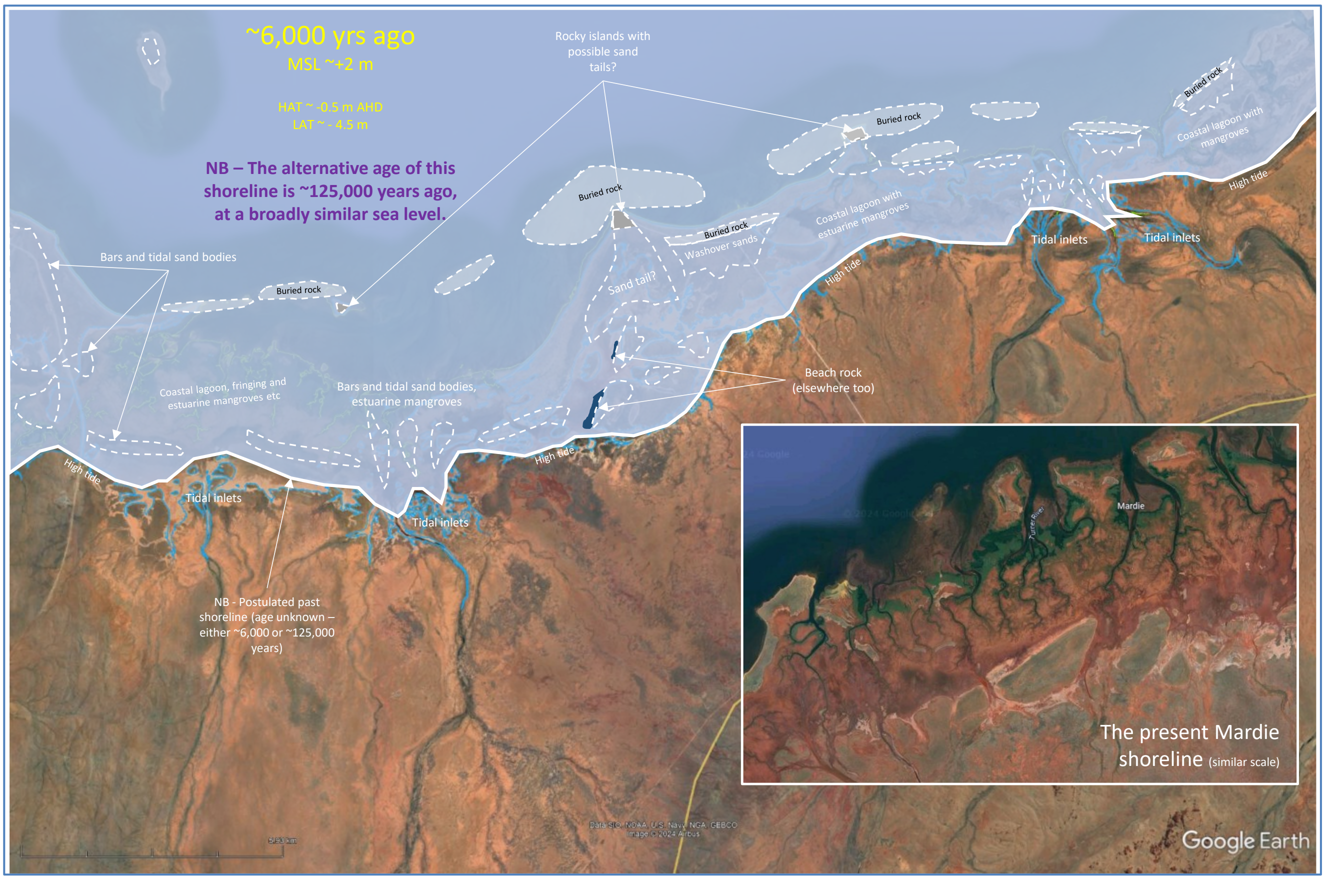

Figure 142. Generalised coastal position and possible features at 6,000 years ago (or 120,000 yrs ago) for the ESSP area. The solid white line indicates the approximate location of high tide. Inset - The present Mardie shoreline is a physical analogy for the ESSP coastline at 6,000 years ago.

Third, and finally, with a fall in MSL of only ~1.5 m, the coastline developed its modern form, with 2-3 km of coastal progradation in places since sea-level highstand, with coastal rotation about Gnoorea Point and with the rocky headlands and bathymetric features controlling most of the key coastal processes (Figure 143).

The example and these figures are intended to help indicate how knowing the true age of the coastal features and deposits can assist assessments of past coastal changes, the potential for rates of change and the processes involved, and therefore how future possibilities can be framed, including the issue of natural changes and of natural systemic resilience.

10.5.1. The importance of knowing the ages of key features

Whilst the above example might seem attractive or even convincing, it is only one of a series of possibilities for past changes. To illustrate their significance, below are a few possibilities associated with assessing potential changes at the area of nascent mangroves (section 9.3.1) to its east.

- If the barrier sands of the Gnoorea spit (Figure 118) and their presumed past extension across the nascent mangroves (Figure 122, Figure 123) are (say) only 500 years old, it indicates that i) the coastline was sandy and subject to strong waves at that time (possibly a cyclone, a period with several cyclones, or neither), and that ii) the shoreline has been able to migrate seawards by about 300 m in that time, producing an area conducive to fringing mangroves through a process of sediment accumulation at the coast, at a rate we can quantify in broad terms. This would indicate that the coastline is relatively resilient to change and the risk to habitats is relatively low.

- In contrast, if the same barrier sands are (say) 6,000 years old, the long-term rates of change are much slower, the inferred coastal resilience is less, so that potential changes brought about by human intervention become more significant.
- Finally, if the same barrier sands are (say) 120,000 years old (the other main possibility), then potential changes brought about by human intervention become very significant indeed – i.e., the coastal sedimentary environments might not be resilient to change and the risk to associated habitats is high.

Thus, it is clear that the determination of the age(s) of some key features and deposits is very important.

- Another significant issue is the timing of the breaching of the barrier – i.e. when the presumed long and thin sand spit that almost reached the mouth of McKay Creek was broken into a series of segments and the individual tidal creeks of the nascent mangrove area were first formed. Creek formation has allowed the development of estuarine mangroves along the creek and landward of the breach. The more recent the breaching, the faster the nascent mangrove system has developed, and the more resilient the area appears.

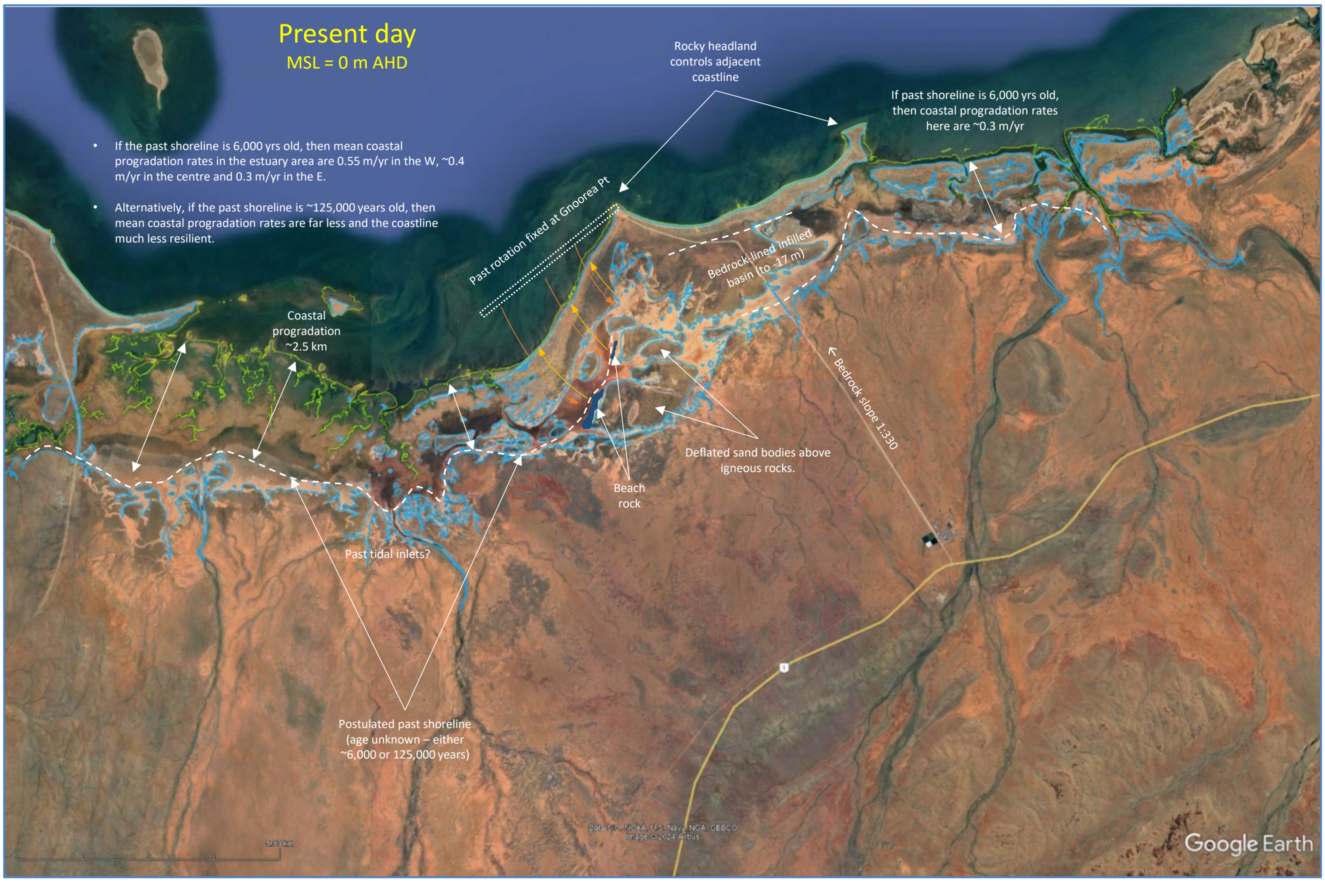

Figure 143. Modern coastline, the past interpreted coastline (white dash) and main interpreted possible features for the ESSP area. Contour lines shown for 0 m AHD (light green) and 2.5 m AHD (blue). The mid-Holocene highstand (~6,000 yrs ago) was 1.5 m to 3 m AHD.

10.6. Method of quantitative assessment

As noted elsewhere (section 9.3.1), te methods of quantitative assessment of future changes in BCHs contain a range of uncertainties.

Firstly, these derive from various data gaps and uncertainties inherent in forming a view of the local and regional coastal geology, processes, sediment transport, environments and habitats.

Secondly, there are inevitable uncertainties involved in the choices made at different stages in the process of predicting the coastal response to future SLR and to episodic events. A noted in section 9.3.1, some simplicities were necessary in describing the modern BCH distributions with elevation. These include assigning the key elevation zones for each BCH and the visual assessment method used to assess the proportion of new ares that might be colonised by the BCH in question at each incremental rise in MSL. There is then the uncertainty in assessing the possible range of effects of pond emplacement, at whatever stage in the next century.

Whilst our analysis indicated that much of the modern BCH distribution was highly consistent with topographic, elevation, substrate and sedimentary controls, a range of additional factors are also of relevance. These additional factors include water salinity, porewater salinity, groundwater salinity, rainfall, percolation, and evaporation. Ecological factors are also relevant, such as the potential for replacement of one BCH by another, and especially in this area, of benthic mat by pioneering estuarine mangroves.

11. Conclusions

11.1. Levels of confidence

Conclusion are provided with the stated level of confidence in each. We use the following definitions[15].

- High confidence - We are very confident in the evidence supporting the conclusion.
  - In this report's context, further research is very unlikely to change the estimates of change and impact.
- Moderate confidence - We are moderately confident in the evidence supporting the conclusion.
  - In this report's context, further research could have an important impact, which may change the estimates of change and impact.
- Low confidence - We have only low confidence in the evidence supporting the conclusion.
  - In this report's context, further research is very likely to have an important impact, which is likely to change the estimates of change and impact.
- Very low confidence.
  - In this report's context, any estimate of change and impact is very uncertain. Further research would certainly have an important impact on estimates of change and impact.

All conclusions are numbered.

11.2. The natural system

11.2.1. The past and present

For past natural changes, the key shoreline units are of unknown age. Assuming that the deposits are all coastal, which seems to be the case based on their stratigraphy, structures and composition, then they relate to sea level near the present. Therefore, there are two main possibilities for their age (section 10.5).

1. The key shoreline units that underpin the future shoreline change are Holocene in age (i.e., ~6000 yrs old or younger). **Very low confidence**.

2. The key shoreline units that underpin the future shoreline change are Last Interglacial in age (i.e., ~120,000 years old, the last time that sea levels were near present levels). **Very low confidence**.

It is also possible that there is a combination of Holocene and Last Interglacial deposits involved.

Further, regarding the regional and local resilience of the BCH species,

3. There have been a very large variety of coastal geomorphic changes throughout the Holocene, and the BCHs are well adapted to their dynamic environments. **High confidence**.

It is also regionally apparent that where coastal barriers are more than 200 m wide, they tend to be resistant to breaching. Therefore,

4. It is unlikely that there will be active breaching of the Gnoorea spit or the barriers in front of the western ESSP region, indicating a degree of stability in the coastal geomorphic configuration in these locations. **Moderate confidence.**

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[15] Derived from https://help.magicapp.org/knowledgebase/articles/210582-how-to-rate-the-quality-of-evidence-your-confiden

11.2.2. The future – SLR over the next century

These statements assume a SLR of 0.9 m over the next century, i.e., roughly an average SLR of 10 mm/yr. For convenience, some aspects of the work, such as the quantitative assessments of habitat change, have used 1.0 m of SLR rather than 0.9 m, but this makes no significant difference to the report's outcomes or conclusions. One way of considering the complex range of likely natural coastal responses along the ESSP region over the next century is note that:

- there is almost certainly insufficient sediment available to raise bed elevations to match the rate of SLR;
- in general, most change in the coastal geomorphic response will come about by landward transport of mud, eroded at the shoreline and deposited landward towards the high tidal flats and shallow basins, and that;
- there will be a complex range of effects of mobile bodies at the shoreline, affecting creek mouths and recovery from erosive events.

Noting these general considerations, there are two possible 'end-member' conclusions from this work, with greatly different implications for the natural change that might occur over the next century, and the changes with the ESSP development in place. These alternatives depend on the age of the past coastline and the rate(s) of accumulation of the mobile sediment bodies in the ESSP area, and their internal adjustments. The rates of change are unable to be determined at present, so that the conclusions cannot be specific. The two end-member alternatives and the implications of each are noted below.

5. The shoreline has prograded 2 to 3 km in the estuary region over the past ~6,000 years. If this is the case, then:
    - Natural processes - The possible changes in the natural processes and geomorphology, and the nature and extent of habitats over the next century would be highly variable along the ESSP's shoreline, ranging from negligible to locally significant and from temporary to possibly permanent. There might be some partial drowning of some areas of the coastal environments. Some localised changes will probably (but not necessarily) be related to episodic events such as cyclones. These changes will not be of regional significance and there would be little overall net change in regional coastal function. **High confidence** if the key assumption is true.

Or

6. The past shoreline is dated at ~120,000 years ago. If this is the case, then:
    - Natural Processes - The changes in the natural processes and geomorphology, and the nature and extent of habitats over the next century would be highly variable along the ESSP's shoreline, ranging from negligible to locally significant and from temporary to effectively permanent. There might be some severe drowning of large areas of the coastal environments, for example of the central and eastern parts of 40 Mile Road W and the back-barrier basin formed by the catchments of 40 Mile Road E and Creeks 7 & 8. There might be lesser drowning of the high tidal area landward of the western ESSP area. Some localised changes will probably (but not necessarily) be related to episodic events such as cyclones. These changes will not be of regional significance and there would be little overall net change in regional coastal function. **Moderate confidence** if the key assumption is true.

There is a need to gain information to determine which of these options can be ruled out and where the evidence leads. This will decrease the considerable uncertainties regarding the potential rates of future change, including the rates of coastal recovery to disruptive events.

11.2.3. Influences of the ESSP development

The two end-member alternatives regarding the ages of coastal sediment bodies are relevant here.

7. If the shoreline has prograded 2 to 3 km in the estuary region over the past ~6,000 years, then the possible effects of the development upon the processes and geomorphology and habitats over the next century are probably only locally significant and then probably even temporarily so. This provides a degree of resilience of the coastline to changes induced by the ESSP projects. **Moderate confidence if the key assumption is true.**

Or

8. If the past shoreline is dated at ~120,000 years ago, then the possible effects of the development upon the processes and geomorphology and habitats over the next century may be locally significant and, in some cases will be permanent. Some localised changes will be related to episodic events such as cyclones. The resilience of the coastline to changes induced by the ESSP projects is poor. **High confidence if the key assumption is true.**

The key possible influences of the development are outlined in section 9.3, and the relative effects of SLR alone compared to SLR plus ponds are detailed in these sections. In general, the major changed factors are:

- changed tidal hydrodynamics;
- change flow patterns during freshwater flood events, notably increased speeds near some pond walls and through areas of new constriction;
- reduced freshwater runoff and sediment availability and thus supply to coastal environments;
- … that together influence the future disposition of BCHs, their capacity to colonise and to recover after disruptive events.

The resulting effects on coastal response are generally less where the affected areas have ample local sediment supply and the capacity to mobilise it, or at least plus some capacity for internal reworking of sediment. For the nascent mangroves, and perhaps more the McKay Creek catchment, the pond-associated response is somewhat dependent upon the age of the key sedimentary bodies involved, and especially of those unconsolidated sedimentary units of sufficient volume to potentially provide material to allow a coastal response to the changed drivers of sediment transport.

Whilst we might assume that (presumed) gradual SLR might produce similarly gradual changes to the coastal geomorphic response, the reality is that the response in some areas will be adjustive (Figure 16), such as for active tidal creeks, but for other features, like spits and barriers, the response might be incremental. Coastal changes are best considered in this light.

9. The influence of episodic events may be significant to fringing mangroves along most stretches of the ESSP coast, but perhaps especially at the nascent mangroves and along the eastern ESSP region. **High confidence.**

10. Episodic events are likely to be of less significance to the BCH outcomes in the eastern ESSP region. **Moderate to high confidence.**

11. Whilst episodic events such as major river floods, cyclone-related waves, currents and surges will influence coastal erosion, transport and accumulation, the likely influence upon the habitats of the ponds is not greatly affected over the century timescale when viewed at the regional scale. **High confidence.**

12. The likely influence upon the habitats of the ponds is not greatly affected over the century timescale at the local scale. **Low to Moderate confidence.**

Regarding the most relevant areas of the ESSP in this context:

13. Over a century timescale, for the McKay Creek catchment system, the effect of the ponds is:
    - negligible-low upon the mangroves. **Moderate confidence;**
    - large on the samphire. **Low to Moderate confidence** and
    - greatest on the benthic mats **(Low confidence)**.
14. Over a century timescale, for the nascent mangrove system, which sits at the mouth of the 40 Mile Road W catchment, the effect of the ponds is:
    - moderate on the mangroves. **Moderate to High confidence.**
    - very large on the samphire. **High confidence.**
    - greatest on the benthic mats. **High confidence.**
15. Over a century timescale, for the combined systems of 40 Mile Road E, and Creeks 7 & 8, the effect of the ponds is:
    - very large on the samphire. **Moderate to High confidence**;
    - moderate on the mangroves. **Low to Moderate confidence**;
    - very large on the benthic mats. **Moderate confidence**.

11.3. Future monitoring, mitigation and adaptation

Should the ESSP go ahead, there may be a need to develop a regime for monitoring, adaptation and mitigation aspects of the ESSP's impacts on the various key BCHs. This report provides a suitable basis on which to describe and define a suite of requirements.

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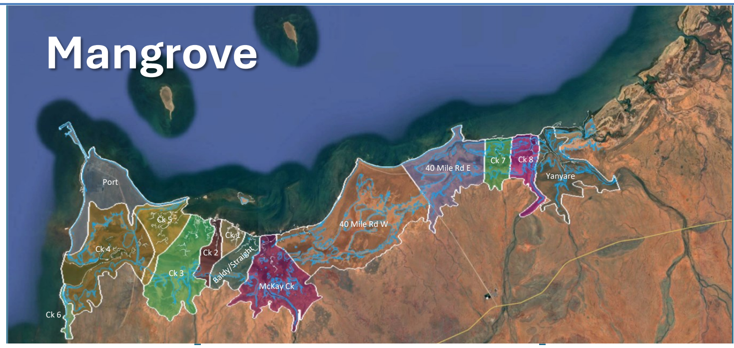
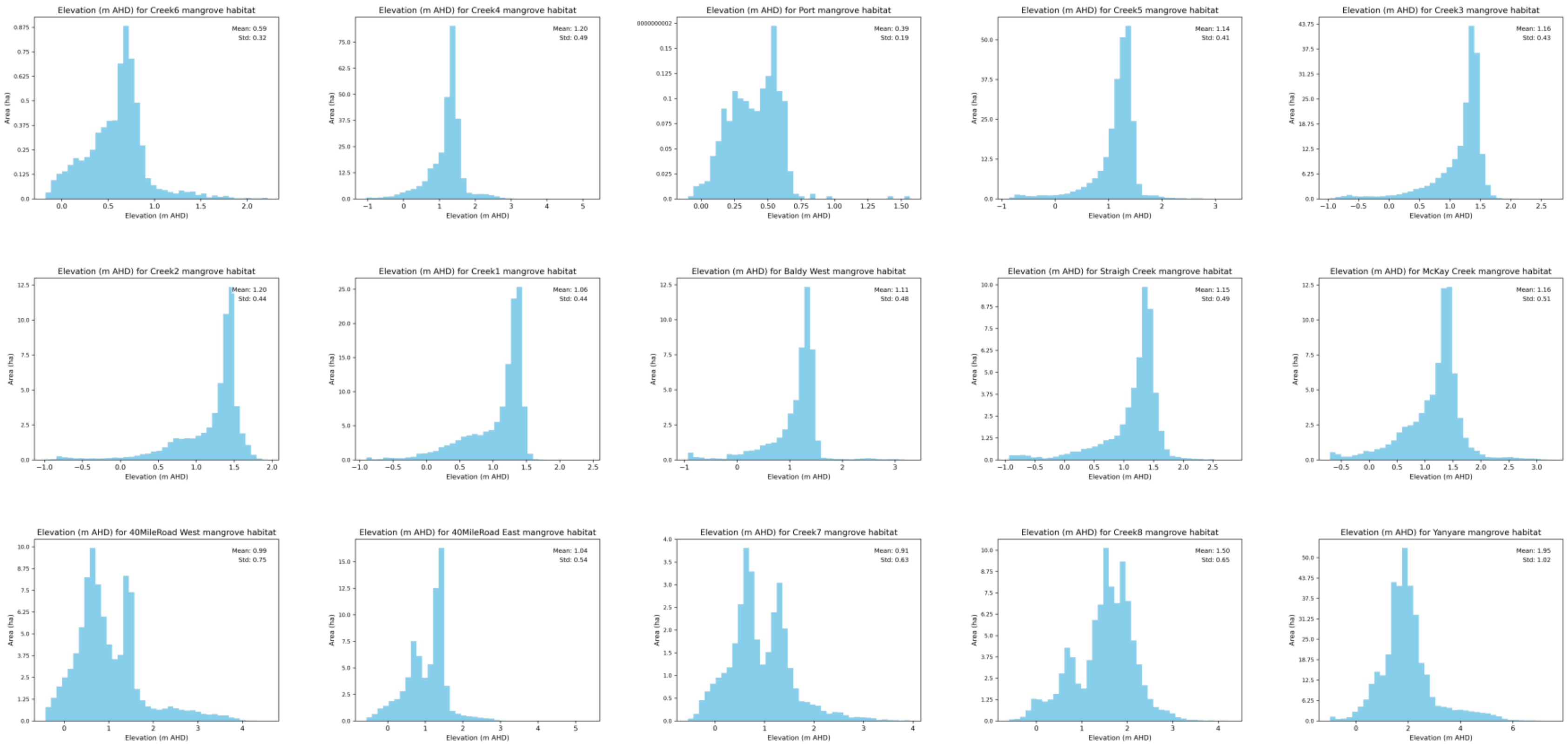
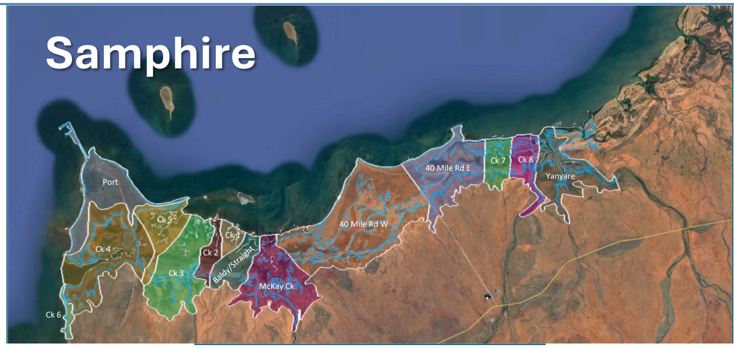
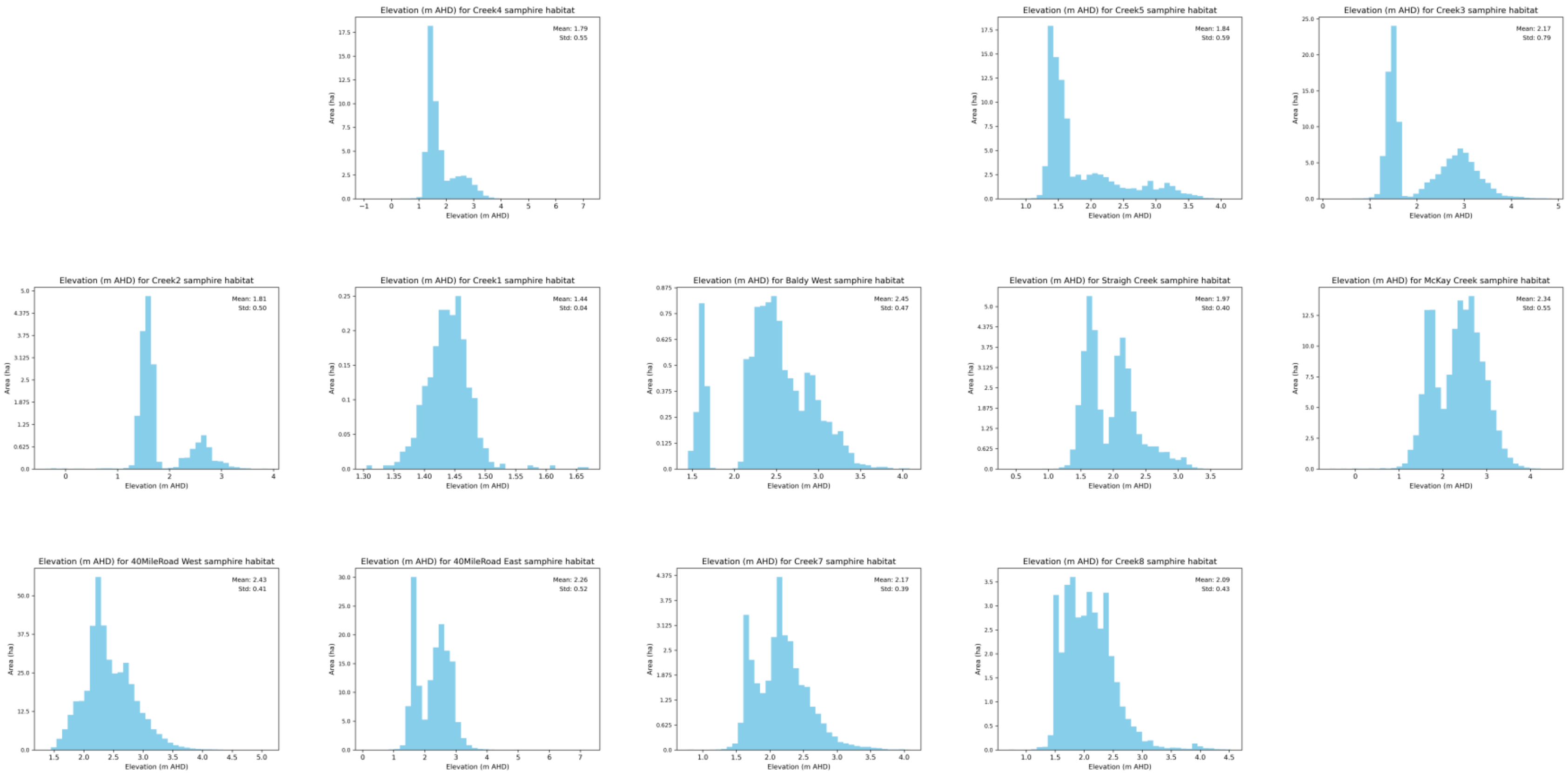
13. Appendices

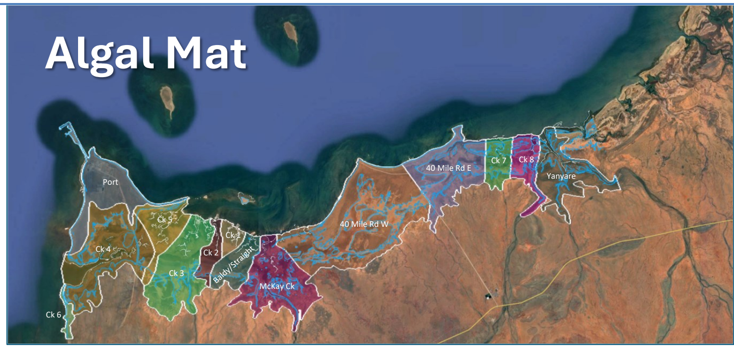
13.1. Distribution of BCHs with elevation for each catchment


Mangrove
Port
Ck 5
Ck 4
Ck 3
Ck 2
Ck 1
Baldy/Straight
McKay Ck
40 Mile Rd W
40 Mile Rd E
Ck 7
Ck 8
Yanyare
Ck 6

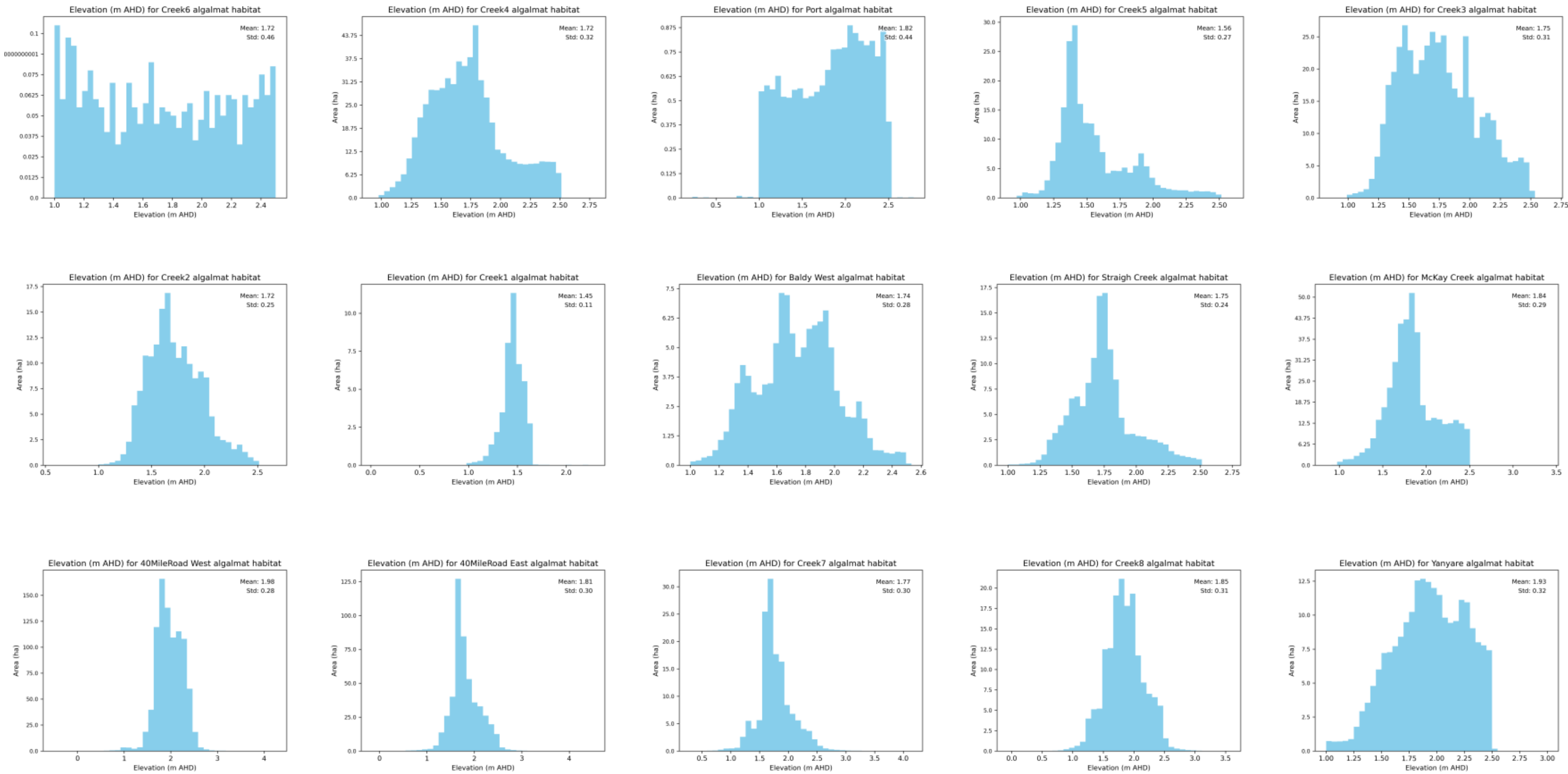

Elevation (m AHD) for Creek6 mangrove habitat
Mean: 0.59
Std: 0.32
Elevation (m AHD) for Creek4 mangrove habitat
Mean: 1.20
Std: 0.49
Elevation (m AHD) for Port mangrove habitat
Mean: 0.39
Std: 0.19
Elevation (m AHD) for Creek5 mangrove habitat
Mean: 1.14
Std: 0.41
Elevation (m AHD) for Creek3 mangrove habitat
Mean: 1.16
Std: 0.43
Elevation (m AHD) for Creek2 mangrove habitat
Mean: 1.20
Std: 0.44
Elevation (m AHD) for Creek1 mangrove habitat
Mean: 1.06
Std: 0.44
Elevation (m AHD) for Baldy West mangrove habitat
Mean: 1.11
Std: 0.48
Elevation (m AHD) for Straigh Creek mangrove habitat
Mean: 1.15
Std: 0.49
Elevation (m AHD) for McKay Creek mangrove habitat
Mean: 1.16
Std: 0.51
Elevation (m AHD) for 40MileRoad West mangrove habitat
Mean: 0.99
Std: 0.75
Elevation (m AHD) for 40MileRoad East mangrove habitat
Mean: 1.04
Std: 0.54
Elevation (m AHD) for Creek7 mangrove habitat
Mean: 0.91
Std: 0.63
Elevation (m AHD) for Creek8 mangrove habitat
Mean: 1.50
Std: 0.65
Elevation (m AHD) for Yanyare mangrove habitat
Mean: 1.95
Std: 1.02
Area (ha)
Elevation (m AHD)


Samphire
Port
Ck 5
Ck 4
Ck 3
Ck 2
Ck 1
Baldy/Straight
McKay Ck
40 Mile Rd W
40 Mile Rd E
Ck 7
Ck 8
Yanyare
Ck 6


Elevation (m AHD) for Creek4 samphire habitat
Mean: 1.79
Std: 0.55
Elevation (m AHD) for Creek5 samphire habitat
Mean: 1.84
Std: 0.59
Elevation (m AHD) for Creek3 samphire habitat
Mean: 2.17
Std: 0.79
Elevation (m AHD) for Creek2 samphire habitat
Mean: 1.81
Std: 0.50
Elevation (m AHD) for Creek1 samphire habitat
Mean: 1.44
Std: 0.04
Elevation (m AHD) for Baldy West samphire habitat
Mean: 2.45
Std: 0.47
Elevation (m AHD) for Straigh Creek samphire habitat
Mean: 1.97
Std: 0.40
Elevation (m AHD) for McKay Creek samphire habitat
Mean: 2.34
Std: 0.55
Elevation (m AHD) for 40MileRoad West samphire habitat
Mean: 2.43
Std: 0.41
Elevation (m AHD) for 40MileRoad East samphire habitat
Mean: 2.26
Std: 0.52
Elevation (m AHD) for Creek7 samphire habitat
Mean: 2.17
Std: 0.39
Elevation (m AHD) for Creek8 samphire habitat
Mean: 2.09
Std: 0.43
Area (ha)
Elevation (m AHD)



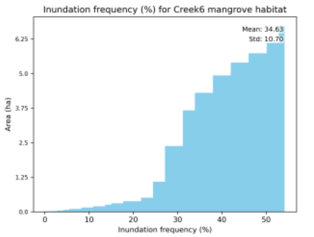
Algal Mat
Port
Ck 5
Ck 4
Ck 3
Ck 2
Ck 1
Baldy/Straight
McKay Ck
40 Mile Rd W
40 Mile Rd E
Ck 7
Ck 8
Yanyare
Ck 6

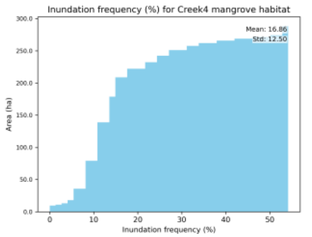


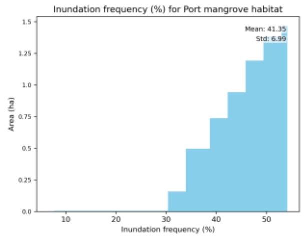
Elevation (m AHD) for Creek6 algalmat habitat
Mean: 1.72
Std: 0.46
Elevation (m AHD) for Creek4 algalmat habitat
Mean: 1.72
Std: 0.32
Elevation (m AHD) for Port algalmat habitat
Mean: 1.82
Std: 0.44
Elevation (m AHD) for Creek5 algalmat habitat
Mean: 1.56
Std: 0.27
Elevation (m AHD) for Creek3 algalmat habitat
Mean: 1.75
Std: 0.31
Elevation (m AHD) for Creek2 algalmat habitat
Mean: 1.72
Std: 0.25
Elevation (m AHD) for Creek1 algalmat habitat
Mean: 1.45
Std: 0.11
Elevation (m AHD) for Baldy West algalmat habitat
Mean: 1.74
Std: 0.28
Elevation (m AHD) for Straigh Creek algalmat habitat
Mean: 1.75
Std: 0.24
Elevation (m AHD) for McKay Creek algalmat habitat
Mean: 1.84
Std: 0.29
Elevation (m AHD) for 40MileRoad West algalmat habitat
Mean: 1.98
Std: 0.28
Elevation (m AHD) for 40MileRoad East algalmat habitat
Mean: 1.81
Std: 0.30
Elevation (m AHD) for Creek7 algalmat habitat
Mean: 1.77
Std: 0.30
Elevation (m AHD) for Creek8 algalmat habitat
Mean: 1.85
Std: 0.31
Elevation (m AHD) for Yanyare algalmat habitat
Mean: 1.93
Std: 0.32
Area (ha)
Elevation (m AHD)

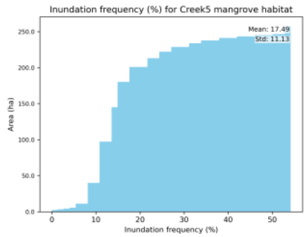
13.2. Frequency of inundation of BCH areas for each catchment

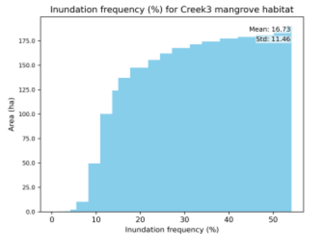

Mangrove
Port
Ck 4
Ck 5
Ck 3
Ck 2
Ck 1
Baldy/Straight
McKay Ck
40 Mile Rd W
40 Mile Rd E
Ck 7
Ck 8
Yanyare
Ck 6

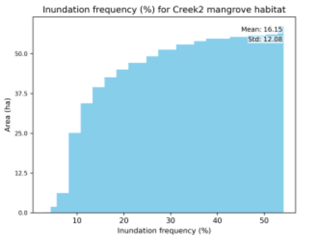

Inundation frequency (%) for Creek6 mangrove habitat
Mean: 34.63
Std: 10.70
Area (ha)
Inundation frequency (%)

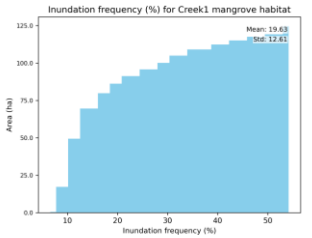

Inundation frequency (%) for Creek4 mangrove habitat
Mean: 16.86
Std: 12.50
Area (ha)
Inundation frequency (%)

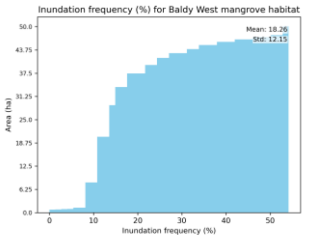

Inundation frequency (%) for Port mangrove habitat
Mean: 41.35
Std: 6.99
Area (ha)
Inundation frequency (%)

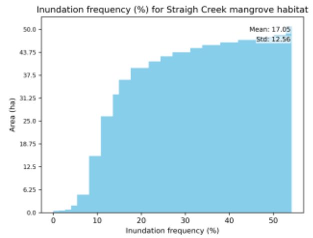

Inundation frequency (%) for Creek5 mangrove habitat
Mean: 17.49
Std: 11.13
Area (ha)
Inundation frequency (%)

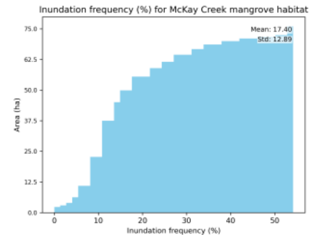

Inundation frequency (%) for Creek3 mangrove habitat
Mean: 16.73
Std: 11.46
Area (ha)
Inundation frequency (%)

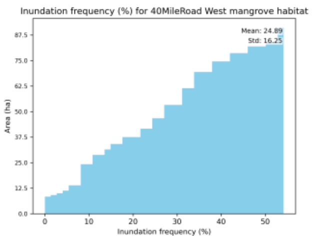

Inundation frequency (%) for Creek2 mangrove habitat
Mean: 16.15
Std: 12.08
Area (ha)
Inundation frequency (%)

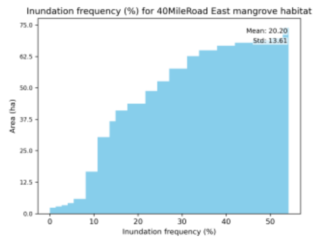

Inundation frequency (%) for Creek1 mangrove habitat
Mean: 19.63
Std: 12.61
Area (ha)
Inundation frequency (%)

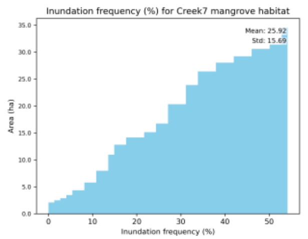

Inundation frequency (%) for Baldy West mangrove habitat
Mean: 18.26
Std: 12.15
Area (ha)
Inundation frequency (%)

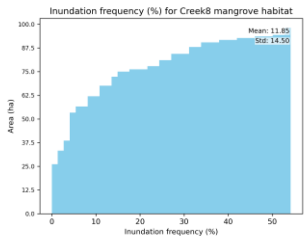

Inundation frequency (%) for Straigh Creek mangrove habitat
Mean: 17.05
Std: 12.56
Area (ha)
Inundation frequency (%)

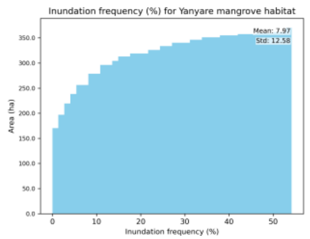

Inundation frequency (%) for McKay Creek mangrove habitat
Mean: 17.40
Std: 12.89
Area (ha)
Inundation frequency (%)

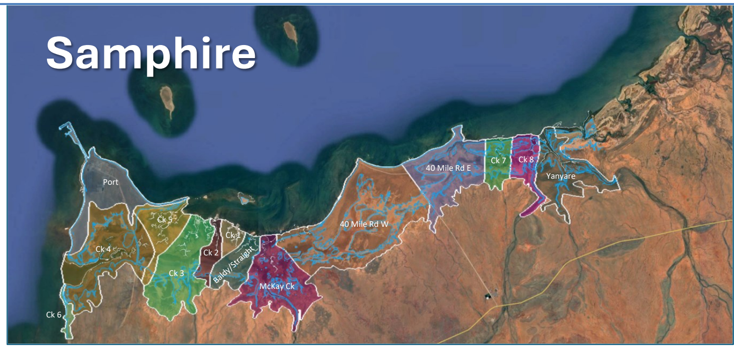

Inundation frequency (%) for 40MileRoad West mangrove habitat
Mean: 24.89
Std: 16.25
Area (ha)
Inundation frequency (%)

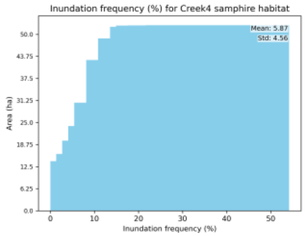

Inundation frequency (%) for 40MileRoad East mangrove habitat
Mean: 20.20
Std: 13.61
Area (ha)
Inundation frequency (%)

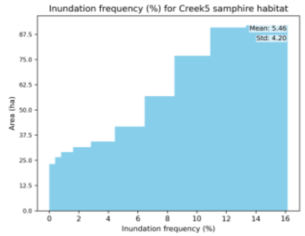

Inundation frequency (%) for Creek7 mangrove habitat
Mean: 25.92
Std: 15.69
Area (ha)
Inundation frequency (%)

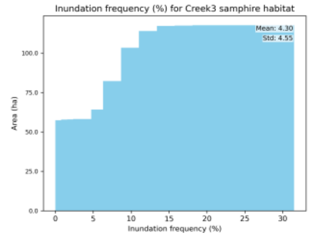

Inundation frequency (%) for Creek8 mangrove habitat
Mean: 11.85
Std: 14.50
Area (ha)
Inundation frequency (%)

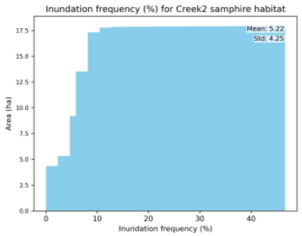

Inundation frequency (%) for Yanyare mangrove habitat
Mean: 7.97
Std: 12.58
Area (ha)
Inundation frequency (%)

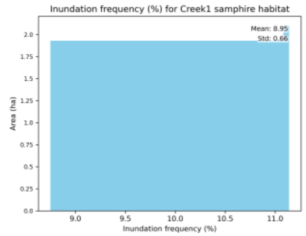

Samphire
Port
Ck 5
Ck 4
Ck 3
Ck 2
Ck 1
Baldy/Straight
McKay Ck
40 Mile Rd W
40 Mile Rd E
Ck 7
Ck 8
Yanyare
Ck 6

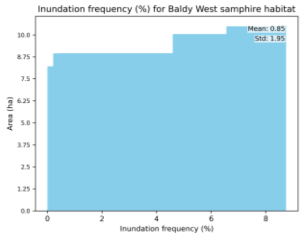

Inundation frequency (%) for Creek4 samphire habitat
Mean: 5.87
Std: 4.56
Area (ha)
Inundation frequency (%)

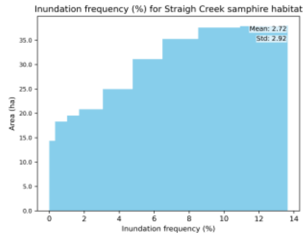

Inundation frequency (%) for Creek5 samphire habitat
Mean: 5.46
Std: 4.20
Area (ha)
Inundation frequency (%)

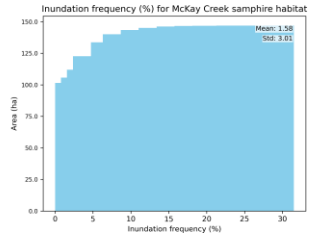

Inundation frequency (%) for Creek3 samphire habitat
Mean: 4.30
Std: 4.55
Area (ha)
Inundation frequency (%)

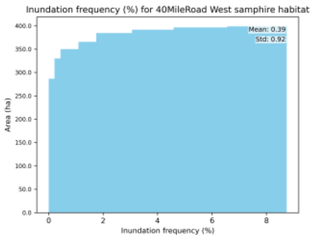

Inundation frequency (%) for Creek2 samphire habitat
Mean: 5.22
Std: 4.25
Area (ha)
Inundation frequency (%)

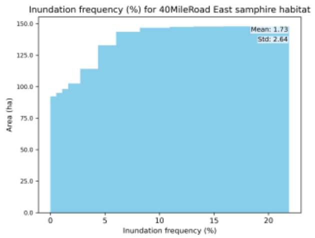

Inundation frequency (%) for Creek1 samphire habitat
Mean: 8.95
Std: 0.66
Area (ha)
Inundation frequency (%)

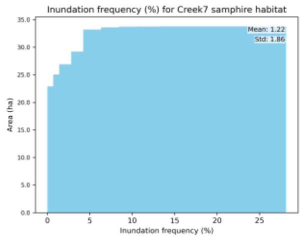

Inundation frequency (%) for Baldy West samphire habitat
Mean: 0.85
Std: 1.95
Area (ha)
Inundation frequency (%)

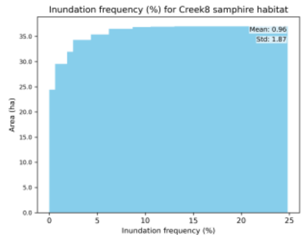

Inundation frequency (%) for Straigh Creek samphire habitat
Mean: 2.72
Std: 2.92
Area (ha)
Inundation frequency (%)

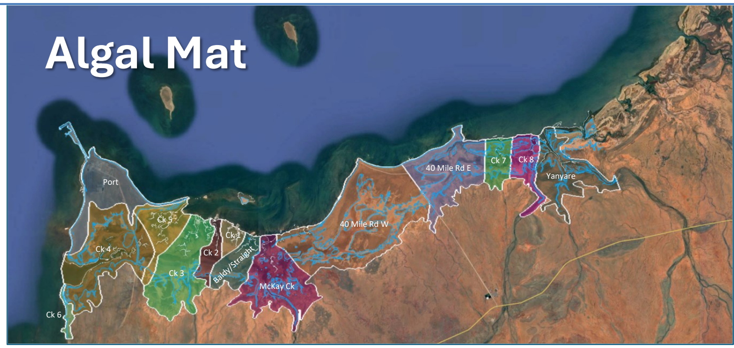

Inundation frequency (%) for McKay Creek samphire habitat
Mean: 1.58
Std: 3.01
Area (ha)
Inundation frequency (%)

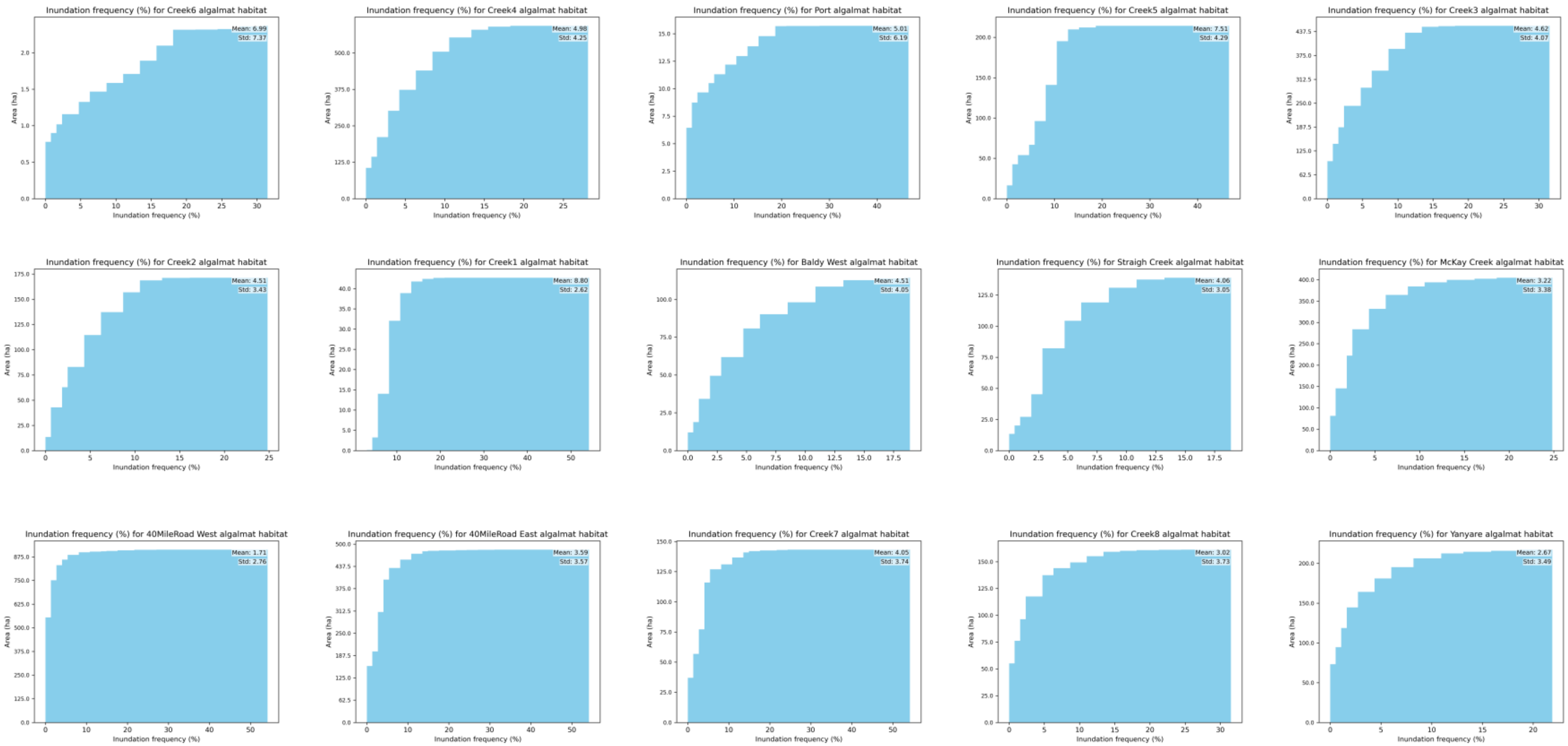

Inundation frequency (%) for 40MileRoad West samphire habitat
Mean: 0.39
Std: 0.92
Area (ha)
Inundation frequency (%)


Inundation frequency (%) for 40MileRoad East samphire habitat
Mean: 1.73
Std: 2.64
Area (ha)
Inundation frequency (%)

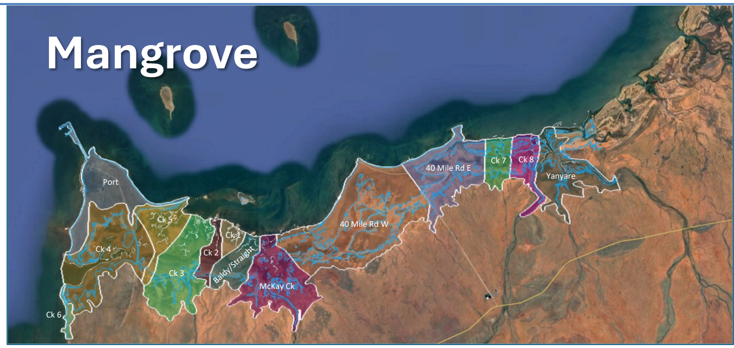

Inundation frequency (%) for Creek7 samphire habitat
Mean: 1.22
Std: 1.86
Area (ha)
Inundation frequency (%)

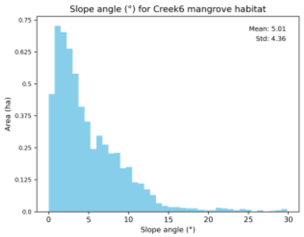

Inundation frequency (%) for Creek8 samphire habitat
Mean: 0.96
Std: 1.87
Area (ha)
Inundation frequency (%)

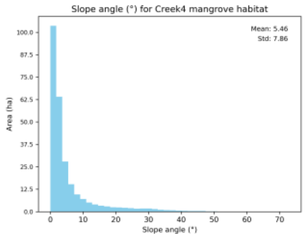

Algal Mat
Port
Ck 4
Ck 5
Ck 3
Ck 2
Ck 1
Baldy/Straight
McKay Ck
40 Mile Rd W
40 Mile Rd E
Ck 7
Ck 8
Yanyare
Ck 6

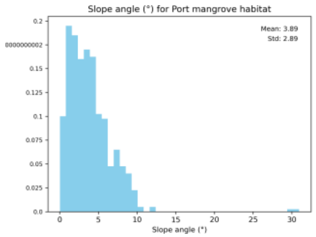

Inundation frequency (%) for Creek6 algalmat habitat
Mean: 6.99
Std: 7.37
Inundation frequency (%) for Creek4 algalmat habitat
Mean: 4.98
Std: 4.25
Inundation frequency (%) for Port algalmat habitat
Mean: 5.01
Std: 6.19
Inundation frequency (%) for Creek5 algalmat habitat
Mean: 7.51
Std: 4.29
Inundation frequency (%) for Creek3 algalmat habitat
Mean: 4.62
Std: 4.07
Inundation frequency (%) for Creek2 algalmat habitat
Mean: 4.51
Std: 3.43
Inundation frequency (%) for Creek1 algalmat habitat
Mean: 8.80
Std: 2.62
Inundation frequency (%) for Baldy West algalmat habitat
Mean: 4.51
Std: 4.05
Inundation frequency (%) for Straigh Creek algalmat habitat
Mean: 4.06
Std: 3.05
Inundation frequency (%) for McKay Creek algalmat habitat
Mean: 3.22
Std: 3.38
Inundation frequency (%) for 40MileRoad West algalmat habitat
Mean: 1.71
Std: 2.76
Inundation frequency (%) for 40MileRoad East algalmat habitat
Mean: 3.59
Std: 3.57
Inundation frequency (%) for Creek7 algalmat habitat
Mean: 4.05
Std: 3.74
Inundation frequency (%) for Creek8 algalmat habitat
Mean: 3.02
Std: 3.73
Inundation frequency (%) for Yanyare algalmat habitat
Mean: 2.67
Std: 3.49
Area (ha)
Inundation frequency (%)

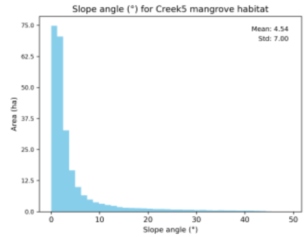
13.3. Bed slopes of BCH areas for each catchment

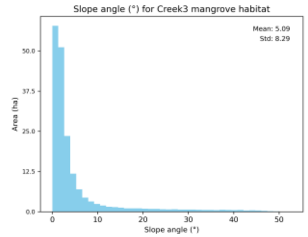

Mangrove
Port
Ck 5
Ck 4
Ck 3
Ck 2
Ck 1
Baldy/Straight
McKay Ck
40 Mile Rd W
40 Mile Rd E
Ck 7
Ck 8
Yanyare
Ck 6

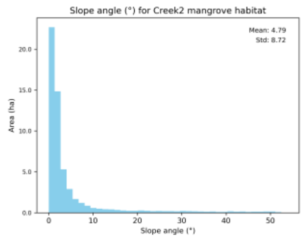

Slope angle (°) for Creek6 mangrove habitat
Mean: 5.01
Std: 4.36
Area (ha)
Slope angle (°)

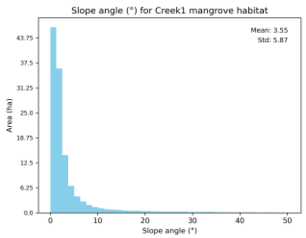

Slope angle (°) for Creek4 mangrove habitat
Mean: 5.46
Std: 7.86
Area (ha)
Slope angle (°)

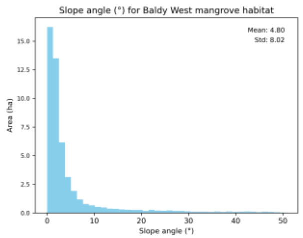

Slope angle (°) for Port mangrove habitat
Mean: 3.89
Std: 2.89
Area (ha)
Slope angle (°)

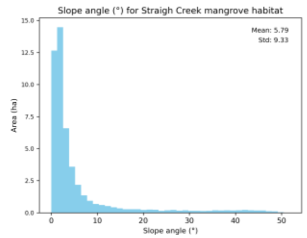

Slope angle (°) for Creek5 mangrove habitat
Mean: 4.54
Std: 7.00
Area (ha)
Slope angle (°)

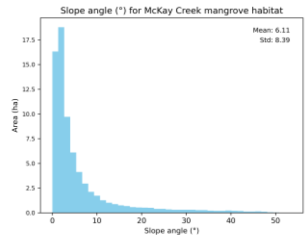

Slope angle (°) for Creek3 mangrove habitat
Mean: 5.09
Std: 8.29
Area (ha)
Slope angle (°)

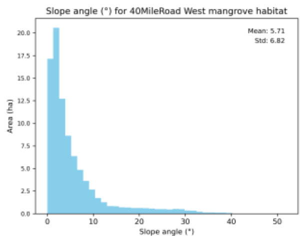

Slope angle (°) for Creek2 mangrove habitat
Mean: 4.79
Std: 8.72
Area (ha)
Slope angle (°)

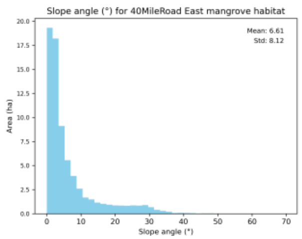

Slope angle (°) for Creek1 mangrove habitat
Mean: 3.55
Std: 5.87
Area (ha)
Slope angle (°)

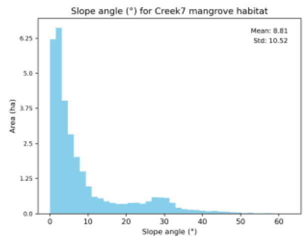

Slope angle (°) for Baldy West mangrove habitat
Mean: 4.80
Std: 8.02
Area (ha)
Slope angle (°)

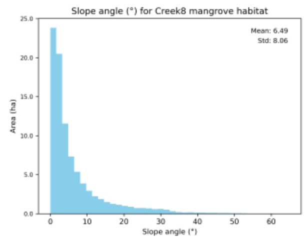

Slope angle (°) for Straigh Creek mangrove habitat
Mean: 5.79
Std: 9.33
Area (ha)
Slope angle (°)

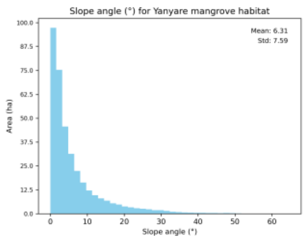

Slope angle (°) for McKay Creek mangrove habitat
Mean: 6.11
Std: 8.39
Area (ha)
Slope angle (°)

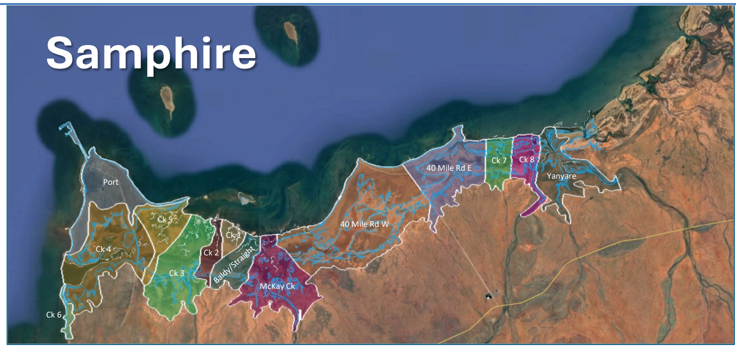

Slope angle (°) for 40MileRoad West mangrove habitat
Mean: 5.71
Std: 6.82
Area (ha)
Slope angle (°)

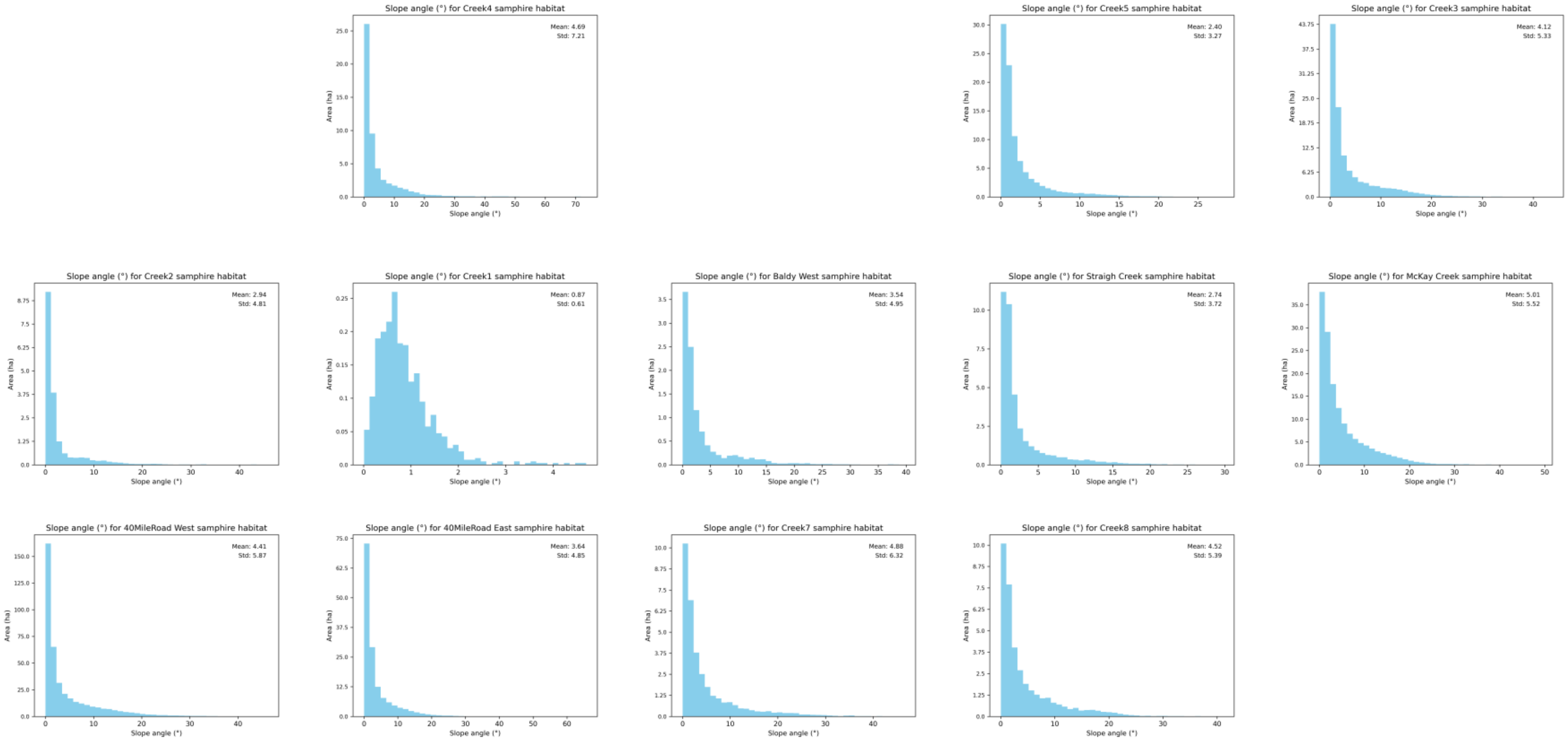

Slope angle (°) for 40MileRoad East mangrove habitat
Mean: 6.61
Std: 8.12
Area (ha)
Slope angle (°)

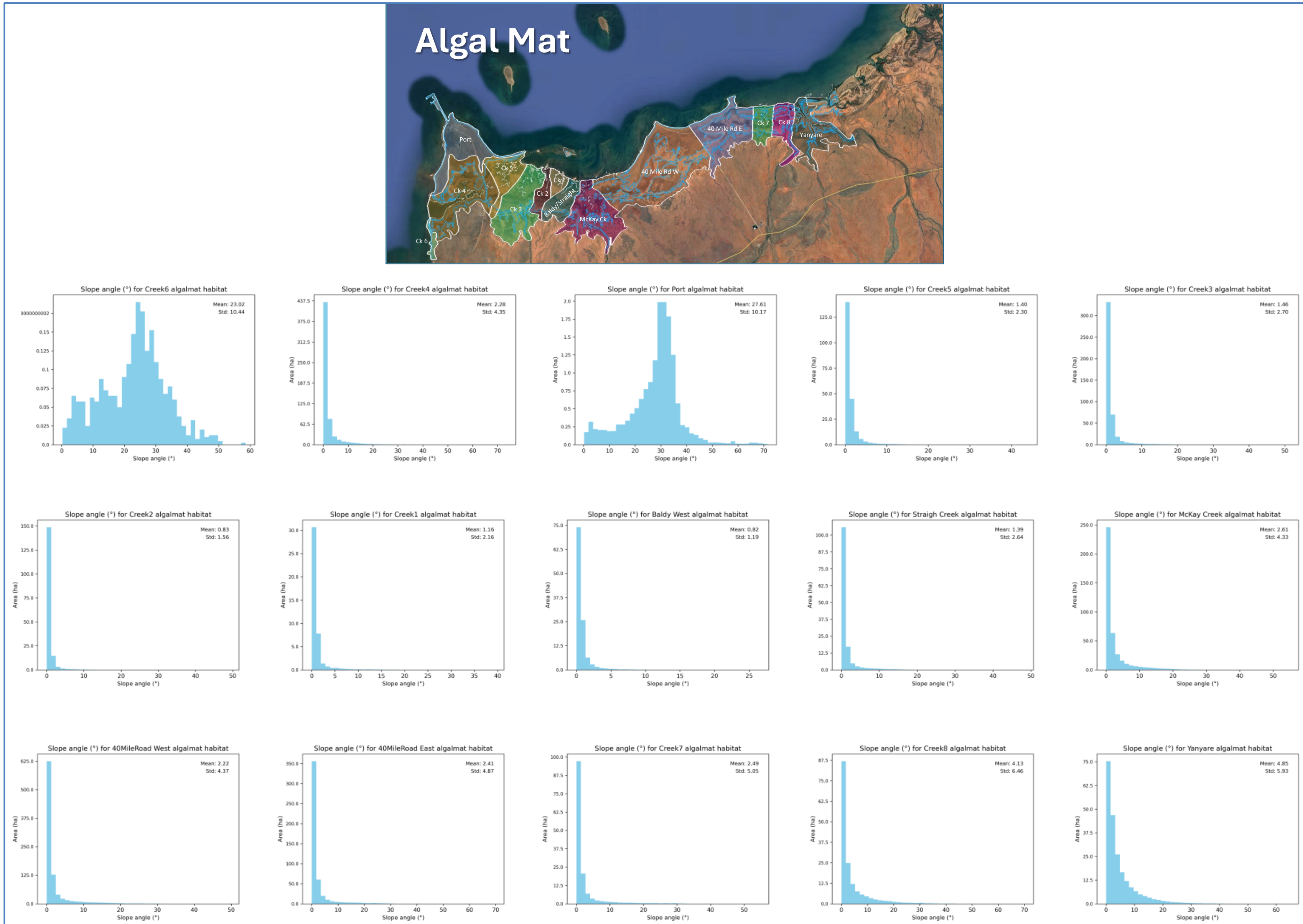

Slope angle (°) for Creek7 mangrove habitat
Mean: 8.81
Std: 10.52
Area (ha)
Slope angle (°)


Slope angle (°) for Creek8 mangrove habitat
Mean: 6.49
Std: 8.06
Area (ha)
Slope angle (°)


Slope angle (°) for Yanyare mangrove habitat
Mean: 6.31
Std: 7.59
Area (ha)
Slope angle (°)


Samphire
Port
Ck 5
Ck 4
Ck 3
Ck 2
Ck 1
Baldy/Straight
McKay Ck
40 Mile Rd W
40 Mile Rd E
Ck 7
Ck 8
Yanyare
Ck 6


Slope angle (°) for Creek4 samphire habitat
Mean: 4.69
Std: 7.21
Slope angle (°) for Creek5 samphire habitat
Mean: 2.40
Std: 3.27
Slope angle (°) for Creek3 samphire habitat
Mean: 4.12
Std: 5.33
Slope angle (°) for Creek2 samphire habitat
Mean: 2.94
Std: 4.81
Slope angle (°) for Creek1 samphire habitat
Mean: 0.87
Std: 0.61
Slope angle (°) for Baldy West samphire habitat
Mean: 3.54
Std: 4.95
Slope angle (°) for Straigh Creek samphire habitat
Mean: 2.74
Std: 3.72
Slope angle (°) for McKay Creek samphire habitat
Mean: 5.01
Std: 5.52
Slope angle (°) for 40MileRoad West samphire habitat
Mean: 4.41
Std: 5.87
Slope angle (°) for 40MileRoad East samphire habitat
Mean: 3.64
Std: 4.85
Slope angle (°) for Creek7 samphire habitat
Mean: 4.88
Std: 6.32
Slope angle (°) for Creek8 samphire habitat
Mean: 4.52
Std: 5.39
Area (ha)
Slope angle (°)


Algal Mat
Port
Ck 5
Ck 4
Ck 3
Ck 2
Ck 1
Ck 6
Baldy/Straight
McKay Ck
40 Mile Rd W
40 Mile Rd E
Ck 7
Ck 8
Yanyare
Slope angle (°) for Creek6 algalmat habitat
Mean: 23.02
Std: 10.44
Slope angle (°) for Creek4 algalmat habitat
Mean: 2.28
Std: 4.35
Slope angle (°) for Port algalmat habitat
Mean: 27.61
Std: 10.17
Slope angle (°) for Creek5 algalmat habitat
Mean: 1.40
Std: 2.30
Slope angle (°) for Creek3 algalmat habitat
Mean: 1.46
Std: 2.70
Slope angle (°) for Creek2 algalmat habitat
Mean: 0.83
Std: 1.56
Slope angle (°) for Creek1 algalmat habitat
Mean: 1.16
Std: 2.16
Slope angle (°) for Baldy West algalmat habitat
Mean: 0.82
Std: 1.19
Slope angle (°) for Straigh Creek algalmat habitat
Mean: 1.39
Std: 2.64
Slope angle (°) for McKay Creek algalmat habitat
Mean: 2.61
Std: 4.33
Slope angle (°) for 40MileRoad West algalmat habitat
Mean: 2.22
Std: 4.37
Slope angle (°) for 40MileRoad East algalmat habitat
Mean: 2.41
Std: 4.87
Slope angle (°) for Creek7 algalmat habitat
Mean: 2.49
Std: 5.05
Slope angle (°) for Creek8 algalmat habitat
Mean: 4.13
Std: 6.46
Slope angle (°) for Yanyare algalmat habitat
Mean: 4.85
Std: 5.93
Area (ha)
Slope angle (°)

13.4. Distribution maps of BCHs within each catchment – present-day distributions

Typical elevation ranges over which each BCH may be considered predominant were identified where a BCH classification covered >25% of the area, in elevation bands of 0.25 m increments. This defined three typical elevation zones:

- 0.5 to 1.5 m AHD. Mangrove predominant.
- 1.5 to 2.5 m AHD. Benthic Mat predominant.
- 2.5 to 3.0 m AHD. Samphire predominant.

Physical changes implied by translating habitat upwards with SLR have been considered visually by plotting the area covered by elevation zones + SLR, for increments of 0.25 m rise (see multiple figures below). These figures are for the ‘no ponds’ scenario, but show the proposed ponds to help visual assessment with other figures.

Mangroves

Translation of the present-day elevation zone for mangroves sees large increases in area with SLR 0.25 to 0.5 m, across the area which is presently mainly occupied by benthic mats. This represents a mostly unrealistic habitat migration, due to differences in sediment, and increasing distance from the sea. For 0.75 to 1.0 m SLR, the translated mangrove habitat zone includes areas of rocky hinterland.

Potential for mangrove habitat to migrate in the manner suggested by the translated elevation zones differs from west to east due to morphology. Towards the west, tidal creek extension may provide a mechanism for migration (equating migration to elevation zone translation is plausible, although considered likely to be an exaggeration). Within the 40 Mile Road W catchment, the translation implies extended distances of migration of mangroves, including to isolated areas with extremely restricted capacity for creek incision. This is considered a very unlikely outcome. In the eastern area, the translated change implies mangroves extending into the existing coastal lagoon, but there is limited tidal area change, and therefore creek extension is anticipated to be limited, i.e., the outcome is possible only.

Benthic Mats

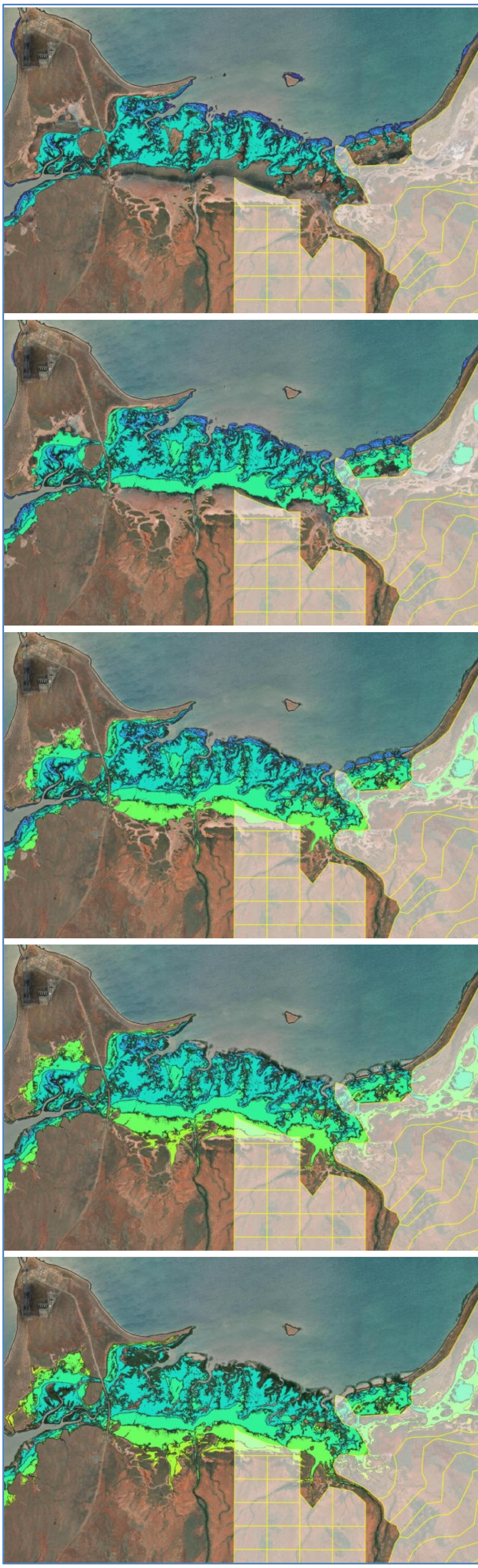
Translation of the present-day elevation zone for benthic mats indicates a progressive reduction of area with SLR, as these elevation zones are shifted from the wide salt flats on to the steeper hinterland. It is considered unlikely that migration of benthic mat habitats would correspond to this translation, because:

- this would effectively rely on mangroves out-competing benthic mats on the near horizontal bed slope of the salt flats;
- a key aspect of benthic mat habitat is the bed slope, which supports extended saturation (when occasionally inundated), leading to hypersalinity, which is more viable habitat for benthic mats than mangroves;
- mobility of silts and muds determines that salt flats have high capacity to evolve progressively with SLR, raising their bed elevation. Depending on sediment supply, a rise in bed elevation may result in a loss of area.

Samphire

Samphire can occur as a small fraction of habitat across a wide range of elevations. Translation of the present-day elevation zone for samphire indicates a small change in spatial distribution with SLR, as they are predominant along the fringe of the benthic mats and the hinterland. This translation also produces a small reduction in area. The ‘newly colonised’ locations include areas adjacent to downslopes that are typical of some samphire communities, but have fewer isolated local basins, that are another type of typical samphire habitat.

The potential for samphire habitat to migrate in the manner suggested by the translated elevation zones is considered a fair first estimate, but the habitat might be reduced to a larger extent because the translation doesn’t effectively account for samphire’s preference for seasonal waterlogging.



Elevation 0.5-1.5m AHD
Modern Mangrove Predominant

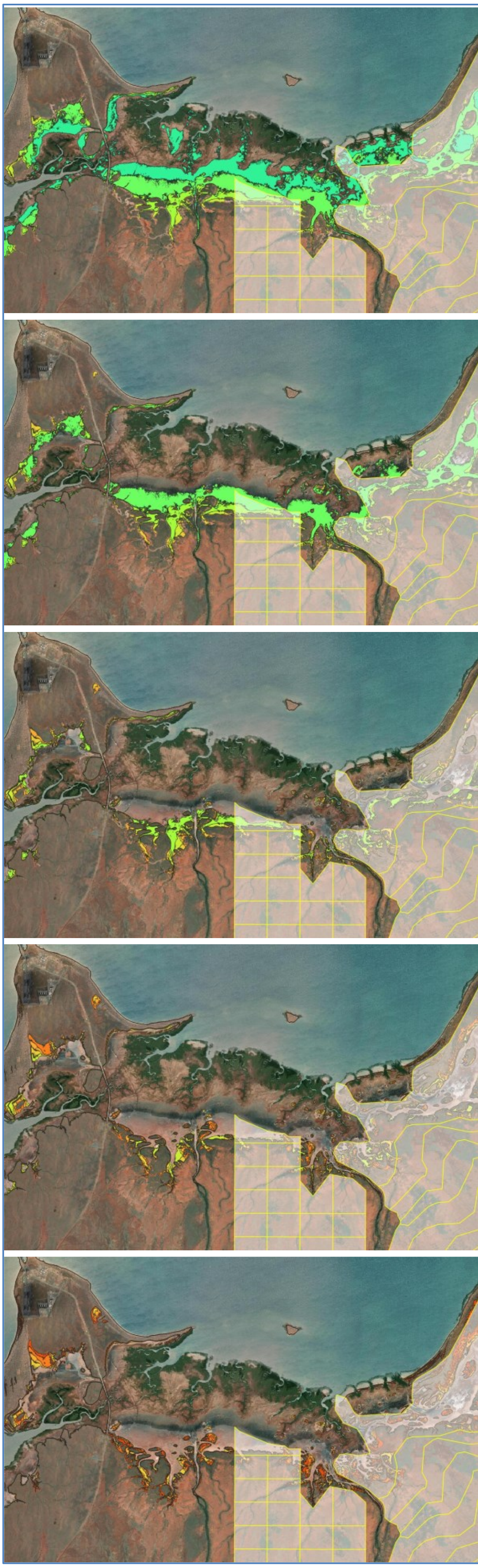
Elevation 0.75-1.75m AHD
+0.25m SLR

Elevation 1.0-2.0m AHD
+0.50m SLR

Elevation 1.25-2.25m AHD
+0.75m SLR

Elevation 1.5-2.5m AHD
+1.00m SLR

Figure A 1. Elevation Zone of Present-Day Mangroves (West), i.e. with no ponds. In all these figures, the proposed ponds are shown only to help visual assessment with other figures..



Elevation 1.5-2.5m AHD
Modern Benthic Mat Predominant

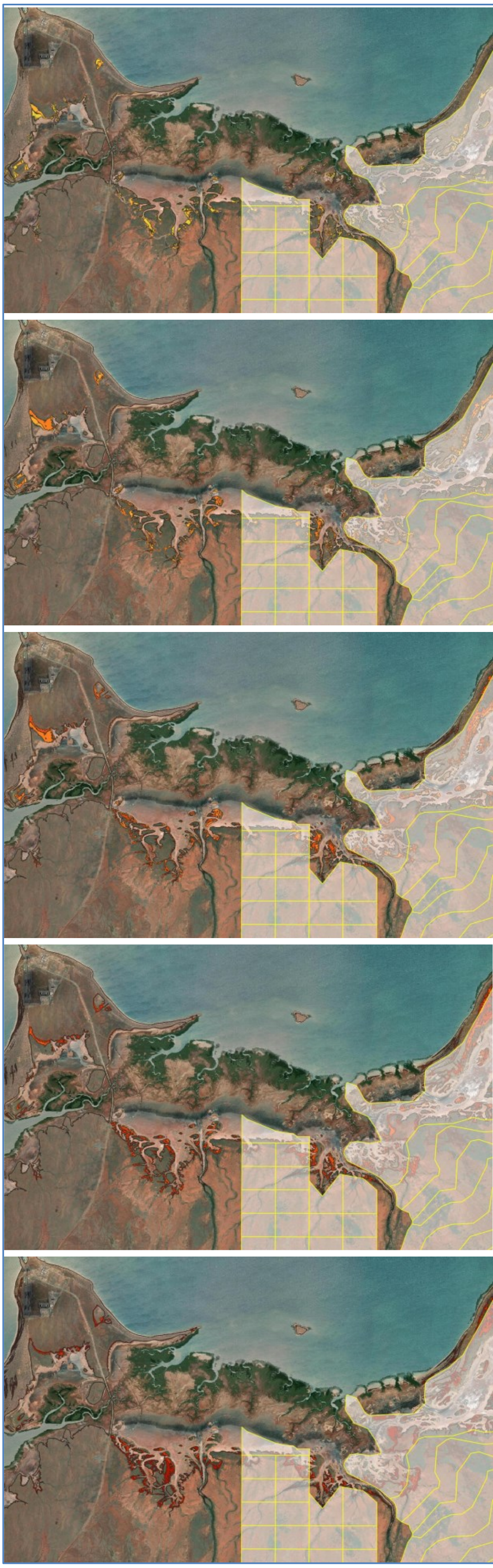
Elevation 1.75-2.75m AHD
+0.25m SLR

Elevation 2.0-3.0m AHD
+0.50m SLR

Elevation 2.25-3.25m AHD
+0.75m SLR

Elevation 2.5-3.5m AHD
+1.00m SLR

Figure A 2. Elevation Zone of Present-Day Benthic Mat (West).



Elevation 2.5-3.0m AHD
Modern Samphire Predominant

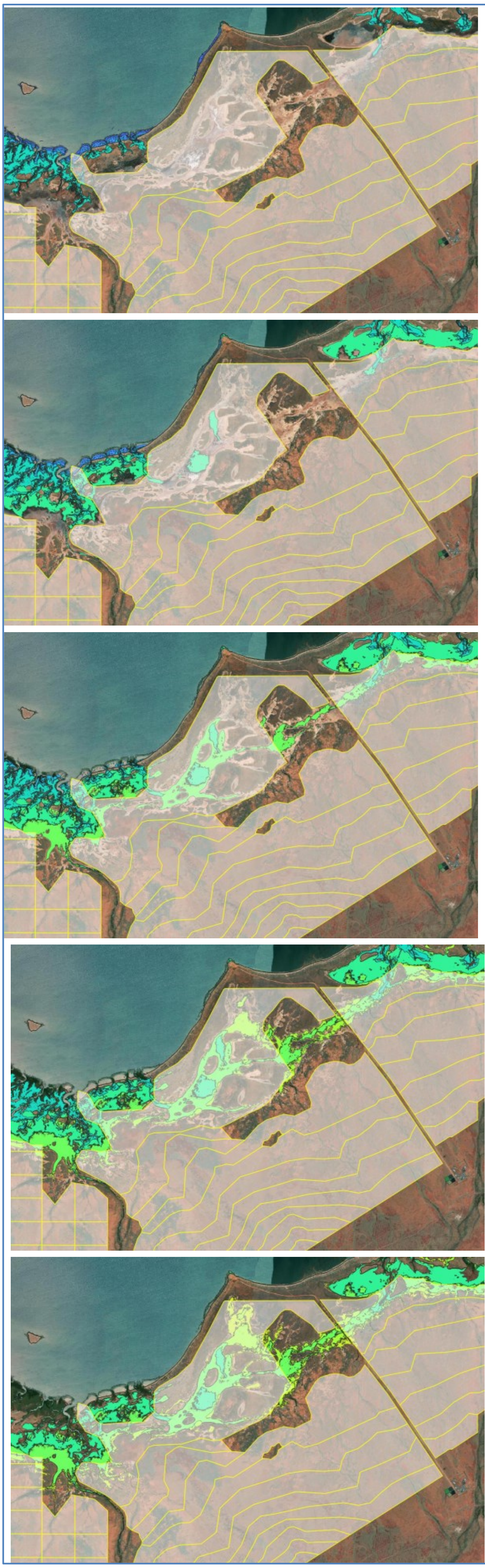
Elevation 2.75-3.25m AHD
+0.25m SLR

Elevation 3.0-3.5m AHD
+0.50m SLR

Elevation 3.25-3.75m AHD
+0.75m SLR

Elevation 3.5-4.0m AHD
+1.00m SLR

Figure A 3. Elevation Zone of Present-Day Samphire (West).



Elevation 0.5-1.5m AHD
Modern Mangrove Predominant

Elevation 0.75-1.75m AHD
+0.25m SLR

Elevation 1.0-2.0m AHD
+0.50m SLR

Elevation 1.25-2.25m AHD
+0.75m SLR

Elevation 1.5-2.5m AHD
+1.00m SLR

Figure A 4. Elevation Zone of Present-Day Mangroves (Central).

Elevation 1.5-2.5m AHD
Modern Benthic Mat Predominant

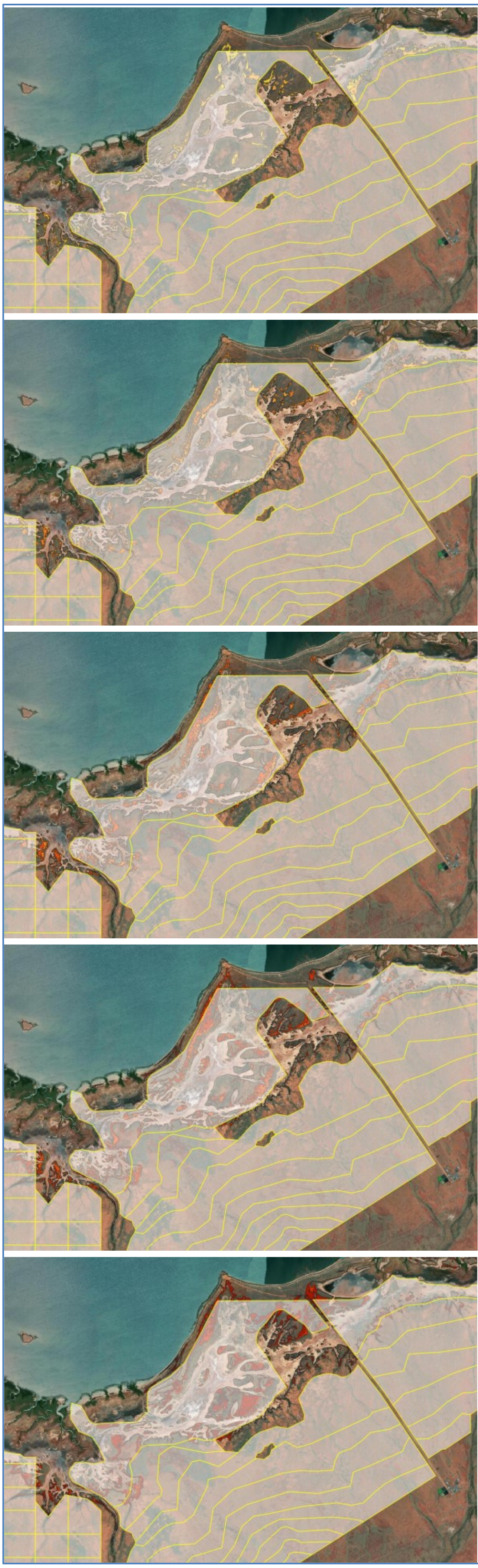
Elevation 1.75-2.75m AHD
+0.25m SLR

Elevation 2.0-3.0m AHD
+0.50m SLR

Elevation 2.25-3.25m AHD
+0.75m SLR

Elevation 2.5-3.5m AHD
+1.00m SLR

Figure A 5. Elevation Zone of Present-Day Benthic Mat (Central).



Elevation 2.5-3.0m AHD
Modern Samphire Predominant

Elevation 2.75-3.25m AHD
+0.25m SLR

Elevation 3.0-3.5m AHD
+0.50m SLR

Elevation 3.25-3.75m AHD
+0.75m SLR

Elevation 3.5-4.0m AHD
+1.00m SLR

Figure A 6. Elevation Zone of Present-Day Samphire (Central).

Elevation 0.5-1.5m AHD
Modern Mangrove Predominant

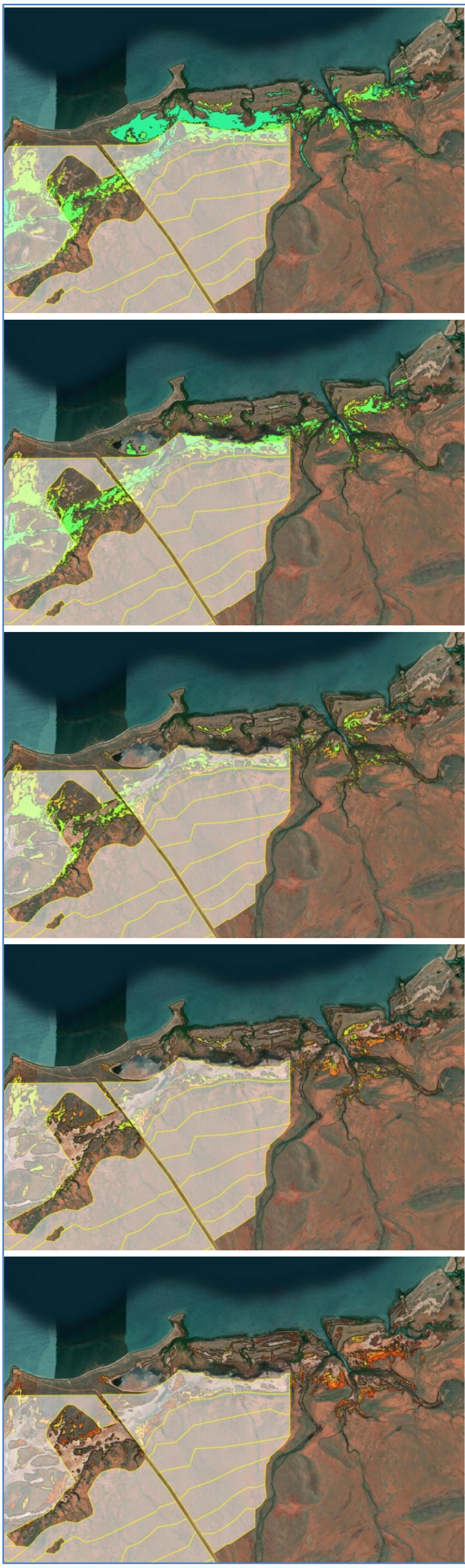
Elevation 0.75-1.75m AHD
+0.25m SLR

Elevation 1.0-2.0m AHD
+0.50m SLR

Elevation 1.25-2.25m AHD
+0.75m SLR

Elevation 1.5-2.5m AHD
+1.00m SLR

Figure A 7. Elevation Zone of Present-Day Mangroves (East).



Elevation 1.5-2.5m AHD
Modern Benthic Mat Predominant

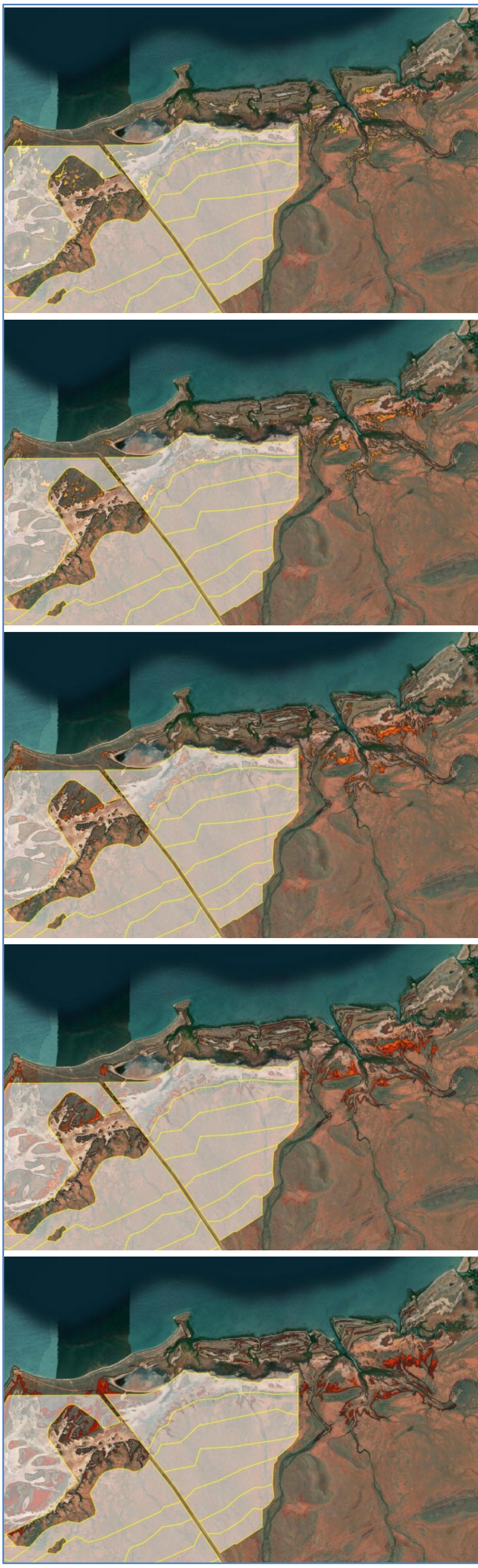
Elevation 1.75-2.75m AHD
+0.25m SLR

Elevation 2.0-3.0m AHD
+0.50m SLR

Elevation 2.25-3.25m AHD
+0.75m SLR

Elevation 2.5-3.5m AHD
+1.00m SLR

Figure A 8. Elevation Zone of Present-Day Benthic Mat (East).



Elevation 2.5-3.0m AHD
Modern Samphire Predominant

Elevation 2.75-3.25m AHD
+0.25m SLR

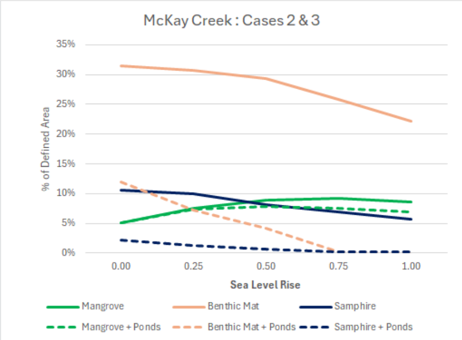
Elevation 3.0-3.5m AHD
+0.50m SLR

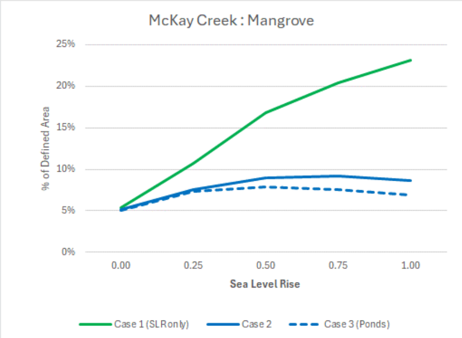
Elevation 3.25-3.75m AHD
+0.75m SLR

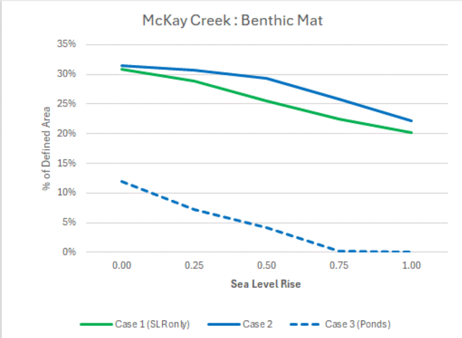
Elevation 3.5-4.0m AHD
+1.00m SLR

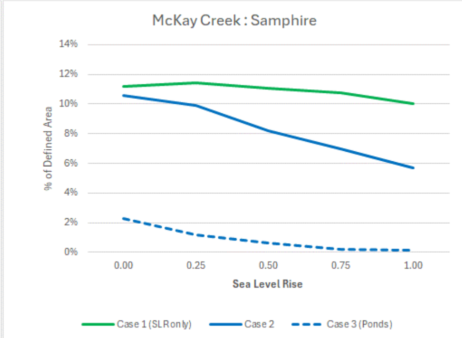
Figure A 9. Elevation Zone of Present-Day Samphire (East)

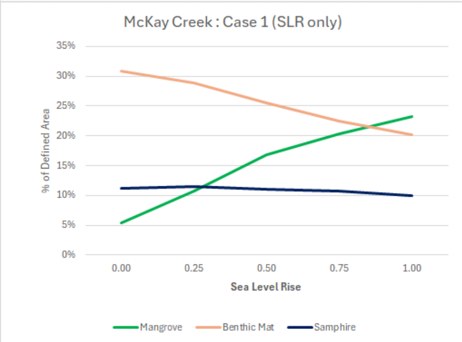
13.5. Plots of changes in BCHs

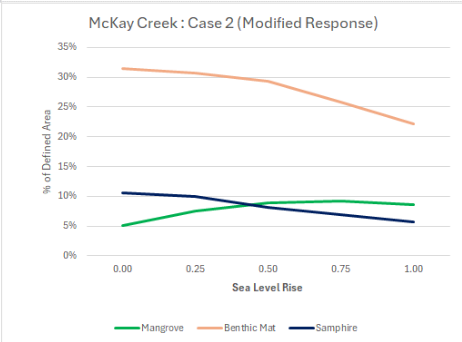

McKay Creek : Cases 2 & 3
% of Defined Area
35%
30%
25%
20%
15%
10%
5%
0%
0.00
0.25
0.50
0.75
1.00
Sea Level Rise
Mangrove
Benthic Mat
Samphire
Mangrove + Ponds
Benthic Mat + Ponds
Samphire + Ponds

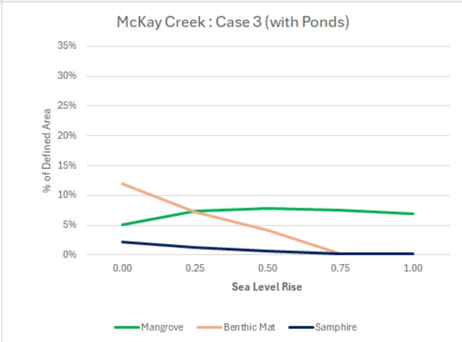

McKay Creek : Mangrove
% of Defined Area
25%
20%
15%
10%
5%
0%
0.00
0.25
0.50
0.75
1.00
Sea Level Rise
Case 1 (SLR only)
Case 2
Case 3 (Ponds)

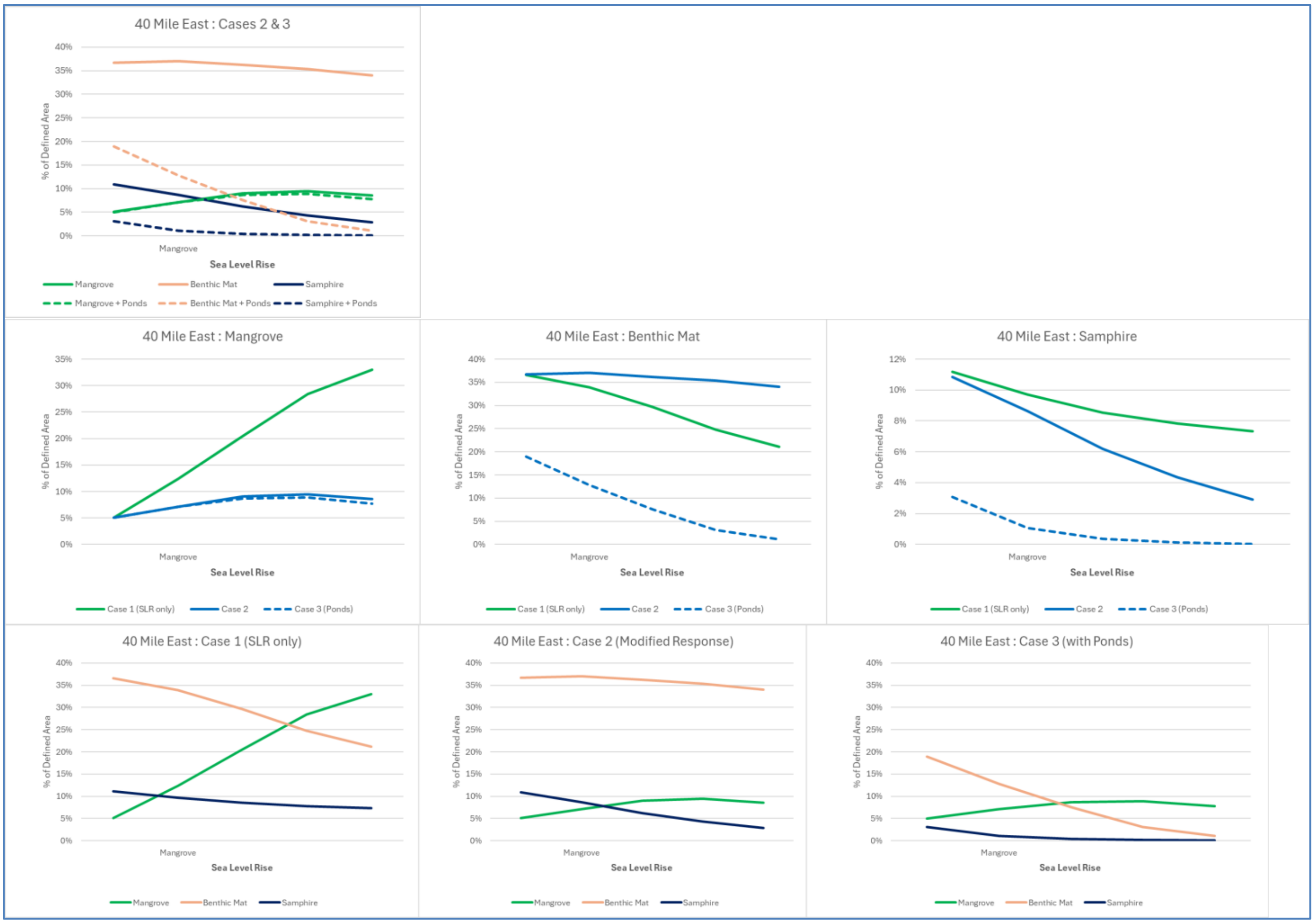

McKay Creek : Benthic Mat
% of Defined Area
35%
30%
25%
20%
15%
10%
5%
0%
0.00
0.25
0.50
0.75
1.00
Sea Level Rise
Case 1 (SLR only)
Case 2
Case 3 (Ponds)


McKay Creek : Samphire
% of Defined Area
14%
12%
10%
8%
6%
4%
2%
0%
0.00
0.25
0.50
0.75
1.00
Sea Level Rise
Case 1 (SLR only)
Case 2
Case 3 (Ponds)

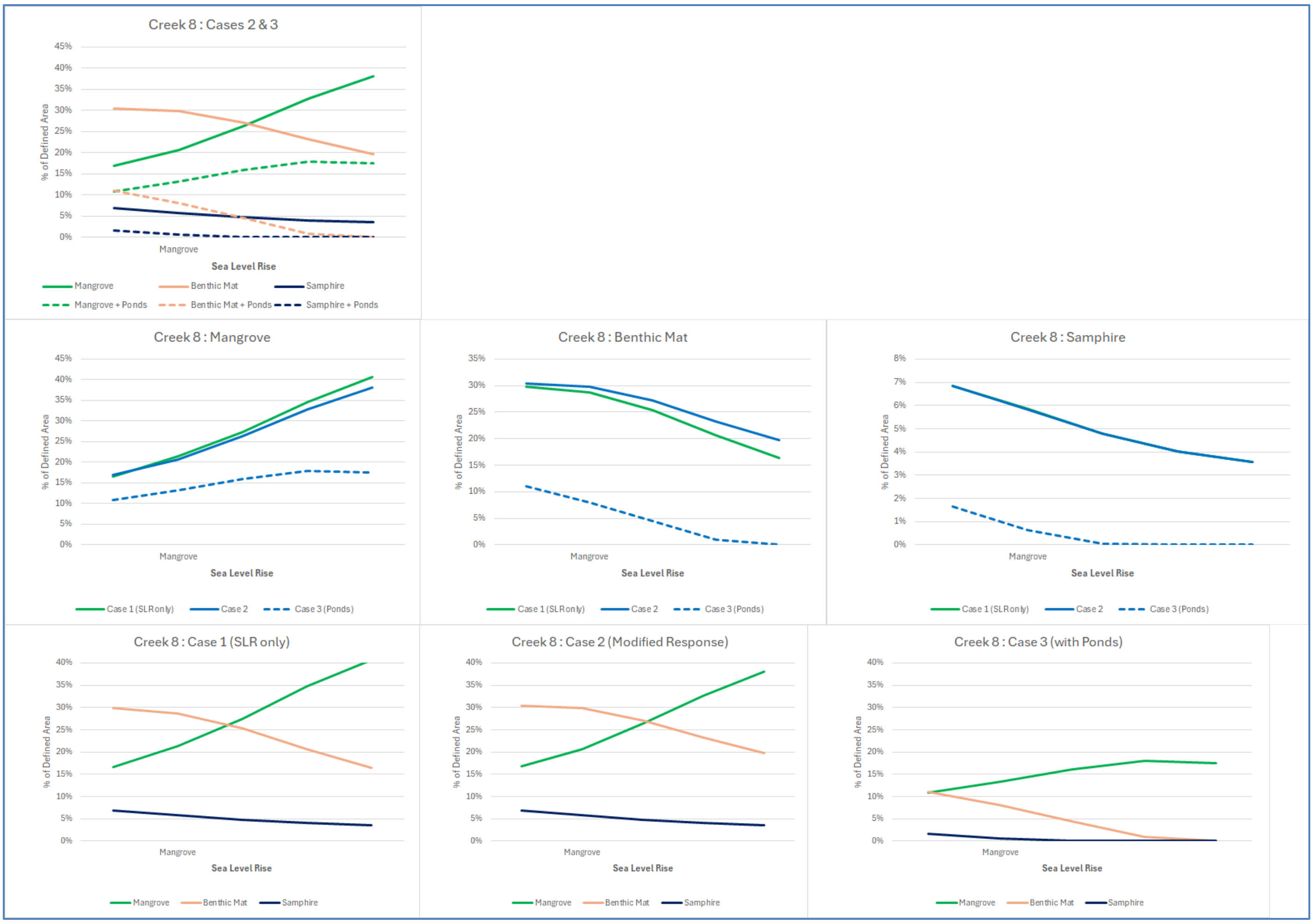

McKay Creek : Case 1 (SLR only)
% of Defined Area
35%
30%
25%
20%
15%
10%
5%
0%
0.00
0.25
0.50
0.75
1.00
Sea Level Rise
Mangrove
Benthic Mat
Samphire


McKay Creek : Case 2 (Modified Response)
% of Defined Area
35%
30%
25%
20%
15%
10%
5%
0%
0.00
0.25
0.50
0.75
1.00
Sea Level Rise
Mangrove
Benthic Mat
Samphire


McKay Creek : Case 3 (with Ponds)
% of Defined Area
35%
30%
25%
20%
15%
10%
5%
0%
0.00
0.25
0.50
0.75
1.00
Sea Level Rise
Mangrove
Benthic Mat
Samphire


40 Mile East : Cases 2 & 3
% of Defined Area
Mangrove
Sea Level Rise
Mangrove
Benthic Mat
Samphire
Mangrove + Ponds
Benthic Mat + Ponds
Samphire + Ponds
40 Mile East : Mangrove
40 Mile East : Benthic Mat
40 Mile East : Samphire
Case 1 (SLR only)
Case 2
Case 3 (Ponds)
40 Mile East : Case 1 (SLR only)
40 Mile East : Case 2 (Modified Response)
40 Mile East : Case 3 (with Ponds)

Creek 7 : Cases 2 & 3
40%
35%
30%
25%
20%
15%
10%
5%
0%
% of Defined Area
Mangrove
Sea Level Rise
Mangrove
Benthic Mat
Samphire
Mangrove + Ponds
Benthic Mat + Ponds
Samphire + Ponds
Creek 7 : Mangrove
Case 1 (SLR only)
Case 2
Case 3 (Ponds)
Creek 7 : Benthic Mat
Creek 7 : Samphire
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
Creek 7 : Case 1 (SLR only)
Creek 7 : Case 2 (Modified Response)
Creek 7 : Case 3 (with Ponds)


Creek 8 : Cases 2 & 3
% of Defined Area
Mangrove
Sea Level Rise
Mangrove
Benthic Mat
Samphire
Mangrove + Ponds
Benthic Mat + Ponds
Samphire + Ponds
Creek 8 : Mangrove
Case 1 (SLR only)
Case 2
Case 3 (Ponds)
Creek 8 : Benthic Mat
Creek 8 : Samphire
Creek 8 : Case 1 (SLR only)
Creek 8 : Case 2 (Modified Response)
Creek 8 : Case 3 (with Ponds)

END